The future scientific challenges for CORDEX

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Disclaimer: Version as of 17th May 2021. Further developments will come in due time.

Preamble

This paper points to future scientific challenges in regional climate modeling that may lead to better informed decision making in regions, as a major contribution to the 4th Scientific Objective of the WCRP Strategic Plan: Bridging to society.

Additional papers will follow, one on the positioning of CORDEX in the new WCRP structure and its contribution to the WCRP scientific objectives and another one on bridging the gap between climate science and society. The latter will contribute to climate services and decision making for adaptation to climate change based on the knowledge and experience gained in local and regional stakeholder dialogues. The CORDEX community has been largely interacting with local stakeholders around the World and successfully collected and shared experiences. These lessons learned are important for the development of the interface of WCRP with society and will be synthesized and further developed in a paper on: How to bridge climate science and society - The CORDEX experience.

While the current paper mostly focuses on dynamical downscaling, a paper with focus on Empirical Statistical Downscaling (ESD) strategies for CORDEX is also being developed and identifies challenges in providing useful information to decision-makers through ESD.

The paper presented here, will form the basis for the **CORDEX Science Plan** together with the upcoming papers on ESD strategies and on bridging climate science with society needs.

General purpose

The purpose of this document is to point out ways forward and future challenges for the CORDEX community. The scientific progress in understanding and modelling of regional phenomena, which are changing due to global climate change, has advanced much over the last decade and the CORDEX community strongly contributed to this (see below). In addition, the advancement of regional climate science was much supported by the success of CORDEX in establishing common coordinated experimental designs for dynamical downscaling that makes coherent ensembles of simulations available to both the climate science and the vulnerability, impacts, adaptation and climate services (VIACS) communities, over many regions of the globe. The focus on several greenhouse gas forcing scenarios (based on the Regional Concentration Pathways (RCPs)) in CORDEX has also been an advantage, as it allows coverage of some of the uncertainties with regard to future emission scenarios, an essential aspect for decision-making. This basic common setup is essential to provide coherent ensembles of Regional Climate Model (RCM) datasets to the VIACS communities and should be maintained as a first tier. However, as RCMs reach finer resolutions and become more complex, it will be essential to consider additional standard designs that are adapted to this new context, and that are defined in collaboration with the regional CORDEX communities.

Standard CORDEX protocols (e.g., format, variables, time periods) contribute to the enhanced use of regional climate simulations, as many of them are available through the ESGF (Earth System Grid Federation). A key challenge is now to ensure that all simulations are available on the ESGF so that the broader community, including the VIACS community, can access the CORDEX data. Moreover, as time and space resolutions become finer and hourly outputs are being requested by users, the planning of archived datasets for future projects gets more demanding and needs further attention. On the finer time- and space scales RCMs can show some of their added value compared to Global Climate Models (GCM).

The CORDEX framework guides coordinated efforts to focus on the **CORDEX scientific challenges,** which are related to the following topics and further elaborated in the text below:

- the added value of downscaling
- convection-permitting modelling
- assessing the role of the human elements on the regional climate change signals and
- the benefits of coupled regional climate models

CORDEX has already achieved several targets. Within the CORDEX framework, started during the early 2010s, an unprecedented number of coordinated RCM simulations has been produced following the first CORDEX protocol: the **CORDEX experiment design for the dynamical downscaling of CMIP5** (Fifth phase of the Climate Model Intercomparison Project). This allows the demonstration of the added value of RCMs (e.g. di Luca et al. 2016, Di Virgilio et al. 2020) and the added value of having a set of coordinated simulations for most of the continental areas of the world (Spinoni et al. 2019, Legasa et al. 2020, Glisan et al. 2019; Ashaq et al., 2020). Though the spatial resolution of the first CORDEX protocol was established at 50km as a first priority, some domains also produced simulations at 25km and 12km resolutions (EURO-CORDEX, Med-CORDEX, CORDEX-SEA). All these sets of simulations allowed the community to identify robust climate change signals over different CORDEX domains (Jacob et al. 2020 and Dosio 2016 for the EURO-CORDEX domain; Sanjay et al., 2017 for the South Asia domain; Maure et al., 2018 for the African domain, among others). Moreover, this unprecedented collaborative effort provided climate information at high resolution for regions highly vulnerable to climate change and where no previous modeling exercises were available (e.g. Maure et al. 2018 for Africa, Cavazos et al.; 2020 for Central America, Supari and Tangang 2020 for South East Asia, Llopart et al. 2020 for South America, among others).

In 2016 **Flagship Pilot Studies (FPSs)** were established with the aim of improving the capability of the models in reproducing regional climate features and producing actionable information for impact studies. FPSs are intended to specifically tackle scientific questions for any given region of the world for which current RCMs are still unable to reproduce the regional climate features adequately. For example, coupled RCMs, including components of the Earth system such as the ocean or atmospheric chemistry, were encouraged and have been used to demonstrate that Regional Earth System Models (RESMs) are able to improve the capability of simulating regional climate features, mainly over those regions where interactions among different components of the climate system have a strong impact on regional climate features (e.g. Di Sante et al. 2019). FPSs have been and are also still encouraged to reach resolutions at convection-permitting scales. Higher resolutions are needed in order to capture the main features of extreme precipitation events, such as intensity and diurnal cycle, for which convection is the key process. So far, the community has submitted a number of proposals applying for FPS status to the CORDEX Scientific Advisory Team (SAT) and many of them have been endorsed. Currently, 13 FPSs over 5 regions of the world are on-going and 4 additional FPSs have been recently endorsed by the CORDEX SAT (cordex.org). Recent studies are tackling some of these topics (e.g. Coppola et al. 2019 and Bettolli et al., 2021 for coordinated convection permitting simulations over Europe and South America, respectively), highlighting the added value of convection permitting simulations over several sub-continental regions of the world. An example of the benefits of increasing model complexity is summarized in Davin et al. 2020 for land-use change impacts on regional climate in Europe.

Additionally, a specific refined protocol, known as the **CORDEX Coordinated Output for Regional Evaluations (CORE)** was developed to ensure contributions to the 6th Assessment Report of the IPCC (AR6). The main goal of the CORDEX-CORE framework is to provide a core set of comprehensive and homogeneous projections across most, if not all, CORDEX domains. For this reason, the CORE framework is ambitious but sufficiently cost-effective to attract participation and produce timely output for the AR6, ensuring a minimum number of available simulations for each CORDEX domain (e.g. Reca Remedio et al. 2019).

The unprecedented coordinating activities led by CORDEX to date have emphasized the need for enlarging the multidimensional matrix of available simulations for different regions, including different RCMs driven by different GCMs under different scenarios. Moreover, CORDEX aims to include a multi-approach framework by including mostly RCMs but also ESD methods and variable-resolution General Circulation Models (VRGCMs). ESD, VRGCM, and RCMs have different strengths and weaknesses, independent of each other. Combined, enlarging the multi-dimensional matrix and providing downscaled scenarios for multiple regions with multiple downscaling approaches represents one of the challenges for CORDEX in the upcoming years. Meeting this challenge may help inform the uncertainty of the regional scale climate change signal.

The lessons learned from what has already been achieved under the umbrella of CORDEX, including the FPSs, CORDEX-CORE, and other new developments from the regional climate modeling community, together with the strong need for providing improved information for users, recommend new challenges be envisioned to drive the community forward. **This calls for more complex models, higher-resolution and a multi-dimensional approach. How to coordinate future modeling developments at regional scales under CORDEX to meet this challenge must be discussed.**

Additionally, in order to improve the usefulness of the data provided for impact studies, a key issue is to improve our understanding of the climate change signal at local-to-regional scales. Better understanding of the local-scale signal requires higher resolution simulations, including convection-permitting resolution simulations, and/or more complex, coupled models. The coordination itself of higher-resolution and/or more complex simulations for smaller domains is one of the present key challenges for the CORDEX community.

Smaller domains with finer resolution

Challenge

There is a certain pressure to produce simulations at increasingly higher resolutions (e.g., 4km or less) in domains that are smaller than the current CORDEX domains, called *convection permitting resolution domains*. As an example, national funding over several countries around the world is available for national VIACS activities aiming at 1-km scale model resolution and national domains. Finer resolution is needed to both improve our understanding of the local scale signal (e.g., over cities, inland waters, and small islands) and improve the provision of actionable climate data for decision making. Providing actionable climate information to decision makers may be best done under the coordination of the common CORDEX framework, as this facilitates proper inclusion of structural uncertainties that are important in the assessment of the climate change signal. Moreover, local change signals are driven by both changes in large-scale, global emission concentrations and changes in local environmental factors like land-use-land-cover changes (LULCC). Understanding what is changing locally and regionally and why, and providing a range of uncertainty for these changes is challenging. The extent to which environmental changes (e.g., Amazon deforestation or other LU LCC that are informed by Shared Socioeconomic Pathways (SSPs)) are included in simulations may be determined in close connection with other WCRP Core Projects (e.g. the Global Energy and Water Exchange (GEWEX) Project and the Climate and Cryosphere (CliC) Project). Additionally, as CORDEX moves to higher-resolutions, ongoing efforts to develop more sophisticated urban schemes may also contribute to both the improvement of the models and their ability to provide useful information at the city level (Daniel et al. 2019). A key challenge for CORDEX is to coordinate the simulations, in order to include the most relevant sources of uncertainty. Hence, the multi-dimensional approach would encompass the design of a set of simulations ideally including different driving GCMs (after climate sensitivity and regional performance analysis), HighResMIP GCMs (Haarsma et al. 2016), RCPs, SSPs, RCMs, and ESD approaches.

Questions

- How can a common setup be defined to assure model ensembles for smaller ("national") *convection-permitting resolution domains*?
- How do we assure reliability with only a few simulations in some *convection-permitting resolution domains?*
- What are the common scientific challenges?

Suggestions

CORDEX will propose a common setup for *convection-permitting resolution domains* in which the CORDEX scientific challenges (Gutowski et al. 206) will be tackled in a community approach using an ensemble of RCM simulations. Common 25-km resolution simulations within CORDEX standard domains will be the basis for further downscaling. CORDEX will also suggest a telescoping nested approach. With the availability of GCM simulations at higher resolution (50 to 25 km), such as those proposed and completed for the HighResMIP experiment, a telescoping strategy needs to be carefully designed. CORDEX will suggest a set of common *convection-permitting resolution domains* within the established CORDEX domains, which will be recommended for inclusion in CORDEX. Scientific questions can then be commonly tackled using the CORDEX high-resolution ensemble produced for these *convection-permitting resolution domains*. The choice of the domains will be guided by objective criteria:

- Is high-resolution observation data available in the region?
- Is the area scientifically interesting in the context of the CORDEX scientific challenges?
- Can an ensemble of simulations over this domain address the CORDEX scientific challenges, including the issue of uncertainty and added value?
- Can the common *CORDEX convection-permitting resolution domains* solve issues that emerge in GCM and high-resolution RCM simulations?
- Is the proposed domain relevant for other WCRP initiatives, such as GEWEX?
- Is the regional/local climate affected by increasing climate-related threats that may enhance the climate-related risks?

The regional CORDEX communities will suggest domains to the CORDEX-SAT, which will give recommendations and comments back to the regional CORDEX communities. The final choice will be made by the regional CORDEX communities and communicated to the CORDEX-SAT for dissemination on the CORDEX website.

The CORDEX coordination strategy could be re-defined along scientific challenges in a way that these challenges are tackled across different *convection-permitting resolution domains* in addition to the common *CORDEX convection-permitting resolution domains*. One key issue is formatting coordination that would pursue the multi-dimensional approach, hence, including recommendations concerning GCM sensitivity, SSPs, RCPs and other regional forcings. It is also important to note that contributions from the community are expected in terms of both performing and analyzing simulations, thus creating opportunities for groups with varied computing capacities and creating synergies between those performing the simulations and those assessing and analysing them.

Increasing complexity

Challenge

As RCMs move towards Earth System Models (ESM), they integrate two-way coupled processes to include dynamic vegetation (carbon cycle), oceans (and sea-ice), more complex precipitation processes, interactive aerosols, lakes, glaciers, etc. Computing time needed increases and a compromise must be made between resolution and domain size.

Moreover, new emerging scenario frameworks, including plausible SSP-RCP combinations, should be tackled within the new CORDEX simulations. There have been recent studies demonstrating that LULCC over several regions of the world can trigger significant temperature and precipitation responses which, in some cases, may reverse the response to increasing GHG concentrations (Findell et al. 2017). The availability of SSP scenarios data for RCMs, including the future evolution of LULCC, represents an opportunity to combine different anthropogenic drivers of climate change.

An additional theme RESMs may be able to address is the feedback of adaptation strategies on regional climates, e.g. LULCC such as reforestation, mitigating technologies such as bio-energy with carbon capture and storage (BECCS), urban growth, and of the impact on regional and remote climates.

Questions

- Can we find a compromise resolution for Regional ESMs so they can still produce coupled simulations over the standard CORDEX domains?
- Or should we aim at sub-domains specific for RESMs, so they can be based on more relevant finer resolutions, and focused on regions to study interesting processes considering the additional processes they integrate?
- How may the regional climate change signal be modulated under future scenarios including changing GHG concentrations (RCPs) and LULCC (SSPs)?

Suggestions

The regional CORDEX communities should discuss the possible compromises and see if it is still possible to produce simulations over the standard CORDEX domains or if the focus should be on specific regions. A suggestion is to launch a CORDEX-MIP on RESMs exploring the regional response including a variety of coupled components to the RCMs. These simulations may be performed on the common CORDEX domains at 50 or 25km resolution and may be used to contribute to the operational CORDEX dataset.

Preliminary exercises including the emerging SSP-RCP framework are being pursued and a protocol for developing a modelling strategy has already been released by the CORDEX SAT. Please find the Second Order Draft here.

Increasing spatial resolution

Challenge

GCMs are using resolutions of 25-50km in HighResMIP for CMIP6, reaching the RCM scale. This resolution might become the standard in CMIP7. Some tests are being done with global models at 1-km resolution for periods of a few months.

Questions

- What resolution are GCMs expected to use in the next 5-10 years?
- What are the RCMs aiming at?
- How can we foster interaction between the modelling groups, learning from each other and stretching collaboration?

Suggestions

Fundamental model behavior changes at resolutions when the use of a convection parameterization is no longer required. This would suggest 4km or less as the target resolution. Are assumptions underpinning other parameterizations (e.g. planetary boundary layer (PBL), radiation, microphysics) still valid at these resolutions? What development work is needed to improve model performance at these resolutions? Convection isn't fully resolved until ~100m (or smaller?) resolution. How does model behavior change over this resolution range?
Looking further ahead, at ~100m resolution is the PBL parameterization still required? And, does a similar fundamental change in model behavior occur?

The CORDEX community should strive to be informed, for instance via the Points of Contacts (POCs) and in contact with the GCM modelling groups and ideally be involved in analysis activities. Moreover, the CORDEX community should seek mutually beneficial collaborative opportunities with the Numerical Weather Prediction community who are also facing similar questions about process representation at these scales.

Overall, it is envisioned that RCMs will lead the simulations over several domains around the world at convection permitting scales, while GCMs will increase resolution but still serve as drivers of the convection permitting RCMs. This will however require that GCMs archive RCM-driving data at higher time frequency.

Exascale computing

Challenge

A new generation of high-performance computers are being established, using Graphics Processing Units (GPUs), specialized processors, etc. There is a general trend of having more processors or processing units instead of increasing the computational power of single processing units. Models' code needs to be adapted to this new computing architecture (e.g. Leutwyler et al. 2017). These changes will also require new evaluation of the newly coded models using this new setup. Moreover, machine learning strategies are also being used for downscaling and emulators (e.g. parameterizations). Hence, it is clear that a variety of new emerging technologies and strategies should be considered to adapt RCMs to these frontier tools.

Questions

- Are the RCMs ready for the new generation of high-performance computers?
- How can the models be adapted?
- How can this adaptation be done in a flexible, generic, hardware independent way?
- How can machine learning emulate and hybridize with RCMs (e.g. parameterizations)?

Suggestions
CORDEX RCMs have similar tasks in bringing code to the new generation of high performance computers. CORDEX can foster the exchange of information about technical aspects concerning the transformation of models to the new generation of high-performance computers.

Data and Infrastructure

Challenge
As already highlighted above, one of the major successes of CORDEX has been its contribution in making available for the community a set of coordinated downscaling simulations covering all land areas of the world. With new simulations and higher resolution, the amount of storage capacity for saving these data sets is expected to rapidly increase and the need for maintaining them becomes a challenging endeavor. As such, there is a strong need for external funding to support the maintenance and growth of the storage capacity. Publication of simulations on the ESGF by all domains needs to be ensured, as this will greatly facilitate scientific analysis and exploitation by end-users (climate services, VIA, National Adaptation Plans, etc).

Questions
- Will the ESGF remain the home of the standard CORDEX projection data?
- Where will data from FPSs be stored and how will access be made open?
- Which new tools are needed to analyze the data as it continues to expand in size?

Suggestions
While the ESGF provides a standard home for climate projection data (from both GCM and RCMs) it remains a non-trivial exercise to publish data there. The ESGF could also provide a home for data related to FPSs. Moreover, the large number of domains and growing data size of CORDEX creates challenges in analyzing the data, especially over multiple domains. CORDEX should foster the creation of tools to simplify data access and facilitate data analysis; to be more efficient for the modeling community, these tools should be Open Access, allowing sharing of their development, their use and their improvements through time. It is also suggested that documentation and guidance on how to access and use the data be provided on the CORDEX web page. A FAQ is now available on the web page.

One last reflection arising from all the above is the need to build comprehensive ensembles, including different key sources of uncertainty, hence, enlarging the multi-dimensional matrix (considering multiple RCMs, multiple driving GCMs, multiple SSPs and RCPs), which may contribute to produce useful information for policy makers and end users.

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