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Seasonality of the hydrological cycle in major South and Southeast Asian River Basins as simulated by PCMDI/CMIP3 experiments

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Abstract

In this study, we investigate how PCMDI/CMIP3 general circulation models (GCMs) represent the seasonal properties of the hydrological cycle in four major South and Southeast Asian river basins (Indus, Ganges, and Brahmaputra and Mekong). First, we examine the skill of GCMs by analysing their simulations for the XX century climate (1961–2000) under present-day forcing, and then we analyse the projected changes for the corresponding XXI and XXII century climates under SRESA1B scenario. CMIP3 GCMs show a varying degree of skill in simulating the basic characteristics of the monsoonal precipitation regimes of the Ganges, Brahmaputra and Mekong basins, while the representation of the hydrological cycle over the Indus basin is poor in most cases, with few GCMs not capturing the monsoon signal at all. Although the models' outputs feature a remarkable spread for the monsoonal precipitations, a satisfactory representation of the western mid-latitude precipitation regime is instead observed. Similarly, most of the models exhibit a satisfactory agreement for the basin-integrated runoff in winter and spring, while the spread is large for the runoff during the monsoon season. For future climate scenarios, winter (spring) $P-E$ decreases over all four (Indus and Ganges) basins due to decrease in precipitation associated with the western mid-latitude disturbances. Consequently, the spring (winter) runoff drops (rises) for the Indus and Ganges basins. Such changes indicate a shift from rather glacial and nival to more pluvial runoff regimes, particularly for the Indus basin. Furthermore, the rise in the projected runoff along with the increase in precipitations during summer and autumn indicates an intensification of the summer monsoon regime for all study basins.

1 Introduction

Substantial anthropogenic climate change-driven changes in the global hydrological cycle (Held and Soden, 2006; Allan, 2011) will largely impact the water demand and supply on regional and global scales. Since almost any human activity, and in particular agriculture and industry, strongly depend on water availability, additional pressures on the on-going economic development and population growth will be associated with such changes (Kundzewicz et al., 2008) and may particularly be strong in areas more vulnerable to drought or flood. The situation is expected to be especially critical for highly-populated regions of South and South-East Asia, whose agriculture-based economies and rapidly developing industrial systems are largely dependent on variable water supplies. Therefore, inferring detailed information about the climate change, its impact on the water resources, and its consequent implications for the socio-economic development sectors is vital for adequate adaptation and mitigation policies in the region.

Despite their structural limitations and ambiguities in the values of crucial parameters (Held and Soden, 2006; Lucarini et al., 2008), General Circulation Models (GCMs) are presently the most powerful tools for simulating the Earth's climate, its natural variability and the impact of anthropogenic forcing. GCMs' simulations under diverse scenarios are used by various scientific communities to inform stakeholders and policymakers on key impacts of climate change and to support the development of efficient mitigation and adaptation policies (IPCC AR4, 2007). In particular, GCMs are extensively being used to understand the effects of global warming on the water cycle at global and regional scale. It is widely accepted that a realistic representation of the hydrological cycle is however non-trivial in these models because the hydro-meteorological processes take place on a vast range of time- and space-scales, including regimes which can be represented only through parameterizations (Hagemann et al., 2006; Tebaldi and Knutti, 2007). Biases due to processes occurring at very small scales can have global impacts: Liepert and Previdi (2012) have shown that most of CMIP3 GCMs have serious problems in conserving the global water mass and that such inconsistencies are truly macroscopic for few models. Such an inconsistent representation of the hydrological cycle cause further biases in the energetics of the climate models (Liepert and Previdi, 2012; Lucarini and Ragone, 2011), and leads to significant uncertainties in the climate change-induced variations of global and regional hydrological regimes.

The hydro-climatology of South and South-East Asia is extremely complex, as monsoonal systems and mid-latitude disturbances (especially in the north-western sector of the region) are involved in determining the seasonality of the precipitation, with vast differences across the region. Therefore, climate change signals involve variations in the geographical distribution, timing and intensity of the South Asian and South-East Asian summer monsoons and the extra tropical cyclones. Hence, it is crucial to realistically represent such large-scale weather systems in order to have a satisfactory representation of the hydrological cycle by the climate models and to be able to have a good representation of the effects of climate change on the hydrology of the region. Goswami (1998), Lal et al. (2001), Kang et al. (2002), Annamalai et al. (2007), Lin et al. (2008) and Boos and Hurley (2013) have been performed in this regard, exhibiting model biases in the spatio-temporal distribution and magnitude of the summer monsoonal precipitation.

As a result, considerable uncertainties exist on the projected changes or the hydrology of South and South-East Asia. For instance, Arnell (1999), by using the Hadley Centre climate models (HADCM3), suggested an increase in the annual runoff for the Asian and Southeast Asian region, whereas Arora and Boer (2001), by using the Canadian Centre for Climate Modelling and Analysis (CCCma) coupled climate model, suggested instead a decrease in it for the Southeast Asian river basin. Linking such contrasting findings with the individual model biases, Nohara et al. (2006) assessed the projected changes in the hydrology of 24 major rivers using the weighted ensemble mean approach from 19 climate models, indicating difficulties of reproducing the observed discharges by any single model.

As a side note, we wish to remark that multi-model ensemble mean climatological estimators should be used with caution, as these are in general ill-defined statistical quantities. The outputs of different models do not form a statistically homogeneous object, given by equivalent realizations of a process. In general, there is no reason to expect that the biases of different models tend to cancel out in a fashion similar to what once may expect from assuming simplistically a sort of law of large numbers. Considering the

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mean as approximating the "truth" and the standard deviation as describing the uncertainty could be highly misleading (Lucarini et al., 2008). For any given diagnostic target variable, the weighted multi-model ensemble estimates do not necessarily outperform any single best model mainly due to the huge structural and physical differences among the ensemble members (Tebaldi and Knutti, 2007). Computing multi-model averages of climate changes signals raise further conceptual problems, because qualitatively different response from different models are averaged and information on the dynamical processes contributing to determining the climate response is lost and quality check of the results becomes extremely difficult. Furthermore, ensemble-averaged results are of little relevance if one wants to provide information on best practices for downscaling, since in this case a specific GCM or few of them can be considered.

Boos and Hurley (2013), attributed the bias in the thermodynamic structure of the summer monsoon as represented by the Climate Model Inter-Comparison Project Phase-3 (CMIP3) and Phase-5 (CMIP5) climate models to an inaccurate representation of the Karakoram–Himalayan orography, which results in negative precipitation anomalies over the Indian region. These findings are in agreement with recent results of the authors, who recently investigated the representation of mean annual hydrological cycle of the four major river basins of South and Southeast Asia (Indus, Ganges, Brahmaputra and Mekong) by the CMIP3 GCMs, reporting specific information for each of the analysed GCM (Hasson et al., 2013). The results suggest the presence of a systematic underestimation of $P-E$ for all basins mainly due to the underestimation of precipitation by XX century. Additionally, looking at climate projections under the SRESA1B Scenario, the analysis of the GCMs results suggests an increase (decrease) in $P-E$ for the Ganges, Brahmaputra and Mekong basins (Indus basin) and increase (decrease or no change) in the risk of hydro-meteorological extremes for the Ganges and Mekong (Indus and Brahmaputra) basins by the XXI and XXII centuries.

As the major weather systems influencing the region (summer monsoon and extra tropical cyclones) feature a clear seasonal cycle of their associated precipitation regimes, analysing the annual cycles of the simulated quantities seems necessary in

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order to assess how well the basic features of these regimes are reproduced by the models. With this goal in mind, the present study investigates the intra-annual distribution of precipitation, evaporation and runoff for the South and South-East Asian river basins (Indus, Ganges, Brahmaputra and Mekong), using the output from the same set of climate models considered in Hasson et al. (2013), for the 1961–2000 period and for the climate scenario SRESA1B. In Hasson et al. (2013), it is shown that a few CMIP3 AOGCMs feature serious water balance inconsistencies for XX century climate (1961–2000) over some of the considered river basins. Here, presenting the intra-annual investigations of the hydrological cycle, we discuss a possible link between such model inconsistencies and the misrepresentation of the seasonal water cycle. We also test whether the models featuring realistic annual averages of the main hydrological basin-integrated quantities feature inconsistencies on the intra-annual scale. The projected seasonal changes in the hydrological cycle under SRESA1B scenario for XXI and XXII centuries, considered in the second part of this study provide additional indications with respect to what presented in Hasson et al. (2013) about the possible future scenarios for the hydrology of the region. In a following study, we will extend our investigations to a recently available dataset of CMIP5 climate models in order to assess how these models represent the regional hydrological cycle after going through an extensive development, introducing higher resolutions, atmosphere and land use and vegetation interaction, detailed aerosols treatment, carbon cycle, etc. (Taylor et al., 2012). Our present findings will serve as a benchmark, providing an opportunity to see how the newly introduced features and enhanced processes, now implemented in several CMIP5 climate models, have impacted the representation of the hydrological cycle over the region.

The paper is structured as follows. In Sect. 2 we discuss the river basins considered in this study and the basic characteristics of their hydrology. In Sect. 3, we briefly describe the CMIP3 simulations used in the analysis and the methodology adopted in order to compute the hydrological quantities. In Sect. 4, we first present the performance of the CMIP3 coupled climate model simulations in terms of their skill in

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reproducing the intra-seasonal variations for the historical climate and then we present the seasonal changes in the same hydrological quantities for the future climates of the XXI (2061–2100) and XXII (2161–2200) centuries under SRESA1B scenario (720 ppm of CO_2 after 2100). Section 5 summarizes the main results of this study.

2 Study area

The study area includes four major river basins of South and Southeast Asia, namely the Indus, Ganges, Brahmaputra and Mekong. These basins are roughly included between 5–40° N and 60–110° E (Fig. 1). Their hydro-climatology is mainly determined by two different large scale climatic features, the South and South East Asian summer monsoon and the western (predominantly winter) mid-latitude disturbances, and their interactions with the local and sub-regional forcing.

The Asian monsoon system has three different, but inter-related components: South Asian, South-East Asian and East Asian monsoons (Janowiak and Xie, 2003). Three of our study basins (Indus, Ganges and Brahmaputra basins) are mainly influenced by the South Asian monsoon whereas the Mekong basin comes under the influence of the South-East Asian monsoon. The Asian Monsoon is generally a thermally driven large scale weather system associated with a temperature gradient between land and ocean (Clift and Plumb, 2008) and with the formation of a warm anticyclone in the middle-upper troposphere ("Monsoon High"), centred above the Upper Tsangpo depression (Böhner, 2006). Generally with an instant onset, the monsoon precipitation starts over the Mekong basin in mid-May, then it extends towards northwest and reach the Brahmaputra, Ganges and Indus basins by mid-June to July (Fasullo and Webster, 2003), and then it features a fairly smooth retreat in October (Goswami, 1998). The onset of monsoon is characterized by an abrupt increase in the daily rainfall, e.g. from below 5 mm day^{-1} to over 15 mm day^{-1} over India, which persists throughout the monsoon season, whereas the retreat of monsoon pertains to a reversal to the dry, dormant conditions (Fasullo and Webster, 2003). Intense precipitations continue throughout the

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summer monsoon season, although often interrupted by sudden breaks (Ramaswamy, 1962; Miehe, 1990; Böhner, 2006). The onset of the monsoon and the duration of the summer breaks are both critical factors, especially for the area of rain-fed agriculture where crops are extremely sensitive to the delays in start of the rainy season or to the prolonged dry periods during summer.

On the other hand, the westerly disturbances reaching the region result from the southern flank of the storm track transporting westward extra-tropical cyclones. The depressions reaching as far east as the region we discuss here, typically originate or reinforce over the Caspian and the Mediterranean Sea, at the east-most extremity of the Atlantic and Mediterranean storm tracks (Hodges et al., 2003; Bengtsson et al., 2007). Such western disturbances typically move eastward along the Karakoram and the Himalayan Arc and eventually weaken and die over the northern India and south of the Indian subcontinent.

The hydrology of the Ganges, Brahmaputra and Mekong basins is dominated by the summer monsoonal precipitation (Annamalai, 2007; Annamalai et al., 2007), with negligible contributions coming from the evanescent winter extra-tropical weather systems. Instead, the Indus Basin hydrology is dominated during winter and spring seasons (peak in March) by the influence of western disturbances mainly in the form of solid precipitation, while in summer (peak in July–August) the monsoonal rainfall contributes critically to the water budget of the basin (Wake, 1987; Rees and Collins, 2006). Hence, the Indus basin is located at the boundary between two different large-scale circulation modes and has a more complex hydro-climatology than the other three basins.

3 Data and methods

3.1 Datasets

In the present study, we have chosen the PCMDI/CMIP3 climate model simulations (Table 1) to investigate the skill of CMIP3 climate models for providing an adequate

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representation of the hydrological cycle over the major river basins of South and Southeast Asia (Indus, Ganges, Brahmaputra and Mekong). Our auditing and the verification of GCMs are based on the historical simulations of XX century climate (1961–2000) under the present-day climate forcing whereas the future changes are extracted for the corresponding time spans of the XXI (2061–2100) and XXII centuries (2161–2200) under the SRESA1B scenario, which is, broadly speaking, median among all of the SRES scenarios. The monthly climatology of the hydrological quantities such as Precipitation (P), Evaporation (E) and Total Runoff (R) are considered for the analysis. The surface upward latent heat fluxes are used to compute the evaporation from all models. For the observational datasets, monthly climatology of basin integrated precipitation is computed from the University of East Anglia Climatic Research Unit (CRU) Time Series (TS) high resolution gridded data version 3.2 (CRU, 2012), while the monthly climatology of historical river discharges (D) from the basins are obtained from the Water and Power Development Authority (WAPDA), Pakistan (Arora and Boer, 2001; Jian et al., 2009).

3.2 Methods

In order to estimate accurately the basin-wide monthly climatology of the hydrological quantities from the gridded datasets, the Voronoi–Thiessen tessellation method is used (Okabe et al., 2000). In the case of climate model gridded datasets, inconsistencies between the land-sea masks of GCMs and the extracted basin boundaries are carefully adjusted to avoid any systematic negative biases in the computed water balances. Such negative biases occur because of the relatively high rate of evaporation than precipitation and no runoff over the coastal grid cells that are treated as wholly sea grid cell by GCMs.

In view of the relatively marginal runoff contribution due to the on-going recession of existing glacier within the Ganges, Brahmaputra and Mekong basins as well as more likely the stable response (both recession and expansion) of these glaciers within the Indus basin (Hewitt, 2005; Scherler et al., 2011), either we postulate minute or no

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corrections by the melt water runoff to the historical discharge climatology of these river basins associated with the glacier recession. See our discussion in a previous paper (Hasson et al., 2013). Monthly means of P, E and R are computed carefully depending on the adjusted land-sea mask for each GCM, for the considered time spans of the last 40yrs of the XX, XXI and XXII centuries using the following equation:

$$\overline{\beta}_i = \int_A \mathrm{d}x\mathrm{d}y \langle\beta\rangle_i, \qquad (1)$$

where $\langle\beta\rangle_i, i = 1, \ldots, 4$ corresponds to the mean monthly climatology of each of the four variables mentioned above, A denotes the area of each considered river basin, and $\overline{\beta}_i, i = 1, \ldots, 4$ corresponds to the basin integrated monthly climatology of all considered variables. Our presented approach is equally applicable to the datasets of any resolution or for any other geographical region providing opportunities of its future applications.

In order to characterize the monsoonal precipitation regime for each river basin, we consider its four basic features – onset *time, retreat time, duration and magnitude* – which are estimated from the models' simulated and observed precipitations. As stated above, the monsoon onset is characterized by an abrupt precipitation increase persisting throughout the monsoon season. In order to quantify such an abrupt increase, we estimate a uniform threshold from the normalized observed monthly precipitation, which is calculated as:

$$\widehat{P}_i = \frac{(P_i - P_{\min})}{(P_{\max} - P_{\min})} \qquad (2)$$

where $i = 1, \ldots, 12$ indicates month of the year. We found that the onset month, estimated from the observed normalized precipitation, is the i-th month satisfying the condition $\widehat{P}_i - \widehat{P_{i-1}} \geq 0.17$. We have verified that this condition gives us the realistic climatic onset months (Janowiak and Xie, 2003; Krishnamurti et al., 2012) for each basin using observational data. Since the monsoon retreat is fairly smooth, such a condition is not equally applicable for estimating its timings. Therefore, taking the total precipitation of the onset month $i(P_{\text{onset},i})$ as a threshold, we define the month of monsoon retreat as j-th month such that the condition $\text{IF}(P_j \geq P_{\text{onset},i} \text{AND} P_{j+1} \sim P_{\text{onset},i-1})\text{ELSE}(P_{j+1} \sim P_{\text{onset},i-1})$ satisfies. The *duration* of the monsoonal precipitation regime is then defined as the period (in our case number of months) going from the onset month i up to the month of its retreat, j. The *magnitude* of the monsoonal precipitation regime is taken as the total amount of precipitation within the monsoon duration. Such procedure is adopted for the models' simulated precipitation regimes to estimate their suggested timings of the onset and retreat months as well as the monsoon duration and its magnitude for each basin. Of course, using monthly data we derive the properties of the monsoon only with rather coarse time resolution, but the proposed approach is sufficient for the goals of this study.

Furthermore, due to the heavy diversions of water from the Indus River for irrigation purposes, the observed discharge into sea at the near-to-sea gauging station substantially underestimates the real discharge from the basin. In order to reconstruct the real discharge into the sea, the amount of diverted water and its annual distribution has to be taken into account. Laghari et al. (2012) reports that approximately 170 mm yr^{-1} of water is annually diverted within the Indus basin. The maximum diversion occurs during the start of the snowmelt season (March–April) till the start of the monsoon season (June–July). This is also evident from the anthropogenically unperturbed discharges at the river inflow measurement stations (RIMs) of the main Indus River at Tarbela and its tributaries (Jhelum at Mangla and Kabul at Nowshera in Pakistan), collected from WAPDA. In view of this fact, the annual amount of diverted water has been redistributed throughout the year according to the total hydrograph of the anthropogenically unperturbed discharges from the mentioned tributaries, and then added to the hydrograph of the observed discharges from the basin. The effect of anthropogenic diversion is instead relatively less important for the remaining river basins.

It is worth mentioning here that the common practice to present the arithmetic mean and its standard deviation as the ensemble mean and its spread (Houghton et al., 2001)

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is intentionally avoided in our analysis. For the reasons described in the introduction, in our analysis we present the so-called ensemble mean values just for indicative purposes.

4 Results

We first discuss the skill of the GCMs in reproducing the basic properties of the seasonal variability of the hydrological cycle in each of the considered basin. In the second part, we present the changes in the monsoon precipitation regime and seasonal changes in the $P-E$ and R quantities under warmer climate conditions.

In Figs. 2–6, the simulated hydrological quantities are shown alongside the observations for the XX century climate, where each model is coded with a different colour and marker; the ensemble mean is shown as a dashed black line, whereas the observed climatological quantity is shown as a solid black line. In Figs. 7–8, we present the future changes of the hydrological quantities for the SRESA1B scenario.

4.1 XX century climate (1961–2000)

4.1.1 Indus Basin

Precipitation

As discussed in Sect. 2, precipitation over the Indus basin comes mostly from the South Asian monsoon circulation in summer and from extra-tropical cyclones in winter and spring. We therefore expect that GCMs feature a bimodal precipitation regime for the Indus basin, showing peaks during the months of March and July. Such a qualitative property is well-represented by most of the models.

For the precipitation regime associated with the western mid-latitude disturbances, there is a fair agreement between models (spread of about 50 mm) in reproducing it, showing correctly that winter and spring are wet seasons for the Indus basin (Fig. 2a).

However, seven out of thirteen models (CNRM, GISS-AOM, GFDL2.0, CSIRO3.0, ECHO-G, PCM and HADGEM1) show slightly delayed maxima for the winter/spring season precipitation, suggesting these in April instead of March. The performance of most of the models in reproducing the overall pattern is quite satisfactory, indicating that these models properly simulate the Northern Hemisphere storm track also in this rather peripheral part of it.

More unsatisfactory is instead the situation for the monsoonal precipitation regime, with most of the models showing serious difficulties in reproducing it. Models remarkably differ with each other in terms of their simulated magnitude and their suggested timings of the onset/departure of the monsoonal precipitation. The most surprising fact is that four models (CGCM2.3.2, GISS-AOM, IPSL-CM4 and INMCM) have been found unable to capture the monsoon signal at all, showing almost no precipitation during the monsoon season (Fig. 2a). The GISS-AOM model neither captures the period with the highest precipitation – actually it predicts the summer monsoon season to be the driest of the year – nor simulates the onset timings and the pattern of the monsoonal precipitation regime. Further investigations are therefore needed in order to understand why these models are unable to describe the realistic monsoon precipitation over the Indus basin as well as in order to find out the factors responsible for such unrealistic features. The CNRM model, showing a quite unrealistic pattern of both winter and summer precipitation regimes, does not capture the bimodal precipitation distribution and suggests too strong precipitations in July (twice the observed values, Fig. 2a). We would like to add here that four of the models discussed above (CNRM, GISS-AOM, IPSL-CM4 and INMCM), feature serious water balance inconsistencies for the Indus basin on an annual time scale (Hasson et al., 2013).

Six out of thirteen models (CNRM, HADGEM1, HADCM3, GFDL2.0, MIROC-HIRES and PCM) agree on the realistic timings of the monsoon onset, which takes place in the month of July (Fig. 6a). ECHAM5 shows an early onset, suggesting it in June whereas two models (CSIRO3.0 and ECHO-G) delay the onset, suggesting it in August. Only two models (HADGEM1 and PCM) realistically reproduce the timings of the mon-

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soon precipitation maximum in July, whereas three models (GFDL2.0, HADADCM3 and MIROC-HIRES) feature a one-month delay, thus having it in August (Fig. 2a). These six models, suggesting a realistic monsoon onset, also agree on a smooth retreat in September. From this, we are led to conclude that models suggesting the realistic timings of the monsoon onset may feature realistic duration of the monsoonal precipitation regime whereas the models suggesting an early (delayed) onset may feature its prolonged (short-lived) duration (Fig. 6b).

Evaporation

This quantity is intimately controlled by soil moisture, insolation, relative humidity of the surface air, and surface winds. Figure 2b shows a better inter-model agreement for evaporation during winter and spring seasons, when minimal evaporation is experienced, than during summer. The disagreement among models, as expected, is much wider during summer. Two models (CGCM2.3.2 and INMCM) show a negligible evaporation during the monsoon period mainly because these models are unable to simulate the monsoon precipitation regime, so that they represent a spuriously dry land. Contrary to this, IPSL-CM4 shows higher evaporation from May to October although it also fails to capture the monsoon signals at all; this may point to some issues in the representation of the land-atmosphere coupling of this model as mentioned by Hasson et al. (2013). The GFDL2.0 model shows the highest evaporation during the monsoon season. Models show quite good agreement regarding the timings of the evaporation maxima in August – a peak flow period – except two models (CNRM and PCM), which simulate the smooth rise of evaporation until July and then its smooth decline till December. From Hasson et al. (2013), we know that these two models do not conserve water for the Indus basin, so that a process which critically depends on soil water availability like evaporation can be seriously affected. The ensemble mean is affected by large amount of evaporation suggested by CNRM model during the monsoon season. As a result, it overestimates the evaporation simulated by most of the models during such period, though providing good approximation for rest of the year.

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$P-E$

Figure 2c shows a negative $P-E$ in June for all models except three models (ECHAM5 is characterized by an early monsoon onset, CNRM shows overall remarkable precipitation and GISS-AOM delays the realistic spring precipitation maxima). This is associated with the negligible precipitation in the pre-monsoon season and the dependence of the evaporation on the moisture contained in the soil resulting from the snowmelt and the spring precipitation. Even during the monsoon period, only four models (CNRM, GFDL2.0, HADGEM1 and ECHAM5) show positive $P-E$ whereas other models suggest it near to zero or negative. IPSL-CM4 model suggests the minimum value of $P-E$ because of the large amount of its suggested evaporation as well as its inability to reproduce the monsoonal precipitation regime. Generally, it is found that the negative or low $P-E$ in the monsoon period is mainly due to the deficiencies in the models in simulating the monsoon precipitation over the Indus basin. The ensemble mean of $P-E$ suggests almost null value for the monsoon season whereas it seems to be reasonably representative of the ensemble members during non-monsoon period. The overall inter-model agreement is better for winter and spring seasons, where a positive water balance is reported, because of the models' better representation of the winter precipitation due to extra tropical cyclones and the temperature-constrained low evaporation rate.

Simulated runoff

In Fig. 2d we show the annual cycle of the simulated runoff and the observed discharge at the river mouth. In general, these two quantities do not perfectly coincide because the discharge at the river mouth, at any time of the year, results from a non-trivial function of the runoff at previous times, in the various regions of the basin, so that there is a natural time-delay between the two quantities. It is a common practice in hydrology to route the runoff using various empirically or physically derived methods (Linear Reservoir approach, Muskingum routing method; Maidment, 1993; Singh and Singh,

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2001, Variable Infiltration Capacity – VIC; Liang et al., 1994; TOPKAPI; Konz et al., 2010) in order to compare it with the observed discharge. In our case, due to the lack of observed runoff data, such routing methods cannot properly be calibrated. However, since we are looking at coarse temporal resolutions (monthly scale) of the basin integrated total runoff quantity and the typical delay time for such basins is roughly of less than (Ganges, Brahmaputra and Mekong Basins) or equal (Indus Basin) to one month, we expect that total runoff (R) and discharge (D) do not substantially differ. Therefore, on the basis of such considerations, we have decided to present the simulated runoff (without applying any routing method) and the observed discharge for each basin in equivalent areal height units (mm).

It is apparent from Fig. 2d that the runoff as simulated by the GCMs is not consistent with the observed discharge of the Indus River. Models show remarkable spread during monsoon period, which is associated with their large spread in simulating the monsoonal precipitation. The ensemble mean generally underestimates the observed river discharge. Interestingly, models agree well with each other on the timings of the spring discharge, which is mainly due to melting of snow accumulated during the winter and in the running spring seasons. This suggests that snow schemes implemented by CMIP3 climate models perform fairly well. CGCM2.3.2 shows relatively high discharge in March and April. Surprisingly, we found that PCM suggests a negative runoff for the period April to September. Our previous analysis (Hasson et al., 2013) shows that the water balance of such model is fairly closed on annual time scale ($P - E = R$), with the minimum value among the studied models. However, our present analysis shows that this model simulates negative runoff from April to September, which further implies serious physical inconsistencies in its water balance. Given the findings of our analysis, the great socio-economic impact of the Indus water availability and the deficiency found in PCM model, we suggest the modellers' communities that the land-surface components of the climate models should be realistically described and tested, particularly for the runoff parameterization schemes.

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4.1.2 Ganges

Precipitation

The hydrology of the Ganges Basin is dominated by the South-Asian summer monsoon, featuring the onset in the month of June, the peak of precipitation from July to August, and the retreat in the month of September (Annamalai, 2007; Annamalai et al., 2007). Figure 3a shows the mean monthly precipitation climatology and illustrates CMIP3 models' skill in reproducing the Ganges' basin monsoonal precipitation regime. First, all models except CNRM – which shows significant precipitation in the early spring – realistically suggest negligible precipitation outside the monsoon period with little differences with respect to the observations. For the monsoon season, the MIROC-HIRES model shows an excellent qualitative as well as quantitative agreement with the observations. Models reproduce realistically the timings of the onset, retreat, maxima and the overall pattern of the monsoonal precipitation regime. In particular, two models (HADGEM1 and GFDL2.0) show patterns in very good qualitative agreement with the observations. Five models (CGCM2.3.2, ECHAM5, GFDL2.0, HADCM3 and MIROC-HIRES) are able to reproduce the timings of the onset (Fig. 6a). However, PCM suggests an early onset and the prolonged monsoon duration by one month whereas five models (CSIRO3.0, ECHO-G, GISS-AOM, HADGEM1 and INMCM) suggest a delayed onset and the duration shorten by one month. For the monsoon retreat, all models show it realistically in September. The rest of the models, suggesting a realistic timing of the onset also suggest realistic monsoon duration. Surprisingly, IPSL-CM4 model is unable to capture the monsoonal signal at all, just as in the case of the Indus basin. CNRM model suggests an unrealistically early and progressive onset in the month of April. All models suggest that precipitation peaks either in July or in August, except PCM, which suggests it in September. Ensemble mean precipitation is placed well in the middle of all models but it underestimates the observed precipitation (CRU, 2012) for the Ganges basin.

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Evaporation

The seasonal cycle of the evaporation is controlled by the onset and decay of the monsoon, because evaporation is strongly affected by soil moisture and insolation. All models are in good qualitative agreement in this respect, even if the quantitative agreement is not so good. The CNRM model shows the highest evaporation throughout the year, whereas IPSL-CM4 features consistently the lowest (Fig. 3b). Four models (CNRM, HADGEM1, MIROC-HIRES and INMCM) show relatively high evaporation in spring whereas all the models except the five models (GISS-AOM, IPSL-CM4, INMCM, HADGEM1 and CGCM2.3.2) show relatively low evaporation during the monsoon season. Quite interestingly, the CNRM model shows a peak of evaporation (June) before the peak of precipitation because it is quite wet already throughout the spring, so that evaporation in June is not moisture-limited, while the presence of heavy cloud cover in July and August limits the effect of direct solar radiation at the surface.

$P-E$

Good agreement is seen among models concerning their simulated $P-E$ between November and May, when the precipitation and evaporation compensate up to a good degree of precision. For all models except IPSL-CM4, which, as discussed before, seems to be heavily biased, $P-E$ is positive in the monsoon season, but the values of the excess of precipitation with respect to the evaporation vary wildly (Fig. 3c). Given the large inter-model uncertainties, it seems quite problematic to give any physical interpretation to the ensemble mean.

Simulated runoff

The agreement among models is similar to what described above regarding the seasonal cycle of $P-E$. Models agree with each other for the lean flow period as well as for the realistic timings of the peak discharges, which typically occur in August and

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September with similar magnitudes (Fig. 3d). However, models show a large spread in the magnitude of their simulated runoffs, which can most probably be attributed to the variations in their simulated monsoonal precipitations. Models also suggest almost negligible snowmelt in the spring season. CNRM suggests high runoff during April and May as well, as it describes a spurious regime of strong spring precipitation. The simulated runoffs from five models (MIROC-HIRES, CNRM, GFDL2.0, HADGEM1 and ECHAM5) generally tend to overestimate the overall observed discharge, either showing an early rise or later drop, or both, of their runoff regime. Conversely, the models underestimating the observed discharge regime either feature a delayed rise in the simulated runoff or an early drop in it, or both. The ensemble mean generally seems to underestimate the observed discharge.

4.1.3 Brahmaputra

Precipitation

Brahmaputra's precipitations are mostly associated with the summer monsoon circulation. However, part of its precipitation comes from small-scale isolated thunderstorms during the pre-monsoon (late-spring) season and an even smaller quantity comes through winter extra-tropical cyclones impacting the northern part of its basin. There is a very good inter-model agreement at qualitative level: all models describe a precipitation regime where the peak is broader than for the Ganges basin. All models agree at quantitative level regarding the winter precipitation, while there is a large inter-model variability concerning the magnitude of the monsoonal and pre-monsoonal precipitations (Fig. 4a). IPSL-CM4 again fails to capture the monsoon signal whereas two models (INMCM and ECHO-G) suggest the lowest monsoonal precipitation amongst all CIMP3 models. HADGEM1 shows the highest precipitation in the pre-monsoon season whereas ECHAM5 suggests the overall highest precipitation regime for the basin. Models seem to agree on the timings of the onset in May. Our analysis suggests that five models (CSIRO3.0, ECHAM5, GFDL2.0, HADCM3 and MIROC-HIRES) realistically

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simulate the timings of the onset and retreat, and so, the monsoon duration (Fig. 6a). Four models (CGCM2.3.2, ECHO-G, HADGEM1 and PCM) delay the onset by one month whereas two models (INMCM and CNRM) delay it by two months.

All models except three (INMCM, ECHO-G and IPSL-CM4) predict the monsoonal precipitation maxima in July. A good agreement is found as far as the retreat is concerned (i.e. September) except for two models (MIROC-HIRES and GISS-AOM), which suggest delayed decay in the month of October. The GCMs generally underestimate the observed precipitation (CRU, 2012) during monsoon season but overestimate it during the rest of the year. The ensemble mean is rather different from most of the models' outputs, because it is strongly biased by four very wet models (ECHAM5, MIROC-HIRES, GISS-AOM and HADGEM1). The ensemble mean also underestimates the observed precipitation during monsoon season but overestimates it during the rest of the year.

Evaporation

There is a very good inter-model agreement throughout the year for the simulated evaporation, with the only exception being the GISS-AOM model, which features the highest evaporation (Fig. 4b). Little inter-model variability exists only in the pre-monsoon season. IPSL-CM4 agrees with other models in terms of its simulated evaporation though it does not capture the monsoon signals for the basin.

$P-E$

Except HADGEM1, all models show a good agreement for their computed $P-E$ during the dry season whereas their large differences exist during the monsoon season, resulting from the large discrepancies found for the precipitation fields (Fig. 4c). Four models (GISS-AOM, ECHAM5, MIROC-HIRES and HADGEM1) suggest relatively high $P-E$ in the monsoon season whereas IPSL-CM4 shows almost null $P-E$ throughout the year. Very few models suggest slightly negative $P-E$ in the pre-monsoon season.

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As in case of precipitation, the ensemble mean also overestimates $P-E$ with respect to most of the models.

Simulated runoff

Models show a good agreement for the lean flow period (late November to late March) as well as for the start of the high flow period (in the month of April) (Fig. 5d). Two models (INMCM and IPSL-CM4) show negligible runoff throughout the year whereas two models (ECHAM5 and MIROC-HIRES) are characterised by an early (delayed) rise (drop) in flows. Most of the models substantially underestimate the observed discharge. Interestingly, the observational dataset suggests that the four wet models are closer to reality than the other ones, which are clustered together towards dry conditions. Obviously, the ensemble mean also underestimates the observed discharge throughout the high flow period.

4.1.4 Mekong

Precipitation

The hydrological regime of the basin is governed by the north easterly and the south westerly monsoonal winds. Models show a good agreement concerning the realistic timings of the onset, retreat and duration of the monsoon (Fig. 6a). A lower but still satisfactory inter-model agreement appears with respect to the observed magnitude (only a slight underestimation) of the monsoon precipitation. In terms of the overall pattern of the monsoonal precipitation regime, six models (CSIRO3.0, GFDL2.0, INMCM, IPSL-CM4 and PCM) suggest realistic timings of the onset in May, whereas six models (ECHAM5, ECHO-G, GISS-AOM, HADCM3, MIROC-HIRES and CGCM2.3.2) suggest an early onset by one month. Only CNRM shows a delayed onset in June. For monsoon retreat, models generally suggest an early drop as compared to the observations. Five models (CSIRO3.0, GFDL2.0, PCM, HADGEM1 and INMCM) suggest the realis-

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tic retreat as well as the monsoon duration as compared to the observations, whereas five models (ECHAM5, ECHO-G, HADCM3, IPSL-CM4 and CGCM2.3.2) suggest expansion of monsoon duration by one month, and similarly two models (GISS-AOM and MIROC-HIRES) by two months. Only CNRM suggests the shrinkage of monsoon duration by two months.

However, three models (CGCM2.3.2, HADCM3 and HADGEM1) suggest low precipitation in the month of July, showing two peaks of precipitation, one in the month of June and one in September respectively. Two models (IPSL-CM4 and INMCM) suggest the lowest monsoon precipitation for the Mekong basin, thus confirming their dryness throughout the investigated region, whereas GFDL2.0 suggests the highest. The ensemble mean, in this case places itself in the middle of models' range.

Evaporation

This basin appears to be the wettest of the four considered here, because evaporation is relatively high throughout the year and with modest difference between the monsoon season and the rest of the year. Most CMIP3 models feature a good degree of agreement in the representation of the evaporation throughout the year, with one model standing out as having the highest evaporation in most months (GISS-AOM). Instead, the outliers with lowest evaporation are the GFDL2.0 model in the first five months of the year and the two models (IPSL-CM4 and CGCM2.3.2) for the monsoon season.

$P-E$

The intra-annual variations of $P-E$ (Fig. 5c) is rather similar to that of precipitation because the seasonal cycle of the evaporation is weak. There is a good agreement among all models on the negative $P-E$ in the dry period, i.e. before April and after October. GFDL2.0 suggests the overall highest amount of $P-E$ whereas INMCM suggests the lowest amount. Just as in the case of precipitation and evaporation, ensemble-mean places itself in the middle of the models' range.

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Simulated runoff

As most of the runoff is generated over the lower Mekong basin, one expects a shorter time delay between runoff and discharge as compared to other basins, so that the comparison at face value between the two quantities is indeed meaningful. In Fig. 5d the annual cycle of the monthly mean simulated runoff shows excellent inter-model agreement during the lean flow period (December to late March). Although there are large differences among few models in terms of their simulated magnitude during the high flow period, most of the models show good agreement in reproducing the timings of the rise in the runoff in May, maxima during August–September and a drop in October. Most of the models underestimate the observed discharge regime of the basin, particularly in the early part of the high flow period due to the delayed rise in flows, so the ensemble-mean also underestimates it. Our results show that the overall pattern of the discharge regime for the Mekong basin is simulated well with some models fairly close to the observations.

4.2 Response to climate change (XXI and XXII centuries)

The overall satisfactory performance of most of the models, in particular for the east-most basins, suggests studying changes in their hydrological cycle associated with the future increase in the GHG forcing. We have, therefore, analysed the changes in the monsoon characteristics and the intra-annual changes in the hydrological quantities for the XXI (13 models) and XXII (10 models) centuries relative to the corresponding XX century under the SRESA1B scenario. Since the changes evidenced in the XXII century climate (2161–2200) are qualitatively very similar (and quantitatively slightly more pronounced) to the changes found for the second half of the XXI century (2061–2100), only the latter are reported in Figs. 7 and 8. Some specific features of the climate change as manifested in the XXII century are discussed separately. Moreover, we discuss in the text all quantities such as precipitation (P), evaporation (E), $P-E$ and runoff R but we only show the latter two in Fig. 8, as we have found that $P-E$ illus-

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trates in more significant ways the changes in the hydrological cycle than precipitation and evaporation taken individually.

Indus Basin

Concerning the general characteristics of the monsoonal precipitation regime, almost all models suggest no change in the onset of the monsoon, except ECHO-G, which suggests an earlier onset of one month for the second half of the XXI century. As for the duration of monsoon, three models (ECHO-G, GFDL2.0 and ECHAM5) suggest the expansion of the monsoon season by one month. Among these three models, the first one predicts a phase retreat (delays in both onset and retreat) of the monsoonal precipitation regime, whereas the latter two only suggest the delayed retreat. Only HADGEM1 suggests the shrinkage of the monsoon duration by one month due to an early retreat (Fig. 7). As far as P is concerned, all models agree on a decrease in spring (except CNRM and GISS-AOM) and winter precipitation (except GISS-AOM, CGCM2.3.2, CSIRO3.0 and IPSL-CM4) and on an increase in summer (except GFDL2.0, ECHAM5, INMCM and IPSL-CM4) and autumn precipitation (except GFDL2.0, HADGEM1, INMCM and IPSL-CM4). Large changes are predicted for summer precipitation, with PCM suggesting the highest increase whereas GFDL2.0 suggesting the highest decrease. For XXII century, only HADCM3 shows an opposite sign of change suggesting more precipitation during winter and spring. The overall decrease in the winter and spring season precipitation is consistent with the northward shift of the Atlantic–Mediterranean storm track expected under anthropogenic warming scenarios (Bengtsson et al., 2007) wherease the increase in the fall precipitation seems to be associated with the strengthening of the monsoonal precipitaion, even though it is still not ascertained how the summer South-Asian monsoon is going to be affected in a global warming scenario (Turner and Annamalai, 2012). Further, decrease in precipitation regime of the mid-latitude disturbances suggests a reduction in the snowfall, which implies a lower snowmelt contribution to the spring runoff. This is a serious issue

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since it poses a great risk for the mass balance of existing HKH glaciers, as well as the timings of the water availability downstream.

It has been found that models largely agree on an increase in evaporation throughout the year. Only three models have an opposite behaviour in spring (ECHAM5, ECHO-G, INMCM), two models in summer (ECHAM5 and GFDL2.0) and one (GFDL2.0) in fall season, due to decreased mositure in the soil. Concerning $P-E$, there is a good inter-model agreement on the negative change during spring season for both XXI and XXII centuries except HADCM3 for the XXII century. Most of the models also agree on the negative change in $P-E$ for winter and fall seasons. For winter season, exceptions are four models (CGCM2.3.2, CSIRO3.0, GISS-AOM and IPSL-CM4) by the XXI century (Fig. 8a). In the XXII century, the HADCM3 substitutes the GISS-AOM model in this list. For the fall season, exceptions are three models (CSIRO3.0, GISS-AOM and MIROC-HIRES) by the XXI century and two models (CSIRO3.0 and ECHAM5) by the XXII century. Most of the models suggest a decrease (increase) in spring (summer) $P-E$ which is similar to the ones in the runoffs.

As the basin receives most of its winter and spring precipitation in the form of snow, a decrease in the spring runoff and in spring precipitation implies a reduced snowmelt contribution to the spring runoff, which can further be linked to a decrease in winter precipitation. On the other hand, an increase in winter runoff but decrease in winter precipitation and spring runoff also suggests that solid precipitation will partially be transformed into a liquid precipitation in such season. Such precipitation instantly contributes to the winter runoff, reducing the delayed effects of snowmelt to the spring runoff.

Ganges Basin

There is no change in the onset timings as well as for the duration of monsoon among the models, except for GISS-AOM, which suggests an expansion of the monsoon season by one month due to its delayed withdrawal (Fig. 7). Furthermore, there is a good agreement among models concerning the winter precipitation decrease. Only exceptions are three models – CSIRO3.0, GISS-AOM and HADCM3 – showing a contrasting behaviour (Fig. 8). A general increase in summer precipitation is predicted by most of the CMIP3 models, except three models (CSIRO3.0, ECHAM5 and IPSL-CM4); same applies for the fall season, except for two models (INMCM and IPSL-CM4). No inter-model agreement is evident for changes in spring precipitation. We remind here that INMCM and IPSL-CM4 feature very serious problems of water conservation for the Ganges basin on mean annual time scale (Hasson et al., 2013). The negative change during dry season and the positive change during wet season may suggest an intensification of the precipitation regime associated with the summer monsoon.

As seen for the Indus basin, there is also a consistent behavior among most of the models on a general increase in evaporation throughout the year. However, two models (HADGEM1 and IPSL-CM4) in winter, five models (CSIRO3.0, ECHAM5, INMCM, HADGEM1 and IPSL-CM4) in spring, four models (CSIRO3.0, GFDL2.0, HADGEM1 and IPSL-CM4) in summer and three models (GFDL2.0, HADGEM1 and IPSL-CM4) in fall show opposite signs, suggesting a decrease in evaporation by XXI century. For the XXII century, a small decrease is suggested by four models (GFDL2.0, HADGEM1, INMCM and IPSL-CM4) in winter, three models (CSIRO3.0, ECHAM5 and INMCM) in spring, three models (CISRO3.0, GFDL2.0, HADGEM1) in summer and four models (GFDL2.0, HADGEM1, INMCM and IPSL-CM4) in fall season.

Concerning $P-E$, the models clearly foresee a decrease in winter and spring seasons by the XXI and XXII centuries, however three models (CNRM, HADCM3 and HADGEM1) are exception for spring season of XXI and XXII centuries and IPSL-CM4 for winter season of the XXII century. The models also agree on its increase in summer (except CSIRO3.0 and ECHAM5) and fall (except INMCM and IPSL-CM4) by the XXI and XXII centuries. Sign of change for the runoff quantitity is similar to that of $P-E$, except during the winter season, where $P-E$ is negative but models agree well for the increasing tendency of the winter runoff. We speculate that such scenario is mainly associated with the increased melting during winter season. There is a negative change in spring runoff except in case of CNRM, which suggests a positive change.

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Brahmaputra Basin

Most of the models suggest no major changes in the timing of the monsoon in the XXI century, except the MIROC-HIRES, which suggests an early onset and a delayed withdrawal by one month, the CGCM2.3.2, which indicates an early onset by one month, and the CNRM, which instead suggests a delayed onset by one month. Almost all models agree on the strengthening of spring, summer and fall precipitations, except two models (ECHAM5 and IPSL-CM4), which indicate such change for the summer and fall seasons only, while the IPSL-CM4 becomes wetter in spring season. There is also a good agreement between models regarding either negligible or small negative change for the winter precipitation except two models (GISS-AOM and HADCM3) for the XXI and only HADCM3 for the XXII century. The observed decrease in the winter season precipitation for both centuries clearly suggest a reduced role of extratropical cyclones, which in curent climate roughly contributes for about 10 % to the total Brahmaputra precipitation as estimated from the observational dataset used in the present study. Also, increases in spring and summer precipitations suggest an intensification of the pre-monsoonal as well as monsoonal precipitation regime of the basin.

Concerning evaporation, most of the models predict an increase throughout the year, showing even better agreement on such change as compared to other basins for both XXI and XXII centuries. For the XXI century, ECHAM5 suggests a small decrease for winter and spring evaporation while IPSL-CM4 suggests its decrease in winter, spring and fall seasons. HADGEM1 shows slight negative changes for winter and fall seasons, whereas GFDL2.0 shows a negative change only for summer season. For the XXII century, negative change in the evaporation is suggested by IPSL-CM4 for fall and winter seasons, by three models (ECHAM5, INMCM and IPSL-CM4) for spring season and by GFDL2.0 for summer season. Most of the models agree on a negative change in $P-E$ in winter and on a positive change in it for the rest of seasons. Exceptions are two models (GISS-AOM and HADCM3) for winter, three models (CSIRO3.0,

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ECHAM5 and IPSL-CM4) for summer, three models (ECHAM5, INMCM and IPSL-CM4) for fall and only IPSL-CM4 for spring season for the XXI century. Two models (GFDL2.0 and MIROC-HIRES) suggest comperatively higher positive change for the summer as compared to other models. We remind here that two of these models (INMCM and IPSL-CM4) feature water balance inconsistencies on annual time scales (Hasson et al., 2013).

Concerning changes in the runoff, there is a good agreement between most of models on an increase in winter runoff despite a decrease in $P-E$, which calls for an increase in snowmelt, while there is no uniform response regarding the spring runoff. The models also agree on a robust increase in the summer runoff, due to the strong increase in $P-E$.

Mekong Basin

Almost all models foresee no significant changes in the timing of the monsoon, except MIROC-HIRES, which suggests a phase advance as well as the shrinkage of the monsoonal precipitation regime by one month by simulating an early onset by one month and an early withdrawal by two months, while the CNRM model foresee a huge variation in the local climate, suggesting a two months delayed onset and a four months delayed withdrawal.

As for the Brahmaputra basin, precipitation is consistently shown to increase during spring, summer and fall seasons by the XXI century. Exceptions to such general trend are six models (CGCM2.3.2, CSIRO3.0, GFDL2.0, INMCM, IPSL-CM4 and MIROC-HIRES) for the spring season, two models (GFDL2.0 and IPSL-CM4) for the summer season and INMCM for the fall season, showing an opposite sign. Most of the models exhibit a decrease in winter precipitation except three (HADCM3, HADGEM1 and INMCM). It is also worth noting that ECHO-G, which overall shows a good skill in simulating monsoon precipitation regime, suggests a large precipitation drop for the spring, summer and fall seasons for the XXII century. The evaporation is expected to increase (decrease) in the summer and fall (spring) seasons, whereas no inter-model agreement

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is found for the XXI century winter seasons. For the XXII century, a negative (positive) change in winter and spring (summer and fall) seasons is predicted by most models. Again, ECHO-G shows a strong negative change in the evaporation during all seasons.

For change in $P-E$, models agree on the positive change in all seasons except for the winter season. Exceptions are two models (HADCM3 and HADGEM1) for winter, five models (CGCM2.3.2, GFDL2.0, INMCM, IPSL-CM4 and MIROC-HIRES) for spring, two models (HADCM3 and IPSL-CM4) for summer and two models (CNRM and INMCM) for fall seasons, showing an opposite sign of change for the XXI century. For the XXII century, three models (ECHO-G, HADCM3, HADGEM1) in winter, four models (IPSL-CM4, INMCM, GFDL2.0, ECHO-G) in spring, two models (IPSL-CM4 and ECHO-G) in summer, and two models (INMCM and ECHAM5) in fall suggest an opposite sign of change. In good agreement with that, we find an increase in summer and fall runoffs but no significant change in the winter and spring runoffs by the end of the XXI and XXII centuries.

5 Discussions and conclusions

In this study, we have analysed the CMIP3 coupled climate models regarding their skill in simulating the intra-annual variations of the hydrological cycle of four major South and South-East Asian rivers (Indus, Ganges, Brahmaputra, Mekong) for the XX century under present-day climate forcing and for the XXI and XXII centuries under SRESA1B scenario. We have also verified whether GCMs' simulated precipitations and total runoffs are in agreement with the historical observations and whether models are able to reproduce the basic properties of the monsoonal precipitation and runoff regimes. We have generally found that models performances are different for each river basin, depending on their ability to represent the different circulation modes that govern their hydrology.

Particularly, the complex interplay of seasonal precipitation regimes over the Indus basin is distinctly represented in the models and reflected in their seasonal precipitation distribution. Our analysis shows that most of the models agree reasonably well in reproducing the pattern of the winter-spring precipitation regime associated with the mid-latitude cyclones, whereas their performance in simulating the basic characteristics of the monsoonal precipitation regime (magnitude of the precipitation, timings of its onset, retreat and the maxima) is more limited, with almost no inter-model agreement. A better agreement is found in the representation of the hydrology of the Brahmaputra and Mekong basins, as compared to the other basins. It is worth mentioning here that only GFDL2.0 suggests the realistic onset timings of the monsoonal precipitation regime for all the four basins. There appears a good inter-model agreement for realistically simulating the runoff during lean flow period, while there is a modest agreement for reproducing the overall pattern of the flow regimes for all study basins. On the other hand, we have found no inter-model agreement for the simulated runoffs during the monsoon season, which is associated with the inability of the models to accurately simulate the monsoonal precipitation over the region.

It is noted that four models (IPSL-CM4, INMCM, CGCM2.3.2 and GISS-AOM) have shown no skill at all in capturing the monsoon signals for the Indus basin and, same applies to one model (IPSL-CM4) for the Ganges and Brahmaputra basins. This is a serious issue that would indeed requires further investigations to point out the governing factors responsible for such inaccuracies. Among these, two models (IPSL-CM4 and INMCM) see also serious water balance inconsistencies for such basins on annual time scale as shown in a companion paper (Hasson et al., 2013). One surprising fact is noted here that PCM erroneously suggests a negative simulated runoff between April and September for the Indus basin and between March and April for the Mekong Basin. This kind of error could not be discovered in a previous paper dealing with annual averages of the hydro-climatological quantities in the region (Hasson et al., 2013); as such inconsistent behaviour was masked in the overall annual budget. In view of this erroneously simulated quantity R, we considered it necessary that the land-surface components of the climate models should be realistically described and tested, partic-

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ularly the runoff parameterization schemes and other relevant quantities which have great societal importance.

Despite a fairly good representation of specific precipitation regimes (winter/spring precipitation over the Indus basin, summer monsoonal precipitation over the Brahmaputra and Mekong basins), CMIP3 models face problems in representing correctly complex regimes with a higher temporal variability and qualitative shifts between different circulation patterns leading to rainfall (interplay of western disturbances and monsoonal rains over the Indus basin, of convective processes and tropical disturbances over the Ganges and Brahmaputra basin), largely controlled by orographically altered (sub-scale) atmosphere–surface energy fluxes over the Tibetan Plateau and related variations of the mid to upper tropospheric circulation modes (Böhner, 2006). In particular, the Indus basin, placed at the end of both the storm track and monsoon influence areas, poses a great challenge to climate models in terms of adequately simulating its complex hydro-climatology.

A second goal reached in this study has been to assess the projections of CMIP3 models for the XXI and XXII centuries under SRESA1B scenario. Our results show that for the Indus basin, models qualitatively suggest an increase in summer and fall precipitation, but it is not easy to assess the reliability of this result standing the above mentioned problems in describing the monsoonal circulation in this area. However, most importantly, models suggest decrease in winter and spring precipitation due to the northward shift of the Atlantic–Mediterranean storm track under warmer climate conditions. Therefore, such robust pattern of climate change not only threatens the renewal of the existing glaciers of the Hindu Kush–Karakoram–Himalaya (HKH) ranges but will also cause existing glaciers to melt due to both, the reduced amount of snow and increasing temperatures. This also implies that there would be smaller snowmelt contribution to the spring runoff under the warmer climates. Given that recently, melt water from glaciers and snowmelt contributes 60 % of the total discharge of the Indus assuring a comparatively stable runoff regime, these findings indicate a shift from a rather glacial and nival to a more pluvial runoff regime for the Indus. Although the con-

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sequences of glacier retreat for runoff regimes has long been overestimated and only recently reassessed through more reliable estimates of (snow and glacier) melt water contribution for major Asian streams (e.g. Immerzeel et al., 2010), climate change and related changes in the annual course of runoff, and in particular, intensified peak flows bear the risks of severe implications for water supply and water availability for households, industry and irrigated agriculture, especially in the downstream areas of the "lifeline" Indus.

For the Ganges basin, models indicate a decrease (increase) in winter (summer and fall) precipitation for the XXI and XXII centuries, with weak inter-model agreement during spring season. For Brahmaputra and Mekong basins, models suggest positive projected change in precipitation during summer, fall and spring seasons however there is a minute negative change during the winter season. This shift in precipitation regime will clearly affect the overall snow accummulation and then the melt contribution to the spring runoff, which is not clear from the ascertained projected changes in it. Overall, models suggests the increased water availability for the monsoon dominated river basins under warmer climate, whereas the reduced water availability is mainly associated with the decrease in precipitational regime of the mid-latitude western disturbances.

Considering our present investigations based on monthly climatology, we suggest that further analysis should focus on a smaller time-scale to study the variability of the onset timings and phase shifts of the annual cycle of the runoff regimes under warmer climate conditions (Lal et al., 2001; Arora and Boer, 2001) – which have a significant practical value for the water management as well as for the agricultural applications. Furthermore, spatially differenciated information within each basin would also be of great utitlity in order to manage water resources and planning mitigation measures in areas affected by substantial climate change. Hasson et al. (2013) together with the present study provide information on area-integrated hydrological quantites for catchments with large transboundary extents but cannot provide information on, for example, future upstream-downstream water availabiliy, changing runoff dynamics

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and related risks (droughts, floods, etc.). Given the practical needs of integrated watershed management, we suggest to supplement model simulations by means of dynamical downscaling, nesting a high-resolution Regional Climate Model (RCM) within a coarser-resolution GCM. State-of-the-art RCMs enable a stepwise (multi-nesting-level) downscaling of GCM outputs down to few Kms horizontal grid-mesh resolution, required to account for the topographic heterogeneity in high mountain environments (Langkamp and Böhner, 2010; Böhner and Langkamp, 2010). We are currently trying to implement a working version of the WRF model (Michalakes et al., 2001) with domain centered over South Asia. This approach can be further extended by coupling suitable spatially distributed hydrological models such as Variable Infiltration Capacity – VIC (Liang et al., 1994), TOPKAPI (Konz et al., 2010) and semi-distributed hydrological model such as University of British Columbia Watershed Model – UBC WM (Quick and Pipe, 1976; Singh, 1995) and Snowmelt Runoff Model – SRM (Immerzeel et al., 2009) to RCMs/GCMs, in order to improve the assessment of the changes in the hydrology of the river basins as a result of changed climate conditions. Such modelling studies on the impacts of changes of the hydrological cycle in South and South-East Asia, from basin to local scales, will be the focus of our future work. The results presented here elucidate that, nonetheless, such downscaling proceduers make sense only if the large scale water budget is well-represented by the GCM within which the nesting is performed. Therefore, it seems relevant for local downscaling communities, currently nesting regional climate models (RCMs) with CMIP3 GCMs, to take into account our results when attempting to construct high-resolution climate scenarios for the region.

Finally, let us mention that in general climate change is only one of the drivers causing significant changes in the hydrology, as economic and social changes pose multiple pressures on the water resources. This is particularly distinct in Asia, where tremendous land-use, structural, and socioeconomic changes are taking place. The concurrence of these effects stresses the need for integrating climate and land use scenarios when analysing and assessing the future water availability.

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Table 1. List of GCMs used in the study. These constitute the subset of all GCMs included in the PCMID/CMIP3 project providing all the climate variables of our interest.

Name and Reference	Institution	Grid Resolution (Lat × Lon)
CNRMCM3. Salas-Meélia et al. (2005)	Météo-France/Centre National de Recherches Météorologiques, France	T63
MRI-CGCM2.3.2 Yukimoto and Noda (2002)	Meteorological Research Institute, Japan Meteorological Agency, Japan	T42
CSIRO3. Gordon et al. (2002)	CSIRO Atmospheric Research, Australia	T63
ECHAM5 Jungclaus et al. (2006)	Max Planck Institute for Meteorology, Germany	T63
ECHO-G Min et al. (2005)	MIUB, METRI, and M&D, Germany/Korea	T30
GFDL2. Delworth et al. (2005)	US Dept. of Commerce/NOAA/Geophysical Fluid Dynamics Laboratory, USA	$2.5^\circ \times 2.0^\circ$
GISS-AOM Lucarini and Russell (2002)	NASA/Goddard Institute for Space Studies, USA	$4^\circ \times 3^\circ$
INMCM3. Volodin and Diansky (2004)	Institute for Numerical Mathematics, Russia	$5^\circ \times 4^\circ$
IPSL-CM4 Marti et al. (2005)	Institute Pierre Simon Laplace, France	$2.4^\circ \times 3.75^\circ$
MIROC (hires) K-1 Model Developers (2004)	CCSR/NIES/FRCGC, Japan	T106
PCM1MODEL Meehl et al. (2004)	National Centre for Atmospheric Research, USA	T42
UKMOHadCM3 Johns et al. (2003)	Hadley Centre for Climate Prediction and Research/Met Office, UK	$2.75^\circ \times 3.75^\circ$
UKMOHadGEM1 Johns et al. (2006)	Hadley Centre for Climate Prediction and Research/Met Office, UK	$1.25^\circ \times 1.875^\circ$

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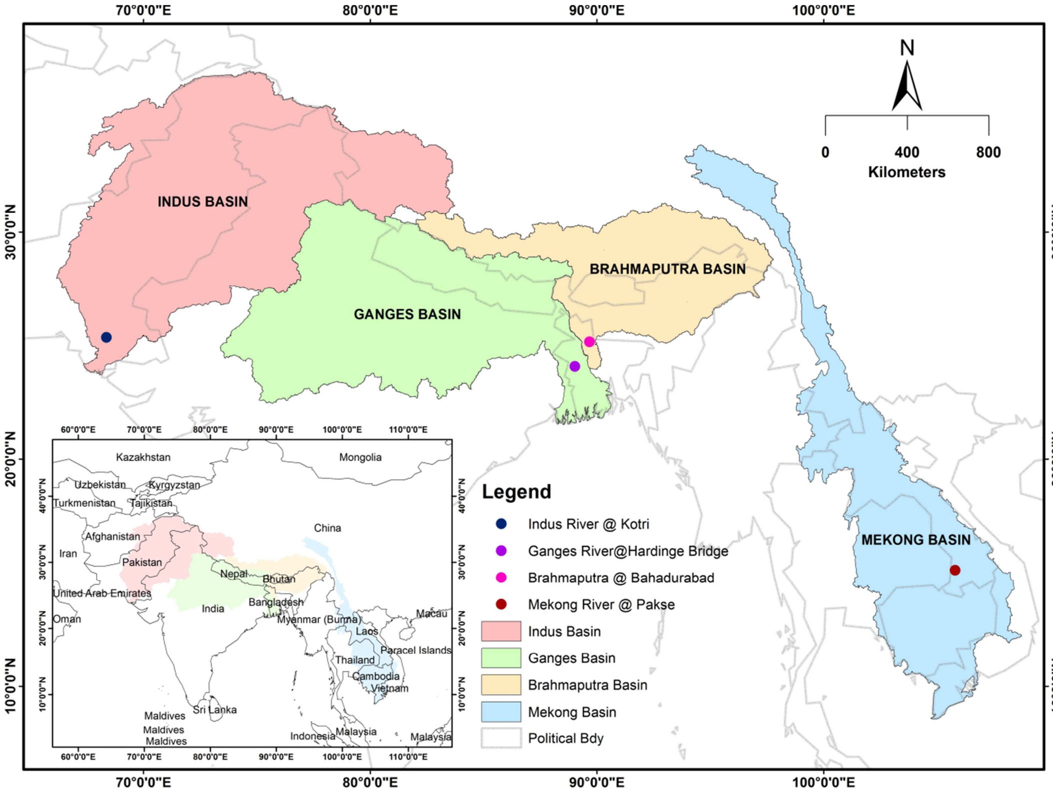

Fig. 1. The four river basins considered in this study: Indus, Ganges, Brahmaputra and Mekong (west to east).

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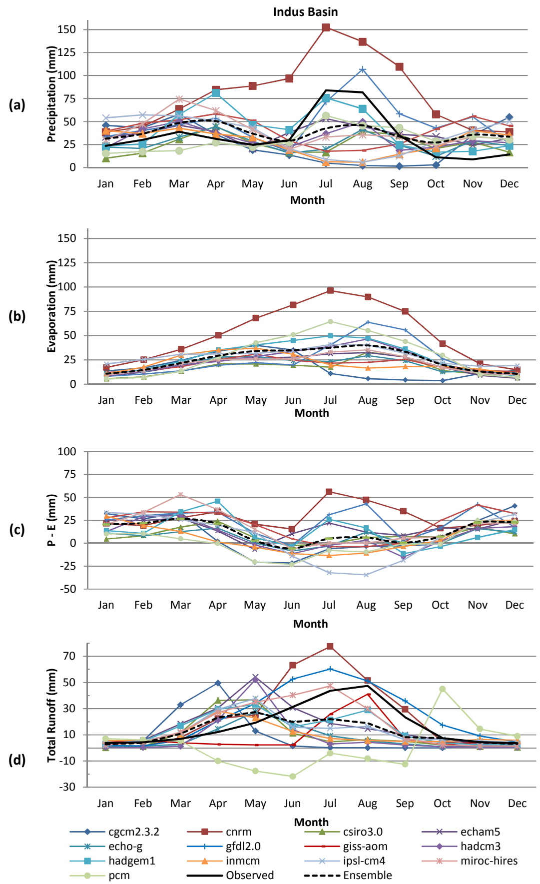

Fig. 2. (a)–(d) XX century annual cycles of considered quantities for the Indus basin: **(a)** P, **(b)** E, **(c)** $P-E$, **(d)** R. Note: as Indus river is highly diverted for irrigation and other purposes, its estimated natural discharge (by adding diverted volume to actual discharge into sea) is shown.

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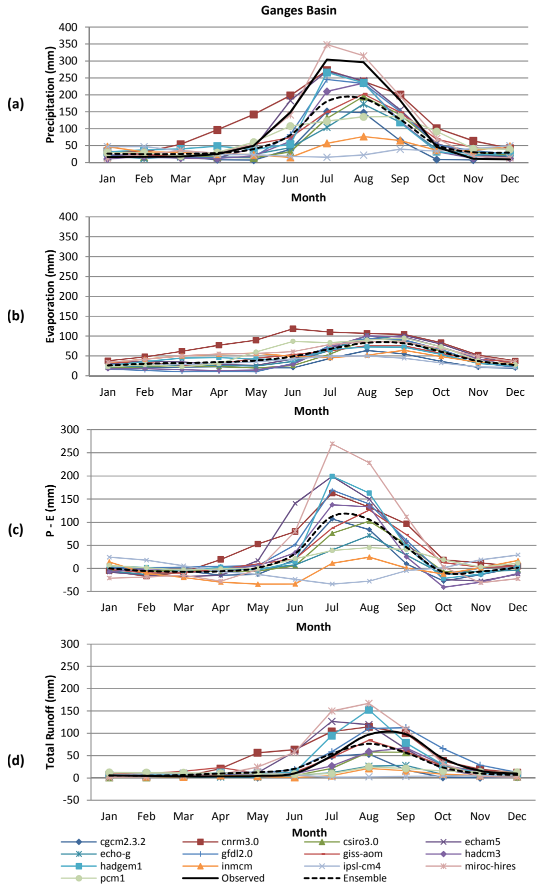

Fig. 3. (a)–(d) XX century annual cycles of considered quantities for the Ganges basin: **(a)** *P*, **(b)** *E*, **(c)** *P* – *E*, **(d)** *R*.

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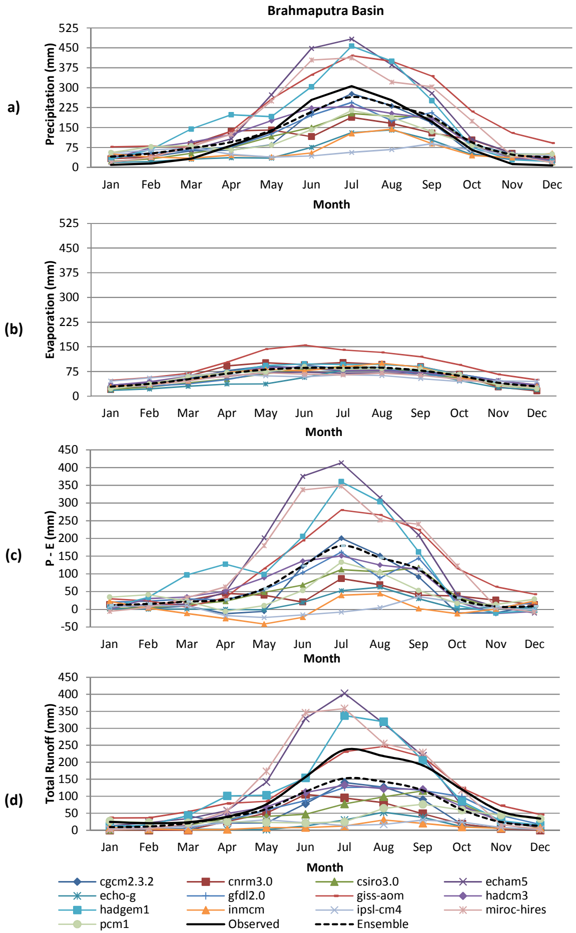

Fig. 4. (a)–(d) XX century annual cycles of considered quantities for the Brahmaputra basin: **(a)** P, **(b)** E, **(c)** $P-E$, **(d)** R.

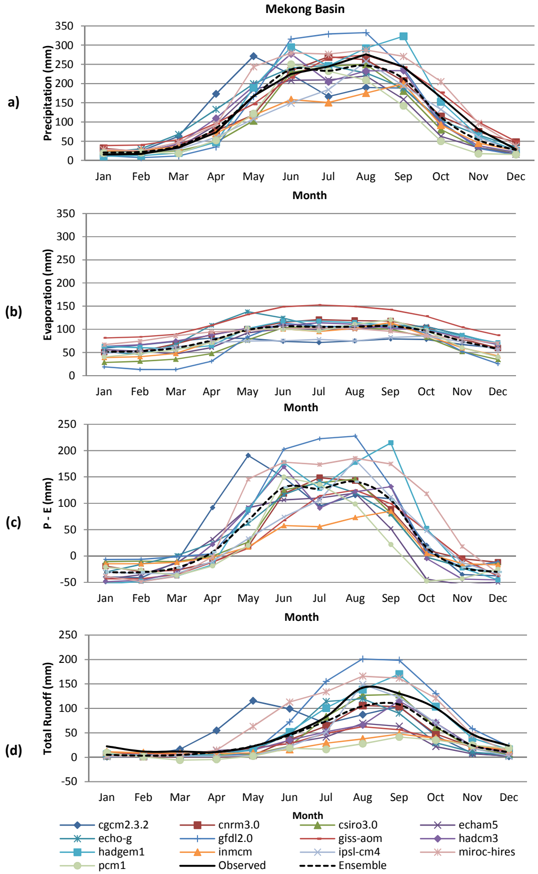

Fig. 5. (a)–(d) XX century annual cycles of considered quantities for the Mekong basin: **(a)** *P*, **(b)** *E*, **(c)** *P* – *E*, **(d)** *R*.

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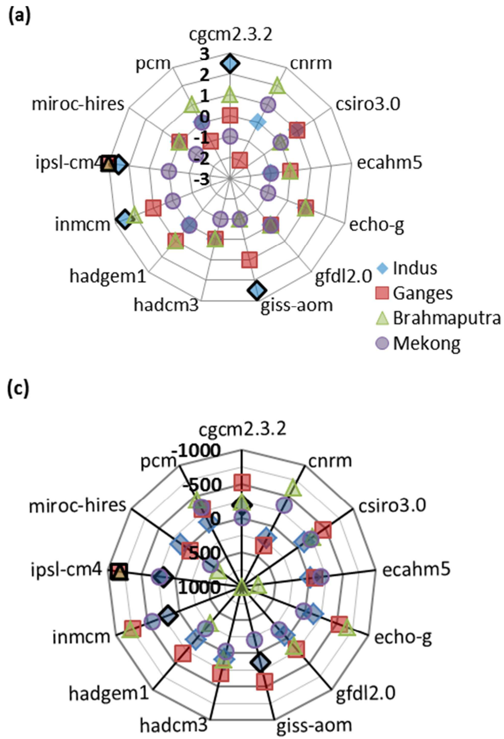

Fig. 6. (a)–(c) Relative to the observations, **(a)** difference in timings of Monsoon onset-month, positive (negative) value indicates delayed (early) onset in months, **(b)** Difference in Monsoon duration, positive (negative) value indicates expansion (shrinkage) in months, **(c)** Monsoon precipitation magnitude in mm yr^{-1}, positive (negative) value indicates overestimation (under-estimation). Note: GCMs which do not simulate Monsoon Precipitation Regime at all for the particular basin (markers with black border) are only shown for indicative purpose.

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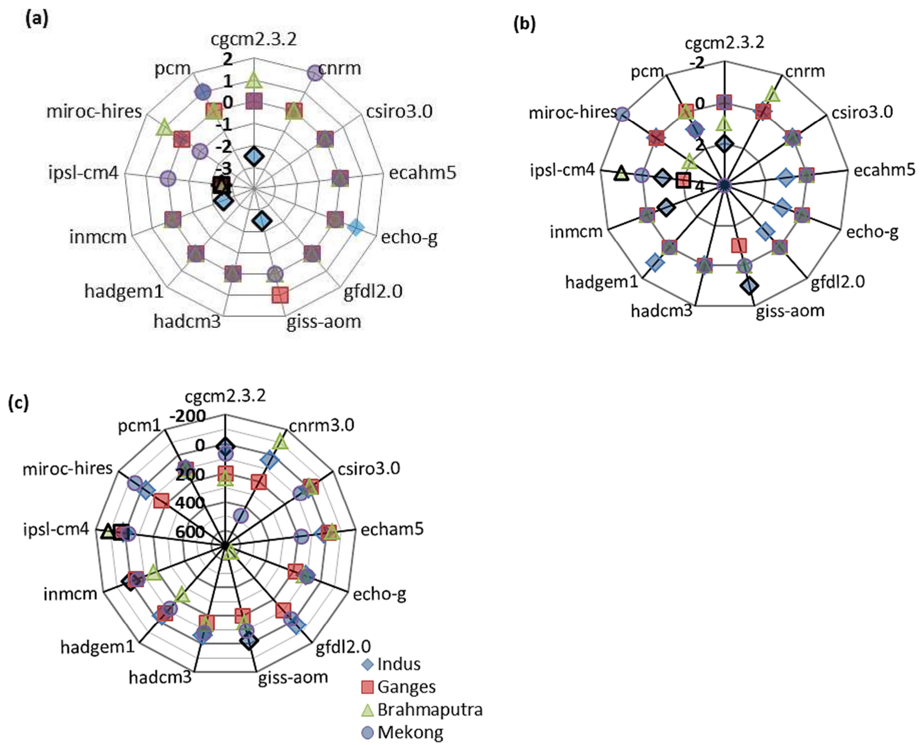

Fig. 7. (a)–(c) Change for the XXI Century Climate (2061–2100) relative to XX Century climate (1961–2000), **(a)** in timings of monsoon onset-month, positive (negative) value in number of months indicates delayed (early) onset, **(b)** in monsoon duration, positive (negative) value in number of months indicates expansion (shrinkage) of monsoon duration, **(c)** in magnitude of monsoonal precipitation in mm yr^{-1}, positive (negative) value indicates increase (decrease). Note: miroc-hires suggests an increase of 1025 mm not shown in **(c)**. Note: GCMs which do not simulate Monsoon Precipitation Regime at all for the particular basin (markers with black border) are only shown for indicative purpose.

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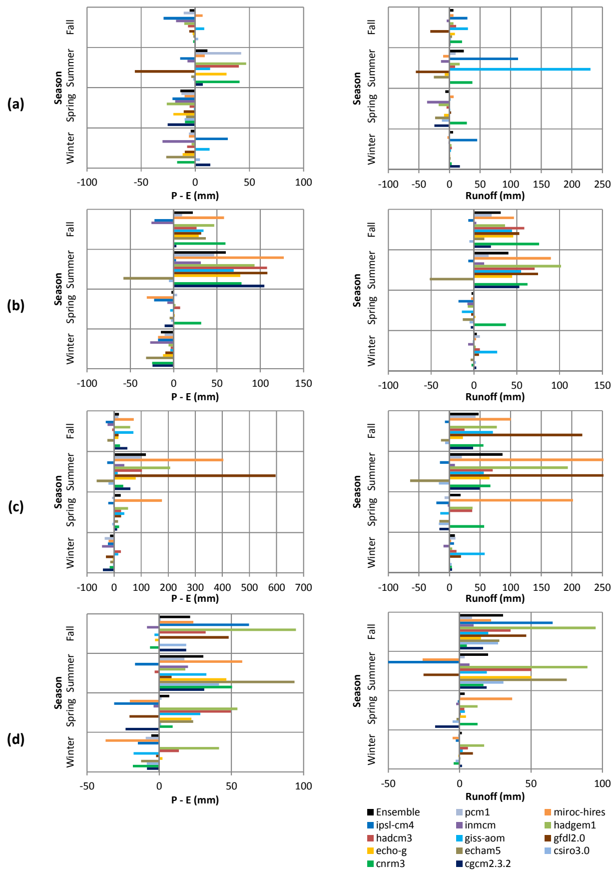

Fig. 8. (a)–(d) Intra-annual changes in $P - E$ (left panels) and R (right panels) for the XXI Century Climate (2061–2100) with respect to XX Century Climate (1961–2000) for the basins, **(a)** Indus, **(b)** Ganges, **(c)** Brahmaputra, **(d)** Mekong. Note: changes in the XXII Century climate (2161–2200) are more pronounced with same qualitative signal.

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