A New Pathway for Absorbing Aerosols' Influence on the Interannual Variability of the South Asian Monsoon

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Aerosol forcing remains the dominant uncertainty and a challenging problem in climate change scenarios. While it is widely documented that anthropogenic activities have significantly contributed to raising the global aerosol concentration in the troposphere, quantification of the influence of tropospheric aerosols on climate has proved difficult because of the large spatial and temporal variability of aerosols, their short lifetimes, their diverse physical and chemical properties, and complex interactions that take place with radiation and microphysical processes. Aerosol particles can influence clouds and the water and energy cycles by directly affecting the radiation balance (the "direct" effect) and by impacting the microphysics of clouds and precipitation (the "indirect" effect). A "semi-direct" effect is also known, consisting of the evaporation of the cloud layer from aerosol absorption of solar radiation, with consequent increase in the amount of solar radiation reaching the surface.

Heavy loadings of aerosols are found in many regions of the globe (e.g., the northern tropical Atlantic, the Amazon, the eastern United States, northern China and the Pacific, and South Asia). Over polluted regions, aerosols can induce a forcing in the atmosphere and at the surface that is up to an order of magnitude larger than that from anthropogenic greenhouse gases, as it is the case for the Indo-Asian haze. Rapid urbanization and population growth in the Indo-Asia-Pacific region has resulted in higher demand of energy and mobility, and thus larger emissions of pollutants. Understanding the effects of aerosols on the spatial distribution and/or duration of summer monsoon rainfall (which accounts for nearly three-quarters of the yearly precipitation over many regions) is important for the health and food security of more than 60% of the world's population.

During the last few years, field experiments [e.g., the Indian-Ocean Experiment (INDOEX), the Aerosol Characterization Experiment (ACE-Asia), the Atmospheric Brown Cloud (ABC) Project] and observational studies, together with new data sources [e.g., remote sensing data, the Aerosol Robotic Network (AERONET) surface-based sun-photometers] have led to a reasonable characterization of the composition [above all, its large black carbon (BC) content] and properties of South Asian aerosols.

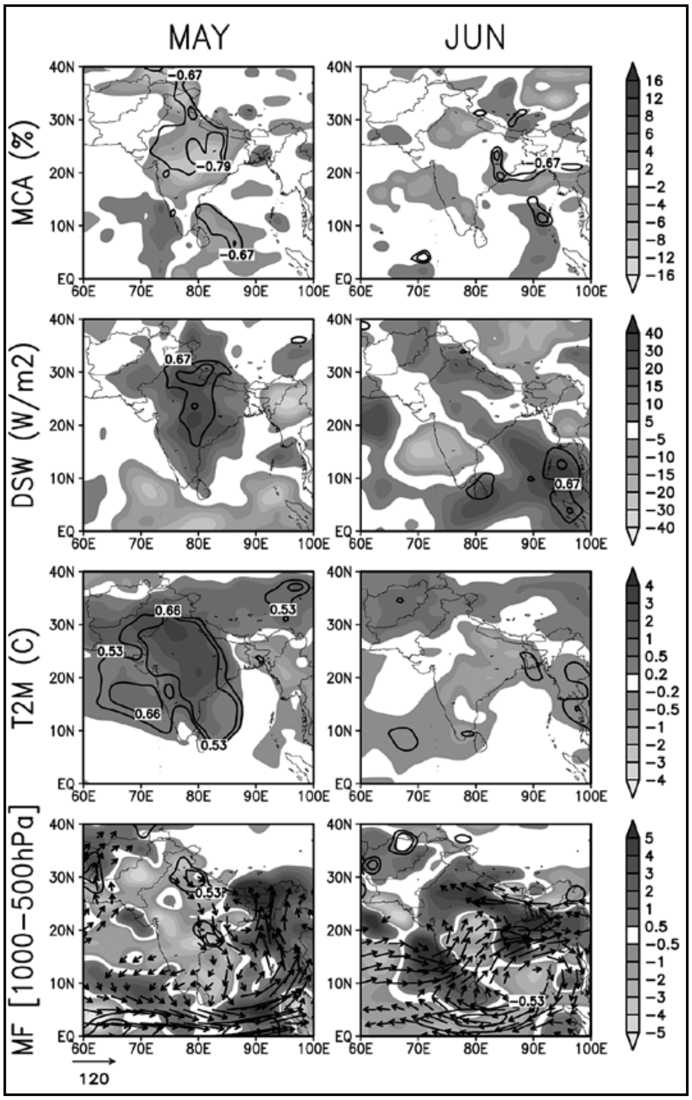
Atmospheric and ocean-atmosphere general circulation models have also been used with quasi-realistic aerosol distributions to investigate the impact of aerosols on the South Asian monsoon, mostly, the climatological rainfall distribution. Several mechanisms have been proposed, including:

- Anomalous heating of air due to shortwave absorption by BC aerosols, which enhances regional ascending motions and thus precipitation in atmospheric general circulation models (Menon et al., 2002).
- Modulation of the summertime meridional sea-surface temperature (SST) gradient from reduced incidence of shortwave radiation over the northern Indian Ocean in preceding winter/spring. Ramanathan et al. (2005) and Chung and Ramanathan (2006) showed that aerosol-induced weakening of the SST gradient (leading to weaker summer monsoon rainfall) more than offset the increase in summertime rainfall resulting from the "heating of air" effect in a coupled ocean-atmosphere model, leading to a net decrease of summer monsoon rainfall. Meehl et al. (2008) recent analysis, also with a coupled climate model but with more comprehensive treatment of the aerosol-radiation interaction, supports findings on the effect of BC aerosols on the Indian summer monsoon rainfall.
- Modulation of the summertime meridional tropospheric temperature gradient from anomalous accumulation of absorbing aerosols against the southern slopes of the Himalayas. The elevated diabatic heating anomaly ("elevated heat-pump," Lau et al., 2006) over the Tibetan plateau in April and May would reinforce the climatological meridional temperature gradient and lead to monsoon intensification in June and July.

It is interesting that none of the proposed mechanisms concern aerosol effects on cloudiness. The aforementioned studies moreover rely heavily on models, many of which are unable to produce realistic spatiotemporal distributions of cloudiness. Climate system models are clearly a valuable tool for investigating the mechanisms underlying aerosol-monsoon interaction, but some caution is necessary as these models are known to have significant, and in many cases, unacceptably large biases in quantities as basic and relevant as the monsoon rainfall distribution and onset. Many of these models also exhibit spurious air-sea interaction over the Indian Ocean in coupled settings (Bollasina and Nigam, 2008).

Our analysis (Bollasina et al., 2008) is complementary to most earlier studies in view of its focus on the interannual variability of aerosol concentration and related monsoon rainfall variations (rather than long-term trend), and because it is observationally rooted. The focus is on the transition period between late spring, when aerosol concentration reaches a peak, and summer, when the monsoon develops. Regional variations of the response are highlighted. The Nimbus-7 Total Ozone Mapping Spectrometer (TOMS) Aerosol Index (AI) provided a measure of monthly averaged aerosol loading for the period 1979–1992.

Excessive aerosols in May over the Indo-Gangetic Plain (IGP) lead to reduced cloud amount and precipitation, increased surface shortwave radiation, and land-surface warming. These relationships are supported by the structure of related vertical motion, diabatic heating and outgoing long-



Regressions on Nimbus-7 TOMS Aerosol Index (blue line in (a) in the figure at the bottom of page 20) during May (left) and June (right) above for (top to bottom): International Satellite Cloud Climatology Project D2 middle cloud amount (MCA, percentage); GEWEX Surface Radiation Budget Project surface downward shortwave radiation (Wm^{-2}, DSW); and ERA-40 m^2 air temperature (T2M, °C); ERA-40 moisture flux (MF, $Kg\ m^{-1}\ s^{-1}$; vectors) and its convergence ($Kg\ m^{-2}\ s^{-1}$; shaded, convergence is positive) vertically integrated between 1000 and 500 hPa. (a) and (b) in the figure at the bottom of page 20 are for the period 1984–1992. The ±0.53 (±0.67) and ±0.66 (±0.79) contour lines show 95% and 99% confidence levels, respectively.

wave radiation (OLR) anomalies. The June (and July) monsoon anomaly associated with excessive May aerosols is of opposite sign over much of the subcontinent (although with a different pattern). The monsoon circulation strengthens and precipitation increases (see figure above and at the bottom of page 20). The following physical picture is suggested: absorbing aerosols are responsible in May for a decrease of cloudiness over India, which leads, above all, to reduced precipitation, increased shortwave radiation at the surface, and heating of the dry ground. The changes may be attributed to the evaporation of the cloud layer (i.e., the semi-direct effect). Indeed, studies have shown that the resulting decrease in cloud cover and albedo can lead to a warming of the surface whose magnitude can be comparable to the cooling from the direct effect (Ackerman et al., 2000). As the season progresses the monsoon intensifies, and although we have not conducted a modelling analysis to connect the anomalous heating of the land-surface in May to increased monsoon rainfall in June and July over both local and remote regions, we argue that the enhancement of the monsoon results from the increased thermal contrast (originating in May), as in the basic monsoon mechanism. Our analysis also shows that the aerosol impact and operative processes over central and western India are quite different, if not opposite, to those over the eastern subcontinent.

The results described suggest that although anomalously high aerosols are associated with deficient precipitation over India in early spring, internal atmosphere–land-surface feedback actually strengthens the monsoon in subsequent summer months. Land-surface processes, once triggered by anomalous aerosol concentration and induced low cloudiness and precipitation, are important mediators in monsoon evolution and hydroclimate. The finding of the significant role of the land-surface in the realization of the aerosol impact is somewhat novel, as best as we can tell, as only heating of the lower troposphere and solar dimming effects on both land and oceans have hitherto been emphasized. Observations at weekly resolution are currently being analyzed at various lead/lag intervals to identify the sequence of physical processes generating the aerosol influence.

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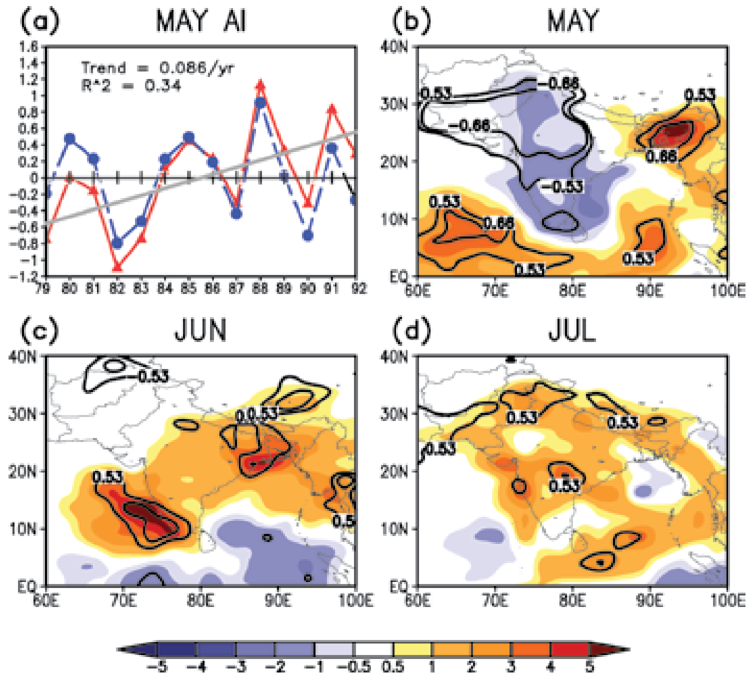
High Spring Indian Aerosol Concentration and Associated Low Precipitation Leads to Strengthened Summer Monsoon



~~RRTMG schemes perform better overall for the CIRC cases than the current CAM schemes.~~ (a): Time series of May Aerosol Index (AI) anomalies over the Indo-Gangotic Plain (red line: original data; blue line: original data after removing trend; grey line: least square fit to original data). The trend is 0.086 yr^{-1} (significant at the 95% confidence level), with $R^2 = 0.34$. (b) – (d): GEWEX Global Precipitation Climatology Project precipitation (mm day^{-1}, shaded) regressed on the May AI time series [blue line in (a)] for: (b) May, (c) June, and (d) July. The ±0.53 and ±0.66 contour lines show the 95% and 99% confidence levels, respectively. See article by M. A. Bollasina and S. Nigam on page 10.