Simulation of Spring to Summer Monsoon Transition over East Asia with an NCAR Regional Climate Model

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1 INTRODUCTION

The Asian monsoon has a profound influence on the social and economic conditions of over 60% of the earth's population. For centuries, successful forecast of monsoon rainfall has been a matter of great concern for the people and countries in Asia and surrounding areas. The Asian summer monsoon regime can be divided into two major components: (a) the east Asia monsoon covering the east Asia, Indochina Peninsula, the South China Sea (SCS), and the tropical western Pacific; and (b) the Indian monsoon encompassing the Indian Ocean, India, the Arabian Sea, and the Bay of Bengal. The Indian monsoon is dominated by summer heavy rainfall over a broad area and interrupted by intraseasonal monsoon breaks (Krishnamurti and Bhalme, 1976), however, the east Asian monsoon has distinctive seasonal rain belt patterns that alternate between quasi-stationary phase and northward jump stage corresponding to the progression of the Mei-Yu (Baiu) system (Tao and Chen, 1987) from spring to summer. Previous studies, both observational and modeling, were mostly focused on events occurring in the two extreme seasons, summer (June-August) and winter (December-February), for the east Asian monsoon. Readers are referred to two review papers (Tao and Chen, 1987; Boyle and Chen, 1987). Climatologically, the rapid establishment of convection over SCS and surrounding regions signals the earliest stage of the onset of the Asian summer monsoon (SCSMEX Science Plan, 1995). Understanding and improving the prediction of weather and climate over the SCS will have enormous impact on the agriculture, social and economic development in countries and regions in Southeast Asia.

Several simulations of the first generation version of the National Center for Atmospheric Research (NCAR) regional climate model (RegCM) have shown that, due to high-resolution topography and soil physics representation, the model can capture the regional patterns of precipitation, temperature, and soil hydrology as affected by the forcing of local terrain and land vegetation cover (e.g., Giorgi and Mearns, 1991; Liu et al., 1994). A summer season climate over the east Asia was simulated with RegCM (Liu et al., 1994) and was used to validate the model's capability to produce basic characteristics of summer monsoon climate over the region. Taking the ridge of the Tibetan Plateau as the western boundary, Liu et al. (1994) simulated the entire process of a summer monsoon over the east Asia and the accompanying rain belt, the paths of tropical storms, and patterns of soil moisture; and validated the RegCM by comparing with the National Centers for Environmental Prediction (NCEP) data sets. The results of the previous simulations (Giorgi and Mearns, 1991; Liu et al., 1994) indicate that the RegCM can simulate reasonably well spatial patterns of atmospheric circulation, precipitation, and ground temperature, especially the terrain-induced local strong precipitation and temperature center. Since only the east half of the Tibetan Plateau was included in Liu et al.'s (1994) simulation, the orographic effect on the monsoon might not be complete.

While the studies on the two extreme monsoons (summer and winter) have advanced our knowledge of regional monsoon phenomena, many aspects of the east Asian monsoon especially the transition between the summer and winter monsoons remain uncertain. Understanding the mechanisms of monsoon onset improves the intraseasonal and interannual prediction. Recently, an international South China Sea Monsoon Experiment (SCSMEX) was recently initiated to provide a better understanding of the key physical processes for the onset, maintenance and variability of the monsoon over Southeast Asia and southern China leading to improved prediction (SCSMEX Science Plan, 1995).

As one of the SCSMEX modeling efforts, we selected the second generation version of the regional climate model (RegCM2) developed at the National Center for Atmospheric Research (NCAR) to simulate the processes of spring to summer monsoon transition over the east Asia with consideration of full effects of the Tibetan

Plateau. The simulation period is March-July 1991, and the model is driven by meteorological conditions obtained from large-scale analyses of observations provided by the European Center for Medium-range Forecast (ECMWF) T63 fields. Our model domain was larger than Lie et al. (1994) and includes northern Indian Ocean, southeast Asia, and northwest Pacific. The whole Tibetan Plateau was inside the domain. The model was evaluated by comparing output with European Centre for Medium-Range Weather Forecast (ECMWF) T63 analysis fields.

2 MODEL DESCRIPTION

2.1 REGIONAL CLIMATE MODEL

During the last few years, a second generation version of the regional climate model, called RegCM2, has been developed by staff and visitors at the NCAR Climate Change Research (CCR) Section. RegCM2 is a modified version of the NCAR/Pennsylvania State University mesoscale model MM4 for climate application. The dynamical structure of RegCM2 is essentially the same as MM4 (Anthes et al., 1987) that is σ-coordinate, primitive equation, grid point limited-area model with compressibility and hydrostatic balance, except for a split-explicit time integration scheme which is used in RegCM2 to improve model efficiency. The physics of RegCM2 includes several components from NCAR Community Climate Model (CCM2) as well as some additional physics parameterization. The radiative transfer package is from the CCM2 and describes the radiative effects of ozone, water vapor, carbon dioxide, oxygen and clouds (Briegleb, 1992). The non-local eddy diffusion formulation of Holtslag et al. (1990) is used for planetary boundary layer calculation. The surface process is parameterized by the latest version of the Biosphere-Atmosphere Transfer Scheme (BATS), which describes the effect of vegetation and interactive soil moisture on the surface-atmosphere exchange of momentum, heat, and moisture (Dickinson et al., 1993). BATS comprises a vegetation layer, a snow layer, and three soil layers and it calculates the full surface hydrological cycle. The precipitation is parameterized by several different schemes. Non-convective precipitation can be represented via an implicit scheme, whereby supersaturated water immediately precipitates, and an explicit scheme including prognostic equations for cloud water and rain water (Hsie et al., 1984). Convective precipitation is parameterized via two cumulus convection schemes: a simplified Kuo-type (Kuo, 1974) formulation (Anthes, 1977; Anthes et al., 1986) and a mass flux scheme which accounts for the effects of penetrative downdrafts (Grell 1993). The readers are referred to Giorgi et al. (1993 a,b) for complete description of RegCM2.

2.2 DOMAIN DESCRIPTION

Figure 1 depicts the topography for the selected domain. The simulation area (6930 km × 7020 km) consists of southeast Asia (including the whole Tibetan Plateau), northwest Pacific Ocean, and northeast Indian Ocean, with center at 30°N, 100°E and a horizontal grid point spacing of 90 km. Sixteen pressure levels were used with the top at 10 mb. The topography data (30' resolution) were obtained from NCAR. The terrain inclines generally from the Tibetan Plateau (with a maximum height 5.3 km) to the edges of the domain. Coastal flat lands and various islands are found in the northern Indian Ocean and the northwestern Pacific Ocean. At the present horizontal resolution, we can identify the basic features of the coastlines and some isolated mountains in southeast Asian continent as well as in islands such as in Borneo, Japan, Philippines, and Sri Lanka.

A soil water availability function was used for computing the soil water content by using 13 specified vegetation types (Giorgi and Bates, 1989). Figure 2 shows the initial vegetation types with the sea surface as the 7th type. Dominant deciduous and coniferous forests cover south and central China, Japan, Korea, and northeast China, while range grass spreads over India,Mongolia, and northwest China. There are small areas of tropical forest in southern India, Taiwan, north Philippines, and Indo-china Peninsula.

2.3 INITIAL AND LATERAL BOUNDARY CONDITIONS

The initial and horizontal lateral boundary conditions for wind, temperature, water vapor, and surface pressure are interpolated from analyses of observations from the ECMWF. For the present study, they were projected on a spectral T63 grid, corresponding to a horizontal resolution of about 2°, and a vertical resolution of 16 pressure levels. The initial conditions were the fields on 00Z March 1, 1991. The RegCM2 was integrated for six months. The lateral boundary conditions were provided via a relaxation method (Anthes et al., 1987) and updated every 12 hours. Boundary condition data are available at 12-hour intervals. Sea surface temperature (SST) was updated daily from the interpolation of a set of observed monthly grid data with a resolution of 2° × 2° (Shea et al., 1992). Note that the present set-up is quite in line with what would be used for coupled RegCM2-Ocean modeling experiment.

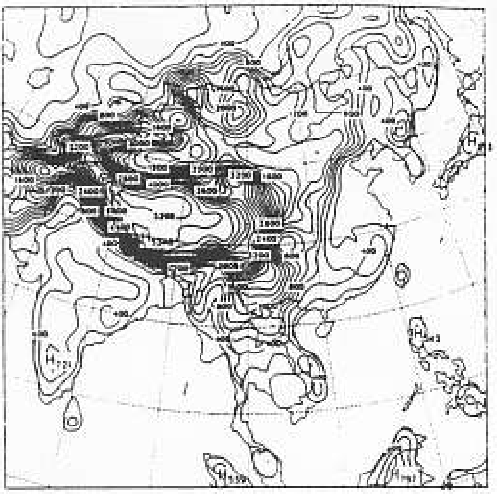

Figure 1 – Model domain and topography over the southeast Asia.

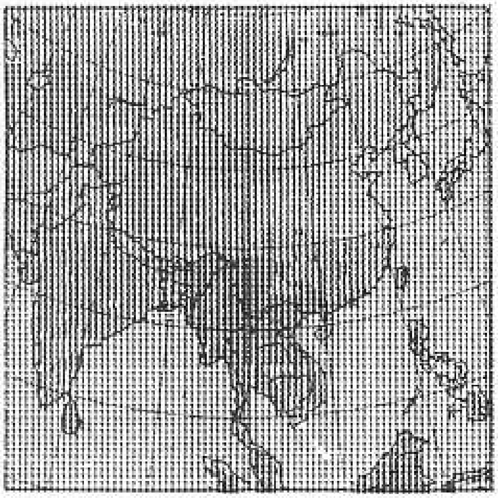

Figure 2 – Surface type: (1) urban land, (2) agricultural land, (3) range/grass land, (4) deciduous forest, (5) coniferous forest, (6) mixed forest, (7) water, (8) marsh, (9) desert, and (10) tundra.

Model Variable	April	May	June
100-mb Height (m)	-14.5	-21.6	-6.58
500-mb Height (m)	-5.98	-6.72	-7.28
Surface Pressure (mb)	0.245	0.678	1.31
700-mb Humidity (g/kg)	0.222	0.199	0.704
Surface Temperature (° C)	-3.3	-4.77	-6.01

Table 1. Overall bias of the model variables.

Model Variable	April	May	June
100-mb Height (m)	26.2	44.1	29.2
500-mb Height (m)	13.9	17.1	11.6
Surface Pressure (mb)	2.11	2.39	3.74
700-mb Humidity (g/kg)	0.753	0.978	1.44
Surface Temperature (° C)	5.63	7.14	8.39

Table 2. Root-Mean Square Errors of the model variables.

2.4 OBSERVED DATA USED FOR COMPARISON

The simulated monsoon transition circulations and related thermal features were compared with the ECMWF analyzed data, including wind, precipitation, and surface air temperature. Since the purpose of this study is to investigate climatological characteristics of Asian monsoon transition, thus, we compute monthly averaged values for various quantities (geopotential height, wind, humidity, precipitation, surface air temperature, etc.). The difference of the simulated and observed of any variable ψ is a function of space (x, y, σ), and time t (in month),

$$\Delta\psi(x_i, y_j, \sigma_k, t) = \psi_s(x_i, y_j, \sigma_k, t) - \psi_o(x_i, y_j, \sigma_k, t). \quad (1)$$

where ψ_s and ψ_o are the variables from simulation and observation, respectively. We define two parameters, the bias and the root-mean-square (RMS),

$$BIAS = \frac{1}{M}\sum_i \sum_j \Delta\Psi(x_i, y_j, \sigma_k, t), \quad (2)$$

$$RMSE_\psi(\sigma_k, t) = \sqrt{\frac{1}{M}\sum_i \sum_j |\Delta\Psi(x_i, y_j, \sigma_k, t)|^2} \quad (3)$$

to evaluate the model performance at level σ_k. Here M is the total number of horizontal points.

The model performance is shown in Tables 1and 2.

3 MONSOON TRANSITION IN EAST ASIA

The spring to summer monsoon transition is featured by (a) weakening of the mid-latitude stationary wave at

500-mb (i.e., weakening of the trough centered about the longitude of Japan), (b) strengthening and northward expanding of the western Pacific subtropical high, (c) along the east Asian coast, from south to north shifting of the low-level north-northeasterly winds to the south-southwesterly winds, and (d) three steady phases of rain belts and two sudden leaps, rapid transitions between the two adjacent phases. From the model simulation during 1 March - 31 July 1991, the first three features can be identified by the time-latitude sections (at 115°E) of 500-mb geopotential height (Figure 3) and 850-mb latitudinal wind component (Figure 4), and the last feature can be seen from the time-latitude section of precipitation (Figure 5) averaged between 110°-120°E. The data are smoothed through a 5-day moving average.

For the time-latitude section (at 115°E) of 500-mb geopotential height, the contour of 5600 m can be regarded approximately the extension of the trough along the east Asian coast. The weakening of the mid-latitude stationary wave can be represented by the northward retreat of this contour (5600 m). Furthermore, the contours of 5840 m and 5880 m can be regarded approximately as the north boundary and the center position of the subtropical high, respectively. The January climatology of 500-mb geopotential field shows that the contour of 5600 m reaches 30°N near the China coast (Crutcher and Meserve, 1970).

The spring to summer monsoon transition (March to July) and associated northward retreat of the stationary wave and the northward progress of the subtropical high and the rain belt can be divided into five phases: (1) early spring gradual northward retreat of the stationary wave; (2) late spring - early summer violent variations of the stationary wave; (3) monsoon onset and rapid northward retreat of the stationary wave and northward progress of the subtropical high and the rain belt; (4) relative steady phase; and (5) violent change of the tropical high's position. Among them, the last three phases during the summer monsoon season were discussed by Ding (1991) and Liu et al. (1994). Note that the following discussion is specific for the spring and summer of 1991.

During the first phase (1 March to 10 April 1991), the 5600 m contour (at 500-mb) was northward shifted from 32°N to 40°N, indicating the northward retreat of the stationary wave (Figure 3). With this retreat, the low-level (850-mb) convergence zone (Figure 4) and the related sporadic rain events (Figure 5) over China also moves towards north from 23°N to 38°N. However, the 5840 m contour was about 22°N with a small fluctuation (Figure 3), indicating the quasi-steady position of the subtropical high with the north bound of 22°N. During the second phase (10 April to 15 May), the 5600 m contour (at 500-mb) was fluctuated between 30°N and 48°N (Figure 3), indicating the violent variation of the stationary wave. The low-level (850-mb) convergence zone was pushed south from 37°N to 27°N and a pre-monsoon rain belt was simulated between 23°-30°N from 20 April to 10 May. The 5840 m contour was slowly fluctuated between 25°N and 22°N (Figure 3), indicating the preparation stage of the summer monsoon onset. The monsoon onset (15 to 20 May) was featured by rapid northward movement of the 5840 m contour (at 500-mb) from 22°N to 35°N (Figure 3), indicating the northward advance of subtropical high. With this advance, the low-level (850-mb) convergence zone (Figure 4) and the related monsoon rain events (Figure 5) over China also moves toward north. After the monsoon onset, there are a relative steady phase (Phase IV, 20 May to 20 June) and a violent phase (Phase V, 20 June - 20 July). During Phase IV, the 5840 m contour (at 500-mb) retreated southward right after the monsoon onset from 35°N and then fluctuated slowly around 32°N (Figure 3). With this quasi-steady state of the north boundary of the 500-mb subtropical high, the low-level (850-mb) convergence zone (Figure 4) and the related monsoon rain events (Figure 5) over China expanded between 24°N and 36°N. During Phase V, the 5840 m contour (at 500-mb) advanced northward to 40°N (Figure 3). With this violet change of the subtropical high position, the low-level (850-mb) convergence zone (Figure 4) and the related monsoon rain events (Figure 5) over China jumped northward between 36°N and 46°N (over the Yellow River area).

4 CONCLUSIONS

In this paper we have presented an application of an NCAR RegCM2 to the simulation of a spring to summer monsoon transition (March-July 1991) over east Asia. The results indicate that the RegCM2 can simulate reasonably well spatial patterns of the atmospheric circulation, precipitation, ground temperature. In particular, it can capture the northward progress of the subtropical high and the rain belt during the spring to summer monsoon transition.

The present simulation provides some special evidence for evaluating the model performance. Spring to summer monsoon transition is governed by weakening of the mid-latitude stationary waves and strengthening and northward expanding of the western Pacific subtropical high. The model successfully simulated the south to north shifting of the low-level north-northeasterly winds to the south-southwesterly winds and associated three steady phases of rain belts and two sudden leaps between the two adjacent phases.

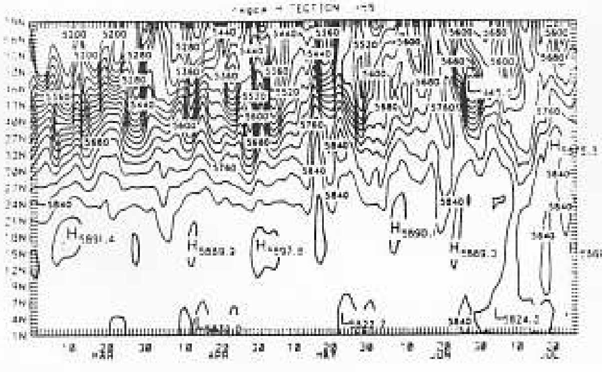

Figure 3 – **Temporal-latitudinalsection of 500-mb geopotential height (m) along 115°E for RegCM2 simulation. A 5-day moving average is applied.**

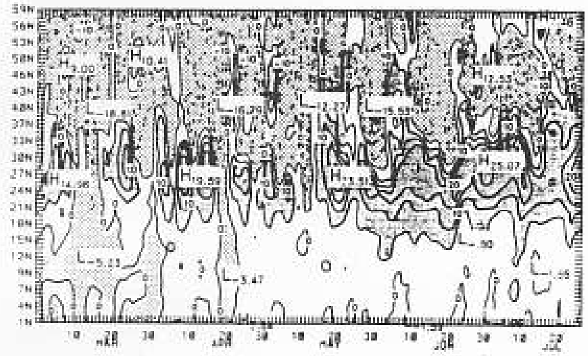

Figure 4 – **Same as Figure 3 except for 850-mb latitudinal wind component (m/s).**

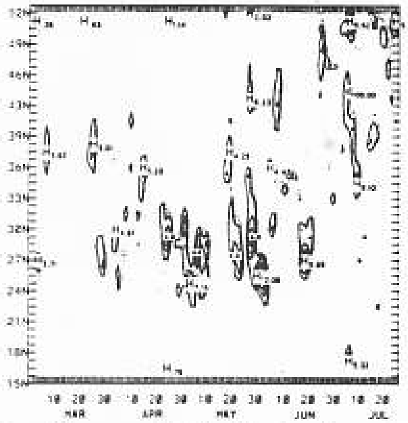

Figure 5 – **Temporal-latitudinalsection of precipitation (mm/day) averaged between 105-115°E for RegCM2 simulation. A 5-day moving average is applied.**

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REFERENCES

Anthes, R.A., E.Y. Hsie, and Y.H. Kuo, 1987: Description of the Penn State/NCAR Mesoscale Model Version 4 (MM4). NCAR Tech. Note, NCAR/TN-282+STR, 66pp.

Boyle, J.S., and T.-J. Chen, 1987: Synoptic aspects of the wintertime east Asian monsoon. *Monsoon Meteorology*, Oxford University Press, 125-160.

Briegleb, B.P., 1992: Longwave band model for thermal radiation in climate studies. *J. Geophys. Res.*, **97**, 7603-7612.

Dickinson, R.E., A. Henderson-Sellers, and P.J. Kennedy, 1993: Biosphere-Atmosphere Transfer Scheme (BATS) version 1E as coupled to the NCAR Community Climate Model. NCAR Tech. Note, NCAR/TN-387+STR, 72pp.

Giorgi, F., G. De Canio, and G.T. Bates, 1993b: Development of a second-generation regional climate model (RegCM2). Part II: Convective processes and assimilation of lateral boundary conditions. *Mon. Wea. Rev.*, **121**, 2814-2832.

Grell, G.A., 1993: Prognostic evaluation of assumptions used by cumulus parameterizations. *Mon. Wea. Rev.*, **118**, 1561-1575.

Krishnamurti, T.N., and H.N. Bhalme, 1976: Oscillation of a monsoon system. Part I: Observational aspects. *J. Atmos. Sci.*, **33**, 1937-1954.

Kuo, H.L., 1974: Further studies of the parameterization of the influence of cumulus convection on large-scale flow. *J. Atmos. Sci.*, **31**, 1232-1240.

Liu, Y., F. Giorgi, and W.M. Washington, 1994: Simulation of summer monsoon climate over east Asia with an NCAR regional climate model. *Mon. Wea. Rev.*, **122**, 2331-2348.

SCSMEX Science Working Group, 1995: *The South China Sea Monsoon Experiment (SCSMEX) Science Plan.* NASA/Goddard Space Flight Center, Greenbelt, 65pp.

Tao, S. and L. Chen, 1987: A review of recent research on the east Asian summer monsoon in China. *Monsoon Meteorology*, Oxford University Press, London, 60-92.