

## Research Article

# Impact of Climate Change on the Characteristics of Indian Summer Monsoon Onset

Savita Patwardhan,<sup>1</sup> Ashwini Kulkarni,<sup>1</sup> and K. Krishna Kumar<sup>2</sup>

<sup>1</sup> Indian Institute of Tropical Meteorology, Pune 411008, India

<sup>2</sup> Qatar Meteorology Department, Doha, Qatar

Correspondence should be addressed to Savita Patwardhan; [patwar@tropmet.res.in](mailto:patwar@tropmet.res.in)

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A high resolution regional climate modeling system, known as PRECIS (Providing REgional Climate for Impact Studies), developed by Hadley Centre for Climate Prediction and Research, UK, is applied for Indian subcontinent to assess the impact of climate change on the summer monsoon onset characteristics. The present day simulation (1961–1990) with PRECIS is evaluated for the characteristics of onset over Kerala, southernmost part of India, where the monsoon sets in over Indian landmass. The meteorological parameters like precipitation, outgoing long wave radiation (OLR), and low level winds are analysed to study the monsoon onset over Kerala. The model is able to capture the sudden and sharp increase of rainfall associated with the onset. The rapid built-up of convective activity over the southeastern Arabian Sea and Bay of Bengal is well represented by the model. PRECIS simulations, under scenarios of increasing greenhouse gas concentrations and sulphate aerosols, are analysed to study the likely changes in the onset characteristics in future, towards the end of present century (2071–2100). The analysis does not indicate significant difference in the mean onset dates in A2 and B2 scenarios. However, the variability of onset date is likely to be more towards the end of the 21st century especially in A2 scenario.

## 1. Introduction

The onset of summer monsoon over the southern tip of Kerala is the vital meteorological phenomenon over India. It is the prime event related to the Indian agriculture and economy. Every year, summer monsoon arrives over Kerala coast (Figure 1) around the end of May/beginning of June. The delay in the onset is an issue of concern to all, from farmers to policy makers. It is very difficult to declare the onset of monsoon. Sometimes, in early May, there can be a bogus onset and the real onset will be delayed [1]. The onset of Indian summer monsoon represents significant transitions in the large scale atmospheric and oceanic circulation in the Indo-Pacific region. There is no widely accepted definition of this monsoon transition. At the surface, monsoon transitions are first revealed by variability in rainfall. Hence at the surface, monsoon onset is recognized as a rapid substantial and sustained increase in rainfall. Although no objective criterion exists for fixing the date of onset, the primary

indicator from the early days of Indian Meteorology has been a sharp and sustained increase in rainfall at a group of adjacent stations [2].

Different criteria are used, by various researchers, to define the monsoon onset over Kerala. Using daily rainfall data from a dense network of rain gauges in Kerala, Ananthkrishnan and Soman [3] derived dates of monsoon onset over Kerala for south and north Kerala separately for the period 1901–1980. They defined the date of monsoon onset over Kerala as the first day of the transition from the light to heavy rainfall category with the provision that the average daily rainfall during the first 5 days after the transition should not be less than 10 mm. With this criterion, they have shown that the mean onset date over south Kerala is 30th of May and for north Kerala is 1st of June with the standard deviation of about 9 days for both. India Meteorological Department (IMD) uses a relatively qualitative method for declaring the onset, using the rainfall over stations located in Kerala, the lower tropospheric winds over Kerala, and

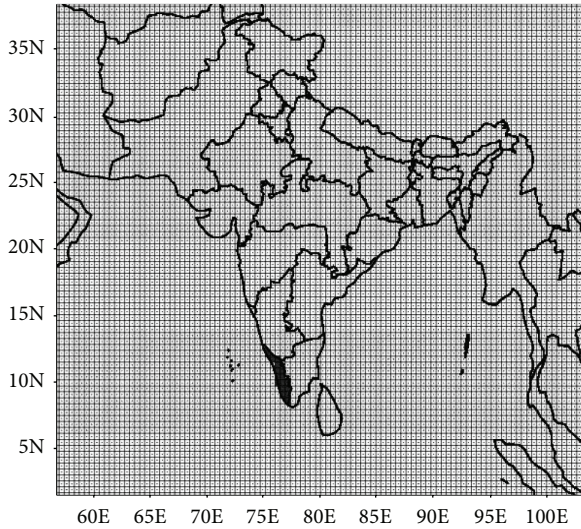


FIGURE 1: Indian domain used for the PRECIS simulations. Shaded region is the state of Kerala.

the moisture available up to 500 hPa [4]. From the long period records of the Indian Meteorological Department, the mean onset date over Kerala is 1st of June with standard deviation of 7.28 days. From 2006, IMD is using the criterion by Joseph et al. [5] that depends on rainfall and circulation variables. Fasullo and Webster [6] used vertically integrated moisture transport instead of rainfall to define onset as well as withdrawal of monsoon. Zeng and Lu [7] defined monsoon onset and retreat using normalized precipitable water index. Xavier et al. [8] proposed an Indian summer monsoon onset index based on reversal of the large-scale meridional temperature gradient in the upper troposphere south of the Tibetan Plateau. Wang et al. [9] have used the 850-hPa zonal wind averaged over the south Arabian Sea ( $5^{\circ}$ – $15^{\circ}$ N,  $40^{\circ}$ – $80^{\circ}$ E) as an onset circulation index of the Indian summer monsoon. Pai and Nair [10] have discussed various definitions of monsoon onset over Kerala (MOK) used by different researchers. Puranik et al. [11] have defined index using OLR and zonal kinetic energy to predict the monsoon onset over Kerala.

Global climate models, the best tool to understand and project the possible changes in climate, have large uncertainties in the simulation of monsoon precipitation compared to its simulation of temperature. All models under IPCC 4th assessment report projected a significant increase in temperature towards the end of the 21st century. However, the response of monsoon rainfall to the increased greenhouse gas concentrations varies from model to model [12], Rajeevan and Nanjundiah 2004 [13]. Bhaskaran and Mitchell [14] studied the changes in southwest monsoon precipitation using Hadley Centre global climate model, HadCM2, and showed that the monsoon onset date over the Bombay latitudes ( $18.975^{\circ}$ N) delays by 10 days in the warming scenario. But the uncertainties in model projections of monsoon behavior are not clear from their study.

Here, we focused on examining the possible changes in the monsoon onset characteristics in the future under the effect of global warming, using a high resolution regional climate model, PRECIS (Providing REgional Climate for Impact Studies). The PRECIS simulation of seasonal monsoon precipitation for the present time slice (1961–1990) is quite similar to the observed, indicating that the model provides an adequate representation of present-day conditions [15]. Before analysing the future climate change scenarios using PRECIS, an evaluation of the model's capability to simulate the summer monsoon onset characteristics has been carried out using the present day (1961–1990) model simulations.

## 2. Data and Methods

**2.1. Regional Climate Model (PRECIS).** PRECIS is an atmospheric and land surface model of limited area (typically  $5,000 \text{ km} \times 5,000 \text{ km}$ ) and high resolution ( $50 \text{ km} \times 50 \text{ km}$ ) developed by Hadley Centre for Climate Prediction and Research, UK, which can be used for simulations over any part of the globe. PRECIS has been configured for Indian domain extending from about  $1.5^{\circ}$ N to  $38^{\circ}$ N and  $56^{\circ}$ E to  $103^{\circ}$ E (Figure 1). Dynamical flow, the atmospheric sulphur cycle, clouds and precipitation, radiative processes, the land surface, and the deep soil are all formulated and boundary conditions are required at the limits of the model's domain. The model is driven at the lateral boundaries by the atmospheric general circulation model HadAM3H [16]. The basic aspects explicitly handled by the model are available in Noguer et al., 2002 [17]. The PRECIS regional model is already being used to generate scenarios for China and southern Africa (PRECIS-Update 2002). The high resolution climate change scenarios, using PRECIS simulations, are developed for the Indian region [15] and are distributed to the various impact user groups in India. Simulations using PRECIS have been performed to generate the climate for present time slice, for the period from 1961 to 1990 (taken as the baseline for model simulations) and for future period, from 2071 to 2100. The future period simulations are carried out for two different socioeconomic scenarios both characterised by regionally focused development but with priority to economic issues in one simulation (A2 scenario) and to environmental issues in the other (B2 scenario). The results for B2 scenarios are similar to A2 scenario but are on the lower side of magnitude. The detailed description of these scenarios is reported in Nakicenovic and Swart [18].

Though the results from the IPCC AR5 models are now available, we have used PRECIS simulations for A2 and B2 scenarios with lateral boundary conditions from IPCC AR4 global model due to its high resolution.

### 2.2. Observed Data Sets

**2.2.1. Rainfall.** The India Meteorological Department has developed a high resolution ( $1^{\circ} \times 1^{\circ}$  lat./long.) daily gridded rainfall data set over the Indian landmass for the period 1901–2004 [19]. The data set is now updated till the year 2013 and is available on request at <http://www.imdpune.gov.in>.

Daily rainfall data from total 1803 stations have been used in developing the gridded data set. The data for the period 1961–1990 is used in the present study for validating the model.

**2.2.2. Outgoing Long Wave Radiation (OLR).** Estimates of OLR from National Oceanic and Atmospheric Administration (NOAA) polar orbiting satellites are used to distinguish areas of deep tropical convection. The National Environmental Satellite Data and Information Service (NESDIS) of NOAA archives the data onto  $2.5^\circ$  lat  $\times$   $2.5^\circ$  long grids [20]. This datum is available from June 1974 to date, except 1978. The data sets are available from the anonymous FTP site <ftp://ftp.cdc.noaa.gov/>.

**2.2.3. Winds at 850 hPa.** The NCEP-NCAR reanalysis data set [21] for the 850 hPa vector winds for the period 1961–1990 is used to examine the zonal kinetic energy in Arabian Sea during the onset phase of southwest monsoon.

**2.3. Method.** Daily rainfall over Kerala is represented by the simple area average rainfall over all the 16 grid points over Kerala (Figure 1). We use the following criterion for the onset of monsoon in PRECIS simulations—when the daily precipitation over Kerala is at least 5 mm and it persists for three consecutive days, then first day is taken as the onset of monsoon. Once the onset date is determined, composite analysis is performed for the parameters, namely, rainfall, low level wind, and the outgoing long wave radiation for preonset, onset, and postonset phases of the monsoon, to examine the onset characteristics simulated in the model baseline simulations (Section 3) and the likely future changes in the characteristics with reference to the above-mentioned parameters (Section 4).

### 3. Evaluation of PRECIS Simulations for Summer Monsoon Onset

Southwest monsoon over India sets in from the southern tip of Kerala. Sudden increase in precipitation over Kerala around the end of May and beginning of June marks the onset. At the onset, rainfall increases substantially and persists for a long period. Ananthkrishnan and Soman [3] have done the superposed epoch analysis of the area weighted rainfall of south and north Kerala relative to the onset date and showed a sharp and spectacular increase of rainfall heralding the monsoon onset.

As the monsoon develops, south-westerlies are established at lower troposphere, over the Arabian Sea and the Indian subcontinent with a strong northward cross equatorial flow off the East African coast and at upper levels, a broad band of east to northeast winds gets established extending across the whole of the tropical Indian Ocean into Africa [22]. Spectacular strengthening of the westerly flow over the Arabian Sea is one of the important aspects of onset of monsoon. Krishnamurti et al. [23] analysed the MONEX data sets and showed that the kinetic energy of zonal winds at 850 hPa over Arabian Sea increases steadily after the onset.

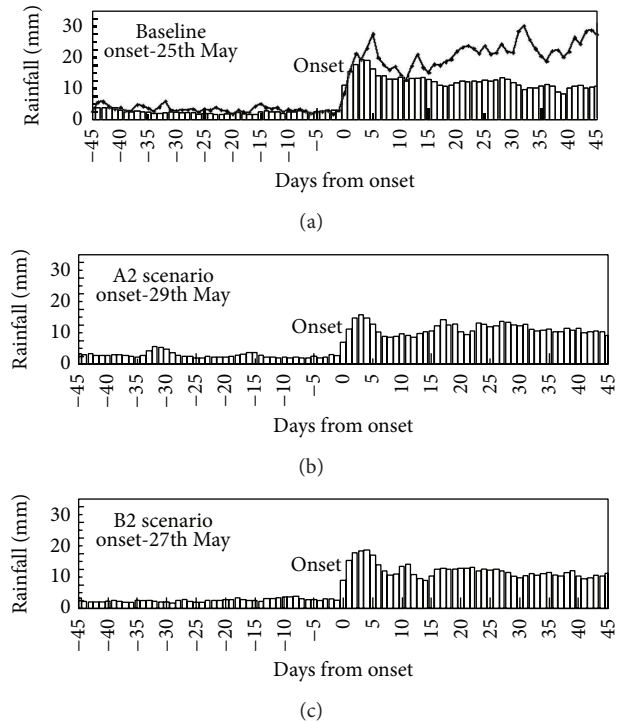


FIGURE 2: Daily rainfall (mm) over Kerala as simulated by PRECIS (bars) from 45 days prior to onset to 45 days after the onset for baseline (a), A2 scenario (b), and B2 scenario (c). The observed daily march of rainfall (line) is shown using IMD gridded data set.

The meteorological parameters like winds at 850 hPa, precipitation, and OLR during 1961–1990 have been analysed for preonset, onset, and postonset phases of the monsoon, to evaluate the model's ability to simulate the onset of summer monsoon over Kerala.

**3.1. Rainfall.** To assess the ability of model in simulating monsoon onset, the daily rainfall series simulated by PRECIS for Kerala are analysed for the present time slice (1960–1990). The criterion defined in Section 2.3 is then applied to the IMD's high resolution daily gridded rainfall data for the same period 1961–1990. It gives 30th of May as the climatological mean onset date of monsoon over Kerala with standard deviation of 12.2 days. The model simulated mean date of monsoon onset over Kerala for 1961–1990 is 25th of May, with slightly low value of standard deviation as 7.7 days. Figure 2 shows the superposed epoch analysis of daily rainfall over Kerala. 0 day indicates the monsoon onset over Kerala. The sharp and spectacular increase in rainfall associated with the monsoon onset is reasonably well represented in the model. Prior to onset, rainfall is less than 5 mm/day. At the onset, rainfall increases substantially and persists for a long period. However, it is seen from the Figure 2(a) that the model simulated rainfall at the onset is less than the observed rainfall for the period 1961–1990.

Once the monsoon sets in over Kerala, it progresses towards northern latitudes to cover the entire country by



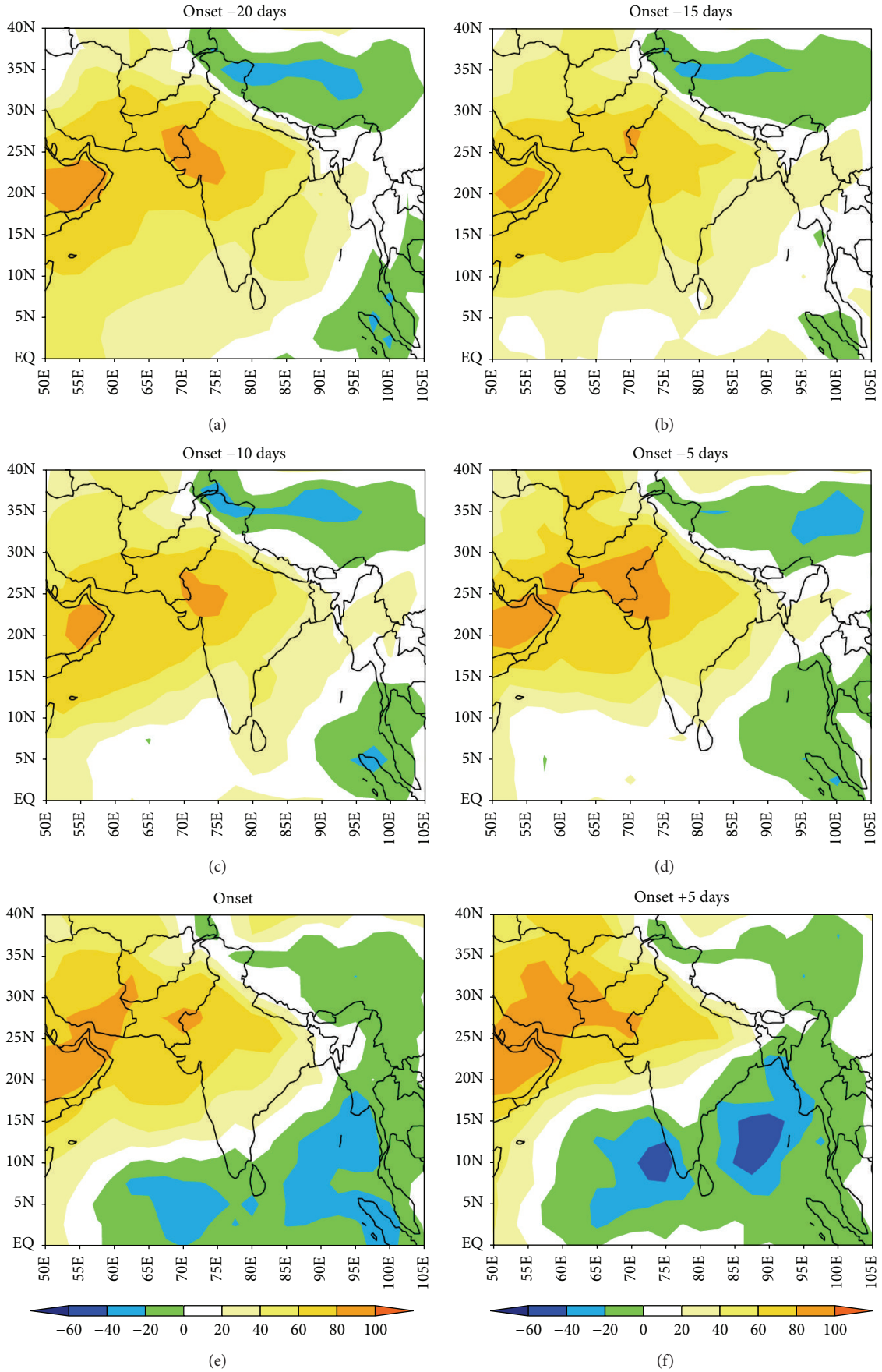


FIGURE 3: Continued.

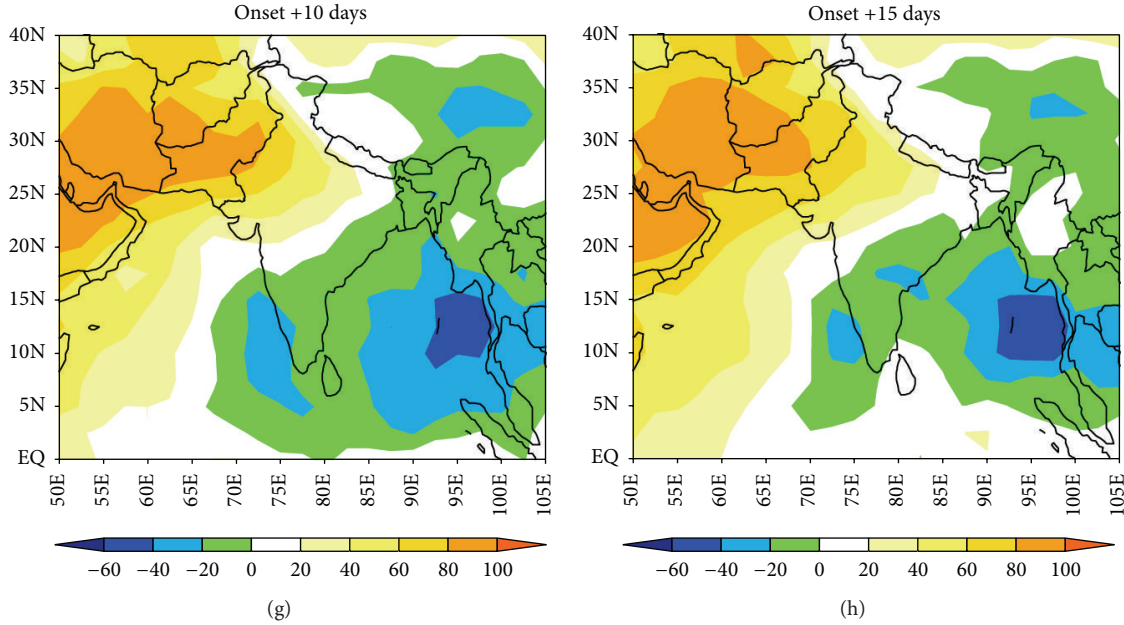


FIGURE 3: Observed OLR anomalies (OLR-220) from NOAA OLR data set at the onset phase (20 days prior to onset through 15 days after the onset).

around 15th July. The normal onset date of monsoon over west Rajasthan is 1st of July as per IMD. The model skills in simulating the northward progress of the summer monsoon are assessed using the model simulated daily rainfall over west Rajasthan. The rainfall over west Rajasthan is the average rainfall over all the 83 grids over west Rajasthan. The criterion used to define onset is similar to the Kerala onset. If the minimum daily rainfall of 1.5 mm is received for three days, then the first day is considered as the onset of monsoon over west Rajasthan. Using this criterion, the mean onset date over west Rajasthan is identified for the model baseline. The model simulated onset date over west Rajasthan is 2nd of July. Even though the model has a slight bias of early onset over Kerala, it reaches over Rajasthan on the date almost as observed; hence it can be seen that the advancement of monsoon is very well captured by the model.

**3.2. Convection.** Since the observed daily precipitation data is available only over the Indian land mask, we used outgoing long wave radiation (OLR) as a proxy for precipitation over the oceanic region. Higher values of OLR imply less convection and hence indicate less cloudiness and rain. According to Kripalani et al. [24] the OLR values 220–240  $\text{Wm}^{-2}$  are associated with rainfall probability 0.7–0.8 and OLR = 180  $\text{Wm}^{-2}$  indicates probability of rainfall greater than 0.9. Outgoing long wave radiation (OLR) serves as a good index of cloudiness and precipitation. The composite OLR pattern for the onset phase of monsoon for the period 1961–1990 is validated using observed OLR data set from NOAA. The composite OLR anomalies taken with respect to 220  $\text{Wm}^{-2}$  are shown in Figure 3. Figure 3 shows that up to 15 days prior to the onset the OLR anomalies in the southeastern Arabian Sea are greater than 20  $\text{Wm}^{-2}$ . Then it gradually

decreases and at the onset OLR anomaly values are less than  $-20 \text{Wm}^{-2}$ . After the onset, convection shifts to east Bay of Bengal and gradually the convective activity decreases over Arabian Sea.

The spatial pattern of the OLR is well simulated by the model but the convection is more in the baseline simulation (Figure 4) as compared to the observed OLR pattern. The simulated OLR pattern reveals that in the model the convection starts building up over southeast Arabian Sea 15 days prior to the onset (OLR anomaly  $< -20 \text{Wm}^{-2}$ ). Five days before the onset, the main convective area shifts to east Bay of Bengal and over southeastern Arabian Sea (OLR anomaly  $< -60 \text{Wm}^{-2}$ ). On the onset day, deep convective clouds (OLR anomaly  $< -60 \text{Wm}^{-2}$  indicating probability of rain  $> 0.9$  according to [24]) can be seen off the Kerala coast. These model results agree well with the study by Soman and Kumar [25]. After the onset, the convective activity over Arabian Sea decreases slowly and increases over northeast Bay of Bengal (OLR anomaly  $< -80 \text{Wm}^{-2}$ ). Northward propagation of the convection is also well reproduced in the OLR pattern (Figure 4). The collocation of model simulated heavy rainfall region with low value of OLR indicates that there is consistency among these parameters in the model (figure not shown).

**3.3. Winds at 850 hPa.** As the summer monsoon develops, at lower troposphere, south-westerlies are established over the Arabian Sea and the Indian subcontinent with a strong northward cross equatorial flow off the East African coast and at upper levels a broad band of east to northeast winds gets established extending across the whole of the tropical Indian Ocean into Africa [22]. In the present study, the development

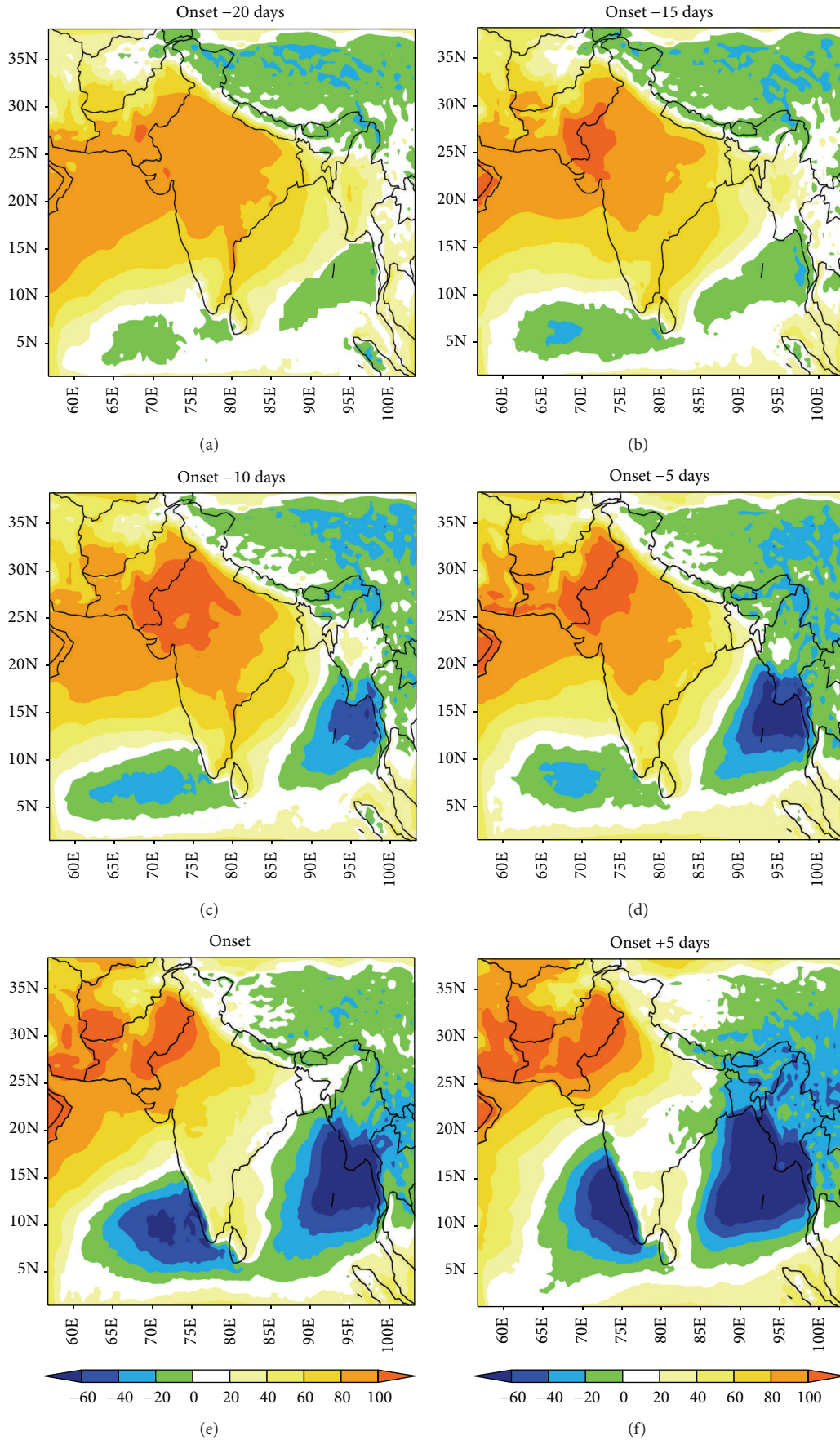


FIGURE 4: Continued.



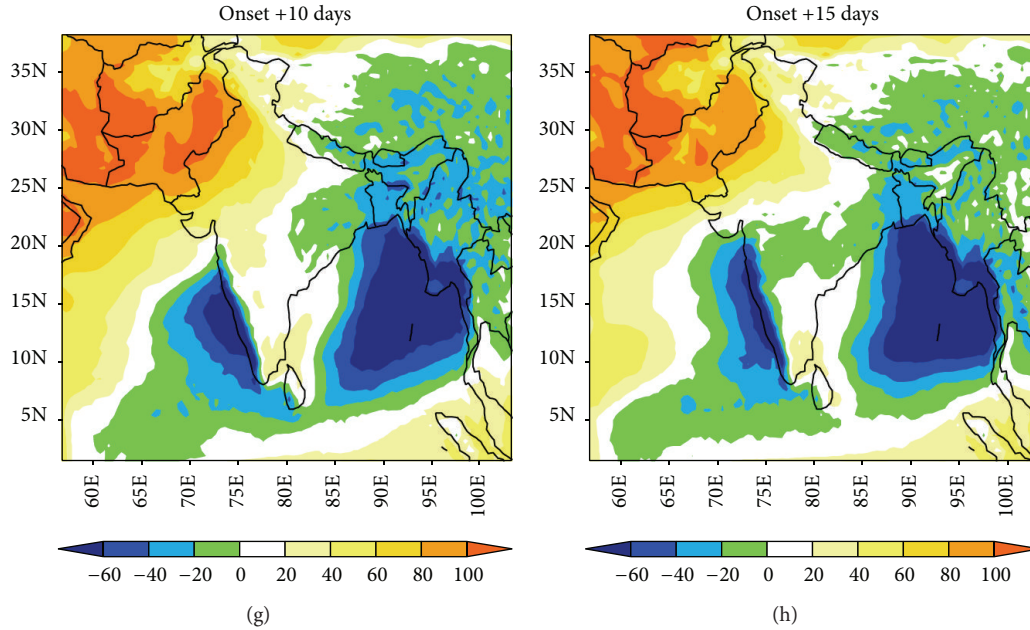


FIGURE 4: Same as Figure 3 but for baseline simulation.

of cross equatorial flow could not be studied, as the model domain is restricted to the Indian region.

The spectacular strengthening of the low level westerly flow over the Arabian Sea is one of the important aspects of the onset of monsoon. During the onset of monsoon over Kerala the low level westerly winds over Arabian Sea strengthen anomalously. To examine this aspect the composite analysis of 850 hPa winds is carried out from the 20th day prior to the onset to 15th day following the onset. Analysis shows that the low level westerlies over Arabian Sea and their rapid intensification after the onset are in good agreement with the observed pattern. After the onset, westerlies extend up to northern latitudes.

Krishnamurti et al. [23] analysed the MONEX data sets and showed that the kinetic energy of zonal winds (ZKE) at 850 hPa over Arabian Sea increases steadily after the onset. Raju et al. [26] analysed the ZKE in Arabian Sea and Bay of Bengal using daily NCEP-NCAR reanalysis data sets. They have shown that the sudden rise in low level kinetic energy can be a potential predictor to declare onset. The model simulated zonal winds at 850 hPa are analysed to see if this steady rise in low level ZKE is captured by the model. Figure 6 shows the ZKE at 850 hPa in the southeast Arabian Sea ( $56^{\circ}\text{E}$ – $70^{\circ}\text{E}$  and  $1.5^{\circ}\text{N}$ – $20^{\circ}\text{N}$ ). It increases from  $20\text{ m}^2/\text{s}^2$  (onset-5 days) to  $50\text{ m}^2/\text{s}^2$  (onset) for the baseline run (upper panel). After the onset it rises steadily up to  $125\text{ m}^2/\text{s}^2$ . The strengthening of westerlies is well simulated by the model. However the model overestimates the ZKE compared to the observed ZKE as seen in the Figure 6.

#### 4. Future Changes in the Onset Characteristics

A comparison between the present time slice (1961–1990) and the future (2071–2100) emission scenarios (A2 and B2) has

TABLE 1: Onset dates of southwest monsoon over Kerala simulated by PRECIS.

	Mean onset date over Kerala	Std. dev. (days)
Observed	1st of June	7.3
Baseline	25th of May	7.7
A2 scenario	29th of May	11.6
B2 scenario	27th of May	9.1

been made to see the possible changes in the monsoon onset characteristics in the warming scenarios. The average onset dates for A2 and B2 scenario are 29th of May and 27th of May, respectively, towards the end of the 21st century, that is, in 2080s. The change in the mean onset date is not significant in future as the variability of the onset dates in 2080s is 11.6 (9.1) days for A2 (B2) scenario. The variability of the onset dates is more in future as compared to the present (Table 1). The time required to advance the monsoon over northwest India is likely to be less in the future scenarios than the baseline. For A2 and B2 scenarios the dates are 25th of June and 27th of June, respectively. The results are comparable for A2 and B2 scenarios. However the magnitude of projections for A2 scenarios is more, being a high emission scenario.

The analysis of the future simulations of PRECIS in warming scenario also identifies the sharp rise in daily rainfall at the onset phase of monsoon towards 2080s in both emission scenarios, namely, A2 and B2. However, the rainfall at the onset phase over Kerala may be less in future as compared to the baseline, as seen from Figure 2.

Figure 5 shows the composite OLR pattern towards 2080s for A2 scenario. It can be seen that the convection at the onset

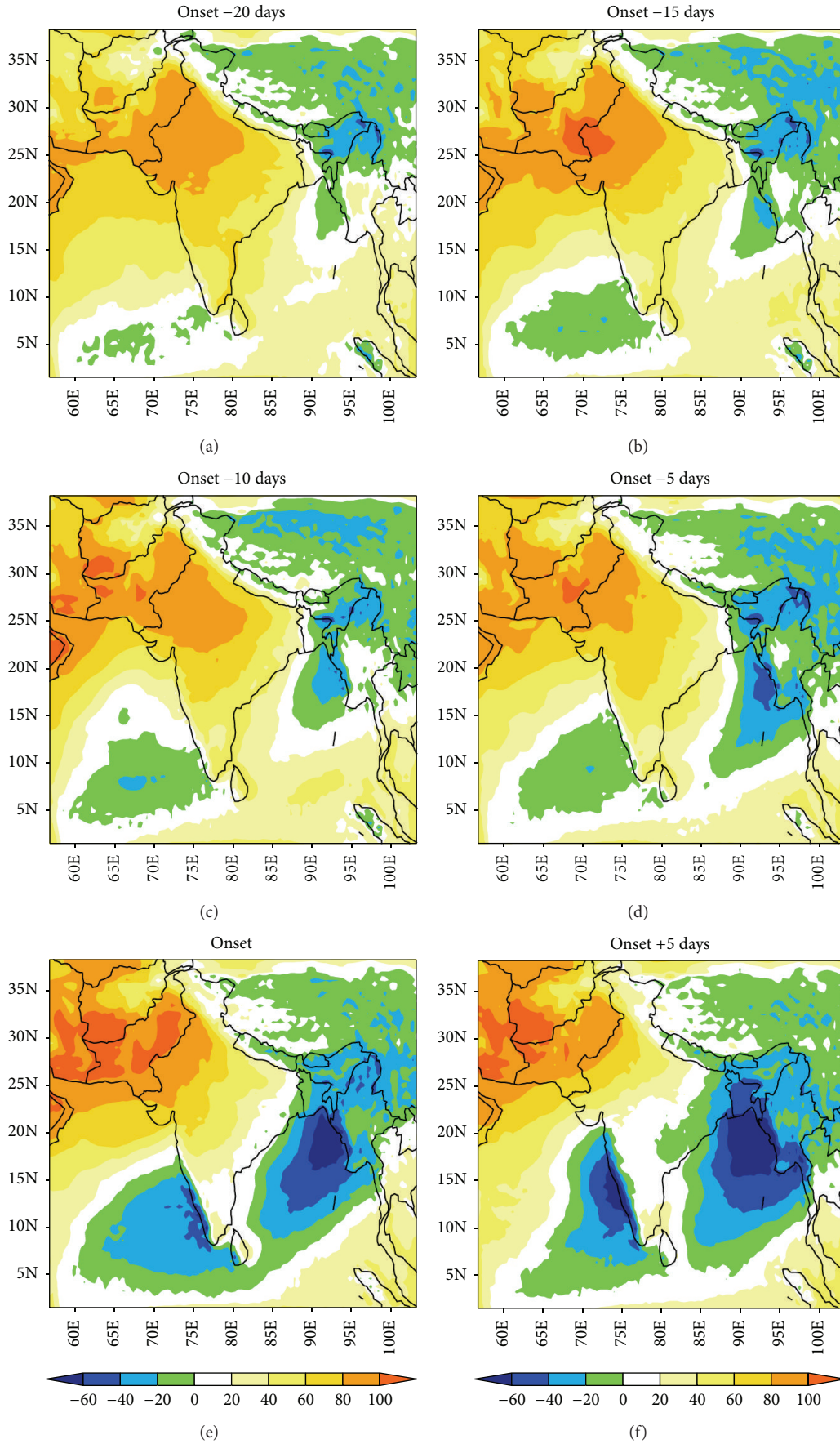


FIGURE 5: Continued.



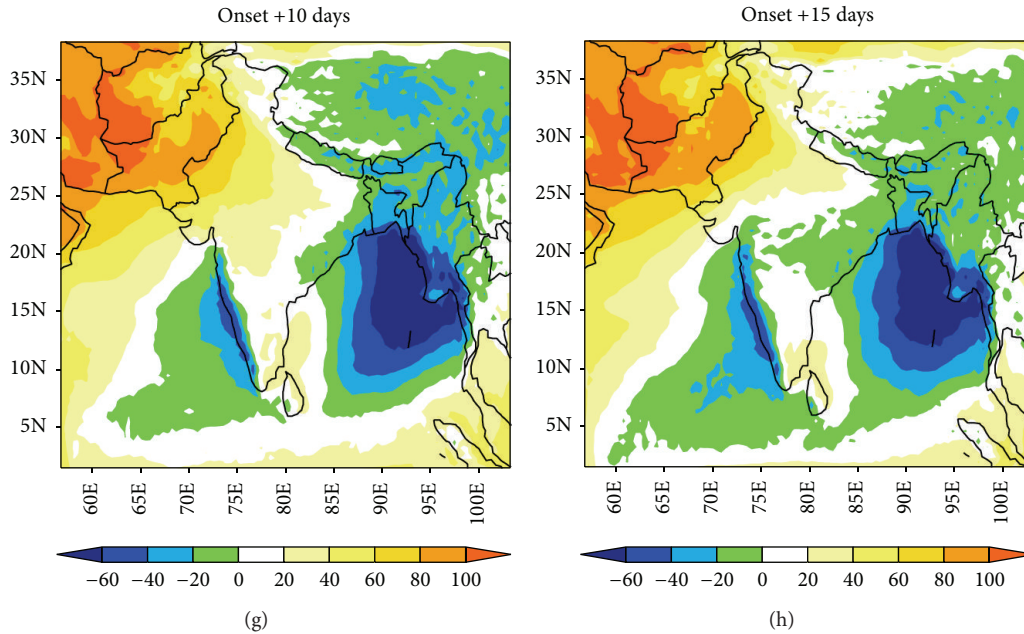


FIGURE 5: Same as Figure 3 but for A2 scenario.

phase in future may not be as deep as in baseline simulation. The OLR anomalies at the onset are  $-40 \text{ Wm}^{-2}$  in southeast Arabian Sea in 2080s as compared to  $-60 \text{ Wm}^{-2}$  in baseline simulation. The deeper convection in baseline simulations at the onset explains the higher rainfall over Kerala, at the onset phase in baseline simulation. The OLR anomaly pattern for A2 scenario is similar to that for B2 scenario (figure is not shown).

Figures 6(b) and 6(c) show the likely changes in ZKE at the end of present century. It can be seen from the figure that towards the end of the century the ZKE may not be as strong as in baseline during the monsoon onset phase. The ZKE over Arabian Sea at the onset phase is more or less the same in both emission scenarios A2 and B2 as shown in Figure 6.

## 5. Conclusions

The high resolution regional climate model, PRECIS, captures the onset of summer monsoon over Kerala reasonably well. The model simulates early onset as compared to the observed onset on 1st of June. The onset characteristics like the sudden and sharp increase in the daily rainfall over Kerala at the onset is well represented by the PRECIS. Model could capture the rise in the convection over southeast Arabian Sea and northeast Bay of Bengal at the time of onset. The steady rise in the zonal kinetic energy of low level winds, with the onset, at the southeast Arabian Sea, is well simulated by the model.

The model simulations under global warming scenario do not indicate significant change in the mean onset date of monsoon over Kerala in future as compared to the baseline. The onset date over Kerala does not differ much in A2 and B2 scenarios. However, the variability of onset date may be

more in future especially in A2 scenario. The convection over the north Indian Ocean at the onset phase of monsoon towards the end of present century may not be as deep as the convection simulated in the baseline run.

These are the studies made using limited number of simulations using single regional climate model. To reduce the uncertainty associated with the projection, one has to have more number of simulations on more high resolution regional climate models. At present these scenario projections may be used with caution, qualitatively instead of the quantitative estimates.

Under the auspices of WCRP, a suite of high resolution regional model simulations has been made available recently to the scientific community, under the program CORDEX (Co-ordinated Regional Downscaling Experiment). The simulations over South Asian region (CORDEX-SA) are available for four models and have been archived at the data portal of Center for Climate Change Research (CCCR) of Indian Institute of Tropical Meteorology, Pune, India. These models are of  $0.44^\circ \times 0.44^\circ$  latitude/longitude ( $\sim 50 \text{ km} \times 50 \text{ km}$ ) horizontal resolution and have been derived using the lateral boundary conditions from CMIP5; however, this set does not include PRECIS. Such type of analysis has not been documented before using PRECIS simulations. Since CORDEX-SA provides the multimodel outputs for historical and RCP4.5 experiments and gives the range of uncertainty of model simulations, one can have more confidence in these projections. The present analysis will be carried out using these multimodel simulations in future.

## Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

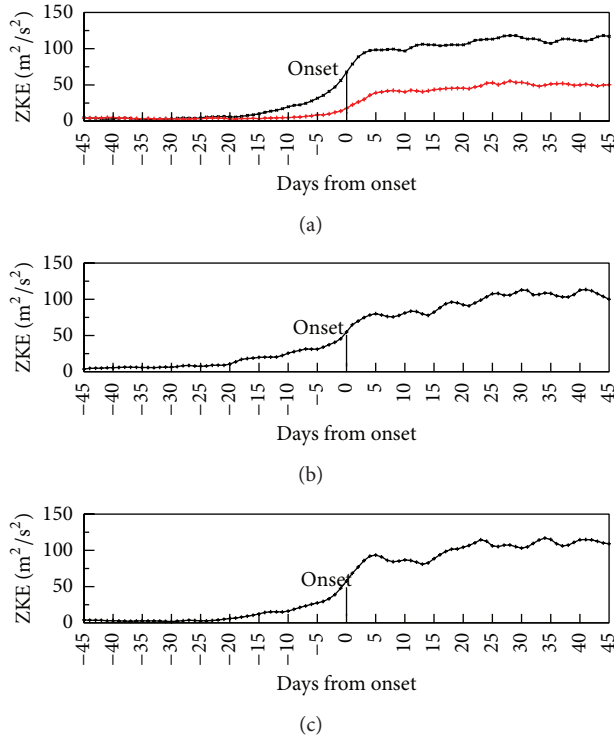


FIGURE 6: Zonal kinetic energy ( $\text{m}^2/\text{s}^2$ ) at southeastern Arabian Sea as simulated by PRECIS for baseline (black) and observed (red) (NCEP/NCAR Reanalysis) (a) for the period 1961–1990 and in the global warming scenarios A2 (b) and B2 (c) for the period 2071–2100.

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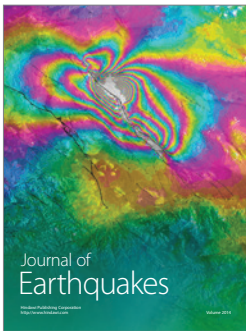
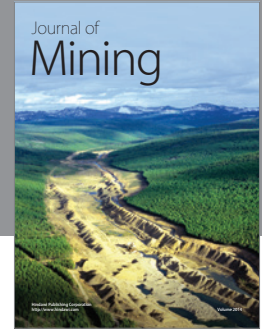
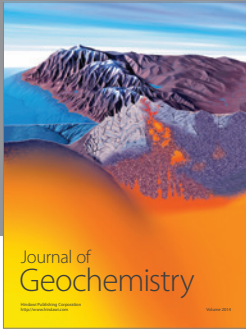
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