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Tropospheric warming over the northern Indian Ocean caused by South Asian anthropogenic aerosols: possible impact on the upper troposphere and lower stratosphere

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Supplementary material

Section S1: AOD satellite observations

In this study we use the last fifteen years (2001 – 2016) of aerosol optical depth at 0.55 µm (AOD) obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument onboard the NASA EOS Terra satellite are used. The MODIS instrument measure a radiance in 36 spectral channels at a spatial resolution ranging from 250 m to 1 km with a 2300 km wide swath, allowing for almost daily global coverage. Terra MODIS (MOD08_M3 V6.1) AOD aerosol products are retrieved using the Deep Blue (DB) algorithm (Mhawish et al., 2019). The algorithm calculates the column aerosol loading at 0.55 µm over land and ocean. The AOD data from MODIS Terra can be downloaded from https://doi.org/10.5067/MODIS/MOD08_M3.061, 2017

AOD data from the Multi-angle Imaging Spectro-Radiometer (MISR) for the same period as MODIS (2001 – 2016) is also used for model evaluation (2020). The MISR sensor onboard the Terra satellite has been operational since 1999. It makes measurements at four spectral bands centered at 443 nm, 555 nm, 670 nm, and 865 nm (Diner et al., 2008). In this study we used, level 3 (MIL3MAE_v4) monthly mean aerosol optical depth at 555 nm wavelength at a spatial resolution of $0.5° \times 0.5°$. The MISR AOD data is available for download at https://doi.org/10.5067/TERRA/MISR/MIL3MJTA.002

Section S2:**Model evaluation**

We evaluate the model performance by comparing simulated AOD (from CTL simulations) with MISR and MODIS data for the spring season. The model simulations show high amounts of AOD over the Indo-Gangetic plain (25º - 35 ºN, 75º - 95º E), consistent with MODIS and MISR observations, despite quantitative differences (Fig. S1). Compared to observations, the model underestimates AOD over the Indo-Gangetic plain by ~18 % than MODIS and overestimates by 14% than MISR. While it underestimates over central India (15º – 24º N, 75º - 82º E) by 20 – 23 % compared to MODIS and MISR. There are differences among satellite observations and between the model and observations. The differences are due to (1) uncertainties in the model transport processes, the emission inventory, and the parameterizations. (Fadnavis et al. 2014, 2015, 2018, 2019) and (2) there are uncertainties in the satellite measurements (Bibi et al., 2015). The comparison of AOD from Aerosol Robotic Network (AERONET), MODIS and MISR show error of 0.03 to 0.05 (Kahn et al., 2007). With model biases present in both the CTL and the perturbed simulations, investigating anomalies removes some of the model bias. In the past Fadnavis et al. (2018, 2019, 2020, 2021a,b) reported model evaluations for AOD, absorbing aerosol index, precipitation, mixing ratio of black carbon aerosol and cloud ice with various measurements.

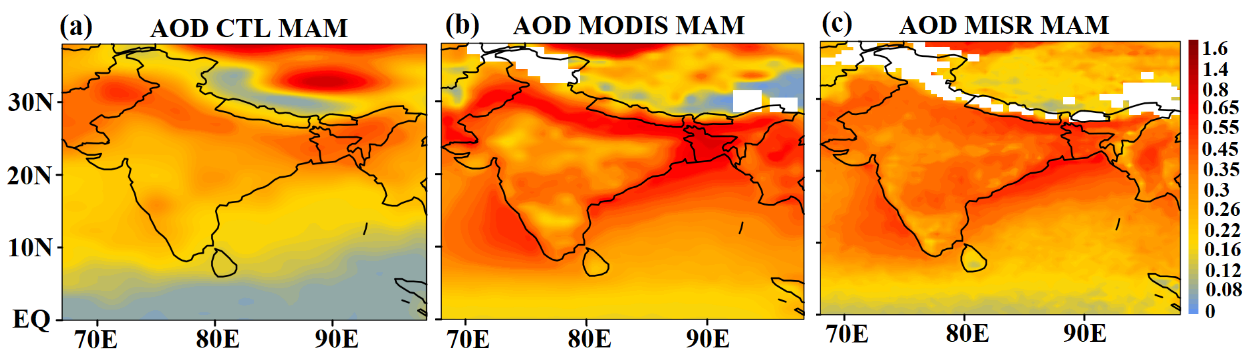

Figure S1: Spatial distribution of AOD average for the spring season for the years 2001 – 2016, from (a) ECHAM6-HAMMOZ CTL simulations, (b) MODIS measurements average for the spring season during 2001 – 2016, (c) MISR measurement average for the spring season during 2001 – 2016**.**

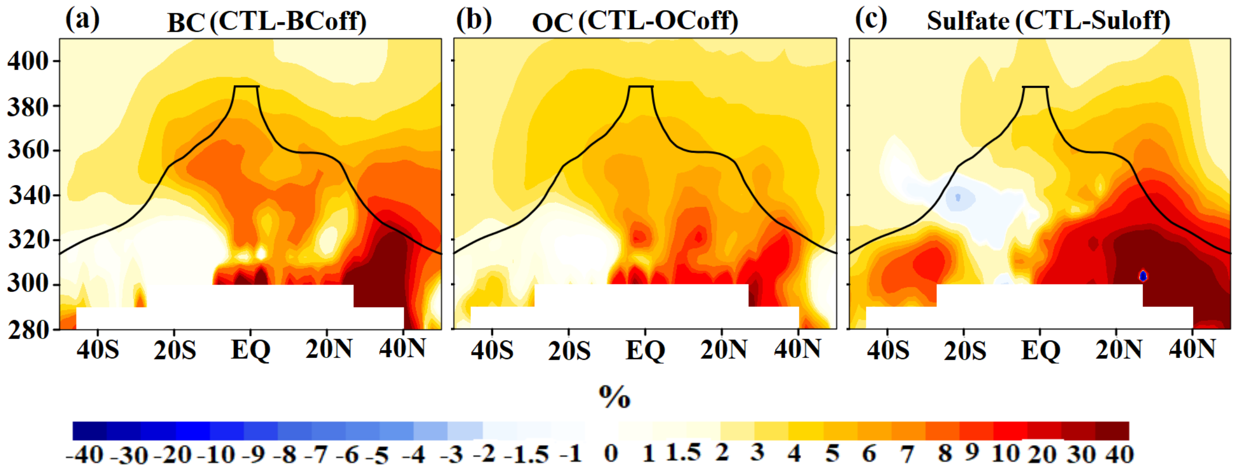

Figure S2: 4: Meridional cross-section over Indian Ocean-western Pacific (averaged 30º E – 140º E and for the spring season for the years 2001 – 2016) of anomalies (%) for (a) BC aerosols from CTL-BCoff simulations, (b) OC aerosols from CTL-OCoff simulations, (c) sulfate aerosols from CTL-Suloff simulations. A black line in Figs. a-c indicates the dynamical tropopause.

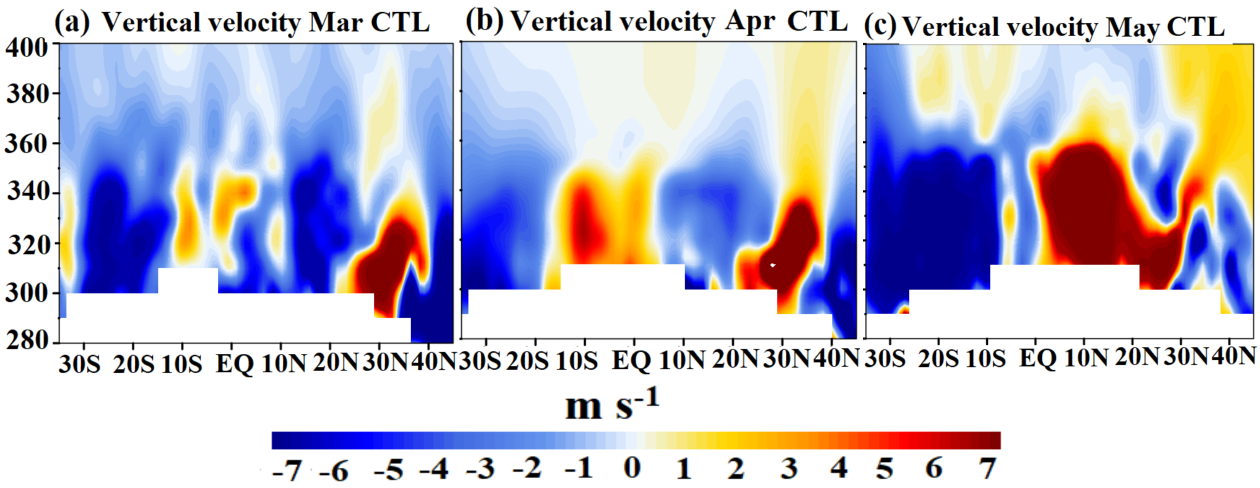

Figure S3: Meridional section of vertical velocities (CTL simulations) for (a) March, (b) April, (c) May, averaged during 2001 – 2016 and over the North Indian Ocean – Western Pacific (65º E – 140º E) (the vertical velocity field has been scaled by 300 and the units are m s^{-1}).

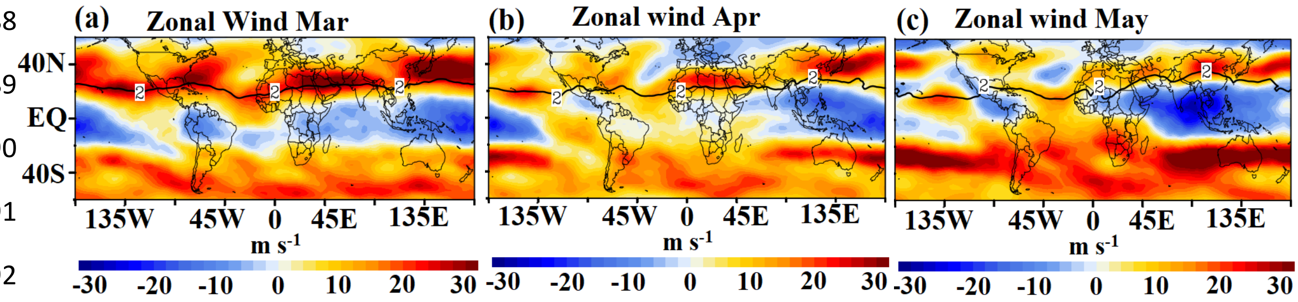

Figure S4: Zonal wind (m s^{-1}) at 360 K potential temperature level from CTL simulations for (a) March, (b) April, (c) May. The potential vorticity (2 PVU) is indicated by the black contour.

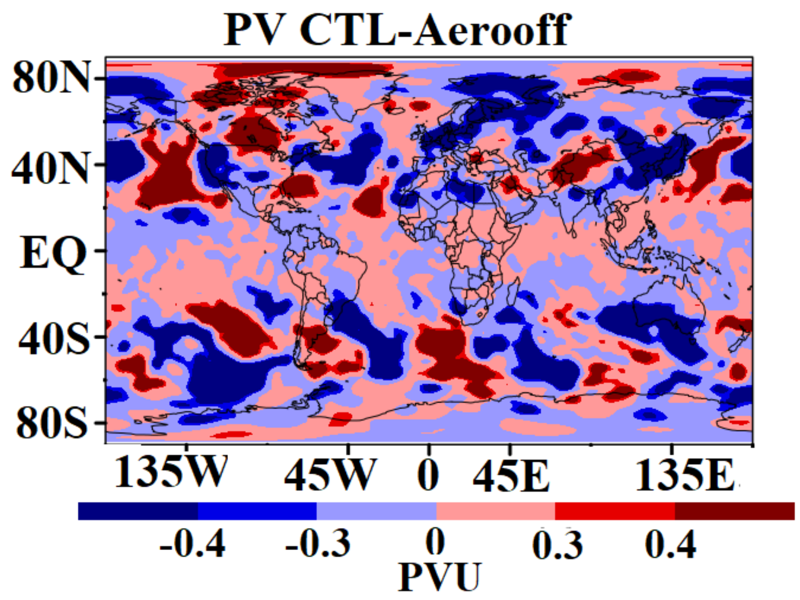

Figure S5: Spatial distribution of anomalies (CTL-Aerooff) of Potential vorticity (PVU) (1 PVU = 10^{-6} m^2 kg s^{-1}) averaged for spring and 350-360K potential temperature levels.

Table-S1: Mean radiative forcing (W m^{-2}) (averaged for spring) at the Top of the Atmosphere (TOA), surface (Surface) and In-atmosphere (TOA- Surface) averaged over the Indo-Gangetic Plan (IGP, Lon:75 – 83º E, lat: 26 – 30º N), Arabian Sea (A.S.: lon: 55 – 70º E, lat: 8 – 20 N), and Bay of Bengal (BoB) (Lon:88 – 92º E, lat:12 – 20º N) from all aerosols (CTL -Aerooff), BC (CTL - BCoff), OC (CTL - OCoff) and sulfate (CTL - Suloff).

CTL-Aerooff			
	TOA (W m^{-2})	Surface (W m^{-2})	In-atmosphere (W m^{-2})
IGP	1.27±0.16	-11.16±0.50	12.44±0.42
A.S	-0.72±0.14	-3.009±0.28	2.27±0.19
BoB	-1.24±0.15	-5.14±0.44	3.89±0.30
CTL-BCoff			
IGP	4.33±0.17	-9.27±0.37	13.61±0.44
A.S	1.24±0.13	-2.56±0.25	3.81±0.23
BoB	1.54±0.26	-3.70±0.49	5.25±0.39
CTL-OCoff			
IGP	-0.44±0.15	-2.56±0.45	2.12±0.42
A.S	-0.216±0.13	-0.49±0.31	0.27±0.10
BoB	-0.41±0.20	-0.79±0.34	0.38±0.19
CTL-Suloff			
IGP	-1.62±0.18	-2.67±0.36	1.05±0.30
A.S	-1.55±0.16	-1.19±0.24	-0.36±0.10
BoB	-2.14±0.17	-2.04±0.44	-0.095±0.032

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