BAMS
Article

The CORDEX-CORE EXP-I Initiative

Description and Highlight Results from the Initial Analysis

Filippo Giorgi, Erika Coppola, Daniela Jacob, Claas Teichmann,
Sabina Abba Omar, Moetasim Ashfaq, Nikolina Ban, Katharina Bülow,
Melissa Bukovsky, Lars Buntemeyer, Tereza Cavazos, James Ciarlo`,
Rosmeri Porfirio da Rocha, Sushant Das, Fabio di Sante, Jason P. Evans,
Xuejie Gao, Graziano Giuliani, Russell H. Glazer, Peter Hoffmann, Eun-Soon Im,
Gaby Langendijk, Ludwig Lierhammer, Marta Llopart, Sebastial Mueller,
Rosa Luna-Nino, Rita Nogherotto, Emanuela Pichelli, Francesca Raffaele,
Michelle Reboita, Diana Rechid, Armelle Remedio, Thomas Remke,
Windmanagda Sawadogo, Kevin Sieck, José Abraham Torres-Alavez,
and Torsten Weber

ABSTRACT: We describe the first effort within the Coordinated Regional Climate Downscaling Experiment–Coordinated Output for Regional Evaluation, or CORDEX-CORE EXP-I. It consists of a set of twenty-first-century projections with two regional climate models (RCMs) downscaling three global climate model (GCM) simulations from the CMIP5 program, for two greenhouse gas concentration pathways (RCP8.5 and RCP2.6), over nine CORDEX domains at ~25-km grid spacing. Illustrative examples from the initial analysis of this ensemble are presented, covering a wide range of topics, such as added value of RCM nesting, extreme indices, tropical and extratropical storms, monsoons, ENSO, severe storm environments, emergence of change signals, and energy production. They show that the CORDEX-CORE EXP-I ensemble can provide downscaled information of unprecedented comprehensiveness to increase understanding of processes relevant for regional climate change and impacts, and to assess the added value of RCMs. The CORDEX-CORE EXP-I dataset, which will be incrementally augmented with new simulations, is intended to be a public resource available to the scientific and end-user communities for application to process studies, impacts on different socioeconomic sectors, and climate service activities. The future of the CORDEX-CORE initiative is also discussed.

KEYWORDS: Climate change; Regional effects; Climate models; Regional models

https://doi.org/10.1175/BAMS-D-21-0119.1
Corresponding author: Filippo Giorgi, giorgi@ictp.it
In final form 15 September 2021

AFFILIATIONS: Giorgi, Coppola, Abba Omar, Das, Giuliani, Glazer, Mueller, Pichelli, Raffaele, and Torres-Alavez—Abdus Salam International Centre for Theoretical Physics, Trieste, Italy; **Jacob, Teichmann, Bülow, Buntemeyer, Hoffmann, Langendijk, Lierhammer, Rechid, Remedio, Remke, Sieck, and Weber**—Climate Service Center Germany (GERICS), Hamburg, Germany; **Ashfaq**—Oak Ridge National Laboratory, Oak Ridge, Tennessee; **Ban**—University of Innsbruck, Innsbruck, Austria; **Bukovsky**—National Center for Atmospheric Research, Boulder, Colorado; **Cavazos and Luna-Nino**—Centro de Investigación Científica y de Educación Superior de Ensenada, Ensenada, Mexico; **Ciarlo`, di Sante, and Nogherotto**—National Institute of Oceanography and Applied Geophysics (INOGS), and Abdus Salam International Centre for Theoretical Physics, Trieste, Italy; **da Rocha**—University of São Paulo, São Paulo, Brazil; **Evans**—Climate Change Research Centre, School of Biological, Earth and Environmental Science, University of New South Wales, Sydney, New South Wales, Australia; **Gao**—Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China; **Im**—Hong Kong University of Science and Technology, Hong Kong, China; **Llopart**—São Paulo State University, São Paulo, Brazil; **Reboita**—Federal University of Itajuba, Itajuba, Brazil; **Sawadogo**—University of Augsburg, Augsburg, Germany

The Coordinated Regional Climate Downscaling Experiment (CORDEX) was created in the late 2000s with the overarching vision to advance climate downscaling science through global partnerships and coordination (Giorgi et al. 2009; Gutowski et al. 2016). Its main goals are to provide a common modeling framework to (i) improve understanding of regional to local processes and feedbacks, and how they affect regional climate variability and change; (ii) assess and improve different regional downscaling techniques [e.g., regional climate models, RCMs (e.g., Giorgi 2019); empirical statistical downscaling (ESD; e.g., Hewitson et al. 2014); variable resolution and uniform high-resolution global atmospheric modeling (e.g., McGregor 2015; Haarsma et al. 2016)]; (iii) produce large multimodel and multi-approach ensembles of downscaled projections for regions worldwide; and (iv) foster communication and interactions across the climate modeling and end-user communities.

The first activities of the CORDEX initiative involved mostly the RCM community and lead to the completion of ensembles of RCM-based projections over regions covering essentially all continents of the globe (e.g., Giorgi and Gutowski 2015). The model horizontal grid spacing was set at ~50 km, a relatively coarse resolution selected to enable broad participation by the RCM community. Different global climate models (GCMs) participating in phase 5 of the Climate Model Intercomparison Project (CMIP5; Taylor et al. 2012) were downscaled, and for the European region a large ensemble of high-resolution projections (grid spacing of ~12 km) was completed as part of the EURO-CORDEX program (Jacob et al. 2013, 2020).

While these first CORDEX activities were very successful in engaging a broad community, the ensembles produced for different regions were highly heterogeneous in terms of size and models involved, both global and regional. For example, relatively large ensembles were produced for domains such as Europe, Africa, North America, South Asia, and Southeast Asia, while comparatively smaller ones were completed for Central and South America, Australia, and Central Asia. This heterogeneity hampered the transferability of know-how from one region to another, and inhibited the coordinated use of CORDEX data for impact studies and climate service activities (except for individual regions such as Europe).

To address this issue, the CORDEX community developed the CORDEX Coordinated Output for Regional Evaluations program (CORDX-CORE; Gutowski et al. 2016), whose main objective is to produce a homogeneous set of twenty-first century projections following a common simulation protocol with a core set of RCMs downscaling a core set of GCMs over all (or most) CORDEX continental-scale domains. The first set of CORDEX-CORE simulations was recently completed using two RCM systems, the RegCM4 developed at the Abdus Salam International

Centre for Theoretical Physics (ICTP; Giorgi et al. 2012) and the REMO model developed at the Climate Service Center Germany (GERICS; Jacob and Podzun 1997; Jacob et al. 2012). As a first step in the analysis of these simulations, a special issue of *Climate Dynamics* on CORDEX-CORE (https://link.springer.com/journal/382/volumes-and-issues/57-5; hereafter CD-SI) was produced, including articles with focus on a wide spectrum of topics. Here we document this first CORDEX-CORE effort, hereafter referred to as CORDEX-CORE EXP-I, and provide a set of examples from the CD-SI illustrating the potential that this new ensemble offers toward the investigation of regional climate change processes, downscaling issues, and application to impact studies and climate service activities. We also provide a discussion of future perspectives of the CORDEX-CORE initiative. Note that we do not discuss here general issues pertaining to regional climate downscaling, as they are already amply treated in a series of review papers (e.g., Gutowski et al. 2020; Giorgi 2019; Giorgi and Gutowski 2015; Rummukainen 2010, and references therein).

The CORDEX-CORE EXP-I simulation protocol

The CORDEX-CORE EXP-I protocol consists of two simulation streams. First, a model evaluation stream in which the RCMs are driven by a reanalysis of observations for a given historical period and the results are compared to actual observations for that period. These experiments, usually referred to as "perfect boundary condition" simulations (Giorgi and Gutowski 2015), have the purpose to assess, and possibly optimize, the model performance when driven by good quality boundary conditions, so that the errors found in the simulations can be mostly attributed to the model internal physics and dynamics.

Second, a model projection stream in which the RCMs are driven by selected GCMs for simulations covering a reference historical period followed by a twenty-first century projection under different greenhouse gas (GHG) representative concentration pathways (RCPs) (Moss et al. 2010). The model evaluation for the reference period aims at assessing how the models reproduce relevant climate statistics during a time slice representing present-day conditions and to possibly identify errors introduced by the GCM boundary conditions. In the CORDEX-CORE EXP-I the model evaluation stream covers the period 1979–2010 with boundary conditions provided by the ERA-Interim reanalysis (Dee et al. 2011), while the model projection stream covers the period 1970–2100.

The participating RCMs were run over 9 of the 14 continental-scale CORDEX domains (Giorgi et al. 2009): Europe (EUR), Africa (AFR), South Asia (SAS), East Asia (EAS), Southeast Asia (SEA), Australia (AUS), North America (NAM), Central America (CAM), and South America (SAM) (Fig. 1). Five standard CORDEX domains were not included: Mediterranean, because it is mostly encompassed by the European domain and it is addressed by the Med-CORDEX initiative using coupled RCMs (Ruti et al. 2016); the Mediterranean–North Africa domain (MENA), because it mostly overlaps with other domains; Central Asia, which is a large but scarcely populated domain; and the two polar regions, for which one of the two participating RCMs (the RegCM4) has not been sufficiently tested. For all domains, the horizontal grid point spacing used by the RCMs is ~25 km, or 0.22° in latitude–longitude coordinates. This is a doubling of resolution with respect to the previous CORDEX simulations. Only for the European domain a higher resolution is used, 12 km (or 0.11° lat × lon), because this is the standard grid spacing in the EURO-CORDEX high-resolution simulations (Jacob et al. 2013, 2020).

For each domain, the RCMs downscaled a core set of three GCMs from the CMIP5 program (Taylor et al. 2012) under forcing from two RCPs, the low-end RCP2.6 (roughly corresponding to a global warming of ~1° ± 0.7°C by 2100 compared to 2005 temperatures; IPCC 2013) and the high-end RCP8.5 (roughly corresponding to a global warming of 4° ± 1.25°C by 2100 compared to 2005 temperatures; IPCC 2013). The three GCMs are HadGEM2-ES (Collins et al. 2011), MPI-ESM-MR (Zanchettin et al. 2013), and NorESM1-M (Zhang et al. 2012). Although it would have been preferable to downscale a larger number of GCMs, the choice of three was based on the availability of computational and human resources estimated by the participating groups. For the European domain a much larger set of high-resolution simulations is available as part of the EURO-CORDEX initiative with both RegCM4 and REMO, as well as other RCMs (Jacob et al. 2020).

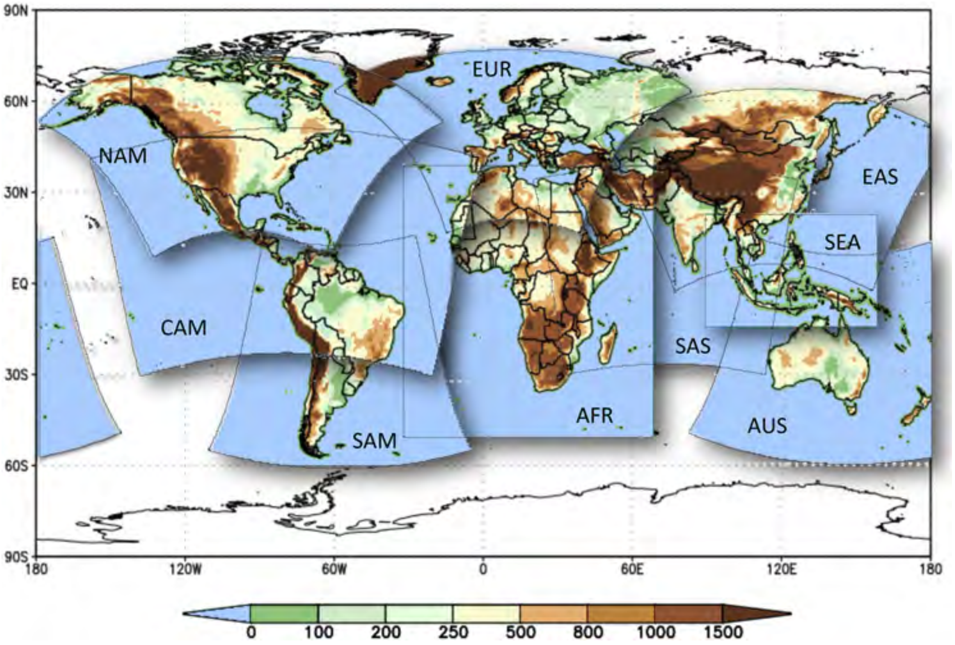

Fig. 1. CORDEX domains used in the CORDEX-CORE EXP-I. The lines indicate the domain's boundaries.

The reason for selecting the three specific GCMs was that, on the one hand, they have high (HadGEM2-ES), medium (MPI-ESM-MR), and low (NorESM1-M) equilibrium climate sensitivity within the CMIP5 ensemble; and on the other hand they perform reasonably well over most CORDEX-CORE domains (e.g., Elguindi et al. 2014; McSweeney et al. 2015). With this selection of scenarios and driving GCMs, the aim is to cover as much as possible the full CMIP5 global temperature projection range as affected by scenarios and climate sensitivity with a minimum set of relatively well performing models. Only two exceptions are present in the RegCM4 ensemble: the HadGEM2-ES over the South Asia domain, which was replaced by MIROC5 (Watanabe et al. 2010) because it fails to simulate the Indian monsoon precipitation (Ashfaq et al. 2017); and the NorESM1-M over the Central America and North America domains, which was replaced by the GFDL-ESM2M (Dunne et al. 2012) because it does not simulate adequately the environment conducive to tropical storm formation over the region. The overall selection of GCMs and scenarios lead to a total of six twenty-first-century projections for each of the nine CORDEX domains and each participating RCM.

To date, two RCM systems have completed the full set of CORDEX-CORE EXP-I simulations, the RegCM4 (Giorgi et al. 2012) and REMO (Jacob et al. 2012). RegCM4 is the fourth-generation RCM system developed at the Abdus Salam International Centre for Theoretical Physics (ICTP), in Trieste, Italy, and its basic structure is described by Giorgi et al. (2012). It is a hydrostatic, sigma-pressure vertical coordinate model using in the present runs 23 vertical sigma levels, more densely distributed in the surface boundary layer. RegCM4 includes multiple parameterization options for the model physics representations, i.e., resolvable scale and convective precipitation and clouds, surface fluxes, land surface processes, radiative transfer, and boundary layer processes. For each domain, physics parameterizations were selected in order to optimize the model performance based on the analysis of a series of ERA-Interim driven preliminary experiments. This analysis focused on biases for variables such as temperature, precipitation, wind and sea level pressure, as well as higher-order statistics, such as precipitation intensity distribution functions. The schemes selected are reported in Coppola et al. (2021). RegCM4 is a public community model used by a large international user community (e.g., Pal et al. 2007), and the set of RegCM4

CORDEX CORE runs was completed by different model users: ICTP, Trieste, Italy (SAM, CAM, EU, AFR, AUS domains); Institute for Atmospheric Physics, Beijing, China (EAS); the Hong Kong University for Science and Technology, Hong Kong, China (SEU); National Center for Atmospheric Research, Boulder, Colorado (NAM); Oak Ridge National Laboratory, Oak Ridge, Tennessee (SAS). The simulations performed at ICTP were completed on the CINECA supercomputing center facilities.

REMO is a hydrostatic RCM which uses hybrid vertical coordinates (Jacob et al. 2012; Remedio et al. 2019) and is developed at the Climate Service Center Germany (GERICS). The model dynamical core is taken from the German Weather Service weather prediction model (Europa Modell), while the physics parameterizations are based on those from the ECHAM 4.5 GCM. For all domains REMO utilizes 27 hybrid sigma pressure levels providing higher resolution in the boundary layer. Differently from the approach used in RegCM4, REMO employs the same physics schemes for all simulation domains, although the values of some parameters of the schemes are customized for the specific climate conditions of the different domains to optimize the model performance. The physics configurations used in the REMO experiments, as well as an overall evaluation of the ERA-Interim driven simulations, are reported in Remedio et al. (2019).

The initial and lateral meteorological boundary conditions for wind components, temperature, moisture, and surface pressure are provided from the ERA-Interim reanalysis or the selected GCMs at 6-hourly intervals. Time-dependent sea surface temperatures (SSTs) are also provided by the forcing models as lower boundary conditions. Greenhouse gas (GHG) concentrations are updated yearly for both for RegCM4 and REMO using observed values for the historical period and scenario values for the future period, as done in the GCMs. At the time of completion of these simulations each RCM was set up to have its own specification of land surface types and background aerosols, which are taken from observations or global model estimates (for the aerosols) for the historical period and are not changed in time for the future scenario period. This is different from the driving GCMs, which use time varying aerosols and land use characteristics, although implemented differently across models (e.g., https://compare.es-doc.org/). In some cases, this has been shown to lead to significant differences between the GCM and RCM projections, e.g., over Europe (Boé et al. 2020), and this is an element that should be considered in assessing the overall uncertainty in the projections. The capability of including time-varying land use and aerosols is being implemented in more recent versions of the two RCMs.

A total of more than 1 petabyte of output data was produced by each RCM system following the standard, quality controlled, format output recommended in the CORDEX protocol (Gutowski et al. 2016; https://cordex.org). The data are stored on the Earth System Grid Federation (ESGF) and are freely available for download and use.

Some illustrative results from the first analysis of the CORDEX-CORE EXP-I simulations

As mentioned, the first analysis of the CORDEX-CORE EXP-I simulations is presented in a CD-SI which includes papers covering a wide range of topics (Table 1). Most papers are based on multimodel and/or multidomain analyses and, although only the paper by Ciarlo` et al. (2021) is specifically devoted to the added value (AV) issue, all papers compare RCM and driving GCM information to assess the gain obtained by the higher-resolution RCMs. Note that some papers include only analysis of one or a subensemble of domains because of the specific focus of the study, or include only the RegCM4 experiments because at the time of completion of the studies the REMO simulations were not yet available. Also, the topics of most of these papers were identified and laid out during a paper-writing workshop held at ICTP in May 2019. Here we present a set of illustrative results from the CD-SI, and for more detail the reader is referred to the original papers.

Table 1. List of papers included in the CD-SI on the first analysis of the CORDEX-CORE EXP-I ensemble.

Type of study	Physical process	Domains	Reference
Circulation			
	ENSO	SAM, AFR, CAM, NAM, EAS, SEA	Torres-Alavez et al. (2021a)
	Tropical storms	CAM, SAS, EAS AUS	Torres-Alavez et al. (2021b)
	Low-level jets	CAM, SAM, AFR, SAS	Torres-Alavez et al. (2021c)
	Monsoons	CAM, SAM, AFR, SAS, EAS, SEA, AUS	Ashfaq et al. (2021)
	Wintertime storms	SAM, AFR, AUS	Reboita et al. (2021)
	Subtropical jets	CAM	Luna-Niño et al. (2021)
	Severe thunderstorms	NAM, SAM, SEA	Glazer et al. (2021)
	Drivers of water budget	EUR, SAM	Llopart et al. (2021)
Evaluations			
	Mean change	ALL	Teichmann et al. (2021)
	Mean change	AUS	Evans et al. (2021)
	Added value	ALL	Ciarlo` et al. (2021)
Impacts/applications			
	Extremes and hazards	ALL	Coppola et al. (2021)
	TOE of heat stress variables	EUR, AFR, SAS, EAS, SEA, AUS	Im et al. (2021)
	Wind and solar energy	AFR	Sawadogo et al. (2021)

First, in an overall assessment of the mean temperature and precipitation biases and change patterns, Teichmann et al. (2021) showed that the respective climate change signals of the CORDEX-CORE RCMs and the selected driving GCMs cover the corresponding spreads (interquartile range) of the entire CMIP5 ensemble to a reasonable extent in most regional domains, which is an important prerequisite for the experiment. In addition, the CORDEX-CORE RCMs generally followed the driving GCMs with respect to the monthly region-average broad climate change patterns, but produced fine-scale detail in response to local forcings (e.g., topography).

Coppola et al. (2021) extended this overall analysis to the changes in a series of extreme event and hazard indices relevant for impact applications. Figure 2 shows a selection of the results of this study. In the figure, for each domain, a representative index is selected and the change is calculated between an end of twenty-first century time slice (2080–99) and the reference period (1995–2014) under the RCP8.5 scenario.

It can be seen that the models project an increase in drought frequency over Central America and the Mediterranean basin, two regions identified as prominent climate change hot spots (e.g., Giorgi 2006); a large increase of heat wave days over Africa; an increase in precipitation extremes throughout North America and an increase in the number of dry days over South America; a strong increase of hot days over East Asia and the India subcontinent; and an increase in cooling degree days through Australia and Southeast Asia. The results, which we recall only provide examples of changes in different illustrative extreme indices for the various regions, are consistent with the expectations of the effects of global warming on the hydrologic cycle (e.g., Trenberth et al. 2003; Giorgi et al. 2019), but it is evident that the RCMs can provide substantial high-resolution detail related to local physiographical features.

The paper by Evans et al. (2021) presents a comprehensive analysis focused on the Australian continent, demonstrating the use of the CORDEX-CORE data to complement existing CORDEX simulations. An existing 14-member CORDEX Australasia ensemble was enhanced to a 20-member ensemble by adding the CORDEX-CORE simulations, creating the largest regional climate projection ensemble for this region. Evaluation of the ensemble showed a good overall representation of recent climate, although with an underestimation of the diurnal temperature range and precipitation across southern Australia. In the latter case, RegCM4 was one of the few models to overestimate southern Australian precipitation. Future projections under the RCP8.5 scenario indicated temperature increases of up to ~5 K in the continental interior by the end of the twenty-first century and ~3 K at the coast. Projected future precipitation changes indicated drying in the southeast, southwest, and northern regions of Australia, with consistency across the majority of CORDEX-CORE members.

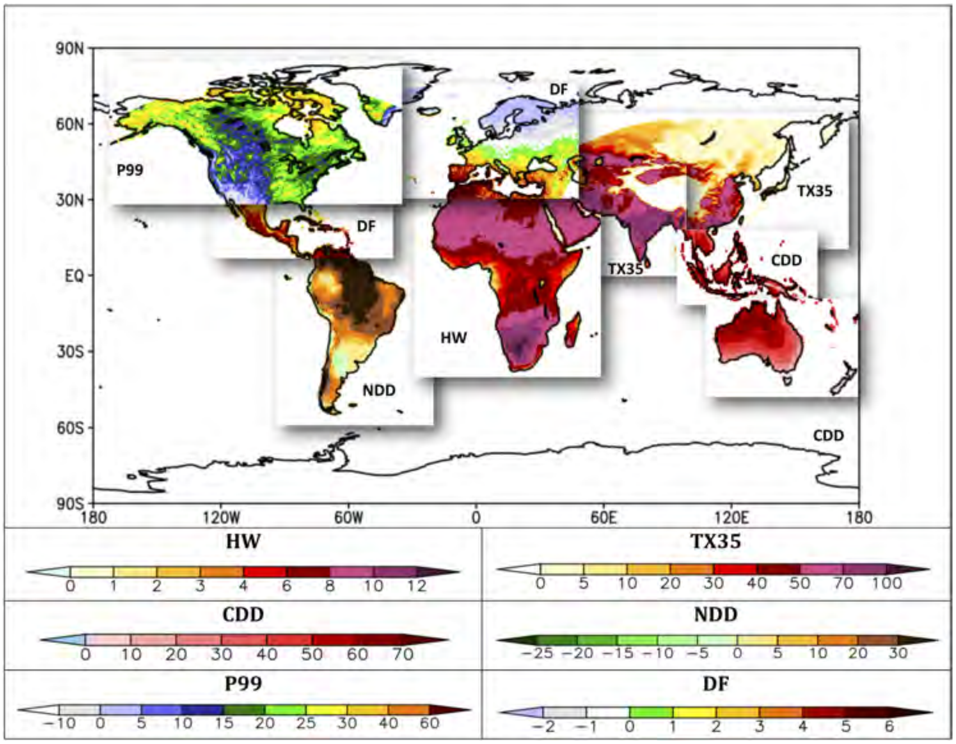

Fig. 2. Change in selected extreme and hazard indices over different domains calculated from the CORDEX-CORE EXP-I simulations. The changes are for 2080–99 minus 1995–2014, RCP8.5. The indices are P99 = 99th percentile of daily precipitation (mm day^{-1}); DF = drought frequency (number of days per decade); NDD = number of dry days; HW = number of heat wave days; TX35 = number of days with maximum temperature above 35°C; CDD = number of cooling degree days. Adapted from Coppola et al. (2021), who describe in detail the underlying calculations.

The issue of AV is still a much debated one (Rummukainen 2016; Giorgi 2019; Lloyd et al. 2020). This is because the AV may depend on many factors, such as variable and region of interest, temporal and spatial scale, processes and statistics being considered, and systematic biases in the driving GCMs and nested RCMs (Di Luca et al. 2012; Giorgi and Gutowski 2015; Torma et al. 2015; Rummukainen 2016; Giorgi 2019). Therefore, the assessment of AV often needs to be targeted. In addition, the climate change signal in the driving GCM and nested RCM systems can be quite different, and the AV in present-day climate statistics does not necessarily imply improved future climate information, so that the AV in future change signals needs to be carefully assessed based on multiple evidence and understanding of underlying processes (e.g., Giorgi et al. 2016).

For all these reasons, although some general metrics of AV have been proposed (e.g., Di Luca et al. 2012, 2013), and although the AV for specific simulations and applications has been identified in many studies (e.g., see Rummukainen 2016; Giorgi 2019, and references therein), comprehensive assessments of the AV have not been published. The CORDEX-CORE EXP-I coordinated dataset offers a unique opportunity to address this issue in a wide ranging context.

The paper by Ciarlo` et al. (2021) represents one such attempts at a comprehensive study of AV. It introduces a new metric of AV, which is based on the integrated distance between observed and simulated probability density functions (PDFs) of daily precipitation events calculated at the grid point level. This metric is especially useful for identifying AV because it is at fine temporal and spatial scales, and in particular for extreme events (tail of the distributions), that the AV should be more evident and relevant for impact applications (Giorgi 2019). Ciarlo` et al. (2021) also extend this metric to the climate change signal, by which integrated

PDF distances are calculated between the PDFs of precipitation in future and present-day time slices (or "PDF change signal"). The potential AV is then measured by the difference between the GCM and RCM PDF changes, and the assumption is that at grid points where the RCM shows AV in present day climate and the difference in GCM and RCM PDF change signals is large, there is AV in the future climate change simulations.

Figure 3 shows an example of the results by Ciarlo` et al. (2021), i.e., the value of the GCM minus RCM difference between the normalized distance of simulated versus observed PDFs, where values greater (lower) than 0 indicate that the RCMs (GCMs) are closer to observations, and thus produce AV. For the European analysis, the large EURO-CORDEX 0.11° resolution ensemble is considered (Jacob et al. 2020), while for the global analysis both the RegCM4 and REMO CORDEX-CORE EXP-I simulations are included (see Tables 1 and 2 of Ciarlo` et al. 2021). In the European analysis, a set of high-resolution gridded observations developed for different subregions is employed (Fantini et al. 2018), while the global analysis utilizes the TRMM dataset (e.g., Huffman et al. 2001) along with other regional datasets. The period of analysis depends on the availability of observed data, but it is mostly 1995–2014.

Two sets of plots are reported, one in which the AV metric is calculated using the entire PDFs and the other in which only the segment of the PDFs above the 99th percentile is considered, thus being a measure of extreme events. It can be seen that AV is found in both cases throughout the entire European area (except for some small isolated spots in the 99th percentile plot), and over most regions globally, with the exception of areas in the western United States, along the Andes chain, and isolated areas in Africa and Asia for the 99th percentile. Note that for some of these areas, and in particular remote areas or areas characterized by complex topography, e.g., across the mountainous western United States, Andes, Africa, and Tibetan Plateau,

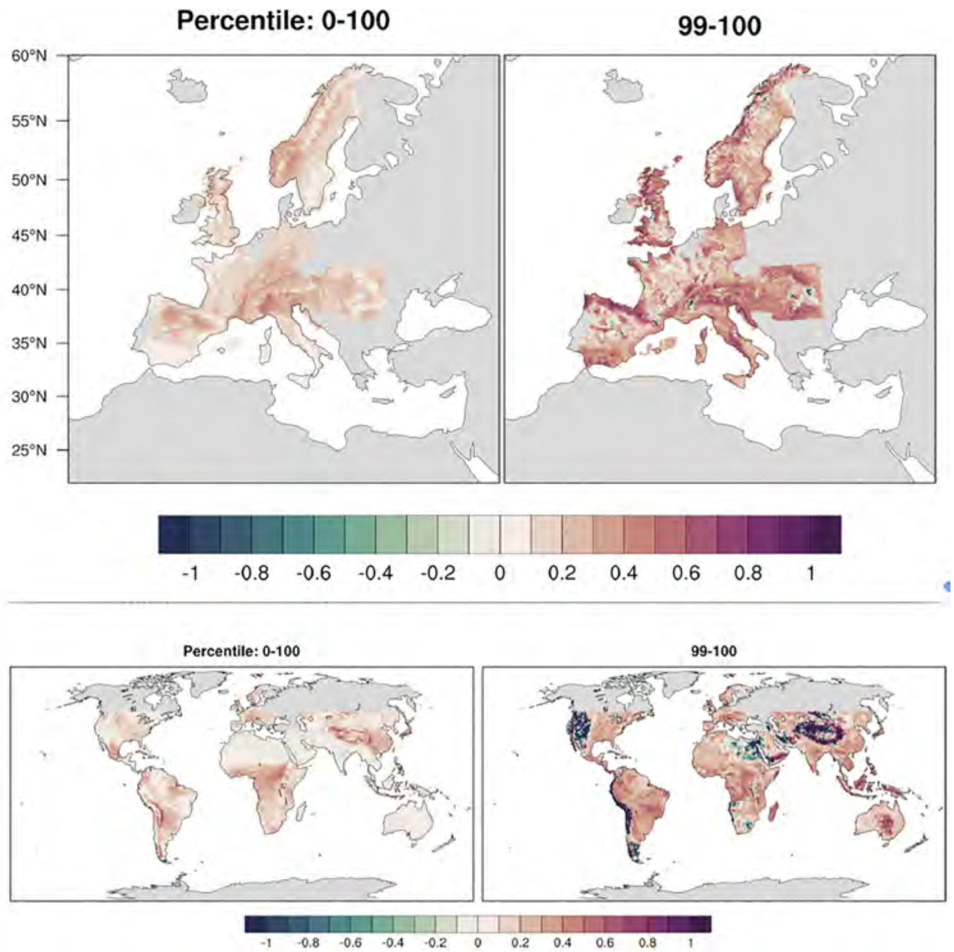

Fig. 3. Added value (AV) of RCMs compared to the driving GCMs as measured by the difference between the normalized distance of simulated vs observed daily precipitation PDFs. Positive values indicate better performance by the RCMs, and thus AV. (top) The EURO-CORDEX high resolution (grid spacing of ~12 km) simulations and (bottom) the CORDEX-CORE EXP-I simulations. (left) The AV index calculated over the entire PDFs and (right) the AV index calculated only for the portion of the PDF above the 99th percentile. Note that, in the top panels, data are reported only for countries and regions for which high-resolution observed datasets were available. Adapted from Ciarlo` et al. (2021), who describe in detail the underlying calculations.

precipitation observations can be heavily undersampled (e.g., Beck et al. 2020), so that a robust model evaluation is difficult and RCMs might be even more realistic than gridded observations (e.g., Lundquist et al. 2019).

Another area where the use of RCMs can be especially beneficial is the simulation of intense mesoscale systems, such as tropical cyclones (TCs). Several papers have analyzed the RCM simulation of TCs over different basins (e.g., Lavender and Walsh 2011; Jin et al. 2016; Fuentes-Franco et al. 2017; Vishnu et al. 2019), also in a climate change context (e.g., Diro et al. 2014; Knutson et al. 2015). However, they mostly focused on individual basins. Taking advantage of the CORDEX-CORE EXP-I dataset, Torres-Alavez et al. (2021a) for the first time considered five TC basins in an RCM-based study: North Atlantic, northwest Pacific, eastern Pacific, north Indian Ocean, and Australasia, looking at both present-day and future climate time slices. A tracking scheme based on relative vorticity and warm core characteristics was used (Hodges 1999), with different threshold values for the RCM and GCM data to account for the respective resolutions and thus allow a consistent intercomparison.

Figure 4 shows the number of days with TC occurrence at a given grid location (grid box) for the RegCM4 CORDEX-CORE EXP-I simulations and the corresponding GCM ensemble over four domains encompassing five TC basins during a present-day time slice (1995–2014). Also shown are observations from the IBTrACS dataset (Knapp et al. 2018) for the same period. It can be seen that the RegCM4 is considerably closer to observations than the GCMs in the northwest Pacific, eastern Pacific, and North Atlantic basin, while it produces too few TCs with respect to both the GCMs and observations in the north Indian Ocean region. The ensembles show a similar performance over the Australasia basin. These results are in line with previous experience with the RegCM4 indicating a substantial dependency of the model's ability to simulate TCs on the specific basin, the physics schemes and the driving GCMs (Diro et al. 2014; Fuentes-Franco et al. 2017). Concerning future changes in TC characteristics, Torres-Alavez et al. (2021a) found a basin-dependent response, with an increase of TC frequencies in the north Indian, northwest Pacific, and eastern Pacific regions, related to an increase in midtropospheric humidity, and a decrease in TC frequency over the North Atlantic and Australasia basins in response to increased wind shear. An increase in future storm rainfall and frequency of most intense TCs was also found in most basins.

In another study, Reboita et al. (2021) focused on wintertime extratropical cyclonic activity over the Southern Hemisphere domains, presenting in this respect the first RCM-based multidomain investigation. Using both an Eulerian and a Lagrangian approach they found a projected future increase in synoptic activity south of 40°S, consistent with a southward displacement of storm tracks, and a decrease in the frequency of cyclones along with a tendency for stronger systems. A significant increase in the intensity and extension of areas affected by precipitation associated with cyclones was found, with a statistically significant trend of individual cyclones to produce more rainfall.

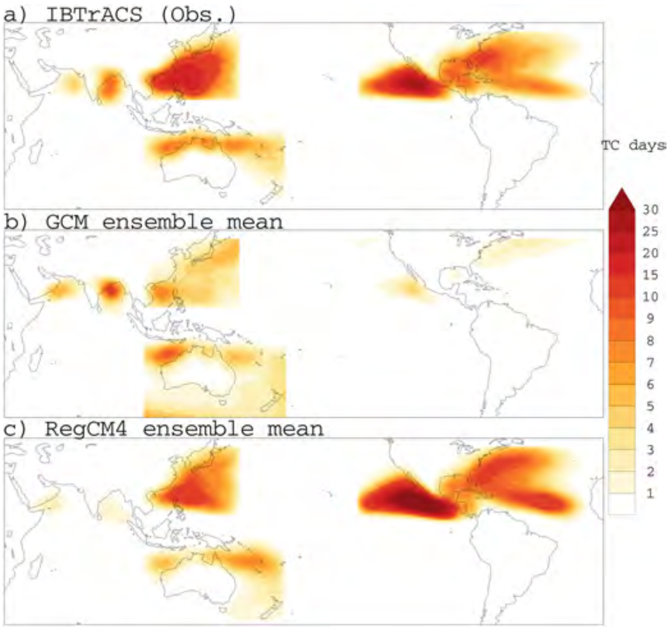

Fig. 4. Number of cyclone tracks crossing a given grid point (TC frequency) in (a) observations, (b) driving GCM ensemble, and (c) RegCM4 CORDEX-CORE EXP-I ensemble. Units are number of TCs per year. Adapted from Torres-Alavez et al. (2021a), who describe in detail the underlying calculations.

Still focusing on the South America domain, along with the European one, Llopart et al. (2021) showed how the analysis of the water budget components can provide important information on understanding the mechanisms underlying regional precipitation changes.

The CORDEX-CORE data can also be used to study regional circulation patterns. We here highlight two such studies from the CD-SI, those of Ashfaq et al. (2021) and Torres-Alavez et al. (2021b). Ashfaq et al. (2021) analyzed nine monsoon regions from seven CORDEX-CORE domains in the set of RegCM4 simulations: CAM, SAM, SAS, SEA, EAS, AUS, and AFR. After a validation analysis showed that the GCM–RCM systems were able to simulate a realistic seasonal evolution of the monsoons, Ashfaq et al. (2021) identified common responses across the different monsoon systems to global warming conditions: a delay in the monsoon onset, a decrease in monsoon precipitation seasonality, and a reduction in rainy season length associated with a decrease in premonsoon precipitation and latent heat release, which in turn inhibited the monsoon transition into deep convection.

The issue of El Niño–Southern Oscillation (ENSO) has been little explored within the context of regional climate modeling, probably because ENSO is a large-scale phenomenon with global teleconnections, and therefore belongs more naturally to the global modeling realm. However, ENSO is an important factor regulating the variability of many regions of the world, especially in the tropics, and the ENSO signal, although originating remotely, can be substantially modulated by local forcings, such as topography or land use (e.g., Arias et al. 2021). It is thus important to investigate whether RCMs can maintain the ENSO signal of the forcing GCMs and can eventually augment it with the representation of local forcings.

Analyses of the ENSO signal in RCMs have been so far focused on individual regions (e.g., Tourigny and Jones 2009; da Rocha et al. 2014; Meque and Abiodun 2015; Endris et al. 2018), but taking advantage of the CORDEX-CORE EXP-I ensemble Torres-Alavez et al. (2021b) investigated different areas significantly affected by ENSO: southern Africa, North and Central America, South America, South and Southeast Asia, and the Arabian–Asian region. Figure 5 shows a regression analysis of the Niño-3.4 index to the boreal winter precipitation in observations, GCM ensemble, and RCM ensemble (both RegCM4 and REMO). It shows that not only are the driving GCMs chosen in the CORDEX-CORE EXP-I able to reproduce the basic ENSO teleconnection patterns of precipitation, but the RCMs also retain the signals well, and in some areas show increased fine-scale agreement with observations, most noticeably over South East Asia, Central and North America, and southern Africa.

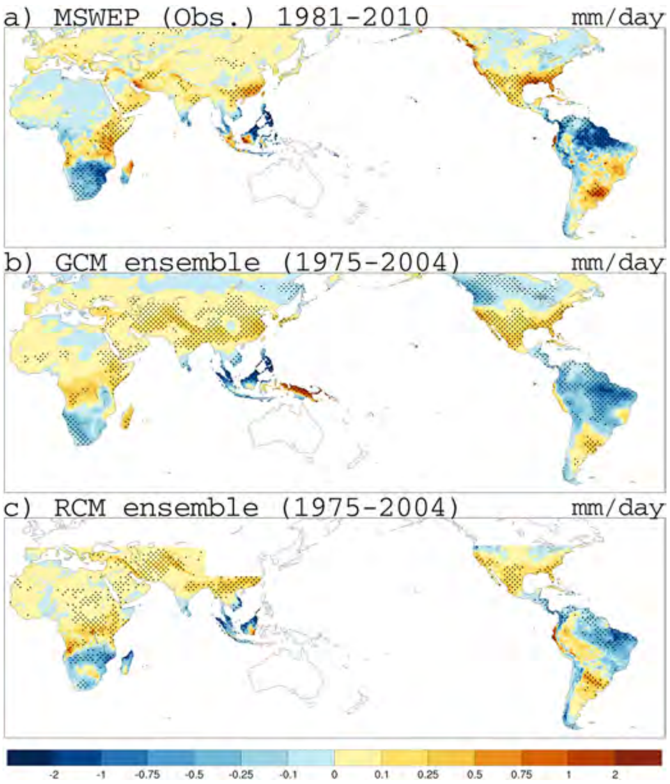

Fig. 5. Regression of the Niño-3.4 index to the boreal winter precipitation in (a) observations, (b) GCM ensemble, and (c) RCM ensemble. Adapted from Torres-Alavez et al. (2021b), who describe in detail the underlying calculations. Dotted areas indicate statistical significance at the 95% confidence level.

Luna-Niño et al. (2021) analyzed the interannual variability of the boreal winter (DJF) subtropical jet stream (STJ) over the Central America, Mexico, and Caribbean regions from the CORDEX CAM RegCM4 simulations during the reference period 1980–2010. They showed that the model captured the STJ variability and its relationship with different teleconnections when driven by the ERA-Interim reanalysis. When driven by the GCMs, the RegCM4 simulated better the principal modes of the Atlantic jet variability than those of the Pacific jet exit region, a result mostly driven by the forcing large-scale GCM fields. However, the regional model had a better representation of the intensity of the Pacific mode, and generated more intense jet cores over both the Atlantic and Pacific oceans, likely due to the greater model resolution. The RCM simulations also captured the sign of the temperature and precipitation anomalies over most areas of the domain as forced by the STJ variability. Their precipitation results over the CORDEX CAM domain are consistent with those in Fig. 5, this signal being linked to a more zonal and intense STJ during El Niño than La Niña.

Another unique application of the CORDEX-CORE EXP-I ensemble is that of Glazer et al. (2021), who analyzed the impact of global warming scenarios on environments conducive to the development of severe thunderstorm systems, such as tornadoes, high winds, and hail. Previous RCM-based work had mostly focused on individual regions (e.g., Trapp et al. 2007), while Glazer et al. (2021) investigated three regions where severe storms have a considerable impact: subtropical South America, eastern India/Bangladesh, and North America. The analysis is based on convective available potential energy (CAPE) and vertical wind shear during the main severe weather seasons. In every region, the frequency of occurrence of environments supportive of severe thunderstorms was projected to increase during the severe weather season months, with a corresponding increase in the number of potential severe weather days and in some cases a shift of the peak month of severe day counts (Fig. 6). Surface warming and moistening sustained a robust increase in CAPE in all regions; however, a poleward displacement of vertical wind shear lead to the displacement of severe environments, for example, over the North American and South American continents (Glazer et al. 2021).

The last two illustrative examples we mention here are of a more applied nature. The first is from the paper by Im et al. (2021), who calculate the time of emergence (TOE; Giorgi and Bi 2009) of temperature and wet-bulb temperature (an indicator of heat stress for the human body) change signals in the CORDEX-CORE RegCM4 simulations and the driving GCMs over multiple domains. Based on three different TOE metrics, they find that over tropical regions, and especially Africa and Southeast Asia, the temperature signals emerge from the end of twentieth-century natural variability already in the first decades of the twenty-first century. For example, Fig. 7 reports the summer temperature TOE over Africa in the CORDEX-CORE EXP-I RegCM4 and GCM runs, along with the elevation dependency of this signal. It can be seen that in the RCP2.6 scenario the RegCM4 projects consistently a later occurring TOE than the GCMs throughout the twenty-first century, while in the RCP8.5 scenario the TOE of the GCMs occurs later thaa in the RCM between 2020 and 2050. These differences in response between the RCM and GCMs can be at least partially attributed to the higher resolution of the RegCM4 in relation to the increase in temperature variability with spatial scale (e.g., Giorgi 2002), which leads to an increase in natural variability at the finer RCM resolution and thus a delayed TOE. Also interesting is that the elevation dependency of the TOE is different in the two ensembles and, in particular, differently from the GCMs, the TOE shift to earlier decades with elevation in the RegCM4 due to a projected enhancement of warming with elevation.

Finally, Sawadogo et al. (2021), investigated the projected changes in different quantities relevant for renewable energy production in Africa from the RegCM4 CORDEX-CORE EXP-I AFR projections under the RCP2.6 and RCP8.5 scenarios. The quantities analyzed were photovoltaic power potential (PVP), concentrated solar power output (CSPOUT), and wind power density (WPD), which depend on model-produced environmental variables such as temperature, solar radiation, and 100-m winds. Sawadogo et al. (2021) first showed that the

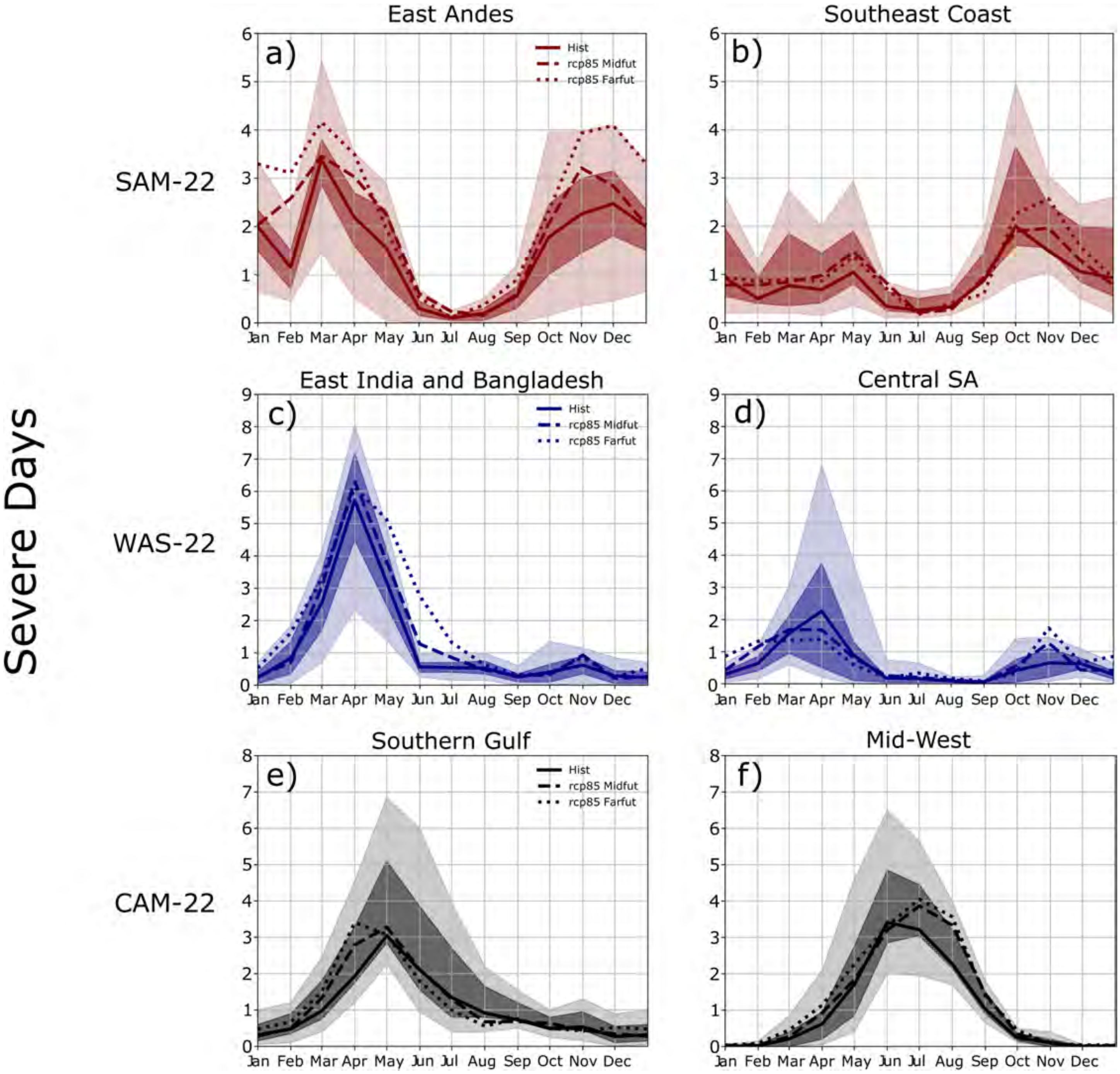

Fig. 6. Annual cycle in severe days calculated over two regions from the South America simulations (dark red): (a) the region east of the Andes and northern Argentina (35°–25°S, 68°–60°W) and (b) the southeast coast of Brazil (35°–20°S, 60°–45°W); two regions from South Asia simulations (blue): (c) East India and Bangladesh (22°–27°N, 87°–93°E), and (d) central South Asia (20°–27°N, 77°–87°E); and two regions from the Central America simulations, including most of the continental United States (black): (e) the southern United States and Gulf Coast (28°–38°N, 95°–78°W), and (f) the midwestern United States (38°–45°N, 50°–80°W). The monthly mean in severe days is calculated from the historical (solid lines), mid-future (2040–59) RCP8.5 (dashed lines), and far-future (2070–99) RCP8.5 (dotted lines) periods in each domain. The darker (lighter) shaded regions represent the 25th (5th) and 75th (95th) percentile region of the severe day counts over the 20-yr mean historical period in each area. Adapted from Glazer et al. (2021), who describe in detail the underlying calculations.

higher resolution of the RegCM4 lead to an improved simulation of several of these variables, in particular the 100-m-level winds. Changes in PVP, CSPOUT, and WPD over different subregions of the African continent showed a prevailing future decrease in PVP and an increase in CSPOUT and WPD, albeit with substantial cross-regional variability.

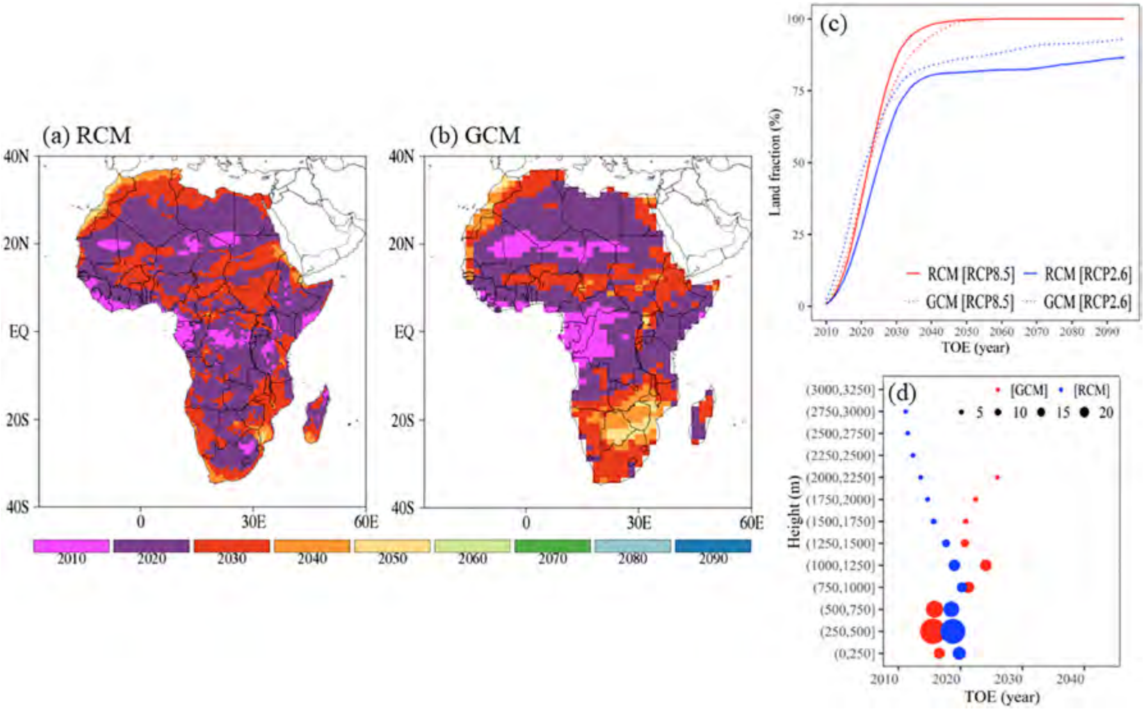

Fig. 7. TOE of summer mean temperature over Africa derived from the (a) RCM and (b) driving GCM ensemble CORDEX-CORE EXP-I projections for the RCP8.5 scenario. (c) Cumulative distribution of land area fractions along the TOE timeframe derived from the RCM and GCM ensemble projections forced by the RCP8.5 and RCP2.6 scenarios. (d) TOE pattern as a function of elevation over Africa. The different size of circle is proportional to the percentage of number of grids included in individual height ranges. Adapted from Im et al. (2021), who describe in detail the underlying calculations.

In summary, the examples briefly discussed here illustrate well the wide range of possible applications of the CORDEX-CORE EXP-I simulations. The reader is referred to the original papers for more detailed discussion of the specific analyses, which represent the basis for eventual further investigations.

Conclusions and future outlook for the CORDEX-CORE initiative

The CORDEX-CORE EXP-I, even though limited to two RCM systems and a small ensemble of driving GCMs, represents the first example of RCMs using a common simulation protocol to produce a homogeneous set of projections over multiple domains covering most land areas worldwide. This is an important step forward within the CORDEX initiative as, on the one hand, it can allow the RCM community to address in a more comprehensive and global way outstanding methodological issues in dynamical downscaling (e.g., the AV), and on the other hand, it constitutes an unprecedented RCM-based high-resolution dataset for application to impact assessment studies and climate service activities. In this paper we have provided some illustrative examples of analyses of these experiments, while further studies are under way (e.g., Weber et al. 2020).

A further evidence of the importance of this dataset is that it is a component of the climate change atlas produced as part of the AR6 of the Intergovernmental Panel on Climate Change (IPCC), which represents the first time in which RCM projections appear in a prominent way in IPCC reports. In addition, the CORDEX-CORE data may provide valuable contributions to a number of programs under the World Climate Research Program (WCRP), such as the Climate Information for Regions unifying theme, the Global Energy and Water Exchanges (GEWEX) core project, the Weather and Climate Extremes and Water for the Food Baskets of the World grand challenges, and the My Climate Risk and Digital Earth lighthouse activities (see wcrp-climate.org).

What are foreseeable future steps in the CORDEX-CORE initiative? The current EXP-I dataset can be enlarged through the inclusion of further simulations with other RCMs, and some efforts are already under way, e.g., the RCM CCLM5-0-15 is being used for simulations over the Africa domain (three GCMs, RCP2.6/RCP8.5). The EXP-I experiments utilized driving GCM simulations from CMIP5, since these were the most advanced projections available at the time of the experiment design and completion. A new generation of GCM projections has become available since then as part of the CMIP6 framework (Eyring et al. 2016), with models of higher resolution and complexity than in CMIP5. CMIP6 models also span a broader range of climate sensitivities than CMIP5 ones (Forster et al. 2020), with possibly different or amplified regional climate responses. Therefore, there is certainly room to extend the CORDEX-CORE simulations to include members of the CMIP6 ensemble as driving GCMs.

In terms of resolution, the philosophy of the CORDEX-CORE approach is to utilize continental-scale domains and cover most, if not all, land regions of the world, and this necessarily poses some limits to the resolution affordable to most groups. The EXP-I initiative has demonstrated that a grid spacing of 25 km is computationally affordable for such types of domains. However, results from EURO-CORDEX (Jacob et al. 2013, 2020) have shown that a further doubling of the resolution, i.e., a grid spacing of ~12 km (or 0.11°), can yield significant additional information (Torma et al. 2015; Prein et al. 2016), sometimes even leading to possible surprises in areas of complex topography (Giorgi et al. 2016). It might thus be desirable to move to a grid spacing of order 10 km as a standard for the next generation of CORDEX-CORE runs, a step probably doable in view of the developments in computing architectures foreseeable in the next few years.

The next fundamental step in regional climate modeling is the transition to nonhydrostatic RCMs being run at convection permitting resolutions of a few kilometers, or CP-RCMs (Prein et al. 2015; Giorgi 2019; Coppola et al. 2020). Simulations of up to several decades length at grid spacings of 1.5–4 km over continental or sub-continental-scale domains have already been carried out, also in a multimodel context (e.g., Rasmussen et al. 2011; Ban et al. 2014; Kendon et al. 2014; Liu et al. 2017; Coppola et al. 2020; Ban et al. 2021; Pichelli et al. 2021). In particular, some recent papers within a CORDEX Flagship Pilot Study (FPS; Gutowski et al. 2016) dedicated to the CP-RCM applications (Coppola et al. 2020) present an overview of the first multimodel experiments of 10-yr simulations at convection permitting resolutions (1.5–3.0 km) for the present day and the end of the twenty-first century (Ban et al. 2021; Pichelli et al. 2021).

Ban et al. (2021) first evaluated the performance of a 23 member CP-RCM ensemble of models driven by the ERA-Interim reanalysis of observations (through an intermediate-resolution model domain). Confirming previous work, they found that the convection-permitting simulations overcome some long-standing limitations of coarse-scale models, such as the early onset during the day of too weak summer convective precipitation, the tendency to trigger too frequently weak precipitation events, and the underestimation of frequency and intensity of high-impact weather extremes, especially at the subdaily scales. More importantly, these improvements were found to be consistent across the different CP-RCMs, with reduced uncertainty across the ensemble compared to corresponding coarser resolution RCMs.

Pichelli et al. (2021) then analyzed an ensemble of CP-RCM simulations for the same Alpine domain and model resolutions, with the models driven by GCMs, still through an intermediate-resolution RCM simulation. They assessed simulated precipitation in 10-yr time slices for the present day and the end of twenty-first century under the RCP8.5 emission scenario, finding that the CP-RCMs amplify most of the future change signals of their coarse resolution counterparts, delivering new insights into future climate over the Alpine region.

The precipitation intensification indicated by the CP-RCMs is more pronounced than previously found, especially at the subdaily scale, leading to a strong increase in the frequency of severe and flood prone rainfall events.

Despite these developments, however, it may still be a number of years before century-scale simulations at convection permitting resolutions over continental-scale domains become the norm for RCMs. The extension of CP-RCM modeling to the CORDEX-CORE framework is thus not trivial. Some possible options in this regard could be (i) identifying sub-continental-scale hot spots of special interest, e.g., highly populated urbanized areas or “food baskets” of the planet (see wcrp-climate.org grand challenge on this issue), for which convection permitting multi-decadal- to century-scale simulations might become more feasible; (ii) targeted regional experiments aiming at specific issues, such as land-use change and urbanization scenarios, coastal environments and small islands, or storyline approaches; and (iii) analysis of specific regional processes or circulations, e.g., monsoons or tropical storms.

Within this context, it is important to enhance the interactions and synergies between the GCM and RCM modeling communities. Global coupled GCMs are being tested in a multimodel framework at grid spacings of a few tens of kilometers (e.g., as part of the High Resolution Model Intercomparison Project, HighResMIP; Haarsma et al. 2016), and thus they should be considered within the CORDEX-CORE framework, an objective that was already framed in the original CORDEX initiative (Giorgi et al. 2009), but so far not sufficiently well explored. It is also likely that over the next decade or so, global convection-permitting models will be developed for application to long-term climate simulations (e.g., Stevens et al. 2019), and in this regard there is much that can be learned from the ongoing very high-resolution activities within the RCM community.

A key objective of the CORDEX-CORE inititative is to build large multimodel ensembles of projections, not only in terms of driving GCMs, but also in terms of RCMs, since the RCM internal physics has been shown to be an important component of the uncertainty range for variables driven by local processes, such as summer convective precipitation (e.g., Déqué et al. 2007; Paeth et al. 2011). Only two RCM systems participated to the EXP-I; however, there are other RCMs which encompass fairly large modeling communities [e.g., WRF (Powers et al. 2017), COSMO-CLM (Rockel et al. 2008), ALADIN/AROME (Termonia et al. 2018), RCA (Strandberg et al. 2014), RACMO (Lenderink et al. 2007)]. It is thus important that also these communities contribute to the next developments of the CORDEX-CORE effort.

Regardless of the future directions in the CORDEX-CORE initiative, which are currently under discussion within the CORDEX community, the EXP-I dataset provides an unprecedented wealth of information for the regional climate modeling, impact, and end-user communities. These data are public and stored at ESGF sites using standard and quality-controlled data formats, and it is therefore desirable that they are analyzed and applied to their full potential. CORDEX-CORE is probably the most representative product of the methodological approach underlying the CORDEX program, and it is thus important that this initiative continues to grow with a new and more ambitious simulation protocol and more extended participation of RCM modeling groups.

Acknowledgments. The CORDEX-CORE data used in this work can be found at the Earth System Grid Federation (ESGF) databanks following the CORDEX output specifications. The CMIP5 data can be found at http://cmip- pcmdi.llnl.gov/cmip5/data_portal.html (CMIP5). The CORDEX-CORE ICTP simulations were carried out at the CINECA supercomputing center in Bologna, while the REMO simulations were performed under the GERICS/hereon share at the German Climate Computing Centre in Hamburg (DKRZ). We acknowledge DKRZ in Hamburg and CINECA in Bologna for providing the high-computing capacity, and the Earth System Grid Federation (ESGF) for hosting the CORDEX-CORE projections. We also acknowledge the World Climate Research Program Working Group on Coupled Modelling and all the modeling groups for computing and providing the CMIP5 simulations that were used as boundary forcing for the CORDEX-CORE experiments. Jason Evans was supported through funding from the Earth Systems and Climate Change Hub of the Australian Government's National Environmental Science Program. The authors also thank three reviewers for their useful comments, which helped to improve the quality of this paper.

References

Arias, P. A., and Coauthors, 2021: Hydroclimate of the Andes Part II: Hydroclimate variability and sub-continental patterns. *Front. Earth Sci.*, **8**, 505467, https://doi.org/10.3389/feart.2020.505467.

Ashfaq, M., and Coauthors, 2017: Sources of errors in the simulation of south Asian summer monsoon in the CMIP5 GCMs. *Climate Dyn.*, **49**, 193–223, https://doi.org/10.1007/s00382-016-3337-7.

——, and Coauthors, 2021: Robust late 21st century shift in the regional monsoons in RegCM-CORDEX simulations. *Climate Dyn.*, **57**, 1463–1488, https://doi.org/10.1007/s00382-020-05306-2.

Ban, N., J. Schmidli, and C. Schar, 2014: Evaluation of the convection-resolving regional climate modeling approach in decade-long simulations. *J. Geophys. Res. Atmos.*, **119**, 7889–7907, https://doi.org/10.1002/2014JD021478.

——, and Coauthors, 2021: The first multi-model ensemble of regional climate simulations at kilometer scale resolution, Part I: Evaluation of precipitation. *Climate Dyn.*, **57**, 275–302, https://doi.org/10.1007/s00382-021-05708-w.

Beck, H. E., and Coauthors, 2020: Bias correction of global high-resolution precipitation climatologies using streamflow observations from 9372 catchments. *J. Climate*, **33**, 1299–1315, https://doi.org/10.1175/JCLI-D-19-0332.1.

Boé, J., S. Somot, L. Corre, and P. Nabat, 2020: Large discrepancies in summer climate change over Europe as projected by global and regional climate models: Causes and consequences. *Climate Dyn.*, **54**, 2981–3002, https://doi.org/10.1007/s00382-020-05153-1.

Ciarlo`, J. M., and Coauthors, 2021: A new spatially distributed added value index for regional climate models: The EURO-CORDEX and the CORDEX-CORE highest resolution ensembles. *Climate Dyn.*, **57**, 1403–1424, https://doi.org/10.1007/s00382-020-05400-5.

Collins, W. J., and Coauthors, 2011: Development and evaluation of an Earth-system model-HadGEM2. *Geosci. Model Dev.*, **4**, 1051–1075, https://doi.org/10.5194/gmd-4-1051-2011.

Coppola, E., and Coauthors, 2020: A first-of-its-kind multi-model convection permitting ensemble for investigating convective phenomena over Europe and the Mediterranean. *Climate Dyn.*, **55**, 3–34, https://doi.org/10.1007/s00382-018-4521-8.

——, and Coauthors, 2021: Climate hazard indices projections based on CORDEX-CORE, CMIP5 and CMIP6 ensembles. *Climate Dyn.*, **57**, 1293–1383, https://doi.org/10.1007/s00382-021-05640-z.

da Rocha, R. P., M. S. Reboita, L. M. M. Dutra, M. Llopart, and E. Coppola, 2014: Interannual variability associated with ENSO: Present and future climate projections of RegCM4 for South America-CORDEX domain. *Climatic Change*, **125**, 95–109, https://doi.org/10.1007/s10584-014-1119-y.

Dee, D. P., and Coauthors, 2011: The ERA-Interim re-analysis: Configuration and performance of the data assimilation system. *Quart. J. Roy. Meteor. Soc.*, **137**, 553–597, https://doi.org/10.1002/qj.828.

Déqué, M., and Coauthors, 2007: An intercomparison of regional climate simulations for Europe: Assessing uncertainties in model projections. *Climatic Change*, **81**, 53–70, https://doi.org/10.1007/s10584-006-9228-x.

Di Luca, A., R. de Elia, and R. Laprise, 2012: Potential for added value in precipitation simulated by high resolution nested regional climate models and observations. *Climate Dyn.*, **38**, 1229–1247, https://doi.org/10.1007/s00382-011-1068-3.

——, ——, and ——, 2013: Potential for small scale added value of RCM's downscaled climate change signal. *Climate Dyn.*, **40**, 601–618, https://doi.org/10.1007/s00382-012-1415-z.

Diro, G. T., and Coauthors, 2014: Tropical cyclones in a regional climate change projection with RegCM4 over the CORDEX Central America domain. *Climatic Change*, **125**, 79–94, https://doi.org/10.1007/s10584-014-1155-7.

Dunne, J. P., and Coauthors, 2012: GFDL's ESM2 global coupled climate-carbon earth system models. Part I: Physical formulation and baseline simulation characteristics. *J. Climate*, **25**, 6646–6665, https://doi.org/10.1175/JCLI-D-11-00560.1.

Elguindi, N., F. Giorgi, and U. U. Turuncoglu, 2014: Assessment of CMIP5 global model simulations over the subset of CORDEX domains used in the Phase I CREMA. *Climatic Change*, **125**, 7–21, https://doi.org/10.1007/s10584-013-0935-9.

Endris, H. S., and Coauthors, 2018: Future changes in rainfall associated with ENSO, IOD and changes in the mean state over Eastern Africa. *Climate Dyn.*, **52**, 2029–2053, https://doi.org/10.1007/s00382-018-4239-7.

Evans, J. P., and Coauthors, 2021: The CORDEX Australasia ensemble: Evaluation and future projections. *Climate Dyn.*, **57**, 1385–1401, https://doi.org/10.1007/s00382-020-05459-0.

Eyring, V., and Coauthors, 2016: Overview of the Coupled Modeling Intercomparison Project Phase 6 (CMIP6) experimental design and organization. *Geosci. Model Dev.*, **9**, 1937–1958, https://doi.org/10.5194/gmd-9-1937-2016.

Fantini, A., and Coauthors, 2018: Assessment of multiple daily precipitation statistics in ERA-Interim driven Med-CORDEX and EURO-CORDEX experiments against high resolution observations. *Climate Dyn.*, **51**, 877–900, https://doi.org/10.1007/s00382-016-3453-4.

Forster, P. M., A. C. Maycock, C. M. McKenna, and C. J. Smith, 2020: Latest climate models confirm need for urgent mitigation. *Nat. Climate Change*, **10**, 7–10, https://doi.org/10.1038/s41558-019-0660-0.

Fuentes-Franco, R., F. Giorgi, E. Coppola, and K. Zimmermann, 2017: Sensitivity of tropical cyclones to resolution, convection scheme and ocean flux parameterization over eastern tropical Pacific and tropical North Atlantic Oceans in the RegCM4 model. *Climate Dyn.*, **49**, 547–561, https://doi.org/10.1007/s00382-016-3357-3.

Giorgi, F., 2002: Dependence of surface climate interannual variability on spatial scale. *Geophys. Res. Lett.*, **29**, 2101, https://doi.org/10.1029/2002GL016175.

——, 2006: Climate change hot-spots. *Geophys. Res. Lett.*, **33**, L08707, https://doi.org/10.1029/2006GL025734.

——, 2019: Thirty years of regional climate modeling: Where are we and where are we going next? *J. Geophys. Res. Atmos.*, **124**, 5696–5723, https://doi.org/10.1029/2018JD030094.

——, and X. Bi, 2009: The Time of Emergence (TOE) of GHG-forced precipitation change hot-spots. *Geophys. Res. Lett.*, **36**, L06709, https://doi.org/10.1029/2009GL037593.

——, and W. L. Gutowski, 2015: Regional dynamical downscaling and the CORDEX initiative. *Annu. Rev. Environ. Resour.*, **40**, 467–490, https://doi.org/10.1146/annurev-environ-102014-021217.

——, C. Jones, and G. Asrar, 2009: Addressing climate information needs at the regional level: The CORDEX framework. *WMO Bull.*, **58**, 175–183.

——, and Coauthors, 2012: RegCM4: Model description and preliminary tests over multiple CORDEX domains. *Climate Res.*, **52**, 7–29, https://doi.org/10.3354/cr01018.

——, and Coauthors, 2016: Enhanced summer convective rainfall at Alpine high elevations in response to climate warming. *Nat. Geosci.*, **9**, 584–589, https://doi.org/10.1038/ngeo2761.

——, F. Raffaele, and E. Coppola, 2019: The response of precipitation characteristics to global warming from climate projections. *Earth Syst. Dyn.*, **10**, 73–89, https://doi.org/10.5194/esd-10-73-2019.

Glazer, R., and Coauthors, 2021: Projected changes to severe thunderstorm environments as a result of 21st century warming from RegCM CORDEX-CORE simulations. *Climate Dyn.*, 57, 1595–1613, https://doi.org/10.1007/s00382-020-05439-4.

Gutowski, W. J., and Coauthors, 2016: WCRP Coordinated Regional Downscaling EXperiment (CORDEX): A diagnostic MIP to CMIP6. *Geosci. Model Dev.*, **9**, 4087–4095, https://doi.org/10.5194/gmd-9-4087-2016.

——, and Coauthors, 2020: The ongoing need for high resolution regional climate models: Process understanding and stakeholder information. *Bull. Amer. Meteor. Soc.*, **101**, E664–E683, https://doi.org/10.1175/BAMS-D-19-0113.1.

Haarsma, R. J., and Coauthors, 2016: High Resolution model Intercomparison project (HighResMIPv1.0) for CMIP6. *Geosci. Model Dev.*, **9**, 4185–4208, https://doi.org/10.5194/gmd-9-4185-2016.

Hewitson, B. C., J. Daron, R. G. Crane, M. F. Zermoglio, and C. Jack, 2014: Interrogating empirical-statistical downscaling. *Climatic Change*, **122**, 539–554, https://doi.org/10.1007/s10584-013-1021-z.

Hodges, K. I., 1999: Adaptive constraints for feature tracking. *Mon. Wea. Rev.*, **127**, 1362–1373, https://doi.org/10.1175/1520-0493(1999)127<1362:ACFFT>2.0.CO;2.

Huffman, G. J., and Coauthors, 2001: The TRMM Multi-satellite Precipitation Analysis (TMPA): Quasi global, multi-year combined sensor-precipitation estimates at fine scales. *J. Hydrometeor.*, **8**, 38–55, https://doi.org/10.1175/JHM560.1.

Im, E.-S., and Coauthors, 2021: Emergence of robust anthropogenic increase of heat stress-related variables projected from CORDEX-CORE climate simulations. *Climate Dyn.*, **57**, 1629–1644, https://doi.org/10.1007/s00382-020-05398-w.

IPCC, 2013: *Climate Change 2013: The Physical Science Basis*. Cambridge University Press, 1535 pp., https://doi.org/10.1017/CBO9781107415324.

Jacob, D., and R. Podzun, 1997: Sensitivity studies with the regional climate model REMO. *Meteor. Atmos. Phys.*, **63**, 119–129, https://doi.org/10.1007/BF01025368.

——, and Coauthors, 2012: Assessing the transferability of the regional climate model REMO to Different Coordinated Regional Climate Downscaling Experiment (CORDEX) Regions. *Atmosphere*, **3**, 181–199, https://doi.org/10.3390/atmos3010181.

——, and Coauthors, 2013: EURO-CORDEX: New high-resolution climate change projections for European impact research. *Reg. Environ. Change*, **14**, 563–578, https://doi.org/10.1007/s10113-013-0499-2.

——, and Coauthors, 2020: Regional climate downscaling over Europe: Perspectives from the EURO-CORDEX community. *Reg. Environ. Change*, **20**, 51, https://doi.org/10.1007/s10113-020-01606-9.

Jin, C. S., and Coauthors, 2016: Evaluation of climatological tropical cyclone activity over the western North Pacific in the CORDEX-East Asia multi-RCM simulations. *Climate Dyn.*, **47**, 765–778, https://doi.org/10.1007/s00382-015-2869-6.

Kendon, E. J., and Coauthors, 2014: Heavier summer downpours with climate change revealed by weather forecast resolution models. *Nat. Climate Change*, **4**, 570–576, https://doi.org/10.1038/nclimate2258.

Knapp, K. R., H. J. Diamond, J. P. Kossin, M. C. Kruk, and C. J. Schreck, 2018: International Best Track Archive for Climate Stewardship (IBTrACS) Project, Version 4. NOAA National Centers for Environmental Information, accessed 18 August 2019, https://doi.org/10.25921/82ty-9e16.

Knutson, T. R., and Coauthors, 2015: Global projections of intense tropical cyclone activity for the late twenty-first century from dynamical downscaling of CMIP5/RCP4.5 scenarios. *J. Climate*, **28**, 7203–7224, https://doi.org/10.1175/JCLI-D-15-0129.1.

Lavender, S. L., and K. J. E. Walsh, 2011: Dynamically downscaled simulations of Australian region tropical cyclones in current and future climates. *Geophys. Res. Lett.*, **38**, L10705, https://doi.org/10.1029/2011GL047499.

Lenderink, G., A. van Ulden, B. van den Hurk, and E. van Meijgard, 2007: Summertime interannual temperature variability in an ensemble of regional model simulations: Analysis of the surface energy budget. *Climatic Change*, **81**, 233–247, https://doi.org/10.1007/s10584-006-9229-9.

Llopart, M., and Coauthors, 2021: Assessing changes in atmospheric water budget as drivers for precipitation change over two CORDEX-CORE domains. *Climate Dyn.*, **57**, 1615–1628, https://doi.org/10.1007/s00382-020-05539-1.

Lloyd, E. A., L. O. Mearns, and M. Bukovsky, 2020: An analysis of the disagreement about added value by regional climate models. *Synthese*, **198**, 11 645–11 672, https://doi.org/10.1007/s11229-020-02821-x.

Luna-Niño, R., T. Cavazos, J.A. Torres-Alavez, F. Giorgi and E. Coppola, 2021: Interannual variability of the boreal winter subtropical jet stream and teleconnections over the CORDEX-CAM domain during 1980–2010. *Climate Dyn*., **57**, 1571–1594, https://doi.org/10.1007/s00382-020-05509-7.

Lundquist, J., M. Hughes, E. Gutmann, and S. Kapnick, 2019: Our skill in modeling mountain rain and snow is bypassing the skill of our observational networks. *Bull. Amer. Meteor. Soc.*, **100**, 2473–2490, https://doi.org/10.1175/BAMS-D-19-0001.1.

McGregor, J. L., 2015: Recent developments in variable-resolution global climate modeling. *Climatic Change*, **129**, 369–380, https://doi.org/10.1007/s10584-013-0866-5.

McSweeney, C. F., R. G. Jones, R. W. Lee, and D. P. Rowell, 2015: Selecting CMIP5 GCMs for downscaling over multiple regions. *Climate Dyn*., **44**, 3237–3260, https://doi.org/10.1007/s00382-014-2418-8.

Meque, A., and B. Abiodun, 2015: Simulating the link between ENSO and summer drought in southern Africa using regional climate models. *Climate Dyn.*, **44**, 1881–1900, https://doi.org/10.1007/s00382-014-2143-3.

Moss, R. H., and Coauthors, 2010: The next generation of scenarios for climate change research and assessment. *Nature*, **463**, 747–756, https://doi.org/10.1038/nature08823.

Paeth, H., and Coauthors, 2011: Progress in regional downscaling of West Africa precipitation. *Atmos. Sci. Lett.*, **12**, 75–82, https://doi.org/10.1002/asl.306.

Pal, J. S., and Coauthors, 2007: Regional climate modeling for the developing world: The ICTP RegCM3 and RegCNET. *Bull. Amer. Meteor. Soc.*, **88**, 1395–1410, https://doi.org/10.1175/BAMS-88-9-1395.

Pichelli, E., and Coauthors, 2021: The first multi-model ensemble of regional climate simulations at kilometer-scale resolution Part 2: Historical and future simulations of precipitation. *Climate Dyn.*, **56**, 3581–3602, https://doi.org/10.1007/s00382-021-05657-4.

Powers, J. G., and Coauthors, 2017: The Weather Research and Forecasting Model: Overview, system efforts, and future directions. *Bull. Amer. Meteor. Soc.*, **98**, 1717–1737, https://doi.org/10.1175/BAMS-D-15-00308.1.

Prein, A. F., and Coauthors, 2015: A review on regional convection-permitting climate modeling: Demonstrations, prospects and challenges. *Rev. Geophys.*, **53**, 323–361, https://doi.org/10.1002/2014RG000475.

——, and Coauthors, 2016: Precipitation in the EURO-CORDEX 0.11° and 0.44° simulations: High resolution, high benefits? *Climate Dyn.*, **46**, 383–412, https://doi.org/10.1007/s00382-015-2589-y.

Rasmussen, R., and Coauthors, 2011: High-resolution coupled climate runoff simulations of seasonal snowfall over Colorado: A process study of current and warmer climate. *J. Climate*, **24**, 3015–3048, https://doi.org/10.1175/2010JCLI3985.1.

Reboita, M. S., and Coauthors, 2021: Future changes in the wintertime cyclonic activity over the CORDEX-CORE Southern Hemisphere domains in a multi-model approach. *Climate Dyn.*, **57**, 1533–1549, https://doi.org/10.1007/s00382-020-05317-z.

Remedio, A. R., and Coauthors, 2019: Evaluation of new CORDEX simulations using an updated Koppen-Trewarths climate classification. *Atmosphere*, **10**, 726, https://doi.org/10.3390/atmos10110726.

Rockel, B., A. Will, and A. Hense, 2008: The regional climate model COSMO-CLM (CCLM). *Meteor. Z.*, **17**, 347–348, https://doi.org/10.1127/0941-2948/2008/0309.

Rummukainen, M., 2010: State-of-the-art with regional climate models. *Wiley Interdiscip. Rev.: Climate Change*, **1**, 82–96, https://doi.org/10.1002/wcc.8.

——, 2016: Added value in regional climate modeling. *Wiley Interdiscip. Rev.: Climate Change*, **7**, 145–159, https://doi.org/10.1002/wcc.378.

Ruti, P., and Coauthors, 2016: MED-CORDEX initiative for Mediterranean climate studies. *Bull. Amer. Meteor. Soc.*, **97**, 1187–1208, https://doi.org/10.1175/BAMS-D-14-00176.1.

Sawadogo, W., and Coauthors, 2021: Current and future potential of solar and wind energy over Africa using the RegCM4 CORDEX-CORE ensemble. *Climate Dyn.*, **57**, 1647–1672, https://doi.org/10.1007/s00382-020-05377-1.

Stevens, B., and Coauthors, 2019: DYAMOND: The DYnamics of the atmospheric general circulation modeled on non-hydrostatic domains. *Prog. Earth Planet. Sci.*, **6**, 61, https://doi.org/10.1186/s40645-019-0304-z.

Strandberg, G., and Coauthors, 2014: CORDEX Scenarios for Europe from the Rossby Centre Regional Climate Model RCA4. Rep. Meteorology and Climatology 116, SMHI, 75 pp., www.smhi.se/en/publications/cordex-scenarios-for-europe-from-the-rossby-centre-regional-climate-model-rca4-1.90274.

Taylor, K. E., R. J. Stouffer, and G. A. Meehl, 2012: An overview of CMIP5 and the experiment design. *Bull. Amer. Meteor. Soc.*, **93**, 485–498, https://doi.org/10.1175/BAMS-D-11-00094.1.

Teichmann, C., and Coauthors, 2021: Assessing mean climate change signals in the global CORDEX-CORE ensemble. *Climate Dyn.*, **57**, 1269–1292, https://doi.org/10.1007/s00382-020-05494-x.

Termonia, P., and Coauthors, 2018: The ALADIN system and its canonical model configurations AROME CY41T1 and ALARO CY40T1. *Geosci. Model Dev.*, **11**, 257–281, https://doi.org/10.5194/gmd-11-257-2018.

Torma, C., F. Giorgi, and E. Coppola, 2015: Added value of regional climate modeling over areas characterized by complex terrain—Precipitation over the Alps. *J. Geophys. Res. Atmos.*, **120**, 3957–3972, https://doi.org/10.1002/2014JD022781.

Torres-Alavez, J. A., and Coauthors, 2021a: Future projections in tropical cyclone activity over multiple CORDEX domains from RegCM4 CORDEX-CORE simulations. *Climate Dyn.*, **57**, 1507–1531, https://doi.org/10.1007/s00382-021-05728-6.

——, F. Giorgi, F. Kucharski, and E. Coppola, 2021b: ENSO teleconnections in an ensemble of CORDEX-CORE regional simulations. *Climate Dyn.*, **57**, 1445–1461, https://doi.org/10.1007/s00382-020-05594-8.

——, and Coauthors, 2021c: Future projections in the climatology of global low-level jets from CORDEX-CORE simulations. *Climate Dyn.*, **57**, 1551–1569, https://doi.org/10.1007/s00382-021-05671-6.

Tourigny, E., and C. Jones, 2009: An analysis of regional climate model performance over the tropical Americas. Part II: Simulating subseasonal variability of precipitation associated with ENSO forcing. *Tellus*, **61A**, 343–356, https://doi.org/10.1111/j.1600-0870.2008.00387.x.

Trapp, R. J., and Coauthors, 2007: Changes in severe thunderstorm environment frequency during the 21st century caused by anthropogenically enhanced global radiative forcing. *Proc. Natl. Acad. Sci. USA*, **104**, 19 719–19 723, https://doi.org/10.1073/pnas.0705494104.

Trenberth, K. E., A. Dai, R. M. Rasmussen, and D. B. Parsons, 2003: The changing character of precipitation. *Bull. Amer. Meteor. Soc.*, **84**, 1205–1218, https://doi.org/10.1175/BAMS-84-9-1205.

Vishnu, S., J. Sanjay, and R. Krishnan, 2019: Assessment of climatological tropical cyclone activity over the north Indian Ocean in the CORDEX-South Asia regional climate models. *Climate Dyn.*, **53**, 5101–5118, https://doi.org/10.1007/s00382-019-04852-8.

Watanabe, M., and Coauthors, 2010: Improved climate simulation by MIROC5: Mean states, variability, and climate sensitivity. *J. Climate*, **23**, 6312–6335, https://doi.org/10.1175/2010JCLI3679.1.

Weber, T., P. Bowyer, D. Rechid, S. Pfeifer, F. Raffaele, A. R. Remedio, C. Teichmann, and D. Jacob, 2020: Analysis of compound climate extremes and exposed population in Africa under two different emission scenarios. *Earth's Future*, **8**, e2019EF001473, https://doi.org/10.1029/2019EF001473.

Zanchettin, D., A. Rubino, D. Matei, and J. H. Jungclaus, 2013: Multidecadal-to-centennial SST variability in the MPI-ESM simulation ensemble for the last millennium. *Climate Dyn.*, **40**, 1301–1318, https://doi.org/10.1007/s00382-012-1361-9.

Zhang, Z. S., and Coauthors, 2012: Pre-industrial and mid-Pliocene simulations with NorESM-L. *Geosci. Model Dev.*, **5**, 523–533, https://doi.org/10.5194/gmd-5-523-2012.