


# Relationship between tropospheric temperature and Indian summer monsoon rainfall as simulated by RegCM3

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**Abstract** Relationship between rainfall and tropospheric temperature (TT) has been examined over the Indian sub-continent during four seasons of the year using Regional Climate Model Version 3.0 (RegCM3). The model has been integrated at 55 km horizontal resolution over India during the years 1980–2000 with prescribed lateral boundary forcing from the 40 years re-analysis (ERA40) of the European Centre for Medium-range Weather Forecasts. Results of this study show that RegCM3 in general is able to capture the spatial distributions of rainfall in all the seasons as compared to the corresponding IMD0.5 gridded rainfall. The model has simulated warmer TT over the Himalayan region in all the seasons as compared to ERA40. However, it is well captured over the peninsular India and the oceanic regions. In the model, larger warming by about 0.5 °C over the northwest and Central India in the summer monsoon months might have lead to lower surface pressure there. Also, the vertical extent of the monsoon trough is found to be up to 500 hPa in the model as compared to that in NCEP/NCAR reanalysis. As a consequence, the simulated monsoon circulation and rainfall are stronger than those observed. The two most important rainfall seasons, the summer monsoon and winter are reasonably well simulated with correlation coefficients (CC) of 0.60 and 0.59 respectively significant at 99 % confidence level with the corresponding observed values of IMD0.5. Further, Indian summer monsoon rainfall (ISMR) and TT

during the contrasting monsoon years are also close to their respective observed values. Temporal CCs between the TT over Tibet, Pakistan and Central India during the summer monsoon season and gridded ISMR values reveals that the TT over Pakistan has been better correlated with the ISMR than those over Tibet and Central India. This relationship has been well supported by the model simulations.

**Keywords** ISMR · Tropospheric temperature · RegCM3 · ERA40 · IMD0.5 gridded rainfall

## 1 Introduction

The summer monsoon rainfall over the Indian sub-continent is very conspicuous in terms of its space and time variability. This monsoon circulation contributes about 80 % of the annual rainfall over most parts of the country while Tamil Nadu receives maximum rainfall during the winter monsoon. The country's agriculture, power generation and industrial production substantially depend on these rains. The most important change in weather over the course of a year is associated with rainfall. Also the mean annual and the seasonal variation of rainfall variability are crucial for the Indian economy, water and agriculture. The rainfall variations over the country occur mainly due to the prevailed weather phenomena such as monsoonal systems and western disturbances. The inter-annual and intra-seasonal variations of monsoon rainfall and the associated phenomena are extensively reported by several scientists over the last several years (Gadgil et al. 2003; Webster et al. 1998; Wheeler and McBride 2005) using observed data and conducting modeling studies. Study has shown that RegCM3 simulates intraseasonal variability of Indian summer monsoon rainfall over India

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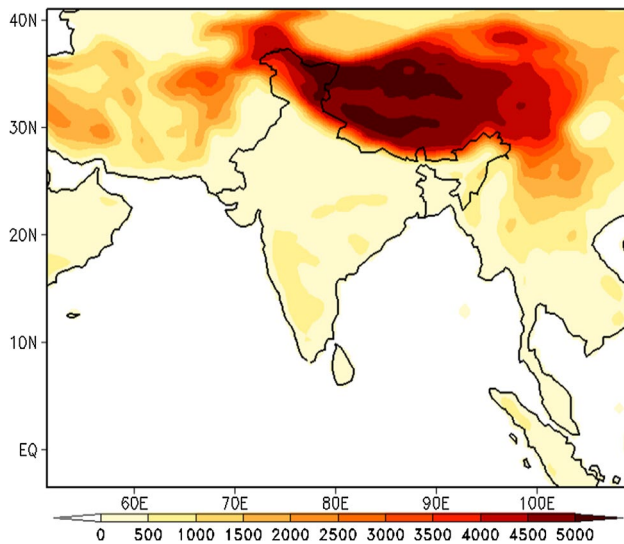
reasonably well during the period 1993–1996 (Dash et al. 2006). The wet–dry spells and active–break phases reasonably agree with those observed.

The most obvious and easily measured changes have occurred in the surface air temperature. Since the troposphere plays a great role in weather and climate related phenomena, it is important to examine the relationship between tropospheric temperature (TT) and Indian summer monsoon. In comparison with the surface air temperature, the upper-tropospheric (200–500 hPa mean) temperature can well indicate the combined effect of zonal and meridional thermal contrasts between East Asia and the adjoint ocean on the East Asian summer monsoon changes. The importance of the seasonal heating of the Tibetan plateau during pre-monsoon and early summer has long been recognized in influencing the intensity of the monsoon circulation and rainfall (Flohn 1957). On inter-annual timescale, the Indian monsoon rainfall has a strong and positive correlation with the pre-monsoon TT anomaly (Verma 1980; Parthasarathy et al. 1990; Singh and Chattopadhyay 1998). In their study, they defined TT as the average temperature of the troposphere between 700 and 200 hPa. The variety of GCMs with fixed SST over South Asia shows that the stronger land-sea and meridional TT contrast at the beginning of the monsoonal season is associated with the greater monsoon precipitation (Meehl 1994). It is well known that the onset of the Asian summer monsoon is concurrent with the reversal of the meridional temperature gradient in the upper troposphere towards the south of the Tibetan Plateau (Li and Yanai 1996). The observed statistical relationship between TT anomaly with the Indian summer monsoon rainfall (ISMR) anomaly has been analyzed by Singh and Chattopadhyay (1998) for the period 1961–1990. Their results indicate that the previous May TT anomaly has a strong and direct relationship with the Indian southwest monsoon rainfall suggesting that warmer/colder TT in May leads to good/bad rainfall over India. Warm air rising over the landmass throughout the troposphere in response to the heating of the Tibetan plateau, causes the inflow of moist air from the ocean towards the continent. TT is more strongly associated with the broad-scale monsoon circulation compared to the regional monsoon rainfall over the Indian subcontinent (Liu and Yanai 2001). Their study showed that the all-India summer monsoon rainfall is positively correlated to the mean TT at 200–700 hPa averaged over Eurasia in summer, while the highest correlation appears in western Eurasia. Variations of the TT over the plateau contribute to the South (East) Asian summer monsoon, via changes of the meridional (zonal) land-sea thermal contrast (Li and Yanai 1996; Zhao et al. 2007). The large increase in the early summer rainfall is

led by the observed strengthening of the pre-monsoon tropospheric land-sea thermal gradient over the Indian monsoon region as indicated by microwave satellite measurements of TTs during the period 1979–2007 (Gautam et al. 2009).

Now-a-days regional models have become useful tools to generate the climatic information at high resolutions. Regional models are increasingly used to examine the circulation and precipitation patterns over several parts of the world. For example, the Regional Climate Model (RegCM) of the Abdus Salam International Centre for Theoretical Physics (ICTP) has been extensively used by several researchers all over the globe as well as in India to examine atmospheric circulation features of different temporal and spatial scales. Dash et al. (2006) successfully simulated the Indian summer monsoon features using RegCM with a horizontal resolution of 55 km. Their study shows that, the Grell convection precipitation scheme has performed better than other available convection schemes in simulating both summer monsoon circulation and rainfall. Their study also indicates that RegCM can be effectively used to study the monsoon processes over the south Asia region. The RegCM version 3 (RegCM3) has also been successfully integrated to simulate the salient features of Indian summer monsoon circulation and rainfall (Dash et al. 2013; Pattnayak et al. 2013). Dash et al. (2013) found that the RegCM3 successfully simulates the 850 hPa westerly flow and the 200 hPa easterly flow. Also the seasonal mean summer monsoon rainfall simulated by the model is close to the Global Precipitation Climatology Centre (GPCC) values. They have also found that RegCM3 successfully simulates the temperature pattern at 500 hPa over the Indian Peninsula and Tibet. Pattnayak et al. (2013) showed that, RegCM3 has overestimated the ISMR and such overestimation has been attributed to the surplus moisture flux over the Arabian Sea as compared to the National Centers for Environmental Prediction and National Center for Atmospheric Research (NCEP/NCAR) reanalysis.

In this paper, we examine the statistical relationship between the seasonal Indian monsoon rainfall and TT over larger area covering Pakistan, the Tibetan Plateau and Central India. A brief discussion of the RegCM3, experimental design and data used for this study are described in Sect. 2. Section 3 discusses the characteristics of climatology of rainfall, TT and sea level pressure during four seasons. Section 4 provides the performance of RegCM3 in simulating the characteristics of summer monsoon rainfall and TT during excess and deficient years. The relationship between TT and ISMR has been described in Sect. 5. Section 6 discusses the vertical extension of monsoon trough. The last Sect. 7 summarizes the conclusions.



**Fig. 1** Domain of model integration along with terrain height (m)

## 2 Experimental design and data used

The ICTP RegCM3 based on the original model of Giorgi et al. (1993a, b) with upgrades described by Pal et al. (2007) is used in this study. The model has been integrated over the Indian region for each of the 21 years 1980–2000 starting from 1st Jan 00 h to 31st Dec 18 h. In all these model integrations, the central longitude and latitude point is chosen at 80°E and 20°N with 99 grid points along the latitude circle and 118 points along the longitudinal circle. The model has been integrated with 150 s time step. The domain of integration covering the region 51.31°E–109.18°E and 3.57°S–40.91°N with approximately 55 km resolution is shown in Fig. 1. The physical parameterization schemes used in this study include the radiation as represented by the CCM3 parameterization of Kiehl et al. (1996), the planetary boundary scheme of Holtslag et al. (1990), the biosphere atmosphere transfer scheme BATS1E by Dickinson et al. (1993), the cumulus parameterization of Grell (1993) with the Fritsch and Chappell (1980) closure assumption. The choice of the domain and physical parameterization schemes is based on the past study conducted by Dash et al. (2006).

The initial and lateral boundary conditions for RegCM3 simulations are obtained from the European Centre for Medium-range Weather Forecasts (ECMWF) reanalyzed dataset of 40 years (ERA40, Uppala et al. 2005) with  $2.5^\circ \times 2.5^\circ$  and 23 pressure levels which are updated four times daily. The Sea Surface Temperatures (SST) have been taken from Global Sea Ice and Sea Surface Temperature (GISST;  $1^\circ \times 1^\circ$  resolution) by Rayner et al. (1996). The elevation data have been obtained from the United States Geological Survey (USGS). USGS Global Land Cover

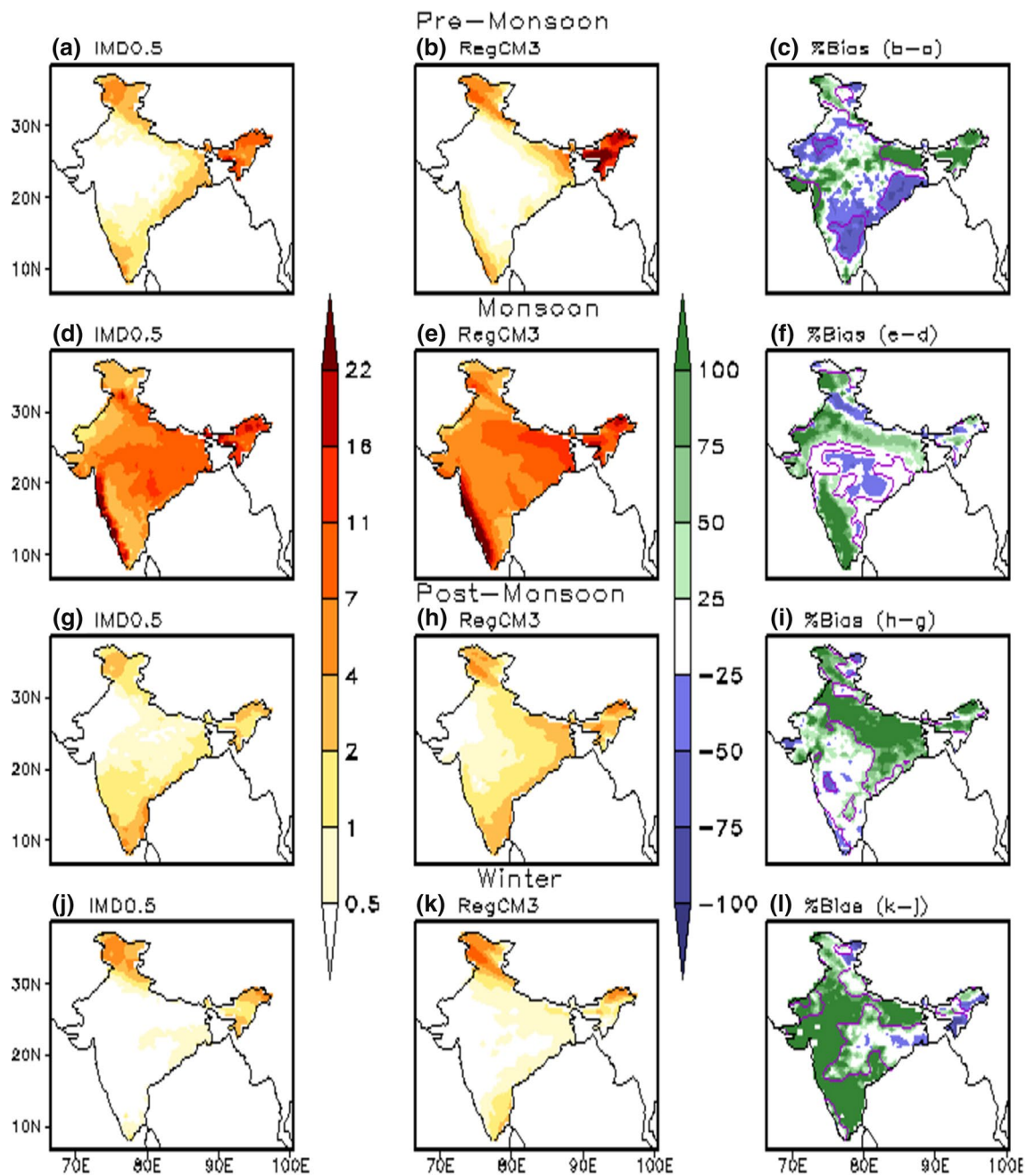
Characterization (GLCC) dataset at 30 min resolution are used to create vegetation and land use file have been downloaded from <http://www.ictp.trieste.it/~pubregcm/RegCM3>. The atmospheric parameters examined in this study include rainfall, TT and Sea Level Pressure (SLP). The model integrated temperature and SLP are compared with those of NCEP/NCAR reanalyzed data sets (Kalnay et al. 1996; Kistler et al. 2001) and the rainfall have been compared with the India Meteorological Department (IMD)  $0.5^\circ \times 0.5^\circ$  gridded rainfall dataset as described by Rajeevan and Bhatte (2009).

## 3 Seasonal mean simulated variables by the model

This section deals with the study of climatological rainfall, TT and SLP simulated by RegCM3 for the period 1980–2000 across all the four seasons. The seasons used in this study is based on the convention of IMD (<http://www.imd.gov.in/doc/termglossary.pdf>) and according to IMD, the entire year has been divided into four seasons namely, winter (January and February), pre-monsoon (March to May), monsoon (June to September) and post-monsoon (October to December). These climate parameters have been averaged over the months and seasons for the entire period of study. These variables have been illustrated in Figs. 2, 3, 4 and 5. The first, second, third and fourth rows of these figures represent Pre-Monsoon, Monsoon, Post-Monsoon and Winter season respectively. These results have been discussed in detail in the following sub-sections.

### 3.1 Climatology of rainfall

The seasonal mean rainfall simulated by the model and the observed values over the Indian land points are shown in Fig. 2. The simulated rainfall is validated against the IMD0.5 gridded rainfall. For this validation purpose, the simulated rainfall has been interpolated on to  $0.5^\circ \times 0.5^\circ$  IMD grids over Indian land points. The model biases with respect to the IMD observed values have been expressed in percentages. The biases significant at 95 % confidence level have been shown in contours over the shaded plot of percentage departure column (Fig. 2c, f, i and l). In the Pre-Monsoon season (Fig. 2a–c) the rainfall patterns over Jammu and Kashmir and North-eastern states of the country are well simulated by the model. However, the model has wet bias of about 25 % over Jammu and Kashmir significant at 95 % confidence level, while a wet bias of 50 % can be seen over North-East (NE) India but not significant. Rainfall in the entire east coast of India is underestimated by the model. In Fig. 2d–f, the model is able to simulate the major rainfall regions over NE India, Western Ghats and the Gangetic Plains during



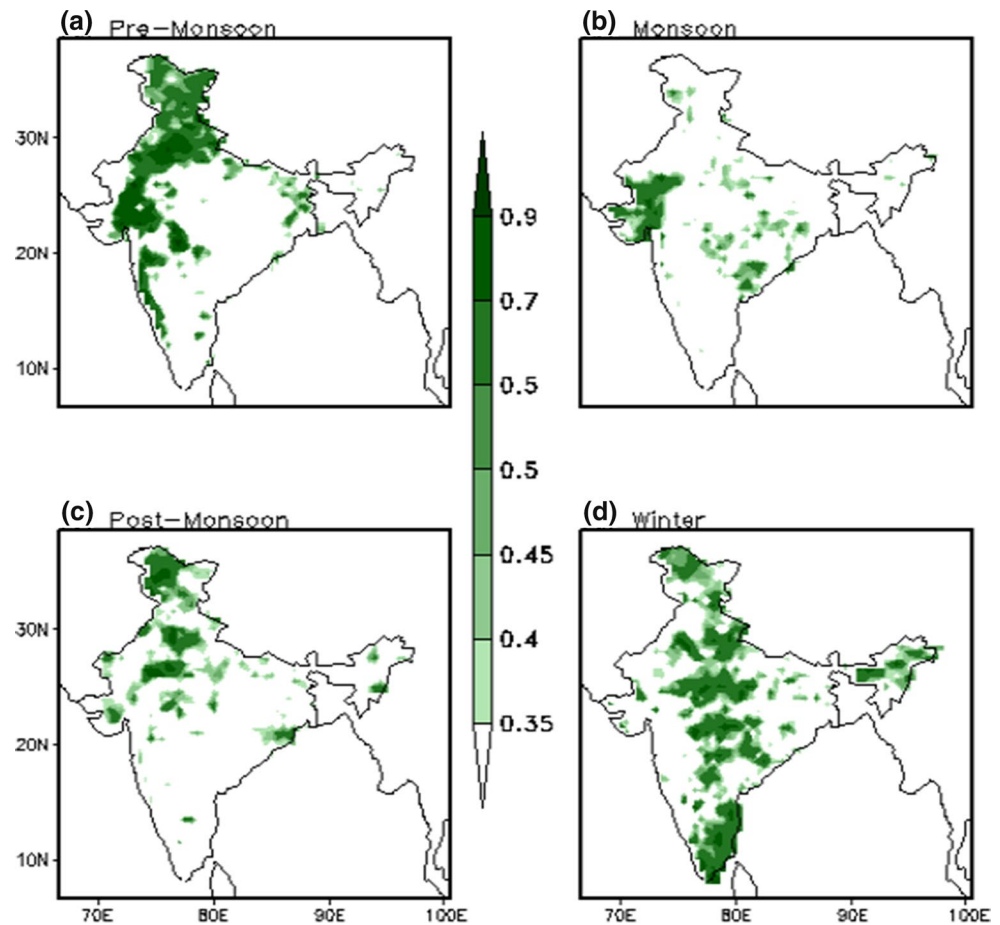
**Fig. 2** Climatological mean rainfall (mm/day) and percentage departures from IMD observations during pre-monsoon, monsoon, post-monsoon and winter seasons for the period 1980–2000. *First column* represents IMD0.5 gridded rainfall, *second column* shows RegCM3

simulated rainfall and the *third column* illustrates the percentage departures of RegCM3 fields from corresponding IMD0.5 values. Bias significant at 95 % confidence level has been shown as contours over the percentage departures

monsoon season. The values of IMD gridded rainfall are about 11–16 mm/day over the Western Ghats, 4–11 mm/day over Central India and 11–22 mm/day over NE India (Fig. 2d). The rainfall values over the corresponding regions in the model simulations are 16–22, 4–11 and 7–16 mm/day respectively (Fig. 2e). Rainfall of magnitude more than 16 mm over the Western Ghats has larger

spatial extension than that observed. The simulated rainfall over Western Ghats has covered more land part than the observed. Rain over most of the parts of India has been overestimated by the model whereas that over Central India, it is underestimated by 25 % which is significant at 95 % confidence level (Fig. 2f). During this season rain over most parts of the country such as Central India,

**Fig. 3** Spatial correlation coefficient of RegCM3 simulated seasonal rainfall with IMD0.5 observed during **a** pre-monsoon, **b** monsoon, **c** post-monsoon and **d** winter seasons for the period of 1980–2000. The *shaded regions* signify that the correlation coefficients are significant at 90 % confidence level

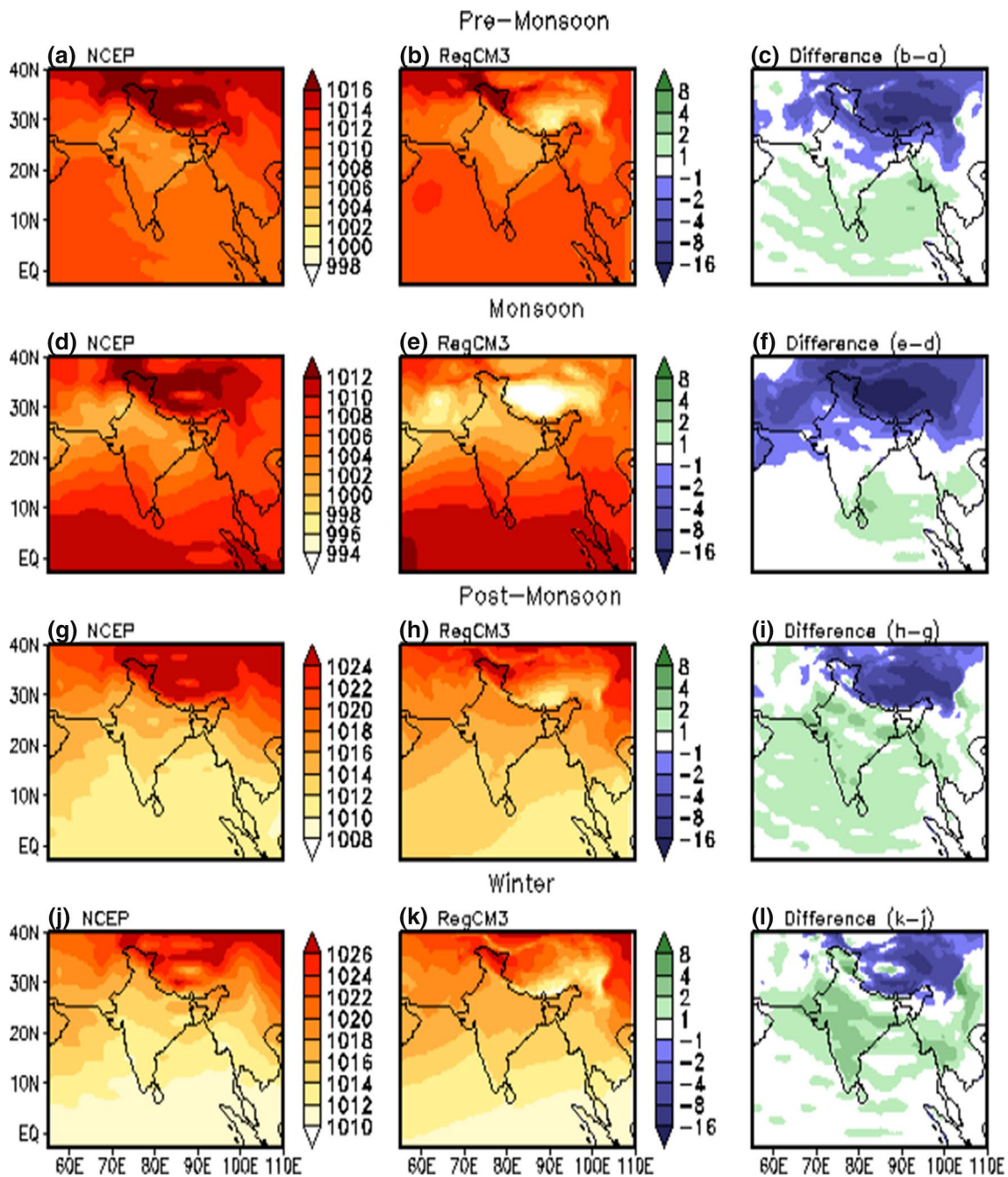


Gujarat, Gangetic plane, Odisha, West Bengal and NE India has bias lying between  $-25$  and  $25$  %. Rain over the Western Ghats is highly overestimated by the model. The third panel of the Fig. 2g–i, presents the rainfall during Post-Monsoon season. The rainfall has been underestimated by the model over Peninsular India while it is overestimated over Jammu and Kashmir, the Gangetic West Bengal and NE India. Last row of the Fig. 2j–l represents winter rainfall. The rainfall is well captured over Jammu & Kashmir and Tamil Nadu region with a slight overestimation. Since the rainfall during winter season is generally less, bias in terms of percentage has been magnified. Thus the positive bias is around 75–100 % over most part of the country. From the above analysis, it can be concluded that the model is able to simulate the spatial distribution of rainfall reasonably well in all the seasons in comparison to the IMD. Similar inference has been made by Pattanayak et al. (2013) in their recent study.

The standard deviations of simulated rainfall over India as a whole are 0.5, 0.9, 0.31 and 0.18 mm/day against the observed values 0.21, 0.54, 0.32 and 0.15 mm/day in pre-monsoon, monsoon, post-monsoon and winter respectively. The model simulated standard deviation values are closer to the respective observed values in post-monsoon

and winter seasons. Calculated Root Mean Square Error (RMSE) in pre-monsoon, monsoon, post-monsoon and winter are 1.25, 1.91, 0.56 and 0.41 mm/day respectively. It is seen that RMSE is more in the seasons with more rainfall such as pre-monsoon and monsoon and relatively less in those with less rainfall seasons like post-monsoon and winter. The correlation coefficients (CC) between the simulated rainfall and the observed rainfall during monsoon and winter seasons are 0.60 and 0.59, which are significant at 99 % confidence level. However, pre-monsoon and post-monsoon rainfall have been relatively poorly correlated (0.34 and 0.10) with respective IMD observed values.

The spatial correlations of model simulated seasonal rainfall with IMD observed values over Indian land have been illustrated in Fig. 3. The CC between the RegCM3 simulated rainfall and IMD observed values have been calculated for each of the grid points for all the seasons for the period 1980–2000. The regions where the CC is significant at 90 % confidence level have been shaded in this figure. During pre-monsoon season, the model has CCs more than 0.6 over Gujarat, Northwest India and Jammu & Kashmir and less than 0.35 over Bihar, Gangetic plain and some parts of Tamilnadu and Northeast India. During the summer monsoon and post-monsoon months (Fig. 3b, c) the



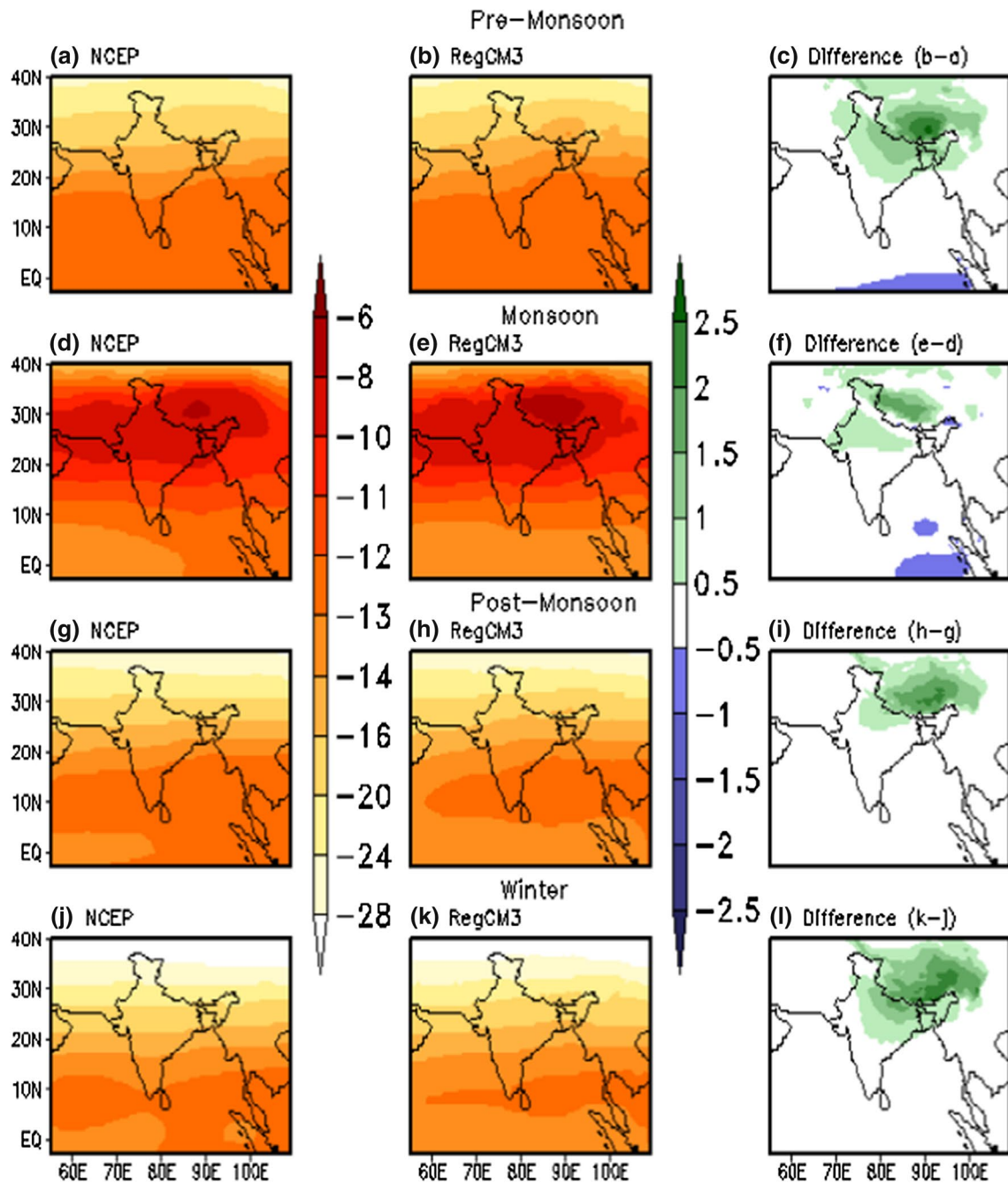
**Fig. 4** Climatological Sea Level Pressure (SLP in hPa) during pre-monsoon, monsoon, post-monsoon and winter seasons for the period 1980–2000. Left panels represent NCEP/NCAR reanalysis, *middle*

*panels* show RegCM3 simulated SLP and the *right panels* show the differences between the two

model simulated rainfall has CC less than 0.35 over peninsula India while rest of the regions of India, it is above 0.35 in both the seasons. The CC is more than 0.6 over Gujarat during monsoon season and it is more than 0.6 during the winter months over most of India. These results indicate that the model has performed well in simulating the seasonal rainfall in all the seasons.

### 3.2 Climatology of sea level pressure

The climatological SLP in the NCEP/NCAR reanalysis and simulated by RegCM3 along with their differences during the four seasons of India have been shown in Fig. 4. RegCM3 simulated SLP climatology has been compared with the corresponding NCEP reanalysis over

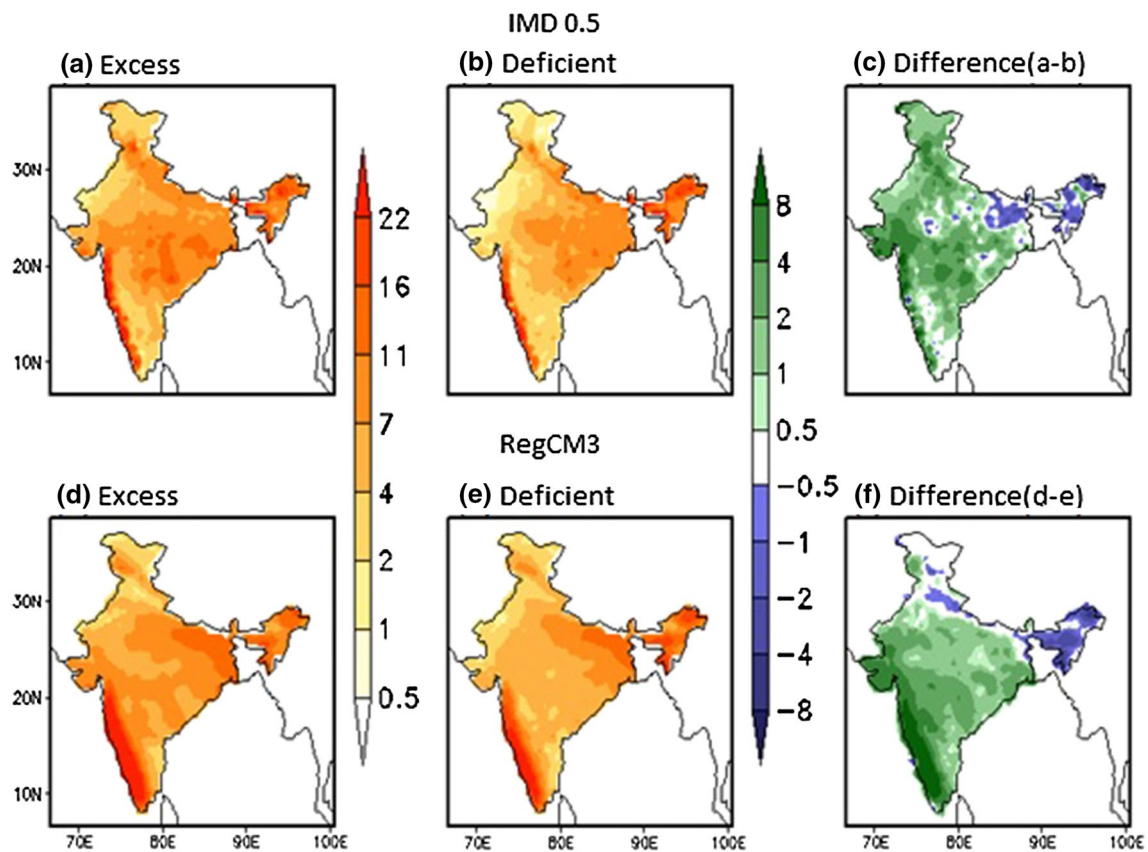


**Fig. 5** Climatological mean tropospheric temperature (TT in °C) during pre-monsoon, monsoon, post-monsoon and winter seasons for the period 1980–2000. *Left panels* represent NCEP/NCAR reanalysis,

*middle panels* show RegCM3 simulated fields and the *right panels* show the differences between the two

the period 1980–2000. Comparison shows that SLP pattern and magnitude simulated by RegCM3 are close to those in NCEP reanalysis. During all the seasons, the model shows dipole structure over the Himalayas and north India. Further, the model has simulated negative and positive biases over the oceans and peninsula India respectively. The model has simulated a trough of low pressure over central India in pre-monsoon

season. During the summer monsoon, the formation of low pressure over the northern India and the adjoining Indo-Gangetic plains is well known. This trough is indicated by the pattern of the pressure distribution and associated circulation in Fig. 4. There is pressure gradient developed towards the Northwest of India up to the southern plains of Pakistan and Afghanistan. Another low-pressure regime is noticed in the simulations of



**Fig. 6** JJAS rainfall (mm/day) in the composites of all-India excess and deficient monsoon rainfall years during 1980–2000. *Top row* represent IMD0.5 gridded values and *bottom row* shows RegCM3 simu-

lated rainfall. *Left, middle and right panels* represent rainfall during composite of excess, deficient years and their differences respectively

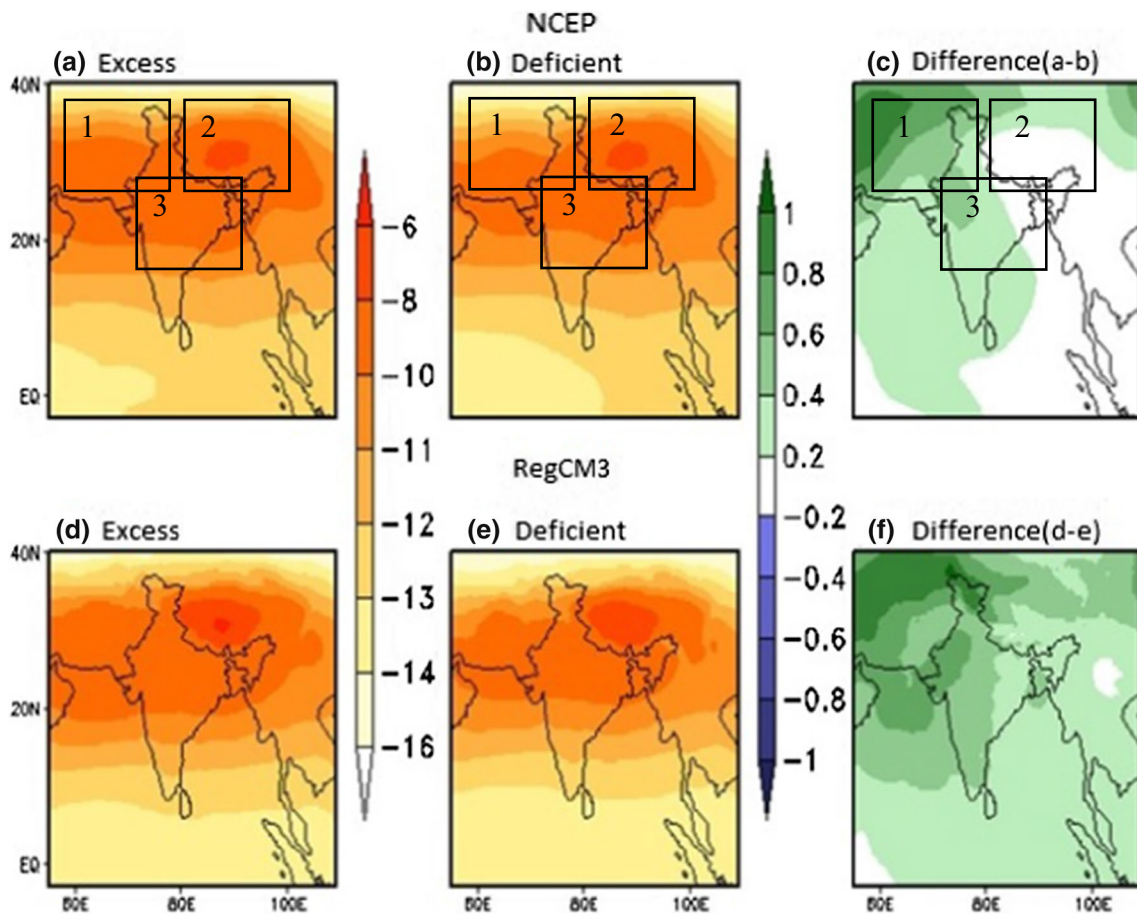
RegCM3 at the foothills of Himalayas and Tibet, which is stronger than the one described earlier. This low over the Tibetan Plateau as simulated in the model is in contrast to the observed high in the region. This anomaly might explain the differences in the magnitude and distribution of ISMR simulated by RegCM3 and those actually observed. In the post-monsoon and winter seasons the model has negative bias over the Himalayas and positive bias over Indian land and its adjoining oceanic parts as compared to the NCEP/NCAR reanalysis.

### 3.3 Climatology of tropospheric temperature (TT)

Figure 5 represents the climatological TT in the NCEP/NCAR reanalysis, RegCM3 simulation and their differences during the four seasons prevailing over India. The TT is equal to the average atmospheric temperature between 700 and 200 hPa pressure levels (Verma 1980; Parthasarathy et al. 1990; Singh and Chattopadhyay 1998). RegCM3 is able to simulate TT close to the reanalysis in all the seasons. Difference fields depict that the warm core over the Tibet and foothills of Himalayas

is overestimated by 2–2.5 °C in RegCM3 simulations as compared to the reanalysis during Pre-Monsoon season. In Monsoon season, the spatial pattern of model simulated TT nearly follows the NCEP/NCAR reanalysis but the warm core over the Himalayas has larger spatial extension than the reanalysis. The warm biases over the Himalayas and over the north central India are about 1.5–2 °C and 0.5–1 °C respectively. The warm bias over north central India has extended from Rajasthan to head Bay through Gangetic planes; this is the normal position of monsoon trough. The warm bias strengthens the monsoon trough and gives rise to stronger monsoon circulation. During Post-Monsoon season, the warm bias over the Himalayas has relatively low magnitude than in the previous seasons but it has covered more regions of India. TT pattern in the Winter season is similar to that in the Pre-Monsoon season, but has less bias. In all the seasons, the model has simulated warm bias over the Himalayas region and well simulated the temperature pattern over oceanic areas. In sum results show that model simulated TT has good agreement with that in NCEP/NCAR reanalysis.





**Fig. 7** JJAS tropospheric temperature (TT in °C) during composites of excess and deficient monsoon rainfall years during 1980–2000. Top row represents NCEP/NCAR reanalyzed TT and bottom row shows RegCM3 simulated TT. Left, middle and right panels represent

TT during composite of excess, deficient years and their differences respectively. The square boxes 1, 2, and 3 represent the regions of Pakistan, Tibetan Plateau and Central India respectively

#### 4 Performance of RegCM3 during excess and deficient summer monsoon rainfall years

The ability of RegCM3 to simulate the excess and deficient summer monsoon rainfall cases and corresponding TT have been depicted in Figs. 6 and 7 respectively. A composite analysis has been carried out by computing the rainfall and TT during all-India excess and deficient monsoon rainfall years. The years having standardized ISMR anomaly greater than 1 are considered as all-India excess years, while years having standardized ISMR anomaly less than  $-1$  are defined as all-India deficient years. Therefore, among 21 years, there are 3 years under the category of excess monsoon rainfall (1983, 1988 and 1994) and 4 deficient monsoon rainfall (1982, 1985, 1986 and 1987) years in IMD observations. Out of the three observed all-India excess years the model has simulated two excess years and two deficient years out of four observed deficient years (Pattnayak et al. 2013). For this study, the excess and

deficient years have been considered based on observed IMD rainfall values. These years have been selected based on the earlier study by Pattnayak et al. (2013).

##### 4.1 Characteristics of rainfall during excess and deficient years

The summer monsoon rainfall values during all-India excess and deficient years from the model and observation are shown in Fig. 6. The left column shows the composite of excess monsoon years, the middle column shows the composite of deficient years and the right column shows the difference between the excess and deficient rainfall. The top panel represents IMD  $0.5 \times 0.5$  gridded rainfall and bottom panel shows RegCM3 simulated rainfall. The values of JJAS in the IMD gridded rainfall dataset are about 16–22 mm/day over the Western Ghats, 7–16 mm/day over Central India and 11–22 mm/day over NE India in excess years (Fig. 6a). The rainfall values over the

corresponding regions in the model simulations are more than 22, 4–16 and 7–16 mm/day respectively (Fig. 6d). During deficient years (Fig. 6b) IMD JJAS rainfall is about 11–22 mm/day over Western Ghat, 7–16 mm/day over Central India and 11–22 mm/day over NE India. RegCM3 simulated rainfall over corresponding regions are 16–22, 4–16 and 4–16 mm/day respectively (Fig. 6e). Rainfall of magnitude more than 16 mm over the Western Ghats is well captured by the model, but it has larger spatial extension than the observed in both excess and deficient years. From Fig. 6 it is observed that the difference between the IMD JJAS rainfall in the all-India excess and deficient years is positive over most of the regions of India except over NE India and few parts of Bihar, The model also shows similar difference in rainfall over NE India. Thus it is inferred that the model is able to capture the major rainfall features during excess and deficient years. It may be mentioned here that in the all-India excess/deficient monsoon years based on the values of ISMR in different regions may have deficient/excess rainfall due to the spatial variability of ISMR.

#### 4.2 Characteristics of TT during excess and deficient years

The comparison of TT during excess and deficient monsoon rainfall years during 1980–2000 is made in Fig. 7. The overall pattern of TT is well simulated by the model in both excess and deficient years. The location of maxima TT over Tibet Plateau is well captured by the model in both the cases; however it is overestimated by 1–2 °C in excess years. The difference of TT between excess years and deficient years is higher over Pakistan region and Northwest India. The difference of TT in excess and deficient years ranges from 0.2 to 0.8 °C in both the model simulation and observation over most part of India and Pakistan. The model simulated TT in excess years is more than that in the deficient years in all the regions over the domain whereas no change in such temperature has been noticed in the NCEP/NCAR reanalysis over the Tibet, NE India, Thailand, eastern part of Bay of Bengal and eastern equatorial Indian Ocean. The higher TT over Pakistan and Northwest India during excess rain years as compared to the deficient years leads to decrease in SLP over monsoon trough region during the summer monsoon season. As a consequence, the monsoon trough is intensified. The model simulations confirm this.

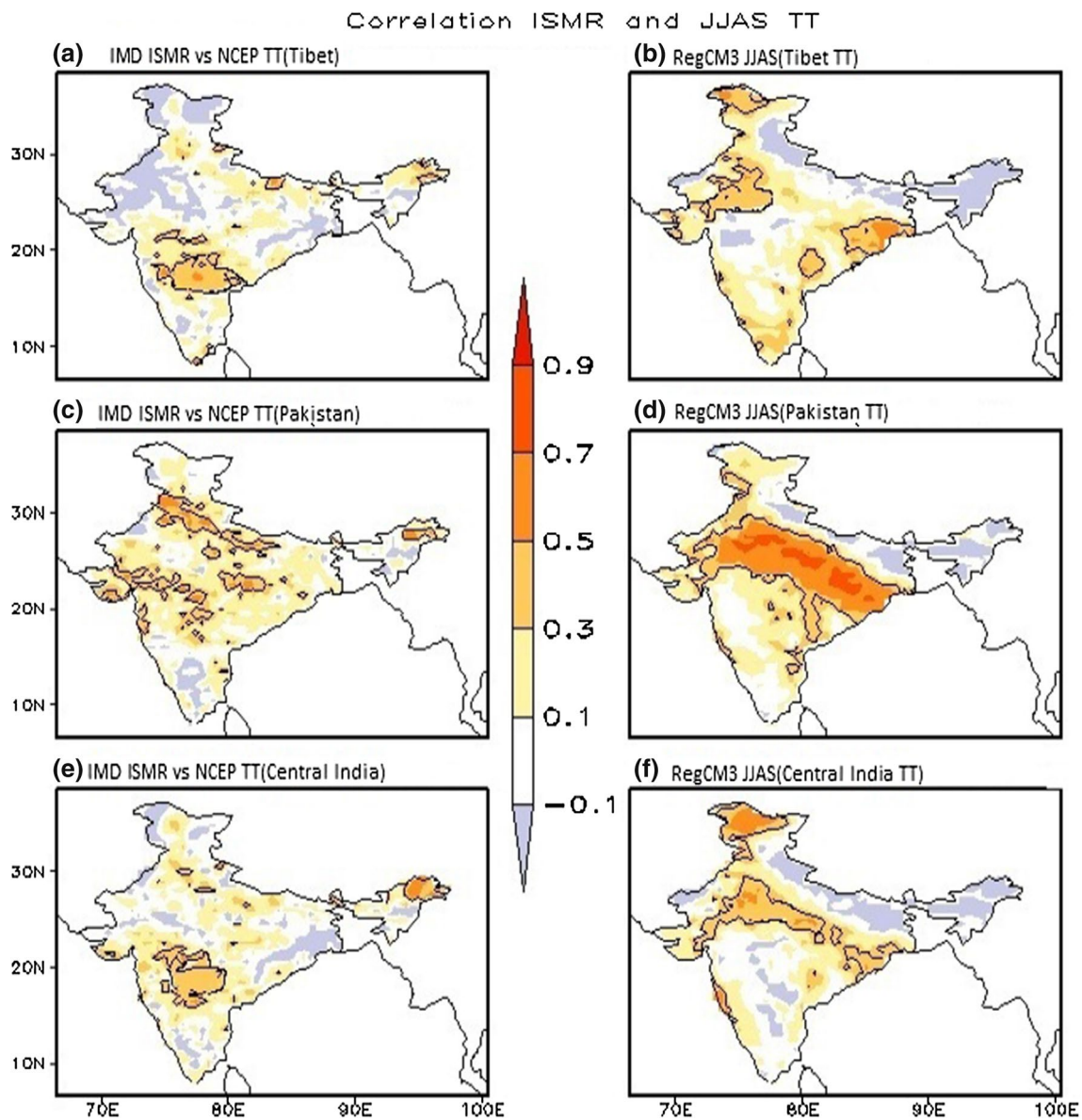
#### 5 Relationship between TT and ISMR

As discussed in the previous section, high TT over Tibet and high temperature gradient over Pakistan strengthens the

monsoon trough and monsoon circulation mainly over Central India as well as other parts of the country. Therefore, these areas along with Central India have been chosen to examine the relation of TT during summer monsoon season with the ISMR. In this section Temporal Correlation Coefficients (TCC) between the TT over Tibet, Pakistan and Central India during summer monsoon season and the gridded ISMR have been computed and analyzed. Before calculating TCC, the area averaged TT over Tibet (80°E–95°E and 25°N–40°N), Pakistan (60°E–75°E and 25°N–40°N) and Central India (73°E–88°E and 15°N–30°N) have been computed. The TCCs between TT in NCEP/NCAR and IMD ISMR have been termed as observed TCC and similarly those between model simulated TT and the simulated ISMR have been termed as simulated TCC. The shaded regions bounded by contour line in Fig. 8 are significant at 90 % confidence level. The upper panel of Fig. 8a, b shows the TCC of TT over Tibet with ISMR, the middle panel (Fig. 8c, d) shows the TCC of TT over Pakistan with ISMR and the bottom panel (Fig. 8e, f) shows the TCC of TT over Central India with ISMR. The observed TCC over Tibet has the values ranging from 0.3 to 0.7 over Maharashtra and interior Andhra Pradesh (Fig. 8a); while the model simulated TCC over the corresponding regions have values less than 0.3 (Fig. 8b). Corresponding simulated TCC has values between 0.3 and 0.7 over Jammu & Kashmir, Central India and Tamil Nadu regions and less than –0.1 over NE India. The observed TCC over Pakistan region and ISMR have the values ranging from 0.3 to 0.7 over Maharashtra and Gangetic Plain (Fig. 8c). The corresponding simulated TCC over Pakistan lies between 0.3 and 0.9 over Central India and Gangetic Plain (Fig. 8d). The model shows stronger correlation than the observed one. The observed TT over Pakistan is positively correlated with ISMR at most of the regions and this fact is well supported by the model. The TCC values are relatively less in case of Tibet in observation as well as in the model. Figure 8e, f, shows that the observed TCC over Central India is higher than that over Pakistan (Fig. 8c, d). Based on this analysis, it may be inferred that the values of TT over Pakistan plays a major role in Indian summer monsoon compared to those over Tibet and Central India.

#### 6 Vertical extent of monsoon trough

The climatological geopotential height for summer monsoon season in NCEP/NCAR reanalysis, RegCM3 simulations and their differences at multiple vertical pressure levels have been shown in Fig. 9. To examine the vertical extent of monsoon trough, standard pressure levels such as 1000, 850, 700 and 500 hPa have been chosen here. RegCM3 simulated geopotential height has been

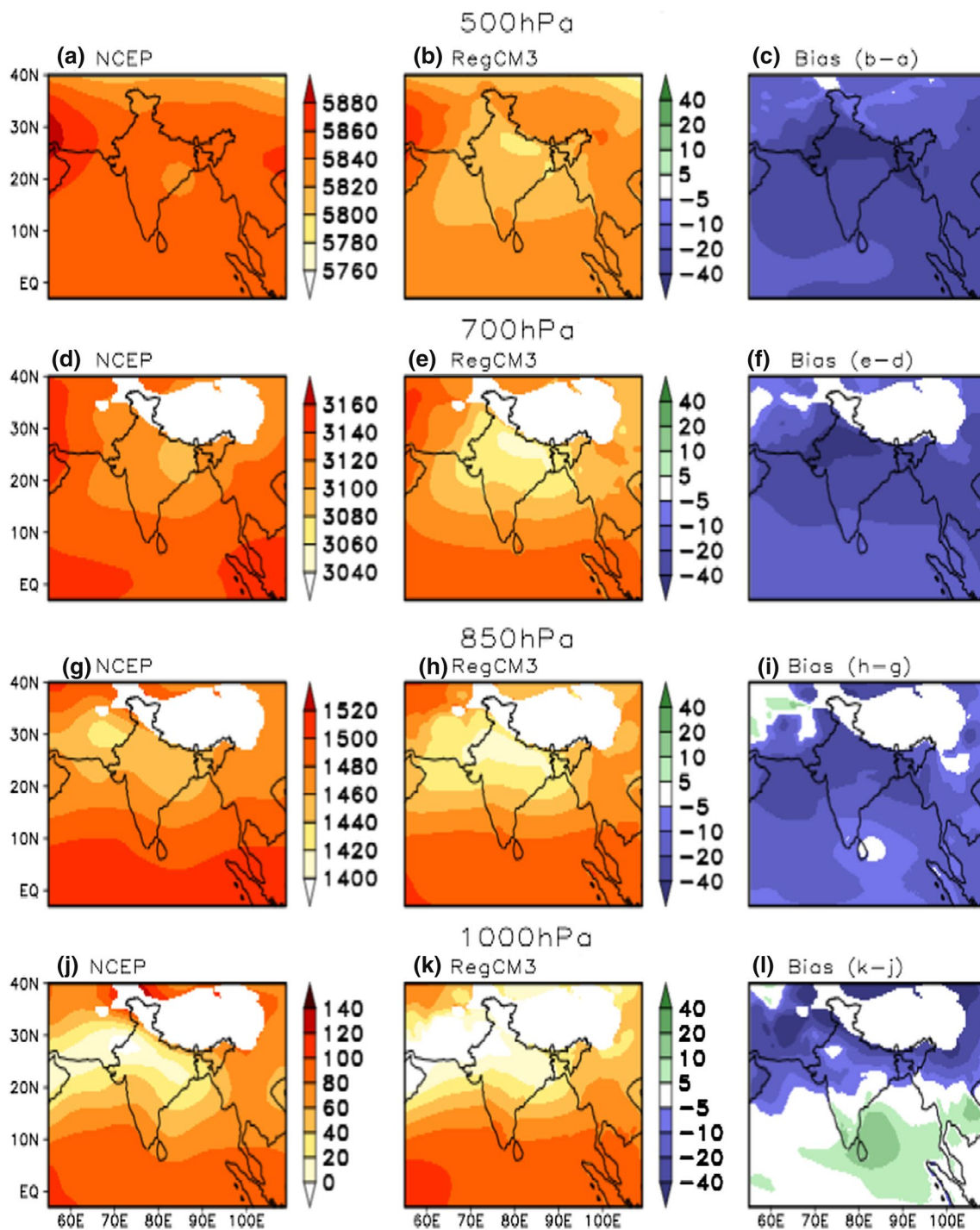


**Fig. 8** Temporal Correlation Coefficient (TCC) of the tropospheric temperature (TT) over Tibet, Pakistan and Central India with ISMR. *Left panel* represents observed TCC (TCC between TT from NCEP/NCAR and IMD ISMR) and *right panels* represent model simu-

lated TCC (TCC between RegCM3 simulated TT and corresponding ISMR). The *top, middle* and *bottom panels* show TCC over Tibet (a, b), Pakistan (c, d) and Central India (e, f) respectively. Contour lines represent CCs significant at 90 % confidence level

compared with the corresponding NCEP/NCAR reanalysis value over the period 1980–2000. The geopotential height pattern shown in Fig. 9 indicates that RegCM3 simulation follows the NCEP/NCAR reanalysis at all the levels; though underestimated. At 1000 hPa, the axis of the monsoon trough is well simulated by model (Fig. 9j, k). But, the simulated monsoon trough is stronger than that in the NCEP/NCAR reanalysis by 5–10 hPa (Fig. 9j, k). Over southern India, the model has positive bias whereas on northern part of India it has negative bias. The simulated

trough is quite prominent at 850 up to 500 hPa, while the corresponding trough is weak in the NCEP/NCAR reanalysis at 700 and 500 hPa. The simulated troughs at all the levels are also stronger by 10–20 hPa compared to the reanalysis. From the above discussion, it is clear that the monsoon trough in the model persists up to 500 hPa while such pattern is absent in the NCEP/NCAR reanalysis. This difference might have contributed to stronger monsoon simulation in the model as compared to the observed one in NCEP/NCAR reanalysis.



**Fig. 9** JJAS climatological geopotential height (m) at 500, 700, 850 and 1000 hPa for the period 1980–2000. *Left panels* represent NCEP/NCAR reanalysis, *middle panels* show RegCM3 simulated geopotential height and the *right panels* show the differences between the two

## 7 Conclusions

In this study, the seasonal characteristics of TT and associated rainfall pattern have been examined over the Indian subcontinent during the four seasons of the year using RegCM3. Results show that the model is able to reproduce

the spatial distribution of rainfall in all the seasons reasonably well as compared to the IMD0.5 gridded rainfall. Further, summer monsoon and winter seasons show better simulated rainfall over Indian land points compared to other two seasons. Model simulated rain values have CC of 0.60 and 0.59 respectively with the corresponding observed

values of IMD0.5 and these values are significant at 99 % confidence level. The spatial correlation of model simulated seasonal rainfall with IMD0.5 gridded values reveals that the CC is more than 0.6 over most of the country during the winter season. During the summer monsoon and post-monsoon months, the model shows CC more than 0.35 over Central India, which is significant at 90 % confidence level. In general, in terms of spatial and temporal correlation, the model performs reasonably well.

The simulated TT has a good agreement with those of NCEP/NCAR reanalysis in all the seasons. The TT pattern is well simulated by the model over oceanic region. Analysis indicates excess warming by about 0.5–1.5 °C over the Himalayas and 0.5 °C over the monsoon trough region during the monsoon season. This temperature rise decreases the surface pressure and hence makes the monsoon rainfall stronger. The model has simulated a dipole like structure in case of SLP in all the seasons. There is negative bias over the Himalayas and positive bias over rest of the regions. The trough of low pressure is quite prominent during pre-monsoon season and it is even stronger during the monsoon season. Also the distribution of geopotential height during the monsoon season at different vertical pressure levels confirms that the vertical extent of the monsoon trough simulated by the model is up to 500 hPa level. The simulated trough is stronger than that in the NCEP/NCAR reanalysis, which again might have contributed to stronger monsoon circulation over India.

A composite analysis has also been made here by examining ISMR and TT during excess and deficient monsoon rainfall years to evaluate RegCM3 simulations. Results show that the model is able to simulate the excess and deficient monsoon rainfall years. The Temporal CCs (TCC) of TT over Tibet, Pakistan and Central India during summer monsoon season with the gridded ISMR have also been discussed in this study. It is found that TT over Pakistan is better correlated with gridded ISMR than that over Tibet and Central India in both the model simulations and observations. In case of observed TCC over Pakistan, most of the regions of India are positively correlated except Tamil Nadu, Nagaland and Tripura which have negative CC. The model also shows correlation patterns similar to those in observation, but stronger than that observed. Thus TT over Pakistan plays relatively more important role in Indian summer monsoon than that over Tibet and Central India. But it is essential to conduct more such studies using data from various other sources and also over longer periods to confirm the results obtained in this study.

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India Meteorological Department (IMD). The atmospheric fields are obtained from the NCEP/NCAR from which reanalysed data have been used for comparison. One of the authors (S K Dash) thanks the Department of Science and Technology, Government of India for the sponsored research project under which this research has been conducted.

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