We have developed a regional climate model, NIES-RAMS, and conducted present and future Asian regional climate simulations which were nested in the results of Atmospheric General Circulation Model (AGCM) experiments. The regional climate model could capture the general simulated features of the AGCM and also some regional phenomena such as orographic precipitation, which were not appeared in the outcome of the AGCM simulation, were successfully produced. The increases of annual mean surface runoff and its large fluctuations are projected in a lot of Asian regions. The seasonal mismatch between water demand and water availability, which should be considered in future water resource assessments, is concerned.

INTRODUCTION

The impact of hydrological change as a result of global warming caused by anthropogenic emissions of greenhouse gases is a fundamental concern. In order to control water resources in the face of drought, flood, and soil erosion, which frequently
present a serious threat to human life and natural ecosystems, risk assessments are being required more frequently by policy-makers.

Though hydrological predictions associated with the global climate change are already being performed mainly through the use of General Circulation Models (GCMs), coarse spatial resolutions and uncertain physical processes limit the available information for water management on a regional scale. Currently, as one of the methods for downscaling the GCM results, dynamical downscaling using a regional climate model (RCM) is in progress.

Higher resolution simulation by a regional climate model is expected to be able to improve regional circulation pattern and mesoscale precipitation such as orographic precipitation resulting from realistic topography.

**MODEL AND EXPERIMENTS**

We have developed a regional climate model, NIES-RAMS (Emori et al., 2001 [1]), which is based on a three-dimentional nonhydrostatic compressible dynamic-equations model (RAMS: Regional Atmospheric Modeling System) developed at Colorado State University (Pielke et al., 1992 [2]).

For dynamical downscaling using a RCM which has consistency with the GCM schemes as much as possible, some of the major schemes of the CCSR/NIES AGCM (Numaguti et al., 1997 [3]), Arakawa-Schubert cumulus parameterization (Arakawa and Schubert, 1974 [4]), large scale condensation, a radiation scheme based on the two-steam k-distribution method (Nakajima et al., 2000 [5]), the Mellor-Yamada level 2.0 turbulence scheme (Mellor and Yamada, 1974 [6], 1982 [7]), and the soil and vegetation model (MATSIRO: minimal advanced treatments of surface interaction and runoff) developed by Takata et al. (2003) [8], are incorporated into the RAMS.

![Figure 1. Simulated region and topography](image-url)
Present (1981-1990) and future (2041-2050) Asian regional climate were simulated by the NIES-RAMS nested in the AGCM experiments results (6 hourly) whose horizontal resolution is T42 spectral truncation (about 2.8 degree in each grid). In the RCM experiments, the domain is about 9,600×7,100 km and represented by 161×119 grids with a spatial resolution of 60 km. Nudging timescale of lateral boundary is 600 s and the nudging points from lateral boundary are 10 grids. In the present Asian climate experiment, observed SST and sea-ice distributions for 1981-1990 (GISST: Rayner et al., 1996 [9]) were used. In the future experiment, a seasonally varying ‘warming pattern’, which is derived from a transient climate change experiment with CCSR/NIES coupled ocean-atmosphere climate model, was added to the observed SST.

RESULTS

**Dynamically downscaled present climate**

Dynamical downscaling using the developed regional climate model (RCM) seems to successfully improve regional circulations.

Figure 2 shows observed and simulated present mean precipitation for 10 years (1981-1990) by CPC Merged Analysis of Precipitation (CMAP; Xie and Arkin, 1997 [10]), the Global Precipitation Climatology Project (GPCP; Huffman et al., 1997 [11]), the CCSR/NIES AGCM, and the NIES-RAMS.

RCM improved regional precipitation pattern such as rain band from the Philippine Islands to the East China Sea and Japan which is associated with Baiu fronts, Tropical depressions. Orographic precipitation, which can be found obscurely in the AGCM, was also clearly produced in the western part of India and the south-facing slope of the Himalayas by the NIES-RAMS. Not all precipitation patterns improved by the nested RCM. Precipitation of GCM in the tropical ocean is much stronger than the observations and its strongest precipitation zone shifted northward.

Basically, the RCM seems to follow GCM but estimates rather more precipitation. Compared to the observations and GCM, RCM overestimates precipitation in the eastern part of China. That is bias produced by the RCM. By investigating this bias of the NIES-RAMS, it was found that low pressure caused convergence, increased water vapor, and excessive precipitation. The excessive precipitation released much latent heat and it increased air temperature and thickness which caused lower pressure. While lateral boundary conditions are nudged by the GCM, the systematic bias in the RCM was caused by this positive feedback.

Figure 3 shows simulated annual mean wind at 850hPa in present climate. Synoptic circulations, middle-latitude westerlies and monsoon westerlies, were reasonably captured by the RCM. Subtropical high simulated by the GCM relatively weaker than that of ECMWF Re-Analysis (ERA15) (not shown). Simulated weak subtropical high in GCM makes the region more affected by the systematic bias of the RCM. That is, over the eastern part of China, meridional wind arises from convergence caused by the
systematic bias. It causes stronger water vapor transport and precipitation. This might be one of the additional reasons of enhanced precipitation in the region.

Figure 2. Observed and simulated annual mean precipitation for 1981-1990 by CMAP (upper left), GPCP (upper right), CCSR/NIES AGCM (lower left), and NIES RAMS (lower right)

Figure 3. Simulated annual mean wind for 1981-1990 by the CCSR/NIES AGCM (left panel) and the NIES RAMS (right panel)
Future climate prediction under the Global warming

About one degree Celsius increase of annual mean 2m air temperature in the tropical region and about 3-4 degree Celsius in the mid-high latitudinal region are projected from the present climate (1981-1990) to the future (2041-2050) (not shown).

As a result of stronger temperature increase in the higher latitudes, the meridional gradient of air temperature became weak and westerlies caused by thermal wind were weakened (Figure 4). El Niño like differences can be found in the projected results by the AGCM under the global warming. Active convection area over the western Pacific Ocean shifted to the eastward. As a result, Walker circulations were modulated and the sinking motions were stronger over the Western Pacific Ocean. This caused the negative anomaly of precipitation in the future climate (Figure 4).

Under the global warming, increase of water vapor and higher air temperature over the land than over the ocean were projected. It enhanced a giant land-sea breeze, Asian monsoon circulation. Monsoon westerlies in the Arabian Sea, which is associated with Somali jet, were projected to be stronger and to bring more abundant water vapor to the

Figure 4. Simulated change of annual mean wind at 500hPa (left panel) and precipitation (right panel)

Figure 5. Simulated change of annual mean vertically integrated water vapor flux (left panel) and surface runoff (right panel)
south of India and the Bay of Bengal (Figure 5). Precipitation was enhanced especially over the mountainous regions, the western part of India and the southern edge of the Tibetan Plateau. Increased vapor flux over the region from the Philippine Islands to the East China Sea which is related with the divergent flow anomaly over the Western Pacific Ocean and increased water vapor was also projected. It increased precipitation in the vicinity of Japan (Figure 4).

As a result of the changes in the synoptic scale flow patterns and precipitation under the global warming, the increase of annual mean surface runoff was projected in a lot of Asian regions (Figure 5). However, the surface runoff changes had regional differences and both the increase and decrease were suggested in summer. It might increase the risk of mismatch between water demand and water availability in the agricultural season.

Projected seasonal hydrological change under the Global warming

For accessing the impact of climate change on hydrological cycles in which seasonal cycles such as snow, soil moisture, and evapotranspiration have important role, it is necessary to investigate seasonal changes of hydrological cycles. 6 regions were selected arbitrarily as shown in Figure 6.

As one example, heat and water flux changes in Tibet are shown in Figure 7. In Tibet, large part of precipitation is produced by large scale condensation scheme and most of the precipitation consists of snowfall in winter. Convective precipitation can be only found in summer. Snow melt occurs in early summer and it increases soil moisture and produces more runoff than precipitation. As soil is getting saturated, latent heat flux becomes dominant in the late summer (not shown).

![Figure 6. Selected 6 regions for investigating the impact of global warming on seasonal hydrological cycles in each Asian region](image_url)

Under the global warming, both temperature and humidity were projected to increase in Tibet (not shown). Snowmelt was projected to occur earlier and increase
runoff and soil moisture in spring. Increase of convective precipitation in summer causes the decrease of cloud cover and net downward longwave radiation and increase of net downward shortwave radiation. Because of increased incoming energy, latent heat was projected to increase a whole year especially in summer. In autumn, rainfall was projected to increase instead of decreasing snowfall due to the warming. Because of the decrease of snowfall, increase of precipitation directly recharges soil moisture in autumn.

Figure 7. Projected seasonal changes of hydrological cycles in Tibet. Changes of heat flux (upper panel) and water flux (lower panel)

**SUMMARY**

We have developed a regional climate model, NIES-RAMS, and conducted present and future Asian regional climate simulations which were nested in the AGCM experiments results. The regional climate model could capture the basic simulated features of the AGCM and also improve some regional phenomena such as orographic precipitation which were not appeared in the outcome of the AGCM simulation.
The increases of annual mean surface runoff and its large fluctuations were projected in a lot of Asian regions. In some regions, the projected seasonal changes of hydrological cycles under the global warming potentially increase the risk of mismatch between water demand and water availability.

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