Author response to Reviewer #1 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 #1

The paper is well written and appropriate for ACP. It provides a good overview of the aerosol conditions over the Indian Subcontinent. The CALIPSO data set is the basis for this and was carefully analysed.

Minor revisions are requested.

We appreciate the summary evaluation and the positive comments.

Abstract: The text is quite lengthy. I would appreciate a compact abstract, just 10-15 lines on methods and data, and a few key results. Many details are given in unnecessarily large detail. Such a detail description can be given in the summary section.

Complied with. The shortened abstract is given below and is also shown enabling Track Changes in the revised version line 9, from P1.

The vertical structure of atmospheric aerosols over the Indian mainland and the surrounding oceans and its spatial distinctiveness and resultant atmospheric heating are characterized using long-term (2007 – 2020) satellite observations, assimilated aerosol single scattering albedo, and radiative transfer calculations. The results show strong, seasonally varying zonal gradients in the concentration and vertical extent of aerosols over the study region. Compared to the surrounding oceans, where the vertical extent of aerosols is confined within 3 km, the aerosol extinction coefficients extend to considerably higher altitudes over the mainland, reaching as high as 6 km during pre-monsoon and monsoon seasons. Longitudinally, the vertical extent is highest around 75°E and decreasing gradually towards either side of the study region, particularly over peninsular India. Particulate depolarization ratio profiles affirm the ubiquity of dust aerosols in western India from the surface to nearly 6 km. While the presence of low-altitude dust aerosols decreases further east, the high-altitude (above 4 km) dust layers remain aloft throughout the year with seasonal variations in its zonal distribution over north-western India. High-altitude (around 4 km) dust aerosols are observed over southern peninsular India and the surrounding oceans during the monsoon season. Radiative transfer calculations show that these changes in the vertical distribution of aerosols result in enhanced atmospheric heating at the lower altitudes during pre-monsoon, especially in the 2 – 3 km altitude range throughout the Indian region. These results have large implications for aerosol-radiation interactions in regional climate simulations.

P2, line 54: Without these field campaigns, one would not know much about, e.g., lidar ratios, used in the CALIPSO data analysis. Such snapshot-like field campaigns are required to get a deep insight in aerosol properties. Without them, nobody would trust the 'larger picture' provided by the CALIPSO data sets.

Thank you for the clarification. The following modification has been made in the revised manuscript in P2, line 47.

Such snapshot-like field campaigns provide deeper insight into the location-specific aerosol properties.

P4, line 103-104: Are these lidar ratios from 23 to 70 sr in agreement with the lidar ratio observations realized during field campaigns such as INDOEX?

Yes, they agree with the lidar ratio observed during INDOEX. CALIOP makes use of different lidar ratios to capture different aerosol species, ranging from 23 sr for clean marine aerosols to 70 sr for polluted continental aerosols at 532 nm wavelength (Kim et al., 2018). The measurements over Maldives showed lidar ratios between 60 to 90 sr (Ansmann et al., 2000). Franke et al., (2001) reported that high lidar ratios, reaching up to 110 sr, are associated to lofted pollution plumes, >70 sr is indicative of small absorbing aerosols, 30 to 36 sr for a mixture of marine and anthropogenic aerosols, and <30 sr for clean marine conditions. Müller et al., (2003) have reported lidar ratios over Maldives to be within 30 to 90 sr for a mixture of clean marine and clean continental aerosols. Franke et al., (2003) obtained lidar ratios between 30 to 100 sr at 532 nm for composite aerosols and between 50 to 80 sr for the absorbing aerosols advected from northern India.

P4, l105-110: When using CALIPSO backscatter observations and MODIS AOT values one has the chance to get the column lidar ratios (AOD divided by the column backscatter). These values should be in harmony with the CALIPSO lidar ratios used in your data analysis.

Such studies are just indications that you did a lot in terms of quality assurance.

Thank you for pointing this out. The following sentences have been added in the revised manuscript in P4, line 100.

The CALIOP aerosol extinction profiles are retrieved from the backscatter signals using lidar ratios as reported in Kim et al., (2018). As an additional quality check, we calculated the lidar ratios separately for a representative month (January 2010) by dividing MODIS AOD with the Level-2 CALIOP column-integrated aerosol backscattering coefficient. Mean lidar ratios of 34.1 sr, 42.6 sr, and 23.3 sr were observed respectively over SR1, SR2 and SR3, which are in good agreement with the past lidar ratio observations surrounding the Indian region (Ansmann et al., 2000; Franke et al., 2001; 2003) and the lidar ratios employed in CALIOP. Furthermore, to overcome this limitation due to uncertainties in lidar ratios, the aerosol extinction coefficient profiles have been normalized using the combined Level-3 Version 6.1 average aerosol optical depth (AOD) from Moderate Resolution Imaging Spectroradiometer (MODIS) on board Aqua and Terra satellites (Wei et al., 2019).

Page 6 is terrible with all the ASSA, OSSA; deltaSSA, eSSA. I had to write down all the abbreviations to get not lost.

We are sorry for the inconvenience. We have replaced the abbreviations OSSA and eSSA with OMI SSA and extended SSA respectively in the entire manuscript and hope this would improve the readability.

P10, l297: Do you know the papers of Hofer et al. (ACP 2017, 2020) on central Asian dust observations (Dushanbe, Tajikistan), and Hu et al. (ACP, 2021) on western China dust observation (Taklamakan area). These papers could be cited.

Hofer, J., Althausen, D., Abdullaev, S. F., Makhmudov, A. N., Nazarov, B. I., Schettler, G., Engelmann, R., Baars, H., Fomba, K. W., Müller, K., Heinold, B., Kandler, K., and Ansmann, A.: Long-term profiling of mineral dust and pollution aerosol with multiwavelength polarization Raman lidar at the Central Asian site of Dushanbe, Tajikistan: case studies, Atmos. Chem. Phys., 17, 14559–14577, https://doi.org/10.5194/acp-17-14559-2017, 2017.

Hofer, J., Ansmann, A., Althausen, D., Engelmann, R., Baars, H., Fomba, K. W., Wandinger, U., Abdullaev, S. F., and Mahmudur, A. N.: Optical properties of Central Asian aerosol relevant for spaceborne lidar applications and aerosol typing at 355 and 532 nm, Atmos. Chem. Phys., 20, 9265–9280, https://doi.org/10.5194/acp-20-9265-2020, 2020.

Hu, Q., Wang, H., Goloub, P., Li, Z., Veselovskii, I., Podvin, T., Li, K., and Korenskiy, M.: The characterization of Taklamakan dust properties using a multiwavelength Raman polarization lidar in Kashi, China, Atmos. Chem. Phys., 20, 13817–13834, https://doi.org/10.5194/acp-20-13817-2020, 2020.

Thank you. Complied with in P11, line 322 in the revised manuscript.

Fig. 2: I would appreciate if OSSA and cSSA would be explained in the figure caption….

Complied with. Modified figure caption in P27, line 791 is as shown below:

Figure 2: Spatial map of OMI SSA (panels a, b, and c) and cSSA (combined SSA; panels d, e, and f). The left, middle, and right panels represent the seasons DJF, MAM, and ON respectively.

Fig.3: Please state in the caption that these observations are taken by CALIOP. What shows the dashed line in Fig.3c?

Complied with. Dotted yellow line in Fig. 3c illustrates the eastward gradient in the extent of vertical intrusion of aerosols. The modified figure caption is shown in P28, line 797 as shown below:

Figure 3: Zonal variation of the CALIOP aerosol extinction coefficient (k_{ext}) 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. Dotted yellow line in Fig. 3c illustrates the eastward gradient in the extent of vertical intrusion of aerosols.

Fig.4, the PDR values are derived from the respective VDR values by using the particle backscatter coefficient profiles. So the PDR profiles are uncertain. How trustworthy they are… should be discussed! For example, the red PDR fields (4b, 4c) show values of 30-40% depolarization ratio as THREE MONTH MEAN VALUES. Such high values cannot be explained by pure mineral dust. Desert dust produces 30% (so yellow colors), and at extreme conditions, close to dust sources, 35% may happen, but only in some cases.

The colour scheme used had some problems. The figure (Fig. 4) has now been remade in the revised manuscript and shows that PDR values above 0.35 to be seldom observed over the study region, and generally staying within 0.35. Prijith et al., (2016) have reported similar values of seasonal mean PDR over the Indian region, staying within 0.35, and occasionally going up to even 0.5.

Fig.5: cSSA, OSSA should be explained in the caption.

Complied with. The modified figure caption in P30, line 807 is shown below:

Figure 5: Zonal variation of cSSA (combined SSA) and OMI SSA in SR1, SR2, and SR3 during DJF, MAM, and ON seasons. The rows from top to bottom correspond to sub-regions SR1, SR2, and SR3 respectively.

References

- Ansmann, A., Althausen, D., Wandinger, U., Franke, K., Müller, D., Wagner, F., & Heintzenberg, J.: Vertical profiling of the Indian aerosol plume with six-wavelength lidar during INDOEX: A first case study, Geophysical Research Letters, 27(7), 963-966, 2000.
- Franke, K., Ansmann, A., Müller, D., Althausen, D., Wagner, F., and Scheele, R.: One-year observations of particle lidar ratio over the tropical Indian Ocean with Raman lidar. Geophysical Research Letters, 28(24), 4559-4562, 2001.
- Franke, K., Ansmann, A., Müller, D., Althausen, D., Venkataraman, C., Reddy, M.S., Wagner, F. and Scheele, R..: Optical properties of the Indo-Asian haze layer over the tropical Indian Ocean. Journal of Geophysical Research: Atmospheres, 108(D2), 2003.
- Hofer, J., Althausen, D., Abdullaev, S. F., Makhmudov, A. N., Nazarov, B. I., Schettler, G., Engelmann, R., Baars, H., Fomba, K. W., Müller, K., Heinold, B., Kandler, K., and Ansmann, A.: Long-term profiling of mineral dust and pollution aerosol with multiwavelength polarization Raman lidar at the Central Asian site of Dushanbe, Tajikistan: case studies, Atmospheric Chemistry and Physics., 17, 14559–14577, https://doi.org/10.5194/acp-17-14559-2017, 2017.
- Hofer, J., Ansmann, A., Althausen, D., Engelmann, R., Baars, H., Fomba, K. W., Wandinger, U., Abdullaev, S. F., and Mahmudur, A. N.: Optical properties of Central Asian aerosol relevant for spaceborne lidar applications and aerosol typing at 355 and 532 nm, Atmospheric Chemistry and Physics., 20, 9265–9280, https://doi.org/10.5194/acp-20-9265-2020, 2020.
- Hu, Q., Wang, H., Goloub, P., Li, Z., Veselovskii, I., Podvin, T., Li, K., and Korenskiy, M.: The characterization of Taklamakan dust properties using a multiwavelength Raman polarization lidar in Kashi, China, Atmospheric Chemistry and Physics., 20, 13817–13834, https://doi.org/10.5194/acp-20-13817-2020, 2020.
- Kim, M.H., Omar, A.H., Tackett, J.L., Vaughan, M.A., Winker, D.M., Trepte, C.R., Hu, Y., Liu, Z., Poole, L.R., Pitts, M.C. and Kar, J.: The CALIPSO version 4 automated aerosol classification and lidar ratio selection algorithm. Atmospheric Measurement Techniques, 11(11), 6107-6135, 2018.
- Müller, D., K. Franke, A. Ansmann, and D. Althausen (2003), Indo-Asian pollution during INDOEX: Microphysical particle properties and single-scattering albedo inferred from multiwavelength lidar observations, J. Geophys. Res., 108(D19), 4600, doi:10.1029/2003JD003538.
- Prijith, S. S., Babu, S. S., Lakshmi, N. B., Satheesh, S. K., and Moorthy, K. K.: Meridional gradients in aerosol vertical distribution over Indian Mainland: Observations and model simulations, Atmospheric environment, 125, 337-345, 2016.
- Wei, J., Peng, Y., Guo, J., and Sun, L.: Performance of MODIS Collection 6.1 Level 3 aerosol products in spatial-temporal variations over land, Atmospheric Environment, 206, 30-44, 2019.