Anthropogenic aerosols and the weakening of the South Asian summer monsoon

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\underline{Aerosols}: much more than “offset” GHGs $\rightarrow$ complex changes in regional water cycle and climate (still not fully understood or even known)

\underline{Monsoon}: driven by differential heating. Aerosols interacts with monsoon heat sources and sinks, and alter the \textit{land-sea thermal contrast}
Global aerosol variations: past and future emissions

- The true magnitude of the GHG warming is not known, as well as climate forcing/sensitivity (e.g., Kiehl 2007)
- Aerosols will continue to play a role in regional climate change
- Realistic predictions of future climate change depend on climate models able to accurately represent not just present climate, but also the changes that have occurred over the past century
- Mitigation of warming by geo-engineering
Anthropogenic aerosols and the SA monsoon

Observational studies (e.g., Ramanathan et al. 2005; Goswami et al. 2006; Kumar et al. 2006; Rajeevan et al. 2008; Dash et al. 2009; Gosh et al. 2009; Lau and Kim 2010): drying trend from the 50s, contradictory results, incomplete physical insight into the large-scale dynamics and mechanisms.

Both aerosol forcing and global warming influence the South Asian monsoon

- Sulfate aerosols: reduction of monsoon precipitation (e.g., Mitchell and Johns 1997; Ramanathan et al. 2005; Meehl et al. 2008)
- Modeling of absorbing aerosols (e.g., Menon et al. 2002; Lau and Kim 2006; Meehl et al. 2008; Collier and Zhang 2009; Sud et al. 2009; Wang et al. 2009)
  - Meridional SST-gradient (Ramanathan et al. 2005; Chung and Ramanathan 2006)
  - Meridional tropospheric temperature gradient by heating (Lau et al. 2006)
- GHGs: Despite a weakening of the tropical circulation, most studies project an intensified monsoon rainfall (e.g., Hu et al. 2000; Meehl et al. 2000; Meehl and Arblaster 2003; May 2004; Ueda et al. 2006; Annamalai et al. 2007; Kripalani et al. 2007; Dairaku et al. 2008)

Was the widespread drying caused by natural variability or human influence?

If the latter, what were the contributions of anthropogenic greenhouse gases and aerosols?

Incomplete treatment of aerosol effects, offline aerosols
Large uncertainties due to a relatively poor model skill for monsoon simulation at regional scale.
The GFDL coupled model and Experiments

- GFDL coupled atmosphere-ocean GCM CM3 (∼200 km, 48 levels; Donner et al. 2011):
  - Improved and more comprehensive representation of aerosol physics and effects, including the indirect ones in liquid clouds; improved parameterization of aerosol-cloud interactions; internal mixing
  - Starting from emissions, aerosols are transported and removed (forward approach)
  - Realistic simulation of the climatological monsoon features at regional scale
  - Simulated aerosol properties compare well with observations

- Historical perturbation experiments (1860-2005):
  - All-forcing (ALL_F): 5 members, natural and anthropogenic forcings
  - Greenhouse and ozone-only forcing (WMGGO3): 3 members, GHGs and ozone
  - Aerosol-only forcing (AERO): 3 members, aerosols
  - Natural-only forcing (NAT): 3 members, solar variations and volcanoes
  - Anthropogenic-only forcing (ANTHRO): 3 members, GHGs, ozone, aerosols, and land use

- Control run (800 years): time-invariant radiative forcing agents fixed at 1860 values
Precipitation trend in observations and CM3 model experiments

AERO = meridional direction; WMGG = along Equator
Circulation changes

WMGG: contraction of convective area, weakening of zonal circulation (Held and Soden 2006; Vecchi et al. 2006)

AERO: counteracting the meridional circulation, broadening and leveling of convergence zone
Schematic of the changes

Thermodynamical (WMGG, zonal) vs. dynamical (AERO, meridional) components of the tropical circulation adjustment to radiative forcing
Changes in Atmospheric Energy Transport

\[ \text{RFP} = \text{change in TOA radiative flux after the forcing agent is introduced and atmosphere adjusts, with fixed SST} \]

(i.e., takes fast feedbacks and interactions into account; e.g., Lohmann et al. 2010)

1981-2000 annual-mean RFP (W m\(^{-2}\)) due to anthropogenic aerosols

-3.6 (mostly I)

JJAS, aerosols

SW cooling (T decrease)

Interhemispheric imbalance

Convergence

Divergence

1981-2000 annual-mean RFP (W m\(^{-2}\)) due to anthropogenic aerosols
Key issues and summary

- The observed change in monsoon rainfall is likely of **anthropogenic** origin and is mainly attributable to **increased aerosols**.
- This perspective focuses on the **slowdown** of the tropical atmospheric circulation brought about by the **aerosol-induced energy imbalance** between the northern and southern hemispheres.
- Aerosols interact with the monsoon circulation mainly through altering clouds (the **indirect effects**).
- Low tropospheric **stability** shows no appreciable change in late spring; the large-scale land-ocean thermal contrast appears to mediate the aerosol impact.
- An important step toward the understanding the impact of climate change at fine scales.
- Useful framework for understanding the combined climate response to aerosols and greenhouse gases.