Temporal evolution of the aerosol radiative forcing due to changing emissions of individual aerosol species and their precursors over the Indian region as estimated using a global climate model CAM6.

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Introduction:

Aerosols are known to play an important role in regulating the Earth's energy budget, by interacting with solar and terrestrial radiation and modifying the cloud properties. They alter radiations by interacting via. different mechanisms further influencing the climate, in terms of climate response and feedback. Quantifying aerosol radiative forcing is an initial step towards understanding the response of our climate system to changes in emissions of aerosols from anthropogenic sources. Therefore it is very important to understand how the changes in emissions of aerosols have resulted in radiative forcing of the climate system on a global as well as regional scale. Aerosols interact with the incoming solar and outgoing terrestrial radiation through aerosol-radiation interactions (ARI) and modify the cloud characteristics through aerosol-cloud interactions (ACI).

Radiative Forcing is a change in the net radiative energy available to the Earth-Atmosphere system. While the elements responsible for this net radiative energy changes (such as aerosols, GHGs, Clouds) are known as forcing agents. Influence of aerosols in altering the balance of incoming and outgoing energy in the Earth-Atmosphere system is quantified as aerosol radiative forcing. It is computed as the change in net radiance (down minus up, solar plus terrestrial) at a given level in the atmosphere, expressed in units of W/m^2. Positive (+) forcing signifies warming while negative (–) forcing represents cooling.

Methodology and Experiment Design:

The representation of aerosols in the GCMs are very complex as different aerosols exhibit different characteristics towards radiation. Black carbon (BC) aerosols shows affinity towards (absorption) SW radiation, while sulfate (SO_4) aerosols tends to scatter SW radiation. We use the definition of effective radiative forcing (ERF), ERF due to *aerosol-radiation interaction (ARI)*, *aerosol-cloud interaction (ACI)*, and *residual (RES)* forcing from Ghan et al. 2012 as:

$$\text{TRF or ERF} = \Delta F \quad ; \quad \text{ERF}_{\text{ARI}} = \Delta(F - F_{\text{clean}})\ ;$$
$$\text{ERF}_{\text{ACI}} = \Delta(F_{\text{clean}} - F_{\text{clean,clear}})\ ; \quad \text{ERF}_{\text{RES}} = \Delta F_{\text{clean,clear}}$$

Whereas, the ERF_{ARI} due to individual aerosols is calculated by:

$$\text{ERF}_{\text{ARI}\,i} = \Delta(F - F_{\text{no}\,i})$$

Experiment Name	Description
E-2010 (PD Simulation)	Aerosols & precursors emission 2010, nudged for 2010 ERA5 meteorology
E-1850 (PI Simulation)	Same as E2010 but with 1850 aerosol emissions
E-YYYY	Same as E2010 but YYYY changes with 1900, 1950, 1960, 1965, 1970, 1975, 1980, 1985, 1990, 1995, 2000, and 2005 aerosol emissions, respectively

Results:

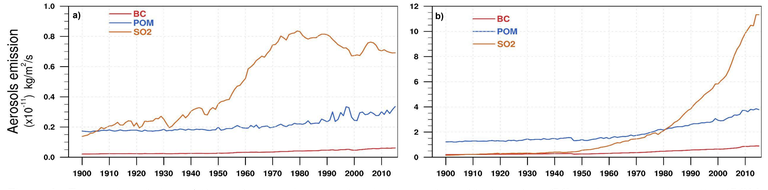

Figure 1: Temporal evolution of the anthropogenic aerosol emissions such as black carbon (BC), primary organic matter (POM), secondary organic aerosols (SOA), and sulphur dioxide (SO_2) from year 1900 to 2015. Panel (a) shows emissions on global scale, while panel (b) shows aerosol emissions over India.

- While the CMIP6 global emission data shows a rapid increase in SO_2 emissions after 1930, reaching maximum at 1980, and a gradual decreasing trend thereafter but, the SO_2 emissions over India have continuously increased since 1950. All other aerosols have gradually increased both globally as well as over India from 1950 onwards.

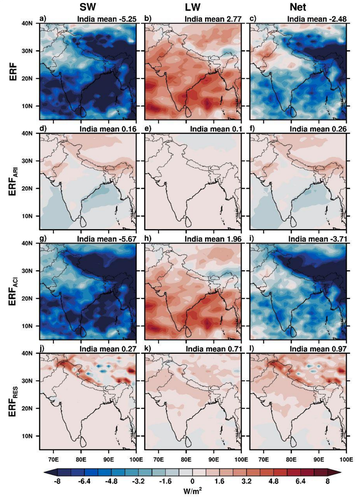

Figure 2: Annual mean Aerosol Radiative Forcing at the top of atmosphere (TOA) over the South Asian region estimated by CAM6 for the year 2010. Panels a, b, and c show the Total or Effective Radiative Forcing (ERF) for SW, LW and net (SW + LW), respectively. Further, panels d, e, and f represent ERF_{ARI}, panels g, h, and i show ERF_{ACI} and panels j, k, and l show the ERF_{RES}, respectively.

Tables shows net ERF, ERF_{ARI}, ERF_{ACI}, and ERF_{RES}.

Forcing	Global	India
ERF	-1.55	-2.48
ERF_{ARI}	**0.29**	**0.26**
ERF_{ACI}	-1.86	-3.71
ERF_{RES}	**0.03**	**0.97**

- The net cooling by ERF is dominated by ERF_{ACI}, while the tendency of ERF_{ARI}, and ERF_{RES} is to warm. Further, a part of cooling from SW ERF_{ACI} is negated by warming from LW ERF_{ACI}.
- An increase in global ERF_{ARI} is noted during the year 1995 while decrease in ERF_{ACI} during same period, precisely due to decreased global SO_2 emissions (precursor to sulfate emissions).
- Furthermore, over India the decrease in ERF_{ARI} as seen in fig 4b, after the year 1980 due to rapid increase in sulfate emissions as illustrated in fig 1b.

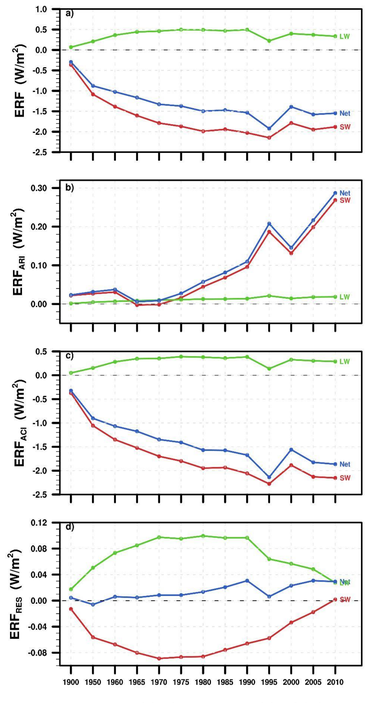

Figure 3: Time series of the decomposition of the global net ERF, ERF_{ARI} ERF_{ACI} and ERF_{RES} in to SW and LW

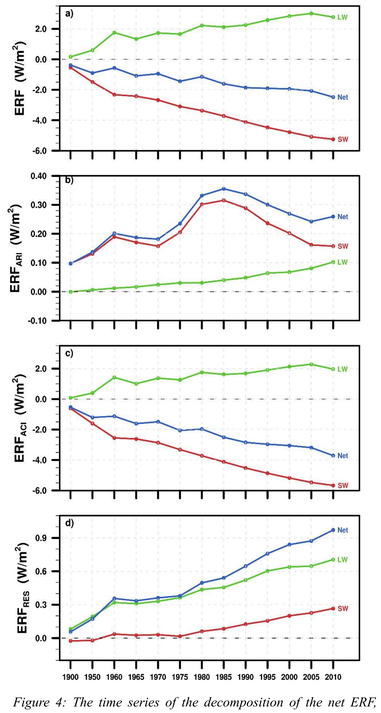

Figure 4: The time series of the decomposition of the net ERF, ERF_{ARI} ERF_{ACI} and ERF_{RES} over India in to SW and LW radiation bands.

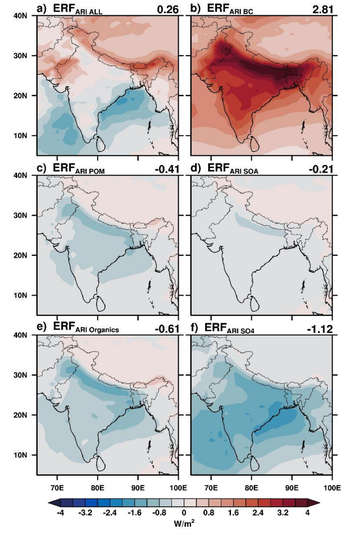

Figure 5: *Annual mean ERF_{ARI} at the top of atmosphere (TOA) over the South Asian region estimated by CAM6 for the year 2010. Panels a, b, c, d, e, and f show the net ERF_{ARI} due to all aerosols, BC, POM, SOA, Organics, and sulfate (SO_4), respectively.*

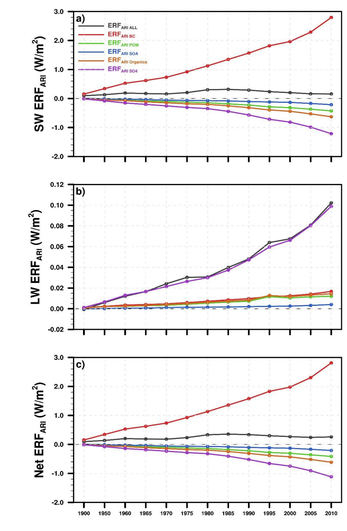

Figure 6: The time series of Annual mean ERF_{ARI} at the top of atmosphere (TOA) over the South Asian region estimated by CAM6. Panels a, b, and c show the SW, LW and net (SW + LW) ERF_{ARI} due to all aerosols, BC, POM, SOA, Organics, and sulfate (SO_4), respectively.

Conclusions

- The increase in anthropogenic aerosols emissions have resulted in cooling of the climate system as evident from a -ve net (SW + LW) ERF at TOA. This cooling of the climate system is dominated by the aerosol induced changes in clouds through a -ve ERF_{ACI}.
- A part of the SW cooling of the climate system is nullified by the LW warming due to changing emissions of aerosols, and aerosol induced changes in clouds and surface albedo.
- A rapid increase in SO_2 emissions after 1980 has decreased the warming trend with decreases in ERF_{ARI} while the dominant cooling trend of the climate system continued with gradual strengthening of ERF_{ACI} over the Indian region.
- Although the increases in SO_2 emissions has been more rapid as compared to increases in BC since the beginning of the second half of the 20th century, overall effect of the aerosols through ARI has continued to warm the atmosphere during the same period thereby suggesting the dominance of warming due to absorption amplification of radiation by the internally mixed BC with other scattering aerosols (Cappa et al. 2012).

References

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