Regional Dynamical Downscaling and the CORDEX Initiative

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Annu. Rev. Environ. Resour. 2015. 40:467–90

First published online as a Review in Advance on July 24, 2015

The *Annual Review of Environment and Resources* is online at environ.annualreviews.org

This article's doi:
10.1146/annurev-environ-102014-021217

Keywords

regional climate modeling, dynamical downscaling, regional climate, CORDEX, RCM, climate change, model evaluation, downscaling added value, regional Earth system modeling, high-resolution modeling

Abstract

We review the challenges and future perspectives of regional climate model (RCM), or dynamical downscaling, activities. Among the main technical issues in need of better understanding are those of selection and sensitivity to the model domain and resolution, techniques for providing lateral boundary conditions, and RCM internal variability. The added value (AV) obtained with the use of RCMs remains a central issue, which needs more rigorous and comprehensive analysis strategies. Within the context of regional climate projections, large ensembles of simulations are needed to better understand the models and characterize uncertainties. This has provided an impetus for the development of the Coordinated Regional Downscaling Experiment (CORDEX), the first international program offering a common protocol for downscaling experiments, and we discuss how CORDEX can address the key scientific challenges in downscaling research. Among the main future developments in RCM research, we highlight the development of coupled regional Earth system models and the transition to very high-resolution, cloud-resolving models.

Contents

1. INTRODUCTION AND HISTORICAL PERSPECTIVE

The development and use of regional climate models (RCMs), also referred to as dynamical downscaling when applied to downscale global climate model (GCM) output, originated in the late 1980s. The idea of utilizing high-resolution limited-area meteorological models to downscale coarse-resolution GCM fields was first proposed through the use of large ensembles of short (3–5 day) simulations (1), essentially following a well-established methodology in weather prediction. The first simulations with RCMs in the so-called climate mode, i.e., for continuous runs longer than the synoptic weather scale, were later produced using driving meteorological lateral boundary conditions (LBCs) from analyses of observations (2) or from GCMs (3). This was a fundamentally new conceptual step toward modern regional climate modeling, as it showed that the performance of RCMs does not deteriorate after a spin-up time of several days. This paved the ground for the first multiyear simulations conducted in the early and mid-1990s (4–9).

Today, a number of RCM systems are available; these have evolved from mesoscale and weather forecast models or as regional configurations of global models. Many institutions worldwide use RCMs, which have proven to be flexible tools employed by a large and often diverse community for a wide variety of applications from regional process and sensitivity studies to paleoclimate and future climate simulations, essentially over all land regions of the world. This flexibility has been important to many scientists, especially in developing regions, enabling them to engage in leading-edge research without requiring the large infrastructure typically needed to run a high-quality GCM. By contrast, the variety and breadth of RCM use require a good understanding of their advantages, limitations, performance, and technical issues. A number of reviews provide a historical perspective of the main developments and debates concerning RCMs (10–20). Two goals of this review are to assess (*a*) the outstanding issues and (*b*) the main future directions in RCM research, in particular, within the context of the emerging need to promote global multimodel programs, such as the Coordinated Regional Downscaling Experiment (CORDEX) (21, 22).

RCMs have been developed to study regional processes and to generate physically based high-resolution climate information at scales of relevance for vulnerability, impact, and adaptation (VIA) studies. The basic strategy of the so-called one-way nesting approach (**Figure 1**), the main one used in dynamical downscaling, consists of first running GCMs to describe the effects of large-scale forcings and processes on the general circulation of the atmosphere, which in turn

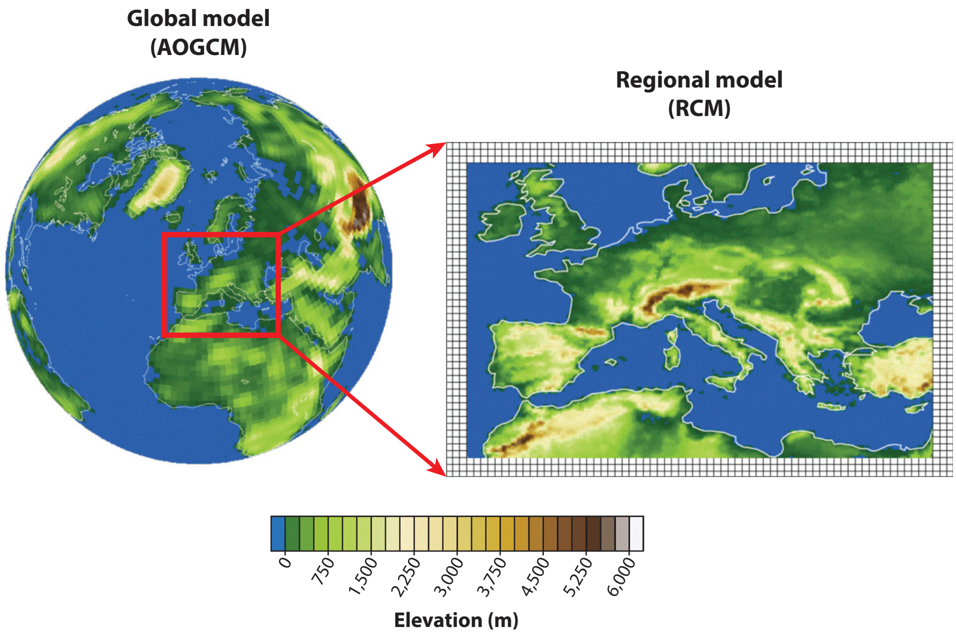

Figure 1

Schematic depiction of the one-way RCM nesting technique. The figure shows the refinement in topography and coastlines that can be obtained from the use of an RCM. The squared area surrounding the RCM interior domain represents the lateral buffer zone. Abbreviation: AOGCM, atmosphere-ocean general circulation model; RCM, regional climate model.

determines the sequence of weather events characterizing the climate of a region. Among such large-scale forcings are those resulting from greenhouse gases (GHGs), variations in solar activity, and major volcanic eruptions; examples of large-scale processes of relevance for regional climate modeling include modes of natural variability [e.g., El Niño–Southern Oscillation (ENSO)] or monsoon circulations.

Taking as input initial conditions (ICs) and LBCs from GCMs, high-resolution RCMs aim to spatially and temporally refine climate information over a given area of interest by describing forcings and phenomena not resolved in GCMs, such as complex topography, land use, coastlines, aerosol direct and indirect effects, and mesoscale circulations. The increased resolution of RCMs should also enable a better representation of spatial and temporal variability and of synoptic/mesoscale systems of relevance for VIA applications, in particular extreme weather events and tropical storms.

Note that RCM nesting is only one of the various downscaling techniques available today; other techniques include high-resolution atmospheric GCMs, variable-resolution GCMs (VARGCMs) (23, 24), and empirical statistical downscaling (ESD) (25). Each of these techniques has advantages and limitations, and the choice of one versus the other is most often dictated by the application at hand and the availability of data and computational resources. We stress, however, that they should not be seen in competition with each other or with GCMs but as complementary ways to increase the reliability and usefulness of regional to local climate information. In many cases, different downscaling approaches can be used together either in parallel (multiple methods applied to the same problem) or sequentially (e.g., RCMs driven by high-resolution atmospheric GCMs or ESD models downscaling RCM output).

An important aspect of regional modeling is that it lends itself easily to fragmentation, as different groups or individuals are often interested in different problems or regional settings. However, the use of common modeling protocols offers invaluable opportunities to better understand models, processes, and uncertainties (e.g., the Climate Model Intercomparison Project (26) for GCM research). Within the RCM community, a number of regional intercomparison projects have occurred (27–34), which have led to considerable improvements in the understanding of RCMs. However, differences in model setups and simulation protocols have made it difficult to transfer knowledge from one regional program to another. It has been recognized that global coordination of such efforts can further advance RCM development, analysis, and application (35), but it was not until the inception of CORDEX that a truly globally coordinated downscaling framework was established. CORDEX represents a major evolution in downscaling research and has now become the main international reference framework for downscaling activities.

On the basis of the premises discussed above, we first review outstanding technical and scientific issues underlying the RCM technique (Section 2) and, in particular, that of added value (Section 3). We then discuss model evaluation issues (Section 4) along with the uncertainties underlying the production of regional climate change information (Section 5). This provides the background for the development of a downscaling protocol (Section 6), a discussion of CORDEX (Section 7), and future research directions (Section 8).

2. THE METHOD AND SOME IMPORTANT TECHNICAL ISSUES

The one-way nesting technique consists of defining an RCM limited-area domain composed of a lateral buffer zone adjacent to the domain boundaries and an inner domain (**Figure 1**). To integrate forward in time, the equations of an RCM require ICs (throughout the entire model domain) and time-dependent LBCs for its prognostic variables, typically wind components as well as temperature, surface pressure, and moisture quantities. The LBCs are applied only in the lateral buffer zone at each model time step, thus allowing the model equations to be freely integrated in the domain interior. The ICs and LBCs can be provided either by global analyses of observations or by GCM simulations. The numerical solution of the RCM is thus determined by a dynamical equilibrium between the information from the LBCs and that from the model equations in the domain interior, with the former having a stronger influence as we move toward the domain boundaries.

In most models, the LBCs are provided using a standard relaxation technique (36) by which a Newtonian term is applied to the model prognostic equations throughout the buffer zone to smoothly drive the numerical solution toward the forcing fields. The boundary forcing can be modulated by varying the size of the buffer zone and the functional form of the relaxation term (37). An alternative approach is spectral nudging (38), in which the Newtonian relaxation term is added to all or some of the model prognostic equations throughout the entire domain, but only to the long-wave component of the model solution, and the model computes the short-wave component. Compared to the standard relaxation, spectral nudging imposes a stronger consistency between the driving GCM and nested RCM large-scale fields. However, the RCM is less free to develop its own circulations and thus offers less potential to take full advantage of the RCM's dynamics and physics.

In the one-way nesting technique, the climatology of an RCM is heavily influenced by the LBCs from the driving GCM. Therefore, if the large-scale climatology of the driving GCM has large systematic errors, for example, the wrong placement of storm tracks or the erroneous simulation of ENSO, these will be transmitted to the nested RCM. Although for large domains, especially in the tropics, the RCM might partially improve some aspects of the driving GCM large-scale errors, the nested model is not intended (nor expected) to fully do so. This problem, which has been referred to as garbage in, garbage out, implies that it is extremely important to analyze in detail the climate of a GCM before using it to drive an RCM, and if large systematic errors are present in the GCM, it is advisable to disregard it for the nesting exercise.

Because RCM nesting involves a number of technical steps, some of which we review in the next sections, RCMs should not be used as black boxes for producing regional climate information, and their performance for a specific configuration and application needs to be analyzed in detail and optimized to the extent possible.

2.1. Selection of, and Sensitivity to, Domain and Resolution

Critical aspects in the design of the configuration of an RCM experiment are the selection of model domain and resolution, two factors that are interconnected because increasing both the domain size and model resolution leads to a rapid increase in the computing resources necessary to run the model. Ideally, the domain size should be large enough to encompass the areas where the main regional forcings and processes affect the climate of the region of interest, and the resolution should be high enough to allow the representation of relevant fine-scale forcings (e.g., topography). These two factors are in direct competition for computing resources, and most often a compromise is necessary in terms of domain size and resolution.

The placement of the domain is important, as the solution in the domain interior may depend on the domain size and location. Early work showed that the placement of the domain, particularly over land regions, can affect the model sensitivity to soil moisture conditions (39). This conclusion was later confirmed by additional studies (18, 19). In general, because larger domains allow the internal model physics and dynamics greater freedom compared to smaller ones, where the LBCs govern more strongly, the model behavior is expected to be influenced by the domain characteristics, depending on specific regional contexts.

There are no precise rules for the selection of a domain but only some indications from past experience. For example, it is advisable to avoid placing domain boundaries over complex terrain, as the topography mismatch between the resolutions of the driving and nested models can cause problems when interpolating the LBCs onto the RCM grid. Also, the domain boundaries should be as far away as possible from the simulation's area of interest to minimize the influence of possible spurious boundary effects. A possible criterion for domain choice is whether or not a threshold size is reached above which the model solution in the region of interest becomes relatively independent of domain size.

Concerning model resolution, the computation requirements for running an RCM increase roughly by a power of three with horizontal resolution if the number of vertical levels is not changed, i.e., a doubling of horizontal resolution implies a factor of about eight increase in computing time required by the model (four times more grid points and halving of the time step). For large domains, this increase is often too demanding and provides a strong constraint on feasible resolution.

An additional constraint is the ratio of driving versus nested model resolutions. Studies using the big-brother protocol (40) found that a ratio of about 10 between the resolution of the driving GCM fields and the nested RCM represents an upper limit to obtaining good downscaling ability by a nested model. This is in fact the maximum ratio used in most RCM applications. If the resolution of an experiment is so high that this ratio is exceeded, an RCM run of intermediate resolution can be used as interface between the coarse-scale GCM and fine-scale RCM runs. This requires the use of RCMs in the multiple nested mode by which LBCs from an RCM, run at intermediate resolution, drive a high-resolution experiment. It has also been shown that a frequency update of six hours for the LBC (and linear interpolation at each model time step) represents the minimum to obtain good model performance (40), and this is the frequency update most commonly used.

It is thus clear that the choice of RCM domain and resolution imposes various constraints, and for optimal results, sensitivity to different factors should be assessed via a series of test experiments before proceeding to production runs.

2.2. Internal Model Variability

The issue of internal variability (IV) of RCMs has been receiving increasing attention following the realization that the IV caused by nonlinear and stochastic processes in the model (e.g., cumulus convection) can be pronounced and can in fact mask, and therefore be confused with, forced signals (41). An early formal study of IV in a regional modeling context (42) found that the effects of IV at the seasonal scale, as measured by the model response to small, random perturbations in ICs and LBCs, can take the form of spatially coherent responses, e.g., a temperature response of up to 1°, which could be misinterpreted as a forced response (e.g., to climate change forcing). Additional early work found substantial IV in an Arctic domain (43) and in relation to soil-atmosphere feedbacks, particularly in the summer (44).

A number of papers have further examined the issue of RCM IV in different regional contexts (45–51). The conclusions emerging from these studies are that the IV depends on season (maximum in the warm season), region (greater in the tropics), domain size (greater for larger domains), and synoptic regime (tied to convective processes and land surface feedbacks). Therefore, the RCM IV needs to be properly considered when extracting signals from underlying noise, for example, in experiments that assess the sensitivity to model physics components (parameterizations or parameter values) or to external forcings (e.g., land conditions, aerosols, or GHGs). This requires the use of long simulations or ensembles of experiments and calls for caution when interpreting results from individual, relatively short experiments.

2.3. Two-Way Nesting

One of the limitations in the one-way nesting technique is the lack of feedback from the RCM fields onto the coarse-scale driving GCM. A limited number of two-way nested studies have occurred (52) in which the RCM and GCM are run concurrently and exchange information in both directions. It was shown that the feedback derived by running an RCM in a two-way nested mode over a domain covering the Maritime Continent improved the global simulation of the GCM through a better representation of tropical convection in that region. However, the importance of this feedback is region dependent. For example, similar two-way experiments carried out over a European domain did not produce a significant improvement in the GCM climate (D. Jacob, personal communication). Despite the potential value of two-way nesting, the technical difficulties and computational requirements associated with running complex global and regional models in a two-way interacting mode have prevented a widespread use of this approach, and other techniques, such as VARGCMs, might be better suited for addressing issues of regional to global feedbacks.

3. ADDED VALUE

The issue of added value (AV) is central to the use of RCMs for climate downscaling purposes. However, the assessment of AV is often difficult, as it depends on many factors, such as scale, regional setting, climatic variable, season, and specific application. A number of studies have attempted to identify and assess the AV of RCMs (5, 53–66), but their conclusions have been problematic because RCMs can both improve and degrade different aspects of GCM simulations.

The AV question needs to be well posed before proceeding to an RCM experiment. Because the primary role of RCMs is to produce information on climate processes and statistics at sub-GCM-grid spatial and temporal scales, varied regional settings and applications offer differing potential for AV (61). Typical examples of settings with high-AV potential are areas where local forcings substantially modulate the climate signal at fine scales, e.g., complex topography and coastlines, land surface heterogeneity, lakes, mesoscale convective systems, and complex aerosol emissions and distributions. Over these areas, an RCM can enhance the climate information produced by GCMs, for example, by improving the spatial distribution of surface climate variables at fine scales. The AV potential can be estimated by extracting the fine, sub-GCM scale portion of the climate signal from the full climate field through different spatial and/or temporal filtering techniques (5, 58, 61).

As an illustrative example of the surface-forcing-induced, fine-scale AV, **Figure 2** compares mean fall precipitation over the Alpine region and surrounding areas in an RCM historical climate run at 0.11° and 0.44° grid spacing and in the corresponding driving GCM (~100 km grid spacing). The model simulated fields, produced with the regional model RACMO (67) nested within the global model EC-EARTH (68), are taken from the EURO-CORDEX experiment (69) and are compared with corresponding high-resolution observations (70). The improvement obtained by the RCM downscaling is visually evident, as fine-scale precipitation maxima and minima forced by the Alpine topography and the Italian coastlines are well captured by the RCM at its highest resolution and are entirely missed by the forcing GCM, with intermediate results at the 0.44° grid spacing. **Figure 2** also provides a quantitative measure of AV via a Taylor diagram (71), which includes information on the model-observation spatial correlations, standard deviations, and centered (i.e., bias removed) root mean square error (RMSE). The Taylor diagram is especially useful as an AV metric for spatial patterns as it filters out the contribution of mean biases, which can depend on the model physics schemes rather than on the fine-scale forcings. In **Figure 2**, the correlations range from 0.2 to 0.7 for the GCM to 0.79 to 0.85 for the RCM, and the normalized standard deviations for the RCMs are mostly closer to 1. This results in lower centered RMSE (distance from the observation value) in the RCM than in the driving GCM, especially in the warmer seasons when convection is more prominent. These conclusions are confirmed by a more general study (72), which additionally finds that, when upscaled to coarser scales, RCMs improve the simulation of spatial precipitation patterns over the Alpine region compared to the driving GCMs.

Another example of context where potential AV is expected from RCM high resolution is the simulation of extreme precipitation events occurring at small temporal and spatial scales. **Figure 3** compares empirical probability density functions (PDFs) of daily precipitation simulated over a region in West Africa by a nested RCM, the corresponding driving GCM, and two sets of observations (one at coarse and one at fine resolution) (73). We see that, even though the mean precipitation is similar in the models and observation products (73), the GCM-produced PDF is closer to the coarse scale observed PDF from the Global Precipitation Climatology Project (GPCP) (74); the RCM-produced PDF is closer to the high-resolution PDF from the Tropical Rainfall Measuring Mission (TRMM) (75); and in particular, it captures the high-intensity tail of this observed distribution, which is missed by the GCMs. **Figure 3** illustrates the very concept of downscaling, whereby the GCM is consistent with the observed large-scale climate statistics, but the RCM produces findings more consistent with the fine-scale statistics. Similar results were found for the Alpine region (72), where the Kolmogorov-Smirnov distance was used as a metric of AV associated with the agreement between two PDFs. Additional examples of AV related to regional circulations include, among others, the simulation of ENSO-related local teleconnections (64), surface marine wind (55), and regional wave patterns (65).

An important aspect of AV analysis is how the presence of AV in the simulation of present-day climate affects climate projections (62). For example, several studies have shown fine-scale

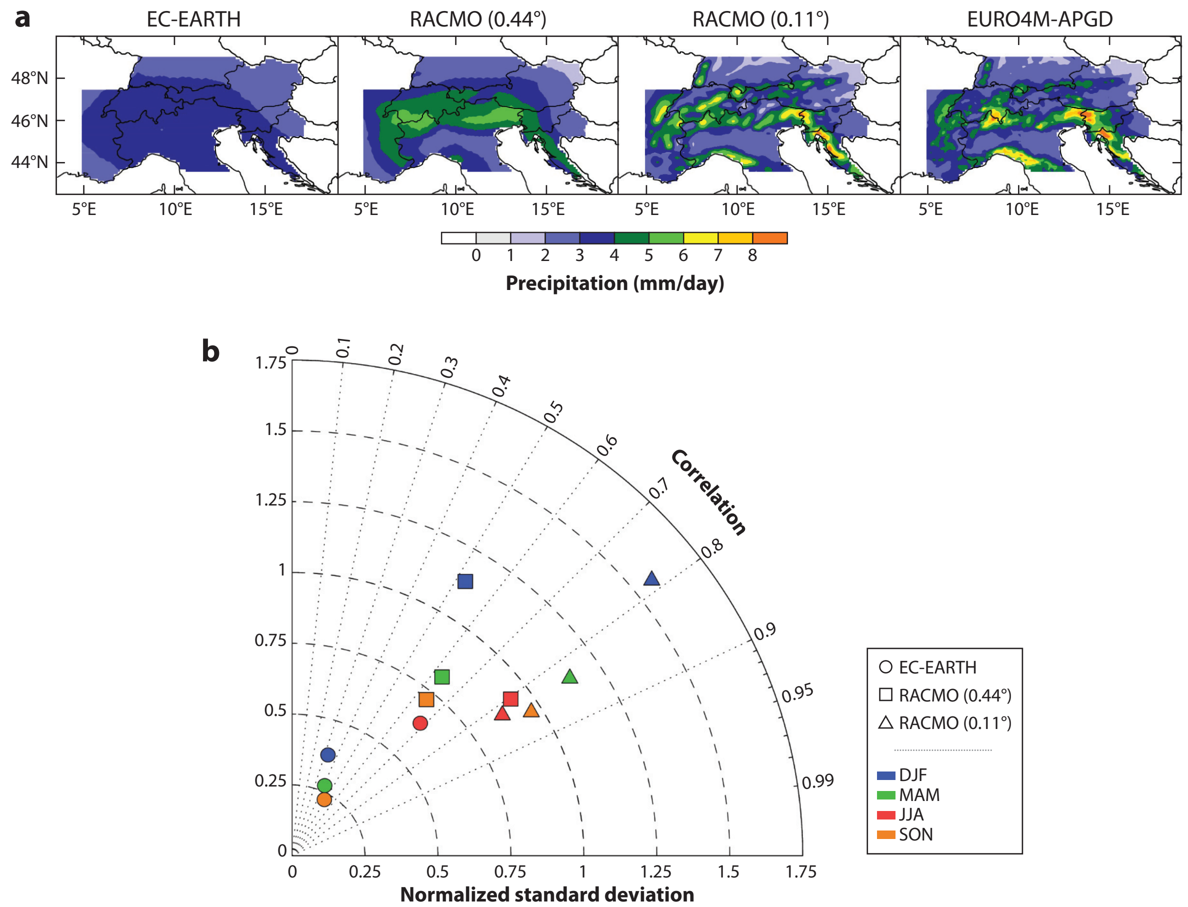

Figure 2

(*a*) Fall (September, October, and November) precipitation over the European Alpine region in a driving global climate model: (*left*) EC-EARTH (68); (*middle*) nested regional climate model RACMO (67) with 0.44° and 0.11° grid spacing; and (*right*) the high-resolution European Reanalysis Observations for Monitoring—Alpine Precipitation Grid Dataset (EURO4M-APGD) (70) for the historical period 1976–2005. The regional and global model data are from the EURO-CORDEX database (69). (*b*) Taylor diagram (71) of seasonal precipitation for the same regional (67) and global (68) model simulations with respect to reference observations (70). The Taylor diagram shows pattern correlation (model versus observations) and normalized spatial standard deviation (model data divided by observations). The distance from the point 1 on the horizontal axis measures the centered (bias removed) root mean square error. Abbreviations: DJF, December, January, and February; MAM, March, April, and May; JJA, June, July, and August; SON, September, October, and November.

structures of the RCM-simulated climate change signal in response to local forcings (e.g., the precipitation shadowing effect by mountain chains, or forcing by land-sea contrasts), leading to results that are different not only in magnitude but also in sign compared to the driving GCMs (5, 62, 72, 76). As another example, different representations of wave patterns and ENSO teleconnections have been found to affect the local climate change signal (64, 65).

In summary, the AV needs to be tied to specific processes and forcings acting at sub-GCM grid scales and thus should not be expected for all aspects of a GCM simulation. This implies that RCMs may be extremely important in specific contexts, where substantial AV has been found (e.g., regions of complex topography), but not particularly beneficial in others (e.g., variables over flat

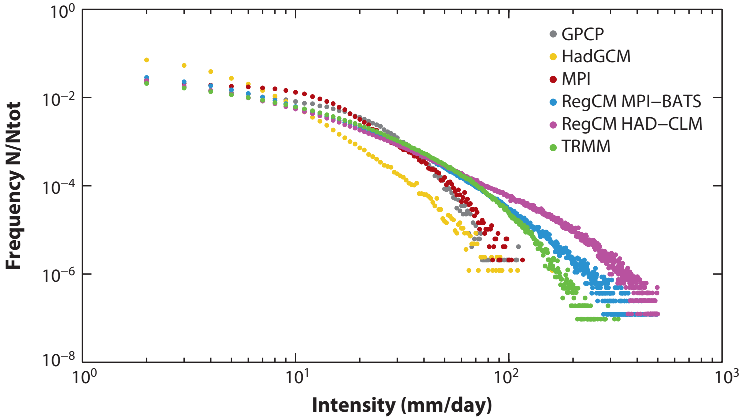

Figure 3

Empirical probability density function (PDF), i.e., frequency versus intensity, of daily precipitation events over the West Africa region in simulations with the regional climate model, RegCM4, (using 50 km grid spacing) driven by the global models MPI and HadGCM (RegCM MPI-BATS and RegCM HAD-CLM, respectively; see Reference 73 for details of the models); coarse-scale Global Precipitation Climatology Project (GPCP), using 1.0° grid spacing observations (74); and fine-scale Tropical Rainfall Measuring Mission (TRMM), using 0.25° grid spacing observations (75). Data are for the historical period 1976–2005 in the models, 1996–2004 for GPCP, and 1998–2009 for TRMM. N is the number of daily precipitation events of a given intensity, and Ntot is the total number of daily precipitation events, so that N/Ntot is the frequency of occurrence of events with a given intensity. A precipitation event is considered one where the daily precipitation amount exceeds 1 mm/day.

regions dominated by large-scale processes and without marked gradients in climatic forcings). It also implies that the potential for AV needs to be carefully explored for a given regional experiment setting and application, possibly using suitable quantitative metrics.

4. MODEL EVALUATION AND DIAGNOSTICS

As described above in Sections 2 and 3, model evaluation is central to regional modeling, as it can be used for different purposes. Numerous papers have provided evaluations of simulations by individual models; however, our focus here is on evaluations of multimodel ensembles with metrics that can provide a common baseline for assessing model performance and can document improvements over time (77). Such common metrics, which have been extensively used in GCM analysis (78), can provide succinct summaries of model performance.

To date, RCMs have had limited evaluations with respect to common sets of metrics, partly because key processes may vary from one region to another. Nonetheless, surface air temperature and precipitation are fields of common interest, and a number of regional programs have used mean biases (model minus observed value) or RMSE averaged over given subregions as standard metrics for intercomparison (29–31, 33, 79).

Taylor diagrams allow a multimetric-based intercomparison of model performance in reproducing spatial patterns, and they have also been used to compare RCM performances over time (80). **Figure 4** shows an example of a PAN-CORDEX view of multiregion, multimodel evaluation of simulations driven by ERA-Interim reanalysis (81) LBCs against the University of Delaware observation data set (82) using a Taylor diagram approach. All models simulate the same time period at the same resolution using the same LBCs. It can be seen that, for December through February

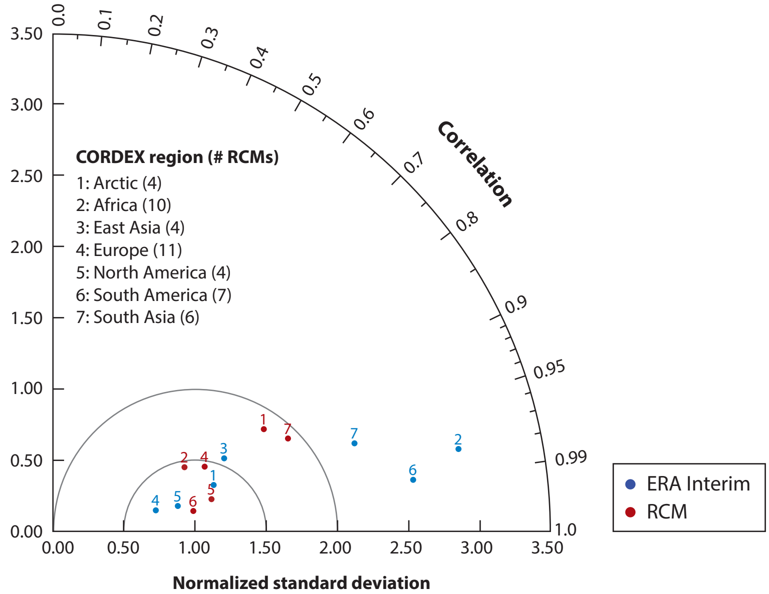

Figure 4

Taylor diagram of precipitation averaged over the period December, January, and February (DJF) for 1991–2007 for the land portions of various CORDEX domains, as produced by an ensemble of regional climate model (RCM) simulations (*red dots*) and the ERA-Interim reanalysis (*blue dots*). The reference precipitation is in the University of Delaware observational climate data set. The number of contributing simulations for each CORDEX region appears in parentheses after the region name. See the domains of the CORDEX regions in **Figure 6**. The arcs represent the centered (bias removed) root mean square errors. Source: J. Glisan, personal communication.

precipitation, simulations for most regions tend to cluster with corresponding ERA-Interim values with relatively high pattern correlations but with a large range in centered RMSE. The reanalysis has especially large centered RMSEs for three CORDEX regions that have substantial areas in the tropics (Africa, South Asia, and South America), where the RCMs exhibit better performance.

Numerous other methods for evaluating RCM performance appear in the literature. An interest common to all regions is the behavior of extremes, in particular for daily precipitation and temperature (e.g., 73, 83, 84). The finer resolution of RCMs generally provides benefits for producing high-intensity precipitation seen in observations (Section 3), but not always (84–87), which is a reminder that good process simulation, not simply finer resolution, is the goal of RCM simulation. A few analyses (86–89) have also shown that the models often exhibit more consistency with observations of physical features and mechanisms leading to extremes, such as synoptic circulation (86) and atmospheric rivers (88), than for the extreme precipitation itself. This highlights the strengths of the models for capturing regional processes well. Model evaluation at subdaily timescales has also shown that RCMs still have problems in reproducing, for example, the observed diurnal cycle of convection because of the behavior of convection parameterization schemes (90), a deficiency that appears to be improved with the use of very fine-scale cloud-resolving models (see Section 8) (91–93).

Key components in developing and applying metrics are observations of high enough quality and spatial and temporal resolution to assess performance on the scales resolved by RCMs. As with global models (77), unsuitable quality can limit the number of fields that one can use. For RCMs, spatial resolution poses important challenges because many regions have limited numbers of observation sites. Efforts have produced high-resolution data sets that can support the regional metrics of RCM performance (70, 94), although one must recognize that the underlying observations may be more coarsely distributed. In addition, even when observations at suitably fine resolution are available, the RCM evaluation may be sensitive to the methods used to produce the observational data sets (95), such as quality-control measures and gridding techniques.

Ultimately, observation-based data sets on scales of a few kilometers require remote sensing (75) or surface-based radar. However, many satellite products are still grounded in the surface network of observation stations. Regional reanalyses, such as the North American Regional Reanalysis (96), can also provide finer resolution details, but in areas of relatively sparse observation networks, the fine-resolution details remain a model product, albeit constrained to a degree by the available observations.

5. UNCERTAINTIES IN REGIONAL CLIMATE PROJECTIONS

The process of producing downscaled climate change projections for VIA assessments is affected by different sources of uncertainty (97, 98). The first step in a regional projection consists of running GCMs for a historical period (say 1850–2014) using observed or reconstructed natural and anthropogenic forcings (GHG concentration, solar activity, volcanic eruptions). This is followed by a transient future climate simulation for the twenty-first century (2015–2100) using scenarios of time-evolving GHG concentrations. A range of time-dependent twenty-first century GHG concentration scenarios has been proposed [called the representative concentration pathways (RCPs)], going from the low-end RCP2.6 and RCP4.5 to the high-end RCP8.5 (99), where the number after RCP indicates the corresponding estimated increase in GHG-induced mean global radiative forcing in watts/square meter by the end of the twenty-first century.

At the GCM level, the range of available GHG emission or concentration scenarios (99), or scenario uncertainty, is especially important for the late twenty-first century decades when different scenarios (or RCPs) substantially diverge (100, 101). Another uncertainty source is associated with the GCM response to a given GHG scenario forcing, often referred to as the GCM structural uncertainty. This is because GCMs have different representations of dynamical and physical processes and thus respond differently to the same GHG forcing. The structural uncertainty provides a substantial contribution to the full uncertainty range both in near-term and late twenty-first century projections (100, 101). A third source of uncertainty is the IV of the GCMs associated with the slow components of the climate system, i.e., the oceans and land. IV can be sampled by carrying out different realizations with varied ocean initial conditions, and it is important especially for near-term projections (100, 101).

After the GCMs are run, their output is used for regional downscaling via RCMs (and/or VARGCMs and ESD) over selected areas of interest. The uncertainties associated with GCM projections are transmitted to RCM projections via LBC forcing. The downscaling step is characterized by uncertainty sources analogous to those of GCMs, e.g., scenario, structural RCM uncertainty, and RCM IV, as well as the possible use of different downscaling techniques (e.g., RCMs versus VARGCMs versus ESD models). In fact, different RCMs can produce substantially different projections even when driven by the same GCM, especially for variables related to convection and for tropical domains (34, 102). Finally, in the assessment of a projection, it is important to evaluate to what extent systematic model errors (by both GCMs and RCMs) affect the projection itself, which we can call systematic error uncertainty.

A full characterization of these uncertainty sources is critical for the provision of climate information for VIA work and, in principle, would require the completion of a multidimensional matrix of simulations sampling the different dimensions of the uncertainty space, i.e., ensembles of multiple scenarios, multiple GCMs, multiple realizations for each GCM, multiple RCMs, and multiple downscaling techniques (103). Given that the size of this matrix can rapidly lead to extremely large ensembles, it is important to design optimal GCM-RCM experiment matrices to best explore the uncertainty space while limiting the ensemble size, and the selection of this optimal matrix is still an active area of research (104). Statistical principles of experiment design should govern the development of appropriate matrices (33), which can allow the extraction of different sources of uncertainty (105).

6. A PROTOCOL FOR PRODUCING REGIONAL CLIMATE CHANGE INFORMATION

Having discussed the main modeling and uncertainty issues related to dynamical downscaling for regional climate change projection, we can combine them into a protocol required to produce regional climate change information.

Step 1 uses perfect boundary condition (PBC) experiments to run RCM experiments over the region of interest using fields from reanalyses of observations as ICs and LBCs. Although reanalyses are affected by errors owing to the scarcity of observations and model inaccuracies (especially in tropical regions), they represent the best approximations to the real world available to test the models. Therefore, assuming that the input from the LBCs is free from large errors, these experiments allow the identification of errors caused by the RCM configuration (physics schemes, domain, etc.). In this mode, because the reanalyses represent actual climate periods, the model can be evaluated against observations for the specific simulated periods not only on a long-term statistical basis but also on an event basis (e.g., for specific ENSO episodes). Once errors are identified, PBC experiments also allow the optimization of the model configuration in terms of its physics, parameters, and domain.

Step 2 involves the analysis and selection of candidate GCMs to drive the RCMs. This is a key step in the downscaling process, as errors in the GCMs are transmitted to the nested models through the LBCs. This analysis should occur for the region of interest and worldwide because teleconnection errors can affect regional behavior. The analysis should consider also both the model performance in reproducing present-day climate and the model sensitivity to future climate conditions. Fields relevant to model nesting should be analyzed (e.g., circulation, temperature, moisture/precipitation) as well as large-scale processes of importance for the climate of the selected region (e.g., modes of variability, monsoons, etc.). Models not capable of reproducing sufficiently well key climate variables and processes should be discarded. GCMs should also be selected so as to cover the range of future climate projections over the region.

Step 3 completes the analysis of GCM-driven RCM runs for a historical period (e.g., 1950–2005). This analysis aims at assessing how the use of LBCs from GCMs affects the RCM performance compared to PBC experiments, thus allowing the characterization of model systematic errors inherited from the driving GCMs. Because there is no assimilation of observed meteorological data for actual periods in these simulations, the analysis needs to occur in terms of climatological statistics, which requires runs of sufficient length (typically a minimum of 20–30 years).

Step 4 completes the analysis of future regional projections. These projections can take the form of continuous runs, say for the historical plus future period 1950–2100, or for multidecadal time slices (e.g., historical 1976–2005 and future 2071–2100), and use the same models selected and analyzed in Steps 2 and 3. Comparing the future and corresponding historical simulations yields climate change patterns and statistics, along with a physical understanding of the changes. Errors identified in Step 3 need to be properly accounted for when assessing the simulated climate change signals.

Step 5 involves postprocessing of the model output. It is possible that, owing to errors present in the model simulations, the output from RCMs may require processing before being used for VIA applications. Such postprocessing can utilize ESD or other techniques, such as pattern scaling (106) and bias correction (107). In addition, there are techniques to optimally filter the ensemble information, e.g., model weighting (108).

7. THE CORDEX FRAMEWORK

From the discussion above in Sections 5 and 6, it is clear that large multimodel ensembles of experiments are necessary to explore different dimensions of the uncertainty space in regional projections and that intercomparison of results is important for a better understanding of downscaling issues. Having recognized this need, the downscaling community has conceived the CORDEX project under the auspices of the World Climate Research Program (**http://wcrp-cordex.ipsl.jussieu.fr/**). CORDEX represents the first attempt at full worldwide coordination of regional downscaling work using a common experimental framework. The CORDEX vision is to advance and coordinate the science and application of regional climate downscaling through global partnerships. Its main goals (21, 22) are as follows:

1. To improve understanding of relevant regional/local climate phenomena, their variability and changes, through downscaling
2. To evaluate and improve regional climate downscaling models and techniques (including both dynamical and statistical downscaling)
3. To produce coordinated sets of downscaled climate projections for regions worldwide
4. To foster communication and knowledge exchange with the users of regional climate information

Figure 5 depicts the common simulation framework of the Phase I CORDEX experiment (21). This essentially follows the protocol described in Section 6, and consists of model evaluation and projection streams using PBC and GCM-driven experiments, respectively. The Phase I CORDEX

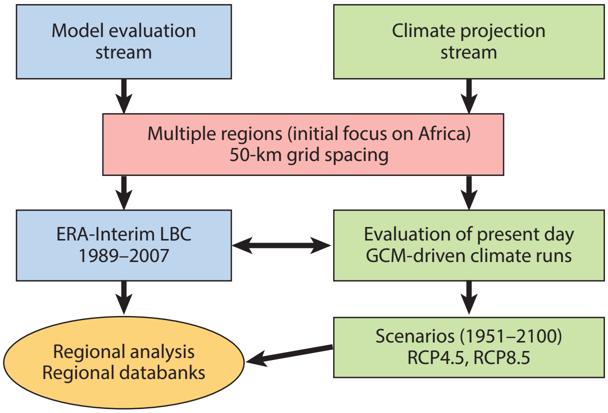

Figure 5

Schematic depiction of the model experiment protocol envisaged in the Phase I Coordinated Regional Downscaling Experiment (CORDEX) framework (21, 22), showing in particular the evaluation and projection experiment streams (see text). Abbreviations: CORDEX, Coordinated Regional Downscaling Experiment; GCM, global climate model; LBC, lateral boundary condition; RCP4.5 and RCP8.5, representative concentration pathways in watts/square meter.

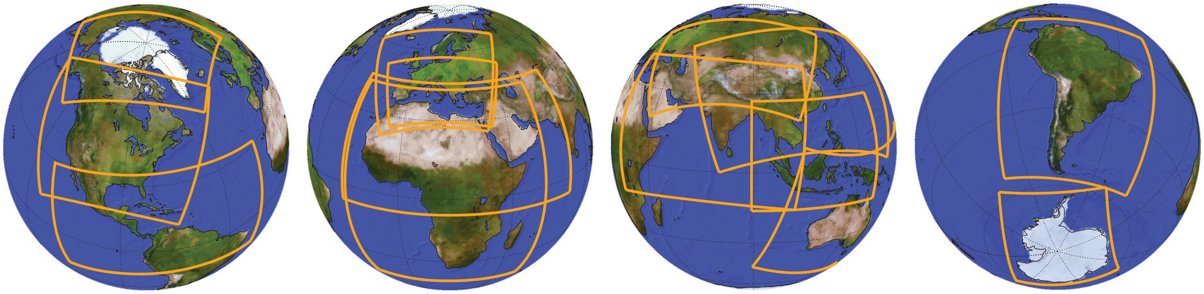

Figure 6

Coordinated Regional Downscaling Experiment (CORDEX) domains. Source: G. Nikulin & E. O'Rourke, personal communication.

framework envisaged that these simulation streams would be completed for large domains covering essentially all land areas of the globe (**Figure 6**) at a grid spacing of ∼50 km (and larger for some regions). The choice of this relatively coarse regional resolution was made to allow broad participation by the downscaling community, and the model output followed a common format for ease of intercomparison (**http://www.cordex.org/index.php/experiment-guidelines/cordex-experiment-protocol**).

To date, numerous experiments have occurred for most CORDEX domains. RCMs have been run for the Africa domain (e.g., **Figure 7**), with several multimodel analyses by African scientists (109–111). Some of the largest differences across models in key variables, such as precipitation, occur in the tropics, where observational sources also show relatively large differences (90). Not surprisingly, substantial discrepancies in climate change projections across models also occur in the tropics, where simulations show differences in sign and magnitude for changes in water cycle variables, such as soil moisture (**Figure 7**). The results point to the need to improve modeling of atmospheric convection and closely linked processes, one target of the fine-resolution goals planned for CORDEX (see Section 7).

Building on a series of European projects (28, 29), the EURO-CORDEX region has been particularly active (69). Approximately 30 groups have completed both PBC experiments and GCM-driven projections over a full European domain at the standard 50 km (∼0.44°) grid spacing and at a finer grid spacing of ∼12 km (∼0.11°), downscaling 12 different GCMs and using 10 different RCMs. This represents an ensemble of unprecedented size and quality, which will enable exploration of many issues related to dynamical downscaling (e.g., AV) and will provide an invaluable source of information for VIA studies. Conversely, the CORDEX activities for the Mediterranean domain (MED-CORDEX) (112) have focused on the development of coupled atmosphere-ocean RCMs. Eight coupled RCM systems for the Mediterranean region have been developed and used to complete twenty-first century projections over the region, showing that the coupling can modulate the climate change signal at the regional scale (113).

Other coordinated sets of experiments have been completed or are currently under way for the Arctic (**http://www.climate-cryosphere.org/activities/targeted/polar-cordex**), South America (30), Central America (114), North America (**https://na-cordex.org**), South Asia (115), East Asia (**https://cordex-ea.climate.go.kr/main/mainPage.do**), and Southeast Asia (**http://www.ukm.my/seaclid-cordex/**) domains, and the results are being ported to specific CORDEX archives and made available for analysis. In addition, as more data become available, regional analysis teams are being set up to facilitate the assessment of models and projections.

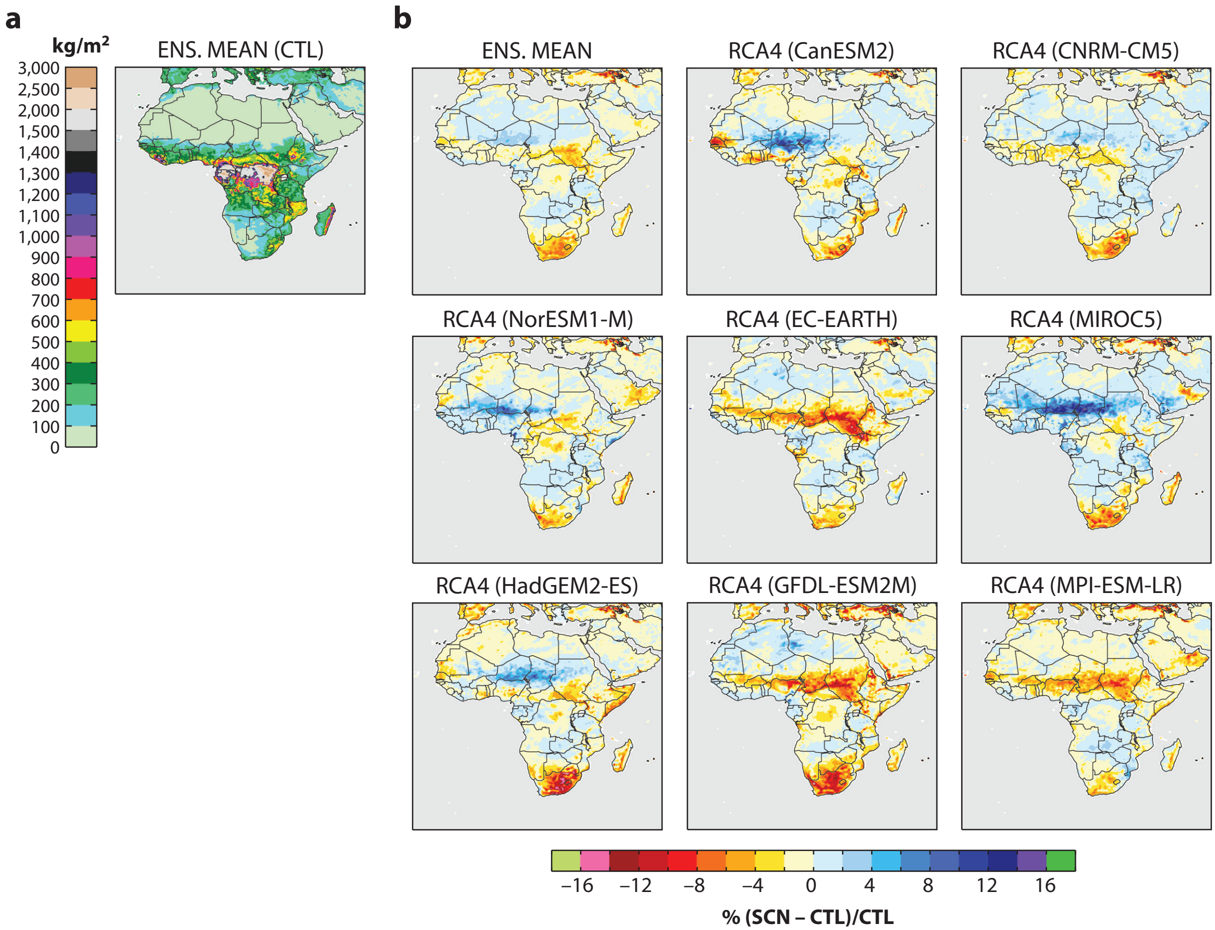

Figure 7

July, August, and September (JAS) soil moisture in CORDEX's (Coordinated Regional Downscaling Experiment's) Africa simulations for the Rossby Center regional climate model, RCA4, driven by various global climate models (GCMs) for the emission scenario RCP4.5 (99). (*a*) Ensemble (ENS) mean soil moisture (in kilograms/square meter) in the control (CTL) (1971–2000) climates. (*b*) The percent change in soil moisture between the scenario (SCN) (2071–2100) and control climates for the ensemble mean and for individual RCA4 simulations driven by the global climate model given in parentheses over each of the nonensemble-mean panels. Source: G. Nikulin, personal communication.

8. OUTSTANDING ISSUES AND FUTURE DIRECTIONS

Although RCM research has greatly developed and matured in the past two decades, the increased resolution of GCMs with improved computing resources and the rapid growth of the community of RCM users call for an ongoing revisitation of the role of RCMs in climate change research.

On the one hand, some of the issues we highlighted here still need further exploration. First is the issue of AV. Quantitative metrics, such as the Taylor diagram, are needed to better identify and characterize more formally AV (61, 62, 72). These metrics are likely process specific but should be general enough to be transferable across regional settings. Analysis is also needed on the limits of AV, because atmospheric energy, and thus AV potential, changes with scale. This leads to the need for greater process-based analysis of the models in terms of their ability to simulate dynamical and physical phenomena relevant for regional climate (e.g., teleconnection responses, meso- and regional-scale circulations, regional energy and water budgets, etc.), which should promote region-specific metrics. More objective criteria and metrics for selecting model domain and resolution are also needed to minimize the sensitivity of results to the experiment configuration.

The extraction of credible information within the climate change context is pivotal for the use of RCM-based information in VIA applications. Natural variability increases at finer scales, and this makes the extraction of clear regional climate change signals, along with their attribution to specific forcing mechanisms (e.g., anthropogenic GHG), more difficult. In addition, uncertainties associated with systematic model errors, IV, and structural configuration (i.e., physics and dynamical schemes), along with the effects of the GCM forcings, need better characterization. This requires the analysis of large amounts of data from different sources (ensembles of GCM and RCM simulations) aimed at distilling the most robust and credible information. This distillation process is an emerging area of research of particular interest within the context of climate service activities and requires increasing interactions between the climate and VIA investigators and the stakeholder communities (116, 117). Within this context, RCMs can play central roles in regional climate change detection and attribution studies by aiming at fine spatial scales, a research area for which the use of RCMs would be highly innovative.

We see two primary areas of future development in regional modeling. The first is the evolution of RCMs into regional Earth system models via the coupling of different components of the climate system. Recognized two decades ago (118), RCMs offer the opportunity of carrying out this coupling at more consistent scales than GCMs. A number of coupled atmosphere-ocean RCMs have already been developed for various regions of the world, such as the Mediterranean (113, 119), the Baltic Sea (120, 121), the Indian Ocean (122), the Caspian Sea (123), and the Arctic (124). One-dimensional lake models have also been coupled to RCMs and applied in various contexts (125–128).

Extensive work has occurred on the interactive coupling between RCMs and aerosol models, of both anthropogenic (sulfate, organic and black carbon) and natural (desert dust) origins, including direct and indirect aerosol effects (129–134). RCM-based studies have investigated the climatic effects of aerosol forcing for regions, such as East Asia (131, 135), West Africa and the Sahel (136, 137), and Europe (134, 138, 139). They have shown that aerosol forcing can have a strong signature on temperature, precipitation, and regional circulations (e.g., the monsoon), sometimes even stronger than that of GHGs. Efforts are also under way to couple online full atmospheric chemistry modules to RCMs (140, 141), which would substantially increase the computational requirements of models, as the chemistry schemes can be more computationally intensive than the RCMs themselves.

Biosphere-atmosphere coupling in RCMs has also received attention. A dynamical vegetation/biogeochemistry model was coupled to an RCM (142, 143), and comprehensive land surface schemes, including dynamical vegetation, biogeochemical cycle, and crop modules (144), are being added into different RCMs. Land-atmosphere interactions are areas where RCMs can be especially useful because land surface characteristics profoundly affect climate change at regional scales (145, 146). Comprehensive land surface schemes also include surface hydrology modules that calculate runoff, which is an input to coupled ocean models, thereby providing a direct tie between the ocean and land components (124).

The second main direction of future RCM research is the transition to very high-resolution models (using 1–5 km grid spacing). At these resolutions, both the dynamics and physics of the models need to undergo substantial development. The hydrostatic dynamical cores used in many present models need to be replaced by nonhydrostatic dynamics. On the physics side, the scale separation assumptions underlying some current physics parameterizations lose validity. A noticeable example is deep cumulus convection given that the few-kilometer scale approaches the resolution at which cumulus dynamics can be explicitly described, and thus deep convection parameterizations may not be necessary. Clearly, substantial model development is necessary to represent processes at the very fine spatial and temporal scales envisioned for the next years, and this development will benefit from greater interactions with the weather prediction community, which already uses models at these resolutions.

Early work on very high-resolution RCM simulations is already available (93, 147–150), providing indications that the climate change signal may substantially change in very high-resolution simulations, particularly for higher-order precipitation statistics (frequency, intensity, extremes, tropical storms). Very high resolution also appears to improve the simulation of the precipitation diurnal cycle through the explicit description of organized convection and cloud processes (91–93). Very high-resolution modeling is an area where RCM research can feed into the development of future global models. This, however, requires the availability of high-quality, fine-resolution surface and atmospheric observations to assess the models, which represents a key bottleneck for many regions of the globe where such data sets are either not available or not assembled and homogenized.

How can CORDEX address these future challenges? RCMs can always be one resolution step ahead of GCMs, and in fact, an increase in the resolution of GCMs will improve the quality of meteorological fields for RCM nesting. As the resolution of some GCMs approaches that of the current CORDEX baseline framework, the baseline resolution of the CORDEX experiments also needs to increase. However, given the large size of the common domains, this increase is necessarily limited, and a doubling of resolution (~25 km grid spacing) for the next CORDEX phase is probably a good compromise between computational and resolution requirements while also covering all of the current CORDEX domains.

This is not optimal, however, for addressing some of the scientific questions outlined above. One possibility being discussed is the use of flagship pilot studies (FPSs) in which smaller subregions are selected for more detailed study. Key factors will guide the selection of FPS regions, such as the availability of fine-scale climatological observations and the occurrence of fine-scale processes recognized as important for a subregion's climate. For such subregions, RCMs could run at a range of resolutions down to convection permitting to test model performance, assess model projections at different scales, and evaluate more fully the AV obtained by the increased resolution, including evaluating when, where, and to what degree downscaling provides AV. Targeted experiments could investigate the importance of specific forcings, processes, and feedbacks (e.g., aerosols and land-use change) and the role of different aspects of model configuration (e.g., convection representation). The FPS framework would also facilitate focus on end-to-end studies going from the climate projections to specific VIA applications using different downscaling techniques (e.g., RCMs and ESD) and addressing the issue of distillation of actionable information.

In conclusion, although the field of regional modeling has rapidly grown in the past decades, much work remains to fully explore its potentials and limitations, particularly in view of the roles that these models can play not only in providing climate information for VIA and policymaking applications but also in enabling a broad scientific community to be directly involved in climate modeling and climate change research. Coordinated efforts, such as CORDEX, provide a framework for exploring the potential of regional modeling that is broadly accessible, thus allowing a wide range of analytic perspectives and downscaling applications.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

ACKNOWLEDGMENTS

This review was partially supported by US National Science Foundation grants ARC1023369, BCS-1114978, and AGS1243106 and US Department of Energy grant DESC0006643.

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