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Anthropogenic aerosols and the weakening of the South Asian summer monsoon

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Observations show that South Asia underwent a widespread summertime drying during the second half of the 20th century, but it is still unclear whether this prolonged trend was due to natural variations or human activities. Here we use a series of climate model experiments to investigate the South Asian monsoon response to natural and anthropogenic factors. We find that the observed precipitation decrease can be attributed almost entirely to man-made aerosols. The drying is a robust outcome of a slowdown of the tropical meridional overturning circulation, which compensates for the aerosol-induced energy imbalance between the northern and southern hemispheres. These results provide compelling evidence of the prominent role of aerosols in shaping regional climate change over South Asia.

The South Asian summer monsoon provides up to 80% of the annual mean precipitation for most regions of India, and has tremendous impacts on agriculture, health, water resources, economy, and ecosystems throughout South Asia (*1*). It is also an important part of the global-scale atmospheric circulation, as its vigorous ascent dominates the boreal summer tropical meridional overturning (the Hadley circulation) (*2*), and has profound remote influences (*3*). A possible long-term (decadal to centennial) shift in monsoon rainfall associated with climate change could have even more far-reaching consequences for the region than natural variations. A number of observational studies have investigated the multi-decadal trend of monsoon rainfall over India, and found a persistent drying trend during the second half of the 20th century (*4–7*). Yet, the root cause of this trend remains unclear.

Both aerosols and greenhouse gases can affect the South Asian summer monsoon. The increase of aerosols and associated decrease in surface solar radiation ("dimming") over South Asia have been well documented (*4, 8*). Climate model experiments suggested that sulfate aerosol may significantly reduce monsoon precipitation (*9*). Recent studies, some of which focused specifically on absorbing aerosols (*4, 8, 10, 11*), postulate as possible mechanisms both surface cooling from reduced surface solar radiation (and consequent reduction of the meridional thermal contrast between the northern and southern Indian Ocean (*5*)) and atmospheric heating due to absorption of solar radiation (*8*).

The warming caused by increased greenhouse gases, meanwhile, may also play a role. Annual mean tropical sea surface temperatures (SST) have increased on average by $\sim$0.5 K since the 1950s. This warming is particularly notable over the Indian Ocean (*12*). Tropical circulation (particularly its zonal component) is expected to weaken in response to an increase in surface temperature since global-mean precipitation, which is controlled by the overall atmospheric energy balance, cannot increase as fast as the lower tropospheric water vapor concentration (the thermodynamical scaling argument) (*13, 14*). Despite a weakening of the monsoon circulation, most studies projected an increase of the seasonal monsoon rainfall under global warming, partly owing to more abundant water vapor (*15*).

We utilize several long-term observational datasets of precipitation to identify possible recent trends in the South Asian monsoon (*16*). The boreal summer (June-September) climatological precipitation has a widespread maximum over central-northern India, which includes part of the vastly irrigated Indo-Gangetic Plain. Our initial focus is on this analysis region (76°-87°E, 20°-28°N), whose location and size are similar to those in (*22*). The CRU data show a marked reduction from the 1950s to the end of the 20th century (Fig. 1). The linear trend of -0.95 mm day^{-1} (50 years)$^{-1}$ is statistically significant at the 95% confidence level (p = 0.04) (*23*). Comparable drying trends are also seen for UDEL and PREC/L. This finding is broadly consistent with the previous studies (*5, 7, 25, 26*), which made use of additional datasets. Although the IMR data show a small downward trend, it is not statistically significant enough. The decrease amounts to 9-11% of the total monsoon rainfall received by the region for CRU, UDEL and PREC/L, and 2% for IMR (see Fig. S4 and SOM).

Even more interestingly, a coherent large-scale pattern emerges: a drying over central-northern India and most of Southeast Asia (consisting of Indochina and the Maritime Continent) coinciding with a wettening over southern India and over northwestern India and Pakistan (Fig. 2). This distinct spatial structure is consistent among the majority of the datasets (see Fig. S5 and SOM). Averaged over the whole country, the Indian summer rainfall underwent a reduction of 4-5% over 50 years (*4, 6, 7*).

Was this observed change of the South Asian monsoon precipitation caused by natural variability or human interference? If the latter, what were the relative contributions of aerosols and greenhouse gases, the two most important anthropogenic climate forcing agents? Answering these questions pose a challenging test case on our fundamental understanding of the core working of the Earth's hydrological cycle, and holds the key to a more reliable projection of regional climate change.

Ensemble simulations with a state-of-the-art coupled atmosphere-ocean global climate model (GCM) provide us a means to attribute the observed long-term trend. The model used here is the

U.S. National Oceanic and Atmospheric Administration (NOAA) Geophysical Fluid Dynamics Laboratory (GFDL) CM3 GCM, which includes an explicit treatment of the aerosol-cloud interactions and aerosol indirect effects (*27*). The model data analyzed in this study cover the period 1951-1999 and come mainly from three sets of historical simulations (1860-2005): (1) a five-member ensemble with all the forcings, natural (solar variations and volcanoes) and anthropogenic (well-mixed greenhouse gases, ozone, aerosols and land use) alike (ALL_F), (2) a three-member ensemble with greenhouse gases and ozone forcings only (WMGGO3), and (3) a three-member ensemble with aerosol forcing only (AERO). The ensemble simulations forced with all the natural forcings only and with all the anthropogenic forcings only are also examined (see SOM).

The all-forcing ensemble (ALL_F) captures the drying trend over central-northern India reasonably well (Fig. 1). The model also simulates a large-scale drying over the eastern Indian Ocean and Southeast Asia, and a moistening over the northern Arabian Sea and western equatorial Indian Ocean, in agreement with the observed pattern over adjacent lands (Fig. 2). These changes are determined to be of anthropogenic origin, as the naturally forced ensemble cannot reproduce the observed pattern (Figs. S6 and S7). Deficiencies in simulating the dynamical interaction of the monsoon flow with the elevated orography of the Tibetan Plateau, owing to the model's relatively coarse horizontal resolution, are likely to be responsible for the substantial disagreement over southern China.

The individual ensembles forced with different forcing combinations clearly indicate that the drying over central-northern India can be attributed to aerosols (AERO) (Fig. 1). The region would become wetter if the model is driven only by greenhouse gases and ozone (WMGGO3). Note that WMGGO3 appears to amplify the trend in AERO, indicating nonlinearity in the total response to both forcings (*29,30*). Aerosols (AERO) also give rise to the changes in the latitudinal direction over Southeast Asia in the all-forcing ensemble (Fig. 2). The reduced precipitation over northern India, Indochina and southern China is accompanied by weaker ascent (Fig. S8). The anomalous subsiding flow moves southward, and then starts to converge in the equatorial region, closing the meridional cell (Fig. S9) and enhancing local precipitation (Fig. 2). This circulation change opposes the regional climatological meridional overturning.

On the other hand, the impact of greenhouse gases and ozone (WMGGO3) is more pronounced around the equator. The main features are the widespread anomalous subsidence over the Maritime Continent and the eastern Indian Ocean, and the enhancement of ascent over the western Pacific to a similar extent (Fig. S8). This zonal dipole pattern is indicative of an eastward shift of the convergence zone. This relatively localized change is accompanied by a weakening of the basin-wide equatorial zonal circulation (*12,13*). Greenhouse gases and ozone also cause the meridional overturning circulation over South Asia and Southeast Asia to slow down, albeit slightly (Fig. S9). Note that the large equatorial subsidence seen in Fig. S9 arises from the decreased ascent over the eastern Indian Ocean (Fig. S8), which is largely part of the zonal adjustment. Aerosol-induced changes are almost opposite along the equator. Ascent is reduced over the western Pacific, but is intensified over the Indian Ocean, giving rise to a westward movement of the convergence zone. This is in addition to a modest strengthening of the zonal circulation.

The impacts of aerosols and greenhouse gases simulated in these GCM experiments can be understood theoretically by separating the tropical circulation adjustment to radiative forcing into its thermodynamical (i.e., due to changes in temperature and atmospheric moisture content) and dynamical (i.e., due to circulation changes caused by non-thermodynamical factors) components (Fig. 3). The former complies with the thermodynamical scaling argument, which dictates that in a warmer climate (e.g., under greenhouse gas forcing) the overall circulation will weaken despite an increase in total precipitation, and vice versa (*12–14,30–32*). In other words, the thermodynamically-induced circulation change scales approximately with the variation in the tropical-mean surface temperature, regardless of the specificities of the underlying forcing (see Figs. S10 and S11 and SOM). The change is manifested mostly in the zonal component of the tropical circulation, which is less constrained than its meridional counterpart (*13, 30*). In stark contrast, a spatially inhomogeneous forcing (e.g., aerosol forcing) is much more efficient in causing a dynamically-induced circulation change, as the coupled atmosphere-ocean system adjusts circulation to compensate for the energy imbalance between the region under the direct influence of the forcing and its surroundings. In doing so, the impact of the forcing (e.g., change in surface temperature) spreads beyond its boundaries (*29, 33*). Since anthropogenic aerosols are located mainly in the northern hemisphere, the boreal summer meridional circulation, of which the South Asian summer monsoon is a major part (*2*), weakens to reduce the energy flow to the southern hemisphere, and thus partially alleviates the interhemispheric asymmetry due to aerosol forcing (see Figs. S13 and S14 and SOM).

This work is distinct from the recent studies with fully coupled climate models (*4, 10*) both in modeling tools and in theoretical explanations. The all-forcing experiments performed with a widely used model failed to produce the observed drying over central-northern India (*10*). Another model achieved that, but only when it was driven by observed aerosol forcing over South Asia and the tropical Indian Ocean (*4*). The representation of aerosol physics in our model is much more advanced than in those models. The main improvements include interactive aerosols, internal mixing and indirect effects. This allows one to simulate aerosol forcing with greater realism. On the theoretical side, we consider the drying fundamentally as part of the global-scale circulation adjustment to an asymmetrical forcing, as opposed to the joint result of a number of regional factors (*4*). An implication of this more expanded view is that non-local aerosol forcing may also affect the South Asian monsoon. Furthermore, the successful decomposition of the overall circulation change into those in the zonal and meridional components of the tropical circulation provides a useful framework for understanding the combined climate response to aerosols and greenhouse gases.

The results discussed here suggest that anthropogenic aerosols have substantially masked the precipitation increase over the monsoon area that would have otherwise occurred purely in response to increased greenhouse gases, and imply that future aerosol emissions are important controlling factors of near-term regional climate change. The outcomes of this study, especially the realistic simulation and theoretical understanding of regional precipitation variations, constitute a concrete step toward unraveling the hydrological impacts of climate change at even finer scales.

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16. Long-term observations of precipitation and sea level pressure (SLP) are used in this study. In order to account for the different sources of measured precipitation and methodologies, four precipitation datasets are considered: the Climate Research Unit (CRU) TS3.0 dataset (*17*), the Indian Meteorological Department (IMR) 1951-2003 high-resolution daily dataset for the Indian region (*18*), the University of Delaware (UDEL) 1900-2008 gridded monthly time series of terrestrial precipitation (Version 2.01) (*19*), and the global 50-year precipitation reconstruction analysis (PREC/L) (*20*). The Hadley Centre HadSLP2 SLP dataset (*21*) is used to infer the long-term changes in the tropical circulation (see Figs. S5 and S11 and SOM).

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23. Two methods are used to estimate the statistical significance of the linear trends. The first one is based on the two-tailed Student's *t*-test (*24*), in which the variance of the residuals is used to estimate the standard error of an observed or simulated trend. It is applied both to the average precipitation over central-northern Indian (Fig. 1) and to individual grid points (Fig. 2). By constructing the probability distribution of natural trends from an 800-year control simulation either for a single realization or for a multi-member ensemble, we can also determine the probability of a trend occurring in the absence of external forcings (see Figs. S3 and S4 and SOM).

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27. The NOAA GFDL CM3 GCM (*28*) implements an improved representation of aerosol effects, including the indirect ones involving liquid clouds. Sulfate, organic carbon and sea salt aerosols act as cloud condensation nuclei. Possible aerosol effects on ice clouds are not included. The horizontal resolution is $\sim$200 km. Approximately half of the 48 vertical layers reside in the troposphere, and the vertical resolution is $\sim$70 m near the surface, and $\sim$1 km near the tropopause. These resolutions are comparable to those of most of current global climate models. The model-simulated climatological monsoon winds and precipitation com-

pare reasonably well with observations (Fig. S2). The orography-related sub-regional features (e.g., the rain-shadow effect over Southeast India and the spatial pattern of precipitation over central-northern India and along the Himalayas) are also simulated realistically. See SOM for more detail.

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Figure 1. Five-year running mean June-September average precipitation anomalies (mm day^{-1}) over central-northern India (76°-87°E, 20°-28°N; see the orange box in the map). Anomalies are calculated as deviations from the 1940-2005 climatology. The black line is based on the Climate Research Unit TS 3.0 observational dataset (CRU). The red, green and blue lines are for the ensemble-mean all-forcing (ALL_F), aerosol-only (AERO), greenhouse gases and ozone-only (WMGGO3) CM3 historical integrations, respectively. The grey shades represent the standard deviation of the 5-member all-forcing ensemble. The least-squares linear trends during 1950-1999 are plotted as dashed lines in the respective colors. The trend ($\pm$ one standard error) (mm day^{-1} (50 years)$^{-1}$) and its p-value based on the two-tailed Student's *t*-test (*24*) (in parentheses) are -0.95 $\pm$ 0.45 (p = 0.04) for CRU, -0.58 $\pm$ 0.21 (p = 0.01) for ALL_F, -0.39 $\pm$ 0.23 (p = 0.09) for AERO, and 0.55 $\pm$ 0.30 (p = 0.07) for WMGGO3. The 50-year trends from the other three observational datasets, which are not plotted to avoid overcrowding the figure, are -0.20 $\pm$ 0.50 (p = 0.70) for IMR, -0.79 $\pm$ 0.47 (p = 0.10) for UDEL, and -0.76 $\pm$ 0.45 (p = 0.10) for PREC/L.

Figure 2. Spatial patterns of the 1950-1999 least-squares linear trends of the June-September average precipitation (mm day^{-1} (50 years)$^{-1}$). The panels are for the Climate Research Unit TS 3.0 observational dataset (CRU), and the ensemble-mean all-forcing (ALL_F), aerosol-only (AERO), greenhouse gases and ozone-only (WMGGO3) CM3 historical integrations. The black dots mark the grid points for which the trend exceeds the 95% significance level ($p < 0.05$) according to the two-tailed Student's *t*-test (*24*). For the model simulations, the black contour lines represent the 1946-1955 average precipitation (mm day^{-1}). The orange boxes denote the area of averaging for central-northern India used in Fig. 1.

Figure 3. Schematic of the large-scale circulation changes caused by greenhouse gases and aerosols. The warming caused by greenhouse gases and ozone (WMGGO3) induces a strong anomalous zonal circulation (red) between the eastern Indian Ocean (weaker ascent) and the

western Pacific (stronger ascent), in addition to a modest weakening of the equatorial zonal circulation (black). Aerosols (AERO) are responsible for an anomalous meridional circulation, which reduces the ascent over the western Pacific and Southeast Asia (purple), and opposes the local Hadley circulation. Besides, the aerosol-induced cooling excites a strong anomalous zonal circulation (red), with stronger ascent over the eastern Indian Ocean and weaker ascent to the east, and strengthens the equatorial zonal circulation (black). The circulation changes in the all-forcing case (ALL_F) result from the overall warming (which is predominant in the longitudinal direction along the equator) and aerosol forcing (which outweighs the warming in the latitudinal direction). A conceptual representation of the climatological circulation is provided for reference.