



Diagnosing whether the increasing horizontal resolution of regional climate model inevitably capable of adding value: investigation for Indian summer monsoon

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Abstract

This study demonstrated the influence of downscaling using the regional climate model (RCM) driven by Era-Interim reanalysis (EIN) in simulating different aspects of the Indian summer monsoon (ISM). It is also examined, whether increasing the horizontal resolution of RCM will inevitably be capable of adding more information to ISM characteristics and its spatio-temporal variability. In this regard, two RCM (at 50 km: Reg₅₀ and 25 km: Reg₂₅) simulations were conducted for six years from 2000 to 2005 for the South Asia Coordinated Regional Downscaling Experiment (CORDEX) domain. The added value (AV) is found to be strongly dependent on region and considered metrics. A slight improvement towards increasing spatial resolution is observed in the simulation of the mean ISM characteristics, while considerable improvements are noticed for the frequency distribution of extremes. The notable improvement in the daily climatology of precipitation is observed over the region of northeast India (~35%) and the Hilly region (~32%) and the lowest improvement over north-central India (~8%). The reduction of anomalously strong northeasterly flow over the southeastern Arabian Sea and strengthening of the moisture laden southeasterly wind flow from the Bay of Bengal in Reg₂₅ compared to Reg₅₀ is consistent with the reduction of dry bias over India in Reg₂₅. The robust improvements are noticed for the heavy precipitation events (probability density function: PDF tails) and mean precipitation due to extreme precipitation events, particularly over the areas characterized by complex topographical features (e.g., the Western Ghats, Indo-Gangetic plains, and northeast India and Hilly regions) as well as over the areas having substantial bias (e.g., central India), indicating its strong sensitivity towards model resolution. The increasing latent heat flux in Reg₂₅ contributes to increasing the moisture and hence rainfall over India. Both simulations apparently simulate many of the ISM characteristics better than the EIN, thereby emphasizing the usefulness of finer resolutions in the better simulation of the Indian monsoon, especially for heavy rainfall. However, the RegCM bias is comparable to or even greater in some places than the EIN bias. This suggests that high-resolution models are important for improving performance; however, it does not necessarily mean that they can have AV for every aspect and all places. Apart from this, the substantial difference in the AV over different regions or aspects highlights the importance of carefully selecting AV matrices for the different areas and characteristics being investigated. RegCM exhibits some systematic biases in precipitation despite substantial improvement due to misrepresentation of dynamical and thermodynamical processes, including northward and eastward propagating convective bands.

Keywords Regional climate model (RegCM) · ISMR · Extreme precipitation · CORDEX-SA · Added value

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1 Introduction

India receives approximately 80% of its annual rainfall during the summer monsoon season [June–September: JJAS] (Gadgil et al. 2004) associated with the Indian summer monsoon (ISM), while the winter monsoon season provides only 10–12% of the annual rainfall (Jena et al. 2016). The Indian summer monsoon rainfall (ISMR) has a profound impact on regulating the climate of the regions. In addition,

it significantly influences the agricultural sector, water management, and power plant and consequently affects the lives of billions of people (Goswami et al. 2006; Turner and Annamalai 2012; Dwivedi et al. 2015) and hence the economy of the country (Gadgil and Gadgil 2006; Turner and Annamalai, 2012). The extreme events during summer monsoon are known to have high social, economic, and ecological impacts (Peterson et al. 2014; York 2018). However, the prediction of the ISMR extremes and their changing characteristics under global warming has remained challenging.

The significant advancement in the global climate models (GCM) in recent decades has led to improvement in the skill of GCM in simulating the large-scale circulation and distribution of ISMR to a reasonable extent; however, they still have a deficiency in capturing the regional scale features as well as dynamical and thermodynamical processes (Turner and Annamalai 2012). It is partly due to the coarser resolution of GCM that is not sufficient to resolve the local scale features (e.g., local orography, land-sea contrast, and small-scale atmospheric features) of a particular region, especially over the complex region like the Indian subcontinent (Kripalani et al. 2007; Jacob et al. 2012; Kumar et al. 2013; Mishra et al. 2020b). Thus, GCM at such coarse resolution can be suitable for investigating large-scale processes but not for fine-scale features of ISM. GCMs also had a lack of skills in representing important physical processes like regional scale convection, advection, moisture transport, orographic drag, and associated land-surface feedback (Saha et al. 2011; Sabeerali et al. 2015; Maharana et al. 2019; Kumar et al. 2020; Mishra et al. 2020a, b). This further limits their use for assessing local climate variability or extreme events (Aldrian et al. 2004). This necessitates increasing GCM resolution to a level that can resolve the Indian region's complex topography. However, high-resolution GCM simulations are not feasible for long periods with limited computer resources.

To this end, high-resolution RCMs have added value in resolving the coastlines and topography (Denis et al. 2003; Lucas-Picher et al. 2011; Kumar et al. 2013, 2020; Choudhary et al. 2019; Bhatla et al. 2020). Numerous efforts have been made to simulate ISMR using RegCM driven by reanalysis over the Indian subcontinents (Srinivas et al. 2013; Dash et al. 2013; Umakanth et al. 2016; Pattanayak et al. 2018; Devanand et al. 2018; Ajay et al. 2019; Bhate and Kesarkar 2019; Maharana et al. 2019; Kumar and Dimri 2020; Kumar et al. 2020; Mishra et al. 2020a, b; Mishra and Dubey 2021; Agrawal et al. 2021; Mishra et al. 2022b). The above studies indicate that the RCMs prove themselves to have more capability than the global climate models in simulating the mean ISMR and its variability. Some recent studies noted that RCM's performance is greatly affected by the inclusion of aerosol components. Aerosol direct radiative effects (Das et al. 2020a) as well as their interaction with snow over the Himalayas-Tibetan Plateau (Das et al. 2020b,

2022), could influence the dynamics of the Indian summer monsoon. Several studies have suggested that the model's horizontal resolution is an important factor in improving the skill of the RCMs (Bhaskaran et al. 2012; Karmacharya et al. 2017; Maurya et al. 2018, 2020; Sinha et al. 2019).

With the discussion mentioned above, one might expect improved fields when downscaled. In principle, a higher resolution should improve the performance by better resolving the capability of complex topography and coastlines. Various studies have demonstrated the skill of RCMs over different regions and compared their performance with GCMs to see the added value of RCMs over GCMs (Feser et al. 2011; Glotter et al. 2014; Torma et al. 2015) and reported substantial improvements for most regions, with some exceptions during different seasons. The study by Anand et al. (2018) and Jayasankar et al. (2021) demonstrated the advantage of high-resolution RCM simulation driven by the global coupled models CMIP5 that might be affected by the existing bias in the parent models. Choudhary et al. (2019) noted the added value of RCMs for ISM characteristics, including onset; however, it varies spatially and particular characteristics. Karmacharya et al. (2017) also reported improved performance of RCMs in simulating the ISM. Sanjay et al. (2017) found that the improvement due to downscaling strongly depends on driving GCMs and RCMs used for downscaling and does not always improve the seasonal mean. A more considerable improvement is expected for the driving GCMs having more considerable biases. On the contrary, some studies did not find any advantage of using RCMs over GCMs. Mishra et al. (2014) made an effort to assess the comparative performance of RCMs (ensemble of RCMs) over CORDEX-SA with corresponding parent GCMs and reported no significant added value of using RCMs over GCMs. Similarly, Singh et al. (2017) also did not find added value in RCM simulations instead ISM features have deteriorated compared to the host GCM.

The performance of RCMs in simulating the mean ISMR and heavy rainfall activities is reported to be improved with the increasing model horizontal resolution (Cherchi and Navarra 2007; Chan et al. 2013; Johnson et al. 2016; Maurya et al. 2018), which can help to explore the spatial distribution of heavy rainfall activity at a high resolution. Maurya et al. (2018) performed several sensitivity experiments to demonstrate the advantage of high resolution. Their study found improving performance for mean monsoon precipitation with increasing resolution to a specific limit, highest performance with 40 km horizontal resolution and further increasing resolution does not show any improvement, and even degradation is noticed. However, their study demonstrated only for some aspects of monsoon (mostly mean only) and used limited indices of added value. These large differences in the finding of the different studies raised the question about the efficiency of high-resolution

RCMs compared to driving GCMs/reanalysis and increased the debates on the benefit or improvement of RCMs over the GCMs. Although the use of different indices of added value demonstration, deferent aspects, and consideration of different regions for averaging (for example, different latitudes and longitudes have been considered to represent central India) also affect the finding substantially. Along these lines, a study by Kumar et al. 2020 reported the considerable dependency of added value on the region and the metric under consideration.

It is reported in the various studies that the bias present in large-scale circulation of driven GCMs is carried forward in the RCMs (Torma et al. 2015). Feser et al. (2011) reported that the added value varies spatiotemporally and with the specific field. A comprehensive assessment of added value for the ISM characteristics is limited. Moreover, accessing the added value of downscaled fields over parent reanalyses or GCMs remains a subject of debate (Di Luca et al. 2013, 2015; Torma et al. 2015; Giorgi and Gutowski 2016) due to the contrasting nature of the findings in different studies. The importance of quantitative added value has been given severe weight recently. These facts motivated us to take the present problem to examine whether the increasing horizontal resolution of the regional climate model does inevitably capable of adding value by the considerably substantial number of added values indices and evaluated for different subregions of India quantitatively. This study is arranged as follows: Sect. 2 deals with the model description, experiment design, and manifold validation/added value measures. Section 3 illustrates the results and discussion. Conclusions are stated in Sect. 4 of the manuscript.

2 Experimental framework and methodology

2.1 Model setup

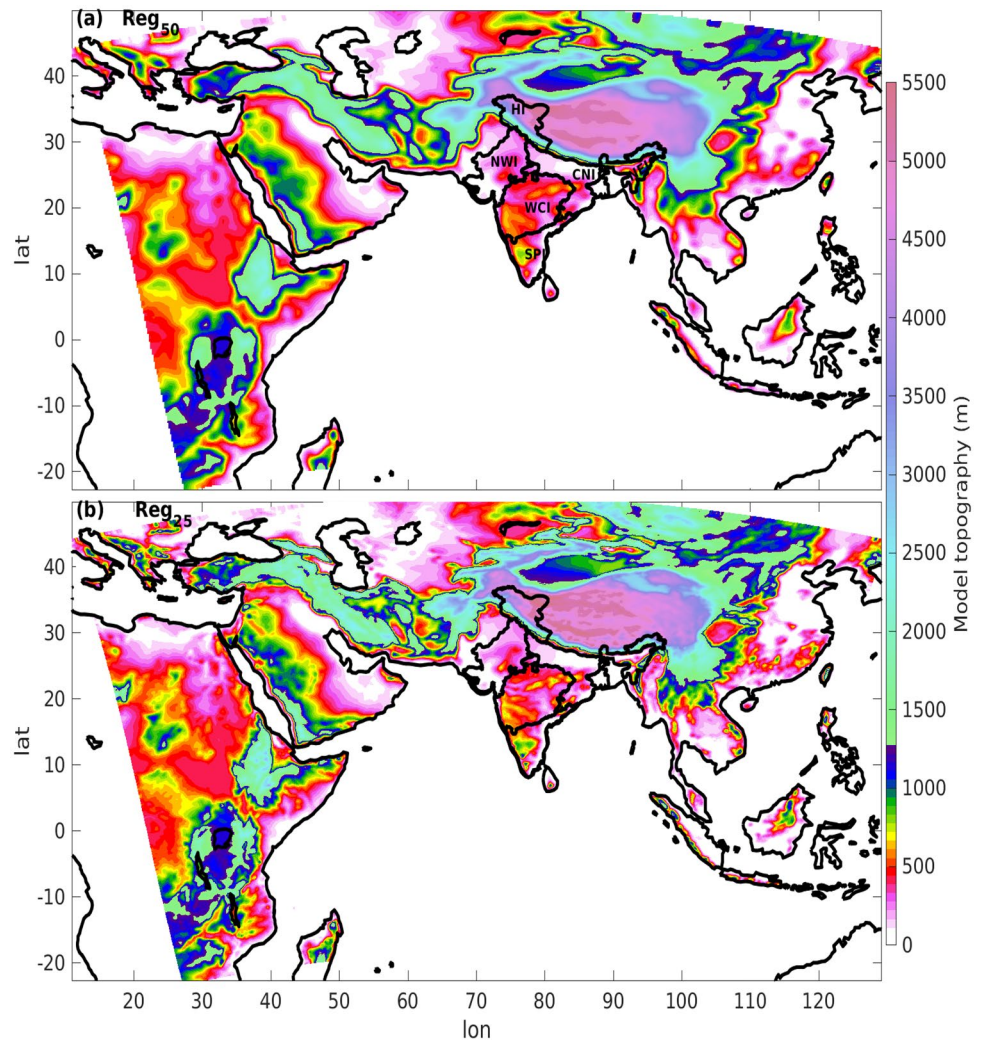
This study employed the regional climate model (RegCM) version 4.5 (RegCM4.5) (Elguindi et al. 2014) to elucidate the advantage of downscaling and investigate the usefulness of increasing horizontal resolution in simulating the mean and extreme rainfall over India. The model is integrated at two horizontal resolutions (50 km and 25 km; hereafter referred to as Reg50 and Reg25) for South Asia Coordinated Regional Climate Downscaling Experiment (CORDEX-SA) (Giorgi et al. 2009) domain [22° S–50° N; 10° E–130° E] (Fig. 1). We use the time steps of 90 s and 30 s for carrying out Reg50 and Reg25. The Biosphere–Atmosphere Transfer (BATS) scheme (Dickinson et al. 1993) and radiative transfer scheme of the global model CCM3 (Kiehl et al. 1996) are adopted for land-surface processes and radiative transfer calculations, respectively. The planetary

boundary layer (PBL) is parameterized with the Holtslag scheme (Holtslag et al. 1990). We have employed the sub-grid explicit moisture scheme of Pal et al. (2000). A mixed convection scheme (MIT over land and Grell over the ocean) based on the previous study (Mishra and Dwivedi 2019) provides a detailed description of the setup used in this study. The 6-hourly varying fields derived from European Center for Medium-Range Weather Forecasting (ECMWF) ERA-Interim reanalysis (EIN) (Dee et al. 2011) are used as initial and lateral boundary conditions for the model run. The weekly sea surface temperature (SST) data are extracted from the National Oceanic and Atmospheric Administration (NOAA) at $1.0^\circ \times 1.0^\circ$ horizontal resolution (Reynolds et al. 2002). The land use data and terrain heights are generated from the United States Geographical Survey at 30 s resolution. The analysis is performed using simulated data from 1 January 1999 to 31 December 2005, excluding spin-up time. This short period consists of two El Niño events (2002, 2004), two La Niña events (2000, 2005), and a normal year (2000), allowing us to assess the model's behavior (sensitivity towards horizontal resolution) for all cases. The selection of a particular set of physics schemes is based on several short sensitivity tests using the same model version (RegCM4.5), which is a very complex, time-consuming, and resource-intensive task to select a configuration that ubiquitously shows the best performance. We found that different schemes offer varying performances over different regions and seasons and selected the best performing schemes (Mishra and Dwivedi, 2019). Using the best-performing scheme, this study presented the assessment of a five years simulation to demonstrate the impact of horizontal resolution on Indian monsoon characteristics. Although five years is not a long simulation time to produce robust statistics, however, it allows us for the preliminary demonstration of the possible impact of horizontal resolution.

2.2 Observational data set used

Daily gridded high resolution $0.25^\circ \times 0.25^\circ$ precipitation dataset obtained from the Indian Meteorological Department (IMD) is used to compare model precipitation. The high-resolution 0.25° gridded data developed by Pai et al. (2014) is very useful for the high-resolution structure of specific mesoscale events (extreme precipitation events). These data have been used previously in many studies (Kumari et al. 2022 and references therein). Apart from this, the precipitation wind at 850 hPa and 200 hPa and temperature were obtained from the most recent ECMWF reanalysis product (ERA5) to demonstrate the model skill for respective parameters. This ERA5 data is available at 31 km horizontal resolution, and various studies reported its good skill equivalent to observational datasets (Mahto and Mishra 2019; Kumari et al. 2022).

Fig. 1 Topography for the South Asia CORDEX region at the two resolutions investigated in this study: (top) 50 km and (bottom) 25 km. Units are in meters. The text inside the Indian land region shows the six Indian homogeneous rainfall zones



2.3 Methodology

Various indices of validation/added value measures such as biases in the mean, the standard deviation, root mean square error (RMSE), spatial and temporal correlation, skill score, percentage improvement, probability distribution function (PDF), Kolmogorov Smirnov (K–S) distance are adopted. The indices used in this study are described in the subsequent section:

Mean fields: The mean fields are computed using the following formula:

$$f^- = \frac{1}{n} \sum_{i=1}^n f_i \quad (1)$$

where f represents fields from the model, observation, or reanalysis for which the mean needs to be computed. f^- represents the mean value of the fields over time, and n represents the number of days. This study focuses on the summer

monsoon season (122 days) over a period of six years, yielding the total number of days (n) equal to 122×6 days.

Skill Score (SS): We adopted a metric based on simulated Root Mean Square Error (RMSE) and Standard Deviation (SD), which have been used in earlier studies (Srivastava et al. 2016, 2018; Dwivedi et al. 2018; Suneet et al. 2019). These metrics are computed for daily precipitation during the JJAS for the study period of 6 years (122*6 days).

For perfect simulation, the RMSE of simulated fields should be less than the SD of observation, or the skill score should be less than one; however, perfect ISMR simulation is very challenging. Thus the lower value of the skill score can be considered as a better skill of the model.

$$\text{Skill Score (SS)} = \frac{\text{RMSE}_{\text{sim}}}{\text{SD}_{\text{Obs}}} \quad (2)$$

where RMSE_{sim} and SD_{Obs} represents RMSE in simulated fields and observed SD in corresponding fields.

Added value or percentage improvement (AV): In this study, AV is considered as the percentage improvement in RMSE, which is computed as follows:

$$AV = \frac{RMSE_{Reg50} - RMSE_{Reg25}}{RMSE_{Reg50}} \times 100 \quad (3)$$

where $RMSE_{Reg50}$ and $RMSE_{Reg25}$ represent the root mean square error in Reg_{50} and Reg_{25} simulations.

Probability density function (PDF): PDF is one of the important indices to quantify the added values of a given variable that describes the complete characteristics of the variable based on the overall distribution of daily precipitation intensity (Torma et al. 2015).

Kolmogorov–Smirnov (K-S) distance: The Kolmogorov–Smirnov (K-S) distance (Shahi et al. 2022; Chakravarty et al. 1967) is one of the quantitative metrics used to measure the goodness of fit test. It computes the maximum vertical absolute difference between two empirical cumulative distribution functions and shows how well a model reproduces observed PDFs (ECDFs). It can range from zero (perfect overlap between the model and observation distributions) to one (no overlap between the two distributions). It is computed as follows:

$$dKS(F, G) = \sup_{t \in \mathbb{R}} |F(t) - G(t)| \quad (4)$$

where F and G are the two ECDFs, and $\sup_{t \in \mathbb{R}}$ represents the supremum function (Chakravarti et al. 1967; Torma et al. 2015).

Northward and Eastward propagation convective bands: The nature of Intraseasonal oscillation (ISO) plays a critical role in the prediction of monsoonal rainfall (Sperber and Annamalai 2008). ISOs during the south Asian monsoon are tightly linked with northward propagating convective bands that evolve from the equatorial Indian Ocean (EIO) and are regulated by the atmospheric conditions over central India (CI). The interaction between large-scale circulation and organized convection further modulates the march of convective bands (Karmakar and Krishnamurti 2019). Therefore, it is worth diagnosing the model's capability in simulating northward-convective bands and associated mechanisms. We estimated the northward and eastward propagation of the convective band following a similar approach of Sabeerali et al. 2013; Di Sante et al. 2019; Mishra et al. 2021). In this regard, the 20–100 day bandpass filtered precipitation anomalies are regressed for each grid against a reference time series. For northward propagation, the reference time series is computed as the average of the 20–100 day bandpass filtered precipitation over the region 12°N – 22°N and 70°E – 90°E , and lag-latitude diagrams are represented for averaged longitude of 70°E – 95°E . Similarly, for eastward propagation, a lag-longitude diagram is represented for average latitude over 5°S – 5°N considering

20–100 day bandpass precipitation anomalies averaged over the region 10°S – 5°N and 75°E – 100°E as reference time.

Atmospheric Stability: We adopted a metric based on the difference of air temperature (ΔAT) in the mid-troposphere (700 hPa) and lower atmosphere (925 hPa) to compute the atmospheric stability, which has been used previously by Pandey et al. (2020).

$$Ast = AT_{700} - AT_{925} \quad (5)$$

where AT_{700} and AT_{925} represent the air temperature at 700 hPa and 925 hPa.

Vertical shear of zonal wind (VSZW): We follow the conventional definition of vertical shear as the difference between lower and upper-level wind, which is mathematically expressed as follows:

$$VSZW = U_{850} - U_{200} \quad (6)$$

where U_{850} and U_{200} are the zonal wind at 850 hPa, and 200 hPa.

3 Result and discussion

3.1 Skill and impact assessments

We began our analysis with the evaluation of the simulation performed by RegCM against the parent-driven reanalysis for the mean state of monsoon characteristics such as precipitation, temperature, and circulation. Additionally, the impact of increasing horizontal is also accessed. Figure 2 represents the JJAS mean precipitation (upper panel) along with the difference map (lower panel) from RegCM simulation (Reg_{50} and Reg_{25}), EIN, and corresponding observation from IMD (Unnikrishnan et al. 2013). It is noticed that IMD shows strong spatial variability, with extremely high rainfall in northeast India at the Himalayan foothills and on the west coast at the windward side of the Western Ghats, while deficient rainfall in the North-Western region at Rajasthan. EIN shows comparatively very less spatial variability of precipitation, and RegCM significantly increases this spatial variability. The improvement in the simulation of spatial features of precipitation distribution is seen in Reg_{50} , which further improves towards increasing the resolution (Reg_{25}). Interestingly it is observed that precipitation not only increases with higher resolution simulations but suppression of precipitation is also noticed over some places, which is in contrast to earlier studies that have reported only increased precipitation with higher resolution simulations over most parts of India (Leung and Qian 2003; Bhaskaran et al. 2012; Sinha et al. 2013). The precipitation over the NEI (Western Ghats; WG and Indo-Gangetic plain; IGP) was highly overestimated (underestimated) in the parent reanalysis, and Reg_{50} tends

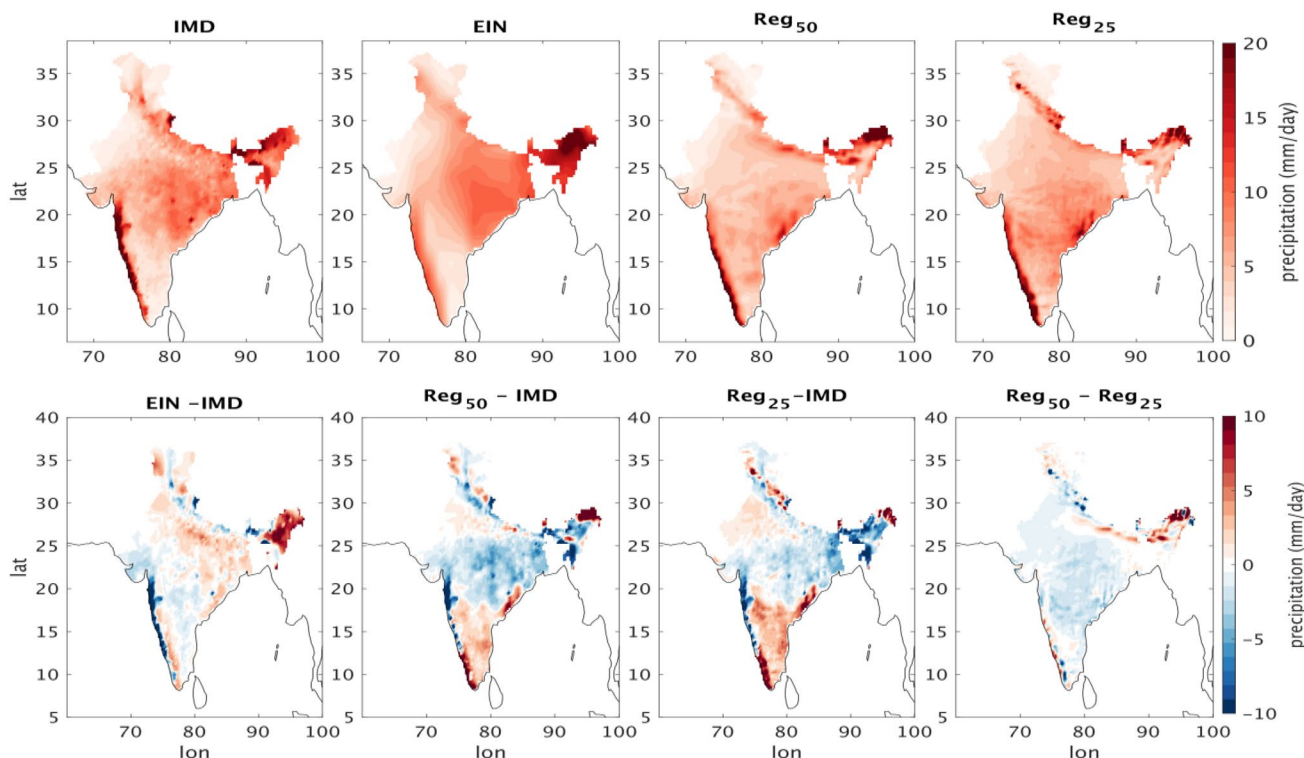


Fig. 2 The JJAS mean precipitation (upper panel) along with the bias (lower panel) from RegCM simulation (Reg₅₀ and Reg₂₅), EIN with respect to corresponding observation from Indian Meteorological Department (IMD)

to decrease(increase) the precipitation over NEI(WG, IGP). The EIN shows a significant amount of precipitation over Central India (CI), which is reduced in Reg₅₀ and further increases with increasing the resolution (Reg₂₅). Overall, the bias decreases notably over most Indian land regions except the southern peninsular region in Reg₂₅ compared to Reg₅₀.

The spatial distribution also seems to be well represented by the RegCM, which shows a higher precipitation amount in JJAS than their driving reanalysis. We also noticed further improvement by increasing the horizontal resolution. However, there are large areas where the RegCM bias is found to be similar to or larger than the bias present in EIN.

Further, simulation skills are estimated for the temporal evolution (intraseasonal) of precipitation over the Indian homogeneous region of rainfall (IHRR) (Parthasarathy 1995; Mishra et al. 2020b) by computing various statistical metrics (for example, root mean square error; RMSE and standard deviation (SD), skill score (SS) and the results are summarized in Table 1. The model shows reasonable performance over most subregions in simulating the intraseasonal variability. However, we observe large variability in model performance over different subregions of India. The model generally shows the highest RMSE over NEI, which is attributed to the model’s deficiency in resolving the complex topography. Additionally, the sparse network of IMD rain gauge stations over these regions might also

Table 1 Statistical evaluation (RMSE and skill score; SS) of Reg₅₀ and Reg₂₅ simulated intraseasonal (JJAS daily fields of all years; 122*6) precipitation and added value (AV)

Regions	RMSE		SS		AV(in %)
	Reg ₅₀	Reg ₂₅	Reg ₅₀	Reg ₂₅	
CNI	6.8	6.25	1.25	1.15	8%
NEI	11.73	7.56	1.85	1.19	35.54%
NWI	5.65	5.16	1.11	1.01	8.67%
WCI	8.67	7.16	2.47	2.04	17.42%
SPI	7.45	6.43	1.2	1.04	13.69%
HR	8.59	5.80	2.09	1.41	32.47%

produce considerable uncertainty in measurements. The skill score is closer to one over NWI, CNI, and WCI, indicating good performance in these regions. Interestingly, the increasing resolution boosts the performance of overall subregions with a varying magnitude of improvement. The highest reduction of RMSE is noticed over NEI. The skill score over NEI is 1.85 in Reg₅₀. It is reduced to 1.1 in Reg₂₅, indicating the sensitiveness of horizontal resolution and highlighting the necessity of high-resolution regional climate modeling over these regions. To make results more prospective, quantitative AV estimates (percentage improvements) for Reg₂₅ relative to Reg₅₀ using

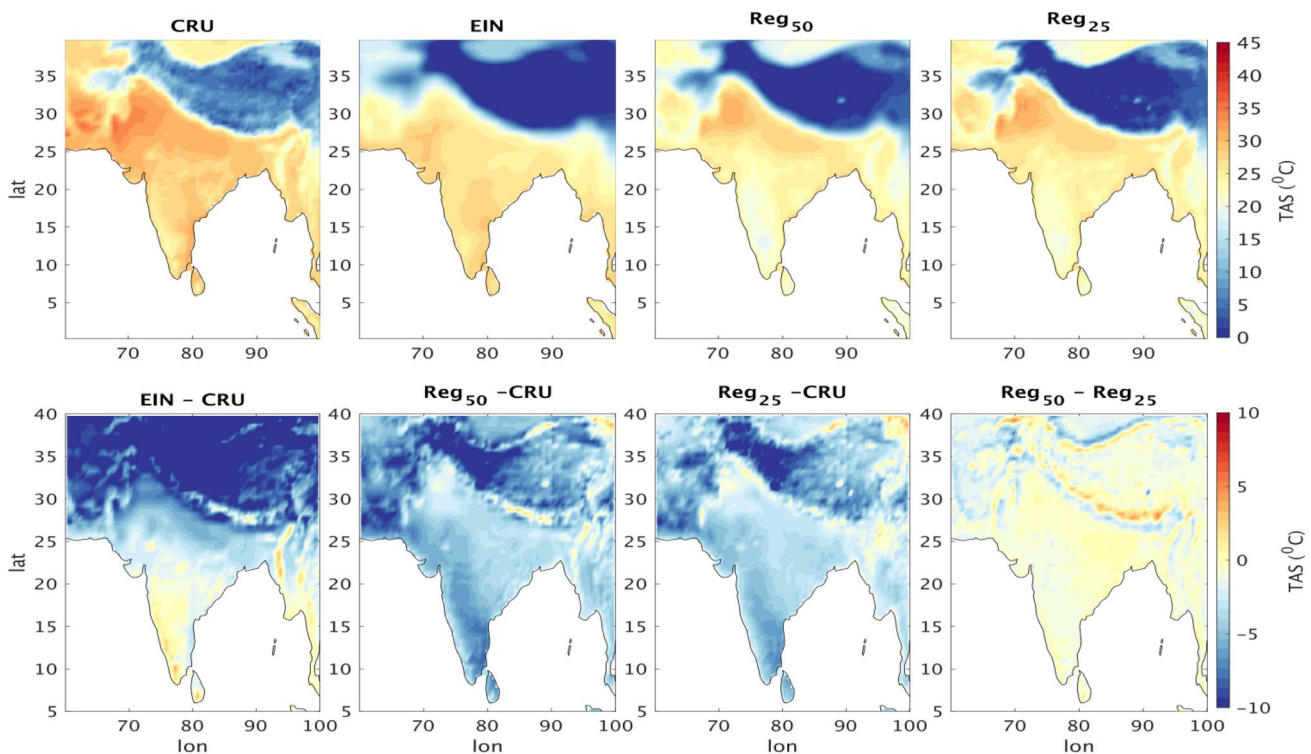


Fig. 3 The surface temperature (upper panel) along with the bias (lower panel) from RegCM simulation (Reg₅₀ and Reg₂₅), EIN with respect to corresponding observation from the climate research unit (CRU)

Eq. (3) are carried out, and the results are summarised in Table 1. Table 1 again confirms the highest improvement over the complex topographic region of NEI (~55%) and HR (~48%) and the lowest improvement over CNI (~9%).

Figure 3 shows the surface temperature (upper panel) along with the difference map (lower panel) from RegCM simulation (Reg₅₀ and Reg₂₅), EIN, and corresponding observation from the climate research unit (CRU) (Harris et al. 2014). The figure shows that both RegCM simulations (Reg₅₀ and Reg₂₅) can reproduce the spatial distribution, consistent with their driving reanalysis. The model is able to distinguish the regions of low and high temperatures clearly. Temperature increases northward from southern India (SI) to northern India (NI). The highest temperature is noticed over North-West India (NWI) around Rajasthan, and the lowest temperature is over Tibetan Plateau (TP). EIN shows a large cold bias (> 10 °C) over Tibetan Plateau and a slightly warm/cold bias SI/along the Indo-Gangetic plain. RegCM simulations also show the cold bias over most parts of India; however, the magnitude of the bias is considerably reduced in RegCM simulation. Further improvement in temperature is noticed with increasing horizontal resolution from 50 to 25 km (temperature is increased with increasing resolution over most of India except small patches), consistent with the improvement in precipitation.

To gain further insight into the differences in mean precipitation bias, we investigate the evolution of climatological daily precipitation for a fraction of total precipitation due to low (< 5 mm) and high (> 20 mm) intensity precipitation for the monsoon season (JJAS) area-averaged over the region CI [69° E–88° E; 18° N–28° N] (Rajeevan et al. 2010) which is core monsoon zone of India represented in Fig. 4. From the figure, it can be observed that Reg₅₀ and Reg₂₅ show quite similar seasonal evolution and intensity for a fraction of total precipitation due to low-intensity precipitation. This shows that the process of generation of low-intensity precipitation is likely to be similar. Reg₅₀ and Reg₂₅ both tend to overestimate the low-intensity precipitation, which further increases with increasing resolution. It may be due to the triggering mechanism of the convective parameterization, which indicates that down-scaling or increasing resolution cannot be expected to be better in every aspect. This is also consistent with the study by White et al. 1999 that reported coarse resolution was more skillful for lighter precipitation while high resolution performed well for heavier precipitation. It demands the tuning of cumulus parameterization rather than increasing resolution to make simulations of low-intensity precipitation better. Reg₅₀ underestimates the high-intensity precipitation associated with mesoscale convective systems; however, this underestimation is considerably reduced in

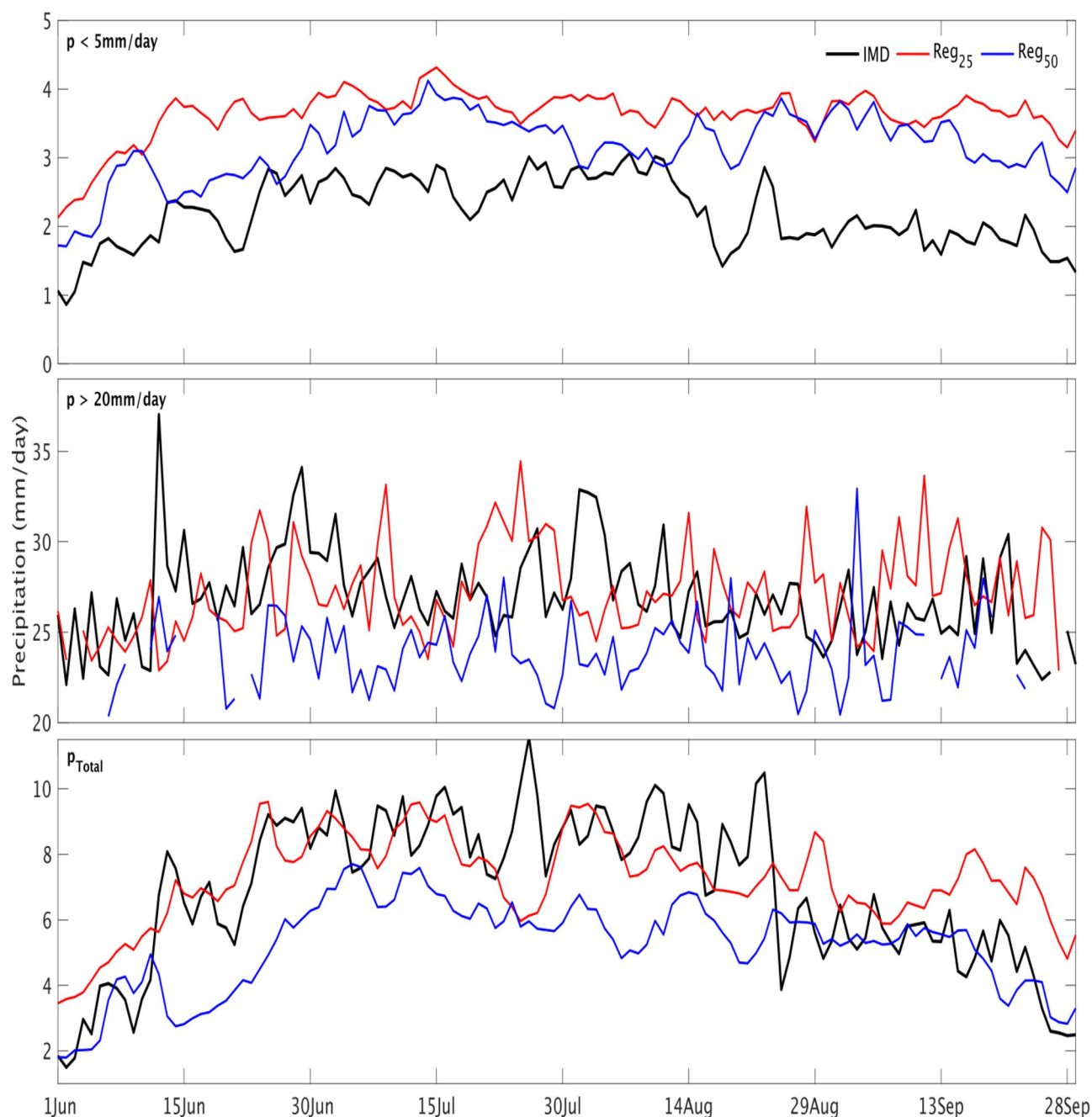


Fig. 4 Daily climatology of precipitation for the fraction of total precipitation due to low-intensity precipitation (<5 mm) (upper panel) and high (>20 mm) intensity precipitation (middle panel), and Total

precipitation (bottom panel) for the monsoon season (JJAS) area-averaged over the region CI [69° E–88° E; 18° N–28° N] for Reg50, Reg25, and IMD

Reg₂₅. The improvement in simulating the seasonal evolution for the high-intensity precipitation in Reg₂₅ may be due to the better capability to resolve the mesoscale process towards increasing resolution. We also observed that high-intensity precipitation's contribution is dominant in total precipitation. Reg₂₅ shows better performance in simulating the total precipitation throughout the monsoon season.

R95 is one of the extreme precipitation measures which is the fraction of precipitation (the 95th percentile of precipitation) accounted for events above the 95th percentile (R95) (Alexander et al. 2006; Torma et al. 2015; Miao et al. 2015). We computed the R95 for Reg₅₀, Reg₂₅, EIN, and IMD on every grid over India for JJAS during 2000–2005. Figures 5 show the map of R95 for Reg₅₀, Reg₂₅, EIN, and IMD. A considerable spatial variation of R95 is noticed in IMD. The

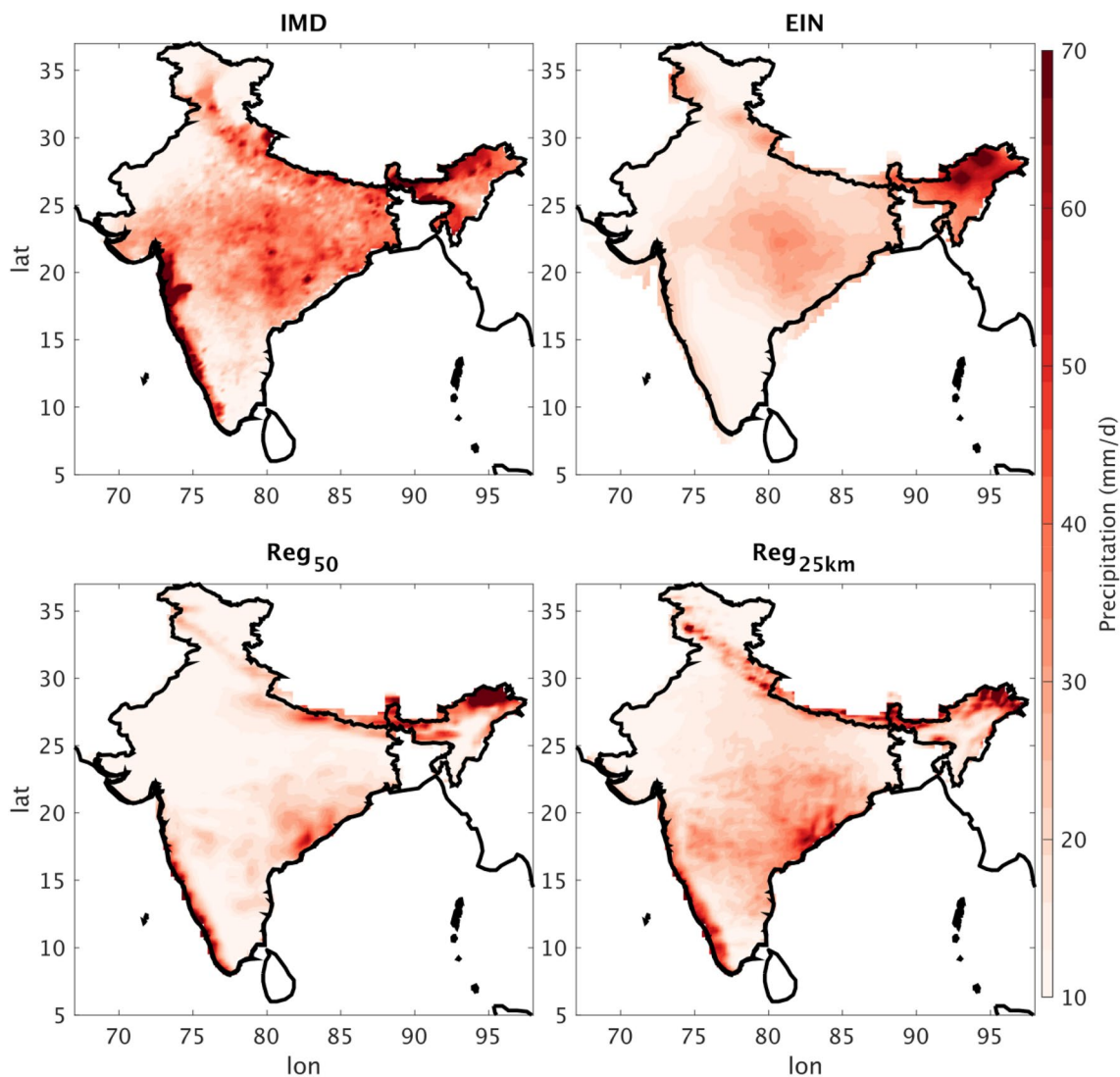


Fig. 5 R95 for Reg₅₀, Reg₂₅, and EIN as well as for IMD on every grid over India for JJAS during 2000–2005

NEI, IGP, and CI show a large value of R95; WG shows a very large value of R95, while SI, NWI, and northern India show a lower value of R95. EIN highly underestimated the R95 value over WG and slightly underestimated over CI, while a slight overestimation is noticed over NEI. Both Reg₅₀ and Reg₂₅ reasonably capture the spatial variation of R95. Both Reg₅₀ and Reg₂₅ show a reasonable improvement in the representation of the R95 value in comparison to EIN. In contrast to EIN, RegCM showed a higher value of R95 over WG and became closer to observation. In contrast to observation, RegCM (Reg₅₀) tends to reduce the R95 over CI; however, Reg₂₅ shows consistent improvement in magnitude as well as spatial variability of R95 over India. The extreme precipitation increases with increasing the resolution over Western Ghat, Central India, and Gangetic plains while reducing over some parts of North-East India. This

improvement in extreme precipitation with increasing resolution may be related to correctly resolving regional-scale features (mesoscale characteristics) of the region in Reg₂₅ compared to Reg₅₀.

Apart from this, we also investigated the added value of downscaling as well as increasing resolution in terms of precipitation intensity. The PDFs of daily precipitation intensities are computed using daily data from EIN, Reg₅₀, Reg₂₅, and IMD over the Indian land region for the summer monsoon season. Figure 6 presents the PDFs for both simulations and EIN, along with the corresponding observed values. Figure 6a reveals the significant differences in the PDFs tails between observation, parent reanalysis, and simulations. IMD shows occurrences up to 600 mm/day. In comparison to observation, EIN has considerably underestimated strong extreme occurrences (PDF tails;

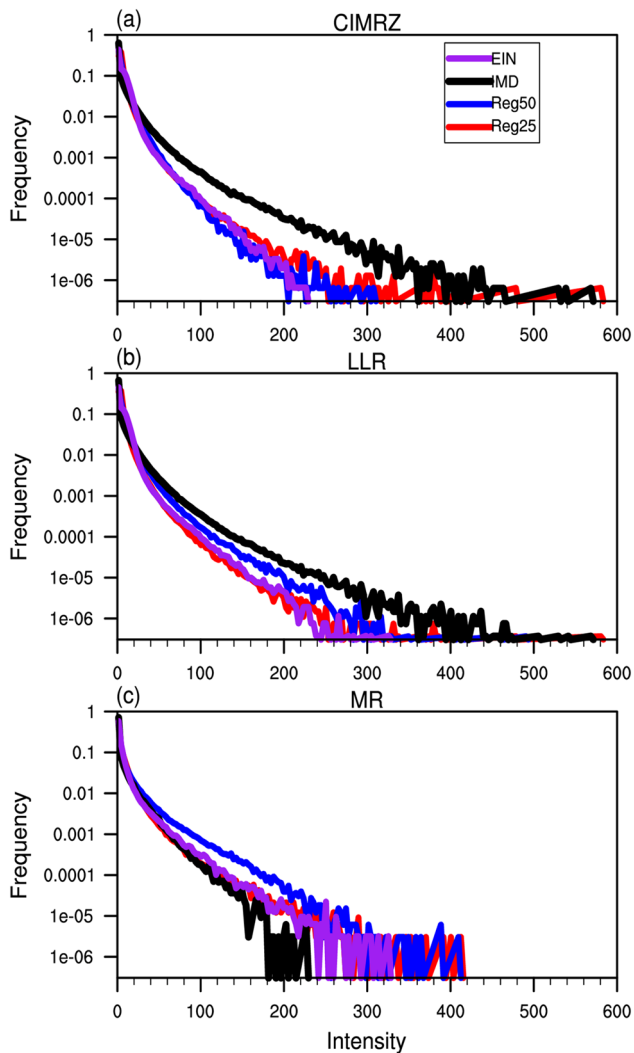


Fig. 6 PDFs of daily precipitation intensities (mm) from EIN, Reg₅₀, Reg₂₅, and IMD for the summer monsoon season (JJAS) over **a** whole India, **b** for the lowland region of India and **c** mountainous region of India

only up to 225 mm/day), ~3 times fewer than observation over the core monsoon zone. Despite having such a vast disparity in the driven EIN, especially for the extremes, both simulations indicate substantially good performance. The intense extreme events increase with downscaling and further with increasing resolution and become closer to observation than coarser resolution. Reg₅₀ captured the events of intensity nearly up to 300. Interestingly, Reg₂₅ shows a good resemblance to observation in simulating the PDF tails. The consistent increase of events intensity indicates the possible improvements in the performance with further increasing the resolution. The Indian land region consists of complex topographical regions ranging from the lowlands to the mountainous areas. It would be worth diagnosing the model's strengths and weaknesses and added value in

simulating the fields over regions of different topographic forcings. We computed the PDFs for the lowlands and mountainous regions in this regard. The regions of landmass having altitudes > 0 and < 1000 m are considered as lowlands, while regions with altitudes > 1000 m are considered as mountainous regions. From Fig. 6b&c, it can be noticed that downscaling shows substantially improved performance over most of the regions; however, further increasing resolution does not show any clear improvement or even degradation of performance is observed for the low land area. The increasing resolution shows the robust improvements for the PDFs of daily mean precipitation over strong orographic forcing mountainous regions, in particular the low as well as moderate-intensity rainfall. However, the notable overestimation with respect to IMD is still observed in both simulations, particularly for PDF tails. However, both simulations are in good resemblance to the parent reanalysis. It indicates that overestimation in RegCM simulations might be partly due to the sparse network data station of the observation and partly due to the model's resolution still not being sufficient to resolve the mesoscale/ smaller-scale processes. It indicates that simulating climate over complex mountainous region plateau is still a challenge for the high-resolution models and demands to improve the complex interactions and formulate model's processes (such as convective parameterizations) that seem to become more important.

To make the results more perspective on the regional scale, we examine the model's comparative performance and assess the impact of increasing resolution for six homogeneous regions (Fig. 7). From the figure, it can be noticed that downscaling shows improved performance compared to parent reanalysis for most of the homogeneous regions. However, the increasing resolution shows improvements over some regions while performance is found to degrade in other regions. For example, over CNI, Reg₅₀ performs better in reproducing the low and moderate-intensity precipitation, while the highest intensity precipitation is observed in the Reg₅₀ (~500 mm) while the Reg₂₅ produces relatively more intense precipitation closer to observation. Over WCI, NEI, and HR, Reg₂₅ was found to be performed better than Reg₅₀ for the precipitation of all intensities, with the highest improvement for PDF tails over the WCI and NEI. For NWI, no notable improvement is observed in reproducing the precipitation of all intensity, and Reg₅₀ shows better performance than Reg₂₅ over NWI.

For more quantitative analysis, we have also computed the point-wise K-S distance between the simulated and observed empirical cumulative distribution functions (ECDFs) of the daily precipitation (Fig. 8). The figure reveals the mixed pattern (positive/negative) of the added value of increasing resolution. It can be noticed that the K-S distance is higher in Reg₅₀ than Reg₂₅ for the complex orography of the forcing region of northeast India,

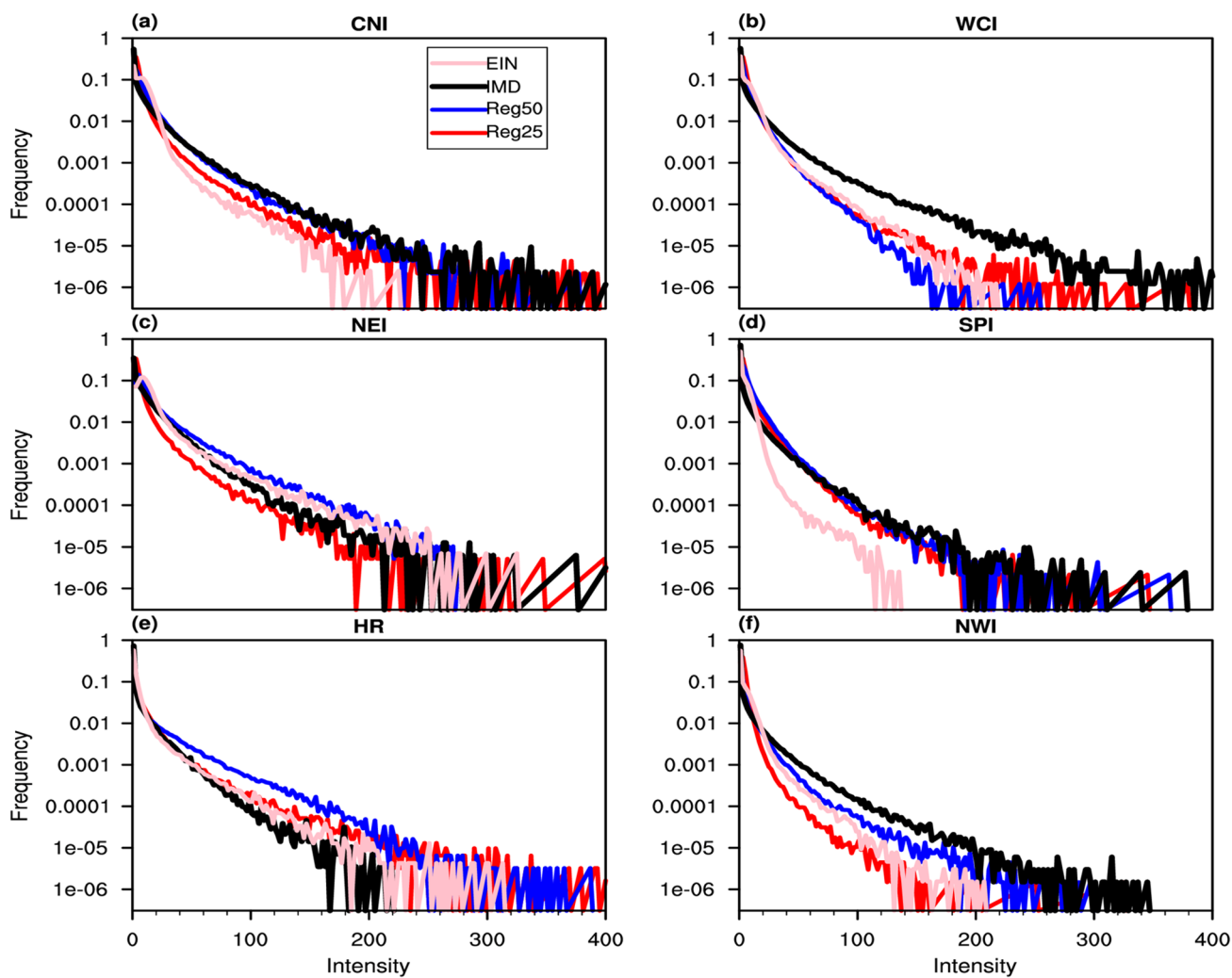


Fig. 7 PDFs of daily precipitation intensities from EIN, Reg₅₀, Reg₂₅, and IMD for the summer monsoon season (JJAS) over **a** CNI, **b** WCI, **c** NEI, **d** SPI, **e** HR, **f** NWI

the Western Ghats, and the mountainous regions of north India. In contrast, the distance is comparable or even lower over Central India in Reg50, indicating that Reg₂₅ is performing better than Reg50 for complex orography of the forcing region of northeast India, the Western Ghats, and the mountainous regions of north India while worsening performance is noticed over most of central India.

The aforementioned discussions of skill assessments with different metrics such as the mean bias, RMSE, correlation, skill score, PDF, K-S distance, and different aspects such as mean precipitation, spatiotemporal variability, precipitation of various intensities, extremes precipitation reveals a notable difference in the AV over different regions or aspects, indicating the fact that added value matrices must be chosen with care for the different regions and characteristics being investigated.

3.2 Physical mechanism

Large-scale dynamics, together with stability, are critical for organized convection over the region and hence activating monsoon rainfall. The lower-level circulation pattern and intensity, especially the Low-level Jet (LLJ), which is the most important dynamic feature over the Indian subcontinent and adjoining oceans, strongly influenced the ISMR (Joseph and Raman 1965; Findlater 1970). Therefore it is worthwhile to investigate AV of increasing resolution in simulating the LLJ. We have shown lower level circulation (winds at 850) for Reg₅₀, Reg₂₅, EIN, and ERA5 in Fig. 9. The figure shows that the simulated spatial distribution LLJ is consistent with ERA5 and parent reanalysis EIN; however, the pattern of cross-equatorial flow is significantly improved with increasing resolution. In general, the strength of cross-equatorial is

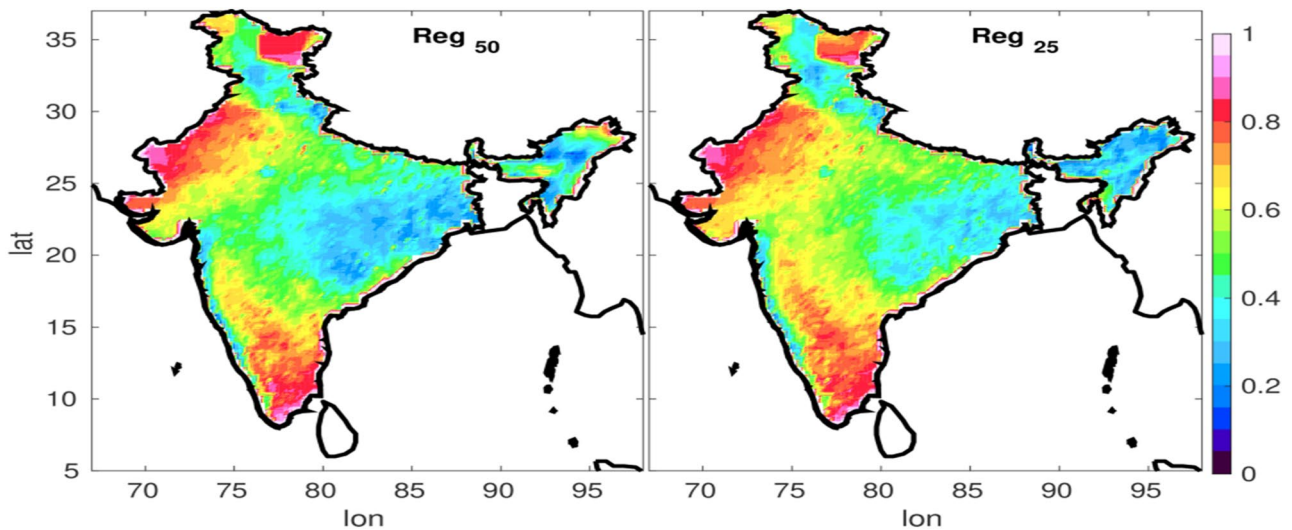


Fig. 8 Kolmogorov–Smirnov (KS) distance for Reg50 (left panel) and Reg25 (right panel)

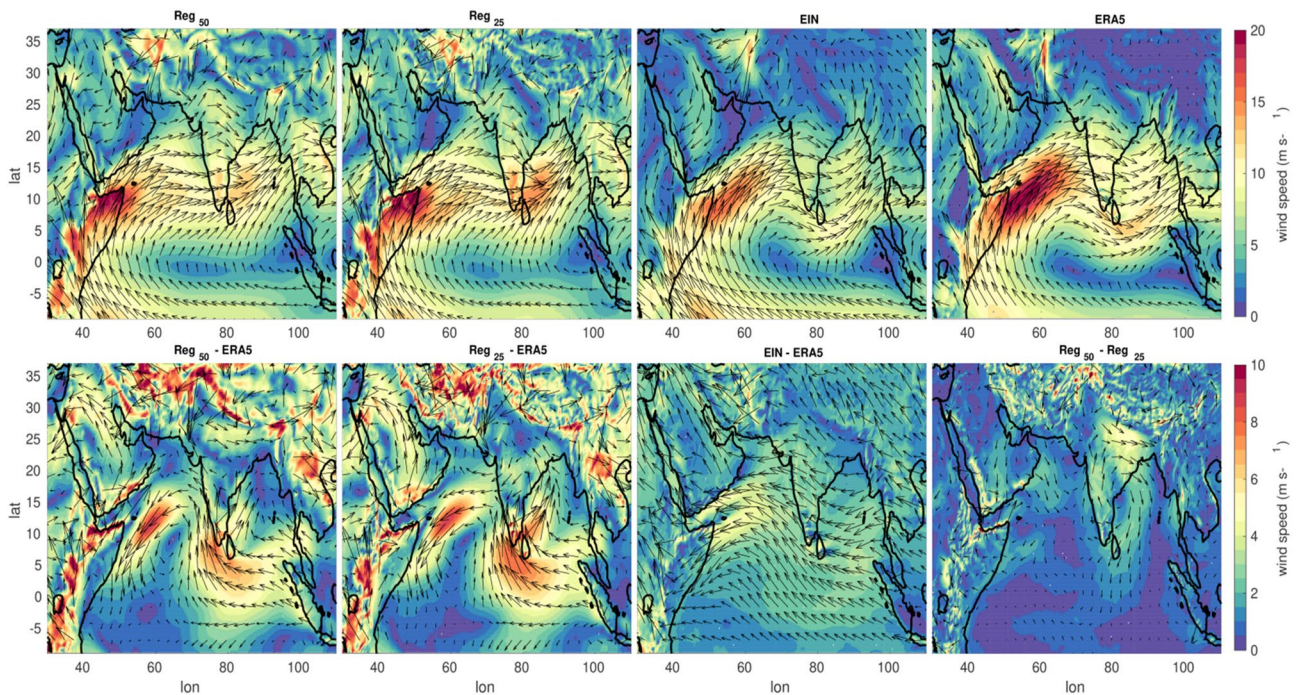


Fig. 9 JJAS mean lower level circulation (winds at 850 hPa) during JJAS for Reg₅₀, Reg₂₅, EIN and ERA5 (upper panel). The difference of Reg₅₀, Reg₂₅, and EIN with respect to ERA5 is shown in the lower

panel. The vectors show direction while shading represents the magnitude of wind speed (in m/sec)

weaker in both simulations compared to ERA5. This is possibly attributed to the weaker strength in the parent reanalysis. The ERA5-driven simulation may improve the simulated wind strength and hence precipitation.

Difference maps depict anomalously strong northeasterly flow over the South-East Arabian Sea (SEAS) in both Reg₅₀, and Reg₂₅, which weakens the strength of cross-equatorial

flow and hence the moisture availability reduces the precipitation over India. However, the strength of this anomalous northeasterly flow is slightly reduced in Reg₂₅, which is consistent with the reduction of dry bias over India in Reg₂₅. The wet bias over southern India is consistent with the southerly flow from the Indian Ocean to SI, which increases the moisture for precipitation and produces wet

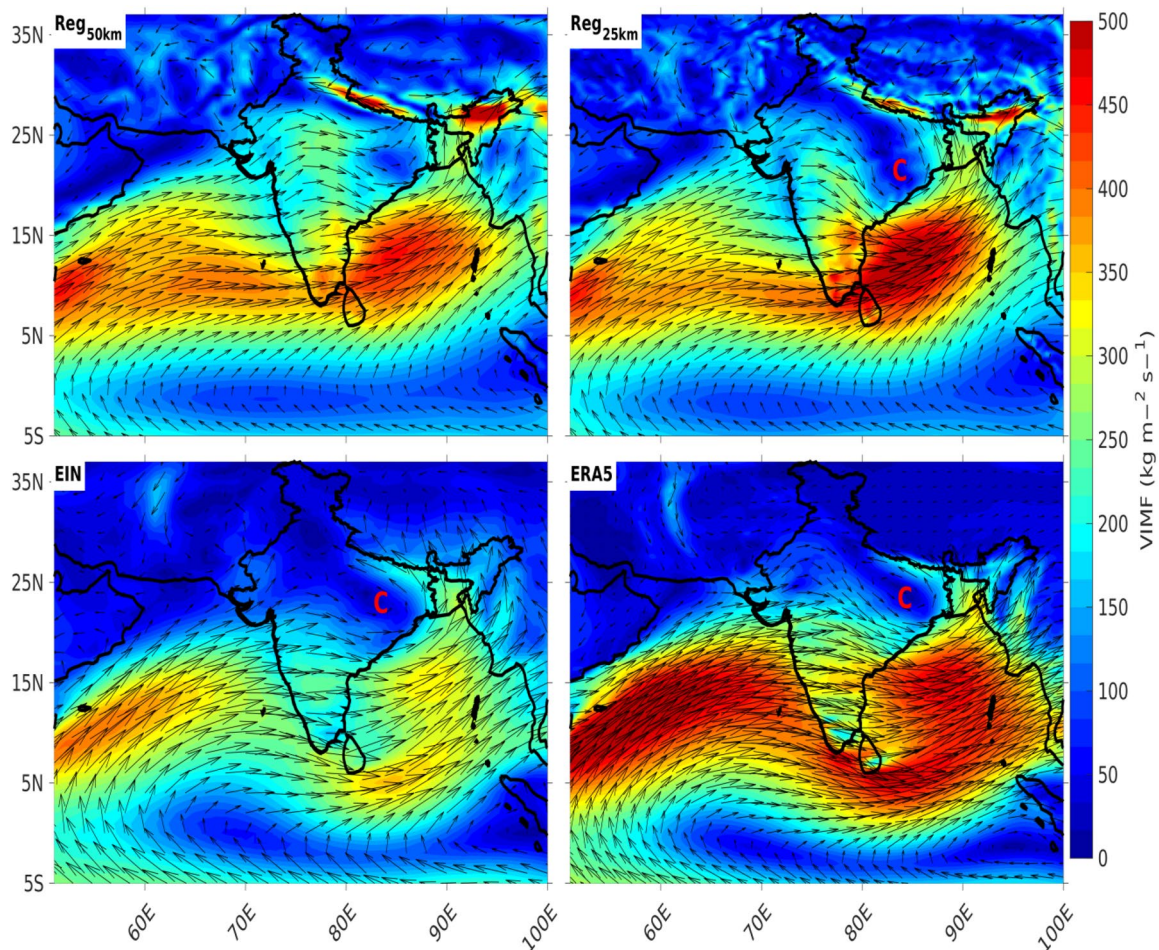


Fig. 10 Vertically integrated moisture transport for Reg₅₀, Reg₂₅, EIN, and ERA5. The shading represents the magnitude of VIMF, while the vector represents its direction. Red ‘C’ over India represents the cyclonic pattern

bias over SI. Reg₅₀ shows strong northwesterly flow over northern India, weakening the moisture-laden southeasterly wind flow from the Bay of Bengal (BoB) and bypassing the moisture from northern India toward China. In contrast to Reg₅₀, the weakening of northwesterly flow over northern India in Reg₂₅ favors strengthening of the moisture-laden southeasterly wind flow from the Bay of Bengal (BoB), which is consistent with its reduced dry precipitation bias over CI compared to Reg₅₀. The difference map of Reg₅₀ and Reg₂₅ shows anomalous northwesterly/southerly flow over the NI/BoB, leading to the reduction of moisture influx over the CI from the NI and BoB in Reg₅₀ compared to Reg₂₅. The improvement in precipitation is found to be interconnected with the corresponding circulation improvements in Reg₂₅ relative to Reg₅₀. Further, we observed fine-scale regional differences in low-level circulation in the Reg₂₅ and Reg₅₀ along the Himalayan foothills and the Western Ghats, likely due to the model’s ability to resolve better the interactions between the orography and the low-level flow at a higher resolution.

Arabian Sea (AS) moisture transport is the key source of moisture source for the Indian summer monsoon (Pathak et al. 2017; Mishra et al. 2020a). Thus it is worth diagnosing the model’s potential as well as the added value (if any) in representing the moisture transport. In this regard, we compared vertically integrated moisture flux (VIMF) from both simulations, EIN and ERA5. Figure 10 reveals that both simulations reproduce the spatial structure of VIMF with a notable discrepancy in magnitude (underestimated). However, this underestimation is slightly reduced in Reg₂₅. This underestimation is possibly driven by the forcing of EIN, which shows considerably less VIMF than ERA5. Interestingly, a cyclonic structure is noticed in the EIN as well as ERA5, which was nearly absent in Reg₅₀. However, Reg₂₅ reproduces this cyclonic structure well, indicating the added value of increasing resolution. This enhanced VIMF magnitude over AS and BoB and correct representation of cyclonic structure might be one of the possible causes of reducing the dry bias in Reg₂₅ compared to Reg₅₀. Apart from this, a considerably higher

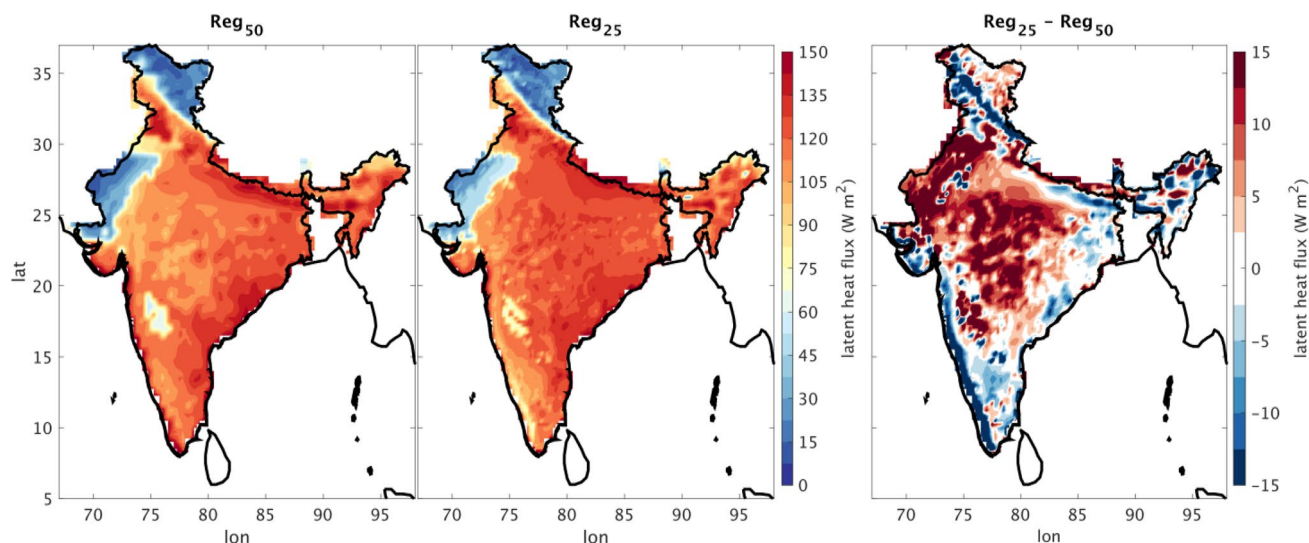


Fig. 11 Surface latent heat flux (LHF) for Reg₅₀, Reg₂₅, and corresponding difference (Reg₂₅–Reg₅₀)

VIMF is noticed in Reg₂₅ than in Reg₅₀, which might be attributed to the wet bias in Reg₂₅.

To investigate the physical mechanism behind improved performance by increasing horizontal resolution in producing more precipitation, we computed the surface latent heat flux (LHF) for Reg₅₀, Reg₂₅, and EIN, as shown in Fig. 11. The figure reveals that LHF is found to increase in most Indian land regions. The LHF is a crucial component of the surface energy balance directly related to evaporation, which contributes to moistening the atmosphere. A higher release of the latent heat into the atmosphere, causing heating and moist convection, leads to more moisture availability at the surface, resulting in more precipitation (Singh et al. 2021). The increased precipitation led to further release of the latent heat into the atmosphere, causing heating and moist convection and hence precipitation. The increased LHF in Reg₂₅ is consistent with increased precipitation.

The precipitation over the region is significantly affected by vertical heating. The stronger mid-tropospheric heating is relative to that of the lower levels, leading to enhanced atmospheric stability (Ast) and weakening precipitation and vice-versa for weaker mid-tropospheric heating than lower levels (Cao et al. 2012). We investigated Ast following Eq. 5, which has been used previously by (Pandey et al. 2020). It could be a good metric to investigate the strength and weaknesses of model physics. One may argue that the Ast is regulated strongly by the large-scale thermodynamic perspective. Thus, how does dynamical downscaling would affect the Ast? The interaction of large-scale thermodynamics and with the local scale features results in modulating the Ast. The possibility of better representation of the topography and planetary boundary layer in high-resolution simulations is intended to investigate added value

for Ast. Figure 12 depicts a reasonable resemblance between model and observation in distinguishing the regions of low and high stability. A strong east–west asymmetry of Ast is noticed at both resolutions over southern India. The lower value is noticed over the southwest and the higher value over the southeast of India. This is also seen in observation, however, the area of low-value Ast is confined to a narrow region (~3 times lesser than the model) parallel to the west coast. The bias map (Fig. 9d, e) indicates a higher underestimation (overestimation) of the Ast over SPI (northeast CI) in Reg₅₀ compared to Reg₂₅. Apart from this, over south CI along the east coast of India, Reg₅₀ (Reg₂₅) more or less shows the contrasting nature of bias, positive in Reg₅₀ and negative in Reg₂₅, with a slightly greater magnitude in Reg₂₅. The higher/lower atmospheric stability results in the weakening/strengthening of convective activity over SPI (CI), leading to weaker/stronger availability of moisture supply and hence suppressed/enhanced precipitation. The wet/dry bias regions are likely to be consistent with the weaker/stronger atmospheric stability in the model compared to observation. The reduction of Ast in Reg₂₅ over CI compared to Reg₅₀ is consistent with the reduction of dry bias. Despite, enhanced Ast over SPI, the intensification of wet bias indicates that the wet bias is not associated with stability (local convective activity) but large-scale dynamics as supported by a convergence of moisture laden wind from the surrounding ocean (Fig. 9).

The convection over the equatorial Indian Ocean that propagates eastward controls ISM's intraseasonal variability (ISV), particularly prolonged breaks condition (Yasunari 1980; Sperber and Annamalai 2008; Sabeerali et al. 2013; Sharmila et al. 2013). Apart from this, the northward propagating convection from the Indian Ocean over the Indian

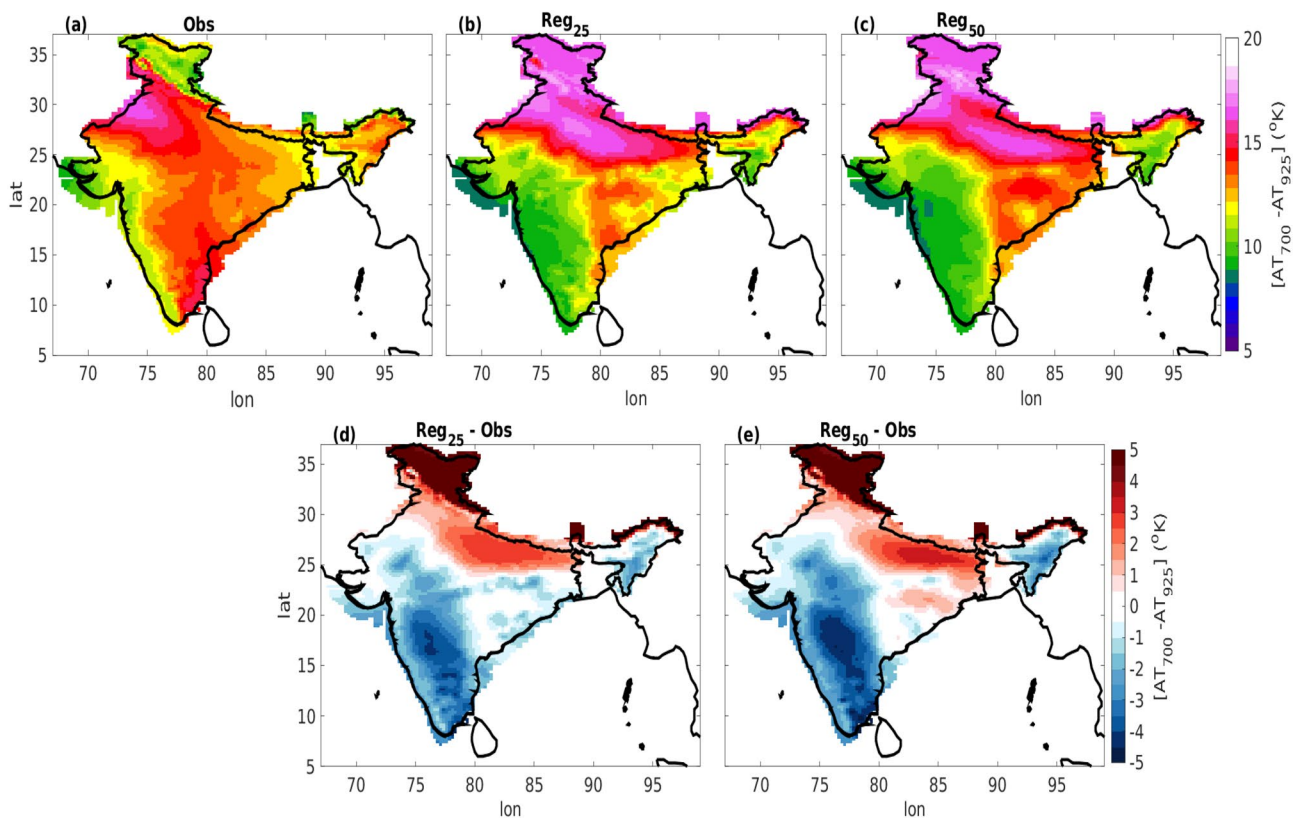


Fig. 12 JJAS mean Atmospheric stability for **a** Observation, **b** Reg₅₀, **c** Reg₂₅ and difference map for **d** Reg₂₅–observation, **e** Reg₅₀–observation

region also contributes to the smaller-scale ISM variability (Webster and Yang 1992; Webster et al. 1999). Thus, investigating the model performance in representing eastward and northward propagating convective bands is worthwhile. It is noticed from Fig. 13 that RegCM shows reasonable skill at both resolutions simulating the propagating characteristics over the Indian land region (north of 3°N). However, Reg25 shows notable improvement over Reg50. Surprisingly over the Indian Ocean (south of the equator), RegCM fails to reproduce the northward propagation even Reg50 is better than Reg25. Similarly, Fig. 14 reveals that both simulations show limited skill in simulating the eastward propagating characteristics in terms of its representation as well as amplitude. However, Reg25 is considerably better than Reg50 in representing the propagation over the western Indian Ocean region (west of 50°E), where, Reg50's propagation is opposite to conservation. Apart from this, over the eastern Indian Ocean region (east of 50°E), the nature of propagation in both simulations is similar, but, Reg25 is in slightly better agreement with observation than Reg50. This weaker propagation of the convection, especially over the Indian ocean, is possibly due to the lack of air-sea interaction in the absence of interactive ocean coupling (Di santé et al. 2019; Mishra et al. 2022a). It is consistent with the study by Di Sante et al. (2019), whose study reported weaker propagation in

the standalone RegCM than observation that improved after coupling with an ocean. The misrepresentation of northward and eastward propagation in RegCM is attributed to the mean ISMR biases.

It is crucial to diagnose the possible cause of differences in propagation bands. The vertical shear of zonal wind (VSZW) plays a vital role in modulating the generation of the barotropic vorticity to the north of convection and hence northward propagation of the convection band (Webster and Yang 1992; Jiang et al. 2004; Mishra et al. 2022a). Therefore, it is inevitable to monitor simulated VSZW to understand the weakness of model monsoon processes associated with northward propagation and hence ISMR. Figure 15 shows the simulated and observed JJAS mean VSZW. In general RegCM bears a close resemblance to observation in reproducing the spatial pattern of VSZW; however, the models exhibit considerable quantitative differences, indicating the model deficiency in simulating the synoptic activity. The simulated spatial distribution of shear is more or less similar at both resolutions. However, strength shows systematic differences. The bias map indicates considerable value addition over the ocean and Indian land regions. The reduction of negative bias over CI in Reg₂₅ leads to enhanced baroclinic instability, which is consistent with the corresponding reduction of dry bias over the same region. The increasing

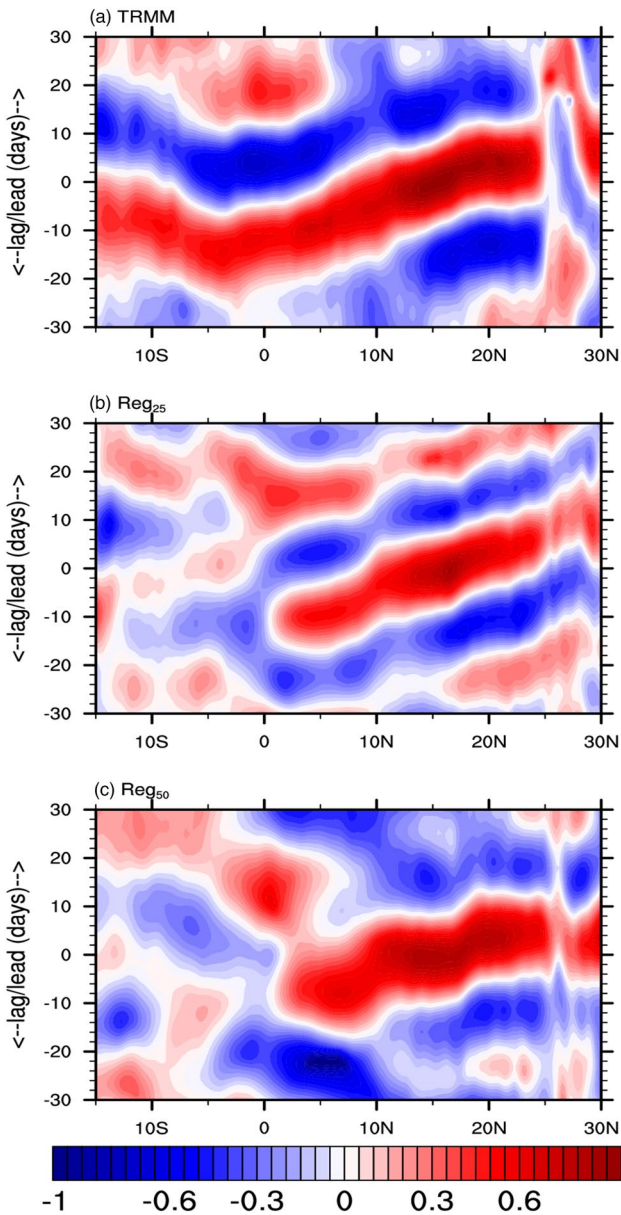


Fig. 13 Northward propagation convective band for **a** observation, **b** Reg₂₅, and **c** Reg₅₀. * Northward propagation is defined as the lag-latitudes regressed anomalies of 20–100 days filtered precipitation averaged over 5° S and 5° N with reference time series averaged for a box over the Tropical Indian Ocean (10° S–5° N to 75° E–100° E)

resolution slightly improves the performance in representing VSZW, improving the representation of northward propagation and hence IMSR.

4 Conclusion

In this paper, we investigated the AV of dynamical downscaling by RegCM nesting concerning the driving EIN Reanalysis over the complex terrain region of the Indian

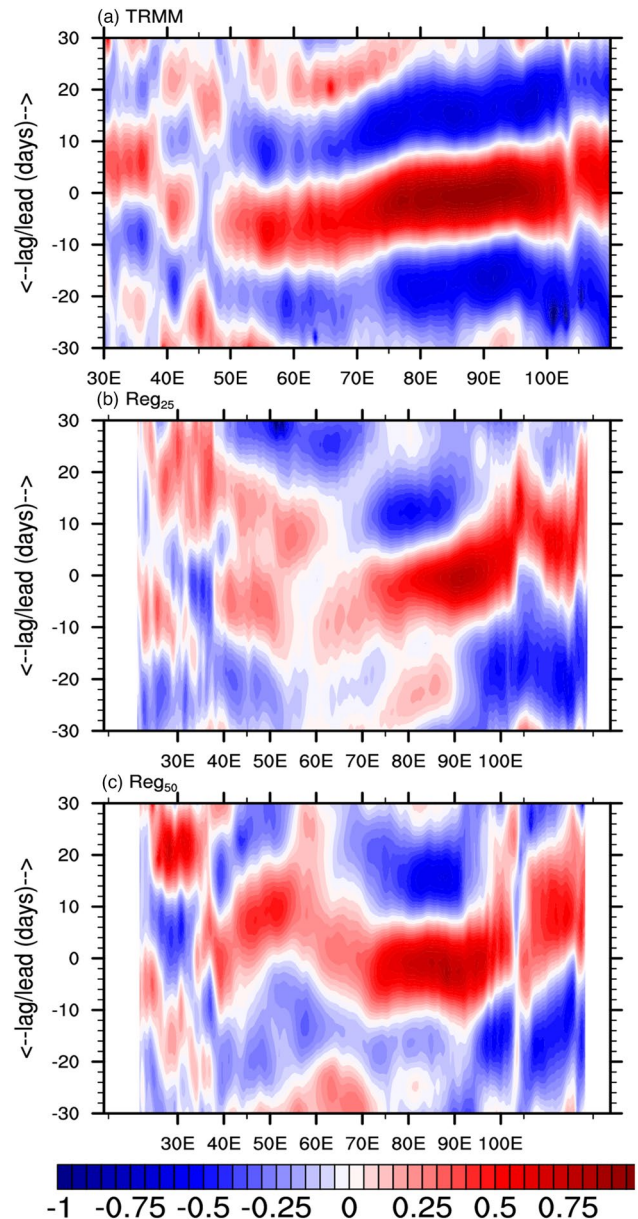


Fig. 14 Eastward propagation convective band for **a** observation, **b** Reg₂₅, and **c** Reg₅₀. * Eastward propagation is defined as the lag-longitude regressed anomalies of 20–100 days filtered precipitation averaged over 5° S and 5° N with reference time series averaged for a box over the Tropical Indian Ocean (10° S–5° N to 75° E–100° E)

subcontinent with particular emphasis on India. We have analyzed the performance of RCM (two resolutions, 50 km, and 25 km) simulations for 6 years, from 2000 to 2005. The evaluation is made in terms of the spatial pattern of mean precipitation, circulation, temperature, the seasonal cycle of precipitation, and daily precipitation extremes tails. A comparison with a high-quality 25 km gridded observational data set of IMD shows substantial AV of RCM downscaling, and results are mostly improved compared to the driving

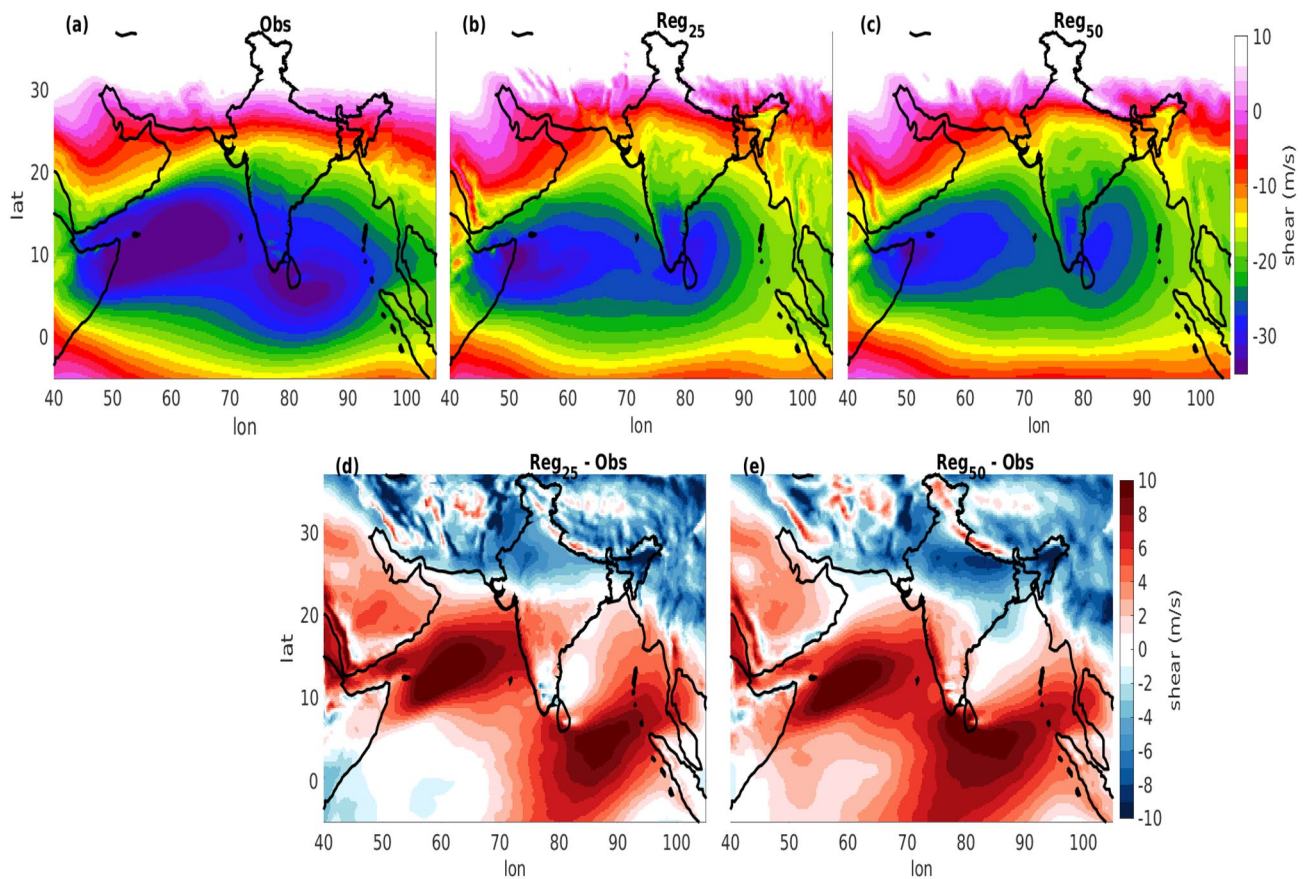


Fig. 15 JJAS mean vertical shear of zonal wind for **a** Observation, **b** Reg₅₀, **c** Reg₂₅ and difference map for **d** Reg₂₅– observation, **e** Reg₅₀– observation

reanalysis. Further increasing the horizontal resolution adds value in simulating many aspects of the Indian summer monsoon, such as the seasonal mean precipitation, temperature, circulation, frequency distribution of daily precipitation, and precipitation extremes.

Moreover, it has also been observed that the added values computed from different metrics vary from region to region. In quantitative terms, for the mean precipitation, the highest improvement is observed over the region of northeast India (~55%) and the Hilly region (~48%) and the lowest improvement over north-central India (~9%). This consistent improvement in the performance towards increasing resolution (the high-resolution (25 km) Reg₂₅ versus low-resolution (50 km) Reg₅₀) may be due to adding more skill to resolve better the interaction of the low-level monsoon flow with the Himalayan orography. The maximum added value is noted over the WG, IGP, and NEI.

A similar observation is noted for the PDFs of daily mean precipitation. Even though increasing resolution improves the simulated precipitation, in particular, the low and moderate-intensity rainfall over strong orographic forcing mountainous regions. However, a notable overestimation is still

observed in both simulations, particularly for PDF tails. It might be partly due to the sparse network data station of the observation and partly due to the model's resolution still not being sufficient to resolve the mesoscale/ smaller-scale processes. It indicates that simulating climate over complex mountainous region plateau is still a challenge for the high-resolution models and demands to improve the complex interactions and formulate the model's processes (such as convective parameterizations) that seem to become more important. The apparent improvement over the complex mountainous regions of NEI, Hilly regions, and the Western Ghats in the higher resolution has been found in the representation of the Spatio-temporal distribution of the Kolmogorov–Smirnov (K-S) distance, wet-day precipitation frequency, and intensity.

Reg₅₀ and Reg₂₅ both tend to overestimate the low-intensity precipitation, which further increases with increasing resolution. It may be due to the triggering mechanism of the convective parameterization, which indicates that downscaling or increasing resolution cannot be expected to be better in every aspect. It demands the tuning of cumulus parameterization rather than increasing

resolution to improve the low-intensity precipitation simulation. In contrast, Reg₅₀ underestimates the high-intensity precipitation associated with mesoscale convective systems; however, this underestimation is considerably reduced in Reg₂₅. The reduction of anomalously strong northeasterly flow over the SEAS and strengthening of the moisture laden southeasterly wind flow from the Bay of Bengal (BoB) in Reg₂₅ compared to Reg₅₀ is consistent with the reduction of dry bias over India in Reg₂₅. These results suggest that higher resolution RCMs have the potential to add more value when downscaling global climate model climate for various characteristics of ISM.

RegCM still exhibits systematic bias despite the substantial improvement, possibly due to misrepresentation of northward and eastward propagating convection band and deficiency in dynamical and thermodynamical processes, demanding further improvement in model physics and tuning of the model parameter. It indicates that increasing horizontal resolution improved the model performance, constituting a strong incentive for trustworthy regional scales climate projections. However, only increasing the horizontal resolution without appropriate recalibration and tweaking the corresponding parameter to adjust the parameterizations is insufficient to attain adequate model performance. Additionally, a notable difference in the AV is observed over different regions or aspects, indicating the fact that AV matrices must be chosen with care for the different regions and characteristics being investigated.

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Author contributions AKM designed the study, carried out the model experiment, processed and analyzed model data, created the figures, and wrote the original draft. AKD and ASD performed formal analysis and reviewed and edited the manuscript. All the authors read the paper and accepted the authors' agreement.

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Data availability The observational datasets used in this study are derived from public resources, and model data will be made available upon reasonable request to the corresponding author.

Declarations

Conflict of interest There is no conflict of interest.

Ethics approval We don't need any ethics approval.

Consent to participate All the authors read the paper and accepted the authors' agreement.

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