

REGIONAL CLIMATE MODEL INTERCOMPARISON PROJECT FOR ASIA

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Phase one of the Regional Climate Model Intercomparison Project for Asia reveals the capacities of regional climate models (RCMs) for simulating the Asian monsoon climate and extreme events as well.

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The scientific community is currently facing new research challenges in estimating the timing and magnitude of regional climate change, analyzing its environmental and socioeconomic consequences,

and providing integrated assessments of the implications of regional change for society and the environment. Global climate models (GCMs) provide useful climate change projections at a continental scale of several thousand kilometers (McAvaney et al. 2001), but their projections at the regional scale, that is, several hundred kilometers and less, are considered unreliable (Mearns et al. 2001; Giorgi et al. 2001). At present, analysis of the coupled atmosphere–ocean GCM (AOGCM) simulations indicates that average biases at regional scales, when simulating present-day climate, are highly variable from region to region and across models. For example, Giorgi and Francisco (2000) find that temperature biases are typically within the range of $\pm 4^{\circ}\text{C}$, but exceed $\pm 5^{\circ}\text{C}$ in some regions, particularly in the winter. They also find that precipitation biases are mostly between -40% and $+80\%$, but exceed 100% in some regions. Thus, a high priority for climate research is to improve the downscaling of GCM climate change to regional scales so that potential impacts can be adequately assessed (Houghton et al. 1995, 2001).

As one of the downscaling techniques, regional climate models have shown promising performance in reproducing the regional detail in surface climate characteristics as forced by regional details, such as topog-

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raphy, lakes, the coastline, and land-use distribution. For regional scales of 10^5 – 10^6 km², regional climate models (RCMs) that are driven by observed boundary conditions generally show area-averaged temperature biases within 2°C and precipitation biases within 50% of the observations (Giorgi et al. 2001). However, Giorgi et al. (2001) have proposed a more systematic and wider application of RCMs to adequately assess their performance and uncertainties in producing the regional climate information. To serve this purpose, intercomparison projects on regional climate modeling are being conducted (Takle et al. 1999; Curry and Lynch 2002; Anderson et al. 2003). The Regional Climate Model Intercomparison Project (RMIP) for Asia has been established to study the performance of an ensemble of RCMs when simulating East Asian climate. Ten research groups from the Asia–Pacific area are currently participating in the project, and eight of them have contributed their simulation results to RMIP’s phase one.

Simulating regional climate poses difficulties, such as capturing effects of forcing and circulation at the planetary, regional, and local scales, along with teleconnection effects of regional anomalies. These processes are characterized by a range of temporal variability scales and can be highly nonlinear. The East Asian summer monsoon is characterized by marked variability at seasonal, interannual, and interdecadal time scales (Fu and Zheng 1998). The uncertain timing of monsoon onset and the irregular pace of its seasonal, northward progression strongly influence water availability for agriculture and urban consumption (Tao and Chen 1987; Wu and Zhang 1998). Interannual changes, such as those linked with the ENSO cycle, affect the frequency of droughts, floods, and other weather extremes that occur during the summer monsoon (Fu and Teng 1993; Ju and Slingo 1995; Fasullo and Webster 2002). Finally, on decadal-to-century time scales, the rapidly growing economy and population of East Asia presents anthropogenic influences that may also alter monsoon behavior (Fu and Zheng 1998; Quan et al. 2003). However, coarse-resolution climate models generally fail to give satisfactory simulations of the East Asian monsoon (Lau and Yang 1996; Yu et al. 2000).

To date, most studies of regional climate change over East Asia have used output of GCMs without applying any downscaling techniques (Hume et al. 1992; Zhao and Wang 1994). However, a relatively high degree of uncertainty exists in the regional climate change information of East Asia from GCMs, which results from the scenario’s construction, such as future emission variations and the GCMs’ modeling of the climate responses to a given scenario. Several researchers have

used RCMs for simulating the regional climate of East Asia. Many of these studies have shown that RCMs can simulate the spatial detail of monsoon climate better than GCMs (Liu et al. 1994, 1996; Fu et al. 1998; Lee and Suh 2000). However, multiyear simulations must be used to provide meaningful climate statistics and to identify significant model errors. Therefore, a more systematic evaluation of RCMs applied for this region is strongly recommended. RMIP seeks to improve further RCM simulations of the East Asian climate by evaluating its strengths and weaknesses in a common framework. The specific objectives of RMIP are

- 1) to assess the current status of East Asian regional climate simulation,
- 2) to provide a scientific basis for further RCM improvement, and
- 3) to provide scenarios of East Asian regional climate change in the twenty-first century based on an ensemble of RCMs that are nested within a GCM.

PROJECT DESIGN. A three-phase simulation program is underway to meet these objectives.

- Phase one: This 18-month simulation (March 1997–August 1998) covers a full annual cycle—East Asian drought and heat waves during the summer of 1997, and flooding in Korea, Japan, and the Yangtze and Songhua River valleys of China, during the summer of 1998. Phase-one tasks entail examining model capabilities to reproduce the annual cycle of monsoon climate and to capture extreme climate events. To date, nine models from five countries have contributed to RMIP’s phase one (Table 1). These include eight limited-area models and one global variable resolution model, the Conformal-Cubic Atmospheric Model (CCAM). Detailed model information is listed in the appendix.
- Phase two: This 10-yr simulation (January 1989–December 1998) assesses the models’ ability to reproduce statistical behavior of the Asian monsoon climate.
- Phase three: Simulations with RCMs driven by GCM output under different forcing scenarios, including changes of atmospheric CO₂ concentration, sulfate aerosol emissions, and land cover are made. Phase-three tasks aim at providing improved climate change scenarios and uncertainty estimates for East Asia through an ensemble of model simulations.

The simulation domain (Fig. 1) covers most of Asia and parts of the surrounding ocean waters in order to encompass the Asian monsoon circulation internally.

Standard resolution is 60 km, resulting in a grid of 111 (latitude) × 151 (longitude) points. Except for Australia's Commonwealth Scientific and Industrial Research Organization (CSIRO) Division of Atmospheric Research Limited Area Model (DARLAM), which uses a polar stereographic projection, all of the participating RCMs use a Lambert conformal projection with standard latitudes at 15° and 55°N. Phases one and two use initial and lateral boundary conditions supplied by the National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR) reanalysis (Kalney et al. 1996), whereas phase three will use output from simulations produced by CSIRO.

VALIDATION DATA.

A key part of RMIP is a comparison of models with observations. To this end, we have assembled a rich database of 710 observing sites for which 514 have daily records. These sites provide observations of temperature and precipitation. We complement this database with gridded analyses of monthly precipitation from Xie and Arkin (1997), for the areas where station data are either sparse or not available, several fields from the NCEP–NCAR reanalysis (Kalnay et al. 1996), and sea level pressure from the Japan Meteorological Agency.

TABLE 1. Properties of participating RMIP models for phase one.

Model	RIEMS	DARLAM	CCAM	JSM_BAIM	RegCM	RegCM2a	RegCM2b	ALT. MM5/LSM	SNU RCM
Group leader	C. Fu	J. McGregor	J. McGregor	Y. Sato	J. Kim	M. Suh	H. Kato	W. Gutowski	D. Lee
Country	China	Australia	Australia	Japan	South Korea	South Korea	Japan	United States	South Korea
Vertical levels	σ -17 levels	σ -18 levels	σ -18 levels	σ -23 levels	σ -15 levels	σ -15 levels	σ -14 levels	σ -23 levels	σ -23 levels
Dynamic process	Hydrostatic	Hydrostatic	Hydrostatic	Hydrostatic	Hydrostatic	Hydrostatic	Hydrostatic	Nonhydrostatic	Nonhydrostatic
Lateral boundary condition	Linear relaxation	Exponential relaxation	Exponential relaxation	ER+spectral coupling	Exponential relaxation	Exponential relaxation	Exponential relaxation	Linear relaxation	Exponential relaxation
Convective scheme	Kuo–Anthes	Arakawa–Gordon	Arakawa–Gordon	Moist convective adjustment	Grell	Kuo–Anthes	Kuo–Anthes	Betts–Miller	Grell
Land surface	BATS	Kowalczyk	Kowalczyk	BAIM	BATS	BATS	NCAR/LSM	NCAR/LSM	NCAR/LSM
Planetary boundary layer scheme	Holtslag	Louis	Louis	Yamada level 2 Louis scheme	Holtslag	Holtslag	Holtslag	MRF	MRF
Longwave radiation scheme	CCM3	GFDL	GFDL	Sugi	CCM3	CCM2	CCM3	CCM2	CCM2
Shortwave radiation scheme	CCM3+ Aerosol	Lacis and Hansen	Lacis and Hansen	Lacis and Hansen	CCM3+ Aerosol	CCM2	CCM3	CCM2	CCM2

INITIAL RESULTS FROM PHASE ONE.

Contour plots over the RMIP domain of seasonal averages in daily mean, maximum, and minimum temperatures (not shown) reveal that all of the models reproduce the observed spatial patterns and annual cycles of these fields. Model temperatures tend to have a cool bias, with a smaller magnitude in the low latitudes. The largest cool biases tend to occur over the arid and semiarid regions of northern China.

Because of their dense station data available for validation, three regions of the mainland part of China, the Japanese islands, and the Korean peninsula (represented by A, B, C, respectively, as shown in Fig. 1) are chosen to evaluate the models' abilities in simulating the surface climate. No ocean points are included in these three regions.

Figure 2 shows model-simulated average temperature biases in these three subregions. The models generally have a cool bias in winter (December–January–February) of about -4°C , except for the Meteorological Research Institute, Japan (MRI) model, which is 5° – 6°C over Korea and Japan, and DARLAM, which shows relatively little bias. The models generally have smaller biases over China than Korea and Japan, though this may be a consequence of averaging over a larger region for China. Most models also have a cool bias in summer (June–July–August), ranging from -4° to -1°C . The exceptions are the Regional Integrated Environmental Model System (RIEMS), which is too warm in all three regions (1° – 3°C), and DARLAM and the MRI model, which are 1° – 3°C too warm over Japan and Korea.

It is also worth noting that Fig. 2 presents significant diversity among the models. Some models have biases of less than $\pm 1^{\circ}\text{C}$, while some models have biases as large as $\pm 6^{\circ}\text{C}$, which is much greater than the average bias values in Houghton et al. (2001), mentioned in the introduction. This inconsistency suggests the need for further systematic evaluation of RCM performance over different regions and across more models, before making any general conclusions.

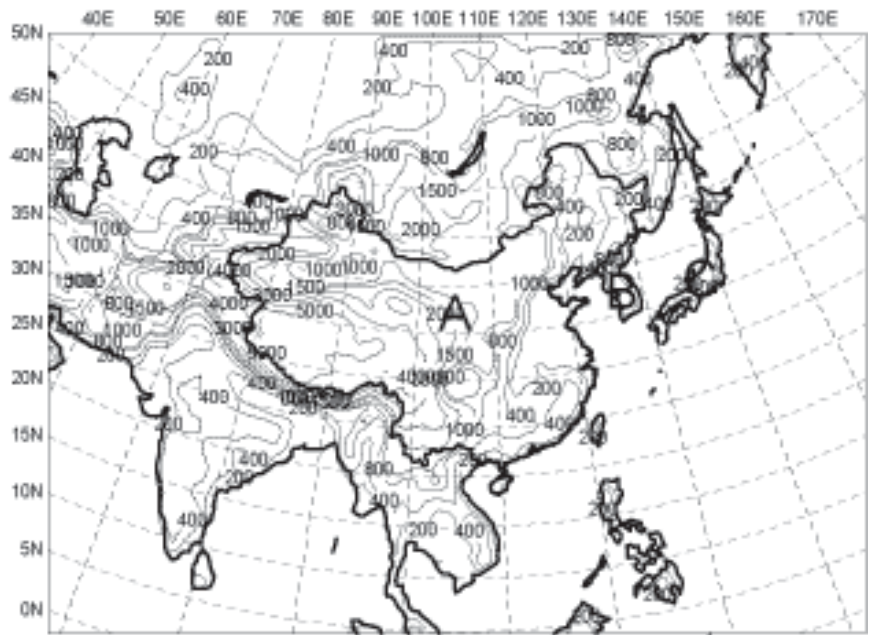


FIG. 1. MIP simulation domain, showing terrain elevations. Letters mark centers of the analysis regions: mainland China (A), Korean peninsula (B), and Japanese islands (C).

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Taking the ensemble average of a group of models is one approach for possibly reducing bias. The simple ensemble average, (i.e., arithmetic average) bias of the nine participating models (last row of Fig. 2) also shows a cold bias in temperature, but less bias than most of the individual models. The mean biases of temperature simulation over China, Korea, and Japan are -2.05° , -0.30° , and 0.01°C , respectively, for the summer of 1998 and -0.96° , -2.99° , and -2.81°C , respectively, for the winter of 1997. These values are close to the average value of temperature biases in Houghton et al. (2001).

Model precipitation usually agrees better with observations in winter than in summer (not shown). The models generally produce too much precipitation in high latitudes, but, overall, tend to reproduce the annual cycle across most of China, Korea, and Japan except in the western arid and semiarid regions. As with temperature, the three areas of the China mainland, Japanese islands, and Korean peninsula are chosen for a quantitative assessment of precipitation bias, which is shown in Fig. 3. In winter, most models show a bias of less than $\pm 30\%$, while in summer most models show a dry bias in Korea, but a wet bias over Japan. There are mixed positive and negative biases from different models over China: CCAM shows a wet bias, while RIEMS and ALT fifth-generation Pennsylvania State University (PSU)–NCAR Mesoscale Model (MM5)/Bonan (1996) Land Surface Model (LSM) show a dry

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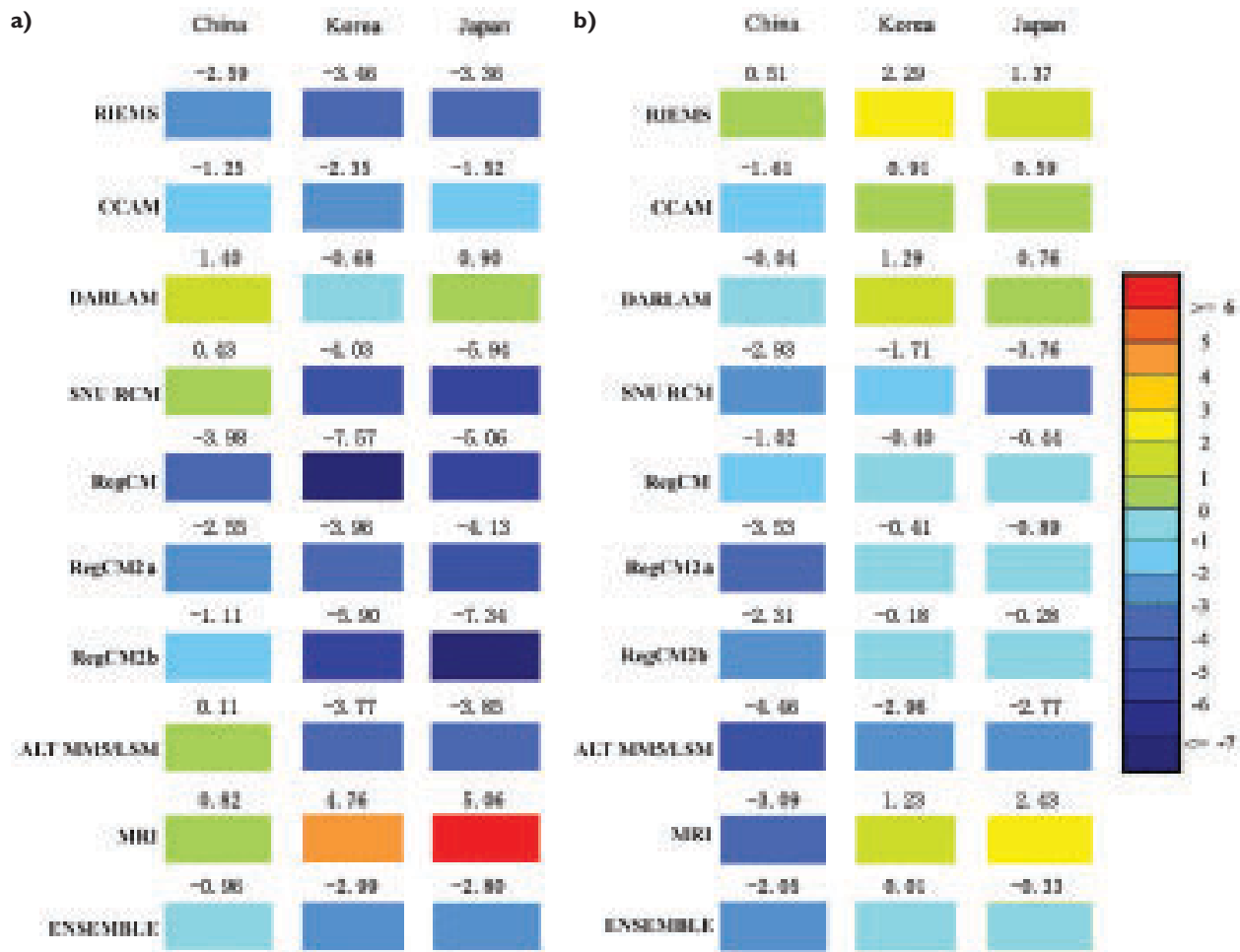


FIG. 2. Seasonal averaged surface air temperature bias ($^{\circ}\text{C}$) in (a) winter 1997 and (b) summer 1998.

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bias. Compared to most individual models, the ensemble average precipitation bias is relatively small in winter 1997, ranging from -5% to $\sim 6\%$. In the summer of 1998, the ensemble average precipitation bias is up to -30% over the Korean peninsula, which is much larger in magnitude than the bias for China and Japan (-6% and 10% , respectively). The above analyses show that the ensemble average results are better than most of the individual models' performance, which suggests that there is value in using an ensemble of RCMs when projecting future climate to get a mean change and range of possible changes. In order to understand the possible reasons for the bias in the surface climate simulation, the atmospheric circulation in both the lower and higher latitudes has been analyzed further and will be presented in other related papers.

One of RMIP's goals is to examine the capacities of regional models to simulate extreme climatic events. During the RMIP phase-one simulation period, two climatic extremes occurred—the drought in North China in the summer of 1997 and heavy rains that

caused severe flooding in the Yangtze River valley and northeast China in the summer of 1998. Most models captured the extreme events of both the summer drought in 1997 and the heavy rainfall in 1998, although the simulated intensities are different from observations. Figure 4, for example, compares the nine simulations against observations for the case of heavy rainfall during 11–20 June 1998 in the Yangtze River valley (framed area in Fig. 4). This period is 15 months into the phase-one simulation period, so model output is strongly a product of model climatology, as opposed to initial conditions. Most models reproduce, to some degree, the heavy rainbelt over the Yangtze valley and its related 850-hPa low-level jet. Simulated south-to-north moisture transport at this level (not shown) appears to explain much of the differences between the models' results. Figure 4 also is an example of the models' tendency to produce too much precipitation at higher latitudes.

More questions are raised than answered by these initial results, such as the following:

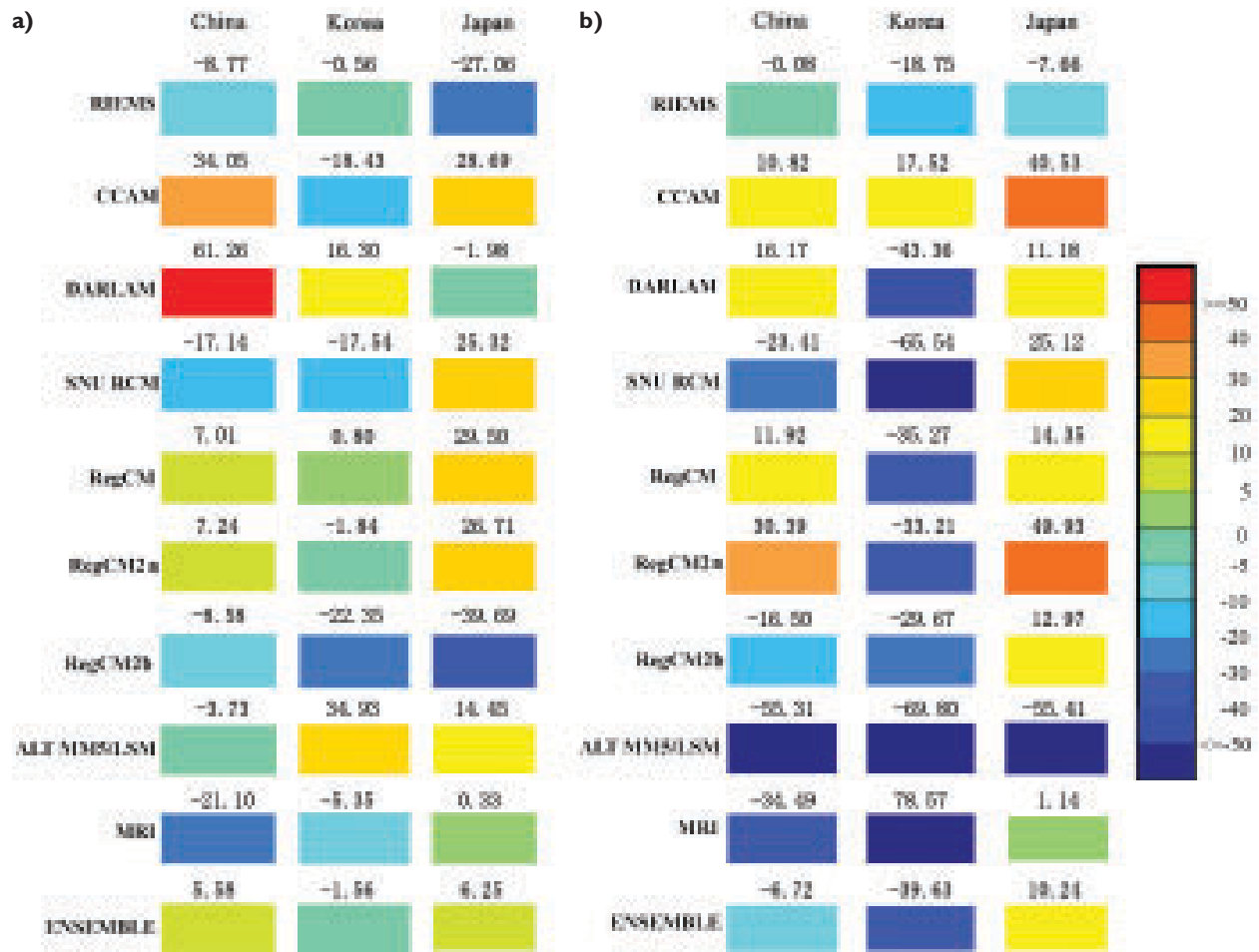


FIG. 3. Seasonal total precipitation bias (%) in (a) winter 1997 and (b) summer 1998.

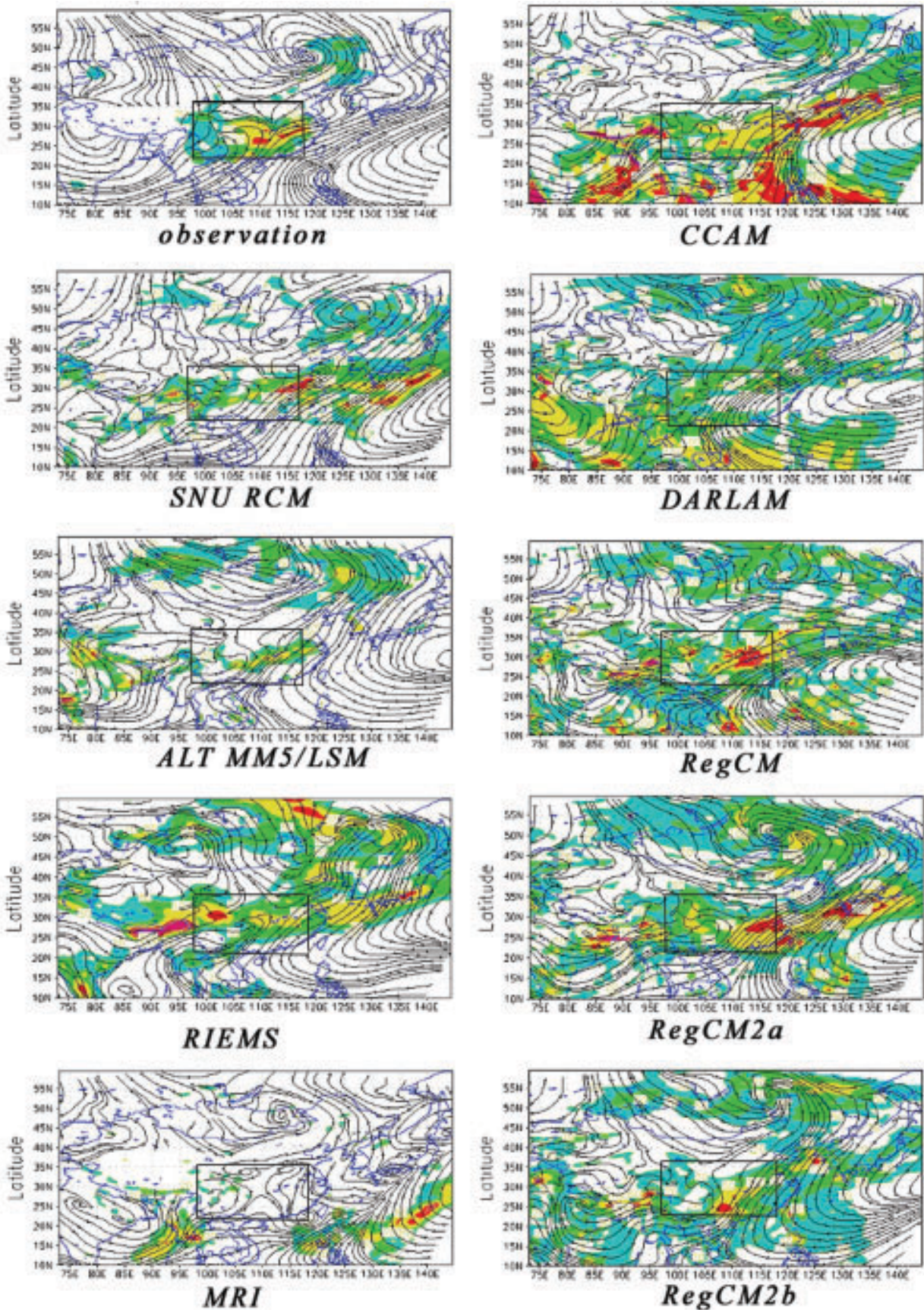
- Are problems in the simulation of precipitation related to the convection schemes, lateral boundary treatment, soil moisture initialization, or microphysics of precipitation?
- Are cold or warm biases over the regions related to cloud simulation, longwave radiation simulation, land surface schemes, or snow and sea ice treatment?

Analysis of these and other questions is continuing, with a focus on comparisons between models that group together according to a dynamical scheme, parameterizations for convection, radiation, etc., or the method for ingesting lateral boundary conditions.

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Phase-two simulations were finished recently, and intercomparison studies are underway. Phase-three simulations, which involve nesting the RCMs within a GCM, are still in the planning stage. These simulations are expected to produce climate scenarios in Asia for part of the twenty-first century as a contribution to the IPCC fourth assessment report.

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Fig. 4. Total precipitation (mm) and 850-hPa streamlines for 11–20 Jun 1998.

model simulations, and all of the other scientists who helped in the model simulations, as well as data collection and preparation. We appreciate the help of Dr. Murari Lal from the Center for Atmospheric Science, Indian Institute of Technology, India, Mr. Jang Hyon Chol from the State Hydrometeorological Administration, North Korea, Mr. Ryu Gi Ryol from the Central Forecasting Institute, North Korea, and Dr. Gomboluudev Purevjav, Mongolia, for their efforts in collecting the station data used for validation. A special acknowledgment goes to the anonymous reviewers for their valuable comments and suggestions for improving the paper.

APPENDIX: THE PARTICIPATING RCM RESEARCH GROUPS AND BRIEF INTRODUCTION OF THEIR MODELS. This section supplements information on the models provided in Table 1.

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- 1) From the START Regional Center for Temperate East Asia, China (TEA-RC), the Regional Integrated Environmental Model System (RIEMS) is used in the RMIP phase-one simulation. This model was developed at TEA-RC, and its dynamic component is the fifth-generation Pennsylvania State University (PSU)-NCAR Mesoscale Model (MM5; Grell et al. 1995). Some important physical parameterization schemes include the Biosphere-Atmosphere Transfer Scheme (BATS; Dickinson et al. 1993), a high-resolution boundary layer scheme, the Anthes-Kuo cumulus parameterization scheme (Anthes 1977; Anthes and Keyser 1983), and the revised NCAR Community Climate Model, version 3 (CCM3) radiative transfer scheme (Briegleb 1992) with aerosol effects. This model has had previous application to the simulation of climate in East Asia. (Fu et al. 2000)
- 2) Atmospheric Sciences Program, School of Earth and Environmental Sciences, Seoul National University (SNU), South Korea, simulations use a version of the Regional Climate Model version 2 (RegCM2a; Giorgi et al. 1993a,b; Lee and Suh 2000), which was developed originally at NCAR. Its dynamic core is the fourth-generation PSU-NCAR Mesoscale Model (MM4).
- 3) From the Atmospheric Sciences Program, School of Earth and Environmental Sciences, Seoul National University, South Korea, a regional climate model SNU RCM, which is used in RMIP's phase-one simulation, is adapted from the MM5 (Grell et al. 1995), coupled with Bonan's (1996) Land Surface Model (LSM) (Lee and Kang 1999).
- 4) From the Central Research Institute of Electric Power Industry, Japan, a revised RegCM2b has been developed and used. Its dynamic component

is the same as RegCM2 (Giorgi et al. 1993a,b), but its radiative transfer scheme is from the NCAR CCM3 (Briegleb 1992). A new land surface scheme model is coupled into the model in place of the original BATS (Dickinson et al. 1993). It has been used previously to simulate both winter and summer climate in East Asia.

- 5) The Commonwealth Scientific and Industrial Research Organization's Division of Atmospheric Research Limited Area Model (DARLAM) has evolved from a semi-Lagrangian model proposed by McGregor (1996). Its physical parameterizations include a canopy scheme with six soil layers for temperature and moisture, the U.S. Geophysical Fluid Dynamics Laboratory radiation scheme, interactive diagnosed clouds, a mass flux cumulus parameterization, shallow convection, and a stability-dependent surface scheme. It has been used to simulate the climate of Australia, New Zealand, and South Africa. Compared to the CSIRO GCM, it shows great improvement in the precipitation patterns (McGregor 1997).
- 6) From Yonsei University, South Korea, a revised Regional Climate Model version 1 (RegCM) (Giorgi 1990) is used for the RMIP phase-one simulation.
- 7) Iowa State University's ALT MM5/LSM (Wei et al. 2002), based on the MM5 (Grell et al. 1995) coupled with Bonan's (1996) LSM, is used in this study. This version gives an alternative to the MM5 simulation from Seoul National University by using the Betts-Miller convective scheme (Betts and Miller 1993) in place of the standard Grell scheme (Grell 1993).
- 8) From the Meteorological Research Institute, Japan (MRI), the MRI regional climate model Japan Spectral Model (JSM)_Biosphere-Atmosphere Interaction Model (BAIM) is composed of three models. The outer model is the MRI-CGCM. The intermediate model is the fine-mesh limited-area model (FLM). The inner model is the JSM. The modified FLM has 16 layers, and a level-two closure is applied to represent the vertical turbulent diffusion. Calculation of the surface flux is based on Monin-Obukhov similarity theory (Sasaki et al. 2000).
- 9) From the Division of Atmospheric Research, Commonwealth Scientific and Industrial Research Organization, Australia, the Conformal-Cubic Atmospheric Model (CCAM) has been developed as a stretched-grid global model with a quasi-uniform grid, derived by projecting the panels of a cube onto the surface of the earth. It can be run in stretched-grid mode to provide high resolution over any se-

lected region. CCAM provides great flexibility for dynamic downscaling from any global model, requiring only sea surface temperatures and far-field winds from the host model (McGregor 1996; McGregor and Katzfey 1998). In the RMIP simulation, it has enhanced resolution of about 60 km over Asia. Model variables are nudged back to the NCEP–NCAR reanalysis outside of the study region.

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