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Advance in Application of Regional Climate Models in China

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Abstract: Regional climate models have become the powerful tools for simulating regional climate and its change process and have been widely used in China. Using regional climate models, some research results have been obtained on the following aspects: 1) the numerical simulation of East Asian monsoon climate, including exceptional monsoon precipitation, summer precipitation distribution, East Asian circulation, multi-year climate average condition, summer rain belt and so on; 2) the simulation of arid climate of the western China, including thermal effect of the Qinghai-Tibet Plateau, the plateau precipitation in the Qilian Mountains; and the impacts of greenhouse effects (CO_2 doubling) upon climate in the western China; and 3) the simulation of the climate effect of underlying surface changes, including the effect of soil on climate formation, the influence of terrain on precipitation, the effect of regional soil degradation on regional climate, the effect of various underlying surfaces on regional climate, the effect of land-sea contrast on the climate formulation, the influence of snow cover over the plateau regions on the regional climate, the effect of vegetation changes on the regional climate, etc. In the process of application of regional climate models, the preferences of the models are improved so that better simulation results are gotten. At last, some suggestions are made about the application of regional climate models in regional climate research in the future.

Keywords: regional climate model; model application; research advance; China

1 Introduction

China has a great population and maintains 21% of the world population with 7% of the world cultivated land. It is very significant to study the climate especially for China whose agriculture is 'rainfed' agriculture primarily. Climate changes and climate disasters both have obvious regional characteristics, therefore, regional climate can influence directly on people's daily life and production activities. It was indicated that the important goal of climate research is to forecast regional climate changes correctly in order to evaluate the possible influence of climate changes accurately. The accurate and reasonable simulation and forecast of region climate in future is the prerequisite for people to make the adaptation to climate change as early as possible. Regional climate models have been the powerful tools to study the climate changes and their mechanism, and forecast the regional climate. For regional climate model has high resolution, it can describe the details of the influences of topography on small and middle scales, surface characteristics and other factors on regional climate changes. So, on the regional scale, the simulation results of regional climate models are better than those of General Circulation Model (GCM). At present, many kinds of regional climate models have been developed in the world (Giorgi, 1990; Giorgi et al., 1993; Bates et al., 1993; Caya and Rene, 1999). Oversea scientists have done much research work on the simulation of the recent and future climate, and extreme weather and climate events using the regional climate models (Lee and Suh, 2000; Leung et al., 2004; Christensen and Chris-

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tensen, 2004; Fowler et al., 2005). In China the studies on the application of regional climate models mainly concentrated on the East Asian monsoon climate, arid climate over western China, the climate effect of underlying surface changes, and the improvement of parameterization of regional climate models. On the basis of literatures, this paper will systematically discuss the advance in the application of regional climate models in China.

2 Descriptions of Regional Climate Models

Giorgi and Bates (1989), Dickenson et al. (1989) firstly succeeded in simulating regional climate by using General Circulation Model (GCM) to offer lateral boundary conditions for the Limited Area Models (LAMs) in the late 1980s, and then the regional climate models began to be developed. Several regional climate models used frequently are introduced as below.

Mesoscale Model 5 (MM5) is the fifth generation mesoscale climate model, which was designed by the Pennsylvania State University (PSU) and National Centers of Atmospheric Research (NCAR) of the United States. The model has detailed physics processes, radiation schemes, and advanced processing technology of initially side value. It can be used to simulate the regional precipitation created by the long time and strong convection process. Mesoscale Model version 3 (MM5V3) and Mesoscale Model version 3.6 (MM5V3.6) were developed in the foundation of the MM5. Tang et al. (2005) imported Biosphere-Atmosphere Transfer Scheme version 1e (BATS1e) into the MM5V3 and developed the MM5BATS.

Regional climate model (RegCM) designed by NCAR is one of the models used most widely. The first generation NCAR RegCM was built upon the NCAR-Pennsylvania State University (PSU) Mesoscale Model version 4 (MM4) in the late 1980s. At present, as more complex physics schemes are used, this regional climate model is developed into the third generation (RegCM3) in the Abdus Salam International Centre for Theoretical Physics (ICTP) (Elguindi et al., 2006). The model has high horizontal and vertical resolutions, fine terrain surface condition and reasonable physics parameter schemes. It was used widely in simulating the East Asian climate, arid climate in the western China and the climate effects of the underlying surface in China.

The researches of regional climate models started at the beginning of the 1990s in China. Institute of Atmosphere Physics, Chinese Academy of Sciences and Nanjing University set up the regional climate system model for temperate East Asia (RCSM-TEA) under the support of the "Project for Scaling the Heights of Science" of the National Eighth Five-Year Plan. Regional integrated environment model system (RIEMS) was developed by the Key Laboratory of Regional Climate-environment Research for Temperate East Asia (RCE-TEA), Chinese Academy of Sciences in 1998. The dynamic component of this model was the same as that of MM5. It was a high-resolution regional model with the coupling of vegetation-climate interaction, which was applied to simulating the East Asian climate and the climate effects of the underlying surface in China.

3 Application of Regional Climate Models

3.1 Simulation of monsoon climate in eastern China

The eastern part of China has East Asian monsoon climate. There precipitation mainly concentrates in summer, and drought and flood disasters mainly occur in summer too. So it is significant for us to simulate summer precipitation reasonably and accurately in the region. Chinese researchers have studied the monsoon climate using different regional climate models, including RegCM, RegCM2, RIMES, MM5, and so on.

As to the simulation of the extreme climate events of East Asian, Luo and Zhao (1997) studied a case of a big flood event in summer (May to August) of 1991 over East Asia using RegCM2 and tested the ability of RegCM2 to simulate the summer anomaly precipitation from the aspects of precipitation, surface temperature and circulation vector field. And Zhao et al. (1997) studied the same flood event using 3 different regional climate models that were developed by Pacific Northwest National Laboratory (PNNL), State University of New York at Albany (SUNYA) and NCAR respectively, and their abilities of simulating regional climate of East Asia were validated. Lu and Chen (1998) simulated the summer precipitation over North China in 1991 and 1994 with RegCM2. The distribution of summer precipitation over North China in 1991 (rainless year) and 1994 (rainy year) was simulated well. But disadvantages of the simulation were that monsoon was stronger and

the ground temperature was higher than observed facts. The land surface scheme of Biosphere Atmosphere Transfer Scheme (BATS) should be improved in order to be suitable for surface characters in China. Shi et al. (2001) developed a regional climate model with many kinds of schemes by improving the land surface schemes, convective precipitation schemes, radiation scheme and planetary boundary layer scheme based on the RegCM2. RegCM2 and the improved RegCM2 were used to simulate anomaly monsoon precipitation process in the summers of 1994 and 1998. Compared to simulation results of the two models, it was found that the results of the improved model were better than those of RegCM2. It is showed that improved regional climate model with parameterization schemes of various physics processes could enhance simulation ability of the model to a certain extent.

As to the simulations of the East Asia circulation field and multi-year average climate, Li and Ding (2004) simulated East Asia circulation and precipitation over China continuously from 1998 to 2002 using RegCM2. The model produced the seasonal characteristics of East Asia circulation and regional climate system of China. It also well revealed the seasonal evolution of monsoon circulation and circulation fields of every layer successfully. The simulated surface temperature of the east part of China was close to the real state. The results well illustrated seasonal changes of precipitation of main climate regions and the advance and withdrawal characteristics of eastern rain belt in China exactly. But the central position of the biggest rain belt was inaccurate, about three latitudes northerly, which did not reflect the distribution characteristic of flood in the southern part and drought in the northern part of China during the period of 1998–2002. The integration time (5yr) was not long enough for studying mean climate state. The model could simulate the average climate characteristic well, but its ability to simulate inter-annual change of the circulation and regional precipitation were not perfect. Xiong (2004a; 2004b) did the continuous 10-year simulation in East Asia from 1 January 1987 to 31 December 1996 using RIMES, and investigated the abilities of RIMES to simulate regional climate of East Asia. The model well simulated the spatial distribution of temperature in different seasons and the change of annual temperature in different regions, meanwhile it also well simulated the seasonal and spatial distribution of precipitation and the change of annual precipitation in different regions. But compared with the position of observed precipitation, the simulated one was northerly.

On the summer rain belt, Fu et al. (1998) simulated the evolution processes of the summer rain belt over the eastern part of China using regional climate system model for temperate East Asia (RCSM-TEA). The experiment simulated the summer rain field in a normal monsoon year (1979) and a wet monsoon year (1991), and continuous 3-year following them. Compared with the observed rain field, the simulation results with RCSM-TEA were better than those from GCMs. But the maximum of correlation coefficients between observed and simulated rainfall was only 0.40.

Besides using RegCM2 from NCAR, some scholars did the simulation research with other mesoscale regional models. Tang et al. (2005) simulated a 6-year (1995–2000) summer climate using the MM5BATS (MM5 coupled with the BATS1E) and surface model, and compared the simulated results with the observed ones. It was found that the simulation results of MM5BATS were better than those of RegCM2. MM5BATS based on the non-hydrostatic mesoscale model MM5V3, but RegCM2 based on the hydrostatic model MM4, that means, the high-level model could improve simulation effect.

An inter-comparison project of regional climate models for Asia that was a joint effort of 10 research groups from Australia, China, Japan, the Republic of Korea, and the United States was sponsored and presided by Key Laboratory of Regional Climate-environment Research for Temperate of East Asia, Institute of Atmospheric Physics, Chinese Academy of Sciences. Every group used a kind of regional climate models (Fu et al., 2004), all kinds of models had the same driven field, land cover and topography data, simulation region and horizontal resolution, and the integration stage was from March 1997 to August 1998. The inter-comparison project concentrated on surface climate elements, such as temperature, precipitation, etc. All the models in the inter-comparison project could recur the primary characteristics of special distribution and annual change of average temperature, the highest temperature and lowest temperature, but all the simulated temperature was lower than their observation values. More than half of the models could simulate the special distribution of precipitation better, and simulated results of winter were

better than those of summer. All the models could reflect main characteristics of seasonal changes of precipitation, but simulated values of precipitation in high latitude were more than the observed values.

3.2 Simulation of arid climate in western China

The western part of China is located in arid and semi-acid area and there is fragile ecological environment. Some regional climate models, such as MM4 nesting GCM, MM5V3.6 and RegCM2, etc., were used for climate simulation research over this region.

The special terrain and thermal effects of the Qinghai-Tibet Plateau play an important role in the formation and development of Chinese climate. Using MM4 and improved GCM, Liu et al. (2004) simulated mean summer climate state of the Qinghai-Tibet Plateau and Northwest China, and distinguished plateau climatic features that GCM could not be illustrated in detail.

On the research of precipitation of mountainous area, Li et al. (2005) simulated a rainfall process in Qilianshan Mountain area from 14 to 17 July 2002 by MM5V3.6 with different horizontal resolutions. The results showed that high horizontal resolution was advantageous to simulate rainfall center position, however, illusive rainfall center might occur at the same time. Low horizontal resolution was advantageous to simulate precipitation, but simulation effect of rainfall center position was worse than that with high horizontal resolution.

As to the climate effects of CO_2 concentration to the western China, Gao et al. (2003) simulated the impacts of greenhouse effects (CO_2 doubling) upon climate change over China, especially over Northwest China using RegCM2. Results showed that mean annual temperature increased by 2.7℃ over Northwest China, which is higher than that over whole China (2.5℃). At the same time, mean annual precipitation also increased by 25% over Northwest China, much higher than that over the whole China (12%). The maximum increase amount of precipitation occurred in winter, then in spring and autumn, the minimum in summer.

3.3 Simulation of climate effect of underlying surface changes

The changes of underlying surface influence the regional climate. Regional climate models, such as GCM, MM5, RIMES, RegCM2, and RegCM3, are powerful tools to assess climate effect of underlying surface changes.

For understanding the functions of underlying surfaces of uniform soil and non-uniform soils in climate development, Qian (1993) made two experiments on underlying surface of uniform soil and one on underlying surface of non-uniform soils with a 3-dimension model on global scale, initial equation model of P-δ mixed coordinate, simulating function of underlying surface on the climate change. The results showed that the basic summer climate characteristics of the monsoon climate area in the Eastern Hemisphere were mainly determined by the land-sea contrast and big topography.

Land-sea contrast and the surface characteristics play the different roles in the formation of climate. Development of general circulation and climate variations in summer were simulated by using a coupled GCM (Qian and Qian, 1996). It was found that land-sea contrast might be the fundamental factor to form the modern general circulation. Under fixed land-sea distribution, the topography and types of land surfaces had the similar effects on the climate variation, but both of them could not change the fundamental pattern of the general circulation. Snow in plateau region played an important role in regional circulation.

Land degradation, heterogeneous underlying surface and returning farmland to forest all bring regional climate effects. Changes in temperature, sensible heat flux and latent heat flux after land degradation over the west of Liaoning Province were studied (Liu et al., 2003); and changes of mean temperature in summer after the degeneration or renewal of vegetation were simulated (Liu and Zhou, 2004) by using climate model MM5V3.5. A case of the local microclimate effect of heterogeneous underlying surface in Heihe region, Gansu Province was simulated by MM5V3 meso-scale model (Gao and Lu, 2001). Using MM5V3, the process of a local precipitation and sensitivity of local environmental factors to two schemes of returning farmland to forest were simulated in the Loess Plateau of the northern Shaanxi Province (Guo et al., 2004). The results showed that vegetation improvement of underlying surface in the northern Shaanxi Province can make the local rain belt shift northward, local precipitation increase and rainfall process prolong.

The vegetation and land use pattern change can result in change of surface physical parameter, which can fur-

ther influence the formation and development of regional climate. It was found that there was difference between regional climates simulated by RIMES under the conditions of real vegetation and ideal natural vegetation in East Asia (Fu and Yuan, 2001). And renewal of ideal natural vegetation on large scale could not only change the climate near ground in East Asia but also influence the intensity of East Asian monsoon circulation in summer. It was an exemplification that the change of land use pattern might influence the global system. Also by using RIMES, the regional climate of Northeast China was simulated on two kinds of underlying surface, potential and present underlying surface, from July 1987 to December 1998 (Yan, 2007). The simulation results showed that there was corresponding relationship obviously between the area with underlying surface change and the area with temperature change, and change of underlying surface could result in regional temperature change. With RegCM3, on the scale of China region, two 15-year integral experiments under the conditions of real vegetation and ideal vegetation respectively were conducted (Gao et al., 2007). It was found that under the conditions of real vegetation, winter and summer monsoon circulations were reinforced and energy balance of underlying surface was changed. And land use change resulted in the increase of annual precipitation in the southern part of China and the decrease in the northern part of China, and remarkable decrease of average annual temperature in the southern part of China.

Terrain and its changes influence the precipitation evidently. Fan and Lu (1999) simulated the influence of terrain and its change on summer precipitation in North China using the RegCM2. It was found that the mountains located in the west and north of North China greatly influenced the summer precipitation of North China. When the height of mountain was decreased, lifting effect of the terrain would be weakened, precipitation on the windward side and leeward side of the mountain would be reduced. With RegCM2, 4-group experiments were designed to study the influence of solar radiation, vegetation and CO_2 concentration on the East Asian monsoon climate in 6kyr B.P. (Zheng et al., 2004). It was indicated that the enlargement of seasonal cycle of insolation, the reduction of perpetual snow and sea ice in high latitude area, and increase of polar sea temperature at 6kyr B.P. led to the weakening of winter continental anticyclones and hence the amplitude of winter temperature declined in China. Using RegCM2 with topography gravity wave drag on subgrid-scale and reasonable snow mass forcing, the anomalous snow cover effects over the western and eastern parts of the Qinghai-Tibet Plateau were simulated based on SMMR (scanning microwave multiband radiometer) pentad snow depth data (Liu et al., 2005). It was found that the abnormal snow cover over the western part of the Qinghai-Tibet Plateau had more obvious effects on the regional atmospheric circulation in the late stage than that over the eastern part of the Qinghai-Tibet Plateau.

As to the climate effect of wetland, the simulation of climate effect of wetland reclamation in the Sanjiang Plain has been done with RegCM3, in which the surface module was based on data of remote sensing and GLCC (Global Land Cover Characteristics) since 2006 (Yan et al., 2006).

4 Parameterization Improvements of Regional Climate Models

There are many physical parameter schemes in the regional climate models, such as land surface scheme, radiation scheme, and planetary boundary layer scheme. The improvement of regional climate models is the incessant improvement process of the physical parameter schemes.

For improvement of the land surface process, He et al. (2001) studied the sensitivity of RegCM2 to scalar roughness lengths, introduced scalar roughness length Z_{0T} and Z_{0q} to BATS. The results showed that calculation precision of the sensible and latent heat flux between surfaces increased and simulated monthly precipitation, mean monthly temperature and specific humidity were more accurate. Tang et al. (2001) introduced the soil-vegetation-atmosphere model to RegCM2, and simulated the sensible and latent heat flux between surface land and vegetation more accurately, which improved the simulation veracity of the distribution of monthly precipitation and mean monthly surface temperature.

When stable airflow gets across anomalistic underlying surface, gravity wave spreading upward will be active because of the uneven terrain. Those waves transmit sizable horizontal momentum to the areas where the waves are absorbed or dissipated. Introducing envelope topography and gravity wave drag to RegCM2, Liu and

Qian (2001) found that with gravity wave drag the model performance on simulation of climate system and climatic factors could be improved to some extent, and the effect of envelop topography on regional climate simulation was less significant than that of gravity wave drag.

Because of limited simulation area, regional climate models must solve the lateral boundary question, which affected the simulation effect of the models. The simplest method was to assume that the lateral boundary is fixed in the simulation process and the research area is apart from the lateral boundary as far as possible. This method is not suitable for the longtime scale research because information outside cannot be imported to the simulated region inside. Therefore, variable lateral boundary should be adopted in the regional climate models. Wei et al. (1998) designed two different lateral boundary treatments to study the effect of lateral boundary on the East Asian summer monsoon rainfall with SUNYA-RegCM (the State University of New York regional climate model). One treatment was exponential relaxation scheme, another adopted 18 buffer layers coupled with exponential as weighing function. It was found that regional climate model with the second scheme could get a better simulation of summer monsoon precipitation both in quantity and in the sudden jump of rainfall belt. On the choice of the nesting lateral boundary, Qian and Liu (2001) chose the districts with bigger system error and smaller system error in a GCM simulation coupled with regional climate model respectively, and found that the error values of the lateral boundary in a GCM had important influences on the simulated results. If the nesting area selected in the smaller error district of the GCM, the effect of regional climate simulation and prediction would be improved obviously than that without such selection of a nesting area.

Because regional climate occurs in the circulation background on big scale and contains the interaction process between disturbed systems on small scale, middle scale, weather scale and planetary scale. Regional climate is restricted by the subsystem of climate system (atmosphere, biosphere, hydrosphere, and so on). This complex process containing a lot of factors on many scales decides the difficulty and complexity of regional climate simulation. So the whole development process of regional climate models and other models would be accompanied with parameterization research.

5 Problems and Prospects

It has been more than ten-year since regional climate models came into being, and scientific workers have obtained plentiful and substantial research results. However, there are still some insufficiencies in the research. 1) The studies on western arid climate in China were less than those on East Asian monsoon climate. 2) As to the research time, the simulations mainly concentrated in summer (e.g. summer precipitation), but the simulations in winter and annual simulations were few, and long-time researches on mean climate condition were devoid comparatively. 3) The effect of precipitation simulation was worse than that of temperature simulation. 4) The regional climate model applications were usually used to study the meteorological phenomena, and the researches about regional climate model coupling with other models were devoid at present.

On the basis of analyses above, in the research on the application of regional climate models in China we should pay more attention to the aspects as below in the next stages. 1) More attention should be given to the simulation research on the frail ecological areas in China, especially the western China in order to exploit resources reasonably and meliorate the local eco-environment; and more simulations about the long time mean climate conditions should be done. 2) The parameterization of the regional climate models should be ameliorated continually in order to improve the veracity and reliability of the simulation results, and the effect of precipitation simulation need to be improved. 3) More simulations on the effect of LUCC should be done, and the effect simulation of suppositional vegetation and ideal vegetation need to be done in order to understand the influence of vegetation changes to the regional climate. 4) The regional climate models should be coupled with the hydrology models and ecosystem models to study the developmental trend of water resources and the influence of underlying surface changes on ecosystem, and the crossover application research should be enhanced.

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