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ORIGINAL ARTICLE

Regional climate downscaling over Europe: perspectives from the EURO-CORDEX community

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Abstract

The European CORDEX (EURO-CORDEX) initiative is a large voluntary effort that seeks to advance regional climate and Earth system science in Europe. As part of the World Climate Research Programme (WCRP) - Coordinated Regional Downscaling Experiment (CORDEX), it shares the broader goals of providing a model evaluation and climate projection framework and improving communication with both the General Circulation Model (GCM) and climate data user communities. EURO-CORDEX oversees the design and coordination of ongoing ensembles of regional climate projections of unprecedented size and resolution (0.11° EUR-11 and 0.44° EUR-44 domains). Additionally, the inclusion of empirical-statistical downscaling allows investigation of much larger multi-model ensembles. These complementary approaches provide a foundation for scientific studies within the climate research community and others. The value of the EURO-CORDEX ensemble is shown via numerous peer-reviewed studies and its use in the development of climate services. Evaluations of the EUR-44 and EUR-11 ensembles also show the benefits of higher resolution. However, significant challenges remain. To further advance scientific understanding, two flagship pilot studies (FPS) were initiated. The first investigates local-regional phenomena at convection-permitting scales over central Europe and the Mediterranean in collaboration with the Med-CORDEX community. The second investigates the impacts of land cover changes on European climate across spatial and temporal scales. Over the coming years, the EURO-CORDEX community looks forward to closer collaboration with other communities, new advances, supporting international initiatives such as the IPCC reports, and continuing to provide the basis for research on regional climate impacts and adaptation in Europe.

Keywords EURO-CORDEX · CORDEX · Climate change · Regional climate models · Regional climate modelling

Introduction

The World Climate Research Programme (WCRP) established the Task Force for Regional Climate Downscaling (TFRCD) in 2009, which created the Coordinated Regional

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climate Downscaling Experiment (CORDEX) initiative to advance and coordinate the science and application of regional climate downscaling through global partnerships (Giorgi et al. 2009). The major goals of CORDEX are as follows: (i) to better understand relevant regional/local climate phenomena, their variability and changes, through downscaling, (ii) to evaluate and improve regional climate downscaling models and techniques, (iii) to produce coordinated sets of regional downscaled projections worldwide, and (iv) to foster communication and knowledge exchange with users of regional climate information. Working towards these goals also helps address WCRP Grand Challenges such as: Water for the food baskets of the world, Clouds circulation and climate sensitivity, Weather and climate extremes, Carbon feedbacks in the climate system, Melting ice and global consequences, and Regional sea-level change and coastal impacts. CORDEX was recently added as a major project under the WCRP auspices and is also included as a diagnostic Model Intercomparison Project (MIP) in CMIP6 (Gutowski et al. 2016). Each regional team can coordinate its own simulations and associated research activities. The EURO-CORDEX community, in particular, has established itself as a key contributor to CORDEX, with more than 30 modelling groups collaborating in the simulation of the European climate, across all scenarios, and making the regional climate model (RCM) data publicly available and accessible in particular via the Earth System Grid Federation (ESGF). Further, many of the groups in the EURO-CORDEX community have contributed with a wide range of simulations of regional climates in other CORDEX regions and have played an instrumental role in defining standards for the ESGF publication.

This community is organized in a way that allows both a high level of coordination as well as flexibility (e.g., dynamic structures to address emergent scientific challenges). EURO-CORDEX celebrated 10 years as an active consortium in 2019. The scientific output along with the substantial contributions to open archives (e.g., Earth System Grid Federation, https://esgf.llnl.gov) marks EURO-CORDEX as a success. However, Europe enjoys many financial and institutional advantages compared with other regions that should not be ignored. Despite this, there are many aspects to EURO-CORDEX's success that do not rely on these advantages but rather on the members' commitment to a strongly coordinated, organized and community-based effort. The authors hope that the lessons learned from the experience of the EURO-CORDEX community can be applied as a model for other CORDEX regions as they evolve.

EURO-CORDEX is driven by scientific challenges, aligned with the first two goals of the WCRP-CORDEX initiative. EURO-CORDEX has made substantial progress in addressing the following specific challenges:

– Added value of regional downscaling with respect to scale, uncertainty, processes, and phenomena (Torma et al. 2015; Giorgi and Gutowski 2015; Prein and Gobiet 2016; Fantini et al. 2018; Coppola et al. 2018a; Soares and Cardoso 2017).
– Impacts of coupled processes and land-atmosphere (L-A) feedbacks in a regional context, Knist et al. (2017) and Davin et al. (2020).
– Improve the understanding of regional phenomena in a climate change context, in particular extreme weather events e.g., heat waves, storms, winds, floods, droughts, precipitation, Termonia et al. (2018) and Belušić et al. (2017) and their attribution to human activities (Stott et al. 2015; Luu et al. 2018; Philip et al. 2018; Kew et al. 2018).
– Cross cutting themes: e.g., water resources/hydrological cycle (Donnelly et al. 2017), energy-climate nexus (Jerez et al. 2015; Tobin et al. 2016; Tobin et al. 2018)

The strategic challenges confronting EURO-CORDEX are closely aligned with the goals of CORDEX mentioned above. Although progress on point (i) has been demonstrated, substantial gaps remain and EURO-CORDEX will need to address the following issues related to point (ii) over the coming years:

– Quality control: EURO-CORDEX certified process-based assessments, which seek to attribute model performance to emerging processes, e.g., conditions originating from the interaction of components of a complex system.
– Creation of climate information through
    – stronger involvement of the statistics community and "big data" analytics strategies as well as stronger engagement with programs and bodies which focus on vulnerability, impacts, adaptation and climate services (VIACS) such as GEWEX (www.gewex.org), Copernicus Climate Change Service (C3S; https://climate.copernicus.eu) and Future Earth (www.futureearth.org).
    – development of approaches to assess the credibility and robustness of multi-model-multi-method ensemble projections, and to synthesize these into user-relevant narratives (Benestad et al. 2017a)
– Knowledge transfer and exchange with the GCM community, in particular by contributing to the WCRP

Grand Challenges relevant for Europe and by quantifying the GCM limitations induced by simulating the climate at low resolution (Giorgi et al. 2016).

As the needs of researchers and policy makers become ever more focused on local to regional impacts and phenomena (including features such as urban environments, hydrology, vegetation, land use) so must EURO-CORDEX evolve.

This manuscript is meant to provide a brief history of EURO-CORDEX and its predecessors ("A brief history of EURO-CORDEX"), the evolution of the community and its current organization ("Organizational structure of EURO-CORDEX"), the EURO-CORDEX modelling framework ("EURO-CORDEX modelling framework"), its scientific advances to date ("Scientific advances") and what these advances mean for the future ("Key messages and outlook").

A brief history of EURO-CORDEX

EURO-CORDEX stems from the achievements of former EU projects on regional climate modelling such as PRUDENCE and ENSEMBLES (Christensen et al. 2007; van der Linden and Mitchell 2009). In launching the CORDEX initiative, WCRP recognized that in order to produce, maintain and continuously analyze large ensembles of regional climate simulations, a large, long-lasting and coordinated community effort is needed. Therefore the EURO-CORDEX community was formed in order to sustain and provide a structure for these activities concentrated on the European domain. As such, EURO-CORDEX has always been a voluntary, self-organized and dynamic community that can grow and evolve with the changing landscape of climate research, high-performance computing and user needs. Due to the fact that EURO-CORDEX builds on the efforts of previous projects and incorporates their lessons, it is also a role model for other CORDEX communities who are engaging in this type of effort for the first time.

Being a voluntary effort without base funding (similar to the larger CORDEX initiative and other endeavors such as CMIP), EURO-CORDEX nevertheless leverages its activities to obtain national and European funding. It also relies heavily on the enthusiasm and engagement of the participating researchers and institutions. The EURO-CORDEX consortium meets yearly in the Climate Service Center in Hamburg, Germany (GERICS). The number of registered participants from the 1st General Assembly (GA) in 2011 to the 8th GA in 2018 grew from 40 to 64, with representatives from 18 European countries (Table 1). At the first meeting, the foundation for the activities of the upcoming years has been laid, including the modelling protocol that forms the backbone of the EURO-CORDEX ensemble. Since then, yearly meetings have provided an opportunity for presenting and discussing the major EURO-CORDEX activities and outcomes, and to decide about future plans and strategies. The EURO-CORDEX community also provided a strong contribution to the two International Conferences on Regional Climate - CORDEX (Brussels, November 2013 and Stockholm, May 2016). In preparation for the Brussels conference the EURO-CORDEX community produced a press release to announce the release of the EURO-CORDEX data (based on studies by Jacob et al. 2014 and Vautard et al. 2013) entitled "New, detailed climate projections for Europe reveal changes in extreme events and open the way for climate change impact studies." Further research activities were discussed including the analysis of low emission scenarios, including the + 1.5 °C and + 2 °C global warming targets, which resulted in recent studies that use many EURO-CORDEX simulations to assess the impacts of these warming targets over Europe (Jacob et al. 2018; Kjellström et al. 2018; Teichmann et al. 2018). General assemblies are also an opportunity to reflect critically on the work performed and address emergent challenges.

EURO-CORDEX is conceived as both a dynamical and a statistical downscaling activity. Modelling groups focusing on dynamical downscaling are using the following regional climate modelling systems: ALADIN-Climate (Colin et al. 2010), CCLM (Böhm et al. 2006; Will et al. 2017; Rockel et al. 2008), HIRHAM (Christensen et al. 2007), RACMO (Van Meijgaard et al. 2012), RCA (Samuelsson et al. 2011), RegCM (Giorgi et al. 2012), REMO (Jacob et al, 2012, 2014), PROMES (Domínguez et al. 2010; Domínguez et al. 2013), WRF (Skamarock and Klemp 2008), and ALARO-0 (Giot et al. 2016; Termonia et al. 2018).

Modelling groups focusing on empirical statistical downscaling (ESD) employ a wide range of approaches (Benestad et al. 2017a; Maraun et al. 2015, 2018; Gutiérrez et al. 2018; Hertig et al. 2018; Soares et al. 2018; Widmann et al. 2019). The two approaches to downscaling are seen as complementary within the EURO-CORDEX community, each with its relative strengths.

Organizational structure of EURO-CORDEX

In order to evolve and adequately address emerging challenges, the EURO-CORDEX community has refined its structure during its existence. Initially, two coordinators were sufficient to manage the dynamically downscaled ensemble. However, new challenges meant that it was necessary to expand the number of coordinating members.

Table 1 EURO-CORDEX General Assembly (GA) participation and milestones

Date	General Assembly	Decisions/milestones	Participants	Countries
11/2011	First	Organize modelling and evaluation activities; create databases in ESGF format, experimental design, requirements for simulations	37	14
01/2012	Second	Collect observational datasets; application of statistical downscaling techniques	44	13
10/2013	Third	Preparation for the International CORDEX conference 2013	28	13
03/2014	Fourth	Enhance integration with impact modelling; focus on science	30	12
01/2015	Fifth	Encompass both statistical and dynamical downscaling methods; scientific focus on land use change impacts	47	13
01/2016	Sixth	New organizational structure; Prepare for 2nd EURO-CORDEX phase; FPS preparations	49	16
01/2017	Seventh	Launch of flagship pilot studies	55	17
01/2018	Eighth	Establish new research themes	64	18

The new structure, shown in Fig. 1, is an outcome of the 6th GA in 2016. There, the EURO-CORDEX community acknowledged that downscaling is achievable through different approaches, and that dynamical and statistical approaches are complementary to each other with different strengths and weaknesses. Both approaches are needed to address the challenges ahead. As a result, there are now two working groups devoted to specifically tackle issues related to dynamical and statistical downscaling, respectively, although they interact with each other.

Further, a third working group was formed explicitly focussing on Climate Information Distillation (CID). As discussed previously, this activity emerged as the scientific community acknowledged the challenges that users face when adopting climate data in decision-making contexts. The vast amounts of data produced from multi-model

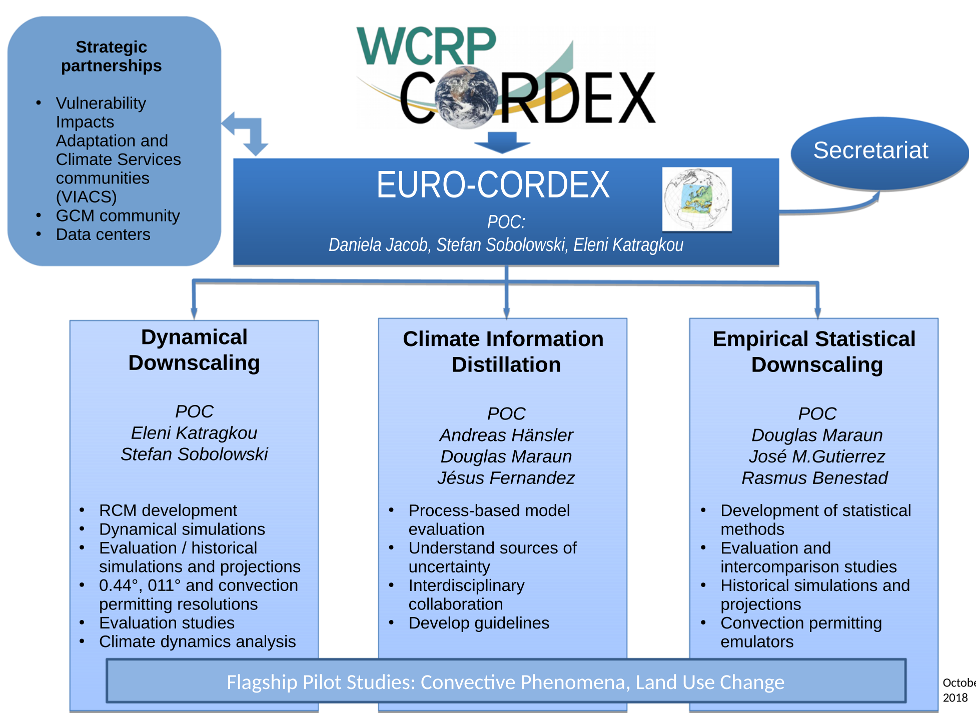

Fig. 1 Organizational structure of EURO-CORDEX based on the decision in the 6th GA. Point of contacts (POCs) are shown for each of the EURO-CORDEX pillars

ensembles with different model combinations make state-of-the-art statistical methods necessary in order to make sense of all the data, however, the statistics community has not yet been widely engaged in the analysis of the data (Benestad et al. 2017b). This activity is seen as crucial to the effective integration and collaboration between EURO-CORDEX and the VIACS/policy communities, as this is where the output of the scientific activity makes its way into decision-making. Deser et al. (2012) pointed out that GCMs produce pronounced chaotic variations on regional scales even over decades, and demonstrated that one model with slightly different initial conditions could produce a wide range of local scenarios. One important question therefore concerns the minimum size of a reliable ensemble that is not susceptible to random fluctuations and the law of small numbers (Benestad et al. 2017b). Given the multiplicity of messages, users may be inadequately prepared to incorporate state-of-the-art climate information or may make inappropriate decisions if messages from limited, non-robust, unreliable subsets of data are adopted (Fernández et al. 2019). Currently, a group of scientists is forming to tackle the issue of CID, including dynamical and statistical downscaling researchers from EURO-CORDEX, but also global climate modelers, atmospheric dynamicists, climate service providers and philosophers. Initial teleconferences took place during spring of 2018 and additional activities are planned.

EURO-CORDEX modelling framework

In order to assure a high-quality and easy to handle ensemble of simulations, the EURO-CORDEX modelling strategy was implemented at the first GA. It consists of a controlled experiment setup containing a fixed simulation domain (Fig. 2), predefined horizontal grid spacings, an evaluation simulation for each model used within EURO-CORDEX and a historical and climate change simulations, following the endorsed CORDEX protocol (Giorgi and Gutowski 2015). The following are the time periods covered by the simulations: Evaluation (ERA-Interim), 1989–2008; Control, 1951–2005; Scenarios, 2006–2100.

Within EURO-CORDEX, one domain with two resolutions is used for the RCM simulations: the EUR-44 domain at 0.44° grid spacing, which is similar to what is used in the first phase of CORDEX experiments, and the EUR-11 domain at 0.11° grid spacing. Therefore, together with an ensemble at the CORDEX standard resolution (at 0.44°), an ensemble of high-resolution regional climate simulations has been created (at 0.11°), aiming at better resolving

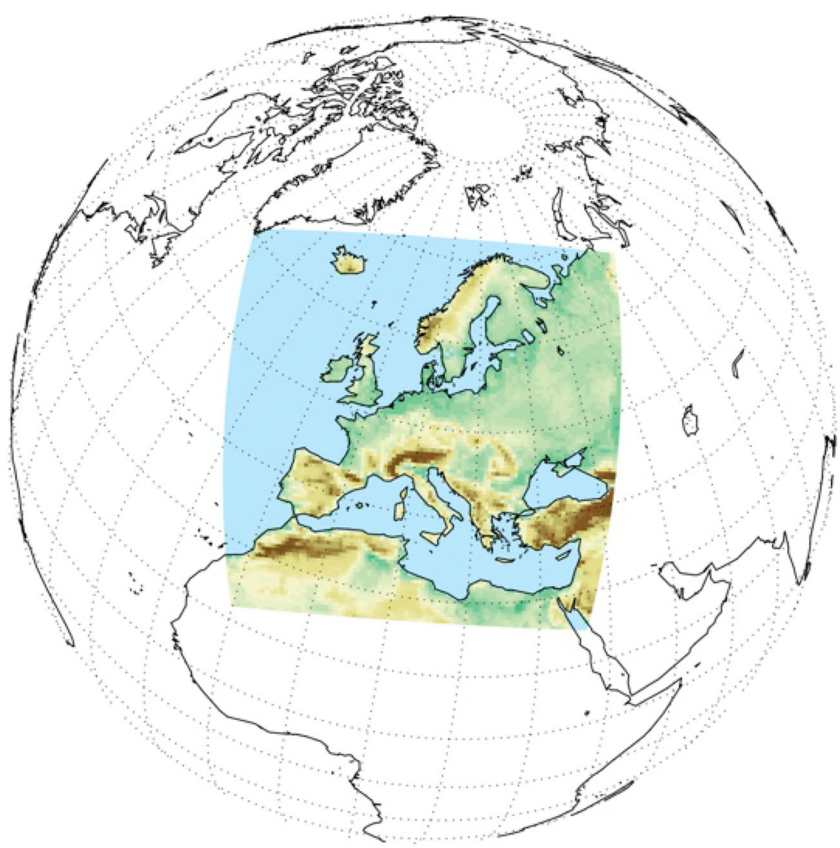

Fig. 2 EURO-CORDEX model domain at 0.11° resolution

meteorological phenomena, including extreme events, over Europe. At both resolutions, three types of experiments are performed: reanalysis-driven evaluation runs designed to assess RCM capacity to properly simulate regional climate in a "perfect" boundary conditions setup, GCM-driven historical simulations, and GCM-driven climate projections designed to assess current and future climate change. GCM simulations are directly downscaled using RCMs (GCM to EUR-11) or via an intermediate step using a EUR-44 simulation which is then downscaled to EUR-11 (GCM to EUR-44 to EUR-11) (Fig. 3). Simulations are accessible via the ESGF data distribution facility at both a resolution of 0.44°, but also at a higher resolution of 0.11° which is unique within the CORDEX framework.

All regional models used in EURO-CORDEX are evaluated using reanalysis-forced simulations (left hand side in Fig. 3) before running regional climate change projections driven by GCM forcing (right hand side in Fig. 3). Evaluation simulations are driven by "quasi-observational" data (ERA-Interim reanalysis; Dee et al. 2011) offering a robust basis for joint evaluation studies, atmospheric process analysis, comparison with previous projects, e.g., ENSEMBLES, and detailed evaluation against observational data. This provides some information about the performance of the individual RCMs over Europe, along with the presence of common systematic biases. Data are quality controlled before being uploaded to the ESGF repository, and best practices on the use of the regionally downscaled ensembles are provided (see https://euro-cordex.net). Furthermore, a joint errata service, accessible via https://euro-cordex.net, has been set in place in order to inform users on erroneous or equivocal simulation output.

In EURO-CORDEX, the choice of the driving GCM for the climate projection runs is largely up to each participating modelling group, given that it is a voluntary effort. This kind of approach can result in an ensemble of opportunity that might suffer from inconsistent climate change signals (Turco et al. 2013) or be biased towards a few preferred GCMs (Fernández et al. 2019). To avoid this, there has been a strong effort within EURO-CORDEX, and also from other initiatives, to analyze the driving GCMs, both regarding their performance (e.g., Cattiaux et al. 2013; McSweeney et al. 2014; Brands et al. 2013; Belda et al. 2015) and the spread of their mean seasonal temperature and precipitation changes (following the methods of Mendlik and Gobiet (2015) and McSweeney et al. (2014), or using a climate classification in Belda et al. (2016) or for their changes in weather regime frequency (Cattiaux et al. 2013). These analyses serve as support in the selection of forcing GCMs, in the sense of performance under current climate, but also in order to span the full spread of the GCM climate change signals over Europe. So while EURO-CORDEX does not explicitly follow a systematic experimental design as proposed by McSweeney et al. (2014) it does incorporate selection criteria. Further, most of the GCMs used in EURO-CORDEX are among those listed as well performing by McSweeney et al. (2014) for Europe. Nevertheless, the GCM-RCM simulation matrix is sparse. Therefore, national projects such as ReKlies-DE (http://reklies.hlnug.de) and international activities such as the EU-funded Copernicus Climate Change Services (C3S; https://climate.copernicus.eu) are supporting EURO-CORDEX in filling this GCM-RCM-simulation matrix in a coordinated effort. There have also been C3S projects for the evaluation and quality control (EQC) of climate model data (https://climatedatasite.net/).

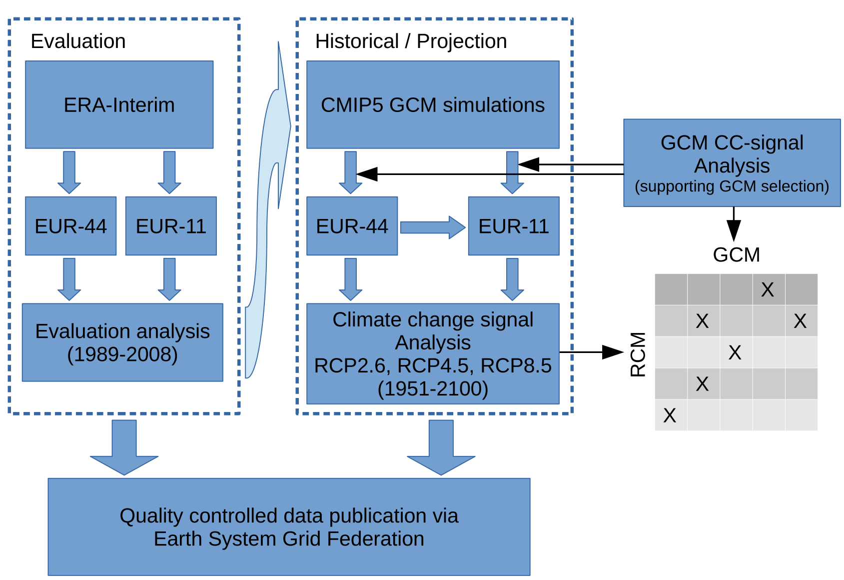

Fig. 3 Schematic description of the EURO-CORDEX experiment protocol. For further details refer to the text

Scientific advances

Early on, EURO-CORDEX committed itself to make data available through open access services such as the ESGF (https://esg-dn1.nsc.liu.se/projects/esgf-liu/) and climate impact web portals (https://climate4impact.eu). The availability of a large multi-model ensemble in a coordinated framework (evaluation, historical and future simulations), on different spatial resolutions and for a range of Representative Concentration Pathways (RCPs) is a significant contribution to the climate science community. It has provided the researchers with a solid basis from which to investigate present and future European climate, and assess uncertainty on continental to regional scales.

At the eighth GA (January 2018), a renewed commitment was made towards community-driven research on high-impact topics with a focus on contributing to the next IPCC assessment report. These topics include the following: urban scale issues, added value, impacts (with a focus on extremes), emergent constraints, interactions/feedbacks, and dynamics/thermodynamics. Another outcome of the GA was the establishment of a EURO-CORDEX errata page where issues noted by modelling teams and users are gathered, described and addressed in an accessible and transparent manner. A third decision was to update and improve model/experiment documentation. This will include synchronizing EURO-CORDEX documentation with ongoing C3S-funded projects.

Evaluation studies and projections of future European climate

The EURO-CORDEX evaluation simulations have served as the data-pool for a series of investigations concerning current European climate and the ability of regional models to accurately represent its state, its range of uncertainty and systematic model biases on a continental (e.g., Kotlarski et al. 2014; Katragkou et al. 2015; García-Díez et al. 2015) or regional level (e.g., Belušić et al. 2017; Dyrrdal et al. 2017). These simulations also provide a basis for assessing the added value, or lack thereof, of regional climate models. One way to look at downscaling is that information is added, with an improved physical understanding (i.e., though explicit inclusion of more processes/phenomena) and more geographical detail. At the same time, the downscaling can also introduce new errors and biases (e.g., additional uncertainties, mismatches between GCM and RCM in terms of parameterizations). The case for added value is where the addition of information dominates over the addition of uncertainty. However, the question of added value also depends on how the results are being used. For example, there is recent work that shows that the biases and uncertainty in GCM-RCM chains are not additive, i.e., uncertainty does not increase with each downscaling step and that RCMs in the EURO-CORDEX framework improve on the GCMs even at larger scales (Sørland et al. 2018).

The added value of higher resolution simulations was also addressed, both directly and indirectly, in a number of studies including dynamical downscaling (Warrach-Sagi et al. 2013; Torma et al. 2015; Casanueva et al. 2016b; Coppola et al. 2018a; Prein and Gobiet 2016; Ivanov et al. 2017; Soares and Cardoso 2017; Fantini et al. 2018; Sørland et al. 2018) and statistical methods (Casanueva et al. 2016a; Soares et al. 2018). Joint evaluation studies also focused on extreme climate events, such as heat waves (Vautard et al. 2013; Lhotka et al. 2017) and extreme precipitation (Fantini et al. 2018), medicanes (Gaertner et al. 2018) or physical process analysis, such as land-atmosphere interactions (e.g., Davin et al. 2016; Knist et al. 2017) and coastal circulations (Cardoso et al. 2016). Many of these examples point to an added value of regional downscaling by including processes or phenomena that are missing from coarser resolution models (e.g., Prein et al. 2015; Cardoso et al. 2016; Davin et al. 2016; Knist et al. 2017; Fantini et al. 2018). In other cases, such as in studies focusing on mean climate conditions involving spatially or temporally averaged fields (e.g., Kotlarski et al. 2014; Casanueva et al. 2016b) and/or phenomena with strong links to large scale circulation (Vautard et al. 2013), the added value is less apparent. However, a comprehensive assessment of added value in CORDEX RCM simulations is still lacking.

The historical and projection simulation datasets are the basis for the investigation of current and future European climate, including investigation of uncertainty stemming from model variability and projection scenarios. Jacob et al. (2014) used the higher resolution (0.11°) EURO-CORDEX simulations to show the overall spatial patterns for temperature and precipitation changes and related indices are similar to those of ENSEMBLES, with a slightly stronger mean precipitation increase over most of Europe and a reduced northwards shift of Mediterranean drying evolution. Bador et al. (2017) investigated the evolution of the record temperatures showing that maximum temperatures above 50 °C can occur at the end of the 21st century under the RCP8.5 scenario. Tramblay and Somot (2018) used the EUR-11 EURO-CORDEX ensemble to investigate the intensity and the time of emergence of the response of Mediterranean extreme precipitation to climate change. They showed a robust north-south pattern with increase (resp. decrease) in the North (resp. South) of the basin. Related to these projected shifts are projected changes in extreme dry spells, which may increase in duration and extent over the Mediterranean basin (Raymond et al. 2019). Jerez et al. (2015) and

Bartók et al. (2017) compared changes in solar radiation projected by global and regional EURO-CORDEX climate models and reported a discrepancy between the results in the GCM/RCM ensembles, namely increasing/decreasing trends for the period 2006–2100 over Europe under RCP8.5. Tobin et al. (2016) analyzed changes in surface wind speed and wind power in Europe, using EURO-CORDEX simulations, and Tobin et al. (2018) assessed general changes in electricity production in Europe. Others have also investigated renewable energy projections and note a more challenging environment for wind energy management in the future (Moemken et al. 2018). Several other studies used the EURO-CORDEX projections to focus on regional/national level (e.g., Smiatek et al. 2016; Rulfová et al. 2016; Ouzeau et al. 2016; Soares and Cardoso 2017; Hosseinzadehtalaei et al. 2018; Bador et al. 2017; Fernández et al. 2019; Huebener et al. 2017; Kjellström et al. 2016; Rajczak and Schär 2017; Púčik et al. 2017; Frei et al. 2018; Termonia et al. 2018; Prein and Gobiet 2016; Stepanek et al. 2016; Cardoso et al. 2018) others applied statistical downscaling methods, to further downscale the regional climate information (e.g., Dosio 2016; Mezghani et al. 2017) while others, after adopting bias adjustment techniques, use EURO-CORDEX data for local applications (Reder et al. 2018; Croce et al. 2018).

EURO-CORDEX simulations were recently used to assess the human influence in recent individual extreme events, together with other projection ensembles, a type of analysis which is called "event attribution" (Stott et al. 2015). EURO-CORDEX does not include pre-industrial simulations but changes between an earlier historical period (e.g., 1971–2000) and a "current climate" period (e.g., 2001–2030) allows to estimate a lower bound of human influence on regional climate events. In this way, Kew et al. (2018) showed that heat waves such as the 2017 summer "Lucifer" heat wave in Southern Europe had a probability that had strongly increased due to human influence. Other cases were studied using EURO-CORDEX, such as the extreme precipitations over the Cévennes mountains range (Luu et al. 2018), the European drought of Summer 2015 in Central Europe (Hauser et al. 2017) the extreme wind stagnation of December 2016 (Vautard et al. 2018), and the winter wind storms of January 2018 (Vautard et al. 2019). The added value of high resolution was demonstrated in particular for the Mediterranean heavy precipitations. As a final example, Giorgi et al. (2016) showed the added value of high-resolution RCMs in the projection of summer precipitation changes over high mountainous areas (e.g., the Alps). An overview of EURO-CORDEX publications can be found in the EURO-CORDEX publication web pages (http://euro-cordex.net).

Flagship pilot studies

The flagship pilot studies (FPS) initiative was established by the CORDEX Scientific Advisory Team as an additional activity to the core work of CORDEX, analogous to the MIPs of Coupled Model Intercomparison Project (CMIP) (Gutowski et al. 2016). These are "bottom up" initiatives and benefit the larger CORDEX/Working Group on Regional Climate (WGRC, https://www.wcrp-climate.org/regional-climate) bodies through linking to the wider climate research community, such as the newly established MIPs and other WCRP core projects. The EURO-CORDEX community submitted two successful FPS applications, one on the climatic impacts of land cover changes and one jointly with the Med-CORDEX community (Ruti et al. 2016; Somot et al. 2018) on convective phenomena through the use of very high-resolution convection-permitting regional climate models (CPRCMs). These computationally intensive projects started up in 2017 and just recently begun to produce results.

FPS I Land Use and Climate Across Scales

Land Use and Climate Across Scales (LUCAS) is a new initiative on coordinated regional climate experiments for Europe including land use change forcing (https://www.hzg.de/ms/cordex_fps_lucas/). It was initiated jointly by EURO-CORDEX and LUCID (Land-Use and Climate, IDentification of robust impacts, http://www.lucidproject.org.au). Land use change (including land cover and/or land management changes) is an important anthropogenic forcing on climate, and its direct biophysical effect on temperature can locally or regionally be of the same order of magnitude as the effect from global greenhouse gas forcing, but there are still uncertainties in magnitude and sign of many land-induced changes (de Noblet-Ducoudré et al. 2012; Lejeune et al. 2017; Perugini et al. 2017; Cherubini et al. 2018). Even more important for impact studies, many numerical experiments have highlighted the strong impact land uses may have on extreme events (e.g., Pitman et al. 2012; Davin et al. 2014; Thiery et al. 2017; Lejeune et al. 2018; Berckmans et al. 2019).

The LUCAS initiative is complementary to the Land Use Model Intercomparison Project (Lawrence et al. 2016) in that LUMIP focuses on the global scale, while LUCAS investigates regional impacts, using higher resolution, closer to the scale at which the biogeophysical effect of LUC has the strongest impacts. Up till now, this human forcing is not accounted for in RCM climate change projections. RCMs have been applied individually for investigating impacts of land use changes on regional climate in different world regions (e.g., see reviews of Pielke et al. 2011; Lawrence and Vandecar 2015; Santanello et al. 2018). Most results are model specific and therefore do not allow one to derive robust conclusions. In LUCAS, for the first time an ensemble of RCMs will be used in coordinated land use change (LUC) experiments, focusing on anthropogenic land cover conversions and potentially on land management practices during its later phase. The LUCAS modelling framework is visualized in Fig. 4.

The overall objectives of LUCAS are (i) to identify robust biophysical impacts of land use change on climate across regional-to-local spatial scales and at various time scales, from extreme events to multi-decadal trends, and (ii) to provide robust information in support of effective land use practices and also help guide decisions on land management from unintended consequences. The questions to be addressed are:

- How sensitive are regional climate models to land use change and how is this interrelated to land-atmosphere coupling in different regions among the suite of models?
- How large is the relative contribution of land use change compared with other forcings in the detection of past and potential future climate trends?
- How do land use practices modulate climate variability? Can local land use change modulate extreme climate conditions?
- What is the effect of spatial resolution on the magnitude and robustness of land use change-induced climate changes?
    - What errors do we make on the downscaled climate change if we ignore land use change? This is especially important for subsequent impact studies.

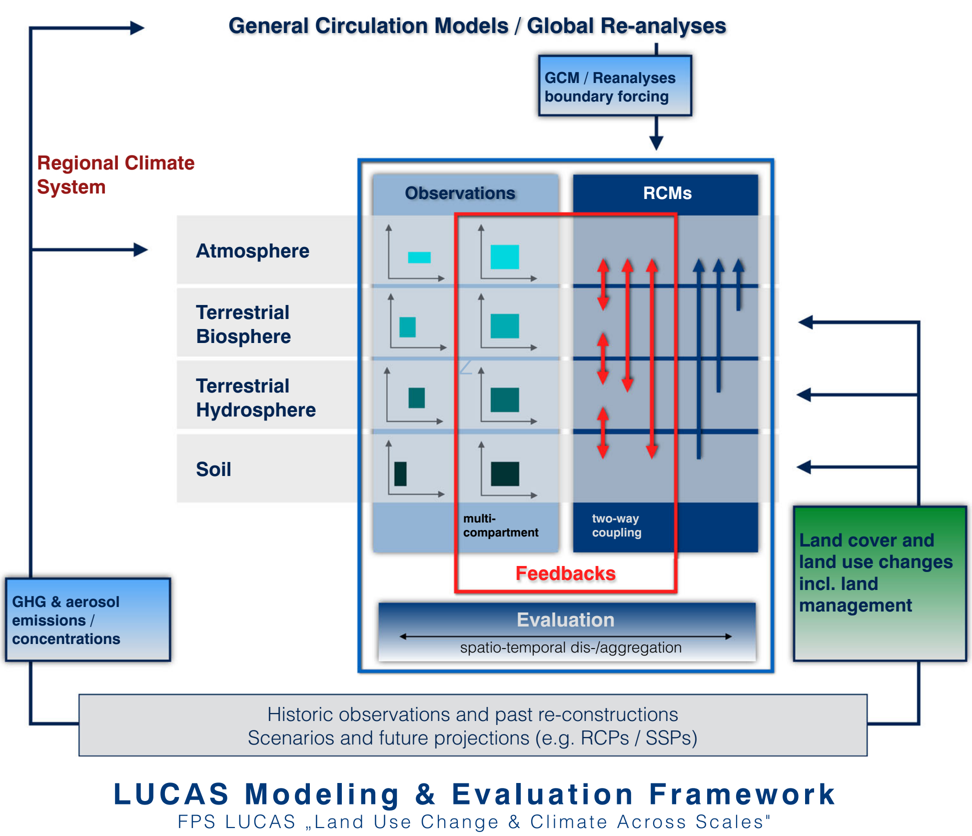

Fig. 4 LUCAS modelling framework. Land use and climate change experiments are performed with several RCMs. They represent processes in atmosphere, terrestrial biosphere, hydrosphere and pedosphere. RCMs which apply a two-way coupling between the atmosphere and the terrestrial components, enable the investigation of land-atmosphere feedbacks. The evaluation experiments are driven by reanalysis data and compared with observational data. Multi-compartment observational data on consistent temporal and spatial scales enable the evaluation of land-atmosphere feedbacks. The climate change experiments are driven by GCMs. Greenhouse gas (GHG) and aerosol concentrations are prescribed to the model simulations according to observed past concentrations for historical time periods, and according to different RCPs for climate change projections. Land cover and land use changes are implemented into the RCMs according to observed past re-constructions for historical time periods, and according to different Shared Socio-Economic Pathways (SSPs), which are linked to certain RCPs, respectively. Additional land use change experiments are designed, for which specific land use forcings are developed and implemented

It is clear that the outcome of these simulations will be limited as long as the representation of surface fluxes, boundary layer turbulence, and cloud microphysics cannot be verified and improved. Therefore, these modelling efforts will be accompanied by field experiments on land-atmosphere feedback (Wulfmeyer et al. 2018), which are currently being evaluated or prepared, e.g., at the TERENO sites (Bogena 2016) and the new Land-Atmosphere Feedback Observatory (LAFO; see https://lafo.uni-hohenheim.de).

Cropland management as well as human water use by water extraction and irrigation is an emerging topic and has the potential to either enhance or dampen temperature extremes (Becker et al. 2013; Davin et al. 2014; Thiery et al. 2017; Keune et al. 2018). Also, the collaboration between the FPS LUCAS on land-atmosphere feedback, the WRCP LoCo community (Santanello et al. 2018) and experiments on land-atmosphere feedback (Wulfmeyer et al. 2018) including groundwater dynamics (Keune et al. 2016) should be intensified.

FPS II convective phenomena at high resolution over Europe and the Mediterranean

The second FPS mobilizes the EURO- and MED-CORDEX communities and aims to bring fresh perspectives and expertise on issues surrounding convective phenomena. Present and future convective extremes and their processes are under investigation with convection-permitting regional climate models (CPRCMs), at resolutions finer than 3 km, over selected sub-regions of Europe and the Mediterranean (Fig. 5). Advanced statistical techniques will also be employed in parallel to evaluate the performance

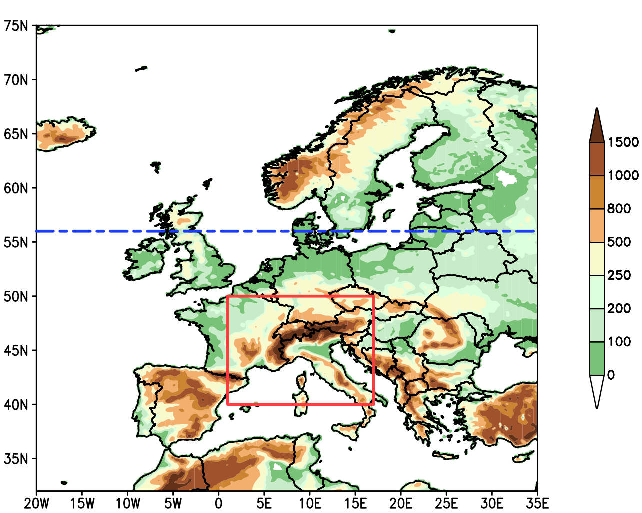

Fig. 5 Mandatory domain for the FPS on convective phenomena (red box). The dashed blue line corresponds to the northern boundary of the Med-CORDEX domain

of dynamical models, to potentially serve as emulators of convective extremes, and to detect and attribute their changes. These so-called emulators use empirical relationships between large scales features and local phenomena such as precipitation in ways similar to statistical downscaling but then add additional detail to obtain, e.g., sub-daily rainfall (Mezghani et al. 2019). The FPS aims to extend these to also include information from the dynamical downscaling. The added value of CPRCMs is well established now, especially for mesoscale convective systems, rainfall extremes, diurnal cycles, regional snow cover, etc. (see Ban et al. 2014; Prein et al. 2015, 2017a; Berthou et al. 2018; Sørland et al. 2018; Lüthi et al. 2019; Scaff et al. 2019). What has not been done as yet, is to explore these advances in an ensemble framework, which will allow us to better estimate uncertainty, quantify robustness and elucidate key driving processes. The added value of explicitly simulating deep convection will be rigorously evaluated with respect to both coarser resolution simulations up to GCM scales and VIACS applications. The CPRCM simulations will also serve as references and help developing convection parameterizations in standard RCMs and GCMs. The availability of observational datasets at very high resolutions in both space and time allows unprecedented evaluation opportunities (e.g., Lussana et al. 2018; Hiebl and Frei 2016, 2018; Frei 2014).

This FPS has three main scientific questions with many attendant sub-topics and questions:

- How do convective events and associated damaging phenomena (heavy precipitation, wind storms, flash-floods) respond to changing climate conditions in different climatic regions of Europe?
- Does an improved representation of convective processes and precipitation at convection-permitting scales lead to downscaled as well as upscaled added value?
- To what extent do lateral boundaries affect convection-permitting model (CPM) performance and how can corresponding errors be reduced?
- Is it possible to complement costly convection-permitting experiments with physically defensible statistical downscaling approaches such as "convection emulators" that mimic CPMs and are fed by output from conventional-scale climate models?

Convective extreme events are a priority under the WCRP Grand Challenge on weather and climate extremes, because they carry both society-relevant and scientific challenges that can be tackled in the coming years. Further, "coordinated modelling programs are crucially needed to advance parameterizations of unresolved physics and to assess the full potential of CPMs" (Prein et al. 2015). The project involves over 20 modelling teams and consists of three modelling steps: test cases, evaluation runs and scenario runs. A presentation of the project and preliminary results appear in Coppola et al. (2018b). Figure 6 shows results from a test case over Switzerland and highlights the ensemble performance in reproducing an extreme Foehn event in November of 2014. The ensemble mean spatial pattern correlations for this event were over 0.90. However, the ensemble exhibits much larger spread for events that are more weakly forced by the synoptic background state and have strong orographic and/or land-ocean interactions. Simulations over climate scales (10 years time slices) under present and future conditions are ongoing. A small ensemble has recently been completed (fall 2019) and a number of investigations are underway with results expected in late 2019/early 2020.

Key messages and outlook

The scientific challenges EURO-CORDEX faces will require broad community-based research. Given the fragmented nature of funding for EURO-CORDEX and CORDEX generally, there is a need for funding that targets these types of research initiatives. Only in this way will significant improvements in fundamental understanding emerge. A non-exhaustive list of directed research

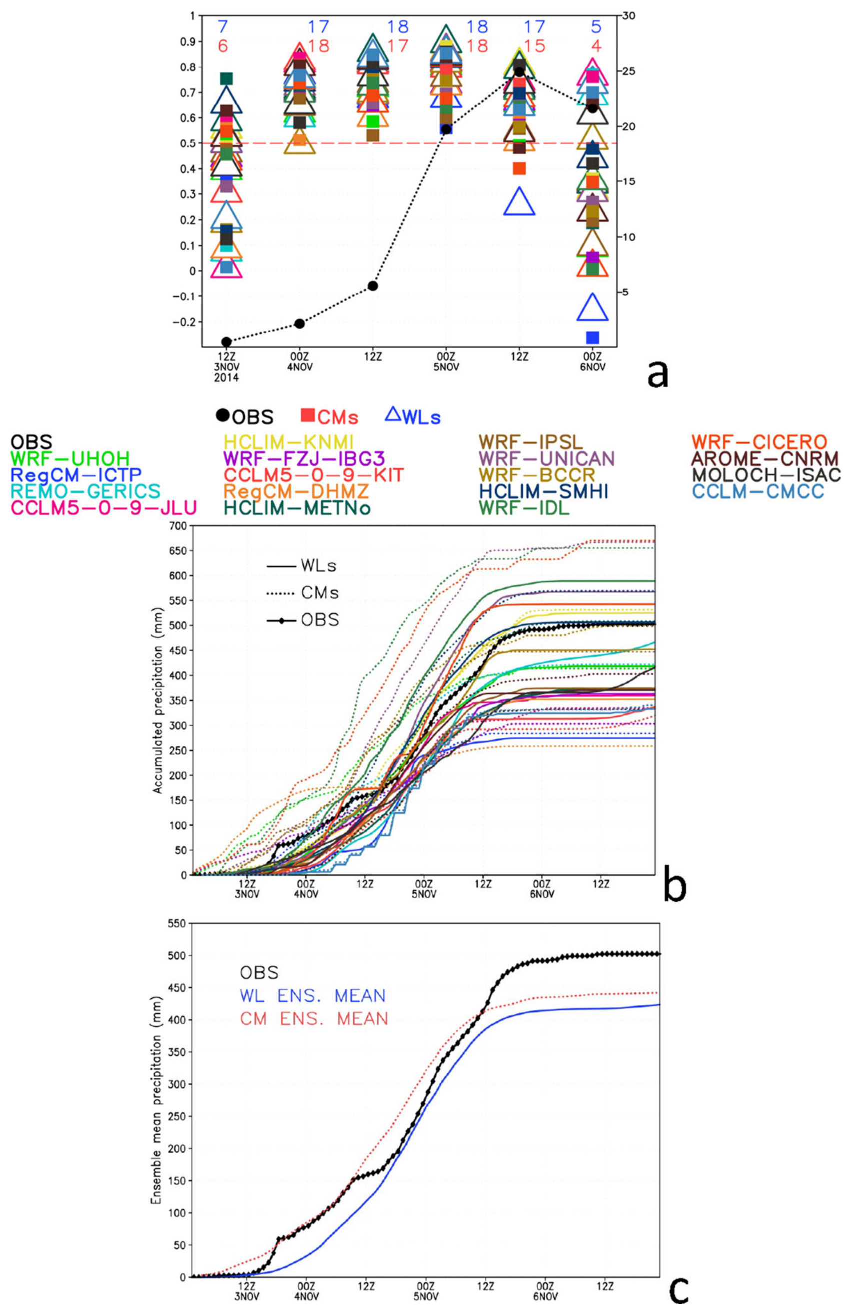

Fig. 6 Time series of 12 hourly accumulated precipitation for a Foehn event over southern Switzerland (black line/dots, in mm on the right hand y-axis) during the event and temporal evolution of the spatial correlation (lefthand y-axis) of the accumulated 12 hourly precipitation between the simulations and observations, panel a. Number of models with a correlation greater than 0.5 for WL simulation (in blue) and CM simulation (in red). Time series of the accumulated precipitation averaged over the region covered by the observations for each model (colored lines) versus observations (black line), panel b. Time series of accumulated hourly precipitation for the ensemble means of the WL and CM simulations versus observations (blue, red and black lines, respectively), panel c (Reproduced from Coppola et al. (2018b))

recommendations are presented below. These are followed by more detailed descriptions of key messages and the future outlook from the EURO-CORDEX community, which include not only research but also necessary expansion of the community to include additional perspectives.

- Research towards a more comprehensive and improved understanding of regional climate processes and their drivers, in particular with respect to extremes and place these within the context of the Sustainable Development Goals and WCRP Grand Challenges.
- Research towards transient continental-scale ensemble kilometer scale modelling (i.e., convection permitting) has the potential to substantially reduce uncertainties in future climate projections and enhance our understanding of high-impact weather events under climate change; the community is moving in this direction but such initiatives require significant and sustained investment in personnel and resources
- Research support for the interdisciplinary community that will be needed to further develop Regional Earth system models that are able to better simulate the human impact on local and regional climate (e.g., vegetation feedbacks, hydrology and water resources, irrigation for agricultural production, urban climate, regional sea-level rise, storm surge modelling, coupled glacier modelling)
- Research that explicitly links observations to model development and improvement through collaborative community efforts that focus on regional and local process studies that make use of, e.g., field campaign data to improve the representation of processes and feedbacks in regional models.

Linking with climate services

In addition to generating a unique dataset to address many scientific issues pertaining to climate downscaling, the first phase of EURO-CORDEX has already had a tremendous impact on the provision of regional climate services. For example, several "official" national climate scenarios (examples include France (http://www.drias-climat.fr), Switzerland (www.ch2018.ch), Austria, Norway (https://klimaservicesenter.no), Spain (http://escenarios.adaptecca.es) and Belgium (http://www.euro-cordex.be) for national climate change adaptation strategies are nowadays based on EURO-CORDEX. In addition, EURO-CORDEX will be at the heart of the coming C3S European climate service for future projections (e.g., the Copernicus Climate Change Service project C3S34b, PRINCIPLES, https://climate.copernicus.eu). It has also been used in proof-of-concept European climate services, for instance to help the energy sector facing climate change impacts and climate variability in developing renewable energies, or water, such as in the C3S CLIM4ENERGY and SWICCA projects (https://climate.copernicus.eu). Operational implementation is currently underway.

Despite the scientific progress and overall success of the EURO-CORDEX initiative, there are a number of challenges confronting it. These challenges are of both scientific and strategic nature. For example, simply generating and disseminating downscaled regional climate projections in the absence of good experimental design and without proper context, guidance and tailoring, will, at best, not serve user communities' needs optimally and, at worst, potentially lead to misleading strategies (Dilling and Berggren 2014). Avoiding such pitfalls will require both scientific advances on uncertainty quantification and verification metrics needed to produce robust and reliable projections, as well as strategic partnerships with outside collaborators in the VIACS communities. EURO-CORDEX is directly addressing these challenges through the establishment of strategic partnerships (e.g., with the CMIP6-endorsed VIACS advisory board (Ruane et al. 2016) and a dedicated effort on CID (Fig. 1).

In the second phase of EURO-CORDEX, the ensemble of EUR-44 and EUR-11 simulations will be extended to serve as a robust basis for further studies and VIACS applications. Additional EURO-CORDEX objectives are to foster the creation of climate information including the interface to users and to integrate empirical statistical downscaling. The new structure of EURO-CORDEX (see Fig. 1) reflects these aims and gives us a good basis for future cooperation and collaborations with the broader community of climate change, sustainability and social transformations researchers. It is an ambitious and exciting platform but one that is timely and has a proven and dedicated community of practice built to support it.

Integrating statistical methods

As noted previously, the volume of data produced in the EURO-CORDEX downscaling activities requires advanced statistical techniques for robust analyses (Benestad et al. 2017a, b). Better integration of these techniques and collaboration with external experts is a key strategic aim for EURO-CORDEX. Steps have already been taken with participation of EURO-CORDEX teams in the EU COST Action ES1102 "VALUE" (Maraun et al. 2015), where statistical downscaling groups organized themselves to systematically investigate statistical downscaling and bias correction methods. In a first experiment, VALUE investigated the downscaling skill of some 50 statistical methods for present climate, when driven with reanalysis-based predictors. These results have recently been published in a special issue (Maraun et al. 2017, 2018; Gutiérrez et al. 2018;

Hertig et al. 2018; Soares et al. 2018). These types of activities have been integrated into the ESD pillar into EURO-CORDEX (Fig. 1), and a new call for the next experiment will be issued shortly. This experiment will investigate the overall skill of statistically downscaled GCMs in present climate and the plausibility and uncertainties of future projections based on statistical downscaling.

Receiving support from computer science

The fields of climate science and climate change impacts heavily rely on computationally-intensive simulations and data centers should be aware of the wealth of data that is to come from the EURO-CORDEX community due to increasing ensemble sizes and heading towards convection-permitting resolutions. For instance, the effort in the setup and performance of CPM simulations was exemplified in latitude-belt runs by Schwitalla et al. (2017) or European, CPM simulations by Leutwyler et al. (2016) and on global scales by Heinzeller et al. (2016). On the other hand the climate modelling community, enabled by ever increasing high-performance computing resources, is facing large challenges related to new, emerging computing paradigms using, e.g., new microarchitectures such as GPUs (Lawrence et al. 2018) and finding more efficient ways to handle and store the massive amounts of data produced by CPM simulations. Additionally, there will be even more requests from VIACS communities for this data and online processing services to reduce the data volume on the server side. VIACS will have to bring together the large amount of high-resolution climate data and the requests of their customers for local climate information. They are challenged by the need of quick answers on the one hand and the desire to deliver high-quality well thought out and crafted products on the other. To address this issue targeted research and development to simplify and democratize data access and analysis and improve guidance for end-users in an era of data volume explosion will be needed. Here, a closer collaboration with the EURO-CORDEX community will help to address the challenges and fulfill mutual requirements.

Fostering cooperation with WCRP activities

The regional activities in WCRP are receiving increased visibility at present, and it is incumbent upon all involved to look for synergies across these activities. EURO-CORDEX, and CORDEX more generally, has a critical role to play in realizing WCRP's new scientfic objectives, in particular objective 4 "Bridging science and society" (WCRP Joint Scientific Committee (JSC) 2019). The EURO-CORDEX community itself is also challenged by the WCRP and CORDEX-specific grand scientific challenges. Some of them can be addressed together with other communities, such as VIACS or the larger climate science community including CMIP6. Here, closer and more active interaction is essential. Besides the scientific challenges, it is also necessary to support VIACS communities by providing well designed, large ensembles of climate simulations in a well-documented and usable way. As a promising development, a robust community has formed around convection-permitting modelling and two successful WCRP-GEWEX sponsored workshops, with strong participation from the EURO-CORDEX community, have been held in Boulder, Colorado. While advances are coming quickly, there are a number of challenges for this community to address (Prein et al. 2017b). EURO-CORDEX and its affiliated Flagship Pilot Studies are right at the forefront of this effort.

Collaboration with the GCM community

Finally, there is a tremendous strategic opportunity for EURO-CORDEX to pursue synergies with climate research activities mainly focused on GCM modelling through the establishment of CORDEX as a diagnostic MIP within the CMIP6 framework. This is also a non-trivial task, since institutional, disciplinary and philosophical barriers often remain between the two communities. However, increasing collaboration is very important, as CPMs are approaching the global scale and can be operated without lateral boundaries (e.g., Schwitalla et al. 2017). There exist a number of opportunities to evaluate upscaled added value, investigate emergent constraints on climate change at regional scales, provide feedback into GCMs to improve parameterizations, and for collaboration with higher resolution, convection-permitting GCMs.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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