Regional Climate Modeling for East-Asian Monsoon System–A Review

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Abstract

In this talk, the application of regional climate models (RCMs) to the study of East-Asian monsoon system is reviewed, including the assessment of possible impacts of land-use and land cover changes on regional climate over East Asia, the regional impacts of global warming due to greenhouse effects, the study of physical processes in the monsoon system, the applications of RCMs to seasonal predictions of East-Asian monsoon rainfall. Several directions that the regional climate modeling community could contribute to both the monsoon studies and the global climate modeling of monsoon systems in general will be also discussed.

Keyword: regional climate modeling, East Asian, monsoon system

1. Introduction

East Asia has a large latitudinal coverage with the highest mountains on the earth and the long coastline. The regional climate over the East Asia is dominated by both the complex monsoon system and the rapid seasonal transitions. It involves complex interactions among tropical, subtropical, and mid-latitude weather and climate systems, and the land-atmosphere-ocean interactions at various spatial and temporal scales, ranging from climatological modulation of planetary general circulations to the local elements, such as terrain slope, vegetation, and land-sea breeze. Regional climate over East Asia and its variation exert significant impacts on human lives and natural ecosystems in the region, especially the available water resources, flood/draught potentials, and agricultural productivity.

Because of the complexity of the East Asian monsoon system, its realistic simulation by climate models has been a challenging task for many years, while it has attracted increasing attention of the climate modeling community. In addition to the continuous improvements of global circulation models (GCMs) in simulating the East Asian monsoon system, one of the significant advancements in the last decade or two has been the applications of regional climate models (RCMs) to the study of East Asian monsoon system. Compared with its global counterpart, the RCMs have been shown considerable improvements in simulating not only the mean but also the variability of the East Asian monsoon system. In particular, the RCMs reproduce better the extreme precipitation events due to the use of higher-resolution that better resolves the land surface properties and mesoscale circulations. In this review, not only will the current status of regional climate modeling for East Asian monsoon system be discussed, but also the future directions in this important area will be highlighted.

2. Historical background

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 and land cover, 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 to improve the simulations and physical understanding of the East Asian monsoon system since their emergence. Liu et al. (1994) are among the first to simulate a summer season climate over East Asia with the RCM developed at the National Center for Atmospheric Research (NCAR_RegCM). They showed that the model could reproduce the basic characteristics of the East Asian monsoon climate and the associated seasonal rain belt migration. The performance of NCAR_RegCM in the simulation of June and January climates over East Asia was verified by Kato et al. (1999), who identified several discrepancies of the model in the region, including the simulated too strong weather systems, cold bias in winter, and overestimated summer rainfall. The NCAR_RegCM was coupled with a sulfate aerosol model by Qian and Giorgi (1999) and was used to study both the indirect and direct effects of aerosols on the regional climate over East Asia. Leung et al. (1999) compared the performances of three RCMs (all were based on the NCAR_MM4 but with different model physical parameterization schemes) in simulating the heavy precipitation during the 1991 summer monsoon over East Asia with the focus on the effects of physical parameterizations on regional climate simulations. Hong et al. (1999) evaluated the performance of the National Centers for Environmental Prediction (NCEP) regional spectral model in the simulation of the East Asian monsoon in July 1987 and 1988. Sasaki et al. (2000) evaluated the performance of the Meteorological Research Institute (MRI) regional spectral model for the cases of January and August 1994, with the focus on the evaluation of a spectral lateral boundary coupling method.

The above-mentioned studies were followed by a surge of the applications of RCMs to the study of the East Asian regional climate with the focus on the monsoon system in the early 21st century, and also several new RCMs have been developed for the region (Fu et al. 2000; Wang et al. 2003). Some major achievements in the study of East Asian monsoon using RCMs will be reviewed in the following sections.

3. Impact of land-use changes

Land use changes modify the exchange of energy, momentum, moisture, and trace gases, affecting the earth's climate. Land use changes are highly inhomogeneous spatially. The high-resolution of RCMs is ideal for assessing the impacts of land use changes at different scales on regional climate. Land use and land cover changes in East Asia have been one of the largest regions in the world. More than 60% of the region has been affected by conversion of natural vegetation into farmland or grassland into semidesert in the past 300 years. These land use/cover changes alter the surface albedo, roughness, leaf area index, and fractional vegetation coverage, etc.

Kanae et al. (2001) found a long-term decreasing trend in the 40 years precipitation observed in Thailand. The trend is apparent only in the monthly mean precipitation during September. Results from the CSU_RAMS simulations showed that, consistent with observations, the effect of deforestation in the Indochina peninsula 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 RCM developed at the International Pacific Research Center (IPRC-RegCM, Wang et al. 2003). 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 summer monsoon rainfall over East Asia.

Fu and Yuan (2001) studied the impact of recovered natural vegetation on the summer climate using the regional integrated environmental model system (RIEMS). They found that recovering the natural vegetation in large scale could have significant effects on the summer climate over East Asia, not only changing the surface climate, but also modifying the summer monsoon circulation to some extent. Sen et al. (2004b) investigated the local and regional effects of vegetation restoration in northern China (90^o-110^oE, 36^o-42^oN) using the IPRC_RegCM, and evaluated whether the changes in rainfall induced by landscape change are large enough to support a restored vegetation cover. Their results suggest that reclaiming the desertified lands through vegetation restoration is quite difficult as the local climate, even after a complete vegetation restoration in a relatively large test area, can hardly support vegetation. This is because rainfall increases but the increase occurs in rainfall intensity and not in rainfall frequency, the latter being probably more important for the maintenance of the restored vegetation in such an environment.

Zheng et al. (2002) studied the regional climate effects of vegetation change in China using the NCAR_RegCM2 and found that the increase in flood events over Yangtze-Huai valleys and the aggravation of north China droughts are likely due to the combined effect of desertification of the northern grassland and southern degradation of evergreen broadleaf trees, with the latter playing a greater role. Fu (2003) also found that the changes in land cover have resulted in significant changes to the East Asian monsoon, including the weakening of the summer monsoon and enhancement of the winter monsoon. As a result, precipitation, runoff, and soil water content are all reduced in many parts of the region, particularly over the northern China. The significant impacts of land cover change on East Asian monsoon climate have also been demonstrated in several other studies (e.g., Wang et al. 2003; Shi and Wang 2003; Gao et al. 2003; Suh and Lee 2004).

4. Regional impact of global 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). The application of RCMs to climate change has been recently reviewed extensively in IPCC 2001. Here only recent advancements in the study of impacts of global warming on the East Asian monsoon are briefly discussed.

Gao et al. (2001) investigated the impacts of greenhouse effects on climate change over China with a revised version of the NCAR_RegCM nested into the Australian CSIRO coupled GCM. In a control simulation, they showed that the simulations of surface air temperature and precipitation over China by the RCM are much improved compared to the simulations by the global coupled model. Results from the sensitivity experiment with doubled CO_2 showed remarkable increase in surface air temperature, especially in winter season and in north China, and a general increase in precipitation in most parts of China.

In a recent study, Chen et al. (2004) studied the regional climate change in East Asia due to doubled CO_2 with an interactive atmosphere-soil-vegetation model nested in the NCAR climate system model (CSM). They found that bout a 20% increase in annual precipitation in coastal areas of central and northern China, but only by 8% in southern China. The strongest warming of up to $4^{o}C$ occurs in summer in northern China. The climate generally tends to be warmer and wetter under doubled CO_2 conditions except for inland areas of northern China, where it becomes warmer and drier. Most of these changes are found to be associated with the more intense East Asian monsoon under doubled CO_2.

The above studies are mainly focused on the mean climate change due to doubled CO_2. The changes in extreme climate events should be equally or even more important to society. Gao et al. (2002) examined the possible changes in extreme climate events over East Asia due to greenhouse effects. They found that both daily maximum and daily minimum air temperature increase in doubled CO_2 conditions, but the diurnal temperature range decreases due to the higher increase of minimum temperature. The number of hot spell days in summer significantly increases while the number of cold spell days in winter decreases. The number of rainy days and heavy rain days increases over some sub-regions of China, most noticeably north China and southeast China.

5. Climate process studies

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. Here we highlight several studies relevant to the East Asian monsoon system.

With the use of the NCAR_RegCM, Qian et al. (2003) found that the increase in both snow cover and snow depth over the Tibetan Plateau in winter can delay the onset and weaken the intensity of the summer monsoon, resulting in a decrease in precipitation in southern China and an increase in the Yangtze and Huai River basins. They showed that snow anomalies over the Tibetan Plateau change the soil moisture and the surface temperature first through the snowmelt process, and then alter heat, moisture and radiation fluxes from the surface to the atmosphere. The modified atmospheric circulation in turn could also affect the underlying surface properties. This interaction is the key to the subsequent climatic changes downstream over China.

The Meiyu/Baiu front genesis is considered to be due to forcing from both land/sea contrast and orographic effect of Tibetan Plateau. Through sensitivity experiment using the CSU-RAMS model, Yoshikane et al. (2001) found that the Baiu front could be generated by two factors: the zonal mean field and the land/sea contrast. Although not a necessary condition, the orographic effect including the Tibetan Plateau intensifies the low-level jet (LLJ) and the precipitation over the Baiu front. Further, the condensational heating is necessary to keep the LLJ to the south of the upper-level jet as observed.

The presence of natural and anthropogenic aerosols in the atmosphere can affect the climate over the regions where aerosol loadings are substantial and the regions that are located downwind, such as the East Asia. 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_RegCM 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. Both direct and indirect aerosol forcings have regional effects on surface climate, with the indirect effect dominating in inhibiting precipitation. Because the size distribution of the cloud condensation nuclei (CCN) is not explicitly simulated, the effect of aerosols on the cloud radiative forcing is heavily parameterized, based on an empirical relationship between CDNC and the mass concentration of the sulfate aerosol.

Tropical cyclones (TCs) are strong synoptic systems. Their representations in global GCMs are far from realistic. Although RCMs can better resolve TCs than GCMs, the intensity is usually much weaker than the observations due to the model resolution currently in use. The possible impact of TCs on summertime circulation over the East Asia was studied by Ahn and Lee (2002) by bogusing TC vortices in a seasonal RCM simulation with the NCAR_RegCM. The model with the bogus TCs showed improvements in the East Asian summer monsoon circulation, suggesting that part of the systematic biases in RCM simulations over the East Asia could be due to the unrealistic simulation of both the intensity and frequency of TCs over the western North Pacific.

The physical and biological interactions between the terrestrial ecosystems and climate are an active area of research in recent years. With a spectral RCM coupled with a new land surface model which includes the dynamical vegetation and carbon dioxide cycle, Mabuchi et al. (2000) studied such interactions over the Japanese Islands and surrounding area. They found that interannual variations of downward short-wave radiation over the land surface were mainly responsible for the interannual variations of vegetation activity. Variations of vegetation activity affected the variations of the net carbon dioxide flux between the land surface and the atmosphere. In turn, these variations affected the interannual variations of carbon dioxide concentrations in the lower troposphere over Japan. Chen et al. (2004) included the interactions between climate and the ecosystem in a study of the climate change over East Asia due to increased atmospheric CO_2 and found that the simulated climate changes are only slightly modified by vegetation feedbacks.

6. Seasonal prediction

During the last decade, significant progress in dynamical seasonal prediction with global coupled atmosphere-ocean GCMs (or AOGCMs) has been made by the meteorological services and scientific community around the world. With AOGCMs potentially making skillful seasonal prediction of the large-scale fields, some investigations have recently started to examine the use of RCMs nested within the 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.

Recently, Ding et al. (2003) presented some initial results of the experimental use of the nested RCM for seasonal prediction since 2001. In their experiments, an AOGCM provides the boundary and initial conditions for the RCM 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 the RCM has some skill in simulating and predicting the seasonal rain belts, showing more areas with positive anomaly correlation coefficient (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. One significant improvement derived from the RCM 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 RCM. Real-time experimental predictions for the summers since 2001 using this nested RCM were made on April 1 of each year.

7. Future directions

Regional climate modeling has proven to be able to improve climate simulations 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, such as East Asia. 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.

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 climate 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 the skill in simulating extreme events. The use of ensemble simulation technique will be important to establish the statistical significance of changes associated with events that have low probability of occurrence.

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 for global monsoon system. 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.

References (omitted, provided by request)