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Assessment of CORDEX-South Asia experiments for monsoonal precipitation over Himalayan region for future climate

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Abstract Precipitation is one of the important climatic indicators in the global climate system. Probable changes in monsoonal (June, July, August and September; hereafter JJAS) mean precipitation in the Himalayan region for three different greenhouse gas emission scenarios (i.e. representative concentration pathways or RCPs) and two future time slices (near and far) are estimated from a set of regional climate simulations performed under Coordinated Regional Climate Downscaling Experiment-South Asia (CORDEX-SA) project. For each of the CORDEX-SA simulations and their ensemble, projections of near future (2020–2049) and far future (2070–2099) precipitation climatology with respect to corresponding present climate (1970–2005) over Himalayan region are presented. The variability existing over each of the future time slices is compared with the present climate variability to determine the future changes in inter annual fluctuations of monsoonal mean precipitation. The long-term (1970–2099) trend (mm/day/year) of monsoonal mean precipitation spatially distributed as well as averaged over Himalayan region is analyzed to detect any change across twenty-first century as well as to assess model uncertainty in simulating the precipitation changes over this period. The altitudinal distribution of difference in trend of future precipitation from present climate existing over each of the time slices is also studied to understand any elevation dependency of change in precipitation pattern. Except for a part of the Hindu-Kush area in western Himalayan region which shows drier condition, the CORDEX-SA experiments project in general wetter/drier conditions in near future for western/eastern Himalayan region, a scenario which gets further intensified in far future. Although, a gradually increasing precipitation trend is seen throughout the twenty-first century in carbon intensive scenarios, the distribution of trend with elevation presents a very complex picture with lower elevations showing a greater trend in far-future under RCP8.5 when compared with higher elevations.

Keywords Monsoonal · Precipitation · RCPs · Himalayan region · CORDEX-SA · Precipitation change · Projections · Climatology · Trend · Uncertainty

1 Introduction

The Himalayan region which is referred to as the 'Water Tower of Asia' (Viviroli et al. 2007; Immerzeel et al. 2010) and third pole of world owing to its vast glaciers feeds some of the major rivers in South Asia. More than 1.5 billion people depend on these rivers to meet the agricultural water demand. Himalayan region is identified as one of the most sensitive areas to global climate change (Xu et al. 2009). Any abnormal change in climatic parameters would pose a serious threat to the sustainability of life in this part of the world. Understanding these climatic changes and other hydro climatic changes require accurate and high resolution precipitation data. Owing to the complex topography, inaccessible terrain and harsh climate the in-situ monitoring of weather has not reached up to the desired level so as to give such high quality data (Fowler and Archer 2006; Winiger et al. 2005; Rasmussen et al. 2012). This underlines

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the need of models which could be employed in properly understanding the climate variability over Himalayan region and its future response to global changes in climate. In this respect, global climate models (GCMs) are being used across the world to study the past and future climate and in impacts research, vulnerability assessments, etc. (Lobell et al. 2008; Mote et al. 2011). However, the GCMs have a coarse spatial resolution which limits its capability to capture the sub-grid scale processes-local climatic forcing and feedbacks in a region like Himalayan region where complex topography gives rise to a wide variety of climate regimes within the region. The regional climate models (hereafter, RCMs) on the other hand due to better representation of topography and sub-grid scale processes in form of parameterization schemes is thought to better represent the regional climate (Giorgi and Mearns 1999).

Though from the studies done in past over the Himalayan region there is a clear picture of consistently increasing temperature over the region (Liu and Chen 2000; Shrestha et al. 1999, 2000; Dimri and Dash 2012) but the precipitation changes depict a complex and uncertain response with models showing substantial variation in the sign and magnitude of change across regions within the Himalayan region (Rajbhandari et al. 2015; Archer and Fowler 2004; Bhutiyani et al. 2010; Kulkarni et al. 2013; Bookhagen and Burbank 2006; Fowler and Archer 2006; Shrestha et al. 1999; Mathison et al. 2013; Kumar et al. 2013; Mishra 2015). For e.g. based on observations the monsoonal precipitation is found to be increasing in Jammu and Kashmir but decreasing in the western Indian Himalayan region (Gautam et al. 2013). In another study, increasing and decreasing trends in Eastern Himalayan region (Sharma et al. 2000), absence of a consistent trend in Central Himalayan region (Shrestha et al. 2000) and decreasing trends in western Himalayan region (Kumar and Jain 2010) are found. A particular trend in western Himalayan region could be indicative of aninteraction of mid-latitude troughs and Eurasian waves (through teleconnections) with southwesterly monsoonal flow which could result in weakening or strengthening of the monsoonal circulation (Raman and Rao 1981; Krishnan et al. 2009; Yadav 2009, 2016). Studies in the past have also reported teleconnections of precipitation over north-west India (which includes western Himalayan region) with sea-surface temperature (hereafter, SST) anomalies in Atlantic Ocean (Kucharski et al. 2009; Yadav 2016). The strength of monsoon could be further attenuated by the fact that due to warming of the climate, when oceans would be heated, it will reduce the land-sea temperature contrast owing to reduced pressure gradient and subsequently less moisture influx from the ocean to the land. However, a study by Dobler and Ahrens (2011) using the regional climate model COSMO-CLM suggests that though there will be increased intensity of rainfall on a rainy day with increasing greenhouse gases emissions and perceptible water in the atmosphere, but there will be reduction in the frequency of rainy days in the Himalayan region from the period 1971–2000 to 2071–2100. The same study also shows a considerable increase in the summer time precipitation in upper Indus basin region but decreases in the central and western Tibetan Plateau. Though there are some conclusive studies also like Ali et al. (2015) using CCAM regional model found the future projections of precipitation in Indus basin to be showing a consistent increase with however the change being slow in far future when compared to near future. Similarly, Rupa Kumar et al. (2006) and Syed et al. (2014) using regional climate model PRECIS reported an increase in monsoon precipitation across entire Himalayan region by 5–50% by the end of twenty-first century. In the work done by Dash et al. (2015) using regional model RegCM4 it is found that precipitation in the Himalayan region is set to increase in future across all RCP scenarios. Revadekar et al. (2011), Sengupta and Rajeevan (2013) and Palazzi et al. (2015) found the Coupled Model Inter-comparison Project Phase 5 (hereafter, CMIP5) models to be projecting wetter conditions in general, in future over Himalayan region. A similar study of precipitation projections carried out by Pandey et al. (2014) using CMIP5 models indicates an increased mean precipitation in future with also a significant increasing trend over eastern Himalayan region for 1901–2099 period. Palazzi et al. (2013) using an ensemble of eight members of the EC-Earth model found an increasing trend of summer monsoon precipitation over the Himalayan region under the most extreme RCP8.5 scenario. Pervez and Henebry (2014) after statistically downscaled projections of a GCM found decreased precipitation in Ganga and Brahmaputra river basin of the study area. Oh et al. (2014) based on analysis of CORDEX-East Asia regional climate models found an increased precipitation by up to 5% across Himalayan region in near future for both RCP4.5 and RCP8.5 scenarios. Nevertheless, due to warming of the atmosphere the precipitation pattern in high altitude regions will possibly change significantly over the coming 100 years as higher temperature could lead to enhanced conversion of snow to rainfall as found by Beniston (2003).

The precipitation distribution in a mountainous area like Himalayan region is a complex subject as the precipitation changes with elevation. In general, precipitation increases with elevation in a mountainous region but sometimes there may be an opposite pattern (Sen and Habib 2000) like Ghimire et al. (2015) found that summer monsoon mean precipitation decreases with elevation over Himalayan region. To understand the effect of elevation on precipitation a number of studies are carried out (Clayton 1982; Loukas and Quick 1994; Marquinez et al. 2003). In the Himalayan region, detailed studies to assess the change in precipitation patterns with elevation is still lacking. Singh et al. (1995) and Singh and Kumar (1997) studied the impact of elevation on precipitation distribution in different basins of Himalayan region. Dhar et al. (2000) studied the precipitation studies carried out for high altitude places in the Himalayan region. Depending upon the topography of a mountain, there may be a continuously increasing precipitation with elevation, and it may begin to decrease above a particular elevation (Singh et al. 1995; Singh and Kumar 1997; Arora et al. 2006). Thus, orography plays very important role in precipitation distribution, which varies significantly at spatial and temporal scales not only within a particular range of elevation, but also from one mountain chain to another.

In this paper, the assessment of CORDEX-SA experiments by Ghimire et al. (2015) for present climate is extended for studying the future projections of precipitation over Himalayan region. It is always useful to make projections using ensemble of models as it presents an opportunity to reduce the uncertainty or the study of its source. No such study of future climate projections is carried out so far using these many regional climate simulations over Himalayan region. Therefore, this study is very important as a contribution to the larger goal of CORDEX project and regional level impact studies.

The paper is organized as follows. Section 2 describes the data and methodology used in the analysis. Section 3 reports the results of the analyses in terms of relative change in precipitation climatology, the distribution of change with elevation, the change in variability, the distribution of trend with elevation and long-term trend analysis. The results are further discussed in Sect. 4. Finally, Sect. 5 concludes the paper and identifies further research areas.

2 Data and methodology

2.1 Study area

The study area includes the great Himalayan Range along with the Hindu-Kush and the Karakoram, Fig. 1a. Not much detail is known about the climatology of the region (Immerzeel et al. 2009; Shrestha et al. 2000). Bookhagen and Burbank (2010) have shown the major factor of the precipitation in this region to be monsoon, which contributes more than 80% of the annual precipitation in the central and the eastern Himalaya, including the Tibetan plateau. However, the contribution for the western Himalayan region is comparatively less. The study area is depicted in the Fig. 1. Figure 1a shows the location of the study area, extending from 23° – 39°N and 68° – 103°E. In this figure, the study area is distinguished from the surrounding areas by different colors based on varying elevations. The region consists of parts of eight countries from Tajikistan to Myanmar, including Afghanistan, Pakistan, India, Nepal, Bhutan and southern parts of China (Palazzi et al. 2013). In Fig. 1b the the topographic variation within the study region is depicted.

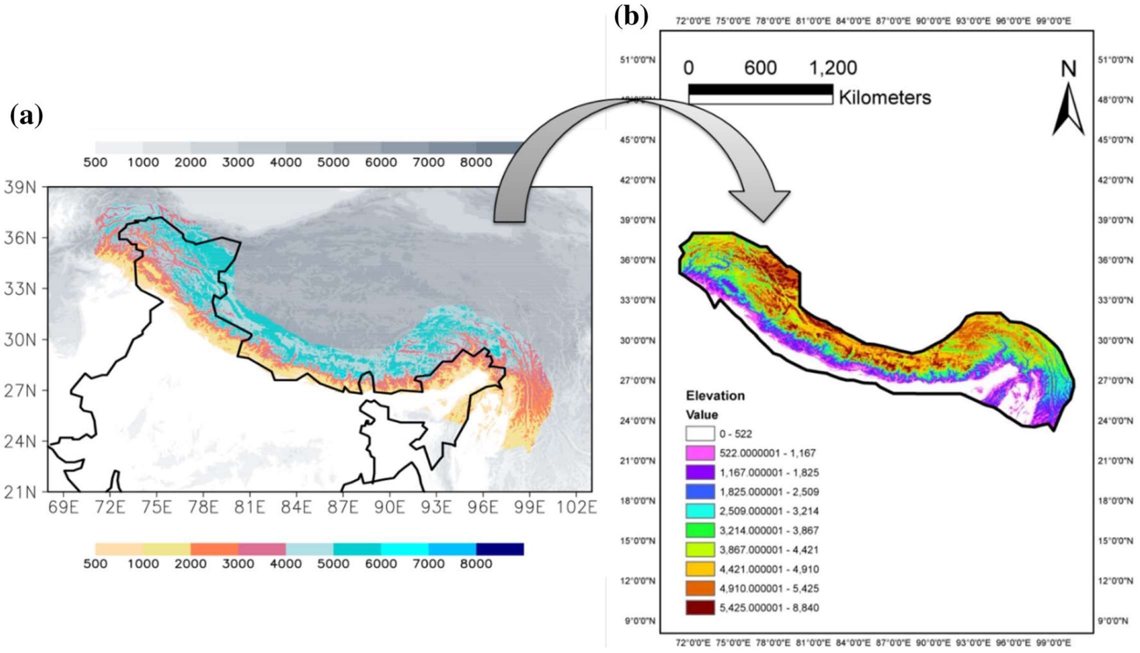

Fig. 1 Topography (metres) over **a** Himalayan and Tibetan region (*grey shaded*) and **b** over study area (*color shaded*) (Ghimire et al. 2015)

2.2 CORDEX-SA and data

Coordinated regional climate downscaling experiment (CORDEX) project under World Climate Research Program (WCRP) aims to develop an international coordinated framework for producing an improved set of regional climate change projections for different domains across the globe (Giorgi et al. 2009). South-Asia (SA) which includes Himalayan region is one of such domains. The present study involves a total of ten CORDEX-SA experiments i.e. ten different RCM-GCM combinations arising from five RCMs forced with eight GCMs which comes from CMIP5 (see Table 1 for details). The daily precipitation data for the CORDEX-SA was originally obtained from Center for Climate Change Research (CCCR), Indian Institute of Tropical Meteorology, Pune, India which maintains the database and is also the coordinating institution of CORDEX-SA. The CORDEX-SA data we have used is available at a spatial resolution of 0.44° (approximately 50 km) at daily temporal resolution.

The JJAS mean precipitation from simulations of 130 years (1970–2099) of CORDEX-SA RCMs is analyzed in the study. The 36 year period of 1970–2005 within the longer 130 year period is considered as present climate in this study. This period is referenced here to analyze the relative changes in future climate from the present climate. The reason for choosing this period as present climate is to maintain consistency and extend the previous work done by Ghimire et al. (2015) and Nengker et al. (2017) who used this period for the evaluation of a similar set of CORDEX-SA experiments as considered in this study for precipitation and temperature respectively. The simulations up to 2005 are based on historical emissions as represented in CMIP5 GCMs (Taylor et al. 2012) which are used as forcings for CORDEX-SA RCMs. Post 2005, the forcing data is generated by GCM simulations based on the representative concentration pathway (RCP) mitigation scenarios (Moss et al. 2010). In the present paper, results for only three RCPs—the RCP2.6 (Van Vuuren et al. 2011a, b), RCP4.5 (Thomson et al. 2011) and RCP8.5 (Riahi et al. 2011) are presented, where the number indicates the anthropogenic radiative forcing in 2100 relative to pre-industrial level (1750). The RCPs experiments are based on multiple gas emission assumptions in the future following various socio-economic pathways (Fujino et al. 2006; Smith and Wigley 2006; Clarke et al. 2007; Riahi et al. 2007; Van-Vuuren et al. 2011a; Hijioka et al. 2008; Thomson et al. 2011). A brief summary of RCPs is given by Van-Vuuren et al. (2011a, b). Future time period is divided into two time slices: near future (2020–2049) and far future (2070–2099) to take into account the near- and long-term changes in the precipitation patterns. The findings with respect to climatic changes for respective time slices would also serve as a basis for appropriate decision making and designing accordingly immediate or long-term plans, policies or adaptation strategies to deal with future changes. In altogether, ten different experiments coming from combination of five different RCMs forced with eight different GCMs are studied here. The data for all the three RCPs and two time slices considered here are not available for all the ten experiments (see Table 2 for more details). Regarding the data availability for different RCPs it is important to mention here that for RCP2.6 the data from only two experiments: ICHEC-EC-EARTH-SMHI-RCA4 and MPI-ESM-LR_REMO2009 were available and so in this case results are presented for these two experiments only. Also for RCP4.5 the data for LMDZ-IITM-RegCM4 was available only up to 2060, for GFDL-CM3-CSIRO-CCAM up to 2070 and for CCSM4-CSIRO-CCAM the near-future data was corrupted in its calendar structure so only near-future projections are analyzed for the first two and far-future for the last one.

2.3 Methodology

First, a brief overview of the monsoonal precipitation distribution existing over the study region is discussed on the basis of present climatology (1970–2005) as obtained from Asian Precipitation—Highly-Resolved Observational Data Integration Towards Evaluation (APHRODITE) (Yatagai et al. 2009). To assess the future changes in summer time precipitation distribution for each CORDEX-SA experiment and their ensemble, percentage change in near future (2020–2049) and far future (2070–2099) precipitation climatology from corresponding present climate (1970–2005) are presented.

The variability existing over each of the future time slices is compared with the present climate variability to determine the extent of fluctuations in inter annual seasonal mean precipitation in future. The variability for each time slice is calculated as the standard deviation of 30 years monsoonal mean precipitation values (36 years for present).

The long-term (1970–2099) temporal distribution of seasonal mean precipitation averaged over Himalayan region starting from present and extending up to the end of twenty-first century (2099) is analysed to detect any overall trend as well as uncertainty among the experiments in simulating the precipitation over this period. For the determination of slope of trend non-parametric Theil-Sen (Sen 1968) slope estimator and for determination of significance of the trend Mann–Kendall (Kendall 1938) non-parametric test is used. These two methods of trend estimation are used in several other previous studies on long-term precipitation data (Zhang et al. 2000; Yue and Hashino 2003; Shadmani et al. 2012; Basistha et al. 2009; Mondal et al. 2012; Gocic and Trajkovic 2013;

Table 1 Details of CORDEX-SA experiments analyzed in the present study. (Source: CORDEX South-Asia Database, CCCR, IITM; http://cccr.tropmet.res.in/cordex/files/downloads.jsp)

S. No.	Experiment name	RCM description	Driving GCM	Contributing institute
1	LMDZ-IITM-RegCM4	The Abdus Salam International Centre for Theoretical Physics (ICTP) Regional Climatic Model version 4 (RegCM4; Giorgi et al. 2012)	IPSL LMDZ4	CCCR, IITM, Pune, India
2	ICHEC-EC-EARTH-SMHI-RCA4	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)	Rossby Centre, Swedish Meteorological and Hydrological Institute (SMHI), Sweden
3	NorESM1-M-CSIRO-CCAM	Commonwealth Scientific and Industrial Research Organisation (CSIRO), Conformal-Cubi Atmospheric Model (CCAM; McGregor and Dix 2001)	NorESM1-M	CSIRO Marine and Atmospheric Research, Melbourne, Australia
4	MPI-ESM-LR-CSIRO-CCAM		MPI-ESM-LR	
5	GFDL-CM3-CSIRO-CCAM		GFDL-CM3	
6	CNRM-CM5-CSIRO-CCAM		CNRM-CM5	
7	CCSM4-CSIRO-CCAM		CCSM4	
8	ACCESS-CSIRO-CCAM		ACCESS	
9	COSMO-CLM	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
10	MPI-ESM-LR-REMO2009	MPI Regional Model (REMO) 2009 (Saeed et al. 2012)	MPI-ESM-LR	Climate Service Center, Hamburg, Germany

Table 2 Data availability for CORDEX-SA experiments under different RCPs and time slices—near future (2020–2049) and far future (2070–2099)

S. No.	Experiment name	Availability (√- available; X- not available)					
		RCP2.6		RCP4.5		RCP8.5	
		Near future	Far future	Near future	Far future	Near future	Far future
1	LMDZ-IITM-RegCM4	X	X	√	X	X	X
2	ICHEC-EC-EARTH-SMHI-RCA4	√	√	√	√	√	√
3	NorESM1-M-CSIRO-CCAM	X	X	√	√	√	√
4	MPI-ESM-LR-CSIRO-CCAM	X	X	√	√	√	√
5	GFDL-CM3-CSIRO-CCAM	X	X	√	X	√	√
6	CNRM-CM5-CSIRO-CCAM	X	X	√	√	√	√
7	CCSM4-CSIRO-CCAM	X	X	X	√	√	√
8	ACCESS-CSIRO-CCAM	X	X	√	√	√	√
9	COSMO-CLM	X	X	√	√	X	X
10	MPI-ESM-LR-REMO2009	√	√	√	√	√	√

Wan et al. 2013; Pranuthi et al. 2014; Venable et al. 2015; Wu et al. 2016; Masson and Frei 2015). In the Theil-Sen slope (hereafter, s.s.) a positive value of s.s. indicates increasing precipitation pattern and a negative value of s.s. indicates decreasing precipitation pattern. The value of Man-Kendall test statistic 'z' indicates likewise. The variation of these changes with elevation in future is also discussed as several other authors have found topographical effect on precipitation distribution in this region and other mountainous regions around the world (Singh and Kumar 1997; Singh et al. 1995; Arora et al. 2006; Hewitt et al. 2005; Arakawa and Kitoh 2012; Clayton 1982; Barros and Lettenmaier 1993; Giorgi et al. 1997). In this respect, difference in trend of future precipitation from present climate existing over each of the time slice is also studied with respect to its distribution with elevation over the Himalayan region.

Supplementary analysis: For the purpose of assessing the range of values in the spatial distribution of monsoonal mean precipitation over the Himalayan region, probability density function (PDF) is studied as a supplementary addition. The precipitation distribution follows gamma distribution (Wilks 2011; Fan et al. 2014) as,

$$f(x|k,\theta) = \frac{1}{\theta^k \boldsymbol{\Gamma}(k)} x^{k-1} e^{-\frac{x}{\theta}},$$

where k and θ are shape and scale parameter of gamma distribution respectively. The PDF of precipitation can give several useful information. The width of PDF indicates the spatial variability and extreme values in precipitation. A positive change in width of PDF curve in future would suggest an increase in precipitation variability.

3 Results

First of all, the observed climatology of summer monsoon precipitation (mm/day) as it exists over the study region (Fig. 2a) is presented for the period 1970–2005 and the altitudinal distribution of its long-term variation (Fig. 2b) is also shown. This is discussed to give a brief idea of monsoon precipitation characteristics over Himalayan region. As the topography and terrain plays an important role in the occurrence, releasing and enhancing of the convection processes, the sharp rise of the Himalayan region from the Ganges and Indus plains cause the maximum precipitation to occur in this region (Medina et al. 2010). The transport of the moisture-laden monsoon clouds from the eastern to the western Himalayan region with its gradual weakening in extent and moisture content along the way causes more precipitation in the eastern Himalayan region compared to the western. APHRODITE shows a clear band of higher precipitation along the southern rim of the Himalayan region extending up to north-east India and the general smaller precipitation towards the west. The vertical interpolation technique used to prepare this dataset is important for the study of precipitation in Himalayas which has a complex topography (Yatagai et al. 2012). Andermann et al. (2011) have compared APHRODITE dataset with rain gauge and five other gridded datasets including TRMM precipitation data for Nepal Himalaya and concluded that APHRODITE provides a good temporal variability on a monthly to annual scale and even in some cases the daily variations. Dimri et al. (2013), Mathison et al. (2013) and Ghimire et al. (2015) have also used this dataset in their studies on model evaluation over Himalayan region. The distribution of long-term trend (1970–2005) of monsoonal

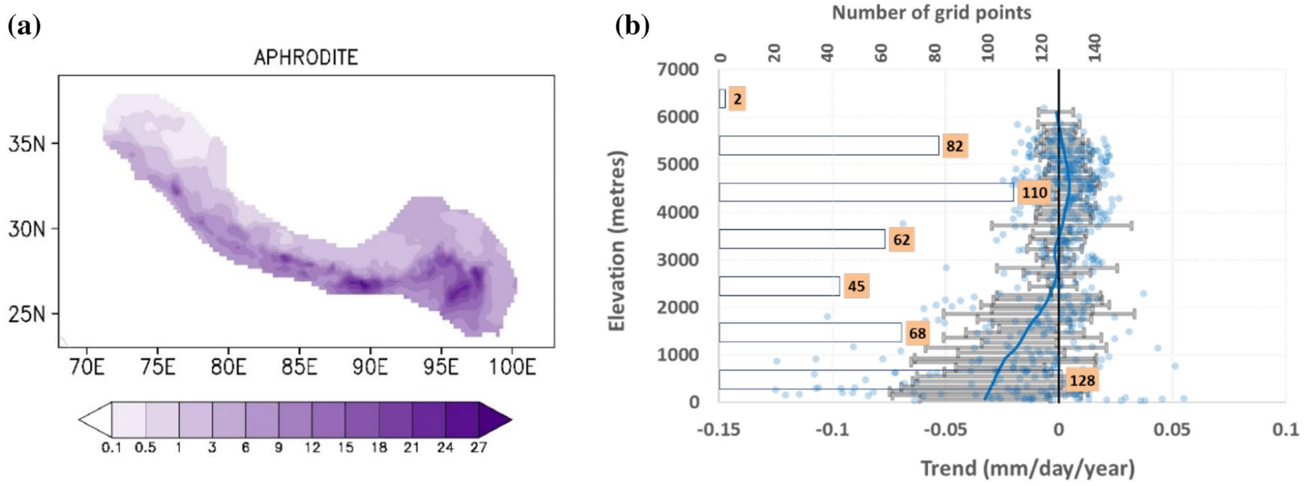

Fig. 2 **a** Observed JJAS precipitation (mm/day) climatology from APHRODITE during 1970–2005 over the Himalayan region as shown in Fig. 1. **b** Distribution of trend (mm/day/year) with altitude for the same where *error bars* show the spatial variability within every 100 m altitude class. The *rectangular bars* with numbers represent the number of grid points falling within each 1000 m altitude range

mean precipitation with elevation over Himalayan region (Fig. 2b) indicates that in general, in the recent past places at lower elevation (less than 2000 m) have experienced decreasing precipitation trend of about 0.025 mm/day/year on an average. Contrarily, in the higher altitudes, opposite scenario can be seen at many of the grid points with no trend to slight positive trend suggesting an increased precipitation over the past as we go up. Also, we see that the places at higher altitudes even though they may be at different locations have underwent similar rate of change in seasonal mean precipitation which is evident from the smaller and reducing spatial variability (in trend) towards higher altitudes. As we go higher up in the Himalayan region, the monsoonal mean precipitation received climatologically tends to get reduced as reported by Ghimire et al. (2015) using the same dataset for the same period i.e. 1970–2005. Most of the orographically lifted moisture tends to precipitate at the lower elevations and in valleys. The places at higher altitudes however, are subject to a colder and drier climate and due to subdued influence of moisture-temperature interplay tend to produce similar responses and climatic signals to atmospheric forcings and feedbacks over varied topography.

Figure 3a–c provides the percentage change in precipitation in near future (2020–2049) from present climate (1970–2005) in case of different RCPs for different CORDEX-SA experiments. For RCP2.6 where data from only two experiments are available—(aa) ICHEC-EC-EARTH-SMHI-RCA4 and (ab) MPI-ESM-LR_REMO2009—they show an almost contrarious spatial distribution of changes. ICHEC-EC-EARTH-SMHI-RCA4 projects a decrease in precipitation in western Himalayan region and increase in eastern Himalayan region while MPI-ESM-LR_REMO2009 projects vice-versa. The ensemble shows impression of ICHEC-EC-EARTH-SMHI-RCA4 due to the higher magnitude of change in that experiment. In fact, these two experiments show similar disagreement in case of other RCPs also. Furthermore, such large differences among model simulations could be due to difference in each RCM's configuration, parameterization physics or different parent GCMs used to drive these RCMs. Similarly, in case of RCP4.5 and RCP8.5 as suggested by ensemble most of the experiments except for ICHEC-EC-EARTH-SMHI-RCA4 show increase in precipitation in western Himalayan region and decrease in eastern Himalayan region (of up to 20% in both the cases). There is not much difference in the distribution of change between the RCPs though the change may get intensive with an intensive RCP scenario. It is interesting to note that there exists an interface in central Himalayan region where a very sharp transition in the sign of change of precipitation is seen. Likewise, in Fig. 4a–c the percentage change in precipitation for far future (2070–2099) is presented. The most remarkable observation is that though there is no much shift in the spatial distribution of the change but there is definitely an intensification of the change in both signs- the dry gets drier and wet gets wetter. For RCP2.6 this change may not be very evident due to the least carbon intensive scenario that this RCP projects. For RCP8.5 as can be seen in Fig. 5 also there is a drying in far future over a better part of the study region but the east–west contrast still exists.

Figures 6 and 7 presents the change in variability of precipitation in near and far future respectively as percentage change in standard deviation of yearly seasonal

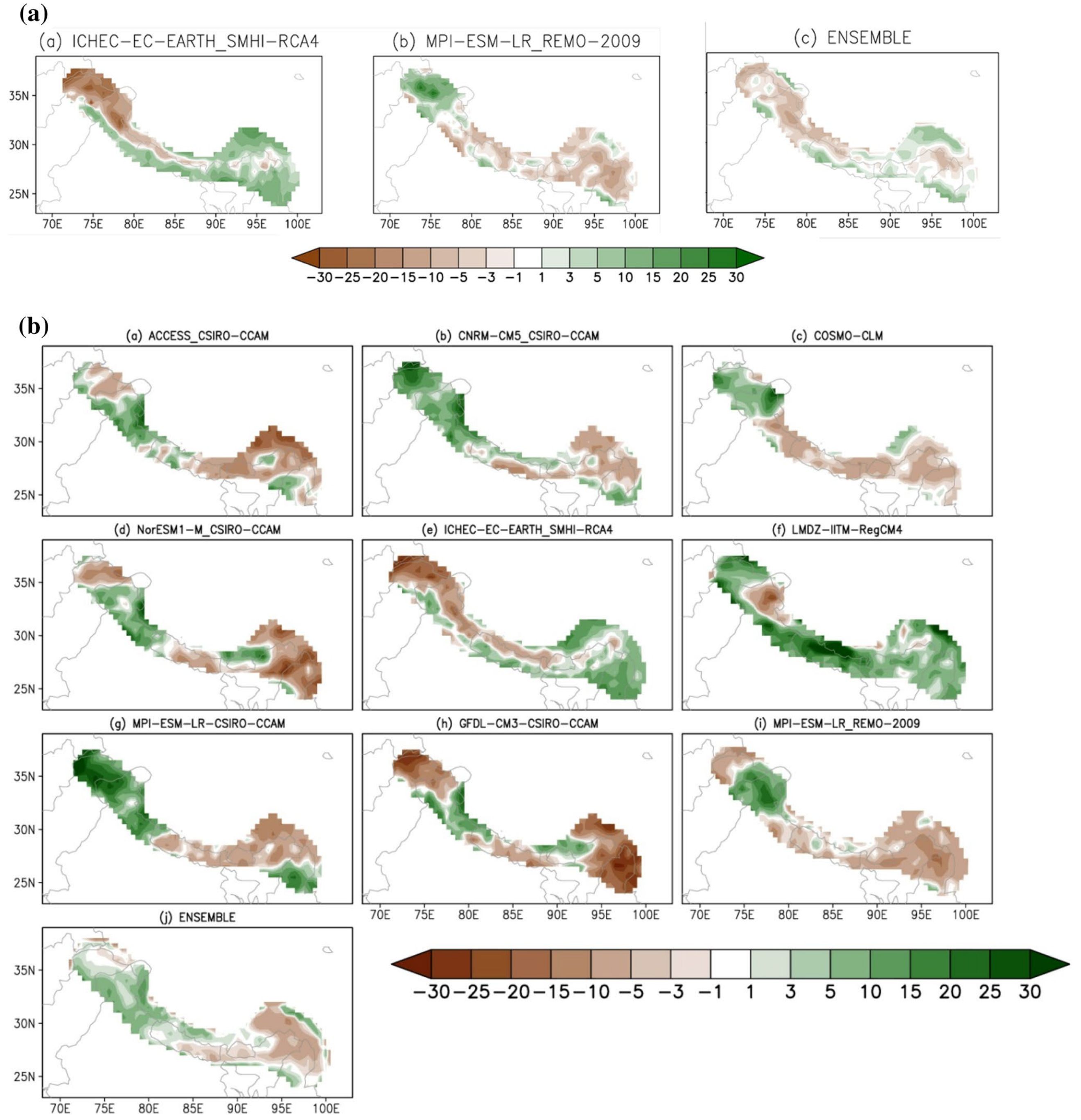

Fig. 3 Percentage change from present climate (1970–2005) in JJAS mean precipitation over Himalayan region in different CORDEX-SA experiments and their ensemble for near future (2020–2049) for **a** RCP2.6, **b** RCP4.5 and **c** RCP8.5

mean precipitation values. It is found that unlike the percentage change in precipitation, the percentage change in variability does not give a conclusive or distinct picture of regional contrast. Simultaneously, it can also be said that the variability or the changes in variability of precipitation over Himalayan region has a very high order of region specific response. Though one thing is evident that variability increases as one moves under least emission scenario towards most carbon intensive scenario and from near to far future (an increase of about 10–20% in both the cases). The eastern Himalayan region may experience a decreased variability but it is difficult to say so for central and western Himalayan region as they show mixed pattern. In tropical mountains the summer time precipitation is found

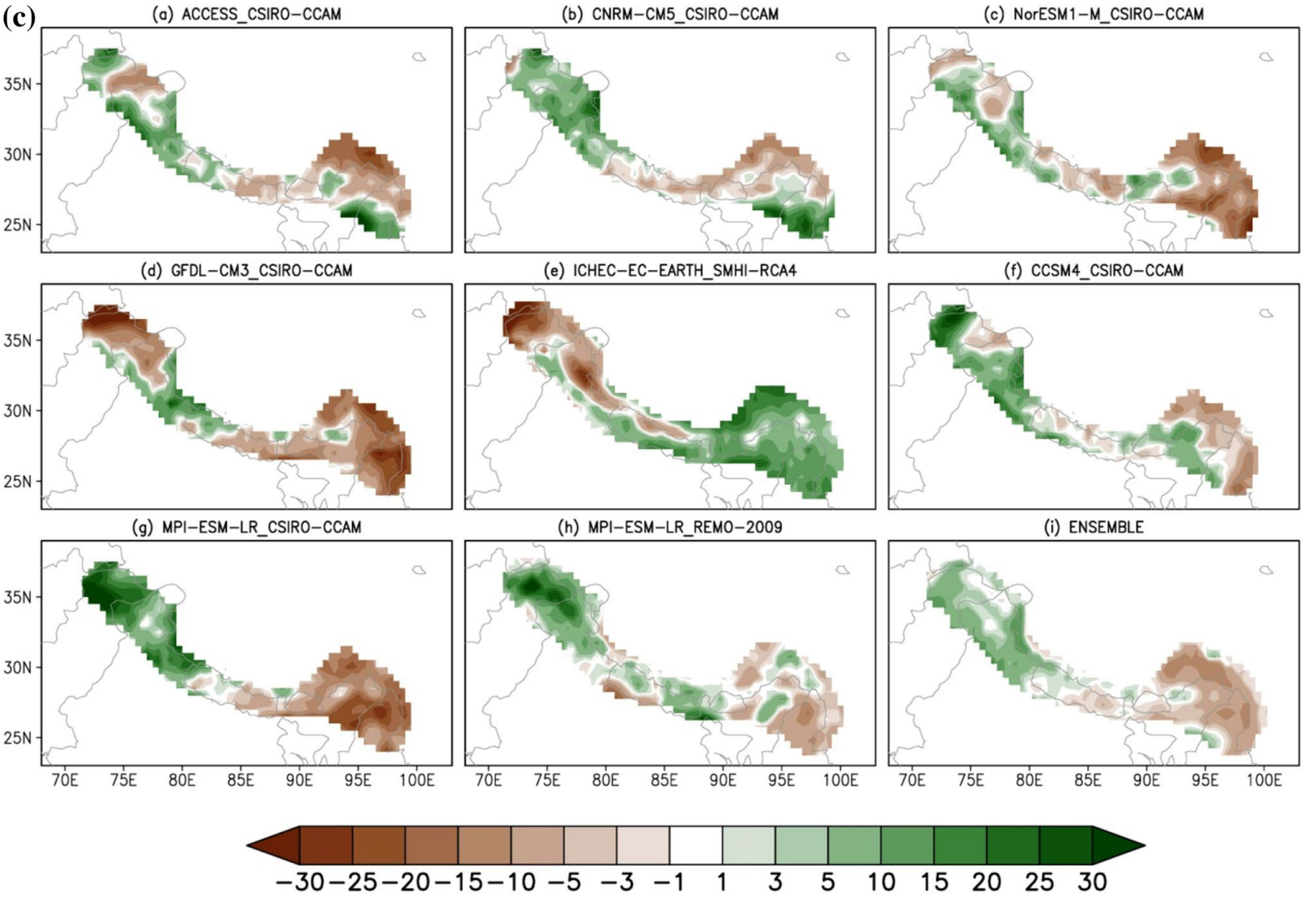

Fig. 3 (continued)

to be sensitively associated with the phase of the Indian-ocean dipole and El-Nino southern oscillation phenomena. (Shrestha et al. 2000; Vuille et al. 2005; Chan et al. 2008). So such natural climate variations superimposed on the regional climate of the higher elevation areas could be responsible for any detectable trend in the variation of precipitation or for that matter any other climatic parameter.

The positioning and features of different mountainous reliefs in the Himalayan region are chief drivers of climate; the merging of different ranges of mountains within this region creates such a complex topography of the area that possible dependence of precipitation patterns on topography still remains poorly defined. The altitudinal variation of difference in seasonal mean trend of future precipitation (mm/day/year) from that of present could give an idea of how rapidly or slowly precipitation would be varying in future at different elevations. From Fig. 8a looking at the red ensemble line for most of the experiments it is found that in the near future under all the three RCP scenarios the lower elevation points as well as high elevation points of up to 4000 m will see an enhanced variability in precipitation indicated by the increased positive trend with respect to the present conditions. The increase in trend magnitude is as high as 0.04 mm/day/year (approximately) in case of RCP8.5 for near-future. High elevation points above 4000 m does not experience much change in the yearly progression of precipitation as indicated by smaller values of change in trend in the near future. In far-future (Fig. 8b) there is a different pattern, as we found that the difference in trend seems to be smaller across the entire elevation profile especially for RCP4.5 where this difference is almost zero. This implies that near-future is going to see a more rapid increase in seasonal mean precipitation by about 0.02 mm/day/year (average) compared with that towards the end of century. This conclusion is based only on the ensemble. There is a large uncertainty in the trend difference which can be inferred from the black error bar. The uncertainty is as high as 0.1 mm/day/year at some elevations. Interestingly, there also seems to be a relationship of uncertainty with the elevation as the inter-model spread gradually reduces while going up. It is important to mention here that the ensemble for RCP2.6 includes only two experiments (see Table 2 for their names) therefore its ensemble cannot be studied in comparison with

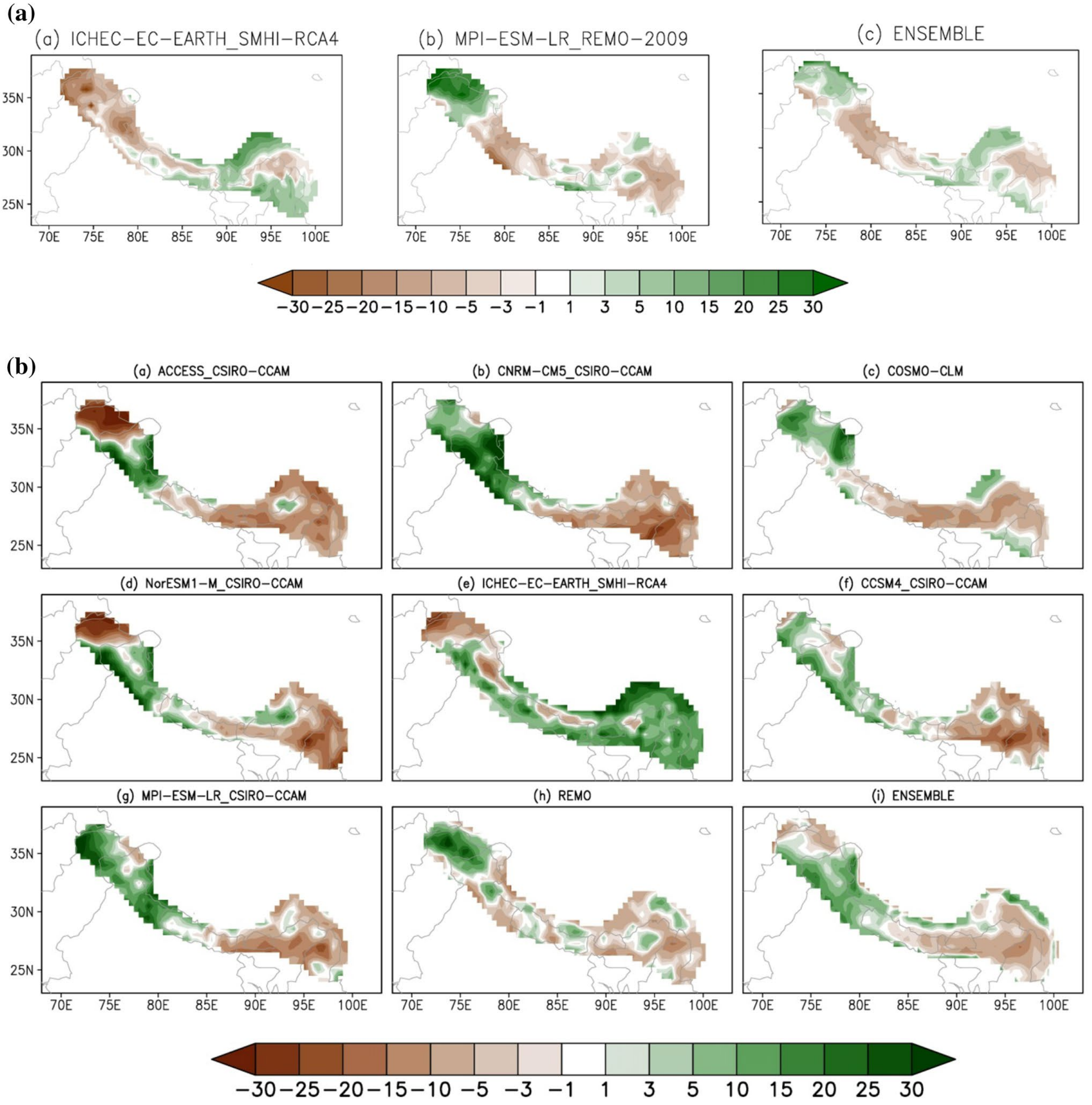

Fig. 4 Same as Fig. 3 but for far future (2070–2099)

other RCPs. Nonetheless, the ensemble seems to be more confident in the trend projections in the higher reaches of Himalayan region where the changes in trend value is also reducing. The physics of different CORDEX-SA RCMs in high altitude (colder and drier) environmental conditions does not differ much in their process representation in giving such a pattern of confidence. The spatial variability in precipitation distribution for the ensemble also seems to reduce at higher elevations as shown by red error bars. A dependency of precipitation change in future with elevation was also reported by Arakawa and Kitoh (2012). A general pattern of increasing precipitation in the western Himalayan region and decreasing precipitation in the eastern Himalayan region which was also evident in the climatology (see Figs. 3, 4) can also be seen in the long-term trend (1970–2099) analysis (Fig. 9) of the monsoon mean precipitation. Intensification of precipitation flux in western Himalayan region could imply in general, an increased influence

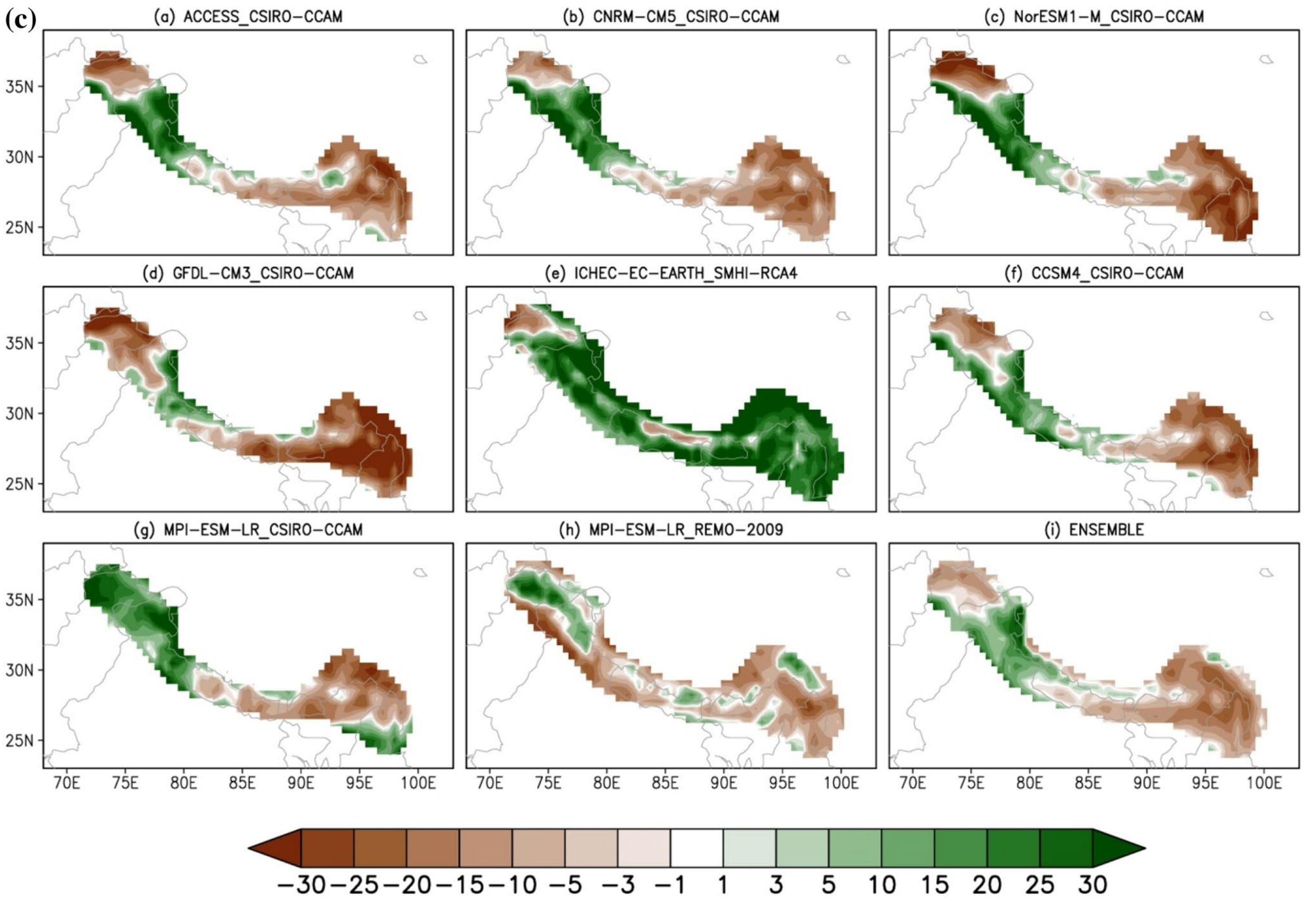

Fig. 4 (continued)

of mid-latitude disturbances (as described for Fig. 3b–c) on monsoonal flows in future. On the other hand, weakening of monsoonal flow in the eastern Himalayan region could be ascribed to the fact that under a warming scenario, when oceans would be heated, it will reduce the land-sea temperature contrast owing to reduced pressure gradient and less moisture influx from the ocean to the land. A dipolar distribution of such changes may also indicate that there could a spatial redistribution of precipitation over Himalayan region in future with no significant change in total precipitation amount (though this does not mean that the intensity will also not change). This is supported by comparison between spatial distribution of precipitation in present and future in form of probability distribution function (see Fig. S1). Here we does not see a significant change in distribution of mean precipitation in future. Further, the dipolar distribution of trends means that there could be a region specific response to changes in climate over the region owing to the complex topography and resulting localized climate patterns. There is an intensification of trend from RCP4.5 to the most intensive emission scenario—RCP8.5. Increasing precipitation in western Himalayan region could be due to lowering of lifting condensation level caused by continuance of anomalous cooling in western Himalayan

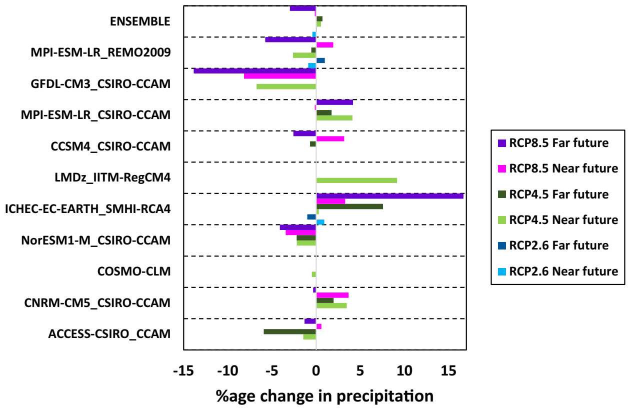

Fig. 5 Mean percentage change in JJAS precipitation averaged over Himalayan region for different RCPs and future time periods in different CORDEX-SA experiments and their ensemble

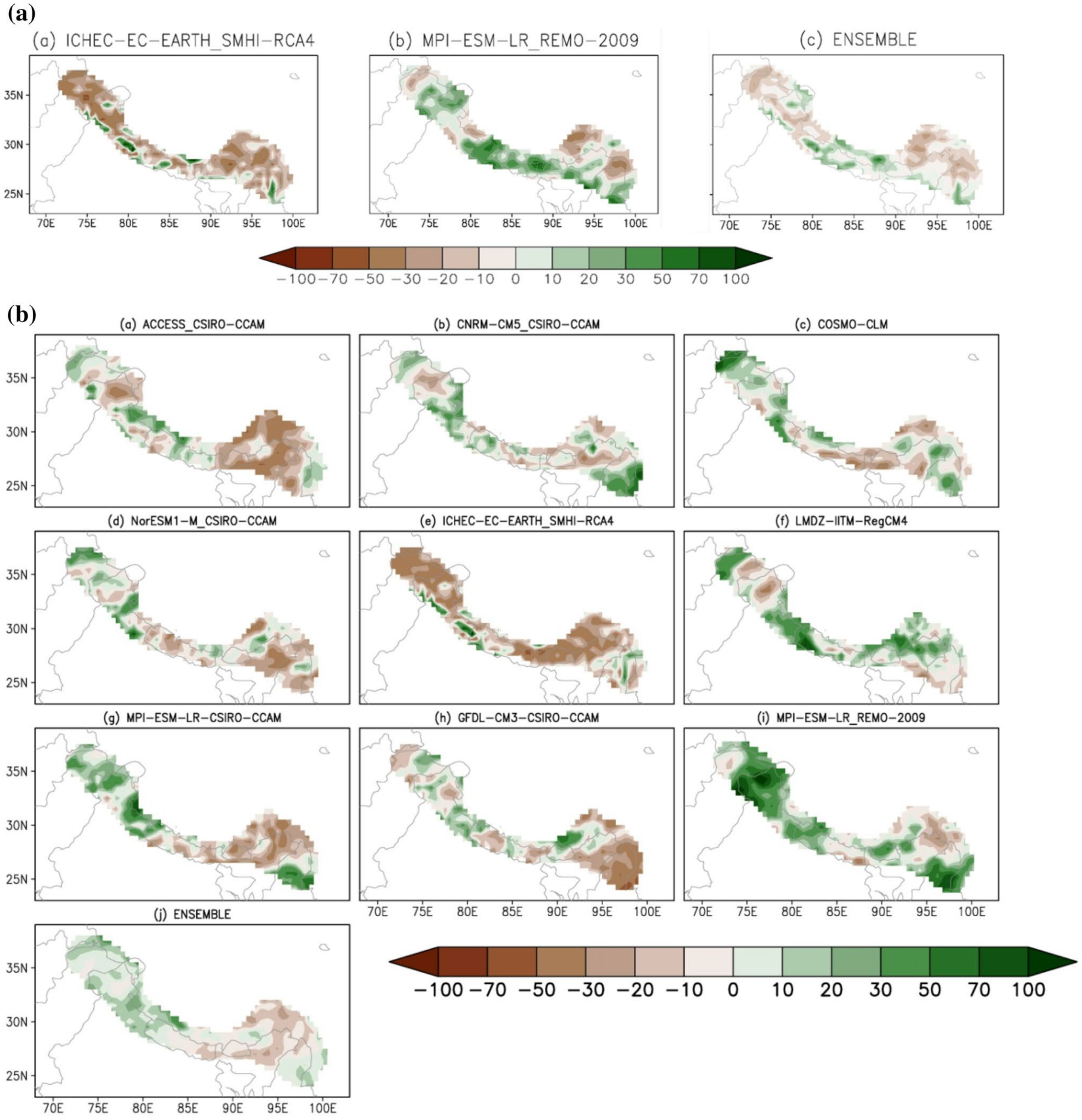

Fig. 6 Change in variability (as percentage change in standard deviation) from present climate (1970–2005) of yearly JJAS mean precipitation in different CORDEX-SA experiments and their ensemble for near future (2020–2049) for **a** RCP2.6, **b** RCP4.5 and **c** RCP8.5

region as reported by others (Archer and Fowler 2004). Other reason could be the enhancing trend in the soil moisture evaporation from the surface at lower elevation in response to greenhouse gas forcing.

Figure 10a–c presents the trend and uncertainty in future projections of JJAS mean precipitation over 130 years (1970–2099) averaged over Himalayan region for RCP2.6, 4.5 and 8.5, respectively. The result from APHRODITE for the period (1970–2005) is also shown to indicate the model biases in present climate. Though it is important to mention here that differences between observations and the model outputs cannot be necessarily due to the bias of the models. Many observational gridded datasets in this region are affected by uncertainties indeed, and in general all kinds of observations tend to underestimate total precipitation (because they neglect the snow component of precipitation

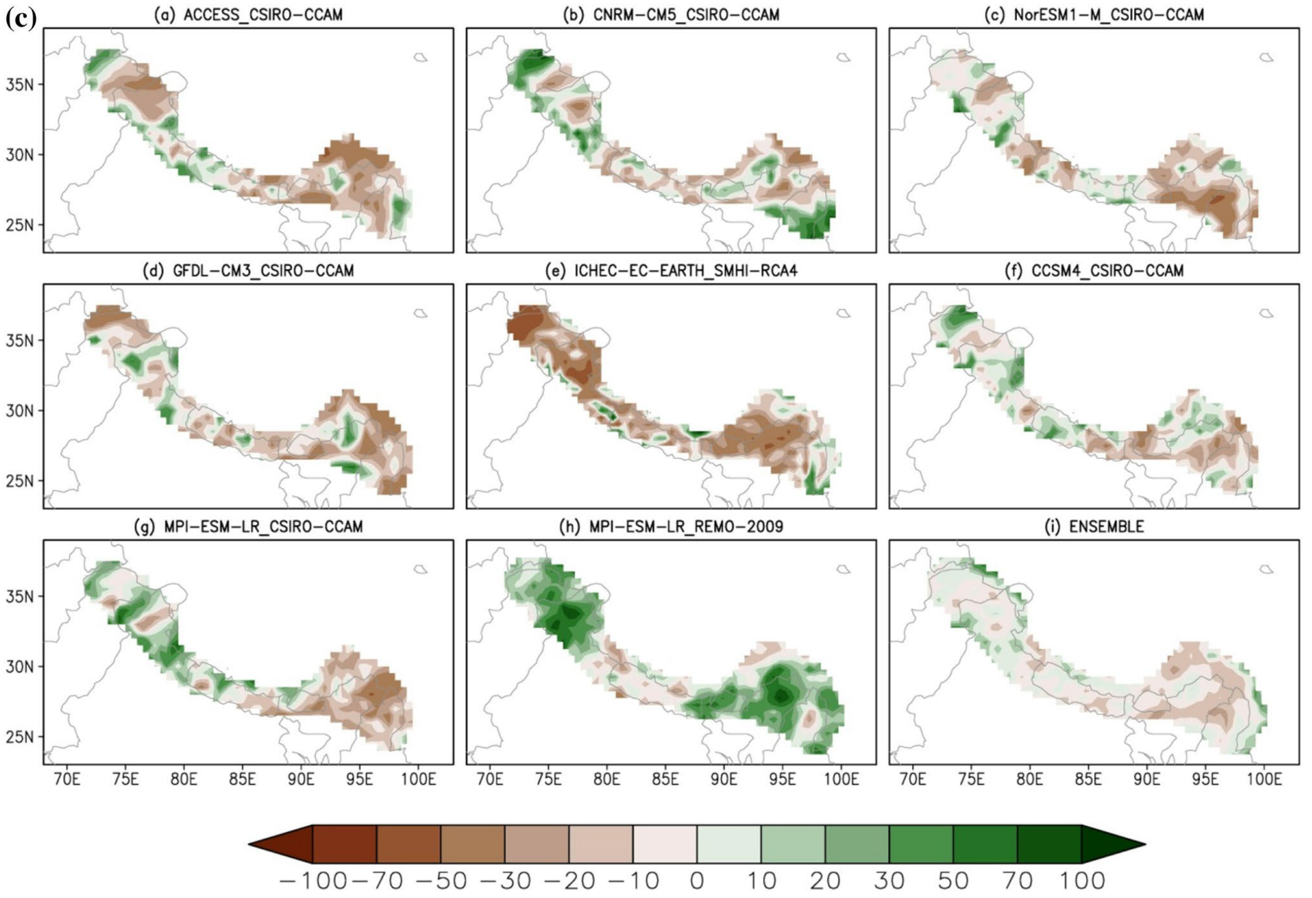

Fig. 6 (continued)

as discussed earlier). Nonetheless there exist significant wet bias in the CORDEX-SA set of experiments over Himalayan region as far as APHRODITE observations are taken as reference which was found by Ghimire et al. (2015) and also by Mishra et al. (2015). In Fig. 10 for RCP2.6 which is the least intensive emission scenario, the ensemble projects an increasing trend but it is non-significant and the slope value is very small. In RCP4.5 scenario, most of the experiments show a significant increasing trend of precipitation as indicated by their ensemble which indicates a strongly significant trend with a positive slope value of 0.004 mm/day/year. Also, it can be seen that in future for some years the seasonal mean precipitation is going above the base line variability value which suggests an increase in variability in future. The uncertainty (shown as shaded) seems to be large between the experiments which is up to 6 mm/day. One more important thing to be pointed out here is that the models are seen to be significantly overestimating the precipitation in the present climate compared with APHRODITE (Fig. S1). Based on a single observational dataset, it might be possible that the models are overestimating the precipitation magnitude in future. It is important to determine from these ensemble projections that whether the models are in general, in agreement with the sign of the change (positive slope) so it could be possible that on an area average, the direction of precipitation change in future is being truly represented. For RCP8.5 also, the ensemble gives similar projection with a strongly significant trend and a slope value of 0.004 mm/day/year as in RCP4.5. These increasing precipitation trend is in agreement with other model studies by Palazzi et al. (2015) who also found an increasing precipitation trend in future over this region. Again as discussed previously, the increases in precipitation could be due to enhanced moisture source from increased local scale surface evaporation or increased influence of mid-latitude disturbances and teleconnections on south-west monsoonal flow.

4 Discussion

Studies carried out in the past project in general, an increasing trend of precipitation across entire Himalayan region (Rupa Kumar et al. 2006; Revadekar et al. 2011; Dobler

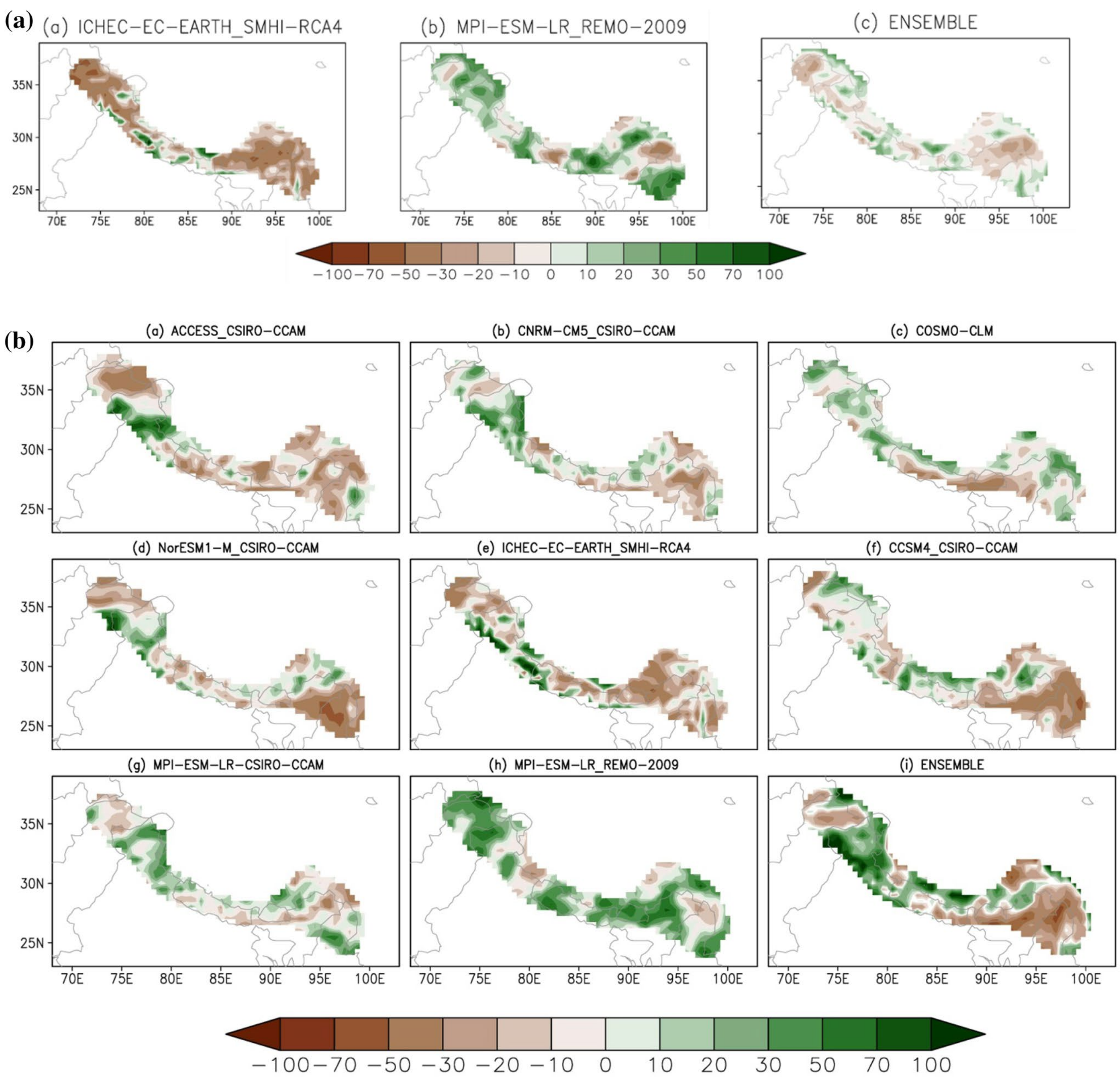

Fig. 7 Same as Fig. 6 but for far future (2070–2099)

and Ahrens 2011; Sengupta and Rajeevan 2013; Syed et al. 2014; Pandey et al. 2014; Oh et al. 2014). However, the CORDEX-SA RCMs considered in the present study project in general, an increasing (decreasing) long-term trend of precipitation in western (eastern) Himalayan region and provide similar results on the change in precipitation on near and far future time scales under various warming scenarios. An increase in precipitation in western Himalayan region in future could be linked with the reinforcing influence of mid-latitude disturbances like westerly troughs and Eurasian waves on monsoonal flow as found in the studies by Ramaswamy (1962), Raman and Rao (1981), Krishnan et al. (2009) and Yadav (2009) but for past or recent past climate. Further, a stronger monsoon climatology over north-west India (which includes western Himalayan region) could be teleconnected with a negative SST anomaly over east equatorial Atlantic Ocean through propagation of a Eurasian (Rossby) wave train from north-west of Europe to north-west of India via Black sea (Yadav 2017). The other teleconnections have also been reported in the

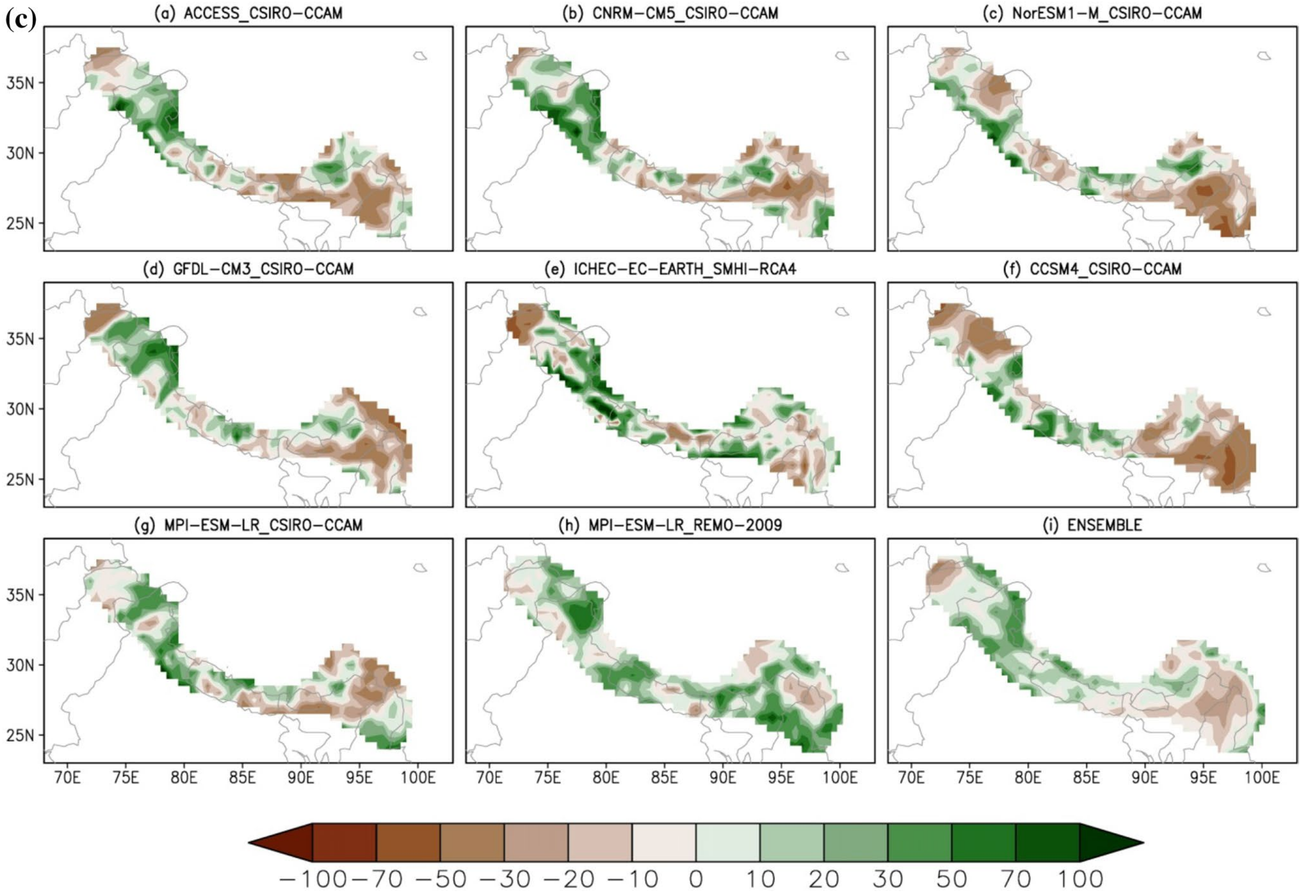

Fig. 7 (continued)

recent past like an increase in surface temperature over Iran (due to mid-latitude wave train that travels from Atlantic to Iran via Europe) could intensify the northerlies and westerlies over Arabian sea which could result in convergence of winds over north-west India, thus favoring deep convection and strengthening of monsoon in the region (Yadav 2016). This moisture or circulation could further get limited spatially within a sub-region of Himalayan region due to dominating role of local topography, thereby giving rise to contrasting wetness to that sub-region and dryness to the other. On the other hand, weakening of monsoonal flow over the eastern Himalayan region (where there is less influence of western disturbance and predominance of south-west monsoon) could be ascribed to the fact that under a warming scenario, when oceans would be heated, it will reduce the land-sea temperature contrast owing to reduced pressure gradient and less (monsoonal) moisture influx from the ocean to the land.

The present results may indicate that under the CORDEX framework where GCM-RCM based approach of using RCM to downscale the global scale features from GCM is applied, may provide a way to capture these teleconnections in the regional climate signals. To explain further, the far-off present atmospheric anomalies which is represented in the GCM simulations are provided to the RCM simulations in the form of lateral and boundary condition forcings. The RCMs through their dynamical downscaling ability are then able to further connect these far-off atmospheric features with the regional climate.

Climate models tend to show significant disagreements in their ability to reproduce the Indian summer monsoon in the present day as well as future projections (Annamalai et al. 2007; Lucas-Picher et al. 2011; Kumar et al. 2013; Shashikanth 2014; Jayasankar 2015). The uncertainty could arise due to lack of skill in model to simulate realistically the Indian monsoon as well as differences in the physics of individual models. The uncertainty in monsoon precipitation in response to global warming is related with two key opposing processes in response to large-scale warming: thermodynamic forcing

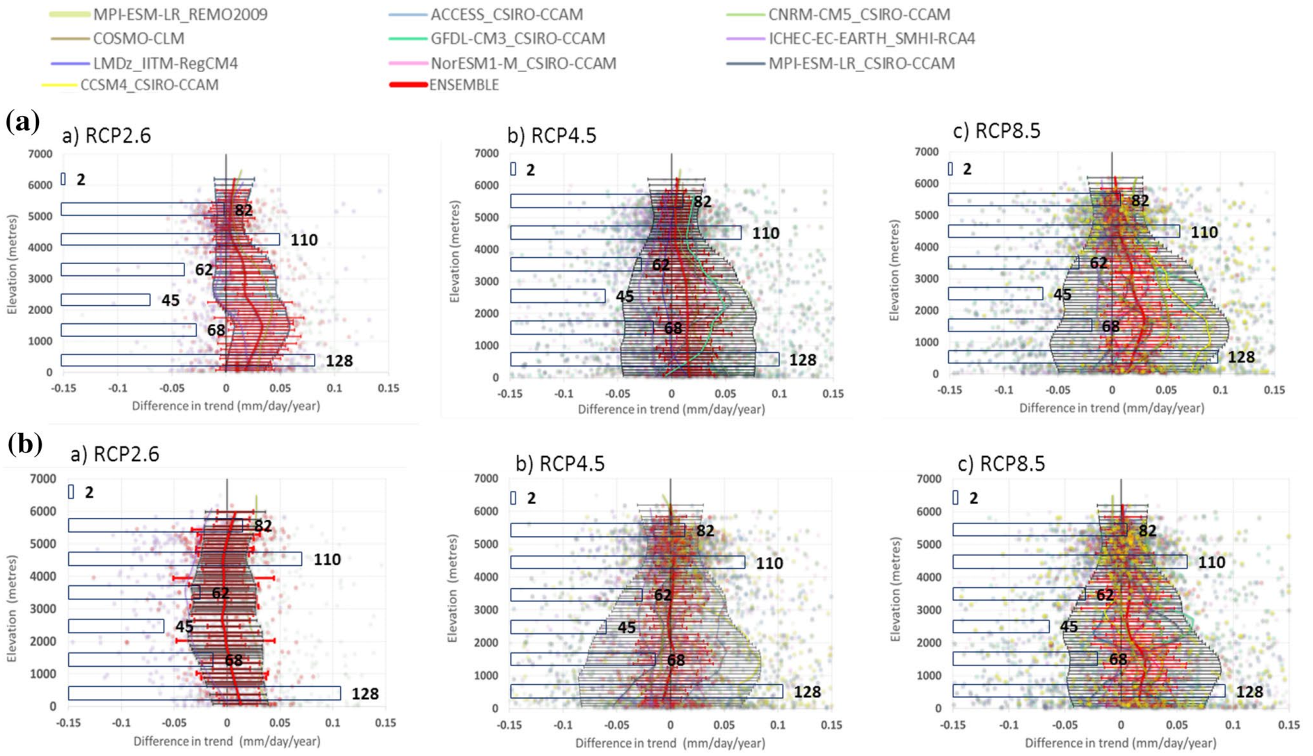

Fig. 8 (**aa–ac**) Near future (2020–2049) change in trend of JJAS mean precipitation (mm/day/year) from present climate (1970–2005) at every grid point over Himalayan region plotted against altitude. The scatter plot of different CORDEX-SA experiments including their ensemble (in *red*) *plotted* in the background (*dots*) with *colors* as shown in legend; the *curves* in *same color* as their corresponding dots represent the mean in 100 m classes of altitude smoothed by LOWESS method. (Cleveland 1979). The *black error bar* shows the model uncertainty as standard deviation between experiments within each 100 m class of altitude and *red error bar* shows the same but for spatial variability of the ensemble. The *rectangular bars with numbers* indicate the number of grid points falling within each 1000 m altitude range. (**ba–bc**) Same as (**aa–ac**) but for far future (2070–2099)

due to increase in atmospheric temperature which causes enhanced moisture and secondly, weakening circulation of the monsoon. (Ueda et al. 2006). The precipitation climatology in mountainous region can vary on inter-annual time scales in response to such changes in large scale circulation caused by the major modes of variation in atmosphere–ocean interactions.

An increased variability in future in Indian summer monsoon could be due to warmer Pacific Ocean in a warming scenario. This corresponds to an enhanced evaporation variability that can be communicated via Walker circulation to the South-west monsoon flow (Meehl and Arblaster 2003). The RCMs forced by an increased sea surface temperature and GCM runs under enhanced greenhouse gases scenario provides the necessary boundary conditions to make the simulated environment respond to warming. On the other hand, a decreased variability of precipitation in future could be due to region specific responses of near surface atmosphere to large scale external forcing which damps out the effect of warming. Such region specific responses could be an anomalous increase in snow cover, or mountain waves, valley scale circulations, etc.

A reduced rate of increase in future precipitation in high altitude regions could be due to long-term reduction in local evaporation from the underlying surface thus providing a weakened source of moisture and limited cloud formation in the model environment. The decrease in local scale surface evaporation could be related to changes in surface conditions and/or surface coverage (presence or absence of snow i.e. positive snow-ice albedo feedback), as well as increase in surface-air temperature under global warming effect (Arakawa and Kitoh 2012).

5 Conclusions

Climate projections are more uncertain for mountain regions compared to plains mainly due to complex orographic dependent climatic regime. In addition, important

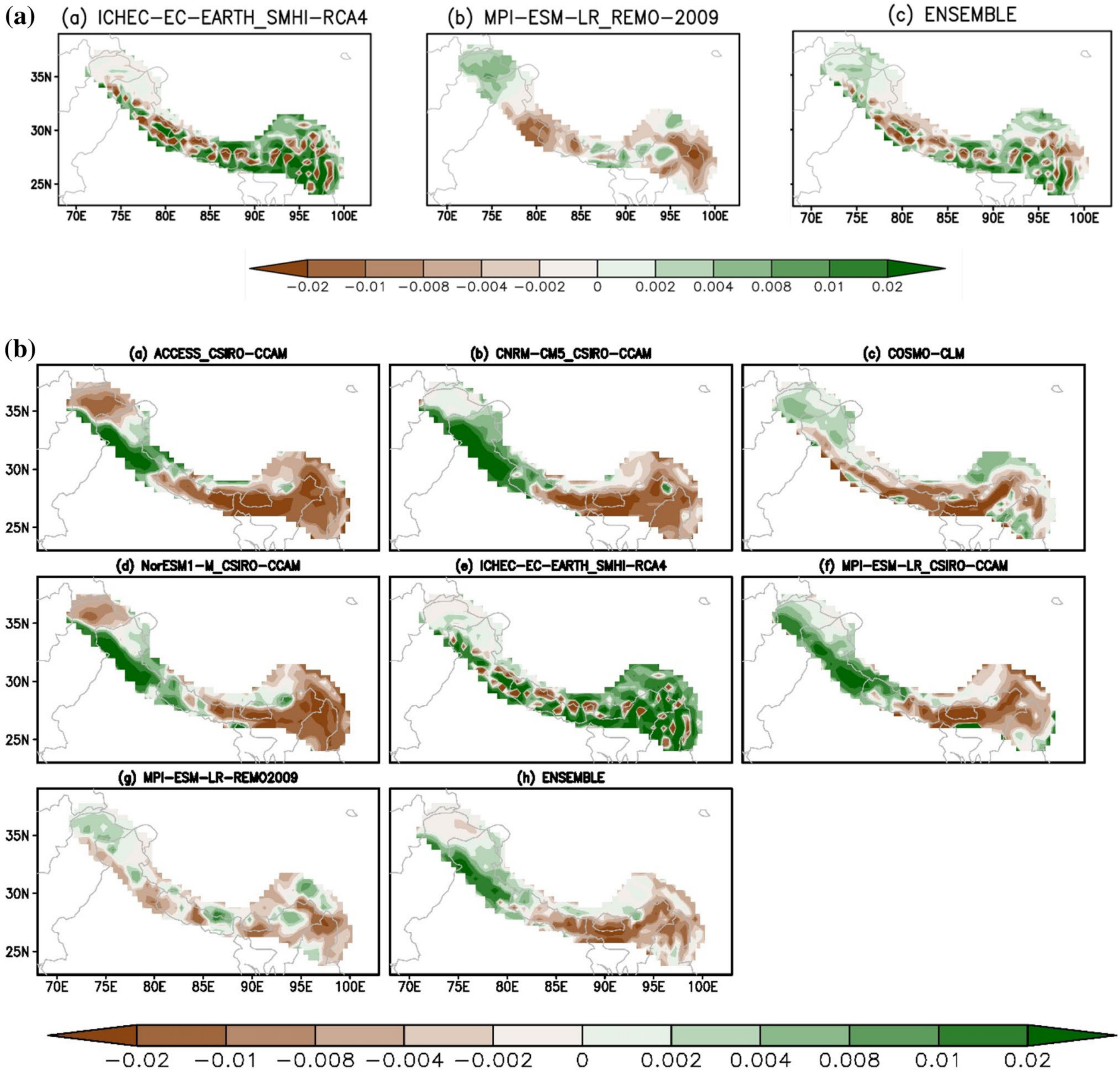

Fig. 9 Spatial distribution of trend of JJAS mean precipitation (mm/day/year) over Himalayan region in different CORDEX-SA experiments and their ensemble over the period 1970–2099 for **a** RCP2.6, **b** RCP4.5 and **c** RCP8.5

climatic variables such as precipitation are inadequately reproduced by experiments than others parameters such as temperature (Palazzi et al. 2015). Simultaneously, it is important to keep analyzing the upcoming simulations for their pattern of changes in climate that they project in future and look for the underlying uncertainties between them. Keeping in view this idea, precipitation changes in future scenarios is studied over Himalayan region from different CORDEX-SA experiments.

The changes in precipitation over the study region presents a complex and uncertain response to climate change with the models exhibiting a regional variation in both the magnitude and sign of the change. Although, there exists a substantial inter-model differences in simulating the amount of future changes in precipitation in space and time, most of the experiments over Himalayan region except for a part of Hindu-Kush region in western Himalayan region shows drier condition. There is in general, a

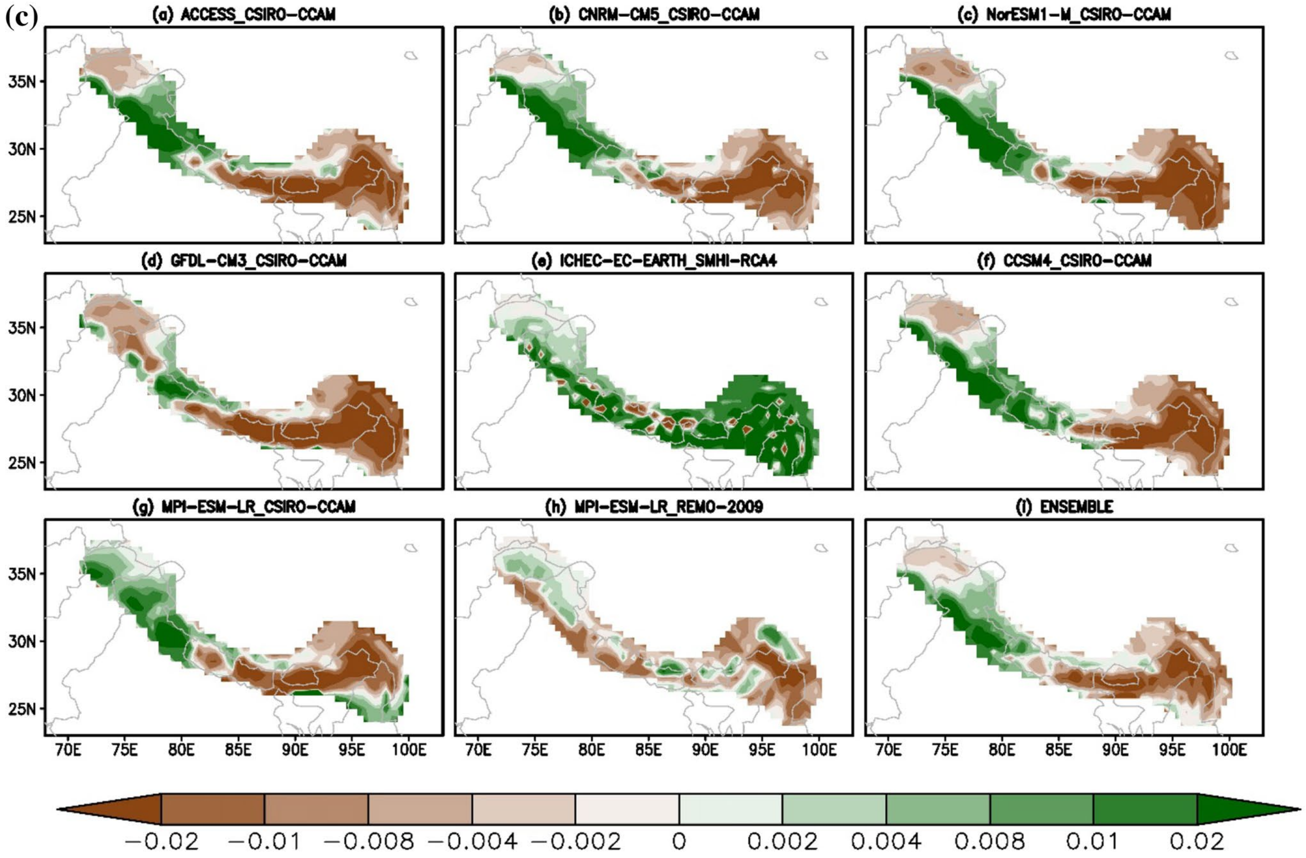

Fig. 9 (continued)

projection of wetter/drier future conditions for western/eastern Himalayan region with an intensification in both signs in far future when compared to near future. Though, averaged over the study region there is a gradual increasing precipitation trend seen throughout the twenty-first century in carbon intensive scenarios.

There is an overall agreement in increasing trend of precipitation for the period 1970–2099 when averaged over the whole region as shown by ensemble. However, when the spatial distribution of trend is analyzed, a general pattern of increasing precipitation in the western Himalayan region and decreasing precipitation in the east of the Himalayan region which was evident in the climatology also can be seen here in the long-term trend (1970–2099) analysis of the monsoon mean precipitation. Further, there also seems to be a relationship of precipitation trend change in future and the related uncertainty with elevation, with both getting reduced at higher elevation.

It should be mentioned that there are a number of important reservations to the results presented here. Modelling of climate of a complex terrain such as Himalayan region is a difficult task owing to a very high order of spatial variation in orography and orography-induced varying climate regimes. In particular, the ability of RCMs to capture snow/rain fractionation can be poor. Moreover, studies in the recent past show that RCMs under CORDEX-SA exhibit large wet bias over the Himalayan region (Ghimire et al. 2015; Mishra 2015) which could mean an overestimation of precipitation in future projections. Therefore, there is a requirement of bias correction of these RCM outputs using a high quality observational dataset before using the data for hydrological or impact studies. Also, there exists uncertainty in the climate projections arising out of various sources- in this case due to different forcings or GCMs or even different inherent RCM physics—which further needs to be quantified to make climate projections with a certain degree of reliability. A multi-model ensemble projection should be considered with extreme caution (Tebaldi and Knutti 2007).

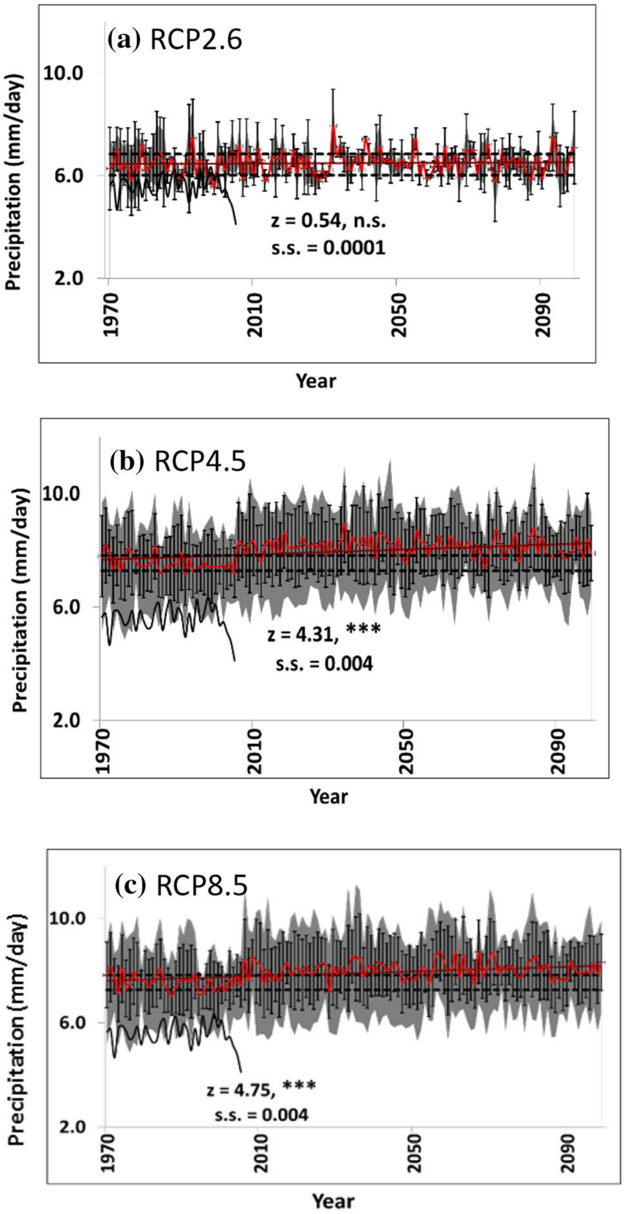

Fig. 10 Time series of JJAS mean precipitation (mm/day) for the 130 year period (1970–2099) averaged over Himalayan region from ensemble of 2 CORDEX-SA experiments for **a** RCP2.6, 7 experiments for **b** RCP4.5 and 9 experiments for **c** RCP8.5. The name of experiments for which the whole 130 year period data was available for different RCPs can be found in Table 2. The *red line* represents the yearly values of JJAS mean precipitation. The *error bars* represent ensemble mean ± 1 standard deviation and the *grey shading* shows the minimum and maximum values over all ensemble members. Also shown are the yearly values of JJAS mean precipitation from observation APHRODITE (*black*) for 1970–2005 to indicate wet bias inherent in the models. *Brown straight line* represents the linear trend (as Theil-Sen slope) in seasonal mean precipitation. The *dashed horizontal black lines* represent ± one standard deviation from the mean of present climate period 1970–2005, which shows the range of baseline variability. 'z' is the Mann–Kendall statistic for test of significance of trend at α = 0.05 where n.s., '*', '**' and '***' implies non-significant, poorly significant (P ≤ 0.05), moderately significant (P ≤ 0.01) and strongly significant (P ≤ 0.001) respectively. 's.s' is the Theil-Sen slope parameter (in units of mm/day/year)

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References

Ali S, Li D, Congbin F, Khan F (2015) Twenty first century climatic and hydrological changes over Upper Indus Basin of Himalayan region of Pakistan. Environ Res Lett 10(1):014007

Andermann C, Bonnet S, Gloaguen R (2011) Evaluation of precipitation data sets along the Himalayan front. Geochem Geophys Geosyst 12(7):1–16

Annamalai H, Hamilton K, Sperber KR (2007) The South Asian summer monsoon and its relationship with ENSO in the IPCC AR4 simulations. J Clim 20(6):1071–1092

Arakawa O, Kitoh A (2012) Elevation dependency of summertime precipitation and its change by global warming over the Tibetan Plateau and the surroundings simulated by a 60-km-mesh atmospheric general circulation model. 気象集誌. 第 2 輯 90(0):151–165

Archer DR, Fowler HJ (2004) Spatial and temporal variations in precipitation in the Upper Indus Basin, global teleconnections and hydrological implications. Hydrol Earth Syst Sci Discuss 8(1):47–61

Arora M, Singh P, Goel NK, Singh RD (2006) Spatial distribution and seasonal variability of rainfall in a mountainous basin in the Himalayan region. Water Resour Manag 20(4):489–508

Barros AP, Lettenmaier DP (1993) Dynamic modeling of the spatial distribution of precipitation in mountainous areas. Mon Weather Rev 121(4):1195–1214

Basistha A, Arya DS, Goel NK (2009) Analysis of historical changes in rainfall in the Indian Himalayas. Int J Climatol 29(4):555–572

Beniston M (2003) Climatic change in mountain regions: a review of possible impacts. In Climate variability and change in high elevation regions: past, present and future. Springer, Netherlands, pp. 5–31

Bhutiyani MR, Kale VS, Pawar NJ (2010) Climate change and the precipitation variations in the northwestern Himalaya: 1866–2006. Int J Climatol 30(4):535–548

Bookhagen B, Burbank DW (2006) Topography, relief, and TRMM-derived rainfall variations along the Himalaya. Geophys Res Lett 33(8):1–5

Bookhagen B, Burbank DW (2010) Toward a complete Himalayan hydrological budget: Spatiotemporal distribution of snowmelt and rainfall and their impact on river discharge. J Geophys Res 115(F3):1–25

Chan RY, Vuille M, Hardy DR, Bradley RS (2008) Intraseasonal precipitation variability on Kilimanjaro and the East African region and its relationship to the large-scale circulation. Theor Appl Climatol 93(3–4), 149–165.

Clarke L, Edmonds J, Jacoby H, Pitcher H, Reilly J, Richels R (2007) Scenarios of greenhouse gas emissions and atmospheric concentrations. US Department of Energy Publications, University of Nebraska-Lincoln, USA

Clayton HL (1982) Distribution and stochastic generation of annual and monthly precipitation on a mountainous watershed in southwest Idaho. Jawra J Am Water Resour Assoc 18(5):875–883

Cleveland WS (1979) Robust locally weighted regression and smoothing scatterplots. J Am Stat Assoc 74(368):829–836

Dash SK, Mishra SK, Pattnayak KC, Mamgain A, Mariotti L, Coppola E, Giorgi F, Giuliani G (2015) Projected seasonal mean summer monsoon over India and adjoining regions for the twenty-first century. Theor Appl Climatol 122(3–4):581–593

Dhar ON, Mandal BN, Kulkarni AK (2000) Review of precipitation studies carried out for high Himalaya in recent years. In: Pangtey YPS (ed) High Altitudes of the Himalaya—II (biodiversity, ecology and environment), vol 2, pp 509–521

Dimri AP, Dash SK (2012) Wintertime climatic trends in the western Himalayas. Clim Change 111(3–4):775–800

Dimri AP, Yasunari T, Wiltshire A, Kumar P, Mathison C, Ridley J, Jacob D (2013) Application of regional climate models to the Indian winter monsoon over the western Himalayas. Sci Total Environ 468:S36–S47

Dobler A, Ahrens B (2008) Precipitation by a regional climate model and bias correction in Europe and South Asia. Meteorol Z 17(4):499–509

Dobler A, Ahrens B (2011) Four climate change scenarios for the Indian summer monsoon by the regional climate model COSMO-CLM. J Geophys Res 116(D24):1–13

Fan F, Bradley RS, Rawlins MA (2014) Climate change in the northeastern US: regional climate model validation and climate change projections. Clim Dyn 43(1–2):145–161

Fowler HJ, Archer DR (2006) Conflicting signals of climatic change in the Upper Indus Basin. J Clim 19(17):4276–4293

Fujino J, Nair R, Kainuma M, Masui T, Matsuoka Y (2006) Multi-gas mitigation analysis on stabilization scenarios using AIM global model. Energy J 27:343–353

Gautam MR, Timilsina GR, Acharya K (2013) Climate change in the Himalayas: current state of knowledge. World Bank Policy Research Working Paper, (6516)

Ghimire S, Choudhary A, Dimri AP (2015) Assessment of the performance of CORDEX-South Asia experiments for monsoonal precipitation over the Himalayan region during present climate: part I. Clim Dyn. doi:10.1007/s00382-015-2747-2

Giorgetta MA, Jungclaus J, Reick CH, Legutke S, Bader J, Böttinger M, Brovkin V, Crueger T, Esch M, Fieg K, Glushak K, Gayler V, Haak H, Hollweg H-D, Ilyina T, Kinne S, Kornblueh L, Matei D, Mauritsen T, Mikolajewicz U, Mueller W, Notz D, Pithan F, Raddatz T, Rast S, Redler R, Roeckner E, Schmidt H, Schnur R, Segschneider J, Six KD, Stockhause M, Timmreck C, Wegner J, Widmann H, Wieners K-H, Claussen M, Marotzke J, Stevens B (2013) Climate and carbon cycle changes from 1850 to 2100 in MPI-ESM simulations for the Coupled Model Intercomparison Project phase 5. J Adv Model Earth Syst 5(3):572–597

Giorgi F, Mearns LO (1999) Introduction to special section: regional climate modeling revisited. J Geophys Res Atmos (1984–2012) 104(D6):6335–6352

Giorgi F, Hurrell JW, Marinucci MR, Beniston M (1997) Elevation dependency of the surface climate change signal: a model study. J Clim 10(2):288–296

Giorgi F, Jones C, Asrar GR (2009) Addressing climate information needs at the regional level: the CORDEX framework. World Meteorol Organ (WMO) Bull 58(3):175

Giorgi F, Coppola E, Solmon F, Mariotti L et al (2012) RegCM4: model description and preliminary tests over multiple CORDEX domains. Clim Res 52:7–29. doi:10.3354/cr01018

Gocic M, Trajkovic S (2013) Analysis of changes in meteorological variables using Mann–Kendall and Sen's slope estimator statistical tests in Serbia. Global Planet Change 100:172–182

Hazeleger W, Wang X, Severijns C, Ştefănescu S, Bintanja R, Sterl A, Wyser K, Semmler T, Yang S, van den Hurk B, van Noije T, van der Linden E, van der Wiel K (2012) EC-Earth V2. 2: description and validation of a new seamless earth system prediction model. Clim Dyn 39(11):2611–2629

Hewitt K (2005) The Karakoram anomaly? Glacier expansion and the 'elevation effect', Karakoram Himalaya. Mt Res Dev 25(4), 332–340.

Hijioka Y, Matsuoka Y, Nishimoto H, Masui T, Kainuma M (2008) Global GHG emission scenarios under GHG concentration stabilization targets. J Global Environ Eng 13:97–108

Immerzeel WW, Bierkens MF, Van Beek LP (2009) Hydrological response of climate change in a glaciated catchment in the Himalayas. In AGU Fall Meeting Abstracts 1, 08

Immerzeel WW, Van Beek LP, Bierkens MF (2010) Climate change will affect the Asian water towers. Science 328(5984):1382–1385

Jayasankar CB, Surendran S, Rajendran K (2015) Robust signals of future projections of Indian summer monsoon rainfall by IPCC AR5 climate models: role of seasonal cycle and interannual variability. Geophys Res Lett 42(9):3513–3520

Kendall MG (1938) A new measure of rank correlation. Biometrika, 81–93

Krishnan R, Kumar V, Sugi M, Yoshimura J (2009) Internal feedbacks from monsoon–midlatitude interactions during droughts in the Indian summer monsoon. J Atmos Sci 66(3):553–578

Kucharski F, Bracco A, Yoo JH, Tompkins AM, Feudale L, Ruti P, Dell'Aquila A (2009) A Gill–Matsuno-type mechanism explains the tropical Atlantic influence on African Indian monsoon rainfall. Q J R Meteorol Soc 135(640):569–579

Kulkarni A, Patwardhan S, Kumar KK, Ashok K, Krishnan R (2013) Projected climate change in the Hindu Kush-Himalayan region by using the high-resolution regional climate model PRECIS. Mt Res Dev 33(2):142–151

Kumar V, Jain SK (2010) Trends in seasonal and annual rainfall and rainy days in Kashmir Valley in the last century. Quatern Int 212(1):64–69

Kumar P, Wiltshire A, Mathison C, Asharaf S, Ahrens B, Lucas-Picher P, Jacob D (2013) Downscaled climate change projections with uncertainty assessment over India using a high resolution multi-model approach. Sci Total Environ 468:S18–S30

Liu X, Chen B (2000) Climatic warming in the Tibetan Plateau during recent decades. Int J Climatol 20(14):1729–1742

Lobell DB, Burke MB, Tebaldi C, Mastrandrea MD, Falcon WP, Naylor RL (2008) Prioritizing climate change adaptation needs for food security in 2030. Science 319(5863):607–610

Loukas A, Quick MC (1994) Precipitation Distribution in Coastal British Columbia. JAWRA J Am Water Resour Assoc 30:705–727

Lucas-Picher P, Christensen JH, Saeed F, Kumar P, Asharaf S, Ahrens B, Wiltshire AJ, Jacob D, Hagemann S (2011) Can regional climate models represent the Indian monsoon? J Hydrometeorol 12(5):849–868

Marquínez J, Lastra J, García P (2003) Estimation models for precipitation in mountainous regions: the use of GIS and multivariate analysis. J Hydrol 270(1):1–11

Masson D, Frei C (2016) Long-term variations and trends of mesoscale precipitation in the Alps: recalculation and update for 1901–2008. Int J Climatol 36(1):492–500

Mathison C, Wiltshire A, Dimri AP, Falloon P, Jacob D, Kumar P, Yasunari T (2013) Regional projections of North Indian climate for adaptation studies. Sci Total Environ 468:S4–S17

Mcgregor JL, Dix MR (2001) The CSIRO conformal-cubic atmospheric GCM. In IUTAM Symposium on Advances in Mathematical Modelling of Atmosphere and Ocean Dynamics (pp. 197–202). Springer Netherlands

Medina S, Houze RA, Kumar A, Niyogi D (2010) Summer monsoon convection in the Himalayan region: terrain and land cover effects. Q J R Meteorol Soc 136(648):593–616

Meehl GA, Arblaster JM (2003) Mechanisms for projected future changes in south Asian monsoon precipitation. Clim Dyn 21(7–8):659–675

Mishra V (2015) Climatic uncertainty in Himalayan water towers. J Geophys Res Atmos 120(7):2689–2705

Mondal A, Kundu S, Mukhopadhyay A (2012) Rainfall trend analysis by Mann–Kendall test: a case study of North-Eastern part of Cuttack district, Orissa. Int J Geol Earth Environ Sci 2(1):70–78

Moss RH, Edmonds JA, Hibbard KA, Manning MR, Rose SK, Van Vuuren DP, Meehl GA (2010) The next generation of scenarios for climate change research and assessment. Nature 463(7282):747–756

Mote P, Brekke L, Duffy PB, Maurer E (2011) Guidelines for constructing climate scenarios. Eos Trans Am Geophys Union 92(31):257–258.

Nengker T, Choudhary A, Dimri AP (2017) Assessment of the performance of CORDEX-SA experiments in simulating seasonal mean temperature over the Himalayan region for the present climate: part I. Clim Dyn. doi:10.1007/s00382-017-3597-x

Oh SG, Park JH, Lee SH, Suh MS (2014) Assessment of the RegCM4 over East Asia and future precipitation change adapted to the RCP scenarios. J Geophys Res Atmos 119(6):2913–2927

Palazzi E, Hardenberg J, Provenzale A (2013) Precipitation in the Hindu-Kush Karakoram Himalaya: observations and future scenarios. J Geophys Res Atmos 118(1):85–100

Palazzi E, von Hardenberg J, Terzago S, Provenzale A (2015) Precipitation in the Karakoram-Himalaya: a CMIP5 view. Clim Dyn 45(1–2):21–45

Panday PK, Thibeault J, Frey KE (2015) Changing temperature and precipitation extremes in the Hindu Kush-Himalayan region: an analysis of CMIP3 and CMIP5 simulations and projections. Int J Climatol 35(10):3058–3077

Pervez MS, Henebry GM (2014) Projections of the Ganges–Brahmaputra precipitation—downscaled from GCM predictors. J Hydrol 517:120–134

Pranuthi G, Dubey SK, Tripathi SK, Chandniha SK (2014) Trend and change point detection of precipitation in urbanizing Districts of Uttarakhand in India. Indian J Sci Technol 7(10):1573–1582

Rajbhandari R, Shrestha AB, Kulkarni A, Patwardhan SK, Bajracharya SR (2015) Projected changes in climate over the Indus river basin using a high resolution regional climate model (PRECIS). Clim Dyn 44(1–2):339–357

Raman CRV, Rao YP (1981) Blocking highs over Asia and monsoon droughts over India. Nature 289:271–273

Ramaswamy C (1962) Breaks in the Indian summer monsoon as a phenomenon of interaction between the easterly and the subtropical westerly jet streams 1. Tellus 14(3):337–349

Rasmussen R, Baker B, Kochendorfer J, Meyers T, Landolt S, Fischer AP, Black J, Thériault JM, Kucera P, Gochis D, Smith C, Nitu R, Hall M, Ikeda K, Gutmann E (2012) How well are we measuring snow: The NOAA/FAA/NCAR winter precipitation test bed. Bull Am Meteorol Soc 93(6):811–829

Revadekar JV, Patwardhan SK, Rupa Kumar K (2011) Characteristic features of precipitation extremes over India in the warming scenarios. Adv Meteorol 2011:1–12

Riahi K, Grübler A, Nakicenovic N (2007) Scenarios of long-term socio-economic and environmental development under climate stabilization. Technol Forecast Soc Chang 74(7):887–935

Riahi K, Rao S, Krey V, Cho C, Chirkov V, Fischer G, Kindermann G, Nakicenovic N, Rafaj P (2011) RCP8.5—a scenario of comparatively high greenhouse gas emissions. Clim Change 109(1–2):33–57

Rupa Kumar K, Sahai AK, Kumar KK, Patwardhan SK, Mishra PK, Revadekar JV, Kamala K, Pant GB (2006) High-resolution climate change scenarios for India for the 21st century. Curr Sci 90(3):334–345

Saeed F, Hagemann S, Jacob D (2012) A framework for the evaluation of the South Asian summer monsoon in a regional climate model applied to MPI-ESM-LR_REMO2009. Int J Climatol 32(3):430–440

Samuelsson P, Jones CG, Willén U, Ullerstig A, Gollvik S, Hansson ULF, Jansson C, Kjellström E, Nikulin G, Wyser K (2011) The Rossby Centre Regional Climate model RCA3: model description and performance. Tellus A 63(1):4–23

Sen PK (1968) Estimates of the regression coefficient based on Kendall's tau. J Am Stat Assoc 63(324):1379–1389

Şen Z, Habib Z (2000) Spatial precipitation assessment with elevation by using point cumulative semivariogram technique. Water Resour Manag 14(4):311–325

Sengupta A, Rajeevan M (2013) Uncertainty quantification and reliability analysis of CMIP5 projections for the Indian summer monsoon. Curr Sci 105(12):1692

Shadmani M, Marofi S, Roknian M (2012) Trend analysis in reference evapotranspiration using Mann–Kendall and Spearman's Rho tests in arid regions of Iran. Water Resour Manag 26(1):211–224

Sharma KP, Moore Iii B, Vorosmarty CJ (2000) Anthropogenic, climatic, and hydrologic trends in the Kosi Basin, Himalaya. Clim Change 47(1–2):141–165

Shashikanth K, Salvi K, Ghosh S, Rajendran K (2014) Do CMIP5 simulations of Indian summer monsoon rainfall differ from those of CMIP3? Atmos Sci Lett 15(2):79–85

Shrestha AB, Wake CP, Mayewski PA, Dibb JE (1999) Maximum temperature trends in the Himalaya and its vicinity: an analysis based on temperature records from Nepal for the period 1971–94. J Clim 12(9):2775–2786

Shrestha AB, Wake CP, Dibb JE, Mayewski PA (2000) Precipitation fluctuations in the Nepal Himalaya and its vicinity and relationship with some large scale climatological parameters. Int J Climatol 20(3):317–327

Singh P, Kumar N (1997) Effect of orography on precipitation in the western Himalayan region. J Hydrol 199(1):183–206

Singh P, Ramasastri KS, Naresh K (1995) Topographical influence on precipitation distribution in different ranges of western Himalayas. Nord Hydrol 26(4–5):259–284

Smith SJ, Wigley TML (2006) Multi-gas forcing stabilization with Minicam. Energy J 27:373–391

Syed FS, Iqbal W, Syed AAB, Rasul G (2014) Uncertainties in the regional climate models simulations of South-Asian summer monsoon and climate change. Clim Dyn 42(7–8):2079–2097

Taylor KE, Stouffer RJ, Meehl GA (2012) An overview of CMIP5 and the experiment design. Bull Am Meteorol Soc 93(4):485–498

Tebaldi C, Knutti R (2007) The use of the multi-model ensemble in probabilistic climate projections. Philos Trans R Soc Lond A Math Phys Eng Sci 365(1857):2053–2075

Thomson AM, Calvin KV, Smith SJ, Kyle GP, Volke A, Patel P, Delgado-Arias S, Bond-Lamberty B, Wise MA, Clarke LE, Edmonds JA (2011) RCP4. 5: a pathway for stabilization of radiative forcing by 2100. Clim Change 109(1–2):77–94

Ueda H, Iwai A, Kuwako K, Hori ME (2006) Impact of anthropogenic forcing on the Asian summer monsoon as simulated by eight GCMs. Geophys Res Lett 33(6):1–4

Van Vuuren DP, Edmonds J, Kainuma M, Riahi K, Thomson A, Hibbard K, Hurtt GC, Kram T, Krey V, Lamarque JF, Masui T (2011a) The representative concentration pathways: an overview. Clim Change 109:5–31

Van Vuuren DP, Stehfest E, den Elzen MG, Kram T, van Vliet J, Deetman S, Isaac M, Goldewijk KK, Hof A, Beltran AM, Oostenrijk R (2011b) RCP2. 6: exploring the possibility to keep global mean temperature increase below 2 degree celsius. Clim Change 109(1–2):95–116

Venable NB, Fassnacht SR, Hendricks AD (2015) Spatial changes in climate across Mongolia. In: Proceedings of the trans-disciplinary research conference: Building resilience of Mongolian Rangelands, Ulaanbaatar, Mongolia, 9–10 June 2015

Viviroli D, Dürr HH, Messerli B, Meybeck M, Weingartner R (2007) Mountains of the world, water towers for humanity: Typology, mapping, and global significance. Water Resour Res 43(7):1–13

Vuille M, Werner M, Bradley RS, Chan RY, Keimig F (2005) Stable isotopes in East African precipitation record Indian Ocean zonal mode. Geophys Res Lett 32(21):1–5

Wan H, Zhang X, Zwiers FW, Shiogama H (2013) Effect of data coverage on the estimation of mean and variability of precipitation at global and regional scales. J Geophys Res Atmos 118(2):534–546

Wilks DS (2011) Statistical methods in the atmospheric sciences, Vol 100. Academic press, San Diego, USA

Winiger MGHY, Gumpert M, Yamout H (2005) Karakorum–Hindukush–western Himalaya: assessing high-altitude water resources. Hydrol Process 19(12):2329–2338

Wu Y, Wu SY, Wen J, Xu M, Tan J (2016) Changing characteristics of precipitation in China during 1960–2012. Int J Climatol 36(3):1387–1402

Xu B, Cao J, Hansen J, Yao T, Joswia DR, Wang N, Wu G, Wang M, Zhao H, Yang W, Liu X (2009) Black soot and the survival of Tibetan glaciers. Proc Natl Acad Sci 106(52):22114–22118

Yadav RK (2009) Changes in the large-scale features associated with the Indian summer monsoon in the recent decades. Int J Climatol 29(1):117–133

Yadav RK (2016) On the relationship between Iran surface temperature and northwest India summer monsoon rainfall. Int J Climatol 36:4425–4438. doi:10.1002/joc.4648

Yadav RK (2017) On the relationship between east equatorial Atlantic SST and ISM through Eurasian wave. Clim Dyn 48(1–2):281–295

Yatagai A, Arakawa O, Kamiguchi K, Kawamoto H, Nodzu MI, Hamada A (2009) A 44-year daily gridded precipitation dataset for Asia based on a dense network of rain gauges. Sola 5:137–140

Yatagai A, Kamiguchi K, Arakawa O, Hamada A, Yasutomi N, Kitoh A (2012) Aphrodite: Constructing a long-term daily gridded pecipitation dataset of Asia based on a dense network of rain gauges. Am Meteorol Soc 93:1401–1415

Yue S, Hashino M (2003) Long term trends of annual and monthly precipitation in Japan. JAWRA J Am Water Resour Assoc 39(3):587–596

Zhang X, Vincent LA, Hogg WD, Niitsoo A (2000) Temperature and precipitation trends in Canada during the 20th century. Atmos Ocean 38(3):395–429