Addressing climate information needs at the regional level: the CORDEX framework

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Introduction

The need for climate change information at the regional-to-local scale is one of the central issues within the global change debate. Such information is necessary in order to assess the impacts of climate change on human and natural systems and to develop suitable adaptation and mitigation strategies at the national level. The end-user and policy-making communities have long sought reliable regional- and local-scale projections to provide a solid basis for guiding response options.

To date, most regional climate-change information has been based on the use of Coupled Atmosphere-Ocean General Circulation models (AOGCMs) enabled by the World Climate Research Programme (WCRP) during the past 30 years (Busalacchi and Asrar, this issue of *WMO Bulletin*). AOGCMs have proved to be the most valuable tools in understanding the processes that determine the response of the climate system to anthropogenic forcings, such as increases in greenhouse-gas (GHG) concentrations and changes in land use and atmospheric aerosol loadings. They have also provided valuable information on climate change at the global to sub-continental scale (IPCC, 2007). Although we have seen significant improvements in these models, especially in the past decade, due to better representation of atmospheric and Earth surface processes and enhanced computational capabilities, the horizontal resolution of most present-day AOGCMs is still of the order of a few hundred kilometres (Meehl et al., 2007). This prevents them from capturing the effects of local forcings (e.g. complex topography and land-surface characteristics) which modulate the climate signal at fine scales.

Coarse resolution also precludes global models from providing an accurate description of extreme events, which are of fundamental importance to users of climate information with respect to the regional and local impacts of climate variability and change. In other words, a fundamental spatial scale gap still exists between the climate information provided by AOGCMs and the input needed for impact assessment work.

In order to circumvent this problem, various "regionalization" or "downscaling" techniques have been developed to spatially refine the AOGCM climate information and bridge this spatial scale gap (Giorgi et al., 2001). They have been traditionally divided into "dynamical" and "statistical" downscaling techniques. Dynamical downscaling (DD) makes use of physically based models, such as high-resolution and variable-resolution global atmospheric models (AGCMs and VARGCMs, respectively) run in "time-slice" mode (e.g. Cubasch et al., 1995; Deque and Piedelievre, 1995) and limited-area "regional climate models" or RCMs (Giorgi and Mearns, 1999).

In statistical downscaling (SD), statistical relationships are first developed between large-scale predictors and regional-to-local-scale predictands and are then applied to the output from climate-model simulations (Hewitson and Crane, 1996). Although many different SD models and techniques exist (e.g. Wilby et al., 2004; Giorgi et al., 2001; Wigley and Wilby, 2000; Hewitson and Crane, 1996), they all share this basic conceptual framework. A number of papers are available in the literature to review downscaling work and discuss the relative merits and limitations of the different techniques (Laprise et al., 2008; Schmidli et al., 2007; Giorgi, 2006; Wang et al., 2004; Leung et al., 2003; Mearns et al., 2003; Murphy, 1999; Giorgi and Mearns, 1999, 1991; McGregor, 1997), and the reader is referred to these papers for such discussions.

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Both dynamical and statistical downscaling tools, which we refer to as regional climate downscaling (or RCD) have been increasingly used to address a variety of climate-change issues and have by now become an important method in climate-change research (Huntingford and Gash, 2005). Particularly in the last decade, the development and use of RCD models have increased tremendously, as proved by an almost exponential increase in the number of peer-reviewed publications on this topic. (For example, searching for the string "regional climate model" in the information system interfaces (ISI) results in fewer than five entries/year up to 1994 to more than 150 in 2008.)

A reasonable question to ask is whether this tremendous development has resulted in an increased use of RCD-based products for climate change impact assessments. With a few exceptions, this is not the case. For example, most regional climate-change material presented in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), and further utilized in impact assessment work, is still based on relatively coarse resolution AOGCM simulations (e.g. Christensen et al., 2007).

What is the reason for the under-utilization of RCD-based products? We believe that a primary reason is the lack of a coordinated framework to evaluate RCD-based techniques and produce ensemble projections of sufficient quality to characterize the uncertainties underlying regional climate change projections. Such frameworks are available for global models, such as the Atmospheric Model Intercomparison Project (AMIP) or the Coupled Model Intercomparison Projects 1-3 (CMIP1-3). The global modelling community has benefited tremendously from such coordination activities in terms of process understanding, model evaluation and generation of climate change projections. Conversely, most RCD studies have been isolated and tied to specific targeted interests, so that a comprehensive picture of regional climate-change projections based on RCD experiments is currently not available.

Recognizing this limitation, WCRP recently formed the Task Force on Regional Climate Downscaling (TFRCD) whose mandate is to:

- Develop a framework to evaluate and possibly improve RCD techniques for use in downscaling global climate projections;
- Foster an international coordinated effort to produce improved multi-model RCD-based high-resolution climate-change information over regions worldwide for input to impact/adaptation work and to the IPCC Fifth Assessment Report (AR5);
- Promote greater interaction and communication between global climate modellers, the downscaling community and end-users to better support impact/adaptation activities.

As a result of the first activities of the TFRCD, and in consultation with the broader scientific community, a framework was initiated called the Coordinated Regional climate Downscaling Experiment (CORDEX). In this article, we describe the status and plans for CORDEX, which mostly resulted from a workshop held in Toulouse, France, 11-13 February 2009 (http://wcrp.ipsl.jussieu.fr/Workshops/Downscaling/DirectionVenue.html) and subsequent discussions.

Producing regional climate projections and associated uncertainties

In this article, we use the term "regional" in a broad sense to indicate the entire range of spatial scales of less than ~10 000 km². With this definition, the task of producing reliable regional climate projections is extremely difficult, since the regional climate change signal is affected by processes that occur at a wide range of spatial scales from the planetary to the synoptic and mesoscale. For example, the effect of increased greenhouse-gas concentrations will affect the general circulation of the atmosphere and the structure of planetary-scale dynamical systems. This large scale climate signature is then modulated at the regional to local level by a multiplicity of forcings, including complex topography, coastlines and aerosol distribution.

While current AOGCMs have proved quite successful in reproducing the main features of the general circulation (IPCC, 2007), they do not represent adequately the effects of regional-to-local-scale forcings. Their performance also generally deteriorates when going from lower- to higher-order climate statistics, such as variability, extremes and weather regimes. In addition, natural climate variability tends to increase as we move from large to fine scales, and this makes the identification of the climate-change signal from the underlying noise more difficult.

While RCD techniques can improve the AOGCM information at fine scales by accounting for the effects of regional forcings, they are still affected by systematic errors in the coarse-scale input data from AOGCMs. For example, the positioning of the storm track in an AOGCM will propagate into the interior domain of a nested RCM. Our imperfect knowledge and model description of physical processes represent a critical source of uncertainty when performing climate projections, which tends to increase as the scale of interest becomes increasingly finer. By virtue of this uncertainty, different models will generally produce different responses to the same climatic forcing (e.g. greenhouse-gas concentration). This uncertainty, which is referred to as "model configuration", is one of the greatest sources of uncertainty in climate projections and propagates directly from global model simulations to all RCD techniques. It compounds with other sources of uncertainty, such as those due to greenhouse-gas emission and concentration scenarios, internal variability and non-linearities in the climate system and, for the downscaling problem, choice of RCD method (Giorgi, 2005). Studies have indicated that the GCM configuration and scenario uncertainties represent the leading sources of uncertainty in climate-change projections, particularly on longer, centennial, timescales. The choice of RCD technique can also be important, whereas the uncertainty related to internal climate variability is mostly important on shorter timescales (e.g. for simulating the climate of 2020-2030) and for higher-order statistics.

In order to provide useful information for impact assessment studies, the uncertainties in regional climate change projections need to be fully characterized and, where possible, reduced. This requires the generation of ensembles of simulations exploring all the relevant uncertainty dimensions. The final goal of this process is the production of probabilistic climate-change information for climatic variables of interest in the form of probability density functions (PDFs). The width of the PDF gives a measure of the uncertainty. The larger the ensemble, the better the uncertainty space can be sampled and explored. A full exploration of the uncertainty space is, however, a daunting task, since it requires the completion of a multi-dimensional matrix of experiments whose number can quickly become extremely large (Giorgi et al., 2008). Figure 1 summarizes the set of areas of uncertainty that need to be covered when producing regional climate- change projections based on RCD products:

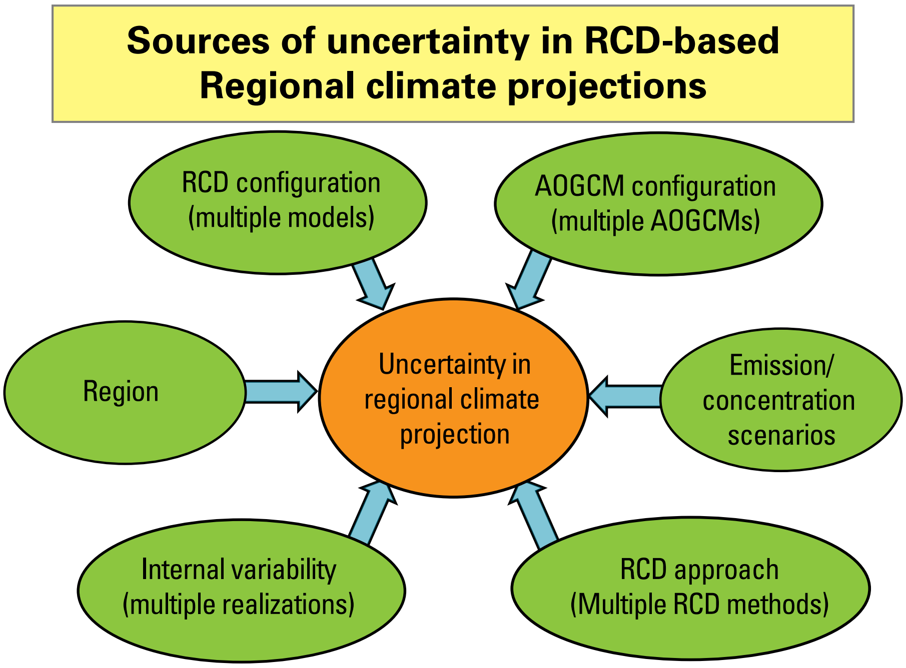

Figure 1 — Schematic depiction of the primary uncertainties in regional climate change projection

1 GHG emission scenarios
2 AOGCM configuration
3 AOGCM internal variability
4 RCD configuration
5 RCD internal variability
6 RCD method
7 Region of interest

Source 1 can be explored by simulating different greenhouse-gas emission scenarios; Sources 2 and 4 by using different AOGCMs and RCD models or, within the same modelling system, different model configurations (e.g. physics parameters); Sources 3 and 5 by performing different realizations of the same scenario each using different initial conditions (most importantly for the slow components of the climate system, such as oceans and vegetation conditions); Source 6 by using different RCD methods (e.g. RCMs and SD models); and Source 7 by applying the RCD models to different regions.

In addition, the reliability of climate-change projections needs to be assessed in view of the credibility of the models. This, in turn, can be measured by the model performance in reproducing observed climate conditions or different climate states observed in the past. Therefore, the process of producing climate-change projections cannot be disentangled from the process of evaluating the performance of the models. What is thus required is an overarching framework that, on the one hand, provides a benchmark for evaluating and possibly improving models and, on the other, a set of experiments that allow us to explore to the maximum extent possible the contribution of the different sources of uncertainty. The CORDEX programme aims to provide such a framework.

The CORDEX framework

CORDEX essentially has the two-fold purpose to provide a framework to evaluate and benchmark model performance (model evaluation framework); and design a set of experiments to produce climate projections for use in impact and adaptation studies (climate projection framework). It is schematically depicted in Figure 2 and described in the following sections.

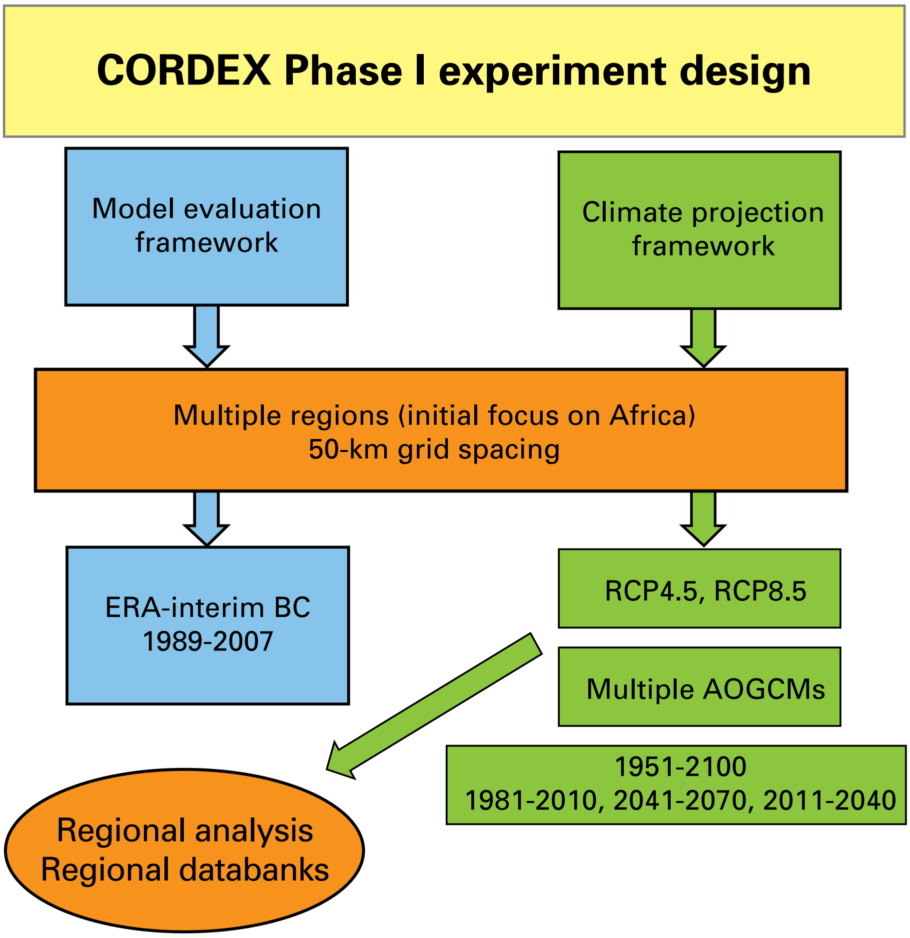

Figure 2 — Schematic depiction of the first phase CORDEX experiment set-up

Model domains and resolution

The choice of common RCD domains is a prerequisite for the development of the model evaluation and climate projection frameworks. The goal of CORDEX is to provide a framework accessible to a broad scientific community with maximum use of results. CORDEX domains therefore encompass the majority of land areas of the world. Figure 3 shows a first selection of common domains (currently still under discussion), where these should be interpreted as interior analysis domains, e.g. not including the lateral relaxation zone in RCMs. This selection is based partly on physical considerations (i.e. inclusion of processes important for different regions), partly on considerations of resources needed for the simulations and partly on the availability of ongoing programmes.

Figure 3 shows five domains covering the entire African, Australian, South American, North American and European continents. The latter three are essentially the same domains used in the projects CLARIS (www.claris-eu.org), NARCCAP (www.narccap.ucar.edu) and ENSEMBLES (ensembles-eu.metoffice.com) and respectively. A domain also includes Central America, together with the equatorial western Atlantic and Eastern Pacific regions, where current projections indicate large changes and possible effects on tropical cyclones. The Asian continent is divided into three domains, one centred on the Indian monsoon, a second on East Asia and a third targeting central Asia. Pan-Arctic and Antarctic domains will also be included, based on experience derived from the respective polar modelling communities (not shown in the figure).

In order to allow wide participation, TFRDC, in consultation with the broader community, decided to make

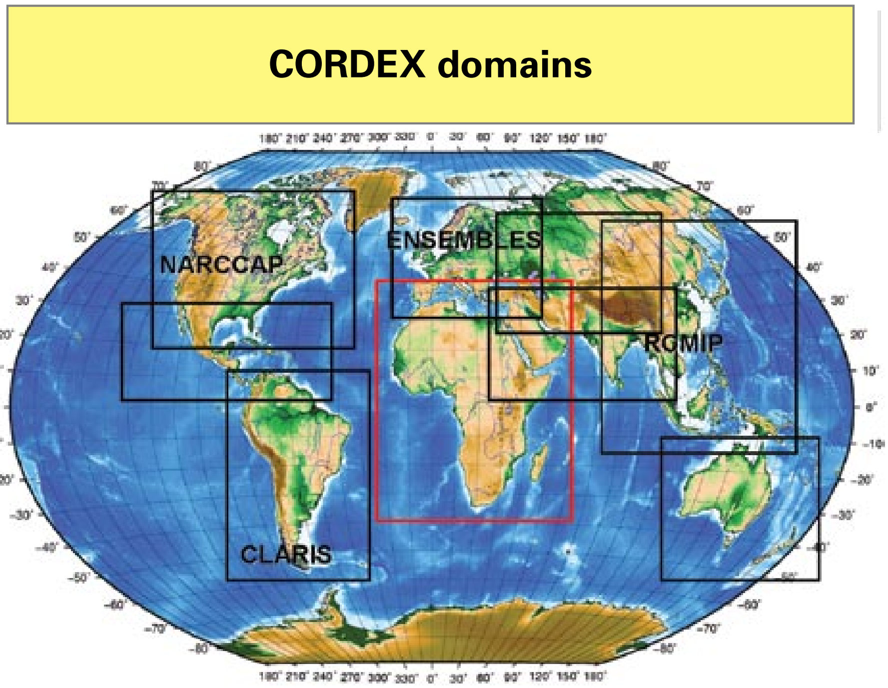

Figure 3— Regional domains planned for the CORDEX experiments (some still under discussion); also indicated are existing projects that make use of the corresponding domain.

the standard horizontal resolution for the first phase CORDEX simulations to be ~50 km (or 0.5 degrees). Today, many groups are running RCMs with considerably higher grid spacing than this (up to ~10 km) and they are encouraged to explore the benefits of increased RCM resolution within the CORDEX framework. Nevertheless, it was felt that a standard resolution, allowing contribution by many groups, would increase the sense of community ownership of the CORDEX project, while also increasing the size of any ensuing RCM scenario set for analysis and comparison purposes.

Model evaluation framework

In order to evaluate the performance of both DD and SD models, a set of so-called "perfect boundary conditions" experiments will be performed for the selected domains. Such experiments utilize analyses of observations to produce fields to drive the RCD models, for example as lateral and surface boundary conditions. Although still derived from (imperfect) models, analyses of observations include information from a varied set of observing systems (surface, atmosphere and remotely sensed) and thus provide the best available conditions to drive RCD models.

The CORDEX framework will initially utilize the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim re-analysis (Uppala et al., 2008), which covers the period 1989-2007 and improves a number of problems found in previous reanalysis products, particularly related to the hydrological cycle in tropical regions. Various efforts are currently underway to update reanalysis products in different centres and these will be used when available.

For model evaluation, a set of diagnostic teams will be formed for each simulated region, whose task will be to design a set of benchmark regional metrics for model evaluation. Observational datasets will need to be obtained/assembled for each region for use in the model evaluation process. This is a particularly delicate task as the evaluation process needs to be carried out at fine spatial scales for which suitable datasets are not always available. It will thus be important to tap into local resources and expertise to enhance current observational datasets to the extent possible.

Climate projection framework

The climate projection framework within CORDEX is based on the set of new global model simulations planned in support of the IPCC Fifth Assessment Report (referred to as CMIP5). This set of simulations includes a large number of experiments, ranging from new greenhouse-gas scenario simulations for the 21st century, decadal prediction experiments, experiments including the carbon cycle and experiments aimed at investigating individual feedback mechanisms (Taylor et al., 2009).

For its initial activities, CORDEX will focus on the scenario simulations. Different from the scenario runs employed in the fourth IPCC assessment cycle, which were based on the SRES GHG emission scenarios (IPCC, 2000), this next generation of scenario simulations is based on so-called reference concentration pathways (RCPs), i.e. prescribed greenhouse-gas concentration pathways throughout the 21st century, corresponding to different radiative forcing stabilization levels by the year 2100. Four RCPs have been selected, with stabilization levels at 2.9, 4.5, 8.5 and 11.2 W/m^2 (referred to as RCP2.9, RCP4.5, RCP8.5 and RCP11.2, respectively). Within CMIP5, the highest-priority global model simulations have been selected to be the RCP4.5 and RCP8.5, roughly corresponding to the IPCC SRES emission scenarios B1 and A1B, respectively. The same scenarios are therefore also planned to be the highest priority CORDEX simulations (Figure 3).

Ideally, all regional model simulations should span the period 1951-2100 in order to include a recent historical period, plus the entire 21st century. For many groups, however, it may prove computationally too demanding to run CORDEX simulations for this entire time span. The 1951-2100 period has thus been divided into five 30-year time slices and participating groups are requested to simulate time slices in the following order of priority 1981-2010, 2041-2070, 2011-2040, 2071-2100, 1951-1980. The first of these (1981-2010) represents the reference period for model evaluation and for the calculation of climate changes. The second priority time slice, covering a future time period, was selected as a compromise between the needs of the impact community in terms of future time horizon and the requirement to obtain a robust change signal. It is requested that all participating groups at a minimum perform these two time slices to have a reasonable set of simulations for analysis and intercomparison.

In the initial phase of CORDEX, it is planned to simulate one realization for each RCP scenario selected, using driving data from multiple global models. In this way, CORDEX will explore the model configuration uncertainty but not the internal variability one. As mentioned above, this should not represent a major drawback, since previous experience has shown that the former is a much more important source of uncertainty when looking at long temporal scales. The sampling of internal variability through multiple realizations is left for the next phases of CORDEX.

Initial focus on Africa

The purpose of CORDEX is to produce a framework valid for multiple domains across the world. Completing a large set of multi-decadal simulations for the entire set of regions shown in

Figure 3 is, however, a formidable task that will require considerable time and resources. In addition, it is useful to test the framework for one region in order to assess its strengths and weaknesses before applying it worldwide. It was therefore decided to select an initial priority region, which we hope will allow a useful matrix of RCD-based scenarios to be generated within the time frame of the IPCC AR5.

Africa was selected as the first target region for several reasons. First, Africa is especially vulnerable to climate change, both because of the dependence of many vital sectors on climate variability (e.g agriculture, water management, health) and because of the relatively low adaptive capacity of its economies. Second, climate change may have significant impacts on temperature and precipitation patterns over Africa, which, in turn, can interact with other environmental stressors such as land-use change, desertification and aerosol emissions. Finally, to date, only very few simulations based on RCD tools are available for Africa, so this region will benefit particularly from the CORDEX framework, from both the research and application points of view. The domain shown in a red frame in Figure 3 will therefore be the initial focus of the CORDEX experiments.

It is fully appreciated that many downscaling groups will favour simulating their "home" domain first and these regional projections are also welcomed in the CORDEX framework. The focus on Africa is mainly to encourage groups that can perform multiple regional climate projections, initially to prioritize Africa and obtain a relatively large ensemble for this region in order to enhance analysis and intercomparison of model results.

Data management

A key aspect of the CORDEX programme will be the management of large amounts of model inputs that it needs and the model outputs and intercomparisons that it will generate. There are two components. First, fine temporal resolution (six-hourly) AOGCM meteorological fields are required as boundary conditions for the RCMs. These need to be stored in a central databank for easy access to the CORDEX modelling community and also in a format standardized across AOGCMs (almost certainly following the official CMIP5 format guidelines). In addition, a fast-track procedure will need to be established in order to transfer data from the AOGCM to the RCD groups.

Second, the output from the RCD simulations will need to be stored in a way that allows easy access to the end-user community, likely also requiring standardization of formats (possibly adhering to the CMIP5 format guidelines). This can prove to be a formidable task in view of the large amounts of data produced by fine-scale climate models. A proposal is being evaluated for creating a distributed network of regional databanks all adhering to the same format and standards for archival and distribution of RCD output, that may be located in various regions/continents. This discussion is still ongoing.

Meeting the challenge:

Given the complex and multi-faceted nature of the CORDEX effort, it is legitimate to ask whether it can actually be successful in delivering the regional climate analysis and information for adaptation, mitigation and vulnerability assessments. Past experience with similar projects (albeit more limited in scope) can provide some guidance in this regard.

One good example is the European project PRUDENCE (Prediction of Regional Scenarios and Uncertainties for defining European Climate Change Risks and Effects (http://prudence.dmi.dk/)). PRUDENCE was an end-to-end project in which multiple global models were used to drive multiple RCMs over a European domain based on forcing from two greenhouse-gas emission scenarios. The results

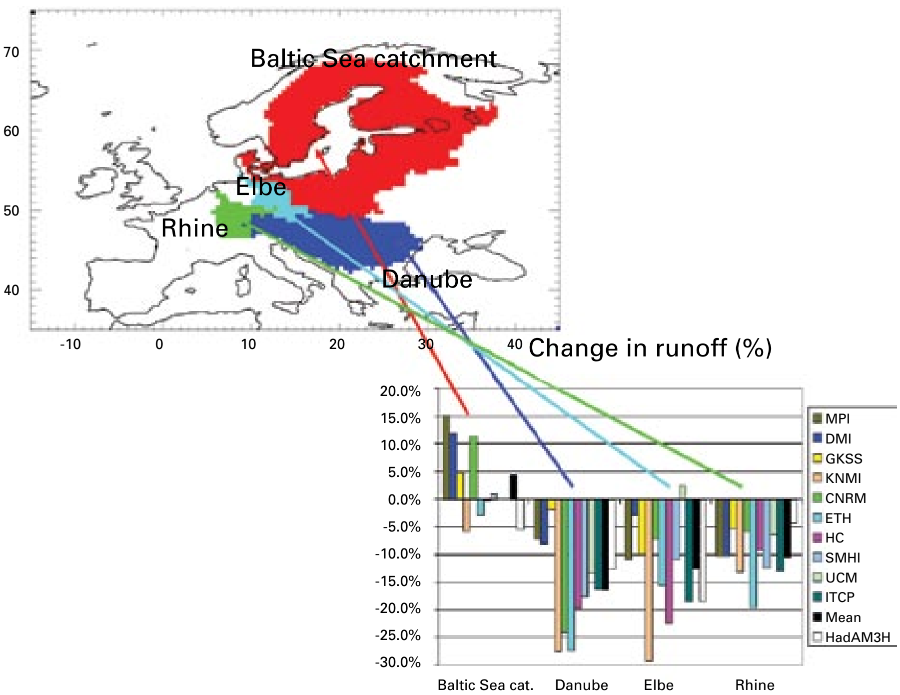

Figure 4 — Change in runoff (%, 2071-2100 minus 1961-2990, A2 scenario) calculated for four European drainage basins by the PRUDENCE multi-model RCM ensemble (from Hagemann and Jacob, 2007)

from the RCM simulations were then used in a range of impact assessment studies ranging from hydrology and agriculture, to health and economy. In the development of the PRUDENCE strategy, communication between the climate modelling and impact communities was essential. In addition, the complementary project STARDEX (Statistical and Regional dynamical Downscaling of Extremes for European regions (http://www.cru.uea.ac.uk/projects/stardex/) conducted similar experiments with different SD tools for intercomparison with the PRUDENCE RCM results.

The main PRUDENCE findings were presented in a special issue of *Climatic Change* in May 2007. Figure 4 (adapted from Hagemann and Jacob, 2007) shows an example of such results, where the output from an ensemble of RCM simulations was used in hydrological impact assessment. Surface runoff, an indicator of excess available water, was calculated for four European drainage basins (Baltic Sea, Danube, Elbe and Rhine rivers) in a set of reference (1961-1990) and future (2070-2100, A2 scenario) simulations with 10 RCMs driven by a single global model (HadAM3H).

The 10 RCMs exhibit a consistent signal of reduced water availability over the Danube, Elbe and Rhine basins, but a mixed signal over the Baltic Sea catchment. These results are attributed to the projected warming throughout Europe and corresponding decreased (increased) precipitation over central-south (north) Europe. This type of signal remains fairly consistent when different GCMs are used to drive the same set of regional models. The type of information in Figure 4 is an important input to guiding future management and planning of water resources at the European, national and even regional scales.

The PRUDENCE strategy can be extended to CORDEX and the Africa focus application will provide an important initial test-bed. Some groups have already started experimenting with the Africa domain within the ERA-Interim driven model evaluation framework. Figure 5 shows examples of such experiments. More specifically, June-July-August precipitation from two models, RegCM3 from ICTP (Pal et al., 2007) and RCA from the Rossby Centre (Jones et al., 2004), is compared with GPCP observations (Gruber and Levizzani, 2008). In addition, the top panels also compare simulated and observed (ERA-Interim) low-level winds from RegCM3. Both models show a generally good agreement with observations for the selected large domain.

Some results based on SD studies for Africa are also available in the literature such as Hewitson and Crane (2006), who use SD models to downscale results from multiple AOGCMs showing how this approach can in fact narrow the uncertainty emanating from global model simulations. These examples indicate that a RCD-based framework can indeed provide valuable climate-change information to guide future impact, adaptation and vulnerability assessments towards defining choices for coping with climate variability and change across Africa.

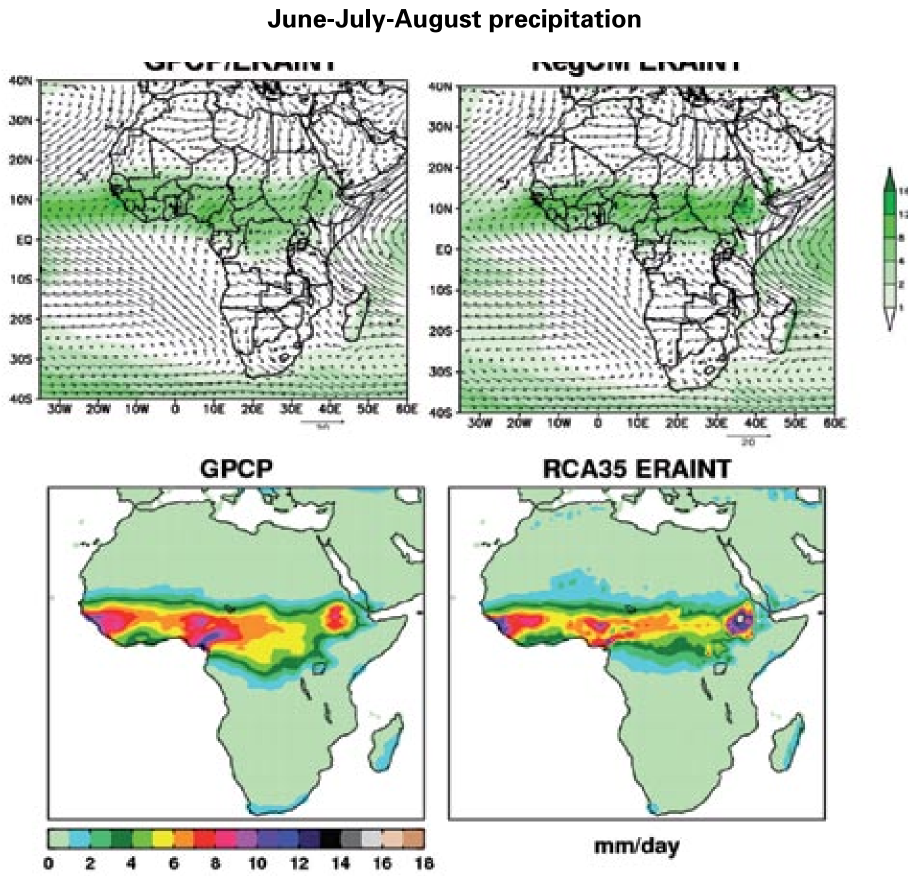

Figure 5 — Mean (1989-2005) June-July-August precipitation (mm/day) over Africa as simulated by RegCM3 (Pal et al., 2007, top right panel) and RCA (Jones et al., 2004, bottom right panel) RCMs driven by ERA-Interim lateral boundary conditions: the simulated precipitation is compared with the GPCP observed precipitation climatology (left panels). The top panels also compare RegCM3 low level (850 hPa) average winds (right panel) with ERA-Interim winds (left panel).

Summary and conclusions

In this article, we present a new framework for regional climate modelling and downscaling, called CORDEX, with the two-fold aim of developing a coordinated framework for evaluating and improving RCD techniques and producing a new generation of RCD-based fine-scale climate projections for identified regions worldwide. We envision that CORDEX will provide a framework for better coordination of RCD-related research and modelling activities within the regional climate modelling and downscaling communities. Past experience has shown that projects such as AMIP and CMIP are invaluable for the global modelling community and CORDEX is essentially structured to play a similar role for the RCD community.

A complementary role of CORDEX is to bridge the existing gap between the climate modelling community and the end-users of climate information. This can be achieved by increasing communication across these two communities and by targeting the structure of the CORDEX experimental and data-management activities to facilitate the use of common standards and formats that will enhance more effective and greater use of the resulting climate information by the end-users.

Here we have described the first design and implementation phase of CORDEX, with an emphasis on the next two-four years (i.e. on the timescale of IPCC AR5). It is envisaged, however, that CORDEX will provide a longer-term framework for continued use and support by the RCD community. While the initial focus is on Africa, as stated earlier, simulations over other domains are welcomed. Similarly, while the initial grid spacing is 50 km, to foster wide participation, groups are encouraged to explore the benefits of increased model resolution as their resources permit, but also in a coordinated fashion with other interested participants. While the initial focus of CORDEX is on 21st century scenario simulations, we plan to extend the CORDEX framework in the future to address the decadal prediction problem also, as research in this area matures sufficiently within the global climate modelling community.

Finally, we stress that it is important that the common interior domains and experiment plans are adopted as much as possible by participating groups so as to facilitate the intercomparison and analysis of models and techniques and the assessment of uncertainties in regional climate-change projections. Coordination of RCD activities is essential for a better understanding of RCD techniques and a more fruitful use of RCD-based products for societal needs.

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Acknowledgements

The authors thank Stefan Hagemann for providing the material for Figure 4.