Supplementary Information for

Aerosols drive monsoon rainfall spatial modulations over the Indian subcontinent: anthropogenic and dust aerosols impact, mechanism, and control

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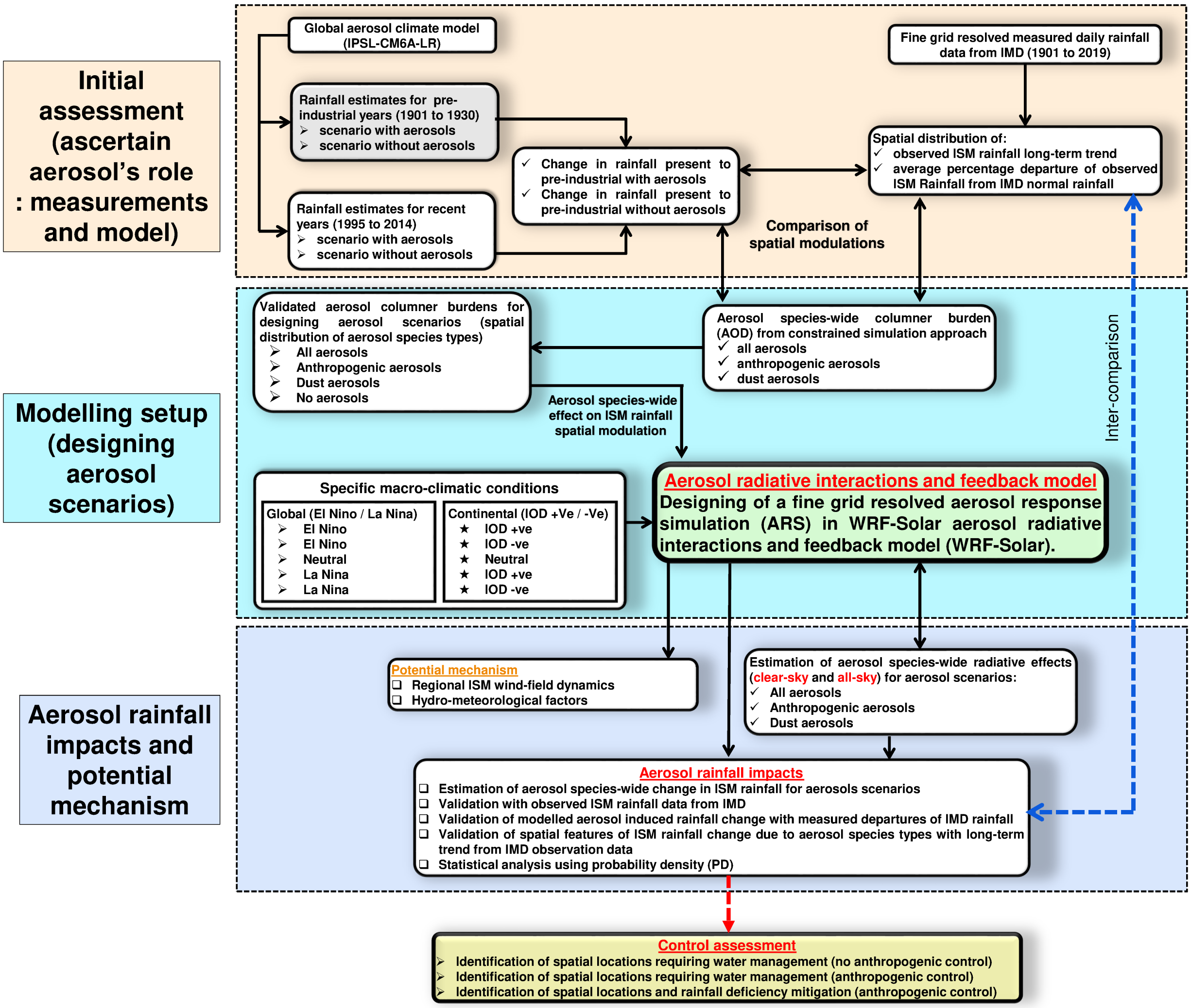

Figure S1 – Integrated modelling framework. Flowchart of the methodology for assessing aerosol-induced change in monsoon rainfall, mechanism, and control targeting anthropogenic aerosols and associated region-wide water-management benefits.

Table S1 – Designed simulations of rainfall for aerosol scenarios under five climatic conditions prevalent during ISM

Simulation No.	Climatic Scenario: Global	Climatic Scenario: Subcontinental	Year	Aerosol Type	Seasonal distribution used for aerosols	Season used for meteorology
1	La Niña	Positive IOD	2010	All	Monsoon (June to September)	Monsoon (June to September)
2				Anthro		
3				Dust		
4				None		
5		Negative IOD	2011	All		
6				Anthro		
7				Dust		
8				None		
9	Neutral	Neutral	2018	All		
10				Anthro		
11				Dust		
12				None		
13	El Niño	Positive IOD	2019	All		
14				Anthro		
15				Dust		
16				None		
17		Negative IOD	2015	All		
18				Anthro		
19				Dust		
20				None		

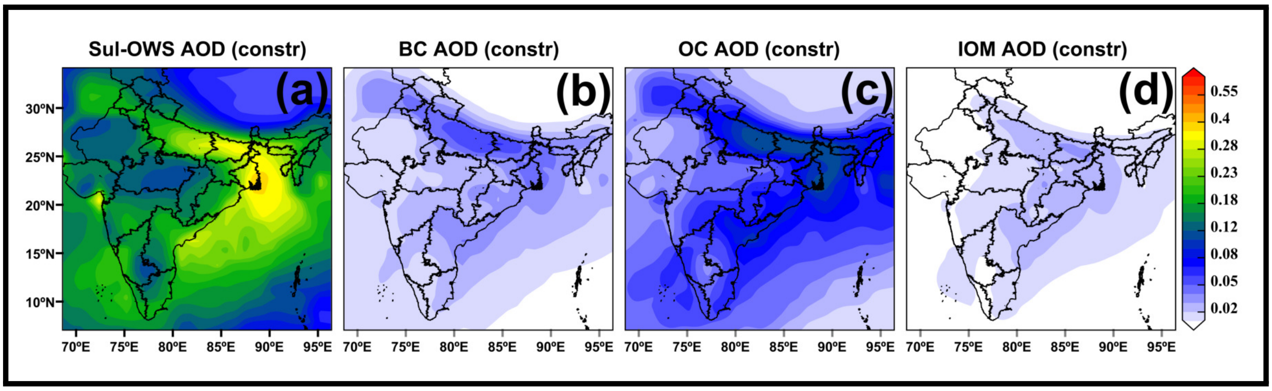

Figure S2 – Spatial distribution of AOD due to (a) sulfate and other water soluble (Sul-ows) aerosols; (b) Black carbon (BC); (c) Organic carbon (OC); and (d) Inorganic matter (IOM) aerosols (Kumar et al., 2018)

The anthropogenic AOD (AOD-anthro) over the Indian mainland (see Figure S1) is primarily due to sulphate and other water-solubles ($AOD_{Sul-ows}$: as large as 0.4), and followed by organic carbon (AOD_{OC}: 0.1-0.2), black carbon (AOD_{BC}: 0.04-0.07), and inorganic matter (AOD_{IOM}: 0.02-0.04). As mentioned in the manuscript, the aerosol species-wide optical properties for the monsoon season are estimated with OPTical properties SIMulation (OPTSIM) Stromatas et al. (2012) (OPTSIM) using the atmospheric layer-wide (19-vertical layers) concentration of aerosol species derived in our previous study Kumar et al. (2018) from the constrained aerosol simulation approach (*constrsimu*).

Table S2 – Comparison (in mm) of modelled aerosol-induced modulations (weakening or strengthening) in monsoon rainfall (averaged over 5-y) with the corresponding modulations obtained from IMD-rainfall (measured departures) for the identified rainfall-excessive, 'R1' and rainfall-deficient, 'R2' regions

	Region 1		Region 2	
	Average[1] (10^{th} Percentile[2]) [Maximum[3]]		Average[1] (10^{th} Percentile[2]) [Maximum[3]]	
	Dust Aerosols	All Aerosols	Anthropogenic Aerosols	All Aerosols
ARS	15 (29) [51]	9 (18) [46]	-17 (-28) [-48]	-16 (-28) [-41]
IMD rainfall	16 (21) [33]		-21 (-29) [-36]	

[1]Average (mm): rainfall increase (deficiency) averaged over the entire 'R1' ('R2')
[2]10^{th} Percentile: rainfall increase (deficiency) averaged over tenth percentile maxima of 'R1' ('R2')
[3]Maximum: rainfall increase (deficiency) averaged over the largest (ten number of gridpoints) of 'R1' ('R2')

A comparison of modelled aerosol-induced modulations (weakening or strengthening) in monsoon rainfall (averaged over 5-y) with the measured modulations (i.e. departures) obtained from IMD-rainfall for the identified 'R1' and 'R2' regions is provided in Table S2. The modelled aerosol-induced rainfall strengthening for 'R1' due to all aerosols (dust aerosols) is about +9 mm (+ 15 mm); the same as above but that of aerosol-induced rainfall deficiency for 'R2' due to all aerosols (anthropogenic aerosols) is about − 16 mm (− 17 mm). Notably, our modelled rainfall deficiency (strengthening) values over R2 (R1) due to anthropogenic (dust) aerosols as mentioned above closely match with the monsoon rainfall deficiency recorded from measurements, i.e. IMD-rainfall departures (deficiency: − 21 mm; strengthening: + 16 mm). The tenth percentile maxima of rainfall deficiency (ten percent of all gridpoints over the region with the maxima of rainfall deficiency) due to all-aerosols for region 'R2' (− 28 mm) and that of rainfall strengthening for region 'R1' (+ 18 mm) mirrors the magnitude of rainfall deficiency (strengthening) from IMD-rainfall departure estimates for region 'R2' ('R1') as − 29 (+ 21) mm. Among the modelled values, the maximum rainfall deficiency (strengthening) is due to anthropogenic: − 48 mm (dust: + 51 mm) aerosols over eastern India (northwestern India) gridpoints for 'R2' ('R1'). The maximum rainfall deficiency over eastern India gridpoints for 'R2' and rainfall strengthening over northwestern India gridpoints for 'R1' as modelled due to all-aerosols as − 41 mm and + 46 mm, respectively, corroborates the corresponding from IMD-rainfall measured departures (deficiency as − 36 mm; strengthening as + 33 mm). The above comparison thereby indicates modelled aerosol-induced (anthropogenic and dust) spatial modulations (weakening and strengthening) of monsoon rainfall and their respective magnitudes over the Indian subcontinent corroborates the measured spatial modulations (departures) in IMD-rainfall. The aerosol-induced spatial changes (weakening and strengthening) of monsoon rainfall as estimated from the model therefore potentially explain the observed spatial modulations from the IMD-rainfall (departures) over the Indian subcontinent. A reasonably good comparison of measured departures with the modelled aerosol-induced spatial modulations indicates that while the estimated normal monsoon (estimated by averaging the last 50 years of IMD-rainfall) used in departure calculation accounts for the fairly consistent impact of greenhouse gases (corresponding to no-aerosol scenario in the designed ARS), the averaged rainfall (for five selected years accounting for the changing meteorological global climatic patterns) comprised the impacts due to regional aerosols. Thereby confirming our hypothesis on the modelled aerosol-induced changes (relative to no-aerosol) using the designed ARS to consistently represent the measured spatial modulations (weakening and strengthening as departures) in the monsoon rainfall driven by regional aerosols over the Indian subcontinent.

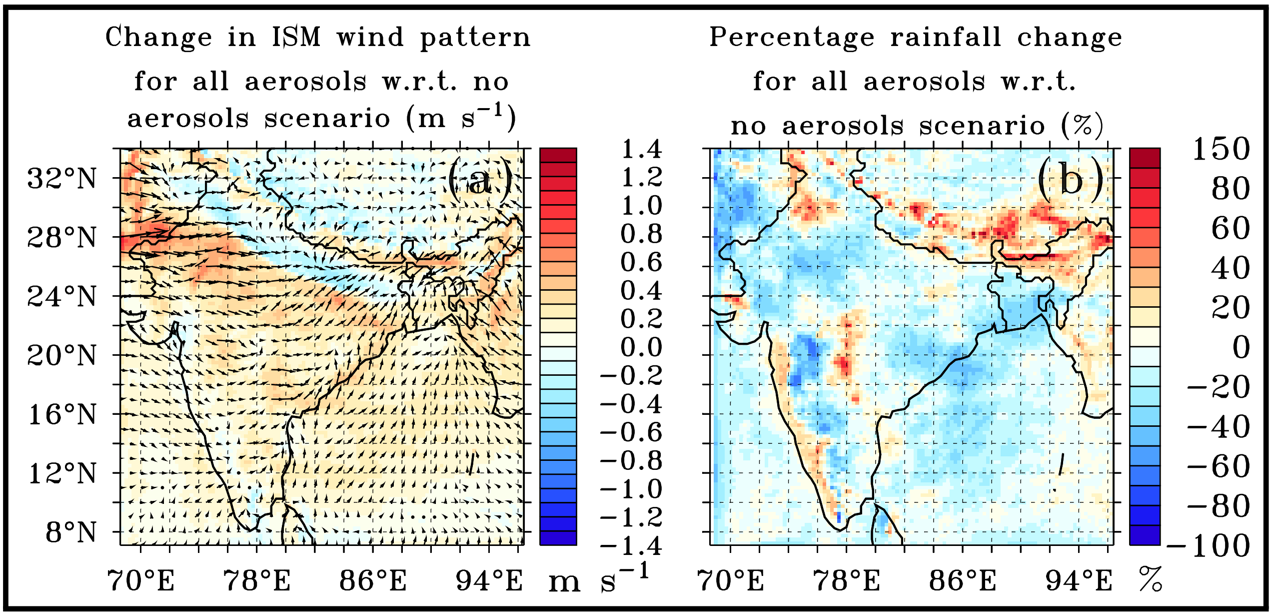

Figure S3 – Spatial distribution of simulated change in (a) wind fields, (b) ISM rainfall due to all-aerosols scenario with-respect-to no-aerosol scenario considering clear-sky aerosol radiative effects

References

Kumar, D. B., Verma, S., Boucher, O., Wang, R., 2018. Constrained simulation of aerosol species and sources during pre-monsoon season over the Indian subcontinent. Atmospheric Research 214, 91–108.

Stromatas, S., Turquety, S., Menut, L., Chepfer, H., Pere, J.-C., Cesana, G., Bessagnet, B., 2012. Lidar signal simulation for the evaluation of aerosols in chemistry transport models. Geoscientific Model Development 5 (6), 1543–1564.