Author response to Reviewer #2 comments

We sincerely thank the reviewer for the valuable comments. Based on the comments we received, careful modifications have been made to the manuscript. Our point-by-point response to the review comments are given below. The comments are marked in bold blue text and our responses are marked in normal black text below each comment.

Reviewer #2

Zonal variations of the vertical distribution of atmospheric aerosols over the Indian region and the consequent radiative effects Kala et al.,

A compilation of vertical profile and horizontal data for atmospheric aerosol properties (SSA, extinction coefficients and depolarization ratios). This group has produced several papers that have similar flavour to this one, primarily taking data and doing radiative forcing calculations using SBDART. The 'novelty' here may be the use of CALIPSO data to build vertical profiles that seem to have been rescaled using surface observations from the various field studies conducted around India, including the ICARB. I don't have any big issues with the paper, except that it doesn't offer anything new in terms of analysis/modelling. The two major concerns would be.

1. There is not much ground validation for the data in terms of comparisons with some ground based or aircraft data collection performed by the team.

A detailed comparison of our results with previous ground-based and aircraft-based lidar observations has been added to the revised manuscript in P10, line 291 as shown below.

Our k_{ext} values are in good agreement with the results of Satheesh et al., (2006) using micro pulse lidar, where the presence of aerosol layers aloft (within 1 – 2 km) during DJF over the urban region of Bengaluru (13.01°N, 77.34°E) was reported. Satheesh et al., (2008) reported the large concentration of aerosols within 2 – 5 km over the inland regions of peninsular India during the Integrated Campaign for Aerosols, gases and Radiation Budget (ICARB). They highlighted the decrease in the vertical extent (from 5 km over Central India to 1 km in the Northern Indian Ocean) and concentration of aerosols (a reduction in the maximum value of k_{ext} in the atmospheric column from 0.4 km^{-1} in Central India to 0.2 km^{-1} in Northern Indian Ocean) as we move meridionally away from the land into the surrounding oceans. Airborne lidar measurements during ICARB reported two Eastern coastal regions in peninsular India, namely Bhubaneshwar and Chennai, to have the vertical extent of k_{ext} as 3 km and 5 km respectively during MAM (Satheesh et al., 2009a). The maximum values of k_{ext} within the atmospheric column were observed be 0.3 km^{-1} and 0.35 km^{-1} respectively. Meanwhile, the southern coastal region Trivandrum had the vertical extent of k_{ext} to be 1.5 km and having a maximum value of 0.15 km^{-1}. It should be noted that all these stations had the maximum value of k_{ext} to be at altitudes above 2 km and not close to the surface. Satheesh et al., (2009a; 2009b) showed how the vertical extent and magnitude of k_{ext} decreases away from the coasts of three regions in the Indian peninsula. The contribution of aerosols above 3 km to columnar optical depth (AOD) was observed to decrease with increasing distance off the shorelines for Chennai whereas it remained more or less independent of distance for Bhubaneshwar. Lidar measurements by Moorthy et al. (2008) reported the presence of high-altitude aerosols even 400 km away from the coasts of Bay of Bengal, with a decreasing vertical extent and concentration (with a maximum value of 0.15 km^{-1} in the k_{ext} profile) away from the Chennai coast. Vaishya et al., (2018) made use of aircraft observations to study the vertical profiles of k_{ext} over Western India (Jodhpur), Central India (Varanasi), and Eastern India (Bhubaneshwar) during the South West Asian Aerosol Monsoon Interactions (SWAAMI) campaign conducted along with the Regional Aerosol Warming Experiment (RAWEX) campaign in June 2016. Peak value in the k_{ext} profile was reported by them to be maximum (0.2 km^{-1}) over Central India and reducing to either side to attain peak k_{ext} values of ~0.1 km^{-1} over Western and Eastern India. Manoj et al., (2020) reported the presence of aerosols above 2 km during the onset of monsoon over Northern India (Lucknow), Central India (Nagpur), North-Western India (Jaipur), Arabian Sea and Bay of Bengal during the SWAAMI aircraft campaign. These observations are in excellent agreement with our observations on the seasonality and zonal gradients in k_{ext} shown in Fig. 3.

2. The 'correction' of the ASSA over the ocean using for profiles uses the OSSA extended over the ocean and obtain a regression factor that was applied to ASSA. This seems arbitrary in some sense. Why not use a physics informed method that uses the differences in temperature profiles, water vapor profiles or PBL heights between the coastal and overland regions to inform the corrections?

The assimilated SSA is constructed from the gridded columnar Aerosol Optical Depth (AOD) and Aerosol Absorption Optical Depth (AAOD); both constructed by assimilating ground-based aerosol measurements with gridded satellite-retrieved products (Pathak et al., 2019) and employing data assimilation techniques that take into account the meteorological (Planetary Boundary Layer height) and topographical factors (elevation) with their inherent spatio-temporal variation. The assimilated Single Scattering Albedo (SSA) demonstrates more accurate columnar SSA values with substantially smaller uncertainties, vis-a-vis satellite-retrieved SSA. However, the assimilated SSA are available only over land regions due to the lack of long-term aerosol measurements over the oceanic regions and the fewer number of observatories. Therefore, we have extended the assimilated SSA over the oceanic regions by using the spatial variation demonstrated by satellite retrieved SSA, which exhibits close agreement with large-scale spatial patterns in assimilated SSA over the inland regions. This method is implicitly considering the local meteorological factors (through the assimilated aerosol products) as well as the realistic spatial distribution of SSA (through the spatial variation by satellite SSA) over the oceanic region obtained from Ozone Monitoring Instrument (OMI). This is based on the rationale that the SSA has higher variability over the land than over the ocean. Satheesh et al., (2010) have shown a higher gradient in SSA over the Arabian Sea and Bay of Bengal is in the north-south direction. Hence, taking this into account, this method employs the extension with the variation of SSA with respect to longitude for every latitude. The extended SSA is compared with previous reports of SSA over the oceanic regions in Table RC1. It can be observed that our extended SSA data values are in better agreement with the previous observations.

Table RC1: Comparison of SSA between previous in-situ observations with the OMI SSA and extended assimilated SSA reported in the present study.

Sl. No.	Region	SSA observations			Period	Reference
		Past	Present	OMI		
1	Bay of Bengal (BoB)	0.93±0.03	0.94±0.02	0.95±0.01	April 1999	Nair et al., (2008)
2	Kaashidhoo	0.9	0.95	0.96	Feb-Mar 1998	Satheesh et al., (1999)
3	Hanimaadhoo	0.93±0.02	0.95	0.96	Nov-Dec 2009	Corrigan et al., (2006)
4	BoB	0.93±0.01	0.94±0.02	0.95±0.01	Mar-Apr 2006	Kedia et al., (2010)
5	AS	0.96±0.01	0.94±0.01	0.94±0.01	Apr-May 2006	Kedia et al., (2010)
6	Kavaratti	0.91±0.01	0.94	0.96	Mar-May 2012	Patel et al., (2015)
7	AS	0.92±0.01	0.93+0.01	0.95±0.01	Mar-Apr 2003	Moorthy et al., (2005)
8	BoB	0.93	0.93	0.94	Dec-Apr 2001	Ramachandran et al., (2005)
9	BoB	0.9	0.94±0.01	0.95±0.01	Feb 2003	Ganguly et al., (2005)

Beyond these two, the manuscript badly needs a comparative evaluation with some model simulations. It is hard to get a sense to understand how this will feedback into improving models (regional and global). There are several runs performed as part of the CMIP6 with GCMs of various resolution and model output from the (AerChemMIP) for example. These should be accessible; how does this dataset compare with these simulations. There is a lot of qualitative description of mixing and gradients that are driven by dynamics. Using a model result to put these in context would be essential and making all the discussion more concrete. Without an accompanying model evaluation, the added value of this product to literature is questionable.

A detailed comparison between our results and AerChemMIP model simulations has been carried out as discussed below and has been added as a supplementary material (P1, line 13) for the revised manuscript.

A detailed comparison of our results with Aerosols and Chemistry Model Intercomparison Project (AerChemMIP) under the Coupled Model Inter Comparison Project (CMIP6) model from Meteorological Research Institute – Earth System Model (MRI-ESM) 2.0 (Yukimoto et al., 2019) is carried out for aerosol extinction coefficient (k_{ext}) and dust AOD. The present study uses data during the time period 2006–2020, and for a comparison, the scenarios considered in AerChemMIP6 are Historical Sea Surface Temperature (HistSST; 2006-2014) and Shared Socioeconomic Pathway (SSP3-7.0; 2015-2020). These two scenarios were chosen to match the time-period between AerChemMIP6 and the present study. The rationale for using these two scenarios for comparison is that they are baseline simulations consistent with observations (Collins et al., 2017; Lund et al., 2019). A short description of the two scenarios is given below:

1) HistSST scenario (Meinshausen et al., 2017): These simulations impose changes that are consistent with observations. The model performances are evaluated against the present climate and observed climate change.
2) SSP3-7.0 scenario (O'Neill et al., 2014): These are gap-filling simulations in the CMIP5 forcing pathways and forms baseline forcing levels for several (unmitigated) scenarios.

Fig. S1 shows the AerChemMIP6 model simulation of k_{ext} for the same location and time period as in the present study (Fig. 3). The results are consistent with our results and exhibit a zonal gradient from the west to the east, even the small hump in the middle being reproduced. The increase in vertical extent and magnitude of k_{ext} over the west during JJAS is also comparable. Even though the model simulations are in good agreement with the zonal gradients and the magnitudes of k_{ext} in Fig. 3 on a larger scale, our results reveal that the AerChemMIP6 simulations are underestimates over finer spatial scales. The high k_{ext} values and its vertical extent in the west (see Fig. 3) around the monsoon season is attributed to the long-range transport of dust aerosols (Banerjee et al., 2019; 2021). The dust AOD values from AerChemMIP6, shown in Fig. S2, also show high values over the west during MAM and JJAS, particularly over SR1. This agrees with our attribution of the dust influence to high k_{ext} over the Indian region (especially over the west) during JJAS and MAM seasons, as shown in Fig. 3 – 4. Our results will therefore prove useful in improving the regional climate model simulations.

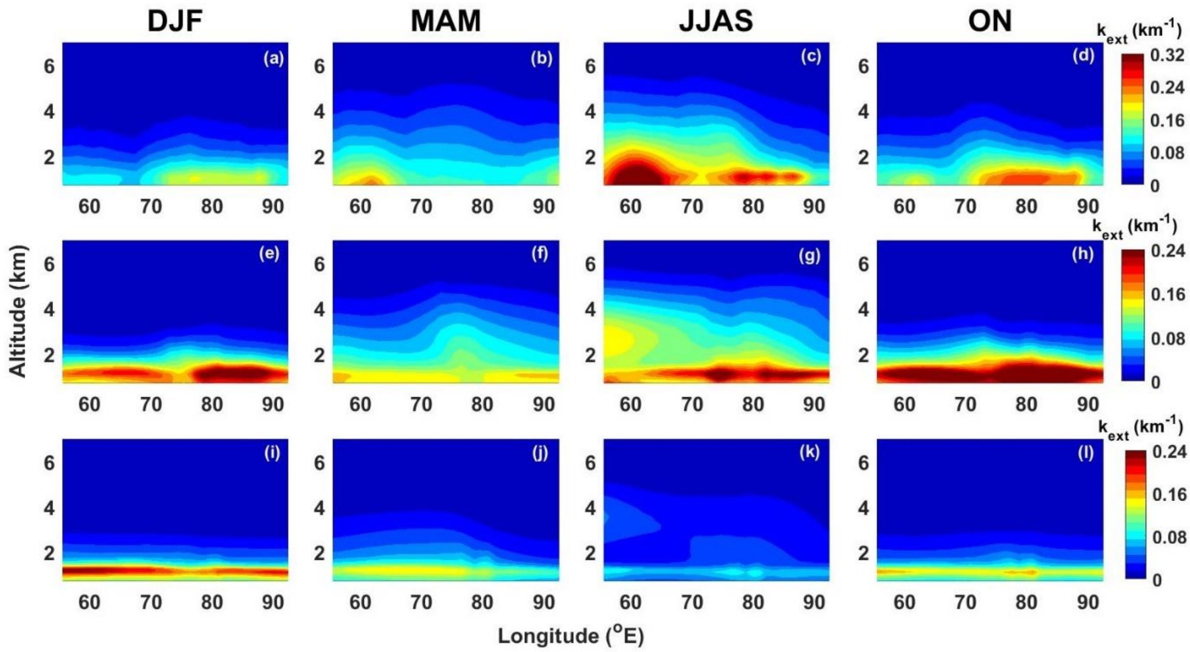

Figure S1: Zonal variation of the aerosol extinction coefficient (k_{ext}) (MRI-ESM2 model simulations) profiles for SR1 (top panel), SR2 (middle panel), and SR3 (bottom panel) sub-regions. Each column corresponds to a particular season, as marked above them.

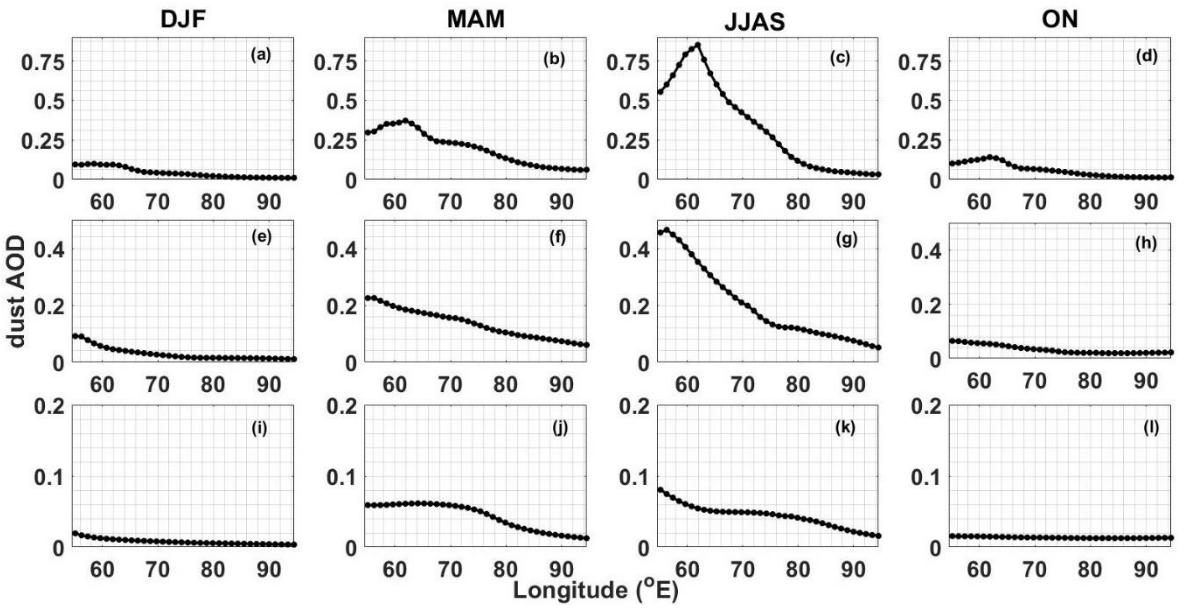

Figure S2: Zonal variation of the dust AOD (MRI-ESM2 model simulations) for SR1 (top panel), SR2 (middle panel), and SR3 (bottom panel) sub-regions. Each column corresponds to a particular season, as marked above them.

Some Specific Comments:

Line 45: Feng et al., 2016 did a detailed evaluation of the radiative forcing due to differences in land and ocean vertical profiles using MPLNet, CALIPSO and WRF-CHEM (doi:10.5194/acp-16-247-2016) and seems highly relevant to work discussed here. How do the calculations on radiative forcing performed here differ or similar to that discussed in that publication?

A comparison with the radiative forcing results of Feng et al. (2016) was carried out and the following section has been added as a supplementary material (P3, line 44) for the revised manuscript.

The present work utilizes observational datasets like CALIOP aerosol extinction coefficient, Moderate Resolution Imaging Spectroradiometer (MODIS) AOD and assimilated SSA to evaluate atmospheric radiative forcing using Santa Barbara DISORT Atmospheric Radiative Transfer (SBDART) model. Feng et al., (2016) used the Rapid Radiative Transfer Model (RRTM) for radiative transfer calculations in the Weather Research Forecasting with Chemistry (WRF-Chem) model. For comparison, the shortwave aerosol-induced atmospheric heating rate (dT/dt) have been estimated using our data sets and SBADART for the same region and time period (55–95˚E and 0–36˚N, March 2012) as in Feng et al., (2016). These results are compared with the control runs for shortwave dT/dt simulations shown in Fig. 4a (land) and Fig. 4d (ocean) in Feng et al., (2016), and are shown in Fig. S3 below. The magnitudes of dT/dt are higher in the present work as compared to Feng et al., (2016), but the vertical variations are more or less similar. The mismatch in the magnitudes of dT/dt is understandable because of two reasons: (1) Our dT/dt calculations make use of a gamut of realistic observations as inputs while the model makes use of simulated parameters as inputs, (2) There is a large underestimation of k_{ext} in the model simulations as compared to the observations (as high as a factor of four), as can be seen in Fig. 2 of Feng et al., (2016). This comparison further elucidates the importance of our results for improving regional climate simulations.

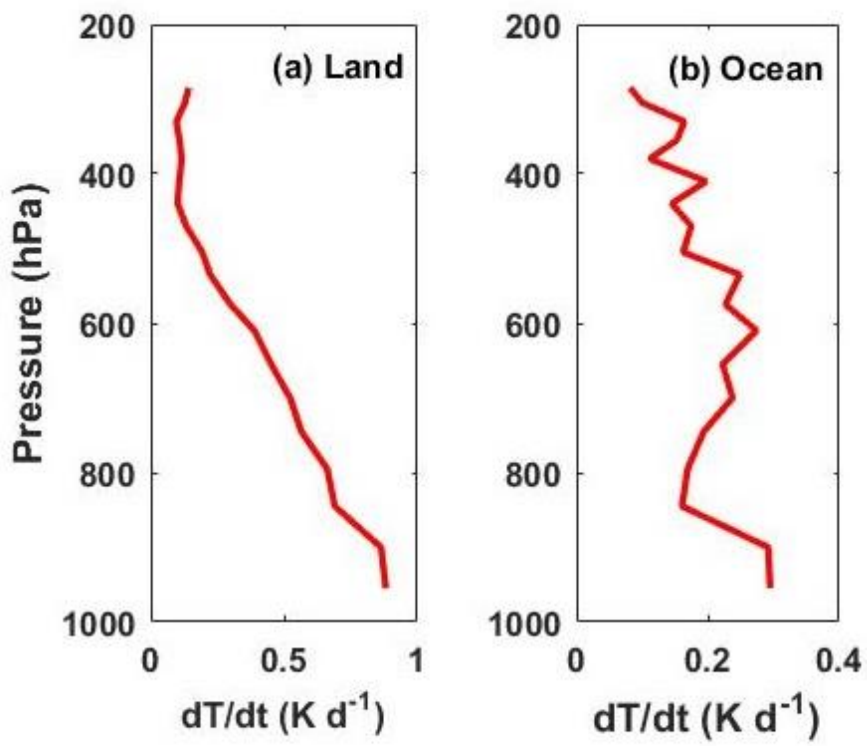

Figure S3: Vertical variation of shortwave aerosol-induced atmospheric heating rate (dT/dt) profiles over (a) Indian mainland and (b) oceanic regions.

Line 204: What dynamics are of importance here? Synoptic, mesoscale or boundary layer?

The dynamics of the atmospheric boundary layer governs the concentration and vertical distribution of aerosols in the lower altitudes whereas mesoscale and synoptic scales have a role in deciding the high-altitude aerosol concentration, through the long-range transported and elevated aerosol layers. Hence, three processes, mainly the long-range transport, accumulation, and dispersion of the aerosols regulate the zonal gradients discussed in the present study (Prijith et al., 2013; Ratnam et al., 2018; 2021).

Table 4: How do these heating rates compare to those being calculated by GCMs and models from AEROChemMIP?

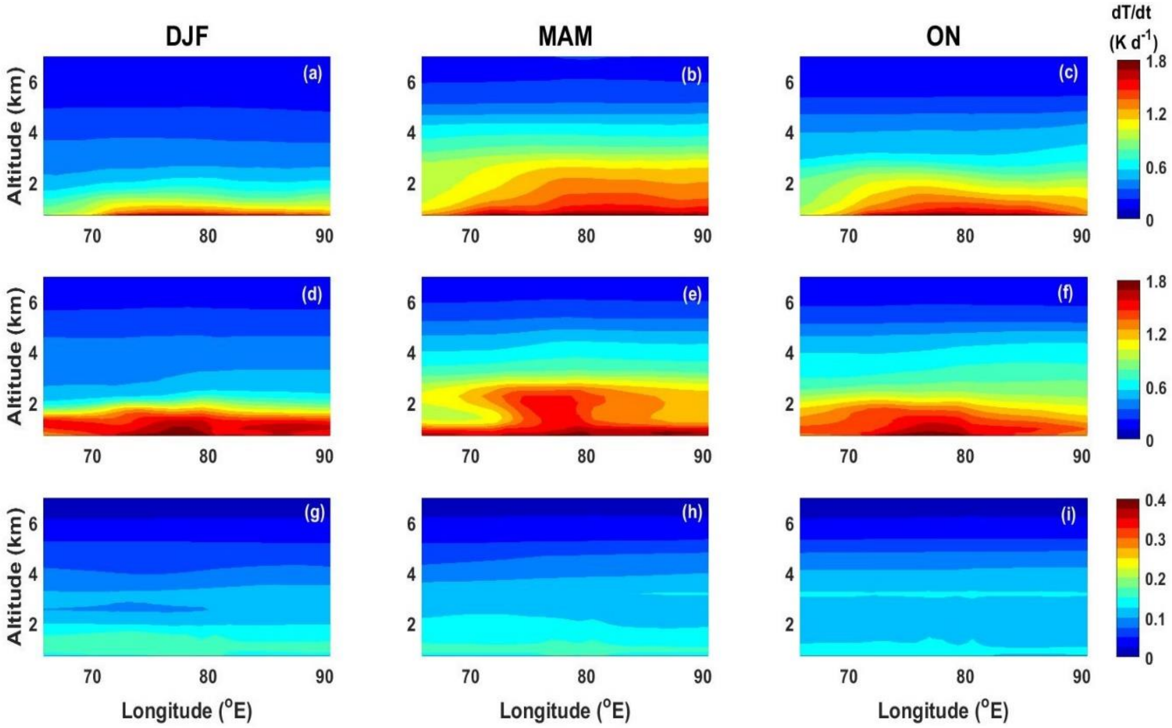

Figure RC4: Zonal variation of GFDL-ESM4 model simulated aerosol-induced atmospheric heating rate profiles (dT/dt) for SR1 (top panel), SR2 (middle panel), and SR3 (bottom panel) sub-regions. Each column corresponds to a particular season, as marked above them.

The dT/dt values from Geophysical Fluid Dynamics Laboratory – Earth System Model (GFDL-ESM4) model for HistSST experiment is shown in Figure RC4. While in general, the zonal variation and the vertical extent of dT/dt agree with our findings (see Fig. 6), the absolute magnitudes do not match, which is quite understandable, as the model simulations do not incorporate the realistic vertical distribution or SSA of the aerosols. dT/dt is higher in GFDL-ESM4 compared to our work (especially in the lower altitudes) possibly due to the underestimation of SSA in GFDL-ESM4, as shown in Mallet et al., (2021), who has categorized GFDL-ESM4 as 'C-' group [i.e., SSA has a negative bias compared to Aerosol Robotic Network (AERONET) measurements]. Hence, GFDL-ESM4 would have lesser SSA (compared to the observations) as input to the radiative transfer calculations, which may be the reason for their overestimation of dT/dt.

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