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Northward Propagation of the Intertropical Convergence Zone and Strengthening of Indian Summer Monsoon Rainfall

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Key Points:
- The dynamics of the Intertropical Convergence Zone has a significant role in changing the characteristics of the Indian monsoon rainfall
- Since 2002, the ITCZ has strengthened and propagated northward, thereby increasing the magnitude of the Indian monsoon rainfall
- The reduced aerosol emissions is the main driver of the changing characteristics of ITCZ, which caused the revival of monsoon rainfall

Supporting Information:
- Supporting Information S1

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Abstract Since 2002, there has been a clear increase in Indian summer monsoon rainfall (ISMR). We demonstrate that this increase is associated with a change in the dynamics of the Intertropical Convergence Zone (ITCZ). Using a recently released reanalysis product from 1980–2016, we show that the ITCZ has strengthened and propagated northward since 2002. Analysis of the total energy budget reveals an increase in energy divergence and atmospheric diabatic heating, which is consistent with the changes in the ITCZ. Although global aerosol optical depth shows a significant positive trend during 1980–2016, it has declined over many parts of India since 2002. We put forward the hypothesis that this is the driver of the changing characteristics of the ITCZ. Our results suggest that changes in the dynamics of the ITCZ, together with changes in the energy/moisture budget, are responsible for the strengthening of ISMR since 2002, consistent with the emergence of a greenhouse gas-induced signal.

Plain Language Summary Indian summer monsoon rainfall (ISMR) is a major component of the Asian summer monsoon, providing 80% of the total annual rainfall in India. Even a small deviation of ISMR from normal has a significant effect on the Indian economy. Thus, understanding the dynamics of ISMR is of critical importance. During the latter part of the 20th century, ISMR experienced a significant reduction in its magnitude, with multiple hypotheses proposed to explain this weakening. However, we show that since 2002, there has been a clear increase in the magnitude of ISMR. We propose that this increase in magnitude is associated with the strengthening and northward propagation of the Intertropical Convergence Zone (ITCZ). Further analysis reveals that aerosol optical depth has decreased over many parts of India since 2002. Therefore, we hypothesize that the reduced aerosol emissions have played a significant role in the revival of ISMR since that time.

1. Introduction

During the latter part of the 20th century, Indian summer monsoon rainfall (ISMR) experienced a significant reduction in its magnitude, especially in the central Indian region, which is regarded as the core Monsoon zone. There has been an observed decrease in the frequency of moderate rainfall events over central India during the monsoon seasons from 1951 to 2000, accompanied by increasing extreme rainfall events (Goswami et al., 2006). Multiple hypotheses have been proposed to explain the weakening of the ISMR. Climate model experiments, forced with natural and anthropogenic forcing, have been used to attribute the observed reduction in ISMR to increases in anthropogenic aerosol emissions (Bollasina et al., 2011). They indicate that higher aerosol emissions in northern India created a cooling effect over the Indian subcontinent, which led to the weakened temperature gradient between the Northern and Southern Hemispheres, eventually reducing ISMR (Bollasina et al., 2011). Alternative hypotheses include a warming of the South Indian Ocean (SIO) as a critical factor in decreasing ISMR (Rao et al., 2010). The warming of the SIO weakens the meridional Hadley circulation via a weakening of the meridional sea surface temperature gradient, which in turn reduces ISMR (Chung & Ramanathan, 2006). Other studies have argued that the warming of the Western Indian Ocean (WIO) has been the main culprit for the observed decrease (Roxy et al., 2015).

Using multiple observational data sets, Jin and Wang (2017) examined whether and how the strength of ISMR has increased, specifically in the early part of the 21st century. They find a robust ISMR increase or revival across the majority of the data sources they considered. In trying to identify the possible causes of the observed increase in ISMR, they showed that while the Indian Ocean warming was higher compared to the Indian subcontinent during 1950–2002, the opposite was true post-2002, with the increased warming of the land and reduced warming of the Indian Ocean (Figure S1 in supporting information). The former condition is hypothesized to lead to the decline in ISMR due to the decrease in land-sea thermal gradient, which weakens the monsoon Hadley circulation and eventually reduces the rainfall over land. However, in recent decades the increased surface temperature over Indian land has resulted in an elevated land-sea thermal gradient and increased rainfall across the Indian subcontinent.

The differential heating between land and Indian Ocean (Figure S1) is thus the current working hypothesis for the leading cause of the changing dynamics of ISMR, both in terms of its weakening during 1950–2002 (Rao et al., 2010; Roxy et al., 2015) and its strengthening since 2002 (Jin & Wang, 2017), and it is considered to be the primary driver of monsoon trends (Lau & Li, 1984; Meehl, 1992). Considering the assumption of land-sea thermal gradient as a primary contributor to ISMR, the 5th assessment report of the Intergovernmental Panel on Climate Change (Stocker et al., 2003) demonstrated the likely enhancement of monsoon rainfall, in agreement with the study described above (Jin & Wang, 2017). However, the spatiotemporal variations of monsoon rainfall over India are not always consistent with the theory of differential heating between land and ocean (Gadgil, 2018). For instance, the temperature gradient anomaly is observed to be negative during years with above-average monsoon rainfall and positive during below-average years (Kothawale & Kumar, 2002). These observations may suggest that a heavy monsoon will be associated with a stronger land-sea thermal gradient only if accompanied by negative Indian Ocean warming anomaly that has a larger magnitude than the land surface warming (Gadgil, 2018).

An alternative, or a possibly related, theory to the land-sea thermal gradient to explain the monsoon dynamics involves the behavior of the Intertropical Convergence Zone (ITCZ) (Blandford, 1886; Gadgil, 2018). During the summer monsoon season, the ITCZ migrates toward the Indian monsoon zone, which usually occurs over the southern equatorial Indian Ocean during boreal winter. This migration is consistently associated with the reversal of the vertical circulation over the Indian region during the summer (Gadgil, 2018), leading to monsoon rainfall over India. Indeed, the spatiotemporal variation of the characteristics of ITCZ can be related to the variability of the monsoon (Schneider et al., 2014). However, an understanding of the mechanisms responsible for the ITCZ location and the associated rainfall intensity is still lacking, especially for the Indian Monsoon region. Therefore, the present study focuses on understanding the dynamics of the ITCZ and its association with ISMR. We analyze the changes in the monsoon from pre- to post-2002 periods (following Jin & Wang, 2017) and the role played by the characteristics of the ITCZ (i.e., its location and strength) in changing the magnitude of ISMR.

2. Data and Methods

Gridded precipitation data are obtained from the Climate Research Unit (CRU, Version ts4.03) product (Harris et al., 2014), which is available at a spatial resolution of 0.5°. In the case of ITCZ characteristics, we use the new European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-5 reanalysis product (Hersbach et al., 2020). ERA-5 represents the most updated versions of both the data assimilation techniques and Earth system model. Recent studies (Beck et al., 2019) have also reported a better performance of ERA-5 compared to other reanalysis products in representing various climatic variables, including precipitation, soil moisture, and evaporation, even in ISMR region (Mahto & Mishra, 2019). Table S1 provides a detailed information pertaining the data used in the present study.

2.1. Definition of the ITCZ and Its Characteristics

Observed precipitation data are usually used to define the ITCZ using a threshold method. The ITCZ can also be identified from satellite-based observations by considering high clouds, outgoing longwave radiation (OLR), and the meridional local precipitation maximum as indicators (Bain et al., 2011; Waliser & Gautier, 1993). Alternatively, the atmospheric mass circulation has been used as an indicator of the ITCZ and has the advantage that it can be used to characterize the large-scale tropical circulation (Byrne et al., 2018). Moreover, ITCZ characteristics beyond location (e.g., width and strength) can be readily calculated using an atmospheric mass-circulation method, which is difficult through satellite-based observations. Considering these factors, we use the atmospheric mass-circulation method for defining the ITCZ.

Here, we define the ITCZ structure in terms of the seasonal zonal mean of the Eulerian-mean meridional stream function (Peixóto & Oort, 1984) for June–September for the Indian monsoon region [70–90°E]. The meridional stream function is a function of latitude and pressure and is calculated as the vertically integrated, mass-weighted meridional wind (v), which is given by

$$\psi = 2\pi a g^{-1} \int_0^p v\cos\phi dp, \tag{1}$$

where a is the radius of the Earth, g is the gravitational acceleration, p is the pressure level, and ϕ represents the latitude. The stream function (ψ) quantifies the zonal-mean circulation of atmospheric mass in kg/s.

To extract information pertaining to ITCZ characteristics, such as location and strength, we perform mass-weighted vertical average of stream function from pressure levels 700 to 300 hPa, as shown in Figure S2. The closest latitude to the equator where the vertically averaged stream function is zero is considered as the ITCZ location (Figure S2). The ITCZ location defined here represents the latitude of the boundary between the southern and northern Hadley cells and represent the northern and southern edges of the ITCZ, respectively, which are defined as the closest latitude near the equator where the meridional derivative of the stream function is zero. Correspondingly, at these latitudes, the time-mean circulation changes from ascending to descending (Byrne et al., 2018).

The strength of the ITCZ is then defined in terms of the bulk vertical velocity (ω_{ITCZ}) as follows:

$$\omega_{ITCZ} = -g\frac{\psi_{ITCZ}}{A_{ITCZ}}, \tag{2}$$

where ψ_{ITCZ} is the total mass transported by the ITCZ, which is the difference in ψ between ϕ_N and ϕ_S (Figure S2); A_{ITCZ} is the ITCZ area, which corresponds to the area between the ITCZ edges, that is, ϕ_N and ϕ_S (Byrne & Schneider, 2016), and is calculated based on Equation 3:

$$A_{ITCZ} = 2\pi a^2(\phi_N - \phi_S). \tag{3}$$

2.2. Atmospheric Energy Budgets

Following Trenberth (1997), we obtain the total energy by vertically integrating from the surface of the Earth to the top of the atmosphere. Here, the total atmospheric energy A_E is a combination of four different energy components, that is, kinetic energy K_E, potential energy P_E, latent energy L_E, and internal energy I_E. The column-integrated moisture is then represented by Equation 4, which is based on Trenberth and Stepaniak (2003):

$$\frac{\partial A_E}{\partial t} = -\nabla .F_A + Q_1 - Q_f - Q_2, \tag{4}$$

where F_A is the total atmospheric transport given by $F_{\mathrm{A}} = F_{ME}+F_K$. Here, F_K is the kinetic energy component; however, its contribution is considered to be negligible to the atmospheric energy transport (Trenberth et al., 2002). F_A predominantly corresponds to the transport of moist static energy ($F_{ME} = F_{DE}+F_{LE}$), which in turn comprises dry, static energy (F_{DE}), and latent heat flux (F_{LE}) components. Moreover, the atmospheric diabatic heating can be represented as

$$Q_1 - Q_f - Q_2 = R_T + F_S, \tag{5}$$

where F_S is the net upward flux through the surface and is given by $F_S = LE+H_S - R_S$ and H_S and LE are the sensible heat flux and latent heat flux through the surface, respectively. R_S is the net downward radiation through the Earth's surface; R_T in Equation 5 represents the net downward radiation through the top of the atmosphere.

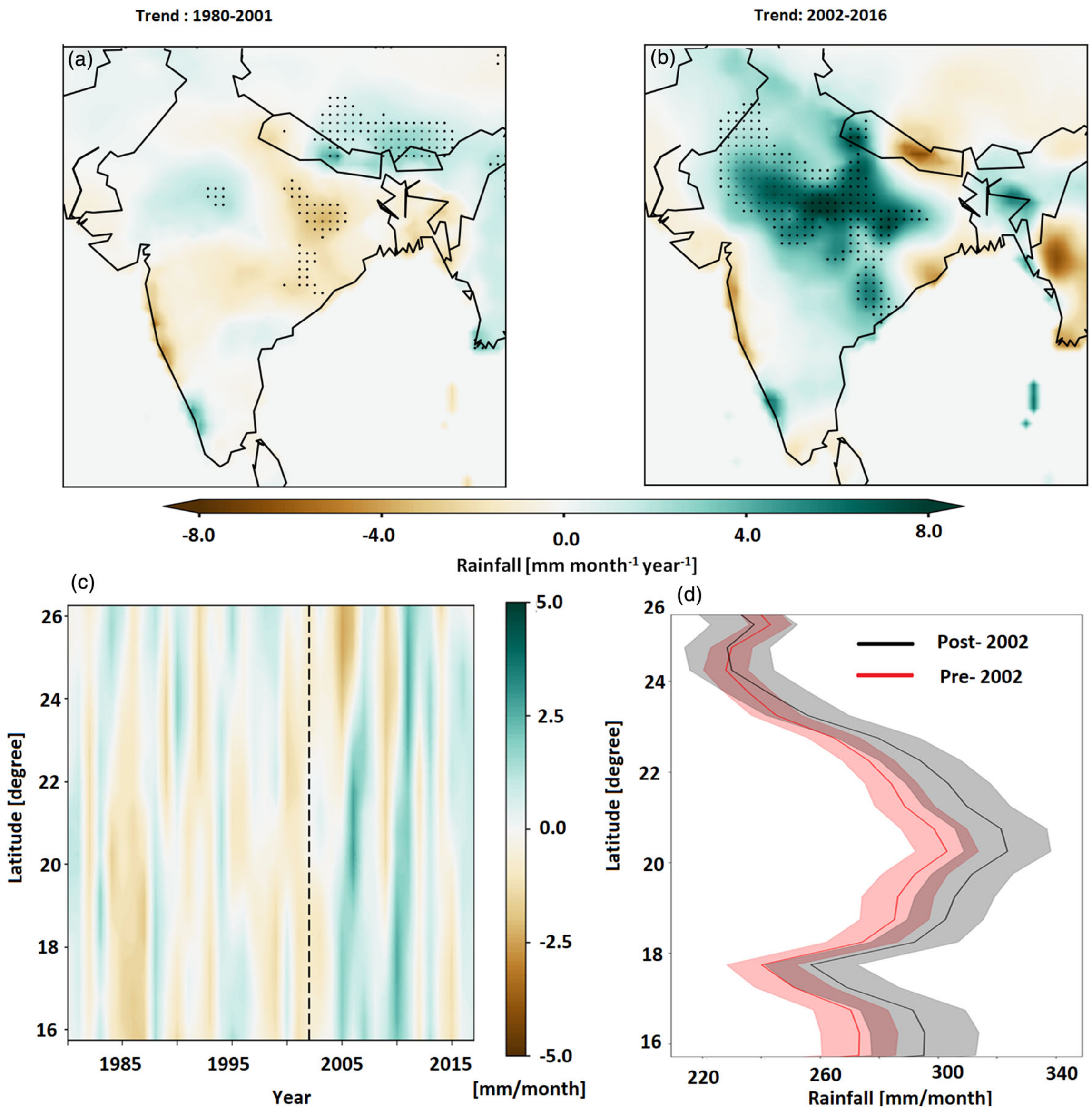

Figure 1. Changes in the monsoon characteristics from pre- to post-2002. (a, b) Spatial pattern of the monsoon linear trends (mm month^{-1} year^{-1}) for 1980–2001 and 2002–2016, respectively. The hatched areas represent the locations where the value of the linear slope is different from zero at the 10% confidence level. (c) Hovmöller diagram showing the latitude wise and yearly changes in precipitation for the Indian region (70°E to 100°E). The vertical dashed line represents the year 2002. (d) Latitude wise changes in precipitation between pre-2020 (red) and post-2002 (black). The thick lines show the multiyear means, and the filled areas around each of the solid lines represent the 90% confidence intervals based on the sampling distribution of the mean.

3. Results

To analyze the recent changes in ISMR, we divide 1980–2016 into two periods, pre- and post-2002. Figure 1a shows the trends in ISMR for pre-2002. We observe a significant decrease in monsoon rainfall over India, especially central and eastern India (Figure 1a), that is consistent with previous studies. When we analyze the post-2002 trend, however, we find the opposite situation (Figure 1b), with central and northern India exhibiting increasing trends in monsoon rainfall. We also investigate how the latitude-wise changes in the rainfall magnitude occur over time. This analysis provides basic information as to whether or not ITCZ dynamics may be playing a role in changing the monsoon characteristics over India. Figure 1c shows a Hovmöller diagram based on anomalies from the 1980–2016 average for the Indian Monsoon region. It is clear from the figure that the monsoon magnitude is increasing post-2002 with an evident northward propagation. Post-2002, the monsoon rainfall has experienced an increase in magnitude further north, specifically in the region between 18°N to 24°N, which includes the core monsoon zone (Figure 1d).

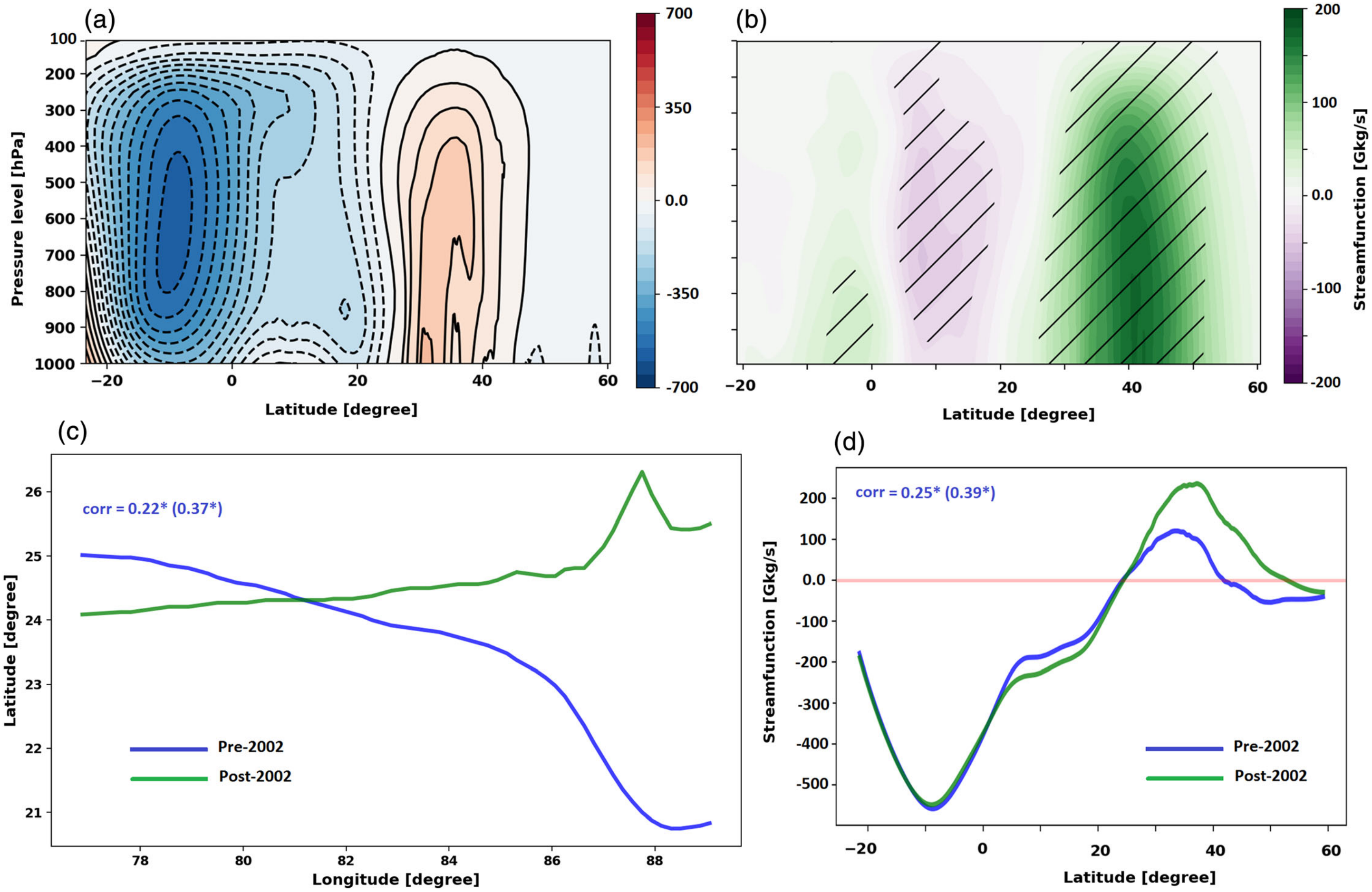

Figure 2. Changes in the ITCZ characteristics from pre- to post-2002. (a) The meridional overturning stream function for the Indian monsoon region (70°E to 90°E) for the period 1980–2016. (b) Change in the stream function between pre- and post-2002. The hatching shows the regions where the changes are different from zero at the 10% level. (c) Longitude wise ITCZ location for pre- and post-2002. (d) Vertically averaged annual- and zonal-mean (70°E to 90°E) meridional stream function (from 700 to 300 hPa with mass weighting) for pre- and post-2002 (green), respectively. The value of the Kendall's tau of the respective ITCZ characteristics with the core monsoon zone (18.5–25.5°N, 74.5–84.5°E) June–September rainfall for 1980–2016 is provided in the inset of the figure. The values inside the bracket represents the correlation from 2002–2016, where "*" indicates correlation values significant at the 5% level.

The results shown in Figure 1 are based on observed precipitation, which we complement with an understanding of the dynamics of the ITCZ. Here, we consider regional zonal mean of the Eulerian-mean circulation to define the ITCZ and its characteristics (see section 2). The monsoonal Hadley circulation, a typical atmospheric meridional circulation for the Indian region during the summer season, is characterized by descending motion over the equatorial Indian Ocean region, with ascending motion that dominates over the Indian land region (Figure 2a). An examination of the changes in the monsoonal Hadley circulation pre- to post-2002 (Figure 2b) shows strengthened ascent over the Indian land region, pointing to the increased monsoonal activity. Consistent with the increase in ascent over land, there is also an increase in the large-scale descending motion over the equatorial Indian Ocean, which extends up to the upper troposphere.

Based on the atmospheric meridional circulation over India, we further extract information pertaining to the ITCZ location and strength. The pre- and post-2002 ITCZ location is shown in Figure 2c, which highlights a clear difference between these two periods. Pre-2002, the ITCZ moves southward. We observe the exact opposite scenario in post-2002, where the ITCZ location moves northward. Moreover, correlation analysis between the ITCZ location and ISMR magnitude is positive and significant, and the association further strengthens for the period 2002–2016. To demonstrate the changes in the strength between the two subperiods, we take the vertically weighted average of the atmospheric stream function (Figure 2d), which points to a strengthening of the monsoonal Hadley circulation in the 2002–2016 period. As with the ITCZ location, we

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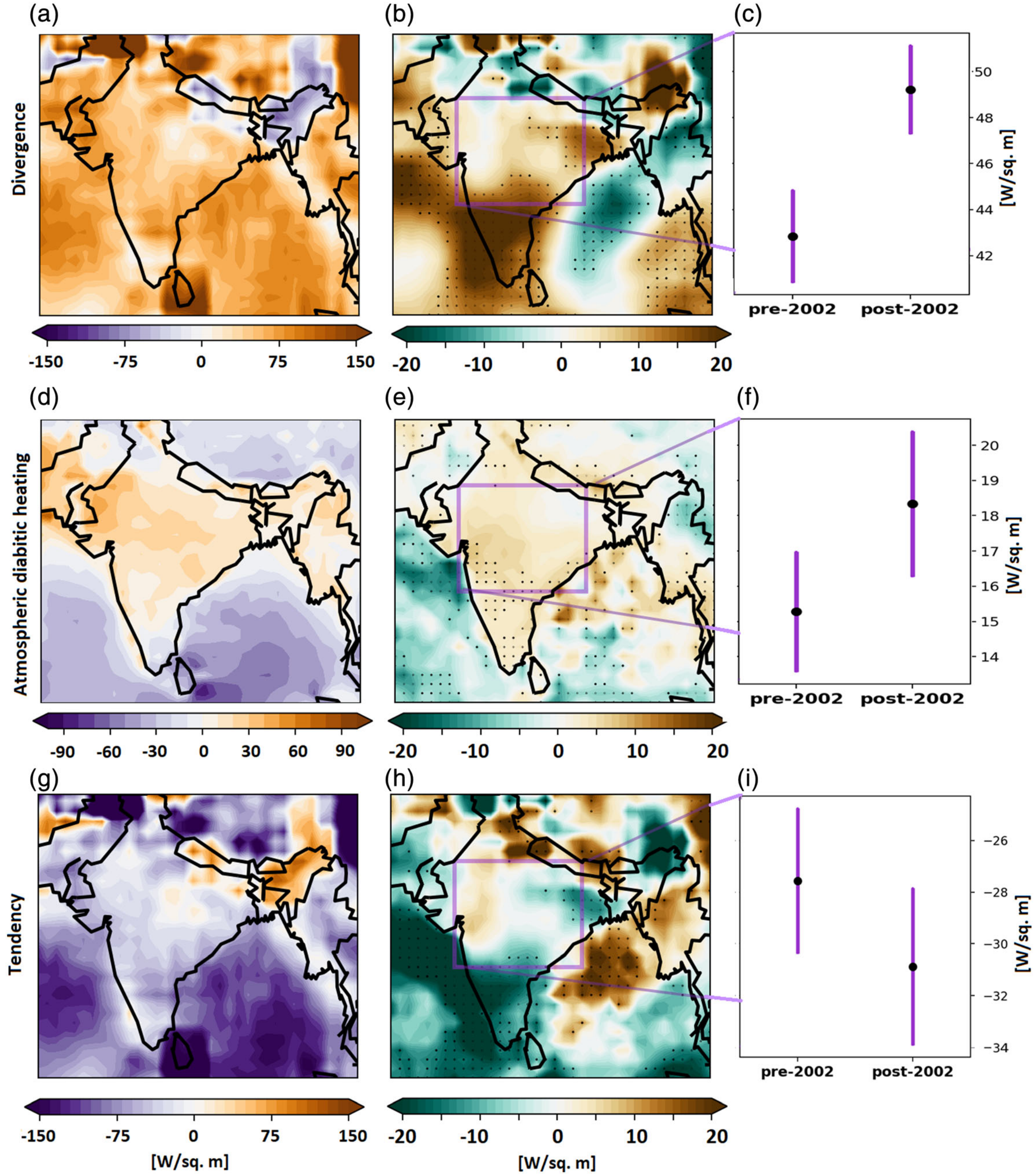

Figure 3. Changes in the energy budget from pre- to post-2002. (a) Spatial variation of the energy divergence ($\nabla. F_A$) for 1980–2016. (b) Changes in energy divergence between pre- and post-2002. The hatched areas represent locations where the energy during the two periods is different at the 10% level. (c) Comparison of the spatial mean of the energy divergence over the core monsoon zone (18.5–25.5°N, 74.5–84.5°E), showed in the pink box in (b), for the pre- and post-2002; the pink bars represent the 90% confidence limits based on the sampling distribution of the mean. Panels (d)–(f) and (g)–(i) are same as (a)–(c) but for the atmospheric diabatic heating and energy tendency ($\frac{\partial A_E}{\partial t}$), respectively.

perform a correlation analysis between ITCZ strength and ISMR magnitude (Equation 2). We notice a significant positive correlation for the period 1980–2016; nonetheless, the correlation value increases when we consider the years from 2002–2016 (inset of the Figure 2d). Overall, our results indicate that the northward propagation of the ITCZ and its concurrent strengthening are responsible for the increased magnitude of the monsoon rainfall over India in post-2002.

Given the influence of the ITCZ characteristics on ISMR, we focus on the changes in the individual components of the column integrated atmospheric energy budget (i.e., tendency, divergence, and atmospheric

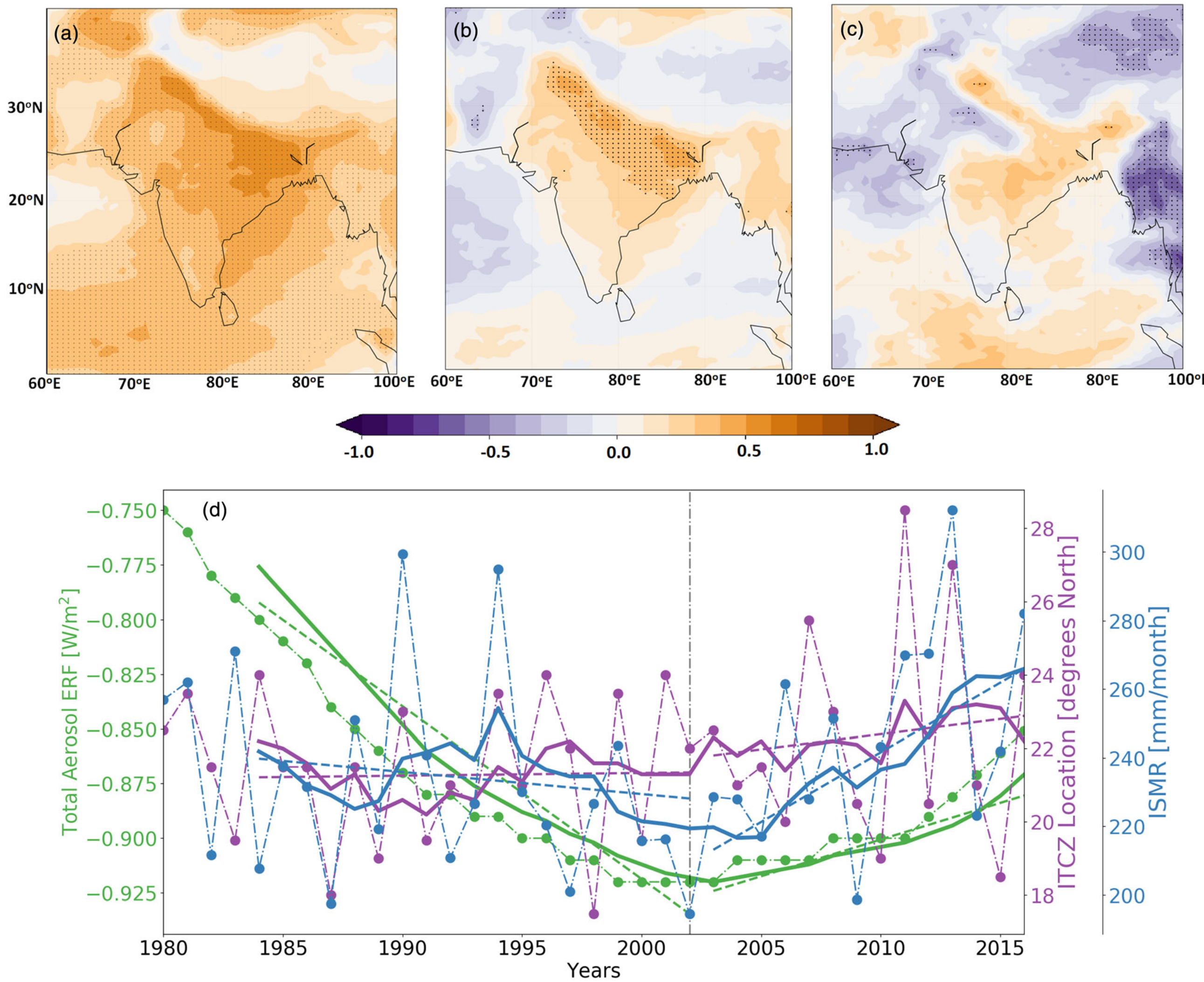

Figure 4. Changes in the aerosol characteristics from pre- to post-2002. (a) Spatial pattern of aerosol optical depth (AOD) trend for complete period (1980–2016) considered in the present study. Trend (b) for pre-2002 and (c) for post-2002 periods. The hatched areas represent the locations where the value of the linear slope is different from zero at the 10% level. Here, the AOD data set for this analysis is procured from the MERRA2 (Gelaro et al., 2017) reanalysis product. As with ERA-5, MERRA2 also shows a strengthening of ITCZ during post-2002 (Figure S4). (d) Time series depicting the global mean effective radiative forcing (ERF) due to anthropogenic aerosols, ITCZ location, and ISMR over core monsoon zone from 1980 to 2016. The solid lines represent the 5-year running mean. The vertical dashed line represents the year 2002. The positive trends are apparent for all the three variables post-2002, and they are significant at the 10% level as estimated from the modified Mann Kendall approach (Hamed & Rao, 1998), which considers both linear and nonlinear trends and is applicable to autocorrelated data. The estimation of pre-2002 trends shows that both anthropogenic aerosol ERF and IMSR were statistically significant.

diabatic heating) over India because previous studies suggested that the ITCZ depends linearly on the energy flux (Adam et al., 2016; Bischoff & Schneider, 2016; Donohoe et al., 2014). Figure 3a shows the spatial mean of the energy divergence component during 1980–2016. During the summer monsoon, the energy divergence is positive over India. Examining changes between pre- and post-2002 (Figure 3b), the positive values persist, with a spatially accumulated energy divergence in the core monsoon zone that is higher in post-2002 than in pre-2002 (Figure 3c). Similar to the energy divergence, the atmospheric diabatic heating is positive over the Indian region (Figure 3d), and larger post-2002 (Figure 3e), even though it is not statistically significant over such a large area as the energy divergence (Figure 3f). The spatial pattern of the energy tendency (Figure 3g) is the exact opposite of what observed for the energy divergence. The changes in the energy tendency between the two periods point to its reduction post-2002 (Figures 3h and 3i).

Given that the individual components of the column-integrated atmospheric energy budget over India have changed significantly from pre- to post-2002, we now focus on analyzing the changes in the water budget components, following Trenberth and Guillemot (1998). Figure S3a shows the spatial mean of the water budget in terms of precipitation minus evaporation (P−E) during 1980–2016. The higher values are generally along the Western Ghats (i.e., core monsoon zone) and the Gangetic Planes, which extend toward the northeastern parts of India. Moreover, the pattern of this spatiotemporal variation is similar to the variation of monsoon rainfall over India (Rajeevan et al., 2008; Vittal et al., 2013), which indicates the precipitation is greater than evaporation, as it is often the case during the monsoon season over India (Gebregiorgis et al., 2018). The change in water budget between pre- and post-2002 shows an increase in (P−E), especially in the core monsoon zone (Figures S3b and S3c), which is consistent with an increase in the magnitude of the monsoon over India (Figure 1b).

While the energy and water budgets are consistent with the changing characteristics of the ITCZ, the question of the major drivers of the observed behavior remains unanswered. One possible mechanism is tied to aerosols, which can induce a strong change in both large-scale atmospheric circulation and regional climate responses (Ming & Ramaswamy, 2011; Wang et al., 2016; Xie et al., 2013). More specifically, the southward shift of the ITCZ (Allen et al., 2015; Hwang et al., 2013; Wang et al., 2016) and the weakened ISMR during the latter part of 20th century have been linked to increases in aerosol optical depth (Bollasina et al., 2011; Li et al., 2018). Therefore, we examine the characteristics of aerosol optical depth and effective radiative forcing (ERF) during monsoon season of our study period. There is a significant positive trend in aerosol optical depth from 1980–2016 (Figure 4a). However, when we divide the period to pre- and post-2002 (Figures 4b and 4c), we notice a weakening of the increase in aerosol optical depth post-2002 (Figure 4c) compared to pre-2002, and a strong negative trend in northwest India. This may have caused the increase in the regional revival of monsoon, together with northward propagation of ITCZ.

To test this further, we examined a suite of climate models from the Coupled Model Intercomparison Project Phase 6 (CMIP6) (Eyring et al., 2016; Table S2) to analyze the impact of aerosols on the changing character of ISMR. However, the CMIP6 models are not able to represent pre- and post-2002 rainfall trends (Table S3); moreover, the observed ISMR variability is outside the range of model internal variability (Figure S5a). Nevertheless, a simple index of the global ERF of anthropogenic aerosols as obtained from Dessler and Forster (2018), refer https://climexp.knmi.nl/getindices.cgi?WMO=LeedsData/total_aerosol_ERF&id= for more details, shows a diametric change in the trends in global ERF from pre- to post-2002 (Figure 4d), which coincides with the changes in ITCZ location and corresponding changes in the trends in ISMR. The changes are also consistent with changes in the characteristics of regional AOD over south Asia, further indicating a role of reduced aerosol emissions in the revival of the ISMR post-2002. Studies have also reported that the anthropogenic aerosols, both local and remote aerosol emissions, are a key driver of changes in summer monsoon rainfall in the Northern Hemisphere during the 20th century (Undorf et al., 2018), in particular, its profound effect is documented for the ISMR (Guo et al., 2016).

4. Summary and Conclusions

Persistent drying of monsoon rainfall during the late 20th century had major impacts on the Indian subcontinent, whose economy relies on the stability and strength of the monsoon. Several hypotheses have been put forward to explain this drying trend, including differential warming between the Northern and Southern Hemisphere and, most recently, the differential warming of the Indian Ocean compared to the Indian land regions (i.e., the decreased land-sea temperature gradient). This decreased land-sea temperature gradient is one of the key drivers that determine the strength of the monsoon. However, it has been suggested that there has been an increase in the land-sea thermal gradient (Jin & Wang, 2017), with more warming inland than the ocean and subsequently increased monsoon over India in post-2002.

We show that the monsoon over India has indeed increased significantly over the period 2002–2016; however, rather than relating these changes to the warming of the land or oceans, we show that these changes are associated with the dynamics of the ITCZ. The excess heating of the atmosphere above the warmed land due to differential heating between land and ocean can only lead to weak convergence in spring and may not explain the strengthened monsoon over India during the summer (Blandford, 1886). Here we consider an alternative theory (i.e., ITCZ-driven monsoons) along with the land-sea thermal gradient to explain the strengthening of the monsoon (Gadgil, 2018). Therefore, by focusing on the dynamics of the ITCZ, we show that the significant northward propagation of its location and a concurrent increase in its strength are responsible for the increase in the magnitude of ISMR in post-2002.

Further, we analyze the total atmospheric energy budgets, to which the ITCZ is linearly related (Bischoff & Schneider, 2016; Donohoe et al., 2014). We show significant changes in the energy budget components, especially in the increase in the divergence of energy and radiative forcings in post-2002. Changes in water budget components, with an increase in (P−E), indicates an increased availability of moisture for the monsoon rainfall. We put forward the hypothesis that the recent changes in aerosol concentrations are responsible for changes in these regional energy and water budgets. Overall, our results suggest that the changes in the ITCZ characteristics, such as location and strength, along with the significant changes in both energy and moisture budgets, lead to the strengthening of summer monsoon over India since 2002.

Data Availability Statement

Data used here can be downloaded from the following: CRU (https://crudata.uea.ac.uk/cru/data/hrg/), ERA5 (https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5), MEERA2 (https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/data_access/), and total aerosol ERF (https://climexp.knmi.nl/getindices.cgi?WMO=LeedsData/total_aerosol_ERF&id=).

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