Chapter 9
Regional Climate Models

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Glossary

Downscaling	Development of climate information at local or regional scale from coarse resolution data or model outputs; both statistical and dynamical methods can be used.
GCM	Global climate model, a climate model based on the general circulation of the atmosphere, often coupled with models of ocean circulation and sea ice.
Mesoscale	In the atmosphere, mesoscale generally refers to horizontal scales that lie between the scale height of the atmosphere (about 10 km) and the Rossby radius of deformation (tens to hundreds of kilometers).
Nudging	Method to reduce the differences between the simulated and observed or imposed states by applying corrections, usually in the form of tendencies to the prognostic equations, based on the differences.
RCM	Regional climate model (also called nested regional climate model), a climate model applied over a limited area with boundary conditions provided by global models or analyses.

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Definition of the Subject and Its Importance

Regional climate models are numerical models that simulate the climate of geographic regions typically covering a few thousand square kilometers to a continent. Most regional climate models include models that describe the atmosphere and the underlying land surface, but a few also include models of ocean and sea ice and atmospheric aerosols and chemistry. Given the atmospheric state at the lateral boundaries, regional climate models simulate regional climate in the context of the evolving global climate. Because regional domains cover only a fraction of the globe, it is computationally more feasible to apply regional climate models at higher grid resolution compared to global climate models to better resolve atmospheric and terrestrial processes and how they respond to regional forcings such as topography and land cover/land use. While global climate models are generally applied at grid resolution of a few hundred kilometers, regional climate models have been more commonly applied at grid resolution of a few tens of kilometers. Therefore, a common application of regional climate models is the dynamical downscaling of global climate simulations to provide regional climate information related to climate change projections or climate predictions. As such, regional climate models have served an important function of providing regional climate scenarios needed to assess a wide range of societal relevant climate impacts such as climate change effects on water resources and ecosystems. Regional climate models are also used to study regional climate processes, particularly those that are related to the water cycle that is inherently multi-scale; so explicitly representing finer scale processes is important to simulate its variations at multiple time and space scales.

Introduction

Regional climate models were first developed in the late 1980s to provide a means to simulate climate features that were not well captured by global climate models (GCMs) because of their coarse spatial resolution. Figure 9.1 shows the representation of surface elevation and land cover/land use in climate models of different horizontal resolutions. At 400 km resolution, which was typical for GCMs in the early 1990s, climate models can only resolve very crude topographic variations and land surface heterogeneities to simulate their effects on large-scale and mesoscale circulation. At 50 km resolution, which is a common resolution used in regional climate models even today, models can begin to realistically capture topographic and land cover features important for regional climate.

The first regional climate model (RCM) was developed and applied to the western USA where regional climate is significantly influenced by the complex terrain not well resolved by GCMs [13,17]. The RCM was adapted from a mesoscale or limited-area atmospheric model that was designed for weather forecasting or short-term simulation of a few days. The model was enhanced for

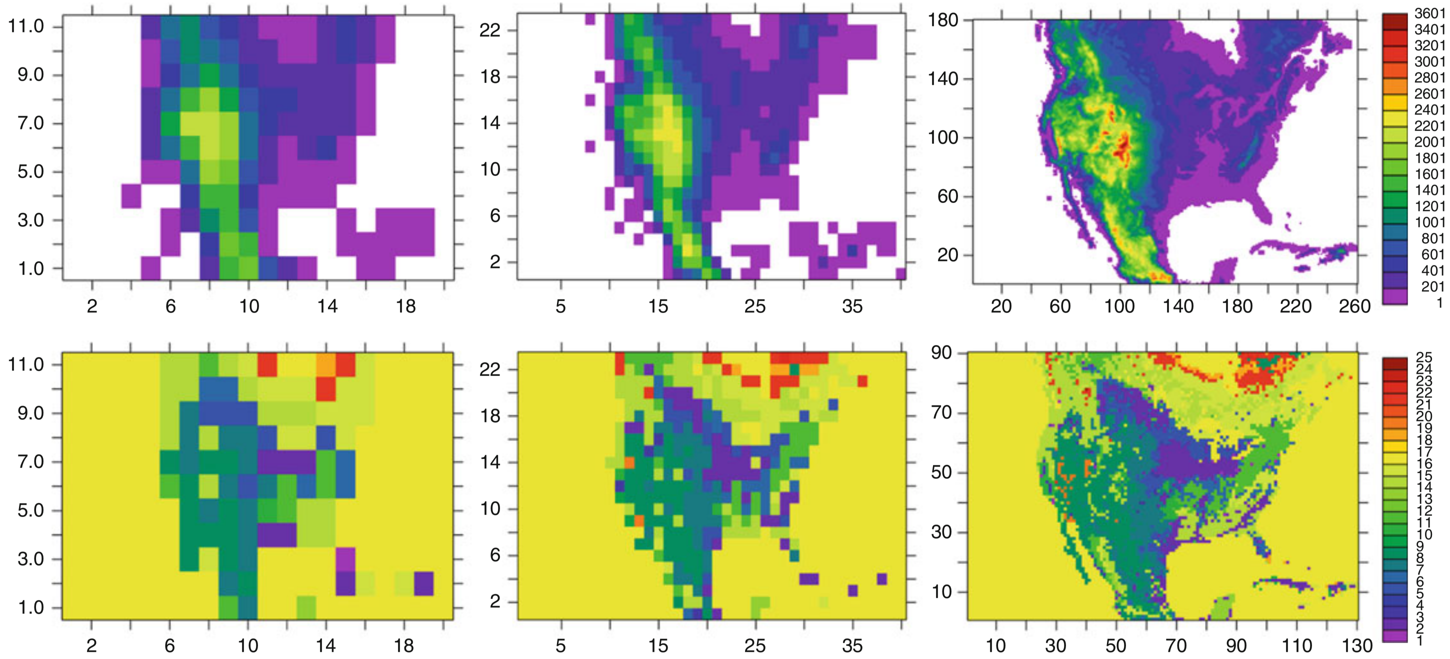

Fig. 9.1 Surface elevation (in meters) (*top row*) and land cover/land use (type) (*bottom row*) represented at 400 km (*left*), 200 km (*middle*), and 50 km (*right*) horizontal resolution in climate models. The land cover/land use types are: *1* urban, *2* dryland crop, *3* irrigated crop, *4* mixed crop, *5* crop/grass, *6* crop/woodland, *7* grass, *8* shrub, *9* mixed shrub/grass, *10* savanna, *11* deciduous broadleaf, *12* deciduous needleleaf, *13* evergreen broadleaf, *14* evergreen needleleaf, *15* mixed forest, *16* water bodies, *17* herbaceous wetland, *18* wooded wetland, *19* barren/sparsely vegetated, *20* herbaceous tundra, *21* wooded tundra, *22* mixed tundra, *23* bare ground tundra, *24* snow/ice, *25* playa. The x- and y-axes show the number of grid points in the domain at the three spatial resolutions

climate simulation by improving the physics representations for processes such as radiative transfer and biosphere-atmosphere exchange at the land surface that governs the energy and water budgets of the climate system. This was achieved by adopting the physics parameterizations used in a GCM. The RCM was driven at the lateral boundaries by atmospheric analysis [17] that provides an observationally constrained and dynamically balanced atmospheric state and global climate simulations [13].

Giorgi and Bates [17] showed, for the first time, that limited-area models could be used to produce long-term (more than a month) continuous simulations, as opposed to prior applications that use limited-area models to simulate weather for just a few days. By comparing the regional simulations with observations and the GCM simulations, it was demonstrated that a mesoscale weather model, with appropriate modifications, could be used for regional climate simulations. Following these pioneering studies, Giorgi et al. [19] further enhanced their RCM by updating the physics parameterizations with newer options available from the GCM, and explored model sensitivity to physics parameterizations and methods of assimilating the lateral boundary conditions. Giorgi and Mearns [16] showed that errors (e.g., measured by the deviation of the model solution from the driving large-scale fields) in limited-area models grow initially during model spin up, but reach an asymptotic value after a few days. At this stage, the climate simulated by the models is defined by the large-scale driving conditions and the model internal physics and dynamics, as well as the regional forcings within the model domain.

Subsequent to the early studies by Giorgi and his colleagues, more regional climate models have been developed following a similar approach and development path. These models have been applied to many regions around the world to assess their simulation skill under different climate regimes such as the monsoon, arid and semiarid deserts, mid-latitude regimes influenced by synoptic systems, and the high latitudes where cryospheric processes are important. As regional climate models became more widely used, questions have been raised about the validity and usefulness of the approach that prompted a series of studies to vigorously assess the various assumptions, and proposed practical or more mathematically well-posed solutions to regional climate modeling (section "Modeling Approach"). Different datasets and approaches have been used to evaluate RCMs, and large model intercomparison projects have been organized to evaluate and intercompare simulations produced by different RCMs (section "Evaluating Regional Climate Models"). At the same time, many studies have applied RCMs to simulate regional climate change that provided insights on climate change impacts. Regional climate models have also been used to study regional climate processes such as the role of land-atmosphere feedbacks on droughts and monsoon precipitation, effects of aerosols and land use on regional climate and the hydrological cycle, and processes leading to extreme climate events. The following sections provide a synopsis of these topics, and discuss the future directions in regional climate modeling. Examples of RCM applications are given in section "Application of Regional Climate Models."

Modeling Approach

How Do Regional Climate Models Work

Regional climate models are numerical models that simulate the climate of a specific region. Although some regional climate models, or regional earth system models, are beginning to include models of ocean, sea ice, and atmospheric aerosol and chemistry coupled to the atmosphere and land components, this review focuses mainly on regional climate models that traditionally include only atmosphere and land components with prescribed sea surface temperature and sea ice.

Similar to global atmospheric models, regional climate models numerically and simultaneously solve the equations of the conservation of energy, momentum, and water vapor that govern the atmospheric state. These equations are based on the Navier-Stokes equations for fluid flow (conservation of momentum) with approximations that apply to the atmosphere, the thermodynamic energy equation (conservation of energy), the continuity equation (conservation of mass), and the equation of state (ideal gas law). These partial differential equations are cast in various forms for different conservative properties and integrated forward in time using dynamical solvers. The solvers are applied to three-dimensional computational domains that are divided horizontally with grid spacing of a few to tens of kilometers and vertically into tens of vertical layers with a model top near 10–50 hPa. In regional climate models, solving these equations on limited-area domains require lateral boundary conditions, which can be derived from global climate simulations or global analyses to describe the large-scale atmospheric states. This method of simulating regional climate using limited-area models with prescribed lateral boundary conditions is called nesting (Fig. 9.2), so regional climate models are also called nested regional climate models to distinguish them from other dynamical frameworks such as global variable resolution or global stretched-grid models that simulate

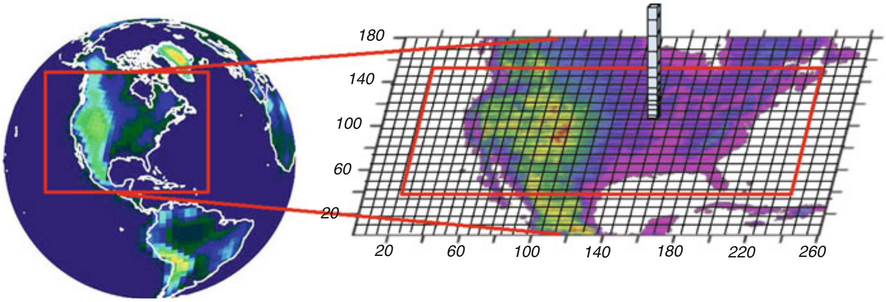

Fig. 9.2 A schematic showing the nesting of a regional climate model within a global climate model. The *right hand* figure shows the regional domain over North America with the horizontal grid (*black lines*), boundary of the buffer zone (*red box*), and a vertical column indicating the atmospheric layers represented by the model

regional climate for specific regions through regional refinement within the global domain.

The most commonly used lateral boundary treatment in nested regional climate models involves the relaxation of the interior flow in the vicinity of the boundary, called the lateral boundary buffer zone, to the prescribed flow [8]. In most models, the same treatment is also applied to the thermodynamics variables. When applied to RCMs, increasing the width of the lateral boundary buffer zone allows stronger control of the lateral boundary conditions to keep the simulated large scales closer to the global simulations or analyses that provide the lateral boundary conditions. Some RCMs have the capability to use nesting to further zoom into smaller regions with increasing grid resolutions. As computational resources increased over time, more RCMs are now formulated using non-hydrostatic dynamics, as the mean vertical motion of the air column within a model grid cell can no longer be assumed negligible at higher grid resolution. In contrast, most GCMs use hydrostatic solvers because the hydrostatic assumption is valid in coarser grids.

Besides numerically solving the momentum, thermodynamics, and continuity equations, climate models, global or regional, include parameterizations of physical processes such as radiative transfer, convection, cloud microphysics, land surface and biosphere-atmosphere exchange, and boundary layer turbulence. These parameterizations calculate the diabatic heating, moistening, and momentum changes due to the various processes. The resulting tendencies or rates of change are included as sources and sinks in the equations of energy, momentum, and water vapor to drive the atmospheric circulation.

Traditionally, GCMs use more sophisticated parameterizations of slow physical processes such as radiation and land surface for more accurate simulations of the global energy budgets, while limited-area models that are developed mainly for weather forecasting and short-term simulations emphasize detailed parameterizations of fast physical processes such as cloud microphysics and turbulence transfer. To simulate regional climate, both fast and slow physical processes are important because of the short spatial scale and long time scale of interest. Therefore many RCMs have adapted parameterizations of slow processes from GCMs, while maintaining the suite of the relatively detailed parameterizations of fast processes used in weather forecasting. Sharing of physics parameterizations between the global and regional models is considered desirable to reduce inconsistency between the simulated and driving large-scale conditions (see section "Modeling Issues" for a discussion of potential issues caused by mismatch of GCM and RCM solutions) and facilitate interpretation of differences simulated by the RCMs and GCMs. Since the first RCM (section "Introduction"), most RCMs developed and in use today still include subsets of physics parameterizations that are adapted from their host GCMs. Driven by high performance computing and the need to improve accuracy, both global and regional climate models are including more and more sophisticated parameterizations for all physical processes, which together with increasing model resolution, demand significant advances in high performance computing to support climate modeling research.

Modeling Issues

The climate of a region is determined by the large-scale atmospheric circulation as well as regional forcings such as topography within the region, and how they interact through various physical and dynamical processes. For example, the regional climate of the US Great Plains is strongly influenced by atmospheric circulation that brings moisture from the Gulf of Mexico during summer. How much precipitation is produced over land depends on moisture convergence, which is influenced not only by large-scale circulation patterns, but mesoscale features such as the Great Plain Low Level Jet, propagating disturbance from the Rocky Mountain, and local moisture sources from the land surface also play an important role. Therefore in the nested regional climate modeling approach, regional climate simulations depend on both the lateral boundary conditions that control the large-scale circulation, regional topography and land cover/land use features being resolved by the model, as well as physics parameterizations that ultimately determine the local changes in the energy, moisture, and momentum as influenced by the large-scale circulation and regional forcings.

Because of the dependence on large-scale circulation, large biases in global climate simulations used to provide lateral boundary conditions could have detrimental effects on the regional climate simulations under the nesting approach. Even if the global climate simulations were perfect, the lateral boundary conditions do not uniquely define the regional climate because the associated boundary value problem (i.e., solving the hyperbolic equations) is ill posed. Relaxation methods such as proposed by Davies [8] convert the hyperbolic equations to the well-posed parabolic form. However, mismatches between the large-scale circulation simulated by the regional models and the imposed atmospheric states at the lateral boundaries that may result from differences in grid resolution, physics, and dynamical formulations between the global and regional models can induce errors that propagate to the interior of the domains and contaminate the regional simulations [56]. This issue also leads to the sensitivity of the simulated regional climate to the domain size and locations of the lateral boundaries – an undesirable feature as it introduces uncertainties to the simulation results.

To address the validity of the nested regional climate modeling approach, a series of idealized numerical experiments have been designed and performed to assess the various assumptions used in regional climate modeling. The idealized experimental framework, known as "Big Brother Experiments (BBE)" [10], addresses modeling issues specifically related to the nested regional climate modeling approach. The Big Brother Experiment protocol consists of performing a high-resolution global climate simulation, referred as the Big Brother, BB, that serves as reference against which a regional climate simulation, referred as the Little Brother, LB, would be compared (Fig. 9.3). The BB, with proper spatial filtering to remove the fine scales to emulate coarse resolution global climate simulations, provides lateral boundary conditions for driving the LB. The differences between the climate simulated by the LB and the reference BB could

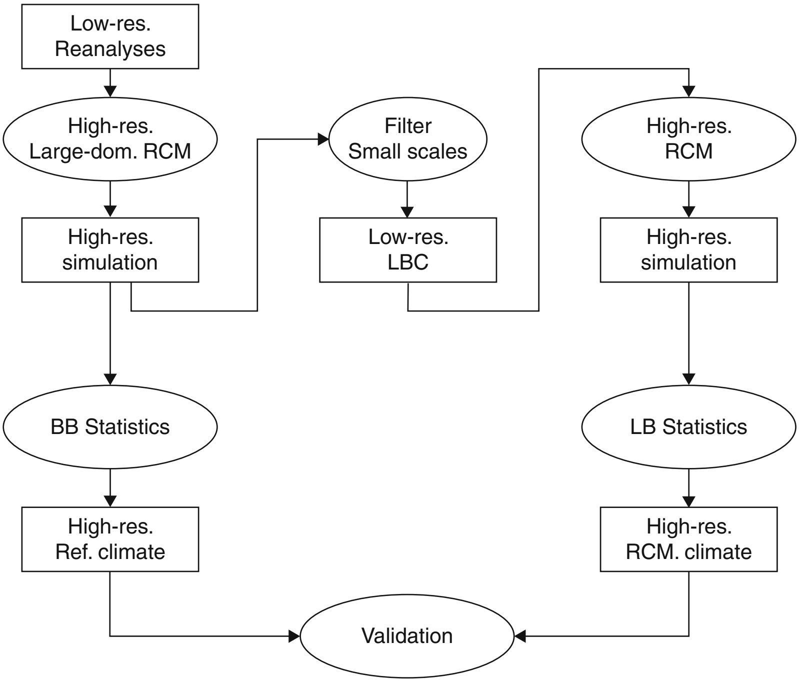

Fig. 9.3 Flow chart of the Big Brother Experiment (BBE). The high-resolution large domain RCM simulation is used as a virtual reality to evaluate the high-resolution simulation generated by the same RCM for a smaller domain achieved through nesting (Source Laprise et al. [31] © 2008 *Meteor. Atmos. Phys.*)

be attributed to the nesting approach of the limited-area model. Unlike the evaluation of real-world simulations that depends on the fidelity of model physics and availability of observational data, the idealized BBE framework allows different nesting-specific issues (e.g., the relaxation treatment and width of the buffer zone, frequency of LBC update) to be evaluated regardless of limitations of model physics and data because deficiencies of the nesting approach can be identified and quantified based on the comparison of the LB and BB alone.

A series of studies using the BBE protocol has been performed, focusing on different modeling issues specific to the nested regional modeling approach. As summarized by Laprise et al. [31], the BBE shows that the LB is capable of generating small-scale features absent from the lateral boundary conditions, and the small-scale features are consistent with the BB. These results demonstrate that the nested regional climate modeling approach does work as designed. That is, given large-scale conditions provided by the GCMs at the lateral boundaries, the RCMs can downscale to produce finer scale features absent from the GCMs. Moreover, the fine scales produced by the RCMs are consistent with what the GCMs would generate if they were applied at similar spatial resolution as the regional models. However, the small scales are not uniquely defined by the lateral boundary conditions and the domain-specific regional forcings, as the interactions between the two can be sensitive to small perturbations in the initial conditions that alter the time evolution of the small scales. The variations produced in regional simulations by perturbations in the initial conditions have been called "internal variability," as they relate to internal processes rather than external or LBC forcings. This issue has also been investigated by others (e.g., [3, 9, 21, 27]) who found that model internal variability depends on factors such as seasons, atmospheric flow regimes, and domain size. This puts a caveat on using single member short (seasonal and sub-seasonal) RCM simulations for model evaluation or hypothesis testing, as internal variability may overwhelm the signals (e.g., model errors or model response to external perturbations) being sought.

To address the issue of internal variability, ensemble modeling with perturbed initial conditions can be performed to quantify the internal variability and its impacts on model errors or model response. Alternatively, different techniques have been developed to constrain the large scales simulated by the regional models by the global climate simulations or global analyses throughout the regional domains. Spectral nudging [2, 28, 44, 54] is one example of such techniques. With spectral nudging, both the regional climate simulation and the global analyses or global climate simulations that provide lateral boundary conditions are decomposed into different spectral components in space. The simulated large-scale spectral components are nudged toward that of the global data using relaxation to provide stronger large-scale constraints on the regional climate simulations than that imposed by the lateral boundary conditions alone. These methods reduce the mismatch between the simulated large scales and the imposed lateral boundary conditions that contaminate the regional simulations. They also reduce internal variability, so simulation with a single initial atmospheric condition may be sufficient to assess model errors or estimate model response to external forcings. On the other hand, the degree of nudging to be applied to constrain the large scales can be rather arbitrary. Also, one may argue that by nudging the large scales of the regional climate simulations toward the global climate simulations, these methods increase the dependence of the regional simulations on the skill of the global models and eliminate the potential for the regional models to improve the large scales through upscaling of mesoscale features that are better resolved by the regional models [43].

Besides some form of large-scale nudging applied throughout the regional model domain, some studies have proposed a different mode of simulating regional climate by applying regional climate models with frequent initialization of the atmosphere to simulate short time segments that are then concatenated to compose the long-term regional climate simulations [45, 47]. This method takes advantage of the time period of limited error growth shortly after model initialization so the mismatch between the simulated and imposed large scale is small even without additional constraints on the large scale in the interior of the model domain. Two-way nesting of global and regional models has also been proposed as an approach to reduce large-scale inconsistency that may develop in one-way nested regional climate models because the upscaled influences of the regional models are included in the global models through feedbacks [40]. Such an approach has only been evaluated in a few studies [26, 41], and the results have been encouraging.

In summary, although the limited-area or nested modeling approach upon which regional climate models are based is an ill-posed boundary value problem, practical solutions such as the relaxation boundary treatment and spectral nudging of the large scale throughout the regional climate model domain have been developed and found to work well for a large number of cases. Furthermore, idealized experiments have confirmed most of the assumptions used in regional climate modeling [31]. However, uncertainty in regional climate simulations remain, owing in part to issues such as physics parameterizations, model resolutions, and initial conditions that are common to both global and regional climate models, and issues such as dependence on the lateral boundary condition, boundary treatment, regional domain size and location, and use of interior nudging that are specific to the nested regional modeling. Reviews and discussions of these issues can be found in Giorgi and Mearns [16], Laprise et al. [31], Leung et al. [35], and Wang et al. [55]. More research is needed to better understand the sensitivity of regional climate simulations to different factors and develop ways to reduce the uncertainty introduced by the nested modeling framework.

Evaluating Regional Climate Models

Model evaluation is important for assessing and documenting model skill and how it may evolve over time as changes and improvements are added to the models. It also provides information needed to understand model behaviors and diagnose model biases, and to assess uncertainties associated with the regional climate simulations. Model evaluation is achieved primarily by comparing model simulations with observations. The most common observation data used in evaluating regional climate simulations are atmospheric data such as 500 hPa height and upper level winds from global analyses, and surface temperature and precipitation from surface meteorological stations (e.g., Climatic Research Unit (CRU) and University of Delaware (UD) datasets), satellite-derived data (e.g., Tropical Rainfall Measurement Mission (TRMM)), and integrated station/satellite products (e.g., Global Precipitation Climatology Project (GPCP) [24] and Climate Prediction Center (CPC) Merged Analysis of Precipitation CMAP) [59]. These data are typically spatially interpolated to uniform latitude/longitude grids.

Both surface temperature and precipitation have high spatial variability due to surface topography and other factors. The effect of topography is relatively easy to account for in surface temperature as it varies with altitude more or less according to the standard temperature lapse rate, but its influence on precipitation is more spatially variable depending on a number of factors such as wind direction and surface slope and aspect. Statistical methods such as Parameter-elevation Regressions on Independent Slopes Model (PRISM) [7] have been developed to account for surface topographical effects in gridded precipitation data. There is a continuing need to develop high temporal and spatial resolution datasets for evaluating regional climate models. Recent efforts in Europe [22] and Asia [60] have made great strides in providing high resolution (0.1° and 25/50 km resolution for Europe and 0.25° and 0.5° for Asia) gridded daily precipitation data for model evaluation and analysis, although differences among datasets can still be substantial in mountain areas due to measurement methods, retrieval algorithms, grid resolutions, and whether topographic effects are explicitly accounted for.

By comparing observed and simulated surface temperature, precipitation, and atmospheric fields, model biases can be identified. However, determining the sources of model errors and thereby providing guidance on reducing model biases requires more information. Observations that can be used to diagnose model errors are more limited. For example, to understand model biases in surface temperature, it is useful to know which components (e.g., net shortwave and longwave radiation and sensible and latent heat fluxes) of the surface energy budgets may be in error. Ground-based measurements of the surface energy fluxes are limited both spatially and temporally. However, some flux data are available from a global network (FLUXNET) of about 400 micrometeorological tower sites that provide continuous measurements, some dating back to 1996. There is a challenge in relating point measurements of surface fluxes with model simulations that represent grid box averages. Satellite retrievals of radiation fluxes are available globally for recent decades, but large differences exist among different datasets such as Clouds and the Earth's Radiant Energy System (CERES) and International Satellite Cloud Climatology Project (ISCCP).

Diagnosing errors in precipitation is even more challenging because precipitation is the end product of many interactive processes. Although precipitation is more directly related to clouds, measurements of cloud macrophysical and microphysical properties are limited. Cloud climatologies are available from ISCCP and CERES, but the grid resolution is relatively coarse (280 km for ISCCP and 1° for CERES) compared to regional models. Furthermore, errors in simulating clouds may be reflecting other problems because myriads of processes can influence the formation and evolution of clouds. Higher temporal and spatial resolution precipitation can provide a means to evaluate temporal variability from diurnal to seasonal, and probability distribution of precipitation rates, which can provide important clues to processes that may not be well represented in models. Some surface hydrological variables such as river runoff and snowpack may also be used to infer model biases in precipitation or combinations of precipitation and temperature biases.

Besides advances in the development of datasets for model evaluation, the methods used to evaluate models have also become more sophisticated. In the 1990s, comparisons of observations and model simulations were mostly limited to seasonal/annual and regional averages, but more studies now also compare observed and simulated temporal and spatial variability such as interannual variability and spatial distributions. With more studies producing longer regional climate simulations, more aspects of the simulations such as diurnal variability, extreme statistics, regime-specific features, frequency distributions, co-variability of different variables (e.g., between temperature and precipitation), and parameters that reflect the strengths of feedback processes have been evaluated (e.g., comparing land-atmosphere coupling strengths between models).

Although model evaluation studies are broadly aimed at understanding and quantifying model biases so model improvements can be made, some efforts also evaluate specific aspects such as precipitation and runoff [32], wind resources [57] of the regional simulations to provide practical guidance on their usefulness to provide climate information for impact assessments and resource management or planning. To support more detailed analyses, the requirements on model outputs have significantly increased as higher temporal frequency model outputs (e.g., hourly and daily) and more simulated state variables and tendencies are becoming more commonly archived.

Besides comparing model simulations with observations, model intercomparison can add significant information to understand and characterize model differences and uncertainties. The Atmospheric Model Intercomparison (AMIP) project [15] was initiated in the early 1990s to determine the systematic errors of global atmospheric models used to simulate long-term climate. Since the first AMIP project, many intercomparison projects have been developed to evaluate climate models used in different simulation modes. Similar coordinated projects have also been initiated to intercompare regional climate simulations since the mid-1990s. The first of such projects is the Project to Intercompare Regional Climate Simulations (PIRCS) [53]. PIRCS includes two phases, with the first phase focusing on simulations of two anomalous years, the 1988 drought and 1993 flood in the US Great Plains, and the second phase comparing multiyear simulations over North America. All simulations were driven by global reanalysis data and observed sea surface temperature. Besides regional climate models, one global stretched-grid model also participated in PIRCS for comparison between two dynamical frameworks for regional climate modeling. Following PIRCS, several intercomparison projects were developed to compare regional climate simulations over the Arctic (ARCMIP) (http://curry.eas.gatech.edu/ARCMIP/) and East Asia (RMIP) [14]. More discussions of intercomparison projects that focus on climate change simulations are provided in section "Dynamical Downscaling."

Applications of Regional Climate Models

Climate Process Studies

An important application of regional climate models is to advance the understanding of regional climate processes. In this context, regional climate models are often used to test hypotheses of how different regional forcings or feedback mechanisms play a role in regional climate variability and change.

For example, Leung et al. [34] used long-term simulations of the western USA to investigate the role of topography on precipitation spatial distribution during El-Nino and La-Nina events. Comparing precipitation during El-Nino years with the 20-year simulated climatology, they found a positive-negative-positive anomaly pattern in the Olympic Mountains and the west side and east side of the Cascades Mountains in the US Pacific Northwest. The pattern was found to be a result of the interactions between the large-scale atmospheric circulation that are influenced by the ENSO conditions and the orientation of the mountains. With atmospheric flow assuming a more southwesterly rather than a westerly direction during El-Nino years, the rain shadow created by the north-south oriented Cascades Mountains is reduced, resulting in more precipitation reaching the lee side of the mountains. Such regional anomaly patterns are generally not found in global reanalyses or global climate simulations because of their coarser resolution, but are consistent with observed precipitation and streamflow anomalies in the region.

Hughes and Hall [25] performed regional climate simulations for the western USA to investigate large-scale and local controls on Santa Ana winds in Southern California. Using a simulation at 6 km resolution, their analysis showed that both large-scale anomaly corresponding to a high pressure over the Great Basins, and local thermodynamic forcing due to surface temperature gradient between the cold desert (Mojave Desert) and warm ocean create pressure gradients that drive offshore winds. The latter was found to be particularly important in determining the timing of Santa Ana winds, which occur more frequently during December when the temperature gradient between the desert and Pacific coast is the largest.

The role of soot on mountain snowpack and hydrology was investigated by Qian et al. [48] using regional climate simulations with and without soot deposition in western USA. Their study shows that soot-induced snow-albedo perturbations increase the surface net solar radiation flux during late winter to early spring. This increases the surface air temperature and reduces snow accumulation and spring snowmelt, causing a trend toward earlier snowmelt. Snow-albedo feedback was found to play an important role in amplifying the soot effects in the mountains.

Riddle and Cook [50] used regional climate simulations to study the mechanism of abrupt rainfall transition in the Greater Horn of Africa. The yearly monsoon jump of about 20° latitude during April and May was found to coincide with abrupt circulation changes associated with the Somali jet that develops during that time. The cross-equatorial branch of the Somali jet brings moisture to the southern slopes of the Ethiopian plateau, which then produces the abrupt rainfall transition in the region.

To investigate why temperature in the central USA has cooled by 0.2–0.8°C in the late twentieth century, instead of warmed as in most continental regions, Pan et al. [46] used a regional climate model and found that under a global warming scenario, increased moisture from the Gulf of Mexico due to warming and increasing occurrence of the Great Plain Low Level Jet (LLJ) in the south and decreasing occurrence in the north enhances atmospheric moisture convergence and cloudiness and precipitation in the central USA. These changes replenish soil moisture during summer, which increases late-summer evapotranspiration and suppresses daytime maximum temperature, and hence the "warming hole." Because of coarse resolution, most GCMs cannot simulate the observed "warming hole" in the late twentieth century.

Regional climate models also offer great potentials to understand the mechanisms of extreme events and their projected changes in the future. For example, Seneviratne et al. (2006) performed two regional climate simulations with and without land-atmosphere interactions to investigate the role of land-atmosphere feedbacks on heat waves in Europe. They showed that soil moisture – temperature and soil moisture – precipitation feedbacks increase summer temperature variability in central and eastern Europe. Under climate change, the region of stronger land-atmosphere coupling shifts northward in response to greenhouse warming to central and eastern Europe, and enhances summer temperature variability and increases the potential for more frequent heat waves in that region.

In the above examples, high resolution is important for the model to reproduce the observed climatology of temperature, precipitation, wind, or snowpack, which in the western USA, Europe, and the Greater Horn of Africa depend strongly on regional orography. High resolution is also important for simulating soot deposition caused by anthropogenic emissions in cities being carried to the mountains downwind, or LLJ and its effects on cloudiness and precipitation. Successful simulations of the base states and model ability to simulate regional forcings and feedback mechanisms (e.g., snow-albedo, soil moisture – temperature feedbacks, LLJ – precipitation coupling) are critical for assessing their role in the observed regional climate phenomena.

Dynamical Downscaling

Dynamical downscaling is an important application of regional climate models, which aims to provide more spatially resolved climate predictions or projections provided by GCMs. Most of the downscaling applications to date are related to climate change projections. Early efforts described the use of an individual RCM to dynamically downscale climate change projections by a specific GCM. Typically only a single emission scenario such as the business-as-usual scenario (1% increase of CO_2 per decade) was used. Although GCMs generally produce simulations that cover preindustrial to 2100, RCM simulations are usually performed only for two time segments of 10–30 years corresponding to a current and a future time period.

Giorgi et al. [18] reported the first set of studies on using a regional climate model to dynamical downscale climate change scenario for Europe and the western Mediterranean basin. The GCM and RCM they used had a spatial resolution of R15 (about 400 km) and 70 km, respectively. The current and future climate corresponds to the equilibrium conditions simulated by the GCM using $1 \times CO_2$ (preindustrial level) and $2 \times CO_2$ (doubling of preindustrial level), respectively. Although the GCM generally reproduced the basic seasonal migration patterns of storm tracks, significant biases were also found in large-scale features such as the location and strength of the North Atlantic jet, cold tropospheric temperature and low tropospheric relative humidity, and underprediction of summer precipitation. Overall, the RCM was found to inherit most of the large-scale biases from the GCM, but the spatial distribution of temperature and precipitation was better simulated due to topographic effects. In addition, the RCM produced more spatially refined temperature and precipitation change scenarios. The RCM also simulated significant sub-GCM-scale changes in surface hydrological variables such as snow depth and runoff.

Following a similar approach, Leung and Ghan [36] used a regional climate model driven by GCM 1 × CO_2 and 2 × CO_2 simulations to produce climate change scenarios for the western USA. However, much more spatially resolved simulations of temperature and precipitation were produced by using a subgrid parameterization of orographic precipitation and vegetation [38, 39]. This method divides a model grid cell into subgrid surface elevation and vegetation classes based on high resolution (1 km) DEM and vegetation data. The influence of topography and vegetation on atmospheric and land surface processes is represented through a parameterization that accounts for orographic effects on clouds, which then affect precipitation and surface hydrology. During postprocessing, surface temperature and precipitation, among other variables, simulated for each subgrid class are mapped geographically to 1 km resolution based on the DEM and vegetation data. This approach greatly improves the simulation of surface temperature, precipitation, and snowpack compared to the GCMs. Their results show that snowpack will potentially be reduced by up to 50% under a 2 × CO_2 scenario. They also found a strong elevation dependence of climate change signals in temperature, precipitation (amount and phase), snow cover, and runoff (see also [1, 20] for a discussion of elevation dependence of climate change signals in mountainous regions).

In the 2000s, as more GCM transient simulations became available and the regional modeling community has grown, more studies have been published that investigated the potential effects of climate change in different climatic regimes or geographical locations. Figure 9.4 shows an example of cold season heavy precipitation (95th percentile) simulated by a GCM and an RCM driven by the GCM boundary conditions, using the same models described by Leung et al. [32], except for a change in the regional domain to cover the conterminous USA. Comparison of the simulated and observed heavy precipitation shows that the RCM reproduced the observed spatial distribution of heavy precipitation better than the GCM primarily because of the increased spatial resolution. As regional climate information is useful for assessing climate impacts and addressing climate adaptation, many studies that involve the use of regional climate models for producing regional climate change scenarios included scientists and stakeholders of the specific regions being studied to focus on subjects both scientifically interesting and societally relevant. The regional human resources and knowledge base that have been tapped have proven beneficial and contributed to more diverse analyses and applications of the climate change results. More examples of these efforts have been summarized in Christensen et al. [5].

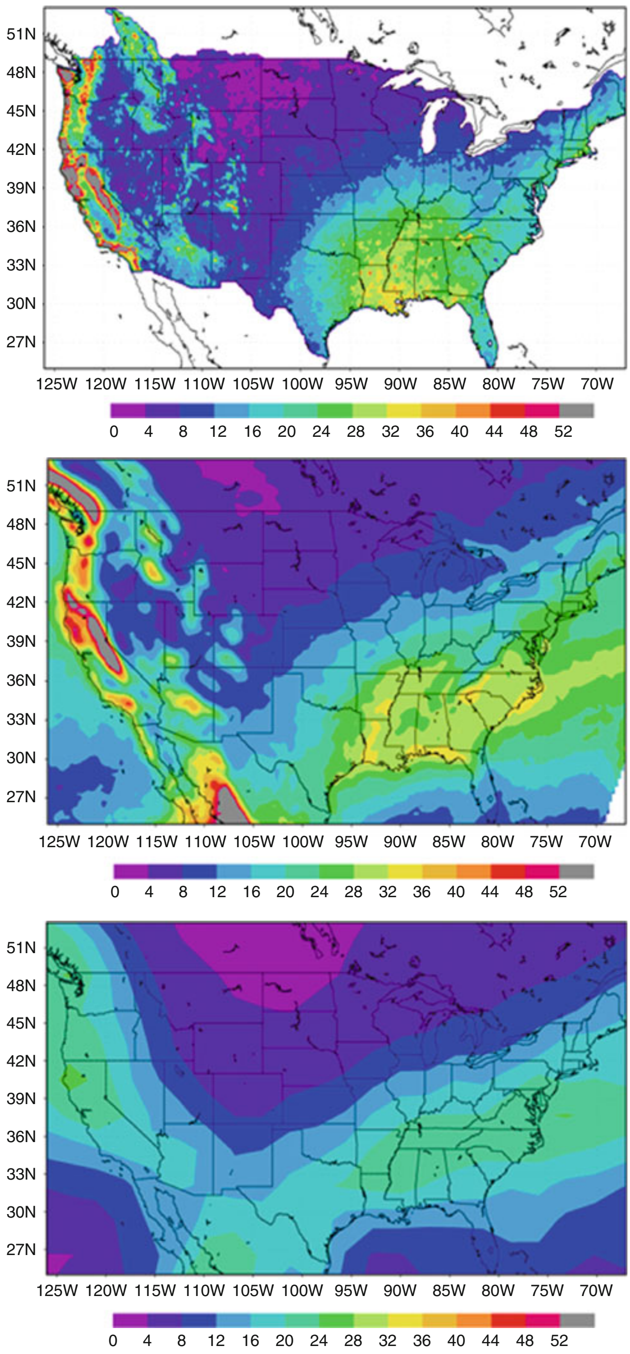

Fig. 9.4 An example of cold season heavy (95th percentile) precipitation simulated by a GCM (*top*) and an RCM (*middle*) and comparison with observation (*bottom*) over the USA. The prominent effects of topography are well captured by the RCM at 36 km grid resolution compared to the GCM, which was applied at roughly 250 km resolution

Besides individual efforts of using a particular RCM to downscale climate predictions or projections from a particular GCM, larger efforts have also been coordinated to develop ensembles of dynamically downscaled simulations. Common to these coordinated efforts is the objective to fill the gap in providing regional climate change scenarios for different geographic regions and to improve the characterization of uncertainty of the scenarios. To this end, an ensemble modeling approach is used in which multiple RCMs are nested within multiple GCMs to generate a matrix of regional climate change scenarios to facilitate the interpretation and characterization of uncertainty of regional climate change. These efforts also enable large, multi-model datasets to be archived following common protocols similar to the AMIP and CMIP efforts adopted by the GCM community over the last two decades.

In Europe, two large coordinated projects, PRUDENCE [5] and ENSEMBLES [23], intercompared regional climate models driven by global reanalysis as well as global climate simulations for the current and future climate. PRUDENCE designed, executed, analyzed, and synthesized regional climate scenario development for Europe. In brief, four GCMs and ten RCMs were involved to produce regional climate scenarios at 50 km resolution, but a few scenarios at 20 km resolution were also produced. Two time slices were simulated by each RCM, corresponding to 30 years of control and future (2071–2100) conditions. Two emission scenarios, A2 and B2, were considered, and some GCMs and RCMs provided multiple ensemble members (using different initial conditions) for assessing internal variability. Although only 28 combinations out of the full matrix of GCM, RCM, and scenario combinations were performed, PRUDENCE provided sufficient model outputs to evaluate the variance due to the four sources of uncertainty: GCM, RCM, scenario, and sampling. Figure 9.5 summarizes the surface temperature and precipitation changes simulated by the regional models for Europe.

One of the main conclusions of PRUDENCE is that the largest source of uncertainty resides in the GCM boundary conditions applied to the RCM [11]. The choice of RCM becomes more important, however, for certain subregions or seasons (summer in particular). Furthermore, many local features and aspects of extremes can vary substantially between RCMs [30] to alter the climate change signal from that simulated by the driving GCM. For example, RCM simulations performed at higher resolution (12 km vs 25 km) reduced the magnitude of future summer drying over southern Europe [4]. This effect could be attributed to the diminished control of the LBCs on RCM simulations during summer, and the general tendency of RCM to produce more precipitation at higher resolutions (e.g., [33, 49]).

Building on the foundation of PRUDENCE, ENSEMBLES is the largest and most comprehensive RCM comparison project conducted to date. Focusing again on Europe, ENSEMBLES utilized 15 GCMs and 11 RCMs to create a large GCM-RCM matrix for a single emission scenario (A1B). Simulations were also performed with reanalysis boundary conditions at 25 km and 50 km horizontal resolution. Interestingly, higher resolution (25 km vs 50 km) did not improve the simulation of large-scale weather types [51] or seasonal precipitation [49] by

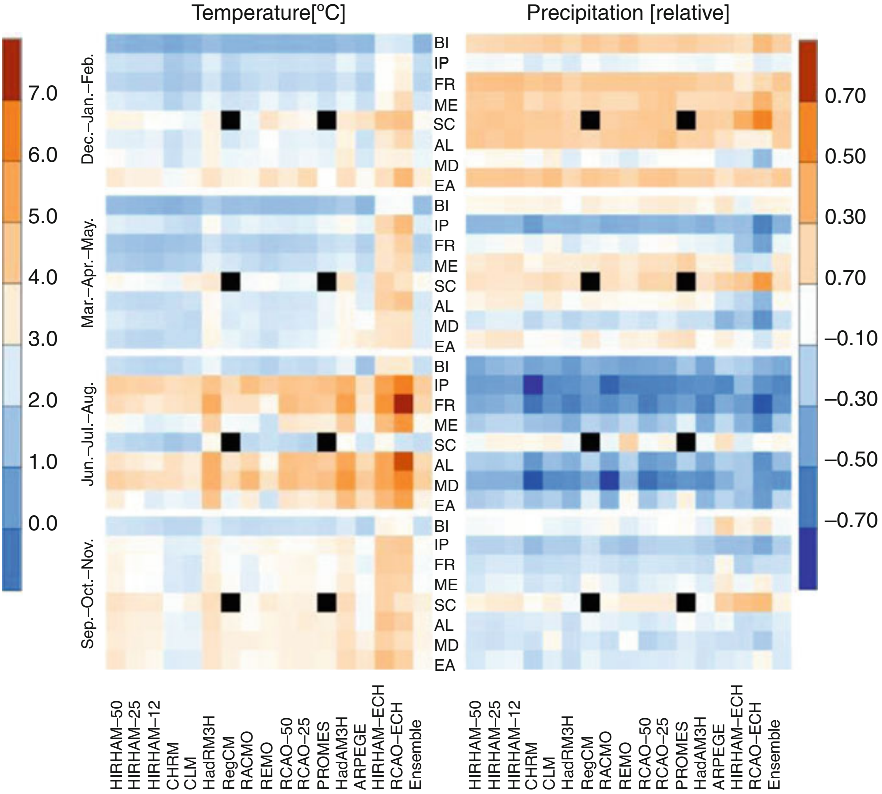

Fig. 9.5 An overview of seasonal changes in surface temperature (degree C) (*left*) and precipitation (relative change) (*right*) simulated by the PRUDENCE regional climate models for different analysis areas (row) and models (column). The analysis areas are: *BI* British Isles, *IP* Iberian Peninsula, *FR* France, *ME* Mid-Europe, *SC* Scandinavia, *AL* Alps, *MD* Mediterranean, *EA* Eastern Europe. Results from 17 regional simulations (some are produced by the same model at different resolutions) are shown, but some simulations did not cover certain geographical areas (shown by the *black squares*) (Source Christensen and Christensen [4] © 2007 *Climatic Change*)

many RCMs, suggesting that physics and/or downscaling approach (i.e., dynamical framework) may be more important than resolution. The most novel aspect of the ENSEMBLES project is the construction and use of a set of metrics to weight models according to their performance to construct an ensemble mean [6]. However, application of the weights to the GCM-forced RCM simulations for the twentieth century did not substantially improve the performance of the multi-model temperature or precipitation mean over the unweighted multi-model mean when averaged over Europe. This suggests that more research is needed to further explore the productive use of ensembles of climate change scenarios to reduce uncertainty.

The North American Regional Climate Change Assessment Program (NARCCAP) [42] is another coordinated project similar to PRUDENCE and

ENSEMBLES, but with a geographic focus on North America. The NARCCAP GCM-RCM matrix includes mapping 4 GCMs with 6 RCMs statistically for a more balanced design for uncertainty analysis. In addition, two high-resolution time-slice global simulations are included for comparison with the RCM simulations over North America. More recently, CORDEX (a COordinated Regional Downscaling EXperiment) has been developed to coordinate regional climate change scenario development for all continents around the world, and to foster international collaborations and promote interactions and communications between the various communities involved in scenario development and applications. The CORDEX design is similar to the multi-GCM/RCM matrix used in PRUDENCE, ENSEMBLES, and NARCCAP, but an additional level of uncertainty being assessed is model dependence on climate regimes and/or geographic locations. Therefore, an important CORDEX effort is to develop and compare climate simulations across different continents. Additionally, CORDEX encourages the development of Regional Analysis and Evaluation Teams to develop a set of regionally specific metrics for model evaluation, collect observational data, design experiments to investigate the added value of RCMs, and evaluate the ensemble of simulations from CORDEX.

Besides climate change, dynamical downscaling has also been applied to the area of seasonal climate predictions, but to a much lesser extent compared to downscaling of climate change simulations. The Multi-Regional Ensemble Downscaling (MRED) is a coordinated project in which multiple RCMs were used to downscale global seasonal climate forecasts for the USA (http://ecpc.ucsd.edu/projects/MRED/). Dynamical downscaling has also been used to develop regional analysis for studying climate variability and trends. Unlike regional analysis such as the North American Regional Reanalysis that assimilates observation data in regional models driven by global analysis, the dynamical downscaling approach assimilates only global analysis, but no additional observational data within the regional model domains to generate regional climate information. As examples, Sotillo et al. [52] used a regional model to downscale global reanalysis to generate a high-resolution 44-year atmospheric analysis for the Mediterranean Basin. Kanamitsu and Kanamaru [29] used a regional climate model at 10 km resolution driven by a global reanalysis in the California Reanalysis Downscaling at 10 km (CaRD10) project to produce 57 years of regional analysis for California.

Although numerous studies that evaluated different aspects of regional climate simulations using observations have demonstrated some skill in simulating regional temperature and precipitation, the skill depends very much on the large-scale data used to drive the model, the model physics, and how the models were configured. More recently, besides asking what ability RCMs have in reproducing observed climate features, the question of whether dynamical downscaling adds values to global climate simulations has become an important topic. Essentially, this begs the question of whether the additional step of running regional climate models as a means to dynamically downscale global climate simulations indeed provides additional (useful) information not available from the global climate simulations.

One way to address this question is to define and apply various metrics to quantitatively measure the added skill or added information provided by the regional models. For example, spatial filters can be used to partition the model-simulated variability to a larger scale that is resolved by the global simulation and a smaller scale that is beyond the limit resolved by the global simulation. The amount of finer scale variability generated by the regional models is considered value added since it provides climate information beyond what the global simulations provide (e.g., [12]). Similarly, spectral decomposition can be applied to simulated quantities such as different components of the surface water budgets and forecast skill to determine the added value of regional modeling.

Another aspect of evaluating the value added by RCMs is to compare dynamical downscaling with statistical downscaling, which is computationally a much cheaper method to produce regional climate information. To date, comparison of dynamical and statistical downscaling methods is limited to a few studies. Wood et al. [58] represent an early effort to apply a simple statistical downscaling method called Bias Correction Spatial Disaggregation (BCSD) to not only global simulations, but also regional climate simulations. The latter is a hybrid approach that combines dynamical and statistical downscaling. Comparing statistically downscaled simulations driven by global and regional simulations with the global and regional simulations, this study showed that hydrologic response to climate change can be enhanced using the hybrid approach compared to applying statistical downscaling directly to the GCM outputs because the RCM simulated larger warming in mountainous areas as a result of snow-albedo feedbacks, which are not captured by GCM or statistical downscaling.

Future Directions

In summary, both idealized experiments and real case applications have demonstrated that nested regional climate modeling is a viable approach for regional climate simulations. However, applications of regional climate models must be exercised with care because many factors can introduce uncertainty in the simulated results. These factors, which include domain size and location, physics parameterization, model resolution, lateral boundary condition and treatment, and use of interior nudging, must be carefully assessed before proceeding to long-term climate simulations. More research is also needed to better understand the sensitivity of regional climate simulations to those factors and develop ways to characterize and reduce uncertainty introduced by the nested modeling framework. As computing resources allow global models to be applied at higher and higher spatial resolution, and alternative approaches such as global variable resolution models become feasible, more research is needed to evaluate and compare different approaches to modeling regional climate to establish their validity and usefulness in addressing different aspects of climate research and applications.

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