MAUSAM, **68**, 4 (October 2017), 607-620

551.582 : 551.501 (540)

Regional climate simulation of present day temperature over India using RegCM3: Evaluation and analysis of model performance

R. K. S. MAURYA, G. P. SINGH, U. K. CHOUDHARY* and S. C. BHAN**

Department of Geophysics, Banaras Hindu University, Varanasi – 221005, India

**India Meteorological Department, Varanasi – 221 005, India*

***India Meteorological Department, New Delhi – 110 003, India*

(*Received 31 March 2015, Accepted 14 August 2017*)

e mail : rksmaurya@gmail.com

सार - भारतीय उपमहाद्वीप में क्षेत्रीय जलवायु मॉडल वर्जन 3 (Regcm3) का प्रयोग करके सतह पर अनुकारी वायु तापमान तथा मध्य वायुमंडल स्तर पर मॉडल निष्पादन के मूल्यांकन पर अध्ययन केंद्रित किया गया है। यह मॉडल 1982-2006 काल के लिए 40 कि. मी. क्षैतिज विभेदन के क्षेत्र पर लगभग 58 डिग्री पूर्व से 102.5 डिग्री पूर्व एवं 5 डिग्री उत्तर से 40 डिग्री उत्तर के लिए प्रयोग किया गया है। निचले क्षोभमंडल (850 एच पी ए) और मध्य क्षोभमंडलीय (500 एच पी ए) स्तर पर तापमान का राष्ट्रीय पर्यावरण पूर्वानुमान केंद्र के आँकड़ा सेट के साथ अनुकारी पुन: विश्लेषण किया गया है। मॉडल परीक्षण परिणाम के लिए विभिन्न साँख्यिकीय मापें जिनका नाम औसत अभिनति त्रुटि, मूल वर्ग मध्य त्रुटि, औसत प्रतिशत त्रुटि और सहसंबंध गुणांक का प्रयोग किया गया है। यह पाया गया है कि भारत में Regcm3 प्रेक्षित औसत सतही जलवायु एवं सतह का और सतह एवं मध्य स्तर की वायु के तापमान की प्रवृत्ति को पकड़ने की क्षमता है। मॉडल से पता चला कि निचले क्षोभमंडल में शीत अभिनतियाँ -4.29 डिग्री सेल्सियस (16.4 प्रतिशत) लेकिन NECP आँकड़ा सेट की तुलना में मध्य क्षोभमंडल में महत्वपूर्ण नहीं थी। वायु का तापमान मध्य क्षोभमंडल के स्तर पर अच्छी तरह पता लग रहा था। वार्षिक सतही वायु तापमान के संबंध में भारत में सह-संबंध गुणांक Regcm3 और NLFCP के बीच काफी अधिक महत्वपूर्ण (0.82) है। भारत में सतही वायु तापमान की प्रवृत्ति NECP के साथ 0.32 डिग्री सेल्सियस और Regcm3 के साथ 0.40 डिग्री सेल्सियस अधिक बढ़े हुए पाए गए थे। भारत के अधिकांश हिस्सों में शीत अभिनतियों के वार्षिक सतही वायुतापमान -2° डिग्री सेल्सियस से 5 डिग्री सेल्सियस की परास में पाए गए थे। जबकि कम ऊँचाई वाले या घाटी के क्षेत्रों में शीतअभिनति -5 °C डिग्री सेल्सियर से ऊपर पाई गई थी और पर्वतीय क्षेत्रों में -2 डिग्री सेल्सियस से नीचे पाई गई थी। अधिकतम वायु तापमान Tmax न्यूनतम वायु तापमान Tmin और औसत वायु तापमान Tave की वार्षिक और मौसमी प्रकृत्तियों के विश्लेषण से पता चला कि भारतीय गंगोत्रीय क्षेत्रों में पश्चिमी हिमालय और उत्तरी पूर्वी भारत में सभी मौसम में बढ़ती हुई प्रवृत्ति पाई गई थी जबकि उत्तरी केंद्रीय भारत में गर्मी के मौसम में और मॉनसून के मौसम में गुजरात राज्य में घटती हुई प्रवृत्ति पाई गई। Regcm3 से पता चला कि निचले क्षोभमंडल में जलवाष्प मिश्रण अनुपात अधिक होने के परिणामस्वरूप मध्य क्षोभमंडल स्तर की अपेक्षा सतही पर अधिक शीतलता थी।

ABSTRACT. The study has focused on the evaluation of model performance on simulated air temperature at surface and mid atmospheric level over the Indian subcontinent using a Regional Climate Model version 3 (RegCM3). The model is used at 40 km horizontal resolution over the domain approximately 58° E-102.5° E & 5° N-40° N for the period of 1982-2006. The temperatures at lower troposphere (850 hPa) and mid tropospheric level (500 hPa) have been simulated with reanalysis dataset of the National Centre for Environmental Prediction (NCEP). Various statistical measures namely Mean Bias Error (MBE), Root Mean Square Error (RMSE), Mean Percentage Error (MPE) and Correlation Coefficients (CCs) has been used to test the model results. It has been found that the RegCM3 is able to capture the main features of the observed mean surface climate and also patterns of surface and mid-level air temperatures over India. The model showed that cold biases were -4.29 °C (16.4%) at the lower troposphere, but insignificant at the mid atmospheric level in comparison to the NCEP dataset. The air temperature was well captured at mid tropospheric level. The CC between RegCM3 and NCEP is significantly high (0.82) over India in respect of annual surface air temperature (SAT). The trends of observed SAT were found to be significant increased by 0.32 °C with NCEP and 0.40 °C with RegCM3 over India. The annual SAT of cold biases ranging between -2 °C to -5 °C was found over major parts of India while cold biases of above -5 °C was found in the regions of low elevation or valley regions and below -2 °C in the mountainous regions. The analysis of annual and seasonal trends of maximum air temperature (Tmax), minimum air temperature (Tmin) and average air temperature (Tave) showed that the increasing trend was found over the Indo-Gangetic plain, Western Himalayas (WH) and North East India (NEI) in all seasons while decreasing trend over the North Central India (NCI) in the summer season and over the state of Gujarat in the monsoon season. The RegCM3 showed higher Water Vapour Mixing Ratio (WVMR) at the lower troposphere resulting more cooling at surface rather than at mid tropospheric level.

Key words – Evaluation and model performance, Regional climate model, Cold biases, Trend, Underestimated, Vertical transport.

1. Introduction

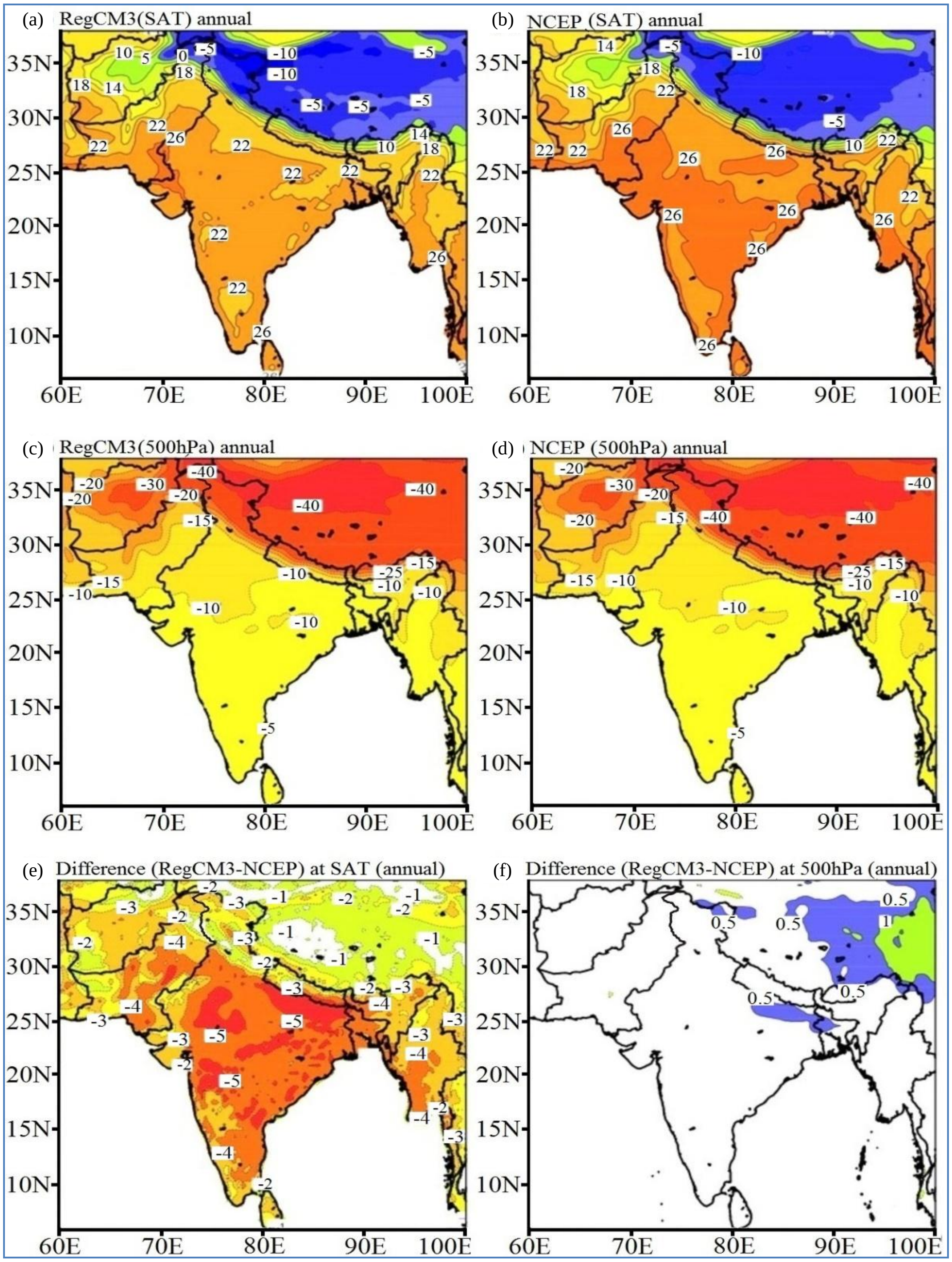
Numerous studies have shown that the surface temperatures are rising over large parts of the world since the beginning of the 20^{th} century. Land surface temperature is a good indicator of the energy balance at the surface of the Earth. It gives an idea about surface-atmosphere interactions and energy fluxes between atmosphere and the ground [Mannstein (1987); Sellers *et al.* (1988)]. Further, atmospheric General Circulation Model (GCM) has shown that the strong summer monsoons are associated with high land temperatures (Meehl, 1994). Therefore, land surface temperature is not only acting as a indicator of climate change, but also due to its control on upward terrestrial radiation, and consequently, the control of the surface sensible and latent heat fluxes exchange with the atmosphere (Aires *et al*., 2001; Sun, 2003). The global warming affects air temperature at surface and mid atmospheric level due to these heat exchanges.

SAT over India has been reported that there exist some smaller sub-regions with statistically significant increasing and decreasing trends (Pant and Rupa Kumar, 1997). The surface temperature over the Indian region shows increasing trend of about 0.4 °C/100 years. The increasing tendency of mean temperature is mainly contributed by the maximum temperature, as the minimum temperature trend is less during the current century (Rupa Kumar *et al.*, 1994). We have computed the climatological means, biases and systematic model errors for the comparison of the model performance with the NCEP reanalysis dataset. In fact, to date, despite the large number of RegCM3 simulations documented in the literature, relatively little attention has been devoted to interannual variability using RegCM3 simulations of sufficient length. In this regard, Giorgi and Shields (1999), Pal *et al*. (2000) and Small *et al.* (1999) presented evaluations of the RegCM3 interannual variability over the continental USA, central Asia and eastern Africa, respectively. Their simulations were driven by analysis of the observations and the model showed a good performance in capturing both the sign and the magnitude of the temperature and precipitation anomalies which occurred in different years over a number of sub-regions of the domains. The performance of RegCMs in reproducing the characteristics of given anomalous seasons over India has been investigated (Dash *et al.*, 2006 and Singh and Oh, 2007). But these studies were only for summer monsoon season and for selected years. In the study of the climate variability, SAT as well as air temperature at mid-level of the atmosphere must be taken into account considering their important roles in deciding the regional climate. That is why we checked the reliability of the model in this sense which was ignored previously.

The aim of this study is to examine the performance of the model in simulating the air temperature annually as well as seasonally at surface and mid atmospheric level and to compare with the observed datasets over India throughout the period 1982-2006. Such analysis can provide additional insights into the ability of the modeling to climatic trends as well as results obtained by future projection due to the climate change. In the present paper, section 2 describes the model set up and experimental designed. Section 3 is devoted to evaluate the model performance through the analysis of annual and seasonal means, the interannual variability and possible causes for model biases over India. Section 4 presents important results of study.

2. Model data and experimental design

RegCM3 is development of the RCM version (Dickinson *et al.*, 1989; Giorgi and Bates, 1989) and several MM4 physics parameterizations were modified to adapt it to longer-term climate simulations. In particular, the radiative transfer scheme of Kiehl *et al.* (1996) and the Biosphere Atmosphere Transfer Scheme were added and the planetary boundary layer (PBL) and convective precipitation schemes of the earlier version were also modified (Giorgi *et al.*, 1993a). The third generation RegCM integrates almost two decades of improvements made in earlier versions in the representation of precipitation physics, surface physics, atmospheric chemistry and aerosols, PBL parameterizations, radiative transfer, and BATS. The dynamical core of RegCM3 is based on the NCAR/PSU Mesoscale Model version-5 (Grell, 1993; Grell *et al.*, 1994) and is a compressible, primitive equation, sigma vertical coordinate, grid point limited area model with hydrostatic balance (Giorgi and Marinucci, 1996a,b; Giorgi and Shields, 1999).



Figs. 1(a-f). Annual climatology of 25 years period (1982-2006) of air temperature (°C): (a) RegCM3 (SAT), (b) NCEP (SAT), (c) RegCM3 (500-hPa), (d) NCEP (500-hPa), (e) difference (RegCM3-NCEP) at SAT and (f) difference (RegCM3-NCEP) at 500-hPa

The RegCM3 is simulated from 1st November, 1981 to 31st January, 2007 (2 months spin-up time) for continuously run at a grid spacing of 40 km with 18σ vertical pressure level. Central point of the model is kept at 23.5° N & 80° E with 111 grids in the north-south and 125 grids in the west-east directions. The model domain has covers the area of 58° E to 102.5° E and 5° N to 40° N. The grids were defined on a Normal Mercator

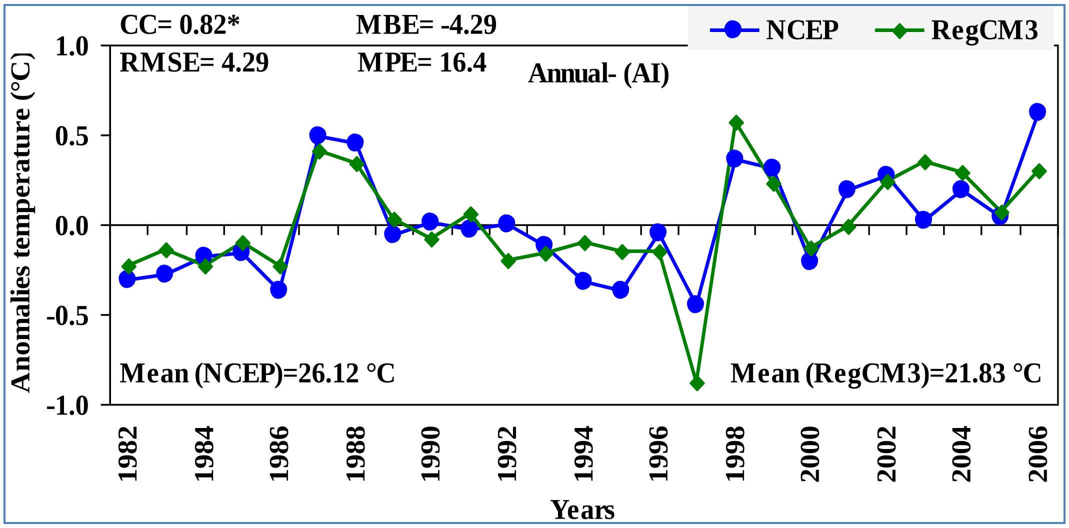


Fig. 2. Interannual variability of mean annual surface air temperature simulated by RegCM3 and NCEP over India during 1982-2006

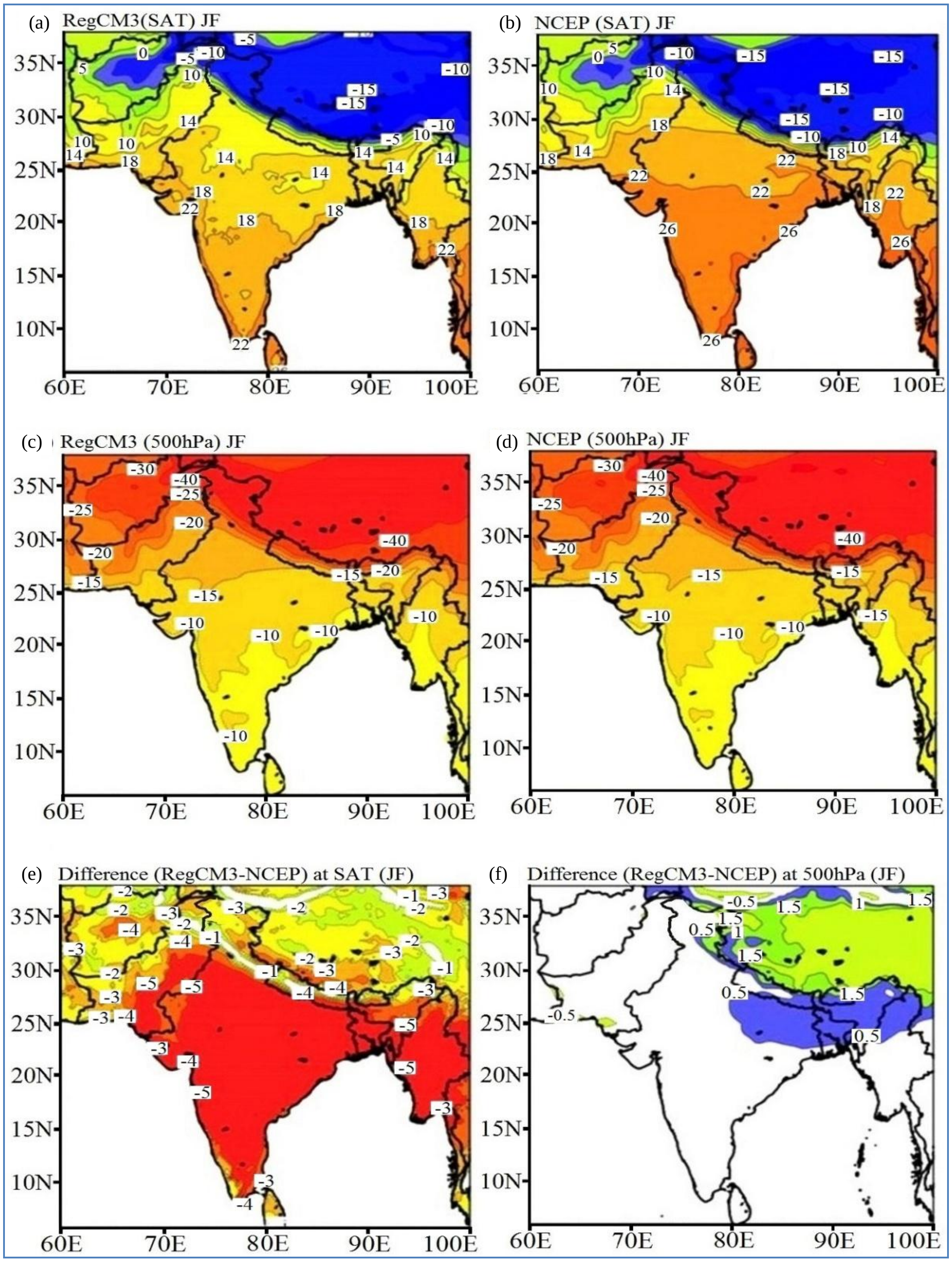
(NORMER) map projection. The terrain height and landuse data for the given domain were generated from the Global Land Cover Characterization (GLCC) global 2 min resolution terrain. The monthly averaged Optimum Interpolated Sea-Surface Temperature (OISST) available from the National Oceanic and Atmospheric Administration (NOAA) for the whole year was horizontally interpolated into the specified domain and also in each time step for the model integration. The lateral boundary conditions for wind, temperature, surface pressure, and water vapor were interpolated from 6 hourly NNRP1 (NCEP/NCAR Reanalysis Product version 1). The NCEP data have a spatial resolution of 2.5° × 2.5°. Soil moisture is initialized as a function of vegetation type. The lateral boundary conditions were updated and fed every 6-hour into the model and the time step of the integration has been kept at 75s.

3. Results and discussion

3.1. *Analysis of annual air temperature*

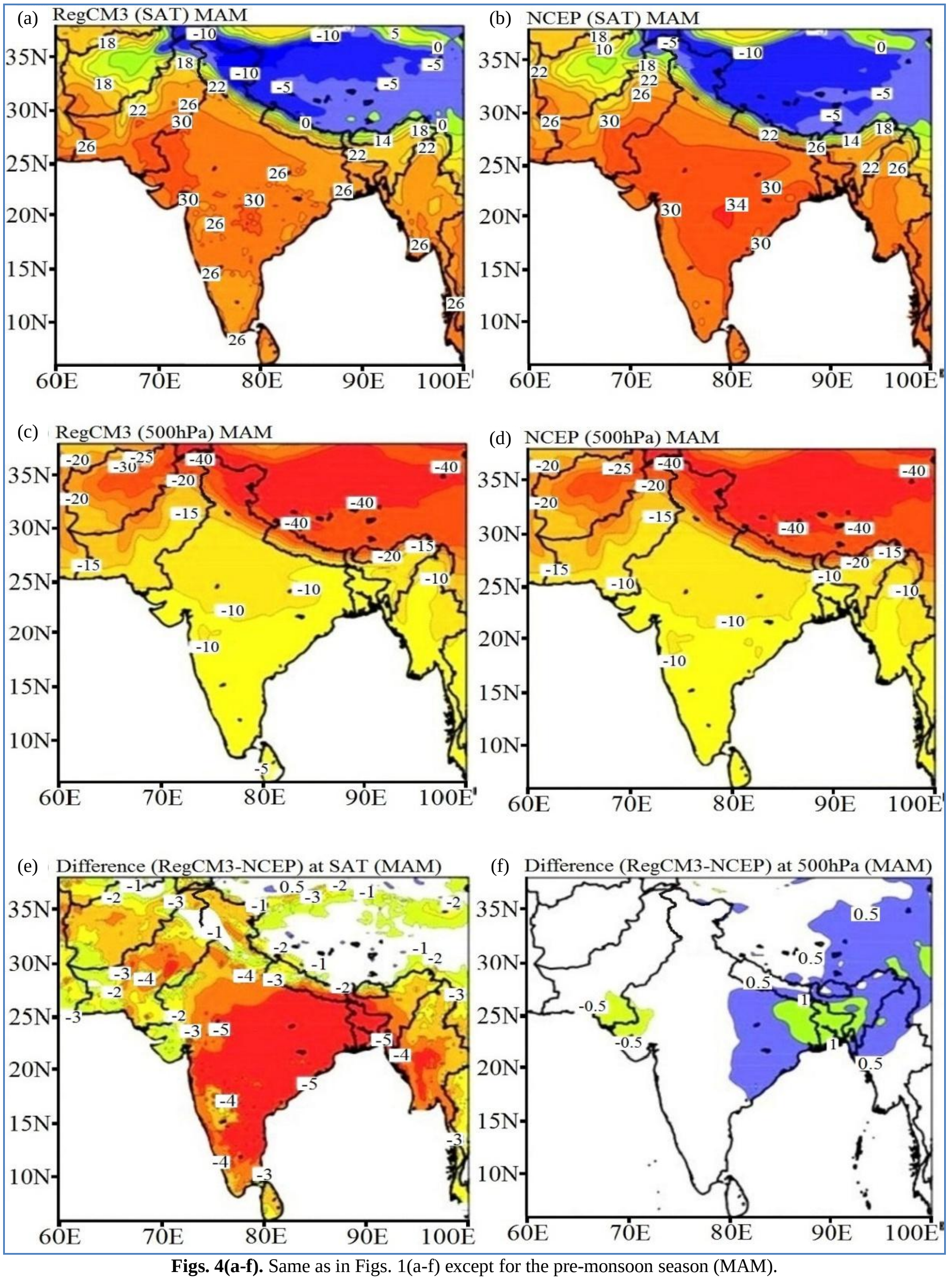
We have analyzed the annual climatology of 25 years period (1982-2006) of air temperature at the surface and 500 hPa atmospheric level simulated with RegCM3 and observed (NCEP reanalysis) dataset [Figs. 1(a-f)]. Fig. 1(a) showed 26 °C SAT over few parts of India (specially over the small parts of Rajasthan and Gujarat states) and 22 °C SAT over larger parts of India in RegCM3 while NCEP [Fig. 1(b)] showed 26 °C SAT over larger parts of India (mainly over the central India, east coast of India and southern northwest India). Lowest SAT below 0 °C can be seen over WH in RegCM3 and NCEP both. The mean annual air temperature at 500 hPa atmospheric level above -5 °C can be seen over the central to southern parts of India and below -10 °C over the central to northern part of India and it was well captured in RegCM3 in comparison to the NCEP [Figs. 1(c&d)]. Difference in SAT between RegCM3 and NCEP exhibited a predominant negative temperature (cold) bias of 4 °C over large parts of India as shown in Fig. 1(e) and highest difference in SAT was found mainly over the central India and lowest difference over the mountainous regions. The model showed cooling (negative bias) over large parts of India as compared to the observed temperature at the surface [Fig. 1(e)] while it well captured the temperature at 500 hPa [Fig. 1(f)]. Overall, RegCM3 well reproduced the observed regional patterns of the air temperature.

RegCM3 and NCEP annual SAT anomalies over all India have been shown in Fig. 2. The performance of model was evaluated by computing MBE, RMSE and MPE for the study of inter-annual variability and compared with the NCEP. The mean annual area averaged SAT was 21.83 °C in RegCM3 and 26.12 °C in NCEP (difference between RegCM3 and NCEP was -4.29 °C) over India in the period 1982-2006. The computation of MBE and RMSE showed the value of -4.29 °C and 4.29 °C respectively over India. The MPE test clearly showed that the model underestimates the cooling by -16.4% during the period of study. The high CCs (CCs = 0.82) indicated good agreement between the model and observed datasets. The cold biases of the model might be due to combination of different additional elements included in RegCM3 such as energy fluxes, surface albedo, clouds and temperature advection (Tadross *et al*., 2006 and Sylla *et al.*, 2012). As a general consideration in the evaluation of the temperatures [Fig. 1(a-f)], it should be recalled that at least in mountainous regions, the observed data may be close or



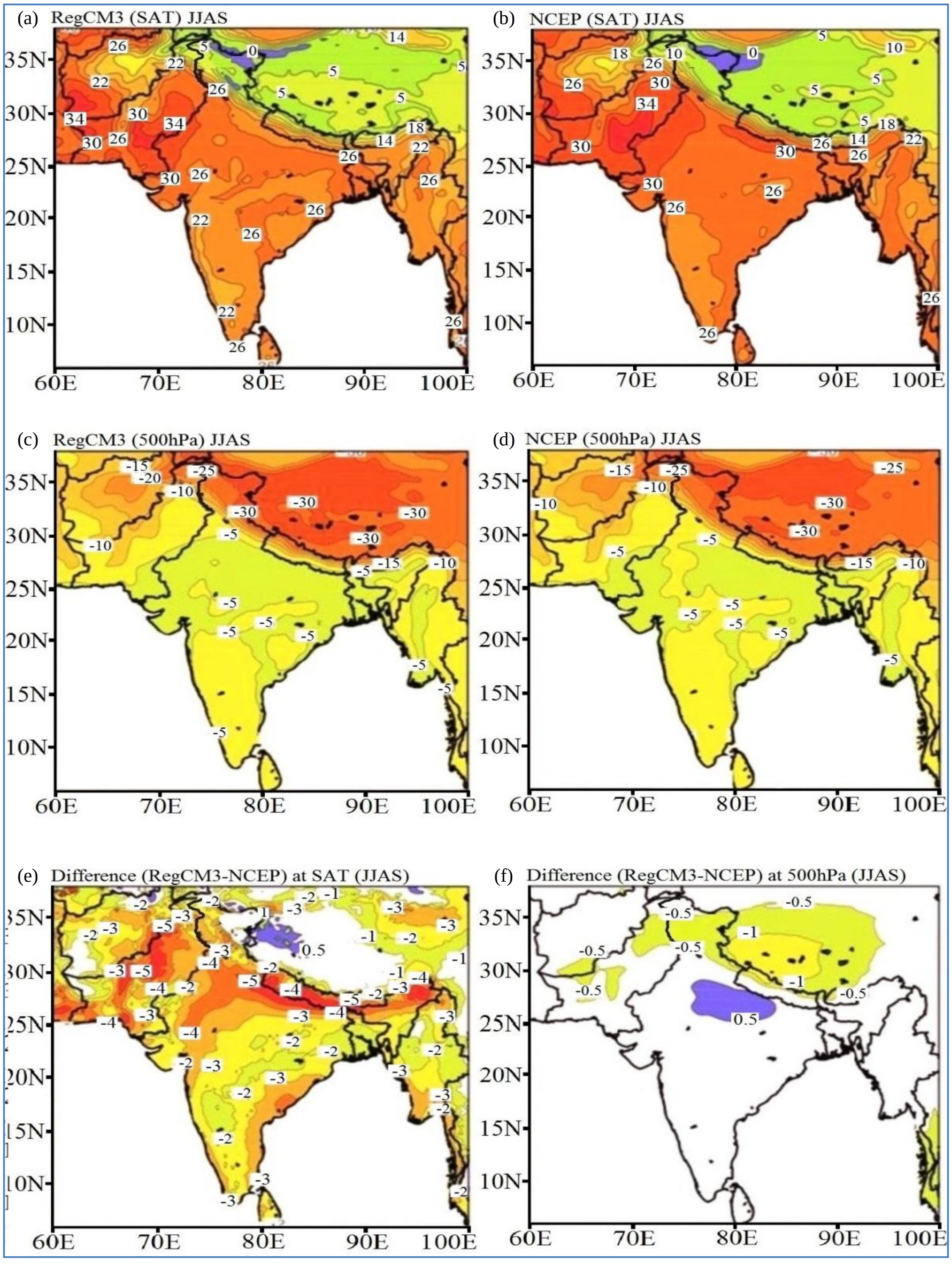
Figs. 3(a-f). Same as in Figs. 1(a-f) except for the winter season (JF)

lowest affected by a cold bias due to the prevalence of low elevation and valley. These results indicated that the RegCM3 may have a more efficient vertical transport of energy and water vapor from the boundary layer to the troposphere. One reason for this behaviour is the use of different planetary boundary layer schemes in the model. The model adopts a non-local boundary layer representation in which the vertical eddy diffusion coefficient follows a prescribed profile between the surface and the boundary layer top which was calculated from the bulk stability of the lower troposphere (Holtslag *et al.*, 1990). In other words, in this non-local scheme, the



Figs. 4(a-f). Same as in Figs. 1(a-f) except for the pre-monsoon season (MAM).

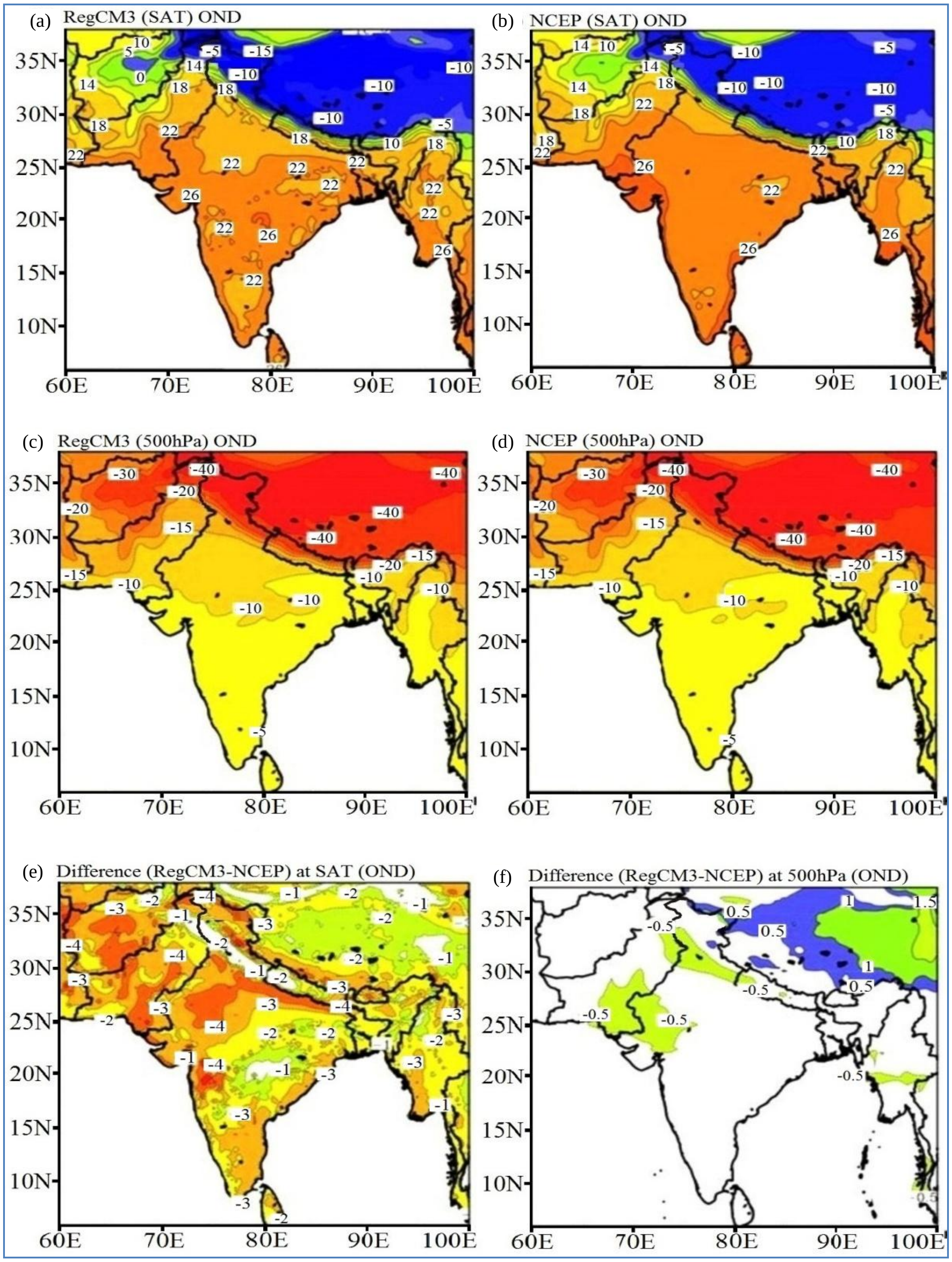
vertical diffusion depends on the bulk stability of the boundary layer. Conversely, NCEP adopts a local formulation in which the vertical diffusion coefficient depends on the local thermal stability (Pope *et al*., 2000). Giorgi *et al.* (1993a) showed that non-local schemes tend to enhance vertical heat and moisture transport compared to local schemes, thereby leading to a relative cooling and drying of the surface in RegCM3. A second possibility of cold biases in RegCM3 may be attributed to the use of different convection schemes. The net effect of convection is to redistribute vertically and in particular transport upward energy and moisture. NCEP and the RegCM3 use



Figs. 5(a-f). Same as in Figs. 1(a-f) except for the summer monsoon season (JJAS)

mass flux cumulus convection schemes. However, the schemes adopt different closures and parameter assumptions and as a result their efficiency in redistributing heat and moisture may be different. This effect would be especially important in the warm season, when cumulus convection is more active.

Several components of the land surface schemes may be contributed to the differences in SAT between the models, for example the treatment of the drag coefficient, the transpiration process, or the simulation of the cycle of snow formation and melting and it is difficult to identify which of them might be important. Regardless of the



Figs. 6(a-f). Same as in Figs. 1(a-f) except for the post monsoon season (OND)

specific cause of the difference in lower level temperatures between the RegCM3 and NCEP this appears to be a systematic effect. It is useful to analyze the trends of simulated SAT by the model in relation to the observed trends in the period 1982-2006. Analysis of model and observed SAT showed an increasing trend of 0.32 °C with NCEP and 0.40 °C with RegCM3 over India. It has been seen that the annual SAT was increased by 0.40 °C during 1901-2000 (Maurya *et al.*, 2010) and RegCM3 showed an increase in annual SAT by 0.40 °C in 25 years (1982-2006). The maximum increase in annual SAT was in recent decades.

3.2. *Seasonal air temperature*

3.2.1. *Winter Season (January and February)*

Figs. 3(a-f) showed the simulated (RegCM3 and NCEP) climatology and difference of winter season (JF) air temperature at the surface and 500 hPa during 1982-2006. Figs. 3(a&b) showed the highest SAT above 18 °C in the RegCM3 and above 22 °C in the NCEP over the southern parts of India and air temperature range of 10 °C to 18 °C can be seen over the northern parts of India in RegCM3 while air temperature range of 14 °C to 22 °C have been found in NCEP over the same regions. The lowest SAT of below 0 °C was noticed over the WH both in RegCM3 and NCEP. Figs. 3(c&d) show the mean air temperature ranging between -40 °C over the WH to -5 °C over southern part of India both in RegCM3 and NCEP at 500 hPa. Quantitative estimates of model temperature biases at surface and 500 hPa have been presented in Figs. 3(e&f). In this regard, a comparison with the NCEP fields should be considered mostly as illustrative because these fields were interpolated onto the model grid over India in RegCM3 and NCEP difference fields. Difference in SAT between RegCM3 and NCEP exhibited a predominantly negative temperature bias of more than -5°C over large parts of India as shown in Fig. 3(e) and lowest difference was over the mountainous regions. Difference between RegCM3 and NCEP air temperature at 500 hPa was showing the positive (warming) bias of 0.5 °C over the NEI as shown in Fig. 3(f).

3.2.2. *Pre-monsoon season/summer season/hot weather season (March, April & May)*

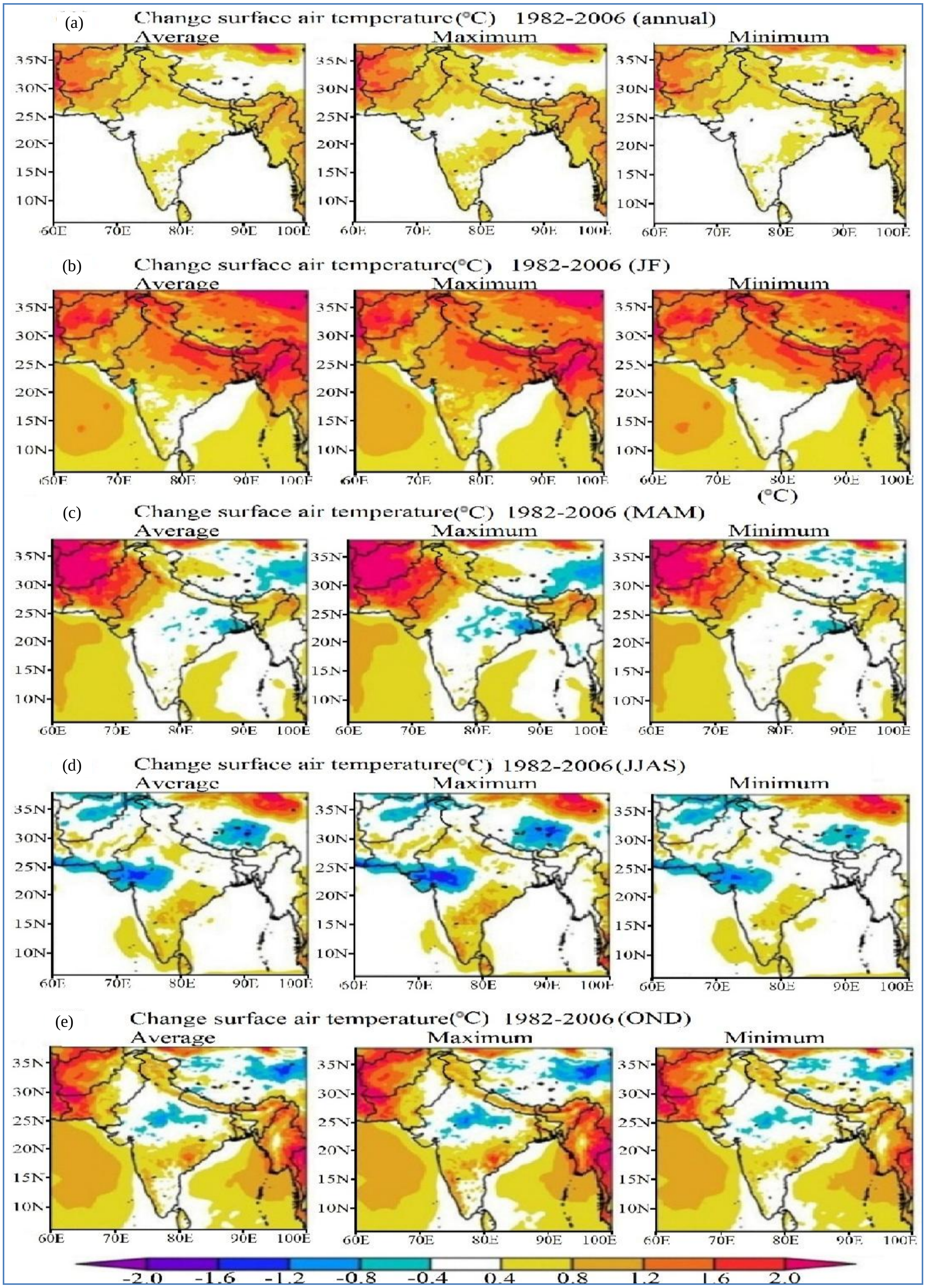
Figs. 4(a-f) presented the climatological seasonal mean and difference in air temperature at the surface and 500 hPa during pre-monsoon season (MAM) over India in the period 1982-2006. Figs. 4(a&b) have shown SAT of above 26 °C in RegCM3 and above 30 °C in NCEP over the central India, North West India (NWI) and Interior Peninsular India (IPI) during MAM. Figs. 4(a&b) also showed SAT ranging between 18 °C to 26 °C in RegCM3 and between 22 °C to 30 °C in NCEP over the West Central India (WCI) and northern parts of India. Similarly, temperature below 0 °C was found over the northwest WH in both RegCM3 and NCEP. Figs. 4(c&d) clearly showed air temperature at 500 hPa ranging between -40 °C over the WH to -5 °C over southern part of India both in the model and NCEP. Estimates of model temperature biases presented in Figs. 4(e&f) showed cooling in SAT between 2 °C to 5 °C over larger parts of India and at 500 hPa the warming (0.5 °C to 1 °C) was noticed over the eastern parts of India. It can be seen that the RegCM3 could reproduce the observed regional patterns of air temperature reasonably well. The temperature fields for the RegCM3 and NCEP were very close to each other. Results also showed that the model has a tendency to underestimate the SAT at surface and overestimate at 500 hPa.

3.2.3. *South-west monsoon/summer monsoon season (June, July, August and September)*

The seasonal mean and difference in air temperature during JJAS in the period 1982-2006 have been shown in Figs. 5(a-f) at the surface and 500 hPa over India. Figs. 5(a&b) presented the climatology of mean SAT of RegCM3 and NCEP respectively. Figs. 5(a&b) showed SAT more than 26 °C in both RegCM3 and NCEP over the central India and NWI. The lowest SAT was found around 0 °C over the WH in both the RegCM3 and NCEP. Figs. 5(c&d) presents mean air temperature at 500 hPa was ranging between -30 °C over the WH to -5 °C over the south India and more than -5 °C over most parts of north India in the RegCM3 and NCEP. Estimates of the model performance computing biases at the surface and 500 hPa are shown in Figs. 5(e&f). Difference in SAT between RegCM3 and NCEP exhibits predominantly negative biases ranging between -1 °C and -4 °C over large parts of India [Fig. 5(e)]. The lowest difference is seen over the IPI and North Central India (NCI) and the mountain regions. The temperature difference between RegCM3 and NCEP at 500 hPa shows that the model has been able to capture the surface air temperature over India [Fig. 5(f)] quite well.

3.2.4. *Post-monsoon season/northeast monsoon season (October, November and December)*

Figs. 6(a-f) shows the climatological seasonal mean and difference in temperature at the surface and 500 hPa during the post-monsoon season (OND) over India for the period 1982-2006. Figs. 6(a&b) shows SAT of more than 22 °C over the central India, north NWI and IPI during post-monsoon season in both RegCM3 and NCEP. It also shows surface air temperature ranging between 18 °C to 22 °C over the north NWI and the NEI in both RegCM3 and NCEP Similarly, lowest SAT of below 0 °C was noted over the northwest WH in both RegCM3 and NCEP. Figs. 6(c&d) clearly show air temperature ranging between -40 °C over the WH to -5 °C over the southern part of India at 500 hPa over India in both model and NCEP. The difference in SAT between RegCM3 and NCEP exhibits predominantly negative air temperature biases ranging between -1 °C to -2 °C over large parts of India [Fig. 6(e)] and the difference is least over the IPI, central India and the mountain regions. The air temperature computed using RegCM3 agrees reasonably well with that of NCEP [Fig. 6(f)].



Figs. 7(a-e). Change (linear regression trend all gridded point) in the annual and seasonal averaged, maximum and minimum SAT (°C/25-yrs) over India during 1982-2006 (RegCM3)

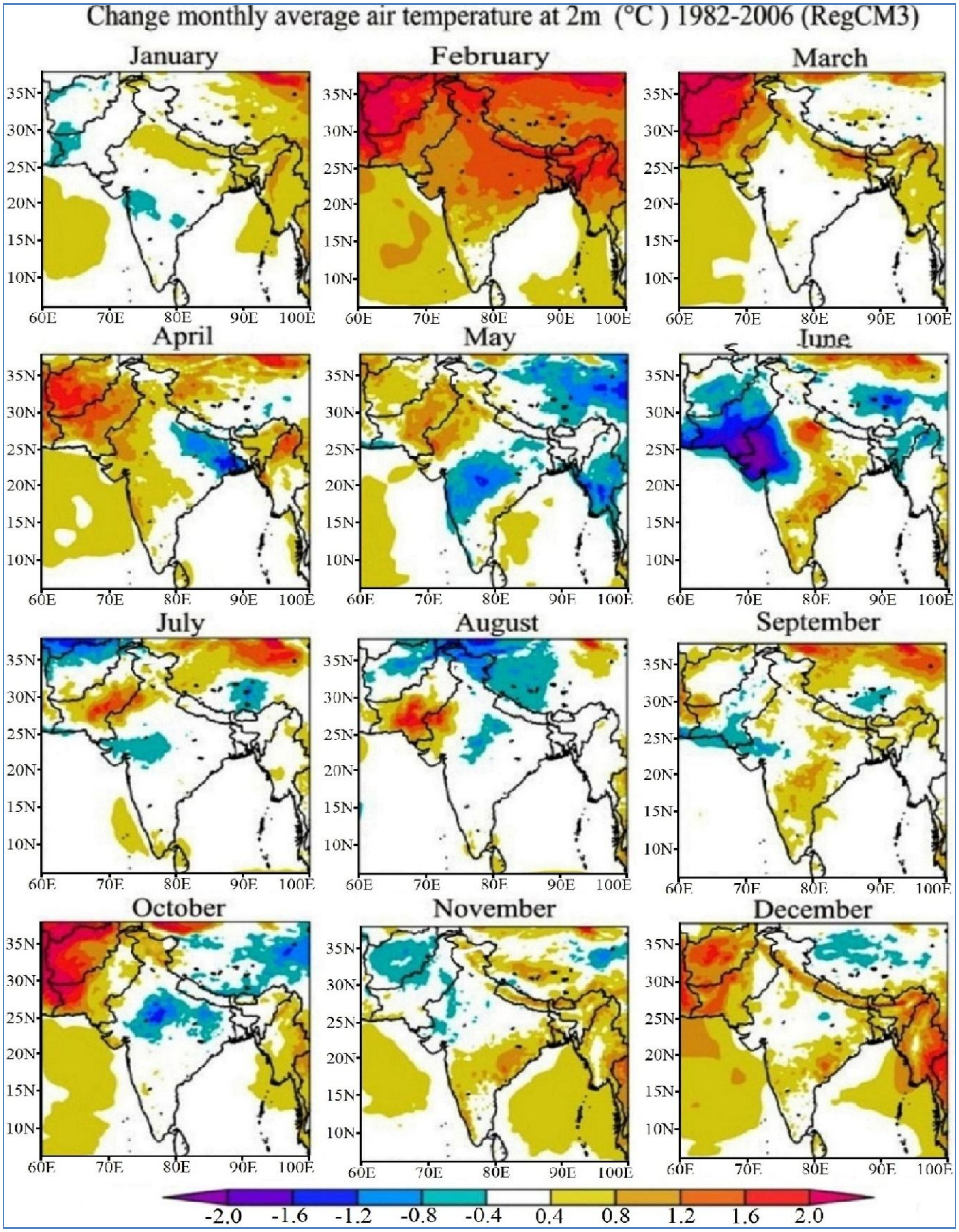


Fig. 8. Same as in Fig. 7 except for the monthly change

Over all, RegCM3 has been able to reproduce the observed regional patterns of seasonal air temperature during winter, pre-monsoon, summer monsoon and post-monsoon seasons reasonably well. The error (negative biases) has been found out to be maximum during winter and pre-monsoon seasons and minimum in summer

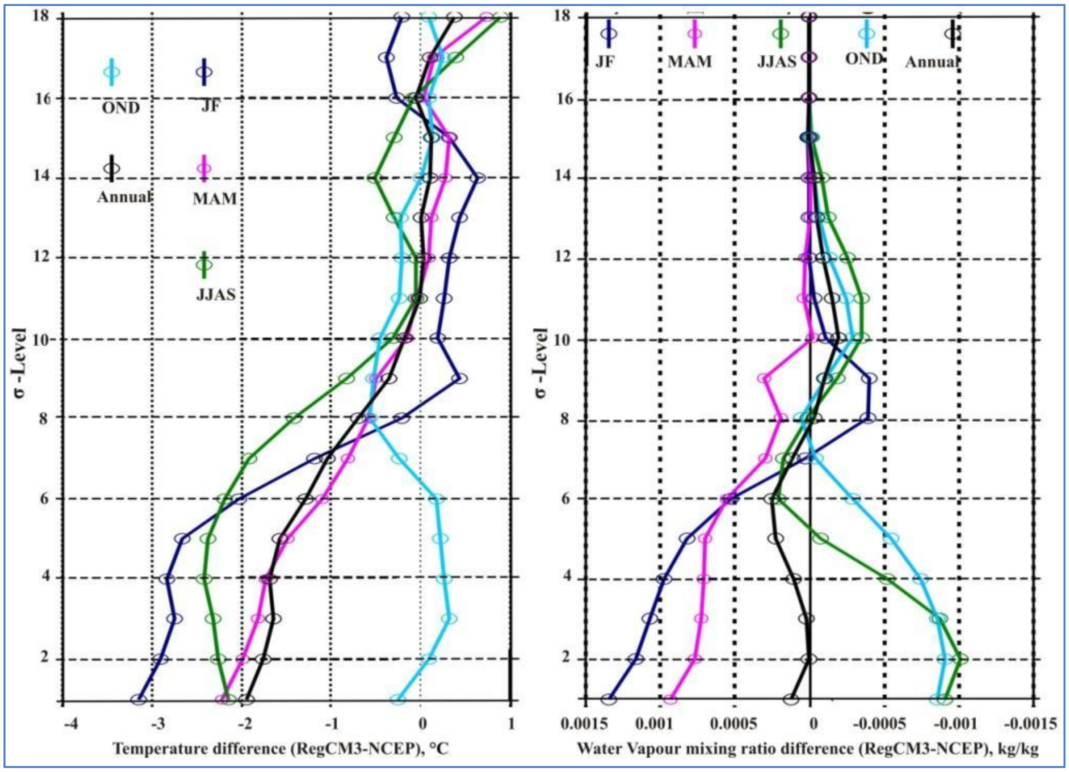


Fig. 9. Difference in vertical profile between the RegCM3 and NCEP reanalysis: temperature (left) and WVMR (right) over India during annual and seasonal at 18σ level

(rainy) and post monsoon seasons. The high negative biases during winter and pre-monsoon seasons may be associated with the intense vertical transport of temperature and water vapour (Giorgi *et al.*, 2004a).

3.3. *Temperature trends*

In order to study the change in temperature, it is useful to analyze the trends simulated by the RegCM3. This can in fact give some insights into the model ability to simulate the regional climate trends and changes in response to either external forcing or inter-decadal modes of internal variability. A good performance in this regards can enhance the confidence in the trends projected for future climate conditions. A method of linear regression trend (°C/25yrs) has been used to study the change in annual and seasonal averaged, maximum and minimum surface air temperature shown in Figs. 7(a-e). Fig. 7(a) showed an increase in annual, maximum and minimum SAT. The SAT increase of the order of 0.4 °C is found over large parts of India. Largest changes were found in maximum SAT than that of average and minimum SAT (above 0.4 °C) mainly over the Himalayas, north parts of India and south peninsular India. Fig. 7(b) (JF season) indicated that the highest increasing trends in average, maximum and minimum SAT were noted over the India-Gangetic plain, WH and NEI. Average and maximum SAT were showing increasing trend over large parts of India while minimum SAT was only to the north of 25° N during winter season. Fig. 7(c) showed MAM season average, maximum and minimum SAT and an increasing trend was noticed over the NWI, NEI and WH and a decreasing trend was found over the NCI. During JJAS season averaged, maximum and minimum SAT an increasing trend was found over the east coast of India and a decreasing trend over the state of Gujarat. As far as post monsoon season [Fig. 7(e)] is concerned, analysis showed an increasing trend over the southern part of India, WH and NEI and decreasing trend over the NWI and central NEI. The highest increase in average, maximum and minimum SAT was found above 1.2 °C over the northern part of India in winter season, above 0.8 °C over NWI in pre monsoon season and above 0.8 °C over the NEI and state of Orissa in post monsoon season. While highest decrease in average, maximum and minimum SAT was noticed over the state of Gujarat (above 0.8 °C in monsoon season) as shown in Fig. 7(d). Analysis of RegCM3 simulated monthly (during period 1982-2006) average SAT change over India has been shown in Fig. 8. Fig. 8 showed highest increase in SAT (above 0.8 °C) during the month of February over the large parts of India, more than 0.4 °C over the NWI during the month of April and May and over large part of the India in the month of June, September, November and December. The highest decrease in SAT (below -0.8 °C) were found over the NCI in April, over the central India in May, October and below -2 °C over the southern NWI in the month of June.

The simulated total moisture transport is illustrated by the vertically integrated temperature and water vapour mixing ratio (WVMR). The seasonal and annual moisture transports at 18σ levels have been shown in Fig. 9 along with their respective differences (RegCM3-NCEP) averaged over the land regions of India. Both experiments exhibit a similar spatial patterns, with high and low temperature and WVMR in all the seasons over India. The magnitudes of averaged air temperature at first level are larger during winter season and smaller during post-monsoon season with the respective difference (RegCM3-NCEP simulation) (left panel of Fig. 9). Similarly, the WVMR component (right panel of Fig. 9) showed the positive differences during winter to pre-monsoon season and negative difference during summer and post monsoon seasons over India. As a consequence, the magnitude of the total moisture convergence was greater in RegCM3-NCEP during JF and MAM season which is consistent with the stronger lower-level convergence and upward motion. The Fig. 9 (right panel) clearly showed high WVMR during JF and MAM seasons in RegCM3 which causes highest negative biases of temperature in RegCM3 and low WVMR in RegCM3 during JJAS and OND season can be linked with the lowest negative biases of temperature in RegCM3 during the same season. Fig. 9 also showed an increased mean WVMR anomalies resulting from the exclusion of mean temperature anomalies increases and *vice versa*.

4. Conclusions

The present study showed a detailed analysis of annual and seasonal changes in temperatures, wind fields and WVMR using RegCM3 model simulated at 40 km resolution from 1982-2006. The model simulation was validated with the observed data sets of NCEP. Different statistical methods have been applied to test the model performance. The important results of the present study are well described below:

(*i*) Annual surface air temperature of cold biases ranging between -2 °C to -5 °C was found over large parts of India, above -5 °C in the regions of low elevation or valley regions while below -2 °C in the mountainous regions. However, RegCM3 showed cold biases of above -5 °C during winter and pre-monsoon seasons while below -3 °C during summer monsoon and post-monsoon season over most parts of India.

(*ii*) The model showed the value -4.29 °C and 4.29 °C in its MBE and RMSE test respectively and it underestimated the cooling (-16.4%) in the MPE test over India. CCs of 0.82 indicate good agreement of model results with the observed datasets. An increasing temperature trend of 0.32 °C with the NCEP and 0.40 °C with RegCM3 was also observed. Seasonal trend of Tmax, Tmin and Tave showed highest increase over the Indo-Gangetic plain, WH and NEI during winter season and decreasing trend over the NCI in MAM season and state of Gujarat during JJAS season.

(*iii*) The magnitude of the total moisture convergence was stronger in RegCM3-NCEP field during JF and MAM seasons and weaker during JJAS and OND seasons. It is due to high cold biases of temperature showed by RegCM3 during JJAS and OND seasons and low cold biases during JJAS and OND seasons.

Acknowledgments

The authors want to acknowledge International Centre for Theoretical Physics (ICTP), Trieste, Italy for providing model and RegCM3 data sets and Department of Science and Technology (DST), Government of India (DST No.:SR/S4/AS:05/2008) for providing fund in the form of project to carry-out research work.

References

Aires, F., Prigent, C., Rossow, W. B. and Rothstein, M., 2001, “A new neural network approach including first-guess for retrival of atmospheric water vapor, cloud liquid water path, surface temperature and emissivities over lan from satellite microwave observation”, *J. Geophysics Res*., **106**, 14887-14907.

Dash, S. K., Shekhar, S. and Singh, G. P., 2006, “Simulation of Indian Summer Monsoon Circulation and rainfall using RegCM3”, *Theor. & Appl. Climatol*., **86**, 161-172.

Dickinson, R. E., Errico, R. M., Giorgi, F. and. Bates, G. T., 1989, “A regional climate model for western United States”, *Clim. Change*, **15,** 383-422.

Giorgi, F. and Bates, G. T., 1989, “The climatological skill of a regional model over complex terrain”, *Monthly Weather Review*, **117,** 2325-2347.

Giorgi, F., Bates, G. T. and Nieman, S., 1993a, “The multiyear surface climatology of a regional climate model over the western United States”, *J. Clim*., **6**, 75-95.

Giorgi, F., Bi, X. and Pal, J., 2004a, “Mean, interannual variability and trends in a regional climate change experiment over Europe: I. Present- Day climate (1960-1990)”, *Clim. Dyn*., **22**, 733-756.

Giorgi, F. and Marinucci, M. R., 1996a, “An investigation of the sensitivity of simulated precipitation to model resolution and its implications for climate studies”, *Mon Weather Rev*, **124**, 148-166.

Giorgi, F. and Marinucci, M. R., 1996b, “Improvements in the simulation of surface climatology over the European region with a nested modeling system”, *Geophys. Res. Lett*., **23,** 273-276.

Giorgi, F. and Shields, C., 1999, "Tests of precipitation parametrizations available in the latest version of the NCAR regional climate model (RegCM) over continental US", *J. Geophys. Res.*, **104,** 6353-6375.

Grell G. A., 1993, "Prognostic evaluation of assumptions used by cumulus parameterizations", *Mon Weather Rev*, **121**, 764-787.

Grell, G. A., Dudhia, J. and Stauffer, D. R., 1994, "A description of the fifth generation Penn State/NCAR Mesoscale Model (MM5)", *NCAR Technical Note*, NCAR/TN-398+STR, p121.

Holtslag, A. A. M., de Bruijn, E. I. F. and Pan, H. L., 1990, "A high resolution air mass transformation model for short-range weather forecasting", *Mon Weather Res*., **118,** 1561-1575.

Kiehl J. T., Hack, J. J., Bonan, G. B., Boville, B. A., Briegleb, B. P., Williamson, D. L. and Rasch, P. J., 1996, "Description of the NCAR Community Climate Model (CCM3)", *NCAR Technical Note*, NCAR/ TN-420+STR, p152.

Mannstein, H., 1987, "Surface energy budget, surface temperature and thermal inertia", *Remote Sensing Applications in Meteorology and Climatology*, Ed. R. A. Vaughan and D. Reidel, NATO ASI Ser. C: *Math. Phys. Sci*., **201**, 391-410.

Maurya, R. K. S., Singh, G. P. and Singh, P. K., 2010, "Change in temperature and precipitation over India and its homogeneous zones during 20th century", *Nava Gavesana*, **1**, 2, 16-33 (ISSN 0976 - 9455)

Meehl, G. A., 1994, "Coupled land-ocean-atmosphere processes and south Asian monsoon variability", *Science*, **266**, 263-267.

Pal, J. S., Small, E. E. and Eltahir, E. A. B., 2000, "Simulation of regional scale water and energy budgets: representation of subgrid cloud and precipitation processes within RegCM", *J. Geophys Res*, **105**, 29579-29594.

Pant, G. B. and Rupa Kumar, K., 1997, "Climates of South Asia" John Wiley & Sons, Chichester, p320.

Pope, V. D., Gallani, M. L., Rowntree, P. R. and Stratton, R. A., 2000, "The impact of new physical parameterizations in the Hadley Centre Climate model", *Clim. Dyn.*, **6**, 123-146.

Rupa Kumar K., Krishna Kumar, K. and Pant G. B., 1994, "Diurnal Asymmetry of surface temperature trends over India", *Geophy. Res. Lett*., **21**, 677-680.

Sellers, P. J., Hall, F. G., Asrar, G., Strebel, D. E. and Murphy, R. E., 1988, "The First ISLSCP Field Experiment (FIFE)", *Bull. Am. Met. Soc*., **69**, 1, 22-27.

Singh, G. P. and Jai-Ho Oh, 2007, "Impact of Indian Ocean sea-surface temperature anomaly on Indian Summer Monsoon Precipitation using a Regional Climate Model", *Inter. Jour. Climatol.*, **27**, 1455-1465.

Small, E. E., Giorgi, F. and Sloan, L. C., 1999, "Regional climate model simulation of precipitation in central Asia: mean and interannual variability", *J. Geophys. Res.*, **104**, 6563-6582.

Sun, L., 2003, "An evolving diversity of ownership forms and implications for the reforms of state owned enterprises, In Achieving High Growth: Experience of Transitional Economies in East Asia", P. Drysdale, Y. Huang, M. Kawai (eds), Routledge, London, UK.

Sylla, M. B., Giorgi, F. and Stordal, F., 2012, "Large-scale origins of rainfall and temperature bias in high resolution simulations over southern Africa", *Clim Res*., **52**, 193-211.

Tadross, M., Gutowski, W., Hewitson, W., Jack, C. and New, M., 2006, "Southern African interannual and diurnal climate variability in the MM5 regional climate model", *Theor Appl Climatol*, **86**, 63-80.