Journal of the Meteorological Society of Japan, Vol. 82, No. 6, pp. 1599–1628, 2004

Regional Climate Modeling: Progress, Challenges, and Prospects

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(Manuscript received 11 September 2003, in final form 15 June 2004)

Abstract

Regional climate modeling using regional climate models (RCMs) has matured over the past decade to enable meaningful utilization in a broad spectrum of applications. In this paper, the latest progress in regional climate modeling studies is reviewed, including RCM development, applications of RCMs to

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dynamical downscaling for climate change assessment and seasonal climate predictions, climate process studies, and the study of regional climate predictability.

Challenges and potential directions of future research in this important area are discussed, with focus on those that have received less attention previously, such as the importance of ensemble simulations, further development and improvement of the regional climate modeling approach, modeling extreme climate events and sub-daily variation of clouds and precipitation, model evaluation and diagnostics, applications of RCMs to climate process studies and seasonal predictions, and development of regional earth system models.

It is believed that with the demonstrated credibility of RCMs in reproducing not only monthly to seasonal mean climate and interannual variability, but also the extreme climate events when driven by good quality reanalysis and continuous improvements in the skill of global general circulation models (GCMs) in simulating large-scale atmospheric circulation, regional climate modeling will remain an important dynamical downscaling tool for providing the needed information for assessing climate change impacts, and seasonal climate predictions, and a powerful tool for improving our understanding of regional climate processes. Internationally coordinated efforts can be developed to further advance regional climate modeling studies. It is also recognized that since the final quality of the results from nested RCMs depends in part on the realism of the large-scale forcing provided by GCMs, the reduction of errors and improvement in physics parameterizations in both GCMs and RCMs remain a priority for the climate modeling community.

1. Introduction

Motivated by the need of regional climate information to understand regional climate change and its impacts, regional climate models (RCMs) were first developed mainly as a dynamical downscaling tool to address global change issues. Since the first successful demonstrations of regional climate modeling by Dickinson et al. (1989), and Giorgi and Bates (1989), much effort has been devoted to the development, evaluation, and application of RCMs. The principle behind regional climate modeling is that given detailed representations of physical processes, and high spatial resolution that resolves complex topography, land-sea contrast, and land use, a limited area model can generate realistic regional climate information consistent with the driving large scale circulation supplied by either global reanalysis data, or a general circulation model (GCM).

RCMs have been used not only to dynamically downscale GCM climate change simulations, but also seasonal climate predictions with similar goals of obtaining useful regional climate information. As such, RCMs have become a critical component in the end-to-end assessment, or prediction system, where RCM bridges the spatial gaps between the GCM and other modeling components such as hydrological models that require regional climate information (e.g., Miller and Kim 1996; Leung et al. 1996). Regional climate modeling has been demonstrated to be able to improve simulation at the regional scales, especially in regions where forcing due to complex orography, or coastlines, regulates the spatial distribution of climate variables (e.g., Giorgi 1990; Jones et al. 1995; Walsh and McGregor 1995; Wang et al. 2000; Wang et al. 2003). The regional climate modeling approach has also been shown to be useful for improving our understanding of climate processes, such as cloud-radiation forcing, cumulus convection, and land surface processes (e.g., Pan et al. 1995; Paegle et al. 1996; Dudek et al. 1996; Bosilovich and Sun 1999; Schär et al. 1999; Barros and Hwu 2002; Sen et al. 2004a,b; Wang et al. 2004a). Earlier reviews on regional climate modeling can be found in Giorgi and Mearns (1991), Giorgi (1995), McGregor (1997), and Giorgi and Mearns (1999).

The objective of this paper is to provide a timely comprehensive review of the latest progress in regional climate modeling. The following areas are covered in this review: RCM development (section 2), applications of RCMs to dynamical downscaling for climate change assessment and seasonal climate prediction (section 3), application of RCMs to climate process studies (section 4), and the study of RCM predictability (section 5). Challenges and potential directions of future research in this important area are discussed (section 6), with focus on areas where less attention has been given previously, such as the importance of ensemble simulations in detecting signals of climate change or climate sensitivity, the application of RCMs to climate process studies and seasonal climate predictions, modeling extreme climate events and sub-daily variation of clouds and precipitation, process-oriented evaluation and diagnostics of model simulations, and the development of regional earth system models.

2. RCM development

2.1 Dynamical issues

There are a large number of RCMs currently in use that incorporate a variety of dynamical treatments. Almost all limited-area models are grid point models, employing a variety of horizontal staggerings for the wind components. An exception is the regional spectral model (RSM), such as the one developed at the National Center for Environmental Prediction (NCEP) by Juang and Kanamitsu (1994), and the one independently developed at the Meteorological Research Institute (MRI) by Kida et al. (1991). RCMs also employ a variety of time integration schemes, including the split explicit scheme used in NCAR RegCM2 (Giorgi et al. 1993a) and semi-implicit schemes. A couple of RCMs such as DARLAM (McGregor and Walsh 1994) and CRCM (Caya and Laprise 1999) permit longer time steps by employing semi-Lagrangian integration.

Most RCMs are formulated using the hydrostatic primitive equations. A few RCMs, such as MM5, CRCM, and RAMS (Liston and Pielke 2000), include nonhydrostatic terms, which allow more accurate representation of phenomena, such as deep convection and mountain waves that may produce large vertical motion when fine grids are used. However, in the context of regional climate modeling, improvement in the simulated climatology from the use of nonhydrostatic formulations has yet to be demonstrated, because most RCMs have been applied at relatively coarse spatial resolution between 30 and 100 km. Some groups have performed multi-year simulations at 10–20 km resolution (e.g., Christensen et al. 1998; Leung et al. 2003a,b). Higher resolution modeling can also be achieved through model nesting to telescopically zoom into finer spatial resolution with one or more levels of nesting, and with the use of nonhydrostatic formulations (Grell et al. 2000).

Similarly, vertical resolution has also gradually increased. Most RCMs use some type of terrain-following pressure coordinates. RAMS and CRCM use terrain-following height coordinates, and the ETA model uses a step mountain vertical pressure coordinate. So far, in the context of regional climate modeling, no study has systematically examined the impacts of different choices of vertical discretization and vertical resolution.

2.2 Limited-area models

Limited-area models require information at their lateral boundaries for all meteorological variables, which can be derived from global reanalyses or GCM simulations. This information is usually incorporated via “one-way nesting”, in conjunction with a boundary relaxation zone. Most RCMs follow a procedure described by Davies (1976), with exponentially decreasing weights and larger buffer zone, as advocated by Giorgi et al. (1993b), to provide a smoother transition between the prescribed lateral boundary conditions and the regional climate simulations.

With “one-way nesting” the RCM circulation could differ from that of the host GCM. This is possible especially when large domains are used, or in the tropical regions where the boundary forcing is relatively weak. Several viewpoints exist as to whether or not this divergence between the RCM and GCM climatology reduces the credibility of regional climate simulations. On one hand, Jones et al. (1995) believe that the synoptic circulation of the RCM should not depart far from that of the driving GCM, and hence conclude that the RCM domain should be fairly small, such that the imposed large-scale circulation at the lateral boundaries can exert strong control over the regional simulation. On the other hand, some regional climate modeling studies, such as McGregor (1997), use large domains with the philosophy that the RCM simulation should be allowed to produce realistic intensities and frequencies for each type of major synoptic system, without necessarily reproducing the daily sequence of the host GCM. With this view, one may argue that RCM is useful not only for producing regional climate information, but also modifying atmospheric circulation at the spatial scales not well represented by the host GCM.

In principle, it would be possible to design a "two-way nested" regional modeling system, where the RCM is run simultaneously with the host GCM, and regularly updates the host GCM in the RCM region. This appears not to have been done yet; in fact it would be cumbersome to fully couple a global and regional model in this manner, because they are typically developed using different numerics and physical parameterizations. Note that similar benefits to "two-way nesting" can be derived from the use of a variable-resolution GCM, as described in the next section. It should also be noted that variable resolution RCMs, as proposed by Qian et al. (1999), also have a good potential to ameliorate some of the boundary condition problems found when the resolutions of the nested RCM and driving GCM are very different.

Another approach to enforce consistency between the large-scale circulation simulated by an RCM and its host GCM is to employ broadscale forcing in the RCM, whereby the broadscale patterns of the RCM are forced to follow those of the host GCM. It was first used by Kida et al. (1991), and further advocated by von Storch et al. (2000), with the use of spectral nudging. This technique implies a modification of the primitive equations throughout the RCM domain, and thus represents a rather different philosophy of dynamical downscaling from the "one-way nested" approach.

RCMs are being increasingly coupled with other component models. Several RCMs are coupled with elaborate surface hydrology schemes, which include river-routing (Leung et al. 1996; CRCM). Döscher et al. (2002) coupled their RCM to an ocean model. A few models, such as ARCSyM (Lynch et al. 1995), are also coupled with sea-ice models. Mabuchi et al. (2000) included the CO2 cycle in an RCM coupled with a biosphere atmosphere interaction model.

2.3 *Variable-resolution global models*

A recent development of regional climate modeling has been the application of variable-resolution global models to regional climate simulations. Variable-resolution global models have been used in numerical weather prediction (NWP) for some years, first in France with the spectral ARPEGE model (Caian and Geleyn 1997) based on the approach of Courtier and Geleyn (1988), then in Canada with the global environmental multiscale (GEM) model (Côté et al. 1998). ARPEGE achieves its variable resolution by applying the Schmidt (1977) transformation to the primitive equations. The Schmidt transformation has the unique property that if it is used to stretch a conformal/isotropic grid, the resulting grid is also conformal/isotropic. ARPEGE has been adopted for regional climate modeling over Europe by Déqué and Piedlievre (1995), typically using a stretching factor of 3.5. Recently, Déqué and Gibelin (2002) have addressed the concern that systematic errors in the low-resolution part of the globe may contaminate the domain of interest. They compared 10-year simulations with prescribed sea surface temperatures (SSTs) for the variable-resolution model, against those for the same model run at uniformly high resolution over the globe. Good agreement between the model climatologies is confirmed over the high resolution region. GEM is formulated on a latitude-longitude grid, stretching is applied separately to the latitudinal and longitudinal directions to achieve a region of high resolution. Fox-Rabinowitz et al. (2000) have applied similar stretching transformations to the Goddard Earth Observing System GCM to produce their regional climate modeling system.

Another global model that uses the Schmidt transformation to achieve variable resolution is the Conformal-Cubic Atmospheric Model (CCAM), as described by McGregor and Dix (2001). CCAM has been used in climate change simulations with a resolution of about 65 km over Australia, employing a stretching factor of 3.3, for both 140 years and two 30 years (McGregor et al. 2002). CCAM has now replaced DARLAM for modeling regional climate at CSIRO.

Variable-resolution global models essentially require no nesting data. For highly stretched applications of CCAM down to around 14 km, it has been considered prudent to also use far-field nudging by the "host" GCM winds to ensure realistic climatology in the coarse part of the domain; the technique then has some conceptual similarities to conventional nested downscaling. An intercomparison of several variable-resolution GCMs is currently being undertaken by the Stretched Grid Model Intercomparison Project (SGMIP). The intercomparison is being run with prescribed SSTs and sea-ice for 12 years with a resolution of about 50 km over North America.

3. Application to dynamical downscaling

3.1 Dynamical downscaling

Dynamical downscaling is the process of deriving regional climate information based on large-scale climate conditions using high-resolution RCMs. Numerous studies have demonstrated that when driven by large-scale conditions such as global analyses, RCMs can realistically simulate regional climate features such as orographic precipitation (Leung and Ghan 1998; Kim et al. 2000; Frei et al. 2003), extreme climate events (Mearns et al. 1995; Kunkel et al. 2002; Wang et al. 2003), seasonal and diurnal variations of precipitation across different climate regimes (Dai et al. 1999; Zhang et al. 2003), and regional scale climate anomalies such as that associated with the ENSO (Leung et al. 2003a,b). When used as a dynamical downscaling tool, RCMs are usually driven by large-scale lateral and lower boundary conditions provided by GCMs to obtain regional climate information that are then used in impact assessment or resource management.

In dynamical downscaling, an important question is whether the information generated by this “extra step” (as opposed to directly using GCM simulations), which is computationally demanding, really adds value. Since the ability of RCMs to reproduce the observed regional climate depends strongly on the large-scale circulation that is provided through the lower and lateral boundary conditions, this question is closely tied to the accuracy of the large-scale boundary conditions. Many studies suggested that higher spatial resolution GCMs seem to provide more realistic simulations of large-scale circulation (e.g., Pope and Stratton 2002; Duffy et al. 2003). However, the importance of model evaluation should be emphasized to help select GCMs that can provide more realistic control simulations over the study region, or configure the RCM domain to avoid placing the lateral boundaries over areas with known GCM biases, such as misplaced large scale features (e.g., jet stream and ITCZ), or erroneous moisture transport (e.g., Seth and Rojas 2003; Rojas and Seth 2003). These, however, are not always possible, because most GCMs have yet to successfully reproduce many features such as those associated with the Asian monsoon (e.g., Sperber and Palmer 1996; Kato et al. 2001). Nevertheless, extensive model evaluation for both GCMs and RCMs should be performed to provide guidance on uncertainty and improve their credible use in climate research.

Even with improved boundary conditions, the skill and value of dynamical downscaling also depend strongly on the presence and strength of the regional scale forcings. These forcings may include orography, land-sea contrast, vegetation cover, lake effects, or they may be anthropogenic such as air pollution, urban heat island, and land and water management. Because regional forcings may extend regional climate predictability, more skillful dynamical downscaling is often reported in studies of the western U.S., Europe, and New Zealand, where topographic effects on temperature and precipitation are prominent. On the contrary, regional modeling results are usually less realistic and more sensitive to model configurations in regions such as the Great Plains in the U.S. and China, especially during the warm season, where regional forcings are weak, and various feedbacks between cloud and radiation, or land and atmosphere, play a more dominant role in determining regional climate and its sensitivity to greenhouse forcing.

In the following two subsections, we will provide dynamical downscaling examples in the areas of climate change and seasonal climate predictions, and examine issues related to whether and how dynamical downscaling may provide added value in those applications.

3.2 Climate change

The use of RCMs in climate change research has grown rapidly over the last decade as indicated by the increasing volumes of literature cited between the Second and Third Intergovernmental Panel on Climate Change (IPCC) reports (IPCC 1996; IPCC 2001). Because the application of RCMs to climate change has been recently reviewed extensively by Giorgi et al. (IPCC 2001), here only some ongoing issues and recent advancements are briefly discussed. Comparing studies that were performed in the early 1990s with those of the late 1990s to early 2000s, gradual improvements are evident in several areas: (1) GCMs are now applied at higher spatial resolution (approximately 200 km rather than 400 km and more vertical levels) to provide more realistic large-scale boundary conditions for dynamical downscaling; (2) RCMs are used more often to downscale transient rather than equilibrium GCM climate change scenarios to provide more useful information for assessing climate change impacts; (3) longer duration, higher spatial resolution (e.g., Christensen et al. 1998), and ensemble RCM simulations (e.g., Leung et al. 2004) are becoming more common to improve signal detection and realism of the control simulations and enable the study of extreme events; (4) both the strengths and weaknesses of dynamical downscaling are better understood through its applications to more diverse geographical regions and model intercomparison and diagnostic studies of current and future climate (e.g., Leung et al. 1999; Takle et al. 1999; Christensen et al. 2001; Pan et al. 2001; Chen et al. 2003); and (5) downscaled climate change scenarios have been used more often in impact assessment research (e.g., Thomson et al. 2002; Bergstrom et al. 2001; Wood et al. 2004), which has motivated more diagnosis and evaluation of regional climate simulations, and provided an important framework for assessing the value of the downscaled climate information.

In the context of climate change, regional forcings may interact with changes induced by greenhouse warming, such as changes in large-scale circulation or direct radiative effects, to generate more discernible regional climate change signals or substantially alter the climate change signals generated by the GCMs. This suggests that dynamical downscaling may provide additional climate information, or "added value" for the study of climate change and its potential impacts. For example, several RCM studies (e.g., Giorgi et al. 1994; Jones et al. 1997; Leung and Ghan 1999; Whetton et al. 2001; Kim et al. 2002; Synder et al. 2002; Leung et al. 2004) have illustrated how regional climate change signals can be significantly different from that projected by GCMs because of orographic forcing and rainshadowing effect. The redistribution of precipitation and hence soil moisture by the complex terrain, and how this redistribution affects climate change signals, has important implications for climate change detection (Giorgi et al. 1997), and assessing climate change impacts in mountains worldwide.

As an example, Fig. 1 shows the ensemble mean snowpack change in 2050 simulated by an RCM driven by the NCAR/DOE Parallel Climate Model (PCM, Leung et al. 2004). The PCM was initialized in 1995, using assimilated ocean conditions and fixed greenhouse gases and aerosols concentrations of 1995. The model was integrated forward with fixed greenhouse gases and aerosols concentrations for the control simulation. In the three ensemble PCM simulations of the future climate, greenhouse

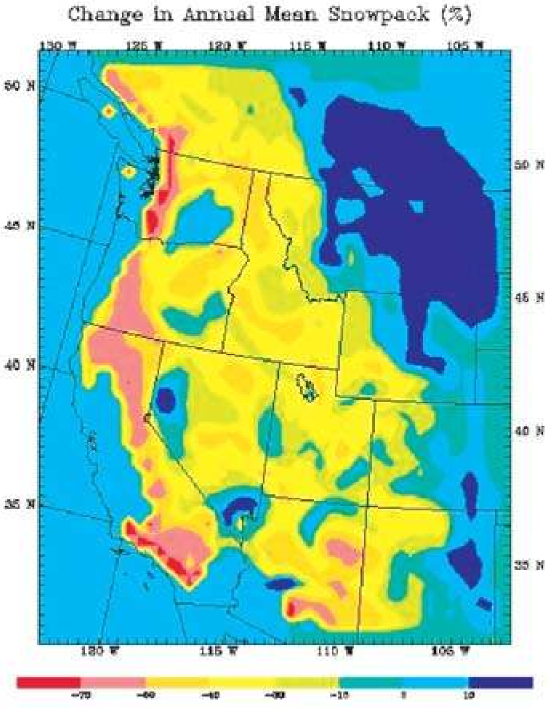

Fig. 1. Percentage change in mean annual snowpack in the western U.S. based on an ensemble of regional climate simulations for the present and future climate (2040–2060) as projected by a global climate model following a business as usual scenario. (Adopted from Leung et al. 2004).

gases and aerosols concentrations follow the business as usual scenario (Dai et al. 2004). The RCM was driven by the PCM control simulation of 1995–2015, and each of the three ensemble PCM future simulations of 2040–2060. The model was applied using a nested configuration with the larger domain covering the continental U.S. and the surrounding oceans at 120 km resolution, and the nested domain covering the western U.S. at 40 km resolution. Large changes in snowpack are found along the coastal mountain ranges.

Figure 2 shows the temperature change simulated by the RCM and PCM. Because the global model does not resolve the coastal mountain ranges at the T42 resolution, larger warming is found over the Rocky Mountains, where snowpack is reduced in the future climate. In the RCM simulations, larger warming is located along the coastal range where snowpack reduction is the highest. These results suggest that snow-albedo feedback effects are important, and they can cause an additional warming of near 1°C. In this example, topography is the main regional forcing that drives a discernible climate change signal. Because of differences in the temperature signals, assessment of hydrologic impacts based on PCM and RCM results can lead to different conclusions. Indeed, Wood et al. (2003) examined this issue with a hydrologic model applied to the Columbia River basin in northwestern U.S. and Canada. They showed that water resources (e.g., runoff and snowpack) display much higher sensitivity to greenhouse warming when RCM rather than PCM simulations were used as inputs. Bias correction and statistical downscaling were applied to both the RCM and PCM outputs before they were used to drive the hydrologic model, which was applied at 1/8 degree (∼10 km) resolution. Interestingly, even after these procedures were applied to both the RCM and PCM outputs, rendering their control simulations almost identical to the observed cli-

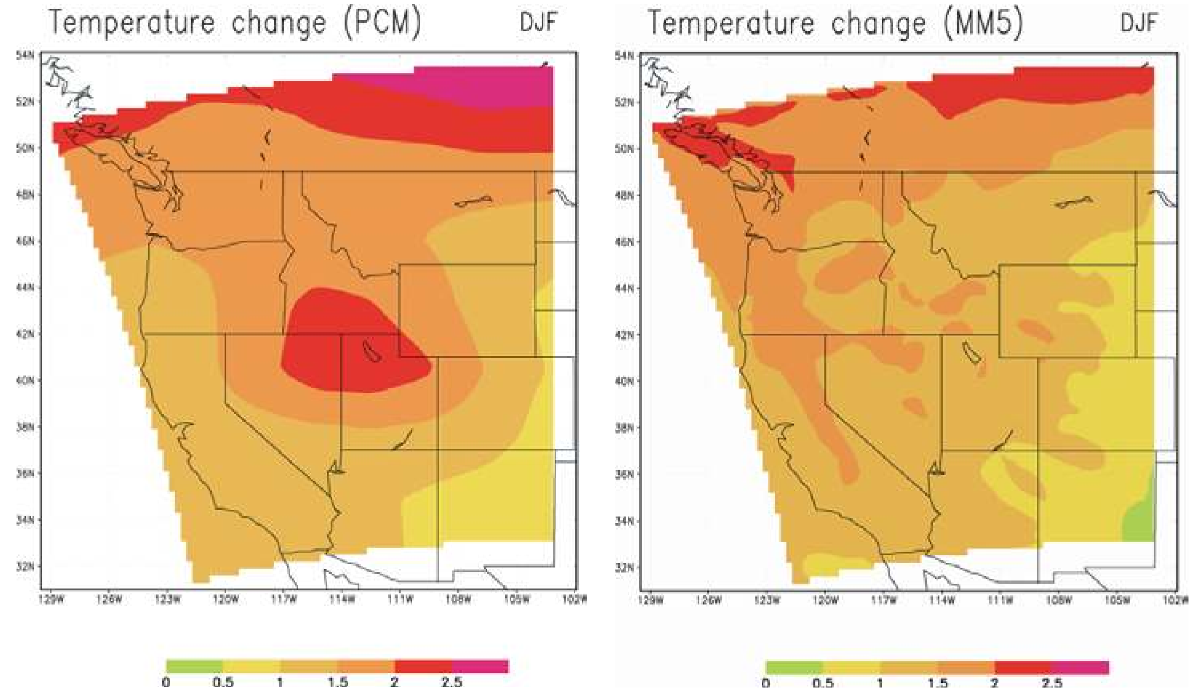

Fig. 2. Mean winter (December–January–February, DJF) surface temperature change in the western U.S. simulated by a global climate model (the NCAR/DOE Parallel Climate Model, PCM, left panel), and a regional climate model based on the Penn State/NCAR MM5 (right panel), driven by the PCM. Temperature changes were calculated as the difference between the ensemble simulation of the future climate (2040–2060) following a business as usual emission scenario and the control climate. (Adopted from Leung et al. 2004).

matology at 1/8 degree resolution, significant differences remain in the hydrologic impacts when the RCM and PCM simulations were used. In this case, the differences probably have a positive impact because the topographic representation, therefore the spatial distribution of warming signal, is clearly more realistic in the RCM than in the PCM.

Besides adding value in climate change assessment in regions with strong regional scale forcing such as topography, dynamical downscaling can also provide improved simulation of higher moment climate statistics (e.g., extreme climate such as intense precipitation, extreme high/low temperatures and frost conditions, and diurnal, seasonal, and interannual variability) for the control climate, and hence more plausible climate change scenarios for extreme events and climate variability at the regional scale. A number of recent regional modeling studies (e.g., Gao et al. 2002; Christensen and Christensen 2003; Leung et al. 2004) show that both the extreme summer and winter precipitation generally increases in a warmer future climate regardless of whether the seasonal/annual mean precipitation is enhanced or reduced depending on changes in atmospheric moisture, temperature, and large-scale circulation under greenhouse warming. Bell et al. (2004) examined a variety of indices to investigate the changes in frequency and intensity of extreme heat waves and cold spells.

Recently, a large, coordinated effort has been initiated by the Prediction of Regional scenarios and Uncertainties for Defining EuropeaN Climate change risks and Effects (PRUDENCE) Project (http://prudence.dmi.dk/), with participation from over 20 research organizations in Europe. The project aims to address and reduce deficiencies in projecting future climate change, quantify the uncertainties in predicting future climate and its impacts, and interpret the results for adapting and/or mitigating climate change effects. As part of this project, eight RCMs are being driven by boundary conditions from two GCMs to produce ensemble simulations of current and future climates for Europe. Through comparison of the RCM simulations driven by different boundary conditions, an assessment can be made regarding the uncertainty and confidence level of the downscaled climate change projections. When the RCM simulations are used to drive impact models, this type of effort is very useful in further clarifying the role of dynamical downscaling in climate change projections and impact assessment.

3.3 Seasonal prediction

During the last decade, significant progress in dynamical seasonal prediction with global AGCMs or coupled atmosphere-ocean GCMs (or AOGCMs) has been made by the meteorological services and scientific community around the world (Goddard et al. 2001). Numerous studies on seasonal predictability have shown that seasonal climate is potentially predictable if significant shifts, or anomalies in the probabilities of different weather regimes that occur over a season are produced when the boundary conditions that force the atmosphere (e.g., SST and land surface conditions such as soil moisture) are strongly perturbed (Palmer and Anderson 1994; Ji et al. 1998; Kusunoki et al. 2001; Palmer et al. 2002). With AGCMs or AOGCMs potentially making skillful seasonal prediction of the large-scale fields, some investigations have recently been undertaken to examine the use of RCMs nested within the AGCMs or AOGCMs to improve seasonal climate predictions at the regional scale. Leung et al. (2003c) recently suggested that seasonal climate forecasting may be a useful framework for testing the value of dynamical downscaling because unlike climate change projections, climate forecasts can be verified.

The following procedures are usually taken in preparing seasonal prediction with a nested RCM:

(1). Derivation of "correct" model climatology: In this step, the RCM is driven by observed boundary conditions, such as the ECMWF or NCEP/NCAR reanalyses. Multi-year to multidecadal simulations must be carried out to provide meaningful climate statistics and variability, and to identify and possibly reduce significant systematic errors through sensitivity experiments.

(2). Hindcasts for a multi-year period: Utilizing the optimal experimental design suggested from step (1), regional climate simulations must be performed with boundary conditions provided by the host AGCM or AOGCM hindcast simulations for at least 10 years. Because errors introduced by the AGCM or AOGCM are transmittable to the RCM (Noguer et al. 1998), biases of the RCM hindcast simulation are generally larger than those driven by observed boundary conditions. To identify regional biases, various indices for evaluating predictive skill may be used, such as the anomaly correlation coefficient (ACC), and the root mean square skill score (RMSSS). One should further compare the systematic errors in the regional simulation and the driving AGCM or AOGCM simulation to examine where errors are reduced due to the use of the RCM.

(3). Develop methods to correct model biases: A system to reduce model systematic errors by statistical methods may be developed and applied to the seasonal prediction produced by the nested RCM based on analysis of error in the hindcasts. A number of statistical correction methods, such as singular value decomposition analysis (SVDA) and canonical correlation analysis (CCA), (Feddersen et al. 1999; Sperber et al. 2001) can be used to correct biases in the RCM hindcasts. This type of correction system can often improve prediction in some specific regions.

(4). Produce ensemble seasonal forecasts with the RCMs: Based on the ensemble seasonal predictions developed using the AGCM or AOGCM to provide initial and boundary conditions for the RCMs (Sivillo et al. 1997; Déqué 1997), dynamical seasonal predictions may be made with the nested RCM and the correction system.

To date, very limited works on the use of RCMs in seasonal prediction have been reported. Cocke and LaRow (2000) used a regional spectral model (FSU-RSM) embedded within an AOGCM to make seasonal predictions with the purpose of studying ENSO impacts on the Southeast United States and western North America. For the boreal winter of 1987 and 1988, when a significant El Nino event occurred, both the global and regional models captured the precipitation difference between the two years, with the regional model showing more realistic spatial details. Fennessy and Shukla (2000) and Mitchell et al. (2001) also reported some successes of using the NCEP ETA model nested within the COLA AGCM to produce hindcast simulations with realistic regional scale features of climate anomalies that are comparable to observations. Nobre et al. (2001) performed a seasonal climate forecast over Nordeste Brazil using predicted SST over the tropical oceans, with the NCEP RSM nested in the ECHAM3 AGCM. They found that regional models could predict the statistics of the weather phenomena during the rainy season of Nordeste, including the probability distribution of area-averaged daily rainfall and the spatial patterns of the frequency and duration of dry spells or heavy precipitation periods. Recently Roads et al. (2003a) nested the NCEP RSM in the global spectral model to perform seasonal forecasts for the continental U.S. and found that the regional model forecasts better depict the precipitation intensity. These results have demonstrated that skillful seasonal predictions are possible using the nested RCMs for some individual seasons and years. However, no results of multi-year or interdecadal hindcasts or real-time seasonal predictions have been reported so far.

Recently, Ding et al. (2003) presented some initial results of the experimental use of the nested RCM developed at the China National Climate Center (NCC) for seasonal prediction since 2001. In their experiments, the NCC_AOGCM provides the boundary and initial conditions for the RegCM_NCC developed based on the NCAR RegCM2, with horizontal resolution of 60 km. To verify the performance of the nested RCM, two 10-year (1991–2001) integrations for the summer (June–August) driven by observed and AOGCM simulated large-scale conditions, respectively, were performed to produce model climatology and hindcasts. Preliminary results have shown that RegCM_NCC has some skill in simulating and predicting the seasonal rain belts, showing more areas with positive ACC than the AOGCM simulations. The best predicted regions with high ACC are located in West China, Northeast China, and North China where the AOGCM also has maximum prediction skill (Fig. 3). One significant improvement derived from RegCM_NCC is the increase of ACC in the Yangtze River valley where the AOGCM shows a very low, or even negative ACC. This improvement is likely related to the more realistic representations of the large-scale terrains in the regional model. Real-time experimental predictions for the summers of 2001–2003 using this nested RegCM_NCC were made on April 1 of each year. As an example, Figure 4 shows the predicted and observed precipitation anomaly patterns for the 2002 summer (June–August), which is characterized by severe droughts in North China, and the wet condition in South China, typical of the mean anomalous precipitation pattern during the last decade. The predicted precipitation pattern captured these major features reasonably well.

The above example indicates the potential applications of nested RCMs to operational dynamical seasonal prediction. More work should be done in the future to improve the representation of physical parameterizations in RCMs, develop longer-range hindcasts, improve the initialization of soil temperature and moisture, and develop new methods to correct model bias. In addition, seasonal prediction of tropical cyclones in different ocean basins, including the frequency and total number of landfalling tropical cyclones and preferred paths, is also desirable (Ahn and Lee 2002). A regional ocean model and oceanic data initialization should be developed and coupled with the nested RCM to improve SST forecast under highly perturbed weather conditions, when air-sea interaction becomes important.

4. Application to climate process studies

RCMs have been widely used in climate process studies in the past decade. Indeed, the use of high spatial resolution to resolve the complex lower boundary conditions and mesoscale weather systems with the improved representation of model physics makes RCMs ideal for improving our understanding of climate processes. Although this area has been quite active in climate research, it has not been emphasized in any previous reviews. Here we provide some examples to highlight the usefulness of RCMs in climate process studies.

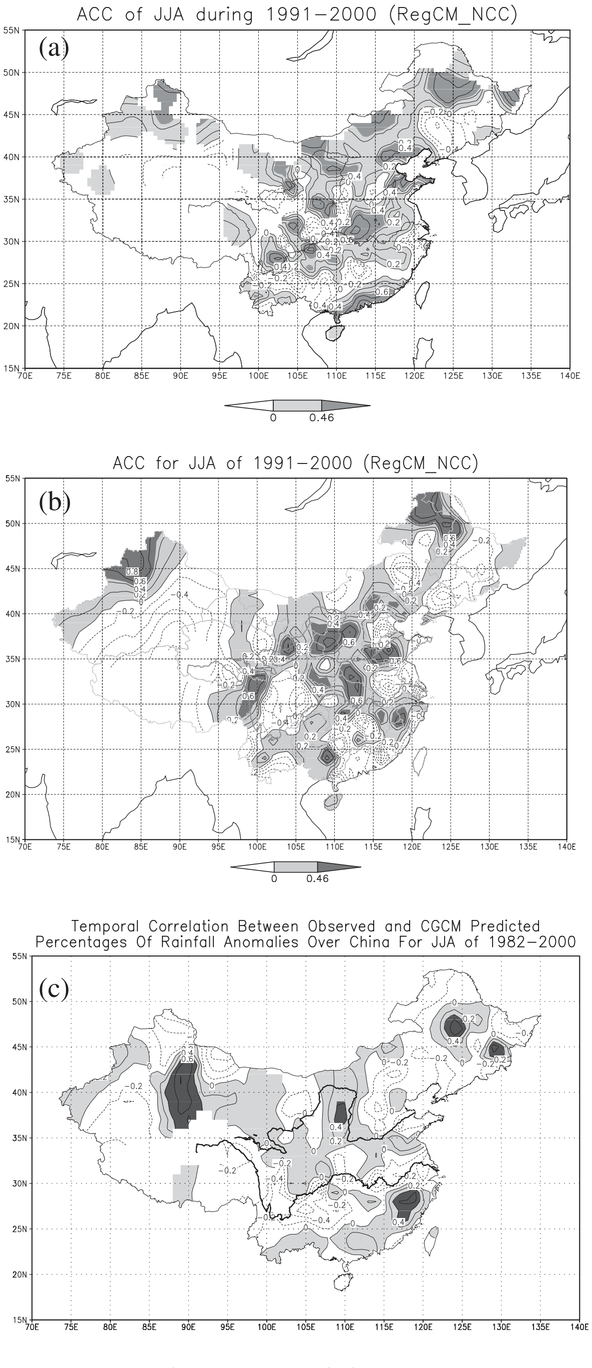

Fig. 3. The patterns of the 10-yr (1991–2000) mean temporal ACC (anomaly correlation coefficient) for the simulated precipitations in China with NCEP data as the boundary (a), the predicted precipitation field in China by RegCM_NCC driven by the coupled GCM (T63L16/T63L30) (b), and the pattern of the 19-yr (1982–2000) mean temporal ACC for the predicted precipitation field in China by the coupled GCM (T63L16/T63L30) (c). The positive correlation is represented by shaded areas. Dark shaded areas denote those regions exceeding 90% significant level. (Adopted from Ding et al. 2003).

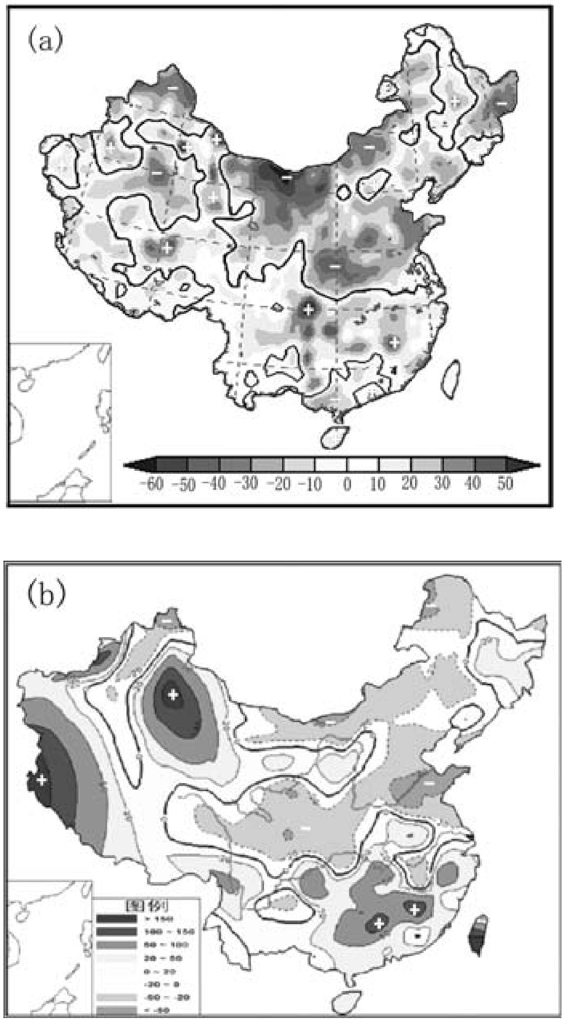

Fig. 4. Precipitation anomaly field for the 2002 summer (June–August) in China (a) predicted by RegCM_NCC and (b) observed from 160 stations in China. Unit: mm day^{-1}. (Provided by Y. Ding 2003).

4.1 Land-atmosphere interaction

The land surface can exert a strong forcing on climate at the global and regional scales through the exchange of heat, moisture, and momentum (e.g., Pielke and Avissar 1990). In turn, it is affected by the feedback from the overlying atmospheric conditions. This land-atmosphere interaction is very complex, and its accurate representation in a climate model is critical to realistic simulation of the global and regional energy and water cycles. Because of their high spatial resolution, RCMs can better resolve land surface heterogeneity and thus better represent feedback processes in the land-atmosphere system, although most RCMs adopt land surface models that were originally developed for AGCMs (e.g., Paegle et al. 1996; Giorgi et al. 1996; Bosilovich and Sun 1999; Schär et al. 1999; Barros and Hwu 2002; Pal and Eltahir 2001, 2002, 2003).

One extensively investigated land-atmosphere feedback process is the positive feedback between soil moisture and precipitation anomalies. Schär et al. (1999) used an RCM to study soil moisture and precipitation feedback and found three key feedback processes. (1) Wet soils with small Bowen ratios can lead to the buildup of a relatively shallow boundary layer, capping the surface heat and moisture fluxes in a comparatively small volume of air, and building up high low-level moist entropy to provide a source of convective instability. (2) The lowering of the level of free convection with wet soil facilitates the release of convective instability. (3) Wet soil decrease thermal emission, increase cloud backscatter, and increase water vapor greenhouse effect to reduce the net shortwave absorption at the surface, further increasing the moist entropy flux into the boundary layer. These three processes act to increase the potential for convective activity and thus precipitation. Using the RSM, Hong and Pan (2000) found that soil moisture modulates the partitioning of surface sensible and latent heat fluxes. This partitioning and the downward mixing of high moist static energy with dry air effectively affect the development of boundary layer and the convective available potential energy (CAPE). In dry (moist) soil conditions, the CAPE is smaller (larger) because of strong (weak) turbulent mixing. As a result, moist soil conditions favor convective activity and precipitation in their simulation, which in turn increases the local soil moisture, thus a positive feedback between soil moisture and precipitation.

However, in some other studies, the feedback between soil moisture and precipitation becomes negative or quite weak (Paegle et al. 1996; Giorgi et al. 1996; Bosilovich and Sun 1999; Kanamitsu and Mo 2003). Pan et al. (1995) demonstrated that the sensitivity of precipitation to initial soil moisture depends on the model convective parameterization. Seth and Giorgi (1998) reported the effects of domain choice on their 1993 summer precipitation simulation, and found that the smaller domain captured observed precipitation better, but the sensitivity to initial soil moisture appeared to be more realistic in the larger domain. Hong and Pan (2000) found, however, weak dependency of the response of precipitation to initial soil moisture on the domain size in the RSM. They suggested that the dependency in Seth and Giorgi (1998) could be related to the dependency of the model simulated low-level jet on model domain size due to model systematic errors. The land-atmosphere interaction is not a local phenomenon; it may be affected significantly by the prevailing large-scale circulation to induce remote effects (Pal and Eltihir 2002). The use of a relatively large model domain, with good model physics parameterizations, should be encouraged in future assessment to thoroughly understand the complex land-atmosphere interactions.

4.2 Topographic effects on regional climate

An original application of RCMs is to improve climate simulation in regions where forcing due to orography regulates the regional climate (Dickinson 1989; Giorgi and Bates 1989; Semazzi and Sun 1997; Indeje et al. 2001). Many previous studies have focused on the important effect of orography on the formation and maintenance of the low-level jets such as that over the U.S. Southern Great Plains that affect moisture transports and regional precipitation. To improve the simulation of orographic precipitation that controls the hydrological cycle in regions with complex terrain, Leung and Ghan (1995, 1998) developed a subgrid orographic precipitation parameterization, and tested it in an RCM for regions with strong subgrid variations in surface elevation and land cover. Their studies show significant impacts of subgrid scale orography on precipitation, snowpack, and streamflow in mountainous regions.

In a recent study, Xu et al. (2004) investigated the effect of the Andes on the eastern Pacific climate using the RCM (IPRC-RegCM) developed at the International Pacific Research Center (Wang et al. 2003). In the Southern Hemisphere cold season, the model reproduces key climatic features including the intertropical convergence zone (ITCZ) north of the equator and an extensive low-level cloud deck capped by a strong temperature inversion to the south (Wang et al. 2004b). In a sensitivity experiment with the Andes artificially removed, the warm advection from the South American continent lowers the inversion height, and reduces the low-level divergence off shore, leading to a significant reduction in clouds and an increase in solar radiation at the sea surface (Fig. 5). In

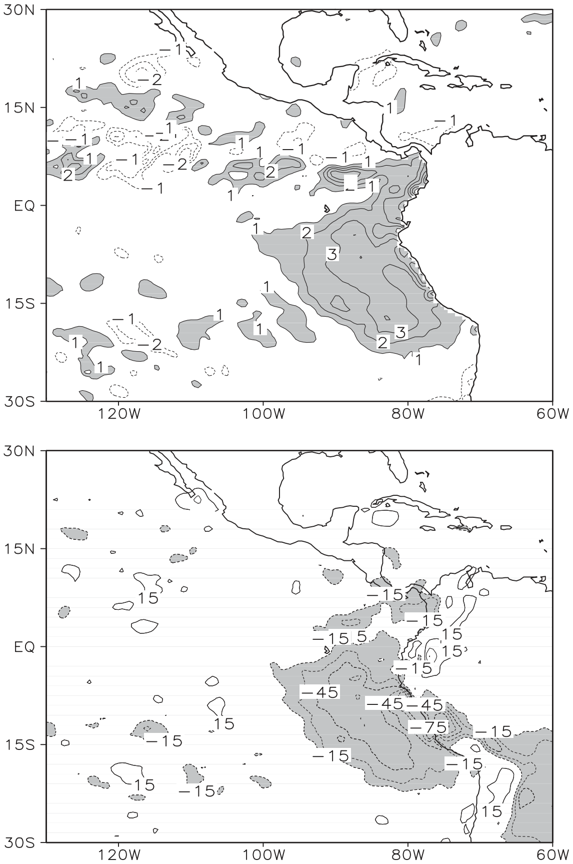

Fig. 5. Differences of vertically integrated liquid water content (10^{-2} mm, upper panel) and downward shortwave radiation flux at the sea surface (W m^{-2}, lower panel) between the control and No-Andes runs, averaged for August–October 1999. Contour interval is 10^{-2} mm and values greater than 10^{-2} mm are shaded in the upper panel. Contour interval is 15 W m^{-2} and values less than -15 W m^{-2} are shaded in the lower panel. (Adopted from Xu et al. 2004).

the warm season, the model simulates a double ITCZ in response to the seasonal warming on and south of the equator, in agreement with observations. Under the same SST forcing, the removal of the Andes prolongs the existence of the southern ITCZ for three weeks, because the intrusion of the easterlies from South America enhances the convergence in the lower troposphere over the local warm SST, and the transient disturbances travel freely westward from the continent, both favoring deep convection south of the equator (not shown). The same sensitivity experiments were repeated with orography used in the T42 AGCMs; the results confirm that an under-representation of the Andes reduces the stratus clouds in the cold season and prolongs the southern ITCZ in the warm season, both acting to weaken the latitudinal asymmetry of the eastern Pacific climate.

Yoshikane et al. (2001) investigated the orographic effects of the Tibetan Plateau and land/ocean heat contrast on the Baiu/Meiyu front using RAMS. Zonally uniform and temporally constant atmospheric fields from the ECMWF analysis were used as initial and lateral boundary conditions. Their results showed that the Baiu/Meiyu front was simulated even when the initial and boundary conditions did not include any signal of regional scale disturbances. A low-level jet is formed along the eastern coast of the Asian continent due to the orographic effects of the Tibetan Plateau and land/ocean heat contrast. The low-level jet transports a great amount of moisture and forms a precipitation zone by the interaction with the upper-level jet streak in the middle latitude. Sensitivity experiments show that the Baiu/Meiyu front forms mainly due to the zonal mean flow and the land/ocean heat contrast, while the orographic effect intensifies the low-level jet and precipitation over the Baiu/Meiyu front. The mechanisms have some similarity to those responsible for the formation of the South Pacific convergence zone (SPCZ), although the heat contrast is much more important for the Baiu/Meiyu front (Yoshikane and Kimura 2003).

4.3 Effect of land use change on regional climate

Land use changes modify the exchange of energy, momentum, moisture, and trace gases, affecting the earth's climate (Charney et al. 1977). Desertification and deforestation are two types of land cover change, which have expanded rapidly during the last century, and have been a major research focus over the last two decades (Nobre et al. 1991; Henderson-Sellers et al. 1993; Polcher and Laval 1994; Xue 1996, among others). Deforestation substantially increases surface albedo and decrease surface roughness. Increased albedo reduces surface net radiation, which then leads to a reduction in evapotranspiration and precipitation. Reduced surface roughness has a similar effect, but through reducing the surface exchange and drag coefficients. Desertification mainly increases surface albedo similar to deforestation and reduces the net radiation at the surface, and cools the surface. This surface cooling usually results in sinking motion and decreases precipitation (Wang and Jenkins 2002).

Land use changes are highly inhomogeneous spatially (Pielke 2001). The high-resolution of RCMs is ideal for assessing the effects of land use changes at different scales on regional climate (Copeland et al. 1996; Pan et al. 1999; Fu 2003; Wang et al. 2003; Sen et al. 2004a,b). Using RAMS, Copeland et al. (1996) assessed the impact of a natural versus current vegetation distribution on the weather and climate of July 1989, and found coherent regions of substantial changes of both positive and negative signs in many surface parameters, such as surface air temperature, humidity, winds, and precipitation throughout the U.S. as a result of land use change. They concluded that current land use in the U.S. has caused summertime surface conditions to be warmer and wetter than what the natural landscape would indicate. Using the NCAR RegCM2, Pan et al. (1999) carried out a similar assessment for three summer months during normal, drought, and flood years and found that the response of precipitation and surface temperature to land use change has strong interannual variations.

Kanae et al. (2001) found a long-term decreasing trend in the 40 years precipitation observed in Thailand, and speculated that the change might be a response of the regional climate to the deforestation in the Indochina peninsula. However, the trend is apparent only in the monthly mean precipitation during Sep-

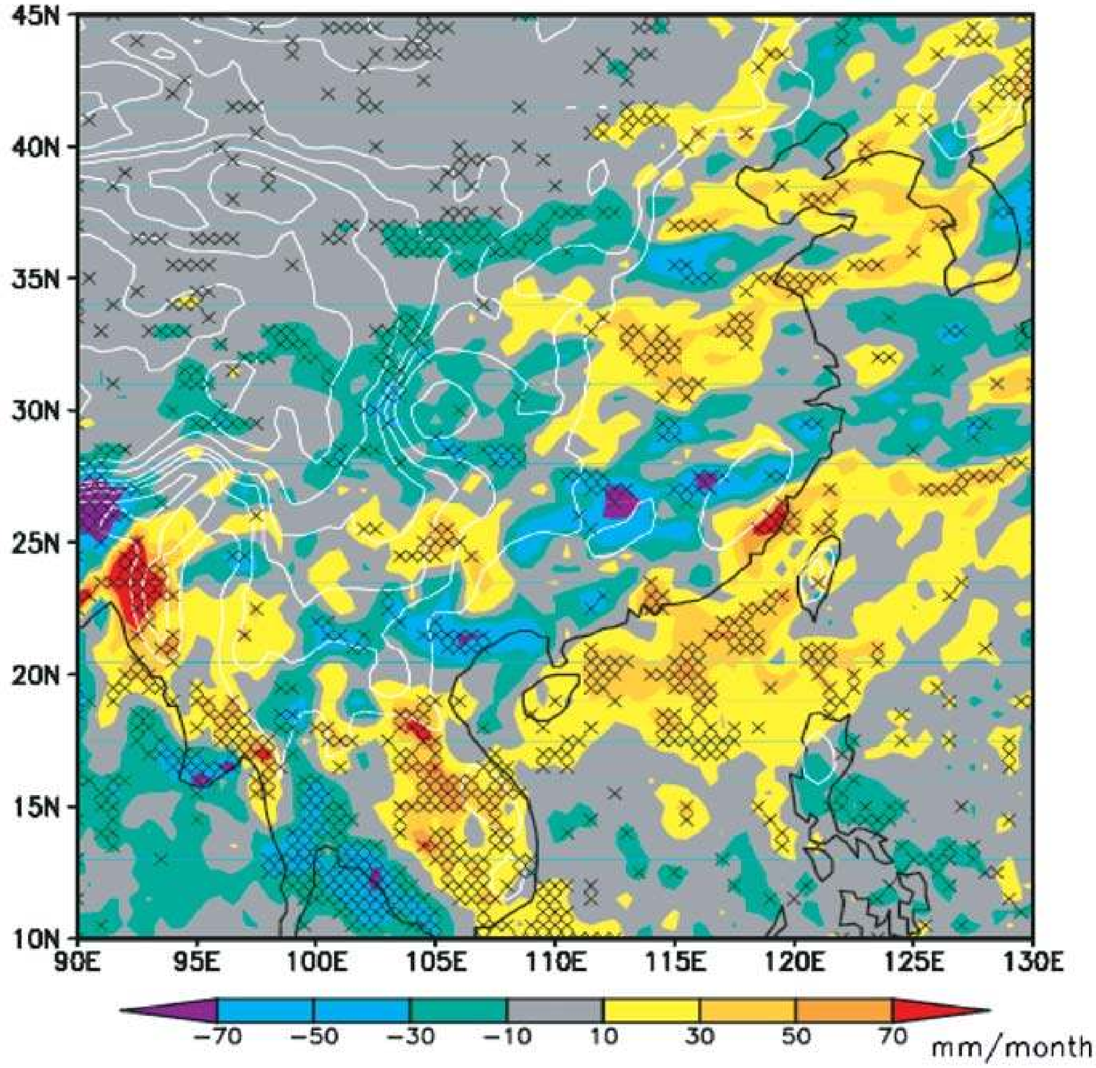

Fig. 6. Spatial distribution of the absolute rainfall change (mm/month; shaded) in June, July, and August 1998 between ensembles with current and reforested vegetation cover in the Indochina peninsula (94°–109°E, 9°–19°N). The hatching is for statistically significant areas at 90% confidence level. The contours show the orography at the 500, 1000, 1500, 2000, 3000, 4000, and 5000 m heights. (Adopted from Sen et al. 2004a).

tember. In order to estimate the effect of the deforestation, they carried out some sensitivity experiments using RAMS. Results showed that, consistent with observations, the effect of deforestation is significant only in September, when the synoptic wind is mild.

In a recent study, Sen et al. (2004a) studied both the local and remote effects of the Indochina deforestation on the East-Asian summer monsoon in the flood year 1998 using the IPRC-RegCM. Since the deforested Indochina peninsula is subject to strong monsoonal flow during summer months, in addition to the local effect, there is a strong remote effect on downstream monsoon rainfall over East-Asia (Fig. 6). In another study, Sen et al. (2004b) investigated the local and regional effects of vegetation restoration in northern China (90°–110°E, 36°–42°N) using the same RCM, and evaluated whether the changes in rainfall induced by landscape change are large enough to support a restored vegetation cover.

Different from other works mentioned above, the studies of Sen et al. (2004a,b) took advantage of ensemble simulations to remove the chaotic noise in the simulations, and performed a significance check for the corresponding response to the land use change. However, similar to other studies, the sensitivity experiments suffer from small sample sizes of several months long in the 1998 flooding year. Therefore, extension to larger samples will be important for assessing the impact of land cover changes on regional climate in future studies.

4.4 Cloud-aerosol-climate interaction

To study climate and climate change, the presence of natural and anthropogenic aerosols in the atmosphere needs to be considered, particularly over regions where aerosol loadings are substantial, or regions that are located downwind (Husar et al. 1997). Aerosols affect climate directly through scattering and absorption of the solar radiation and, to a less extent, trapping the thermal radiation, thus inducing a strong diurnal variation of the radiative forcing on the surface (Russell et al. 1999). In addition to the direct effect, aerosols affect climate indirectly through changing cloud droplet number concentration (CDNC) and cloud liquid water path, lifetime and geographical extent. Although the direct effect is relatively known, the indirect effect of cloud-aerosol-climate interaction is much less well understood, which is an area in climate modeling that requires further improvement (IPCC 2001).

Figure 7 illustrates the processes and variables of the cloud-aerosol-climate connection. Climate models need to include the factors that control the cloud condensation nuclei (CCN) which depends on the size distribution of water-soluble species (sulfates, organics, sea salt and nitrates), and the degree of solubility and the mixing ratio of individual species within a given size fraction. Although considerable progress has been made in recent years to include in GCM parameterizations for aerosol-cloud droplet interaction and explicit microphysics for cloud water/ice content, inadequate understanding of the processes, in particular those affecting the CDNC, contributes significantly to uncertainties in estimating aerosol effects on climate (IPCC 2001). The individual components in Fig. 7 are currently being developed, such as the chemical transport model (CTM), to simulate the aerosol mass and size distribution, and the warm and cold cloud models, to simulate the cloud droplet and ice nuclei concentrations (see NACIP 2002). However, a lack of computational efficiency and accurate parameterizations results in various inconsistent and disjoint parameterizations currently used in GCMs.

Efforts to include the interactive coupling of the climate and aerosols were made by Qian and Giorgi (1999), Qian et al. (2003), and Giorgi et al. (2002, 2003) using the NCAR RegCM2 and a simple radiatively active sulfate aerosol model for climate simulations over East Asia. Both direct and indirect aerosol effects are represented and evaluated. It is found that the aerosol distribution and cycling processes show substantial spatial and temporal variability, and that both direct and indirect aerosol forcings have regional effects on surface climate, with the indirect effect dominating in inhibiting precipitation. Because of the use of a one-moment parameterization for cloud microphysics, which predicts mixing ratios of water vapor, cloud liquid and ice waters, rainwater, snow and graupel, and number concentration of cloud ice (e.g., Reisner et al. 1998), the size distribution of the CCN is not explicitly simulated; consequently its effect on the cloud radiative forcing is heavily parameterized, based on an empirical relationship between CDNC and the mass concentration of the sulfate aerosol. In addition, although cloud water/ice content is predicted from cloud microphysical scheme in most RCMs, cloud cover is generally diagnosed. Consequently, the diagnosed cloud cover might not be realized in the radiation calculation. Therefore, a consistent cloud-aerosol-climate interactive scheme is required to simulate the cloud cover, and cloud liquid/ice water path and number concentration that are the primary parameters for cloud radiative forcing calculations.

5. Regional climate predictability

5.1 Uncertainties in driving fields

The climatology of an RCM is determined by a dynamical equilibrium between the large-scale forcing provided through the lateral boundary conditions and regional characteristics produced by internal physics and dynam-

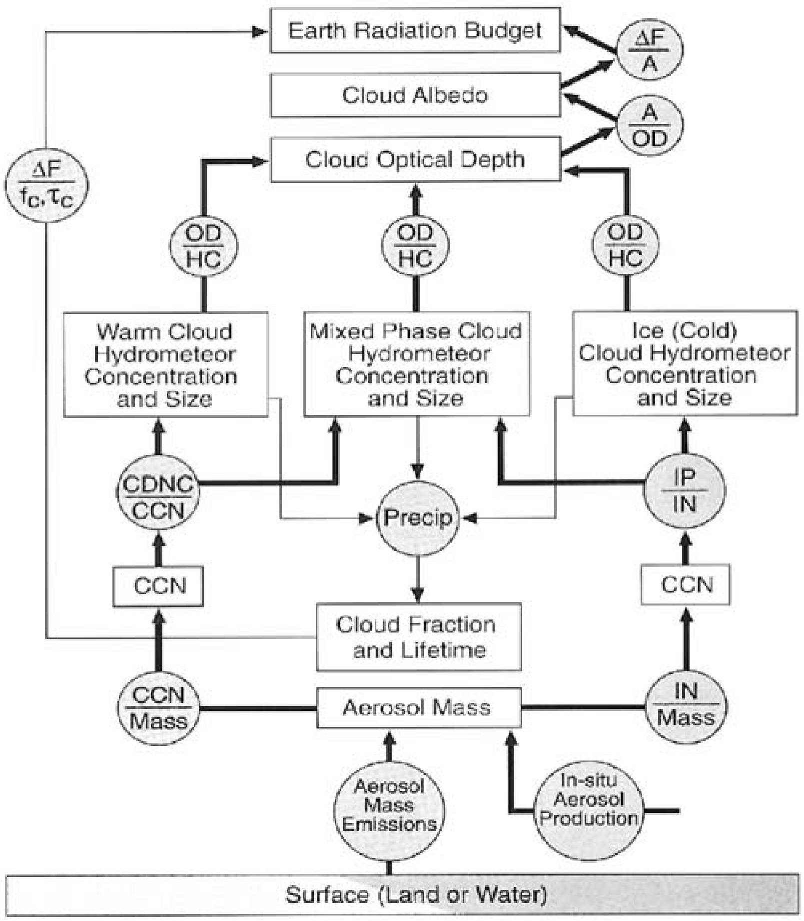

Fig. 7. Flow chart showing the processes linking aerosol emissions/production, cloud condensation nuclei (CCN), cloud droplet number concentration (CDNC), ice nuclei (IN), ice particles (IP), optical depth (OD), hydrometeor (HC), albedo (A), cloud fraction (f_c), cloud optical depth (τ_c) and radiative forcing (ΔF). (Adopted from IPCC 2001, Fig. 5.5).

ics of the regional model (Giorgi and Mearns 1999). As already discussed in section 3.1, biases of a nested RCM may be partly attributed to the inaccuracy of the large-scale driving fields. Therefore, the skill of an RCM in dynamical downscaling applications is highly dependent upon the skill of the driving GCM.

In general, the results of an RCM are better when it is forced by the reanalysis data than embedded in a GCM (e.g., Mo et al. 2000; Rojas and Seth 2003). However, substantial differences exist among several reanalysis datasets, in particular, in the lower-atmospheric circulation and water vapor flux. For example, diagnosis of the mean behavior of the Asian summer monsoon, and its interannual and intraseasonal variabilities, shows significant differences between the ECMWF and NCEP/NCAR reanalysis data in several aspects (Annamalai et al. 1999). Therefore, it is a necessary step to evaluate the skill of an RCM using realistic large-scale boundary conditions before it is nested into a GCM.

Although current generation GCMs have shown improved skills in simulating the present-day climate compared with previous generations (IPCC 2001), the performance of GCMs in reproducing the observed monthly, seasonal, and interannual variabilities varies from region to region, and across models. A number of RCM experiments clearly show that spatial patterns produced by RCMs are in better agreement with observations than the driving fields because of the better representation of orographic forcing and land surface conditions; however, the biases of an RCM are not necessarily smaller than that of the driving GCM (Laprise et al. 2000; Achberger et al. 2003). In this regard, it is still a priority for the climate modeling community to reduce model bias through improving physics representations in both GCMs and RCMs.

5.2 Uncertainties in the nested RCM

Given perfect driving fields, uncertainties in the nested RCM still exist and may result from unphysical treatment of lateral boundary conditions, inconsistency in dynamics and physics between the regional model and the large-scale model that provides the driving fields, unrealistic representation of physical parameterizations, and internal flow-dependent instabilities of the chaotic climate system at the regional scales.

To increase the consistency between the large-scale driving fields and the RCM solutions, and ensure a smooth transition from the driving fields at the lateral boundary to the regional model interior, most RCMs have employed the relaxation method in a buffer zone next to the lateral boundaries (see section 2.2). Marbaix et al. (2003) provide practical guidelines for choosing relaxation coefficients through sensitivity experiments. Orographic blending in the buffer zone, proposed by Jones et al. (1995) and Hong and Juang (1998), is useful and effective in reducing systematic biases of the regional model influenced by dynamical uncertainty when steep orography appears in the buffer zone. The big-brother experiment (BBE) is a methodology for testing the downscaling abilities of nested RCMs and can be used to identify impacts and/or sensitivity of various parameters, such as domain size and location, resolution jump, and update frequency for minimizing most of the model errors related to the one nesting approach (Denis et al. 2001).

RCMs are increasingly using higher resolutions (e.g., Christensen et al. 1998; Leung et al. 2003a,b). Generally, RCMs produce, to a certain degree, better results with increased spatial resolution (e.g., Mo et al. 2000), especially for extreme events (e.g., Christenson et al. 1998; Christensen and Christenson 2003; Wang et al. 2003; Zhang et al. 2003). On the other hand, model resolution can modulate the effects of both forcings and physical parameterizations (Laprise et al. 1998; Kato et al. 1999). The increase of resolution does not necessarily lead to the improved model performance. With increasing grid resolution, RCMs become sensitive to internal/external forcings represented by model physical parameterizations (Nobre et al. 2001). Therefore, careful selections or improvements of physical parameterizations, such as convective parameterization, are necessary for meaningful simulations at very high resolutions to reduce the uncertainties due to the scale dependency of physical parameterizations (Molinari and Dudek 1992). However, this is a challenging task since the performance of different parameterization schemes usually shows regional and seasonal dependencies, and sensitivity to a combination of other physical parameterizations in the model (e.g., Giorgi and Shields 1999; Gochis et al. 2002).

5.3 Regional model predictability

Significant progress has been made in the development and improvement of the regional climate modeling technique, including not only a number of newly developed RCMs but also coupling with various components of the climate system such as ocean, hydrology and chemistry/aerosols. These achievements have considerably increased RCM predictability and credibility. Driven by reanalysis large-scale fields, present RCMs at about 50 km horizontal resolution have temperature biases generally within 2°C, and precipitation biases within about 50% of observation, respectively (IPCC 2001, p. 601). The predictability of RCMs is limited mainly by uncertainties in driving fields and those in the nested regional model parameterizations and chaotic nature of the climate system.

Since RCMs share many features of limited area models (LAMs) used in weather prediction mode, predictability of LAMs is related to that of RCMs to a certain degree, although there are fundamental differences. One of the important topics concerning predictability of LAMs is whether the regional models generate meaningful small-scale features that are absent in the initial and lateral boundary conditions (Laprise 2000; De Elía et al. 2002). With a so-called perfect-model approach similar to the BBE, De Elía et al. (2002) found that LAMs could recreate the right amplitude of small-scale variability that might be absent in driving fields, but is incapable of reproducing it with precision required by a root-mean-square measure of error, implying that RCMs can add values to climate statistics rather than to daily weather events (Denis et al. 2001). Vidale et al. (2003) studied the predictability and uncertainty in an RCM using multiyear ensemble simulations over Europe to assess the ability of the RCM in representing the natural interannual variability on monthly and seasonal time scales. They showed that the RCM has skill in reproducing interannual variability in precipitation and surface temperature, while the predictability varies strongly between seasons and regions. In general, the predictability is weakest during summer and over continental regions due to the weak large-scale forcing in the summer season, and discrepancies in the land surface model.

Another related topic is the study of internal variability of an RCM, which is related to nonlinearity of the model physics and dynamics. Giorgi and Bi (2000) investigated the internal variability of an RCM using a random perturbation that was applied to the initial and lateral boundary conditions. They found that the response was not sensitive to the origin, location, and magnitude of the perturbation, but mostly tied to synoptic conditions, seasons and regions. Christensen et al. (2001) performed multiyear RCM simulations, in which one year of lateral boundary condition was used as the driving forcing, while the soil moisture was allowed to retain its memory of initial conditions. They found that in spite of the same large-scale forcing, the climatologies showed substantial differences among the simulations, due to the model internal variability in response to land-atmosphere interactions even after several years of simulation. This long-lasing effect of soil moisture might have two consequences: on one hand, the long memory of initial condition might extend the predictability; on the other hand, uncertainty in the initial soil moisture might cause persistent errors, limiting the potential predictability.

The predictability of RCMs can be improved using ensemble methods with perturbed initial conditions, or model physics (Yang and Arritt 2002) or different models such as the super-ensemble approach proposed by Krishnamurti et al. (1999). Wandishin et al. (2001) showed that an ensemble with five members at 80 km horizontal resolution could significantly outperform a single higher-resolution 29-km simulation in precipitation forecasts. The super-ensemble technique can yield forecasts with considerable reduction in forecast error compared to the errors of the member models, or the simple ensemble mean (Krishnamurti et al. 1999). The super-ensemble technique has potential to be adopted to increase the RCM predictability and thus the credibility for RCMs to be used for climate change assessment.

Currently model-produced climate variability generally increases with increasing spatial resolution in both GCMs and RCMs. Regional climate predictability may increase up to a certain regional resolution, or at least similar to large-scale predictability (Leung et al. 2003c). It is generally believed that ever-increasing spatial resolution with current RCMs could not simply increase regional climate predictability, which may strongly depend on how accurate are the representation of clouds and precipitation processes in RCMs. Research aiming at not only understanding natural climate variability, but also reducing systematic errors in both GCMs and RCMs, will continuously increase regional climate predictability.

6. Challenges and prospects

6.1 Dynamical downscaling

When used as a downscaling tool, RCMs are usually driven by large-scale lateral and lower boundary conditions provided by GCMs with a one-way nesting approach. By this nesting approach, using similar physics representations in the RCM and GCM can reduce inconsistency between the large-scale conditions simulated by the two models, and minimize ambiguity in interpreting differences between the RCM and GCM simulations. This approach has been adopted in the development of some RCMs including the NCAR RegCM2, which uses physics parameterizations of the NCAR Community Climate Model, the NCEP RSM, which is a regional extension of the NCEP global spectral model.

However, because current physics parameterizations may not scale properly over a large range of spatial scales, one may argue that sharing the same physics parameterizations, particularly for clouds and convection, may not yield the best downscaling skill. Studies have shown that the large-scale circulation simulated by the RCM and GCM are generally in good agreement, whether or not the two models share identical physics parameterizations. This is particularly true when the RCM is applied to relatively small domains, where lateral boundary conditions exert major control over the large-scale features simulated by the RCM. However, differences between the RCM and GCM physics parameterizations, especially land surface models and cumulus convection schemes, can still complicate the interpretation of differences between the GCM simulated and downscaled climate variables such as surface temperature and precipitation, and the corresponding climate change signals. That is, one cannot easily distinguish whether the differences arise because of regional forcing or difference in physics representations. Arguably, even if the same physics representations are used in both models, it remains unclear whether differences between the GCM and RCM simulations are related to regional forcings or sensitivity of the physics parameterizations to the spatial resolution at which they are applied.

The utility of RCMs in downscaling research is still being argued. Two issues remain critical at the center of the debate. First, with all known and hidden biases in GCM simulations, can RCMs be expected to provide realistic regional climate information for global change research or improve seasonal climate prediction? That is, does dynamical downscaling really add valuable information or merely add spatial details that are intricately tied to the GCM and RCM model biases that render them useless? Second, with or without biases in the GCMs, errors will be introduced in the dynamical downscaling, because of limitations in the model physics, numerics, and nesting techniques. How should regional simulations, with known biases, be used to advance global change research and seasonal climate prediction? Although this latter issue is not unique to regional modeling (GCMs face the same problem because of inherent model biases), it has been more relevant to dynamical downscaling because regional simulations are often used as inputs by other models for assessing climate change impacts, or using seasonal prediction for managing resources. The ability to reproduce the observed conditions lends credibility to the end-to-end approach for impact assessments or resource management.

The issue of climate change impacts, adaptation, and mitigation requires the use of regional climate change scenarios. RCMs will remain an important dynamical downscaling tool for providing the needed information. Since society is more vulnerable to changes in the frequency or intensity of extreme events (e.g., drought and flood, extreme high/low temperature) rather than the mean climate states, future applications of RCMs in climate change study will require demonstration of skill in simulating extreme events. The use of ensemble simulation technique will be more important to establish the statistical significance of changes associated with events that have low probability of occurrence. With advances in high performance computing, both GCMs and RCMs are being applied at increasingly higher spatial resolution. More studies need to be performed to understand and document model behaviors at higher spatial resolutions, and address possible issues that could arise in applying physics parameterizations beyond the spatial scales intended. It is also important that any improvement in skill with increasing spatial resolution be carefully evaluated to avoid creating a false sense of advancement. Lastly, current assessments of climate change effects are done mostly using an offline modeling approach where climate simulations are used to drive process models, such as hydrologic models, to estimate climate change impacts. Because feedback effects are important (as shown in the snowpack example in section 3.2), coupled regional modeling systems are more useful for examining climate impacts and assessing adaptation and mitigation strategies. More research is needed in developing these regional modeling systems that represent feedback effects at the proper spatial and temporal scales.

6.2 RCM development and improvement

With increasing computer power and increased confidence in the applicability of RCMs, several trends are becoming apparent in the new developments. There is a general move to even finer resolution, both horizontally and vertically. With the finer resolution, there is also a trend to further adoption of non-hydrostatic formulations, which could allow increasingly accurate simulation of phenomena such as tropical cyclones. Another issue related to the increase in model resolution is the applicability of current physics parameterizations at very high resolution, as indicated in section 6.1. Even with the resolution currently used in many regional climate modeling studies, physical parameterizations for subgrid scale processes need to be improved.

As in most GCMs, the treatment of cloud processes, both at grid-resolved and subgrid scales, is still a difficult problem in RCMs. In particular, applicability of a particular cumulus parameterization scheme may be region-dependent, indicating the potential dependence of convective activities upon their large-scale forcing with different triggering mechanisms. This however is not well understood, and therefore will remain an unsolved problem for climate modeling studies. While some modelers choose the best schemes for the interested regions through comprehensive sensitivity experiments, development of new cumulus parameterization schemes that are not strongly scale/region dependent will remain an important area where the regional climate modeling community can make significant contributions.

Subgrid-scale stratiform cloud process is also an area that needs to be improved (Pal et al. 2000). For most RCMs, only grid resolved cloud liquid/ice water content is predicted by the explicit cloud microphysics scheme, while cloud cover and cloud optical properties are generally diagnosed. As such, inconsistency between cloud cover and cloud water/ice content usually exists, and studies of Leung et al. (1999) and Wang et al. (2000) have shown that different treatments of clouds and their representations in the radiative transfer schemes can result in large differences in the regional climate simulations through various feedback mechanisms. Specifically, the prognostic cloud microphysical scheme implies grid-scale saturation, while the diagnostic or empirical schemes for cloud cover do not necessarily require such a condition (Wang et al. 2003). Therefore, introducing cloud fraction as a prognostic variable in current cloud microphysics schemes needs to be examined for RCMs, as was previously investigated for GCMs (e.g., Bechtold et al. 1993; Tiedtke 1993).

The inclusion of cloud-aerosol interaction becomes possible using the two-moment cloud microphysics scheme, which predicts both the mixing ratio and total number concentration of liquid/ice water as prognostic variables. Chen and Liu (2004) recently developed the warm cloud parameterization based on statistical analysis of results from a detailed model considering cloud drop activation, drop growth by vapor diffusion, and drop collision, coalescence, and breakup. This scheme responds sensitively to the effect of aerosol types on CCN and the timing of rain initiation. Most importantly, the effective radii of cloud drops and raindrops are simulated, so that their effects on radiation can be included more realistically. Precipitation development is thought to be more efficient in cold-cloud compared to that in warm clouds, particularly for mid-latitude weather systems that have a deeper mixed-phase zone. Yet, the modeling of mixed-phase cloud microphysics is rather difficult, due to its great complexities. The ice-phase cloud processes, which is too complicated to handle with the traditional bulk parameterization scheme, can be resolved via the physical approach of Chen and Liu (2004), in which two more moments to resolve the shape and density of ice particles should be added. Nevertheless, significant effort is required before it can be used in RCMs.

6.3 Model evaluation and diagnostics

Much has been learnt about RCMs through previous evaluation and diagnostic studies applied to many different regions around the world. As discussed throughout this review, the importance of model evaluation and diagnostics cannot be over-emphasized. However, limited by available observational data and data storage capacity for model outputs, previous studies have focused more on evaluating general aspects of regional climate such as regional mean precipitation and temperature, and their seasonal variations and spatial distributions. Few studies have examined the 3-D structures of the atmosphere, and diagnosed the relationships among various variables at different temporal and spatial scales to provide more complete and process-based understanding of when and why models fail to capture certain climate features. Model diagnostic approaches that have been developed by the mesoscale modeling community can be applied, with emphasis on statistical behaviors, rather than case by case model-observation comparison. These types of investigations need to be pursued more extensively and in depth in the future for model improvement and better characterization of model uncertainties.

Future studies are also required to investigate climate aspects that are more region-specific. Examples are orographic precipitation, regional hydrologic cycle, monsoon features, and tropical cyclone and thunderstorm activities. In addition, similar to the fingerprinting method used in climate change detection and attribution, model evaluation and diagnostics can make use of inter-variable relationships or fingerprints in the model outputs and observations to better characterize model biases. Regional climate information will likely be used in a larger variety of applications, such as assessment or seasonal prediction of air quality and activity of tropical cyclones. Climate features that are important for realistic simulations of these phenomena will need to be more carefully evaluated at the appropriate temporal and spatial scales. Furthermore, additional insights can be gained by examining and evaluating the end products of these applications.

6.4 Modeling extreme climate events

As indicated in the IPCC 2001 report, previous studies have shown the capability of RCMs in reproducing monthly to seasonal mean climate and interannual variability, when driven by good quality driving fields. However, more analysis and improvements are needed of model performance in simulating climate variability at daily to sub-daily time scales. In particular, the increased resolution of RCMs can allow simulation of a broader spectrum of weather events to improve simulation of daily precipitation intensity distributions. Such a skill is extremely important to give confidence of the model-simulated climate sensitivity or climate change scenarios. This is a great value that can be added to both climate modeling and prediction from the dynamical downscaling approach.

Although most current RCMs can produce more realistic statistics of heavy precipitation events than the driving GCMs (e.g., Christensen and Christensen 2003; Frei et al. 2003; Huntinford et al. 2003; Wang et al. 2003), they are still suffering relatively low skills in reproducing the daily precipitation intensity distributions. This deficiency seems not to be due to the uncertainties of the driving fields, but most likely model resolution and physics parameterizations of the RCM. An example is the inability of most climate models in simulating the diurnal cycle of precipitation and the partitioning of precipitation between convective and stratiform (Dai et al. 1999). Future work thus should focus on the improvement of model physics, so that the daily intensity distribution and diurnal cycle of precipitation can be simulated realistically. This is especially important for assessment studies of global climate change impacts.

6.5 RCM intercomparison

In the last decade, several RCM intercomparison projects have been carried out to identify different or common model strengths and weaknesses. These include Modeling European Regional Climate Understanding and Reducing Errors (MERCURE) over Europe (Christensen et al. 1997), Project to Intercompare Regional Climate Simulation (PIRCS) over the United States (Takle et al. 1999), Regional Model Intercomparison Project (RMIP) over Asia (Fu et al. 2003), International Research Institute/Applied Research Centers (IRI/ARCs) regional model intercomparison over South America (Roads et al. 2003b), and the Arctic Regional Climate Model Intercomparison (ARCMIP, http://curry.eas.gatech.edu/ARCMIP). These studies show that synoptic-scale systems are simulated in good agreement with observations by the better models, while there exists significant disagreement among models and from region to region, and season to season.

Although some aspects have been learnt from different model intercomparison projects, the achievements might not be as originally expected. The common weaknesses in the previous intercomparison studies lie in several aspects. First, only limited regions with very limited models were involved and some of the participating models were not developed independently. Second, most variables compared were model outputs generated by complex physics parameterizations, such as precipitation and surface air temperature; less attention was given to diagnose the processes leading to the differences among different models. Third, there have not been any efforts to perform sensitivity experiments by replacement of one or more components from one model to another to examine the strength and weakness of different individual physics parameterization schemes. Finally, few studies compared the surface energy balance, cloud radiation forcing, and diurnal cycle of simulated clouds and precipitation. Therefore, it is expected that these weaknesses should be avoided in the future in order to maximize the results from different model intercomparison projects, and to improve RCMs and regional climate modeling studies.

6.6 Climate process studies

Application of RCMs to climate process studies is an active area of research in the community. However, there are several limitations in previous studies. First, when driven by reanalysis data or GCM output with the one-way nesting approach, the RCM response to any internal forcing in the model domain does not affect large-scale fields significantly, in particular when a relatively small model domain is used. The use of a large integration domain may mitigate this effect if the RCM can produce an accurate large-scale response in the large model domain. However, some studies have indicated that the use of a large domain could degrade the skill of the RCM in reproducing the large-scale circulation due to model deficiencies. Further improvements of RCMs, including variable-resolution global models, may partially reduce such uncertainties. Second, most previous studies generalize the finding based on case studies of particular years and seasons. This is problematic since the large-scale circulation varies from year to year and from season to season. Future studies need to be performed for multiple years to examine the ability of the model in reproducing intraseasonal, interannual, interdecadal variabilities. Finally, single simulation could not distinguish the physical response reliably, because of the chaotic nature of the atmospheric motion. Ensemble simulations are therefore strongly recommended in future sensitivity studies to understand regional climate processes.

RCMs will be a very useful tool for understanding climate processes in the future because of its use of reanalysis data as driving fields, high spatial resolution and advanced model physics representations. In addition, the feasibility for the next generation GCMs to be applied at spatial resolution comparable to that currently used in RCM simulations creates an urgent need to develop physical parameterizations for high spatial resolution simulations. Such new parameterizations are expected to be scaleable for applications at different spatial resolutions. RCMs can be used as test beds for such developments, since they can cover relatively small domain driven by observed lateral boundary conditions and they can be used to test the suitability of new development in different geographical regions. In this sense, the regional climate modeling community can lead the way in parameterization development for GCMs, as already suggested by Leung et al. (2003d).

6.7 Limited-area high-resolution versus variable-resolution global modeling

Variable-resolution global models provide a number of advantages as RCMs. Because such a model is an atmospheric GCM in its own right, it provides a straightforward alternative to the concept of a "two-way nested" RCM. It can thus avoid, in a dynamically consistent manner, the dilemma of whether the daily synoptic patterns of the RCM and host GCM need to be similar. It also avoids the potential for incompatibilities between the physical parameterizations of the host and nested models. An obvious advantage of a variable-resolution global model is the greatly reduced amount of data needed from a previous coupled GCM simulation. A further advantage is that it is fairly easy to impose conservation of mass and moisture in a global model, whereas it is extremely difficult to properly achieve in a limited-area RCM.

There are a few disadvantages of variable-resolution global models, as compared to limited-area RCMs. The traditional concern regarding variable-resolution climate models is whether the model parameterizations, in particular those for cumulus convection and cloud cover, can be applied over the range of grid sizes. Although such difficulties have not been found to occur in practice, this issue needs to be investigated systematically in future studies. We believe that both high-resolution RCMs and variable-resolution global models will continue to be widely used in regional climate studies and seasonal climate predictions.

6.8 Towards integrated regional earth system modeling

Coupled GCMs are increasingly evolving into "Earth Systems Models". It is inevitable that many RCMs will also follow this path (Giorgi 1995). As the validity of the regional climate modeling approach has been increasingly established through model evaluation and applications, RCMs are now being used to investigate more diverse climate and environmental change and prediction issues. When applied at the appropriate spatial scales, RCMs can more accurately represent spatial variations of climate forcings such as topography, lakes, and land-sea contrast, and human influence such as air pollution and land/water use. Therefore, RCMs can be an integral component of regional earth system models to study climate change, aerosol effects and air pollution, sea level rise and storm surge, and land, water, crop, and carbon management strategies.

There has been significant effort in recent years in developing regional modeling systems where RCMs are coupled in core or offline with hydrological models (Leung et al. 1996; Miller and Kim 1996), lake models (Bates et al. 1995), crop models (Thomson et al. 2002), ocean and sea ice models (Lynch et al. 1995; Döscher et al. 2002), terrestrial ecosystem models (Mabuchi et al. 2000; Lu et al. 2001), chemistry/aerosol models (Qian and Giorgi 1999; Qian et al. 2003; Giorgi et al. 2002, 2003), and air quality models (Grell et al. 2000) with encouraging results. Due to the complexity of various feedbacks, and often mismatch of temporal/spatial scales among various parts of the earth system, integration of different model components needs to proceed expeditiously to determine the appropriate temporal/spatial scales for integration, and evaluate offline versus online coupling strategies.

7. Concluding remarks

Regional climate modeling has proven to be able to improve climate simulation at the regional scales, especially in regions where forcings due to complex orographic effect, land-sea contrast, and land use, regulate the regional distribution of climate variables and variations. The regional climate modeling approach has also been shown to be useful for improving our understanding of various climate processes, such as land-atmosphere interaction, cloud-radiation feedback, topographic forcing, and land use change, as discussed in section 4. Significant progress has been made in the area of the application of RCMs to global change research and seasonal climate predictions as dynamical downscaling tools during the last decade. Progress has also been made in both understanding and improving the regional climate predictability.

It is generally believed that with both the demonstrated credibility of RCMs' capability in reproducing not only monthly to seasonal mean climate and interannual variability, but also the extreme climate events when driven by good quality reanalysis and the continuous improvements in the skill of GCMs in simulating large-scale atmospheric circulation, regional climate modeling will remain an important dynamical downscaling tool for providing the needed information for assessing climate change impacts and seasonal climate prediction, and continue to serve as a powerful tool for improving our understanding of regional climate processes.

Several areas need to be further developed or improved, such as (1) the inclusion of cloud-aerosol interactions based on higher moments mixed-phase cloud microphysics parameterization so that more accurate cloud-radiation-climate interactions can be modeled with high-resolution RCMs; (2) understanding the model behaviors at high-spatial resolutions to address issues that could arise in applying physics parameterizations, in particular the cumulus convective parameterization schemes beyond the spatial scales originally intended; (3) examination of the relationships among various variables at different temporal and spatial scales to provide more complete and process-based understanding of the model biases and the failure to capture certain climate features; (4) improvement of model physics parameterizations so that the daily precipitation intensity distribution and diurnal cycle of clouds and precipitation can be simulated realistically; (5) use of ensemble simulations to improve signal detection of climate change or climate sensitivity; and (6) development and application of regional earth system modeling systems, so that the complex feedbacks among various climate system components can be considered consistently and interactively. It is our belief that internationally coordinated efforts can be developed to advance regional climate modeling studies. Finally, since the final quality of the results from nested RCMs depends in part on the realism of the large-scale forcing provided by GCMs, the reduction of errors and improvement in physics parameterizations in both GCMs and RCMs remain a priority for the climate modeling community.

Acknowledgments

The preparation of this review article is stimulated by a group discussion at The 2nd Workshop on Regional Climate Modeling for Monsoon System held in Yokohama, Japan, March 4–6, 2003, co-sponsored by the Frontier Research System for Global Change (FRSGC) and GAME International Science Panel (GISP). International Pacific Research Center Contribution Number 297 and School of Ocean and Earth Science and Technology Contribution Number 6477.

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