

Simulation and Comparison Between Mid-Holocene and Preindustrial Indian Summer Monsoon Circulation Using a Regional Climate Model

Stefan Polanski^{*1}, Annette Rinke², Klaus Dethloff², Stephan J. Lorenz³, Yongbo Wang² and Ulrike Herzschuh^{2,4}

¹Freie Universität Berlin, Institute for Meteorology, Carl-Heinrich-Becker-Weg 6-10, D-12165 Berlin, Germany

²Alfred Wegener Institute for Polar and Marine Research, Research Unit Potsdam, Telegrafenberg A43, 14473 Potsdam, Germany

³Max Planck Institute for Meteorology, Bundesstraße 53, D-20146 Hamburg, Germany

⁴Potsdam University, Institute for Earth and Environmental Sciences, Karl-Liebknecht-Straße 24-25, 14476 Potsdam, Germany

Abstract: The regional climate model HIRHAM has been applied over the Asian continent from 0°N to 50°N and 42°E to 110°E to simulate the Indian monsoon circulation under past and present-day conditions. The model is driven at the lateral and lower boundaries by the atmospheric output fields of the global coupled Earth system model ECHAM5-JSBACH/MPIOM for 44-years-long time slices during the mid-Holocene and the preindustrial present-day climate. Simulations with a horizontal resolution of 50 km are carried out to analyze the regional monsoon patterns under different external solar forcing and climatic conditions. The focus is on the investigation of the HIRHAM simulated summer monsoon circulation and the comparison of the regional atmospheric circulation and precipitation patterns between the paleo- and the preindustrial climate. Due to mid-Holocene changes in the atmospheric circulation with a reduced and southward shifted monsoonal flow across Arabian Sea and Bay of Bengal, an increase of summer rainfall at the windward slopes of western and southern Himalayas as well as over southern India and decreased rainfall over central India appear which is in agreement with proxy-derived precipitation reconstructions. During the mid-Holocene as well as for the present-day climate the same driving mechanisms for the summer monsoon in extreme wet monsoon years related to regional SST anomalies in the Indian Ocean and convective processes can be verified. Positive (negative) SST anomalies in the northern Indian Ocean enhance (inhibit) the local convection associated with a deepening (weakening) of the low pressure and trigger wet (dry) rainfall anomalies.

Keywords: Mid-Holocene, present-day, Indian Summer Monsoon, Regional Climate Model, extreme rainfall, reconstructions.

1. INTRODUCTION

In mid-Holocene secular variations of the orbital parameters changed the insolation over the northern hemisphere with a maximum increase of +35 W/m² in summer and a decrease of -20 W/m² in winter compared to preindustrial present-day climate [1, 2]. These external changes in incoming solar radiation could exert a strong impact on the global and regional climate. Paleoclimatic reconstructions reveal significant changes in the Asian monsoon intensity during the Holocene. Around 6000 years before present (e.g., [3, 4]) the Indian monsoon penetrated further into the inner domain of the Asian continent implying a wetter climate. Modeling studies related this enhancement of the monsoon to the impact of changing solar summer insolation on climate (e.g., [5-7]). The enhanced annual solar cycle affected a higher meridional temperature gradient between the Eurasian land surface and the Indian Ocean with an intensified cross equatorial monsoonal wind and moisture advection over the Arabian Sea and the Bay of Bengal and

more rainfall in summer. General circulation models of the atmosphere (AGCMs) are often used to simulate the large-scale atmospheric circulation and the related monsoon circulation. Owing to the coarse horizontal resolution, global AGCMs are not able to capture regional-scale atmospheric circulation and precipitation processes, which strongly depend on the topography, realistically. Therefore regional climate models (RCMs) are nested in an AGCM to increase the horizontal resolution for a special area of interest by applying the method of dynamical downscaling. At the lower and lateral boundaries RCMs are driven by global model data or data analysis. Several RCM simulations have been carried out for the Indian monsoon region for present-day which show a good agreement in the general monsoon patterns compared to observations. Furthermore, related to the better horizontal resolution of these models, an added value compared to the driving data can be identified especially in the mountain areas, even if the realistic simulation of rainfall has to be further improved particularly due to the cumulus convection parameterization (e.g., [8-11]).

In this study the focus is on the analysis of the HIRHAM simulated Indian summer monsoon circulation and the

*Address correspondence to this author at the Freie Universität Berlin, Institute for Meteorology, Carl-Heinrich-Becker-Weg 6-10, D-12165 Berlin, Germany; Tel: +49 30 838 71149; E-mail: stefan.polanski@met.fu-berlin.de

comparison of the regional atmospheric circulation and precipitation patterns between the past and the present climate. According to this, the decadal climatology over the 44-years-long time slices and the monsoon behavior in selected wet and dry monsoon years have been investigated and compared between mid-Holocene (called “6k”) and present-day (called “0k”) climate. After a short introduction of the HIRHAM model, the setup of the model simulations and the reconstructed relative moisture index are presented (Section 2). In Section 3 the simulation results for the atmospheric circulation and the precipitation in summer for the two climatic periods and the driving mechanisms for anomalous rainfall years are analyzed. In addition, the calculated relative annual rainfall anomalies are compared with paleoclimatic reconstructions based on the moisture index. Finally, concluding remarks summarize the main results (Section 4).

2. MODEL AND RECONSTRUCTIONS

2.1. Regional Climate Model HIRHAM

The regional climate model HIRHAM used in this study has been developed by Christensen *et al.* [12]. It has been recently adapted to the Asian region by Polanski *et al.* [11]. The dynamical part of the model is based on the hydrostatic limited-area model HIRLAM (High-Resolution Limited Area Model) [13] with prognostic equations for horizontal wind components, temperature, specific humidity, cloud water content, and surface pressure. The physical parameterizations for radiation, land surface processes, sea surface sea-ice processes, planetary boundary layer turbulence, gravity wave drag, cumulus convection, and large-scale condensation are taken from the general circulation model ECHAM4 [14]. Details of the model dynamics and physics can be found in the given references. The integration domain in the Asian region (see Fig. 1) covers an area between 0°N to 50°N and 42°E to 110°E, including the high topography of the Tibetan Plateau and the Himalayas as well as the northern Indian Ocean. The model domain includes 110×100 grid points and a horizontal resolution of 0.5°. The vertical discretization consists of 19 irregularly spaced levels in hybrid σ -p coordinates from the surface up to 10 hPa.

At the lateral and lower boundaries, HIRHAM has been forced by the atmospheric output fields of the coupled global Earth system model ECHAM5-JSBACH/MPIOM (called “ECHAM5”), which has been developed at the Max Planck Institute for Meteorology in Hamburg [15]. The ECHAM5 simulations have been run with a horizontal resolution of 3.75° and 19 vertical levels in hybrid σ -p coordinates for 600 years starting in mid-Holocene and preindustrial modern climate [16]. The lateral forcing includes all prognostic

variables except the cloud water content. The information from the lateral boundaries is transferred into the model interior by a boundary relaxation [17] in a 10-grid-point-wide boundary zone with boundary data updated 2 times a day every 12 hours. At the lower boundary, ECHAM5 sea surface temperatures have been used and updated daily.

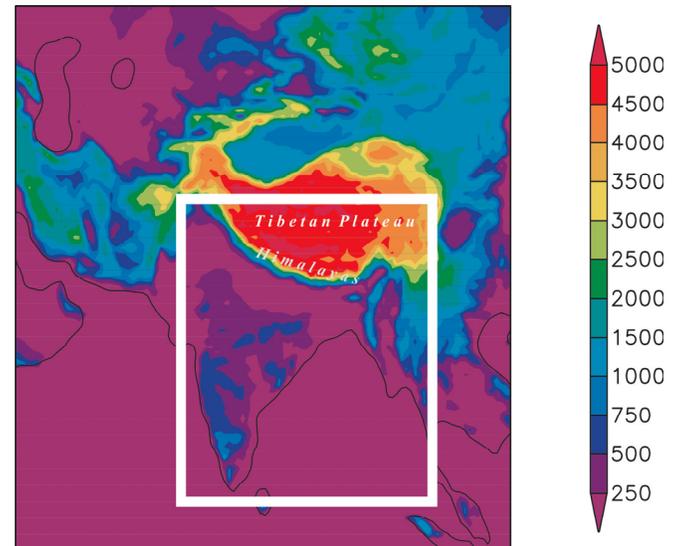


Fig. (1). Integration domain and height of the orography (m, colours) of HIRHAM. Additionally, the monsoon domain is marked by the white box.

According to the ECHAM5 experimental setup, the orbital configurations for 6k and 0k are based on Laskar *et al.* [2]. For both 44-years-long simulations, the composition of greenhouse gases has been set to the preindustrial values concerning PMIP - the Paleoclimate Modelling Intercomparison Project [18] to consider the orbital conditions as single external forcing (see Table 1).

2.2. Reconstructed Moisture Index

The HIRHAM simulated rainfall changes between 6k and 0k are compared with 55 reconstructed paleo-data derived from different archives like lake sediments and cave deposits applying various proxies, which have been collected in the monsoonal regions of Central Asia covering 70°E-130°E and 20°N-50°N encompassing most parts of China, Mongolia, northern India and Kyrgyzstan [4]. The moisture signals from the separate studies have been translated and synchronized into a qualitative moisture index of a five-part scale: the lowest (highest) value indicates the driest (wettest) intervals for each site since 18000 years. The moisture scales are relative and have been constructed for each 100 year interval during the Holocene period. However, here only the 6k values were used.

Table 1. Orbital Configurations and Boundary Conditions for HIRHAM Simulations 6k and 0k

Experiment	Orbital Configurations (Laskar <i>et al.</i> , 2004)			Greenhouse Gases (PMIP)		
	Eccentricity (%)	Precession (°)	Obliquity (°)	CO ₂ (ppm)	CH ₄ (ppb)	N ₂ O (ppb)
6k	1.868	180.9	24.105	280	760	270
0k	1.672	282.0	23.446	280	760	270

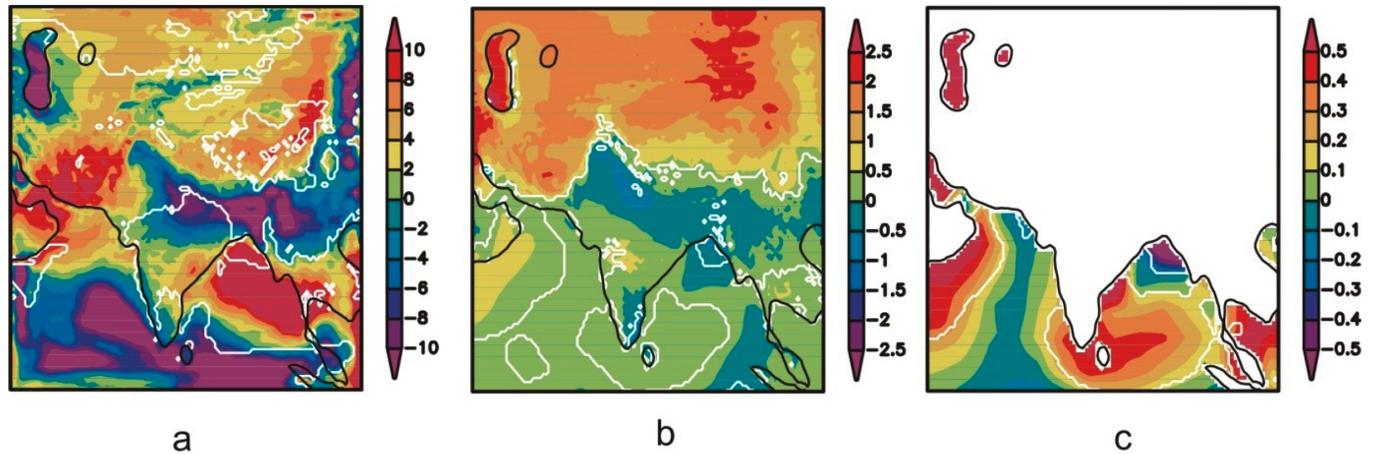


Fig. (2). Anomalies of (a) net solar radiation balance at the surface (W/m^2), (b) 2m air temperature ($^{\circ}\text{C}$) and (c) SST ($^{\circ}\text{C}$) for HIRHAM “6k minus 0k”; summer monsoon (JJAS). The white line represents the areas where the anomalies are statistical significant at the 95% confidence level.

3. CLIMATIC CHANGE DURING MID-HOLOCENE SUMMER MONSOON

3.1. Variation in Net Radiation and 2m Air Temperature Between 6k and 0k

Fig. (2) describes the changes in the climatic conditions for the summer monsoon season (JJAS) between 6k and 0k. Shown are the anomalies in net radiation balance at the surface (solar insolation minus thermal emission), 2m air temperature and sea surface temperature (SST), simulated by the HIRHAM model. For 6k, the net radiation balance at the surface indicates an increase north of 30°N , in southwestern Asia and in northern Bay of Bengal of up to 10 W/m^2 implying a stronger diabatic heating in those regions in 6k compared to 0k. On the other side, a decreased radiation balance during 6k appears in northern India including the Himalayas. Moreover, positive SST anomalies occur in the western Arabian Sea as well as in the central and southern Bay of Bengal. These changes in the external solar forcing and in the diabatic heating source, which show a statistical significance within a confidence interval of 95% in most parts, modify the meridional temperature gradient between

Eurasian land surface and the Indian Ocean, particularly due to the warmer Eurasian continent of up to $+2^{\circ}\text{C}$ in 6k. Furthermore, the intensification of the moisture transport towards the continent within the low-level monsoonal wind and the regional rainfall patterns depend on these external forcing mechanisms.

3.2. Simulated Circulation and Rainfall Changes, and Comparison with Reconstructions

Changes in the external forcing parameters and in the diabatic heating source have an impact on the circulation and rainfall patterns [7]. In Fig. (3) the mean summer monsoon (JJAS) wind fields at 850 hPa are illustrated for the HIRHAM simulation during 6k and 0k. For 6k the model simulates a weakening and southward shift of the near-surface southwestern monsoonal winds over the Arabian Sea and the Bay of Bengal compared to 0k. These changes in the large-scale summer monsoon circulation influence the precipitation signals in summer statistically significant (see Fig. 3). During 6k, a precipitation increase over southern India and a decrease over central India and the Bay of Bengal occur. Furthermore, the wind circulation during 6k

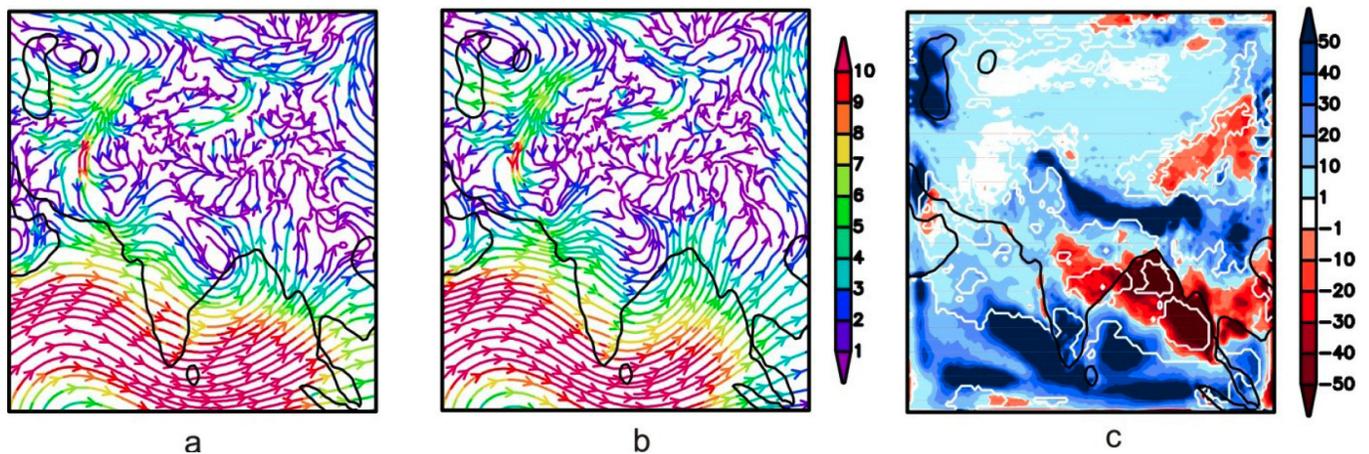


Fig. (3). 850-hPa wind fields (streamlines) and wind speed (m/s; colours) for (a) HIRHAM 0k and (b) HIRHAM 6k. (c) Precipitation anomalies (mm; colours) for HIRHAM “6k minus 0k”; summer monsoon (JJAS). The white line in (c) marks the areas where the anomalies are statistical significant at the 95% confidence level.

favors an intensification of moisture advection at the windward slopes of the western and southern Himalayas caused by the redirection of the near-surface cross Equatorial Jet over Pakistan [7]. Thus, the uplifting processes are intensified in 6k accompanied with more rainfall in that region.

Such moisture changes during the Holocene have been described by paleoclimatic reconstructions based on a relative moisture index of Wang *et al.* [4] (see Fig. 4). The figure compares the HIRHAM simulated relative annual rainfall anomalies and the reconstructed paleoclimatic moisture index. In some areas, especially in northwestern India and along a gradient over central and northeastern Tibetan Plateau, there is a good agreement between the model simulation and the reconstructions. However, the model and the reconstructions disagree in southeastern and eastern parts of the Tibetan Plateau, where the model simulates less rainfall in 6k while the reconstructions indicate a positive anomaly. These wetter summer climate conditions shown by the moisture index are also reproduced by other global paleoclimate modeling studies especially over East Asia [7, 19]. This is related to different regional atmospheric circulation structures as well as different model physics and parameterization schemes between the HIRHAM model and the global model simulations. Due to the high spatial variability of the moisture signal and reconstruction-inherent uncertainties a higher resolution of paleoclimatic reconstructions would be necessary to better compare model- and proxy-based moisture anomalies.

Fig. (4) further shows that HIRHAM simulates more annual rainfall over the Arabian Sea, the Arabian Peninsula, south to the Caspian Sea and in the western Himalayas during 6k. The most part of annual rainfall is influenced by summer rainfall events. The increase over the Arabian Sea

and the surrounding areas is associated with the higher SSTs (see Fig. 2) going along with the enhancement of local convection related to an intensified moisture convergence, a stronger upward motion of moisture and a higher instability in the vertical column of the troposphere [11]. Analogously, the negative rainfall anomalies over northern Bay of Bengal are connected to lower SSTs and a reduction of local convective processes.

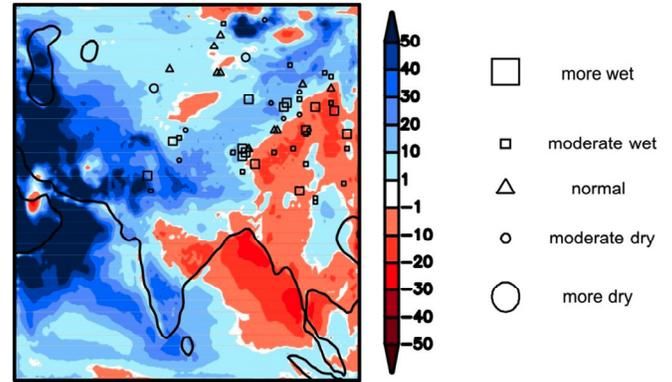


Fig. (4). Annual precipitation anomaly (%; colours) for HIRHAM “6k minus 0k” and reconstructed moisture index (symbols; dimensionless; [4]).

3.3. Wet and Dry Summer Monsoon Composites

To further investigate the summer monsoon rainfall changes between 6k and 0k, typical rainfall anomaly patterns between strong (wet) and weak (dry) monsoon (years) have been analyzed for both time slices. The selection of the anomalous wet and dry composites is done following the criteria of Farrara and Yu [20]. Monsoon years are defined as anomalous wet (dry), if the summer (JJAS) precipitation

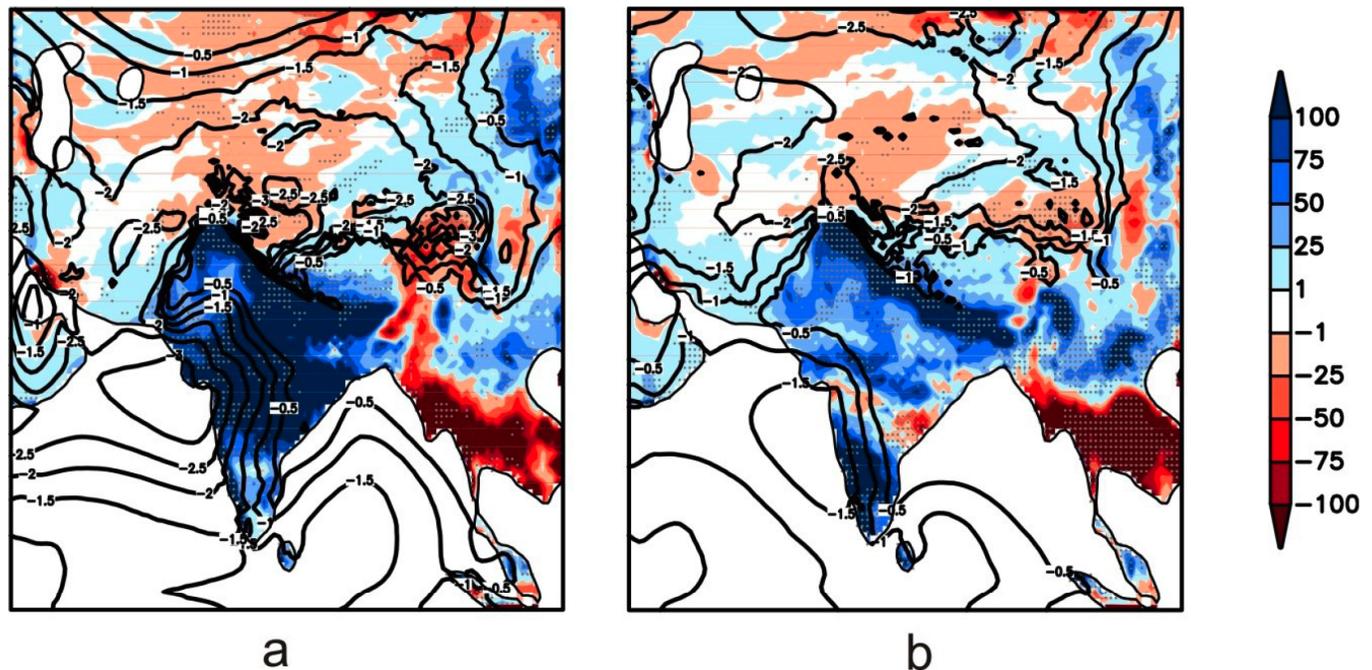


Fig. (5). Anomalies of precipitation “wet minus dry” (mm; colours) and mean sea level pressure “wet minus dry” (hPa; contour lines in steps of 0.5 hPa) for (a) HIRHAM 0k and (b) HIRHAM 6k; summer monsoon (JJAS). The grey dots mark the areas where the anomalies are statistical significant at the 90% confidence level.

averaged over the monsoon domain (see Fig. 1) [21] is more (less) than 0.5 standard deviations above (below) the climatological mean.

Fig. (5) shows that during both 6k and 0k the spatial large-scale pattern of the precipitation differences “wet minus dry” are quite similar. This is an indication that the driving mechanisms of extreme summer monsoon rainfall are similar in both periods. Particularly similar regional patterns of rainfall anomalies are simulated over the Himalayas and in southeastern Asia. In contrast, for the 6k time slice the HIRHAM model simulates more rainfall over southern India and in southeastern Himalayas already seen in the summer climatology (see Fig. 3c). Less rainfall in 6k is estimated over central and northern India. These precipitation anomalies are strongly associated with changes in the atmospheric circulation, which is represented in the figure by the differences in the mean sea level pressure fields (see Fig. 5). In years of strong monsoon during 6k a southward shift and decrease of the low pressure area from northern Arabian Sea and central India towards southwestern India occurs. This is related to the southward shift of the positive rainfall anomaly “wet minus dry” from central to southern India compared to 0k (see Fig. 5). That shifting low pressure area is statistically significant.

The SST changes over the Indian Ocean (see Fig. 6) are one of the most important drivers for the modified atmospheric circulation and rainfall patterns in wet and dry years. In 0k the pronounced warm SST anomaly in the northern Arabian Sea is associated with intensified local convection. Additionally a depression of the mean sea level pressure field in that region appears during strong monsoon years, which impacts on the simulated wet rainfall anomalies over northern and central India. In contrast, cold SST anomalies in the southern Arabian Sea inhibit the local

convection and weaken the near-surface depression with the consequence of a drier southern India. The same spatial SST anomaly pattern occurs during 6k. The warm SST “wet minus dry” anomaly over northern Arabian Sea again drives consistent positive, but smaller rainfall anomalies over the Himalayas and in the Gangetic Plains. Compared to 0k, in 6k a slightly colder, but not statistically significant, SST anomaly has been simulated in the northern Bay of Bengal, which increases the mean sea level pressure and causes the smaller rainfall amounts in Bangladesh, in southeastern Asia and in central India.

The white dots in Fig. (7) indicate that the wet rainfall anomalies, described in Fig. (5), are related to those regions, which represent the areas of strongest convective activity over land areas associated with a strong moisture convergence shown as positive anomalies “Precipitation minus Evaporation” as well as a strong upward motion in the middle troposphere at 500 hPa. This relationship is approved for both 6k and 0k. In 6k the strongest convective activity during wet years occurs over the central and eastern Himalayas as well as over southern India. In 0k a large area of convective activity over India is simulated, which is reduced in 6k as a result of the shifted atmospheric circulation patterns.

The analysis confirms that the summer monsoon rainfall in years between strong and weak monsoonal activity is driven by the SST, the local convective activity and the atmospheric circulation [11, 22-24]. These same mechanisms are identified here in 6k as well as in 0k. Changes in the distribution of rainfall anomalies “wet minus dry” can be attributed to shifting regional atmospheric circulation patterns driven by modified regional SST anomalies in the Indian Ocean. The convection over land surface areas is driven by large-scale moisture advection from the Indian

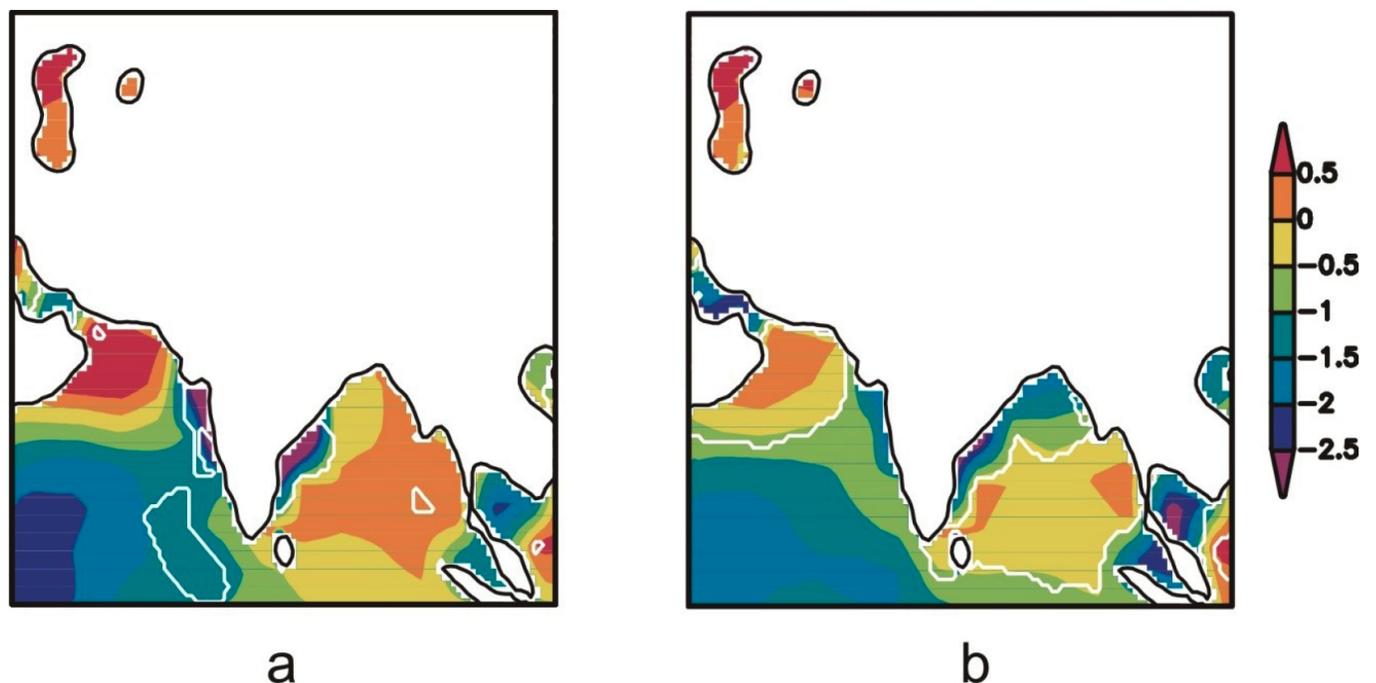


Fig. (6). SST anomalies “wet minus dry” (°C) for (a) HIRHAM 0k and (b) HIRHAM 6k; summer monsoon (JJAS). The white line represents the areas where the anomalies are statistical significant at the 95% confidence level.

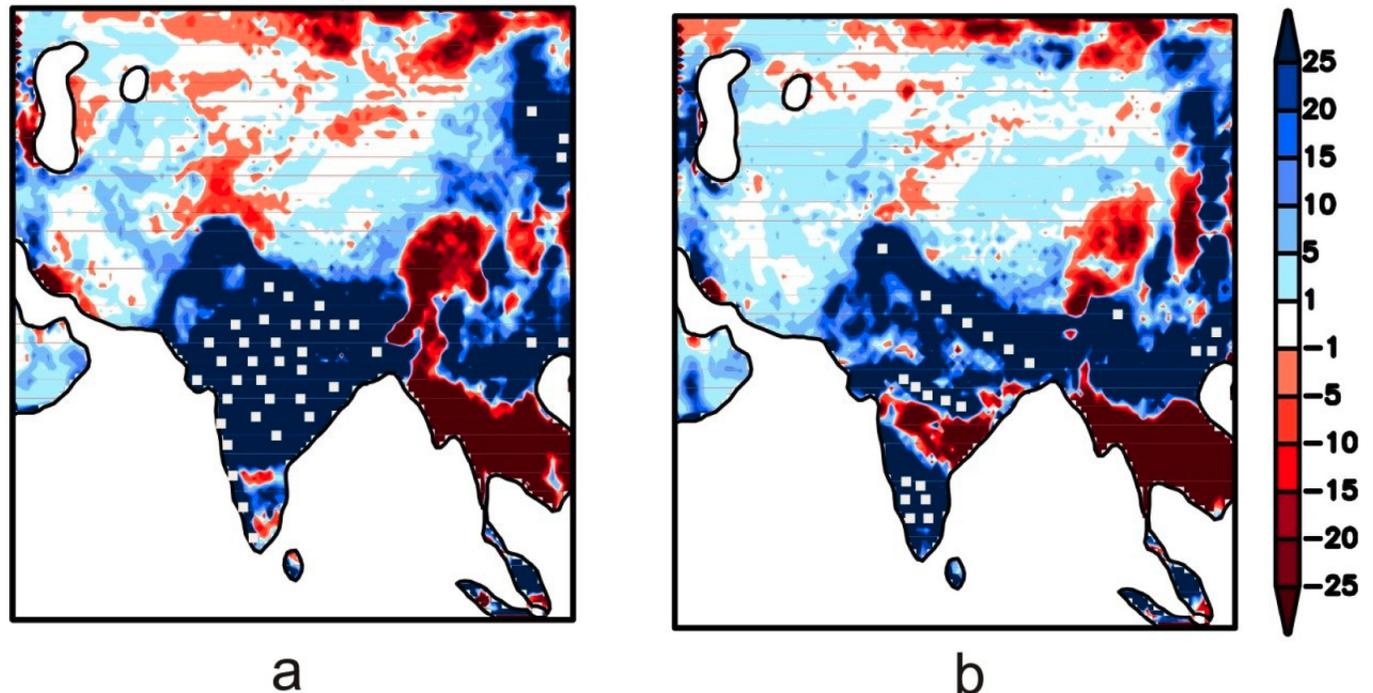


Fig. (7). Anomalies of Precipitation minus Evaporation (P-E) “wet minus dry” (mm; colours) for (a) HIRHAM 0k and (b) HIRHAM 6k; summer monsoon (JJAS). The white dots mark the areas with positive anomalies in both P-E and vertical velocity (ω) at 500 hPa.

Ocean and a strong upward motion of water vapor over land related to enhanced instability and moisture convergence.

4. CONCLUSIONS

A paleoclimatic experiment with 44-years-long simulations for the mid-Holocene (6000 years before present; 6k) and the preindustrial modern climate (0k) has been used to investigate precipitation and atmospheric circulation changes and to analyze the driving mechanisms of the extreme Indian summer monsoon years. Significant external changes in the solar radiation during mid-Holocene influenced the Asian regional climate as well as the monsoon intensity. Differences in the large-scale atmospheric circulation fields induced regional circulation changes and an increase of summer rainfall over southern India and a decrease over central India and the Bay of Bengal according to a southward shift and decreasing wind in the lower troposphere. Due to the redirection of the near-surface Cross Equatorial Jet over Pakistan, in 6k more rainfall had been calculated over the windward slopes of the western and southern Himalayas compared to 0k. A comparison with paleoclimatic reconstructions based on a moisture index [4] had shown that over the central and northeastern Tibetan Plateau and in northwestern India a good agreement between the simulated and reconstructed annual rainfall anomalies “6k minus 0k” exists. However, a disagreement was found over the eastern and southeastern Tibetan Plateau, where the model simulates drier and the proxies reconstruct wetter conditions in 6k. To evaluate the highly regional-scale rainfall patterns based on paleoclimatic reconstructions, especially associated with the mountains, a better spatial resolution of proxy data is needed.

Anomalous strong (wet) and weak (dry) monsoon (years) are strongly influenced by both dynamical (atmospheric circulation) and thermal changes (SST). During strong monsoon years in 6k a southward shift and decreased low pressure area from northern and central Arabian Sea towards southwestern India occurred. This was related to a southward shift of the wet rainfall anomaly from central to southern India. In 6k as well as in 0k the same driving mechanisms for the summer monsoon in extreme wet monsoon years related to SST anomalies in the Indian Ocean could be verified. Positive (negative) SST anomalies enhanced (inhibited) the local convection with a deepening (weakening) of the low pressure area and finally wet (dry) rainfall anomalies.

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CONFLICT OF INTEREST

Declared none.

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