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Simulation of Indian summer monsoon circulation and rainfall using RegCM3

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With 7 Figures

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Summary

The Regional Climate Model RegCM3 has been used to examine its suitability in simulating the Indian summer monsoon circulation features and associated rainfall. The model is integrated at 55 km horizontal resolution over a South Asia domain for the period April–September of the years 1993 to 1996. The characteristics of wind at 850 hPa and 200 hPa, temperature at 500 hPa, surface pressure and rainfall simulated by the model over the Indian region are examined for two convective schemes (a Kuo-type and a mass flux scheme). The monsoon circulation features simulated by RegCM3 are compared with those of the NCEP/NCAR reanalysis and the simulated rainfall is validated against observations from the Global Precipitation Climatology Centre (GPCC) and the India Meteorological Department (IMD). Validation of the wind and temperature fields shows that the use of the Grell convection scheme yields results close to the NCEP/NCAR reanalysis. Similarly, the Indian Summer Monsoon Rainfall (ISMR) simulated by the model with the Grell convection scheme is close to the corresponding observed values. In order to test the model response to land surface changes such as the Tibetan snow depth, a sensitivity study has also been conducted. For such sensitivity experiment, NIMBUS-7 SMMR snow depth data in spring are used as initial conditions in the RegCM3. Preliminary results indicate that RegCM3 is very much sensitive to Tibetan snow. The model simulated Indian summer monsoon circulation becomes weaker and the associated rainfall is reduced by about 30% with the introduction of 10 cm of snow over the Tibetan region in the month of April.

1. Introduction

It has been demonstrated that for examining the weather/climate features in greater detail, regional models are more suitable than the global models. Computationally it is affordable to increase the resolution of regional models so as to resolve regional climatic features reasonably well. Various regional models have been used for a wide variety of applications including operational weather forecasting, studies of the present-day climate and possible future climates over a number of regions throughout the world (Mesinger, 1984; Dickinson et al., 1989; Giorgi, 1990; Dudhia, 1993; Walsh and McGregor, 1995; Bhaskaran et al., 1996; Ji and Vernekar, 1997). Simulation of the Indian summer monsoon circulation features and the associated rainfall by a numerical model have been the most challenging problems so far. There have been some attempts to simulate monsoon features and extreme weather events over India by regional models. Bhaskaran et al. (1996) simulated the Indian summer monsoon using a regional climate model with a horizontal resolution of 50 km nested with global atmospheric GCM. Their study showed that regional model derived precipitation is larger by 20% than GCM. Ji and Vernekar (1997) simulated the summer monsoons of 1987 and 1988 by using the National Centers for Environmental Prediction (NCEP) Eta model nested in the Center for Ocean-Land-Atmosphere (COLA) GCM. Their comparative studies showed that for 1987, the Eta model simulates deficient summer monsoon rainfall over northern and peninsular India and the Indonesian region and excess rainfall over southeast China, Burma and the sub-Himalayan region compared to 1988.

Prasad et al. (1997) studied the impact of humidity field on the track and intensity of cyclones using India Meteorological Department's (IMD) regional model. They showed that initial humidity analysis influences the convection process during the integration of the model and with the prescription of near saturation values of relative humidity (80%) in the storm field, the 24 and 48 hr forecast positions are very close to the respective observed positions. Rama Rao et al. (2001) studied the impact of satellite derived moisture profiles on precipitation forecast by using the same IMD model. Mandal et al. (2003) examined the performance of a regional atmospheric model, which is the modified version of the regional model developed in collaboration with the Naval Research Laboratory (NRL) and North Carolina State University in forecasting tropical cyclones over the Bay of Bengal and its sensitivity to horizontal resolution. The structure, intensity and track of the cyclones were found to be well simulated in the model for finer resolution compared to the coarse resolution. The Pennsylvania State University (PSU)/National Center for Atmospheric Research (NCAR) mesoscale model MM5 has been used in a number of studies for the simulation of tropical cyclones. Patra et al. (2000) made a comparative study on the performances of MM5 and Regional Atmospheric Modelling System in simulating the Bay of Bengal cyclones. Trivedi et al. (2002) used MM5 to examine the impact of initial conditions on the simulation of Orissa supercyclone in 1999. Azadi et al. (2001) used MM5 to simulate western disturbances during January 1997 over the Indian region and to predict precipitation associated with it. Bhaskar Rao et al. (2004) simulated many observed features of the Indian summer monsoon such as sea level pressure, 925 hPa temperature, low level wind and precipitation using MM5.

Although the Regional Climate Model (RegCM) has been used widely for various mesoscale studies (Qian and Giorgi, 1999; Pal et al., 2000; Giorgi et al., 2003), it has not been tested to study the characteristics of circulation features and associated rainfall over India so far. The objective of this paper is to evaluate the performance of RegCM3 in simulating the Indian summer monsoon circulation and rainfall. Since convection is the most important physical process in the tropics, attempts have been made to identify the suitable convection scheme to be used in RegCM3 for simulating summer monsoon rainfall over the whole country as well as for its different regions. In order to examine the performance of RegCM3 to changes in land surface processes, sensitivity experiment has also been conducted with and without snow over Tibet, which due to its extremely high elevation acts as a mechanical barrier as well as a heat source/sink.

A brief description of the RegCM3 and experiment design is given in Sect. 2, Sect. 3 discusses the simulation results and final considerations are presented in Sect. 4.

2. Model description and experiment design

RegCM3 is an upgraded version of the ICTP regional climate model RegCM2 originally developed by Giorgi et al. (1993a, b). It is a compressible, grid point model with 14 vertical layers and hydrostatic balance. There are two categories of landuse such as MM4 vegetation and Global Land Cover Characterization (GLCC) which determine surface properties like albedo, roughness, moisture etc. at each grid point. MM4 vegetation has 13 different types and GLCC has similarly 20 types of lands. The model dynamical core is essentially the same as that of the hydrostatic version of MM5 (Grell et al., 1994). The model includes cumulus parameterization schemes, large scale precipitation scheme, planetary boundary layer (PBL) parameterization, state-of-the-art surface vegetation/soil hydrology package, the Biosphere-Atmosphere Transfer Scheme (BATS), Ocean flux parameterization, pressure gradient scheme, explicit moisture scheme, the radiative transfer scheme and the ocean-atmosphere flux scheme.

The complete RegCM3 modelling system consists of four modules: TERRAIN, ICBC, REGCM and Postprocessor. While conducting sensitivity studies, these program modules are run in sequence for defining the model domain and map projection, interpolating the number of latitude–longitude points over the domain, setting the terrain heights and landuse categories in to the model grids, generating first-guess pressure level fields on model grids, horizontally interpolating terrestrial and isobaric meteorological data from a latitude–longitude mesh to a variable high-resolution domain on either Mercator, Lambert or Polar stereographic projection, calculating map-scale factors and Coriolis parameter for the model, generating first-guess surface and upper air observations on the model grid by objective analysis, vertically interpolating pressure level data to the model's sigma coordinate and for time integration and plotting the output results.

In this paper we analyse simulations with two convection schemes. The first is the simplified Kuo-type parameterization described by Grell et al. (1994), which has been widely used for many years. This scheme uses convective instability and moisture convergence as a measure to parameterize cumulus convection. The precipitation is initiated when the moisture convergence in a vertical column exceeds a certain threshold and the vertical sounding is convectively unstable. Once convection is initiated, a fraction of the moisture convergence goes into precipitation while the remaining fraction moistens the atmospheric column following a prescribed vertical profile. The vertical moistening depends on the local relative humidity i.e. more moisture is allocated at drier points. This scheme is mostly used when the grid size is greater than 30 km in the model. It produces much convective rainfall but less resolved scale rainfall.

The second scheme we test was developed by Grell (1993) and it has also been widely used within both the MM5 and RegCM modeling frameworks. This is a mass flux scheme that includes the moistening and heating effects of penetrative updrafts and corresponding downdrafts. Due to the simplicity of the mass flux scheme, any closure assumption can be adopted to complete the scheme. The scheme estimates the properties of the convection and the closure assumption specifies the amount of convection that occurs in order to achieve the desired rate of stabilization. The mass flux approach is more physically consistent than the empirical adjustment approach. The scheme can use two closure assumptions, the so-called Arakawa-Schubert (AS) and the Fritsch-Chappell (FC) type closures. In the former, available buoyant energy is assumed to be released by the cumulus cloud system instantaneously at each time step, while in the latter the buoyant energy release occurs with a temporal scale of 30 minutes. The Grell scheme with AS closure is suitable for larger grid sizes greater then 30 km and comparably more expensive than other schemes. It tends to produce much convective as well as resolved scale rainfall whereas the Grell scheme with FC closure is suitable for smaller grid sizes between 10 to 30 km and keeps balance between the convective and the resolved scale rainfall. Considering the importance of the convective processes during the Indian summer monsoon season, it becomes necessary to choose the proper convection scheme and the closure assumption in the model to correctly represent the ISMR. Giorgi et al. (1993b) present a number of sensitivity experiments to different parameters in the Grell scheme. After a few initial test experiments, we decided to use the Arakawa-Schubert closure, which yielded generally better results for our region.

In this paper, RegCM3 has been integrated for simulating the Indian Summer monsoon circulation and associated rainfall in four years from 1993 to 1996 in order to investigate its suitability in simulating seasonal mean monsoon features. In all these model integrations, the central longitude and central latitude is chosen at 80° E and 20° N (Fig. 1) with 101 grid points along the latitude circle and 115 points along the longitudinal direction. It approximately encompasses the region 55° E to 105° E and 5° S to 45° N with a grid point spacing of 55 km using a Mercator projection. Terrain heights and land use data are generated from a global data set produced by the United States Geographical Survey (USGS) at 30 minute resolution. All simulations cover the period of 1st April to 30th September. The lateral boundary conditions necessary to run the RegCM3 were obtained from reanalysis of observations from the European Centre for Medium Range Weather Forecasts (ECMWF)

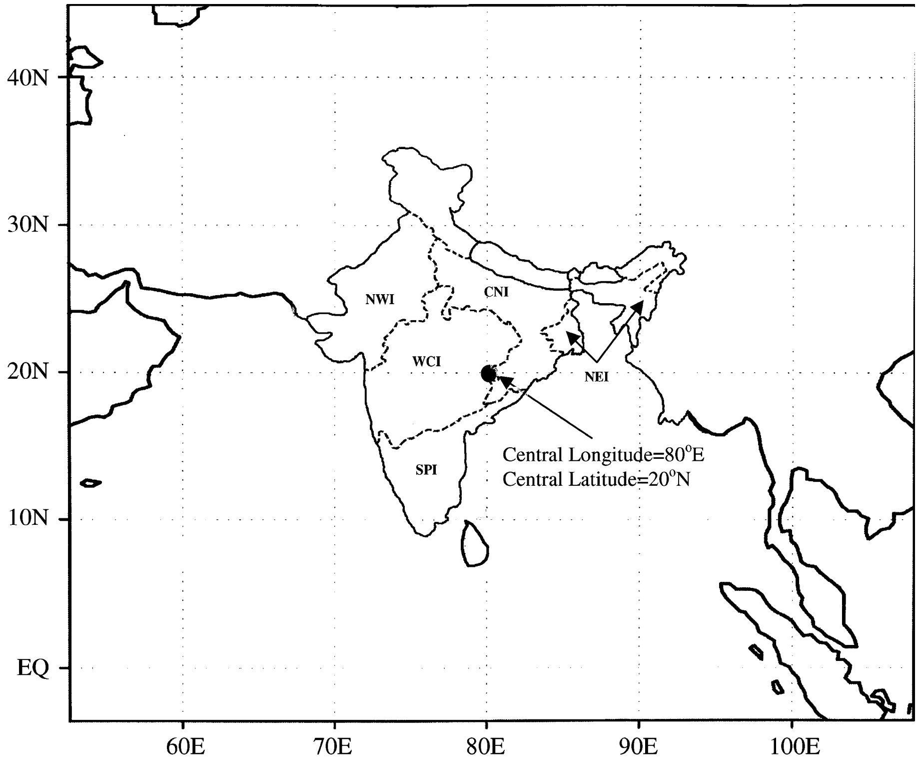

Fig. 1. Model domain used in RegCM3 and the five homogeneous zones of India such as North West India (NWI), West Central India (WCI), Central Northeast India (CNI), North East India (NEI) and South Peninsular India (SPI)

and Sea Surface Temperature (SST) for the simulated periods were obtained from a National Oceanic and Atmospheric Administration (NOAA) monthly dataset. Figure 1 also shows the Indian region along with its five homogenous zones following Parthasarathy et al. (1995) such as North West India (NWI), West Central India (WCI), Central Northeast India (CNI), North East India (NEI) and South Peninsular India (SPI) for the rainfall comparison study.

3. Results

3.1 Simulation of mean monsoon features and rainfall

In this section, the important characteristics of some of the Indian summer monsoon circulation features such as the Findlater jet at 850 hPa, the easterly jet at 200 hPa and the temperature at 500 hPa are studied in detail and are compared with corresponding fields from the NCEP/NCAR reanalysis.

The composites of the four years of winds show that the maximum strength of the JJAS mean westerly wind at 850 hPa is 16 m/s when using the Grell scheme (Fig. 2a) and 14 m/s when using the Kuo scheme (Fig. 2c). Similarly, the maximum strength of the JJAS mean wind at 200 hPa over the Indian Ocean is 18 m/s for the Grell scheme (Fig. 2b) and 14 m/s for the Kuo scheme (Fig. 2d). The difference (Grell – Kuo) fields in Fig. 2(e) and (f) indicate that the lower and upper level winds simulated with the Kuo scheme are generally weaker than those obtained using the Grell scheme. At 850 hPa, the westerlies over the Arabian Sea and Indian peninsula are stronger with the Grell scheme than the Kuo scheme by 2.4 m/s. Figure 2 shows that the Grell scheme simulates mean monsoon wind values at 850 hPa in line with the NCEP/NCAR reanalysis, which shows a jet core of 16 m/s (Fig. 2g). A similar agreement is found for the 200 hPa easterlies over the Arabian Sea and Indian Peninsula, with maximum values of about 20 m/s (Fig. 2h). Thus, the characteristics of the upper level monsoon winds are reasonably well simulated by RegCM3 when using the Grell convection scheme, while the model performance deteriorates when using the Kuo parameterization.

Figure 3(a, b) depict the model simulated JJAS mean temperature at 500 hPa with the Grell and Kuo schemes, respectively. As shown in these

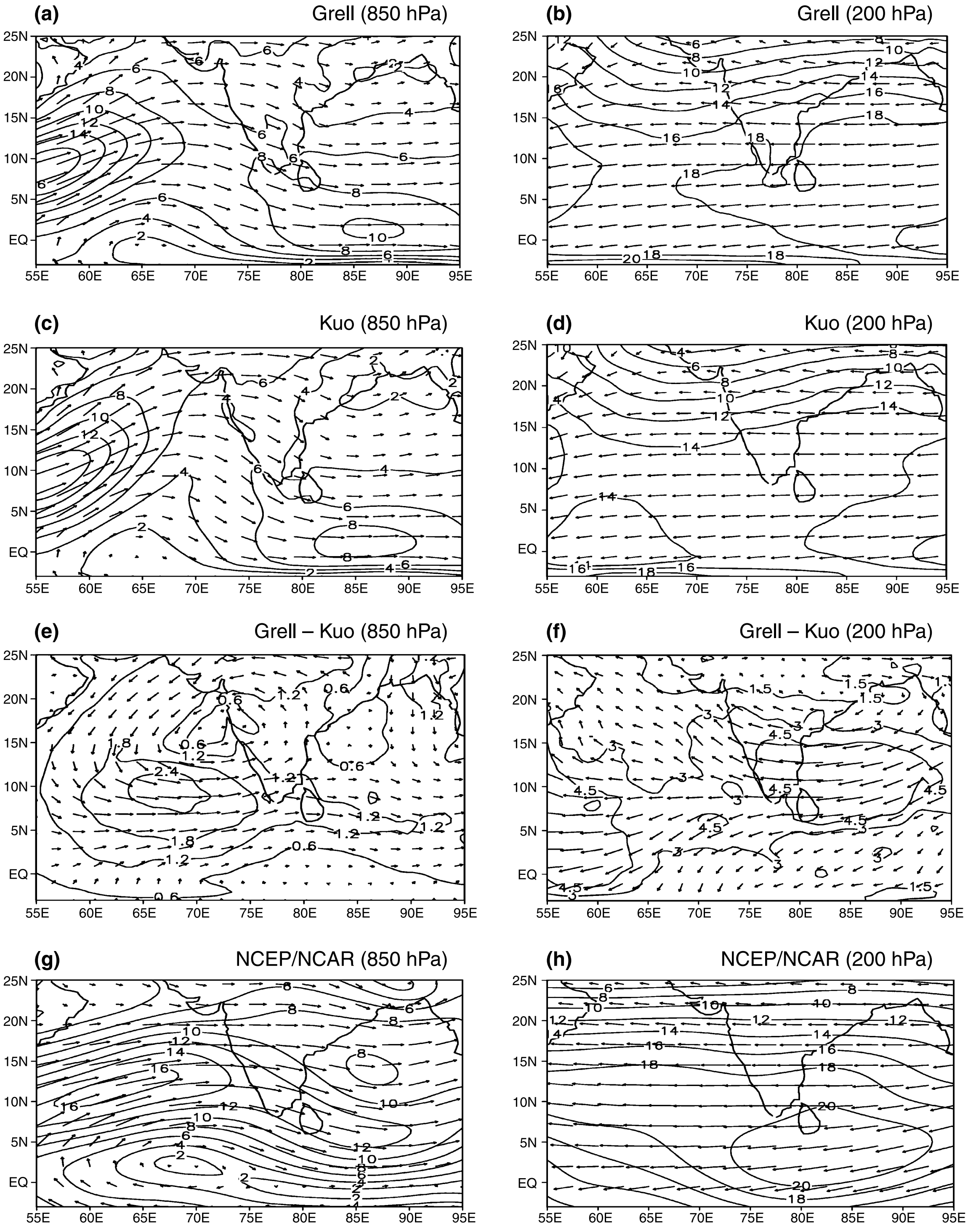

Fig. 2. JJAS average wind (m/s). The left and right panels refer to levels 850 hPa and 200 hPa respectively. (**a**) and (**b**) are winds simulated by RegCM3 with the Grell scheme whereas (**c**) and (**d**) are those with the Kuo scheme, (**e**) and (**f**) are wind differences (Grell – Kuo) and (**g**) and (**h**) are NCEP/NCAR reanalysed winds

figures, the mean maximum temperature over Tibet is 272 K for the Grell run and 274 K for the Kuo run. The corresponding mean temperature at 500 hPa in the NCEP/NCAR reanalysis is 272 K (Fig. 3c), which therefore indicates that the Grell scheme exhibits a better performance in simulating temperature patterns at 500 hPa over the Indian Peninsula and Tibet.

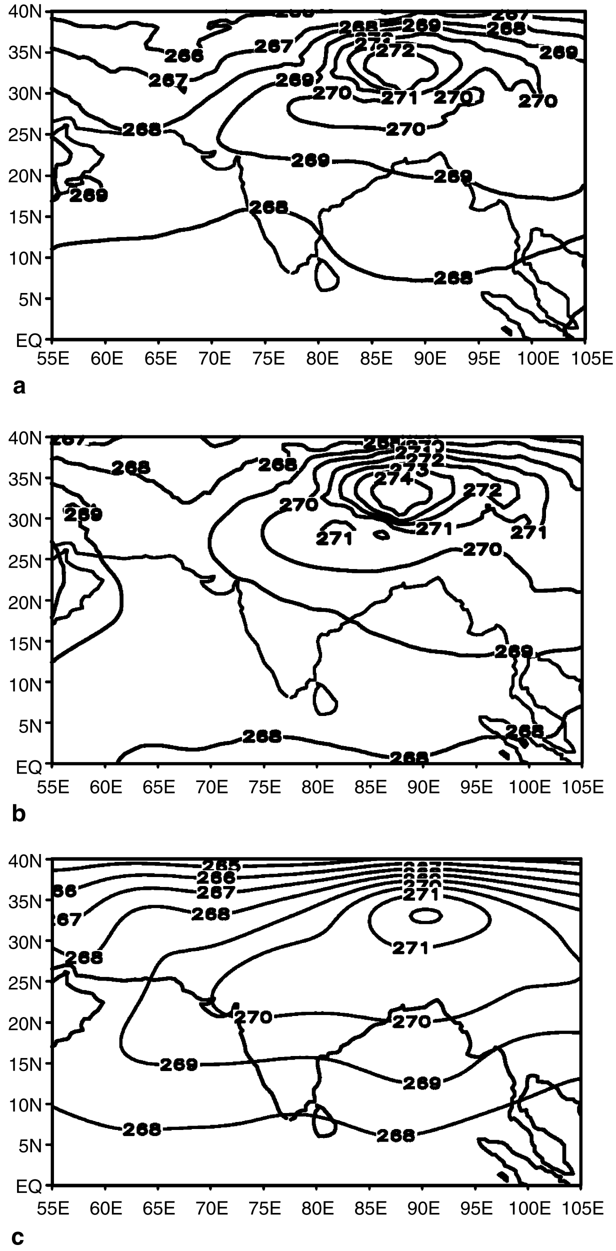

Fig. 3. JJAS average temperature (K) at 500 hPa for (**a**) Grell and (**b**) Kuo convection schemes and (**c**) NCEP/NCAR reanalysis

Figure 4(a, b) show the four years composite JJAS accumulated rainfall simulated by the Grell and Kuo convection schemes, respectively. In the Grell run (Fig. 4a), the model simulates rainfall of about 120 cm over northeast India, 140 cm over foothills of the Himalayas, 80 cm over the east coast and about 260 cm over the Western Ghats. When using the Kuo scheme (Fig. 4b), the model simulates rainfall of about 80 cm over northeast India, 120 cm over foothills of the Himalayas, 40 cm over the east coast of India and about 150 cm over the Western Ghats. The corresponding observed values in the GPCC dataset are 120 cm, 150 cm, 90 cm and 270 cm, respectively (Fig. 4d). Figure 4(c) shows JJAS rainfall difference between the Grell and Kuo runs. The Grell scheme simulates greater precipitation amounts over the Western Ghats (120 cm), the foothills of the Himalayas (40 cm), the east coasts of India (50 cm) and northeast India (60 cm). Comparison of GPCC and simulated rainfall with the two convection schemes shows that the amount and distribution of rainfall simulated by RegCM3 when using the Grell parameterization is closer to observations.

Figure 5(a–f) compare the simulated JJAS mean rainfall over All India and its five homogeneous zones for the years 1993 to 1996, along with the composite of the four years, with the corresponding observed values in the IMD dataset. Note that the ISMR is characterized by considerable spatial variability (Mooley and Parthasarathy, 1984; Parthasarathy et al., 1995; Dash et al., 2002) and hence it is essential to examine the quality of the RegCM3 simulated rainfall over different regions of India.

As seen from the Fig. 5, a good agreement is found between the rainfall simulated with Grell scheme and the IMD observed rainfall over All India, NWI, WCI and SPI in all four years. Conversely, precipitation is underestimated over CNI and NEI. In addition, the Grell scheme consistently simulates more rainfall than the Kuo scheme in all years for All India and its five homogeneous zones. As a result, validation against both the GPCC and IMD datasets shows that the precipitation simulated with the Grell convection scheme is more realistic than that simulated by the Kuo scheme.

Figure 6(a–d) depict the standardized daily monsoon rainfall anomaly over India in the years 1993 to 1996 respectively as simulated by RegCM3 using Grell convection scheme. These figures exhibit the intraseasonal variability of ISMR in each of the years of study. In order to examine whether the intraseasonal variability in the model simulated rainfall agrees with the observed active–break phases and wet–dry spells of Indian summer monsoon, the synoptic conditions recorded by IMD have been studied in detail. It may be noted that during JJAS, the four

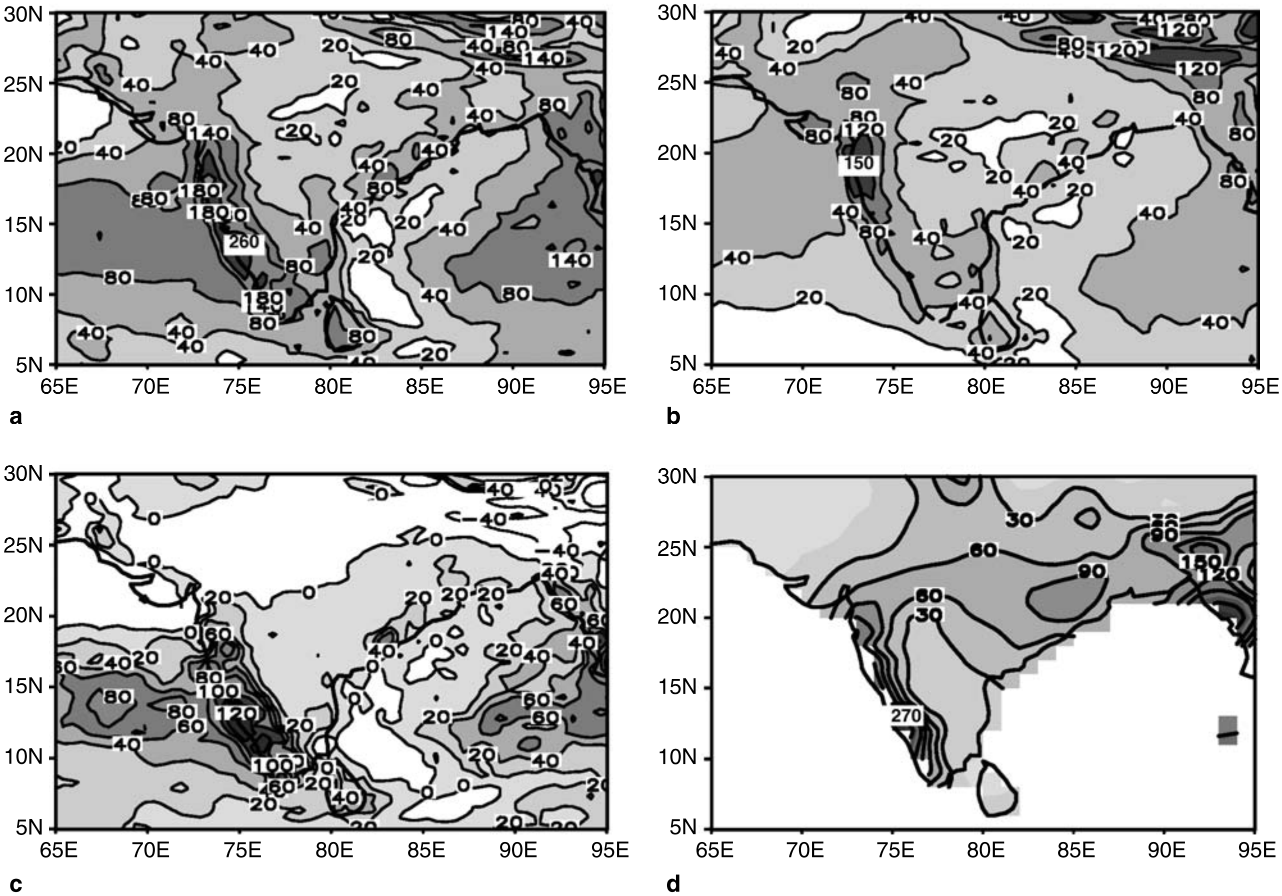

Fig. 4. JJAS average accumulated rainfall (cm) for (**a**) Grell, (**b**) Kuo, (**c**) Grell – Kuo and (**d**) GPCC rainfall

months of monsoon, the performance of monsoon is not uniform. There are periods of strong monsoon activities due to disturbances like monsoon depressions and there are also days when the rainfall decreases over major part of the country. Usually, the monsoon depressions move over India from southeast to northwest resulting in heavy rains in and around the areas through which they traverse. During monsoon breaks, there is increase of rainfall along the foot hills of the Himalayas due to shifting of the monsoon trough towards the northern part of the country and the rainfall almost ceases over central India. Such monsoon conditions are known as breaks particularly when they last for more than two days (Ramamurthy, 1969). It may be noted that as per the practice of IMD, break/active conditions in monsoon are normally determined in the months July and August but not in June and September.

The daily rainfall amounts simulated by RegCM3 using Grell scheme over the whole of India have been computed for JJAS in the years from 1993 to 1996. The standardized anomaly of these have been represented in Fig. 6(a–d) by vertical bars. The simulated active and break monsoon conditions are compared with the respective observed break/active days defined by IMD. Based on observed rainfall in 1993, there were short spells of monsoon break conditions during the period from 20th July to 24th August. Similarly, in the same year active monsoon conditions prevailed during 10th and 17th July. In Fig. 6(a), the observed dates of break and active monsoon conditions are depicted by solid and shaded arrows below and above the vertical bars respectively. Based on Fig. 6(a), one can infer that model simulated active/break days in 1993 compare well with those observed. Similarly, based on observed rainfall in 1994, 1995 and 1996, there were short spells of monsoon break conditions during the periods from 1st to 12th July, 11th to 20th August and 1st to 5th July respectively. The model results also show similar

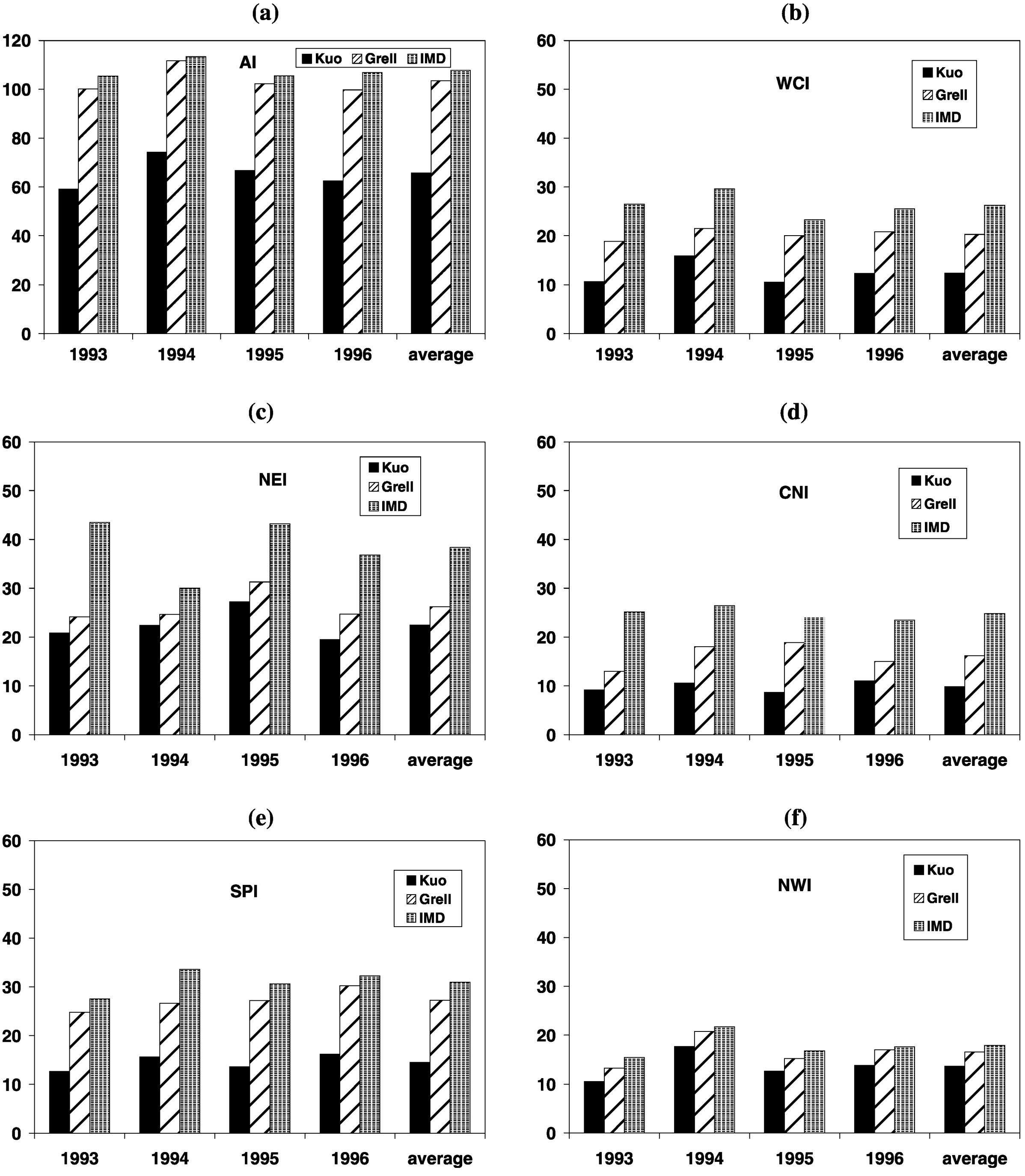

Fig. 5. Comparison of JJAS mean rainfall (cm) over All-India and its five homogeneous zones simulated by RegCM3 in Kuo and Grell convection schemes with IMD observed rainfall

break conditions in Fig. 6(b–d) with few exceptions. In 1995, the model simulates the break monsoon conditions from 12th to 14th August whereas the actual observed dates were from 12th to 17th August. Similarly in 1996, the model fails to simulate the active phases of monsoon observed during the period 21st and 22nd August. However, active monsoon phases simulated by RegCM3 in the years 1994 to 1996 in general show good agreement with the observed wet monsoon periods. Thus, it may be inferred that for all the four years from 1993 to 1996, RegCM3 simulates intraseasonal variability of Indian summer monsoon rainfall over India reasonably well. The wet–dry spells and active–break phases reasonably agree with those observed.

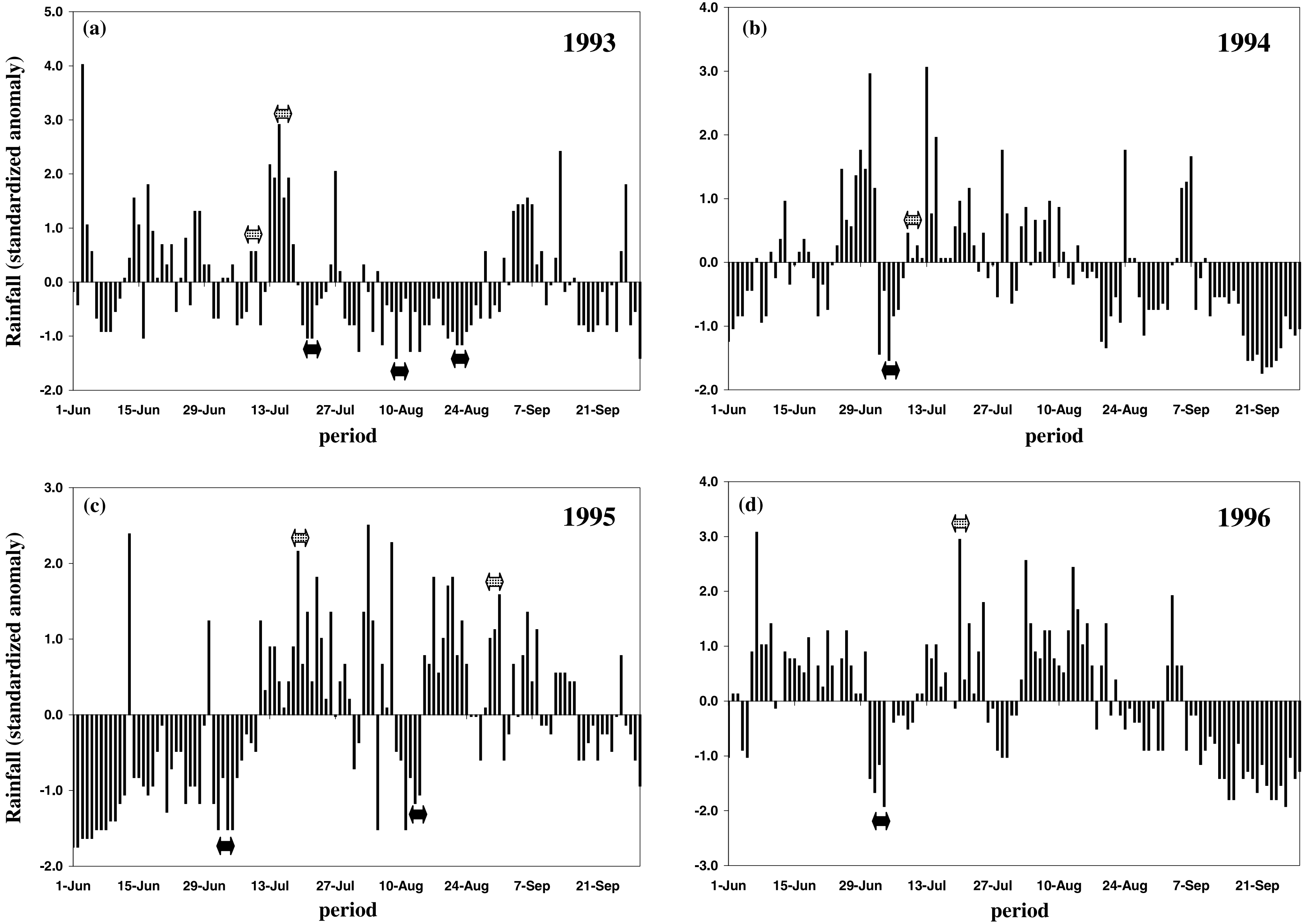

Fig. 6. Standardized anomaly of daily rainfall over India in JJAS as simulated by RegCM3 for the years 1993–1996. The solid and shaded arrows below and above the vertical bars represent the days of break and active monsoon phases respectively as reported by IMD

3.2 Effect of Tibetan snow depth

The Tibetan Plateau, due to its extremely high elevation, has been recognized as the heat source/sink in summer/winter (Murakami, 1987) for the monsoon circulation over India. It also acts as a mechanical barrier and affects the flow pattern around it. He et al. (1987) showed that the presence of the Tibetan Plateau has important effect on the horizontal distribution of the mean tropospheric temperature in the evolution of Asian monsoon. The Grell scheme, which shows a generally good performance in reproducing the basic monsoon circulation and rainfall features in Sect. 3.1, is used here to examine the sensitivity of model simulated Indian summer monsoon circulation and precipitation to changes

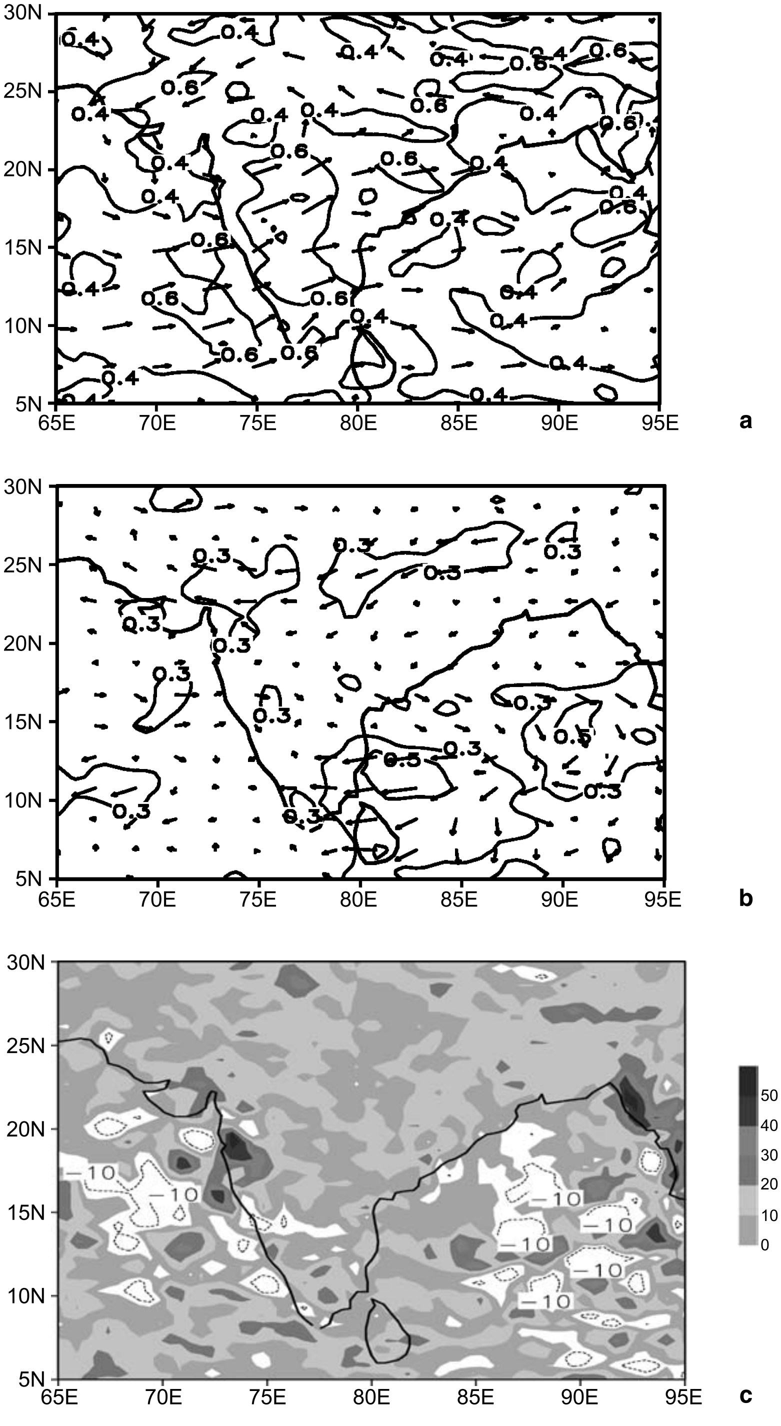

Fig. 7. JJAS differences (no-snow minus snow) of winds (m/s) at (**a**) 850 hPa, (**b**) 200 hPa and (**c**) rainfall (cm)

in Tibetan snow depth. An initial April snow cover is prescribed over the Tibetan region covering 28° N to 40° N and 70° E to 100° E. Although this is an idealized experiment, the choice of this region of snow cover and corresponding snow depth was based on NIMBUS-7 SMMR satellite observations. This is the same region used in the experiments of Ose (1996). The simulations in Sect. 3.1 are referred to as "no-snow" and the simulations in this Section as "snow" experiments.

The differences (no-snow minus snow) in the four-year composite winds at 850 hPa and 200 hPa are reported in Fig. 7(a) and (b) respectively. The westerly wind at 850 hPa over the Arabian Sea and Indian peninsula are stronger in the no-snow experiment than in the snow experiment (Fig. 7a) by 0.6 m/s. Similarly, differences of wind at 200 hPa (Fig. 7b) show stronger easterlies over the Arabian Sea, Indian Peninsula and the northern part of the country in the no-snow experiment. Therefore we find that Tibetan snow during spring induces relatively weak lower level monsoon westerlies and higher level monsoon easterlies. Figure 7(c) depicts the differences of the four year composites of JJAS mean rainfall simulated by the model over India. Greater rainfall amounts are mostly simulated in the no-snow experiment than in the snow experiment. More specifically, in the no-snow experiment more rainfall is found over the Western Ghats, the foothills of the Himalayas, North West India, Central Northeast India and North East India. Conversely increased precipitation is found in the snow experiment over the Arabian Sea and the Bay of Bengal. Quantitatively, it is found that, in the snow experiment, Indian summer monsoon rainfall decreases by about 37%, 38%, 20% and 25% for 1993, 1994, 1995 and 1996, respectively. In general, RegCM3 simulates weaker monsoon winds and lower associated rainfall in response to the prescribed spring snow depth over the Tibetan area. As mentioned earlier, these results only indicate that RegCM3 responds to changes in the snow depth reasonably well. It is necessary to conduct several sensitivity experiments with variations in the snow depth over Tibet before arriving at any conclusions regarding the mechanism of its influence on the summer monsoon circulation and rainfall.

4. Conclusions

Although the RegCM modeling system has been widely used for different regional climate studies (Giorgi and Mearns, 1999), it has not been extensively tested over the South Asia region, particularly concerning the simulation of Indian summer monsoon. In this paper, RegCM3 has been integrated over the Indian region to (i) evaluate the model performance in simulating some of the salient features of Indian summer monsoon mean circulation and rainfall using two available convection schemes (the modified Kuo and the Grell schemes); and to (ii) investigate the model response to land surface change such as snow depth over Tibet.

Results indicate that RegCM3 successfully simulates some important characteristics of the Indian summer monsoon circulation, such as the 850 hPa westerlies and the 200 hPa easterly flow. Also, the seasonal mean summer monsoon rainfall simulated by RegCM3 is close to the corresponding GPCC values when the Grell convection scheme is used, although the observed precipitation is underestimated over Central North India and North Eastern India. In general, the Grell scheme performed better than the Kuo scheme in simulating both the monsoon circulations and rainfall. In a sensitivity experiment, the prescription of 10 cm initial April snow depth over Tibet leads to a reduction of All India monsoon rainfall of about 30%, which demonstrates that RegCM3 simulations are sensitive to the prescribed land surface feature, particularly snow. In sum, our preliminary study indicates that RegCM3 can be effectively used to study monsoon processes over the South Asia region. We also plan to study the sensitivity of the simulated snow effects to model domain, resolution and physics parameterizations in more detail.

Acknowledgements

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