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ADVANCES IN MODELING (LR LEUNG, SECTION EDITOR)

Coordinated Experiments for Projections of Regional Climate Change

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Abstract We review coordinated efforts for producing regional climate projections through dynamical and statistical downscaling tools driven by global climate model output. Such projections are affected by multiple sources of uncertainty both at the global model and at the downscaling levels. The characterization of these uncertainties and the production of robust regional to local projections for use in impact studies require the completion of properly designed large ensembles of experiments. Toward this purpose, several regional coordinated efforts have been conducted in the past, particularly involving regional climate models, but because of the lack of a common experiment protocol, the transfer of know-how across them has been difficult. This problem is being addressed in the Coordinated Regional Downscaling Experiment (CORDEX), a framework designed to produce the next generation of worldwide high-resolution regional climate projections through a fully coordinated experiment protocol.

Keywords Regional climate projection · Downscaling · Regional climate modeling · Statistical downscaling

Background and Introduction

The issue of regional climate projection is central to the provision of climate change information needed in vulnerability, impacts, and adaptation (VIA) assessment studies. The primary tools available today to generate climate projections are coupled global climate models (GCMs); however, their horizontal spatial resolution, currently order of 1°, is too coarse for many needs of VIA applications. As a consequence, different regional climate downscaling (RCD) techniques are used to produce climate change information at sub-GCM resolution scales [1]. These techniques include the use of limited area regional climate models (RCMs [2]), empirical statistical downscaling (ESD [3]) methods, and variable and high-resolution atmospheric GCMs (VARGCMs [4] and HIRGCM [5], respectively).

All RCD techniques use as input large-scale variables produced by GCMs or reanalyses of observations to generate spatially refined climate information. For the case of RCMs, the models need initial and time-dependent atmospheric boundary conditions (typically wind, temperature, moisture, and surface pressure) as well as sea surface temperature (SST) and, when relevant, sea ice conditions (e.g., sea ice extent and surface temperature). VARGCMs and HIRGCMs are generally forced only by externally prescribed SSTs, while different ESD methods may require different large scale forcing inputs.

The process of producing future regional climate projections through downscaling is affected by multiple sources of uncertainty which may compound in a cascade process [6]. On the GCM side, the primary uncertainty sources are associated with future greenhouse gas (GHG) and aerosol emission/concentration scenarios (or "scenario" uncertainty, usually sampled by simulating a range of GHG/aerosol concentration scenarios); the response of different models to the same GHG/aerosol forcing, often also dependent on the model systematic errors

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(or "structural" uncertainty, usually sampled by using ensembles of models); and the internal variability of the climate system (or "internal variability" uncertainty, usually sampled by completing different realizations of the same scenario run). These uncertainties are then transmitted to the downscaled projections through the provision of the GCM forcings and are compounded by analogous uncertainty sources in the downscaling itself (e.g., RCM structural and internal variability uncertainty) and by the uncertainty associated with the use of different downscaling methods (e.g., RCMs vs. ESD). In addition, climate variability increases at finer scales [7] which makes the extraction of forced climate change signals from the underlying natural variability more difficult.

The characterization of the robustness and uncertainty underlying regional climate projections, which is paramount to the proper use of such projections in VIA applications, requires the use of multi-model, multi-method approaches. This realization has given impetus to the development of coordinated programs sharing common protocols in order to facilitate the analysis, intercomparison, and synthesis of different simulations. On the GCM side, for example, the Coupled Model Intercomparison Project (CMIP) series has provided a common framework toward the production of coordinated GCM global projections (e.g., CMIP3 [8], CMIP5 [9]). The CMIP programs have led to a tremendous advancement in the understanding of models and climate change issues, generating datasets that have been used by a large and growing scientific community.

On the downscaling side, a number of regional RCD intercomparison projects have been implemented, which have certainly led to advances in the knowledge of regional modeling tools and projections. However, because of differences in simulation designs, it has been difficult to transfer know-how across regional settings. This problem was already recognized in the mid-2000s [10], but only with the inception of the Coordinated Regional Downscaling Experiment (CORDEX [11, 12]), has a common experiment protocol been developed for generating large RCD-based ensembles of climate projections over regions worldwide. CORDEX represents a fundamental advance in the coordination of RCD research and provides the main current framework for RCD activities related to regional climate change science.

In this paper, we first discuss the rationale behind the need for coordinated RCD projects ("Why RCD-Coordinated Projects?" section), we then provide a brief review of past regional projects ("A Brief Review of Coordinated Regional Projection Projects Prior to the CORDEX Program" section), and finally we discuss the main developments within the CORDEX program ("The Coordinated Regional Downscaling Experiment" section). We do not present a review of downscaling techniques and issues, since a number of review papers are already available in the literature, which any user of RCD techniques is advised to read ([1–5, 13–21]).

Why RCD-Coordinated Projects?

By its very nature, regional downscaling lends itself to fragmentation, as different communities are often interested in different problems or have varied needs and technical requirements. However, the use of common experimental protocols facilitates the analysis and intercomparison of results and offers clear added opportunities to better understand models, processes, and projections. On the one hand, large ensembles covering the different dimensions of the uncertainty space (e.g., scenario, structural, and internal variability) are needed to properly characterize the full uncertainty range in projections [22]. On the other hand, ensembles are necessary to provide robustness and credibility to the projections through different lines of evidence, such as intermodel agreement, identification of underlying processes common to the models, and consistency with observed trends.

A further important role of coordinated multi-model experiments is the identification of common systematic errors. For example, it has been shown that most RCMs tend to underestimate precipitation over the La Plata basin, when forced by either GCM or reanalysis fields [23]. As another example, various generations of RCMs for the European region exhibit a tendency to be excessively dry during the summer over southeastern Europe [24]. Similarly, a common systematic bias in RCMs for North America is the underestimation of winter topographic precipitation over the southeastern USA in conjunction with excessive rain on the lee side of the western US ranges [25]. Since coordinated experiments have shown that such errors are shared by most models, it is likely that they are symptomatic of basic model deficiencies in simulating underlying relevant processes and can therefore significantly affect regional projections [26].

By the same token, multi-model experiments can highlight in robust ways the added value of downscaled information compared to the driving GCMs, an issue that is central to the downscaling exercise [27]. A typical example is the added value of high-resolution RCMs in simulating topographically induced precipitation patterns along with daily precipitation intensity distributions and extremes [28, 29], also within the context of climate change simulations [30].

An important conclusion found through the use of coordinated multi-model RCD experiments is the substantial contribution of intermodel RCM structural uncertainty to the overall uncertainty of regional projections. This is illustrated in Fig. 1, derived from the European project PRUDENCE [31], which shows the fractional contributions to the total projection uncertainty for different variables, of the GCM and RCM structural uncertainties, the internal GCM variability, and the emission scenario uncertainty. Even though the full uncertainty ranges were only partially covered in the PRUDENCE ensemble, it can be seen that for variables such as winter temperature and precipitation, which are mostly driven by large-scale processes,

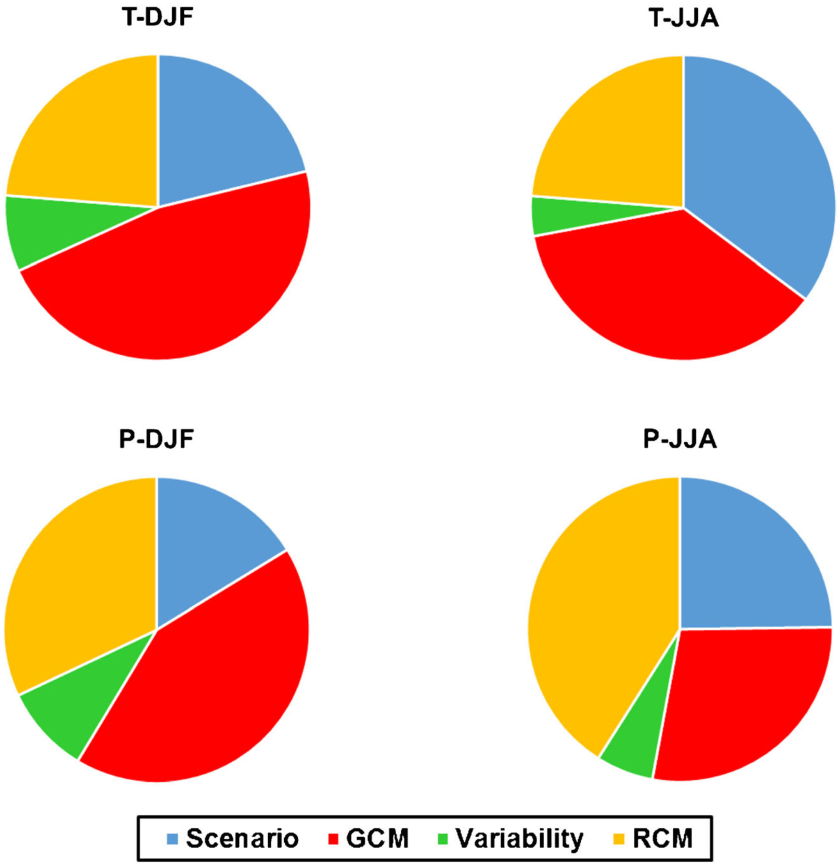

Fig. 1 Fractional contributions of different sources of uncertainty to the full uncertainty range in the PRUDENCE projections (2071–2100 vs. 1960–1990; high-end A2 scenario) averaged over the European region for different variables. *T-DJF* is winter temperature; *T-JJA* is summer temperature; *P-DJF* is winter precipitation; *P-JJA* is summer precipitation. "*GCM*" indicates the GCM structural uncertainty (four GCMs), "*Variability*" the internal variability uncertainty (three realizations for one GCM/RCM pair), "*Scenario*" the scenario uncertainty (high-end and low-end scenarios), "*RCM*" the RCM structural uncertainty (nine RCMs). The data are adapted from [31]

the contribution of RCM structural uncertainty is relatively small. In contrast, for summer precipitation, which is more related to local convective processes, the RCM and GCM structural uncertainty contributions are comparable. This conclusion is not obvious, since it challenges the notion that the boundary forcing dominates the RCM response at broad subcontinental scales, at least in contexts for which the RCM representation of local processes (e.g., summer convection) is important. A similar conclusion was found in the AMMA project over West Africa [32], the North America Regional Climate Change Assessment Program (NARCCAP) project over North America [33], and the CORDEX project over South America [34], where different RCMs or RCM configurations (e.g., physics schemes) provided quite different subcontinental scale precipitation change responses even when driven by the same GCM.

In fact, often the climate response (e.g., precipitation change) in RCMs vs. the driving GCMs can be different not only in magnitude but also in sign [28, 33]. While in some cases this can be clearly attributed to local forcings (e.g., fine-scale topographic features [28]), in others it may simply be related to the different physics representations in the models. Similarly, the change patterns calculated by different RCD techniques (e.g., RCM vs. ESD) have been often shown to substantially vary across methods [3]. These results highlight that in order to fully characterize uncertainties and arrive at the most robust possible conclusions, it is essential to assess and use approaches based on multi RCD models and techniques.

The design of a coordinated experiment requires a common and internally consistent simulation protocol in order to maximize the comparability of results. This is especially important when dealing with downscaling techniques. For example, RCM simulations are sensitive to model resolution and domain specifications [35], and often different physics options within the same model system provide better performances in different regions [36]. Similarly, ESD techniques can be highly variable in terms of their input, output, and assumptions, and the observations necessary to calibrate them can be of varied quality and density across regions [3, 20, 21].

In addition, the analysis of RCD models needs to be based on multiple criteria. Common performance metrics across different regions can provide a measure of systematic model behaviors. However, regionally specific and process-based analyses provide additional ways to evaluate the model performance for different regional contexts and thus yield a more thorough assessment of the RCD ensemble.

Another critical issue in the experiment design is the choice of GCM/RCD matrix used for the downscaled projections, especially if this matrix is sparse. Often, the selection of driving GCMs has been based on the availability of the proper set of time varying GCM output variables for downscaling ("ensemble of opportunity"). However, the GCM selection should actually be based on well-designed criteria, for example, the model performance over the target region or globally, and the representativeness of the driving models of the full GCM range in regional responses [37, 38]. Clearly, the extraction of robust regional information from multiple and varied sources of different quality is a research challenge in itself, which requires a careful design of simulation strategies.

A Brief Review of Coordinated Regional Projection Projects Prior to the CORDEX Program

Although RCD tools have been essentially used for all land regions of the world, to date, only a limited number of coordinated projects have been carried out based on the use of RCMs or ESD techniques. A set of major RCM coordinated projects is reported in Table 1. The different projects generally utilized different experiment designs (e.g., simulation length or scenarios), but they mostly shared a basic approach consisting of a model evaluation stream using reanalyses of observations to drive the RCMs and, for the projects that included future climate projections, a model projection stream in which the RCMs were driven by different GCMs.

The first attempt at coordinating RCM simulations under a common framework was PIRCS [39], in which ensembles of up to 13 RCMs were run for the two extreme cases of the summer 1988 (drought) and 1993 (flood) over the continental USA with a grid spacing of 50 km. Even if limited in length, these experiments emphasized the usefulness of using model ensembles to expose common behaviors despite differences in convective and land surface parameterizations. Also covering the continental USA was the more recent project NARCCAP [40], in which a simulation matrix was (partially) populated, comprising six RCMs and four driving GCMs under one GHG emission scenario. The NARCCAP program resulted in the production of relatively large projection ensembles that are widely used for a range of VIA applications [33].

The European research community has been extremely active in regional climate modeling. A series of RCM projects funded by the European Commission were completed in the late 1990s (MERCURE [41]), mid-2000s (PRUDENCE [42]), and late 2000s (ENSEMBLES [43]). In particular, PRUDENCE was a landmark project for RCM research in that for the first time a relatively well-populated experiment matrix was completed for present day and future climate 30-year time slices (grid spacing of 50 km), including four GCMs, nine RCMs, and two GHG emission scenarios. This matrix allowed a robust characterization of both systematic model errors [24] and future changes in climatologies, variability and extremes for the European region [44, 45], including the assessment of different sources of projection uncertainties [31]. In addition, PRUDENCE encompassed a series of VIA assessment studies that allowed an evaluation of the application value of RCM-derived information [46]. The framework of PRUDENCE was then augmented by the subsequent project ENSEMBLES in which a larger and more coordinated GCM-RCM matrix was completed with models at higher horizontal resolution (grid spacing of 25 km) and longer simulations (full twenty-first century transient runs), along with a more detailed exploration of model errors, improvements, and weighting techniques [43, 47–49].

Coordinated multi-RCM projects for tropical monsoon regions include AMMA for West Africa [32, 50], RMIP for East Asia [51], and CLARIS(-LPB) for South America [52]. In all cases, the RCMs were able to reproduce the basic monsoon circulation and seasonal precipitation patterns, however with

Table 1 Set of major regional coordinated RCM projects, prior to the inception of CORDEX

Acronym	Name	Region
PIRCS [38]	Project to Intercompare Regional Climate Simulations	North America
NARCCAP [39]	North America Regional Climate Change Assessment Program	North America
MERCURE [40]	Modeling European Regional Climate, Understanding and reducing Errors	Europe
PRUDENCE [41]	Prediction of Regional Scenarios and Uncertainties for Defining European Climate Change Risks and Effects	Europe
ENSEMBLES [42]	Ensemble-based Predictions of Climate Changes and their Impacts	Europe
AMMA [46]	African Monsoon Multidisciplinary Analysis	West Africa
RMIP [47]	Regional Model Intercomparison Project	East Asia
CLARIS (-LPB) [48]	A Europe-South America Network for Climate Change Assessment and Impact Studies (-La Plata basin)	South America
ARCMIP [50]	Arctic Regional Climate Model Intercomparison Project	Arctic
BALTEX [52]	Baltic Sea Experiment	Baltic Sea drainage basin

different levels of performance across models and some common systematic errors [53]. An important conclusion of these projects was that over tropical domains the internal RCM physics (especially convective and land surface schemes) had a substantial role in determining the model performance and climate change response with respect to the lateral boundary forcing [32, 53].

A further RCM intercomparison project to highlight is ARCMIP [54], in which an ensemble of RCMs, both atmosphere only and coupled atmosphere-ocean-sea ice, were used to simulate the climate of the Arctic region. This is an especially challenging region for climate models since many processes and circulations in the Arctic are poorly understood and their representation in climate models depends strongly on the physical schemes utilized. Specifically, in ARCMIP, the RCMs were evaluated against an intensive observation campaign that occurred in 1997–1998 and provided the grounds for a detailed and multi-variable model assessment [55].

The development of coupled atmosphere-land-ocean RCMs is one of the main areas of strong development in regional modeling research [2], and a major contribution to this development was given by the BALTEX project [56], in which coupled RCM systems were developed to study in an integrated way the water and energy cycles, climate change, variability and extremes, and impacts on the biogeochemical cycle of the Baltic Sea drainage basin. Coupled atmosphere-land-ocean RCM systems have been developed also for the Mediterranean Sea [57, 58], the Caspian Sea [59], and the South Asia [60].

In contrast to the substantial development of RCM multi-model programs, ESD development has been more fragmented. There have been some ESD intercomparison studies [61–64] but often ESD efforts have specific goals, and partly as a consequence, many varied types of applications (e.g., [65–68]). The rich variety of methods and applications demonstrates the flexibility of ESD but has also hindered the development of coordinated multi-method programs. Some studies have intercompared ESD and RCM performances (e.g., [69–72]), and the results have generally suggested both advantages and limitations of the two approaches. Concerning VARGCM and HIRGCM downscaling, several systems are today available [4], but only limited coordinated intercomparison efforts for present day climate conditions have been conducted to date [73, 74].

The Coordinated Regional Downscaling Experiment

The Coordinated Regional Downscaling Experiment (CORDEX) program was launched under the auspices of the World Climate Research Program (WCRP) with the vision to advance regional climate research and application through downscaling [11, 12]. Specifically, among the CORDEX goals, we highlight the assessment and improvement of RCD models and techniques and the enhanced understanding of regional climate change processes, projections, and uncertainties. CORDEX is based on the production of large ensembles of multi-technique and multi-model simulations following a common simulation protocol across regions worldwide in order to facilitate intermodel, cross-technique, and cross-domain analyses.

The CORDEX phase I experiment framework [11, 12] included a model evaluation stream based on forcing data from the ERA-interim reanalysis of observations [75] and a model projection stream based on downscaling multiple CMIP5 GCMs by multiple RCMs and ESD techniques over a set of 14 domains covering essentially all land areas of the world (www.cordex.org). In addition, the project is also intended to encompass available VARGCM and HIRGCM models. For the RCMs, a model grid spacing of 50 km was adopted as baseline in order to enhance participation by a wide community, and the Africa domain was selected as the highest priority because of the pronounced vulnerability of this continent to global warming and the lack of local infrastructure to carry out climate projections.

The CORDEX phase I activities have resulted in the completion of present day and/or projection ensembles of differing sizes for most domains, including Africa [76], Europe [77], the Mediterranean [78], the Arctic [79], South Asia [80], East Asia [81], Southeast Asia [82], South America [83], North America [84], Central America [85], the Middle-East North Africa (MENA [86]), and Central Asia [87]. Of particular relevance are the EURO-CORDEX [77] and MED-CORDEX [78] initiatives. In the former, large multi-model ensembles have been completed at two nominal resolutions, 0.44° and 0.11°, resulting in an unprecedented set of high-resolution projections for use in VIA studies. Conversely, Med-CORDEX has focused more on the development and use of coupled Regional Earth System Models for the Mediterranean basin including atmosphere, ocean, river, and aerosol components applied to the assessment of the interactions across these components in modifying regional climate change signals. For example, it was shown that both ocean coupling [88] and aerosol forcings [89] can have substantial impacts on the climate patterns over the Mediterranean basin.

Figure 2 shows an example of the simulation of fall precipitation over the European Alps in an ensemble of EURO-CORDEX and MED-CORDEX GCMs, 0.44° and 0.11° km resolution RCMs for a present day period (1976–2005) along with the corresponding change patterns for the end of the twenty-first century (2071–2100) under the RCP8.5 emission scenario [90]. Comparison with a high-resolution observation dataset [91] first illustrates the added value of high-resolution RCMs in capturing the spatial detail of topographically induced precipitation (top panels). The bottom panels then show how the fine scale representation of Alpine topography can

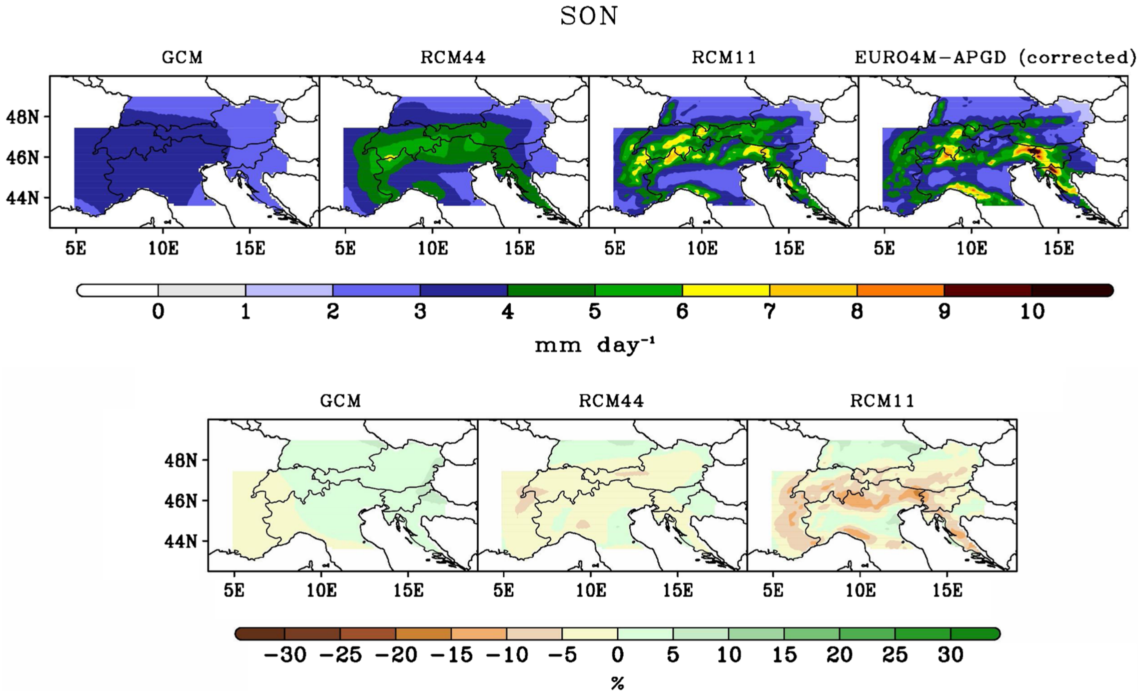

Fig. 2 Fall (September–October–November or *SON*) precipitation in an ensemble of four driving GCMs and six nested RCMs run at resolutions of 0.11° and 0.44° (RCM44 and RCM11, respectively) over the Alpine region in the EURO-CORDEX and MED-CORDEX initiatives. The *top panels* show the mean precipitation (mm/day) for the present day period (1975–2004) and compare the model data with a high-resolution observation dataset [87] (in the *last panel to the right*, observations include a gauge undercatch correction as described in [28]). The *bottom panels* show the corresponding mean precipitation change (units of % of present day values) for the period 2070–2099 with respect to 1975–2004 under the RCP8.5 greenhouse gas concentration scenario [86]. The figure is adapted from [28]

substantially affect the precipitation change signal (compared to the driving GCMs) both in sign and in magnitude. Other studies have then shown the importance of resolution for the simulation of precipitation intensity distributions and extremes [28, 92].

In addition to highlighting the role of resolution for regional projections, the CORDEX phase I activities emphasized the importance of large multi-model ensembles, since for example, the changes in phenomena such as monsoon precipitation [32, 80] and tropical storms [85] are found to strongly depend on the model physics configurations. Unfortunately, however, the number of simulations available for different CORDEX regions is highly variable and this inhomogeneity has made it difficult to carry out homogenous assessments across regions.

These considerations have provided the main guidelines for the ongoing discussions on the design of the CORDEX phase II framework [2], which is currently planned to encompass two components. The first, referred to as Common Regional Experiment framework (or CORDEX-CORE), envisions the completion of a common minimum ensemble of projections for all CORDEX domains by a core set of RCMs downscaling a core set of GCMs and scenarios at nominal resolutions in the range of 10–25 km. This baseline common ensemble would then be incrementally populated over the different regions by additional available experiments and by information derived from ESD methods. While the details of this CORDEX-CORE framework are still being discussed, this approach would guarantee the availability of a homogeneous core ensemble across all CORDEX regions.

The second component of the CORDEX phase II framework is the concept of Flagship Pilot Studies (FPSs). FPSs are intended to be frontline research projects aimed at addressing in detail targeted science questions relevant to specific regional settings. A typical example is the downscaling to horizontal nominal resolutions of few kilometers through the use of convection-permitting non-hydrostatic models [93, 94], which is one of the primary areas of future development in RCM research [2]. Other examples would be the rigorous comparison of projections by different downscaling or post-processing techniques (e.g., RCMs, ESD and bias correction [95]) or the assessment of regional to local forcings, such as land use change and aerosols. While it would be difficult to carry out these studies for the continental scale CORDEX domains, they can be addressed within specific targeted regions. FPSs are expected to be bottom-up initiatives, with proposals submitted by regional communities and eventually endorsed by CORDEX after an evaluation process (www.cordex.org).

Complementing these phase II activities is the development of a CORDEX ESD framework. To date, this has occurred through a series of workshops [96] that have designed a program aimed at evaluating strengths and shortcomings of a variety of ESD methods themselves and in comparison with dynamical downscaling. The workshops developed the protocols for an initial intercomparison experiment focused on a portion of South America with relatively high-density and high-quality observations to calibrate and assess the ESD output. The primary objectives for this initial case are to delineate the relative skills of different statistical downscaling approaches when applied to a common source of predictors and predictands and to assess the added value that ESD can provide from coarse scale predictor fields taken from GCMs. As the ESD framework progresses, the ESD efforts will have a foundation for expanding to blend evaluations of both dynamical and statistical downscaling.

Final Considerations

In this paper, we have reviewed the issue of coordinated efforts to produce regional climate projections through RCD techniques. The call for large multi-model and multi-method ensemble approaches stems from the need of producing robust regional climate information based on multiple lines of evidence and of properly characterizing the different sources of uncertainty in regional projections. Until recent years, individual regional coordinated projects have provided valuable information on the behavior of ensembles of downscaled projections; however, these efforts lacked cross-project coordination in terms of simulation and analysis protocols.

The completion and application of regional downscaled projections is a fast growing area of research by a wide and varied community, so that it is important to fully understand the value, limitations, and uncertainties of such projections. Coordinated experiments thus play a fundamental role in this regard by providing a rigorous framework to assess RCD models and regional climate projections. Climate change information for VIA application can be derived by a multitude of sources, such as GCMs, RCMs, ESD, and post-processing techniques (bias correction), often diverging not only in magnitude but also in sign and affected by the presence of model systematic errors. The distillation of robust information from these multiple sources hinges upon the availability of large ensembles based on carefully designed simulation protocols and fully evaluated models, which can optimally be obtained only through the development of coordinated multi-model experiments.

The CORDEX program is designed to address these problems and provide a common platform for coordinating regional downscaling activities in order to produce more homogenous and quality controlled regional projection information and to facilitate transfer of know-how across regions and with the VIA community. As a result of its first phase activities, CORDEX has steadily grown in the last few years, as demonstrated for example in two major Pan-CORDEX conferences (November 2013 in Brussels and May 2016 in Stockholm) with more than 400 abstracts submitted. As detailed in the previous section, the discussions on the design of the second phase CORDEX activities are currently under way.

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Compliance with Ethical Standards

Conflict of Interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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