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Key Points:

- Aerosols could suppress greenhouse gases-forced intensification of rainfall in monsoon and post-monsoon seasons for several years
- Aerosols will dominate monsoon and post-monsoon precipitation patterns until the mid-21st century under a very high emissions trajectory
- Local aerosols show a stronger influence on monsoon precipitation patterns throughout the 21st century relative to remote aerosols

Supporting Information:

Supporting Information may be found in the online version of this article.

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Anthropogenic Aerosols Delay the Emergence of GHGs-Forced Wetting of South Asian Rainy Seasons Under a Fossil-Fuel Intensive Pathway

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Abstract With continued fossil-fuel dependence, anthropogenic aerosols over South Asia are projected to increase until the mid-21st century along with greenhouse gases (GHGs). Using the Community Earth System Model (CESM1) Large Ensemble, we quantify the influence of aerosols and GHGs on South Asian seasonal precipitation patterns over the 21st century under a very high-emissions (RCP 8.5) trajectory. We find that increasing local aerosol concentrations could continue to suppress precipitation over South Asia in the near-term, delaying the emergence of precipitation increases in response to GHGs by several decades in the monsoon season and a decade in the post-monsoon season. Emergence of this wetting signal is expected in both seasons by the mid-21st century. Our results demonstrate that the trajectory of local aerosols together with GHGs will shape near-future precipitation patterns over South Asia. Therefore, constraining precipitation response to different trajectories of both forcers is critical for informing near-term adaptation efforts.

Plain Language Summary Agricultural production, water availability, and the economy in South Asia depend closely on reliable rainfall. While much of this depends on monsoon season rainfall, the pre-monsoon season and the post-monsoon season are also important for these sectors. Understanding how and why South Asian rainfall patterns in these seasons are likely to change is, therefore, relevant for adaptation, planning, and infrastructure resilience. Multiple external climate forcers and natural climate variability influence South Asian rainfall. We examine how increasing greenhouse gases (GHGs) and changing anthropogenic aerosol distributions—two key forcers - shape seasonal rainfall patterns across South Asia using large-ensemble climate simulations for a very high emissions pathway. Our findings show that anthropogenic aerosols, which have a predominantly weakening influence on rainfall, could suppress the enhancement of monsoon and post-monsoon season rainfall projected in response to GHGs by several decades. Aerosols continue to be important influences on rainfall patterns in the region for at least the next few decades, after which the influence of GHGs will dominate. While aerosols from other regions have historically influenced regional rainfall, we find that local aerosols are primarily responsible for the projected changes in rainfall patterns.

1. Introduction

Anthropogenic aerosols have affected multiple aspects of the Earth's climate system by modulating the Earth's energy budget and influencing cloud properties (Sato & Suzuki, 2019; Szopa et al., 2021). Their effects are particularly strong over East and South Asia, where their current concentrations are among the highest worldwide (Samset et al., 2019; Singh et al., 2019). In fact, anthropogenic aerosols have been identified as a stronger driver of historical changes in South Asian monsoon precipitation than greenhouse gases (GHGs) (Z. Li et al., 2016; Singh et al., 2019). In contrast to most other regions, aerosol concentrations are projected to increase over South Asia for the next few decades even with moderate air-quality policies (Lund et al., 2019; Samset et al., 2019; Figure S1 in Supporting Information S1). Few studies examine how the trajectory of aerosols is likely to influence future precipitation patterns over South Asia and most risk assessments rely on the climate response to GHGs (Persad et al., 2022).

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Aerosols influence climate through various processes including modification of the radiation budget, tropospheric lapse rates, and cloud microphysical properties, and altering thermal and moisture gradients that govern the large-scale circulation (J. Li et al., 2022; Szopa et al., 2021). High aerosol concentrations across the Northern Hemisphere (NH) have shifted the Intertropical Convergence Zone (ITCZ) southward, weakening the NH monsoon circulation and suppressing monsoonal precipitation (Z. Li et al., 2016). The effect of aerosols on South Asia precipitation depends on their composition, spatial distribution, emission sources, meteorology, and cooling efficacies (Persad & Caldeira, 2018; Westervelt et al., 2020). Black carbon from fossil fuel combustion and biomass burning dominates aerosol loading during the pre-monsoon (March–May) and post-monsoon (October–December) seasons, while a mix of anthropogenic aerosols, mineral dust, and sea salt aerosols occur in the monsoon (June–September) season (Z. Li et al., 2016; Westervelt et al., 2020). Anthropogenic aerosols have suppressed ∼30–50% of the global mean warming caused by GHGs since the mid-twentieth century (Szopa et al., 2021; Persad et al., 2022), offsetting warming-driven intensification of rain-producing systems such as atmospheric rivers (Baek & Lora, 2021) and the Asian monsoons (Ayantika et al., 2021; Singh et al., 2019).

The influence of future aerosol radiative forcings is likely to differ from the historical period due to shifts in the spatiotemporal distribution of aerosols (Samset et al., 2019). While the influence of anthropogenic aerosols on South Asian monsoon in the twentieth century has been identified (e.g., Bollasina et al., 2014; Singh et al., 2019), it remains unclear how such projected changes in aerosol forcings with rising GHGs will shape future precipitation patterns over South Asia. Further, there is limited research on how these external forcings influence pre-monsoon and post-monsoon, despite the importance of precipitation in these seasons for water resources and agricultural activities across the region (Sengupta & Nigam, 2019; Sinha et al., 2019).

Understanding how changing GHGs and global aerosol burdens could shape seasonal precipitation patterns in the coming decades is important for anticipating risks to food security, water availability, and regional development. Wilcox et al. (2020) showed that reducing anthropogenic aerosols could increase Asian summer monsoon precipitation by 2050. However, the time of emergence of seasonal precipitation changes across the region in response to increasing GHG forcing, and role of local and remote aerosols on future precipitation patterns in different seasons remains unclear. In this study, we: (a) examine the spatial and temporal responses of seasonal mean precipitation to GHGs and anthropogenic aerosols (AAER) over South Asia in the pre-monsoon, monsoon, and post-monsoon seasons, (b) quantify the time of emergence of the seasonal mean precipitation above response to GHGs and the competing influence of aerosols, and (c) assess the relative influence of aerosols emitted locally and from other remote regions on seasonal precipitation patterns.

2. Data and Methods

2.1. Data

We use "ALL-forcing" (40 members) and "all-but-one-forcing" simulations from the Community Earth System Model Version-1 Large Ensemble (CESM1-LE) during 1920–2080. The "all-but-one-forcing" CESM1-LE includes fixing either anthropogenic aerosols (XAER; 20 members), GHGs (XGHG; 20 members), biomass burning aerosols (XBMB; 15 members until 2029), or Land-use/land-cover changes (XLULC; 5 members until 2029) at 1920 conditions while all other forcings follow historical and future evolution under the RCP8.5 pathway (Deser et al., 2020). Using these simulations, we derive the response to each forcing (GHGs, AAER, BMB, and LULC) following Deser et al. (2020). (Note, AAER refers to anthropogenic aerosols only). We use a single model rather than a multi-model framework because: (a) the CESM1-LE allows us to fully characterize internal variability; (b) CESM1-LE "all-but-one-forcing" design considers interactions between forcings, unlike single forcing simulations. Therefore, the response for each forcings includes any effects resulting from such interactions, which we find are largely additive (Figure S2 in Supporting Information S1); (c) the three models that have provided similar simulations through the CMIP6 Detection and Attribution project use the ssp2-4.5 scenario, rendering comparisons with the CESM1-LE challenging; (d) two of these CMIP6-generation models (CanESM5 and GISS-E2-G-1) have large biases in South Asian monsoon climatology (Katzenberger et al., 2021).

We compare observed precipitation from Climatic Research Unit (∼0.50° × 0.50°) (Harris et al., 2020) and Global Precipitation Climatology Centre (∼1° × 1°) (Schneider et al., 2014) with CESM1-LE simulated precipitation during the climatological period (1950–1979) over South Asia covering India, Pakistan, and Bangladesh. CESM1-LE reasonably reproduces the spatial pattern of seasonal precipitation climatology (1950–1979) although with wet biases over eastern India in the pre-monsoon season and southern India in post-monsoon season, and a southward shift of the core-monsoon precipitation zone (Figure S3 in Supporting Information S1). Observed regional average seasonal precipitation anomalies and trends across South Asia fall within the CESM1-LE spread (Figures S4a–S4f in Supporting Information S1). Further, observed standard deviations are within the range of standard deviation estimated from individual ensemble members, calculated from the corresponding 10-year running mean precipitation during the climatological period (Figure S4g in Supporting Information S1). Moreover, observed grid cell-level trends also fall within the CESM1-LE spread over most of South Asia (Figures S4h–S4p in Supporting Information S1).

2.2. Time of Signal Emergence

We use precipitation anomalies relative to the climatological period to estimate the time of emergence of the forced signal in seasonal precipitation from natural variability. Given the high variability, we smooth precipitation anomalies using a 30-year LOWESS smoother (Cleveland, 1981). The time of emergence is defined as the year when the smoothed precipitation anomalies in ALL-forcing or individual forcing simulations exceed noise for at least 10 consecutive years (Hawkins et al., 2020). Noise is calculated as 2 × standard deviation (σ) of ensemble mean precipitation in the ALL-forcing simulations over the climatological period. Signal-to-noise ratio (S/N) is calculated as the ratio of the ensemble mean precipitation changes relative to climatological noise. The time of emergence is sensitive to the definition of noise. Therefore, we also compare these time of emergence estimates using noise from the 10-year running mean of precipitation from observations and individual ensemble members following Lehner et al. (2017).

2.3. Local and Remote AOD Contribution to Aerosol-Forced Precipitation Changes

We examine the influence of local and remote AOD on precipitation patterns and quantify their contribution to seasonal precipitation changes during 2020–2049 relative to climatology. We select this time-period due to the projected increases in local AOD and decreases in remote AOD. Local AOD is estimated as the grid cell level or area-weighted average over South Asia, and remote AOD is the area-weighted average across 0°–60°N excluding South Asia. Note that local AOD isn't solely representative of local emissions, as it can be influenced by both local and remote emissions.

Previous studies have used targeted simulations with limited ensemble members (Bollasina et al., 2014; Singh et al., 2019) to isolate the influence of aerosols in different regions on South Asian precipitation. In the absence of large ensemble simulations that isolate different regional aerosols, we quantify the influence of local and remote AOD on seasonal precipitation using the following multiple regression model:

$$P = \alpha \times \mathrm{AOD}_L + \beta \times \mathrm{AOD}_R + \varepsilon \quad (1)$$

where P indicates ensemble mean precipitation in AAER; AOD_L and AOD_R denotes ensemble mean local AOD and remote AOD, respectively. ε represents unaccounted precipitation changes. To assess the relative importance of local and remote AOD on seasonal precipitation, we standardize α and β by multiplying them with $\sigma(\mathrm{AOD}_L)$ and $\sigma(\mathrm{AOD}_R)$ and dividing by $\sigma(P)$. Finally, to quantify the contribution of local and remote AOD changes to precipitation changes during 2020–2049 relative to climatology, we use the following equations:

$$\Delta P_{\mathrm{AOD}_L} = \alpha \times \Delta\mathrm{AOD}_L \quad (2)$$

$$\Delta P_{\mathrm{AOD}_R} = \beta \times \Delta\mathrm{AOD}_R \quad (3)$$

$$\varepsilon = \Delta P - \left(\Delta P_{\mathrm{AOD}_L} + \Delta P_{\mathrm{AOD}_R}\right) \quad (4)$$

where $\Delta P_{\mathrm{AOD}_L}$ and $\Delta P_{\mathrm{AOD}_R}$ indicate precipitation changes driven by changes in local and remote AOD, respectively. ΔP indicates average precipitation changes under AAER. $\Delta\mathrm{AOD}_L$ and $\Delta\mathrm{AOD}_R$ indicate average changes in local and remote AOD, respectively, in AAER. Local and remote AOD are correlated in some areas during the monsoon and pre-monsoon season. However, there is negligible influence of this collinearity on the regional-average and grid-level regressions as indicated by low variance inflation factor (<2) across South Asia (Figures S5a–S5g in Supporting Information S1). Residuals from the regression model over majority of

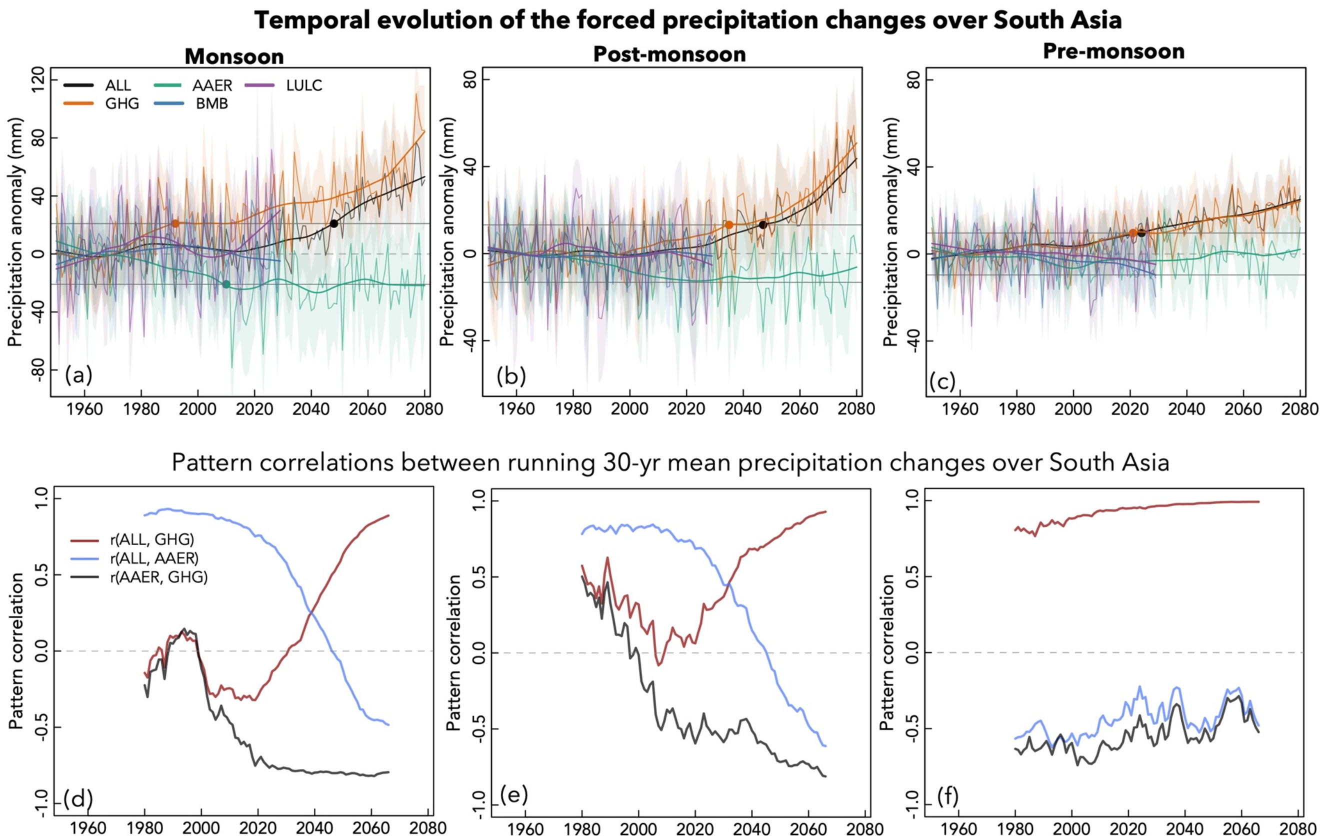

Figure 1. Temporal evolution of seasonal precipitation over South Asia. Time series of (a) monsoon, (b) post-monsoon, and (c) pre-monsoon season precipitation changes relative to 1950–1979 in response to ALL-forcing and individual forcings. Shading in each panel shows the ensemble spread (ensemble mean $\pm 0.5\sigma$). Solid gray lines in each panel indicate noise (2σ) of ensemble mean precipitation over South Asia. Thin lines show ensemble-averaged precipitation changes and thick lines show the 30-year smoothed changes relative to 1950–1979. Dots indicate the time of signal emergence. (d and e) Pattern correlations between centered running 30-year mean precipitation changes over South Asia in ALL and GHGs (red), ALL and AAER (blue), and GHGs and AAER (black) for all seasons.

South Asia are independent (Ljung-Box test, Ljung & Box, 1978) and follow the normal distribution (Anderson Darling test, (Anderson & Darling, 1952)) at 5% significance level (Figures S5h–S5m in Supporting Information S1), indicating the suitability of a linear regression model to quantify the local and remote AOD contributions to aerosol-forced precipitation changes.

3. Results

3.1. Seasonal Precipitation Response to Anthropogenic Forcings and Time of Emergence

We find that monsoon and post-monsoon season precipitation changes in the 20th and 21st century are affected by competing influences from AAER and GHGs (Figure 1). For instance, regional-averaged monsoon precipitation in the ALL-forcing simulations remains stationary until the 2010's and increases sharply thereafter, emerging above climatological noise by the late-2040s (Figure 1a). The opposing influences of GHGs and AAER result in ALL-forcing monsoon precipitation remaining stationary until the early-21st century and subsequently increasing in response to GHGs as the drying influence of aerosols stabilizes (Figure 1a). In the absence of aerosol forcing, precipitation increases in response to GHGs emerge above noise around the 1990's. This suggests that AAER could suppress the emergence of the GHGs-forced signal by up to 5 decades (Figure 1a).

In the post-monsoon season, the forced signal of increasing precipitation in the ALL-forcing experiments emerges in the 2040s, approximately a decade after it emerges in response to GHGs alone (Figure 1b). AAER-forced precipitation declines between approximately the 1950s and 2020s, suggesting that aerosols suppress the emergence of the GHGs-forced wetting signal (Figure 1b). In contrast, ALL-forcing pre-monsoon (March-May) precipitation experiences a limited influence of aerosols and increases monotonically since the early-21st century

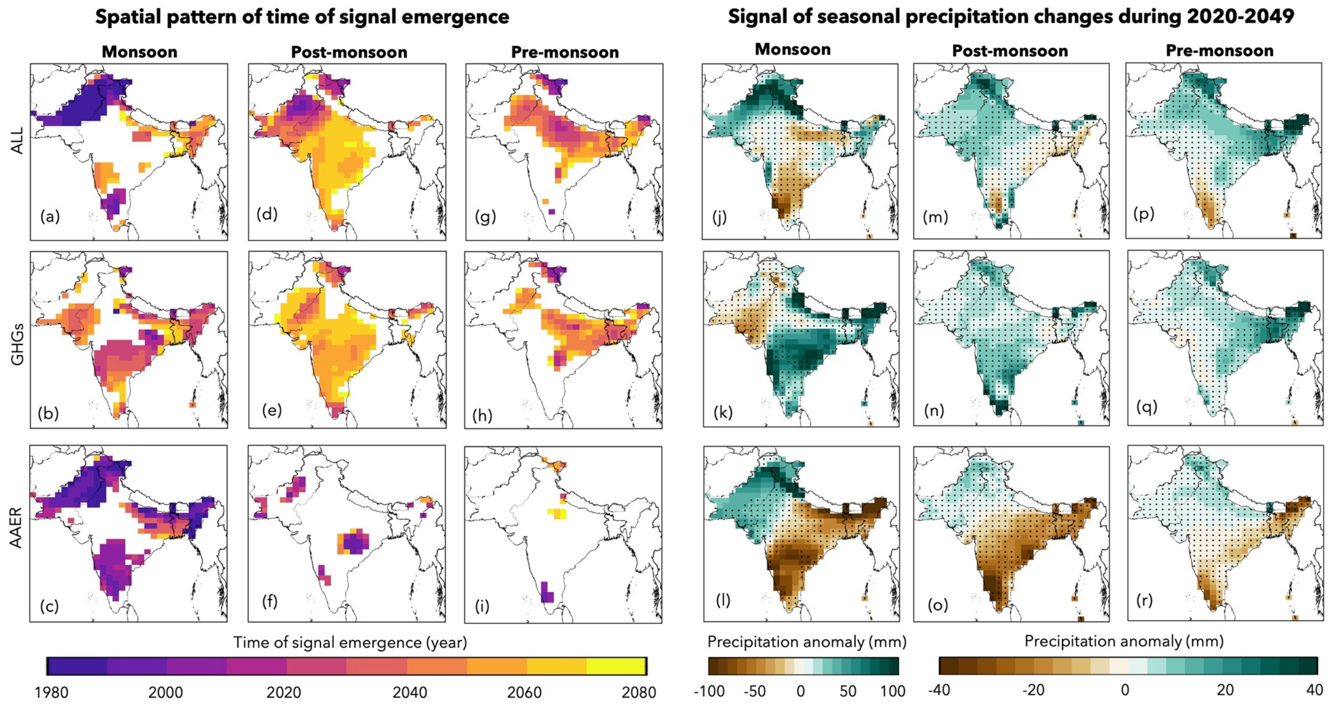

Figure 2. Spatial pattern of time of signal emergence in seasonal precipitation over South Asia. (a–i) Decade in which the forced signal in monsoon precipitation first emerges across South Asia in response to ALL-forcings, GHGs, and AAER. (j–r) Signal-to-noise in seasonal precipitation changes. Color shadings indicate signal (ensemble-mean) in seasonal precipitation changes in ALL, GHGs, and AAER during 2020–2049 relative to 1950–1979. Dots indicate grid cells where the precipitation change does not exceed noise (signal-to-noise ≤1).

in the ALL-forcing simulations, closely following the response to GHGs, and emerging in the early 2020s (Figure 1c). BMB and LULC-forcings have a relatively limited effect on seasonal precipitation, except during the monsoon season where LULC-forced precipitation increases in the early 21st century. Because these simulations are limited to 2029, we focus the remaining analysis on the response to AAER and GHGs.

We compare the spatial pattern of the 30-year mean precipitation response to individual forcings and ALL-forcings using pattern correlations (Figures 1d–1f). Consistent with signal emergence in regional-averaged precipitation, the spatial pattern of ALL-forcing precipitation changes has stronger similarity with AAER-forced changes than GHGs-forced changes in the monsoon and post-monsoon seasons until the ~2040s, while GHGs dominate the pre-monsoon precipitation changes over the entire period (Figures 1d–1f). Pattern correlations of monsoon precipitation changes between ALL-forcing and AAER are strongly positive between the 1980s and 2020s (Figure 1d), whereas those between ALL-forcing and GHGs are weakly negative till ~2030s, increasing thereafter and exceeding the correlation between ALL-forcing and AAER by the 2040s. Likewise, pattern correlations of post-monsoon precipitation changes between GHGs and ALL-forcing exceed the AAER and ALL-forcing correlations in the 2030s (Figure 1e). These findings coincide with the time of emergence of the GHGs-forced increases in ALL-forcing precipitation (Figures 1a and 1b). We observe similar results over North Central India (Figure S6 in Supporting Information S1), the climatologically wetter sub-region of South Asia (Figure S3 in Supporting Information S1). Further, our results are sensitive to the definition of noise; observed estimates of noise result in later emergence (Figure S7 in Supporting Information S1).

3.2. Spatial Pattern of Emergence in Seasonal Precipitation

The time of emergence of ALL-forcing precipitation varies widely across South Asia in all seasons (Figure 2). In the monsoon season, the combined effects of AAER and GHGs are evident in the spatial pattern of precipitation emergence (Figures 2a–2c and 2j–2l). Emergence in ALL-forcing precipitation occurs in the 1980s over the northwestern region and parts of southern India, after the 2040s in parts of the western and northeastern regions and after the 2080s in central India (Figure 2a). GHGs-forced precipitation shows emergence over central India by the early-21st century (Figure 2b), indicating that the lack of emergence in ALL-forcing is due to the offsetting influence of aerosols. The pattern of precipitation changes in 2020–2049 confirms that the signal in ALL-forcing does not exceed noise due to the offsetting influences of GHGs and AAER. The observed wetting over northern India and Pakistan and drying over parts of southern India are consistent with the AAER-forced changes and the time of emergence in AAER (Figures 2c and 2l). By 2050–2079, ALL-forcing precipitation intensifies significantly over parts of northeastern and central South Asia due to the dominant wetting influence of GHGs (Figure S8 in Supporting Information S1).

Likewise, ALL-Forcing precipitation emergence in the post-monsoon season is shaped by AAER and GHGs (Figures 2d–2f and 2m–2o), with increased precipitation over northwestern South Asia by 2020–2049 and across South Asia by 2050–2079 (Figure 2m; Figures S8d and S8e in Supporting Information S1). The forced signal emerges in the late-twentieth to early-21st century over northwestern South Asia and in the 2060s over parts of central and southern India (Figure 2d). GHGs-forced wetting emerges over central and southern India by the 2040–2050s (Figure 2e, Figure S8 in Supporting Information S1). However, the AAER-forced drying offsets the influence of GHGs during 2020–2049 over central, southern, and eastern South Asia, suppressing precipitation intensification in ALL-forcing by a decade (Figures 2e, 2f, 2n and 2o). In the pre-monsoon season, ALL-forcing precipitation resembles the GHGs-forced emergence patterns, with increased precipitation across the Indo-Gangetic Basin and northeastern India in 2020–2049 and 2050–2079 (Figure 2g–2i, 2p–2r; Figures S8g–S8h in Supporting Information S1). The signal of GHGs forcing emerges in these areas around the 2020s.

3.3. Local Versus Remote Aerosol Influence on Seasonal Precipitation

Our analysis indicates that aerosols will shape precipitation changes over South Asia in coming decades, though their influence may differ from the twentieth century because of geographical shifts in aerosol burdens (Samset et al., 2019). In the RCP8.5 CESM1-LE simulations, regional-average AOD over South Asia increases until ~2030s in all seasons and then stabilizes (Figures 3a–3c, Figure S1 in Supporting Information S1), while remote AOD starts declining by the 2000s in the monsoon season and after the 2020s in other seasons, likely associated with potential air-quality regulations over North America, Europe, and East Asia (M. Li et al., 2017). Regional-average precipitation in AAER during the monsoon and post-monsoon seasons declines over the twentieth and early-21st century, stabilizing around the same time as local AOD (Figures 3a and 3b, Figure S1 in Supporting Information S1). Since both local aerosols and remote aerosols can modulate rainfall over South Asia (Singh et al., 2019), we employ multiple linear regression to quantify the relative influence of local and remote aerosols on AAER-forced precipitation changes in CESM1-LE.

Local and remote aerosols have substantial influence during the monsoon and post-monsoon seasons throughout the 20th and 21st century (Figures 3d–3f). However, their relative contributions are still uncertain (Guo et al., 2015; Krishnan et al., 2016; Liang et al., 2016; Shindell et al., 2012). We find that during the monsoon season, local aerosol loading suppresses precipitation, while remote aerosol loading enhances precipitation over South Asia (Figure 3d), consistent with Singh et al. (2019). Local aerosols weaken the monsoonal circulation and rainfall through aerosol-precipitation interactions, while NH cooling associated with remote aerosols shifts the ITCZ southward altering rainfall over India (Z. Li et al., 2016; Singh et al., 2019). The drying impact of local AOD remains stationary throughout the study period, while the influence of remote AOD weakens through the 21st century, possibly due to geographic shifts in aerosol loading or warming suppressing their influence (Figure 3d). In the post-monsoon season, local and remote AOD has a drying and wetting influence on precipitation, respectively (Figure 3e). Their influence is strongest in the early part of the record, weakens until the 2020s and strengthens thereafter. During the pre-monsoon season, both local and remote AOD coefficients are small and negative (Figure 3f).

Local AOD changes strongly influence monsoon and post-monsoon precipitation in 2020–2049, affecting a larger number of grid cells across South Asia (Figures 4a–4c). Regression coefficients of local AOD are significantly negative across most of South Asia in the monsoon season, across southern, central, and northeastern areas in the post-monsoon season, and in southern India during the pre-monsoon season (Figure S9a–S9c in Supporting Information S1). Consequently, local AOD increases contribute to significant precipitation reductions over these areas during 2020–2049 (Figures 4d–4j). Remote AOD shows a weak influence on precipitation changes, except for precipitation enhancement over northwestern South Asia during the monsoon season (Figures 4e–4k; Figures S8d–S8f in Supporting Information S1), largely arising from neighboring land regions (Figure S10 in Supporting

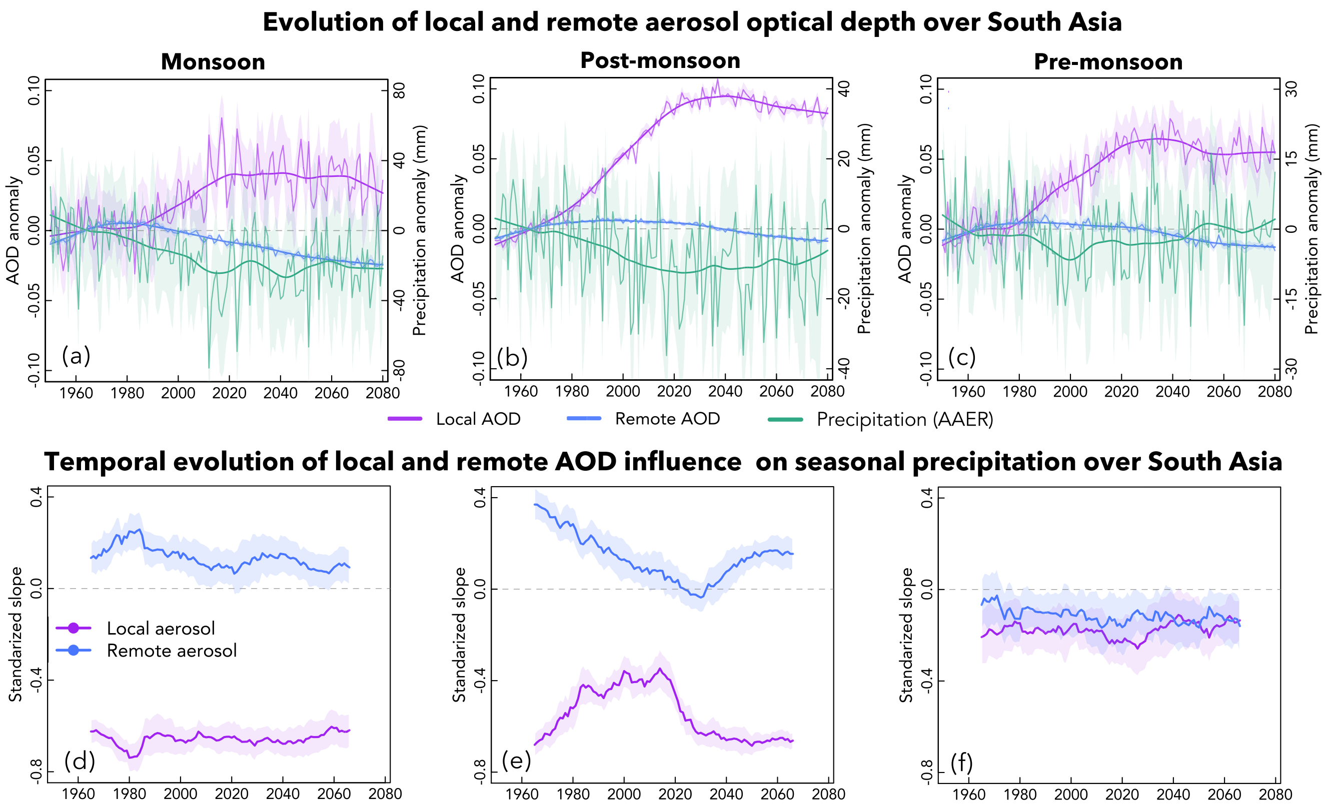

Figure 3. Local and Remote Aerosol Loading. (a–c) Seasonal AOD and precipitation anomalies (thin lines) relative to 1950–1979 and 30-year moving average anomalies (thick lines). (d–f) Standardized slope of local and remote AOD anomalies from regressions over each 30-year centered moving window. Shading in each panel shows the ensemble spread (ensemble mean $\pm 0.5\sigma$).

Information S1). During the post-monsoon season, opposing influences from over Europe and the eastern US relative to the Indian Ocean and parts of Asia, seem to cancel each other out. Thus, these AOD changes have a negligible influence on precipitation changes (Figures 3b and 4h). Overall, local AOD changes predominantly shape the spatial pattern of AAER-forced precipitation changes in all seasons. Further, local and remote AOD contributions explain most of the AAER-forced precipitation changes in 2020–2049 across South Asia, except in high terrain areas such as western Himalayas and Western Ghats in the monsoon season (Figures 4f–4l).

4. Summary and Discussion

Future aerosol trajectories have important implications for changing seasonal rainfall patterns over South Asia and other regions, yet their effects are understudied. Wilcox et al. (2020) demonstrate that reducing aerosols emissions could enhance Asian summer monsoon precipitation by 2050 under the SSP2-4.5 scenario. However, the time of emergence of the GHG-forced signal across South Asia and the relative influence of local versus remote aerosols on future precipitation patterns have not yet been quantified in various seasons. Our study makes the following novel contributions toward understanding these different anthropogenic factors influences the future trajectory of South Asian precipitation patterns. *First,* anthropogenic aerosols-related drying is likely to suppress the emergence of precipitation increases due to GHGs by up to 5 decades in the monsoon season and 1 decade in the post-monsoon season. *Second*, future precipitation changes during these seasons are likely to differ from the historical period during which the spatial pattern of changes was dominated by aerosols. Under the RCP8.5 scenario, monsoonal precipitation patterns will transition from aerosol-driven to GHGs-driven by the mid-21st century, consistent with Wilcox et al. (2020). *Third*, local aerosols have a stronger influence than remote aerosols on precipitation patterns in the monsoon and post monsoon seasons and the strength of influence of the local aerosols remains largely stationary.

We highlight several limitations of this study. Our analysis relies on a single model with a single future emissions scenario—RCP8.5, due to limited availability of "all-but-one-forcing" simulations from other models.

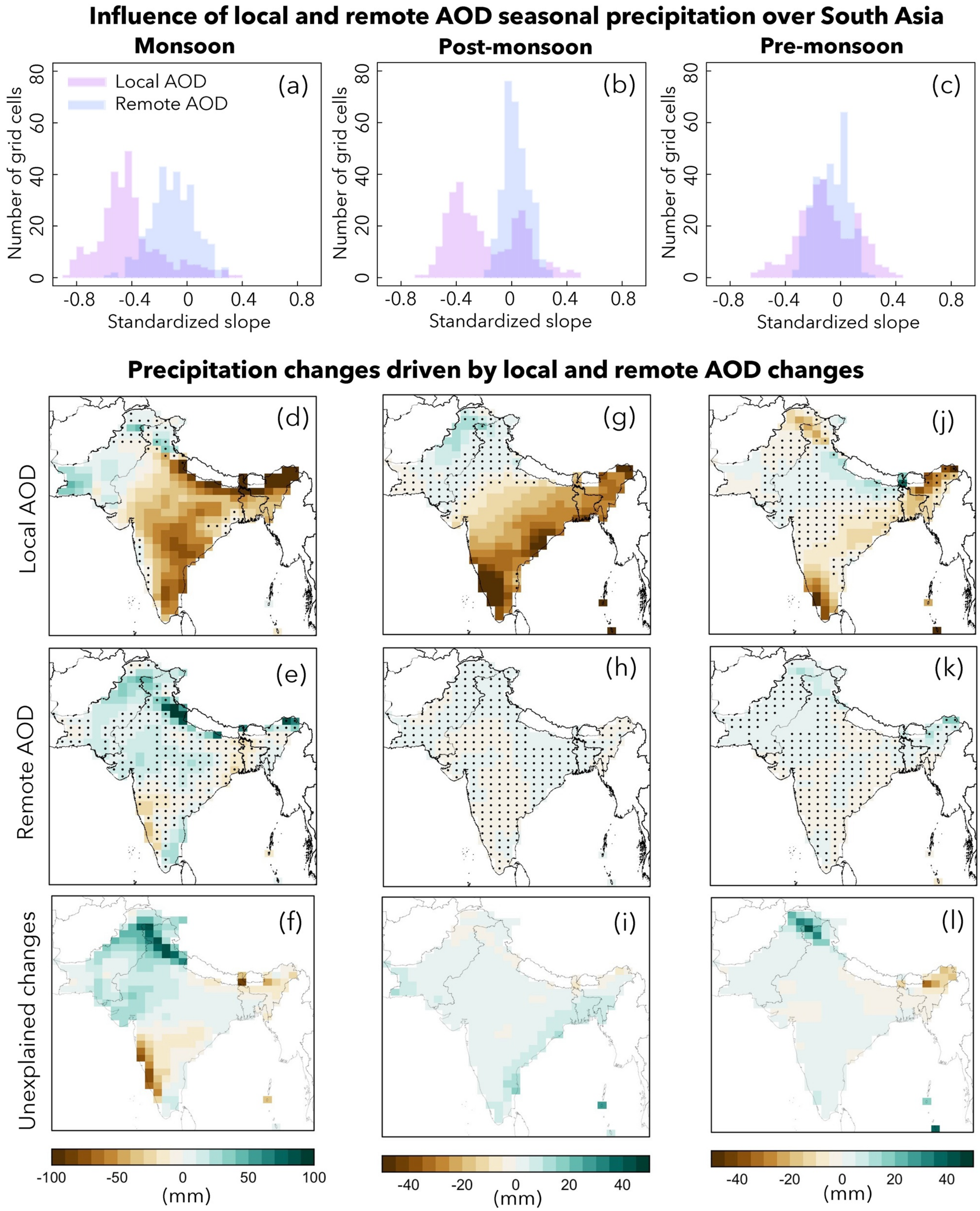

Figure 4. Contributions of local and remote aerosols to aerosol-forced precipitation changes in 2020–2049: (a–c) Distribution of standardized slopes of local and remote AOD from the multiple linear regression (refer Figure S9 in Supporting Information S1 for standardized coefficients maps). (d–k) Precipitation changes driven by local and remote AOD changes in each season relative to 1950–1979. Dots indicate grid cells with insignificant (at 5% significance level) influence from local and remote AOD on precipitation. (f, i, and l) AAER-precipitation changes unexplained by local and remote AOD changes.

Quantifying the inter-model uncertainties in precipitation responses to various forcings and consequently, the time of emergence of the forcing signal, would require a larger suite of models. Further, the simulations used here don't account for irrigation's influence on precipitation changes, which could alter monsoon precipitation patterns through regional land-atmosphere dynamics (Cook et al., 2020; McDermid et al., 2023). Additionally, the RCP8.5 scenario represents an increasingly unlikely high-emissions future (Hausfather & Peters, 2020), due to the ongoing transition to renewable energy resources and the goal of ~30% cut in methane emissions by 2030 (Allen et al., 2021). While our findings are based on the RCP8.5 scenario, they can still offer insights into climate responses to various forcing (Schwalm et al., 2020). Further, the overall global mean temperature response under this scenario does not deviate substantially from medium emissions scenarios until the mid-21st century (Lee et al., 2023; Lund et al., 2019) and sulfate emissions from South Asia increase in SSP2-4.5 and SSP3-7.0 over this time period (Guo et al., 2021). Further, projected near-term reductions in both aerosol emissions under measures to improve air quality could offset the benefits of lower GHGs forcings in the current trajectory when compared to the RCP8.5 scenario (Quaas et al., 2022). Aerosol trajectories in different future scenarios are highly uncertain over South Asia (Lund et al., 2019), yet there is an urgent need to understand how they could influence one of the region's most critical resources. Ongoing efforts such as Regional Aerosol MIP would be valuable for assessing such climatic responses to possible regional aerosol trajectories and their uncertainties (Wilcox et al., 2022).

Local air pollution emissions will determine the near-term evolution of South Asian climate along with GHGs. Therefore, understanding such aerosol-climate interactions is relevant for informing regional stakeholders to plan for associated consequences over South Asia. Aerosol buildup before and during monsoon has already negatively affected agricultural production across the Indo-Gangetic Plains, India's breadbasket (e.g., Burney & Ramanathan, 2014). Our results indicate that if aerosol emissions continue to increase, precipitation could decrease in the near-term over parts of South Asia rather than increase in response to GHGs alone, further exacerbating such negative effects on agriculture. Nevertheless, GHGs-induced wetting is likely to emerge by the mid-21st century under the RCP8.5 scenario as aerosol emissions stabilize, causing precipitation increases in all three seasons and these increases could be amplified if aerosols concentrations decline faster than estimated under this scenario. Anticipating such potential non-linear precipitation trajectories are critical for ensuring food security, water security, and resilience in South Asia.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

All datasets used in this study are publicly available. Observed precipitation datasets from Global Precipitation Climatology Centre are available at https://psl.noaa.gov/data/gridded/data.gpcc.html and from Climatic Research Unit are available at https://crudata.uea.ac.uk/cru/data/hrg/cru_ts_4.05/cruts.2103051243.v4.05/pre/. The CESM1 ALL-forcing and all-but-one-forcing LE simulations are available from http://www.cesm.ucar.edu/projects/community-projects/LENS and http://www.cesm.ucar.edu/experiments/cesm1.1/LE/#single-forcing, respectively.

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