REGIONAL CLIMATE RESEARCH

Needs and Opportunities

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Workshop participants assessed current approaches to climate downscaling and recommended future paths for regional climate research.

Recognizing an urgent need to involve the research and application communities to advance regional climate research, the U.S. National Science Foundation and the Department of Energy sponsored the Workshop on Regional Climate Research: Needs and Opportunities on 2–4 April 2001 at the National Center for Atmospheric Research, Boulder, Colorado.

Regional climate forcings including mountains, land–water contrast, urban effect, and islands can produce statistically significant climatic signals such as those related to orographic precipitation, sea breezes, lakes, and urban heat island effects. A physical definition of regional climate may be possible based on the sphere of influence of the regional climate forcings and response. According to Intergovernmental Panel on Climate Change (IPCC; Houghton et al. 2001), regional climate is defined by geographic or climate features that are generally homogeneous, or by political boundaries. With this definition, the upper limit on the regional scale is subcontinental, and the lower limit is practically dictated by the resolution of data and models—currently roughly 10–50 km.

When regional climate research began in the late 1980s, global climate models (GCMs) at roughly 300–500-km resolution were considered inadequate for producing climate information needed for assessing impacts of climate change and variability. Two areas of research now fill the gap between global climate modeling and local to regional applications. These areas—statistical and dynamical downscaling—utilize statistical relationships between large-scale circulation and regional climate and limited area models or regional climate models (RCMs) to derive regional climate information. Currently GCMs not only provide large-scale conditions for downscaling, but they may also generate regional climate information, either through high-resolution modeling or embedding higher spatial resolution in limited areas of interest within variable-resolution global models.

Downscaling has been successful in weather forecasting for about two decades. Weather forecasts made using mesoscale models embedded in global forecast models at various operational centers now routinely have spatial resolutions of 10–30 km.

In climate research, downscaling has been used in a wide range of applications. One of the most extensively tested uses of downscaling is in projecting regional climate change and its impacts on crops, water resources, and terrestrial ecosystems. More recently

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researchers have begun testing downscaling in seasonal climate forecasting. Seasonal climate forecasting is an important framework for establishing the value of downscaling because observations can be used to evaluate forecast skills in a way similar to verification of weather forecast skills. Research in coupling downscaling techniques with crop, hydrologic, and other process models also help us examine the value of downscaling in end-to-end prediction systems. End-to-end systems are used to assess the effects of climate change or seasonal forecasts by integrating and coordinating numerical experiments and analyses using global climate models, downscaling techniques, and process models.

Despite much progress in regional climate research, many climate researchers are not familiar with the work of the past decade. The demand for higher spatial resolution regional climate information has been steadily increasing. Yet there is no consensus on what can be accomplished or how the goal can be achieved. Priorities needs to be set for future research. Program managers need better guidance to help develop research agendas for the future, especially in light of limited resources. This is not only important for the next phase of the U.S. National Assessment (www.usgcrp.gov/usgcrp/nacc/) and IPCC (www.ipcc.ch/), but may lead to beneficial applications of seasonal climate forecasts.

The Regional Climate Workshop provided a forum to address these issues. The workshop aimed to 1) assess current approaches used in downscaling; 2) inform program managers of the status of regional climate research; and 3) define a future path for regional climate research. The workshop was attended by 68 invited participants from the international research community. (See www.esig.ucar.edu/rcw/index.html for the agenda, participants, presentations, and discussion questions.) The workshop addressed the regional climate problem, global climate modeling, statistical and dynamical downscaling, data and model diagnostics and validation, and downscaling applications. Based on the workshop presentations and discussions, we summarize the main research issues and recommendations below.

THE REGIONAL CLIMATE PROBLEM. A main challenge for climate modeling is to understand the sources and sinks of energy, moisture, and momentum. Relationships between climate forcing and response are often very complex; systematic errors are commonly found in current models. Main sources of errors are related to model representation of clouds and cloud feedback, feedbacks between model components, and three-dimensional response to the distribution of atmospheric moisture.

We will soon see GCMs with 100-km grid spacing, which most agree will provide realistic global climate and large-scale circulation for downscaling. There is general consensus that long-term 10-km resolution global coupled atmosphere–ocean GCM (AOGCM) simulations are not possible in the foreseeable future.

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Experience with numerical weather prediction shows that increased spatial resolution usually leads to better forecasts. In climate modeling, higher spatial resolution may lead to improvements in some aspects of the simulations and degradation in others. Although the overall simulations seem to improve with higher spatial resolution, there is a need to further evaluate the impacts of spatial resolution on climate simulations.

Because of parameterization, existing GCM/RCM processes cannot be simply scaled to finer resolutions. Furthermore, at resolutions around 10 km, current physics parameterizations may not be adequate and problems will arise as the separation between what should be explicitly resolved and parameterized becomes ill defined.

Although downscaling provides enhanced details of climate simulations, there is a need for more research to evaluate the statistical structures of climate signals at various spatial scales to answer the question of whether predictability of the climate system is improved with regional, over global, modeling. An important question with ever-increasing spatial resolution in climate models is how climate variability increases with spatial resolutions. This has important implications for designing numerical experiments to determine climate signals as those related to greenhouse warming. With stronger climate variability (temporally) at the higher spatial resolutions, more model realizations will be needed to improve the signal-to-noise ratio for detecting the climate signals. It is suggested that climate variability will indeed increase as model resolution increases, but maybe only to a certain point, probably near 1° (~100 km). It is postulated that eventually increased spatial resolution does not increase variability. This limit of predictability needs to be defined through future work.

In sum, then, it is not clear what spatial resolution the modeling community should be aiming for. Should it be defined by limiting model errors, limits of climate predictability or signal to noise, computational constraints, or end users' needs? In practice, the resolution is constrained by the climate modeling community's "pain threshold." In addition, no matter what resolution goals prove suitable, there is a general consensus that finding one model suitable for all scales is not achievable, anyway.

There are no conclusive answers to what aspects of large-scale conditions need to be correctly simulated in order to result in successful downscaling. This may be impact specific and depend on the amount of mesoscale activity present in the regions. Research needs to be driven by specific goals or problems. Similarly, measures of success of downscaling are dependent on applications.

To develop credible high-resolution climate simulations for impact assessment, a logical approach is to use multiple GCMs with multiple ensembles and force multiple RCMs. This task greatly exceeds our current computational limits. It is not clear when this could be accomplished or if alternative approaches can be developed. An example of alternative approaches is factor analysis, which could reduce the dimensionality of the experiment. Research is needed to evaluate what methods to use to generate ensembles of statistical and dynamical downscaling results. This may include perturbing initial and lateral boundary conditions, use of different models, perturbing model parameters, bootstrapping and resampling techniques, and use of residuals from statistical downscaling to create ensembles. Various techniques should be explored and evaluated.

GLOBAL CLIMATE MODELING. GCMs that run at current resolutions of 200–500 km offer some solutions to regional climate modeling problems but produce biases in the simulated climate state. Regional temperature biases are up to +/−5°C, and precipitation biases are between −40% and +60%. Errors are larger as grid scale is approached and at shorter temporal scales. Multiple models are useful for assessing uncertainty where larger differences exist among models and ensemble simulations.

To model regional climate, variable-resolution atmospheric GCMs (AGCMs) use the stretched grid (SG) approach. Unlike RCMs, SG-AGCMs can simulate climate without updating (lateral) boundary conditions and thereby avoid numerical problems associated with treatments of lateral boundary conditions. Disadvantages of SG-AGCMs include the cost of calculations for grid points outside the regions of interest, and limits imposed by the ratio of maximum grid interval to grid stretching on the efficiency of downscaling.

With higher-resolution SG-AGCMs, there is a need to further test the applicability of physics parameterizations for the range of grid scales used in the models. As SG-AGCMs are relatively new, intercomparison of SG-AGCMs is needed to evaluate and intercompare model performance.

Another alternative to modeling regional climate is the use of high-resolution AGCMs in time-slice experiments. In time-slice experiments, coarse-resolution AOGCMs are first used to perform transient or time-dependent global climate simulations. Time-slice simulations are then performed for the entire globe using coarse AOGCM forcings (such as SSTs) for a subperiod of the transient experiment with high-resolution AGCMs. This approach is feasible with current models and computing resources, and overall results look more realistic in the high-resolution simulation than the coarse-scale simulation. However, results are dependent on the forcing from the coarse-resolution AOGCM runs, and spatial resolution is limited to 50–100 km because of computational constraints.

Since high-resolution time-slice experiments are also relatively new, more work is needed to test various strategies for experiments and the validity of results because most AGCMs have not been tested at high spatial resolution. Evaluation of results is particularly limited by the limited number of runs and large volume of simulation outputs.

To utilize high-resolution AGCM runs at 1° or higher resolution, one needs improved infrastructures such as data gathering, analyses, intercomparison, and joint experiments.

GCMs—indeed all climate system models—come with another caveat, as well. Current climate system models are incomplete because important climate processes such as biogeochemical effects of CO_2 are not represented. Numerical experiments with land use change show that human-induced land use changes may have as large an impact on the regional climate system as the radiative effects of CO_2. Currently, there are efforts to couple biogeochemical models with climate system models to understand the effects of land use change. One major difficulty, however, is the lack of historical global data for emission (e.g., CO_2) and

RECOMMENDATIONS

DOWNSCALING

- We need to develop physics parameterizations for higher spatial resolution global or regional climate models. Such parameterizations may be scaleable for applications at different spatial resolutions. Regional climate models can be used as test beds for such development.
- Coordinated intercomparison and diagnostics of models (GCMs, RCMs, and SD) are needed. This will require an infrastructure for experimental protocols and community participation.
- We need to quantify predictability at the regional scale. Climate variability increases with spatial resolution, but perhaps only up to a point. Regional predictability may increase or at least be similar to larger-scale predictability at a certain regional resolution.
- Different ways of generating ensemble simulations with RCMs need to be explored to improve signal to noise or estimating uncertainty.

EVALUATION AND DIAGNOSTICS

- Need to further develop regional observational datasets. Downscaling may be useful to fill data gaps. Communications between the modeling and data communities needs to be improved.
- Intervariable relationships, higher-order statistics (e.g., frequency of extreme and variability), and teleconnections (relationships and integral constraints between large scale and regional scales) need to be more widely used to measure downscaling skill.
- Evaluating circulation is an alternative way to evaluate surface variables. Downscaled climate in process models (e.g., hydrologic models) and secondary variables should be used more often in evaluating downscaling techniques and value.
- Archiving of higher temporal frequency outputs is needed for more detailed evaluation.

APPLICATIONS

- Regional climate information needs to be easy to obtain, use, and validate.
- To produce more realistic future climate scenarios for impact assessment, use of realistic driving forces and more complete representation of climate components are needed. Climate system models are moving toward incorporating biogeochemistry and lakes. Regional prediction of complex physical and socioeconomic systems is also needed for integrated assessment.
- We need to involve stakeholders in determining the resolution of regional climate information required in different impact assessments.
- Other applications of regional climate information, such as storm surges or air quality, should be tested.

OVERALL

- Impact assessments in the past required patching together isolated modeling, diagnostics, analyses, and assessment studies with disparate goals. We need coordinated end-to-end prediction systems to test the whole approach of impact assessment.
- Seasonal prediction is a useful framework for assessing the added value of downscaling because results can be evaluated with observations. Projects utilizing various approaches for seasonal prediction can show whether downscaling can improve accuracy in addition to providing greater spatial detail. Such experiments could lead to seasonal forecasts for various applications. Improvements in seasonal predictions using the superensemble approach demonstrate the value of utilizing as many models as available.
- Funding agencies tend to support model applications or projects that produce predictions more than development or evaluation of models that are used in making predictions. This problem needs to be addressed.
- All downscaling techniques have been shown to be valid and produce useful results. Research on the various downscaling methods should proceed along parallel paths to the limit of funding availability.

vegetation, among others, to help estimate their effects or signatures through time. Climate studies that neglected important effects such as land use change should by treated as sensitivity or vulnerability studies.

REGIONAL CLIMATE MODELING. In using RCMs, lateral fluxes into and out of a region are fixed according to the large-scale conditions provided. Although this strongly constrains the integral properties of regional simulations, RCMs are able to determine the distribution of climate features within the model domain. Applications of RCMs in the Baltic Sea Experiment (BALTEX) and the Swedish Regional Climate Modeling Programme (SWECLIM) projects, for example, have convincingly demonstrated that regional climate modeling is a valid downscaling technique and that RCMs can be used in full coupling with other models such as hydrologic and sea ice models to yield realistic results.

Problems with regional climate simulations become, however, more evident at small spatial and temporal scales. Running pairs of RCM simulations driven by large-scale analyses and GCM outputs allow evaluation of error sources arising from model internal components versus lateral boundary conditions. Sensitivity to model domain (size and location) depends on whether large-scale forcings originate from within or outside of the regional domain. Selection of model domain to avoid known errors in GCMs (e.g., location of jet stream) may improve RCM simulations.

An outstanding technical issue with RCMs is related to the treatments of lateral boundary conditions. Ideally one should specify the inflow boundary and use an open outflow boundary to reduce numerical errors. In practical terms, this is not possible. Errors in the simulation system may arise when the imposed inflow boundary evolves to a state different from the imposed outflow boundary by the time the parcel reaches that side. Practical solutions using sponge or simple nudging of lateral boundary conditions seem to work for regional modeling. These methods progressively match the model solutions to the prescribed large-scale conditions near the lateral boundaries by applying linear weightings to the model-predicted and prescribed tendencies (sponge) or relaxing the model-predicted variables toward the prescribed large-scale conditions (nudging) until they become identical at the outermost lateral boundaries.

At the meeting, a "big-brother" experiment was described where an RCM is run at high spatial resolution over a large domain (big brother) and results are spatially filtered to coarser resolutions to mimic global simulations and used to drive the same RCM in a smaller domain at the same high resolution (little brother). Results show that a resolution jump of 10 from the large-scale conditions to the finescale is the upper limit for the RCM (little brother) to be able to regenerate the high-resolution information of the large domain (big brother). This type of experiment needs to be extended to longer time periods and other regions to check for robustness of conclusions. The results can provide useful guidance for selecting spatial resolutions of global and regional models in downscaling experiments.

One challenge for regional modeling is that RCMs need higher spatial resolution to maintain an edge over GCMs. With the need and practical experience going into higher and higher spatial resolutions, regional modeling can become a strong component for developing parameterizations (e.g., unified parameterizations for convective and stratiform clouds) that are scalable. The regional modeling community can lead the way in parameterization development for GCMs.

STATISTICAL DOWNSCALING. The main concept of statistical downscaling (SD) is to derive statistical transfer functions between large-scale (GCM) variables and local variables of interest. Downscaling temperature is not difficult, but downscaling precipitation is much more problematic. Whether SD is adding value can be assessed using verification statistics or feeding SD results to impact models (e.g., streamflow) and validating secondary variables. Practical considerations for developing an SD scheme involve the selection of appropriate predictor variables, predictor spatial representation, domain size and location, types of transfer functions, and definition of temporal scales such as season.

Two outstanding issues with the SD method are whether strong predictor variables for the current climate carry climate change signals, and whether predictor–predictand relationships can be assumed stationary so that they can be used in future climate conditions. The first issue needs to be addressed because the choice of predictors may change even the signs of the downscaled climate change signals. On the second issue, recent experiments with RCM predictor–predictand relationships suggest that the stationarity assumption is not invalidated under future climate forcing provided the choice of predictors is judicious. Furthermore, investigating changes in the frequency of occurrence and pattern associated with each mode of variability in the simulated future and present climate can help determine whether the future climate is spanned by the events of present climate conditions. There is a fundamental need for further systematic evaluation of these issues.

New challenges for SD include downscaling of extreme events or subdaily processes (equally so for RCMs), and evaluation of combinations of variables (e.g., relationships between temperature and precipitation) rather than single variables. An important "spinoff" is the use of SD predictor–predictand relationships for evaluating internal consistency in GCMs and RCMs compared with observations.

Intercomparison of downscaling techniques may help focus efforts on subsets of techniques and evaluate how much downscaling contributes to the total uncertainty in climate change scenarios. The few studies performed so far show that SD and RCM have similar skill in simulating the mean and variability of present climate conditions. However, significant differences exist between SD and RCM downscaled future climate conditions. This is partly explained by the fact that SD experiments typically employ only a subset of the boundary information used by RCMs. Therefore, future SD versus RCM intercomparison studies need more carefully designed experiments to ensure greater parity of forcing conditions.

DATA DIAGNOSTICS/VALIDATION. Statistical tools can be used to identify and assess differences among models or between models and observations. Such tools include local assessment using gridpoint simulation and station data, multivariate analyses that probe covariance structure, and methods to assess spatial and temporal variability (e.g., different forms of eigen analyses, pattern correlation). Though computationally demanding, long ensemble simulations are required to yield statistically significant results. Furthermore, one needs to establish what constitutes an acceptable model, which, as noted above, may be application dependent.

Data diagnostic/validation tools can help evaluate the added value of downscaling in aspects such as reduction in mean bias, improved stochastic behavior, more realistic variance, better spatial variability, and improved tail or extreme behavior. More sophisticated tests are required beyond the comparison of gridpoint averages. Furthermore, on diagnosing downscaled climate change results, decomposing the climate change signals into components of atmospheric circulation response, atmospheric moisture response, and associated precipitation changes are useful for improving climate change detection and model evaluation. They also offer an opportunity to quantitatively bias-correct the downscaling outputs for impact assessment.

Many techniques used in diagnosing high-resolution numerical weather forecasts can be useful for diagnosing and evaluating regional climate simulations. Examples include analyzing effects of land–sea breeze, effects of topography on precipitation, understanding the sensitivity of simulations to physics paramterizations and spatial resolutions, and evaluating mesoscale climatology such as that of the mesoscale vortices and mesoscale convective complex, which have climatological significance and possess longer intrinsic predictability than previously thought. Many mesoscale observations exist in the central United States for this type of evaluation.

In addition, it is important to look at climate elements such as storm tracks, relationships between means and anomalies of large-scale circulation and complex topography, atmosphere and land interactions, and signatures in snowpack, glaciers, and runoff for better evaluation and diagnostics of model behaviors.

All of these projects require good observations availability. The lack of high-density observational networks has been a major hindrance to the development and evaluation of downscaling techniques. At the meeting, it was suggested that more effort be focused on the use of cheaper instruments over wider regions, more use of data from large-scale experiments where more detailed data are available, and development of alternative model evaluations for data-sparse regions.

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APPLICATIONS OF DOWNSCALING. Does downscaling add value to impact assessments? The answer depends on the applications; climate researchers and impact assessors may have different perspectives on this.

Regional climate information can make a difference in assessing climate change impacts on agriculture, for instance. The assessment of agricultural impacts will require longer and higher-resolution regional climate change information, more extensive tests of methodologies, and developing methods to estimate uncertainty in climate scenarios. Agricultural impacts should also be evaluated within the larger context of the socioeconomic system.

Downscaling is also important in paleoclimate studies because many interactions in the climate system cannot be modeled using coarse-scale models. Examples are effects of vegetation, lakes, and glaciers at the subcontinental scale. Coupling regional climate models with other process models allow sensitivity experiments to be performed to evaluate various processes important in reconstructing climates in the paleoclimate records.

Seasonal climate forecasting may be a useful framework for testing the value of downscaling since climate forecasts and their applications can be verified. Long-term reanalyses data may also be used as a surrogate for climate change to test the added value of downscaling. Recent work suggests that more accurate and spatially detailed climate forecasts can be made with downscaling using regional climate modeling. Superensemble techniques (where seasonal climate forecasts are statistically extracted from all available dynamical forecasts together with information on the respective model errors) statistically improve the accuracy of seasonal forecasts. Further testing or routine use of such a technique will require more participation and coordination of the research community.

A weak link in hydrologic applications is the necessary step of bias-correcting the climatic simulations or projections (e.g., matching the observed and simulated large-scale properties) to yield realistic hydrologic conditions for impact assessment. A community effort is needed to develop and archive model climatologies based on long-term simulations so that bias-correction can be developed based on statistical characterization of model behaviors. Different bias-correction procedures need to be evaluated because they may modify the simulated climate change signals and introduce another level of uncertainty.

Current work in impact assessment is a compromise between spatial resolutions, duration of simulation, and needs of the user community. There is always a mismatch between what the users need and the kind of information that can be provided by the climate community. Although high-resolution information is desired, its usefulness may be limited by uncertainty or accuracy of the information.

It is anticipated that the next phase of climate impact assessment may require regional climate system models to address issues such as urban air quality, heat island effects, lake effects, and storm surges. Dynamical downscaling appears to be the only possible approach for assessing air quality and urban effects because such applications require comprehensive meteorological data and involve complex process interactions that may not be robustly described using statistical relationships based on historical conditions. New applications may also require regional climate information at spatial resolutions that downscaling techniques have not been tested in the past. A hybrid downscaling approach such as combining dynamical and statistical methods may be useful for yielding high-resolution regional climate information.

Another potential value of downscaling that may be explored in the future is its application to generating climatology in regions with little observational data, although validation of downscaling results in such regions remains a challenge.

With the tremendous pace of research being done on regional climate, we hope frequent assessment of the research approaches and agendas can be performed to advance the science and meet the needs of the user community.

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