

Uncertainties in the regional climate models simulations of South-Asian summer monsoon and climate change

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Abstract The uncertainties in the regional climate models (RCMs) are evaluated by analyzing the driving global data of ERA40 reanalysis and ECHAM5 general circulation models, and the downscaled data of two RCMs (RegCM4 and PRECIS) over South-Asia for the present day simulation (1971–2000) of South-Asian summer monsoon. The differences between the observational datasets over South-Asia are also analyzed. The spatial and the quantitative analysis over the selected climatic regions of South-Asia for the mean climate and the inter-annual variability of temperature, precipitation and circulation show that the RCMs have systematic biases which are independent from different driving datasets and seems to come from the physics parameterization of the RCMs. The spatial gradients and topographically-induced structure of climate are generally captured and simulated values are within a few degrees of the observed values. The biases in the RCMs are not consistent with the biases in the driving fields and the models show similar spatial patterns after downscaling different global datasets. The annual cycle of temperature and rainfall is well simulated by the RCMs, however the RCMs are not able to capture the inter-annual variability. ECHAM5 is also downscaled for the future (2071–2100) climate under A1B emission scenario. The climate change signal is consistent between ECHAM5 and RCMs. There is warming over all the regions of South-Asia

associated with increasing greenhouse gas concentrations and the increase in summer mean surface air temperature by the end of the century ranges from 2.5 to 5 °C, with maximum warming over north western parts of the domain and 30 % increase in rainfall over north eastern India, Bangladesh and Myanmar.

Keywords Regional climate model · RegCM4 · PRECIS · South-Asia · Monsoon · Climate change · Uncertainty

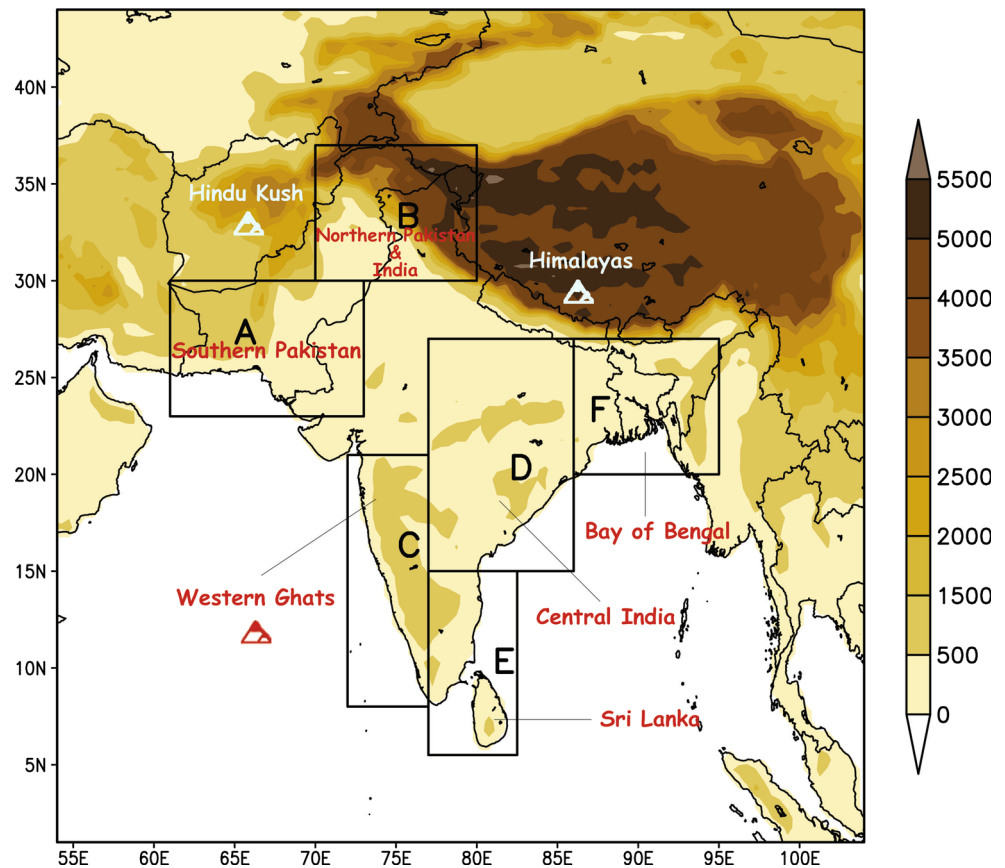
1 Introduction

The geographic patterns of South-Asia are very complex, with extensive mountain ranges; the Himalayan mountain system (extending over Bhutan, Nepal, India, Pakistan and Afghanistan) includes Karakoram and the Hindu-Kush mountain range that stretches between central Afghanistan and northern Pakistan and other, lesser ranges that extend out from the Pamir Knot (Fig. 1). This great wall of high mountains system effectively closes the region from the mid-latitude influences of Central-Asia and plays an important role in shaping the unique climatic characteristics of the region. There are large river basins, plateaus, deserts and a long coastline flanked by the Arabian Sea, the Bay of Bengal and the north Indian Ocean. These complex geographical features pose a great challenge to climate models aiming at reproducing the observed climate and its variability. South-Asian summer monsoon (SASM) rainfall is the backbone of the agriculture based economies of the region and directly affects the very livelihood of more than 1 billion people living in this region. Climate models generally have difficulties in reproducing both the position and variation of the monsoon rain bands of SASM, because

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Fig. 1 Domain (1–44°N and 51–104°E) of the RCMs. Surface elevation in meters (shaded) and Boxes represent the selected regions of South-Asia



of their inability to resolve the monsoon convective processes and the complex regional heterogeneity (Sabin et al. 2013).

The main tools to produce climate change projections based on emission scenarios are general circulation models (GCMs). These models generally well simulate the features of the present-day climate at the global and continental scale (Houghton et al. 2001) and the climate projections are widely used to study the impacts of the climate change on water resources, agriculture and different components of the climate system (e.g. Russell et al. 2000; Gregory et al. 2002; Hu and Wu 2004; Wang 2005). In the recent decades many studies have focused on the SASM in the GCM simulations (Krishnamurti et al. 2002, 2006; Kang et al. 2004; Kang and Shukla 2005; Wang et al. 2005). However, recent studies show that these GCMs have varying skills in simulating climatology and inter-annual variability of observed rainfall because of the large systematic and random biases in simulating the SASM (Kar et al. 2011; Acharya et al. 2011). Several reasons could be behind the poor performance of these models in simulating the SASM. One of the reasons is the coarse resolution of GCMs that affects their ability to predict detailed rainfall variability and provide limited information about the climate change impacts at regional and sub-regional scales (Busuioc et al.

1999; Acharya et al. 2011). Very high resolution global GCM of Meteorological Research Institute of Japan with 20-km horizontal resolution has been fairly successful in resolving the SASM orographic precipitation maxima along mountains of the Western Ghats and Myanmar (e.g., Kitoh and Kusunoki 2009; Mizuta et al. 2012; Krishnan et al. 2012; Rajendran et al. 2012). Conducting long climate simulations using such high-resolution GCMs remains a major challenge because of the huge computational requirements. One common method for obtaining fine scale regional information is to dynamically downscale the GCM outputs using a regional climate model (RCM). Due to higher resolution, RCMs are able to better resolve atmospheric fields, allowing the representation of small-scale processes like meso-scale cyclones and related weather phenomena. Detailed description of geographical features in RCMs like topography and land-surface characteristics interact with the atmosphere and result in better estimation of orographic precipitation (Feser 2006). In recent years, the RCMs have been increasingly used in climate change studies (e.g. Giorgi and Lionello 2008; Pal et al. 2004; Onol and Semazzi 2009; Gao et al. 2012; Kumar et al. 2006; Taylor et al. 2007; Akhtar et al. 2008; Almazroui 2012; Wang et al. 2004) as well as climate research including diagnostic studies (e.g. Wang et al.

2004; Liu et al. 2011) and climate sensitivity studies (e.g. Messager et al. 2004; Martinez-Castro et al. 2006; Sen et al. 2004a, b; Bozkurt and Sen 2011). RCM output is widely used in climate impact research (IPCC 2007a, b) on the assumption that a more realistic simulation of present-day climate implies more reliable projections of future climate change (Paeth and Mannig 2012). Recently in the review by Feser et al. (2011) on the added value to the GCMs data by RCMs concluded that the regional models can add value, but only for certain variables and locations. Therefore it is important to first assess the uncertainties related to RCMs over South-Asia before the high resolution data is used in the study of impacts of climate change on different socio-economic sectors like water resources and agriculture.

The model-based climate change studies usually include a present-day simulation in addition to the simulation of future climate based on different socio-economic scenarios. The primary reason to run the models for recent-past or present-day climate is to check the performance of the model relative to the observations, and it also provides a baseline climate by which the future climate projections are compared. In IPCC fourth Assessment report (IPCC 2007a, b) it was reported that most of the climate models are capable in simulating main features of climate system but still they have uncertainties. Since the RCMs take the output of GCMs at their boundaries, the uncertainties in the input (output of GCM) will be propagated in the RCM when applied to a specific region. Therefore, a complete evaluation of GCMs outputs on regional scale together with the evaluation of RCMs is required to assess the reliability of results from the regional climate change studies. A comprehensive study on such type of uncertainties in RCM projections was performed by Giorgio and Francisco (2000) using five coupled atmospheric ocean GCMs (AOGCMs) for different scenarios. They concluded that the leading source of uncertainty in RCM simulations comes from different climate models and with different scenario by AOGCMs. They suggested that these uncertainties will be transmitted to regionalization techniques used for the detailed information of a region from the GCMs. Using four RCMs and two GCMs, Duffy et al. (2006) assessed the different aspects of present-day climate simulations in the Western US. They showed that both RCMs and GCMs have similar overestimation of precipitation. They suggested that GCMs have influential role on the regional model precipitation bias. To investigate RCM's role as source of bias it is conventional to drive the RCMs by the re-analysis dataset at the boundaries (e.g. Han and Roads 2004; Sylla et al. 2010). Evaluating RCMs through an investigation of systematic errors helps in understanding the model performance and dynamical downscaling abilities (Bergant et al. 2007) and helps in

understanding the uncertainties in the future climate. Boberg and Christensen (2012) showed that owing to a broad tendency of climate models to show systematic biases in warm and dry climates result in the regional amplification of global warming. The Mediterranean summer temperature projections were reduced by several degrees for individual models when they applied bias correction conditioned on temperature over Europe. Moreover, an evaluation of RCM is desirable to provide a usable baseline statistics for the assessment of seasonal predictions and climate change scenarios simulated with RCMs (Seth et al. 2007). Frei et al. (2006) suggested that the formulation of regional models adds significantly to the uncertainty in scenarios of summer precipitation extremes over Europe. It is therefore not a waste of resources if multi-model ensemble systems, devoted to estimating scenario uncertainties, include a set of RCMs nested into the same GCM.

Most of the studies both with GCMs and RCMs over South-Asia agree in increasing temperatures and a weakening of the SASM dynamics in future. However, for the projected changes in precipitation there is much less agreement. Annamalai et al. (2007) and Kumar et al. (2006) found increasing precipitation amounts and Ashfaq et al. (2009) found a suppression not only in the monsoon dynamics but also in the South-Asian summer precipitation due to enhanced GHG emissions. There are many examples of model verification and climate change studies using RCMs that involve downscaling of GCMs by single RCM over South-Asia. Dash et al. (2006) applied the RCM RegCM3 to study the Indian summer monsoon circulations and rainfall using two convective parameterization schemes and found that RegCM3 is capable of simulating the Indian summer monsoon rainfall and circulation. Islam (2009) used the RCM PRECIS to generate future projections of rainfall and temperature over Bangladesh and suggested that simulated rainfall is not directly useful in the assessment of impacts on water resources and therefore the calibration of the RCM output is needed. Islam et al. (2011) performed different experiments of domain size over the Bangladesh using the RCM PRECIS, in order to get the information about the least possible domain size. Kumar et al. (2006) also used the RCM PRECIS for future scenario projections over India. They evaluated the RCM for the recent past and concluded that model has good skills in depicting the annual mean surface climate over Indian region, however they did not focus on the SASM climate. There are few studies that focused Pakistan using RCM, Islam et al. (2009) studied future changes in the frequency of warm and cold spells over Pakistan using the PRECIS. They showed decreasing trend in cold spells and increase in the number of hot days in the future over Pakistan. Dobler and Ahrens (2011) used regional model COSMO-CLM and showed decreasing trends in the monsoon's

strength by the end of twenty-first century due to reduced rain day frequency in the RCM.

These studies focused on different aspects of climate and RCMs, over South-Asia but did not pay much attention to the uncertainties associated with the RCMs with reference to the driving global datasets for the SASM. The purpose of the study is not to compare the performance of RCMs in simulating the SASM over South-Asia but to study the sensitivity of RCMs to different boundary conditions. Some of the questions addressed are: What are the differences between the observed datasets over South-Asia, which are used to evaluate the performance of the models? What is the effect on the simulation of climate, when different global datasets are downscaled with single RCM? How different RCMs behave while downsampling same global dataset? Can these differences between RCMs simulations with respect to driving global datasets be explained with the low level large scale circulation changes? and then finally we look at the climate change signal over South-Asia simulated by GCM and downscaled climate change signal of the same GCM.

In this paper we first describe the model, data and numerical experiments (Sect. 2). Results are discussed in Sect. 3, while summary and conclusions are presented in Sect. 4.

2 Models, data, experiments design and methods

2.1 Models

The numerical experiments are carried out using the ICTP Regional Climate Model version 4 (RegCM4) and Providing Regional Climates for Impact Studies (PRECIS) version 1.9.2 of Hadley Centre.

RegCM4 is documented by Giorgi and Anyah (2012). It is an augmented version of the model of Giorgi et al. (1993a, b). The dynamical core the Fifth-Generation NCAR/Penn State Mesoscale Model MM5 (Anthes and Warner 1978), planetary boundary layer (Holtslag et al. 1990) and land surface process schemes (Dickinson et al. 1993) are the same as in Giorgi et al. (1993a, b). Radiative transfer processes are described using the scheme of the NCAR CCM3 (Community Climate Model 3; Kiehl et al. 1996) as implemented by Giorgi et al. (1999) while ocean–atmosphere fluxes follow the parameterization of Zeng et al. (1998). RegCM4 is hydrostatic, compressible; sigma-p vertical coordinate model run on an Arakawa B-grid. RegCM4 includes several options for describing convective precipitation. The scheme used here is that of Grell (1993), which is a mass-flux based parameterization accounting for penetrative updrafts and downdrafts and including different closure assumptions. Resolved-scale

precipitation is described by the scheme of Pal et al. (2000), which is an explicit moisture scheme accounting for the sub grid-scale variability in clouds and the evaporation and accretion of precipitation. RegCM4 was run at horizontal resolution of 50 km with rotated mercator map projection.

A complete description of the model PRECIS and its parameterization schemes is given in Jones et al. (2004). The PRECIS RCM is based on the atmospheric component of HadCM3 (Gordon et al. 2000), it uses MOSES 2.2 (Essery et al. 2003) which is the improved version of MOSES1 (Cox et al. 1999) land surface scheme. Radiative processes are modeled to be dependent on atmospheric temperature and humidity, concentrations of radiatively active gases, concentrations of sulphate aerosols and clouds. Model uses sigma co-ordinates for the four bottom levels, purely pressure co-ordinates for the top three levels and combinations for in between levels. For horizontal discretization improvement in the accuracy of the split-explicit finite difference scheme Arakawa B grid (Arakawa and Lamb 1977) has been used. A mass flux penetrative convective scheme (Gregory and Rowntree 1990) is used with an explicit downdraft (Gregory and Allen 1991) and includes the direct impact of vertical convection on momentum (in addition to heat and moisture) (Gregory et al. 1997). Large scale precipitation from layer cloud is dependent on cloud water content, with allowance made for the greater efficiency of precipitation when the cloud is glaciated. PRECIS uses rotated latitude–longitude projection, where the equator lies inside the region of the interest. PRECIS was run at the horizontal resolution of $0.44^\circ \times 0.44^\circ$, which gives a minimum resolution of ~ 50 km at the equator of the rotated grid.

2.2 Data and experiment design

In case of RegCM4, the sea surface temperature (SST) data for European Center for Medium Range Weather Forecast (ECMWF) reanalysis ERA40 simulation is prescribed from Global Ice Coverage and Sea Surface Temperature (GISST) dataset with a resolution of 1×1 degree (Rayner et al. 2003). Bilinear interpolation method was applied to interpolate the forcing fields horizontally and simple linear interpolation was applied to transfer the GCM outputs into the RegCM4 vertical sigma coordinate. The model topography and landuse are obtained from the 10-min United States Geological Survey (USGS) and Global Land Cover Characterization at 10 min resolution (GLCC, Loveland et al. 2000) datasets, respectively. The number of vertical levels was defined as 18 sigma levels (top of the model at 5 hPa).

Observed time-dependent field of SST and sea-ice (HadISST dataset) are used as lower boundary conditions

Table 1 Experiments design

Global data	RCMs			
	RegCM4		PRECIS	
	RF	A1B	RF	A1B
ECHAM5	1970–2000	2070–2100	1970–2000	2070–2100
ERA40	1970–2000		1970–2000	

in the ERA40 reanalysis simulation in case of PRECIS. The model was run with 19 vertical levels of pressure, lowest at ~ 50 m and highest 0.5 hPa.

The climate simulations defining the 30-year climatology between 1970 and 2000 were performed using RegCM4 and PRECIS with lateral boundary conditions driven from ECMWF reanalysis dataset ERA40 data (Uppala et al. 2005), with a grid spacing of $2.5^\circ \times 2.5^\circ$ interpolated onto the RegCM4 resolution and one GCM—Intergovernmental Panel on Climate Change (IPCC) Forth Assessment Report (AR4) simulations of MPI-ECHAM5 (Roeckner et al. 2003). The design of the experiments is given in Table 1. Both the RCMs are run for 30 years period each for the RF period (1970–2000) and for the future (2070–2100) A1B socio-economic scenario, with the lateral boundary conditions driven from ECHAM5 GCM. In A1 scenario family considers future world of very rapid economic growth, global population that peaks mid-century and declines thereafter, and rapid introduction of new and more efficient technologies. A1B considers a balance across all sources. Major underlying themes are economic and cultural differences and capacity-building, with a substantial reduction in regional differences in per capita income. The first year of these simulations are discarded from the analysis to allow for model spin up. The model domain is shown in Fig. 1. The domain encompasses the entire South-Asia region (approximately $50\text{--}105^\circ\text{E}$ and $0\text{--}45^\circ\text{N}$) at a horizontal grid spacing of ~ 50 km. The naming convention used in the study for different RCM experiments is as follows, RegCM4-ERA40: ERA40 downscaled with RegCM4, RegCM4-ECHAM5: ECHAM5 downscaled with RegCM4, PRECIS-ERA40: ERA40 downscaled with PRECIS, PRECIS-ECHAM5: ECHAM5 downscaled with PRECIS, RegCM4(ECHAM5-ERA40): difference between RegCM4(ECHAM5) and RegCM4(ERA40) and similarly PRECIS(ECHAM5-ERA40): difference between PRECIS-ECHAM5 and PRECIS-ERA40.

For the evaluation of the dynamically downscaled outputs and RCMs performance, the simulation results were compared with the driving fields from ERA40 reanalysis data and the gridded datasets of Climate Research Unit (CRU) of the University of East Anglia, UK (Mitchell and

Table 2 Selected regions of South-Asia

	Location	Elevation (m)	Climate	Main precipitation season
Region A	Southern Pakistan and Western India	0–1,500	Arid and hyper-arid	Summer
Region B	Northern Pakistan and India	500–5,000	Dry sub-humid	Summer and winter
Region C	Western Ghats	0–1,000	Humid	Summer
Region D	Central India	0–1,000	Moist and dry sub-humid	Summer
Region E	Southern India and Sri Lanka	0–500	Dry sub-humid	Winter
Region F	Bangladesh and adjoining areas	0–500	Humid	Summer

Jones 2005) and University of Delaware, UDEL (Willmott and Matsuura 1998) data for air temperature and precipitation. Global Precipitation Climatology Project (GPCP) monthly precipitation dataset (Adler et al. 2003) from 1979 to 2009 combines observations and satellite precipitation data into $2.5^\circ \times 2.5^\circ$ global grids is also used. The CRU and UDEL data are available at 0.5° grid spacing over the land areas only. The observed datasets are also used to see the uncertainties in the observations.

2.3 Methods

The SASM is defined as the season from June to September (JJAS), in which South-Asia receives precipitation associated with the monsoon phenomenon in summer.

First the two RCMs (RegCM4 and PRECIS) are run with observed initial and the so called perfect lateral boundary conditions of ERA40 reanalysis in order to see the biases in the RCM simulations. Then ECHAM5 is downscaled with both the RCMs. The downscaled temperature and precipitation is compared with the driving reanalysis and GCM fields along with the two observed temperature and precipitation datasets. The large scale circulation patterns and specific moisture at 850 hPa is also compared, so that the biases in the regional simulations can be well understood.

Due to the extent of the model domain, which has diverse climate and terrain features, we defined six different sub-regions to look into the regional performance of the models (see Fig. 1). Six sub-regions are selected on the basis of Rao and Ramamurty (1968) climate classification explained in Table 2.

Model performance is further studied for both the climate variables using Taylor diagrams. Taylor diagrams are a convenient way of comparing different models using three related parameters: standard deviation, correlation with observed data and centered root mean square error (RMSE). As can be seen from Fig. 7, the observed data lies at the point marked CRU. The green circles centered at the RF point represent loci of constant RMSE and the circles centered at the origin represent loci of constant standard deviation. Correlation is represented as cosine of the angle from the x-axis. Models with as much variance as observation, largest correlation and least RMSE are considered best performers on the Taylor diagram. RMSE is calculated for the area averaged values over the selected regions of SASM for the inter-annual variability.

The future climate change signal is assessed by calculating the changes in the temperature, rainfall, moisture transport and annual cycle, for A1B future (2071–2100) scenario with respect to baseline period (1971–2000). Both changes in the spatial patterns and over the selected regions are calculated.

3 Results and discussion

Before we start the evaluation of the climate models, it is important to understand the differences between different observational datasets over South-Asia. Station based observed precipitation is likely to be underestimated for various reasons, including a low elevation station bias (especially over the high mountainous area), sparse network of stations and a gauge undercatch bias. This underestimate can be up to 30 % or even more (Adam and Lettenmaier 2003). Similarly the station based temperature observations can have warm bias due to station elevation. The CRU dataset is based on only 73 stations for temperature and 213 stations for precipitation over South-Asia. UDEL has used variable number of stations that can be different for each month and year. Some of their station records were created by merging several station records.

We first provide an evaluation of the model climatology for the relevant variables analyzed here, namely precipitation, temperature (Sects. 3.1, 3.2) and the uncertainties associated with the RCMs with respect to driving global datasets. Moisture transport at 850 hPa is compared in order to understand the uncertainties in the simulations and to assess the ability of the model to simulate typical circulation patterns and moisture fluxes. The annual cycle and the inter-annual variability over the six sub-regions of SASM are presented in Sect. 3.3. Finally the climate change signal is discussed in Sect. 3.4.

3.1 Mean surface temperature

Figure 2a, b, show the mean (1971–2000) surface air temperature ($^{\circ}\text{C}$) of CRU and the difference in UDEL with respect to CRU for SASM. Both the observations show similar spatial pattern and mean value of temperature over most of the region. The major differences appear over Hindu Kush-Himalaya (HKH) mountainous region. Both the station based datasets differ up to 5°C and the difference is not spatially uniform. At some regions CRU is warmer and at other regions UDEL is warmer. ERA40 is cooler over the northern Pakistan and Himalayas region compared to CRU and the difference is above 4°C (Fig. 2c). The quantitative analysis of the observations and models simulated temperature ($^{\circ}\text{C}$) is illustrated in Fig. 5a, b, averaged for the six sub-regions of South-Asia (Fig. 1) over the time period of 1971–2000 (averages for sub regions are calculated only for land grid points). Figure 5b also illustrates the RMSE. Both the observations are also consistent over all the selected sub-regions with mean temperature difference variations are within $0\text{--}2^{\circ}\text{C}$ and the RMSE is <0.2 but the RMSE is about 1.0 in Region C i.e. over western Ghats, showing higher differences in the inter-annual variability among the observations. Mean surface air temperature is more than 28°C over most of the plain areas of the Indian subcontinent. Whereas the mean temperature is below the freezing point in the northern parts of the domain, over HKH region.

The two driving datasets ERA40 and ECHAM5 for the simulations of RCMs in the current study have different climatology of the mean temperature (Fig. 2c, d). ECHAM5 is warmer than ERA40 reanalysis, over most of the domain. The difference is more than 4°C over plain areas of Pakistan and along the foothills of Himalayas. The difference can be more clearly seen in Fig. 2e, where we can see the difference in the mean surface temperature is more than 8°C . The mean bias and the spatial pattern are quite similar when ECHAM5 is compared with CRU (Fig. 2d). The ECHAM5 GCM is poorly simulating the mean surface temperature and is much warmer over the South-Asian domain, whereas ERA40 reanalysis is closer to observations. When these two global datasets are downscaled with RCMs, the mean surface temperature shows a different behavior. The RegCM4-ERA40 and RegCM4-ECHAM5 show very similar mean temperature and the spatial pattern (Fig. 2f, g) and correspondingly the PRECIS-ERA40 and PRECIS-ECHAM5 also show very similar mean temperature and the spatial pattern (Fig. 2i, j). RegCM4 has cold bias over the whole domain and this cold bias is more than 5°C over the high mountains in the north of Pakistan and India (Fig. 2f, g). On the other hand PRECIS has a warm bias of more than 2°C over the central parts of Pakistan but the cold bias over the northern

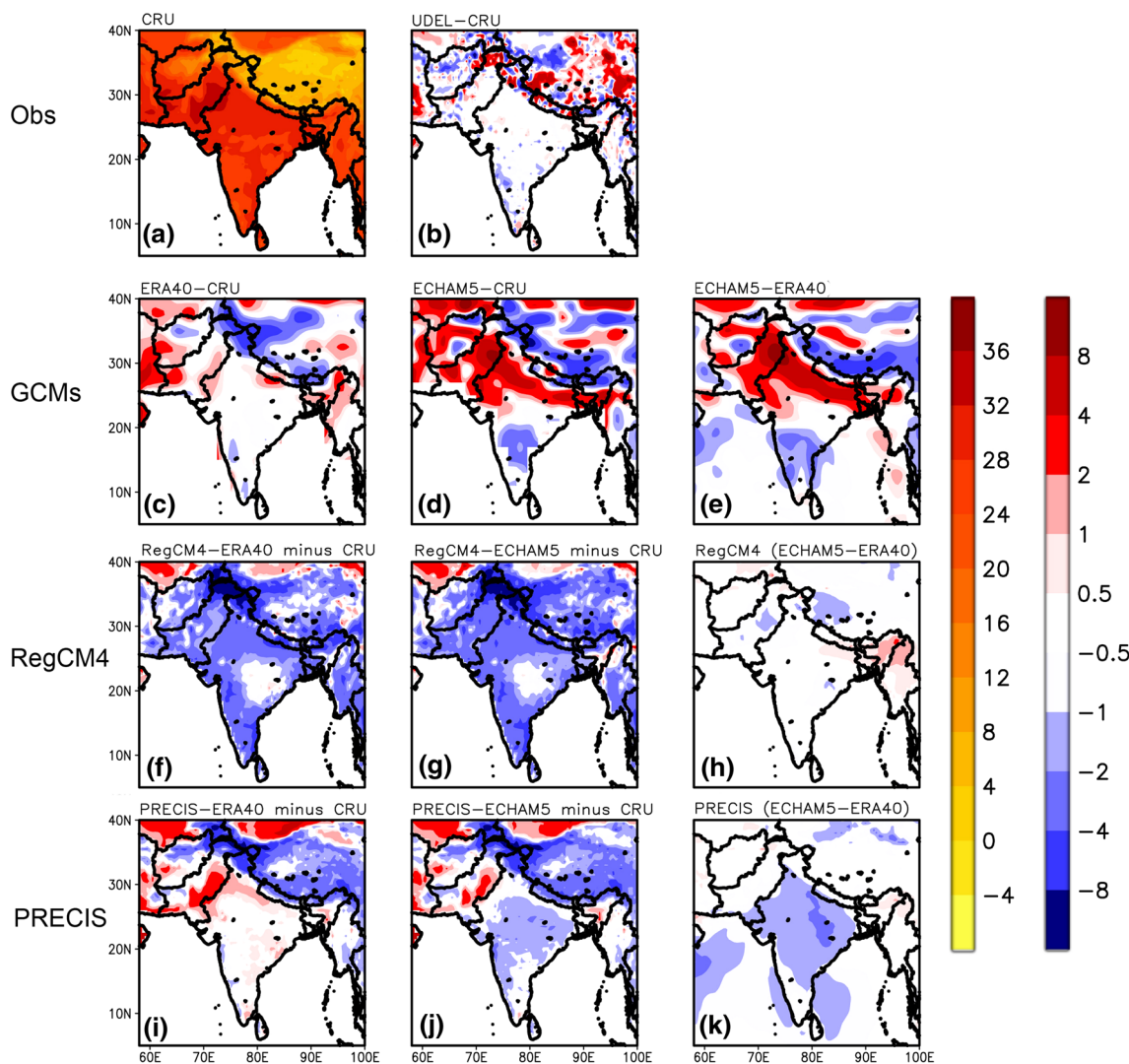


Fig. 2 a CRU mean (1971–2000) surface temperature (°C); Mean (1971–2000) temperature(°C) difference, b UDEL minus CRU c ERA40 minus CRU, d ECHAM5 minus CRU, e ECHAM5 minus ERA40, f RegCM4-ERA40 minus CRU, g RegCM4-ECHAM5 minus

CRU, h RegCM4-ECHAM5 minus RegCM4-ERA40, i PRECIS-ERA40 minus CRU, j PRECIS-ECHAM5 minus CRU, k PRECIS-ECHAM5 minus PRECIS-ERA40

high mountains is similar to that of RegCM4 (Fig. 2i, j). However it should be kept in mind that observed temperature is likely to be underestimated for various reasons discussed earlier. Generally the spatial gradients and topographically-induced structure are captured and simulated values are within a few degrees of the observed values. For the mean temperature over the selected regions, the Fig. 5a, b show that the maximum mean temperature for the season is around 30 °C occurs in Region A and minimum around 18 °C in Region B. Whereas for rest of the Regions C, D, E and F the mean temperature is between 25 and 30 °C range. The biases in RegCM4 are higher and underestimates the mean temperature for all six regions whereas PRECIS simulations of mean temperature

are more consistent with observations and have small values of RMSE. The RMSE values are exceptionally high over Region B, especially for RegCM4.

The global driving datasets ECHAM5 and ERA40 have very large differences in the mean temperature (Fig. 2e) but after downscaling with the RCMs i.e. in case of PRECIS(ECHAM5-ERA40) and RegCM4(ECHAM5-ERA40) the difference in the mean temperature is very small (Fig. 2h, k). It should be noted here that in case of RegCM4-ERA40, the observed SSTs of GISST dataset were used and in case of PRECIS-ERA40, the observed SSTs of HadISST dataset were used instead of ERA40 SSTs. However the difference between the observed SSTs and ERA40 SSTs is not large (not shown) and therefore the

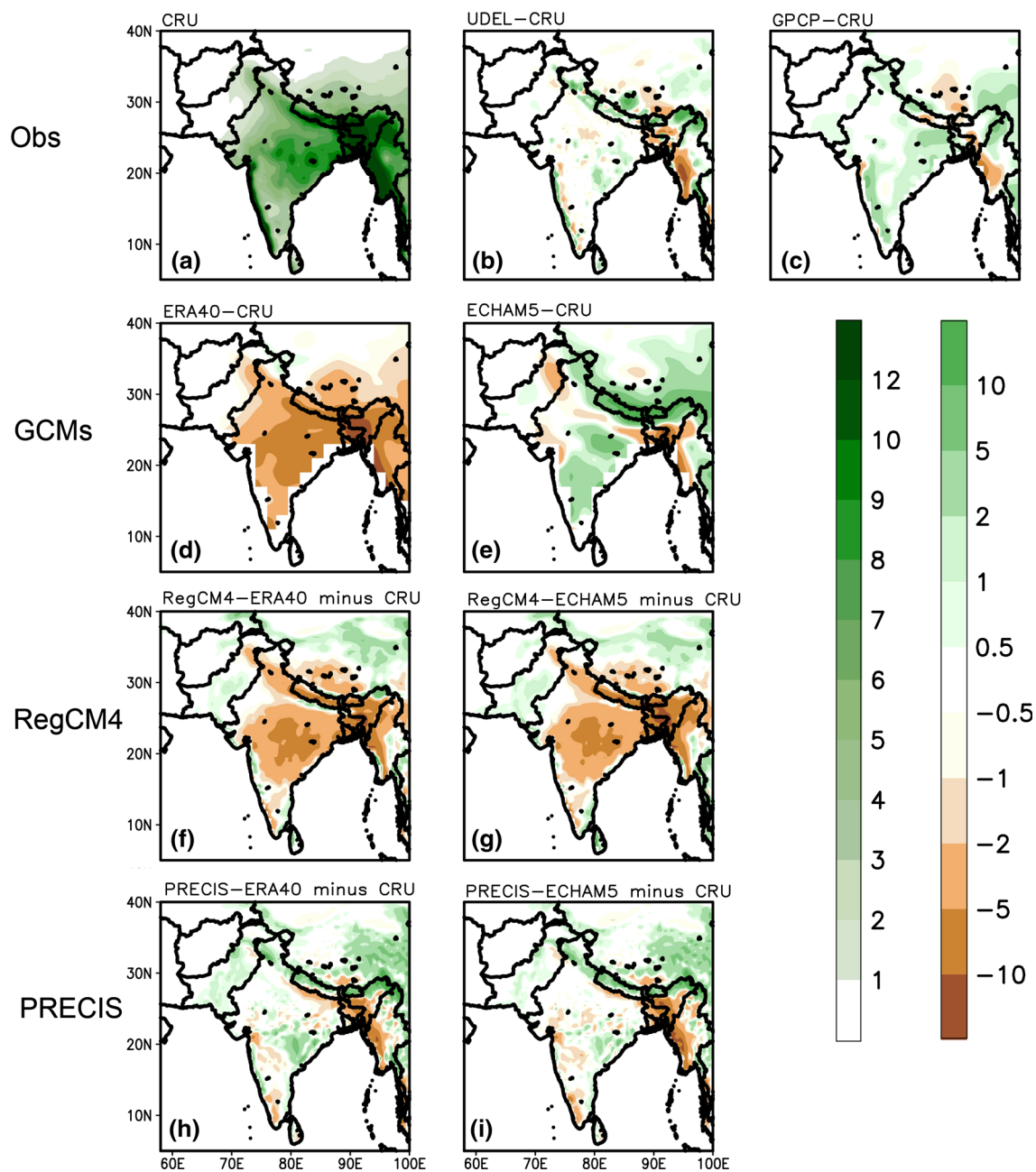


Fig. 3 a CRU mean (1971–2000) precipitation (mm/day); Biases in mean (1971–2000) precipitation (mm/day) with respect to CRU, b UDEL, c GPCP, d ERA40, e ECHAM5, f RegCM4-ERA40, g RegCM4 -ECHAM5, h PRECIS-ERA40, and i PRECIS-ECHAM5

convergence in the simulated mean temperature after downscaling different global datasets with the same RCM cannot be attributed to the difference in SSTs.

Some degree of the bias in global datasets and RCMs especially over HKH region in simulating SASM temperature can be explained by the uncertainty in the observations. There are large differences in temperature between the global datasets ECHAM5 and ERA40 but after downscaling with RCM the differences are considerably reduced, this is the case with both the RCMs. Both the

RCMs are developing their own climatology which is not very sensitive to the boundary conditions. There seems to be systematic biases in the RCMs over South-Asia, which is similar to the findings of Boberg and Christensen (2012) over Mediterranean region. Secondly the biases in both RCMs are different although they are downscaling same global dataset, for example RegCM4 is colder over most of the domain and PRECIS is warmer over southern Pakistan and colder over HKH region. These differences seem to come from the difference in the RCM physics.

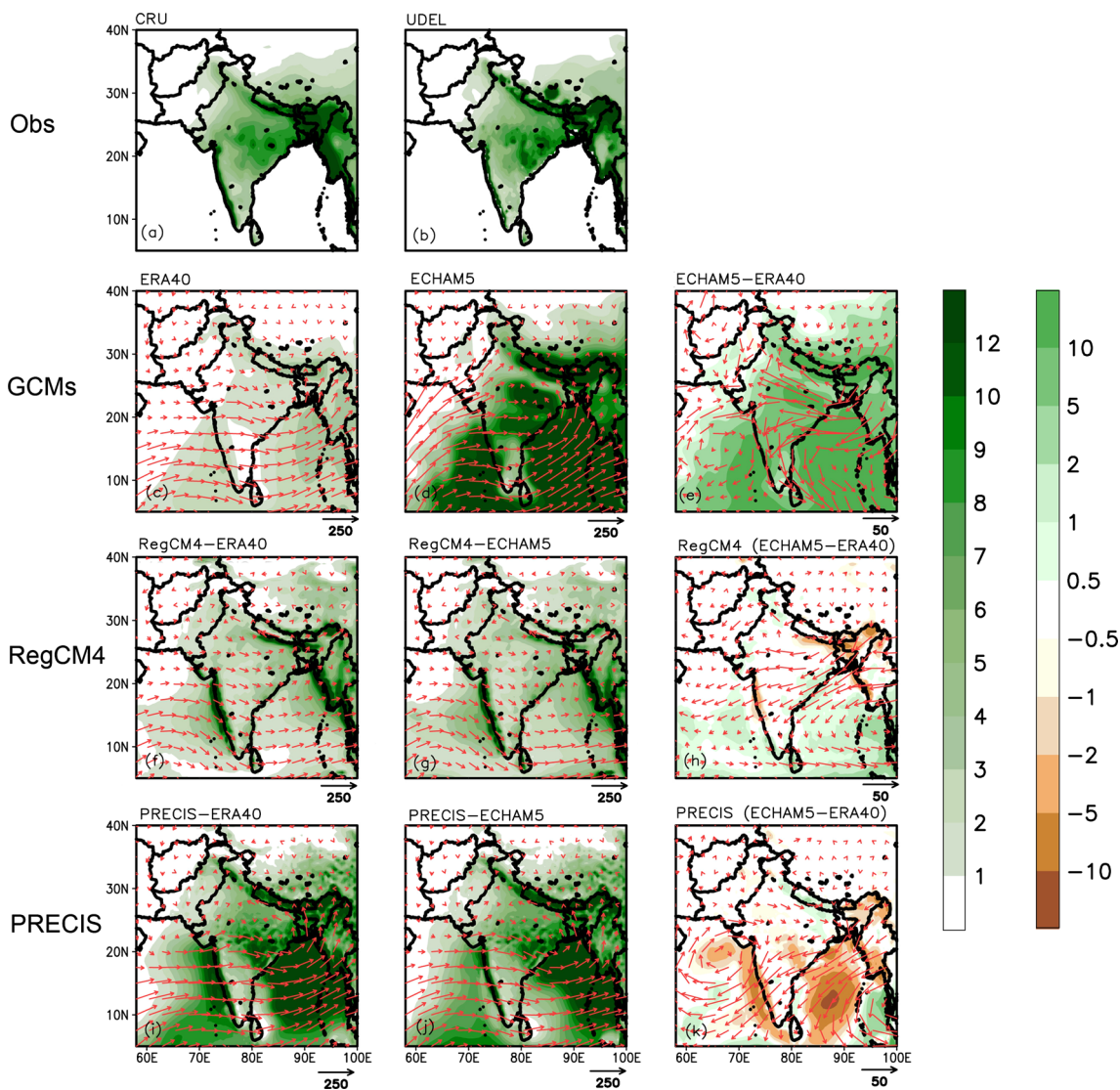


Fig. 4 Mean (1971–2000) precipitation (mm/day), **a** CRU, **b** UDEL; Mean (1971–2000) precipitation (mm/day) and moisture transport (m/s), **c** ERA40, **d** ECHAM5, **e** ECHAM5-ERA40, **f** RegCM4-ERA40, **g** RegCM4-ECHAM5, **h** RegCM4-ECHAM5 minus RegCM4-ERA4,

i PRECIS-ERA40, **j** PRECIS-ECHAM5 and **k** PRECIS-ECHAM5 minus PRECIS-ERA40. The values of moisture transport are scaled by 1,000

3.2 Mean precipitation and low level circulation

The differences in observational mean (1971–2000) JJAS precipitation (mm/day) precipitation are shown in Fig. 3b, c. UDEL and GPCP are drier over Myanmar and Bangladesh and the differences are above 5 mm/day. Whereas GPCP is wetter over western Himalayas, central India and western Ghats. Both the observations show similar mean value and spatial distribution of rainfall in the summer monsoon season. The mean precipitation is above 10 mm/day over the western Ghats and the adjoining areas of bay of Bengal. Another maxima of rainfall can be seen over central India, where mean rainfall is between 6 and 10 mm/day. The monsoon penetrates into northern Pakistan along

the foothills of Himalayas but the mean rainfall remains below 6 mm/day over northern India and Pakistan. The difference between the observations for the mean rainfall over different selected regions remains below 1 mm/day and the RMSE is also small (Fig. 5c, d). The ERA40 reanalysis shows similar spatial distribution of rainfall but the amount of rainfall is underestimated whereas in case of ECHAM5 GCM the rainfall is overestimated over central India and Bay of Bengal (Fig. 4c, d).

When ERA40 and ECHAM5 are downscaled with RegCM4, the mean rainfall climatology is similar, both in terms of mean value and spatial distribution (Fig. 4f, g). The behavior of PRECIS RCM is also similar (Fig. 4i, j), but the amount of rainfall is more over western Ghats and

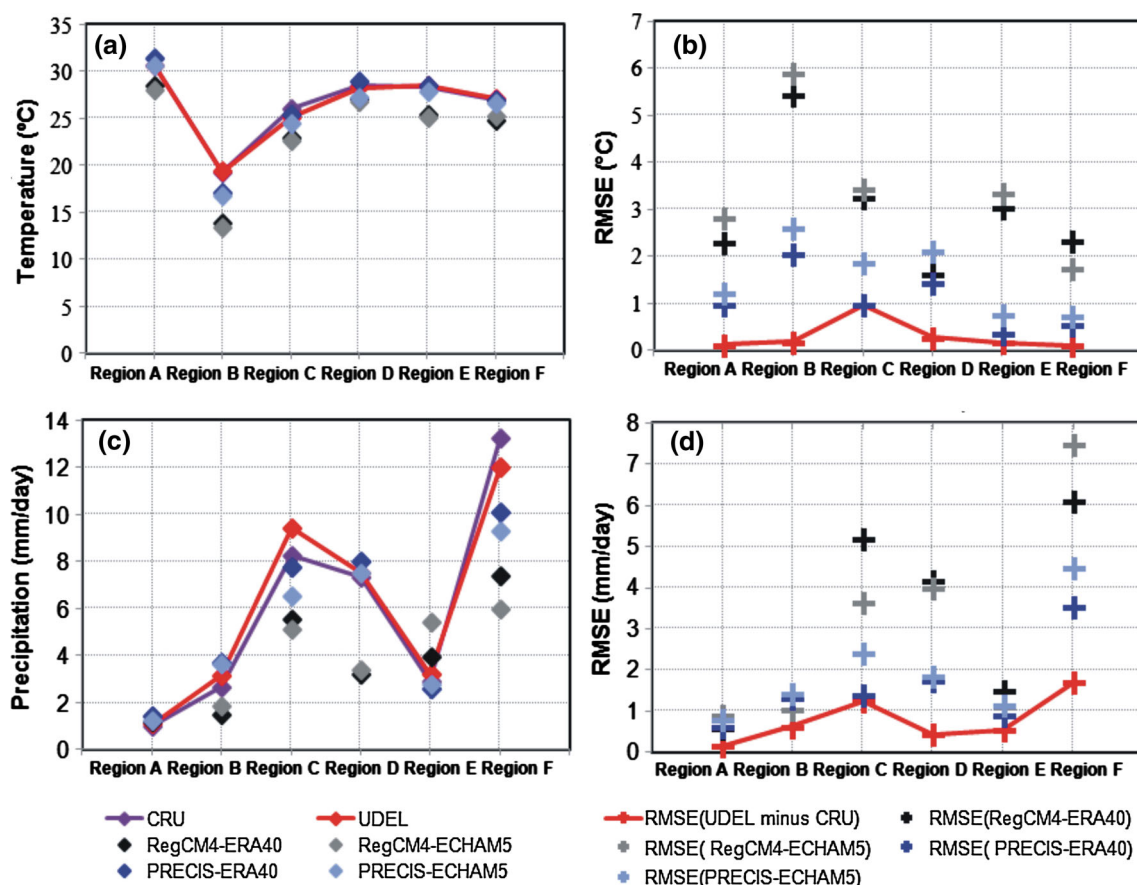


Fig. 5 Thirty-year mean (1971–2000) seasonal (JJAS). **a** Temperature (°C), **b** RMSE of temperature (°C), **c** precipitation (mm/day), **d** RMSE of precipitation (mm/day). For six selected regions of South-Asia. Solid lines joins the observational values

Bay of Bengal in case of PRECIS-ERA40. Both the RCMs are showing almost the same spatial pattern of precipitation irrespective of the boundary data, for example the precipitation in ECHAM5 is wide spread and the values are much higher compared to the downscaled precipitation with RegCM4, which is similar to RegCM4-ERA40. The RegCM4 is underestimating the mean rainfall over central India and also the penetration of monsoon into Pakistan is not very well simulated, whereas PRECIS climatology is closer to CRU (Fig. 3f, i). The underestimation of precipitation over Bangladesh, Myanmar and western Ghats (Fig. 3h, i) is comparable to differences in the observed CRU and GPCP precipitation (Fig. 3b, c). The RegCM4(ECHAM5-ERA40) shows very small difference between two simulations (Fig. 4h) whereas PRECIS(ECHAM5-ERA40) shows less rainfall over western Ghats and Bay of Bengal in case of PRECIS-ECHAM5 (Fig. 4k), which is contrary to the driving global model ECHAM5 rainfall. The ECHAM5 has wet bias over central India and Himalayas (Fig. 3e).

To further investigate the differences between the simulated and observed mean rainfall and inter-annual variability of the error, we illustrate the quantitative analysis

over the selected regions. Figure 5c, d show the mean rainfall and its RMSE values for different simulations. The maximum mean rainfall occurs in Region F which is above 12 mm/day and the minimum rainfall, around 1 mm/day occurs for Region A. Figure 5c clearly shows underestimation of ERA40 and ECHAM5 downscaled with RegCM4, whereas the downscaling of ERA40 and ECHAM5 with PRECIS show relatively consistent results with CRU data for all regions. However, in Region A, all simulations have consistent results with CRU data and thus have very small values <1.0 of RMSE. A few exceptions are also present, which include relatively high value of RMSE for UDEL in Region C, and downscaled ECHAM5 with RegCM4 is overestimating rainfall in Region E and underestimating mean rainfall over Region F by around 7 mm/day. Results of PRECIS show underestimation in Region F especially in case of ERA40 which has a relatively large RMSE value around 3.5. The spread in the mean rainfall and RMSE is maximum over the Regions (C and F) i.e. over western Ghats and Bangladesh, which receive heavy amount of rainfall during the monsoon.

To understand the biases and the difference between the global driving datasets and the downscaled rainfall, we

investigate the large scale moisture transport. Figure 4c, d show the mean moisture transport (m/s) at 850 hPa in ERA40 and ECHAM5 respectively, the values of moisture transport are scaled by 1,000. The monsoon circulation is stronger in ECHAM5 compared to ERA40, the low-level jet (LLJ) across the Somali coast over the Arabian Sea flows over the southern parts of South-Asia into the Bay of Bengal hits the western Ghats and produce rainfall. LLJ is the main artery through which the moisture is fed into the flow of the monsoon circulation (Bin Wang 2006). The circulation over the Bay of Bengal has more cyclonic curvature in ECHAM5, which brings more moisture inland over the central India. This difference can be clearly seen in Fig. 4e. This stronger monsoon circulation is responsible for the overestimation of rainfall in ECHAM5 over most parts of the domain (Fig. 4d).

The moisture transport has reduced over the whole domain after downscaling with RegCM4. Although the low level circulation is much stronger in ECHAM5 compared to ERA40 but it is interesting to note that LLJ and the associated monsoon circulation has become weaker in case of RegCM4-ECHAM5 and RegCM4-ERA40 compared to ECHAM5 and ERA40 respectively (Fig. 4f, g). This decrease in the circulation might be linked to the cold bias over the whole domain in RegCM4. The circulation is relatively stronger in PRECIS compared to RegCM4 (Fig. 4i, j) which is comparable to driving global datasets. The inland flow of moisture from Bay of Bengal into central India and also along the foot hills of Himalayas can be seen in the moisture transport difference ECHAM5-ERA40 (Fig. 4e) but after downscaling the moisture transport difference has reduced (Fig. 4h, k). This explains almost no difference in precipitation over central India and along the foot hills of Himalayas up to Pakistan in case of RCMs (Fig. 4h, k). The moisture transport along the LLJ in the Arabian Sea has also reduced resulting in the less precipitation over western Ghats (Fig. 4h, k) in case of RegCM4(ECHAM-ERA40) and PRECIS (ECHAM5-ERA40). The reduced precipitation over western Bay of Bengal can be explained as the result of weaker monsoon circulation in case of PRECIS (ECHAM5-ERA40) but RegCM4(ECHAM-ERA40) is showing almost no change in the precipitation associated with weaker monsoon circulation (Fig. 4h, k).

As in the case of temperature, some degree of the bias in global datasets and RCMs over western Ghats, Bangladesh and Myanmar, in simulating SASM precipitation can be explained by the uncertainty in the observations. ECHAM5 is much wetter over most parts of the domain compared to ERA40 but after downscaling with RCM the differences are considerably reduced. Again RCMs are developing their own climatology which is not in agreement with the driving global datasets precipitation. Kar et al. (2011) and

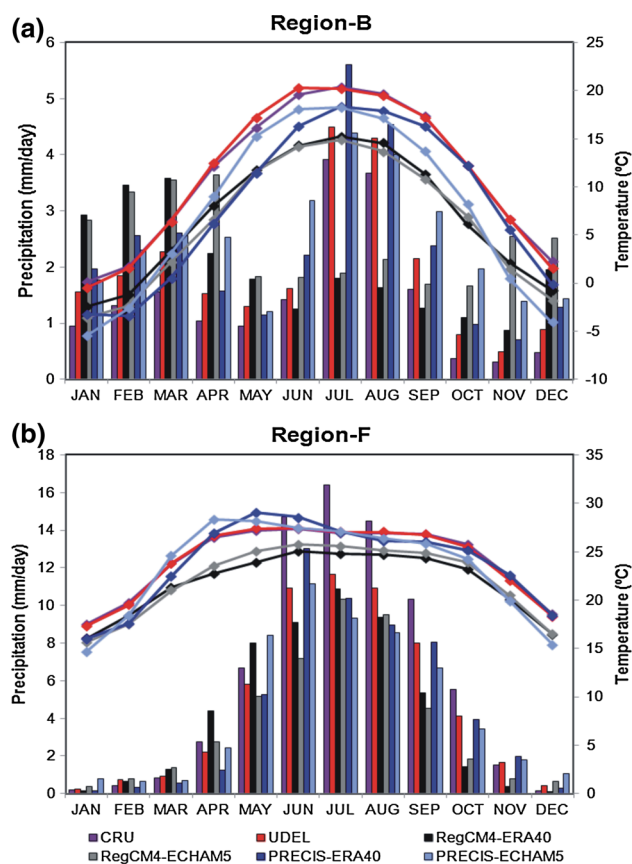
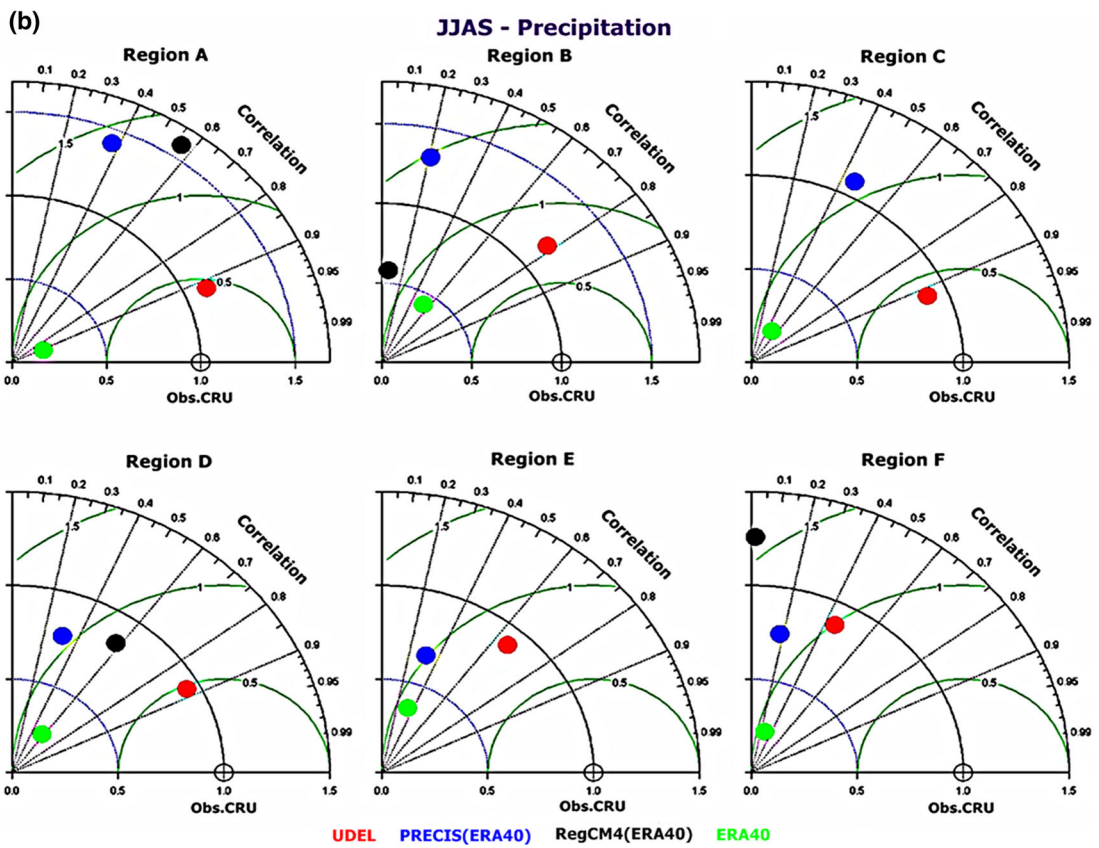
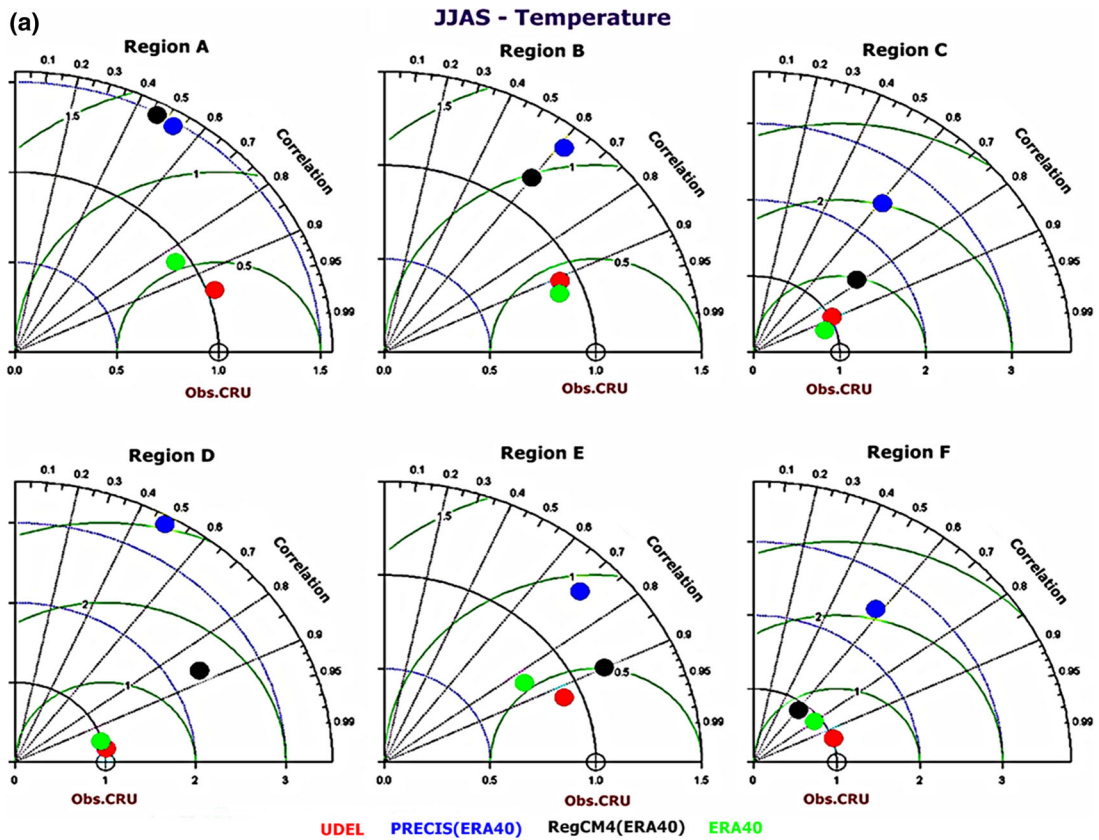


Fig. 6 Annual cycle for precipitation (mm/day) in colored bars and temperature (°C) in colored lines for the period 1971–2000, **a** Region B and **b** Region F

Acharya et al. (2011) also found that models have systematic as well as random biases in simulating SASM precipitation. Also the biases in both RCMs are different although they are downscaling same global dataset. RegCM4 is dryer over most of the domain, which seems to be linked with weaker monsoon circulation. PRECIS is dryer only over Bangladesh and Myanmar and the strength of monsoon circulation is comparable to driving global datasets. These differences in precipitation also seem to come from the difference in the RCM physics as it was in case of temperature.

3.3 Annual cycle and the inter-annual variability

The mean annual cycles of the simulated monthly temperature (°C) and rainfall (mm/day) over Region B and F are shown in Fig. 6a, b, respectively. Only two selected regions are shown for brevity. Two peaks of precipitation are visible in the annual cycle over Region B, first peak in the winter months from January to March and second peak of SASM from July to September. The months of May and June are the pre-monsoon and the months of October and November are the post-monsoon periods over this region.



◀ **Fig. 7** Taylor Diagram for JJAS season over all the selected regions. **a** Temperature ($^{\circ}\text{C}$) and **b** precipitation (mm/day); with CRU as RF point: X-axis denotes normalized observed standard deviation and green curves indicate RMSE values

Both the RCMs are capturing the two peaks in the annual cycle of precipitation over Region B but both the models are over estimating the mean precipitation in the winter months. RegCM4 is under estimating the rainfall in the monsoon period as discussed in the previous sections and peak in the winter season is higher compared to the monsoon months. The annual cycle of rainfall over Region F is better captured compared to Region B, although there is slight under estimation of rainfall during the monsoon months (Fig. 6b). It is interesting to note that the annual cycle in case of RegCM4-ERA40 and RegCM4-ECHAM5 is very similar also in terms of magnitude and the situation is similar in case of PRECIS. The annual cycle of temperature is also captured by both the RCMs. The cold bias in RegCM4 is more as compared to PRECIS throughout the year for both the regions.

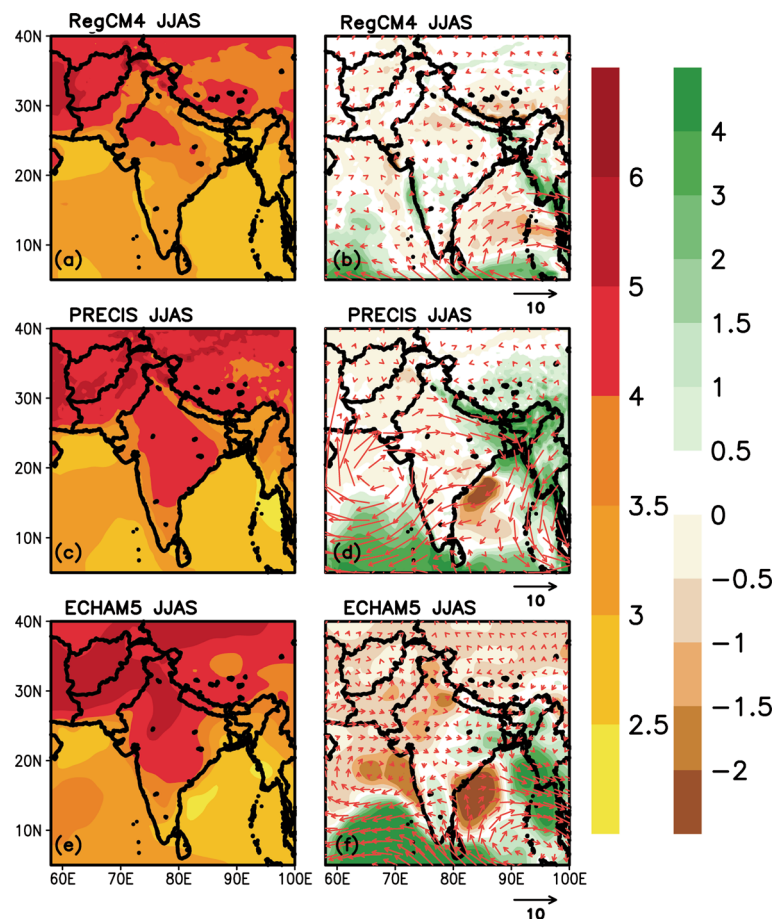
The Taylor Diagrams (Taylor 2001) are used for the qualitative analysis of temperature and precipitation, to help understand the inter-annual variability in terms of correlation, standard deviation and RMSE over the selected regions of South-Asia for the period 1971–2000. The Taylor Diagrams are computed from the spatially and seasonally averaged time series for different selected regions. Four datasets UDEL (observed), ERA40 (reanalysis), and ERA40 downscaled with RegCM4 and PRECIS have been compared with the observed dataset CRU.

The analysis of temperature (Fig. 7a) shows that the correlations of the observed and reanalysis datasets, UDEL and ERA40 tend to remain above 0.8 in all the regions. These datasets also exhibit low RMSE and the variability is quite close to the observed RF data. The downscaled ERA40 with RegCM4 has its correlations varying between 0.5 and 0.9. It can be observed that the RMSE for RegCM4 tends to remain below 1.5 in all the regions. The standard deviation of RegCM4 shows large differences, where it is closest to the observations in Regions B, E and F i.e. in Northern Pakistan and India, Southern India/Sri-Lanka, and Bangladesh. Whereas RegCM4 shows more than double standard deviation over central India. The correlations are almost consistent with RegCM4 but show high variability (standard deviations) in case of the downscaled ERA40 with PRECIS. The RMSE values for PRECIS are large, the value has become more than 3 in Region D. A close inspection of the analysis shows that the downscaled ERA40 by RegCM4 has produced better results in terms of variability and RMSE as compared to the downscaled ERA40 by PRECIS, though the correlations for both the models remain nearly consistent in the Regions A, B and F.

The precipitation analysis (Fig. 7b) indicates, once again large differences between RCMs and observations for the six regions of South-Asian domain. The dataset for UDEL gives very good correlation values in Regions A and C where the values are above 0.9. Moreover, Regions B and D also exhibit fairly good values for correlations with a range between 0.78 and 0.88. Whereas the two observational datasets are not consistent in terms of inter-annual variability in the Region E and F where the correlations tend to become as low as 0.5. The variability of UDEL with RF to the CRU is quite less in all the regions. However, the RMSE for UDEL remains below 1.0 in all the regions. The variability in the reanalysis data ERA40 remains below 0.5 of the normalized standard deviation. As far as the RMSE is concerned, the values tend to remain below 1.0 for ERA40 in all the regions. However, the correlations are higher for the Region A where its value goes above 0.9. The values remain between 0.4 and 0.6 for the Regions B, C and D and between 0.2 and 0.4 for the Regions E and F. The downscaled ERA40 by RegCM4 gives very low values for correlations in the Regions B and F. Nevertheless, they are slightly better for the Regions A and D where the values remain between 0.5 and 0.6. The variability of the RegCM4 is above the observation in the Regions A, C, E and F; and below the observations in the Regions B and D. The RMSE is very large in case of RegCM4-ERA40 (Fig. 7b) over Region C and E, so the black dot is outside the figure limits and not visible. The downscaled ERA40 with PRECIS gives a good consistency with the variability of the observed dataset, yet it can be seen that the correlations are highly compromised. The highest value it gives is merely 0.43. The RMSE of the PRECIS also gives high values but remains below 1.5. Besides the relatively low correlations, the downscaled estimations tend to give much higher variability and RMSE from the observed CRU data.

Generally the inter-annual correlations are better, both in case of observations and RCMs for temperature as compared to precipitation, similarly the RMSE is also higher in case of precipitation. The standard deviations for the inter-annual variability of precipitation are less, especially in case of ERA40. Vidale et al. (2003) studied the predictability and uncertainty in an RCM using multiyear ensemble simulations over Europe. They showed although the RCM has skill in reproducing inter-annual variability in precipitation and surface temperature, but the predictability varies strongly between seasons and regions. The predictability is weakest during summer and over continental regions due to the weak large-scale forcing in the summer season, and discrepancies in the land surface model. The inter-annual variability over most of the sub-regions of South-Asia is not well captured, same as in case of Europe (Vidale et al. 2003) during summer season.

Fig. 8 Climate change for JJAS season (2071–2100 minus 1971–2000) for temperature ($^{\circ}\text{C}$), **a** RegCM4-ECHAM5, **c** PRECIS-ECHAM5, **e** ECHAM5; and precipitation (mm/day) and moisture transport, **b** RegCM4, **d** PRECIS, **f** ECHAM5



3.4 Climate change

The spatial patterns of temperature and precipitation change for A1B future (2071–2100) scenario with respect to baseline period (1971–2000) are shown in Fig. 8. Warming over the whole Indian subcontinent associated with increasing greenhouse gas concentrations is visible and the summer mean surface air temperature rise by the end of the century ranges from 2.5 to 5 $^{\circ}\text{C}$. Kumar et al. (2006) downscaled HadAM3H with PRECIS and also found the annual mean surface air temperature rise by the end of the century ranges from 3 to 5 $^{\circ}\text{C}$ in A2 scenario. The spatial pattern of increase in temperature is consistent for both the RCMs and the GCM. The magnitude of warming in ECHAM5 is higher, compared to RCMs. PRECIS shows slightly higher change in temperature compared to RegCM4, which can also be seen over the selected regions (Fig. 9a). The warming seems to be more pronounced over Pakistan and the northern western parts of the domain. Regions A, B and D show the maximum increase in temperature, above 4 $^{\circ}\text{C}$ by the end of twenty-first century.

The precipitation change in ECHAM5, PRECIS-ECHAM5 and RegCM4-ECHAM5 indicate maximum increase over Bangladesh and northeast India for A1B

(Fig. 8). The increase in precipitation is relatively less in RegCM4 compared to PRECIS which estimates more than 3 mm/day rise in summer monsoon rainfall in future scenarios i.e. 30 % increase over Bangladesh and adjoining areas (Fig. 9). Islam et al. (2008) found increase in the projected rainfall over Bangladesh and the rate of increase in the mean annual rainfall was 1–2.5 mm/day. Over rest of the land areas of the domain, the change in rainfall is not pronounced. The slight decrease in the rainfall is observed only over Region A but this decrease is not appreciable, as this region receives very little rainfall during the monsoon. There is decrease in the rainfall more than 2 mm/day over western Bay of Bengal in ECHAM5 and PRECIS, ECHAM5 also shows the decrease in rainfall over Arabian Sea. However this decrease is not that prominent in case of RegCM4. Northern Pakistan and India (Region B) does not show appreciable change in the precipitation (Fig. 9b), which is contrary to the findings of Dobler and Ahrens (2011). They used COSMO-CLM RCM and found that parts of northwestern India are projected to face a decrease in the monsoon rainfall amount of over 70 % within this century due to decrease in the number of depressions moving toward the northwestern parts of India from Bay of Bengal. Figure 8b, d, f also show the change in the

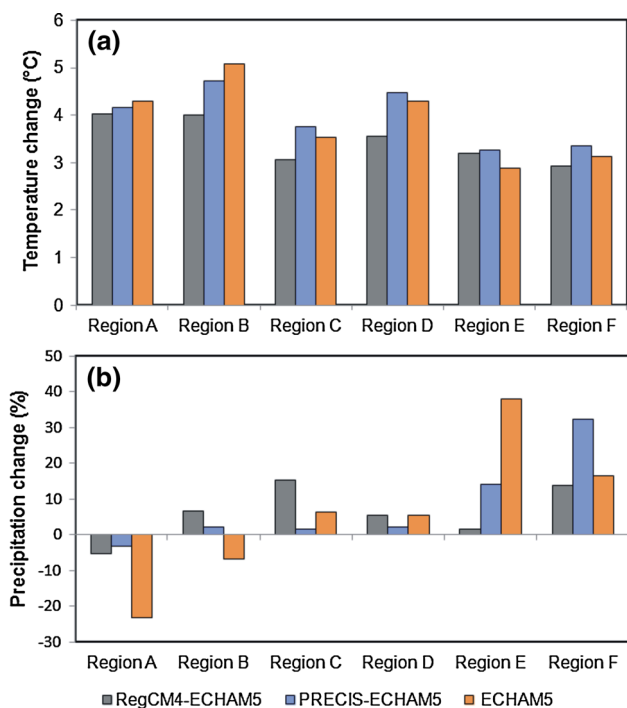


Fig. 9 Climate change in JJAS season (2071–2100 minus 1971–2000) for different selected regions. **a** Temperature (°C) and **b** precipitation change (%)

moisture transport for A1B future (2071–2100) scenario with respect to baseline period (1971–2000). The changes in the moisture transport can be understood by looking at the mean moisture transport in the baseline period Fig. 4 and comparing it with the changes. It can be seen that circulation has become weaker over the Arabian Sea in ECHAM5 and PRECIS-ECHAM5, which could be the reason for the decreased precipitation over eastern Arabian Sea in case of ECHAM5 but there is almost no change in precipitation in case of PRECIS-ECHAM5. RegCM4-ECHAM5 does not show any change in the moisture transport over the Arabian Sea. There is also disparity among the RCMs and GCM for the changes in the moisture transport over Bay of Bengal. The monsoon circulation has strengthened in ECHAM5 and RegCM4-ECHAM5, whereas the circulation is weaker in case of PRECIS-ECHAM5. The increase in precipitation over Bangladesh and neighboring areas is visible in all the models but it is difficult to explain these changes with respect to changes in moisture transport in case of PRECIS-ECHAM5. If we look at the differences in specific humidity (not shown) all models are consistent in showing increased humidity over Bay of Bengal, Bangladesh and neighboring areas.

Changes in the annual cycle of temperature and precipitation for Region B and Region F are shown in Fig. 10. Changes in the temperature in different months of the year are not correlated with the changes in the precipitation in

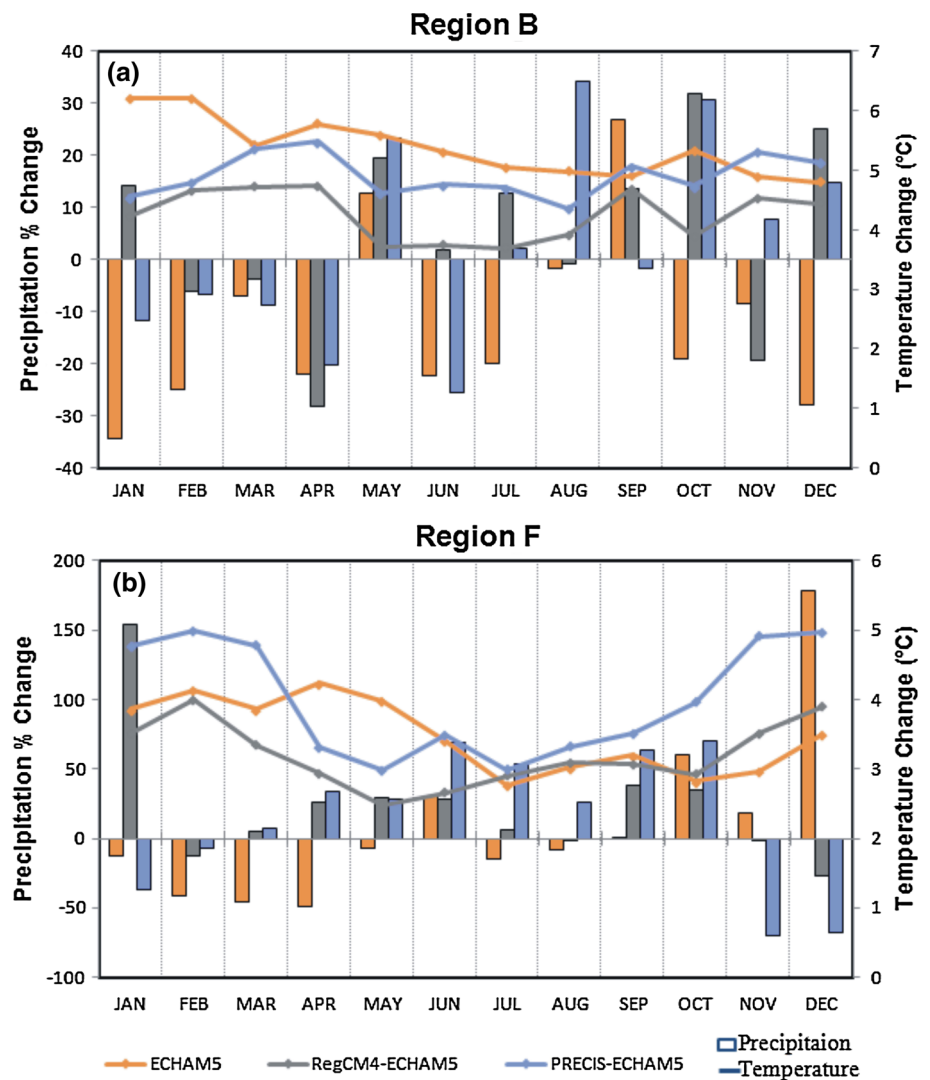
both regions. Both the RCMs are showing similar variability in the annual cycle of temperature in Region B. The increase in temperature is more in ECHAM5 about 5 °C or more compared to RCMs. The maximum change in temperature is seen in ECHAM5 in January and February. The RCMs and GCM are consistent in precipitation variability from February to May, whereas in the SASM period there is heterogeneous variability in the precipitation change over Region B. Both RCMs and GCM are showing slight increase in precipitation during summer monsoon over Region F. The increase in temperature is also very similar about 3 °C during summer monsoon months.

RCM is a part of the modelling process and the chain of procedures in which uncertainties and inferences at each level can impact outcomes at subsequent levels. This chain has been referred to as the cascade of uncertainty or uncertainty explosion (Mitchell and Hulme 1999; Henderson-Sellers 1993 and Jones 2000). The interpretation of differences between the GCM simulated and downscaled climate variables such as surface temperature and precipitation, and the corresponding climate change signals can be difficult to understand because of the differences between the RCM and GCM physics parameterizations e.g. in land surface models and cumulus convection schemes. It is difficult to discriminate whether the differences arise because of regional forcing or difference in physics representations. Even if the same physics representations are used in both models, it remains uncertain whether differences between the GCM and RCM simulations are related to regional forcings or sensitivity of the physics parameterizations to the applied spatial resolution. Both GCMs and RCMs are impacted by uncertainties that weaken confidence in end projections and limit the usefulness of those end projections in planning and policy decisions. Ultimately, choices must be made about which driving GCM and RCM to use, and for every choice there are combinations left unconsidered. Such uncertainties can be considered as an unavoidable part of climate modelling (Foley 2010).

4 Summary and conclusions

The ERA40 reanalysis and ECHAM5 GCM are down-scaled by two RCMs (RegCM4 and PRECIS) over South-Asia for the summer monsoon in order to estimate the uncertainties in the RCMs in reproducing the present day climate (1971–2000). The spatial and the quantitative analysis over the selected climatic regions of South-Asia is performed for the mean climate and the inter-annual variability of temperature, precipitation and circulation. Generally the spatial patterns and topographically-induced structure are captured and simulated values are close to

Fig. 10 Change in JJAS season (2071–2100 minus 1971–2000) annual cycle for precipitation (mm/day) in *colored bars* and temperature ($^{\circ}\text{C}$) in *colored lines* for the period 1971–2000. **a** Region B and **b** Region F



observations. ECHAM5 is warmer than ERA40 reanalysis, over the most of the domain. The difference is reaching up to 8°C over plain areas of Pakistan and along the foothills of Himalayas. RegCM4 has cold bias over the whole domain and this cold bias is more than 5°C over the high mountains in the north of Pakistan and India. PRECIS has a warm bias of more than 2°C over the central parts of Pakistan but the cold bias over the northern high mountains is similar to that of RegCM4. The RegCM4 has a dry bias over central India and also the penetration of monsoon into Pakistan is not very well simulated, whereas PRECIS climatology is more close to observation. Although the global driving datasets ECHAM5 and ERA40 have very large differences in the mean temperature and rainfall spatial distribution but after downscaling with the RCMs the differences are reduced considerably.

The annual cycle of temperature and rainfall is well simulated by the RCMs over different selected climatic regions, however both the RCMs have poorly captured the

inter-annual variability. In case of temperature, downscaled ERA40 by RegCM4 has produced better results in terms of variability and RMSE as compared to the downscaled ERA40 by PRECIS, though the correlations for both the models remain nearly same. For precipitation the two observational datasets are not consistent in terms of inter-annual variability over Bangladesh and southern India, where the correlations tend to become as low as 0.5 showing the uncertainties in the observations over these regions. Both the RCMs show very low values of correlations, <0.5 over most of the selected regions and RMSE is also high for precipitation inter-annual variability. The two RCMs are further applied to downscale ECHAM5 GCM for the period 2071–2100 under A1B emission scenario. The driving GCM and RCMs have a consistent climate change signal over South-Asia. The projections show warming for the entire domain for the future and there is $2.5\text{--}5^{\circ}\text{C}$ increase in the mean surface air temperature, the northern parts of the domain are projected to have

maximum increase in temperature and 30 % increase in rainfall over Bangladesh and neighboring areas by the end of twenty-first century.

There are differences between different observational temperature and precipitation datasets. The difference between the temperature over high mountains is going up to 4 °C. The precipitation difference between station based observational datasets and the observed satellite merged products is around 4 mm/day. These differences should be taken into account while evaluating the climate models over South-Asia. Large differences in temperature and precipitation between the global datasets ECHAM5 and ERA40 are reduced after downscaling with RCMs. Both the RCMs have systematic biases in simulating SASM and RCMs seem to be relatively insensitive to the boundary conditions and are developing their own climatology. The biases in both RCMs are different although they are downscaling same global dataset and these differences appear to come from the difference in the RCM physics. The changes in the mean and spatial patterns of precipitation after downscaling can be explained by the changes in the low level circulation and moisture, in the baseline period. But it is difficult to link the changes in the precipitation with the changes in the circulation in the future climate.

Further research is required to further understand the uncertainties in the RCMs and the driving GCMs. COordinated Regional Climate Downscaling EXperiment (CORDEX) project over South-Asia will provide the opportunity to analyze number of GCMs downscaled by number of RCMs to address the unanswered questions.

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References

- Acharya N, Kar SC, Mohanty UC, Kulkarni MA, Dash SK (2011) Performance of GCMs for seasonal prediction over India—a case study for 2009 monsoon. *Theor Appl Climatol* 105:505–520
- Adam J, Lettenmaier DP (2003) Adjustment of global gridded precipitation for systematic bias. *J Geophys Res* 108:1–14. doi:10.1029/2002JD002499
- Adler RF, Huffman GJ, Chang A, Ferraro R, Xie P, Janowiak J, Rudolf B, Schneider U, Curtis S, Bolvin D, Gruber A, Susskind J, Arkin PA (2003) The version 2 global precipitation climatology project (GPCP) monthly precipitation analysis (1979–present). *J Hydrometeorol* 4:1147–1167
- Akhtar M, Ahmad N, Booij MJ (2008) The impact of climate change on the water resources of Hindukush-Karakorum-Himalaya region under different glacier coverage scenarios. *J Hydrol* 355:148–163. doi:10.1016/j.jhydrol.2008.03.015
- Almazroui M (2012) Dynamical downscaling of rainfall and temperature over the Arabian Peninsula using RegCM4. *Clim Res* 52:49–62
- 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. doi:10.1175/JCLI4035.1
- Anthes RA, Warner TT (1978) Development of hydrodynamic models suitable for air pollution and other mesometeorological studies. *Mon Weather Rev* 106:1045–1078
- Arakawa A, Lamb VR (1977) Computational design and the basic dynamical processes of the UCLA general circulation Model. *Methods in Computational Physics* 17:173
- Ashfaq M, Shi Y, Tung WW, Trapp RJ, Gao X, Pal JS, Dickenbaugh NS (2009) Suppression of south Asian summer monsoon precipitation in the 21st century. *Geophys Res Lett* 36:L01704. doi:10.1029/2008GL036500
- Bergant K, Belda M, Halenka T (2007) Systematic errors in the simulation of European climate (1961–2000) with RegCM3 driven by NCEP/NCAR reanalysis. *Int J Climatol* 27:455–472. doi:10.1002/joc.1413
- Boberg F, Christensen JH (2012) Overestimation of Mediterranean summer temperature projections due to model deficiencies. *Nat Clim Chang*, 18, March 12, 2012. doi:10.1038/NCLIMATE1454
- Bozkurt D, Sen OL (2011) Precipitation in the Anatolian Peninsula: sensitivity to increased SSTs in the surrounding seas. *Clim Dyn* 36(3–4):711–726. doi:10.1007/s00382-009-0651-3
- Busuioc AH, Storch V, Schnur R (1999) Verification of GCM generated regional seasonal precipitation for current climate and of statistical downscaling estimates under changing climate conditions. *J Clim* 12:258–272
- Cox PM, Betts RA, Bunton CB, Essery RLH, Rowntree PR, Smith J (1999) The impact of new land surface physics on the GCM sensitivity of climate and climate sensitivity. *Clim Dyn* 15:183–203
- Dash SK, Shekhar MS, Singh GP (2006) Simulation of Indian summer monsoon circulation and rainfall using RegCM3. *Theor Appl Climatol* 86:161–172
- Dickinson RE, Henderson-Sellers A, Kennedy P (1993) Bio-sphere-atmosphere transfer scheme (BATS) version 1e as coupled to the NCAR community climate model. Tech Rep, National Center for Atmospheric Research Tech Note NCAR. TN-387+STR, NCAR, Boulder, CO
- 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(D24104). doi:10.1029/2011JD016329
- Duffy PB, Arritt RW, Coquard J, Gutowski W, Han J, Iorio J, Kim J, Leung LR, Roads J, Zeledon E (2006) Simulations of present and future climates in the western U.S. with four nested regional climate models. *J Clim* 19:873–895
- Essery RLH, Best MJ, Betts RA, Cox PM, Taylor CM (2003) Explicit representation of subgrid heterogeneity in a GCM land surface scheme. *J Hydrometeorol* 4:530–543
- Feser F (2006) Enhanced detectability of added value in limited-area model results separated into different spatial scales. *Mon Weather Rev* 134:2180–2190
- Feser F, Rockel B, Storch H, Winterfeldt J, Zahn M (2011) Regional climate models add value to global model data: a review and

- selected examples. *Bull Am Meteorol Soc* 92:1181–1192. doi:[10.1175/2011BAMS3061.1](https://doi.org/10.1175/2011BAMS3061.1)
- Foley AM (2010) Uncertainty in regional climate modelling: a review. *Prog Phys Geogr* 34:647–670. doi:[10.1177/0309133310375654](https://doi.org/10.1177/0309133310375654)
- Frei C, Schöll R, Fukutome S, Schmidli J, Vidale PL (2006) Future change of precipitation extremes in Europe: intercomparison of scenarios from regional climate models. *J Geophys Res* 11:D06105
- Gao X, Shi Y, Zhang D, Giorgi F (2012) A high resolution climate change simulation of the 21st century over China by RegCM3. *Chin Sci Bull* 57:1188–1195. doi:[10.007/s11434-011-4935-8](https://doi.org/10.007/s11434-011-4935-8)
- Giorgi F, Anyah RO (2012) Evolution of regional climate modeling: the road towards RegCM4. *Clim Res* 52:3–6
- Giorgi F, Francisco R (2000) Evaluating uncertainties in the prediction of regional climate. *Geophys Res Lett* 27(9): 1295–1298
- Giorgi F, Lionello P (2008) Climate change projections for the Mediterranean region. *Glob Planet Change* 63:90–104
- Giorgi F, Bates GT, Nieman S (1993a) The multi-year surface climatology of a regional atmospheric model over the Western United States. *J Clim* 6:75–95
- Giorgi F, Marinucci MR, Bates GT (1993b) Development of a second generation regional climate model (RegCM2). Part I: boundary layer and radiative transfer processes. *Mon Weather Rev* 121:2794–2813
- Giorgi F, Huang Y, Nishizawa K, Fu C (1999) A seasonal cycle simulation over eastern Asia and its sensitivity to radiative transfer and surface processes. *J Geophys Res* 104:6403–6423
- Gordon C, Cooper C, Senior CA, Banks H, Gregory JM, Johns TC, Mitchell JFB, Wood RA (2000) The simulation of SST, sea ice extents and ocean heat transports in a version of the Hadley Centre coupled model without flux adjustments. *Clim Dyn* 16:147–168
- Gregory D, Allen S (1991) The effect of convective scale downdrafts upon NWP and climate simulations. In: Preprints, 9th conference on numerical weather prediction, Denver. Amer Meteor Soc, pp 122–123
- Gregory D, Kershaw R, Inness PM (1997) Parametrization of momentum transport by convection. II: tests in single-column and general circulation models. *Q J R Meteor Soc* 123:1153–1183
- Gregory D, Rowntree P R (1990) A mass flux convection scheme with representation of cloud ensemble characteristics and stability dependent closure. *Mon Weather Rev* 118:1483–1506
- Gregory PJ, Ingram JSI, Anderson R, Betts RA, Brovkin V, Chase TN, Grace PR, Gray AJ, Hamilton N, Hardy TB, Howden SM, Jenkins A, Meybeck M, Olsson M, Ortiz-Montasterio I, Palm CA, Payn TW, Rummukainen M, Schulze RE, Thiem M, Valentin C, Wikinson MJ (2002) Environmental consequences of alternative practices for intensifying crop production. *Agric Ecosyst Environ* 88:279–290
- Grell GA (1993) Prognostic evaluation of assumptions used by cumulus parameterizations. *Mon Weather Rev* 121:764–787
- Han J, Roads J (2004) U.S. climate sensitivity simulated with the NCEP regional spectral model. *Clim Change* 62:115–154. doi:[10.1023/B:CLIM.0000013675.66917.15](https://doi.org/10.1023/B:CLIM.0000013675.66917.15)
- Henderson-Sellers A (1993) An antipodean climate of uncertainty. *Clim Change* 25:203–224
- Holtslag A, de Bruijn E, Pan HL (1990) A high resolution air mass transformation model for short-range weather forecasting. *Mon Weather Rev* 118:1561–1575
- Houghton JT, Ding Y, Griggs DJ, Noguer M, van der Linden PJ, Xiaosu D (eds) (2001) Climate change 2001: the scientific basis: contributions of working group I to the third assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge
- Hu ZZ, Wu Z (2004) The intensification and shift of the annual North Atlantic Oscillation in a global warming scenario simulation. *Tellus Ser A* 56:112–124
- IPCC (2007a) Climate Change 2007: the Physical Science Basis. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge
- IPCC (2007b) Climate change 2007, impacts, adaptation and vulnerability. In: Parry ML et al (eds) Contribution of working group II to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge
- Islam AKMS, Bhaskaran B, Arifin BMS, Murshed SB, Mukherjee N, Hossain BMTA (2011) Domain size experiment using PRECIS regional climate model for Bangladesh. In: Proceedings of the 3rd international conference on water and flood management, vol 2, Dhaka, pp 891–898
- Islam N (2009) Understanding the rainfall climatology and detection of extreme weather events in SAARC region: part II-Bangladesh, vol 29. SMRC, p 36
- Islam MN, Rafiuddin M, Ahmed AU, Kolli RK (2008) Calibration of PRECIS in employing future scenarios in Bangladesh. *Int J Climatol* 28:617–628
- Islam S, Rehman N, Sheikh MM (2009) Future change in the frequency of warm and cold spells durations over Pakistan simulated by the PRECIS regional climate model. *Clim Change* 94:35–45. doi:[10.1007/s10584-009-9557-7](https://doi.org/10.1007/s10584-009-9557-7)
- Jones RN (2000) Managing uncertainty in climate change projections—issues for impact assessment: an editorial comment. *Clim Change* 45:403–419
- Jones RG, Noguer M, Hassell DC, Hudson D, Wilson SS, Jenkins GJ, Mitchell JFB (2004) Generating high resolution climate change scenarios using PRECIS. Met Office Hadley Centre, Exeter
- Kang I-S, Shukla J (2005) Dynamical seasonal prediction and predictability of monsoon. In: Wang B (ed) *The Asian monsoon*. Praxis Publishing Ltd, Chichester, pp 585–612
- Kang I-S, Lee J, Park CK (2004) Potential predictability of summer mean precipitation in a dynamical seasonal prediction system with systematic error correction. *J Clim* 17:834–844
- Kar SC, Acharya N, Mohanty UC, Kulkarni MA (2011) Skill of monthly rainfall forecasts over India using multi-model ensemble schemes. *Int J Climatol*. doi:[10.1002/joc.2334](https://doi.org/10.1002/joc.2334)
- Kiehl JT, Hack JJ, Bonan GB, Boville BA, Briegleb BP, Williamson DL, Rasch PJ (1996) Description of the NCAR Community Climate Model (CCM3). NCAR Technical Note NCAR/TN-420 + STR, 143 p
- Kitoh A, Kusunoki S (2009) East Asian summer monsoon simulation by a 20-km mesh AGCM. *Clim Dyn*. doi:[10.1007/s00382-007-0285-2](https://doi.org/10.1007/s00382-007-0285-2)
- Krishnamurti TN, Stefanova L, Chakraborty A, Kumar TSVV, Cocke S, Bachiochi D, Mackey B (2002) Seasonal forecasts of precipitation anomalies for North American and Asian monsoons. *J Meteorol Soc Jpn* 80:1415–1426
- Krishnamurti TN, Mitra AK, Yun W-T, Kumar TSVV (2006) Seasonal climate forecasts of the Asian monsoon using multiple coupled models. *Tellus* 58A:487–507
- Krishnan R, Sabin TP, Ayantika DC, Kitoh A, Sugi M, Murakami H, Turner AG, Slingo JM, Rajendran K (2012) Will the South Asian monsoon overturning circulation stabilize any further? *Clim Dyn*. doi:[10.1007/s00382-012-1317-0](https://doi.org/10.1007/s00382-012-1317-0)
- Kumar RK, Sahai AK, Krishna 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* 90:334–345
- Liu S, Liang X-Z, Gao W, He Y, Ling T (2011) Regional climate model simulations of the 1998 summer China flood: dependence on initial and lateral boundary conditions. *Open Atmos Sci J* 5:96–105
- Loveland TR, Reed BC, Brown JF, Ohlen DO, Zhu Z, Yang L, Merchant JW (2000) Development of a global land cover characteristics database and IGBP DISCover from 1 km AVHRR data. *Int J Remote Sens* 21(6–7):1303–1365
- Martinez-Castro D, Porfirio da Rocha R, Bezanilla-Morlot A, Alvarez-Escudero L, Reyes-Fernandez JP, Silva-Vidal Y, Arritt RW (2006) Sensitivity studies of the RegCM3 simulation of summer precipitation, temperature and local wind field in the Caribbean Region. *Theor Appl Climatol* 86:5–22
- Messenger C, Gallee H, Brasseur O (2004) Precipitation sensitivity to regional SST in a regional climate simulation during the West African monsoon for two dry years. *Clim Dyn* 22:249–266. doi:10.1007/s00382-003-0381-x
- Mitchell TD, Hulme M (1999) Predicting regional climate change: living with uncertainty. *Prog Phys Geogr* 23:57–78
- Mitchell TD, Jones PD (2005) An improved method of constructing a database of monthly climate observations and associated high resolution grids. *Int J Climatol* 25:693–712
- Mizuta R, Yoshimura H, Murakami H, Matsueda M, Endo H, Ose T, Kamiguchi K, Hosaka M, Sugi M, Yukimoto S, Kusunoki S, Kitoh A (2012) Climate simulations using MRI-AGCM3.2 with 20-km grid. *J Meteorol Soc Jpn* 90A:233–258. doi:10.2151/jmsj.2012-A12
- Onol B, Semazzi FHM (2009) Regionalization of climate change simulations over the eastern Mediterranean. *J Clim* 22:1944–1961
- Paeth H, Manning B (2012) On the added value of regional climate modeling in climate change assessment. *Clim Dyn* doi:10.1007/s00382-012-1517-7
- Pal JS, Small E, Eltahir E (2000) Simulation of regional-scale water and energy budgets: representation of Subgrid cloud and precipitation processes within RegCM. *J Geophys Res* 105:29579–29594
- Pal JS, Giorgi F, Bi X (2004) Consistency of recent European summer precipitation trends and extremes with future regional climate projections. *Geophys Res Lett* 31:L13202
- Rajendran K, Kitoh A, Srinivasan J, Mizuta R, Krishnan R (2012) Monsoon circulation interaction with Western Ghats orography under changing climate—projection by a 20-km mesh AGCM. *Theoret Appl Climatol*. doi:10.1007/s00704-012-0690-2
- Rao YP, Ramamurti KS (1968) Climatology of India and neighbourhood, F.M.U. Rep No I-2, India Meteorological Department
- Rayner NA, Parker DE, Horton EB, Folland CK, Alexander LV, Rowell DP, Kent EC, Kaplan A (2003) Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *J Geophys Res* 108(14):4407. doi:10.1029/2002JD002670
- Roeckner E, Bäuml G, Bonaventura L, Brokopf R, Esch M, Giorgetta M, Hagemann S, Kirchner I, Kornbluh L, Manzini E, Rhodin A, Schlese U, Schulzweida U, Tompkins A (2003) The atmospheric general circulation model ECHAM5. Part I: model description, vol 349. Max Planck Institute for Meteorology Report, p 127
- Russell GL, Miller JR, Rind D, Ruedy RA, Schmidt GA, Sheth S (2000) Comparison of model and observed regional temperature changes during the past 40 years. *J Geophys Res* 105:14891–14898. doi:10.1029/2000JD900156
- Sabin TP, Krishnan R, Ghattas J, Denvil S, Dufresne J-L, Hourdin F, Pascal T (2013) High resolution simulation of the South Asian monsoon using a variable resolution global climate model. *Clim Dyn*. doi:10.1007/s00382-012-1658-8
- Sen OL, Wang Y, Wang B (2004a) Impact of Indochina deforestation on the East-Asian summer monsoon. *J Clim* 17:1366–1380
- Sen OL, Wang B, Wang Y (2004b) Regreening the desertification lands in northern China: implications from a regional climate model experiment. *J Meteorol Soc Jpn* 82(6):1599–1628
- Seth A, Rauscher SA, Camargo SJ, Qian JH, Pal JS (2007) REGCM3 regional climatologies for South America using reanalysis and ECHAM global model driving fields. *Clim Dyn* 28:461–480. doi:10.1007/s00382-006-0191-z
- Sylla MB, Coppola E, Mariotti L, Giorgi F, Ruti PM, Dell’Aquila A, Bi X (2010) Multiyear simulation of the African climate using a regional climate model (RegCM3) with the high resolution ERA-interim reanalysis. *Clim Dyn* 35:231–247
- Taylor KE (2001) Summarizing multiple aspects of model performance in a single diagram. *J Geophys Res* 106(7):7183–7192. doi:10.1029/2000JD900719
- Taylor MA, Centella A, Charlery J, Borrajero I, Bezanilla A, Campbell J, Rivero R, Stephenson TS, Whyte F, Watson R (2007) Glimpses of the future: a briefing from the PRECIS Caribbean Climate Change Project. Caribbean Community Climate Change Centre, Belmopan, p 24
- Uppala SM, Kållberg PW, Simmons AJ, Andrae U, da Costa Bechtold V, Fiorino M, Gibson JK, Haseler J, Hernandez A, Kelly GA, Li X, Onogi K, Saarinen S, Sokka N, Allan RP, Andersson E, Arpe K, Balmaseda MA, Beljaars ACM, van de Berg L, Bidlot J, Bormann N, Caires S, Chevallier F, Dethof A, Dragosavac M, Fisher M, Fuentes M, Hagemann S, Hólm E, Hoskins BJ, Isaksen I, Janssen PAEM, Jenne R, McNally AP, Mahfouf JF, Morcrette JJ, Rayner NA, Saunders RW, Simon P, Sterl A, Trenberth KE, Untch A, Vasiljevic D, Viterbo P, Woollen J (2005) The ERA-40 re-analysis. *Q J R Meteorol Soc* 131:2961–3012. doi:10.1256/qj.04.176
- Vidale PL, Lüthi D, Frei C, Seneviratne SI, Schär C (2003) Predictability and uncertainty in a regional climate model. *J Geophys Res* 108(18):4586. doi:10.1029/2002JD002810
- Wang GL (2005) Agricultural drought in a future climate: results from fifteen global climate models participating in the Intergovernmental panel for climate change’s 4th assessment. *Clim Dyn* 25. doi:10.1007/s00382-005-0057-9
- Wang B (2006) *The Asian monsoon*. Springer/Praxis Publishing, New York, pp 134–139
- Wang YQ, Leung LR, McGregor JL, Lee DK, Wang WC, Ding YH, Kimura F (2004) Regional climate modeling: progress, challenges and prospects. *J Meteorol Soc Jpn* 82:1599–1628
- Wang B, Ding Q, Fu X, Kang I-S, Jin K, Shukla J, Doblas-Reyes F (2005) Fundamental challenge in simulation and prediction of summer monsoon rainfall. *Geophys Res Lett* 32:L15711. doi:10.1029/2005GL022734
- Willmott CJ, Matsuura K (1998) Global air temperature and precipitation: regridded monthly and annual climatologies (Version 2.01). Center for Climatic Research, Department of Geography, University of Delaware, Newark, DE (data available at climate.geog.udel.edu/~climate)
- Zeng X, Zhao M, Dickinson RE (1998) Intercomparison of bulk aerodynamic algorithms for the computation of sea surface fluxes using TOGA COARE and TAO data. *J Clim* 11:2628–2644