2.3 OBSERVATIONAL EVIDENCE FOR ABSORBING AEROSOLS' INFLUENCE ON THE SOUTH ASIAN SUMMER MONSOON. ARE COUPLED MODELS READY FOR PROBING MECHANISMS?

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1. INTRODUCTION

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 the raising of 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 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" effects). 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 US, 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 emission 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) would be of some importance for the health and food security of more than 60% of the world's population.

2. AEROSOLS OVER SOUTH ASIA

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 coupled general circulation models (AGCMs and CGCMs, respectively) 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. Essentially, two mechanisms have been proposed:

- Anomalous heating of air due to shortwave absorption by BC aerosols, which enhances regional ascending motions and thus precipitation (Menon et al. 2002). Similarly, the elevated diabatic heating anomaly from anomalous accumulation of absorbing aerosols against the southern slopes of the Himalayas (the "elevated heat-pump", Lau et al. 2006) over the Tibetan plateau in April

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and May would reinforce the climatological meridional temperature gradient and lead to monsoon intensification in June and July. More recently, Collier and Zhang (2008) found that absorbing aerosols enhance pre-monsoon precipitation, but internal negative feedbacks actually lead to decreased precipitation during the active monsoon months. All these studies were carried out with AGCMs.

- Modulation of the summertime meridional 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 CGCM, leading to a net decrease of summer monsoon rainfall. Meehl et al.'s (2008) analysis, also with a CGCM but with more comprehensive treatment of the aerosol-radiation interaction, supports Ramanathan et al.'s findings on the effect of BC aerosols on the Indian summer monsoon rainfall.

A AGCM sensitivity study to a wide range of aerosol optical depth and absorption has been recently carried out (Randles and Ramaswamy 2008), providing a first assessment of model's response to variation of aerosol parameters.

The aforementioned studies rely heavily on models. 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.

3. IMPACT OF INTERANNUAL VARIATIONS OF ABSORBING AEROSOLS BASED ON OBSERVATIONS

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 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 to land-surface warming. These relationships are supported by the structure of related vertical motion, diabatic heating and 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 (Fig. 1).

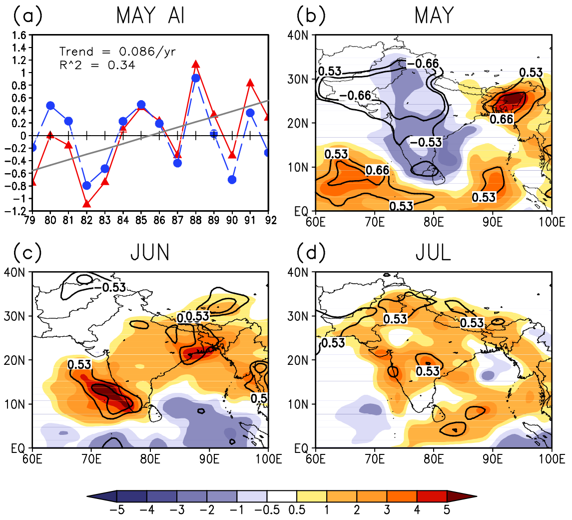

Figure 1. (a): Time series of May AI anomalies over the IGP (red line: original data; blue line: original data after removing trend; grey line: least square fit to original data). The trend is 0.086 yr-1 (significant at the 95% confidence level), with R2 = 0.34. (b)-(d): GPCP precipitation (mm day-1, 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.

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 (Fig. 2).

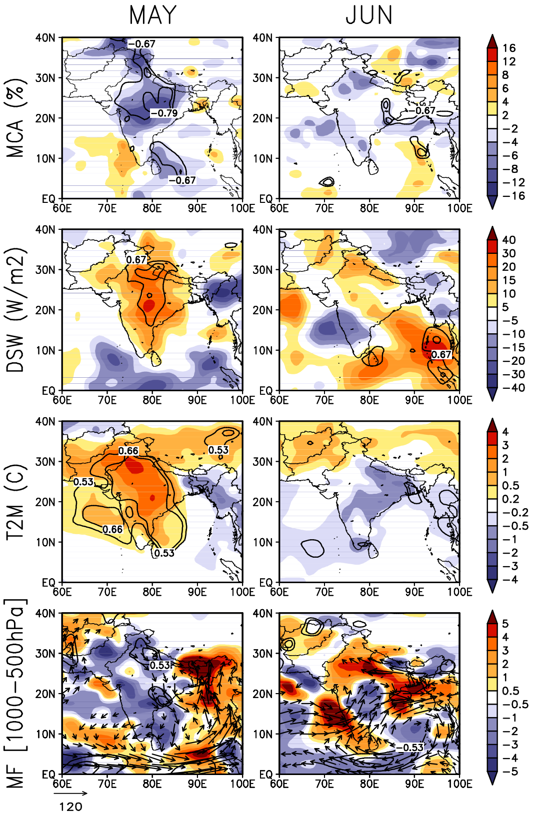

Figure 2. Regressions on May AI (blue line in Fig. 1a) during May (left) and June (right) for (top to bottom): ISCCP D2 middle cloud amount (MCA, %); GEWEX-SRB surface downward shortwave radiation (W m-2, DSW); ERA-40 2-m air temperature (T2M, ℃); ERA-40 moisture flux (MF, Kg m-1 s-1; vectors) and its convergence (Kg m-2 s-1; shaded, convergence is positive) vertically integrated between 1000 and 500 hPa. (a) and (b) are for the period 1984-1992. The ±0.53 (±0.67) and ±0.66 (±0.79) contour lines show the 95% and 99% confidence levels, respectively.

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 modeling 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.

4. AIR-SEA INTERACTIONS IN THE INDIAN OCEAN IN COUPLED MODELS

It is known that the air-sea linkage is a fundamental mechanism regulating the evolution of the monsoon. However, in this respect many of the models used in aerosol-impact studies exhibit spurious biases and deficiencies.

The veracity of air-sea interactions in the Indian Ocean during the South Asian summer monsoon as simulated by CGCMs is examined (Bollasina and Nigam 2008). Representative simulations of the 20th Century climate, produced as part of the Intergovernmental Panel on Climate Change Fourth Assessment Report, are the analysis targets along with observational data.

The analysis shows the presence of large systematic biases in boreal summer precipitation, evaporation, and sea surface temperature, often exceeding 50% of the climatological values. Many of the biases are pervasive, being common to most simulations (Fig. 3).

The representation of air-sea interactions is also compromised.

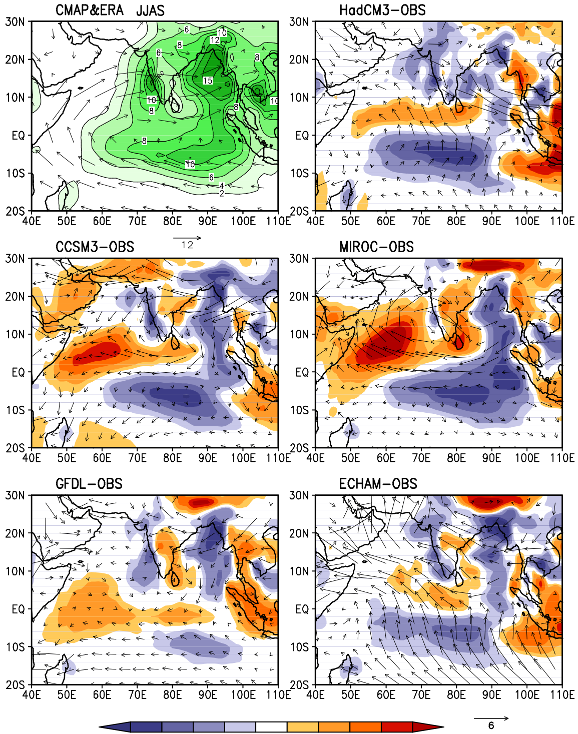

Figure 3. Seasonal mean (Jun-Sep; JJAS) precipitation (mm day^{-1}) and 850-hPa winds (m s^{-1}) for observations (top left) and differences model-observations (other panels).

Coupled models tend to emphasize local forcing in the Indian Ocean as reflected by their large precipitation-SST correlations, at odds with the weak links in observations which suggest the importance of non-local controls. The evaporation-SST correlations are also differently represented, indicating atmospheric control on SST in some models and SST control on evaporation in others (Fig. 4). The Indian monsoon rainfall-SST links are also misrepresented: the former is essentially uncorrelated with antecedent and contemporaneous Indian Ocean SSTs in nature, but not so in most of the simulations.

Overall, coupled models are found deficient in portraying local and non-local air-sea interactions in the Indian Ocean during boreal summer. In our opinion, current models cannot provide durable insights on regional climate feedbacks nor credible projections of regional hydroclimate variability and change, should these involve ocean-atmosphere interactions in the Indian basin.

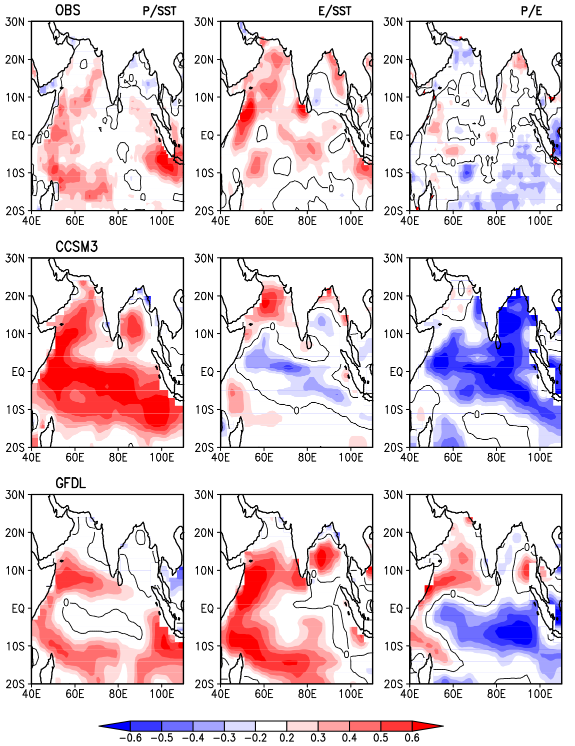

Figure 4. June-August average pointwise and simultaneous correlations between precipitation and SST (left column), evaporation and SST (middle column), and precipitation and evaporation (right column) for observations (top), CCSM3 (middle), and GFDL (bottom). The zero-correlation contour is also displayed.

5. CONCLUSIONS

The results described here 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.

It is also suggested that some caution is necessary in over relying on models in predicting the response to aerosol loading in that region.

6. REFERENCES

Ackerman, A .S., O. B. Toon, D. E. Stevens, A. J. Heymsfield, V. Ramanathan, and E. J. Welton, 2000: Reduction of Tropical cloudiness by soot. *Science*, **288**, 1042, doi: 10.1126/science.288.5468.1042.

Bollasina, M., and S. Nigam, 2008: Indian Ocean SST, evaporation, and precipitation during the South Asian summer monsoon in IPCC-AR4 coupled simulations. *Clim. Dyn.*, doi:10.1007/s00382-008-0477-4.

Bollasina, M, S. Nigam, and K.-M. Lau, 2008: Absorbing aerosols and summer monsoon evolution over South Asia: an observational portrayal. *J. Climate*, **21**, 3221-3239.

Chung, C. E., and V. Ramanathan, 2006: Weakening of North Indian SST gradients and the monsoon rainfall in India and the Sahel. *J. Climate*, **19**, 2036-2045.

Collier, J. C., and G. J. Zhang, 2008: Aerosol direct forcing of the summer Indian monsoon as simulated by the NCAR CAM3. *Clim. Dyn.*, doi:10.1007/s00382-008-0464-9.

Lau, K.-M., M. K. Kim, and K.-M. Kim, 2006: Aerosol induced anomalies in the Asian summer monsoon- the role of the Tibetan Plateau. *Clim. Dyn.*, **26**, 855-864, doi:10.1007/s00382-006-0114-z.

Meehl, G. A., J. M. Arblaster, and W. D. Collins, 2008: Effects of black carbon aerosols on the Indian monsoon. *J. Climate*, **21**, 2869-2882.

Menon, S., J. Hansen, L. Nazarenko, and Y. Luo, 2002: Climate effects of black carbon aerosols in China and India. *Science*, **297**, 2250-2253.

Ramanathan, V., and Coauthors, 2005: Atmospheric Brown Clouds: Impacts on South Asian Climate and Hydrological Cycle. *PNAS*, **102**, 5326-5333.

Randles, C. A., and V. Ramaswamy, 2008: Absorbing aerosols over Asia: A Geophysical Fluid Dynamics Laboratory general circulation model sensitivity study of model response to aerosol optical depth and aerosol absorption. *J. Geophys. Res.*, **113**, D21203, doi:10.1029/2008JD010140.