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Key Points:
- *Drying-wetting-drying* trend over India, Southern China, and Northern China is observed in the last few decades of the 20th century
- Previous work failed to give a holistic explanation for three regions simultaneously, while this study attributes observed trend to aerosol
- The CMIP5 models with more complex treatment of aerosol-cloud interaction capture the observed pattern better

Supporting Information:
- Supporting Information S1

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Changes in Extreme Rainfall Over India and China Attributed to Regional Aerosol-Cloud Interaction During the Late 20th Century Rapid Industrialization

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Abstract Both mean and extreme rainfall decreased over India and Northern China during 1979–2005 at a rate of 0.2%/decade. The aerosol dampening effects on rainfall has also been suggested as a main driver of mean rainfall shift in India and China. Conflicting views, however, exist on whether aerosols enhance or suppress hazardous extreme heavy rainfall. Using Coupled Model Intercomparison Project phase 5 (CMIP5) multimodel ensemble, here we show that only a subset of models realistically reproduces the late-20th-century trend of extreme rainfall for the three major regions in Asia: drying in India and Northern China and wetting in Southern China, all consistent with mean rainfall change. As a common feature, this subset of models includes an explicit treatment of the complex physical processes of aerosol-cloud interaction (i.e., both cloud-albedo and cloud-lifetime effects), while simulation performance deteriorates in models that include only aerosol direct effect or cloud-albedo effect. The enhanced aerosol pollution during this rapid industrialization era is the leading cause of the spatially heterogeneous extreme rainfall change by dimming surface solar radiation, cooling adjacent ocean water, and weakening moisture transport into the continental region, while GHG warming or natural variability alone cannot explain the observed changes. Our results indicate that the projected intensification of regional extreme rainfall during the early-to-mid 21st-century, in response to the anticipated aerosol reduction, may be underestimated in global climate models without detailed treatment of complex aerosol-cloud interaction.

Plain Language Summary Over Asia, a robust pattern of *drying-wetting-drying* trend over three most populated regions (India, South China, and North China, respectively) have been observed in the past few decades. Yet the cause of the 30-year trend is rather unclear, with conflicting arguments on the importance of natural variability, the greenhouse gas, land cover, and aerosols. Most of the previous studies, however, fail to provide a holistic explanation for all three major regions simultaneously. The aerosol-cloud interaction-induced oceanic cooling, as we show here, provides a critical piece in reproducing the past trend. Only a fraction of climate models with complex treatment of aerosol-cloud interaction capture the observed pattern; thus, unconstrained model data set provides biased outlook of extreme rainfall in this region.

1. Introduction

Extreme heavy rainfall and associated hazardous flooding lead to severe property damage and causality. Assessment of historical variability and trend in extreme rainfall provides constraints on the fidelity of model-based future projection, which has been widely used for urban planning and infrastructure design. The upward trend of 20th-century global extreme rainfall is largely attributed to anthropogenic emission of greenhouse gases (GHGs; Min et al., 2011) and is expected to continue into the 21st century (Sanderson et al., 2017). At the regional scale like Asia, trend in extreme rainfall (e.g., RX1day, the average of 12 daily maximum rainfall in each month of the year) is quite spatially heterogeneous, but a general feature is drying over India and Northern China and wetting in Southern China in the late 20th century (see trends calculated under various time periods in Dash et al., 2009; Day et al., 2018; Ma et al., 2015; Singh et al., 2014).

Various explanations for multidecadal rainfall trend over Asia have been proposed such as internal climate variability of oceanic originating from Indian ocean (Roxy et al., 2015) or Pacific ocean (Li et al., 2010), GHG warming, and local land cover changes (Paul et al., 2016). The role of aerosols in modulating monsoonal rainfall was under also heavy investigation (Lau et al., 2008; Li et al., 2016; Liu et al., 2017), motivated by a strong increase in anthropogenic aerosol emission associated with rapid economic growth of the two most populous nations (Smith et al., 2011). Anthropogenic aerosols have been long recognized as a major forcer of global climate (Charlson et al., 1992; Ramanathan et al., 2005), with discernible influences on globally averaged rainfall (Salzmann, 2016). Numerous modeling studies also found aerosol perturbation tends to mute regional rainfall (Bollasina et al., 2011; Li et al., 2015; Ramanathan et al., 2005; Zhang et al., 2017; Zhang & Li, 2016) over Asian regions, with ocean temperature adjustment playing a critical role (Ganguly et al., 2012; Xu & Xie, 2015). Aerosols' role on extreme rainfall, however, is rather unclear. Studies have suggested that aerosols tend to suppress light rainfall and thus facilitate a shift of rainfall toward heavy events (Qian et al., 2009; Y. Wang, 2015), while our recent work drew opposite conclusions showing a strong suppression effects for various definitions of extreme rainfall (L. Lin et al., 2016; Z. Wang et al., 2016). Specifically, L. Lin et al. (2016) showed that aerosol perturbation leads to a global reduction of mean rainfall, RX1day, the monthly maximum consecutive 5-day precipitation (RX5day), the total precipitation from the days with daily precipitation exceeding 95th percentile of daily rainfall distribution (R95p), about 18 days in a year), and the number of days with daily precipitation more than 10 mm (R10). Moreover, the sensitivity of change (%/°C) due to aerosol is several times larger than GHGs that enhance the rainfall.

In resolving this apparent contradiction in aerosols' role, our analysis here aims to provide a holistic explanation for the entire Asia, which is often missing in previous studies that are usually limited to either East Asia (Day et al., 2018; Menon et al., 2002; Y. Wang et al., 2016) or South Asia (Bollasina et al., 2011; Singh et al., 2014). It is also noteworthy that to remove the subjective nature of region selection with arbitrary rectangular boxes in many studies, all following results are based on the boundary of each nation and the long-recognized climatic division of Northern and Southern China (see Methods in the supporting information for details).

2. Results

2.1. Observational Extreme Rainfall Trend

Based on various reanalysis products and observational data set, the late 20th century to early 21st century (1979–2005) decline of extreme rainfall over India and Northern China is at 0.3 mm/decade (0.2%/decade), while the wetting over Southern China is at 0.2 mm/decade (Figure 1). The general pattern of *drying-wetting-drying* remains the same for mean rainfall (Figure S1**,** bottom panels) and extreme rainfall under a weaker definition (RX5day in Figure S1**,** top panels), but with smaller magnitude at 0.1–0.2%/decade. The change in RX1day is more heterogeneous than RX5day or mean rainfall (Ghosh et al., 2012), which justifies our use of normalized EOF1 in Figure 1 to extract the dominant pattern of long-term trend. The same pattern of *dry-wet-dry* is also evident in the decadal trend calculated at each grid points (Figure S2 with stippling indicating significant changes). It is also important to note although the various observational data sets (Table S1) embody a range of uncertainty for the late 20th-century trend (individual panels in Figure S3), the general agreement among the eight data sets is high with a pattern correlation amounting at 0.5 to 0.8.

2.2. Change in Extreme Rainfall in Different Groups of Coupled Model Intercomparison Project Phase 5 Model Simulation

Figures 1a–1c divide all Coupled Model Intercomparison Project phase 5 (CMIP5) model experiment driven by all historical forcing (GHGs, aerosols, ozone, and natural forcing) into three groups based on model treatment of aerosol-cloud interaction following Ekman (2014) and C. Wang (2015) (see Methods in the supporting information for the detailed criteria and Table S2 for the list of models in each group). Although all models reasonably simulate the climatological rainfall (Figure S4), Group A models (with direct effect only) has completely missed the main features of regional rainfall trend with a simulated wetting trend at India (0.2%/decade) and Northern China (0.1%/decade; Figure 1a), leading to a negative pattern correlation with observed trend (Figure 2a). The model performance improves when more complicated aerosol-cloud schemes are included. Especially when cloud-albedo and cloud-lifetime effects are both present (Group C), trend in all three major regions are well captured (Figure 1c), with a negative trend of RX1day for India (−0.1%/decade) and Northern China (−0.1%/decade) and a strong wetting trend over Southern China (0.2 mm/decade).

The pattern correlation between Group C models and observation is significantly positive, despite a small value of 0.1–0.2 (Figure 2a). The small value is understandable, because the anomaly center is not precisely at the same location in model and observation despite a broader agreement of regional trend. However,

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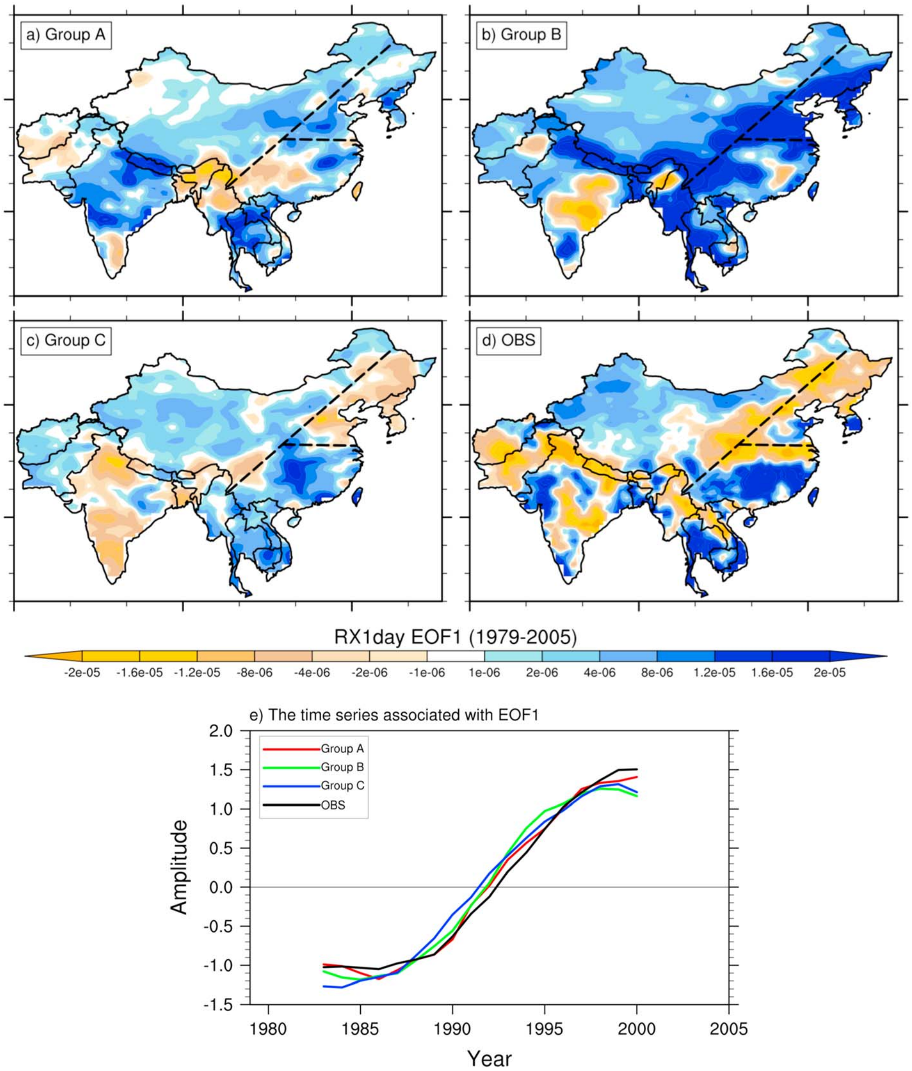

Figure 1. (top) Leading EOF pattern (unitless) of RX1day change (1979–2005) in (a–c) CMIP5 model simulations and (d) multiple sets of observations. The simulations are driven by all historical forcing, but the 12 models in Group A (a) include only aerosol direct effect, the five models in Group B (b) include both direct and cloud albedo effects, and the 14 models in Group C (c) additionally include cloud lifetime effects. (e) The standardized time series of RX1day associated with EOF1.

considering the noise level (horizontal shadings in Figure 2a) indicated by the pattern correlation between a large sample of 27-year trends in the preindustrial control simulation (Figure 2d) and observation, the positive pattern correlation between Group C and observation in Figure 2a is deemed significant, while the pattern correlation for the other two groups is close to zero or negative. Similar results are also found when the temporal correlation of rainfall time series (1979–2005) is compared. Although there are larger correlation values of 0.4 to 0.6, only Group B and C simulations are significantly positive (see Figure S14 for more details).

Previous attribution studies based on global climate model experiments with *all forcing*, *GHG-only*, and *aerosol-only* concluded that aerosols provide a critical piece in properly simulating long-term trend of mean rainfall (Bollasina et al., 2011), which is reaffirmed for extreme rainfall (RX1day) here in Figure S5. The first-row panels of Figure S5 show that GHG warming tends to enhance regional rainfall (except for a slight drying over Southern China), which is completely contrary to the observations. On the other hand, the *all minus GHG* response is highly similar to the observation (Figure S5, third row), especially for the Group C models. The aerosol-only forcing tend to suppress land rainfall (Figure S5, second row), consistent with numerous

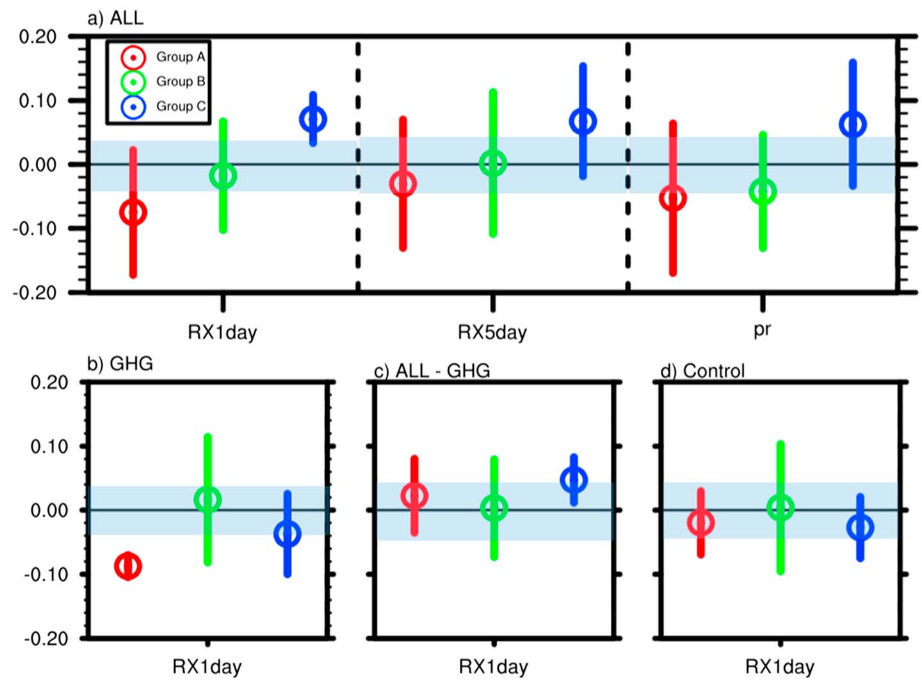

Figure 2. (a) The pattern correlation between the simulated trend in historical simulation (all forcing: Groups A, B, and C) and the observation for RX1day (as shown in Figure S2), RX5day, and mean rainfall over India, Northern China, and Southern China (the pattern correlation calculated over entire Asia is similar). The vertical lines denote one standard deviation. Note that Group C models always have a positive pattern correlation with observation. (b–d) Same as RX1day in (a) but for GHG-only, all minus GHG, and PI control (spatial patterns of trends shown in Figure S5). The horizontal blue shading is shown as the noise level, which is calculated as the pattern correlation coefficient between PI control simulation and observation in (d).

studies on both South and East Asia regions. Therefore, we infer from the single forcing analysis that the drying tendency due to aerosols serves as the key ingredient for the models to reasonably capture the observed trend, although we cannot completely rule out the role of other forcings (such as volcano or ozone) due to data availability.

The contribution of natural variability to regional rainfall trend can be profound especially for a shorter period (e.g., the recent intensification of mean rainfall over South Asia since early 2000s; Myhre et al., 2015), thus making attribution to external factors (if any) difficult. The possible argument that the observed drying-wetting-drying pattern is caused by natural variability alone needs scrutiny. In Figure 2d, we randomly sampled many 27-year periods in the preindustrial control simulation from 22 available models (mean pattern shown in Figure S5, fourth row, with an expected minimal trend due to random phase cancellation), and we calculated pattern correlation between simulated and observed 1979–2005 trend. The closer-to-zero pattern correlation in the preindustrial control simulation (Figure 2d) dismisses the explanation that observed trends can be due to natural variability alone. In contrast, under the aerosol-only forcing, Group C models (Figure 2c) has a higher positive pattern correlation than GHG-only simulation (Figure 2b). This leads to a better performance of the Group C models in the all-forcing historical simulation (Figure 2a, and see Figure S6 for consistent results of other precipitation metrics).

2.3. The Importance of Simulating Complex Aerosol-Cloud Interaction

The difficulty of models with aerosol direct effect alone (Group B in Figure 1) to capture the century-long temperature trend is well known. CMIP3-class models (most of which did not include aerosol indirect effect) tended to overestimate the 20th-century global warming. Motivated by this, many CMIP5 models include aerosol indirect effects (Table S2) but with different levels of complexities. Some only considered the cloud-albedo effects through which aerosols increase cloud droplets number and thus cloud brightness, while some further included the formulation that smaller cloud droplets prolong cloud lifetime, which

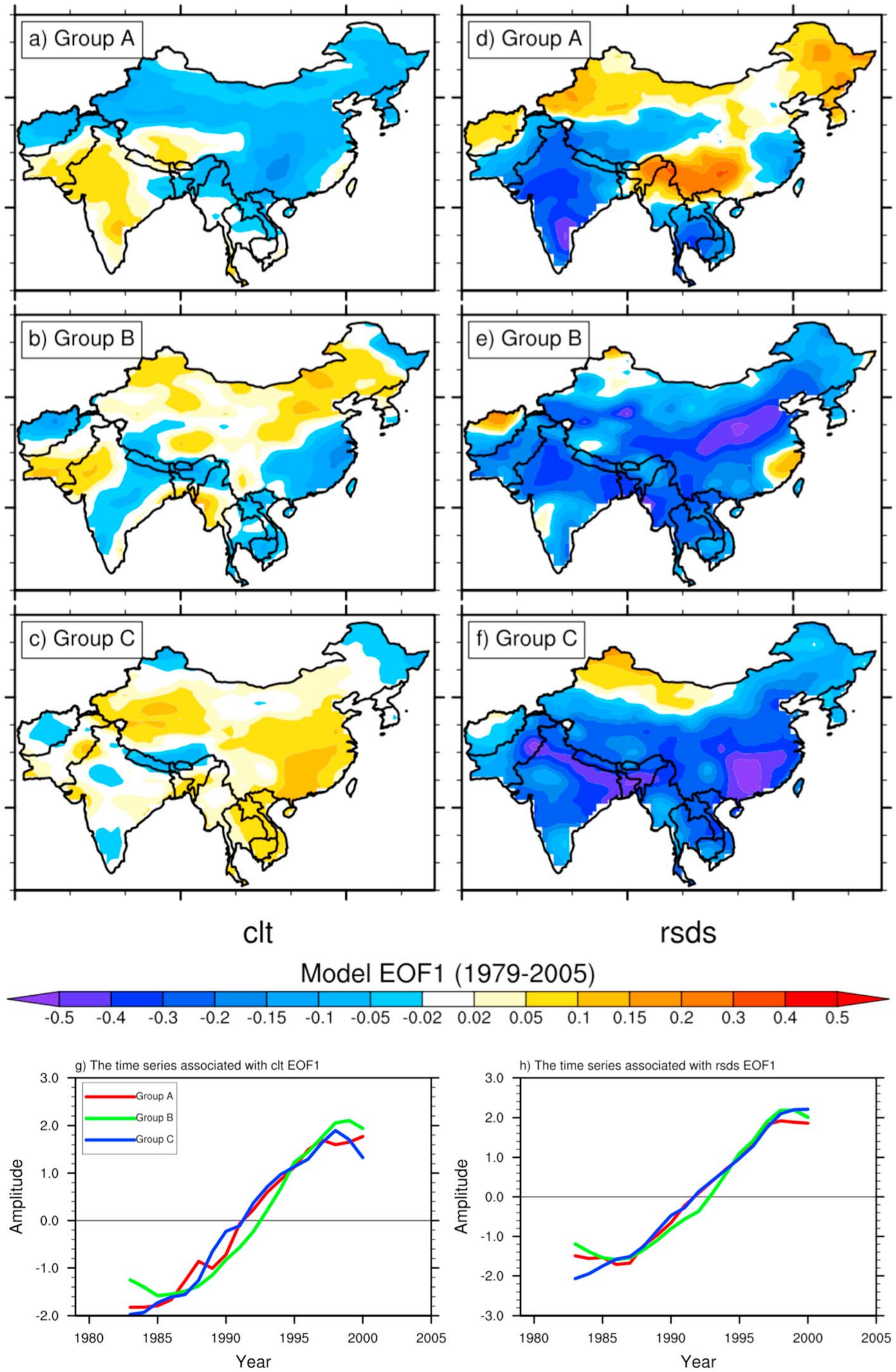

Figure 3. Leading EOF pattern (unitless) of total cloud fraction (*clt*, a–c on the left) and surface downward shortwave radiation flux (*rsds*, d–f on the right) in model simulations. All simulations are separated into the three model groups as in Figure 1, with 12, 5, and 14 members, respectively. The standardized time series associated with EOF1 are shown in the bottom.

boosts cloud cover fraction and thus stronger solar radiation reflection. We next show a suite of diagnostics to demonstrate why Group C models outperform their peers in capturing long-term extreme rainfall trend.

The increase in cloud fraction is found to be largest in Group C, in contrast to Group A models that simulate a decrease in cloud cover over China (Figure 3). The larger increase in cloud fraction (0.5–1.5%/decade; Figure S7c) leads to surface radiation decrease (Figure 2f), consistent with the observational record (Table S4). The

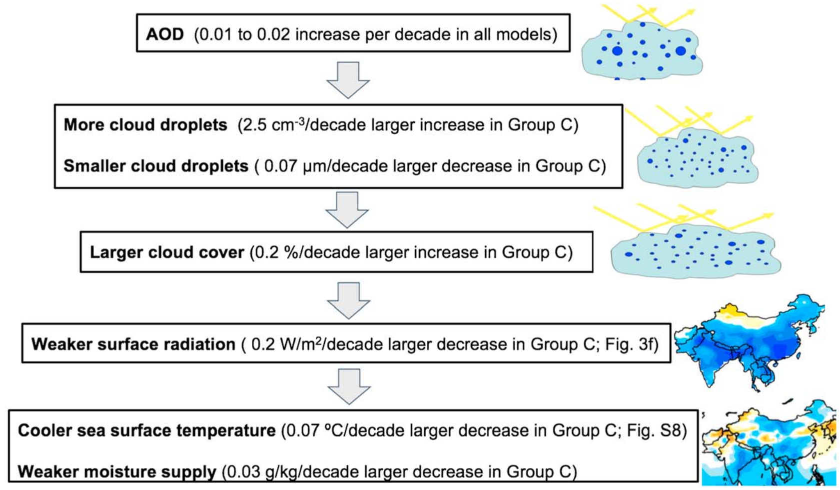

Figure 4. A schematic summarizing the impact of aerosols on cloud microphysics and macroproperties and then radiation budget and large-scale climate, which gives rise to the strong responses in mean and extreme precipitation. The numbers (mostly showing the difference between Group C models and other models) are extracted from the regional average in Table S4.

surface *dimming* cools land and adjacent ocean (Figure S8, left), more so in Group C models, with less oceanic evaporation and weaker atmospheric moisture inflow (Figure S8, right) that spawns changes in extreme rainfall.

The aerosol effect on cloud microphysics, cloud cover, and consequently on large-scale dynamics are summarized in Figure 4. In Group B models, aerosol effect on cloud albedo is prescribed in simple formulas as opposed to the explicit treatment of microphysical processes as in Group C. The larger cloud cover increase (by 0.2% per decade) and stronger dimming effects (by 0.2 W/m^2 per decade; Figure 3e) as in Group C models suggest that the cloud-lifetime effect is critical in the overall negative radiative forcing of aerosols. The main reason for the underperformance of Group B models is that although the aerosol trend is similar across all three groups (Figure S7, right), effective cloud droplet radius decreases by 0.1% for Group C models that is consistent with larger cloud droplet numbers (increase by 0.2%; Figures S9b and S9d). The changes in these microphysical properties are completely missing in Group B models (see large white areas in Figures S9a and S9c). To confirm the logic chain of *cloud microphysics* -> *cloud cover* -> *radiation budget* as summarized in Figure 4, we also show in Figure S10 that within the 14 Group C models, those with larger cloud droplet number concentrations tend to reduce cloud droplet size and simulate a larger the cloud cover, which eventually produces a stronger dimming effect at the surface.

How robust is the physical argument made above? While the aerosol effects on microphysical properties are well known in many in situ studies, the long-term change in cloud macroproperties due to aerosols (as depicted by the arrow from Boxes 2 to 3 in Figure 4 and large cloud cover increase as simulated by Group C models; Figure S7c) is more uncertain, potentially due to the buffering effect from the covarying meteorological conditions, distinctive responses from different cloud types (e.g., stratus, shallow cumuli, and deep convective clouds), and nonlinear feedback from large-scale dynamics (Fan et al., 2016; Y. Lin et al., 2016; Seifert et al., 2015). A previous study also found that in an atmosphere-only simulation (using Community Earth System Model version 1-Community Atmosphere Model 5, CESM1-CAM5), the long-term cloud fraction evolution in Asia is not sensitive to aerosol perturbation when the ocean temperature is not responding (Y. Wang et al., 2016).

Since our analysis aims to provide a unified explanation to the India and China trend, we did not explicitly discuss the East Asia monsoon (or South Asia monsoon) response. However, the muted land-ocean thermal contrast (Figure S8, left column) and weakened monsoonal circulation (shown as the surface wind vector in Figure S8, right column) in response to a stronger aerosol forcing (hereby inferred as Group C minus Group A/B in Figure S8) generally agrees with previous CMIP5 analysis in the larger land cooling (e.g., Figure 3f in

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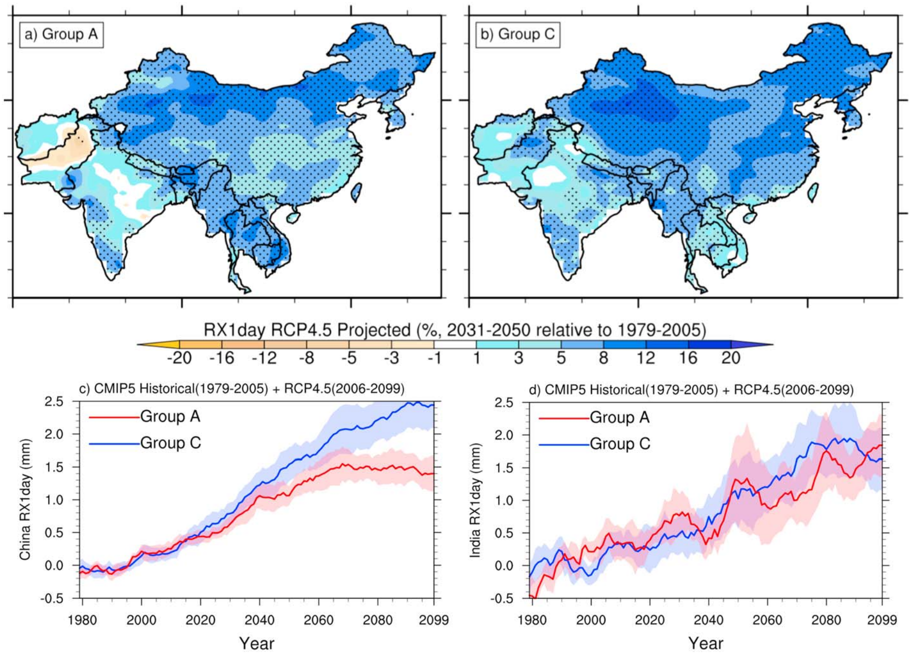

Figure 5. (a and b) Model projected relative changes in RX1day (unit: %) between present-day (1979–2005) and mid-21st century (2031–2050) under RCP4.5 scenarios for Groups A and C. Regions where changes are significant at ≥90% confidence level from a two-sided *t* test are stippled. (c and d) Model simulated RX1day (unit: mm, relative to the 1979–2005 average) over China and India. The red and blue shadings denote one standard deviation of models in Groups A and C.

Song et al., 2014) and wind anomaly from the coast toward the ocean (e.g., Figure 2f in Song et al., 2014). The India portion also shows similar enhanced land cooling and southward wind anomaly (Figure S8).

2.4. Implications for Future Projections of Regional Extreme Rainfall

The end of century climate change would be dominated by GHG forcing and fundamental properties of the atmosphere (such as cloud dynamics and convection) because of the diminishing aerosol forcing (Myhre et al., 2015). But it should be noted that since the developing world is going through a rapid *clean air* process like the Western world experienced since the 1970s, the transition in next few decades might be a unique period in human history when a major anthropogenic climate forcing reverses its course (another example being the recovery of ozone hole). We here examine the implication of our results on future projection of regional extreme rainfall.

Group C models with larger aerosol cooling in the past and a better performance in capturing extreme rainfall trend project a stronger future increase in Asia extreme rainfall (Figure 5). Under a moderate emission scenario (Representative Concentration Pathway 4.5, RCP4.5), increase in RX1day projected by Group C models is 2 mm at 2031–2050 (14% of present-day value), 50% larger than projected by Group A models. Note that the anthropogenic aerosol emissions in the most developing countries (including China) is expected to decrease in the first half of the 21st century, but the temperature response (and thus precipitation increase) will lag the forcing change. This explains why the difference between the Groups A and C continue to be prominent throughout the second half of the 21st century (China in the Figures 5c and S11c for the RCP8.5 case). On the other hand, South Asia emission will not decrease until later 21st century; thus, it has small effect on enhancing the rainfall, which explains the little difference between Group A and C projections (Figures 5d and S11d).

3. Summary

Changes in occurrence of rainfall extreme events are important for climate adaption and infrastructure planning. Over Asia, a robust pattern of drying-wetting-drying over three most populated regions (India, South China, and North China, respectively) has been consistently shown in previous studies. Yet the cause of the 30-year trend during the last few decades of the 20th century is rather unclear, with conflicting arguments on the importance of natural variability, the GHG, land cover, and aerosols. Most of the previous studies, however, fail to provide a holistic explanation for all three major regions simultaneously, which is the objective of our study.

The main conclusion of our climate model-based analysis is that aerosol emission, which increases rapidly during the last few decades, provides the main driving force to the regional precipitation changes, while the GHGs and natural variability fail to explain the changes in all three regions. Beyond the conclusion that models with aerosol forcing can better simulate the rainfall trend, we go one step further to show that models with advanced treatment of aerosol-cloud interaction (e.g., cloud lifetime effect) can better capture the rainfall trend. This suggests the inclusion of complex parameterization schemes in CMIP5 models, often developed based on small-scale process studies, eventually leads to major improvement of simulating large-scale long-term trend of climate, an encouraging sign for the climate modeling community.

We lastly comment why the trend over 1979–2005 is the focus of this attribution analysis. There are two reasons the starting year of our analysis is set to 1979. (a) Four of the eight data sets used here that have daily rainfall records only started from 1979, including the APHRODITE direct observations. (b) Our analysis aims to answer the question of whether anthropogenic aerosols play a role in the decadal trend of climate. Thus, we want to maximize the forcing within the examined period. Extending the analysis back into mid-20th century is not helpful because the rapid industrialization (and aerosol emission) only started in the end of 1970s (especially for China).

The 1979–2005 period (*historical* as defined in CMIP5 protocol) witnessed rapid increases in aerosol emission at an unprecedented rate over Asia. For the *future* 2005–2015 era, CMIP5 global climate models assumed a slight increase or level off in the emission (Figure S12), while the satellite observations suggest different trajectories (especially for India; Figure S13a). The potential inconsistency in model assumption and recent observations precluded an accurate assessments of aerosol effects during the more recent period (i.e., after 2005). The next generation of CMIP6 models provide an emerging opportunity to advance our understanding of aerosol impact on extreme rainfall, because (a) they are driven by updated aerosol emission changes (with a stronger increase over Asia up to 2015, as in orange line in Figure S12) and (b) some of them include additional microphysical effects on deep convection system (Rosenfeld et al., 2008) that are potentially important for occurrence of extreme events (Fan et al., 2015), especially working in conjunction with absorbing aerosols (Lau & Kim, 2006).

While the cloud microphysical research community has provided ample evidence that individual storms may be enhanced by the presence of aerosols (e.g., biomass burning or dust), the novelty of our study is that it clarifies the contradicting views of aerosol influence on the long-term change in extreme rainfall. With the detailed diagnostics in our paper that relate microphysical properties, cloud fraction, radiation budget, and climate circulation, we emphasize the cooling and dampening role of aerosols. This study bridges the knowledge gap between two communities and is likely to spur new analysis over other regions/periods, especially when the upgraded CMIP6 model results become available.

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