ORIGINAL PAPER

Simulations of Indian summer monsoon using RegCM: a comparison with ERA and GFDL analysis

M. M. Karadan[1] · P. V. S. Raju[1] · Akhilesh Mishra[2]

Abstract

A comprehensive understanding of the variation of Indian summer monsoon (ISM) features is necessary for accurate prediction of seasonal and sub-seasonal scale meteorological parameters. In this study, the summer monsoon features over India are investigated using RegCM simulations over South Asia Coordinated Regional Downscaling Experiment (SA-CORDEX) domain with 45-km spatial resolution. The initial-boundary data are derived from the European Centre for Medium Range Weather Forecasts Re-Analysis (ERA) and Geophysical Fluid Dynamics Laboratory (GFDL) analysis for the period 1989 to 2005. For both model simulations, mixed convection scheme (Emmanuel over ocean and Grell over land), Holtslag planetary boundary layer (PBL) scheme and biosphere atmospheric transfer system (BATS) land surface scheme are used throughout the experiment. The simulation results are validated with Climatic Research Unit (CRU) observations of precipitation and temperature. The spatial distribution of precipitation and temperature is reasonably simulated with ERA and GFDL analysis as compared with CRU observation. However, the simulation of precipitation and temperature with ERA analysis iscloser to CRU observations as compared with GFDL analysis. The seasonal scale (JJAS) simulation of precipitation with ERA and GFDL illustrates wet bias (2 mm per day) as compared to CRU observation, whereas temperature simulated with ERA indicated warm bias (1 °C) and GFDL depicts cold bias (2 °C) against CRU observations. The wind magnitude and distribution of ERA simulations show considerably higher magnitude over the western Himalaya which is connected to low values of specific humidity over the same terrain as compared with GFDL.

1 Introduction

The monsoon over India stands of pronounced prominence to the people in this area as a country's economy considerably depends on summer monsoon rainfall which receives more than 70% of its total annual rainfall. The Indian summer monsoon rainfall (ISMR) is a vital phase of total annual phase of rainfall over the region. It has an immediate onset round the commencement of June and a relaxed withdrawal in late September and early October (Goswami et al. 2016). The North Indian Ocean plays a major role in strong interannual variability of the rainfall over India as the land-sea meridional thermal contrast and the sea surface temperature (SST) are indispensable in the Indian summer monsoon succession (Webster and Yang 1992; Mohanty et al. 2002). The SST anomalies are the chief precursory signal to the performance of rainfall and its variability during the summer monsoon season (Chandrasekar and Kitoh 1998). A low surface pressure over the northern Arabian Sea is prompted by a positive phase of hemispheric SST anomaly. This causes an enhancement in meridional temperature gradient over the subcontinent, and it further strengthens the tropical easterly jet (TEJ) and low-level westerly jet (WJ). Substantially, it leads to a negative surface pressure variance and an abnormal cyclonic circulation over the terrain. This creates a conducive environment for increased seasonal mean ISM rainfall (Karmakar et al. 2020).

The occurrence of prolonged breaks in rain during the summer monsoon season leads to drought situation in the country, which can rigorously affect the Indian subcontinent (Rajeevan et al. 2006; Raju et al. 2010). Therefore, accurate prediction of rainfall and temperature during the summer season is significant for effective management strategies in agriculture, health and irrigation, etc. Presently, several meteorological centres

✉ P. V. S. Raju
pemmani@gmail.com; pvsraju@jpr.amity.edu

[1] Centre for Ocean Atmospheric Science and Technology (COAST), Amity University Rajasthan, Kant Kalwar, Jaipur, Rajasthan, India

[2] National Centre for Medium Range Weather Forecasting, Noida, UP, India

around the globe use statistical techniques for prediction of rainfall and temperature at seasonal scale, but these approaches have revealed less prediction skill. Hence, the precipitation and temperature prediction on the monthly to seasonal scale stays as a major interesting assignment over South Asia. The scale interactions are particularly multifaceted which are further problematic by the effect of complicated orography over the Himalayas and land-ocean-atmospheric interactions. The general investigation on the rainfall over India is based on the development of multiple regression equations for long-range all-India monsoon rainfall on the basis of certain regional or global parameters (Thapliyal 1987). Few studies revealed that long-range forecasts need multiple parameters instead of two or three (Gowariker et al. 1991; Gowariker et al. 1989). The prediction of rainfall with reduced uncertainties with more economic value will be more feasible with numerical models (Hawkins and Sutton 2009). It has been validated that regional climate models have moderately sensible abilities in forecasting the summer monsoon flow and accompanying rainfall over the Indian subcontinent (Bhaskaran et al. 1996; Raju et al. 2015). The regional climate model simulations exhibit better performance with 20% improved skill than the global circulation models (Bhaskaran et al. 1996). Rao et al. (2004) found that mesoscale model MM5 with a horizontal resolution of 30 km simulates the observed monsoon features and rainfall reasonably well.

The forecasting skill is the relative accuracy of the prediction over some reference prediction (Murphy 1993). The bias correction in the regional climate model improves the skill of precipitation and temperature prediction at lesser spatial scales (Choudhary and Dimri 2019, Schellander et al. 2017). Tiwari et al. (2016) found that RegCM is a beneficial tool for better skill in simulating the precipitation over North India. It is revealed that the total rainfall was well characterized in RegCM using the Grell convective precipitation scheme with the Arakawa-Schubert closure assumption. Furthermore, the seasonal precipitation of summer monsoon is more enhanced in combined RegCM-Regional Ocean Model System (ROMS) over the Indian region (Ratnam et al. 2009). Additionally, a model using MM5 advocates that the Grell scheme is superior in simulating summer monsoon circulation and associated precipitation over India during an active period of monsoon of July 1998 in comparison with the convective schemes Kuo and Betts-Miller (Singh et al. 2011). Also, the summer monsoon features over India are well simulated by RegCM with the grouping of mixed convection scheme (Raju et al. 2015).

The objective of the study is to analyse inter-comparison of RegCM simulations over South Asia (Fig. 1) within the Co-Ordinated Regional Climate Downscaling Experiment (CORDEX) forced with European Centre for Medium Range Weather Forecasts Re-Analysis (ERA) data and Geophysical Fluid Dynamics Laboratory (GFDL) data
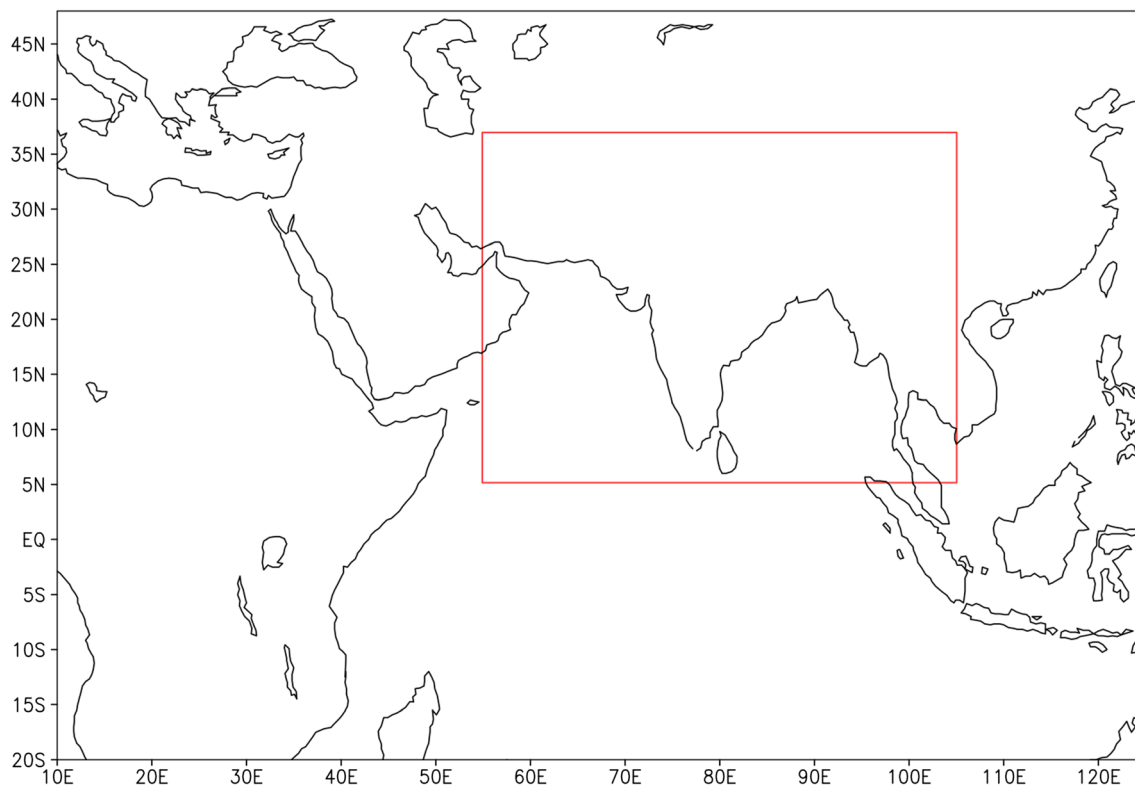

Fig. 1 South Asia CORDEX domain for the simulations. Rectangular box represents the region used for the analysis

Table 1 The RegCM configuration used in this study

Model	RegCM v411
Dynamics	Hydrostatics
Resolution	45 km horizontal and 18 σ-vertical levels
Model domain	South Asia CORDEX domain
Central latitude	16.93
Central longitude	67.18
Map projection	NORMER
Boundary conditions	EIN75, GFDL
SST	OI_WK–OISST weekly optimal interpolation
Convective closure assumption	Fritsch and Chappel (1980)
Land surface parameterization	BATS
Cumulous convection scheme	Mixed scheme (Emmanuel over ocean and Grell over land)
Boundary layer scheme	Holtslag PBL (Holtslag et al. 1990)
Moist physics scheme	Explicit moisture (SUBEX, Pal et al. 2000)
Analysis period	1989–2005
Validation	CRU precipitation and temperature

analysis. CORDEX is a framework of the World Climate Research Programme (WCRP) to assess regional climate downscaling methods in producing reliable climate information for influence and variation studies (Giorgi et al. 2009).

Fig. 2 JJAS climatology (mm day^{-1}) of **a** CRU, **b** ERA, **c** GFDL, **d** ERA-CRU and **e** GFDL-CRU
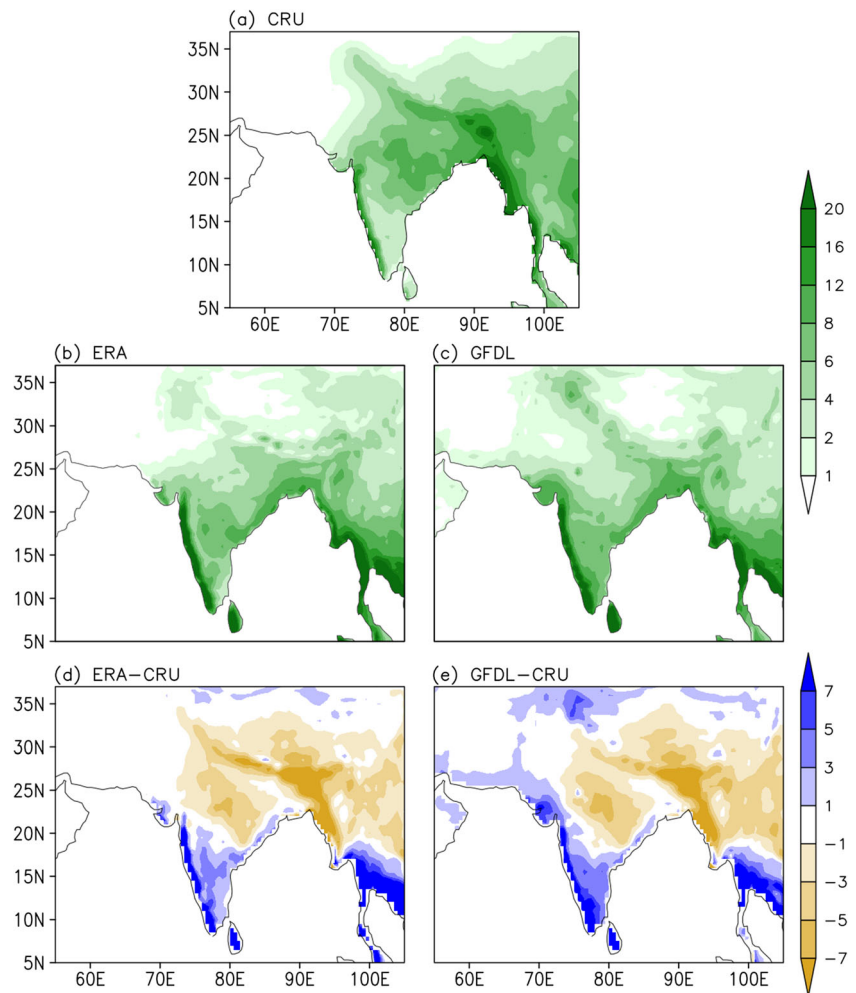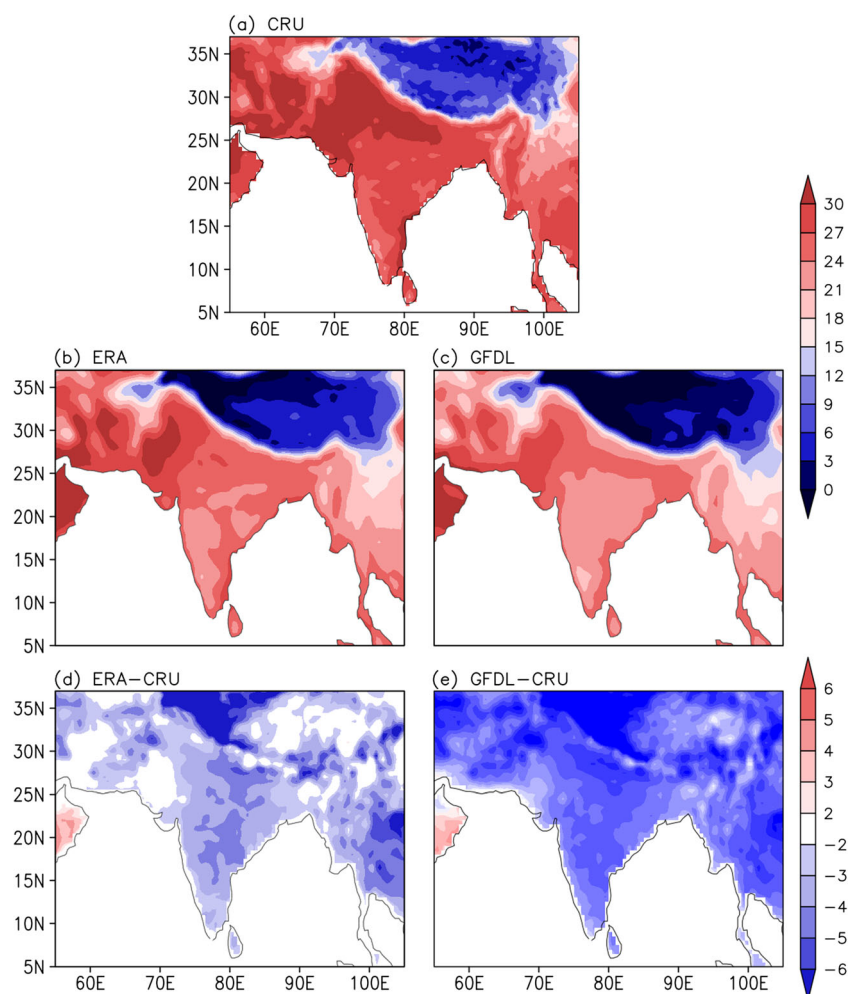
Fig. 3 JJAS temperature climatology of **a** CRU, **b** ERA, **c** GFDL, **d** ERA-CRU and **e** GFDL-CRU

2 Model

Regional climate models have been technologically advanced in order to upsurge the horizontal and vertical resolutions for climate prediction using coarse grid global circulation model outputs as initial and boundary conditions (Giorgi 1990). RegCM is one such regional model system; it has been constantly developed over more than two decades (Giorgi 1990) through systematic revisions to the model dynamics and physics (Giorgi et al. 1993a, b; Pal et al. 2007; Giorgi et al. 2012). RegCM is initially developed by the National Center for Atmospheric Research (NCAR) and is supported by the International Centre for Theoretical Physics (ICTP), Italy. The preliminary version of RegCM (RegCM1) got released in 1989 and the modern version came out in 2010 (RegCM4). The transitional versions are RegCM2 (1993), RegCM2.5 (1999) and RegCM3 (2006). Besides, it can be applied to any region of the world with grid spacing of up to about 10 km (hydrostatic limit). It can be applied for a wide range of studies, from process studies to palaeoclimate and future climate simulation. The latest version of RegCM (version 4.7) comprises the development of a non-hydrostatic

dynamical core. The regional climate model with mixed convection scheme (viz., Emmanuel over land and Grell over ocean) simulates the summer monsoon precipitation fine in terms of spatial distribution and intensity as matched with the other individual convection schemes (Raju et al. 2015).

3 Data and experimental design

The datasets handled for the investigation are ERA Interim and GFDL which are simulated by RegCM4 (source: cccr.tropmet.res.in/home/data_portals.jsp) within the time period of 1989 to 2005. The outputs have alignment of South Asia CORDEX RegCM4.11 with 0.44° spatial resolution. Out of the South Asia CORDEX, the Indian subcontinent region is chosen for the analysis. These spatial distributions are assessed with that of Climatic Research Unit (CRU) monthly observational data of precipitation and temperature of 0.5° horizontal resolution (Mitchell and Jones 2005). The model cumulous convection scheme applied was the mixed scheme having Emmanuel over ocean and Grell over land. The
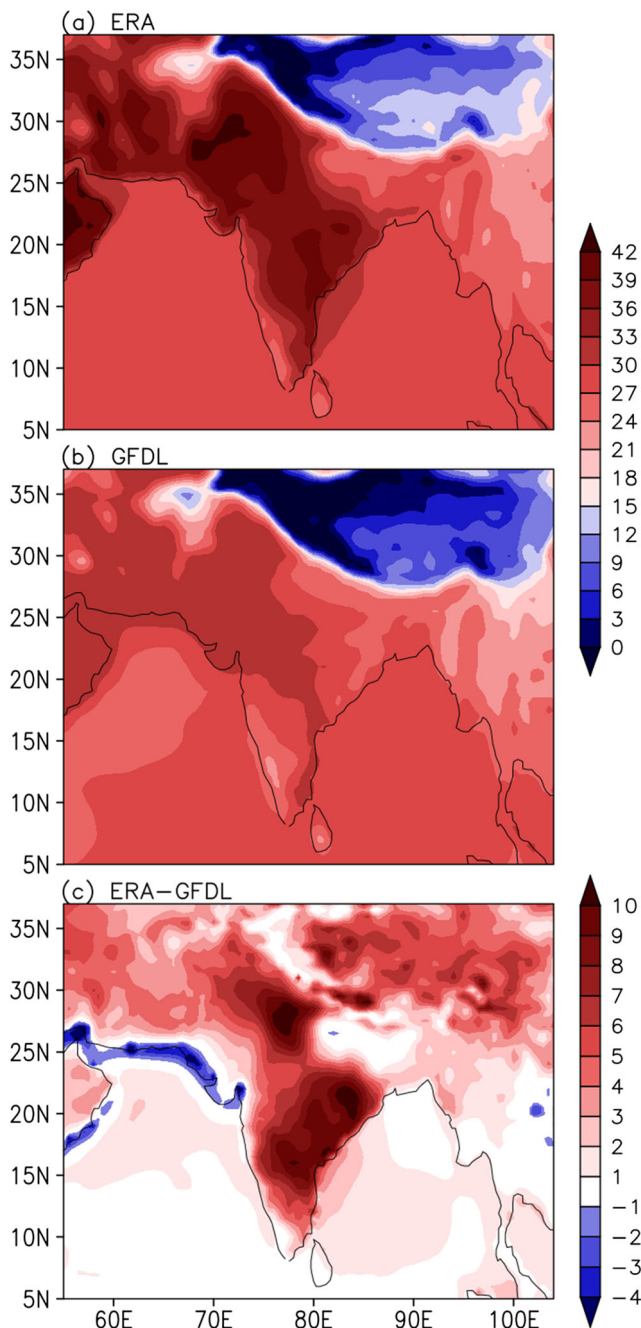
Fig. 4 Distribution of maximum temperature (°C) distribution of **a** ERA, **b** GFDL and **c** ERA-GFDL

Fig. 5 Distribution of minimum temperature (°C) distribution of **a** ERA, **b** GFDL and **c** ERA-GFDL

boundary layer scheme preferred was Holtslag PBL (Holtslag et al. 1990). Furthermore, the moist physics scheme designated was explicit moisture (SUBEX, Pal et al. 2000) (Table 1).

4 Results and discussion

The Indian summer monsoon features over India for the period 1989 to 2005 are elucidated with RegCM simulation forced with ERA and GFDL analysis. The systematic bias of
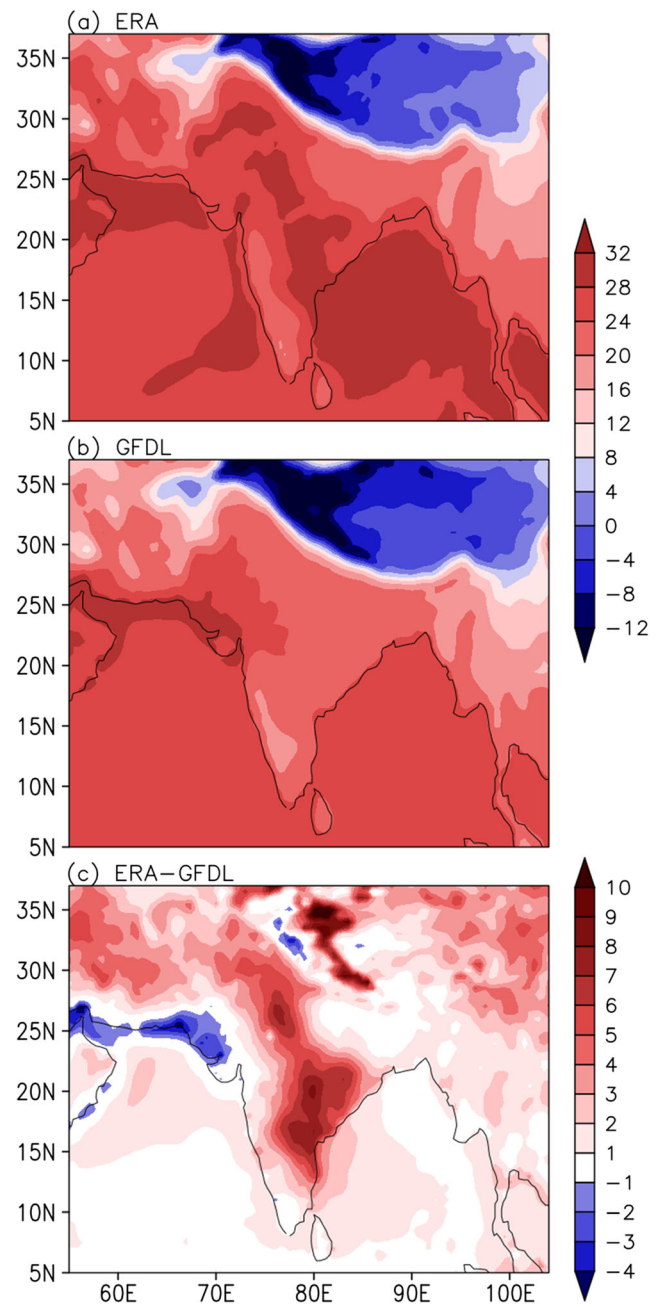
these two simulations was carried out with CRU-derived precipitation and temperature. CRU observation pertains over land region; therefore, the model simulation is presented only over the Indian subcontinent. Furthermore, annual cycle and interannual variabilities of the precipitation and temperature over the Indian domain are presented.

4.1 Precipitation

The spatial distribution of JJAS precipitation of CRU and model simulation with ERA and GFDL analysis is depicted
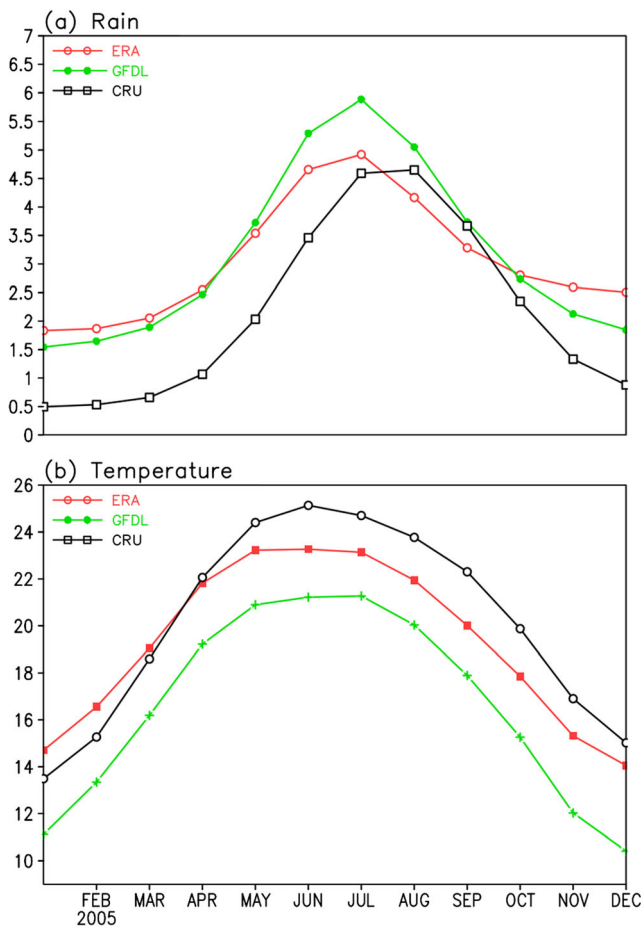
Fig. 6 Annual cycle of **a** rainfall (mm day^{-1}) and **b** temperature (°C)

in Fig. 2. The observed rainfall delineated the maximum precipitation over the west coast, Central India and northeast belt over India (Fig. 2a). These precipitation zones are the pronounced qualities during the summer monsoon season from June to September over the Indian region. The precipitation with ERA and GFDL analysis reveals that the model has the capability to simulate the precipitation characteristic over India; however, few differences are noticed in both ERA and GFDL over the South Indian peninsula, northeast belt (particularly along the foothills of Himalaya) and Central India (Fig. 3b, c). The difference of model simulations with respect to CRU observation reveals that both the ERA and GFDL show wet bias over southern Indian peninsula and west coast of India but dry bias over the north and northeast Indian region. However, the GFDL depicts higher precipitation over the southern Indian peninsula, Central India and northeastern part of India as compared with ERA (Fig. 2d, e).

4.2 Temperature

The climatological features of observed and model-simulated temperatures during the summer monsoon season are presented in Fig. 3. Through the observed temperature, it is noticed that over the northwest Indian subcontinent receives the maximum temperature and this zone extends up to the Himalayan foothills (Fig. 3a). Also, ERA shows more intense values in the semiarid region of northwest India than GFDL. However, the Indian subcontinent is depicting a moderately similar situation for both the datasets. ERA exhibits a warm bias over southern Andhra Pradesh, Telangana and northeastern Tamil Nadu. The difference with respect to CRU observations depicts that both simulations with ERA Interim and GFDL found cold bias; however, through ERA, less cold bias is noticed as compared to GFDL (Fig. 3d, e). The large cold bias which arises in GFDL analysis may be due to the initial condition.

Furthermore, the spatial distribution of maximum and minimum temperatures simulated with ERA Interim and GFDL analysis and the difference between ERA and GFDL are presented in Figs. 4 and 5. Simulations of ERA have depicted higher maximum temperature distribution over the entire subcontinent as compared to GFDL. In particular, the temperature of 40 °C is noticed in the northwestern region and southeast part of India (Fig. 4a). Geographically, these sections fall under the arid-semiarid regions. The difference in maximum temperature between ERA Interim and GFDL illustrates the maximum temperature departure is found to be maximum over the southeastern part of India and north Indian region with more than 5 °C (Fig. 4c). The minimum temperature distribution is simulated with ERA Interim and GFDL analysis and the difference is depicted in Fig. 5. The minimum temperature is higher over the Bay of Bengal and the belt of the southeast-northwest region over India in ERA Interim analysis and also over the Himalayan region as compared to GFDL simulations (Fig. 5a, b), whereas GFDL shows higher minimum temperature zone over northern Gujarat. The differences in ERA Interim and GFDL are clearly shown in Fig. 5c with cold bias of more than 5 °C in GFDL analysis over the southeastern part of India. Overall, it is found that the model simulates cold bias in GFDL analysis as compared to the simulation with ERA Interim analysis.

4.3 Annual cycle and interannual variability

The monthly climatology of the observed and modelled precipitation and temperature over India (70–90° E, 8–35° N) simulated with ERA Interim and GFDL analysis, along with the observed data, is illustrated in Fig. 6. The area-averaged monthly climatology of precipitation (Fig. 6a) indicates that both CRU and model-simulated precipitation show the annual cycle of precipitation pattern over India and the maximum amount in JJAS season. However, in the summer monsoon season, ERA Interim is closer to the attribute of CRU against GFDL simulation. It is observed that both GFDL and ERA
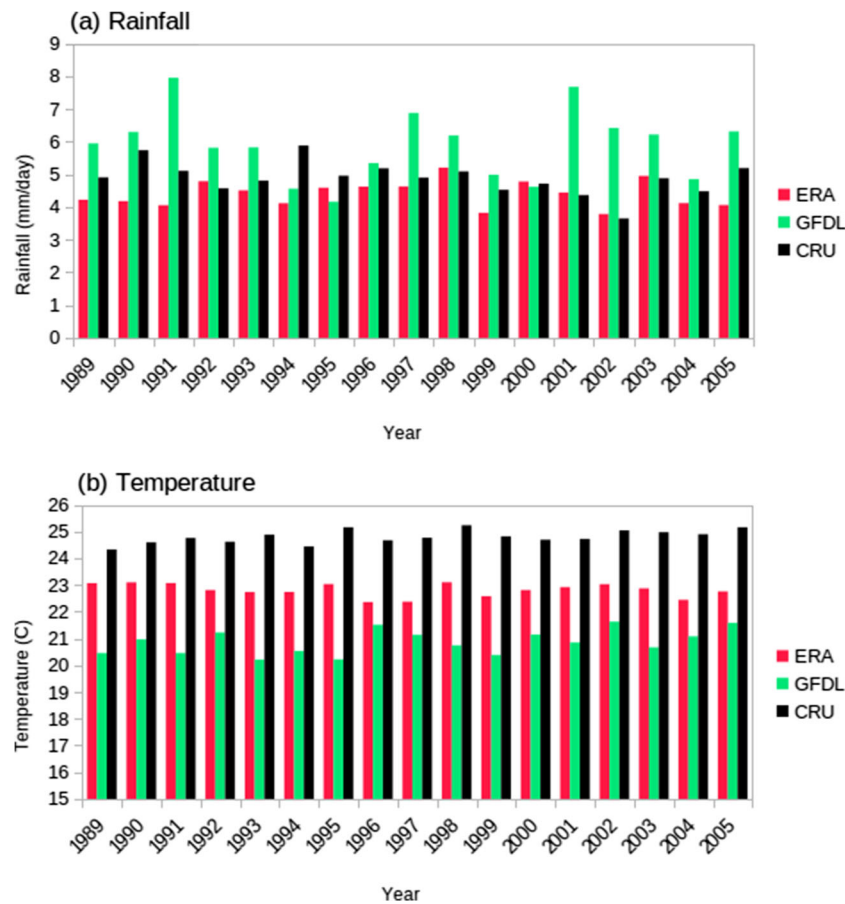
Fig. 7 Interannual variability of **a** rainfall (mm day^{-1}) and **b** temperature (°C)

Interim have a slight variation and a large difference against the CRU observation during the winter monsoon season. By the commencement of the winter monsoon season, GFDL comes back with the trend it had in the pre-monsoon season. The minimum amount of rainfall is recorded by the CRU which was in the December, January and February (DJF) season. As our focus is on JJAS, ERA characteristics are better depicted the same with respect to GFDL. The annual cycle of area-averaged temperature is presented in Fig. 6b. Simulations with GFDL analysis represent warm bias from January to April, and cold bias from May to December, whereas the simulations with ERA Interim show warm bias throughout the year. Although the ERA Interim analysis depicts large warm bias with respect to CRU observation during the winter season, it is in close agreement during the summer monsoon season over India. On the other hand, simulation with GFDL analysis is in close agreement with CRU observation during the winter monsoon season over India as compared to the summer monsoon season. The interannual variability of precipitation and temperature of CRU and the model simulations averaged over the Indian region (70–90° E, 8–35° N) during the summer monsoon (JJAS) season is illustrated in Fig. 7. The simulations clearly indicate that the ERA Interim well simulated JJAS precipitation during 1989–2005 over India

and is in good agreement with the observed precipitation. The simulation with GFDL overestimates the precipitation with respect to CRU observations (Fig. 7a). Similarly, the interannual variability of temperature depicts both simulations are underestimated; however, the ERA Interim simulation is in good synchronization with observed CRU temperature for all the monsoon seasons as compared to GFDL, whereas the GFDL underestimated the temperature with a variation of approximately 3-5 °C with respect to CRU observation.

4.4 Wind and specific humidity

The spatial distribution of wind for the simulations of ERA Interim and GFDL analysis is illustrated in Fig. 8. Both the ERA and GFDL depict the general monsoon circulation over the South Asian region; i.e. the wind is blowing southwesterly, and strong low-level Somali jet is the prominent feature during the summer monsoon over India (Fig. 8a, b). The simulations with ERA Interim analysis depict strong Somali jet with a magnitude of more than 10 m s^{-1} (Fig. 8a). Furthermore, the northern Arabian Sea and south of the Bay of Bengal depict strong wind in ERA Interim simulation as compared with GFDL analysis. These features are clearly reflected in the difference between ERA Interim and GFDL analyses of the
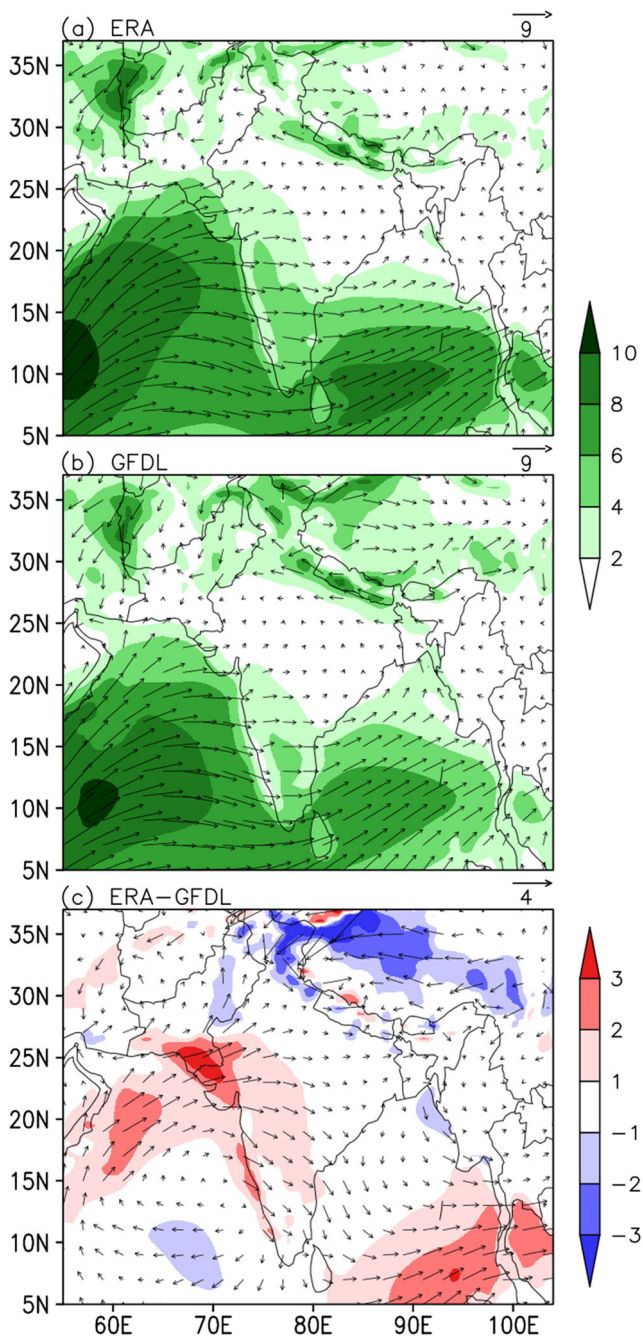
Fig. 8 Wind speed and direction at 10 m for **a** ERA, **b** GFDL and **c** ERA-GFDL (m s^{-1})

Fig. 9 Specific humidity at 2-m level of **a** ERA, **b** GFDL and **c** ERA-GFDL (g kg^{-1})

intense surface circulation over the northwest region of Gujarat, western Himalayan sector and southern parts of Myanmar (Fig. 8c). Also, in Central India, it has an analogous surface circulation pattern for both ERA and GFDL. But in the western Himalaya section, it shows a great wind pattern alteration in which GFDL dominates. On the other hand, ERA Interim exposes more intense wind pattern than the GFDL in both land and sea. In particular, the patterns shown by ERA Interim dominate over GFDL pattern particularly in the western parts of the Arabian Sea, southern peninsular India and the
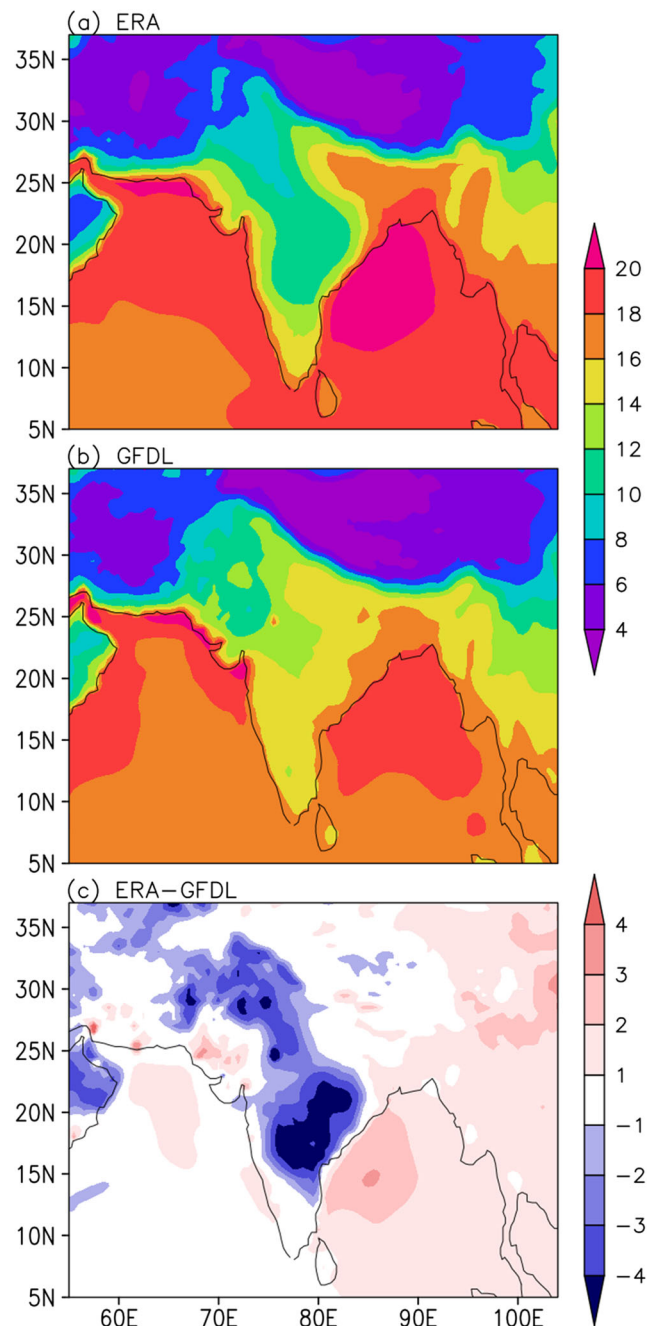
Bay of Bengal. Then, the central-east region where the monsoon trough is found shows some similar behaviour between ERA and GFDL. The specific humidity at 2-m level simulated with ERA Interim and GFDL analyses is represented in Fig. 9. The high value of specific humidity is noticed over the Arabian Sea and the southwest Bay of Bengal in the simulations of ERA Interim data (Fig. 9a), whereas the simulations with GFDL indicate higher values of specific humidity over southeastern as well as northwest regions of India (Fig. 9b). The difference between ERA Interim and GFDL clearly depicts

the negative value of specific humidity over the belt of south-east India, extending to the northwest region during the summer monsoon. This indicates the presence of low specific humidity during the monsoon season in ERA Interim than GFDL simulation (Fig. 9c). These results are consistent with previous results that zones of higher (lower) value of maximum (minimum) surface temperature (Figs. 4 and 5) in ERA indicate low (high) specific humidity over the Indian region.

4.5 Intra-seasonal variability

The intra-seasonal variation of rainfall and zonal wind over the Indian region during JJAS for the period 1989 to 2005 is shown in Figs. 10 and 11, respectively. Both the ERA and GFDL depict the seasonal variation of rainfall distributed from the equator up to 25° N. Furthermore, in 1989, ERA shows more precipitation distribution than GFDL pattern (Fig. 9a, b), while simulation with ERA exhibits comparatively intense rainfall during JJAS as compared to the simulation with GFDL. The rainfall in 1990 is well simulated over the southern peninsular India by both ERA and GFDL for the JJAS season which was recorded as a normal rainfall year

(Gadgil et al. 2005). The precipitation of 1991 reveals that GFDL has more rainfall peculiarities over west peninsular India than that of ERA during the summer monsoon. The particulars of 1992 unveil that both have almost similar distribution characteristics in which southern India represents the intense rainfall as usual. The year 1995 has exhibited similar rainfall for both forcing. Then, the 1996 GFDL simulation represents predominant monsoon rain. It should be noted that a great event of El Niño had formed in 1997 and had dissipated in 1998 (Gadgil et al. 2005). During 2001, 2001 and 2005, the ERA and GFDL characteristics show a distinct distribution. The years 2003 and 2004 have similar peculiarity for the season (Fig. 10c). Overall, GFDL has a principal ascendancy over ERA in respect of rainfall which is clearly found to be an overestimation from CRU observations. Similarly, the zonal wind pattern simulated with ERA Interim and GFDL is illustrated in Fig. 11. Both simulations with ERA Interim and GFDL show significant summer monsoon variability of zonal wind for 1989 to 2005. However, the extreme monsoon years (excess and deficit rainfall seasons) are well simulated with ERA Interim as compared with GFDL analysis. For example, the year 2002 is the anomalous drought condition which was
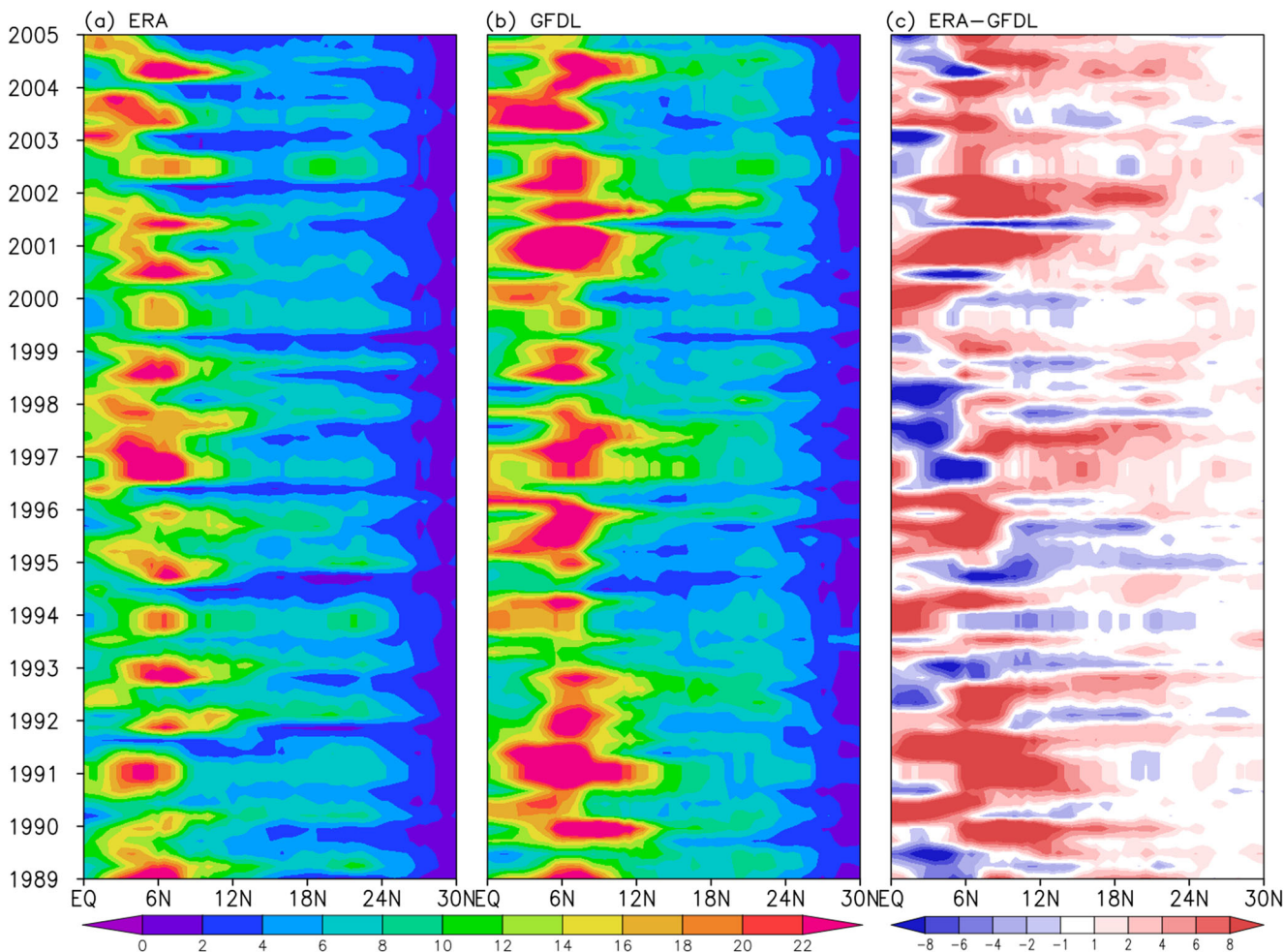

Fig. 10 Time-latitude structure of rainfall averages over (70–90° E) during the Indian summer monsoon (JJAS)
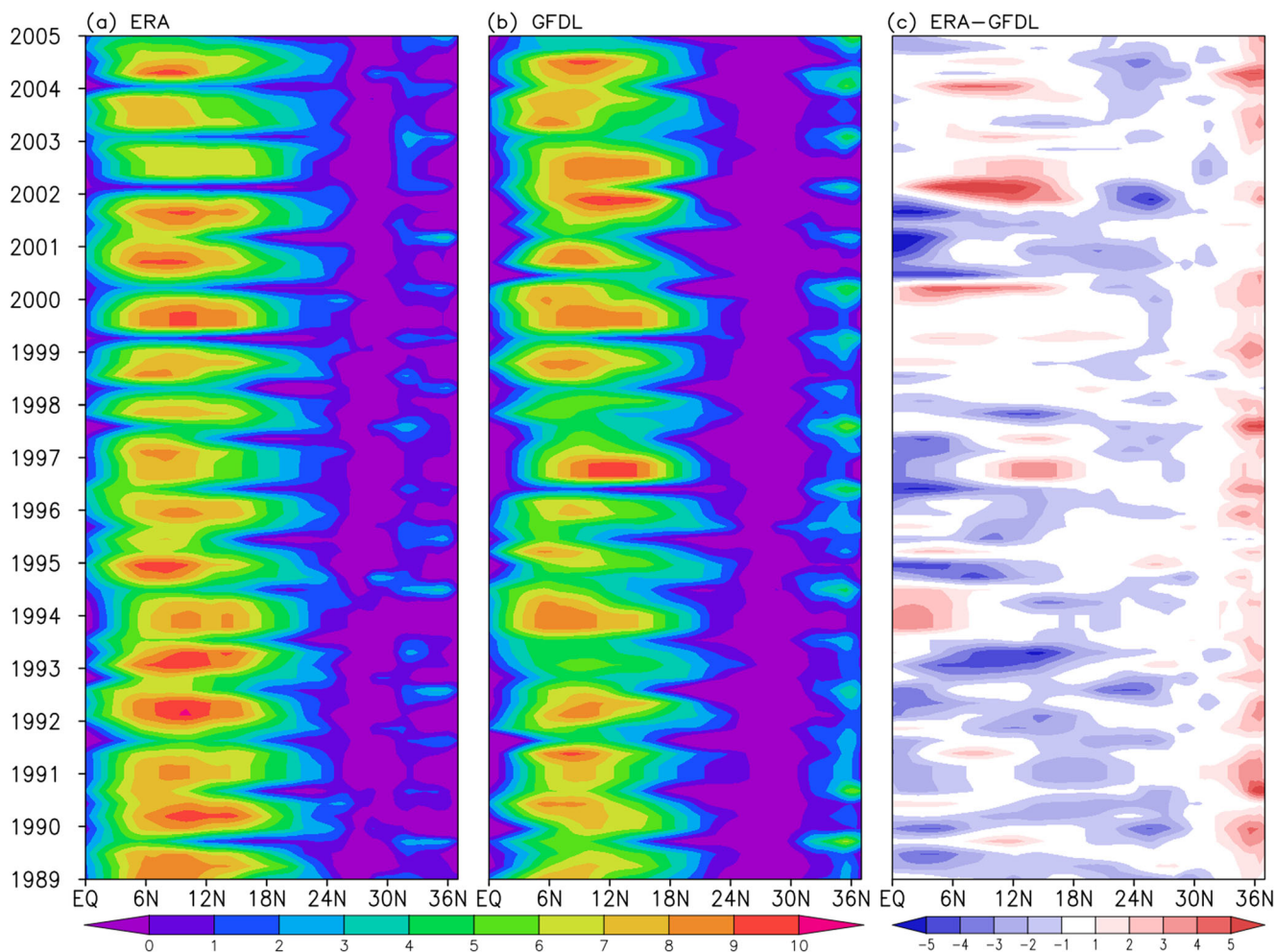
Fig. 11 Time-latitude structure of zonal wind averages over (70–90° E) during the Indian summer monsoon (JJAS)

well simulated in ERA Interim analysis with weekly wind distribution. Similarly, during excess monsoon season of 1994, the strong zonal wind was simulated with ERA analysis as compared with the simulations of GFDL analysis.

5 Conclusions

The RegCM simulations over South Asia CORDEX domain forced with ERA Interim and GFDL analysis for the period 1989 to 2005 are investigated. The following broad conclusions are drawn from this study:

- The simulations forced with ERA and GFDL show wet bias over southern Indian peninsula and western Indian region, but dry bias over the north and northeastern part, whereas the GFDL depicts higher precipitation over the southern Indian peninsula, Central India and northeastern part of India as compared with ERA.
- The cold bias is observed in both simulations; however, ERA indicates relatively warmer characteristics than

GFDL. Furthermore, the maximum and minimum temperatures depicted in ERA are warmer over southeast and northwest India with respect to GFDL simulations.

- The annual cycle of precipitation and temperature reveals that both simulations represent the large variation during the winter monsoon as compared to the summer season. The simulation with ERA is in good agreement with CRU observation during the summer monsoon season. The interannual variability during the summer monsoon season over India reveals that simulation with GFDL overestimates (underestimates) precipitation (temperature) during 1989 to 2005.
- Both ERA Interim and GFDL simulations show significant seasonal variability of zonal wind and precipitation during the monsoon season during 1989 to 2005. However, the extreme monsoon years (excess and deficit rainfall seasons) are well simulated with ERA Interim as compared with GFDL analysis.

The present study clearly indicates the performance of RegCM simulation with ERA and GFDL initial conditions,

and the former is in reasonably good agreement with the CRU observations. Further improvement can be accomplished by considering appropriate land surface schemes and moisture initialization in the model. Improved high-resolution climate simulations for various homogeneous meteorological subdivisions over India will be helpful for policy makers.

Author's contributions M.M Karadan: data archiving and preparation of the figures and initial draft of the manuscript. P. V. S. Raju: conceptualization of the study, manuscript finalization with support of co-authors. Akhilesh Mishra: interpretation of the results and helping in preparation of the manuscript.

Compliance with ethical standards

References

Bhaskaran B, Jones RG, Murphy JM, Norguer M (1996) Simulation of the Indian Summer Monsoon using a nested regional climate model: domain size experiments. Clim Dyn 12:573–578

Chandrasekar A, Kitoh A (1998) Impact of localized sea surface temperature anomalies over the equatorial Indian Ocean on the Indian summer monsoon. J Meteor Soc of Japan 76(6):841–853

Choudhary A, Dimri AP (2019) On bias correction of summer monsoon precipitation over India from CORDEXSA simulations. Int J Climatol 39(3):1388–1403

Fritsch JM, Chappell CF (1980) Numerical prediction of convectively driven mesoscale pressure systems part I: convective parameterization. J Atmos Sci 37:1722–1733

Gadgil S, Rajeevan M, Nanjundiah R (2005) Monsoon prediction—why yet another failure. Curr Sci 88(9):1389–1400

Giorgi F (1990) Simulation of regional climate using a limited area model nested in a general circulation model. J Clim 3:941–963

Giorgi F, Coppola E, Solmon F, Mariotti L, Sylla MB, Bi X, Turuncoglu UU (2012) RegCM4: model description and preliminary tests over multiple CORDEX domains. Clim Res 52:7–29

Giorgi F, Jones C, Asrar GR (2009) Addressing climate information needs at the regional level: the CORDEX framework. World Meteorological Organization Bulletin 58(3):175

Giorgi F, Marinucci MR, Bates GT, De Canio G (1993b) Development of a second-generation regional climate model (RegCM2) part II: convective processes and assimilation of lateral boundary conditions. Mon Weather Rev 121(10):2814–2832

Giorgi F, Marinucci MR, Bates GT (1993a) Development of a second-generation regional climate model (RegCM2). Part I: boundary-layer and radiative transfer processes. Mon Weather Rev 121(10): 2794–2813

Goswami BN, Rao S, Sengupta D, Chowdary S (2016) Monsoons to mixing in the Bay of Bengal: multiscale air-sea interactions and monsoon predictability. Oceanography 29:18–27

Gowariker V, Thapliyal V, Kulshrestha SM, Mandal GS, Sen Roy N, Sikka DR (1991) A power regression model for long range forecast of southwest monsoon rainfall over India. Mausam 42:125–130

Gowariker V, Thapliyal V, Sarker RP, Mandal GS, Sikka DR (1989) Parameteric and power regression models: new approach to long-range forecasting of monsoon rainfall in India. Mausam 40:115–122

Hawkins E, Sutton R (2009) The potential to narrow uncertainty in regional climate predictions. Bull Amer Meteor Soc 90:1095–1108

Holtslag AA, De Bruijn EI, Pan H (1990) A high resolution air mass transformation model for short-range weather forecasting. Mon Weather Rev 118:1561–1575

Karmakar N, Chakraborty A, Nanjundiah RS (2020) Influence of global sea-surface temperature on ultra-low-frequency variability in Indian summer monsoon rainfall. Quart J Roy Meteor Soc 146:904–921

Mitchell TD, Jones PD (2005) An improved method of constructing a database of monthly climate observations and associated high-resolution grids. Int J Climatol 25:693–712

Mohanty UC, Bhatla R, Raju PVS, Sarkar A (2002) Meteorological fields variability over the Indian seas in pre and summer monsoon months during extreme monsoon seasons. J Earth Syst Sci 111:365–378

Murphy AH (1993) What is a good forecast? An essay on the nature of goodness in weather forecasting. Wea Forecasting 8:281–293

Pal JS, Giorgi F, Bi X, Elguindi N, Solmon F, Gao X, Ashfaq M (2007) Regional climate modeling for the developing world: the ICTP RegCM3 and RegCNET. Bull Amer Meteoro Soc 88(9):1395–1410

Pal JS, Small EE, Eltahir EA (2000) Simulation of regional-scale water and energy budgets: representation of subgrid cloud and precipitation processes within RegCM. J Geophys Res Atmos 105(D24):29579–29594

Rajeevan M, Bhate J, Kale JD, Lal B (2006) High resolution daily gridded rainfall data for the Indian region: analysis of break and active monsoon spells. Curr Sci 91(3):296–306

Raju PVS, Mohanty UC, Hsu HH (2010) A study on drought features of the Indian summer monsoon 2002. Meteorog Atmos Phys 108(1–2):43–55

Raju PVS, Bhatla R, Almazroui M, Assiri M (2015) Performance of convection schemes on the simulation of summer monsoon features over South Asian CORDEX domain using RegCM-4.3. Int J Climatol 35(15):4695–4706

Rao DVB, Ashok K, Yamagata T (2004) A numerical simulation study of the Indian Summer Monsoon of 1994 using NCAR MM5. J Meteorol Soc Japan 82:1755–1775

Ratnam JV, Giorgi F, Kaginalkar A, Cozzini S (2009) Simulation of the Indian monsoon using the RegCM3-ROMS regional coupled model. Clim Dyn 33:119–139

Schellander GT, Wang Y, Meier F, Weidle F, Wittmann C, Kann A (2017) On the forecast skill of a convection-permitting ensemble. Geosci Model Dev 10:35–56

Singh AP, Singh RP, Raju PVS, Bhatla R (2011) Comparison of three different cumulus parameterization schemes on Indian summer monsoon circulation. Int J Ocean Clim Syst 2(1):27–43

Thapliyal V (1987) Prediction of Indian monsoon variability evaluation and prospects including development of a new model. In: The climate of China and global climate, Ye D, Fu C, Chano J, Yoshino M, Eds China Ocean Press pp. 397–416

Tiwari PR, Kar SC, Mohanty UC, Dey S, Sinha P, Raju PVS, Shekhar MS (2016) On the dynamical downloading and bias correction of seasonal scale winter precipitation predictions over North Indian. Quart J Roy Meteor Soc 142:2398–2410

Webster PJ, Yang S (1992) Monsoon and ENSO: selectively interactive systems. Quart J Roy Meteor Soc 118(507):877–926