BAMS Article

The Worldwide C3S CORDEX Grand Ensemble

A Major Contribution to Assess Regional Climate Change in the IPCC AR6 Atlas

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ABSTRACT: The collaboration between the Coordinated Regional Climate Downscaling Experiment (CORDEX) and the Earth System Grid Federation (ESGF) provides open access to an unprecedented ensemble of regional climate model (RCM) simulations, across the 14 CORDEX continental-scale domains, with global coverage. These simulations have been used as a new line of evidence to assess regional climate projections in the latest contribution of the Working Group I (WGI) to the IPCC Sixth Assessment Report (AR6), particularly in the regional chapters and the Atlas. Here, we present the work done in the framework of the Copernicus Climate Change Service (C3S) to assemble a consistent worldwide CORDEX grand ensemble, aligned with the deadlines and activities of IPCC AR6. This work addressed the uneven and heterogeneous availability of CORDEX ESGF data by supporting publication in CORDEX domains with few archived simulations and performing quality control. It also addressed the lack of comprehensive documentation by compiling information from all contributing regional models, allowing for an informed use of data. In addition to presenting the worldwide CORDEX dataset, we assess here its consistency for precipitation and temperature by comparing climate change signals in regions with overlapping CORDEX domains, obtaining overall coincident regional climate change signals. The C3S CORDEX dataset has been used for the assessment of regional climate change in the IPCC AR6 (and for the interactive Atlas) and is available through the Copernicus Climate Data Store (CDS).

KEYWORDS: Climate change; Downscaling; Regional models; Ensembles; Data quality control; Climate services

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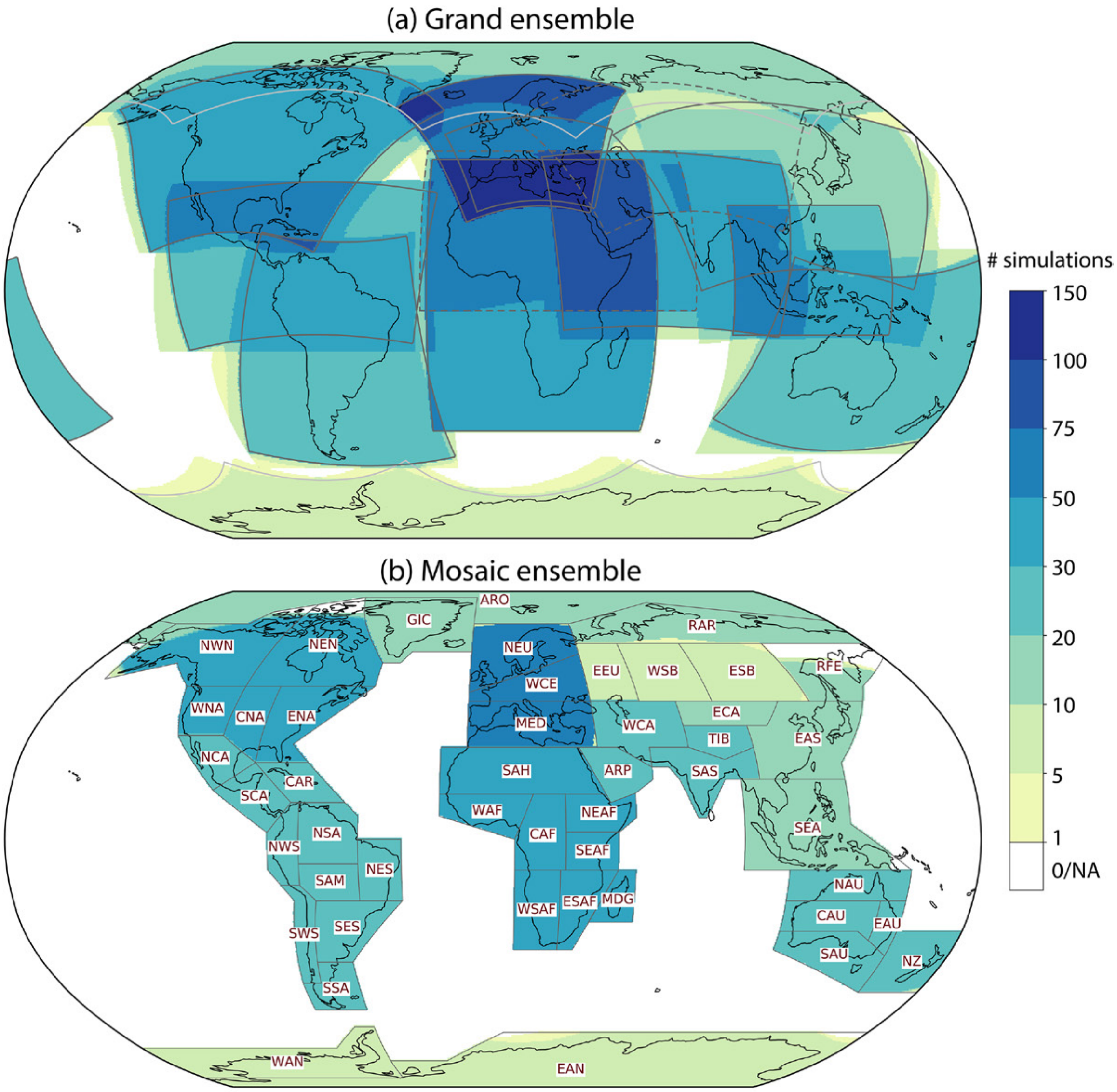
The Coordinated Regional Climate Downscaling Experiment (CORDEX; https://cordex.org), implemented under the auspices of the World Climate Research Program (WCRP), represents the first attempt at a global coordination of high-resolution regional climate projections using a common experimental framework (Giorgi and Gutowski 2015; Gutowski et al. 2016). CORDEX provides spatially detailed climate change projections from a plethora of regional climate models (RCMs) applied over large continental areas, at horizontal grid spacing ranging from ~12 to 50 km. These high-resolution climate projections represent both the regional spatial and temporal variability better than their driving global climate models (GCMs), which are limited by their coarse spatial resolution (Giorgi 2019). Therefore, the CORDEX data are more appropriate for vulnerability, impact, and adaptation studies (Coppola et al. 2021b; Giorgi and Gutowski 2015; Jacob et al. 2020; Lennard et al. 2018). CORDEX data have become authoritative for regional climate change information in other initiatives, such as the Mediterranean Assessment Report,[1] the Arab Climate Change Assessment Report,[2] the Swiss Climate Change Scenarios,[3] the French DRIAS climate service,[4] the Assessment of Climate Change over the Indian Region (Krishnan et al. 2020), the Spanish National Adaptation Plan Scenarios,[5] and the IPCC Sixth Assessment Report (AR6; IPCC 2021a), where CORDEX has been extensively used as a new line of evidence to assess future regional climate projections and uncertainties, in particular in the chapters dealing with regional information and the Atlas (Doblas-Reyes et al. 2021; Gutiérrez et al. 2021a; Ranasinghe et al. 2021; Seneviratne et al. 2021).

[1] www.medecc.org/first-mediterranean-assessment-report-mar1/
[2] https://archive.unescwa.org/publications/riccar-arab-climate-change-assessment-report
[3] www.nccs.admin.ch/nccs/en/home/climate-change-and-impacts/swiss-climate-change-scenarios.html
[4] www.drias-climat.fr
[5] https://escenarios.adaptecca.es

The CORDEX ensemble has allowed to explore more regional climate uncertainties (scenarios, driving models, internal variability, RCM configuration) than any past RCM intercomparison project, such as PRUDENCE, NARCCAP, CLARIS, or ENSEMBLES (Christensen and Christensen 2007; Curry and Lynch 2002; Déqué et al. 2012; Fu et al. 2005; Mearns et al. 2012; Solman et al. 2013; Takle et al. 1999; van der Linden and Mitchell 2009). Particularly, the global scale of the CORDEX initiative, which has engaged an unprecedented number of modeling groups, resulted in the generation of large ensembles of regional climate projections over the 14 official continental-scale domains that are the backbone of CORDEX activities worldwide (see Fig. 1a), with different modeling centers contributing to different domains, and simulations performed at resolutions ranging from ~50 km (default in most domains) to ~12 km. Moreover, the common archiving protocol (Christensen et al. 2020) and the collaboration with the Earth System Grid Federation (ESGF; Cinquini et al. 2014) have made freely available a massive dataset of regional climate change projections driven by a subset of the global simulations provided by the Coupled Model Intercomparison Project phase 5 (CMIP5) under different emission scenarios. CORDEX regional projections constitute the state-of-the-art dataset for regional climate change impact and adaptation studies (an updated inventory with existing simulations—both those published on ESGF and those available from modeling centers—is available at the CORDEX website[6]).

[6] https://cordex.org/data-access/regional-climate-change-simulations-for-cordex-domains

In this context, the latest report of the IPCC required globally homogeneous data for regional climate change assessment worldwide. However, at an early stage in the preparation of the Working Group I (WGI) contribution to AR6 in 2019, data availability on ESGF was patchy and heterogeneous across domains. This spatial heterogeneity was partially alleviated by the CORDEX-CORE initiative (Coppola et al. 2021b; Giorgi et al. 2022; Gutowski et al. 2016; Remedio et al. 2019; Teichmann et al. 2021), providing homogeneous future regional climate projections across most domains at ~25-km resolution for a few RCMs nested into a number of selected driving GCMs. However, in spite of this massive community effort, the publicly available ensembles from the ESGF were too small in some domains. One of the reasons for the apparent lack of CORDEX simulations on ESGF over certain domains was the inherent complexity of the data publishing protocol and the lack of human resources to undertake this task. Strong metadata reformatting and quality checks are required before publication of model simulations on ESGF. Many modeling



IPCC AR6 Reference regions		CORDEX domain
Acronym	Name	
NWN	North-Western North America	NAM
NEN	North-Eastern North America	
WNA	Western North America	
CNA	Central North America	
ENA	Eastern North America	
NCA	Northern Central America	CAM
SCA	Southern Central America	
CAR	Caribbean	
NWS	North-Western South America	SAM
NSA	Northern South America	
NES	North-Eastern South America	
SAM	South American Monsoon	
SWS	South-Western South America	
SES	South-Eastern South America	
SSA	Southern South America	

IPCC AR6 Reference regions		CORDEX domain
Acronym	Name	
GIC	Greenland/Iceland	ARC
ARO	Arctic-Ocean	
RAR	Russian Arctic	
NEU	Northern Europe	EUR
WCE	Western and Central Europe	
MED	Mediterranean	
SAH	Sahara	AFR
WAF	Western Africa	
CAF	Central Africa	
NEAF	North Eastern Africa	
SEAF	South Eastern Africa	
WSAF	West Southern Africa	
ESAF	East Southern Africa	
MDG	Madagascar	
WAN	Western Antarctica	ANT
EAN	Eastern Antarctica	

IPCC AR6 Reference regions		CORDEX domain
Acronym	Name	
WSB	West Siberia	CAS
ESB	East Siberia	
EEU	Eastern Europe	
WCA	West Central Asia	WAS
TIB	Tibetan Plateau	
SAS	South Asia	
ARP	Arabian Peninsula	
RFE	Russian Far East	EAS
ECA	East Central Asia	
EAS	East Asia	
SEA	South East Asia	SEA
NAU	Northern Australia	AUS
CAU	Central Australia	
EAU	Eastern Australia	
SAU	Southern Australia	
NZ	New Zealand	

Fig. 1. Number of historical simulations available from the worldwide C3S CORDEX dataset for (a) the multidomain grand ensemble and (b) the single-domain mosaic ensemble. Gray lines in (a) correspond to the boundaries of the 14 CORDEX domains (see Table 2), which are exceeded in many cases by the actual simulation domains. Gray lines in (b) correspond to the IPCC AR6 WGI reference regions (Iturbide et al. 2020) which are used to create the mosaic [note that CORDEX domains assigned to each region are shown in the table below, following Gutiérrez et al. (2021a) but including the CAS domain for EEU, WSB, and ESB regions]. Note that MED- and MENA-CORDEX domains are not used in the mosaics because they are overlapped by other domains with a higher number of simulations.

Table 1. List of surface variables (all at daily resolution) archived in the worldwide C3S CORDEX dataset. Italics are used for spatial static variables (with no temporal axis), which provide information on the grid used by the models. Note that the European (EUR) and Mediterranean (MED) domains provide 26 variables and some of them at subdaily temporal aggregation.

No.	Variable	Code	Units
1	Precipitation	pr	kg m^{-2} s^{-1}
2	Near-surface air temperature	tas	K
3	Daily minimum near-surface air temperature	tasmin	K
4	Daily maximum near-surface air temperature	tasmax	K
5	Near-surface wind speed	sfcWind	m s^{-1}
6	Near-surface specific humidity	huss	1
7	Near-surface wind speed (northward)	vas	m s^{-1}
8	Near-surface wind speed (eastward)	uas	m s^{-1}
9	Near-surface relative humidity	hurs	%
10	Evaporation	evspsbl	kg m^{-2} s^{-1}
11	Sea level pressure	psl	Pa
12	Surface air pressure	ps	Pa
13	Surface radiation (shortwave downwelling)	rsds	W m^{-2}
14	Surface radiation (longwave downwelling)	rlds	W m^{-2}
15	Total cloud fraction	clt	%
16	*Land area fraction (land/sea mask)*	*sftlf*	*%*
17	*Surface altitude*	*orog*	*m*

groups did not have the funds and/or expertise to accomplish such a task. This paper presents the work carried out under the Copernicus Climate Change Service (C3S; Buontempo et al. 2022) over the past three years to address this problem and assemble a worldwide CORDEX dataset aligned with IPCC AR6 activities and timelines. Moreover, the spatial consistency of the resulting regional climate change projections is assessed worldwide following two main approaches introduced in the literature to produce regional climate information with global coverage.

The grand ensemble approach (Legasa et al. 2020; Spinoni et al. 2020; Zittis et al. 2019) pools together all available simulations across domains for each gridbox. This approach maximizes the number of simulations available for some regions and it might be particularly beneficial for some regions in South Asia or northern South America (see Fig. 1a). However, it leads to a spatially varying ensemble size across grid points. Although this may create spatial artifacts (e.g., border effects) in the results, recent evidence suggests that, in large ensembles, this approach does not produce inconsistencies at the domain boundaries (Spinoni et al. 2021), at least when looking at mean precipitation and temperature. Moreover, a preliminary analysis by Legasa et al. (2020) quantified the uncertainty related to the choice of the domain in the Mediterranean area, using the Europe and Africa domains. They showed that the variability in the simulated climate change signal for this region is primarily determined by the model combinations (GCM–RCM pairs) and less by the domain. Similarly, Zittis et al. (2019) did not find a clear and consistent advantage in selecting one of these two domains for the Mediterranean area.

Alternatively, in the mosaic approach, the results from different domains are overlaid according to a given order of priority, using each CORDEX domain for the area it was intended to simulate and discarding results close to the domain boundaries. The mosaic approach avoids potential artifacts that may arise in overlapping regions, but may result in small ensembles for regions where information is available from multiple domains. For instance, simulations from the South Asia domain might not accurately represent the climate of central Africa (e.g., if models were tuned to perform best in the South Asia region). This approach was used to present global CORDEX-CORE results (Coppola et al. 2021a) and in the worldwide assessment in the IPCC AR6 Atlas chapter (Gutiérrez et al. 2021a), as illustrated in Fig. 1b.

This paper is organized as follows. First ("Assembling a worldwide CORDEX dataset" section), we describe the worldwide CORDEX dataset, including the protocol followed to consolidate this global dataset based on CORDEX output ("Data selection, curation, and quality control" section), the description of the resulting dataset (hereafter, the C3S CORDEX dataset; "The C3S CORDEX dataset" section), and the new metadata compiled to describe the simulations ("Model documentation" section); moreover, the "Use of the data in the IPCC AR6 WG1 report and additional resources" section describes how this dataset was used in the IPCC AR6 report as a new line of regional evidence. Second ("Consistency of the climate change signal across CORDEX domains" section), we investigate the consistency of the regional climate change projections, particularly in areas where different domains overlap ("Consistency in overlapping domains" section), and compare the two above mentioned approaches to produce regional climate information ("Mosaic and grand-ensemble climate change signals" section).

Assembling a worldwide CORDEX dataset

Data selection, curation, and quality control. The data selection and curation activities followed under the C3S for the consolidation and assembly of a worldwide C3S CORDEX dataset encompassed several tasks.

Inventory of all available simulations. In coordination with the CORDEX International Project Office, an inventory of all available simulations was created, including those available from the modeling centers but not yet published on ESGF. This inventory is available on the official CORDEX website,[7] updated as of December 2020. The inventory contains information to identify the simulations, such as the domain, driving GCM and ensemble member, RCM, scenario, and the institution that carried out the simulations, among others. It also contains useful information related to the availability of the simulations: namely, 1) whether they are available from the ESGF, stored in another dedicated repository, or not publicly available (modeling centers should be contacted to get access); 2) the license (restricted, noncommercial, or unrestricted); and 3) the contact person for each particular simulations. The inventory has also a comments section, describing specific features for each simulation.

[7] https://cordex.org/data-access/regional-climate-change-simulations-for-cordex-domains

Completing ESGF simulations. Two main priorities have shaped the C3S CORDEX dataset, both enforced by the requirements of the IPCC AR6 WGI assessment report: 1) the number of simulations for every region should be sufficient to estimate regional climate change uncertainties, and 2) simulations should be publicly available (e.g., on ESGF) before 31 January 2021. In this respect, several domains had very few simulations available on ESGF at the start of this work, such as the polar (ARC and ANT) and the Asian (CAS, EAS, and SEA) CORDEX domains. Therefore, data publication for these domains was prioritized contacting modeling centers to retrieve their simulation data and help them to curate (see quality control section below) and publish the data on ESGF before the IPCC deadline. This task also involved the publication on ESGF of many publicly available simulations in dedicated repositories. This was the case for several simulations from CCCMA, ISU, NCAR, UA, and UQAM [see institutions in Diez-Sierra et al. (2022, their Table 2)] in the North American CORDEX domain. This publication task (see below) resulted in an expansion of the ESGF CORDEX dataset as of 31 January 2021 (meeting the IPCC cutoff deadline), although there are still unpublished simulations that are available through

Table 2. Number of simulations available in the C3S CORDEX dataset per domain (codes as in ESGF specification; see also http://cordex.org/domains) and by horizontal grid resolution (11, 20, 22, 44 stand for 0.11°, 0.22°, and 0.44° resolution, respectively, in the original rotated coordinates, and the suffix "i" indicating regular geographic latitude/longitude interpolated domains). Numbers in parentheses denote the simulations that are replicated at both 0.22° and 0.44° resolution. The Mediterranean domain includes experiments with only atmosphere (the standard for other domains) and atmosphere–ocean coupled regional climate models. Note that simulations used in the IPCC AR6 are in boldface, using the highest resolution available when replicated.

CORDEX domains	Code	Resolutions	Evaluation	Historical	RCP2.6	RCP4.5	RCP8.5
1) South America	SAM	20, **22, 44**	1, 2, 4	3, 6, 14	0, 6, 6	3, 0, 13	3, 6, 13
2) Central America	CAM	**22, 44**	3, 2 (1)	9, 15 (1)	6, 5	0, 3	9, 14 (1)
3) North America	NAM	**22, 44**	5, 6 (4)	17, 13 (10)	3, 1	5, 6 (1)	17, 13 (10)
4) Europe	EUR	**11**	14	65	29	26	63
5) Africa	AFR	**22, 44**	4, 8 (1)	10, 33 (1)	9, 13	1, 22 (1)	10, 29 (1)
6) South Asia	WAS	**22, 44**	3, 3	9, 17	8, 6	0, 17	9, 17
7) East Asia	EAS	**22, 44**	1, 2	6, 5	6, 0	0, 5	6, 5
8) Central Asia	CAS	22, 44	2, 1	4, 2	4, 0	1, 2	4, 2
9) Australasia	AUS	**22, 44, 44i**	3, 4, 0	9, 16, 6	9, 0, 0	0, 13, 5	9, 13, 5
10) Antarctica	ANT	**44**	3	6	2	3	5
11) Arctic	ARC	**22, 44**	2, 10 (2)	1, 11 (1)	0, 1	1, 6 (1)	1, 12 (1)
12) Mediterranean	MED	11, 44	2, 5	2, 6	0, 1	1, 5	2, 6
13) Middle East North Africa	MNA	22, 44	1, 2 (1)	2, 6 (2)	0, 1	0, 6	2, 6 (2)
14) Southeast Asia	SEA	**22**	3	13	6	6	12

other means, e.g., in domains with a large number of simulations already available (e.g., EURO- and AFR-CORDEX) or domains with dedicated repositories, such as MED-CORDEX (www.medcordex.eu).

Selection of simulations and variables. CORDEX provides simulations at various spatial and temporal resolutions. The standard horizontal grid spacings of about 50, 25, and 12.5 km are typically referred to as 0.44°, 0.22°, and 0.11°, or simply 44, 22, and 11, corresponding to the native resolution in degrees of a rotated longitude–latitude geographical projection used by many of the participant models. The standard temporal aggregations provided go from hourly to monthly resolution. The C3S CORDEX dataset was assembled considering a grand ensemble with all available simulations for the standard 0.44°, the CORDEX-CORE 0.22°, and 0.11° at daily temporal aggregation (note that the C3S provides additional temporal frequencies and variables for the European and the Mediterranean domains). For the European domain, only the large 0.11° ensemble (Coppola et al. 2021a; Vautard et al. 2021) was included, whereas for the MED-CORDEX domain, only a few simulations were considered (as mentioned above, this domain is already covered by several other domains). One originality of the MED-CORDEX ensemble is to include a large ensemble of fully coupled RCMs for which ocean variables are also available but were not considered in the C3S request (SST projections are available through the IPCC Interactive Atlas, however). Regarding variable selection, the 15 most downloaded variables (see Table 1) were selected based on the statistics from the Swedish ESGF node and the ESGF dashboard (Fiore et al. 2019); these numbers also revealed that daily was the most demanded temporal frequency. Additionally, two time invariant variables were included: the land–sea mask and terrain elevation. So, all in all, the worldwide C3S CORDEX dataset comprises regional projections from all 14 CORDEX domains (Fig. 1a) for the 15 variables listed in Table 1 (plus land–sea mask and elevation), for daily temporal resolution.

The evaluation, historical and representative concentration pathways (RCP; Moss et al. 2010; van Vuuren et al. 2011) scenarios constitute the different standard experiments provided by CORDEX. Evaluation simulations are nested into reanalysis (ERA-Interim reanalysis; Dee et al. 2011). This so-called perfect lateral boundaries experiment allows for an evaluation of the RCM quality, relative to ERA-Interim. We used the common 30-yr period 1979–2008, established originally in the CORDEX protocol, although the shorter period 1990–2008 was considered in some cases. Historical simulations, using lateral boundary conditions from CMIP5 simulations under the historical scenario, were run for 1950–2005, except for models covering shorter periods (e.g., 1970–2005 or 1980–2005). These simulations can be used to evaluate the GCM–RCM pair, and also as a reference for comparison against future scenario runs. Future scenario simulations (2006–2100) follow the boundary conditions from CMIP5 projections using RCP forcing scenarios. The RCP scenarios included in the C3S CORDEX dataset are RCP2.6, RCP4.5, and RCP8.5, as they were, by far, the most downscaled. Models providing no scenario simulations were not included in the dataset since it is intended for climate change assessment. Simulations interpolated to a regular geographic latitude/longitude grid were only considered when the original simulation on the native computational grid projection was not available.

Quality control. A goal of this initiative is to ensure that all CORDEX data, regardless of origin, can be processed with identical workflows. Therefore, all the simulations (both those existing on ESGF and the new simulations gathered from modeling centers) were quality controlled following both the CORDEX archive specifications (Christensen et al. 2020) and the climate and forecast (CF) conventions, using the quality assurance tool for climate data QA-DKRZ[8] (version 0.6.7-55). This quality checker looks for non-CF-compliant files, metadata errors or inconsistencies in the global attributes and in the file names, omissions of required CORDEX metadata, incompatible temporal dimension of the data and plausible ranges. As a result, a number of simulations were discarded due to critical problems with the data (e.g., value ranges not consistent with the units). Some examples are ANT-CORDEX simulations for the CCAM-2008 RCM, due to the incorrect interpolation of sea ice area fraction (problem reported by the modeling center) and SAM-44 simulations for the ICTP-RegCM4-3_v4 (driven by MPI-ESM-MIR_r1i1p1), due to inconsistencies in the time variable. Other metadata problems were fixed, and changes were annotated in the CORDEX inventory[9] of the GitHub IPCC Atlas repository (Iturbide et al. 2021) to keep track of ESGF and C3S CORDEX differences.

[8] https://github.com/IS-ENES-Data/QA-DKRZ

[9] https://github.com/IPCC-WG1/Atlas/blob/devel/data-sources/CORDEX_simulations_ATLAS.xlsx

The C3S CORDEX dataset. The dataset resulting from the selection, curation and quality control process was published on the C3S Copernicus Climate Data Store (CDS) under the catalog "CORDEX regional climate model data on single levels,"[10] which includes a complete dataset description. Moreover, basic diagnostic and simple evaluation indices were computed and made available along with the dataset.[11] The entire data volume is 235 TB in size. The C3S CDS provides this worldwide C3S CORDEX dataset with a high operational service level, including dedicated personnel, user support with a help desk, and infrastructures, which build on three dedicated distributed replicas of the dataset. Note that the C3S CORDEX dataset is a "frozen" subset of the CORDEX data archived on ESGF as of 31 January 2021 (ESGF is a live federated repository), with quality-controlled and homogenized metadata. The CORDEX

[10] https://cds.climate.copernicus.eu/cdsapp#!/dataset/projections-cordex-domains-single-levels?tab=doc

[11] https://confluence.ecmwf.int/display/CKB/Evaluation+of+CDS+climate+projections

dataset used in the IPCC AR6 Atlas and Interactive Atlas is a subset of the C3S CORDEX dataset (see "Use of the data in the IPCC AR6 WG1 report and additional resources" section).

Table 2 summarizes the information on the number of simulations per domain and the horizontal grid resolutions which form the worldwide C3S CORDEX dataset. Additionally, this table highlights the subset used for the IPCC AR6 (IPCC 2021a), particularly for the Atlas and the Interactive Atlas (Gutiérrez et al. 2021a). In the Atlas, the per domain mosaic ensembles were built pooling together all available resolutions and interpolating the results to a common 0.5° regular grid (except for the European domain where only the highest horizontal grid resolution was used); a complete description of the simulations used is available at the official GitHub Atlas repository (Iturbide et al. 2021), in the AR6 Annex II (IPCC 2021b: Annex II, 2021) and in the AR6 Atlas SM (Gutiérrez et al. 2021b).

Most of the simulations indicated in this table under the "22" resolution label correspond to the CORDEX-CORE initiative (Coppola et al. 2021b; Giorgi et al. 2022; Gutowski et al. 2016; Teichmann et al. 2021), designed to provide homogeneous regional climate projections for most of the inhabited land regions using nine of the CORDEX domains (Fig. 1a) at 0.22° resolution: North America (NAM), Central America (CAM), South America (SAM), Europe (EUR), Africa (AFR), South Asia (WAS), East Asia (EAS), Southeast Asia (SEA), and Australasia (AUS). Due to the high computational requirements, only three GCMs were selected to provide boundary conditions, representing high, medium, and low (HadGEM-ES, MPI-ESM-LR/MPI-ESM-MR, and NCC-NorESM, respectively) climate sensitivity in the CMIP5 ensemble at a global scale (using MIROC5, EC-Earth, GFDL-ES2M, respectively, as an alternative in some domains). CORDEX-CORE focuses on a low and a high emission scenario, RCP2.6 and RCP8.5, respectively. Two RCMs were the most frequently used for this initiative (REMO and RegCM4), and a third one (COSMO-CLM) provides simulations over some of the domains. For the SEA-CORDEX domain, in addition to the CORDEX-CORE, a number of simulations have also been carried out at 0.22° resolution, as reported in Tangang et al. (2020).

Figures 2 and 3 provide further details about the GCMs and RCMs participating in each experiment.

Experiment: historical — Driving GCM_run / Domain	EUR	AFR	NAM	WAS	CAM	AUS	SAM	SEA	ARC	EAS	MNA	CAS	ANT	MED
HadGEM2-ES_r1i1p1	9	8	5	2	4	3	5	4		3	1	2	1	
MPI-ESM-LR_r1i1p1	9	6	8	4	2	3	3	1	3	2		1		1
NorESM1-M_r1i1p1	8	4	1	4	2	4	3	2	1	2		1	1	
EC-EARTH_r12i1p1	8	4	1	2	1	1	1		2	1	2		1	
CanESM2_r1i1p1		4	6	2	3	3	3		4					
CNRM-CM5_r1i1p1	10	2	1	2	2		1	2		1	1	1		1
MPI-ESM-MR_r1i1p1		2	2	2	2	1	1	2	1	1	1	1		1
GFDL-ESM2M_r1i1p1		1	5	2	3	1	2				2			
MIROC5_r1i1p1		2		2	1	1	2							
EC-EARTH_r3i1p1	4	2	1						1	1			1	
IPSL-CM5A-MR_r1i1p1	5	1		1	1		1							1
EC-EARTH_r1i1p1	4	2						1					1	
CSIRO-Mk3-6-0_r1i1p1		1		2	1		1							
IPSL-CM5A-LR_r1i1p1	1	1		1				1						
ACCESS1-0_r1i1p1						4								
MPI-ESM-LR_r2i1p1	3	1												
ACCESS1-3_r1i1p1						3							1	
MPI-ESM-LR_r3i1p1	3	1												
GFDL-ESM2G_r1i1p1	1	1												
CCSM4_r6i1p1											1			
HadGEM2-ES_r2i1p1					1									2
MPI-ESM-MR_r2i1p1					1									
	65	43	30	26	24	24	23	13	12	11	8	6	6	6

Experiment: RCP2.6 — Driving GCM_run / Domain	EUR	AFR	NAM	WAS	CAM	AUS	SAM	SEA	ARC	EAS	MNA	CAS	ANT	MED
HadGEM2-ES_r1i1p1	6	6	1	2	3	3	3	2		2		1	1	
MPI-ESM-LR_r1i1p1	4	4	1	4	2	2	3	1		1		1		
NorESM1-M_r1i1p1	3	4	1	4	2	3	3	2		2		1		
EC-EARTH_r12i1p1	5	3	1	1	1		1		1		1		1	
CanESM2_r1i1p1														
CNRM-CM5_r1i1p1	5											1		1
MPI-ESM-MR_r1i1p1		1		1	1	1	1	1		1				
GFDL-ESM2M_r1i1p1					1									
MIROC5_r1i1p1	2	2		2	1		1							
EC-EARTH_r3i1p1	1													
IPSL-CM5A-MR_r1i1p1														
EC-EARTH_r1i1p1														
CSIRO-Mk3-6-0_r1i1p1														
IPSL-CM5A-LR_r1i1p1	1	1												
ACCESS1-0_r1i1p1														
MPI-ESM-LR_r2i1p1	1													
ACCESS1-3_r1i1p1														
MPI-ESM-LR_r3i1p1														
GFDL-ESM2G_r1i1p1	1	1												
CCSM4_r6i1p1														
HadGEM2-ES_r2i1p1														
MPI-ESM-MR_r2i1p1														
	29	22	4	14	11	9	12	6	1	6	1	4	2	1

Experiment: RCP4.5 — Driving GCM_run / Domain	EUR	AFR	NAM	WAS	CAM	AUS	SAM	SEA	ARC	EAS	MNA	CAS	ANT	MED
HadGEM2-ES_r1i1p1	5	3		1	1		3	2		1	1	1	1	
MPI-ESM-LR_r1i1p1	3	4	2	2	1	1	2		1	1				1
NorESM1-M_r1i1p1	3	1		1		1	1		1					
EC-EARTH_r12i1p1	4	3	1	1	1	1	1		1	1	1			
CanESM2_r1i1p1		4	5	2		3	3		3					
CNRM-CM5_r1i1p1	6	2	1	2			1	1		1	1	1		1
MPI-ESM-MR_r1i1p1				1				1			1	1		
GFDL-ESM2M_r1i1p1		1	1	2		1	1				1			
MIROC5_r1i1p1		1		1		1	2							
EC-EARTH_r3i1p1	1	1	1						1	1			1	
IPSL-CM5A-MR_r1i1p1	2	1		1			1							1
EC-EARTH_r1i1p1	1	1						1					1	
CSIRO-Mk3-6-0_r1i1p1		1		2			1							
IPSL-CM5A-LR_r1i1p1				1				1						
ACCESS1-0_r1i1p1						3								
MPI-ESM-LR_r2i1p1	1													
ACCESS1-3_r1i1p1						2								
MPI-ESM-LR_r3i1p1														
GFDL-ESM2G_r1i1p1														
CCSM4_r6i1p1											1			
HadGEM2-ES_r2i1p1														2
MPI-ESM-MR_r2i1p1														
	26	23	11	17	3	13	16	6	7	5	6	3	3	5

Experiment: RCP8.5 — Driving GCM_run / Domain	EUR	AFR	NAM	WAS	CAM	AUS	SAM	SEA	ARC	EAS	MNA	CAS	ANT	MED	
HadGEM2-ES_r1i1p1	9	8	5	2	4	3	5	4		3	1	2	1		143
MPI-ESM-LR_r1i1p1	10	5	8	4	2	3	3	1	4	2		1		1	128
NorESM1-M_r1i1p1	8	4	1	4	2	4	3	2	1	2		1	1		99
EC-EARTH_r12i1p1	8	3	1	2	1	1	1		2	1	2				76
CanESM2_r1i1p1		3	6	2	3	3	3		4						69
CNRM-CM5_r1i1p1	9	2	1	2	2		1	1		1	1	1		1	70
MPI-ESM-MR_r1i1p1		2	2	2	2	1	1	2	1	1	1	1		1	45
GFDL-ESM2M_r1i1p1		1	5	2	3	1	1				2				39
MIROC5_r1i1p1		2		2	1	1	2								29
EC-EARTH_r3i1p1	4	2	1						1	1			1		27
IPSL-CM5A-MR_r1i1p1	5	1		1	1		1							1	26
EC-EARTH_r1i1p1	4	2						1					1		20
CSIRO-Mk3-6-0_r1i1p1		1		2	1		1								14
IPSL-CM5A-LR_r1i1p1		1		1				1							11
ACCESS1-0_r1i1p1						3									10
MPI-ESM-LR_r2i1p1	3	1													10
ACCESS1-3_r1i1p1						2							1		9
MPI-ESM-LR_r3i1p1	3	1													8
GFDL-ESM2G_r1i1p1															4
CCSM4_r6i1p1											1				3
HadGEM2-ES_r2i1p1					1									2	8
MPI-ESM-MR_r2i1p1															1
	63	39	30	26	23	22	22	12	13	11	8	6	5	6	**849**

Fig. 2. Global climate models participating in CMIP5 (rows), used as boundary conditions for the C3S CORDEX regional simulations in the different domains and experiments (columns). Each cell indicates the number of simulations available for historical, RCP2.6, RCP4.5, and RCP8.5 experiments. For the Mediterranean domain, only atmospheric simulations are listed. Note that evaluation simulations are not included in the table (there is one for each nonempty historical cell in the table).

Experiment: historical — RCM / Domain	EUR	AFR	NAM	WAS	CAM	AUS	SAM	SEA	ARC	EAS	MNA	CAS	ANT	MED
RCA4	10	14	2	10	10		10	2	6		5			
RegCM4	3	5	6	9	7	3	5	8		3	2	2		3
REMO	8	9	3	4	3	3	4	3		3		3		
WRF	5		6			8	1				1			
RACMO	8	3											3	
CRCM5		2	10		4				2					
HIRHAM5	8	1	1						1	1			1	
CCLM4-8	4	4				2								1
CCLM5-0		3				3				4				
COSMO-crCLIM-v1-1	8			3										
CanRCM4		2	2						2					
CCAM-2008						5								
HadREM3-GA7-05	5													
ALADIN6	4													
Eta							3							
ALARO-0	1											1		
ALADIN5	1													1
MAR311													2	
LMDZ4NEMOMED8														1
RRCM									1					
	65	43	30	26	24	24	23	13	12	11	8	6	6	6

Experiment: RCP2.6 — RCM / Domain	EUR	AFR	NAM	WAS	CAM	AUS	SAM	SEA	ARC	EAS	MNA	CAS	ANT	MED
RCA4	4	5	1	5	5		5		1		1			
RegCM4	2	3		3	3	3	3	3		3				
REMO	9	9	3	4	3	3	4	3		3		3		
WRF														
RACMO	5	2											2	
CRCM5														
HIRHAM5	2													
CCLM4-8	2													
CCLM5-0		3				3								
COSMO-crCLIM-v1-1				2										
CanRCM4														
CCAM-2008														
HadREM3-GA7-05	2													
ALADIN6	1													
Eta														
ALARO-0	1											1		
ALADIN5	1													1
MAR311														
LMDZ4NEMOMED8														
RRCM														
	29	22	4	14	11	9	12	6	1	6	1	4	2	1

Experiment: RCP4.5 — RCM / Domain	EUR	AFR	NAM	WAS	CAM	AUS	SAM	SEA	ARC	EAS	MNA	CAS	ANT	MED
RCA4	6	10	2	10	3		10	2	4		3			
RegCM4				6			1	4			2	2		2
REMO	5	2		1			1							
WRF	1					6	1				1			
RACMO	4	2											2	
CRCM5		2	6											
HIRHAM5	3	1	1						1	1			1	
CCLM4-8	4	4				2								1
CCLM5-0										4				
COSMO-crCLIM-v1-1														
CanRCM4		2	2						2					
CCAM-2008						5								
HadREM3-GA7-05														
ALADIN6	1													
Eta							3							
ALARO-0	1											1		
ALADIN5	1													1
MAR311														
LMDZ4NEMOMED8														1
RRCM														
	26	23	11	17	3	13	16	6	7	5	6	3	3	5

Experiment: RCP8.5 — RCM / Domain	EUR	AFR	NAM	WAS	CAM	AUS	SAM	SEA	ARC	EAS	MNA	CAS	ANT	MED	
RCA4	10	14	2	10	10		10	2	6		5				215
RegCM4	3	5	6	9	6	3	4	7		3	2	2		3	149
REMO	6	8	3	4	3	3	4	3		3		3			136
WRF	6		6			6	1				1				50
RACMO	8	2											2		43
CRCM5			10		4				2						42
HIRHAM5	8	1	1						2	1			1		37
CCLM4-8	4	4				2								1	35
CCLM5-0		3				3				4					30
COSMO-crCLIM-v1-1	8			3											24
CanRCM4		2	2						2						18
CCAM-2008						5									15
HadREM3-GA7-05	4														11
ALADIN6	4														10
Eta							3								9
ALARO-0	1											1			8
ALADIN5	1													1	8
MAR311													2		4
LMDZ4NEMOMED8														1	3
RRCM									1						2
	63	39	30	26	23	22	22	12	13	11	8	6	5	6	**849**

Fig. 3. Regional climate models providing future projections in the C3S CORDEX dataset (rows) for the different domains and experiments (columns). Each cell indicates the number of simulations available for historical and scenario (RCP2.6, RCP4.5, and RCP8.5 pathways) experiments.

Model documentation. The availability of comprehensive model documentation is vital to allow for informed use of the data, considering key factors which may explain different model results (e.g., different parameterization assumptions, use of interactive aerosols, the complexity of the land surface model, or the use of other interactive components—lakes, cities, etc.). This is a time-consuming task, and the CMIP community has developed technologies and tools to facilitate this through the Earth System Documentation (ES-DOC; https://es-doc.org) project. As a result, documentation of the contributing GCMs is available for the different CMIP versions (e.g., structured metadata are readily available[12] for the CMIP5 global models used as boundary conditions for the CORDEX simulations presented here). Unfortunately, this is not the case in general for the CORDEX initiative, which provides, under the CORDEXP ES-DOC project,[13] centralized and harmonized model documentation only for some models contributing to EURO-CORDEX.

[12] https://search.es-doc.org/?project=cmip5&documentType=cim.1.software.ModelComponent

[13] https://search.es-doc.org/?project=cordexp

Information describing the CORDEX RCMs is usually hard to find in the literature. When available, this information is scattered in single-model studies (e.g., Sørland et al. 2021), which often do not consider the exact model version used in CORDEX or in ensemble studies focusing on particular processes where only the material relevant to the process is included in the summary tables (e.g., Nikulin et al. 2011; Vautard et al. 2013; Gutiérrez et al. 2020; Knist et al. 2017). Moreover, given the ever-increasing number of contributions to CORDEX, new model versions appear which are not described in the existing literature.

The activities carried out within the framework of the C3S required close contact and exchange with the modeling centers contributing simulations for the different domains. This facilitated gathering common information on the different RCMs contributing to CORDEX regarding the various components and other simulation details. A repository with metadata from the CORDEX RCM ensemble has been compiled as part of the worldwide CORDEX dataset (Diez-Sierra et al. 2022), enabling future updates and backtracking to this publication. This information is not exhaustive and other studies provide more detailed information on particular components for particular CORDEX domains [e.g., Gutiérrez et al. (2020) on aerosol treatment in EURO-CORDEX]. This table extends the information gathered for the IPCC WGI AR6 Annex II on models (IPCC 2021b: Annex II) by including the domains and other useful information (e.g., details on parameterizations). While partial, this table can help users of CORDEX data to understand the key differences between simulations until a full description is finally collected in ES-DOC. A critical aspect is the clarification of the differences between ESGF model versions. This information is lacking in ES-DOC since such discrepancies are often unrelated to model configuration and commonly arise due to simulation reruns or GCM nesting details. This information is crucial to users since some model versions can sometimes be preferred over others, depending on the application. This information is either unavailable or scattered in technical reports when publicly available. Most of this information has been gathered by personal communication in this work.

One example of the information that can be gathered from the metadata collected is to identify the models performing a transferability experiment (Takle et al. 2007), by applying the same model configuration to different domains. Models tend to be tuned for a specific/home domain, usually that of the modeling group, where most of the model tests are carried out. For example, models developed in Europe are likely to better represent European (say, midlatitude) climate. When these models are used on a tropical or polar domain, results may be suboptimal. The ability of an RCM to perform well when transferred to a different domain is a desirable quality, since this gives plausibility to their ability to simulate a changing climate. In CORDEX, models such as CanRCM4, CCAM, CRCM5, HIRHAM5, or REMO provide examples of transferability experiments. As an alternative, several models adapted their configuration to the different CORDEX domains. For example, RACMO2 has a European (RACMO22E), tropical (RACMO22T), and polar (RACMO21P) configuration. The adaptation usually refers to the tuning of specific parameters (e.g., RCA4, RegCM4) or a particular selection of physical parameterizations (e.g., RegCM4, WRF, CCLM), especially the convective scheme.

The first four columns in the model description table (Diez-Sierra et al. 2022, their Table 1) map directly onto the ESGF identifiers for the RCM model, downscaling realization, domain, and institute. This allows a potential user to quickly find the metadata corresponding to a particular simulation on ESGF and easily compare it to others. It is worth mentioning the diverse meaning used in practice for the RCM model and downscaling realization identifiers. The latter typically refers to reruns of a given simulation, e.g., due to errors, or slight perturbations to the configuration. The comments column provides information on the actual meaning of these alternative realizations of a given simulation for the same domain, driving model and future scenario. It is usually not advisable to include several of these realizations in ensembles, at the risk of double counting a given model or using simulations which are not fit for purpose. The RCM model identifier, on the other hand, labels distinct model versions, likely to produce quite different results. For example, several WRF configurations, differing mainly on the physical parameterizations used to represent different phenomena, are labeled separately due to their distinct behavior (Katragkou et al. 2015). Other modeling teams considered these different parameterization settings as different simulation realizations, instead. Or even the same RCM model name and realization identifiers represent different model configurations depending on the domain (see, e.g., RegCM4-7 v0). There are also distinct RCM model names (e.g., REMO2009 and REMO2015) which correspond to the same model and configuration.

The experimental design of the simulations is also important for certain applications or analyses. For example, some simulations are produced by global stretched-grid models (e.g., CCAM), which require global atmospheric nudging to keep the circulation close to that of their driving GCM. This differs from the lateral boundary forcing used in RCMs. Some RCM simulations also used spectral nudging techniques (von Storch et al. 2000), which keep the large-scale RCM circulation close to that of their driving GCM also in the interior of the domain. Others used bias adjusted GCM input (Bruyère et al. 2014). While these approaches are valid in general, attention should be paid when comparing simulations with different experimental designs. For instance, when the consistency of GCM and RCM results is evaluated, simulations driven with spectral nudging are likely to be more consistent than unnudged ones. Similarly, those simulations driven by bias-adjusted GCM fields are also likely to be more skillful in historical model assessments. All these particular details of the simulations can be found in Diez-Sierra et al. (2022) and used as potential explanatory factors in any subsequent evaluation or analyses. Note that this information is provided for all CORDEX simulations available, and not just for those included in the C3S CORDEX dataset ("The C3S CORDEX dataset" section). For consistency, some experimental designs were excluded from this worldwide dataset ("Data selection, curation, and quality control" section).

Use of the data in the IPCC AR6 WG1 report and additional resources. CORDEX has been extensively used as a new line of evidence in the IPCC AR6 WGI report (IPCC 2021a), in particular in the chapters dealing with regional information and the Atlas (Doblas-Reyes et al. 2021; Gutiérrez et al. 2021a; Ranasinghe et al. 2021; Seneviratne et al. 2021). The main source of information was the worldwide C3S CORDEX dataset and the particular domains and simulations used in different chapters and sections are described in the chapters' supplementary material. In the case of the Atlas and Interactive Atlas (Gutiérrez et al. 2021a), the GitHub Atlas repository (Iturbide et al. 2021, 2022) contains detailed provenance information as well as aggregated data for mean temperature and precipitation using the IPCC AR6 reference regions (Iturbide et al. 2020), which can be directly used to generate some of the figures of this paper (see the code and data availability section). In particular, the CORDEX domains considered (discarding those with small ensembles and/or overlapped by other domains) are detailed in Table 2. The repository also provides scripts and notebooks to reproduce some of the key figures of the Atlas chapter.

Consistency of the climate change signal across CORDEX domains

In this section, we assess the consistency of the C3S CORDEX dataset across domains, focusing in particular on model biases and climate change signals in regions where several domains overlap. It is important to identify and account for cases where simulated signals differ across domains in overlapping regions. These apparent conflicts could be due to the specific configurations used in the different domains (e.g., the set of GCM/RCM pairs and model versions), but there could also be other contributing factors, such as domain size or position, which are important to understand. This section explores such overlaps and formulates recommendations on how to interpret any differences.

We extend a previous analysis performed over the Mediterranean region (e.g., Legasa et al. 2020) by assessing the consistency of climate change signals for mean temperature and precipitation across all regions where the C3S CORDEX dataset domains overlap. To avoid local gridbox variability we use the new subcontinental reference regions (see Fig. 1b) used in the IPCC AR6 (Iturbide et al. 2020) and check the consistency of the spatially aggregated simulations.

For every pair of overlapping domains (see Fig. 1a), we use the common subensemble of GCM–RCM pairs—i.e., the same RCM driven by the same GCM—and intercompare their evaluation and historical simulation biases, and climate change signals obtained from different domains. The RCP8.5 scenario is chosen to maximize data availability (see Table 2, Figs. 2 and 3) and the projected climate change signal (Dosio et al. 2020; van Vuuren et al. 2011). All the analyses were performed at daily aggregation. Similar biases and climate change signals indicate a consistent performance of the GCM–RCM pair, whereas differences indicate inconsistencies that should be analyzed more in-depth. Following the procedure used in the IPCC AR6 Atlas, all model results were regridded using a first-order conservative remapping to a regular 0.5° horizontal resolution grid. This is the same grid considered in the bias-adjusted ERA5 reanalysis data (WFDE5; Cucchi et al. 2020), employed as the reference to compute biases. In this way, simulation and observational databases can be directly compared to obtain performance measures. We focused on near-surface air temperature (tas) and precipitation (pr) and considered only those simulations that overlap more than 90% of the grid cells with the regions analyzed (with the exception of the simulations over the Africa CORDEX domain for the Mediterranean regions, which had a slightly smaller overlap ~85%). The resulting aggregated data are available for reproducibility and reusability in the GitHub IPCC Atlas repository (Iturbide et al. 2021).

Apart from the C3S CORDEX dataset, we also include in the analyses the driving model of the different simulations, that is, ERA-Interim reanalysis data and CMIP5 GCM output.

The evaluation period considered is 1986–2005. Mean biases for near-surface air temperature are calculated as the simple difference of the spatial and temporal average between either CORDEX evaluation/historical simulations or the corresponding ERA-Interim/CMIP5 driving data and WFDE5: $\text{bias}_{\text{tas}} = \overline{\text{tas}} - \overline{\text{tas}}_{\text{WFDE5}}$. Biases for precipitation are calculated as relative differences (%): $\text{bias}_{\text{pr}} = 100\,[(\overline{\text{pr}} - \overline{\text{pr}}_{\text{WFDE5}})/(\overline{\text{pr}}_{\text{WFDE5}})]$. Climate change signals (deltas) are calculated for the far future 20-yr period 2081–2100, relative to the historical period 1986–2005, as differences (K) for temperature and relative differences (%) for precipitation: $\text{delta}_{\text{tas}} = \overline{\text{tas}}_{\text{Fut}} - \overline{\text{tas}}_{\text{Hist}}$ and $\text{delta}_{\text{pr}} = 100\,[(\overline{\text{pr}}_{\text{Fut}} - \overline{\text{pr}}_{\text{Hist}})/\overline{\text{pr}}_{\text{Hist}}]$, respectively. Biases and deltas were computed both seasonally (for DJF and JJA) and considering the whole year.

Consistency in overlapping domains. Biases and delta changes for the regions with more considerable overlaps in Central and South America (Fig. 4), Europe, Africa and Southwest Asia (Fig. 5), and Asia (Fig. 6) have been computed for each individual GCM–RCM pair and its driving GCM.

In general, there are remarkable similarities between the biases for different overlapping domains, with some exceptions. For instance, for the northern central America reference region (NCA), RCA4 exhibits systematically wetter biases in the Central American domain, compared to in the North American CORDEX domains (Fig. 4a, right), though the climate change signals seem to cancel out these biases and are remarkably more similar. In the South American monsoon reference region (SAM), RegCM4-3 shows drier biases (Fig. 4d, bottom right) in the Central American than in the South American domain, but this difference disappears for RegCM4-7. RCA4 also presents different biases in the Arabian Peninsula (ARP) for precipitation when the Africa and the Middle East North Africa domains are compared (Fig. 5b). REMO2009 exhibits systematically colder biases in South Asia than in Africa domain for the ARP, SEAF, and NEAF reference regions (Fig. 5c, left), and REMO2015 presents drier biases for the ARP reference region (Fig. 5c, right). Some of these differences are likely due to the target region being too close to the domain boundaries and, thus, maybe lacking sufficient spatial spinup (Matte et al. 2017) or missing important drivers in the simulation domain, or due to different model configurations (see Diez-Sierra et al. 2022).

When analyzing the overlapping climate change signals, we find that future regional climate projections exhibit greater similarities, relative to the historical biases, between the model results obtained from different CORDEX domains. Delta changes seem to cancel out most of the different biases described above. As a result, delta changes for the same region are very similar from different overlapping simulations when the same GCM–RCM pairs are selected. For instance, only REMO2015 and RegCM4-3 present substantial differences when climate change signals are analyzed. REMO2015 presents some differences when the South Asia and Africa domains are compared for the ARP, SEAF, and NEAF regions (Fig. 5c, right). RegCM4-3 and REMO2015 display some differences when the Central and South America domains are compared for the NWS, NSA, and SAM regions (Figs. 4c,d).

Overall, the results in Figs. 4–6 show that domain choice is less relevant than the choice of the GCMs and RCMs when comparing the simulations at regionally aggregated scale. This suggests that the grand ensemble approach could be appropriate to generate regional climate information for specific applications, pooling together all available information which is

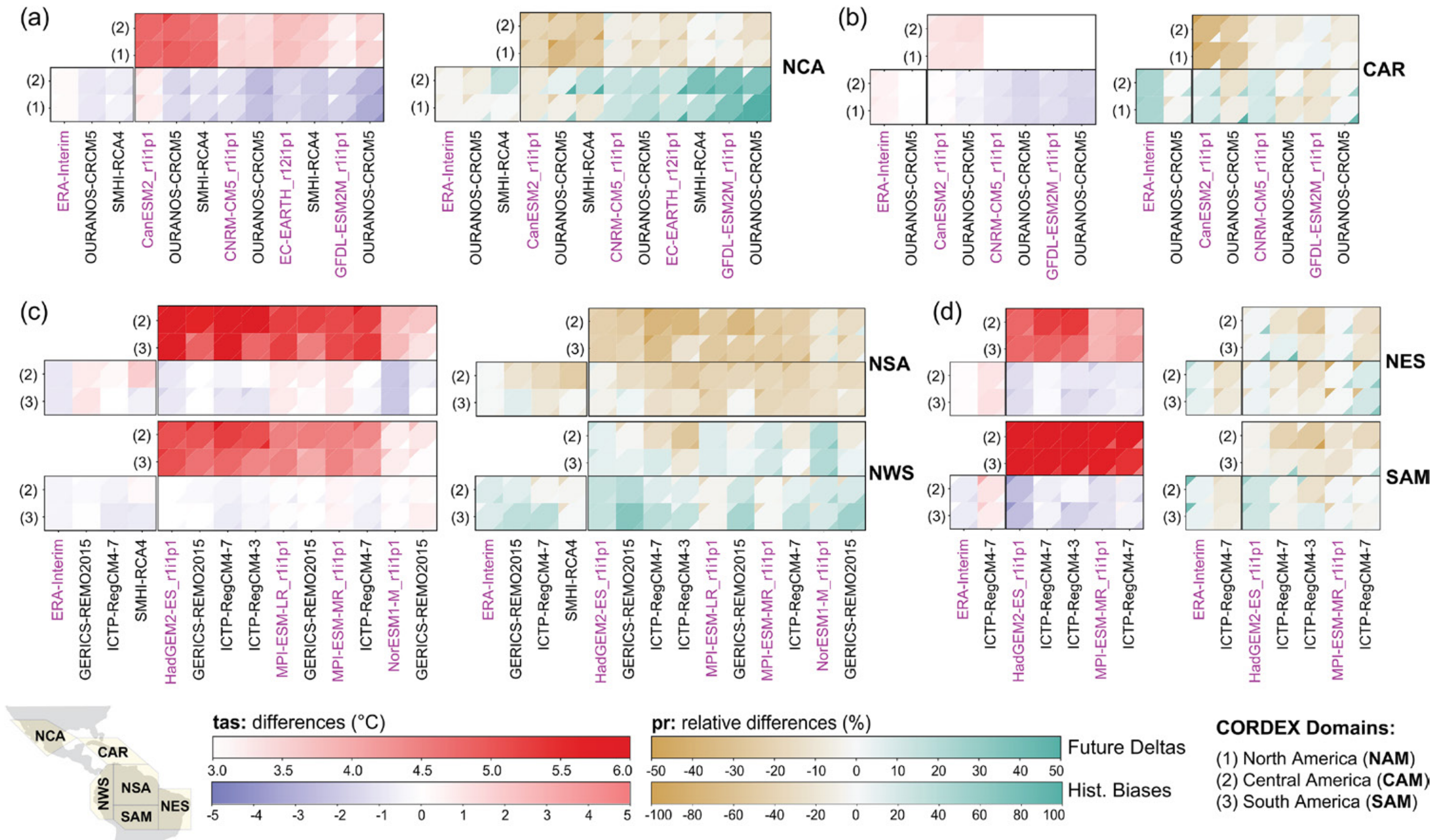


Fig. 4. Biases and future delta changes of regional overlaps for the American regions: (a) northern Central America (NCA), (b) Caribbean (CAR), (c) northern South America (NSA) and northwestern South America (NWS), and (d) northeastern South America (NES) and South American monsoon (SAM). Labels indicate the reference regions used in the IPCC AR6 (see Fig. 1b). Numbers in parenthesis indicate CORDEX domains. Columns correspond to the models (driving model labels highlighted in magenta followed by the RCMs nested into that model, in black text). The panels intercompare the biases (bottom) and the climate signals (top) for the different CORDEX domains providing simulations for the same geographical regions. Colored cells show the biases or climate change signals considering the whole year (central color), the boreal summer months (JJA, upper-left corner), and the boreal winter months (DJF, lower-right corner).

suitable for the particular region (see "Model documentation" section). This is further assessed in the next section by comparing the mosaic (single-domain) and grand-ensemble approaches.

Mosaic and grand-ensemble climate change signals. Practitioners are often confronted with CORDEX datasets from multiple domains (e.g., EURO-, Africa-, MENA-, and Med-CORDEX for Mediterranean areas), which could produce different signals. In this section, we extend the results obtained in the previous section by calculating the climate change signals from different CORDEX multimodel ensembles obtained from the mosaic (single-domain) and the grand-ensemble approaches; the results are compared with those corresponding to the raw CMIP5 GCM results, weighted based on their use as boundary forcing in CORDEX simulations in each ensemble (following Boé et al. 2020). Only those CMIP5 models that drive CORDEX simulations for every particular ensemble are included in the CMIP5 ensembles. Climate change signals are calculated using all simulations shown in Fig. 1a and described in Table 2 and Figs. 2 and 3 except for the Mediterranean domain simulations. All the simulations present the same weight for the different (single-domain) mosaic ensembles, while for the grand ensemble, common GCM–RCM pairs are previously averaged to avoid duplicate information. The goal of this section is to provide users with some preliminary information, albeit at a broad spatial scale (IPCC reference regions), to inform dataset selection for their particular applications.

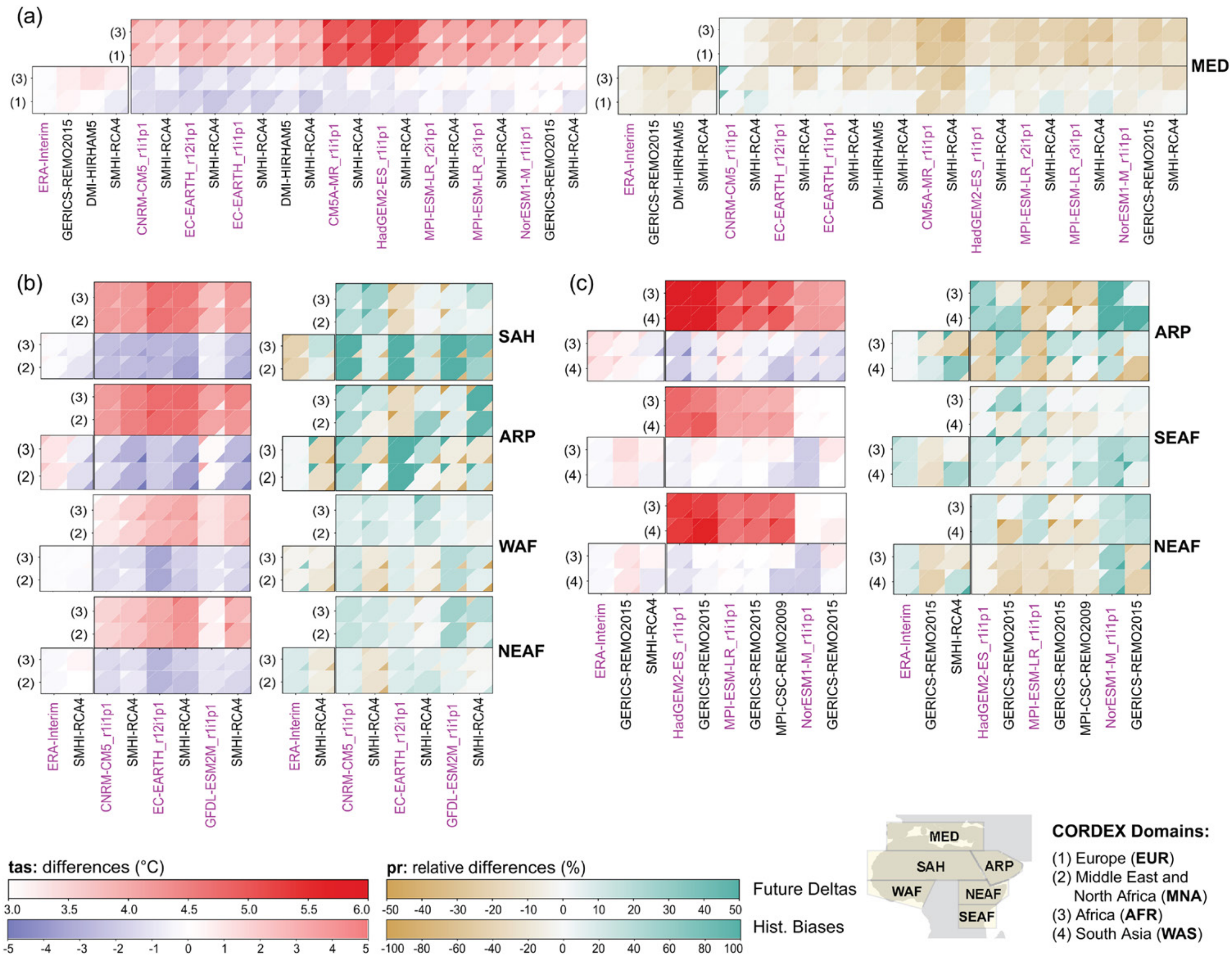


Fig. 5. As in Fig. 4, but showing the overlap assessment for Europe, Africa and the Middle East regions: (a) Mediterranean (MED), (b) Sahara (SAH), Arabian Peninsula (ARP), western Africa (WAF), Northeastern Africa (NEAF), and (c) ARP, Southeastern Africa (SEAF), and NEAF.

Figures 7 and 8 show the climate change signals for temperature and precipitation, respectively. The figures highlight that the grand ensemble might be beneficial for some regions where the "home" domain (i.e., the domain selected for a specific region to create the mosaic approach) provides few simulations (see Fig. 1b). For example, this is the case for the ECA region, where the home domain (EAS) contributes with 11 simulations, while WAS and EAS domains contribute with 9 and 5 simulations, respectively. Note that there are regions where even the grand ensemble provides relatively small ensembles (e.g., the EEU region is overlapped by a total of 8 simulations, 5 provided by CAS domain and 3 by EUR).

For temperature (Fig. 7), there are remarkable similarities between the CMIP5 ensemble, the CORDEX grand ensemble and the per-domain ensembles calculated with the mosaic approach. Per-domain ensembles with higher number of simulations are, in general, closest to the grand ensemble. The CMIP5 ensemble (black box) exhibits major differences with respect to the CORDEX grand ensemble (red bar) for the reference regions NWN, EEU, and ECA. These regions have seasonal snow cover, handled by the land surface model, and likely differ between the RCM and the driving GCM. In fact, regions with more permanent snow cover (TIB region for instance) show better agreement. In particular, the differences between

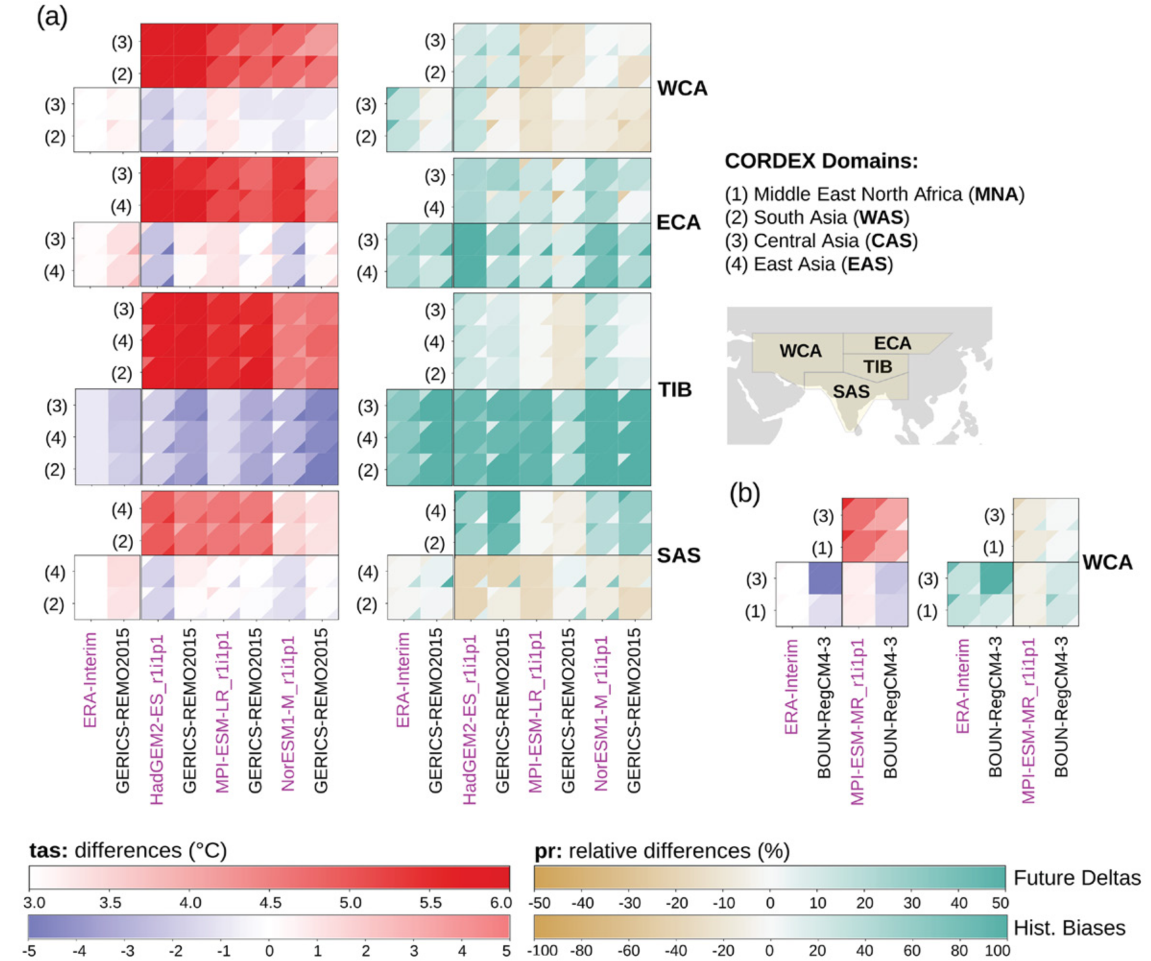


Fig. 6. As in Fig. 4, but showing the overlap assessment for the Asian regions: (a) west Central Asia (WCA), east Central Asia (ECA), Tibetan Plateau (TIB), and SAS (South Asia), and (b) WCA.

CMIP5 and CORDEX ensembles for the EEU region might also originate from temperature discontinuities between CORDEX domains over the Ural Mountains (Spinoni et al. 2021). Note also that NWN, ECA, and EEU regions are overlapped by some domains with relatively small individual ensemble sizes, which could also increase the difference between the ensemble means. Per-domain mosaic ensembles show substantial variability for the South American monsoon (SAM) region. It is due to a combination of sampling uncertainty (the number of simulations for each ensemble is quite different: 6 for CAM and 21 for SAM) and to the inconsistent delta of the RegCM4-3 common pair (7.3° and 5.9° for CAM and SAM, respectively).

For precipitation (Fig. 8), the ensembles calculated with the different approaches for every region exhibit more variability than those obtained for temperature. However, CORDEX grand ensembles generally agree with the CMIP5 ones except for the regions SEA, NEAF, SAH, NES, and NWS. The differences between the per-domain mosaic ensembles for these regions are mainly caused by both the different number of simulations available per domain and the scarce precipitation in these regions. Note that small changes of precipitation projected in areas with scarce precipitation can result in substantial relative changes as in the case of the CC-NorESM1-M_REMO2015 model for the ARP region. This is not the case for the NWS region (northwestern South America) or NEAF and WAF in Africa. Mosaic ensembles in NWS exhibit opposite directions of change even though the number of ensemble simulations is similar in both domains (22 and 21 per CAM and SAM, respectively). GCM–RCM pairs for CAM and SAM domains exhibit systematic disagreements in those regions located in South America. The same GCM–RCM pairs result in a greater value of near surface temperature for CAM than

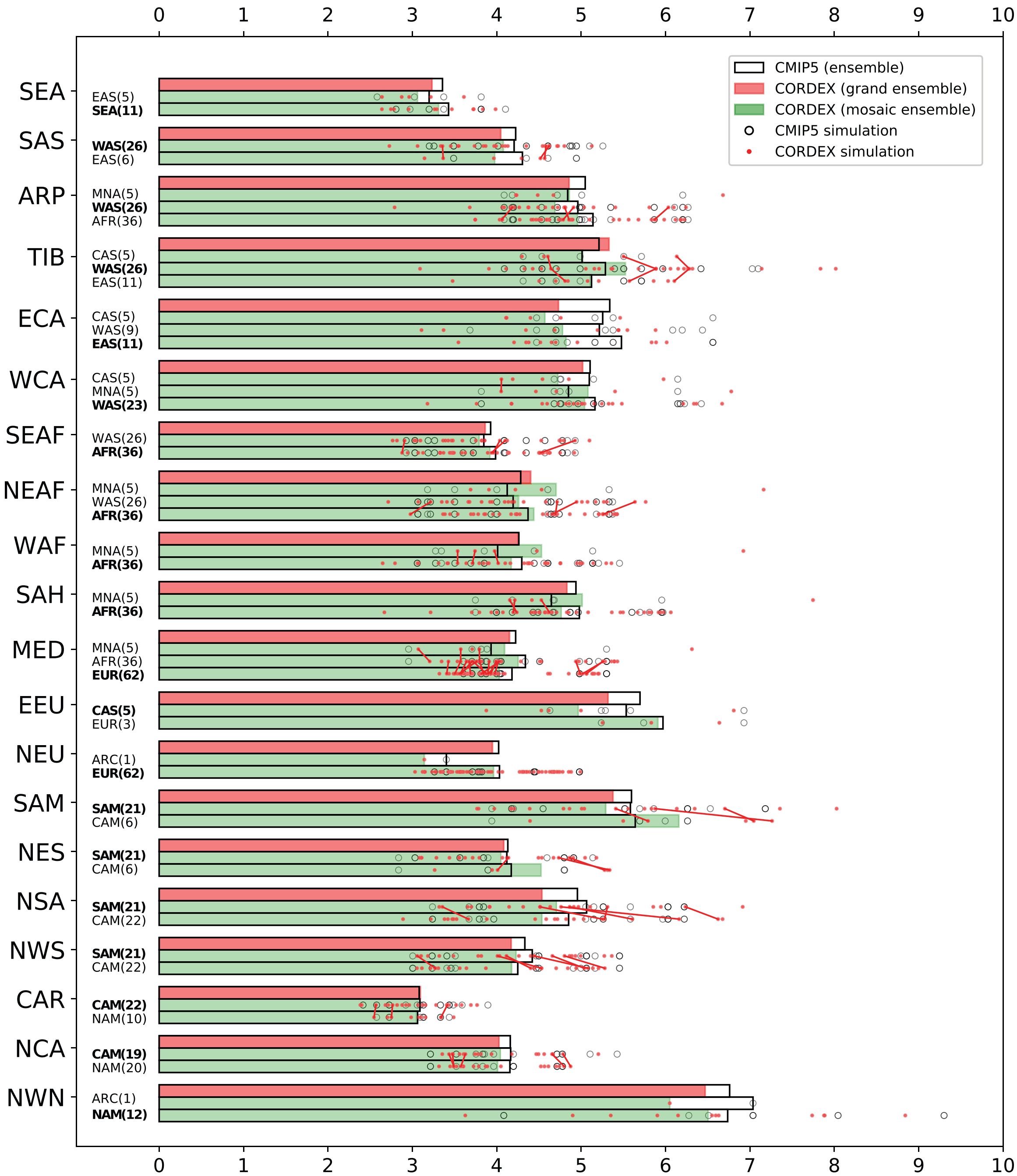


Fig. 7. Climate change signals for temperature. Top and bottom *x* axes correspond to the projected increase in Celsius degrees. The *y* axis corresponds to the subcontinental reference regions used in the IPCC AR6. Red bars correspond to the CORDEX grand ensembles. Green bars correspond to the CORDEX ensembles per domain (mosaic single-domain ensembles). The number of CORDEX simulations used for every particular mosaic single-domain ensemble are indicated in parentheses. Bold domains correspond to the home CORDEX domain for every region (see Fig. 1b). Boxes with black frames correspond to the CMIP5 ensemble. Red lines connect CORDEX simulation pairs (GCM–RCM) for different domains (so longer red lines mean larger discrepancies between the domains for the same model). Individual simulations (points in the figure) are not included for the grand ensemble since it is built pulling together all the simulations from the different domains (points over the corresponding green bars in the figure).

for SAM and a lower value of precipitation for CAM than for SAM. This makes us suspect that the choice of the domain could have some impact in these regions (SAM, NES, NSA, and NWS). This inconsistency deserves further investigation since both ensemble patterns are broadly consistent with their driving GCMs. Still, an insufficient spatial spinup (Matte et al. 2017) might create artifacts in this area close to the SAM domain boundary. In regions,

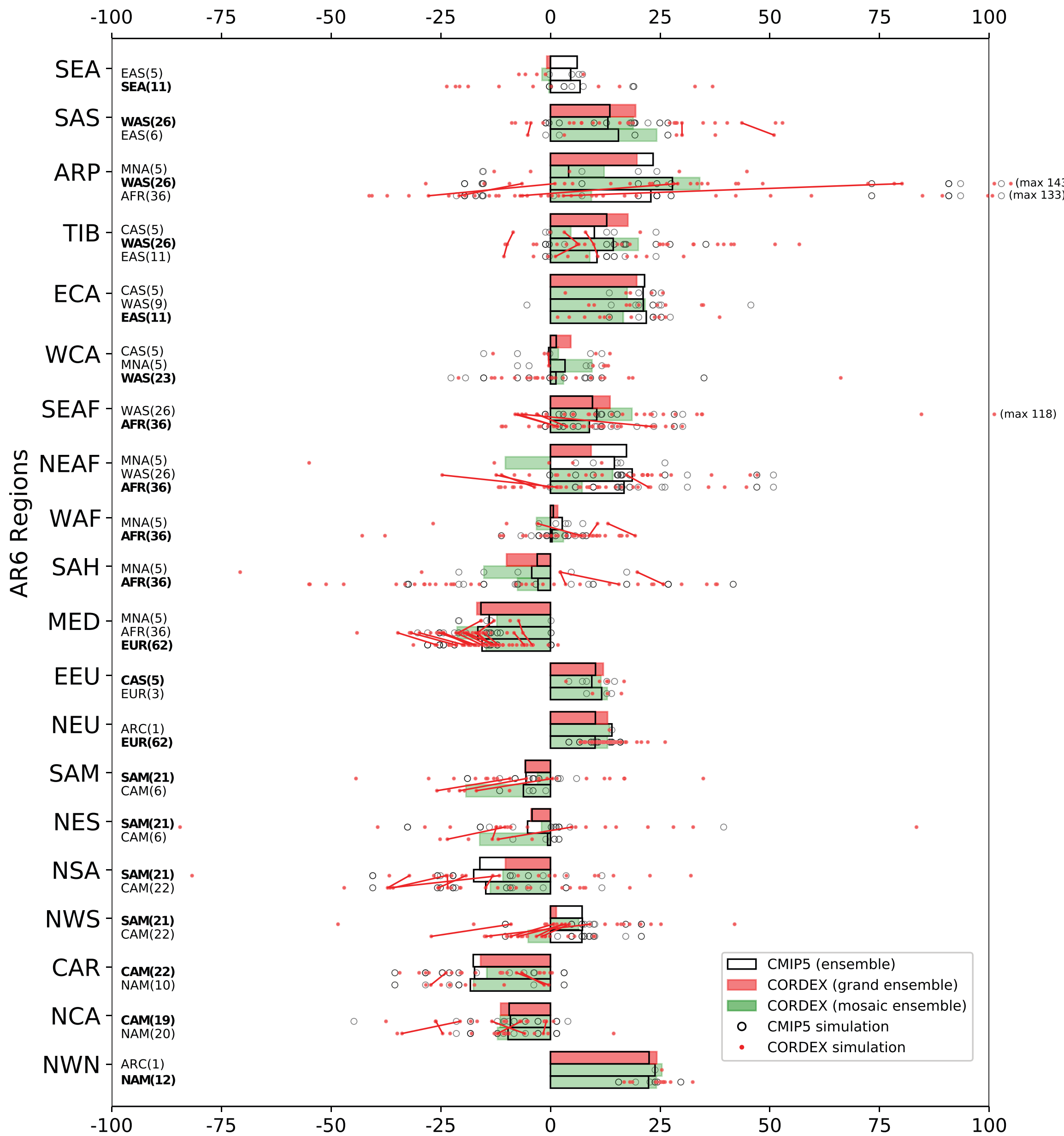


Fig. 8. As in Fig. 7, but for precipitation. Top and bottom *x* axes correspond to the value of the relative climate change signal for precipitation (%). Outliers beyond 100% change are shown on the margin (out of scale but indicating the maximum value reached in parentheses).

such as WAF, where the precipitation change signal is small due to opposite projections, the small sample in CORDEX domains such as MNA can also determine the direction of change in the mosaic ensemble. A deeper analysis, considering the changes in processes and other lines of evidence region by region [see, e.g., Dosio et al. (2020) for WAF], would be required to understand the discrepancies among ensembles summarized in Fig. 8.

Note that the results shown in Fig. 8 are reasonable considering that future precipitation projections generally show low robustness in the change in most areas of the world for the main reference datasets (CMIP5 and CORDEX). In fact, those analyzed regions where the IPCC WGI AR6 predicts confident changes in the precipitation for the long-term period and the RCP8.5 scenario (NWN, CAR, NEU, MED, ECA) show very good agreement across the CORDEX grand ensemble, the mosaic ones, and the CMIP5 ensembles at this coarse spatial scale. Finally, CORDEX ensemble results obtained for both variables generally exhibit more variability in the mosaic approach, consistent with the use of a smaller number of simulations.

Conclusions

This article presents the work done over the past three years in the framework of the Copernicus Climate Change Service (C3S) to assemble a worldwide CORDEX dataset globally consistent and aligned with IPCC AR6 activities and deadlines. This work required close contact and exchange with the modeling centers producing simulations for CORDEX. The protocol followed required 1) creating an inventory of all available simulations, in coordination with the CORDEX project office, 2) gathering existing simulations available from modeling groups in areas with scarce published data, such as the polar and the Asian domains, and supporting their curation, standardization, and publication on ESGF, 3) assembling and making available on the C3S-CDS a globally homogeneous quality-controlled dataset for a subset of the 15 most popular variables, and 4) collecting common information on the RCM components (atmosphere, land) and forcings (aerosols, ocean surface) in a summary table, which constitutes the most comprehensive metadata available for the CORDEX ensemble to date. The C3S CORDEX dataset is available through the C3S-CDS along with detailed documentation (the original simulations are available from ESGF); the RCM summary tables are available from Zenodo, to enable future updates.

Additionally, the resulting dataset has been studied in the present paper analyzing the spatial consistency and potential differences arising in areas where domains overlap both for the global CMIP5 and the CORDEX domain results. For these areas, cross-domain consistency was assessed by comparing average model biases and climate change signals for regional averages and mean variables. Note that regional differences would be expected across the CMIP5 and CORDEX datasets when considering climate at smaller scales and/or extreme rather than mean variables at large scale, where regional models are expected to provide added value; see, for example, the differences for mountainous and coastal regions (Giorgi et al. 2016; Demory et al. 2020). Our analysis only covered the regions overlapping several domains, excluding areas where there are known inconsistencies between driving GCMs and RCMs, such as central Europe (Boé et al. 2020). In this region, CMIP5 projects a higher increase in summer temperature changes than CORDEX.

Overall, the results show coincident biases and, especially, climate change signals for the same GCM–RCM pairs across domains. For temperature, the climate change signals obtained for the C3S CORDEX grand ensemble, single-domain (mosaic) ensembles, and the CMIP5 driving models are consistent for most regions analyzed. Only northwestern North America, eastern Europe, and east Central Asia exhibit major differences between CMIP5 and CORDEX ensembles, which could be due to major differences in seasonal snow cover representation in global and regional climate models, although this deserves further investigation since other discrepancies, such as aerosol treatment, could also play a role. Note also that these regions are overlapped by some domains with relatively small individual ensemble sizes, which could also increase the difference between the ensemble means. For precipitation, the variability is higher and mosaic ensembles exhibit larger fluctuations due to the small number of simulations in some of the domains. Regions with confident climate change signals tend to show good agreement between the CORDEX grand ensemble, the mosaic ones, and the CMIP5 ensembles.

These results support the use of the C3S CORDEX dataset for worldwide studies. The assembly of grand ensembles pooling the data available from different domains for a particular region can be considered in regions where the home domain provides few simulations. However, caution must be taken in regions where local feedback may dominate the projections. In such cases, it is very important to assess the projections using the domain which includes all relevant forcing mechanisms. As an example, experience in the South American monsoon region, indicates that the Central American domain prevents a proper representation of the large-scale dynamics in the region, which is too close to the domain boundaries and does not allow for sufficient spatial spinup. Therefore, the Central American domain should not be used to study future projections there. Likewise, other regions near domain boundaries would need detailed analyses before use.

The above activities contribute to supporting the CORDEX and ESGF communities and the preparation and documentation of the CORDEX dataset used in the IPCC report (IPCC 2021b: Annex II). The open resources for data documentation and exploitation, as well as some aggregated datasets developed as part of the IPCC activities are available from the IPCC GitHub Atlas repository (Iturbide et al. 2021). Despite this major effort to unearth existing CORDEX simulations, there are still regions in the world covered by a small number of future projections, which poorly explore the uncertainties involved in regional climate simulation. Therefore, one of the next CORDEX challenges to provide regional information globally is to fill this gap by balancing the amount of simulations in the different domains. Also, stronger coordination would be desirable within and across CORDEX domains regarding the experimental design (GCM–RCM–SSP combinations, GCM internal variability sampling, etc.) in order to maximize the exploration of uncertainties and the potential to interrogate the resulting dataset.

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The author list is written by contribution (from JDS to JBM), then in alphabetic order. The conceptualization of the research was developed by JDS, MI, JMG, JF, and ASC. The investigation was carried out by JDS, MI, JMG, JF, JM, ASC, EZ, GN, GL, EK, KB, JBM, MGD, and AP. Simulations and metadata information were provided by JF, JM, GN, BA, AA, MA, MB, EB, SC, SCC, OBC, JMC, EC, LC, MED, VD, JPE, RF, HF, DJ, SJ, JK, KK, CK, MLK, RL, PL, SM, PM, PN, TO, HJP, BO, DP, IP, FR, ARR, JS, FS, SS, CS, FT, CT, PT, MT, CT, EvM, RV, KWS, KW, GZ. Visualization (figures and tables) were prepared by JDS and JF. Project administration was done by JMG, AH, and AB. The original draft preparation of the paper was written by JDS, JMG, and JF. All authors contributed to data curation and to writing, revising, and editing the final draft.

The authors declare that they have no conflict of interest.

Data availability statement. The worldwide C3S CORDEX dataset is publicly available through both C3S-CDS (https://cds.climate.copernicus.eu/cdsapp#!/dataset/projections-cordex-domains-single-levels) and ESGF (https://esgf-data.dkrz.de/search/cordex-dkrz/) under the Creative Commons Attribution license CC-BY 4.0 with the exception of the simulations from the following RCMs: BOUN-RegCM4-3 model (for Central Asia and Middle East and North Africa domains) and RU-CORE-RegCM4-3 model (for Southeast Asia domain) which are distributed under CC-BY-NC 4.0. A complete description of the subset of simulations used for the IPCC AR6 (IPCC 2021b), particularly for the Atlas and the Interactive Atlas (Gutiérrez et al. 2021b), is available at the official GitHub Atlas repository (Iturbide et al. 2021) and in AR6 Annex II (IPCC 2021b: Annex II). This repository contains aggregated information for different variables and open resources for data exploitation. Common information on the RCM components is available on Zenodo (version 2.1, as of this publication), enabling future updates and backtracking to this publication (Diez-Sierra et al. 2022). The code used to produce main results is available at Zenodo (https://doi.org/10.5281/zenodo.7010026).

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