Chapter 16
Regional Climate Change Scenarios

J. Sanjay, M.V.S. Ramarao, M. Mujumdar and R. Krishnan

1 Introduction

The information about long-term (century-scale) climate change is needed to develop national or regional adaptation and mitigation policies. The reliable climate information will be useful and actionable only when they are available at the sub-continental to regional scales. The coarser spatial resolution and systematic error (called bias) of global climate models (GCMs) limits the examination of possible impacts of climate change and adaptation strategies on a smaller scale. The grid interval of atmosphere-ocean coupled GCMs (AOGCMs) used in the Coupled Model Intercomparison Project phase 5 (CMIP5; Taylor et al. 2012) ranges from 1.0° to 3.8°. The CMIP5 models indicate large bias in the monthly cycle of near surface air temperature and precipitation climate over the Indian region, particularly at elevations over the Himalayas (Flato et al. 2013). Recently, the stand-alone atmospheric GCMs run at higher resolution than AOGCMs have been made possible with high-performance computer systems to provide complementary regional-scale climate information. The advantages of a 20-km grid atmospheric GCM in simulating the Indian climate have been identified, especially the complex features of the Indian summer monsoon, including improved regional precipitation (Rajendran and Kitoh 2008; Krishnan et al. 2013). Another approach is the use of an atmospheric GCM with variable grid-point resolution zooming over the region of interest. The global simulation using telescopic zooming to a high resolution of more than 35 km over India was shown to provide improved representation of the organized convective activity over the South Asian monsoon region and in realistically capturing the regional details of the precipitation variability and their links to monsoon circulation (Sabin et al. 2013). However, as large computer resources are needed, the model integration period and number of ensemble members is

J. Sanjay (✉) · M.V.S. Ramarao · M. Mujumdar · R. Krishnan
Indian Institute of Tropical Meteorology, Earth System Science Organization, Pune, India
e-mail: sanjay@tropmet.res.in

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limited for such high-resolution atmospheric GCMs. Therefore, modellers rely on dynamical and/or statistical downscaling methods to make available higher-resolution, long-term climate data for impact and adaptation studies in specific regions.

The dynamical downscaling method using high resolution limited area regional climate models (RCMs) utilizes the outputs provided by AOGCMs as lateral boundary condition to provide physically consistent spatiotemporal variations of climatic parameters at spatial scales much smaller than the AOGCMs' grid. The RCMs by resolving the topographical details, coastlines, and land-surface heterogeneities allow the reproduction of small-scale processes and information that are most useful for impact assessment and in decision making for adaptation (Flato et al. 2013). Past research have studied the ability of individual RCMs to capture the general features of the Indian climate, particularly the summer monsoon climate (e.g. Krishnakumar et al. 2011; Dash et al. 2013 and the references therein). These studies showed that in general RCMs reproduce the precipitation seasonal mean and annual cycle quite accurately, although individual models can reveal significant biases in some sub-regions and seasons. In addition to the RCM-related bias, more errors and uncertainties in the downscaled climate can be inherited from the driving AOGCMs through the lateral boundary conditions. Parts of these uncertainties for the present climate can be addressed by generating a collection of simulations by driving the same RCM with different AOGCMs. The other sources of uncertainty in our understanding of the future climate change need to be addressed using the RCMs in a similar manner were addressed in CMIP5 using AOGCMs. Several different emission scenarios such as the Representation Concentration Pathways (RCPs) need to be used to force the RCMs so as to properly sample the uncertainty linked to future changes of the external forcing of the climate system. Similarly, by using several RCMs or a group of simulations with one RCM perturbed in its representation of the physics, parts of the uncertainties associated with how changes in external forcing factors control the climate need to be assessed. Finally, several simulations with each RCM driven with the same RCP scenario but with different initial conditions need to be generated to understand to what extent is the future climate change signal masked/amplified by natural variations of the climate system. The detailed evaluation of RCM-produced projections and a full classification of these underlying uncertainties are necessary for providing valuable information for assessing regional climate change vulnerability and impact application studies. The computer resources needed to generate such large ensembles of RCM outputs vary, depending on a number of factors (e.g. time step; horizontal and vertical resolutions; domain size; time period of simulation; and coupling system with additional models for ocean, land surface or terrestrial vegetation), but are quite demanding.

The World Climate Research Programme CORDEX (Coordinated Regional climate Downscaling Experiment; Giorgi et al. 2009; http://wcrp-cordex.ipsl.jussieu.fr/) initiative aims to foster international partnership in order to produce an ensemble of high-resolution past and future climate projections at regional scale, by downscaling several AOGCMs participating in the CMIP5. This ensemble can be used to demonstrate uncertainties on the regional scale or to obtain probabilistic climate change information in a region. The CORDEX South Asia component led by the Centre for Climate Change Research (CCCR) at the Indian Institute of Tropical Meteorology (IITM) aims to develop such multi-model ensemble of high-resolution (50-km) past and future climate projections over the South Asia region. The goal of this collaborative initiative is to generate robust national climate change information through dissemination of CORDEX South Asia datasets for regional climate change impact assessments and for developing adaptation strategies. The available RCM outputs under the CORDEX South Asia initiative are archived and published on the CCCR-IITM climate data portal (http://cccr.tropmet.res.in/cordex/files/downloads.jsp). Table 1 provides the basic references for these RCMs, their driving AOGCMs and the contributing partner modelling institutes. These datasets will shortly be accessible from the CCCR-IITM Earth System Grid Federation (ESGF) data node, which was the climate model data dissemination mechanism used for CMIP5. Some of these simulations have been analysed in terms of Indian precipitation extreme indices, its associated intermodal variability,

Table 1 List of CORDEX South Asia regional climate model (RCM) experiments

Experiment name	RCM description	Driving GCM	Contributing institute
LMDZ4 (IPSL)	Institut Pierre-Simon Laplace (IPSL) Laboratoire de Me´te´orologie Dynamique Zoomed version 4 (LMDZ4) atmospheric general circulation model (Sabin et al. 2013)	IPSL Coupled Model version 5 (IPSL-CM5-LR; Dufresne et al. 2013)	Centre for Climate Change Research (CCCR), Indian Institute of Tropical Meteorology (IITM), India
CCLM4 (MPI)	COnsortium for Small-scale MOdelling (COSMO) model in CLimate Mode version 4.8 (CCLM; Dobler and Ahrens 2008)	Max Planck Institute for Meteorology, Germany, Earth System Model (MPI-ESM-LR; Giorgetta et al. 2013)	Institute for Atmospheric and Environmental Sciences (IAES), Goethe University, Frankfurt am Main (GUF), Germany
RCA4 (ICHEC)	Rossby Centre regional atmospheric model version 4 (RCA4; Samuelsson et al. 2011)	Irish Centre for High-End Computing (ICHEC), European Consortium ESM (EC-EARTH; Hazeleger et al. 2012)	Rosssy Centre, Swedish Meteorological and Hydrological Institute (SMHI), Sweden
RegCM411 (GFDL) RegCM445 (GFDL)	The Abdus Salam International Centre for Theoretical Physics (ICTP) Regional Climatic Model version 4 (RegCM4; Giorgi et al. 2012)	Geophysical Fluid Dynamics Laboratory, USA, Earth System Model (GFDL-ESM2 M-LR; Dunne et al. 2012)	CCCR, IITM
REMO (MPI)	MPI Regional model 2009 (REMO2009; Teichmann et al. 2013)	MPI-ESM-LR (Giorgetta et al. 2013)	Climate Service Center, Hamburg, Germany

and up to 100-year return periods (Mishra et al. 2014). Here, we compare the outputs of the downscaled RCMs to those of the driving AOGCMs over the recent climate. It is important first to generally assess the ability of the CORDEX RCMs to simulate the general characteristics of the Indian climate (e.g. seasonal distribution of temperature and precipitation, and summer monsoon season climatology) and, second, to examine whether the downscaled simulations add value to those by the driving GCMs. Therefore, we focus not only on the main climate statistics, but we inspect also the ability of the RCMs to reproduce the temperature and precipitation seasonal cycle in sub-regions over India. Further, we analyse the changes in seasonal mean 2-m air temperature and precipitation to show the spread in average climate conditions by the middle of the century (2031–2060) for the Indian sub-continent.

2 Models and Experiments

2.1 CORDEX South Asia Models

The models used for CORDEX South Asia (listed in Table 1) describe the atmosphere and its coupling with the land surface. This ensemble includes four RCMs and a variable grid atmospheric GCM. The dynamics and physics set up for each model differ, but the regional domain at 50-km horizontal resolution is common to all RCMs as specified by the CORDEX experiment protocol (http://wcrp-cordex.ipsl.jussieu.fr/index.php/experiment-guidelines/cordex-experiment-protocol), covering West and South Asia region, and we present results within the interior model domain over the Indian sub-continent (e.g. Fig. 1). This ensemble consists of five 140-yr transient downscaled regional climate change simulations during the time period 1950–2100 and taking 6-hourly lateral and monthly ocean surface boundary conditions from four AOGCMs that participated in the CMIP5 RCP4.5 scenario experiments (listed in Table 1). It may be noted that two RCM experiments viz. CCLM4 (MPI) and REMO (MPI) were driven with the same MPI-ESM-LR AOGCM. Also RegCM411 RCM outputs are only available for the historical 1950–2005 period. The latest version of this RCM (RegCM445) includes an updated physics, in particular a more comprehensive representation of the land surface processes. The temporal evolution of the greenhouse gas concentrations is prescribed in the RCMs similar to that used by the CMIP5 AOGCMs, based on the observed values for the historical period and based on the RCP4.5 scenario for the future projection period. The remaining anthropogenic and natural forcings such as ozone and aerosols are kept constant. The regional land cover and land use changes are also not included in these downscaled climate simulations over South Asia.

The comparison of model results to the reference climate in the period 1976–2005 is presented to demonstrate how large biases the state-of-the-art RCMs shows when forced by lateral boundary conditions from AOGCMs. The quality of the simulations over India is assessed using the monthly mean 2-m air temperature and

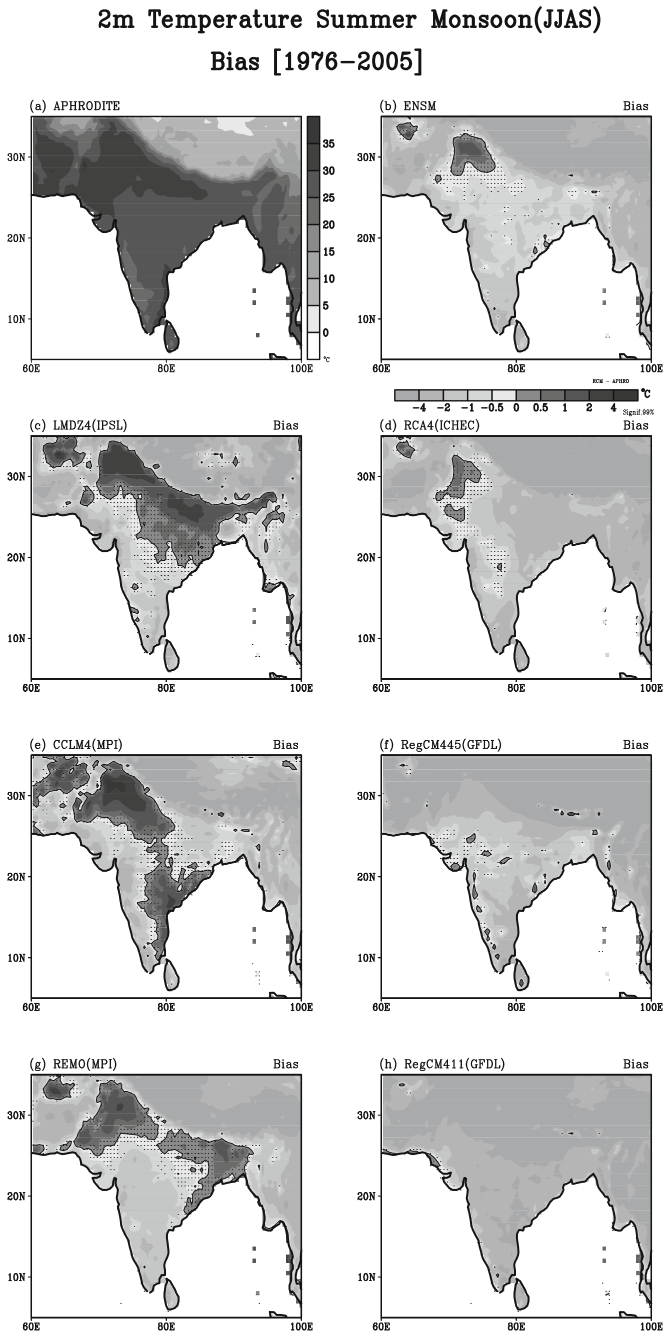

Fig. 1 **a** Summer monsoon (JJAS) season mean 2-m air temperature (°C; APHRODITE) for 1976–2005 and biases of 2-m air temperature (°C) in the CORDEX South Asia simulations driven by CMIP5 AOGCM historical experiments: **b** multi-model ensemble mean (ENSM) and **c**–**h** six different CORDEX RCMs listed in Table 1. Stippling denotes areas where the 30-year mean differences are not statistically significant at the 1 % level using Student's *t* test

the rain gauge-based global land precipitation dataset available at 0.5° spatial and monthly temporal resolution from the Asian Precipitation—Highly-Resolved Observational Data Integration Towards Evaluation of Water Resources (APHRODITE 1951–2005; Yatagai et al. 2012). This dataset is constructed to represent grid box average observations, allowing direct comparison to model results. The monthly model outputs from the CORDEX RCMs and the driving CMIP5 AOGCMs are bi-linearly interpolated to the APHRODITE spatial resolution. The seasonal averages for the Indian summer monsoon (June–September; JJAS) and post-monsoon (October–December; OND) months are computed. The annual averages (ANN) are also calculated. These seasonal and annual averages are computed for each year in 30-year periods both for the baseline period (1976–2005) and for a future time period (2031–2060). The Student's t test at the 1 % significance level is used to determine the robustness for the climate change signal in the future period and for differences between the simulated and reference climate in the baseline period.

3 Results and Discussion

3.1 Simulated Baseline Climate (1976–2005)

The simulated 2-m air temperature climate over India is in relatively good agreement with the reference climate. The summer monsoon seasonal mean differences are generally smaller than 1 °C (Fig. 1), although statistically significant differences above 2°C exist in parts of north India and the adjoining Himalayan mountain region. The six-member ensemble mean (Fig. 1b) is closer to observed temperature over the central India than the individual simulations for the summer monsoon season (Fig. 1c–f). This is due to the cancellation of the biases of opposite signs in the models when added over this region. It may be noted that the two RCMs viz. CCLM4(MPI) and REMO (MPI) driven with the same CMIP5 AOGCM show different temperature bias patterns, particularly over the western parts of India. The REMO (MPI) was reported to have a larger annual mean cold bias over the entire west Asia when compared with the driving CMIP5 MPI-ESM-LR (Teichmann et al. 2013). It is also found from the comparison of the spatial pattern of temperature in two versions of the RegCM4 driven with the GFDL-ESM2 M that the latest version of this RCM (RegCM445; Fig. 1f) has to some extent reduced the larger cold bias in the earlier version of the same model (RegCM411; Fig. 1h). Compared to the APHRODITE dataset, precipitation in CORDEX South Asia RCMs six-member ensemble mean is slightly underestimated during summer in the central and Indo-Gangetic plains over India, while significant overestimation is found over parts of south peninsula (Fig. 2b). However, the ensemble mean is closer to reference precipitation than most individual simulations for the summer monsoon season (Fig. 2c–f). This is because the biases of opposite signs in the models over parts of

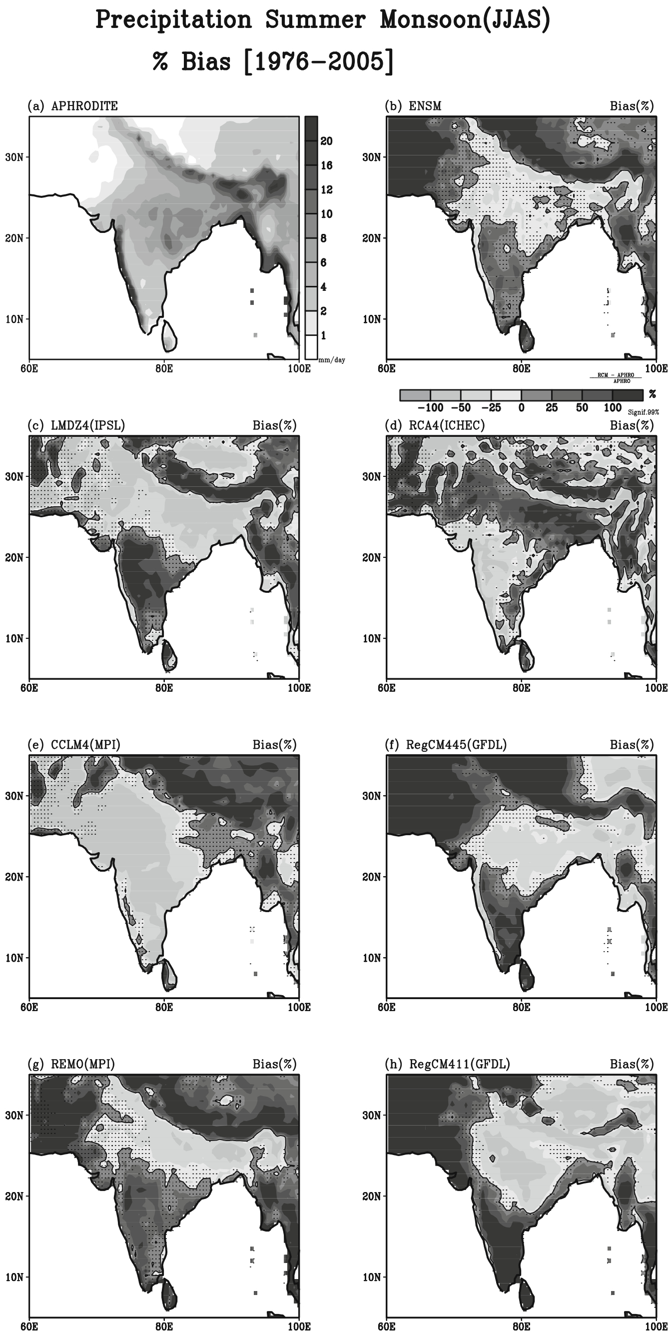

Fig. 2 **a** Summer monsoon (JJAS) season mean precipitation (mm day^{-1}; APHRODITE) for 1976–2005 and biases of precipitation (%) in the CORDEX South Asia simulations driven by CMIP5 AOGCM historical experiments: **b** multi-model ensemble mean (ENSM) and **c**–**h** six different CORDEX RCMs listed in Table 1. Stippling denotes areas where the 30-year mean differences are not statistically significant at the 1 % level using Student's *t* test

south India tend to cancel each other when added, cf. LMDZ4 (IPSL) and RCA4 (ICHEC) in Fig. 2. The summer monsoon season wet bias seen in REMO (MPI) over the central and southern parts of India (Fig. 2g) was also found for the simulated annual mean precipitation with this RCM, while the driving MPI-ESM-LR had a dry bias over this region (Teichmann et al. 2013). The relatively lesser wet biases over south India in the latest version of RegCM4 (Fig. 2f) compared to the earlier version of this model (Fig. 2h) have also to some extent contributed to the improved spatial pattern of precipitation in the six-member ensemble mean.

Table 2 summarizes the climatological skill of 2-m temperature in the CORDEX historical experiments and the corresponding driving CMIP5 AOGCMs in simulating summer monsoon (JJAS), post-monsoon (OND) seasonal and annual means for the 30-year period 1976–2005 over the South Asia land areas (60–100°E, 5–35° N). In general, it is found that the RCMs and their driving AOGCMs tend to underestimate the spatial mean and overestimate the standard deviation over this large domain. The pattern correlation with APHRODITE is found to be relatively improved for all the RCMs in comparison with their driving AOGCMs in both seasons and annually. The spatial variability simulated by individual models relative to APHRODITE is assessed using a Taylor diagram (Taylor 2001; Fig. 3a). It is seen that the individual RCMs and their driving AOGCMs consistently yield higher Taylor skill in simulating the annual mean 2-m temperature distribution over land areas in South Asia. These models tend to overestimate the spatial mean precipitation for both seasons and annually in this 30-year period over this region (Table 3). The RCMs consistently show higher magnitude of spatial standard

Table 2 Performance of 2-m temperature (°C) climatology (1976–2005) averaged over land grid points in South Asia (60–100°E, 5–35°N)

Experiment name	Spatial mean			Standard deviation			Pattern correlation		
	JJAS	OND	Annual	JJAS	OND	Annual	JJAS	OND	Annual
APHRODITE	23.4	14.8	18.4	8.7	11.8	10.9	–	–	–
LMDZ4 (IPSL)	22.0 (22.0)	12.1 (11.0)	16.1 (15.2)	10.3 (10.8)	13.2 (13.9)	12.5 (13.1)	**0.98** (0.96)	**0.99** (0.98)	**0.99** (0.98)
RCA4 (ICHEC)	20.1 (18.8)	9.2 (10.7)	13.7 (14.3)	10.8 (9.1)	14.2 (12.4)	13.3 (11.6)	**0.99** (0.97)	**0.99** (0.98)	**0.99** (0.98)
CCLM4 (MPI)	21.9 (22.5)	12.8 (11.4)	16.6 (16.6)	10.3 (10.0)	13.7 (11.8)	13.0 (11.6)	**0.98** (0.94)	**0.99** (0.97)	**0.99** (0.96)
RegCM445 (GFDL)	19.0 (23.2)	9.8 (13.4)	13.1 (17.5)	11.2 (10.6)	13.4 (12.6)	12.9 (12.2)	**0.97** (0.96)	**0.98** (0.97)	**0.98** (0.97)
REMO (MPI)	21.5 (22.5)	10.2 (11.4)	15.1 (16.6)	10.4 (10.0)	13.2 (11.8)	12.6 (11.6)	**0.99** (0.94)	**0.99** (0.97)	**0.99** (0.96)
RegCM411 (GFDL)	18.5 (23.2)	8.2 (13.4)	12.0 (17.5)	10.2 (10.6)	13.1 (12.6)	12.5 (12.2)	**0.97** (0.96)	**0.99** (0.97)	**0.98** (0.97)

The spatial skill for the six different CORDEX RCMs listed in Table 1 are compared with (in parenthesis) the corresponding CMIP5 AOGCM historical experiment used to drive the RCMs. The bold text shows the improved performance of the RCM relative to its driving AOGCM

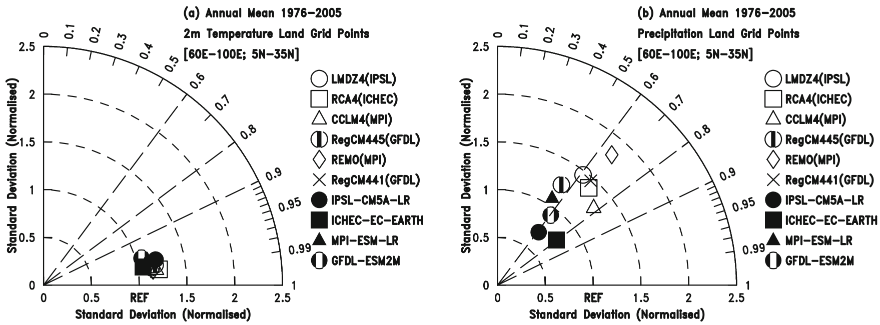

Fig. 3 Taylor diagram for the annual mean **a** 2-m air temperature (°C) and **b** precipitation (mm day^{-1}) climatology (1976–2005) averaged over land grid points in South Asia (60–100°E, 5–35°N). The radial coordinate shows the standard deviation of the spatial pattern, normalized by the observed standard deviation. The azimuthal variable shows the correlation of the modelled spatial pattern with the observed spatial pattern. The distance between the reference (REF) dataset (APHRODITE) and individual points corresponds to root-mean-square error (RMSE). The diagram shows the skill for the six different CORDEX RCMs listed in Table 1 and for the four CMIP5 model historical experiments used to drive the CORDEX South Asia RCMs

Table 3 Performance of precipitation (mm d^{-1}) climatology (1976–2005) averaged over land grid points in South Asia (60–100°E, 5–35°N)

Experiment name	Spatial mean			Standard deviation			Pattern correlation		
	JJAS	OND	Annual	JJAS	OND	Annual	JJAS	OND	Annual
APHRODITE	4.7	1.0	2.2	4.2	1.3	1.8	–	–	–
LMDZ4 (IPSL)	5.2 (3.1)	1.6 (1.4)	2.7 (1.7)	5.6 (2.8)	1.9 (1.2)	2.7 (1.3)	0.61 (0.62)	**0.78** (0.71)	**0.61** (0.61)
RCA4 (ICHEC)	5.2 (5.7)	1.5 (1.4)	2.7 (2.8)	5.4 (3.0)	1.8 (1.4)	2.6 (1.4)	0.66 (0.76)	0.81 (0.91)	0.68 (0.79)
CCLM4 (MPI)	4.7 (5.5)	1.4 (1.6)	2.5 (2.6)	4.8 (3.7)	1.3 (1.4)	2.4 (1.7)	**0.80** (0.63)	0.72 (0.73)	**0.78** (0.60)
RegCM445 (GFDL)	5.2 (5.0)	1.8 (1.2)	3.2 (2.4)	3.1 (4.2)	2.0 (1.1)	2.3 (2.0)	0.54 (0.56)	0.07 (0.70)	**0.54** (0.53)
REMO (MPI)	6.0 (5.5)	2.0 (1.6)	3.2 (2.6)	6.5 (3.7)	2.7 (1.4)	3.3 (1.7)	**0.65** (0.63)	**0.74** (0.73)	**0.66** (0.60)
RegCM411 (GFDL)	5.1 (5.0)	1.8 (1.2)	3.0 (2.4)	6.0 (4.2)	1.8 (1.1)	2.7 (2.0)	0.46 (0.56)	0.69 (0.70)	**0.67** (0.53)

The spatial skill for the six different CORDEX RCMs listed in Table 1 are compared with (in parenthesis) the corresponding CMIP5 AOGCM historical experiment used to drive the RCMs. The bold text shows the improved performance of the RCM relative to its driving AOGCM deviation for precipitation than APHRODITE observations suggesting that the high-resolution downscaling has overestimated the spatial variability of precipitation over this region. The simulated spatial patterns relative to APHRODITE (Table 3) vary among the RCMs and are found to be better than the driving AOGCMs in both seasons only for few individual RCMs viz. LMDZ4 (IPSL), CCLM4 (MPI) and REMO (MPI). The Taylor diagram for the annual mean precipitation distribution over land areas in South Asia (Fig. 3b) shows the large spread in the Taylor skill between the individual RCMs and their driving AOGCMs.

Figure 4 presents the monthly 2-m air temperature (left panels) and the precipitation (right panels) annual cycle for the period 1976–2005 simulated in the individual RCMs and their driving AOGCMs for the central, south-west and

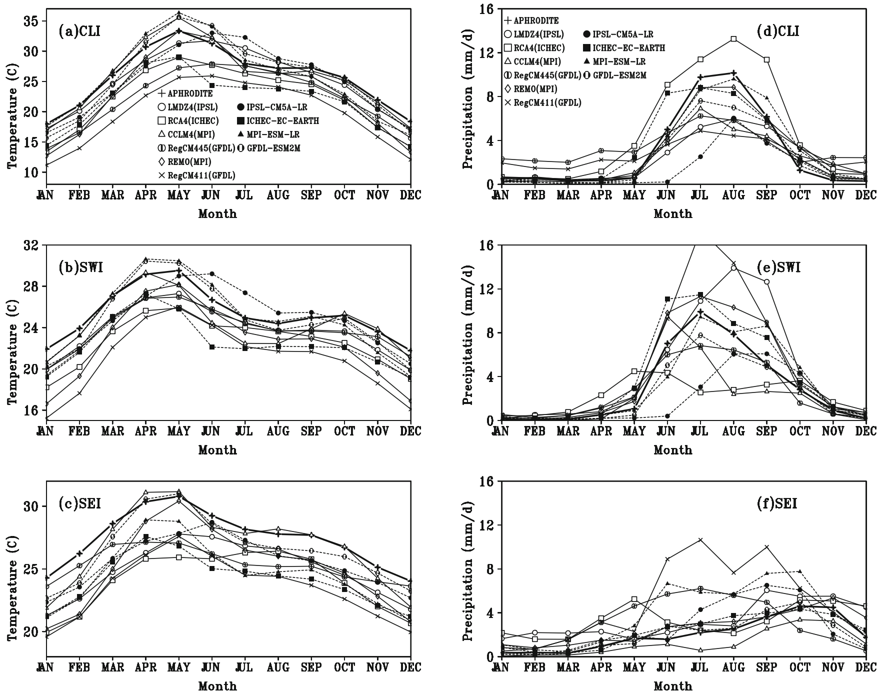

Fig. 4 Mean seasonal cycle for the period 1976–2005 of (*left panels*) 2-m air temperature (°C) and (*right panels*) precipitation rate (mm day^{-1}) for the six different CORDEX RCMs (*thin lines*) listed in Table 1 and for the four CMIP5 models (*dashed lines*) used to drive the RCMs used in the CORDEX South Asia historical experiments. The observed values based on APHRODITE (*thick line*) are used as reference. The analysis used the land grid points in the sub-regions **a**, **d** Central India (CLI; 20–25°N, 78–82°E), **b**, **e** South-West India (SWI; 20–25°N, 78–82°E), and **c**, **f** South-East India (SEI; 20–25°N, 78–82°E)

south-east sub-regions over India. All the models simulate the phase of the seasonality in temperature well than the amplitude relative to APHRODITE observations in the three sub-regions. The individual model skill in simulating the seasonal cycle of temperature is summarized for the three sub-regions in Table 4. The root-mean-square error (RMSE) normalized with the APHRODITE annual range in temperature reveals that three RCMs viz. LMDZ4(IPSL), RCA4(ICHEC) and CCLM4(MPI) are able to outperform their driving AOGCMs in simulating the amplitude of seasonality in temperature over central India. The correlation coefficient between the model simulated and APHRODITE annual cycle of temperature further confirms that these RCMs improve not only the amplitude but also the phase of the temperature seasonality compared to their driving AOGCMs over central India. However, the RCMs are in general not able to improve the amplitude or the phase of the annual cycle of temperature over the hilly regions in south-west India and the drier regions in south-east India. Despite large inter-model variations found in the simulated precipitation seasonality, some RCMs appear to agree relatively closer with APHRODITE than their driving AOGCMs at least in capturing the phase of the seasonality over the three sub-regions (Fig. 4; right panels). However, the individual model skill summarized in Table 5 shows that only LMDZ4 (IPSL) is able to show an added value compared to its driving AOGCM in simulating the amplitude and phase of the seasonality in precipitation for all three sub-regions over India.

Table 4 Performance of 2-m temperature (°C) monthly annual cycle climatology (1976–2005) averaged over land grid points in three sub-regions: Central India (CLI; 20–25°N, 78–82°E), South-West India (SWI; 20–25°N, 78–82°E) and, (c) South-East India (SEI; 20–25°N, 78–82°E)

Experiment name	Normalized RMSE			Correlation coefficient		
	CLI	SWI	SEI	CLI	SWI	SEI
LMDZ4 (IPSL)	**0.11** (0.16)	0.22 (0.21)	0.39 (0.31)	**0.97** (0.93)	**0.97** (0.83)	0.91 (0.92)
RCA4 (ICHEC)	**0.23** (0.25)	**0.36** (0.37)	0.53 (0.49)	**0.99** (0.98)	0.91 (0.95)	0.86 (0.98)
CCLM4 (MPI)	**0.08** (0.13)	0.18 (0.16)	**0.17** (0.44)	**0.99** (0.97)	0.93 (0.98)	**0.98** (0.98)
RegCM445 (GFDL)	0.26 (0.11)	0.22 (0.15)	0.35 (0.14)	0.92 (0.99)	0.95 (0.99)	0.94 (0.97)
REMO (MPI)	0.21 (0.13)	0.41 (0.16)	0.38 (0.44)	**0.99** (0.97)	0.96 (0.98)	0.96 (0.98)
RegCM411 (GFDL)	0.40 (0.11)	0.58 (0.15)	0.58 (0.14)	0.95 (0.99)	0.93 (0.99)	**0.98** (0.97)

The root-mean-square error (RMSE) normalized with the APHRODITE annual range and the correlation coefficient between the simulated and APHRODITE annual cycle for the six different CORDEX RCMs listed in Table 1 are compared with (in parenthesis) the corresponding CMIP5 model historical experiment used to drive the RCMs. The bold text shows the improved performance of the RCM relative to its driving AOGCM

Table 5 Performance of precipitation (mm day^{-1}) monthly annual cycle climatology (1976–2005) averaged over land grid points in three sub-regions: Central India (CLI; 20–25°N, 78–82°E), South-West India (SWI; 20–25°N, 78–82°E) and, (c) South-East India (SEI; 20–25°N, 78–82°E)

Experiment name	Normalized RMSE			Correlation coefficient		
	CLI	SWI	SEI	CLI	SWI	SEI
LMDZ4 (IPSL)	**0.81** (1.09)	**0.66** (0.99)	0.72 (0.71)	**0.93** (0.82)	**0.90** (0.63)	**0.86** (0.74)
RCA4 (ICHEC)	0.65 (0.37)	1.23 (0.37)	0.99 (0.29)	**0.96** (0.94)	0.53 (0.98)	0.63 (0.93)
CCLM4 (MPI)	0.66 (0.30)	0.71 (0.29)	**0.51** (1.10)	0.96 (0.97)	0.82 (0.91)	**0.96** (0.76)
RegCM445 (GFDL)	0.84 (0.44)	0.54 (0.35)	1.22 (0.22)	0.95 (0.99)	0.96 (0.99)	0.25 (0.90)
REMO (MPI)	0.35 (0.30)	0.33 (0.29)	**0.45** (1.10)	**0.98** (0.97)	**0.98** (0.91)	**0.92** (0.76)
RegCM411 (GFDL)	0.97 (0.44)	1.21 (0.35)	1.88 (0.22)	0.96 (0.99)	0.98 (0.99)	0.54 (0.90)

The root-mean-square error (RMSE) normalized with the APHRODITE annual mean value and the correlation coefficient between the simulated and APHRODITE annual cycle for the six different CORDEX RCMs listed in Table 1 are compared with (in parenthesis) the corresponding CMIP5 model historical experiment used to drive the RCMs. The bold text shows the improved performance of the RCM relative to its driving AOGCM

3.2 Simulated Climate Change (2031–2060)

The simulated summer monsoon 2-m air temperature patterns are changing between 1976–2005 and 2031–2060 for the RCP4.5 scenario (Fig. 5). The ensemble mean of five-members indicate large increase of above 1.5 °C over the central and northern parts of India (Fig. 5a). The individual model simulations show very different response over India (Fig. 5b-f), with LMDZ4 (IPSL) indicating a warming that is above 2.0 °C higher than in RegCM445(GFDL) by middle of the twenty-first century for most parts of the country. The ensemble mean summer monsoon precipitation change for the same period indicates less than 25 % drying in the central and eastern parts of India and moistening of similar magnitude over the rest of India (Fig. 6a). However, for most parts of India, this ensemble mean change is not found to be statistically significant. Also some of the individual models indicate precipitation changes of similar magnitude with opposite sign in these regions (Fig. 6b–f). Further, these precipitation changes are also not statistically significant, implying that the CORDEX RCMs simulated change in summer monsoon precipitation over India are uncertain not only in magnitude but also in sign.

The analysis of the CORDEX multi-RCM temperature and precipitation projections for South Asia land areas for the period 1950–2100 (Fig. 7) shows that for RCP4.5 scenario the annual mean warming is likely to be in the range 1.0–2.0 °C by 2030, 1.8–3.0 °C by 2060 and 2.0–3.1 °C by 2090 relative to the 1976–2005 period (Fig. 7b). The summer monsoon precipitation projections for this region

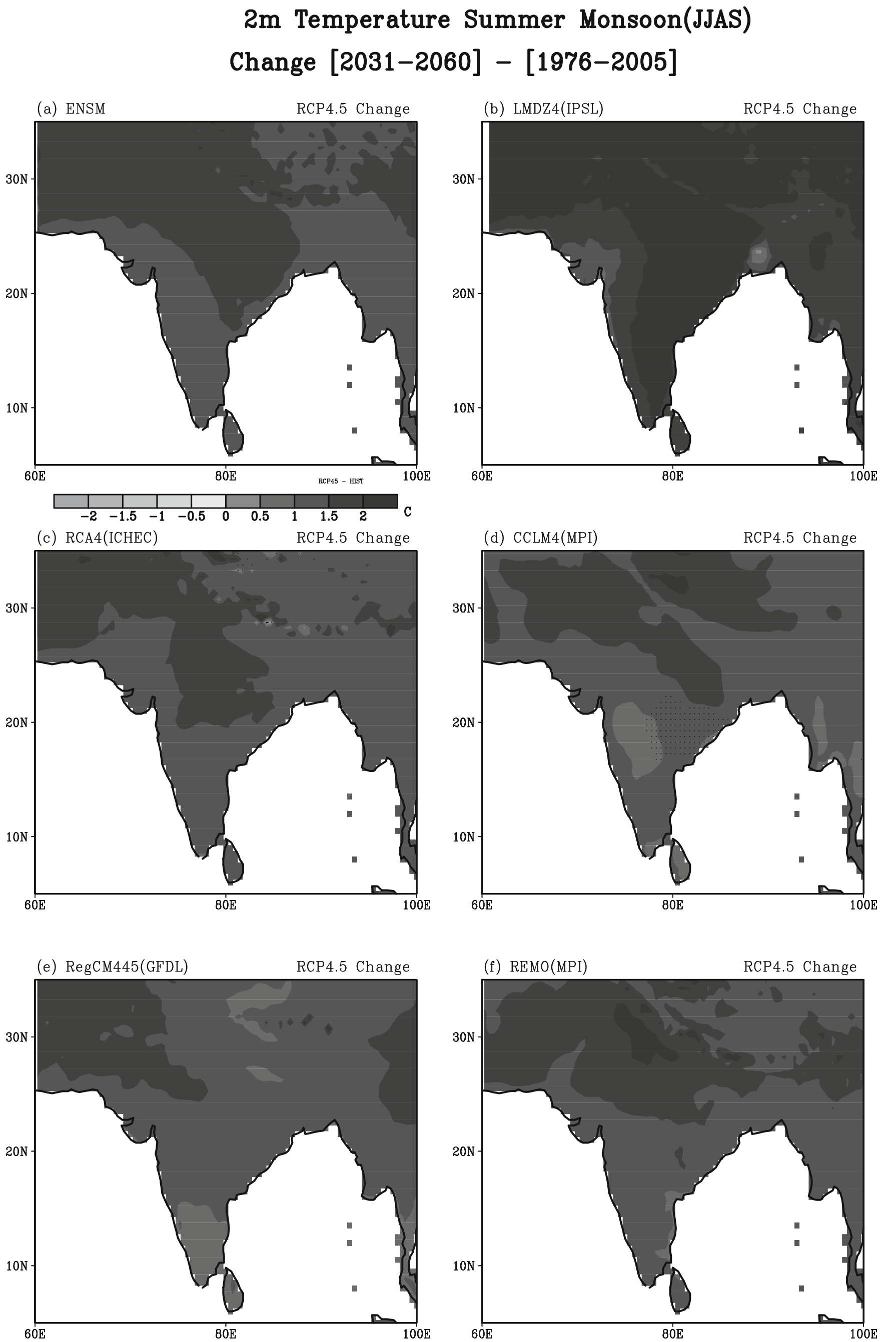

Fig. 5 Summer monsoon (JJAS) season mean 2-m air temperature (°C) changes in 2031–2060 with respect to 1976–2005 for the CORDEX South Asia simulations driven by CMIP5 AOGCM RCP4.5 scenario experiments **a** multi-model ensemble mean (ENSM) and **b**–**f** five different CORDEX RCMs listed in Table 1. Stippling denotes areas where the 30-year mean changes are not statistically significant at the 1 % level using Student's *t* test

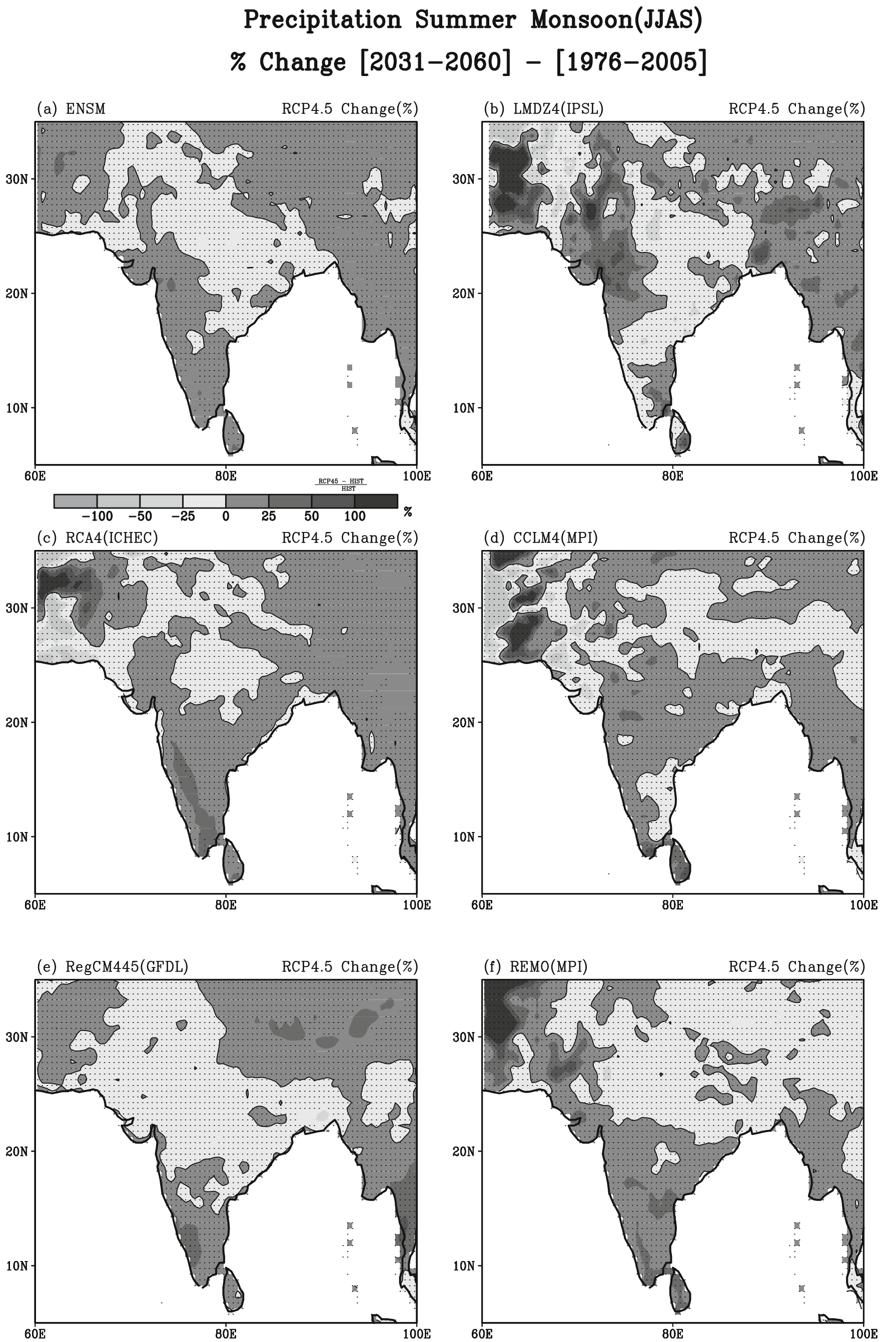

Fig. 6 Summer monsoon (JJAS) season mean precipitation changes (%) in 2031–2060 with respect to 1976–2005 for the CORDEX South Asia simulations driven by CMIP5 AOGCM RCP4.5 scenario experiments **a** multi-model ensemble mean (ENSM) and **b–f** five different CORDEX RCMs listed in Table 1. Stippling denotes areas where the 30-year mean changes are not statistically significant at the 1 % level using Student's *t* test

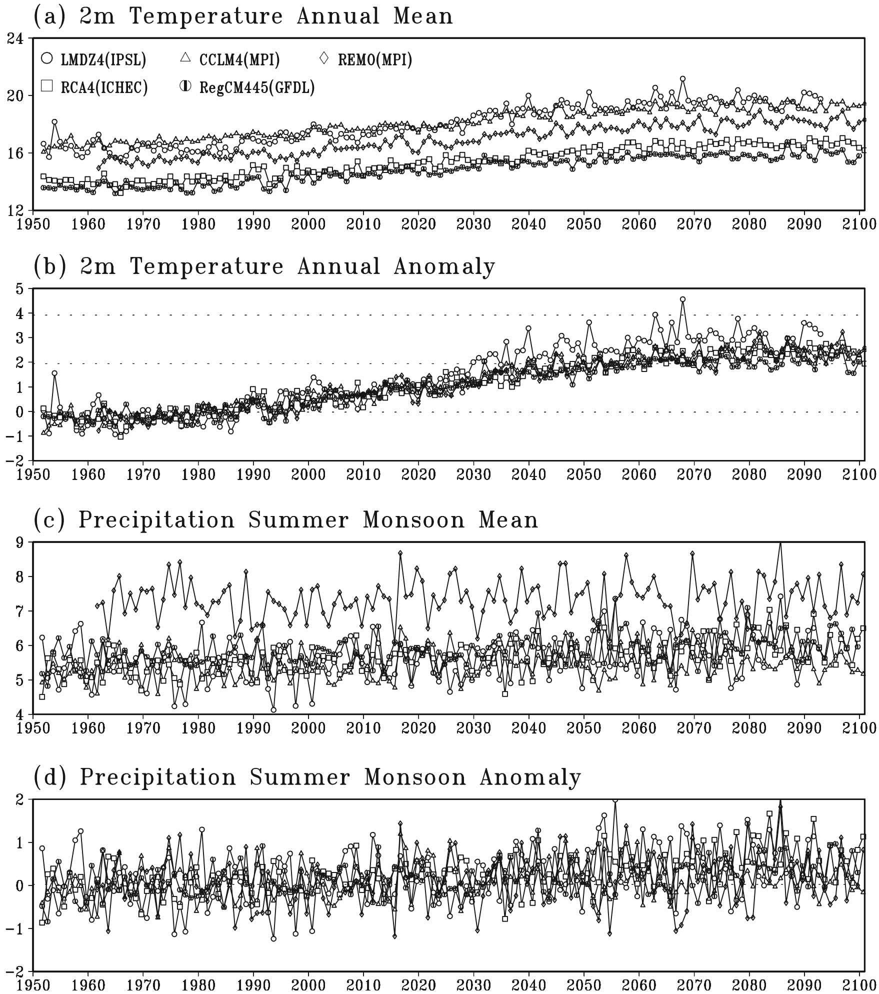

Fig. 7 Time series for the period 1950–2100 of: 2-m temperature (°C) annual **a** mean and **b** change relative to 1976–2005; and precipitation (mm day^{-1}) summer monsoon (JJAS) season **c** mean and **d** change relative to 1976–2005, averaged over land grid points in South Asia (60–100°E, 5–35°N) for the five different CORDEX RCMs listed in Table 1

show large spread among the individual models for the entire analysis period (Fig. 7d) suggesting that these downscaled precipitation projections are not reliable.

The percentile distribution of near-surface air temperature or precipitation gives insight into the spatial and temporal patterns of their extremes (e.g. 90th percentile). The mid-term (2031–60) projections in the RCP4.5 scenario experiments for South Asia during summer monsoon months (June-September) are shown in Fig. 8 and Fig. 9, displaying mid-term changes in extreme temperature (Fig. 8) and precipitation (Fig. 9) for the CORDEX South Asia RCMs (right-hand panels) and their

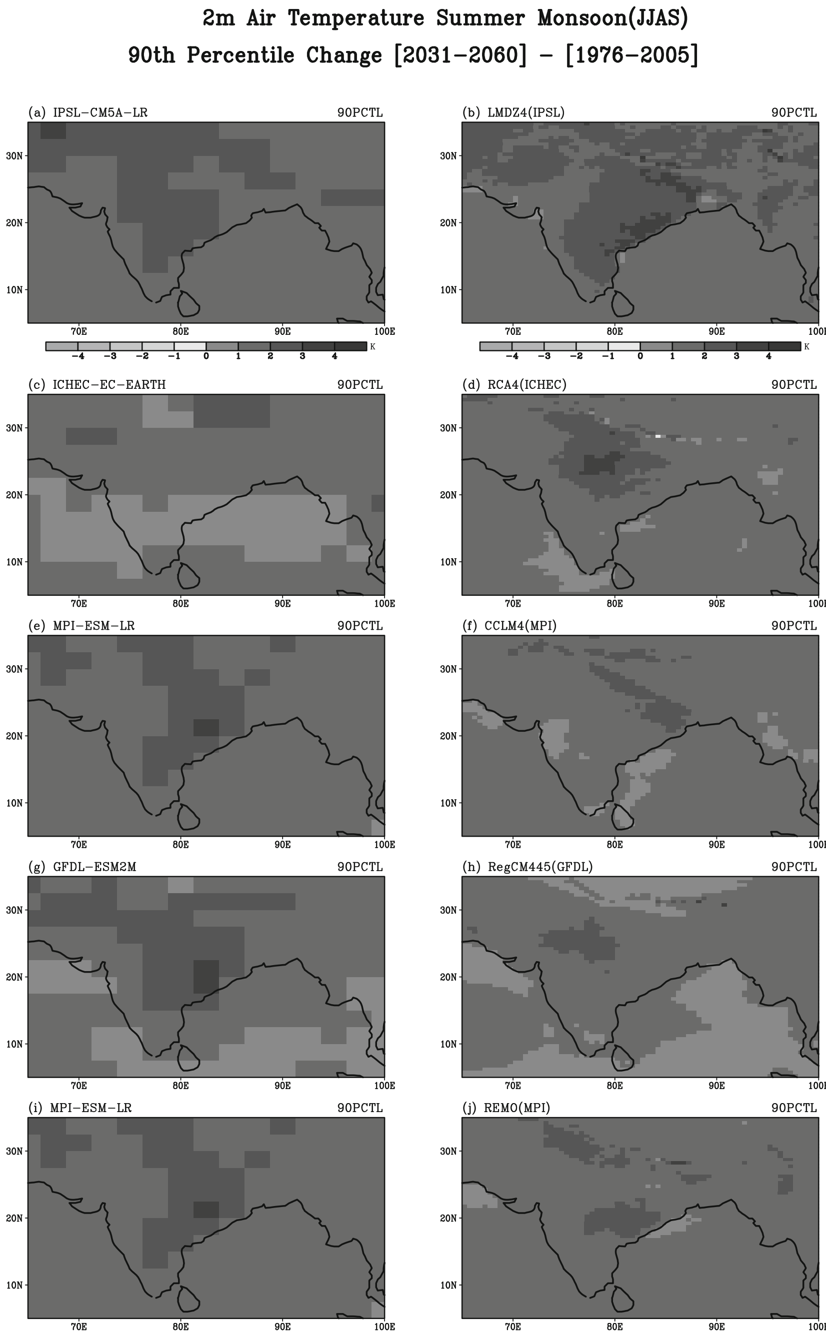

Fig. 8 Changes in the 90th percentile of the daily distribution of 2-m air temperature (°C) during summer monsoon months (June–September) in the 30-year period 2031–2060 with respect to 1976–2005 for the five CORDEX South Asia simulations (*right panels*) driven by CMIP5 AOGCM RCP4.5 scenario experiments (*left panels*) listed in Table 1

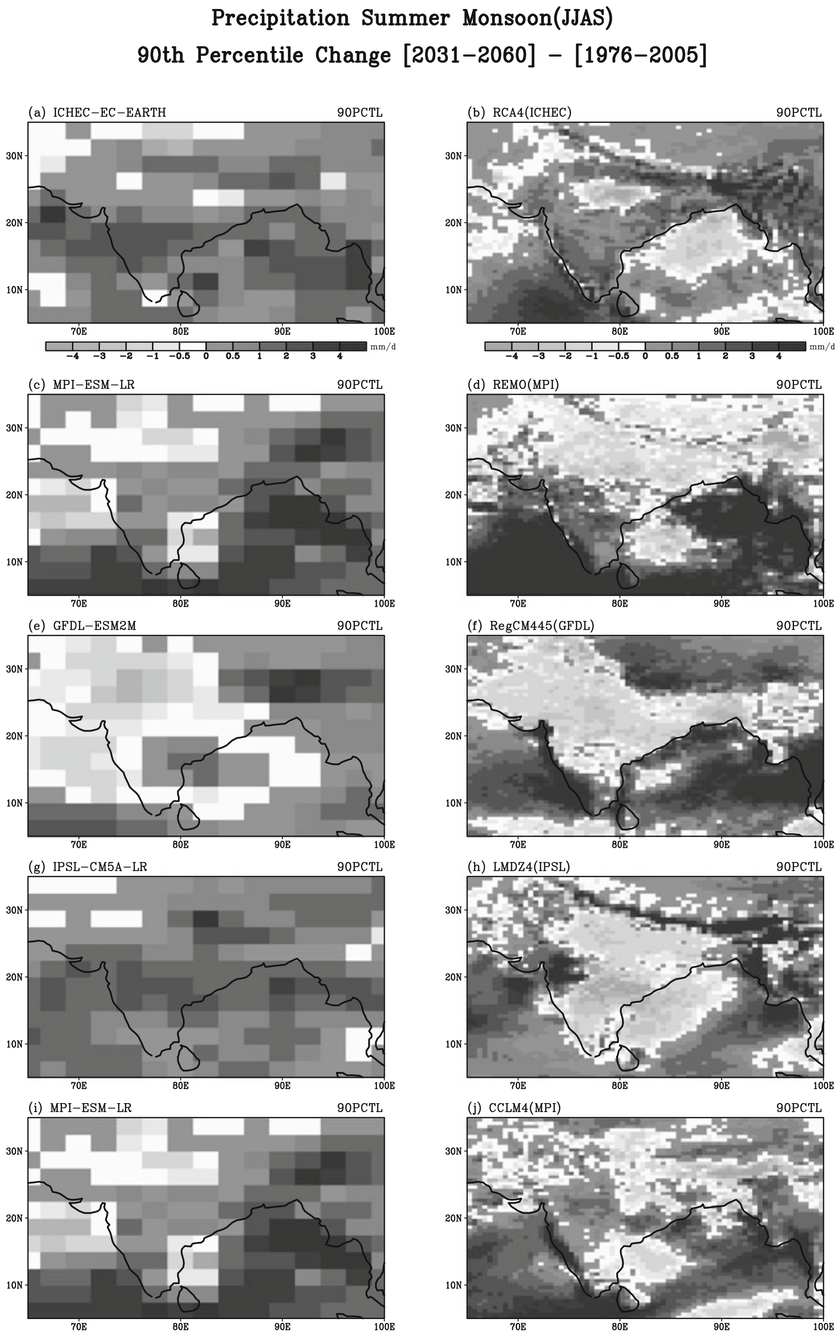

Fig. 9 Changes in the 90th percentile of the daily distribution of precipitation (mm day^{-1}) during summer monsoon months (June–September) in the 30-year period 2031–2060 with respect to 1976–2005 for the five CORDEX South Asia simulations (*right panels*) driven by CMIP5 AOGCM RCP4.5 scenario experiments (*left panels*) listed in Table 1

corresponding driving coarser resolution CMIP5 AOGCMs (left-hand panels) relative to the reference period 1976–2005. Most of the AOGCM projections (Fig. 8, left-hand panels) show a warming of 2–3 °C extending from the eastern region to the interior north India, with the highest changes of more than 3 °C over the eastern coast of India. The downscaled spatial patterns of the mid-term changes for the extreme temperatures in CORDEX South Asia RCMs indicate lesser summer monsoon seasonal warming over India (Fig. 8, right-hand panels). The mid-term changes in the summer monsoon precipitation for the downscaled CORDEX RCMs show different spatial patterns than that for their driving CMIP5 AOGCMs (Fig. 9). While most of the AOGCMs indicate an increase in extreme precipitation over central and peninsular India (Fig. 9, left-hand panels), the projected changes for few downscaled RCMs during the same period indicate decreases in extreme precipitation over central India (Fig. 9, right-hand panels).

Finally, it is noted that this small ensemble of five transient 140-year simulations samples only a small part of the total uncertainty range. However, it was shown that this small ensemble of climate change simulations were useful in order to demonstrate the uncertainties related to RCM formulation and boundary conditions in a physically consistent manner at the regional scale. A much larger ensemble containing more forcing AOGCMs, emission scenarios and ensemble members sampling the natural variability will be needed to explore the full uncertainty ranges. Therefore, the preliminary results presented here need to be updated for CORDEX South Asia using regional climate change metrics covering broader uncertainty ranges.

4 Summary

- The geographical distribution of surface air temperature and seasonal precipitation in the present climate for land areas in South Asia is strongly affected by the choice of the RCM and boundary conditions (i.e. driving AOGCMs), and the downscaled seasonal averages are not always improved. However, some RCMs are generally able to better simulate the annual cycle of temperature, particularly over central India.
- The dynamically downscaled summer monsoon temperature projections for the RCP4.5 scenario indicate mean warming of more than 1.5 °C for the period 2031–2060 over the central and northern parts of India, while the annual warming range over South Asia land areas is 1.8–3.0 °C by 2060.
- The results based on the available small ensemble of five RCM projections for the RCP4.5 scenario suggest that the summer monsoon precipitation change for the period 2031–2060 are uncertain not only in magnitude but also in sign, and the large spread of their area averages over South Asia land areas question the reliability of these downscaled precipitation projections for applying in regional climate change impact assessment studies.

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