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Key Points:

- Observations show a significant change in La Niña seasonal rainfall over South Asia after 1980
- Central Indian rainfall reduction during post-1980 La Niñas is attributed to tropical Pacific SST changes and tropical Indian Ocean warming
- ISM rainfall over central India during La Niña years likely to decline further with increasing tropical Indian Ocean warming

Supporting Information:

- Supporting Information S1

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La Niña's Diminishing Fingerprint on the Central Indian Summer Monsoon

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Abstract La Niña years tend to provide increased Indian summer monsoon (ISM) rainfall. However, observations show 6–8% reduction in ISM rainfall during post-1980 La Niñas relative to pre-1980. Using a suite of atmospheric general circulation model experiments, we replicate this observed phenomenon and attribute it to a combination of weakening La Niña events themselves plus strongly warming tropical Indian Ocean. We demonstrate that half of the ISM rainfall reduction during post-1980 La Niñas can be attributed to changes in the spatial pattern and intensity of La Niña within the tropical Pacific Ocean. Warmer eastern-equatorial Pacific Ocean temperatures during post-1980 La Niñas weaken the Walker circulation, resulting in large-scale anomalous subsidence over the Indian subcontinent, thereby inhibiting the deep convection that drives ISM rainfall. Further, we demonstrate the declining central ISM rainfall during La Niña years with increasing tropical Indian Ocean warming, which has several serious concerns for regional water resources and stability.

Plain Language Summary Historically, wetter conditions of Indian summer monsoon (ISM) during June to September of La Niña years are important for water resources in particular groundwater recharge. Observations from recent decades, however, show a reduction of 6–8% in ISM rainfall during post-1980 La Niñas relative to pre-1980 La Niñas, which is a serious concern for regional water resources and stability particularly if the trend continues. Using a suite of atmospheric model experiments, we replicate this observed phenomenon and attribute it to weakening La Niña events combined with a strongly warming tropical Indian Ocean. Model simulations indicate that 50% reduction in ISM rainfall during post-1980 La Niñas can be attributed to changes in the spatial pattern and intensity within the tropical Pacific Ocean. The tropical Pacific east-west atmospheric circulation pattern (Walker circulation) is crucial for deep convection over the South Asian region. We show that warmer eastern equatorial Pacific Ocean temperatures during post-1980 La Niñas weaken the Walker circulation, resulting in inhibition of deep convection over the Indian subcontinent, thereby reducing ISM rainfall. Furthermore, we demonstrate that ISM rainfall over central India during La Niña years is likely to decline with increasing tropical Indian Ocean warming, which has several important implications for agriculture and economy of the Indian subcontinent.

1. Introduction

The Indian subcontinent is one of the world's most densely populated regions, with over one billion people dependent on the monsoon modulated environment for their livelihood (Singh et al., 2019). The Indian summer monsoon (ISM) rainfall provides 80% of the annual rainfall and strongly impacts the agriculture and economy of South Asia. Hence, changes in the ISM rainfall amount have far-reaching impacts on the region's surface and groundwater resources, agriculture, economy, and overall stability (Asoka et al., 2017).

The ISM is best considered as a regional land-atmosphere-ocean coupled system subject to local feedback as well as remote influences of different modes of global climate variability. The El Niño–Southern Oscillation (ENSO) is a dominant and highly consequential mode of climate variation on Earth, which is known to influence ISM variability on interannual time scale (e.g., Ropelewski & Halpert, 1987). ENSO's irregular swings between El Niño and La Niña result in global disruptions of seasonal weather patterns,

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agriculture, and ecosystems, including the ISM. The ISM is also subject to multiscale interactions within the tropical climate system. While remote factors of the ISM such as ENSO explain 40% variance of the ISM rainfall (Webster et al., 1998), local factors like the monsoon intraseasonal oscillation are further modulated by slowly varying forcing such as ENSO (e.g., Dwivedi et al., 2015). Generally, the ISM season strengthens (weakens) during the developing La Niña (El Niño) years compared to ENSO neutral years (Webster et al., 1998). ISM rainfall shows substantial spatial variability with the heaviest rainfall along the Western Ghats, northeast India, and over central India, where central Indian rainfall serves as a good indicator for the overall strength of ISM variability in synoptic, subseasonal, and interannual scales (Krishnamurthy & Shukla, 2008). Long-term trends in ISM rainfall characteristics over India have been studied extensively (Goswami et al., 2006; Singh et al., 2014). While a recent study using coral-based reconstructed data argued a multicentury trend of intensifying South Asian monsoon (Bryan et al., 2019), most of the observational studies suggest that the mean ISM rainfall, especially over central India, has reduced significantly over the second half of the twentieth century (Annamalai et al., 2013; Bollasina et al., 2011; Roxy et al., 2015), even projected to be shortened by the end of twenty-first century (Sabeerali & Ajayamohan, 2018). Recent studies argued that the reduction in the tropospheric thermal gradient associated with relatively strong and monotonic warming of the tropical Indian Ocean (IO) and simultaneous cooling over land weaken the ISM (Roxy et al., 2015). Yadav and Roxy (2019) pointed out warm eastern equatorial IO sea surface temperature (SST) for drying of north ISM rainfall in the last two decades. In contrast, several studies have attributed the weakening of the ISM to a combination of changes to land use land cover (Paul et al., 2016), to irrigation (Cook et al., 2015), and to anthropogenic aerosol concentration in the atmosphere (Bollasina et al., 2011). However, despite the role of land-atmosphere feedback associated with human activities, we aim to test the hypothesis that oceanic forcing spanning the tropics has a major role (Giannini et al., 2003) on the recent weakening in the ISM, particularly in the context of the expected increases in ISM rainfall during La Niña years.

Several studies have investigated changes in El Niño characteristics due to greenhouse warming (Cai et al., 2018; McPhaden et al., 2011; Yeh et al., 2018); however, less attention has been given in studying the La Niña-South Asian monsoon teleconnection changes. La Niña teleconnections are not a simple mirror image of El Niño teleconnections due to the asymmetry and nonlinearity of ENSO (An et al., 2007; Timmermann et al., 2018), and this has several important implications. Earlier research has suggested that the ENSO-ISM teleconnections have weakened in recent times (Feba et al., 2019; Krishnamurthy & Kirtman, 2003; Kumar et al., 1999). However, due to the paucity of long-term observational data, it remains unclear if the recent changes in ENSO, particularly changes in La Niña, are a part of centennial changes observed in the past (Tejavath et al., 2019). Nonetheless, we must know the details of La Niña changes and its teleconnections under greenhouse warming in recent decades, especially for the impact on ISM rainfall. Recent studies suggested that tropical IO SST experienced a warming trend in the boreal summer of 1977–2010 La Niñas, compared to 1958–1976 (Abish et al., 2018; Chowdary et al., 2006), which may be related to persistent warm anomalies from preceding strong El Niños. Aneesh and Sijikumar (2018) highlighted a significant reduction in ISM rainfall during post-1980 La Niñas compared to pre-1980 La Niñas. However, the response to any changes in background physical mechanisms over the tropical Pacific and its combined impact with tropical IO warming remain unexplored. Therefore, several key questions remain unanswered: how has the rainfall amount changed in recent La Niña years over the broader South Asian region in different seasons? What are the changes in background physical mechanisms for the recent changes in La Niña-ISM teleconnections? What are the individual and combined impact of the tropical Pacific changes and IO warming on South Asian rainfall during La Niña years?

These observations and unexplored questions mandate a shift in focus to La Niña. The historically wetter ISM during La Niña years plays a crucial role in replenishing soil moisture and groundwater, therefore, critical for agriculture and water resource sustainability. Much of the research is focused on the drought associated with El Niño years. But, a reduction in wet ISM rainfall is equally detrimental. On the other hand, ISM rainfall simulation skill using the state-of-the-art global climate models are critical to rainfall projections. However, such simulations remain challenging due to several stubborn systematic biases (e.g., dry bias over central India region; Samanta et al., 2018), the inability to capture emerging sources of predictability (e.g., central Pacific ENSO; Wang et al., 2015), and the lack of comprehensive understanding of ENSO-ISM teleconnection, especially La Niña-ISM teleconnection in recent decades. Therefore, it is critical to understand

the changes in background physical processes during recent La Niñas to better understand La Niña-ISM teleconnections and improve ISM simulation skill in climate models.

This study provides a quantitative and mechanistic understanding of the observed changes in seasonal South Asian rainfall, with a focus on the ISM, during post-1980 La Niña compared to pre-1980 La Niña conditions, using a set of observational data sets and an atmospheric general circulation model (AGCM). We also explore the combined impact of gradual increase in the tropical IO warming along with tropical Pacific SST changes on South Asian rainfall by applying up to 4 °C warming over the tropical IO in AGCM simulations. Our study reveals the likely impact of seasonal rainfall during La Niña years with increasing tropical IO warming.

2. Methods

We used monthly rainfall data from Climate Research Unit (CRU) TS4.01 (1950–2016; 0.25×0.25 ; http://data.ceda.ac.uk/badc/cru/data/cru_ts/cru_ts_4.01/data/pre/) and India Meteorological Department (IMD) RF0p25 data sets (1950–2016; Pai et al., 2014). Monthly SST data were used from ERSSTv5 (Huang et al., 2017; <https://www.esrl.noaa.gov/psd/data/gridded/data.noaa.ersst.v5.html>; 1950–2016). The La Niña years were selected based on the conventional approach; that is, if three-consecutive overlapping three-month SST anomalies over the Niño 3.4 region (170°W–120°W, 5°S–5°N) remains less than -0.5 °C, we considered the year as a La Niña year. Following NOAA, we adopted the time-varying 30-year base period (https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_change.shtml). Another approach of La Niña year selection based on seasonal SST anomalies (Gill et al., 2015) also shows similar rainfall reductions (Figure S1). Monthly air temperature, specific humidity, sea level pressure, and wind components were used from NCEP-NCAR reanalysis products (Kalnay et al., 1996). Monthly latent heat flux and 10-m wind were used from WHOI-OA flux products (1950–2016; <http://oafux.whoi.edu/data.html>). All the data sets were detrended before analysis. Earlier studies showed 1980 as a reasonable transition for ENSO-ISM teleconnection changes (Aneesh & Sijikumar, 2018; Kucharski & Abid, 2017). We, therefore, define the year 1980 as the threshold year. We considered all the developing La Niña years before 1980 and after 1980 as pre- and post-1980 La Niña years, respectively. Seasonal composite difference of the variables is calculated between post-1980 La Niña (1983, 1984, 1988, 1995, 1998, 1999, 2000, 2005, 2007, 2008, 2010, 2011, 2016) and pre-1980 La Niña (1954, 1955, 1964, 1970, 1971, 1973, 1974, 1975) years. We show seasonal climatological results only for La Niña years throughout (unless otherwise stated), for pre-monsoon (March–April–May or MAM), monsoon (June–July–August–September or JJAS), and post-monsoon (October–November–December or OND) season. The region 18°N–28°N, 72°E–85°E denotes central India.

2.1. AGCM Simulations

AGCM experiments were performed to examine the impact of pre-1980 and post-1980 La Niña conditions over the tropical Pacific on Indian rainfall. Further experiments were carried out to explore the role of tropical IO warming on ISM rainfall during La Niña years. The AGCM used in this study is ECHAM 4.6 (Roeckner et al., 1996) from the Max Plank Institute in Hamburg (HAM), a branch of the European Centre (EC) for Medium Range Weather Forecasts. We ran this model at T106 resolution ($\sim 1.125^\circ \times 1.125^\circ$) with 19 vertical levels and daily outputs were obtained. ECHAM 4.6 has been widely used to study atmospheric responses to tropical SST anomalies (Samanta et al., 2019; Zhang & Karanaskas, 2017).

The first set of experiment (set-1) was the control simulation forced by monthly SST climatology (1950–2016) everywhere at the lower boundary. Further, two sets of experiments (set-2 and set-3) were performed differing only in the prescribed monthly SST fields at the lower boundary. In set-2 and set-3 experiments, SST anomalies were added on top of monthly climatologies only over the area of interest, keeping the other regions as invariant (i.e., climatologies). The set-2 experiment consists of two experiments (Pre_Pac and Post_Pac) aiming to isolate the impact of tropical Pacific (30°S–30°N, 120°E–65°W) SST anomalies during pre- and post-1980 La Niña conditions. Composite pre-1980 La Niña and post-1980 La Niña SST anomalies were added over the tropical Pacific region for Pre_Pac and Post_Pac experiments, respectively. The set-3 experiments were designed to test the combined role of different levels of tropical IO (30°S–30°N, 20°E–120°E) warming with post-1980 La Niña conditions over the tropical Pacific. A warming level from 0.5 °C to 4 °C with steps of 0.5 °C was used over the tropical IO (Table S1). The experiments Postpac_IOxx

denote the set-3 experiments, where xx indicates warming level (in °C) on top of climatology. As we show differences in AGCM simulations, the rainfall bias in AGCM simulation is canceled out. A simple taper barrier with one half the magnitude of the SST anomaly instead of zero SST anomaly was used for reducing the possible impact of spurious SST gradients along the boundaries of prescribed anomalies/warming. Each AGCM experiment was integrated for 30 years and the first 5 years were discarded given that it takes a few years for this model to reach an equilibrium state with SST forcing (Samanta et al., 2019). We show seasonal climatology of 25 years. For consistency with the observational analysis, the SST forcing in AGCM simulations was also used from ERSSTv5 data.

3. Results

La Niña years generally are associated with abundant monsoon (JJAS) rainfall over the Indian subcontinent and over Southeast Asia during the post-monsoon (OND) season. However, instrumental rainfall observations from CRU of post-1980 La Niña (i.e., La Niña during 1981–2016) indicate significant changes in rainfall patterns during the three seasons (pre-monsoon or MAM, monsoon or JJAS, and post-monsoon or OND; Figures 1a–1c). During the pre-monsoon, an increase in observed rainfall over central and northeast India is seen, with a decrease in east China (Figure 1a). This increased pre-monsoon rainfall over India may be a consequence of increased pre-monsoon irrigation and increased vegetation over India (Lee et al., 2009). Consequently, increased pre-monsoon rainfall over India can lead to decreased land-sea thermal contrast and reduced monsoon rainfall. Of particular interest is the reduction in monsoon rainfall over central India that extends over northeast India during the monsoon season (Figure 1b). Over central India, the monsoon rainfall reduction is up to 2.4 mm/day (Figure 1b). This is equivalent to a reduction of 8% in central Indian rainfall during post-1980 La Niña ISM compared to pre-1980 La Niña (Figure 1b). We also note an increase in rainfall over south India and part of western Ghats during post-1980 La Niña. This observation is consistent with an earlier study focussing only on ISM rainfall reduction during 1980–2011 period La Niñas (Aneesh & Sijikumar, 2018). The monsoon rainfall reductions during post-1980 La Niña are also observed over parts of northeast Africa, and Yemen. While most parts of southeast Asia and northeast Africa experienced an increase in post-monsoon rainfall during post-1980 La Niña, the majority of India experienced reduced rainfall during the post-monsoon period (Figure 1c). For the middle-east Asia region, ENSO teleconnection is contrasting, and historically, the main rainy season post-monsoon receives reduced rainfall during La Niña years. Our results indicate further drying of the middle-east region during post-1980 La Niñas (Figure 1c). It may be related to changes in post-1980 IO SST and winter storm activity (Kamil et al., 2017). Consistent with CRU observations, IMD observational data set also documents similar changes (Figures 1d–1f) in rainfall patterns during post-1980 La Niña (up to 6% reduction in ISM rainfall), thereby confirming that the results are not just artifacts of data processing. Furthermore, these seasonal rainfall changes, particularly the reduction in ISM rainfall during post-1980 La Niña, are robust to the selection criteria of La Niña years (Figure S1). Results are consistent even after the exclusion of cooccurring Indian Ocean Dipole years (1975, 1998, and 2005, following Hameed, 2018; Figure S2) or stronger La Niña years (1973 and 1998; Figure S3).

Next, we consider whether or not these observed post-1980 La Niña rainfall changes are driven by post-1980 La Niña SST changes in the tropical Pacific. The tropical IO shows a rapid surface warming rate compared to the other basins of the world oceans; monsoon season SST indicates a long-term trend of up to 2 °C/century over the western IO since 1901 (Roxy et al., 2014). It is also observed that rapid eastern Pacific SST warming is highly correlated with the overall drying of central Indian rainfall during ISM (Roxy et al., 2014). After removing long-term trends our results suggest that during post-1980 La Niña tropical IO warming is almost uniform throughout the basin, which is more pronounced in monsoon and post-monsoon than in pre-monsoon (Figures 2a–2c and S4). However, mean eastern Pacific SST increases up to 0.8 °C (significant at a 95% confidence level) in all the seasons of post-1980 La Niña compared to pre-1980 La Niña (Figures 2a–2c). The anomalous post-1980 La Niña eastern Pacific SST warming and the weakening of zonal SST gradients over the tropical Pacific weaken the strength of tropical Pacific Walker circulation during post-1980 La Niñas (compared to pre-1980 La Niña) seen in the circulation composites at lower and upper levels (Figures 2 and S5). This is indicated by central Pacific La Niña or La Niña Modoki (Ashok et al., 2007) like wind patterns with a descending branch over central Pacific. The presence of an upper level anomalous cyclonic wind pattern over the Tibetan Plateau and west Asia and the lower level anticyclonic wind pattern

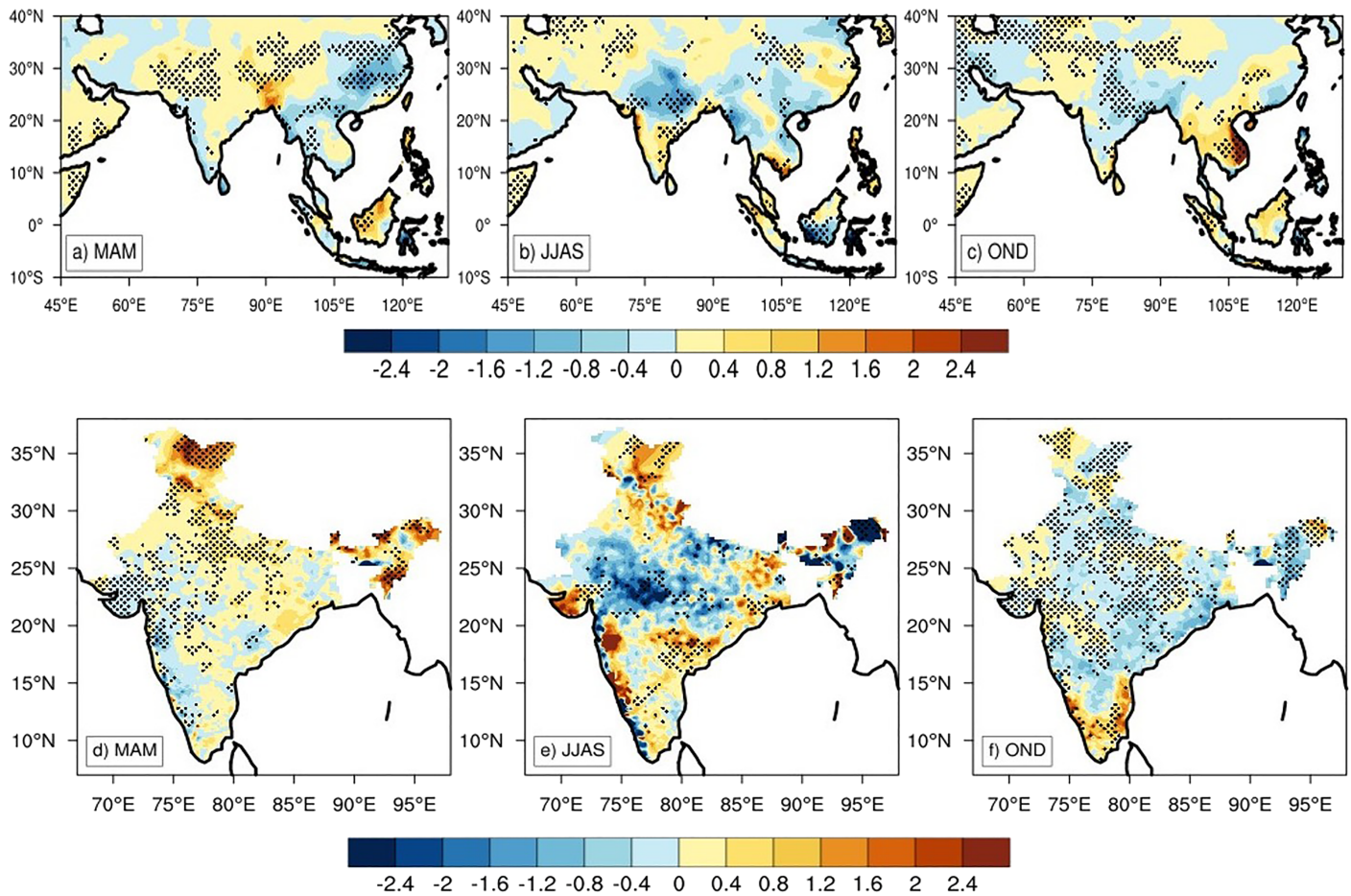


Figure 1. Composite seasonal rainfall changes (in mm/day) during La Niñas (post-1980 La Niña minus pre-1980 La Niña) from observations. Seasonal rainfall changes from (a–c) CRU observations and (d–f) IMD observations. Dotted regions indicate 95% confidence level. Seasons are mentioned in the legend. MAM=pre-monsoon, JJAS=monsoon, OND=post-monsoon.

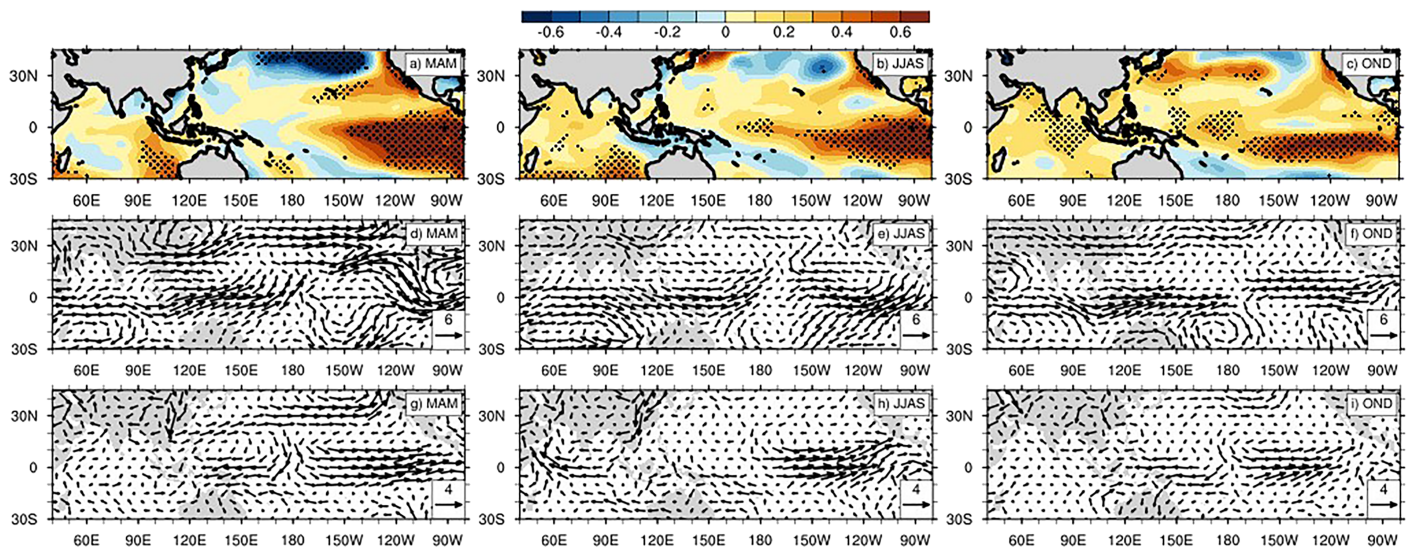


Figure 2. Composite seasonal sea surface temperature (SST; in °C) and large-scale wind pattern (in m/s) changes during La Niñas (post-1980 La Niña minus pre-1980 La Niña) from observations. (a–c) SST, (d–f) 200-hPa wind pattern, and (g–i) 850-hPa wind pattern. Dotted regions in (a)–(c) indicate 95% confidence level. Seasons are mentioned in the legend. MAM=pre-monsoon, JJAS=monsoon, OND=post-monsoon.

over the Arabian Sea during ISM indicate suppression of deep convection over the Indian subcontinent (Figures 2d–2f). Analysis of the zonal atmospheric circulation cell over the northern equatorial region (5°N – 15°N) and the equatorial region (5°S – 5°N) clearly suggests the reduction in convection over the Indian subcontinent and a La Niña Modoki-like changes in post-1980 La Niña period (Figure S5). The upper and lower level velocity potential differences also confirm the post-1980 Niña changes and reduction in ISM convection (Figure S6). Further analysis of post-1980 minus pre-1980 La Niña differences in surface wind speed, latent heat flux, sea level pressure, integrated vapor transport, and moist static energy (Figure S7) supports the reduction in ISM rainfall during post-1980 La Niñas. Midtropospheric drying and cold air intrusion is seen in air temperature anomalies over the Indian landmass during post-1980 La Niña (Figures S7j–S7l) may be related to the inhibition of deep convection (Samanta et al., 2013). All these changes clearly demonstrate the overall post-1980 La Niña changes in air-sea interaction processes and atmospheric circulation, implying weakening ISM convection and rainfall. These changes are also indicative of a La Niña Modoki-like patterns in post-1980 La Niñas and consistent with an earlier study (Cai et al., 2015) showing a weakening of La Niña Walker circulation under greenhouse warming.

Although the ISM region is far from the core convection associated with La Niña, the tropical wave dynamics (Rodwell & Hoskins, 1996) provides an atmospheric bridge which enables post-1980 La Niña changes to regulate ISM rainfall and duration by modulating tropospheric temperature gradient (Goswami & Xavier, 2005). Therefore, tropical wave dynamics provide an additional but a consistent explanation of post-1980 La Niña changes and associated weakening of Walker circulation. However, it is not straightforward to demonstrate the background physical processes accounting for these changes from such conceptual explanations based on observational analysis. Therefore, based on the above results, we hypothesize two background processes that play a key role in the changes of the post-1980 La Niña patterns: (1) the La Niña pattern and intensity itself changed in the tropical Pacific and (2) a weaker La Niña pattern and intensity over tropical Pacific combined with tropical IO warming results in drying of the ISM. These two hypotheses would not only constitute plausible explanations for post-1980 La Niña ISM rainfall reductions but also describe the strengthening (weakening) of Southeast Asian (middle-east) rainfall during the post-monsoon period, which has several important implications such as for agriculture and regional climate.

To evaluate these hypotheses, and rigorously establish causality, in addition to a control experiment (set-1), two sets of AGCM experiments (set-2 and set-3) are performed by forcing monthly SST anomaly intensity and patterns over the tropical Pacific Ocean and SST climatology elsewhere (Table S1). The control experiment can simulate observed rainfall climatology very well, including the orographic rainfall gradient over the western Ghats and northeast India during the monsoon season (Figure S8). The seasonal rainfall difference (Post_Pac minus Pre_Pac) pattern over India (Figures 3a–3c) is similar to that estimated from the instrumental observations shown in Figure 1, especially during the monsoon and post-monsoon season. Despite a little southward shift of reduced ISM rainfall zone (Figure 3b), set-2 experiment results support our first hypothesis that the changes in tropical Pacific SSTs during post-1980 La Niña weakens La Niñas; that is, warmer post-1980 La Niña SSTs (compared to pre-1980 La Niña) in the eastern Pacific (Figures 2a–2c) induce a reduction of ISM rainfall (Figures 3a–3c). This reduction is enabled via weakening in the strength of Walker circulation during post-1980 La Niñas (compared to pre-1980 La Niñas) by anomalous anticyclone at 850 hPa and corresponding circulation at 200 hPa (Figures 3d–3i) over the Indian region. The reduction in central Indian rainfall during post-1980 La Niña years is 4%, that is, half the reduction seen from the observations (Figure 1). This suggests that the La Niña changes in tropical Pacific account for over half of the reduction in ISM rainfall over central India.

We now turn our attention to the contribution of strong warming in the tropical IO. The 2°C warming scenario in set-3 experiments represents the overall long-term observed trend (Roxy et al., 2014), and the 3 – 4°C warming experiments mimic the future warming scenario. These experiments indicate that as basin-wide tropical IO warming increases from 0.5°C to 4°C , central Indian rainfall further decreases, with higher levels of reduction corresponding with increasing warming (Figure 4), which likely emerges a new competition between land-sea thermal contrast and Intertropical Convergence Zone movement (Figure S9). The SST patterns of set-3 experiments (Figure S10) closely match with the cluster-4 SST pattern of Sahastrabudhe et al. (2019) that likely is the contributor for reduced ISM rainfall over the Indian subcontinent in post-1980 La Niñas. As the central Indian rainfall decreases with warmer tropical IO, there is a corresponding exponential increase in rainfall over the eastern equatorial IO, indicating the oceanic dominance in the

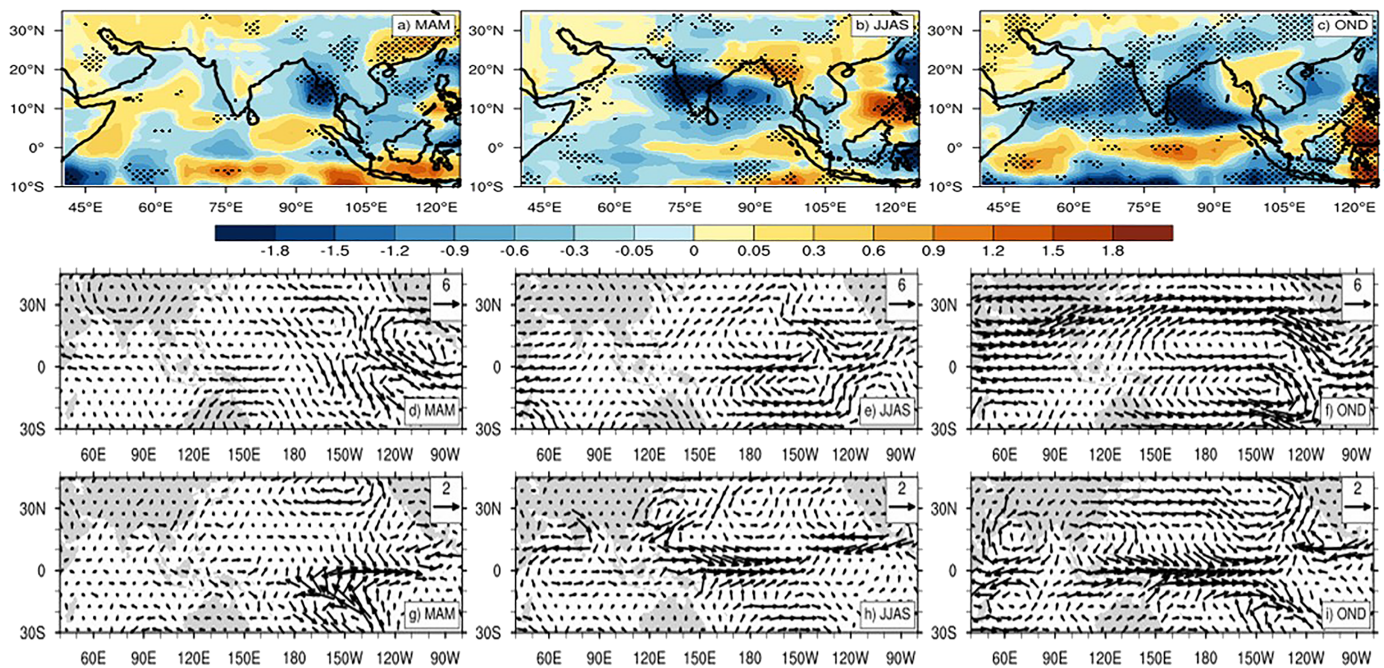


Figure 3. Impact of tropical Pacific sea surface temperature (SST) changes during La Niñas on seasonal rainfall (in mm/day) and wind pattern (in m/s) from AGCM simulations. (a–c) Seasonal rainfall changes (Post_Pac minus Pre_Pac). (d–f) The 200-hPa wind pattern changes (Post_Pac minus Pre_Pac). (g–i) Same as (d)–(f) but for 850-hPa wind pattern. Dotted regions in (a)–(c) indicate 90% confidence level. Seasons are mentioned in the legend. MAM=pre-monsoon, JJAS=monsoon, OND=post-monsoon.

competition between land and ocean for the rainfall (Figure S11). We found that the suppression of ISM rainfall over central India is up to 19% with 4 °C during La Niñas compared to pre-1980 La Niña condition. These intriguing results suggest that background changes in post-1980 La Niñas combined with warmer IO lead to suppression of rainfall over central India.

4. Discussion

La Niñas typically favor wetter summer monsoon over South Asia by strengthening the favorable Walker circulation teleconnection pattern. These frequent wet monsoon years are crucial for groundwater recharge, sustainable water resources, and agriculture. From an analysis of instrumental observations, we confirm a significant reduction in ISM rainfall over central India during post-1980 La Niñas. In recent decades (post-1980 La Niña), the ISM rainfall has declined by 8%, which has a significant impact on socioeconomic sectors. Through targeted AGCM experiments, we found that the warming of tropical IO along with a weakening of La Niña events causes ISM drying during post-1980 La Niñas. With these idealized simulations, we estimate that over 50% of ISM rainfall reduction over central India during post-1980 La Niña can be attributed to the weakening of La Niña pattern and intensity resulting in weaker east-west SST gradient over tropical Pacific and weaker Walker circulation, compared to pre-1980 La Niña. The remaining reduction is due to a combination of basin-wide warming in the tropical IO and tropical Pacific Ocean changes. In our experiments with post-1980 La Niña pattern in the tropical Pacific combined with increasing warming in the tropical IO (set-3), we found that weakening La Niña patterns can suppress ISM rainfall over central India (up to 19% reduction at 4 °C IO warming). The overall changes in tropical Pacific condition during post-1980 La Niña and shifting to La Niña Modoki-like patterns (i.e., central Pacific events) result in anomalous circulation patterns and drying of ISM. Crucial question for the climate community to resolve appear to be why are recent La Niñas weaker than pre-1980. While the focus of many recent studies has been on the connection between warming trend and El Niño events, investigating the La Niña patterns and its teleconnections are equally important.

One cannot neglect other potential factors for observed rainfall changes during post-1980 La Niña, such as the role of Pacific decadal oscillation (Krishnamurthy & Krishnamurthy, 2014), Atlantic zonal mode (Sabeerali et al., 2019), poleward shift of the jet stream over the north Atlantic (Chang et al., 2001),

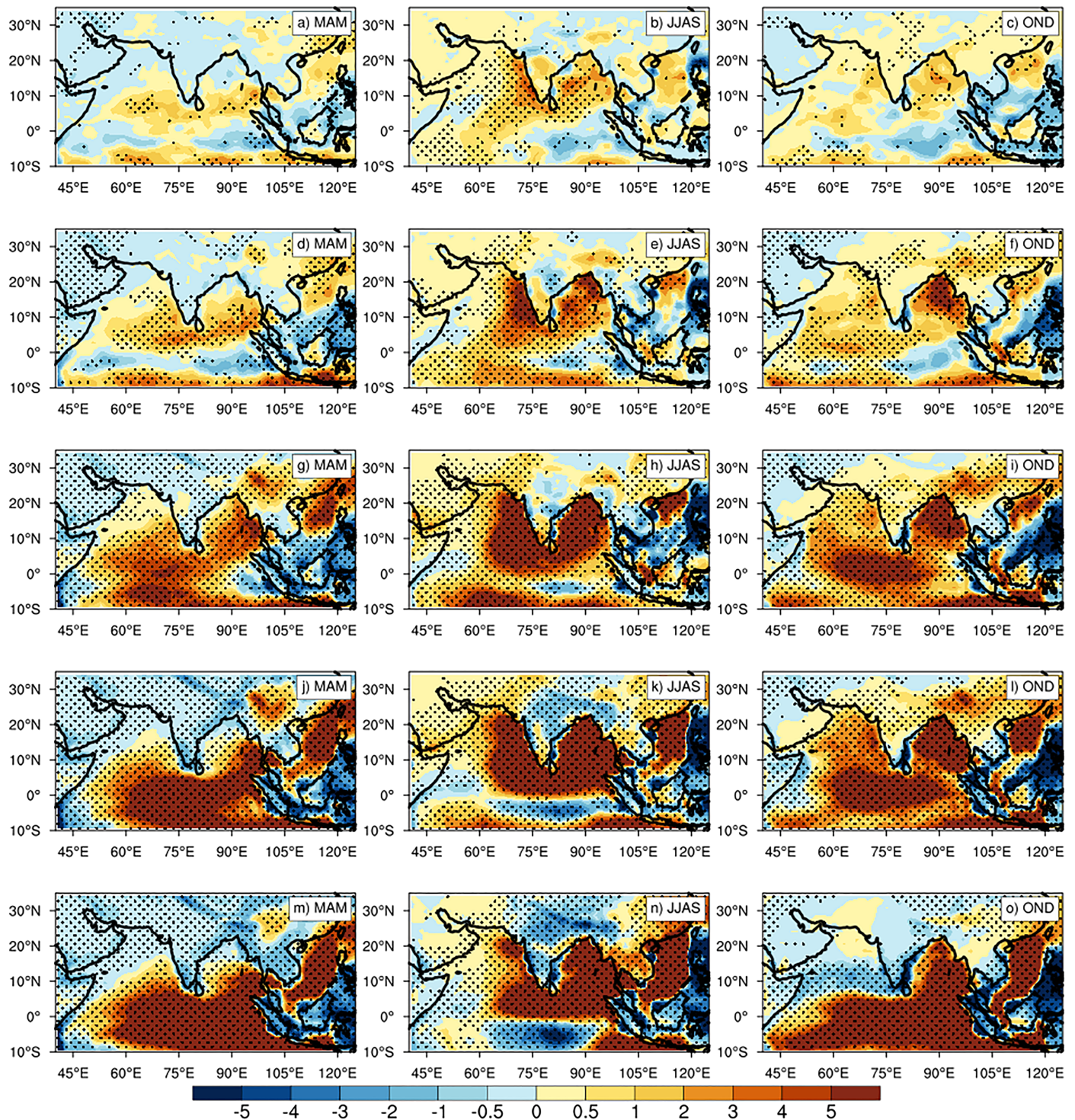


Figure 4. Combined impact of tropical Indian Ocean (IO) warming and post-1980 La Niña tropical Pacific SSTs on seasonal rainfall changes (in mm/day) from AGCM simulations. Seasonal rainfall changes with post-1980 La Niña tropical Pacific condition and increasing level of IO warming is shown relative to control simulation: (a–c) 0.5 °C, (d–f) 1 °C, (g–i) 2 °C, (j–l) 3 °C, and (m–o) 4 °C. Dotted regions indicate 90% confidence level. Seasons are mentioned in the legend. MAM=pre-monsoon, JJAS=monsoon, OND=post-monsoon.

weakening and poleward shift of low-pressure systems activity in a warmer climate (Sandeep et al., 2018), or even multidecadal to centennial changes in the ENSO-ISM teleconnection (Shi & Wang, 2019; Srivastava et al., 2018). On the other hand, earlier studies suggested that the correlation between ISM rainfall and

eastern Pacific SSTs or between ISM rainfall and ENSO does not obey the interdecadal oscillation, even though ISM rainfall and ENSO indices do follow a common interdecadal variation individually (Krishnamurthy & Goswami, 2000). It should be kept in mind that the limited instrumental record is merely a representative of ISM rainfall variability. Low-frequency modulation in the relationship between any two climate time series (such as La Niña-ISM rainfall relationship) can appear deceptively deterministic, or even periodic, but in fact, do not essentially reflect beyond typical stochastic behavior of random processes, and needs, therefore, a careful interpretation (Gershunov et al., 2001).

A growing Indian subcontinent population in the twenty-first century needs improved predictions of seasonal rainfall and long-term projection, to better advise decision making for watershed management, and disaster risk reduction. Reduction in ISM rainfall during La Niña years can be alarming for recharging ground-water and hydrological systems. Here we not only highlight the diminishing fingerprint of recent La Niña years on ISM rainfall associated with changes in background state of Indo-Pacific region but also provide important insights into the possible impact of La Niña rainfall with increasing tropical IO warming. Results also confirm that diminishing central Indian ISM rainfall during La Niña years are largely not due to changes in land use land cover and agricultural mismanagement, rather warmer ocean conditions over tropical Indo-Pacific Oceans are responsible for it, which is a consequence of increasing global greenhouse gas concentrations. Our results can serve as a catalyst for future South Asian monsoon research.

Acknowledgments

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