Responses to the comments of Anonymous Referee - 2

We appreciate and are thankful to the summary observations on the importance of this work and positive recommendation of both the reviewers. There are several comments intended to improve the clarity of the work and its quality. We have addressed all these comments carefully and our point-by-point responses to these are given below. The referee comments are shown in red font and our responses to these are given below in black font.

Comment 1: Page-3, Lines 26-30: Clarify on any seasonal variation of the externally mixed continental aerosol model used here (from which the phase function is obtained). Is it seasonally and spatially varying (as the aerosol type undergoes a signifcant spatio- seasonal variations, which is also stated in Page-4, Lines 6-14). If same phase unction is used in all seasons, what is the sensitivity (typical values, preferably in percentage) of the estimated ARF to any expected variations in the assumed phase function? SSA and AOD are already described in the manuscript.

This is an important point. Unlike aerosol optical depth (AOD) and single scattering albedo (SSA), there are no extensive ground-based and / or air borne measurements of aerosol size distributions available to generate gridded datasets for estimating the aerosol phase function. As such, we have used phase functions corresponding to appropriate aerosol models from the Optical Properties of Aerosols and Clouds (OPAC) [Hess et al. 1998] in order to estimate ARF using SBDART. The estimated RMS uncertainties are around 2.2 % (1σ) across the 8 streams of Legendre moments used in the radiative transfer model. While AOD and SSA are the most contributing factors to ARF, phase function plays a relatively less significant role as ARF is the integrated effect over the hemisphere (not angular).

In order to estimate the sensitivity of ARF estimates to the expected variations in the above aerosol phase function, we have simulated the ARF (at Top of Atmosphere (TOA), surface and within atmosphere) for the representative month of January-2009, over the entire Indian region. Each of these simulations were carried out by incorporating Legendre moments of aerosol phase function corresponding to each of the continental aerosol models provided in OPAC along with columnar, assimilated AOD and SSA in SBDART. The uncertainty of ARF w.r.t. that phase function is then estimated as one standard deviation across the multiple ARF simulations. This analysis has revealed that the RMS uncertainty (1σ) in ARF at TOA, surface and in atmosphere is around 4 %, 0.22 % and 0.05 % respectively. This shows that the present ARF estimates corresponding to assimilated aerosol products are substantially robust w.r.t. expected variations in aerosol phase function; however further improvement in accuracies of the ARF estimation is possible, when realistic size distribution data are generated in future.

This discussion has been included as Appendix A, Page No. 26, Line No. 13-16 and Page No. 27, Line No. 1-12 in the revised manuscript.

Comment 2: Clarify on the altitude profile of aerosols used in the RT simulations. Discussion of the results and some of the inferences drawn (e.g. Page-11; Lines 13-18) are based on the altitude profile of aerosols. While the statements in Page-11, Lines 13-18 are valid, it is to be seen if they are the result of the altitude variation of aerosol profiles used in the present RT calculations.

We highly appreciate this comment, which like the previous one, would help to better characterize the ARF and its vertical variation, which is more useful in climate implication studies. However, in the present work, we have used only columnar AOD and SSA and a typical value of aerosol scale height of 1.45 km. This point is included on Page No. 6, Line No. 5-6 in the revised manuscript.

Recent measurements over the Indian region using aircrafts and balloons have shown that aerosol properties do vary with altitude and this variation has seasonal dependency. However, the available data are not adequate to generate a gridded database for the vertical distribution of SSA and AOD representative for the entire region and for different seasons. We are in the process of collating the available data from airborne measurements over the Indian region, carried out during different campaigns since 2007 and would definitely be attempting this once a strong database emerges. The possibility of this improvement is indicated in the revised manuscript on Page No. 11, Line No. 18-23.

Comment 3: Statement on the uncertainty in the CERES-derived instantaneous TOA Shortwave radiative fluxes should be included.

In the present work, we have employed the shortwave (SW) radiative flux (instantaneous) provided by CERES-SSF1Deg (Single Scan Footprint) product. These TOA flux data are further averaged for a given month in order to estimate the monthly averaged, instantaneous flux for that location/grid point. We have observed that the RMS uncertainty (1σ) corresponding to this monthly averaging of instantaneous shortwave flux measurements is around 9 W m $^{-2}$ (over land). In addition, the monthly CERES SW flux measurements also suffer from the uncertainties arising from those in calibration of CERES instrument (1 W m $^{-2}$) and radiance to flux conversion process (1 W m $^{-2}$) [Su et al., 2015]. These details are now provided in the revised manuscript (Page No. 15, Line No. 12-15).

Comment 4: Clarity on the estimation of diurnal mean ARF may be provided (like the integration of instantaneous ARF from sunrise to sunset or in terms of solar zenith angle, or otherwise). Equations (1-3) are local time dependent at any given location.

We are thankful to the reviewer for suggesting this addition. Accordingly, the following explanation is included in Page No. 6, Line No. 10-14, 16-20 and 22-25 of the revised manuscript.

The upward and downward shortwave fluxes at the TOA and surface, (in the wavelength range 0.2 to 4 µm) are computed using SBDART for each hour from 6 am (approximate local sunrise time in IST) to 6 pm (approximate local sunset time in IST) for each grid point. The net radiative fluxes are then estimated (considering upward negative and downward positive) for 'with aerosol' and 'without aerosol' conditions and then ARF is estimated as the difference between the net fluxes for the two conditions as has been described in Equations 1-2.

The ARF values estimated in Equations 1-3, which are specific to a solar-zenith angle (or time of the day) for a given location, are further averaged (over the period of 12 hours) and
then halved in order to estimate the diurnally averaged shortwave ARF for the given grid point.

Comment 5: Figure-8; Pages 15-16: This needs to be clearly understood. As represents the difference between instantaneous AS RAD_{TOA} and $CERES_{TOA}$ (Eq.7). Ideally, this difference would be zero as the CERES fluxes as well as the assimilated AS RAD_{TOA} are highly reliable (the former is directly estimated from the observed radiances through appropriate ADMs - which is pivotal in the global radiation budget estimates - while the later account for surface albedo and observed aerosol properties). Any biases in either of them would be very small or insignificant. Hence the RMS differences in $_{AS}$ (having magnitude of 40-60 Wm-2) would arise from the uncertainties (random errors rather than bias) in CERES fluxes and estimated AS RAD_{TOA}. In order to understand this properly, please provide the following: (i) mean of $CERES_{TOA}$ fluxes for different seasons and annual mean, (ii) corresponding mean differences between instantaneous AS RAD_{TOA} and $CERES_{TOA}$, (iii) typical uncertainties in AS RAD_{TOA} and $CERES_{TOA}$ and (iv) statement on which factors contributed to δ_{AS} shown in Fig.8.

Yes, this is very important. As suggested by the reviewer, the annual and seasonal mean of instantaneous CERES measured TOA fluxes averaged over the Indian region are provided in the Table 1. The details of different seasons considered here are as described in Line No. 29-30, Page No. 15 of the manuscript. The corresponding annual and seasonal mean estimates of difference between the TOA fluxes estimated using assimilated products and CERES measurements (δ_{AS} = AS RAD_{TOA} - $CERES_{TOA}$) are also provided in the Table 1. It is to be noted that the standard deviation values provided in the Table 1 correspond to annual and seasonal averaging of respective variables over the domain and are representative of the statistical variations.

Table 1: Annual and seasonal mean CERES TOA flux measurements (instantaneous) and difference between AS RAD_{TOA} and $CERES_{TOA}$ in W m $^{-2}$

	Annual	MAM	ON	DJF
CERES TOA flux	133.12 ± 54.06	139.29 ± 59.65	127.16 ± 42.25	126.87 ± 47.68
δ_{AS}	61.01 ± 29.78	51.51 ± 8.90	76.01± 43.49	58.46 ± 28.53

Following the suggestion from the reviewer, we have estimated the uncertainties in AS RAD_{TOA} which primarily originate from those in assimilated AOD and SSA as well as from averaging of AS RAD_{TOA} over the satellite crossing duration. The uncertainties in the AS RAD_{TOA} due to those in assimilated aerosol products are estimated following the procedure similar to that is explained in Appendix A, Line no. 19-27, Page no. 25 from the manuscript for the two representative cases of January-2009 and May-2009 and the typical value of RMS uncertainty (1σ) in AS RAD_{TOA} is around 5.8 W m $^{-2}$. Further, the RMS uncertainty (1σ) due to temporal averaging of AS RAD_{TOA} over the duration corresponding to expected variation in the satellite crossing time is observed to be 7.6 W m $^{-2}$. The details about the uncertainties in instantaneous TOA flux measurements by CERES are as provided in the reply to the 3rd comment from the reviewer.
From the Table 1 and the above discussion of uncertainties, it is clear that the estimated RMS difference between the AS RAD_{TOA} and $CERES_{TOA}$ (i.e. RMS (δ_{AS}) which is varying from 40 to 70 W m ^{2} for annual mean case) is substantially contributed by the uncertainties in AS RAD_{TOA} and $CERES_{TOA}$. In addition, the uncertainties in MODIS surface reflectance datasets and the assumed aerosol phase function would also be implied in the AS RAD_{TOA} and would reflect in RMS (δ_{AS}). It is to be noted here that although the assimilated aerosol products have demonstrated much better confirmation with independent ground-based direct measurements [Pathak et al., 2019] vis-a-vis satellite-based products, over regions where the ground-based measurements are less dense or sparse, assimilated aerosol properties would tend to be very close to or nearly same as their satellite counterparts which suffer from substantial uncertainties and biases [Zhang and Reid, 2006, Jethva et al., 2014, 2009] as discussed in Pathak et al., (2019) (the part -1 paper). As such, to further reduce the differences between the model-estimated (using assimilated products) and CERES measured TOA fluxes, it is required to have denser network of ground-based aerosol measurements. In addition, incorporating spatio-temporally varying aerosol phase function datasets and vertical profiles of aerosol extinction and SSA is expected to reduce the differences further. The above points are included on Page No. 17, Line No. 6-27 and Page No. 18, Line No. 1-6 of the revised manuscript.

Comment 6: Figure 2a; Page 7, Lines 21-23: What led to the positive values of TOA ARF over the east Peninsular India? Low SSA? Over Himalayas, it might be because of high surface reflectance. Over NW India, surface reflectance and low SSA might have contributed. State clearly.

The positive TOA forcing over eastern Peninsular India (Figure 2a, 5a from the manuscript) arises primarily due to lower columnar SSA values (0.7 to 0.85) during winter as well as pre-monsoonal months as demonstrated in Figure 1d and 1h, Page no. 5 of the manuscript. These low SSA values indicate the increased presence of Black Carbon (BC) which can be largely associated with large anthropogenic activities (this region has several major harbours, industries and large urban conglomerates such as Chennai (13.08 N, 80.27 E), Vijayawada (16.51 N, 80.65 E), Visakhapatnam (17.68 N, 83.21 E), Bengaluru (12.97 N, 77.59 E), Bhubaneswar (20.30 N, 85.42 E)). We agree with assessment from the reviewer regarding positive TOA forcing over the dust-dominated, arid regions from north-western India and Himalayan foothills. The discussion regarding this is included in Section 4.1, Page No. 11, Line No. 24-29.

Comment 7 Page-7, Line-8: Can the month May be treated as representative of summer and pre-monsoon? See the other parts of the manuscript where summer (JJA) and pre- monsoon (March-May) are clearly discriminated (e.g., Line 27, Page-15).

We are sorry for this oversight. The month May forms part of the pre-monsoon season and is corrected accordingly on Page No. 7, Line No. 13 of the modified manuscript.

Comment 8. Page-4, Lines-7, 12: Add Figure number (Fig.1)

Thanks a lot for pointing this out. Appropriate figure number has been added on Page No. 4, Line No. 10 and 16 from the revised manuscript.

Comment 9. Proper usage of brackets while citing reference (e.g., Page-2, Lines 13, 15).

Thanks; complied with.

Comment 10. Page-7, Line-10: Change "... atmosphere As..." to "... atmosphere. As..."

We are sorry for this typo. The suggested correction has been incorporated on the Page No. 7, Line No. 15 of the revised manuscript.

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