A Numerical Simulation Study of the Indian Summer Monsoon of 1994 using NCAR MM5

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(Manuscript received 8 August 2003, in final form 30 June 2004)

Abstract

In this study, the National Center for Atmospheric Research Mesoscale Model, NCAR MM5 adopted for the Indian region has been integrated for a four month period from 1 May 1994, to study the Indian summer monsoon during the months of June, July and August. This version of the MM5 mesoscale model has a horizontal resolution of 30 km, and 23 vertical levels. The initial and boundary conditions are taken from NCEP/NCAR reanalysis data available at 2.5° grid interval, and interpolated to the model domain.

The results indicate that the NCAR MM5 model simulates many observed features of the Indian summer monsoon on a regional scale, which otherwise cannot be simulated using a global general circulation model. The simulated features of sea level pressure, 925 hPa temperature, low level wind flow are compared with NCEP and precipitation fields with GPCP. Significant features of the monsoon circulation, such as the monsoon trough, heat low over northwest India, and mesoscale precipitation patterns are well simulated. The model precipitation is also well simulated with the strengths and locations of the maxima and minima agreeing with the observations. The advancement of the monsoon current during the onset phase, as simulated by the model, is evaluated by comparing the pentad rainfall during June, 1994, with the advancement of monsoon reported by the India Meteorological Department. Model simulated area averaged time series of precipitation, and 850 hPa geopotential for five different zones covering the Indian subcontinent are evaluated through correlation, root mean square error, bias and threat score.

1. Introduction

Atmospheric General Circulation Models (AGCM) are designed and developed to study different aspects of climate. Innumerable experiments have been performed to study differ-

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ent aspects of climate, starting from the simulation of mean climate of different seasons, to the inter-annual variability and sensitivity experiments. By now several AGCMs have been developed with differences in the use of numerical methods for the solution of the differential equations; parameterization of sub-grid scale physical processes like convection, radiation and boundary layer processes. The technological advances in computers during the last few decades have made possible at the present time, to use the AGCMs with an equivalent horizontal grid of about 200 km. It has been well established that the AGCMs are capable, in general, of simulating the mean climate, and some of the AGCMs are qualitatively able to capture the mean Asian summer monsoon rainfall distribution. In recent years, attempts have been started to simulate the climate features on a smaller scale of few tens of kilometers, in order to explore the possibility of simulating the regional climate characteristics, which could not be simulated with the rather coarser AGCM resolution. In general, the initial and boundary conditions for the integration of the regional climate models (RCMs) are taken from AGCM output at regular time intervals. This implies that the finer regional characteristics over a particular region, which otherwise cannot be obtained without a very high resolution AGCM, can be obtained by the RCM.

Regional climate studies can be found in literature since the late 1980s. Giorgi and Mearns (1999), Kato et al. (2001), Nicolini et al. (2002) present information on the state-of-the-art. There is a wide spectrum of regional climate models, such as, Regional Climate Model, or RegCM (see Giorgi and Mearns 1999; Kato et al. 2001 for details of this model and for climate studies that were carried out with this model), Colorado State University Regional Atmospheric Modeling System (CSU/RAMS), IPRC-RegCM (Wang et al. 2003), the Max-Planck-Institute/Danish Institute, HIRHAM; the UKMO unified model, regional climate model of MRI/JMA etc. These models, and several others, have been used to study the different climate problems related to different regions around the world. As examples, some of the papers that address climate variability, and related topics of different regions, are provided as

examples here; a few of these papers also study the climate change scenarios, along with present day climate simulations as control. These are, over the United States (Dickinson et al. 1989; Giorgi 1990; Giorgi et al. 1994; Dai et al. 1999), Australia (McGregor and Walsh 1993, 1994; Walsh and McGregor 1995), New Zealand (Renwick et al. 1998), Europe (Giorgi et al. 1990; Giorgi and Marinucci 1996a, 1996b), south Africa (Joubert et al. 1999), south America (Nicolini et al. 2002; Misra et al. 2002), east Asia (Kida et al. 1991; Liu et al. 1994; Hirakuchi and Giorgi 1995; Sasaki et al. 1995; Fukutome et al. 1999; Kato et al. 1999; Leung et al. 1999; Kato et al. 2001; Mabuchi et al. 2000), China (Zheng et al. 2002; Liu et al. 2003; Wang et al. 2003), east Africa (Sun et al. 1999a, 1999b) and India (Bhaskaran et al. 1996, 1998; Bhaskar Rao et al. 2001) etc. Several studies suggest that the finer features of the regional climate are better simulated by the regional climate models, as compared to those by GCMs or reanalysis. For example, Kato et al. (2001) show that the ReGCM gives a better simulation of the rainfall bands over Japan, as compared to the community climate model it has been nested with. As per Misra et al. (2002), regional climate model simulation over south America, carried out using the regional spectral model of NCEP, gives a reasonable interannual variability over south America, better than NCEP/NCAR reanalysis, due to better reproduction of Outgoing Longwave Radiation (OLR) at both high frequency (3–30 days), and intraseasonal (30–60 days) scales of variability. They conclude that study over austral summer season, during three contrasting phases of ENSO cycle, during 1998–99. Nicolini et al. (2002) use DARLAM in a one-way nested model with an AGCM to simulate south American climate during June and January. They found significant improvement of simulated near surface temperature and MSLP in nested model climatology over the GCM climatology. They could simulate a better Bolivian High during summer, which the GCM failed to simulate.

Simulation of Asian Summer Monsoon (ASM) has been the focus of many studies, due to its anomalous characteristics in the tropical circulation. The AGCM simulations have mixed success in this respect that different studies claim simulation of certain features of the

ASM, which were attributed to the use of certain schemes of sub-grid scale processes. Some model studies have been made to study the impact of increased horizontal resolution, and the results indicate that though the general circulation features improve, the smaller scale circulation features may deteriorate (Sperber et al. 1994; Stephenson et al. 1998; Chandrasekhar et al. 1999). The ability, and the limitations of the AGCMs in simulation of the Indian summer monsoon, have been discussed by Sperber and Palmer (1996) and Gadgil and Sajani (1998). Proper simulation of the Indian monsoon climate, with its typical circulation features of the seasonal reversal of winds associated with contrasted heating of Asiatic land mass and north Indian Ocean is a necessary benchmark for the performance of any model. The influence of orography, with western Ghats on the west coast of the Indian subcontinent; mountain ranges of the Myanmar on the eastern side, and the high Himalayan mountain range on the northern side, has been demonstrated by AGCM simulations of Asian monsoon climate (Hahn and Manabe 1975; Bhaskar Rao et al. 1991; Fennessy et al. 1994). Apart from orography, the monsoon trough plays an important role in the generation of small low-pressure systems, which form over the head of the Bay of Bengal and move northwest, giving useful precipitation to a major part of the country. While the AGCMs are successful to simulate the important monsoon transient low pressure systems and depressions, the frequency of the simulated disturbances is less than those observed, due to the possible limitations of the horizontal resolution (Ashok et al. 1998; Ashok et al. 2000). Use of RCMs may aid in better simulation of such phenomena, and thereby improve the simulation of the mean seasonal regional rainfall features.

Bhaskaran et al. (1996) simulated the Indian summer monsoon, using a RCM with a horizontal resolution of 50 km nested with global AGCM. This simulation study of the precipitation for four monsoon seasons, including two normal, one strong and one weak monsoon seasons, using RCM have shown improvements than AGCM. The variability of the RCM precipitation is strongly correlated with AGCM, on both the daily and seasonal time scales. This RCM simulated precipitation indicates meso-

scale distribution associated with orography. This study also shows that the RCM derived precipitation is larger by 20% than AGCM, but insensitive to RCM domain size. This study shows successful simulation of intraseasonal oscillations associated with monsoon depressions, and the northward migration of the regional tropical convergence zone. Bhaskaran et al. (1998) reported the simulation of 30–50 day observed intraseasonal oscillation, associated with northward propagation of monsoon trough in RCM. These results have been validated with ECMWF data. The RCM derived precipitation anomalies were associated with the intraseasonal variation, and with strong precipitation near the foot hills of the Himalayas, which could not be observed in AGCM results. Bhaskar Rao et al. (2001) attempted to simulate the Asian summer monsoon of 1997, using the Japan Meteorological Agency Regional Climate Model with a horizontal resolution of 40 km, nested with JMA global analysis data. This study reports the simulation of heat low, monsoon trough and upper level subtropical ridge. The simulated precipitation indicates mesoscale distribution associated with orography.

In this study an attempt has been made to simulate the Indian summer monsoon regional climate during 1994, using a high resolution mesoscale model, NCAR MM5 (National Center for Atmospheric Research Mesoscale Model Version 3.5) embedded in a global reanalysis derived grid, with the aim to examine the simulation of regional features of the monsoon climate. The reason for choosing the year 1994 is the intense interest in the climate of that year due to the occurrence of a strong positive Indian Ocean Dipole event (Saji et al. 1999) that caused excess of summer rainfall over large parts of India (Behera et al. 1999; Ashok et al. 2001, 2003). The nesting of the model with the global analysis will allow us to assess the performance of the model over the Indian region, and to identify the deficiencies, if any, so that further modifications could be attempted to facilitate a more realistic simulation. NCAR MM5 has been used for studies of mesoscale phenomena with short time integrations. In the hierarchy of NCAR mesoscale models, Mesoscale Model version 4 (MM4) has been modified as ReGCM suitable for regional climate studies,

and was used by Giorgi and many others as noted earlier. As the NCAR MM5 is suitable for long integration (Dudhia and Bresch 2002), it is used in the present study for the simulation of Indian summer monsoon.

2. Details of the numerical model and the simulation experiment

2.1 Brief description of NCAR MM5 and datasets

The NCAR MM5 used in this study is a primitive equation, non-hydrostatic model developed and distributed through the National Center for Atmospheric Research (NCAR). The details of the model are given by Grell et al. (1994). The present version of the NCAR MM5 has 23 sigma levels and the option to choose the region of the model domain and the horizontal resolution. The NCAR MM5 also provides different options for the physical processes of radiation; explicit cloud scheme, convection parameterization, planetary boundary layer parameterization and soil physics. The details of the options used in the present study are given in Table 1. For resolvable scale precipitation, simple ice scheme of Dudhia (1989) is used. In this scheme ice phase is assumed below 0°C, where cloud water is assumed to be cloud ice, and rain as snow and no super cooled water is permitted. Similarly snow is assumed to melt above 0°C. Grell (1993) scheme is used for the sub-grid scale convective process. In this scheme a single cloud is observed with up-draft and downdraft fluxes, and compensating motion determining the heating and moisture profiles. This scheme is suitable for grid size of 0–30 km. The radiative processes have been computed by using Dudhia's shortwave radiation scheme and Rapid Radiative Transfer Model (RRTM) for the long wave radiation (Mlawer et al. 1997). The land-surface processes have been computed using Oregon State University Land-Surface Model (OSU-LSM), as given by Chen and Dudhia (2001). In this scheme the soil moisture and temperature are predicted at 4 layers (10, 30, 60 and 100 cm thick), and also the canopy moisture and water equivalent snow depth. This scheme uses a diagnostic equation to obtain the skin temperature, and makes use of vegetation and soil type to compute evapotranspiration. For the planetary boundary layer parameterization, Medium

Table 1. Details of NCAR MM5

Model type	Primitive equation, Non-hydrostatic model
Domain of integration	34.9289 E–115.069 E 15.7883 S–41.9843 N
Vertical resolution	23 sigma levels
Horizontal resolution	30 km
Convection scheme	Grell
Explicit moisture scheme	Simple Ice (Dudhia)
PBL scheme	MRF
Radiation scheme	Dudhia scheme for shortwave radiation. Rapid Radiative Transfer Model for longwave radiation
Surface scheme	OSU/Eta Land–Surface Model
	Heat and moisture fluxes from ground are considered
	Viscous sub-layer for moisture
Sea Surface Temperature	Real SST

Range Forecast model is adopted following Hong and Pan (1996), which uses five layers in the lowest 1 km, and a surface layer of 100 m thickness.

The NCEP/NCAR reanalysis fields for 1994, available at 2.5° resolution, are used to validate the model simulated fields. To validate the monthly mean precipitation distribution for June, July and August, 1994 corresponding monthly mean precipitation fields from GPCP, available at 2.5° resolution are used. To compare the daily time series of precipitation over different zones, rainfall observations at individual stations as reported by the India Meteorological Department, have been used along with NCEP reanalysis fields at 2.5°. The model topography has been computed from the Global topography data available at 10 minutes interval. The model topography derived at the 30 km resolution is shown in Fig. 1.

Fig. 1. Model topography at 30 km resolution. Units are in meters. Contours interval is 100 m.

2.2 Initial and boundary conditions

The NCEP/NCAR Reanalysis data (Kalnay et al. 1996; hereafter referred to as NCEP) for 1994 is used to determine the initial and boundary conditions required for the model integration. The NCEP data available at every 12 hr (00 and 12 UTC), and at a resolution of 2.5 degree both in latitude and longitude, are used to generate the necessary initial fields and the boundary conditions for the model integration. The necessary meteorological variables are specified at the outer rows and columns at every 12 hour interval. The interior nest four points are relaxed towards the boundary values, with a relaxation constant which decreases linearly away from the boundary values. At the lower boundary Sea Surface Temperature (SST), snow cover and sea ice are provided at every 12 hour and are interpolated for the model time step.

2.3 Numerical experiments

The NCAR MM5 has been integrated for 123 days, starting from 1st May, 1994 till 31st August, 1994. The model domain is chosen as 15.7883°S – 41.9843°N ; 34.9289°E – 115.069°E covering the Indian subcontinent and the neighbourhood regions of interest. This integration is performed to study the regional climate features for the months of June, July and August, which represent the Indian summer monsoon. The month of September is not examined, as the monsoon flow retreats over the Indian region during this month. The boundary values of the atmospheric prognostic variables, are provided at every 12 hours from the NCEP

data. Real SST fields have been computed at the required grid points from the NCEP data. The model output is retrieved once a day corresponding to 00 UTC, and used for the computation compared to assess the model performance. Model bias, and Root Mean Square Error (RMSE) for certain variables, have been computed to study the model performance.

3. Results

The results are presented in two sections, as Simulated Morphology and as Statistics. The morphology part contains the description of the distribution features of the MM5 simulation, and their comparison with NCEP fields. The simulated fields are presented for a smaller domain covering the region of interest, i.e. the Indian subcontinent and neighbourhood. The statistics part contains the description, and discussion of model evaluation parameters, such as correlation, RMSE, bias and threat score.

3.1 Simulated Morphology

The results from the model output at 850 hPa and 200 hPa for the months of June, July and August, 1994 are presented along with the NCEP fields. The mean monthly patterns of sea level pressure, 925 hPa temperature, and wind flow at 850 hPa and geopotential at 200 hPa are presented here and discussed. The model derived rainfall during the individual months is compared with the data from GPCP version 2 combined precipitation data set of the Global Precipitation Climatology Project (GPCP) (Huffman et al. 1997b). The pentad rainfall pattern over the Indian subcontinent is analysed for a 30 day period, starting from 1 to 30 June in order to evaluate the model's ability to properly simulate the onset phase of the Indian summer monsoon.

a. Mean sea level pressure

The sea level pressure patterns for the NCEP and MM5 are presented in Fig. 2. In the month of June the model could predict the heat low over north India, with its location and strength agreeing with the NCEP, with the simulated pressure over the Indian subcontinent being up to 2 hPa lower. The model could reproduce the ridge on the western part of the south peninsular India, seen in the NCEP field but displaced to the east. Interestingly, the model also in-

Fig. 2. Mean Sea Level pressure (hPa) for June, July, August 1994. Contours are drawn at 2 hPa interval. Left panel shows NCEP reanalysis field and right panel shows MM5 field.

indicates the presence of a trough line off the west coast of India, which could not be seen in the NCEP/NCAR reanalysis. This off-shore west coast trough is often generally reported by the India Meteorological Department as associated with heavy precipitation on the windward side of western Ghats. In July the model shows the formation of the monsoon low over northwest India, extending towards Arabia and the head of the Bay of Bengal, in agreement with NCEP reanalysis. The formation of the monsoon trough, extending from northwest India to the head of the Bay of Bengal over the Indian subcontinent is very well simulated by the model. However, the model predicts slightly strong pressure gradients over the subcontinent. The simulated low over northwest India in July is more intense than that for August, in agreement with the NCEP. Similarly, the esti-

mated pressure gradient is weaker over central and south India in August as compared to July, which also agrees with NCEP data. Though the model estimated pressure gradient varies from north to south India, similar to the NCEP, it is weaker over central and south India.

The described features indicate that the model could reasonably simulate the establishment of the monsoon flow over the Indian region, the intensification of the monsoon system from June to July, and the weakening from July to August. The realistic simulation of the monsoon during June–August 1994, i.e., west coast off-shore trough in June, the monsoon low over northwest India, the monsoon trough extending from Arabia–northwest India–head of the Bay of Bengal, demonstrate that the MM5 is capable of simulating the Indian summer monsoon reasonably well.

Fig. 3. Temperature (C) at 925 hPa for June, July and August, 1994. Contours are drawn at 1 degree interval. Left panel shows NCEP reanalysis field and right panel shows MM5 field.

b. Temperature at 925 hPa

The model simulated monthly mean air temperatures at 925 hPa, for 00 UTC are compared with the corresponding NCEP reanalysis field (Fig. 3). This is the lowest model level for which NCEP field is available. In June, the model simulated distribution of temperature agrees with NCEP. MM5 predicts the temperature higher by 1° and 2° over peninsular India and over Arabia. The temperature contours indicating a warm region extending from northwest India to the Bay of Bengal agrees to some extent with NCEP. In July the model simulates a warm region over north India and Arabia, agreeing with NCEP. However, the model predicts higher temperatures over north India by 2°. The warm region observed over the northwest Bay of Bengal in the NCEP field, could

also be approximately simulated. For August, MM5 simulates a warm region over north India and Arabia, where as NCEP field shows the maximum shift over Arabia, with temperature decreasing towards north India. It is to be noted that MM5 predicts the warm region over northwest India and Arabia satisfactorily during the three months, but overestimates it. Warm protruding region from north India to the Bay of Bengal during the three months, is fairly well simulated agreeing with NCEP reanalysis. It is also observed that MM5 slightly underestimates the temperatures over the north Arabian Sea. Since the meridional temperature gradients are important in monsoon circulation, the performance of MM5 seems to be satisfactory as the simulated temperature distribution agrees with NCEP reanalysis field.

c. Winds at 850 hPa

The model simulated wind flow at 850 hPa, along with NCEP reanalysis field, is presented in Fig. 4. In June the model flow indicates the presence of monsoon southwesterly over the west Arabian Sea, with a strength of 15–20 m/sec, which agrees very well with the reanalysis, although the peak speed is displaced westwards by about 10°. The wind pattern clearly shows the monsoon flow over the Arabian Sea and the Bay of Bengal converging in to the monsoon trough. The reanalysis data shows the westerly winds over the Bay of Bengal turn and flow northeastward towards Myanmar. MM5 has simulated this meridional change in direction well. In July the model simulation shows strengthening of the monsoon flow over the western Arabian Sea. The strength of the monsoon westerlies over the western Arabian Sea, is noted to be over estimated by about 5 m/sec than the NCEP. The MM5 simulation shows a good formulation of the monsoon trough over north India, extending from the head of the Bay of Bengal to Rajasthan in northwest India. A maximum wind speed of 15 m/sec over the Bay of Bengal is simulated by MM5, which is a little higher than NCEP. In August, the MM5 simulation shows slight weakening of the southwesterlies over the western Arabian Sea, as compared to July. Although winds over the Bay of Bengal are weak, the observed westward shift of maximum over the Bay of Bengal is simulated by the model. The flow from north over mid-east Asia is also well simulated by the model. These features indicate a realistic simulation of the low level monsoon flow over the Indian subcontinent and neighbouring seas.

d. Geopotential at 850 hPa

The model simulated monthly mean geopotential field at 850 hPa is compared with NCEP reanalysis (Fig. 5). In June, the model predicts low over northwest India agreeing with NCEP. However the model simulated low is slightly intense, but is lacking in its extension towards the east. In July, the simulated geopotential shows the characteristics of the monsoon trough orienting from northwest India to the head of the Bay of Bengal, agreeing with NCEP. It is observed that the model simulated geopotential is lower over the Indian subcontinent as compared to NCEP, but with stronger

north-south gradient. In August, the model predicts weakening of the north-south gradient from July, which agrees with NCEP. However, the model simulated gradient is weaker than NCEP, indicating that the model simulates the monsoon circulations slightly stronger in June and July, and slightly weaker in August.

e. Geopotential at 200 hPa

The 200 hPa geopotential for the model and the NCEP, are presented in Fig. 6. In June the distribution shows a high over north India elongated zonally. Correspondingly the model simulation shows a similar distribution, but weaker than NCEP. In July, the high is observed over northwest India and east Arabia where as the model simulates the high over north India extending eastwards, with a maximum over the Himalayas. The north-south gradient of the geopotential agrees with NCEP both in June and July. In August, NCEP reanalysis field indicates the high over north India extending eastward, where as the model field estimates the high region over the Himalayas. In the model simulation the north-south gradient of the geopotential is slightly more than the NCEP. The model simulates the subtropical ridge satisfactorily, but with the centre displaced eastwards as compared to NCEP. In all three months, the model simulated field indicates a shift of the maximum towards east over north India, compared to NCEP. It is also noted that the geopotential values are less in the model simulation, as compared to NCEP, indicating slightly colder troposphere in the model simulation. This cold bias seem to be more over the Tibetan plateau, and orography may be responsible for the shift in the maximum towards east.

f. Rainfall

The model simulated precipitation is evaluated through comparison of monthly rainfall for June, July and August; pentad rainfall during June, and daily time series for 1 June–31 August. The model derived rainfall during the individual months is compared with the corresponding data from GPCP (Fig. 7). The GPCP monthly rainfall data available at 2.5° resolution are used (Huffman 1997a). The precipitation pattern for June shows that the monsoon is established over most of the country, except central and northwestern parts of India. The

Fig. 4. Wind vectors at 850 hPa for June, July and August, 1994. Wind speed contours are drawn corresponding to 2, 5, 10, 15 and 20 m/sec. Left panel shows NCEP reanalysis field and right panel shows MM5 field.

Fig. 5. Geopotential height (gpm) at 850 hPa for June, July and August, 1994. Contours are drawn at 10 gpm interval. Left panel shows NCEP reanalysis field and right panel shows MM5 field.

model precipitation indicates two maxima, one over the west coast of India and the other over Bangladesh, northeast India and Myanmar coast. The location of the model precipitation maxima, and the minimum over the southeast peninsula, agree fairly well with GPCP. The model precipitation shows mesoscale distribution over eastern parts of India, Bangladesh and over other regions which are not noted in the GPCP, possibly due to coarse resolution. The MM5 precipitation in July shows the establishment of the monsoon system over the entire country. The model predicted a maximum over the Bay of Bengal, extending over Myanmar where as the GPCP data show, the maximum over the north of the Bay of Bengal extending westwards over to eastcentral India. The model also simulated another maximum over the west coast, agreeing in location but not

magnitude, with the GPCP. However, MM5 predicted much less rainfall over eastcentral India in contrast to GPCP. Relative dry region over northwest India and Arabia are realistically simulated. MM5 predicts low rainfall over the southeast peninsular India where as GPCP shows low rainfall over Sri Lanka and adjoining regions. For August, MM5 precipitation shows a maximum over a wide region of southeast Arabian Sea, which differs from GPCP where the maximum is confined to a small region off the west coast. Model precipitation also shows a maximum over the head of the Bay of Bengal extending towards Myanmar, where as the GPCP data shows a wider region covering north of the Bay of Bengal, Myanmar and eastcentral India. A dry region over northwest India agrees with GPCP. The MM5 simulated features of maxima of rainfall, along with the

Fig. 6. Geopotential height (gpm) at 200 hPa for June, July and August, 1994. Contours are drawn at 50 gpm interval. Left panel shows NCEP reanalysis field and right panel shows MM5 field.

western Ghats and over Myanmar mountains; higher rainfall over central India agree with the results of Bhaskaran et al. (1996). In all, the MM5 simulation shows reasonable estimation of precipitation during June, July and August, fairly agreeing with the GPCP data. It is of interest to note that the MM5 simulation shows mesoscale distribution of precipitation over land corresponding with orography.

To study the onset phase of the Indian summer monsoon, the simulated pentad rainfall distribution over the Indian region for the 30 day period of 1–30 June, 1994 are presented in Fig. 8. The first pentad corresponds to the period 1–5 June; the second for 6–10 June and so on. The rainfall pentads produced from the model are compared with the advancement of the southwest monsoon during 1994, as reported by the India Meteorological Department

(IMD). IMD reported the onset dates of the southwest monsoon of 1994 (India Meteorological Department, 1995), which indicates the advancement (Fig. 9). From these observations, it is noted that the monsoon current advances over the Indian region as two branches, one from the Arabian Sea and another over the Bay of Bengal, and that the advancement is not gradual but take place as pulses. The following observations can be made. The monsoon current is first observed over the Bay of Bengal around 21 May. The Arabian Sea branch of the monsoon touched the southern tip of the Indian Peninsula on 27 May, and advanced northward reaching 20°N latitude around 12 June. Correspondingly, the Bay of Bengal branch established over Myanmar around 27 May, and advanced westward, touching the 80°E longitude over central India around 11 June. The mon-

Fig. 7. Monthly mean precipitation (mm/day) for June, July and August, 1994. Left panel shows GPCP field and right panel shows MM5 field. Contours are drawn at 0.2, 1, 2, 4, 8, 12 and 18 mm/day.

Fig. 8. Pentad rainfall (mm) accumulated for 5 day period during the period 1–30 June, 1994. Contours are drawn at 1, 2, 5, 10, 20 and 50 mm.

soon current then advances northwestwards, reaching northwest India around 30 June. These observations help us to qualitatively compare the model simulated precipitation distribution during the onset phase.

The first pentad simulation (Fig. 8a) shows isolated rainfall over the Indian subcontinent mainly along the west coast and east Arabian Sea, and also along the east coast. Another region of heavy precipitation is noted over north-

Fig. 9. Advancement of southwest monsoon 1994 (from Mausam 1995).

east India and the Myanmar coast. This period, incidentally, is the onset of the monsoon over southern India. IMD analysis (Fig. 9) indicates the establishment of monsoon up to 18°N over the west coast of India, and over the eastern parts of 88°E , covering northeast India and Myanmar which demonstrates the model's ability to simulate the monsoon onset.

From 5 to 10 June, the IMD observations indicate slight northward movement of the Arabian Sea branch touching 20°N over the west coast, and the Bay of Bengal branch reaching 85°E ; the model simulation during this period (Fig. 8b) shows only a slightly more advancement of the Arabian Sea branch, and the Bay of Bengal branch than those of the IMD. The second pentad simulation also shows increased precipitation over the west coast, with a northward shift over the central parts of the Bay of Bengal extending over Bangladesh, in conformation with the northward advancement of the Arabian Sea branch, and westward advancement of the Bay of Bengal branch of the monsoon current.

IMD observations on 15 June also show further northward advancement of the Arabian Sea branch up to 23°N , and the westward ad-

vancement of the Bay of Bengal branch to 80°E . Correspondingly, the third pentad (Fig. 8c) shows eastward shift of the west coast maximum and increased rainfall over central India, which suggests the advancement of both the Arabian Sea and Bay of Bengal branches of the monsoon system over to central India. The third pentad model rainfall clearly shows the westward shift of the Bay of Bengal branch, and its merging with the Arabian Sea branch, agreeing with IMD observations.

The fourth pentad shows increased precipitation over central India, and advancement of monsoon current northwards and westwards. This distribution shows the onset of the monsoon over eastcentral India. The IMD observations show very little advancement on the western flank over central India during the period 15–20 June. Correspondingly the fourth pentad of the model show decreased precipitation over westcentral India. The IMD observations show little westward advancement of the monsoon current during 20–25 June, and the corresponding 5 pentad of the model doesn't show any further advancement, except slight increase of the rainfall over central India. Correspondingly, the fifth pentad shows increased precipitation over the peninsular India and eastern parts of central India. The IMD observations on the 30 June, indicate onset over the northwest Indian region. The sixth pentad shows increased precipitation over eastcentral India, and reduced precipitation over the west coast.

The above description of the model derived rainfall pentads, indicate that the model could simulate the march of the precipitation belt, corresponding to the Arabian Sea and the Bay of Bengal branches of the Indian summer monsoon system. A comparison of the onset of the monsoon over the Indian subcontinent, as reported by IMD, with the model derived advancement during the onset phase of the monsoon is made. It may be inferred qualitatively that the model could predict the northward advancement of the Arabian Sea branch, and westward advancement of the Bay of Bengal branch of the monsoon current satisfactorily. The model could not simulate advancement over northwest India, where the mean rainfall is meager. A more detailed analysis will be carried out separately to evaluate the perfor-

Fig. 10. Representative areas for the five zones considered for evaluation of precipitation.

mance of MM5 for the simulation of the onset phase of the monsoon.

3.2 Statistics

The model zone is divided into five zones as shown in Fig. 10, covering mainly the Indian subcontinent and small parts of the surrounding seas. Statistical estimates of the mean, correlation coefficient, Root Mean Square Error (RMSE) and bias have been computed for geopotential at 850 hPa and the precipitation, to evaluate the model performance. For precipitation, threat score has been additionally computed for the categories of <5; 5–10; 10–20 and >20 mm/day. The statistics have been computed for the 92 day time series from 1 June to 31 August, 1994. The significance of the correlation coefficient values are obtained from 2-tailed *t*-test. As per this, for 92 observations, a correlation coefficient value of 0.17 has 90%; 0.20 has 95% and 0.27 has 99% significance.

a. Model statistics of 850 hPa geopotential

The area averaged time series of the 850 hPa geopotential of both the model output and NCEP field for the five zones are presented in Fig. 11. For all the five zones, the increasing and decreasing trends of the model predicted geopotential seem to have some agreement with NCEP field, but tend to be poor from days 45 to 70. The MM5 fields are underestimated as

Fig. 11. Time series of geopotential (gpm) for NCEP and MM5 for the five zones as noted in Fig. 10. First day of the time series correspond to 1 June, 1994.

compared to NCEP. The model statistics for the 850 hPa geopotential are presented in Table 2. The correlation coefficients are more than 0.4 with 99% significance. The RMSE has a minimum value of 18, for the zone 5, and maximum of 36 for zone 3. Correspondingly the model bias has negative values for all zones, with a maximum of –25 for zone 3. This parameter which is an indication of the atmospheric pres-

Table 2. Model diagnostic statistics for area averaged geopotential (gpm) at 850 hPa for the five different zones. Statistics are computed between NCEP observations and MM5.

Period: June, July, August of 1994

Zone	NCEP Average	MM5 Average	COR	RMSE	BIAS
1	1418.59	1409.40	0.60	22.88	-9.19
2	1424.73	1410.16	0.68	27.11	-14.56
3	1442.06	1416.32	0.65	36.43	-25.74
4	1458.16	1446.83	0.41	19.10	-11.32
5	1453.40	1446.46	0.52	18.64	-6.94

sure variation, shows a regional simulation with a slight negative bias.

b. Model statistics for precipitation

To evaluate the model prediction capability of precipitation, daily precipitation observations of rain gauge stations, were collected from Indian Daily Weather Reports (IDWR) published by IMD. 10 to 15 representative stations for each zone have been selected, for which continuous data was available. Time series of the area averaged precipitation, for each of the zone from IDWR, NCEP and MM5 are then computed. These data have been used to compute the model diagnostic statistics. The area averaged time series are presented in Fig. 12. For all five zones, NCEP time series show smaller amplitude than those of IDWR and MM5. For the three zones of north India, i.e. zones 1, 2 and 3, IDWR show large amplitudes indicating heavy spells of rainfall. Correspondingly, MM5 indicates heavy rainfall spells with amplitude larger than NCEP but less than IDWR. It is to be noted that MM5 shows many dry spells over zone 1 as compared to IDWR, indicating a bias towards dryness over the arid zone of northwest India. The performance of MM5 seems to improve for zone 2, and is much better for zone 3. It is known that the north-eastern parts of India, which comes under zone 3, receives maximum rainfall during the summer monsoon season, and MM5 predicts rainfall amounts closer to the observations. For zone 4, NCEP are underestimates compared to IDWR, while MM5 estimates are more than the

Fig. 12. Time series of precipitation (mm/day) for NCEP, IDWR and MM5 for the five zones. First day of the time series correspond to 1 June 1994.

IDWR. It is also noted that many of the maximum rainfall events are simulated by MM5, though overestimated, sometimes up to 100%. Zone 4 is the zone covering western Ghats, known to receive the second maximum rainfall after northeast India. MM5 yielded many events of maximum rainfall, but overestimated. For zone 5 covering the southeast Peninsular India, the southern part is known to receive

Table 3. Model diagnostic statistics for area averaged rainfall (mm/day) for the five different zones. Statistics are computed between IDWR observations and MM5.

Period: June, July, August of 1994

Zone	IDWR Average	MM5 Average	COR	RMSE	BIAS
1	7.59	4.08	0.04	9.78	-3.50
2	10.59	5.46	0.20	9.74	-5.13
3	11.38	11.99	0.10	10.90	0.60
4	11.13	18.83	0.45	13.29	7.70
5	3.18	6.2	0.20	7.28	3.01

less rainfall. NCEP indicates more rainfall than IDWR on many days, while MM5 overestimates the maximum on many occasions. This zone also has eastern Ghats range along the east coast, with the topography heights to be about half of western Ghats. It may be inferred that MM5 produces precipitation more than the observations due to orographic forcing, as noted for zone 4. It may be summarized that MM5 could simulate the maximum precipitation events for zone 3 satisfactorily, overestimated for zones 4 and 5, and underestimated for zones 1 and 2. It may also be inferred that MM5 performance is better than NCEP, due to its 30 km resolution to resolve mesoscale systems.

The model diagnostic statistics of area averaged rainfall were computed for MM5, IDWR and NCEP. It is noted (not presented) that NCEP correlated with IDWR in the range of 0.4 to 0.55 with a negative bias for zones 1, 2 and 4, and positive bias for zones 3 and 5. The model diagnostic parameters of correlation, RMSE and bias for IDWR observations and MM5 derived precipitation are shown in Table 3. The statistics between MM5 and IDWR, indicate that MM5 underestimates the precipitation for zone 1 with negligible correlation. This is a dry region and MM5 seems to have strong negative bias. For zone 2, which is the region of central India, MM5 has a correlation of 0.2 with negative bias. For zone 3, MM5 predicts the average, the same as IDWR, with a small bias of 0.6, but with a low correlation of 0.1. For zone

Table 4. Threat scores for different categories of area averaged daily precipitation (mm/day) computed for MM5 against IDWR observations for the five different zones.

Category (mm/day)	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5
<5.0	0.37	0.33	0.08	0.21	0.51
5.0–10.0	0.14	0.08	0.14	0.33	0.10
10.0–20.0	0.08	0.17	0.33	0.18	0.05
>20.0	N.O.	N.O.	0.11	0.17	N.O.

N.O. = No observation in the specified range.

4, the MM5 average is more than the IDWR average by 50%, with positive bias of 7.7. The correlation is highest among all the zones with a value of 0.45, significant at 99% level. This is the region covering the western Ghats, and MM5 is noted to overestimate the maximum, but the high correlation indicates more coincidences of the maximum precipitation occurrences. For zone 5, MM5 overestimates the IDWR mean with the bias nearly equal to the average and with a correlation of 0.2. These statistics indicate that the MM5 has reasonable performance for all zones, except the northwest region, where rainfall is meager. Positive correlations for zones 2, 4 and 5, with 95% significance, indicate the possible capability of MM5 for use in quantitative precipitation estimation and prediction. The threat scores for different categories of area averaged daily precipitation computed for MM5 against IDWR observations are presented in Table 4. The Threat Score is a measure of the skill of a forecast of a particular event. The value ranges from 0-1, where 0 indicates no skill and 1 corresponds to a perfect forecast. The threat scores for different zones seem to have maximum values between 0.34 to 0.5. For zone 1, the threat score is 0.37, corresponding to less than 5 mm/day of rainfall, which has the maximum number of observations. For zone 2, the maximum threat score is 0.33 for precipitation less than 5 mm/day. For zone 3, the threat score has a maximum of 0.33 in the category of 10 to 20 mm/day. For zone 4, the maximum threat score is 0.33 for the category of 5–10 mm/day. For zone 5, the threat score is the highest with 0.51 for the precipita-

tion category of less than 5 mm/day. The analysis of threat scores indicate that MM5 has some predictive capability for zones 2, 3 and 4, where the precipitation is generally high for the daily precipitation up to 20 mm/day. Where as for zones 1 and 5, where the precipitation is generally low, MM5 shows good predictability of precipitation less than 5 mm/day.

It is to be noted that models lose their day to day predictability beyond a few days, but model derived monthly and seasonal rainfall may be useful for extended and long range forecasting. MM5 seem to have reasonable estimates of the pentad rainfall during the onset phase of the monsoon. A more detailed analysis will be taken up in the future regarding the evaluation of the onset phase, and intra seasonal variability, after performing model integration for a few consecutive monsoons.

3.3 Summary and conclusions

The evolution of summer monsoon circulation over India and the neighbourhood region is simulated using NCAR MM5, with a horizontal resolution of 30 km. The model is integrated for a four month period from 1 May 1994 to 31 August 1994. The initial and the boundary conditions have been taken from NCEP Reanalysis data, available at 2.5 degree resolution. The mean features of the monsoon circulation during the three representative months of June, July and August are obtained and compared with NCEP fields.

It is observed that the NCAR MM5 model could simulate many of the observed features of the monsoon circulation satisfactorily agreeing with NCEP reanalysis. The model simulated mesoscale features due to the high resolution, which could not be noted in NCEP. The model could simulate features of the monsoon circulation, such as the position of the monsoon trough, heat low over the northwest India, and sub-tropical ridge at upper levels. It is interesting to note that the MM5 indicates the presence of an off-shore trough in the monsoon westerlies off the west coast during June. This feature, not reproducible by AGCMs due to the coarser resolution, and their inability to model western Ghats properly at that resolution, is many times reported by the Indian Meteorological Department (IMD) in association with the occurrence of heavy precipitation along the

west coast, as seen by the time series for zone 4 presented in Fig. 12. The strengthening of the heat low over northwest India from June to July, and then its weakening from July to August are also simulated. However, the model predicted weaker pressure gradients over central and south India in August as compared to NCEP. MM5 simulated air temperatures are warm by about 1–2°, but with the north-south gradient nearer to NCEP. Simulation of the temperature and its meridional gradient are essential for proper simulation of the monsoon circulation. MM5 predicts the monsoon westerlies over the Arabian Sea reasonably, but slightly underestimated during June and overestimated during July and August. Correspondingly the strength of the Bay of Bengal branch is simulated well during June, slightly overestimated during July and underestimated during August. Though there are some discrepancies, the MM5 simulation is reasonable with respect to the location of the monsoon trough, presence of monsoon westerlies, and the meridional temperature gradient.

A comparison of the model simulated rainfall with GPCP indicates that MM5 is capable of capturing the essential features. The maxima over the west coast of India, and the Bay of Bengal during June are well simulated. Dry region of the southeast peninsula is also simulated by the model. The increase of precipitation over central India during July could be obtained by MM5. MM5 underestimated the precipitation during August, with a northward shift in the dry region over the Bay of Bengal. MM5 shows mesoscale distribution of precipitation and relation to orographic forcing. The onset phase of the monsoon is examined by studying the pentad rainfall during June. It is noted that the model could simulate the propagation of the monsoon current in terms of the Arabian Sea and the Bay of Bengal branches over the Indian subcontinent as evident from the pentad rainfall fields. MM5 predicted more dryness over northwest India, where the mean precipitation is low and more variable. Though it cannot be expected that the model can provide daily occurrence of precipitation, an attempt is made to study the model simulated time series to understand the model behaviour. It is noted that the model could simulate heavy precipitation events, which are generally ob-

served in the region of northeast India (zone 3) with a strength comparable to station observations. MM5 could also simulate heavy precipitation events for the region of western Ghats (zone 4), but sometimes overestimated. The performance of MM5 is better than NCEP, whose amplitudes are small. The model has some discrepancy over zone 1 (northwest India) and zone 5 (southeast peninsula), which receive low amounts of rainfall during the summer monsoon season. A further evaluation of MM5 for the simulation of rainfall associated with the onset phase and transient disturbances will be taken up as further study through the conduct of few more numerical experiments for consecutive seasons.

This simulation experiment of the monsoon regional climate is promising, as the MM5 could predict many of the observed monsoon features. The model simulations will be examined in more detail, and more experiments will be performed with respect to the simulation of mesoscale vortices and monsoon lows and the intra-seasonal variability as future studies.

Acknowledgments

One of the authors, DVBR acknowledges the support from JAMSTEC, Japan through a visiting research fellowship to carry out this work at FRCGC, Japan. The authors thank the anonymous reviewers for their comments, which improved the contents of this paper.

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