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Do dynamic regional models add value to the global model projections of Indian monsoon?

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Abstract Dynamic Regional Climate Models (RCMs) work at fine resolution for a limited region and hence they are presumed to simulate regional climate better than General Circulation Models (GCMs). Simulations by RCMs are used for impacts assessment, often without any evaluation. There is a growing debate on the added value made by the regional models to the projections of GCMs specifically for the regions like, United States and Europe. Evaluation of RCMs for Indian Summer Monsoon Rainfall (ISMR) has been overlooked in literature, though there are few disjoint studies on Indian monsoon extremes and biases. Here we present a comprehensive study on the evaluations of RCMs for the ISMR with all its important characteristics such as northward and eastward propagation, onset, seasonal rainfall patterns, intra-seasonal oscillations, spatial variability and patterns of extremes. We evaluate nine regional simulations from Coordinated Regional Climate Downscaling Experiment and compare them with their host Coupled Model Intercomparison Project-5 GCM projections. We do not find any consistent improvement in the RCM simulations with respect to their host GCMs for any of the characteristics of Indian monsoon except the spatial variation.

We also find that the simulations of the ISMR characteristics by a good number of RCMs, are worse than those of their host GCMs. No consistent added value is observed in the RCM simulations of changes in ISMR characteristics over recent periods, compared to past; though there are few exceptions. These results highlight the need for proper evaluation before utilizing regional models for impacts assessment and subsequent policy making for sustainable climate change adaptation.

Keywords Regional models · CORDEX · Added value · Evaluation · Indian monsoon

1 Introduction

The Indian Summer Monsoon Rainfall (ISMR), during June to September, contributes to 70–80 % of the total annual rainfall in India, and has major socio-economic impacts on the population. Monsoon rainfall contributes to the river flow and ground water recharge and hence is the major source of the water for various activities. Agricultural activities in India are mainly dependent on ISMR and agricultural sector is the major contributor to the Indian economy (Gadgil and Gadgil 2006). ISMR is affected by various external (global) and internal processes. External processes such as ENSO events (Mooley and Parthasarathy 1983; Goswami and Xavier 2005), Indian ocean warming (Saha et al. 2014; Rao et al. 2010, 2012; Roxy et al. 2014), Pacific cyclones (Kumar and Krishnan 2005; Annamalai et al. 2013; Saha et al. 2014), Eurasian snow cover (Hahn and Shukla 1976) and Altantic multi-decadal oscillation (Dugam et al. 1997; Goswami et al. 2006a, b; Kodra et al. 2012) affect the strength and appearance of the ISMR. There are various internal

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processes such as land-surface processes (Saha et al. 2011; Pathak et al. 2014), orography (Salvi et al. 2013) which also affect the variability of the monsoon. These external and internal factors give rise to various spatial and temporal variability in the ISMR on daily, intraseasonal, subseasonal, interannual, and decadal to multi-decadal time-scales.

ISMR has been affected by climate change, in terms of all its characteristics and is already reported in literature. The weakening of monsoon after 1950 was observed by Roxy et al. (2014, 2015) and Saha et al. (2014), while increasing trend of extremes was found by Goswami et al. (2006a, b) and Rajeevan et al. (2008), with significant increase in spatial variability (Ghosh et al. 2012). The onset and withdrawal of Indian monsoon has been reported to undergo a delayed and early shift, respectively, during 1976/77 (Sabeerali et al. 2014; Sahana et al. 2015). Changes are observed in intraseasonal variability specifically, statistically significant increasing trend in the frequency of dry spells and intensity of wet spells, and statistically significant decreasing trend in the intensity of dry spells (Singh et al. 2014). Despite these visible signals of climate change, the new generation Coupled Model Intercomparison Project 5 (CMIP5) climate models are reported to fail in simulating the key characteristics of Indian monsoon (Sabeerali et al. 2014). Though there are certain improvements in CMIP5 models compared to CMIP3 suits in monsoon simulations, specifically in terms of northward propagation, time for peak monsoon and withdrawal (Sperber et al. 2013); still they fail to simulate the trends of monsoon rainfall, post-1950 weakening of monsoon circulation (Saha et al. 2014) and thermodynamic consistency with tropospheric temperature gradient (Sabeerali et al. 2014). This is partially attributed to the failure of coarse resolution models in simulating fine resolution process such as orography, land surface feedback and problems in cloud parameterization resulting overestimation of convective precipitation fraction.

Regional models are presumed to simulate well the regional processes with their fine spatial resolution and region specific parametrization. However, recent literature on evaluation of regional models make this claim debatable. Feser et al. (2011) showed that the added value by applying RCM to the simulation by GCM is region and variable specific. Racherla et al. (2012) have shown the added valued by a RCM is non-significant, where Weather Research and Forecasting (WRF) model was used and the simulations of changes were compared with the parent GCM GISS model E2 (Schmidt et al. 2006). They have concluded that simulating climatology does not ensure better simulation of changed climate and RCMs fail to improve the simulations of changed climate, as projected

by parent GCMs. Boberg and Christensen (2012) observed the limitations of RCM in simulating even the climatology, in terms of over estimation of temperature in Mediterranean. Laprise (2014) commented on the inadequacy of sample size used in the experiment made by Racherla et al. (2012) and concluded that the failure of RCM attributes to the use of smaller sample size and more internal variability; however, Shindell et al. (2014) have shown that the climate change signal in GISS E2 is more than its internal variability. The recent regional model outputs available through Coordinated Regional Climate Downscaling Experiment (CORDEX) have also been evaluated in various studies. There is a strong disagreement across literature on the evaluation of CORDEX models. Torma et al. (2015) have found significant improvement in climate simulations by CORDEX models in Europe. On contrary to that, Glotter et al. (2014) claimed that useful improvements are not visible in CORDEX Simulations for US, specifically for agricultural impacts assessment, though there are certain improvements which are related to fine scale geographic features. This disagreement attributes to the use of different metrics and also to the selection of different regions around globe, and hence this reconfirms the conclusion made by Feser et al. (2011), that evaluation of downscaled simulations are region and variable specific.

Understanding the behavior of Indian monsoon in changing climate is one of the greatest research challenges for climate science, and the state-of-the-art GCMs are still not adequate in simulating the regional distribution of monsoon rainfall (Turner and Annamalai 2012). This is due to the specific regional characteristics of South Asian Monsoon, and hence evaluating monsoon simulations of RCMs should be based on region specific characteristics. RCMs do not correct the bias present in large scale circulation or SST and they are used to add value to the precipitation field at the regional scale. In this study we aim to quantify this added value in the RCM simulations and hence the simulations of precipitation by GCMs and RCMs are compared. The simulations by CORDEX models have been evaluated either for extremes only in terms of return levels of historic period (Mishra et al. 2014) or in terms of bias in precipitation and temperature (Mishra 2015); however, estimation of valued addition by CORDEX models to their parent GCMs for monsoon specific characteristics such as, northward and eastward propagation of intra-seasonal variations, onset, active and break cycle etc. are still overlooked. Here, we present the first comprehensive evaluation of CORDEX models for monsoon specific characteristics and compare them with the performances of their parent GCMs. The next section presents the details of data used in this study.

2 Data

Here we use four sets of data: (1) the regional model outputs or the CORDEX simulations, (2) simulations by their parent GCMs, (3) the reanalysis data, (4) observed gridded long term precipitation data.

2.1 CORDEX simulations: regional model outputs

Here we use the daily climate variables (wind velocity at 850 hPa and precipitation) simulated by 9 regional CORDEX models. We evaluate them for various characteristics of ISMR. CORDEX RCMs were forced with the CMIP5 GCMs and were run at a resolution of 50 km (0.44°) over CORDEX South Asian Domain. Table 1 provides the details of the CORDEX outputs used in this study. The nine simulations, used here were obtained from 4 regional models forced with 9 CMIP5 GCMs. The regional models are: Conformal-Cubic Atmospheric Model (CCAM), Consortium for Small-scale Modeling-Climate Limited-area Modelling (COSMO-CLM), Rossby Center Regional Atmospheric Model version 4 (RCA-4), and Regional Climate Model version 4 (RegCM4).

CCAM, developed by Commonwealth Scientific and Industrial Research Organisation (CSIRO) for dynamical downscaling (Mcgregor 2006), is an Atmospheric Global Climate Model formulated on the conformal-cubic grid (Nguyen et al. 2014). COSMO-CLM4, which is jointly developed by the COnsortium for Small-scale Modelling (COSMO) and the climate version of limited area (local area or LM) community for the regional climate modelling and operational forecast (Davin et al. 2011), is a non-hydrostatic model. RCA4 was developed by Rossby Centre, Swedish Meteorological and Hydrological Institute (SMHI), and is based on the numerical weather prediction (NWP) model HIRLAM (Berg et al. 2013), is a hydrostatic model (Samuelsson et al. 2011). RegCM4 model is limited area model, developed by Abdus Salam International Centre for Theoretical Physics (ICTP). It is a compressible, grid point model with 14 vertical layers and hydrostatic balance (Elguindi et al. 2010; Ji et al. 2011). These RCMs are forced with the boundary conditions provided by ERA-interim (for evaluation runs) and CMIP5 GCMs (details are shown in Table 1).

2.2 CMIP5 GCMs data

To understand the added value in the simulations of Indian monsoon by regional CORDEX models, here we compare them with their corresponding parent/ host GCMs. These GCM simulations belong to the Coupled Model Inter-comparison Project 5 (CMIP5). CMIP5 datasets are archived by the Program for Climate Model Diagnosis and Intercomparison (PCMDI) and here we use the same. Details of the CORDEX RCMs and corresponding CMIP5 GCMs are given in Table 1. Simulations by both, the CORDEX RCMs and CMIP5 GCMs, are compared with the observations, which are either gridded observed data or reanalysis data.

The CMIP5 GCMs corresponding to CORDEX RCMs are: ACCESS1-0, CNRM-CM5, GFDL-ESM2 M, GFDL-CM3, IPSL-CM5A-LR, MPI-ESM-LR, EC-EARTH, NorESM1-M. Though GCMs show poor performance in simulating rainfall, specifically associated with monsoon (Saha et al. 2014); there are certain improvements in new generation models. Sabeerali et al. (2013) found that IPSL-CM5A-LR, GFDL-CM3, MPI-ESM-LR show skill in simulating propagation characteristics of monsoon. Sharmila et al. (2015) have observed that NorESM1-M and MPI-ESM-LR are better in simulating monsoon characteristics: JJAS ISM, JJAS std dev, seasonal cycle, seasonal migration and ISO variance. A detailed review on performances of CMIP5 models in simulating monsoon (Sperber et al. 2013) reveals that NorESM1-M and IPSL-CM5A-LR showed skill in simulation the characteristics of the Asian summer monsoon. However; the inability of GCMs in capturing the regional processes and convective parametrization necessitates use of RCMs and it is required to evaluate the performance of RCMs too before using them for impacts assessment.

2.3 Gridded precipitation data over India

Gridded rainfall data at a spatial resolution of $1° \times 1°$ is used as one of the observational dataset, and is provided by India Meteorological Department (IMD). This gridded data was developed by Rajeevan et al. (2006), where they considered 1384 stations (quality controlled) which had a minimum 70 % data availability during the analysis period in order to minimize the risk of generating temporal inhomogeneities in the gridded data due to varying station densities. They used the method proposed by Shepard (1968) for interpolating station rainfall data into regular grids including the directional effects and barriers. The data may be used for long term trend analysis as a fixed rainfall network was used in the preparation.

2.4 Reanalysis data

Understanding the characteristics of Indian monsoon not only requires precipitation data over Indian landmass, but also over oceans as well other variables such as humidity, wind velocity etc. over a relatively larger region. Hence, we use reanalysis data for understanding some of the characteristics of Indian monsoon, such as, onset, northward and east ward propagation, and they are not always possible

Table 1 GCMs and RCMs used

GCM	CORDEX RCM	Acronym GCM	Acronym RCM	Availability for duration
Commonwealth Scientific and Industrial Research Organization (CSIRO) and Bureau of Meteorology (BOM), Australia	Commonwealth Scientific and Industrial Research Organization (CSIRO), Conformal-Cubic Atmospheric Model (CCAM)	ACCESS1.0	CCAM(ACCESS)	1970–2005
Centre National de Recherches Meteorologiques / Centre Europeen de Recherche et Formation Avancees en Calcul Scientifique, France	Commonwealth Scientific and Industrial Research Organization (CSIRO), Conformal-Cubic Atmospheric Model (CCAM)	CNRM-CM5	CCAM(CNRM)	1970–2005
NOAA Geophysical Fluid Dynamics Laboratory, USA	Commonwealth Scientific and Industrial Research Organization (CSIRO), Conformal-Cubic Atmospheric Model (CCAM)	GFDL-CM3	CCAM(GFDL)	1970–2005
Max Planck Institute for Meteorology (MPI-M), Germany	Commonwealth Scientific and Industrial Research Organization (CSIRO), Conformal-Cubic Atmospheric Model (CCAM)	MPI-ESM-LR	CCAM(MPI)	1970–2005
Norwegian Climate Centre, Norway	Commonwealth Scientific and Industrial Research Organization (CSIRO), Conformal-Cubic Atmospheric Model (CCAM)	NorESM1-M	CCAM(BCCR)	1970–2005
Max Planck Institute for Meteorology (MPI-M), Germany	COnsortium for Small-scale MOdelling (COSMO) model in CLimate Mode version 4.8 (CCLM)	MPI-ESM-LR	CCLM4(MPI)	1951–2005
Irish Centre for High-End Computing (ICHEC), European Consortium ESM (EC-EARTH)	Rossby Centre regional atmospheric model version 4 (RCA4)	EC-EARTH	RCA4(ICHEC)	1951–2005
NOAA Geophysical Fluid Dynamics Laboratory, USA	The Abdus Salam International Centre for Theoretical Physics (ICTP) Regional Climatic Model version 4 (RegCM4)	GFDL-ESM-2 M	RegCM4(GFDL)	1951–2005
Institut Pierre-Simon Laplace, France	The Abdus Salam International Centre for Theoretical Physics (ICTP) Regional Climatic Model version 4 (RegCM4)	IPSL-CM5A-LR	RegCM4(LMDZ)	1951–2005

with just precipitation information over land mass. Here we use three reanalysis data which are available at a relatively finer resolution compared to others. We present brief descriptions of these datasets.

Japanese 55-Years Reanalysis (JRA-55) data (Ebita et al. 2009; Harada et al. 2013) was prepared by Japanese Meteorological Agency (JMA) and is available from 1958 (pre satellite to recent years) with daily/monthly 3, 6 and 24 hourly temporal resolution (varying with variable). Here, we consider total precipitation (3-hourly, $0.5616° \times 0.5625°$) and u-wind (6-hourly and $1.25° \times 1.25°$) at 850 hPa for our present analysis.

ECMWF Interim reanalysis (ERA-Interim) data (Dee et al. 2011; Mooney et al. 2011), developed by ECMWF (European Centre for Medium-Range Weather Forecasts) is available from 1979 (post satellite period). Here, we use 12 hourly total precipitation data at $0.75° \times 0.75°$ resolution and u-850 data at $1.5° \times 1.5°$ resolution for the time period of 1979–2005.

Modern Era Retrospective-analysis for Research and Applications (MERRA) data (Rienecker et al. 2011; Boilley and Wald 2015) developed by NASA's Global Modeling and Assimilation Office is available from 1979 at a spatial resolution of $1/2° \times 2/3°$. In the present analysis we use, total surface precipitation and u-wind at 850 hPa for the period of 1979–2005.

3 Evaluations based on monsoon characteristics

First, we evaluate the climate simulations by regional models along with their parent GCMs for the climatology/ mean conditions of monsoon characteristics. RCM, GCM and observed simulations have been brought a common resolution of 0.5° before comparison. Here we consider climatology of rainfall for June to September, bias at finer resolution, onset of monsoon, northward and eastward propagation of intraseasonal variability and extremes as the key characteristics. Brief description of these characteristics along with the evaluation of GCMs and RCMs are presented in the following subsections.

## 3.1 Evaluation of GCMs for large scale circulations

First we evaluate the GCMs based on the variables, winds at 850, 200 hPa and the sea surface temperature. We find that different GCMs have mixed patterns of biases in the absolute wind velocity at 850 hPa (Fig. SF1); however, almost all of them have negative bias in the southerly component. We also find that all the GCMs have very strong negative bias in the wind velocity at 200 hPa (Fig. SF2). We also plot the climatology of vertical shear, computed as

the difference between U component at 200 and 850 hPa (Fig. 1). This provides the starting and end of easterly vertical shear, when this difference changes its sign from positive to negative and negative to positive, respectively. These indicators are large scale circulation proxy measures of the characteristics of south-west monsoon (Sahana et al. 2015). EC-Earth, GFDL-ESM-2M and MPI-ESM-LR simulate well the starting and end of easterly vertical shear. For SST, almost all the GCMs have negative bias over the Indian Ocean, the Bay of Bengal and the Arabian Sea (Fig. 2).

3.2 Spatial variation and bias

Indian monsoon rainfall has significant spatial variability, with extremely high rainfall in the north east India at Himalayan foothills and in the Western coast at the wind ward side of the Western Ghats; whereas very low rainfall in the North Western region at Rajasthan (Fig. 3(a)). GCMs, being a very coarse resolution model fail to capture this finer resolution spatial variability. RCMs, which work at a finer resolution are supposed to capture these spatial variability. Here, we find that different CORDEX RCMs simulate the spatial variability at different locations; however they fail to simulate the overall pattern of spatial variation (Fig. 3). As for example, all the CCAM regional models simulate good amount of rainfall in the Himalayan foothill irrespective of their parent GCMs, but they fail to simulate high rainfall over the Western coast (Fig. 3(f1, f2)–(j1, j2)). On the other hand the RegCM4 simulations produce high rainfall over the Western Ghats, but fail to simulate impacts of the Himalayan orography in the North-East (Fig. 3(b1, b2)–(c1, c2)). We find that the same regional models simulate similar characteristics irrespective of the use of different GCMs. The CCLM4 RCM simulates the orographic effects of both Western Ghats and North East India (Fig. 3(e1, e2)), while others fail at least for one region. For RCA4, the simulation of spatial variability gets worsen compared to the parent GCM EC-Earth, which simulate the orographic precipitation quite satisfactorily (Fig. 3(d1, d2)).

We also compute the bias in rainfall simulations by both RCMs and their parent GCMs, with respect to the gridded observed data. The bias obtained from the multi-model simulations of RCM and GCM look similar (Fig. 4(a1)–(a2)) and hence the improvement with computationally expensive regional models is not visible. We also present the scatter plots obtained with absolute bias for individual RCMs with their parent GCMs (Fig. 4(b)–(k)). The scatter points for all RCMs/ GCMs lie close to 45° line showing no improvements in bias in the RCM simulations compared to their parent GCMs for Indian Monsoon rainfall.
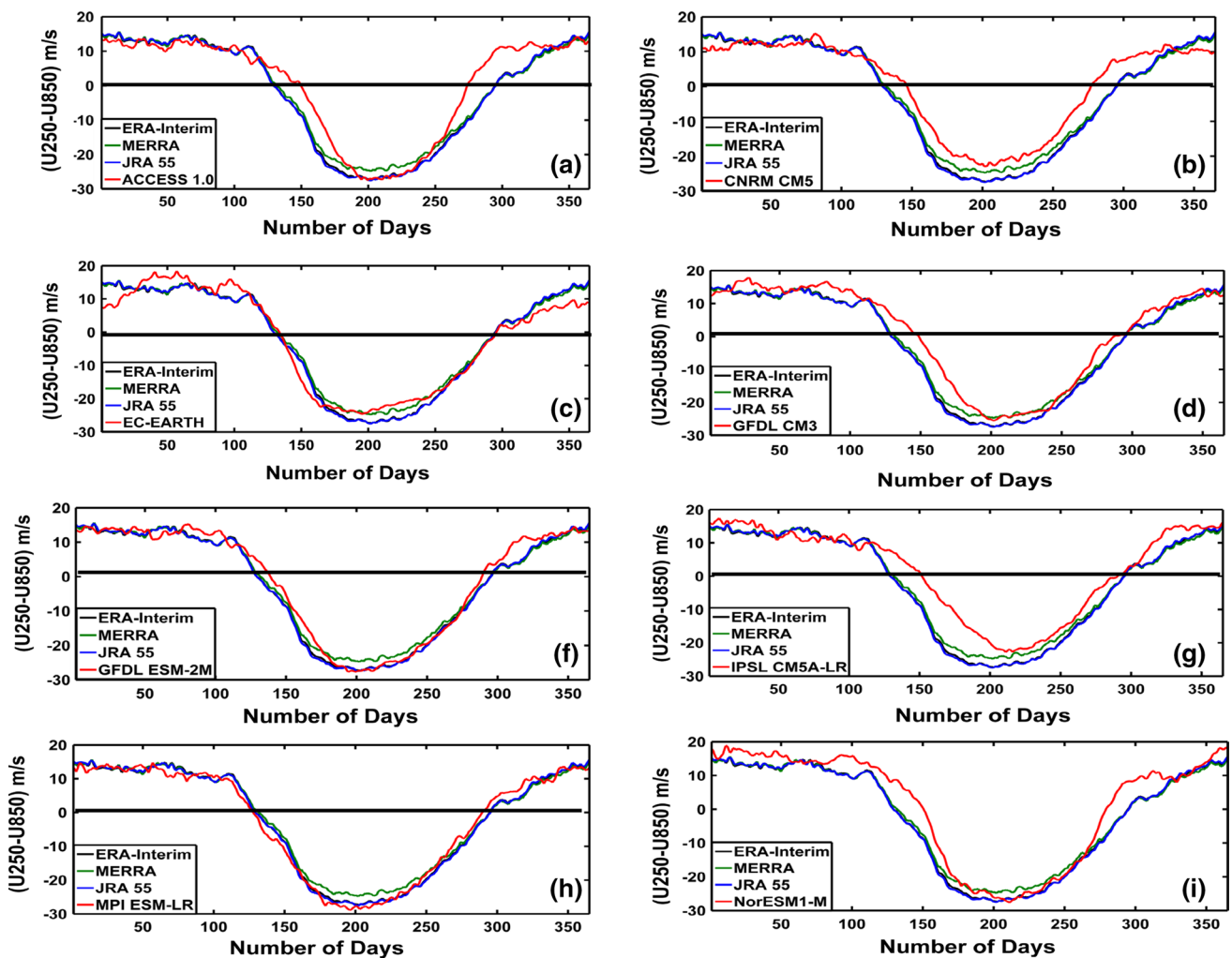
Fig. 1 Climatology of Easterly vertical wind shear for three rea-
nalysis data sets (JRA-55, ERA-Interim and MERRA) and CMIP5
GCMs. It is computed as difference between U component at 250 and
850 hPa over the Arabian Sea (5°N–20°N and 45°E–80°E) for the
period of 1979–2005. This provides the starting and end of easterly
vertical shear, when this difference changes its sign from positive to
negative and negative to positive, respectively. These indicators are
large scale circulation proxy measures of the characteristics of south-
west monsoon (Sahana et al. 2015)

3.3 Climatology of monsoon rainfall

We consider the spatial average of AIMR to compute the
climatology for the summer monsoon period, June to Sep-
tember. The spatial extent used for computing the area
average of precipitation is the Indian domain (6.5°–38.5°N,
66.5°–100.5°E) with masking over the oceanic region. We
use the period 1970–2004, considering the availability of
precipitation data from IMD as well all the 9 RCMs and
their parent GCMs. The observed climatology show grad-
ual increase of rainfall from June after onset, reaching peak
during July–August and then decrease towards September,
followed by monsoon withdrawal. We find that the clima-
tology obtained from Multi-Model Average (MMA) of both
GCMs and RCMs are significantly different from that of

observed (Fig. 5(a)). This is individually true for majority
of the RCMs and their parent GCMs (Fig. 5(b)–(j)). Except
RegCM4, all other regional models simulate climatology
of AIMR poorer than their parent GCMs. We also find that
same RCMs show similar performance irrespective of their
parent GCMs. As for example, all the CCAM simulations
show monsoon climatology similar, which is increased pre-
cipitation during June with a gradual decrease to Septem-
ber, although their parent GCMs have different climatol-
ogy of AIMR. The GCMs ACCESS 1.0 and NorESM1-M
simulate the climatology of monsoon quite well, but when
they are forced to RCMs, the performances worsen. We
only find improvement by regional model simulations over
the parent GCM, when RegCM4 is applied to the GCM,
IPSL-CM5A-LR. The rest of the RCMs do not show any
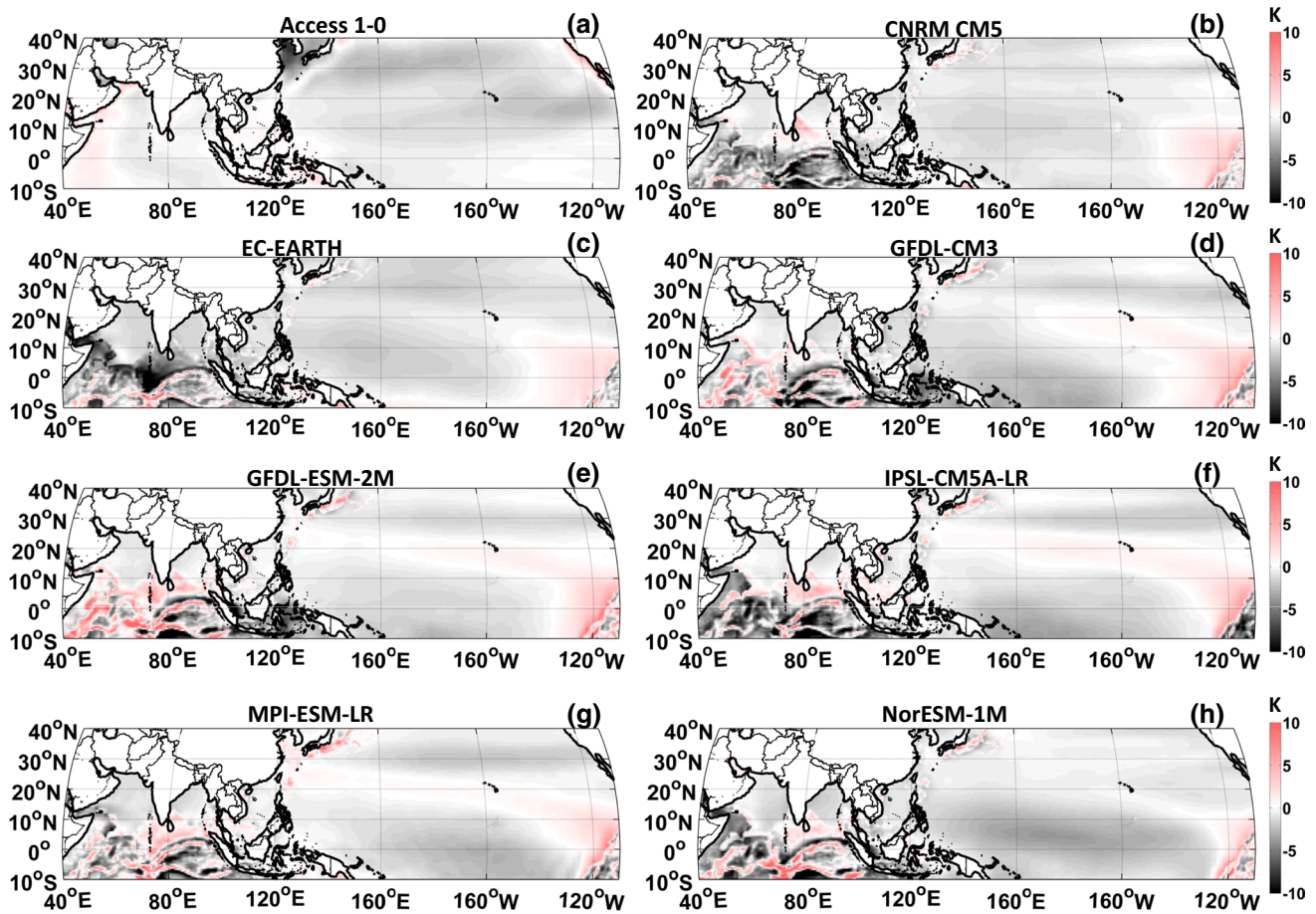
Fig. 2 Bias in simulated spatial pattern and variability of monthly sea surface temperature (SST) field by CMIP5 GCMs, when compared with observed data (MERRA Reanalysis data) during 1979–2005 for JJAS months

added value in simulating the climatology on ISMR. The probable reason behind good simulations by RegCM when applied to IPSL-CM5A-LR is that the monsoon precipitation simulations by the host GCM is worst among the models considered here. The other reason would be the use of better physics parameterization in RegCM. For monsoon simulations, RegCM4 uses (Ali et al. 2015; Hassan et al. 2015) better parameterization schemes: a combination of convection schemes, such as, Grell scheme over land (Grell 1993) and Emanuel scheme over ocean (Emanuel 1991) and this is best suited over South Asia (Hassan et al. 2015). Grell scheme was observed to show skills in simulating precipitation over land (Bhatla and Ghosh 2015) and South Asia (Ali et al. 2015) whereas Emanuel scheme over the ocean (Davis et al. 2009; Ali et al. 2015). Land-Surface Model—CLM3.5 (Oleson et al. 2008) is used in RegCM4, and this includes a physical representation of the coupling between the water, energy and carbon cycles (Reboita et al. 2014; Sellers et al. 1997). Tiwari et al. (2015) found that simulated surface temperature and precipitation are better represented in CLM scheme for the Himalayan region.

These schemes probably result into the improvements by RegCM4 compared to other regional simulations.

3.4 Onset of monsoon

Establishment of widespread rain along the western coast of Indian peninsula marks the Onset of Indian Summer Monsoon (ISM). Though onset is generally identified as an increase in the precipitation, it is associated with building up of vertically integrated humidity, strengthening of the low level westerly wind over the south western India and an increase in the kinetic energy (Krishnamurti 1985). Based on the background state essential for the establishment of onset, several onset identifying indices have been evolved. The Hydrological Onset and Withdrawal Index [HOWI] (Fasullo and Webster 2003; Sahana et al. 2015), the Onset Circulation Index [OCI] (Wang et al. 2009) and the tropospheric temperature gradient based index [ΔTT] (Xavier et al. 2007) are the few among the widely used and comparatively reliable onset indices. HOWI is derived with vertically integrated moisture transport, and computation of
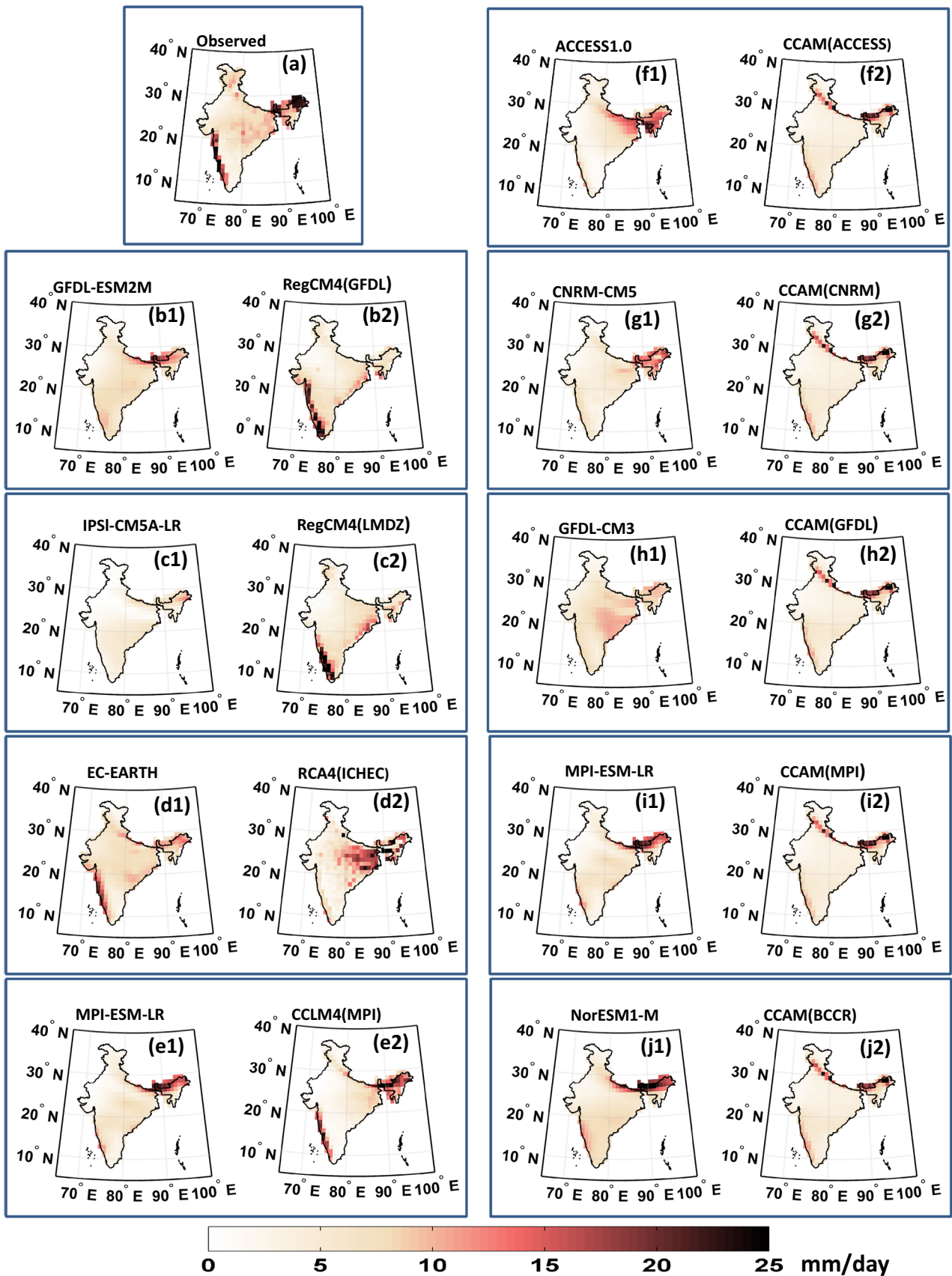
ΔTT needs temperature at multiple pressure levels. Due to the data requirements of multiple variables and non-availability of these variables for majority of RCM simulations in CORDEX public domain, we select OCI for our analysis, which is defined by the 850-hPa zonal wind averaged over

the southern Arabian Sea (SAS) from 5°N to 15°N, and from 40°E to 80°E. ISMR onset is defined as the day when OCI exceeds 6.2 m/s with the provision that for the following consecutive 6 days also OCI exceeds 6.2 m/s (Wang et al. 2009).

We compute the onset date with the three reanalysis data sets JRA-55, ERA-Interim and MERRA for the period 1979–2005. We plot the onset dates and their interannual variability with box-plots using the three reanalysis data sets, and find that they show similar mean onset date (Table 2) and its variability (width of the box) (Fig. 6). The
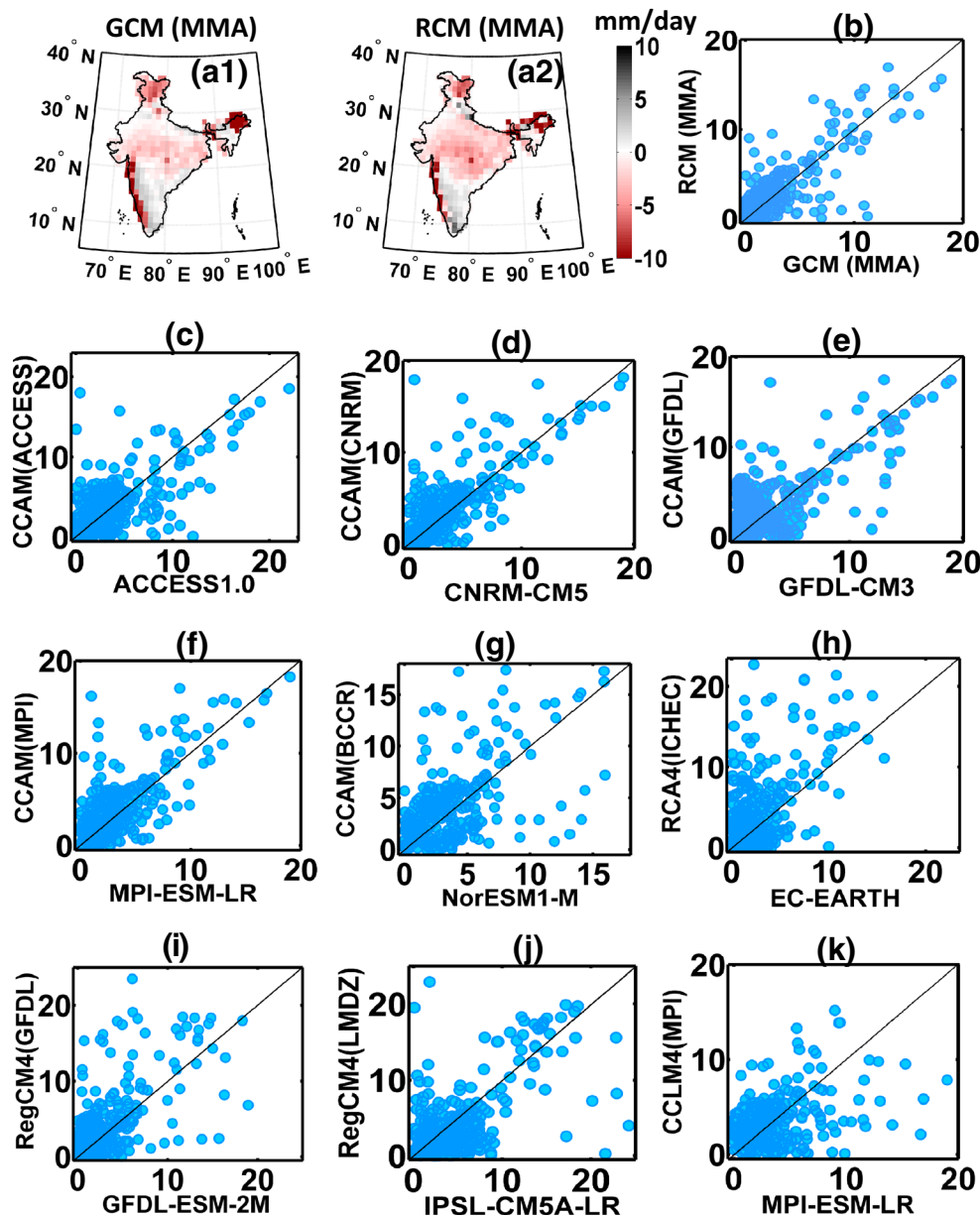
Fig. 4 Bias in the simulations of ISMR by CMIP5 GCMs and their CORDEX RCMs, when compared with observed data. Similar patterns and magnitudes of biases are observed for multi-model average of GCMs (**a1**) and their corresponding RCMs (**a2**). The individual scatter plots (**b–k**) of absolute bias (mm/day) for GCMs and their corresponding RCMs also convey the same
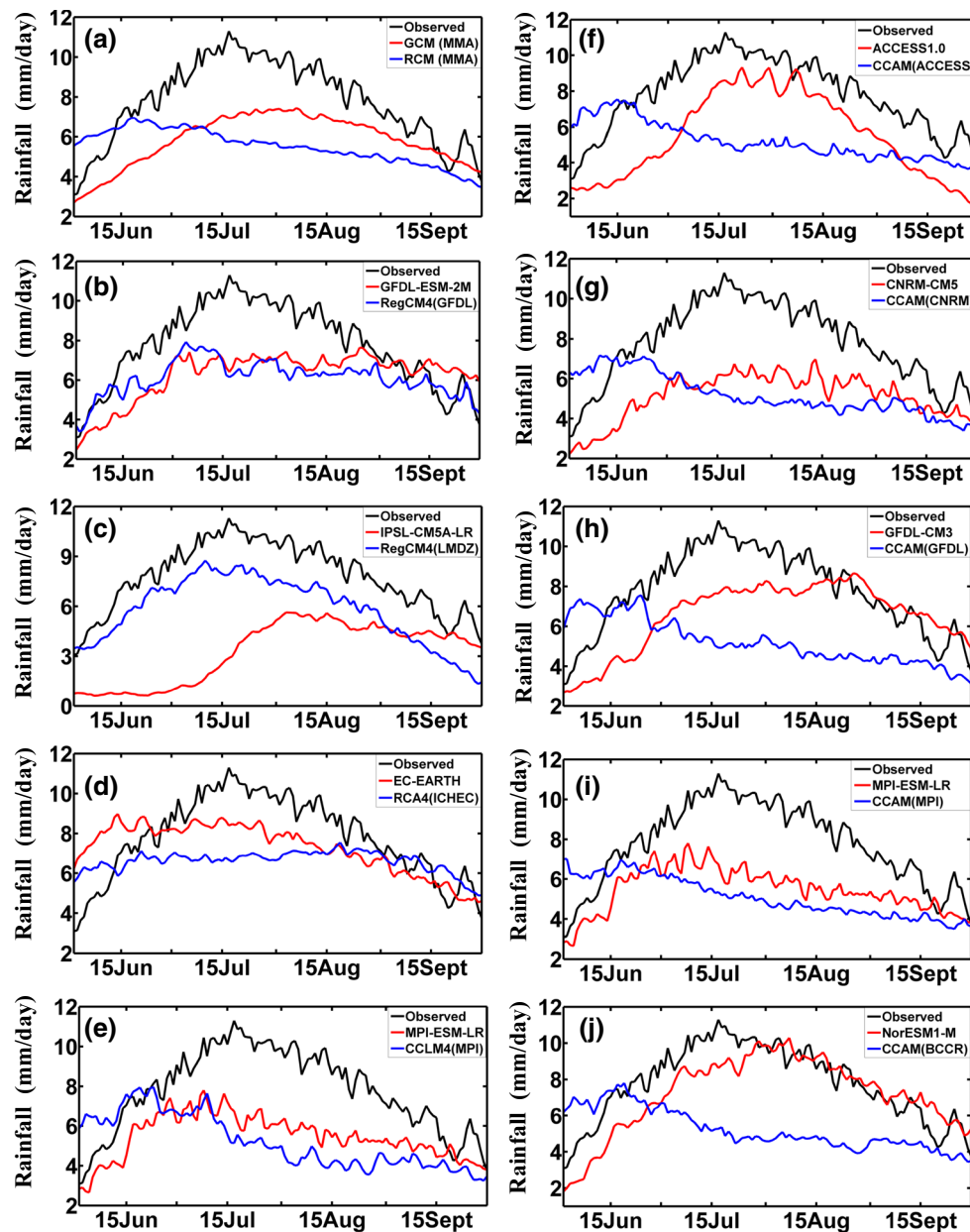
Fig. 5 Climatology of ISMR as simulated by CMIP5 GCMs and their corresponding CORDEX RCMs. No improvements are observed in RCM simulations with respect to their host GCMs (**b**–**j**) except RegCM4 (LMDZ) (**c**). This is also reflected in (**a**); where, multi-model average is plotted

Table 2 Mean onset dates

JRA-55	ERA-Interim	MERRA	EC-EARTH	RCA4 (ICHEC)	MPI-ESM-LR	CCLM4 (MPI)
151	151	150	145	152	149	136
30-May	30-May	29-May	24-May	31-May	28-May	15-May

red dots are outliers in the box plot. We use two CORDEX RCMs [i.e., ICHEC (RCA4): RCA4 and MPI (CCLM4): CCLM4] and their corresponding parent CMIP GCMs [EC-EARTH: ECE and MPI-ESM-LR: MPI] for computation of simulated onset. Here the RCMs are selected based on the data availability. We find that the simulation of onset is improved in RCA4 compared to its parent GCM EC-Earth; whereas, the same is worsened for CCLM4, as compared to
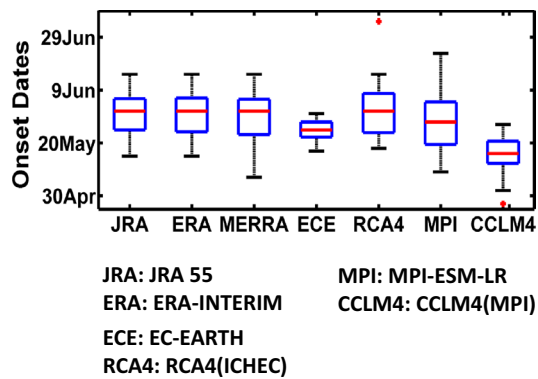
Fig. 6 Monsoon onset dates as computed from the three reanalysis data (JRA-55, ERA-Interim and MERRA) as well two CMIP5 GCMs and their corresponding RCMs. It is based on u wind at 850 hPa averaged over 5°–15°N, 40°–80°E, and known as Onset Circulation Index (OCI). Due to non-availability of outputs, the evaluation is only restricted to two models

the GCM MPI-ESM-LR. We avoid use of precipitation data in computation of onset specifically because they are often associated with 'bogus onset', which is due to pre-monsoon shower (Fasullo and Webster 2003; Sahana et al. 2015).

3.5 Intra-seasonal variability of monsoon rainfall

Intraseasonal variability of ISMR is characterized by the fluctuations in the monsoon strength with in a season, in terms excess or low rainfall spells with an average duration of 3–7 days. These spells are known as active or break spells (Rajeevan et al. 2010; Annamalai and Slingo 2001) and, are derived with the daily rainfall anomaly during the peak monsoon months (July and August) over core monsoon zone varying roughly from 18.0°N–28.0°N and 65.0°E–88.0°E (Rajeevan et al. 2010). The fluctuations in rainfall are associated with movement of the monsoon trough (Blanford 1886; Singh et al. 2014), which is the trough of low pressure runs down from Punjab to Gangetic Plains, and is associated with the cyclonic vortices that brings rains over India during Active phase. The trough moves to Himalaya foothills during break period and brings rainfall over Himalaya foot hills with break phase of monsoon over the rest of the part of the country (Blanford 1886). According to Singh et al. (2014), the active spells are associated with lower level cyclonic circulations (850 hPa), monsoon lows, depressions and cyclonic activities that bring abundant amount of rainfall; whereas break spells are associated with low level divergence. These fluctuations of rainfall of the ISMR have significant importance and policy implications as long and intense break may lead to drought whereas short spelled and intense active spells may lead to flood (Singh et al. 2014; Gadgil and Kumar 2006). These conditions of uneven spatial and temporal
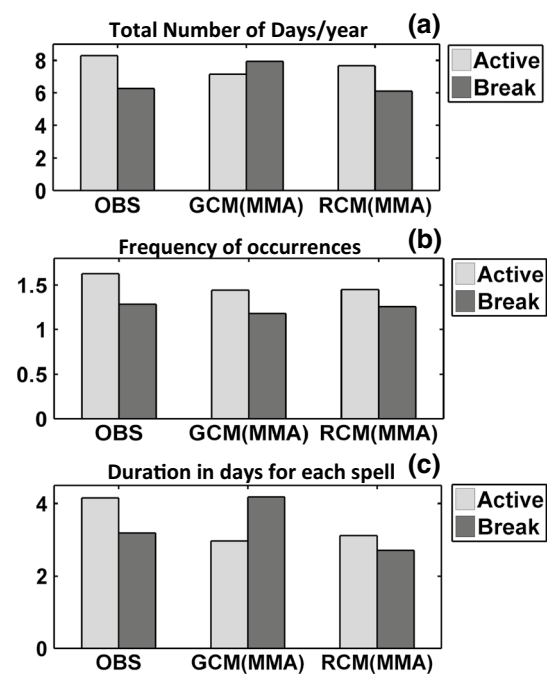
Fig. 7 Intra-seasonal oscillations of Indian Monsoon as computed from observed data with the evaluation of GCMs and corresponding RCMs. The total number of days in a season, the frequency of occurrences and the duration of active and break spells are presented in (**a**), (**b**) and (**c**) respectively. 9 GCMs are used and the duration of evaluation period is 1970–2005

pattern of rainfall may have adverse impact on agriculture activities (Annamalai and Slingo 2001).

Frequency (numbers/ year) and mean duration of active and break spells for the Indian summer monsoon are derived with observed data, the simulations by 9 CORDEX RCMs and their corresponding parent GCMs, as mentioned in Table 1. We use gridded data at 1° × 1° resolution, provided by IMD, as observed data over the core monsoon zone as described in Rajeevan et al. (2010) for the peak monsoon months July and August, during 1970–2004. We follow the following methodology to identify active and break spells.

1. The daily rainfall during July and August is spatially averaged over core monsoon zone.
2. Anomaly of spatially averaged rainfall is computed by subtracting the climatology daily mean from the core monsoon zone rainfall. The climatology is taken over the core monsoon zone during 1970–2005 for the months July and August (Rajeevan et al. 2010).
3. The standardized anomaly is obtained by dividing the anomaly with climatological daily standard deviation.
4. The break spells are identified as the periods during which the standardized rainfall anomalies are less than −1.0, consecutively for 3 days or more. Similarly

the active periods are identified as the periods during which the rainfall anomalies are more than +1.0, consecutively for 3 days or more (Rajeevan et al. 2010; Singh et al. 2014).

The characteristics of active and break spells, i.e. total number of days, duration and frequency of spells, as computed from observed data, GCM and RCM simulations are presented in Fig. 7. The number of active days is slightly higher than that of break days in observed data. MMA derived from GCMs show slightly higher number of break days, which gets rectified in regional model simulations (Fig. 7(a)). The frequency of occurrences of active and break spells are simulated well by both GCMs and RCMs (Fig. 7(b)). The observed data shows that the duration of active spell is slightly higher compared to break spells, which is not simulated by GCMs, but correctly simulated by RCMs (Fig. 7(c)); though the RCMs provide modest improvements only in simulating intra-seasonal variability.

3.6 Northward and eastward propagation of intra-seasonal oscillations

There are two types of tropical intraseasonal oscillations (ISO): boreal winter and boreal summer. Here, we focus on Boreal Summer Intra-Seasonal Oscillation (BSISO), which has two modes: eastward (10–20 days) and northward (30–60 days) propagations (Singh et al. 2014; Annamalai and Slingo 2001; Sabeerali et al. 2013). BSISO is associated with the fluctuation in the convective activities over the tropical convergent zone (TCZ) and circulation which leads to the intraseasonal variability (active and break spells) in the Indian monsoon rainfall (Annamalai and Slingo 2001; Goswami 2005; Singh et al. 2014). After the initiation of the Intra-Seasonal Oscillation (ISO), center of convection moves in northward and eastward directions from central equatorial ocean.

To derive the propagation characteristics of boreal summer intraseasonal oscillation we follow the methodology proposed by Sabeerali et al. (2013). We calculate the daily rainfall anomalies which is defined as the departure from the climatological annual cycle (sum of annual mean and first three harmonics) and then we apply a 20–100 day Lanczos bandpass filter to the daily anomalies during JJAS. The filtered precipitation anomaly are regressed at different time lags with respect to the reference time series, which is created by taking the average of the filtered precipitation anomalies over the core monsoon zone (12°N–22°N, 70°E–90°E) for the northward propagation and along the equatorial Indian ocean (10°S–5°N, 75°E–100°E) for the eastward propagation. The details of the methodology are available in Sabeerali et al. (2013). We present the characteristics plot of northward and eastward propagation as

derived with all the three reanalysis data (JRA-55, ERA-INTERIM and MERRA) for the period of 1979–2005. We find very good agreement between them, with greater than a 2-D correlation value of 0.95 between any of the two reanalysis for either propagation (Fig. 8).

We compute the same with the CMIP5 GCMs (Figs. 9, 10(a1)–(i1)) and their RCMs from CORDEX (Figs. 9, 10(a2)–(i2)). We find that, except CCAM forced with CNRM and CCLM4 forced with MPI-ESM-LR, all other regional models simulate eastward propagation poorer than their parent GCMs. For northward propagation, only CCLM4 forced with MPI-ESM-LR show some improvements, that too marginal. This poses a serious science question that is it really possible to have better regional simulation of monsoon, when the large scale monsoon circulation gets disturbed. This is probably reflected in almost all the characteristics of Indian monsoon, as discussed in this study.

3.7 Extremes

Extremes of Indian monsoon have been a key area of research interest among researchers considering the debates associated with intensification of extremes in warming environment (Goswami et al. 2006a, b), inconsistent trend and non-homogeneity of trends in extremes over large region (Ghosh et al. 2009), spatial non-uniformity and increasing spatial variability of trend (Ghosh et al. 2012) etc. High population in India results to higher vulnerability to extremes and hence projection of extremes is of immense importance. A recent study (Mishra et al. 2014) has indicated the poor performance of CORDEX RCMs, in simulating extremes which we examine further by comparing them with the projections of the parent GCMs. We use block maxima method, where each season (JJAS) is considered as a block. The seasonal maxima are fitted with Generalized Extreme Value distribution (GEV) for computing 50 years return levels (Coles 2001; Katz et al. 2005; Ghosh et al. 2012).

Suppose 'x' represents the annual maxima of daily precipitation in a given series, then the GEV distribution is defined by;

$$F(x; \mu, \alpha, \xi) = \begin{cases} \exp\left\{-\left[1 - \frac{\xi(x-\mu)}{\alpha}\right]^{-\frac{1}{\xi}}\right\} \\ 1 + \xi(x-\mu)/\alpha > 0 \quad \xi \neq 0 \\ \exp\left\{-\exp\left[-\frac{(x-\mu)}{\sigma}\right]\right\} \quad \xi = 0 \end{cases} \quad (1)$$

where μ is the location parameter, $\sigma > 0$ is scale parameter and ξ is shape parameter. Depending on the shape parameter, GEV has three special cases, pointedly, the Gumbel ($\xi = 0$), Frechet ($\xi > 0$) and Weibull ($\xi < 0$) distributions. Further, the p year return level [which represents the (1/p)
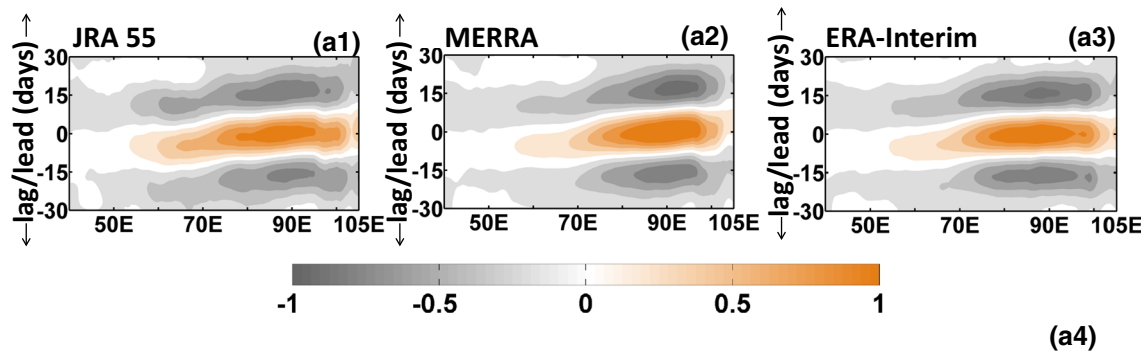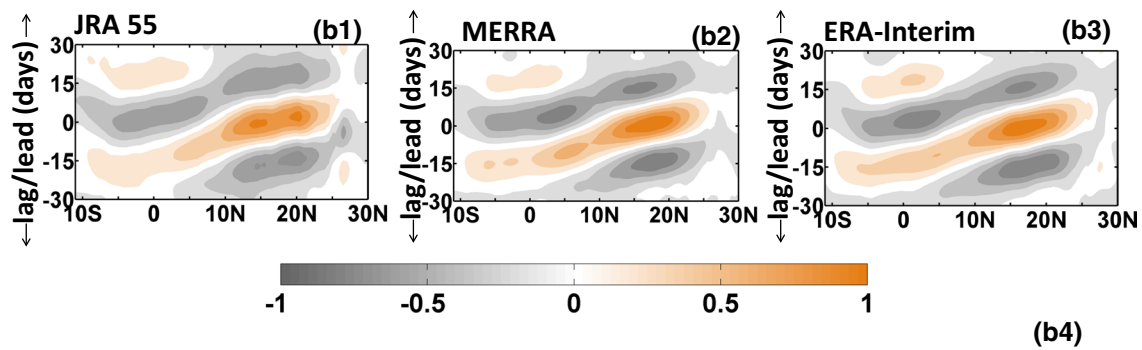
Fig. 8 Eastward (**a1**–**a3**) and northward propagations (**b1**–**b3**) of Boreal Summer Intra-seasonal Oscillations by reanalysis datasets JRA-55, MERRA and ERA-Interim. The eastward and northward propagations are illustrated by lag-longitude and lag-latitude diagrams respectively, for regressed 20–100 days band pass filtered precipitation anomalies averaged between 5°S–5°N (for eastward propagation) and 70°E–95°E (for northward propagation) for the period of 1979–2005 (Sabeerali et al. (2013)). The 20–100 day band pass filtered precipitation anomalies averaged over 10°S–5°N and 75°E–100°E are used as reference time series for regression. It is 12°N–22°N and 70°E–90°E for northward propagation. The reanalysis datasets have good agreement among themselves as evident from their cross-correlation ((**a4**) and (**b4**))

% probability of exceedance] is obtained by inverting the distribution function of the GEV (Eq. 1);

$$F^{-1}(1-p;\mu,\alpha,\xi) = \begin{cases} \mu - (\alpha/\xi)\left\{1 - \left[-\ln(1-p)\right]^{-\xi}\right\} & \xi \neq 0 \\ \mu - \alpha ln\left[-ln(1-p)\right] & \xi = 0 \end{cases} \quad (2)$$

The goodness of fit test is performed using Kolomogorov-Smirnov (KS) test at 5 % significance level. A nonparametric kernel distribution (Bowman and Azzalini 1997) is fitted, instead of GEV, to those grids, where the AM violates the KS test (Vittal et al. 2013).
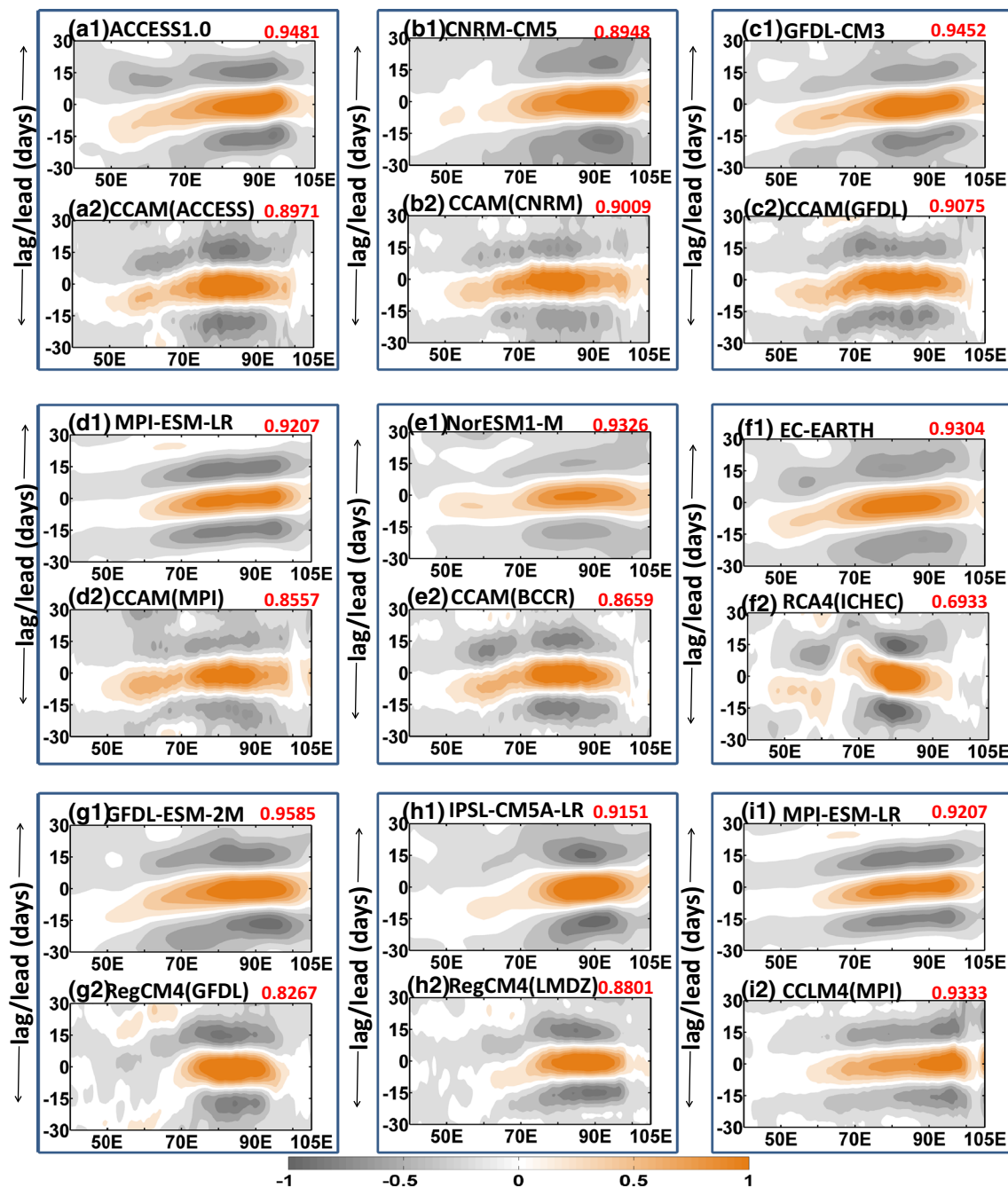
Fig. 9 Eastward propagations for CMIP5 GCMs (**a1**–**i1**) and their CORDEX RCMs (**a2**–**i2**). The time period considered is years 1970–2005. The 2-D correlation between the propagation plots obtained with each GCM/ RCM and JRA-55 are presented in their corresponding subplot

We present the 50 years RL obtained from observed data (Fig. 11(a)), GCM simulations (Fig. 11(b1)–(j1)) and RCM simulations (Fig. 11(b2)–(j2)) during 1971–2004. The observed data shows higher RL values for western coast and North-East India. All the CMIP5 models, considered here, fail to simulate the same. The RCM, CCAM, forced with ACCESS, CNRM-CM5, GFDL-CM3 and MPI-ESM-LR overestimate the extremes in the Northern India and the spatial variabilities get disturbed. RegCM4 is observed to simulate better the spatial variability of Indian monsoon extremes when forced with GFDL-ESM2 M. CCLM4, forced with MPI-ESM-LR also shows good improvement over its parent GCM. Overall, there is no consistency in RCM projections in terms of adding values to the simulations made by parent GCMs; though there are very few exceptions, which show marginal improvements.
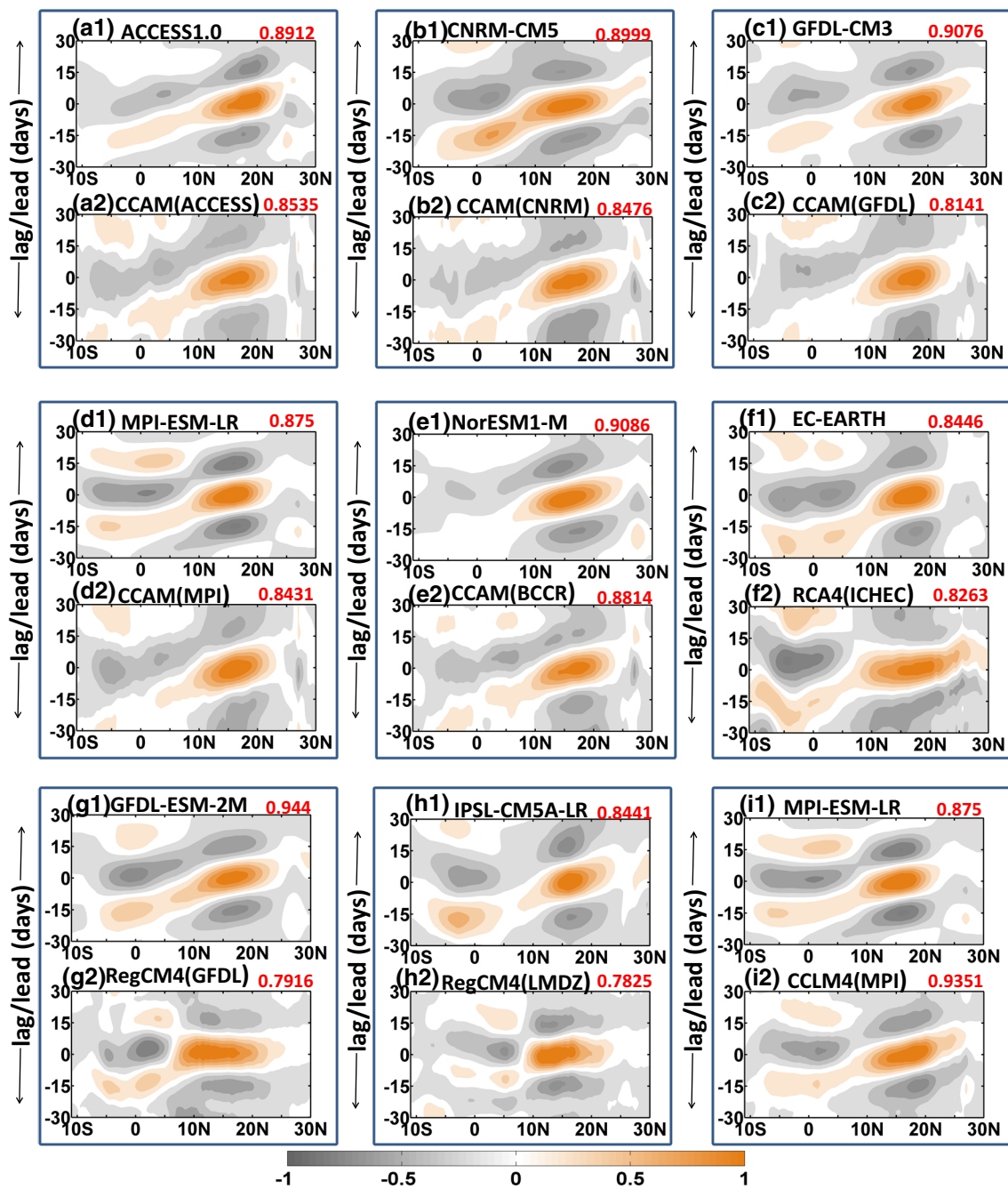
Fig. 10 Northward propagations for CMIP5 GCMs (**a1**–**i1**) and their CORDEX RCMs (**a2**–**i2**). The time period considered is years 1970–2005. The 2-D correlation between the propagation plots obtained with each GCM/ RCM and JRA-55 are presented in their corresponding subplot

3.8 Recent changes in monsoon characteristics

It is argued in recent literature (Racherla et al. 2012) that, simulating mean or climatology well by a climate model does not ensure its ability to project changes under perturbed condition or forcings; and hence it is important to understand its ability to simulate the changes. This hypothesis was proposed by Racherla et al. (2012) and has been further followed partially by Salvi et al. (2015) for

evaluating statistical downscaling in non-stationary environment. Here, we evaluate the CORDEX RCMs in simulating the changes during the recent period. We consider the period of 1951–2004 for our analysis and divide it into two equal halves; 1951–1977 and 1978–2004 to estimate the changes. We first compute the changes in the mean rainfall at 0.01 significance level (Fig. 12). The observed data show overall decrease in monsoon rainfall except few areas in the North-Eastern region. Here we restrict our analysis only to
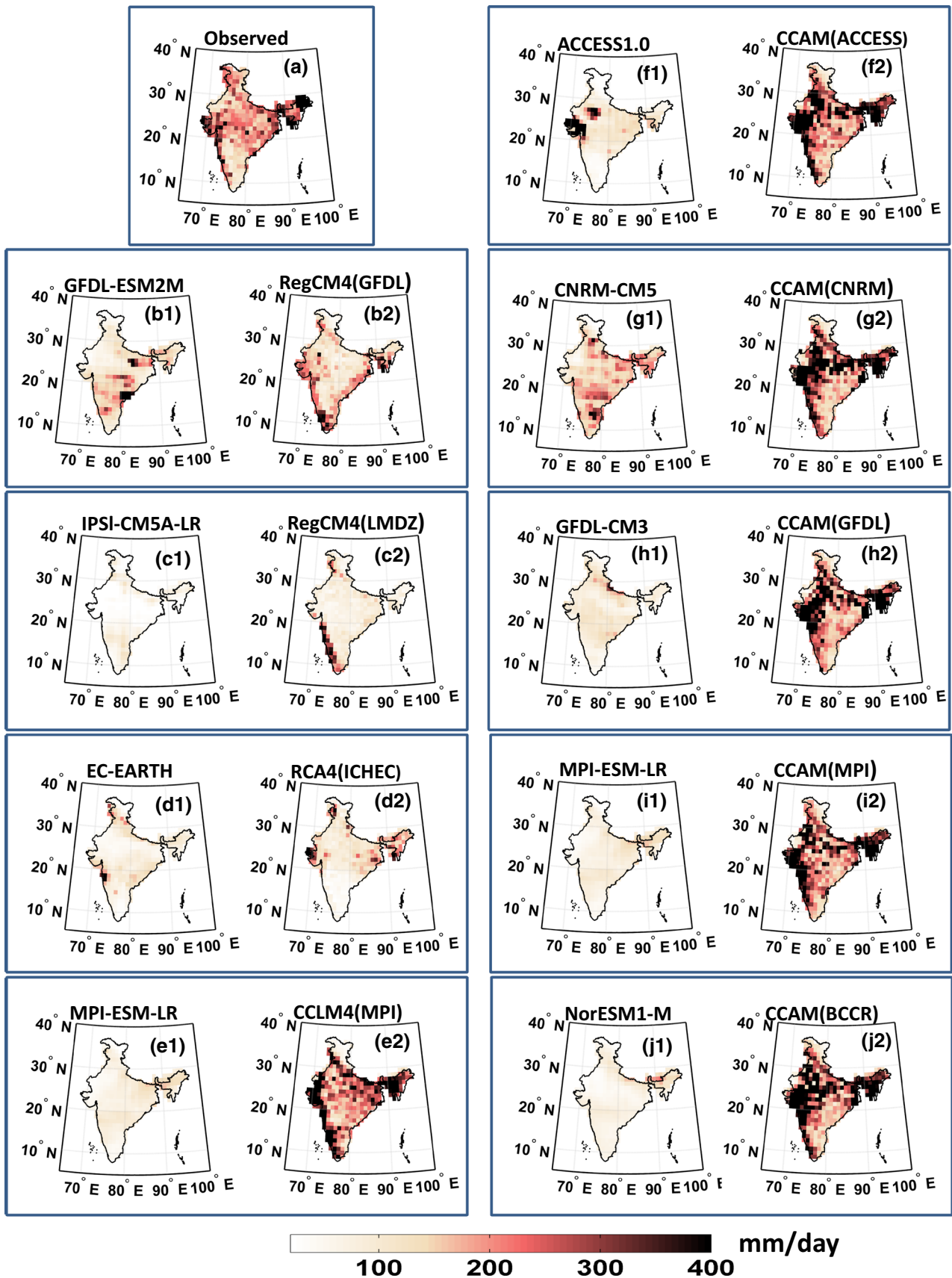
50 year RL (considered as extremes) of ISMR (mm/day) for the periods, 1971–2004, computed from observed data (**a**), 9 CMIP5 GCMs (**b1**–**j1**) and their CORDEX RCMs (**b2**–**j2**)

4 RCMs considering the availability of post 1950 data for both, the RCMs and their parent GCMs. The GCMs fail to simulate the weakening of monsoon in recent years and this has already been reported by Saha et al. (2014). RegCM4
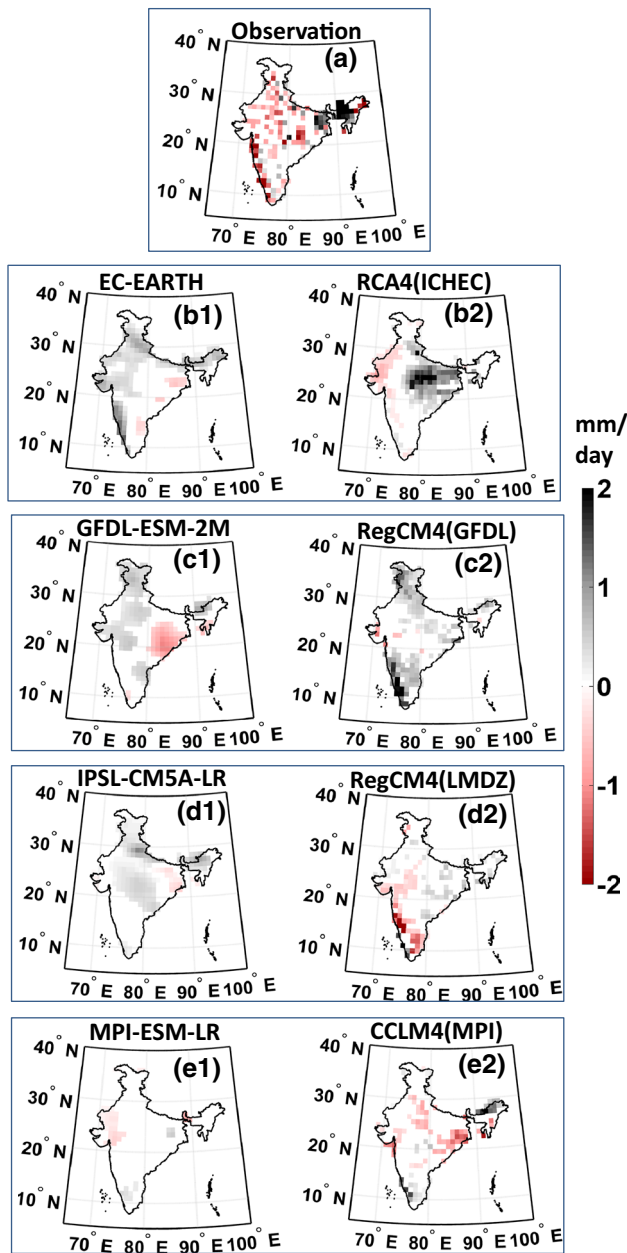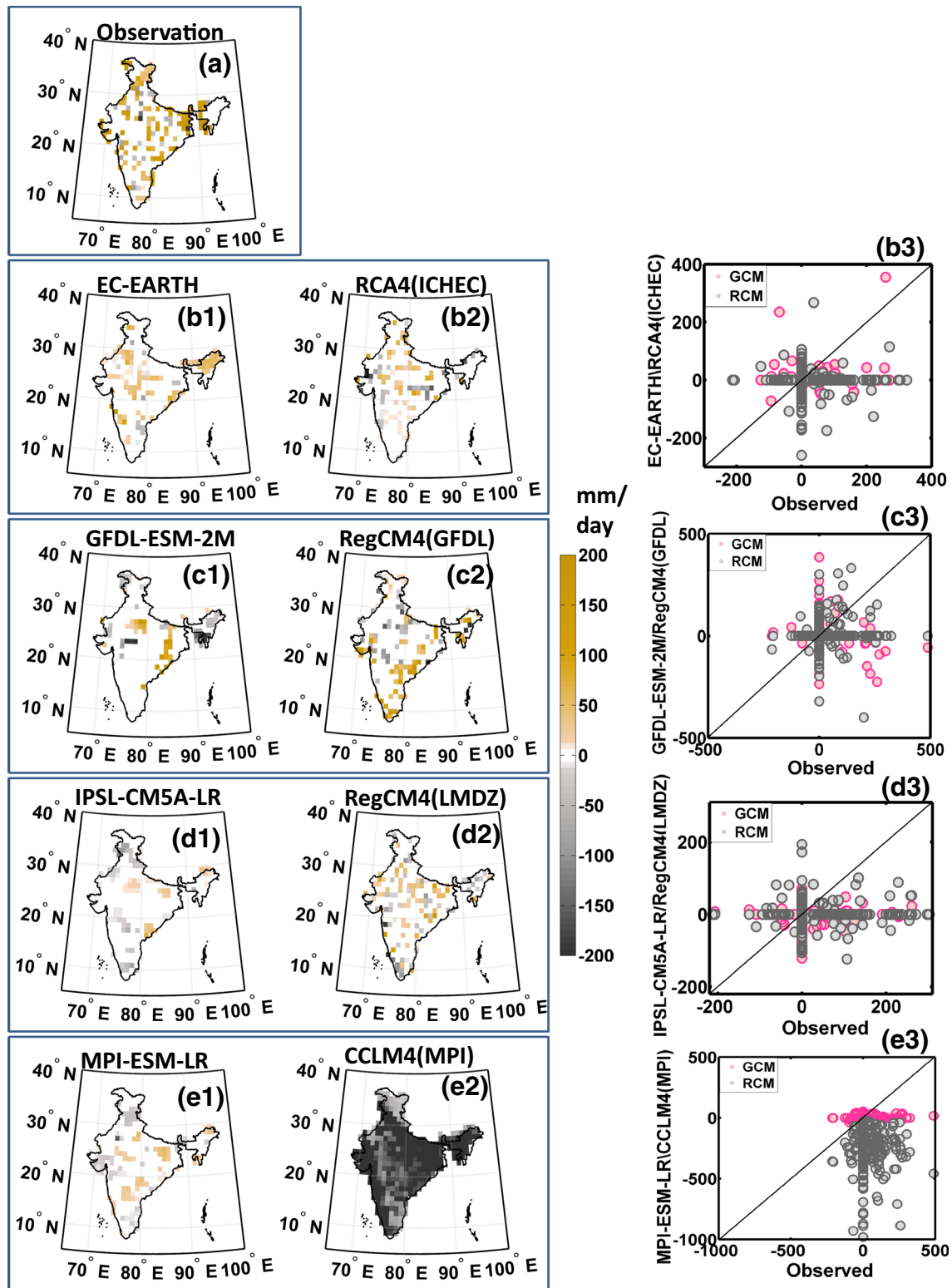

Fig. 12 Changes in mean ISMR (mm/day) from observed data (**a**), four CMIP5 GCMs (**b1**–**e1**) and their CORDEX RCMs (**b2**–**e2**). The changes are computed as the difference between the mean rainfall of the periods, 1951–1977 and 1978–2004 with 10 % statistical significance. Due to non-availability of longer period data, the evaluation is restricted to 4 models

(LMDZ) and CCLM4 (MPI) improve the simulations of changes at regional level in some areas although not in others. The other two RCMs fully fail to simulate the correct sign of changes in regional summer monsoon rainfall. The other important information coming out of this analysis is that the performances of regional models in simulating the changes in rainfall do not really depend on the same of their parent GCMs. Hence, ranking the GCMs based on their skill in simulating rainfall and then using the best for regional modeling may not be a recommended method, though this is widely practiced. Rather, the skill should be measured based on the simulation of geophysical processes resulting changes in monsoon, possibly following the methods suggested by Saha et al. (2014).
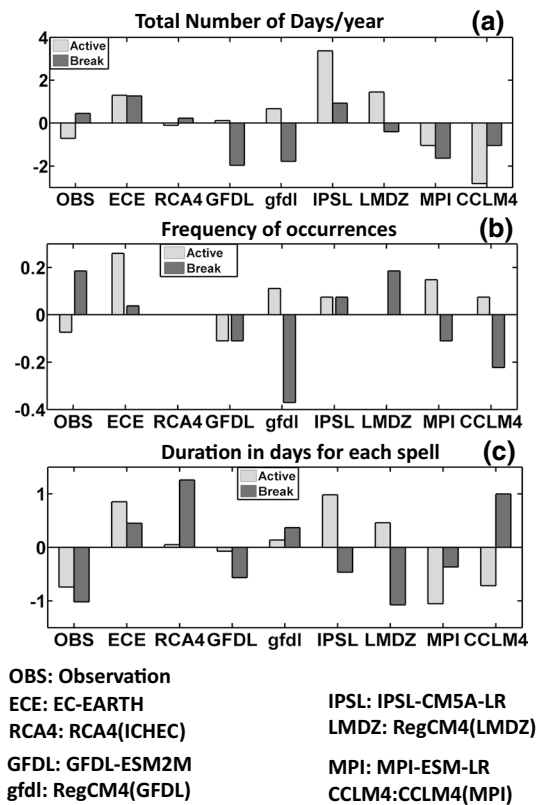
We also evaluate the RCMs based on their ability to simulate the changes in extremes in terms of their return levels. The statistically significant changes in the 50 year RL between two time periods are estimated with bootstrapping approach, following Kharin and Zwiers (2005), by sub-sampling (with repetition) the seasonal maxima intensity for 1000 times. These new samples are used to re-estimate the 50 year return levels. The changes in the 50 year return levels between two time periods are statistically significant, when their corresponding 60 % confidence intervals (20–80 percentile) do not overlap, which approximately corresponds to a 20 % statistical significance level. The changes, as computed from observations, show spatially non-uniform changes (Fig. 13(a)), which are also reported in Ghosh et al. (2012). The number of grid points that do not show any statistical significant changes in extremes is maximum followed by number of grids having increasing changes in extremes. There is no specific spatial pattern in the changes of extremes as computed from observed data. The GCM simulations also show spatially non-uniform changes, but with a specific pattern, which is the clustering of grid points having same sign of changes (Fig. 13(b1)–(e1)). The spatially non-uniform pattern of changes in extremes are getting improved in RCM simulations, as compared to their parent GCMs visually, except CCLM4 (MPI) (Fig. 13(b2)–(e2)). The CCLM4 model shows spatially uniform decreasing changes in extremes which is entirely different from that of observed and hence not reliable for extremes. The scatter plot of computed changes from simulations (both RCMs and GCMs) and observations at grid scale are presented in Fig. 13(b3)–(e3). The RCMs do not show the improvements at fine grid level with respect to parent GCMs, possibly because such a fine resolution of simulations of extremes is still a challenge in climate science.

We also compute the changes in total number of days, occurrences and duration of active and break spells from observed data and compare with the same derived from simulations (Fig. 14). The observed data shows decrease in

Fig. 13 Changes in 50 year RL (considered as extremes) of ISMR (mm/day) between the periods, 1951–1977 and 1978–2004, computed from observed data (**a**), four CMIP5 GCMs (**b1–e1**) and their CORDEX RCMs (**b2–e2**). Figures (**b3**)–(**e3**) show the scatter plot of the changes in extremes (mm/day) for individual GCM's (*pink*) and corresponding RCM's (*black*) with those of observed data. We use bootstrap approach, with 1000 time re-sampling with repetition, to estimate the significant changes in 50 year RL rainfall intensity between the two time periods at 20 % significance level

OBS: Observation
ECE: EC-EARTH
RCA4: RCA4(ICHEC)
GFDL: GFDL-ESM2M
gfdl: RegCM4(GFDL)

IPSL: IPSL-CM5A-LR
LMDZ: RegCM4(LMDZ)

MPI: MPI-ESM-LR
CCLM4:CCLM4(MPI)

Fig. 14 Mean changes in the characteristics (as mentioned in Fig. 8) of active and break days for observed data, four CMIP5 GCMs [i.e., EC-Earth: ECE, GFDL-ESM-2 M: GFDL, IPSL-CM5A-LR: IPSL and MPI-ESM-LR: MPI] and their corresponding CORDEX RCMs [i.e., ICHEC (RCA4): RCA4, RegCM4 (GFDL): gfdl, RegCM4 (LMDZ): LMDZ and CCLM4 (MPI): CCLM4]. The changes are computed between the time periods 1951–1977 and 1978–2004

active days and increase in break days (Fig. 14(a)). None of the GCMs and RCMs simulates the correct sign of this combination. The frequency of active period has reduced and break period have increased as derived from observed data (Fig. 14(b)). However, here also GCMs and RCMs fail to simulate the correct changes of combination. Observed data show the decrease in average duration of both active and break spells (Fig. 14(c)). GFDL and MPI GCMs show correct sign of the combination, but all RCMs fail to simulate the same. Hence, we conclude that the regional models do not add value in simulating the changes of intra-seasonal variability of Indian Summer Monsoon.

3.9 Dependence on GCM performance

Further we test the hypothesis that the improvements by an RCM in simulating monsoon precipitation depends on the performance of the parent GCM in simulating large scale circulation. We consider the bias in SST at Indian Ocean (IO), Pacific Ocean (PO), starting and end days of easterly

vertical shear as the large scale circulation indicators. The improvements by RCMs (negative sign shows degradation) with respect to their corresponding parent GCMs are scatter plotted (Fig. 15) with the biases of the same GCMs in simulating these large scale circulation patterns. We do not find any specific pattern or correlation emerging out of the scatter plots except for the SST over IO. The results show that improvements are more when the bias is also more, which is exactly opposite to the hypothesis. Depending on the results we reject the hypothesis that good improvements in precipitation by RCMs may not need low bias in large scale circulation by the parent GCMs. Similar patterns (Fig. 3(f2)–(j2)) of error by the same RCMs forced with different GCMs also indicate the same.

4 Summary and conclusion

In the present analysis, we tested the ability of the 9 CORDEX RCMs in capturing the Indian summer monsoon characteristics and compare them with their corresponding parent/ host CMIP5 GCMs. We do not find any consistent added value in the simulations of the characteristics of Indian monsoon by CORDEX RCMs in comparison to their corresponding parent CMIP5 GCMs. Though there are few region specific improvements in some of the characteristics by few CORDEX RCMs; they are inconsistent across different models and different characteristics. We further find that some of the synoptic scale circulation characteristics such as northward and eastward propagation of intraseasonal variations have actually deteriorated in regional model simulations when compared with the parent GCMs. This poses a serious concern on the reliability of regional models when the monsoon circulation gets disturbed in the simulations. This also points that the non-consistent marginal improvements in some of the characteristics for few RCMs are probably coincidental and may not really point to significant value addition to the simulations by parent GCMs. Critical evaluation of RCMs also involves testing the added value in terms of simulations of changes in climate variables. Earlier studies (Racherla et al. 2012). applied to different case studies show RCMs are good in simulating mean condition but fail to simulate changes. Here, we plot (Fig. 16) the bias in simulated mean rainfall by RCMs and the errors in simulated changes by the same model. We find no association between the two. As for example, COSMO-CLM has highest bias in simulated mean rainfall but lowest error in simulated changes. This further establishes the conclusions derived by Racherla et al. (2012). In the present study, for Indian monsoon, we get very limited added skill of RCMs in simulating changes. Inconsistency in the added value remains across RCMs and hence use these CORDEX simulations for impacts assessment and policy making
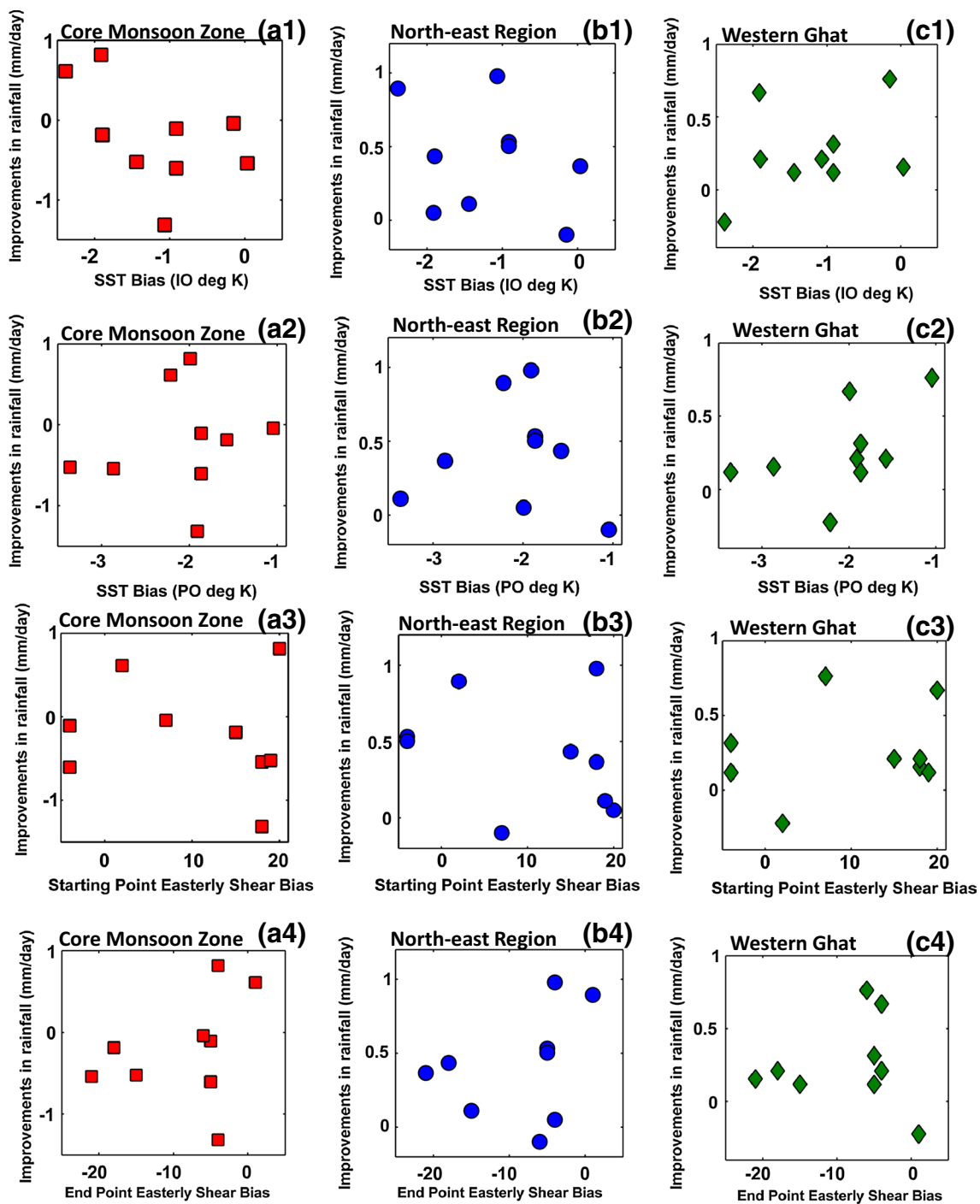
Fig. 15 Scatter plots of bias in SST (monthly JJAS) over Indian Ocean [IO] (**a1**, **b1** and **c1**), Pacific Ocean [PO] (**a2**, **b2** and **c2**), starting (**a3**, **b3** and **c3**) and end (**a4**, **b4** and **c4**) days of easterly vertical shear for CMIP5 GCMs (with respect to MERRA) with improve-ments in simulations of JJAS rainfall by RCMs with respect to host GCMs for core monsoon zone (**a1**, **a2**, **a3** and **a4**), North-east region (**b1**, **b2**, **b3** and **b4**) and Western Ghat (**c1**, **c2**, **c3** and **c4**). The period is 1979–2004

needs to be seriously scrutinized. The next step should be to understand the reason behind the failure of RCMs, in add-ing value to the simulations by parent GCMs; rather than adding few more regional simulations in the data archive. We speculate that the failure of RCMs probably attribute to either poor representation of ocean atmosphere interactions or poor selection of nested region. Indian monsoon is gov-erned by large scale circulation and thermodynamics guided by SST and wind circulations with transport of moisture from both the oceans and terrestrial sources (Pathak et al.
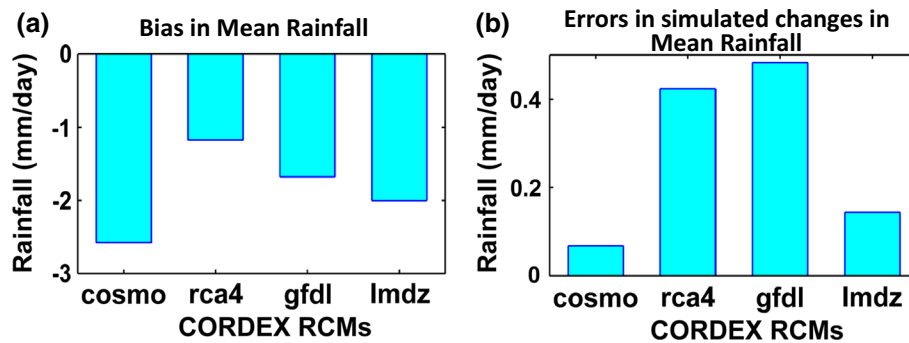
Fig. 16 Bias in simulated mean rainfall by CORDEX RCMs-cosmo: CCLM4 (MPI), rca4: RCA4 (ICHEC), gfdl: GFDL-ESM-2 M, lmdz: RegCM4 (LMDZ), when compared with observed data (**a**) for the period of 1970–2004. Errors in simulated changes in mean rainfall for the same RCMs, when compared with observed data (**b**). The changes are computed as the difference between the mean rainfall of the periods, 1951–1977 and 1978–2004. Due to non-availability of longer period data, the evaluation is restricted to 4 models

2014). As the south west monsoon is a product of land-atmosphere-sea interactions, reliable regional simulations should consider the land-atmosphere-sea coupled framework. The regional models used in CORDEX have land surface component; however, the atmosphere-ocean coupling is still missing, which probably is the reason behind the failure of RCMs in improving the precipitation field. It should be noted that major contribution of moisture for Indian monsoon comes from oceanic sources (~80 %) and hence the representation of atmosphere-sea coupling would probably be essential. The RCMs are mostly forced with GCM simulated SST. It would be interesting to first test if the regional coupled ocean atmospheric model improves the synoptic scale processes as opposed to the deterioration observed in the present CORDEX simulations, which are forced with SST rather than coupling. This needs multiple hypothesis driven regional model experimentation. Our study calls for reevaluation of regional models, understanding of regional processes, improving representation of regional processes in RCMs and adding value to the simulations of parent GCMs before blindly using them for impacts assessment and adaptation.

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