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RESEARCH ARTICLE

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Summer monsoon over northeastern India during the last millennium

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Abstract

Analysing three high resolution coupled model simulations for the Medieval Climate Anomaly (MCA) and Little Ice Age (LIA) regimes, available as the last millennium simulations of the PMIP3, we find that Northeastern Indian summer monsoon rainfall (NEISMR) did not change appreciably from the MCA to the LIA. This is in contrast to the signals in the rest of the Indian region. Our results from all the models suggest that, during the MCA, the simulated 100-hPa tropical easterly jet (TEJ) becomes relatively more intense than that during LIA, due to a stronger Tibetan High. This strengthening of the TEJ results in an associated increase in relative vorticity at the 500 hPa over the Head Bay of Bengal and neighbouring east coast of the Bay of Bengal. This results in higher moisture availability and increased summer monsoon rainfall in the neighbourhood, including the central Indian region, during the MCA. However, the simulations do not show any such changes over northeastern India, indicating a relatively stable simulated NEISMR from MCA through LIA. Furthermore, just as the current day observations, the simulated correlations between the NEISMR with various concurrent ENSO indices are weak and statistically insignificant during the MCA and LIA regimes. Interestingly, an analysis of time-slice simulations for the MCA and LIA from an atmospheric general circulation model broadly agree with the above conclusions, indicating that the tropical ocean and atmospheric coupling may not have played a major role in the northeast climate.

KEYWORDS

ENSO and NEISMR, Indian summer monsoon, last millennium, little ice age, medieval climate anomaly, northeastern Indian summer monsoon, PMIP3 data analysis, tropical easterly jet

1 | INTRODUCTION

The Indian sub-continent, home to more than 1.3 billion people, receives about 70–75% of its annual rainfall (Figure 1a) during June–September months (henceforth JJAS), and known as the Indian summer monsoon season (e.g., Pant and Kumar, 1997). The mean area-averaged Indian summer monsoon rainfall (ISMR) over the last 100 years is about 890 mm (Pattanaik, 2012). Northeastern India (NEI; $\approx 89.5°–98.5°$E and $21.5°–29.5°$ N; see Figure 1b), spread over about 262,230 km^2 with a population of about 46 million, is one of the two highest raining

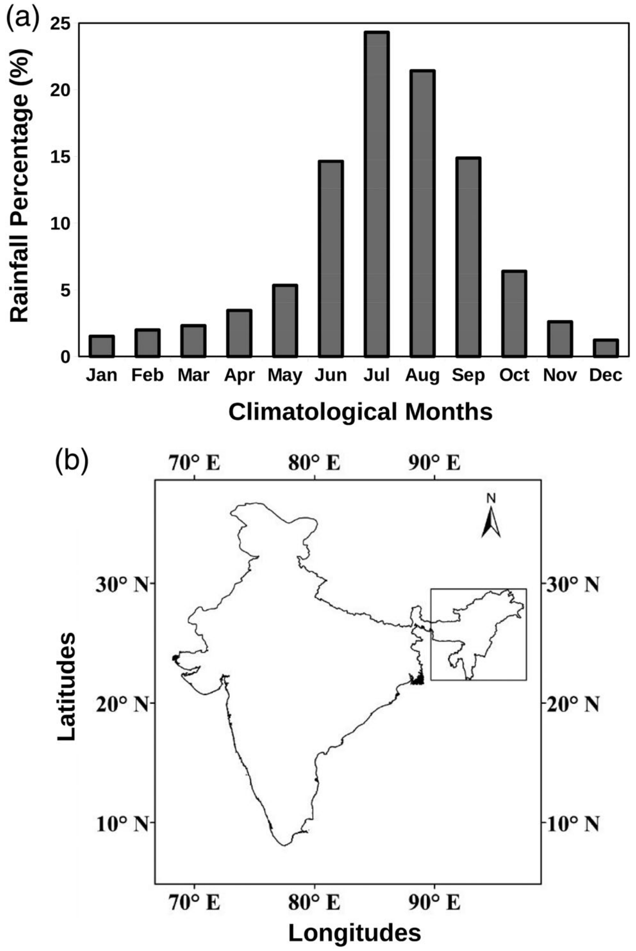

FIGURE 1 (a) The area-average climatological monthly rainfall over the Indian region India as a percentage of annual rainfall, and (b) study area of the northeastern India, enveloped by a box, bounded by 89.5°–98.5°E and 21.5°–29.5°N, over the Indian region. The gridded rain gauge-based gridded rainfall data at 1° × 1° resolution from the India Meteorological Department (Rajeevan *et al.*, 2005) for the 1960–1990 were used to generate (a)

regions in India, with an area-averaged seasonal rainfall of 152 cm (Parthasarathy *et al.*, 1995). In fact, the highest annual rainfall of ~12,000 mm in the world occurs at Cherrapunji of NEI, and in recent ~2 decades, at the neighbouring Mawsynram, 80 km away (Jain *et al.*, 2013).

The ISMR is strongly influenced by the El Niño-Southern Oscillation (ENSO; see Ashok *et al.*, 2019 and the references therein). The gravest EOF mode of the interannual variability of the ISMR variability for the 1871–1990 period, deciphered from rainfall records from 306 stations, has a dipolar structure (Parthasarathy *et al.*, 1996), with the signal in NEI in an out-of-phase relation with most of India (Shukla, 1987; and Figure 10a in a more recent study by Guhathakurta and Rajeevan, 2008). In addition, the correlations between the summer monsoon rainfall over central and northwestern parts of India with that over northeastern India are weak, and even negative (Parthasarathy, 1984). While a few stations in northeastern India may have positive correlations with rainfall elsewhere in India, in general, the rainfall variability of NEI is not in the same phase as that of many other summer monsoonal homogeneous zones of India. A cluster analysis of the reconstructed Asian summer precipitation dataset for the 1470–2013 period shows (see Figure 2c of Shi and Wang, 2018) NEI in the same cluster along with western and southern East China, and southern Japan. However, rest of India falls in cluster 1, along with the north Asia, especially yellow river basin in northeastern China. This suggests that the variability of NEI monsoon may also be related to climate drivers that force the reasons clustered along with it. Unlike most of India, NEI summer monsoon rainfall (NEISMR), over the JJAS season, is not correlated with the ENSO (Soraisam *et al.*, 2018). This can be attributed to its location being far beyond the Tropical Pacific and the anomalous divergence (convergence) fields at 850 hPa (200 hPa) induced by the El Niño (see Figure 4b of Webster *et al.*, 1998). The Indian Ocean and northern Bay of Bengal (BoB) are claimed to be moisture sources for the summer rains over NEI (Breitenbach *et al.*, 2010).

Paleo-research has been useful to determine whether the projected climate changes are unprecedented, and also helps us in attribution studies. Paleo-records help us to ascertain whether changes in the association of two climate phenomena seen from the current observations of a limited span of 130–150 years, such as the ISM and ENSO, for example, is just statistical sampling. The last millennium (LM; CE 850–1850) period has been the best-documented era prior to modern-observations.

The LM can be compared to the climate of the recent 'historical period (1850 onwards)', given the similar orbital parameters; however, there have been sunspot activity and solar irradiance changes (e.g., IPCC, 2013). In many regions over the globe, the period is marked by two strong and well-recognized climate regimes the Medieval Climate Anomaly (MCA; CE 950–1250)—which is also known as the Medieval Warm Period, and Little Ice Age (LIA; CE 1400–1850). Past-climate simulations, supported by various proxy-observations (Sinha, *et al.*, 2007; Sanwal *et al.*, 2013; Polanski *et al.*, 2014; Dixit and Tandon, 2016; Rehfeld and Laepple, 2016) suggest that during the MCA, large continental-scale regions could have been as warm as temperatures observed during the first half of the 20th century, prior to the exacerbation of the anthropogenic contribution. These climate-regimes are also distinct from the radiative forcing in the sense that the LIA is marked by volcanic-induced aerosols, while at least part of the MCA experienced little of such forcing, and a relatively constant solar

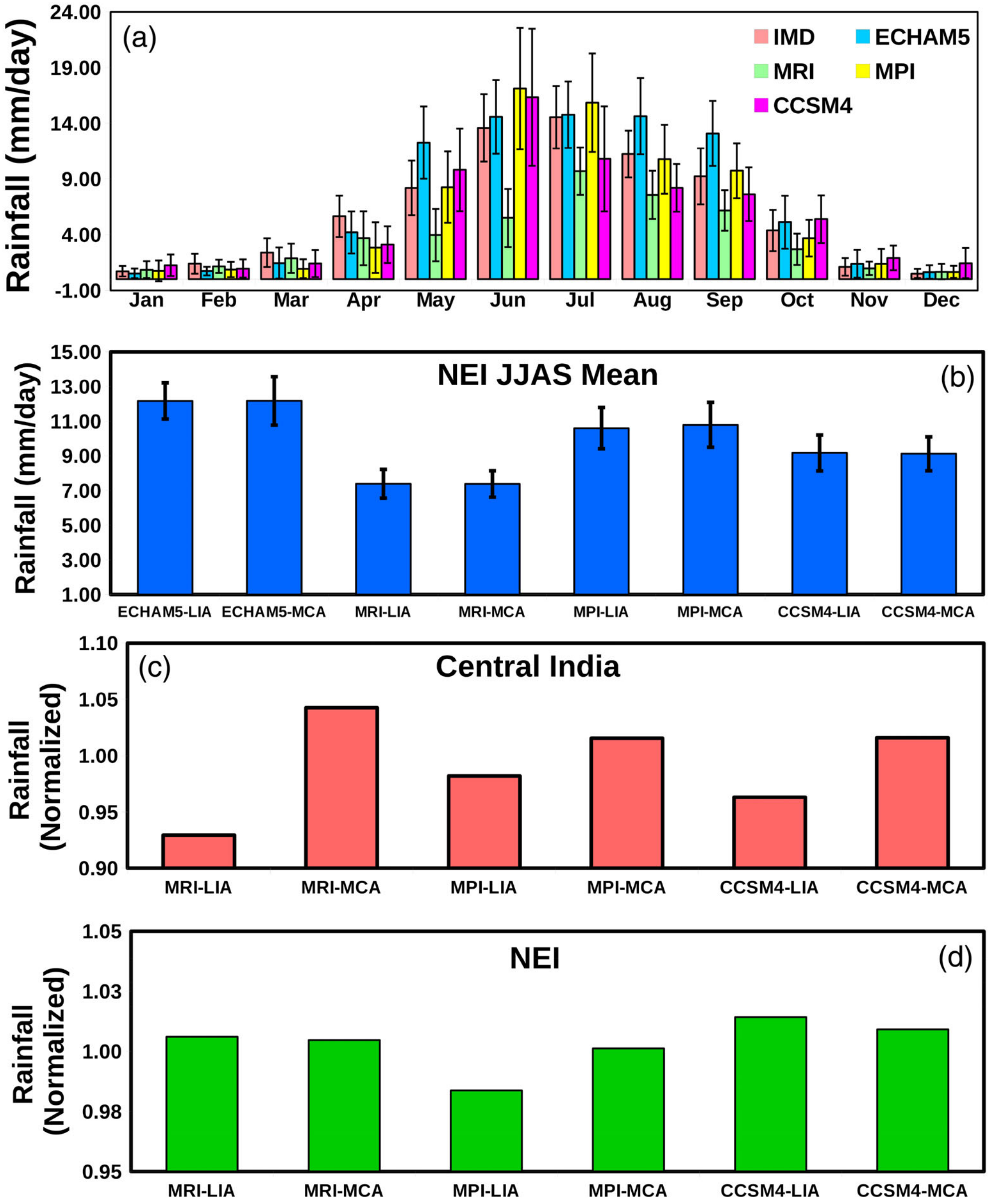

FIGURE 2 (a) Annual cycle of observed area-averaged NEI rainfall (mm·day^{-1}) for the period 1961 to 1990, and those from the historical simulations of three PMIP3 models of CCSM4, MRI, MPI, and that of ECHAM5 model (b) area-averaged climatological NEI precipitation during JJAS season for MCA period (defined as 935 CE to 1,034 CE for PMIP3 models, and 935 CE to 964 CE for ECHAM5) and LIA (1,735–1,834 CE for PMIP3 models, and 1,735–1764 CE for ECHAM5) (c) simulated normalized area-averaged JJAS precipitation over central monsoon (Central India) region for the aforementioned 100 years of MCA by the PMIP3 models, and those from 100 years of LIA, and (d) same as (c) but for northeastern India. The normalization of the rainfall has been performed by dividing the simulated climatological rainfall of MCA (100 years) or LIA (100 years) by the total simulated climatological rainfall (1,000 years) available from PMIP3 models

forcing, indicating 'a quiet period of relatively little forcing' (Neukom *et al.*, 2015). A few recent studies suggest that a relatively strengthened Asian summer monsoon during the MCA compared to the LIA is likely associated with larger-scale land-sea temperature contrasts (Man *et al.*, 2012; Shi, 2016; Shi *et al.*, 2016). However, while many PMIP3 simulations also suggest a relatively wetter MCA (Tejavath *et al.*, 2019), many of these models do not indicate a significant difference in the meridional land-sea temperature contrast between the Indian landmass and the Indian Ocean to its south. A subsequent study using atmospheric general circulation model simulations by Tejavath *et al.* (2021) also show relatively wetter MCA compared to LIA.

A modelling study by Fallah and Cubasch (2015) shows that Asian mega droughts during the LM are mostly linked with the El Niño-events, which is in agreement with a proxy-reconstruction study by Cook *et al.* (2010). A study by Tejavath *et al.* (2019), through an analysing nine multi-model PMIP3 simulations, also suggests confirms that ENSO-ISMR correlations are statistically significant throughout LM, similar to the present-day observations. Interestingly, the study by Tejavath *et al.* (2019) shows a higher number of strong El Niños relative to La Niñas during the MCA, and vice versa during the LIA. Notwithstanding that, the simulated Indian summer monsoon climate was relatively warm and wet during the MCA and cold and dry during the LIA. According to Changes in simulated divergence/convergence patterns in the Indian monsoon region in congruence with multi-centennial east–west shifts in the Walker circulation over the tropical Indo-pacific result in an apparent reduction of the ENSO impacts on the ISMR by virtue of their signatures that are opposite to that of the El Niño events dominant during MCA and La Niñas during LIA. Another multi-model study by Yang *et al.* (2020) shows strong ISM during the MWP is due to the accelerated eastward propagation of low-level moist westerlies across India. A study by Polanski *et al.* (2014) shows thermal gradients between the BoB and the Indian subcontinent drives the majority of the summer monsoon rainfall over NEI during the LM. A multi-model study by Kamae *et al.* (2017) shows more summer monsoon insolation during the MCA compared to LIA over the Indian subcontinent and NEI. Although the variability of ISMR during the LM has been is now being studied using models, no studies, including those mentioned above, on the NEI particularly from the modelling perspective.

Figure S1a depicts the annual cycle of the monthly rainfall over the NEI and that over the Central Indian region. It is clear that the summer monsoon rainfall over the NEI is higher than that over the central Indian region. Figure S1b suggests an insignificant trend, based on a two-tailed Student's *t*-tailed test, in the area-averaged summer monsoon rainfall over the NEI as well as that for the Central India for the 1960–1990 period. The insignificant trend over the NEI is in conformation with the statistically insignificant trend in the area-averaged NEISMR for the 1970–2005 period (Soraisam *et al.*, 2018). The result is also corroborated by the insignificant trend in the annual rainfall area-averaged over the NEI for the same period (Dash *et al.*, 2012). However, several other regions in India for which a relatively well-sampled station observations are available, record decreasing summer monsoon rainfall since 1950s (e.g., Dash *et al.*, 2011; Mishra *et al.*, 2012; Guhathakurta *et al.*, 2015; Krishnan *et al.*, 2016). Furthermore, while studies such as Goswami *et al.* (2006) suggest an increase in the extreme rainfall events over central India), the extreme rainfall events in NEI are decreasing in the last few decades (Goswami *et al.*, 2010). The topography of the region, and its distance from Central India, may be reasons behind such discrepancies. Whether climate variability in NEI may be distinct from that over other regions of India in the past will be interesting, as the region has the highest density of biodiversity.

Importantly, majority of proxy-studies for NEI are based on local records of vegetation samples. Interestingly, the evolution of climate during the LM in the NEI may also have been subject to local topography, among other factors, as shown in a review by Mehrotra *et al.* (2014). Mehrotra *et al.* (2014) emphasize the spatial-diversity in the climate evolution in the NEI during the MCA and LIA. Even a 1°–2° difference seems to matter owing to the topography. For example, some of these palynological studies suggest warmer and humid conditions during MCA and moderately humid LIA in the sampled locations of the NEI (Chauhan and Mandaokar, 2006; Bhattacharyya *et al.*, 2007; Nautiyal and Chauhan, 2009; Basumatary and Bera, 2010; Tripathi *et al.*, 2017); the authors attribute these changes to vagaries in monsoon. In contrast, a weakening of the Southwest Monsoon since 900 BP in lower Assam (Dixit and Bera, 2012), and a generally cold-dry to cold-moist oscillation of climate in the highland state of Sikkim, concurrent with the global LIA and MCA signals (Sharma and Chauhan, 1999) have been suggested. Further north between 27° and 28° N, warm and moist conditions from 2,500 BP till today are indicated (Sharma and Chauhan, 2001; Bhattacharyya *et al.*, 2007). Mehrotra *et al.* (2014) call for a 'need to create a definite terminology and/or quantify a spatio-temporal scale for future studies on paleo-vegetation-based paleoclimate records'.

In addition, Agrawal *et al.* (2012)'s analysis of a sedimentary section from Arunachal Pradesh in the north-east Himalaya indicates a stable climatic condition during 1,200 years BP to present. A speleothem record from the Wah-Shikar cave record (Gupta *et al.*, 2019) indicates a relatively wet condition during MCA and mixed conditions and even mega-floods during the LIA. These studies suggest that the climate across NEI throughout the LM may have been uniform, unlike other Indian regions.

Past-climate simulations provide valuable information in complementing findings from proxy observations, and hopefully reconcile with some of these paleo-observations, thereby leading to a more cohesive conclusion. They help in deciphering potential background dynamical mechanisms. With this aim, we analyse outputs from multiple coupled-model simulations under the PMIP3 protocol, as described in Section 2. In Section 3, we analyse the results from the model, compare them with the proxy data and investigate the associated dynamics. In Section 4, we present our conclusions.

2 | DATASETS USED AND METHODOLOGY

We use datasets for the MCA (935–1,034 CE) and LIA (1735–1834 CE) periods from LM simulations of three PMIP3 models—the Community CCSM4 (CCSM4), MRI-CGCM3 (MRI) and MPI-ESM-P (MPI). These periods have been chosen so that the initial years of these epochs are compatible with those of the time-slice experiments of the ECHAM5 simulations, described later, whose outputs are also analysed. The CCSM4, MRI and MPI models' atmospheric component resolutions (Latitude × Longitude × Vertical levels) are 288 × 192 × L26, 320 × 160 × L48, and 196 × 98 × L47, respectively. The PMIP3 is an initiative by the World Climate

Research Programme (WRCP); JSC/CLIVAR working group on coupled models and the International Geosphere and Biosphere Programme (IGBP; PAGES) (Braconnot *et al.*, 2012). The resolutions of these three models are higher than many other PMIP3 models, and therefore, potentially better-suited to capture NEI climate, which, owing to the large variations in the vegetation and topography, shows a high spatial variability (Mohapatra *et al.*, 2011; Das and Siddique, 2012). Furthermore, these models capture the evolution of the Indian summer monsoon during the historical period well, and the simulated LM evolution is in agreement with that of a majority of the models (Tejavath *et al.*, 2019). These models also differ in their representation of the historical temperature/precipitation scaling over South Asia (Rehfeld and Laepple, 2016), spanning a certain range of dynamical behaviour. We ensured that the results are insensitive to change in the definition of the MCA and LIA periods by analysing the simulations for the slightly different periods we followed in Tejavath *et al.* (2019) (figures not shown).

We validate the corresponding historical simulations of the models by comparing the simulated mean seasonal rainfall statistics over NEI, for the 'present day'—that is, 1961–1990. For this, we use these CMIP5 historical data and the rain gauge-based gridded rainfall data at 1° × 1° resolution from the India Meteorological Department (IMD; Rajeevan *et al.*, 2005). Any model that simulates relevant climate statistics such as the present day is also expected to reasonably simulate the last millennium climate as well (e.g., Tejavath *et al.*, 2019), given that the orbital parameters were not much different, and the feedbacks associated with anthropogenic aerosols and greenhouse gases were minimal. We also perform an analysis of the 30-year time-slice simulations for the MCA and LIA, carried out at the Max Planck Institute for Meteorology (MPIM) Germany, using the ECHAM5 atmospheric general circulation model (AGCM) with T106 (~1.125° × 1.125°) horizontal resolution (Roeckner, *et al.*, 2003). The SST and sea-ice cover distribution from the transient coupled simulations, of the ECHO-G model (Wagner *et al.*, 2007) are prescribed for time-slice experiments with the ECHAM5 model; other forcings (GHGs, Solar constant values, orbital parameters) are identical to the ECHO-G model set up. The higher resolution of the ECHAM5 model improves the representation of the hydrological cycle, which is important for our analysis; the model; however, tends to overestimate precipitation at steep orographic slopes (Hagemann *et al.*, 2006). As the atmospheric component of the MPI-ESM is the ECHAM5 model, a comparison of the MPI outputs with the ECHAM5 atmospheric-only simulation will delineate the importance of the tropical coupled oceanic processes—or the lack thereof—for NEI. Note that the ECHAM5 simulations are available only for 30 years each, that is, MCA spans from 935–965 CE and LIA from 1735–1765 CE.

For consistency with the observed rainfall data sets, all the simulated data sets are regridded to 1° × 1° resolutions. Keeping the continuity of the weather regardless of the geographic boundaries, following Soraisam *et al.* (2018), NEI domain has been chosen as a rectangular region bounded by 89.5°E through 98.5°E and 21.5°N through 29.5°N (Figure 1b).

The moisture flux convergence has been computed as the sum of moisture convergence and advection. We use the well-known NINO3 index, obtained by area-averaging the SST anomalies over the 5°S to 5°N and 150° to 90°W, to represent the ENSO variability. We employ the linear

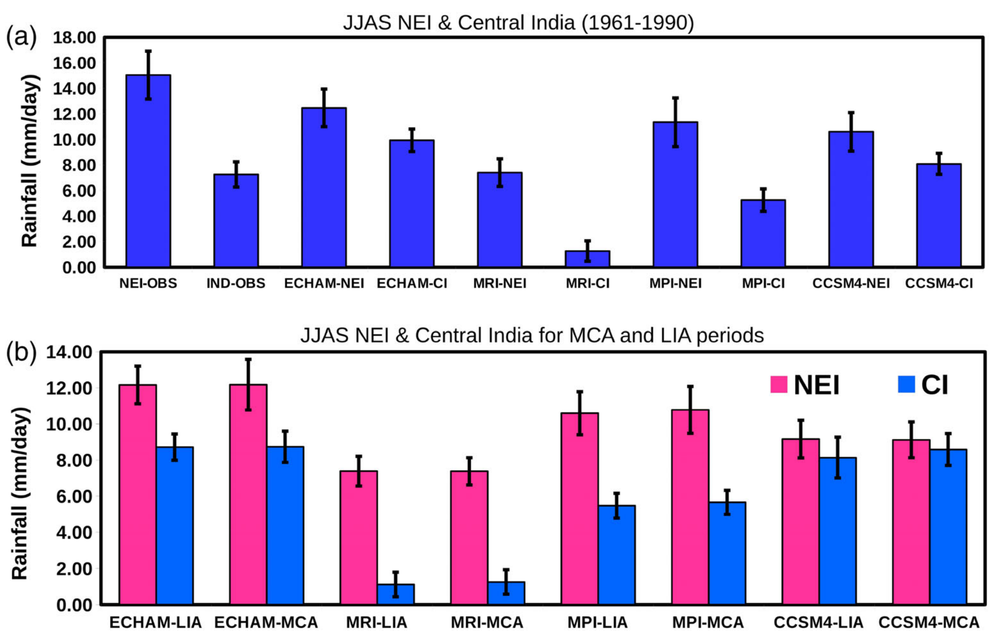

FIGURE 3 (a) Area-averaged climatological JJAS precipitation over northeastern India for the 1961–1990 period simulated by the ECHAM model and three PMIP3 models. (b) Area-averaged climatological JJAS precipitation over Central India for 100 years of MCA and LIA simulated by the PMIP3 models. Here NEI – Northeast India, IND – Central IndiaError bars are also shown anomaly correlation analysis. Statistical significance for correlations, and that for difference of means, is evaluated using the corresponding two-tailed Student's *t*-tests. The normalized mean summer rainfall in MCA or LIA, for each model has been obtained by dividing the corresponding simulated mean summer rainfall in MCA or LIA by the sum of that over MCA and LIA.

3 | RESULTS

3.1 | Simulated seasonal rainfall and circulation across NEI during the MCA and LIA

The simulated area-averaged monthly mean rainfall over NEI for the present-day period (1960–1990) from the three CGCMs and the ECHAM AGCM (Figure 2a) suggests that the evolution of the simulated seasonal cycle of the rainfall conform well to the observations. In general, the magnitude of the simulated monthly area-averaged rainfall is comparable to that from the observations, although the one simulated by the MRI model is smaller than in the observations, particularly for May and June. A similar inference can be drawn from the mean simulated monsoon rainfall for the above period (Figure 3a). The magnitude of the ECHAM5 simulation for the JJAS season is realistic, suggesting that tropical ocean–atmosphere coupling may not be a major driver of the NEI climate. Notably, the summer monsoon rainfall from the ECHAM peaks later in the year relative to the observations and other models. The highest magnitude of area-averaged NEISMR is simulated by the ECHAM AGCM in both regimes, closely followed by the MPI model (Figure 2b). We should, however, be mindful of the relatively-short span of the ECHAM5 simulations. All the further analysis will only involve the PMIP3 models.

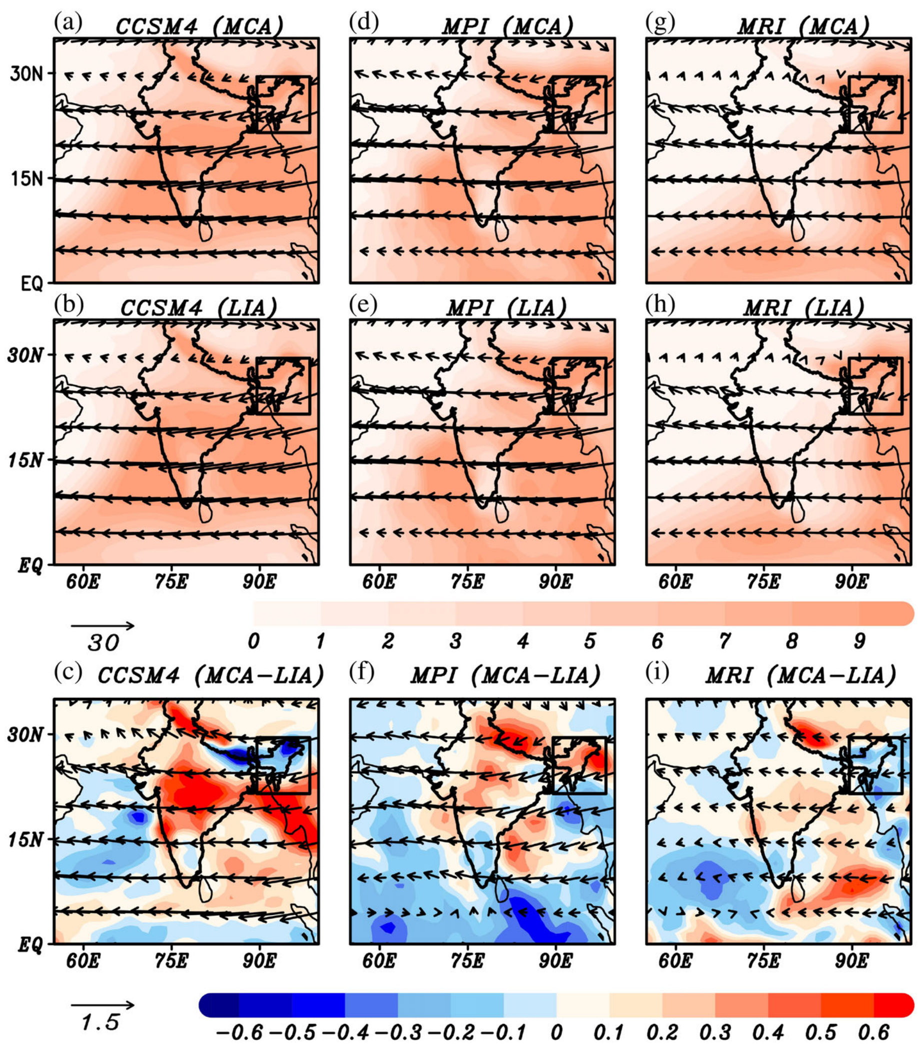

FIGURE 4 Panels (a), (d), and (g) show climatological precipitation (mm·day^{-1}) and 100 hPa wind circulation (m·s^{-1}) during JJAS season during MCA as simulated by three PMIP3 climate models. Panels (b), (e) and (h): Same as panels (a), (d) and (g) but for the LIA period (1,735–1834 CE). Panels (c), (f) and (i) show the climatological differences between MCA and LIA for the models. Northeastern Indian region is marked by a black box

The simulated normalized summer monsoon rainfall area-averaged over the central/core-monsoon region (74.5°–86.5°E and 16.5°–26.5°N, following Goswami *et al.*, 2006; henceforth, CMR) from the MCA to LIA is presented in Figure 2c, with actual climatological values in Figure 3b. The simulated CMR decreases by 6% to 11%, from MCA to LIA (Figure 2c). The difference of the simulated rainfall between the MCA and LIA by the CCSM4 and MPI models (Figure 3b) is statistically significant at 90% confidence level, and for the MRI, significant at 85% confidence level. This conforms to the results from nine PMIP3 models by Tejavath *et al.* (2019), which show that the summer monsoon rainfall over India decreased from the MCA to LIA, in agreement with several proxy studies (e.g., Yadava and Ramesh, 2005; Sinha, *et al.*, 2007; Dixit and Tandon, 2016). The difference from the ECHAM model is not statistically significant.

The corresponding normalized area-averaged NEISMR for the MCA and LIA from each PMIP3 model is presented in Figure 2d. Contrary to the CMR, difference (to be sure, only about 2%) between the simulated summer NEISMR between the MCA and LIA across all models is statistically insignificant. It is also to be noted that the simulated area-averaged mean seasonal rainfall over NEI for the present-day period from each model is not significantly different from the rainfall during the MCA or the LIA (Figure 3b), indicating that the NEI region has been insensitive to centennial changes in the forcing. The response of the models is unequivocal.

The interannual *SD* of the NEISMR for the present day, as seen from the IMD rainfall datasets, is higher than that for the CMR (see Table S1). This is also well-simulated, although the simulated standard deviations are weaker than the observations. Interestingly, unlike the mean rainfall, the standard deviations of the NEISMR show relatively higher inter-epochal variations as compared to those for the CMR.

All the three models simulate the tropical easterly Jet stream (TEJ) over the Peninsular India, associated with the Tibetan High (Figures 4c, f and i), qualitatively similar to is present-day observations (figure not shown). The simulations point to a stronger TEJ during the MCA relative to the LIA (Figures 4, f and i), which is normally

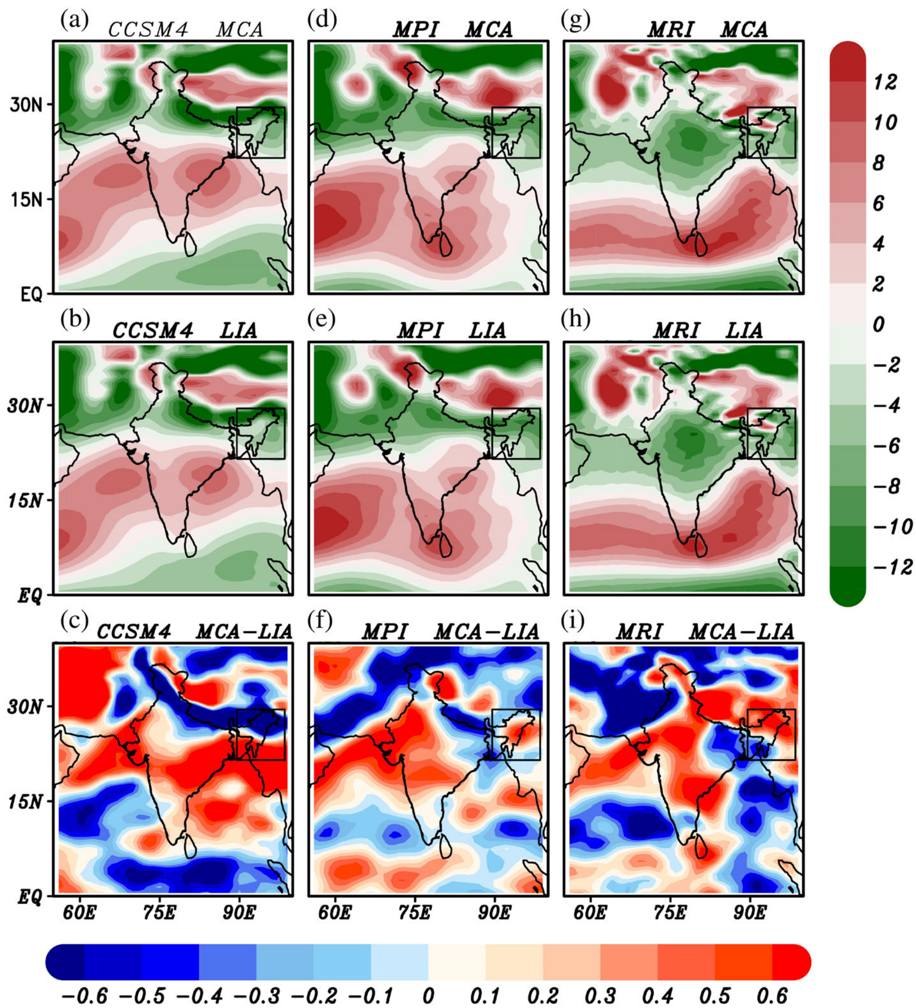

FIGURE 5 Same as Figure 4, but with simulated climatological 500 hPa relative vorticity (X $10^{-5}S^{-1}$) instead of 100 hPa circulation

associated with a high summer monsoon rainfall over the central-Indian region. The spatial distribution of the summer rainfall difference from MCA to LIA (MCA-LIA) over the NEI is positive in MPI simulations (Figure 4f) while they are negative in other two models (Figure 4c and g). However, we should be mindful of the earlier discussion that, the difference when area-averaged and normalized, is weak, and insignificant over the NEI (Figure 2d), unlike over Central India (Figure 2c)

3.2 | TEJ changes and impacts on the ISMR

The analysis of the PMIP3 simulations by Tejavath *et al*. (2019) suggests that a centennial westward shift of the overturning Walker Circulation in the tropical Indo-pacific could be a potential reason for the relatively high ISMR during the MCA. This, however, does not preclude any other large scale circulation changes, which may manifest an increase in the ISMR during the MCA.

Tropical dynamics suggest that the presence of the entrance of TEJ over the BoB facilitates strong convection over BoB and neighbouring coastal regions of India. Briefly, the TEJ originates over the Western Pacific and BoB. Quasi-geostrophic dynamics Section (9.5.2 of Hoskins and Wang, 2006) suggest that the westward intensification of easterlies in the TEJ over the BoB and adjoining Indian region results in an ageostrophic convergence and upward motion at the mid-troposphere, and consequently, enhanced rainfall. We find an increase in the simulated 500 hPa relative vorticity (Figures 5a-h) on the central east coast of India, particularly near to the Head BoB and/or over the neighbouring Indian region, where we see a higher summer monsoon rainfall during MCA (Figures 4c, f and i). While the difference in relative vorticity over NEI looks high in Figure 5c, this is just due to its strong climatological magnitude (e.g., Figures 5a,b). The differences in the area-averaged 500 hPa vorticity (Figure 6) confirm that the simulated circulation changes are relatively weak over the NEI relative to CMR in all models, considerably so in two. This suggests that the strengthened TEJ during the MCA is a factor for the enhanced rainfall over the CMR during the MCA. This change in simulated TEJ during the MCA, however, does not affect NEISMR. This may be because the NEI is farther from a moisture source such as Head BoB region, relative to, say, the east coast peninsular India. Indeed, the simulated mid-level moisture flux convergence changes into NEI between MCA and LIA (Figure 7), unlike that into the east coastal Indian region and/or around the Head BoB, is small.

3.3 | Association between the ENSO and NEISMR

Just as the present-day observations (Soraisam *et al*., 2018), the simulated rainfall over NEISMR during both MCA and LIA is insignificantly correlated at 95% confidence level with the NINO3 index (area-averaged sea surface anomalies over 5° S–5° N and 150° –90° W; Figure 8). We have also ascertained that the correlations do not turn significant even if we use the NINO3.4 index, which reflects the activities of both canonical and Modoki ENSOs (Ashok *et al*., 2007; Weng *et al*., 2007).

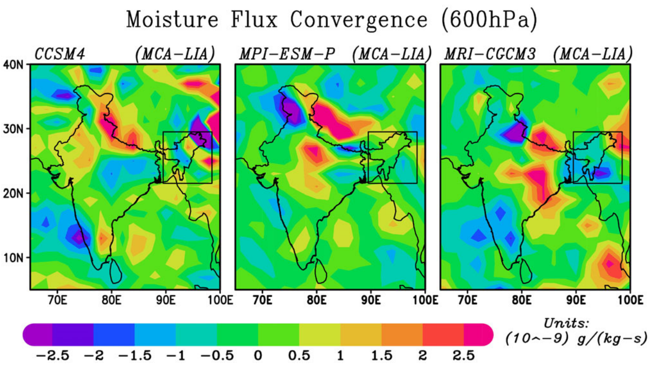

FIGURE 7 Distributions of simulated 600 hPa differences between MCA and LIA in the time-averaged JJAS moisture flux convergence (10^{-8} g/(kg-s)

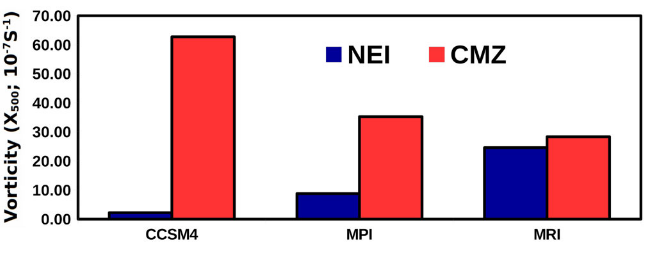

FIGURE 6 Area-averaged differences in simulated mean JJAS 500 hPa vorticity (MCA and LIA) for the three PMIP3 models

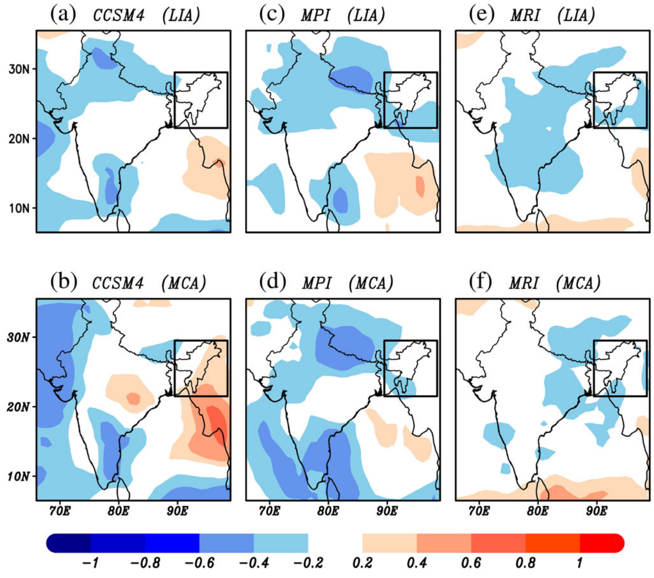

FIGURE 8 Spatial distribution of correlations between the $NINO_3$ index and local precipitation during JJAS season for the LIA (top panels) and MCA (bottom panels) simulated by the three PMIP3 models

4 | SUMMARY

Several proxy-based studies, and a recent analysis of nine PMIP3 model outputs (Tejavath *et al*., 2019), show that the ISMR during the MCA was relatively higher than that during the LIA. Tejavath *et al*. (2019) also show a significant negative association between ENSOs and the Indian summer monsoon rainfall (ISMR), which; however, seems to be subject to modulations by centennial large-scale overturning circulation changes in the tropical Indo-Pacific. Several studies based on rain-gauge observations point out that Northeastern Indian summer monsoon rainfall (NEISMR), in general, does not vary synchronously with the summer monsoon rains over the rest of the Indian region, although there have been indications from some proxy studies of such covariability during LM in some pockets. In this paper, using the MCA and LIA simulations from three coupled models (CCSM4, MRI-CGCM3 and MPI-ESM-P), we find that, unlike the rest of India, the NEISMR differences over NEI from the MCA to LIA are as low as 2% and also small compared to present-day conditions. The model simulations show that the NEI summer monsoon rainfall is insensitive towards changes in the forcing during the last millennium, and on centennial timescale, decoupled from the response of the rest of India. These results broadly agree with some proxy data-based studies such as Agrawal *et al*. (2012), Gupta *et al*. (2019), Sharma and Chauhan (2001), Bhattacharyya *et al*. (2007).

All the simulations indicate a strengthening of the tropical easterly jet (TEJ) at 100 hPa during the MCA relative to the LIA. This results in anomalous convergence over the North BoB, and an enhancement of monsoonal rainfall along the CMR. The mechanism can be explained by the classical theory of how the TEJ affects the precipitation (Hoskins and Wang, 2006). The analysis also shows that ENSO, in all periods, hardly has an impact on the NEISMR. Also, the mechanisms that potentially play a role in the warm and wet MCA, and cold and dry LIA over the major Indian regions -the multi-centennial tropical Indo-pacific Walker circulation that affects the ENSO impacts on India (Tejavath *et al*., 2019), and changes associated with the TEJ - do not seem to influence the NEISMR, at least in our PMIP3 results. That is why it's almost constant magnitude from MCA through the LIA.

Incidentally, a recent model study by Ratna *et al*. (2019) indicates some changes in the temperatures in the East Asia through the last millennium, which may have been driven by the external factors. In light of this as well as our results, it is possible that NEI is a spatial node from the context of centennial climate variability.

Our model results are in qualitative agreement with the results from several proxy data-based studies such as Agrawal *et al*. (2012), Gupta *et al*. (2019), Sharma and Chauhan (2001), Bhattacharyya *et al*. (2007). It will of course be imperative to diagnose the reasons behind the disagreement between the models and a few proxy studies in NEI. Given the high spatial variability of the climate across the NEI, Among other things, it needs higher resolution paleosimulations. Notwithstanding it, an immediate implication, when the synergy of the models with observations for the current day period are concerned (also see Soraisam *et al*., 2018), is that future climate change over NEI may not necessarily be like that over the other regions of India.

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AUTHOR CONTRIBUTIONS

Ashok Karumuri: Conceptualization; methodology; project administration; supervision; writing - original draft; writing-review & editing. **Bidyabati Soraisam:** Formal analysis; methodology; validation; visualization; writing - original draft; writing-review & editing. **Charan Teja Tejavath:** Methodology; resources; visualization; writing - original draft; writing-review & editing. **Ulrich Cubasch:** writing - original draft; writing-review & editing.

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