

Dear Reviewers and Editor,

We would like to thank all the reviewers again for the time spent to evaluate our work and for the useful and constructive comments they gave which help to improve our work. We also acknowledge the editor. Here we submit a final version of manuscript which includes all proposed changes during the discussion that we think are necessary to be made in the revised manuscript. Thanks again for your contribution.

Note that our answers are in blue in the following text. The actual changes made in the manuscript is in *italics*.

Anonymous Referee #1

The authors present a method that expands the aerosol vertical profiles retrieved with nadir-pointing lidars to locations away from the lidar's nadir track that is based on matching radiances with a collocated imaging multispectral radiometer. The method, which includes a self-contained ability to test the reliability of the profiles constructed off the track, is tested using CALIPSO and MODIS data. Finally, a case study is performed, that presents scientific results.

Overall, I believe the manuscript is generally well written and contributes a useful and potentially important scientific tool although there are several minor, mostly grammatical errors, that I have listed. I therefore, recommend that it be considered for publication after minor revisions.

Issues throughout the paper:

- In some cases, there is a space between a value and the unit km and in some cases there is no space.

Using a space is preferred but in any case it should be consistent.

Thanks to this comment, we have made changes throughout the paper to be consistent to use a space between a value and the unit.

- Use of LaTeX '-' vs '–' (two minus signs) is not used properly in some places.

We are not using LaTeX, but we have replaced all '–' in the context, and been consistent to use '-'.

- Equations before 'where' should have commas after them.

We have put commas after Equations 1-5, since they are all connected with a 'where' or 'which'.

- There are cases of Table.X and Figure.X which obviously should not have a period. There are also cases of Fig.X and Tab.X that don't have a space after the period which they should have.

We have fixed the format of using abbreviated or not abbreviated form of 'Figure' and 'Table' in context.

- In table captions the period is missing after the table number.

We have added period after the table number in table captions.

- Maybe use 'lon' instead of 'long' to be consistent with the 3 letter use of 'lat'.

5 We thank author's recommendation, but we think both 'long' and 'lon' are commonly used for abbreviation of longitude, and we decide not to change it.

- In almost all cases of parenthetical cites with more than one cite there is no space after the semicolon. There should be.

10 The citation in the context is done through Cite While You Write™. We thank the reviewer for pointing it out and have added space in between cited works.

- In the table titles, except for the 'Table X.' the rest of the caption should not be bold.

We have made sure that only 'Table X.' is bold in the title.

- Please indicate the processing versions of the CALIPSO and MODIS products.

15 We have added to the data part that all CALIPSO products used in the work are from Version 4.20, and MODIS products used in the work are from MODIS Collection 6. The following lines have been added to the text on page 4, lines 14-15:

"CALIPSO products used in the work are from Version 4.20."

The following lines have been added to the text on page 4, lines 19-20:

"MODIS products used in the work are from MODIS Collection 6."

20

Comments with a particular location:

- Page 1, Line 28: The cite uses [] when it should use ().

The brackets have been changed.

25 ● Page 2, Line 5: The reference used here is rather old and is cloud specific. What about Levy et al. (2013).

We thank reviewer for the suggestion. The suggested reference has been added to the citation.

“R. C. Levy, Mattoo, L. A. Munchak, L. A. Remer, A. M. Sayer, and N. C. Hsu. *The collection 6 modis aerosol products over land and ocean. Atmospheric Measurement Techniques*, 6:159–259, 2013. doi: 10.5194/amtd-6-159-2013.”

● Page 4, Line 5: The MODIS radiances are also provided at 250 m (bands 1–2) and 500 m bands (1–7) and I am pretty sure these are used for the official aerosol product.

We thank reviewer for the comment. MODIS visible bands are provided with better resolutions, however, 1 km resolution is used in the work to be consistent with infrared bands.

● Page 4, Line 6: Again the the references here could be better and more up-to-date. Consider using Levy et al. (2013) and Platnick et al. (2017).

10 We thank reviewer for the suggestion. The suggested references have been added to the citation.

“R. C. Levy, Mattoo, L. A. Munchak, L. A. Remer, A. M. Sayer, and N. C. Hsu. *The collection 6 modis aerosol products over land and ocean. Atmospheric Measurement Techniques*, 6: 159–259, 2013. doi: 10.5194/amtd-6-159-2013.

Steven Platnick, Kerry G. Meyer, Michael D. King, Galina Wind, Nandana Amarasinghe, Benjamin Marchant, G. Thomas Arnold, Zhibo Zhang, Paul A. Hubanks, Robert E. Holz, Ping Yang, William L. Ridgway, and J’ôme Riedi. *The MODIS cloud optical and microphysical products: Collection 6 updates and examples from Terra and Aqua. IEEE Transactions on Geoscience and Remote Sensing*, 55(1):502–525, January 2017. doi:10.1109/TGRS.2016.2610522.”

● Page 4, Line 26: The operators and brackets should not be italicised.

20 The operators and brackets have been changed.

● Page 4, Eq 1: Use italics (math mode) for variables $F(i,j;m) \rightarrow F(i,j;m)$.

The equation has been changed.

$$F(i, j; m) = \sum_{k=1}^{K=4} \left(\frac{r_k(i, j) - r_k(m, 0)}{r_k(i, j)} \right)^2 ; m \in [i - m_1, i + m_2], \quad (1)$$

● Page 4, Eq 1: In the summation notation the lower variable is an index. The upper variable should be the upper value of the index. In this case both are the same variable.

25 We have changed the upper value of the index to 4. Please see the change above.

● Page 4, Line 30: $K = 4$? Related to previous comment.

We have changed the upper value of the index to 4. Please see the changes above.

● Page 4, Line 31: I think I understand why these bands are chosen but maybe have a bit of explanation. We thank the review for the comment. We have added following explanation to the text on page 5, lines 14-16:

5 “The bands are chosen for their widely accepted usage in retrieving cloud properties, including cloud cover, cloud top properties (CTP/CTT/CTH), and cloud phase (Ackerman et al., 1998; Baum et al., 2012; Baum et al., 2000) as well as aerosol properties (Sayer et al., 2014; Levy et al., 2013; Remer et al., 2013).”

● Page 5, Eq 2: Use italics (math mode) for variables $D(i,j;m) \rightarrow D(i,j;m)$.

10 The equation has been changed.

$$m_1 = m_2 = \begin{cases} 200; \dots \dots D_m \leq 30 \\ 200 + D_m; \dots D_m > 30, \end{cases} \quad (2)$$

● Page 5, Line 9: The asterisk in $(m^*, 0)$ is weird.

We thank the reviewer for the comment. The asterisk is used to specify that from all potential donors, the most suitable match is chosen to be the donor for the specific recipient. We modified the line to clarify this in the context on page 5, line 25.

15 this in the context on page 5, line 25.

“...which means, the selected donor, noted with asterisk $(m^*, 0)$, is closest to the recipient and has sufficiently similar radiances.”

● Page 5, Line 12: ‘of construction’ \rightarrow ‘of the construction’.

The sentence has been changed as suggested.

20 ● Page 6, Eq 5: Inconsistent use of italics. MR should not be italicized (use MR) and N should be italicized. Note other usages of MR below.

The equation has been changed, as well as the usages of MR in the explanation.

$$\mathrm{MR} = (\mathrm{Agree}_{cr} + \mathrm{Agree}_{cd} + \mathrm{Agree}_{ce}) / N, \quad (5)$$

● Page 6, Line 30: ‘km AGL’ \rightarrow ‘km above AGL’.

25 Since the AGL stands for above ground level, we think no change is needed here.

● Page 7, Line 15: ‘donors meets’ \rightarrow ‘donors that meet’.

The sentence has been changed as suggested.

- Page 7, Line 18: ‘air column’ → ‘air columns’.
The sentence has been changed as suggested.
- Page 7, Line 19: ‘air column’ → ‘air columns’.
The sentence has been changed as suggested.
- 5 ● Page 7, Line 29: ‘This is resulted’ → ‘This results’.
The sentence has been changed as suggested.
- Page 7, Line 29: ‘of TBM’ → ‘of the TBM’.
The sentence has been changed as suggested.
- Page 7, Line 32: ‘by total’ → ‘by the total’.
- 10 The sentence has been changed as suggested.
- Page 7, Line 33: ‘in reconstructed’ → ‘in the reconstructed’.
The sentence has been changed as suggested.
- Page 8, Line 1: ‘in reconstructed’ → ‘in the reconstructed’.
The sentence has been changed as suggested.
- 15 ● Page 8, Line 11: Use LaTeX `\times` instead of ‘x’.
The manuscript is not prepared in LaTeX. We apologize for the inconvenience.
- Page 8, Line 16: ‘In reality, this’ → ‘This’.
The sentence has been changed as suggested.
- Page 8, Line 29: Use LaTeX `\times` instead of ‘x’.
- 20 The manuscript is not prepared in LaTeX. We apologize for the inconvenience.
- Page 8, Line 30: ‘surrounding Bohai’ → ‘surrounding the Bohai’.
The sentence has been changed as suggested, as well as other sentences with the same issue.
- Page 9, Line 13: ‘heating. Average’ → ‘heating. The average’.
The sentence has been changed as suggested.
- 25 ● Page 9, Line 16: ‘C, average’ → ‘C, the average’.
The sentence has been changed as suggested.
- Page 9, Line 20: ‘AOD, especially’ → ‘AOD, with especially’.
The sentence has been changed as suggested.

- Page 9, Line 26: ‘with CALIPSO’ → ‘with the CALIPSO’.

The sentence has been changed as suggested.

- Page 9, Line 27: ‘hour of’ → ‘hours of’.

The sentence has been changed as suggested.

- 5 ● Page 9, Line 27: ‘using 10’ → ‘using the 10’.

The sentence has been changed as suggested.

- Page 9, Line 31: ‘have larger’ → ‘have a larger’.

The sentence has been changed as suggested.

- Page 10, Line 9: ‘to alter our’ → ‘to improve our’.

- 10 The sentence has been changed as suggested.

- Page 10, Line 10: ‘for study’ → ‘for the study’.

The sentence has been changed as suggested.

- Page 10, Line 12: ‘using SRM’ → ‘using the SRM’.

The sentence has been changed as suggested, as well as other sentences with the same issue.

- 15 ● Page 10, Line 16: ‘6.%’ → ‘6%’.

The extra period has been removed.

- Page 10, Line 18: ‘with sufficient’ → ‘with a sufficient’.

The sentence has been changed as suggested.

- Page 10, Line 25: ‘on SRM’ → ‘on the SRM’.

- 20 The sentence has been changed as suggested.

- Page 10, Line 25: ‘a power’ → ‘an important’.

The sentence has been changed as suggested.

- Page 10, Line 26: ‘well off’ → ‘not’.

The sentence has been changed as suggested.

- 25 ● Page 16, Table 3: Identify the abbreviations in the headers.

Thank for the suggestion, we add the following footnote to the Table 3.

*“*No Sig’ stands for ‘no signal’ and ‘Surf’ stands for ‘surface and subsurface’ portions of the measured columns.”*

- Page 20, Figure 3: ‘with 30km’ → ‘with a 30km’.
- Page 20, Figure 3: σ should be in italicized.

We thank reviewer for the suggestion. After considering other review’s comments, Figure 3 has been removed from the manuscript and the order of figures has been changed accordingly.

Anonymous Referee #2

The authors use the cloud construction algorithm developed by Barker et al. to construct vertical profile of aerosols. The algorithm seems to be exactly the same as the algorithm of Barker et al. with a different spatial resolution (a 5 km resolution for the lidar instrument). The study is focused on aerosol vertical profiles. They construct a 201 km wide of global aerosol profiles over two time periods. They test the algorithm by the same method discussed by Barker et al. They also evaluate the aerosol optical depth computed over nadir and off-nadir view regions and compare with the aerosol optical depth derived from AERONET.

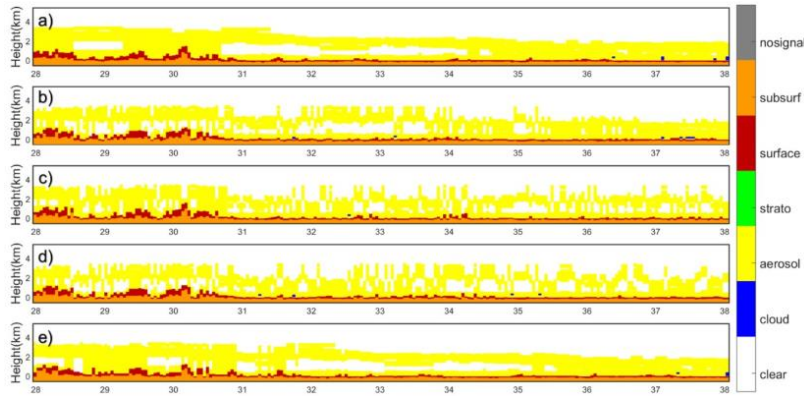
I have serious concerns on this version. First, the algorithm developed by Barker et al. uses near infrared and infrared channels. I expect that the algorithm does not work for aerosols for two reasons. Aerosol signals in near IR and IR channels are very weak and I am surprised that the algorithm works for aerosols. In addition, aerosol signal in the upward radiance is very small over land. The variability of visible radiance over land is dominated by the variability of surface reflectance. Again, I expect that the Barker algorithm does not work for aerosols especially over land. These lead me to wonder why the algorithm works. There is no physical explanation provided in the manuscript. The authors need to explain reasons why the authors expect that the Barker algorithm works for aerosols. The current manuscript is written in a way that the authors took the algorithm and found it works for aerosols.

We would like to thank the reviewer for the questions.

The algorithm we used, developed by Barker et al.(2011), utilized 0.62–0.67, 2.105–2.155, 8.4–8.7, and 11.77–12.27 μm channels from MODIS, or simply denoted as bands 1,7,29 and 32. Among these bands, bands 1 and 7 are also used for MODIS aerosol retrieval. Therefore, we believe the algorithm can also work for aerosols, as assumed in Barker et al.(2011). We did notice that the choice of channels might not be as beneficial for aerosols as they are for clouds, and the sensitivity to aerosols might rely more on using visible channels, and the signal from aerosols could be much weaker.

We had done the following test in order to test and possibly optimize the algorithm for application on aerosols. We collected 30 days of CALIPSO profiles in 2015 with clear-sky condition and heavy aerosol loading at the east coast of China. We expected the manually selected cloudless dataset with heavy loading events would give a clear answer to whether the algorithm could work for aerosols or not. We

test the following combination of radiance bands: 1) using bands 1, 7, 29 and 32 used by Barker et al.(2011); 2) using bands 1 and 7 only; 3) using visible bands 1, 2, 3 and 4. We tested the performance of using these combinations by reconstructing the profile with dead-zone setting for 30 and 100 km.



5 **Figure AC1** Reconstruction of CALIPSO profile passing the east coast of China on 3 January 2015 with dead-zone setting for 100 km.

A typical result is shown in the following figure, where the panel a is the original profile, panel b to d corresponds to combination 1 to 3, panel e shows the results of choosing the closest pixels outside the dead-zone. The results we got from this test indicate that the original combination used by Barker et al.(2011) could get a pretty successful reconstruction (on average 81.9% and 75.2% matching rate at 30 and 100 km, respectively), which means it can be used to construct aerosol vertical structure. In comparison, using visible channels only have lower matching rate (around 60-70%), especially when aloft aerosol layer are present. The closest pixel method, on the other hand, has very high matching rate at 30 km, but as the dead-zone range increases or if the aerosol layer is not continuous, the simple horizontal shift leads to more errors.

In conclusion, based on the test results with heavy aerosol loading events, the algorithm works for aerosols with the channels selected in Barker et al.(2011). Since the decision is to use the original method, and to keep the method section concise, we decide not to include this part in the main text. On the other hand, we have added following brief explanation to the text on page 5, lines 14-16:

“The bands are chosen for their widely accepted usage in retrieving cloud properties, including cloud cover, cloud top properties (CTP/CTT/CTH), and cloud phase (Ackerman et al., 1998; Baum et al., 2012; Baum et al., 2000) as well as aerosol properties (Sayer et al., 2014; Levy et al., 2013; Remer et al., 2013).”

5 Second, the authors compare the aerosol optical depth for validation of, essentially, the Barker’s algorithm. Figure 7 clearly shows that MODIS AODs agree with AERONET AOD better than “nadir” and “expanded”. MODIS instruments have a full coverage of Earth. Therefore, comparison of AOD presented in the paper does not show any advantage of the aerosol-constructing algorithm compared to MODIS. The authors need to show the validation of constructed aerosol vertical profiles, perhaps
10 compared with ground-based observations to demonstrate the advantage of constructing aerosol profiles. The authors also need to show how the error in the vertical aerosol profiles reduces, compared with nadir view only, when constructed aerosol profiles are used.

For reviewer’s second concern, we want to clarify that we did not intend to get a ‘better’ quantification of AOD by expanding active profiles to nearby regions. After all, the active pixel being
15 matched to the passive column could only provide an estimate of the column condition, which is not expected to be better than actual measurements MODIS made there. The advantage of this algorithm is really to help infer a profile and related vertical information, as shown in Figure 2 and original Figure 6 (now Figure 5), which passive-only cannot obtain.

We have added and modified the lines (page 12, lines 17-20) in Section 5 to illustrate this point.

20 *“The method in this work is not intended to get a precise quantification of aerosol profile, but to provide an estimate of the column’s vertical structure. We did expect, to some extent, the estimation could be improved through calculations with constrains such as the column AOD measured by passive sensor at the exact location of the recipient pixel, which will need a lot more work in the future. In addition, since lacking of more suitable pixels is responsible for about half of the mismatching results, we are
25 looking forward to launching more satellites with active and passive sensors, and possibly combining data from multiple satellite systems.”*

As for reviewer’s suggestion to validate the constructed aerosol vertical profiles with ground-based observations, given the difficulty of evaluating the aerosol vertical structure (AVS) retrieval due to scarcity of AVS measurements, in the original manuscript, we took one step back and compared the column total with ground-based AERONET sites.

Thanks to reviewer’s comment and also same comment from reviewer #2, we made our best effort to find measurements we were able to compare with. We found the Asian dust and aerosol lidar observation network (AD-Net) when we looked for ground-based lidar stations with freely downloadable data. AD-Net is a lidar network for continuous observations of vertical distributions of Asian dust and other aerosols in East Asia. The sites contribute to the WMO GAW Program, and form the East Asian component of the GAW Aerosol Lidar Observation Network (GALION). Although cooperative stations in China didn’t provide data sharing, we found some data that we were able to compare at Seoul station (37.5N,127.0E).

Seoul station has a standard lidar system in AD-Net, which is a two-wavelength (1064 nm, 532 nm) polarization sensitive (532 nm) Mie-scattering lidar, plus a 532 nm Raman (Shimizu et al. 2004). Based on the ground track, the A-Train sensors made overpass near the station for a total of 6 days during our case study in spring 2015. However, 4 out of these 6 days were heavily cloudy. For the remaining 2 days, March 7th and April 24th, the comparisons among ground-based lidar profiles, CALIPSO profiles at shortest distance and RXS-expand profiles averaged 25 km around the location of Seoul station are shown in the following figure, which is the new Figure 6 in the revised manuscript.

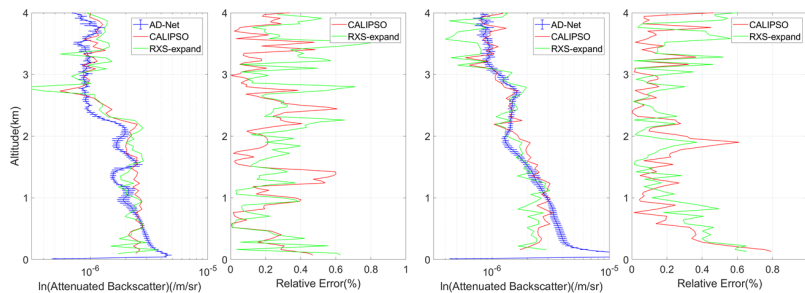


Figure 6 Comparisons among ground-based lidar profiles of 532 nm attenuated backscatter coefficient products (units: $m^{-1}sr^{-1}$, averaged 2 hours within satellite overpass), CALIPSO profiles at shortest distance and RXS-expand profiles averaged 25 km around the location of Seoul station

25 km around the location of Seoul station. The two plots on the left are from 7 March 2015, and the two plots on the right are from 24 April 2015.

The CALIPSO measurements we used for comparisons are level 1.5 data product of attenuated backscatter profiles, which clouds, overcast, surface, subsurface, and totally attenuated samples have been removed before being averaged to a 20 km horizontal resolution. In this case, RXS-expand profiles are based on the same products. The ground-based measurements used for comparison are the 532 nm attenuated backscatter coefficient products, averaged within 2 hr before and after the satellite overpass with 15 min time resolution.

For the aerosol layer 0-4 km above the ground, the relative error between CALIPSO profiles and ground station profiles are on average 21.6% on March 7th, and 18.7% on April 24th. The distances between station and ground track are 51.0 km on the first day, and 50.1 km on the second. Between RXS-expand profiles and ground station profiles, the average relative error is 27.9% and 23.4%, respectively.

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We made the decision to add following lines to Section 4.3, on page 10-11, as well as a few related sentences in the abstract and summary.

“In the three-month period, the Asian dust and aerosol lidar observation network (AD-Net) site at Seoul, Korea (37.5N,127.0E) provided measurements of atmospheric profiles that we were able to compare with those constructed in the surrounding area using the SRM method. Seoul station has a

standard lidar system in AD-Net, which is a two-wavelength (1064 nm, 532 nm) polarization sensitive (532 nm) Mie-scattering lidar, plus a 532 nm Raman (Shimizu et al., 2004). Based on the ground track, the A-Train sensors made overpass near the station for a total of 6 days during that spring. However, 4 out of these 6 days were heavily cloudy. For the remaining 2 days, 7 March and 24 April, the comparisons among ground-based lidar profiles, CALIPSO profiles at shortest distance and RXS-expand profiles averaged 25 km around the location of Seoul station are shown Fig. 6.

The CALIPSO measurements used for comparisons are level 1.5 data products of attenuated backscatter profiles, which clouds, overcast, surface, subsurface, and totally attenuated samples have been removed before being averaged to a 20 km horizontal resolution. In this case, RXS-expand profiles are based on the same products. The ground-based measurements used for comparison are the 532 nm attenuated aerosol backscatter coefficient products, averaged within 2 hr before and after the satellite overpass with 15 min time resolution.

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Anonymous Referee #3

Aerosol vertical structure (AVS) determines much of the climate impact of aerosol in the atmosphere, but it is difficult to measure with the spatial and temporal coverage needed for many applications. This study uses the spectral radiance matching (SRM) method, which infers AVS from column measurements
5 by matching them to similar measurements with collocated vertical profiles, to construct global AVS from MODIS and CALIOP data. The paper is well organized, and the methods section is especially clearly written.

Although collocated AERONET data is widely used to validate MODIS aerosol, its use in a case study for this manuscript does not seem sufficient to evaluate the AVS retrieval. This is undoubtedly
10 difficult, because the scarcity of AVS data that makes this study so valuable also leaves little basis for comparison. However, airborne field campaigns and ground-based lidar networks do measure vertical profiles of clouds and aerosol on a smaller scale, and given the global MODIS/CALIOP record to choose from, it should be possible to use some of these measurements to validate the satellite AVS.

We thank reviewer's understanding of the difficulty of evaluating the AVS retrieval due to scarcity
15 of AVS measurements, and we made our best effort to find measurements we were able to compare with.

We found the Asian dust and aerosol lidar observation network (AD-Net) when we looked for ground-based lidar stations with freely downloadable data. AD-Net is a lidar network for continuous observations of vertical distributions of Asian dust and other aerosols in East Asia. The sites contribute to the WMO GAW Program, and form the East Asian component of the GAW Aerosol Lidar Observation
20 Network (GALION). Although cooperative stations in China didn't provide data sharing, we found some data that we were able to compare at Seoul station (37.5N,127.0E).

Seoul station has a standard lidar system in AD-Net, which is a two-wavelength (1064 nm, 532 nm) polarization sensitive (532 nm) Mie-scattering lidar, plus a 532 nm Raman (Shimizu et al. 2004). Based on the ground track, the A-Train sensors made overpass near the station for a total of 6 days during our
25 case study in spring 2015. However, 4 out of these 6 days were heavily cloudy. For the remaining 2 days, March 7th and April 24th, the comparisons among ground-based lidar profiles, CALIPSO profiles at shortest distance and RXS-expand profiles averaged 25 km around the location of Seoul station are shown in the following figure, which is the new Figure 6 in the revised manuscript.

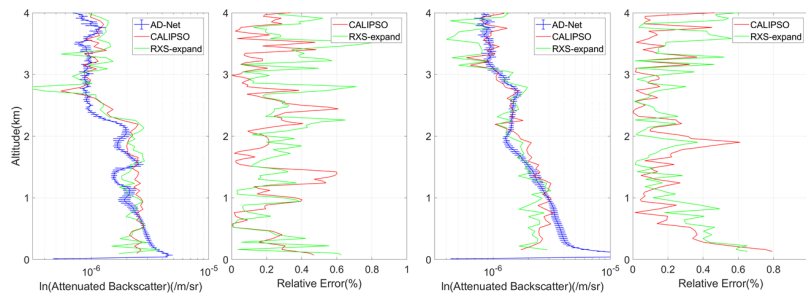


Figure 6 Comparisons among ground-based lidar profiles of 532 nm attenuated backscatter coefficient products (units: $\text{m}^{-1}\text{sr}^{-1}$, averaged 2 hours within satellite overpass), CALIPSO profiles at shortest distance and RXS-expand profiles averaged 25 km around the location of Seoul station. The two plots on the left are from 7 March 2015, and the two plots on the right are from 24 April 2015.

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For the aerosol layer 0-4 km above the ground, the relative error between CALIPSO profiles and ground station profiles are on average 21.6% on March 7th, and 18.7% on April 24th. The distances between station and ground track are 51.0 km on the first day, and 50.1 km on the second. Between RXS-expand profiles and ground station profiles, the average relative error is 27.9% and 23.4%, respectively.

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The results from the comparisons agreed in general. Previous studies found that there were considerable disagreement between CALIPSO measurements and ground-based lidar measurements; in most studies,

the differences were found to be around 20% (Mamouri et al., 2009; Wu et al., 2011; Kim et al., 2008; Chiang et al., 2011). For example, Mamouri et al. (2009) compared CALIPSO attenuated backscatter coefficient profiles with a ground-based lidar in Athens, Greece, and they found the agreement on the order of $-10\pm 12\%$ for cloud-free daytime measurements between 3 and 10 km, while the differences between 1 and 3 km were much larger ($-34\pm 34\%$).

In addition, we want to clarify that we did not intend to get a precise quantification of aerosol profile through the scene construction method. After all, the active pixel being matched to the passive column is intended only to provide an estimate of the column's vertical structure. We did expect, to some extent, the estimation could be improved through calculations with constrains such as the column AOD measured by passive sensor at the exact location of the recipient pixel, which will need a lot more work in the future.

We made the decision to add following lines to Section 4.3, on page 10-11, as well as a few related sentences in the abstract and summary.

"In the three-month period, the Asian dust and aerosol lidar observation network (AD-Net) site at Seoul, Korea (37.5N, 127.0E) provided measurements of atmospheric profiles that we were able to compare with those constructed in the surrounding area using the SRM method. Seoul station has a standard lidar system in AD-Net, which is a two-wavelength (1064 nm, 532 nm) polarization sensitive (532 nm) Mie-scattering lidar, plus a 532 nm Raman (Shimizu et al., 2004). Based on the ground track, the A-Train sensors made overpass near the station for a total of 6 days during that spring. However, 4 out of these 6 days were heavily cloudy. For the remaining 2 days, 7 March and 24 April, the comparisons among ground-based lidar profiles, CALIPSO profiles at shortest distance and RXS-expand profiles averaged 25 km around the location of Seoul station are shown Fig. 6.

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For the aerosol layer 0-4 km above the ground, the relative error between CALIPSO profiles and ground station profiles are on average 21.6% on 7 March, and 18.7% on 24 April. The distances between station and ground track are 51.0 km on the first day, and 50.1 km on the second. Between RXS-expand profiles and ground station profiles, the average relative errors are 27.9% and 23.4%, respectively. The results from the comparisons agreed in general. Previous studies found that there were considerable disagreement between CALIPSO measurements and ground-based lidar measurements; in most studies, the differences were found to be around 20% (Mamouri et al., 2009; Wu et al., 2011; Kim et al., 2008; Chiang et al., 2011).”

We also added and modified the lines (page 12, lines 17-20) in Section 5 for clarification of the purpose of the SRM method.

“The method in this work is not intended to get a precise quantification of aerosol profile, but to provide an estimate of the column’s vertical structure. We did expect, to some extent, the estimation could be improved through calculations with constrains such as the column AOD measured by passive sensor at the exact location of the recipient pixel, which will need a lot more work in the future. In addition, since lacking of more suitable pixels is responsible for about half of the mismatching results, we are looking forward to launching more satellites with active and passive sensors, and possibly combining data from multiple satellite systems.”

Specific comments:

Page 2, lines 1-23. I’m surprised not to see any mention here of ground-based lidar networks, which are sometimes used in combination with CALIOP data; or of the shorter-lived NASA CATS lidar that was aboard the ISS.

We thank the reviewer for the suggestion and we added the following lines to the content, as a separate paragraph after the first one on page 2, lines 16-20.

“The development of lidar technology helped provide these vital missing piece of information. Ground-based lidar systems have been stationed at various locations and also used in field campaigns to measure the vertical and horizontal distribution of aerosols (Welton et al., 2000; Welton et al., 2002; Badarinath et al., 2010). Ground-based lidars provide measurements on the fixed locations on timescale of minutes to hours, depending on the specific type of lidar used in the experiment. Limited by the

stationary setting, ground-based lidars could not achieve true global coverage, nevertheless, network of ground-based lidars (e.g. MPL-NET, EARLINET, AD-NET) provide key insights to atmospheric study and are involved in validation of satellite sensors (Kovacs et al., 2004; Mamouri et al., 2009; Pappalardo et al., 2010)."

5 Page 6, lines 18-21. These cloud cover rates seem very low. For passive sensors, 70% is a reasonable ballpark estimate for the fraction of the globe covered by clouds at any given time. Most such clouds would occupy only a small part of the vertical column (and as the paper states, almost never at high altitudes) but the numbers still seem difficult to reconcile. Have you calculated the global cloud cover from the column perspective, for comparison?

10 We thank the author for the question and comment. We made it more clear in the revision that the numbers in Table 2 refers to cloud occurrence as percentage they occupied in the vertical column. We calculated this occurrence rate according to CALIPSO VFM products, which was scaled for vertical and horizontal resolution (Hunt et al. 2009). However, it is true that the numbers in the table underestimated the amount of clouds in actual atmosphere. As we stated, CALIPSO's signal can be totally attenuated
15 beneath clouds and possibly making cloud layers below showed up as "no signal". The horizontal cloud coverage between 60°N and 60°S for the tested periods in April and September 2015 are 68.7% and 71.3%, respectively.

We added and modified the lines on page 7, lines 7-13 to address this comment.

20 *"Table 2 summarizes frequencies of occurrences of atmosphere conditions. These numbers refer to the occurrence of atmospheric features as percentage they occupied in the vertical column. We calculated this occurrence rate according to CALIPSO VFM products, which was then scaled for vertical and horizontal resolution of the products (Hunt et al., 2009).The majority of conditions were identified as clear. Above 8.2 km clear arrays occur over 90% of the time. Aerosols and clouds occurred below 8.2 km, in about 7% and 5% of the cells, respectively. Note that arrays identified as 'no signal' represent 16
25 - 18% of cells in this layer; CALIPSO's signal can be totally attenuated beneath opaque clouds and certain aerosols. This indicates that the numbers in Table 2 likely underestimated the amount of clouds and aerosols in actual atmosphere."*

Page 6, Figure 2. This is fascinating. It would be interesting to see a more detailed discussion of the contrast between 0-2 km and 2-4 km, which appear to distinguish local aerosol from aerosol undergoing long-range transport.

We thank the author for the suggestion. We add more discussion about the contrast between 0-2 km and 2-4 km into the last paragraph on page 7, lines 21-31.

“Height-resolved global AOD maps (averaged for a $2^\circ \times 2^\circ$ lat/long grid) based on the two selected periods are shown in Fig. 2. In the near-surface layer, 2 km above ground level (AGL), in April, relatively high aerosol loadings are found in the cross-Atlantic African dust transport, Saudi Arabia, and India. In September, dust dynamics are much weaker but much biomass burning is apparent in the Brazilian Amazon and Southern Africa. This seasonal trend of dust and smoke is more obvious in the layer 2-4 km AGL. Aerosol in this layer aloft are expected to be undergoing long-range transport. In April, the thickest dust layers are found slightly inland of the western coast of Africa, around $12.5^\circ N$, $5.5^\circ E$, and in the centre of Saudi Arabia around $24.5^\circ N$, $42.5^\circ E$. The shift of AOD distribution between surface layer and layer above is logical, and indicates the movement of dust layers as the aerosol loadings are transported towards the oceans. In September, this contrast is harder to observe as the dust dynamic is weaker, but similar trends are found in the biomass burning regions. In addition, persistent high aerosol loadings in both 0-2 km and 2-4 km AGL are found in India and the east coast of China with mixed sources of natural aerosols and pollutants. The results could be affected by the local topography.”

Page 8, Figure 3. This plot is somewhat difficult to read. A different color scheme may make the drop in the matching rate at the ITCZ easier to spot, but I’m having trouble seeing any other patterns.

We agree with the reviewer that Figure.3 is rather vague for the information we tried to convey. In fact, we think Figure.3 does not give enough extra information on its own, other than these results given in Figure.4. Therefore, we make a decision to remove this figure and related sentences, change the order of figures accordingly.

Technical comments:

Page 6, line 14. “Losing”.

Page 8, line 19. “CALIOP profiles”.

The sentence has been changed as suggested.

Analysis of Global Three-Dimensional Aerosol Structure with Spectral Radiance Matching

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10 **Abstract.** A method is assessed which expands aerosol vertical profiles inferred from nadir-pointing lidars to cross-track locations next to nadir columns. This is achieved via matching of passive radiances at off-nadir locations with their counterparts that are collocated with lidar data. This spectral radiance matching (SRM) method is tested using profiles inferred from CALIPSO lidar observations and collocated MODIS passive imagery for the periods 10-25 April and 14-29 September 2015. CALIPSO profiles are expanded out to 100 km on both sides of the daytime ground-track. Reliability of constructed profiles
15 that are removed from the ground-track by N km are tested by requiring the algorithm to reconstruct profiles using only profiles that are removed from it along-track by more than N km. When sufficient numbers of pixels/columns are available, the SRM method can correctly match ~75% and ~68% of aerosol vertical structure at distances of 30 km and 100 km from the ground-track, respectively. The construction algorithm is applied to the east coast of Asia during spring 2015. Vertical distributions of different aerosol subtypes indicate that the region was dominated by dust and polluted dust transported from the continent. It
20 is shown that [atmospheric profiles and aerosol optical depths \(AOD\)](#) inferred from ground-based measurements agree with those constructed by the SRM method. [For profiles, the relative errors between those measured by ground-based lidar and those constructed in the surrounding area are similar to the relative errors between ground-based station and CALIPSO overpass at closest distance. For AOD, the measurements from ground-based network agree with those inferred from constructed aerosol structure,](#) better than direct observations from CALIPSO, and close to those inferred from MODIS
25 radiances.

1 Introduction

Aerosol vertical structure (AVS) plays an important role in Earth's climate system. Aerosols affect changes in radiative fluxes by scattering and absorbing solar radiation, as well as modifying cloud physical properties (IPCC, 2013). Studies of Saharan dust transport (Guerrero-Rascado et al., 2008) and Pacific air-pollutant transport (Xu et al., 2019) indicate that AVS is a key
30 parameter needed to evaluate the production, transport, and removal of aerosols. Considering the effect of external and internal mixing of aerosols during this process, understanding AVS also helps improve descriptions of optical properties of aerosols.

Similarly, the presence of aerosols induces diverse cloud responses by acting as condensation and ice nuclei (Breon et al., 2002; Textor et al., 2006) ~~(Breon et al., 2002; Textor et al., 2006)~~. Therefore, detailed information of AVS is necessary to understand the vertical structure of clouds and precipitation (Guo et al., 2018).

The current understanding of AVS is limited by the amount of observations made across the globe. Traditional techniques
5 rely on airborne campaigns to collect aerosols using filters on in-situ instruments (Moosmuller et al., 2009). Recently, however, the amount of relevant information has been boosted by the advent of satellite-based remote sensing. The passive sensor MODERate resolution Imaging Spectroradiometer (MODIS), on-board the Terra and Aqua satellites since 1999 and 2003, respectively, has provided global measurements almost daily (Platnick et al., 2003; Levy et al., 2013). MODIS data are used routinely to infer aerosol optical depth (AOD). Such inferences, however, lack information pertaining to AVS. The inability
10 to separate aerosols layers leads to difficulties in interpreting aerosol transport as high near-surface concentrations can overpower thinner layers transported aloft. In addition, MODIS is not well-suited to distinguish aerosol type, thereby making it difficult to study aerosol variations in time, space, and combinations of emission sources.

The development of lidar technology helped provide these vital missing piece of information. Ground-based lidar systems have been stationed at various locations and also used in field campaigns to measure the vertical and horizontal distribution of
15 aerosols (Welton et al., 2000; Welton et al., 2002; Badarinath et al., 2010). Ground-based lidars provide measurements on the fixed locations on timescale of minutes to hours, depending on the specific type of lidar used in the experiment. Limited by the stationary setting, ground-based lidars could not achieve true global coverage, nevertheless, network of ground-based lidars (e.g. MPL-NET, EARLINET, AD-NET) provide key insights to atmospheric study and are involved in validation of satellite sensors (Kovacs et al., 2004; Mamouri et al., 2009; Pappalardo et al., 2010).

The Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) satellite, launched in 2006, provides greater insight into AVS (Winker et al., 2009). CALIPSO’s active sensor, the Cloud–Aerosol Lidar with Orthogonal Polarization (CALIOP), has the ability to resolve vertical structures of optically thin clouds and aerosols at the global scale. Yet, with its narrow nadir-viewing geometry, CALIPSO repeatedly samples only 0.2% of Earth every 16 days (Kahn et al., 2008). This low frequency and small coverage makes it difficult to study regional AVS with CALIPSO products.

Collocation of passive and active sensors can, however, provide synergistic insights. The A-Train constellation, which
25 includes Aqua and CALIPSO, has made many breakthroughs. Satellites of the A-train constellation are in a 705-km sun-synchronous polar orbit, with an equator-crossing time of about 1330h local solar time, and are in close proximity to one another. The success of the A-Train has led to plans to launch other active–passive satellites, such as the Earth, Clouds, Aerosols and Radiation Explorer (EarthCARE) Mission (Illingworth et al., 2015). China has its own plan to launch a multi-
30 functional observation satellite equipped with a High Spectral Resolution Lidar (HSRL), a Mie-Lidar, and a wide-swath cloud and aerosol imaging spectrometer targeting, amongst other things, AVS. Recognizing the limitations of using either passive sensors or active instruments, ideas for combining active-passive observations, both ground-based and space-borne, have been advanced and tested (Barker et al., 2011; Miller et al., 2014; Forsythe et al., 2000; Hutchison et al., 2006; Sun et al., 2016).

In the current study, global three-dimensional (3D) distributions of AVS are constructed utilizing CALIPSO and MODIS (Aqua) observations. 3D aerosol structure is constructed by selecting and substituting potential *donors* (pixels from CALIPSO profiles) to off-nadir *recipient* pixels within MODIS's swath based on similarity of their multi-spectral radiances. It is proposed that expansion of CALIPSO's aerosol vertical profile into the cross-track direction can fill gaps between CALIPSO tracks, thereby allowing near-global estimation of AVS.

Construction of AVS follows the method of scene construction proposed by Barker et al. (2011) for the EarthCARE mission. In essence, if a *donor* and a *recipient* pixel have sufficiently similar radiances, their vertical structures and column properties of clouds and aerosols are also assumed to be similar, implying that the *donor's* properties can be assigned to the *recipient*. This method, referred to here as spectral radiance matching (SRM), has been tested with respect to clouds. Barker et al. (2011) constructed 3D distributions of clouds and computed broadband radiative fluxes using 1D and 3D radiative transfer models. Results for $\sim 100 \text{ km}^2$ domains showed good consistency when compared to measurements from Clouds and the Earth's Radiant Energy System (CERES) (Loeb et al., 2005; Loeb et al., 2007). The quality of active-passive retrievals was further analysed by Barker et al. (2014).

The objective of this study is to construct and analyze global 3D AVS with two 16-day repeat cycles of A-Train data from 10-25 April and 14-29 September 2015. AVS distributions from two seasons are compared to MODIS and CALIPSO quantities. This gives an indication of how use of MODIS-only or CALIPSO-only data might be affected by gaps in observations. To test the reliability of the constructed AVS, profiles along-track are *reconstructed* based on the same algorithm used for *construction*. The matching rate between reconstructed and measured profiles provide an approximation of the success of SRM method for aerosols.

This paper is organized as follows. Section 2 provides a brief background on the datasets used here. Section 3 reviews the SRM method, including construction and reconstruction algorithms. Section 4 assesses global construction results for two 16-day repeat cycles. The last subsection presents a case study of 3-month observations along the east coast of Asia. AOD and occurrence frequency of aerosol subtypes are analysed. Section 5 provides a summary as well as commentary on limitations of the scene construction algorithm for aerosols and scope for future applications.

2 Data

The SRM method for atmosphere scene construction is based on cloud and aerosol properties synergistically retrieved from active and passive sensors. In this study, we use data from CALIPSO and Aqua satellites, which make observations close in space and time (Savtchenko et al., 2007). Before CALIPSO exited the A-Train on September 13, 2018, it was flying about 73 seconds behind Aqua with its MODIS. Due to sun-glint, CALIPSO was positioned 215 km to the anti-solar side of Aqua's ground-track at the ascending node (vice-versa on the descending node), but the wide swaths of MODIS guarantee constant collocation. Hereinafter, unless stated otherwise, "ground-track" refers to CALIPSO's.

2.1 CALIPSO product and MODIS product

CALIPSO carries the three-channel elastic backscattering Cloud–Aerosol Lidar with Orthogonal Polarization (CALIOP) with passive infrared and visible imagers (Winker et al., 2002). CALIOP observes the vertical and horizontal distribution of cloud and aerosol layers, which are reported in the Level 2 vertical feature mask (VFM) product (Vaughan et al., 2009). VFM products are recorded in nominal increments of 15 consecutive laser pulses, which is equivalent to a distance of 5 km along-track. Vertical resolution of the VFM product varies from 30 to 300 m (Hunt et al., 2009; Winker et al., 2010), and it is stored as a sequence of feature classification flags with 5515 element arrays (i.e., as an $N \times 5515$ matrix, where N is the number of pixels recorded in the file). Each array is identified as either: clear air (1), cloud (2), tropospheric aerosol (3), stratospheric aerosol (4), surface (5), subsurface (6), no signal (7) or invalid (0 stands for bad or missing data). In this study, the VFM product was treated as the “true” indicator of atmosphere structure. This means that uncertainties in the product propagate to analyses of results derived from it. To minimize this impact, only arrays identified with high confidence - cloud-aerosol discrimination (CAD) scores larger than 70 - were used. In addition, attention was paid to extinction quality assurance (QA) flags. For most constructed scenes, only aerosols layers with a QA flag of 0 and 1 were included. This helped avoid large errors that can stem from the nonlinear behaviour of the AOD retrieval (Huang et al., 2015a). [CALIPSO products used in the work are from Version 4.20.](#)

The MODIS passive sensor has 36 channels spanning visible to thermal wavelengths. MODIS Level 1 products contain calibrated radiances at 1 km resolution (MYD021KM) and are used to infer several key properties of clouds and aerosols (Kaufman et al., 2002; Minnis et al., 2008; Levy et al., 2013; Platnick et al., 2017). Pixel locations and ancillary information (MYD03) are used by the algorithm discussed in the next section. Because MODIS retrieval errors increase with solar and viewing zenith angles (Kato and Marshak, 2009), analyses were restricted to between latitudes 60°N and 60°S . [MODIS products used in the work are from MODIS Collection 6.](#)

MODIS’s wide swath (2330 km cross-track) ensures collocated observations with CALIPSO. Their narrow collocation track is referred to as the active–passive retrieved cross-section (RXS) (cf. Barker et al. (2011)). In the following sections, the actual RXS is referred to as “RXS-nadir”, while the RXS as expanded by the SRM method, up to 100 km on both sides of the RXS-nadir, is referred to as “RXS-expand”.

As CALIPSO products are provided at 5 km resolution, and MODIS products at 1 km, they were merged using a grid formed by latitude and longitude of the first and the last laser shot with cross-track width doubled to ensure the grid is larger than 1 km. Radiances, solar zenith angle, and solar azimuth angle geolocated within each grid were averaged. In terms of surface type, if one grid contains both land and sea flag from MODIS, it was redefined as a mixed surface type. The same grid size was applied to the RXS-~~extend~~expand.

3 Method

3.1 Spectral radiance matching (SRM) method

Barker et al. (2011) proposed a scene construction algorithm to extend cloud-aerosol profiles in the RXS-nadir to nearby off-nadir positions. They also provided a *reconstruction* algorithm to assess the *construction* algorithm's performance. The construction algorithm is based on matching spectral radiances of nadir pixels with those of off-nadir pixels, while the reconstruction algorithm mimicks the process by setting a *dead zone* around RXS pixels and filling them with other RXS pixels that reside outside the dead zone. The method is reiterated briefly here for the convenience of readers.

To match and substitute the most suitable *donor* at location $(m,0)$ on the RXS for each off-nadir *recipient* at location (i,j) in the passive swath $j \in [-J,-1] \cup [1,J]$, the SRM method computes a cost function $F(i,j;m)$ during daytime as

$$F(i,j;m) = \sum_{k=1}^{K=4} \left(\frac{r_k(i,j) - r_k(m,0)}{r_k(i,j)} \right)^2; m \in [i - m_1, i + m_2] \quad (1)$$

where r_k is MODIS radiance for the k^{th} band, $m \in [i - m_1, i + m_2]$ is the range of potential donors along the RXS. Potential donors also need to satisfy: 1) the same underlying surface type as the recipient; 2) similar solar zenith and solar azimuth angles as at the recipient; 3) $|\text{CAD}| \geq 70$. See Barker et al. (2011) for details explaining each condition. For this study, $K = 4$ was used (0.62–0.67, 2.105–2.155, 8.4–8.7, and 11.77–12.27 μm). The bands are chosen for their widely accepted usage in retrieving cloud properties, including cloud cover, cloud top properties (CTP/CTT/CTH), and cloud phase (Ackerman et al., 1998; Baum et al., 2012; Baum et al., 2000) as well as aerosol properties (Sayer et al., 2014; Levy et al., 2013; Remer et al., 2013).

To ensure the number of potential donors for far off-nadir recipients, search range was adopted from Sun et al. (2016) and defined as

$$m_1 = m_2 = \begin{cases} 200; \dots; D_m \leq 30 \\ 200 + D_m; \dots; D_m > 30 \end{cases} \quad (2)$$

where D_m is the shortest distance between recipient and RXS. $F(i,j;m)$ is then ordered from smallest to largest, and the Euclidean distance between a potential donor at $(m,0)$ and the recipient at (i,j) is calculated as

$$D(i,j;m) = \Delta L \sqrt{(i - m)^2 + j^2} \quad (3)$$

where ΔL is horizontal resolution (1 km) of MODIS radiance measurements. The most suitable donor is found by solving

$$\arg \min_{m^* \in \{1, (m_1 + m_2 + 1) f\}} \{D(i,j;m^*)\}; f \in (0,1) \quad (4)$$

which means, the selected donor, noted with asterisk (m^*), is closest to the recipient and has sufficiently similar radiances. $f = 0.15$ was used here rather than 0.03 as in Barker et al. (2011). This is because CALIPSO aerosol products have lower resolution (5 km) than cloud products (1 km).

The reconstruction algorithm, on the other hand, is designed to evaluate the performance of the construction algorithm, since the reconstructed results along the RXS can be compared to the actual observations. A dead zone centred at the recipient

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($i,0$) is set by defining the selection range for potential donors as $[i-m_1, i-n] \cup [i+n, i+m_2]$. By barring selections of potential donors from the nearest $\pm n$ pixels, the reconstruction process is forced to resemble the filling of an off-nadir recipient removed from the RXS by n pixels. The results of reconstruction thus gives an approximate indication of how well the SRM method can be expected to perform.

5 3.2 Theoretical best matching (TBM) method

Differences between reconstructed profiles and CALIPSO observations can have two main causes: 1) the SRM method does not select the best matching donor from the potential donors; and 2) the profiles for the actual best matching donor and the recipient differ. To analyse the contribution of these two causes, a *theoretical best matching* (TBM) method was devised to purposely select the most suitable donor from the potentials. In theory, the result from TBM method is the best that can be expected from the SRM method as defined. If for every column along the ground-track, there exists an identical column within range but outside the dead zone, the TBM method would reconstruct the original profiles perfectly. Therefore, differences between the TBM method's reconstructed profiles and original profiles indicate the influence of the second cause. Differences between reconstructed profiles from the TBM method and constructed profiles from the SRM method, on the other hand, indicate the influence of the first cause.

The TBM method of reconstruction is calculated by comparing CALIPSO's VFM for each potential donor (constrained by *dead zone*) to that of the recipient. The comparison between reconstructed results and a VFM is categorized as shown in Table 1. Results of each array are classified as either 'agree' or 'disagree' for clear (1), cloud (2), or aerosol (3 = tropospheric, 4 = stratospheric). Recipient arrays that are identified as 'no signal' are (7) and 'invalid' (0), and are not counted when comparing with possible donors as the actual scenes at these elements are unknown. Recipient arrays that are identified as surface (5) or subsurface (6) are also not counted as matches of these two feature types are considered less important. On the other hand, arrays classified as no signal, invalid, surface, or subsurface for potential donors are counted as 'disagree' when comparing to the *recipient*. Hence, a matching rate can be calculated as

$$MR = (A_{agree_{cr}} + A_{agree_{cd}} + A_{agree_{ae}}) / N \quad (5)$$

where N is the total number of VFM arrays measured along the ground track that are identified as clear air, clouds or aerosols.

The potential donor with largest MR is selected as the donor for the TBM method.

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4 Results and Discussion

Results are presented in three subsections. The first two diagnose the construction algorithm while the third employees it specifically to the east coast of Asia.

4.1 Expansion of active-passive retrieved cross-section (RXS)

This section presents results of constructed and reconstructed aerosol properties using two full CALIPSO 16-day repeat cycles in 2015, and a comparison of the TBM results against original observations. From 10 - 24 April and 14 - 29 September, CALIPSO functioned normally except during a boresight diagnostic and alignment on 18 September, losing about half of that day's data. Because MODIS retrievals of aerosol properties depend mainly on visible wavelengths, only daytime observations were used in this study.

Table 2 summarizes frequencies of occurrences of atmosphere conditions. These numbers refer to the occurrence of atmospheric features as percentage they occupied in the vertical column. We calculated this occurrence rate according to CALIPSO VFM products, which was then scaled for vertical and horizontal resolution of the products (Hunt et al., 2009). The majority of conditions were identified as clear. Above 8.2 km clear arrays occur over 90% of the time. Aerosols and clouds occurred below 8.2 km, in about 7% and 5% of the cells, respectively. Note that arrays identified as 'no signal' represent 16 - 18% of cells in this layer; CALIPSO's signal can be totally attenuated beneath opaque clouds and certain aerosols. This indicates that the numbers in Table 2 likely underestimated the amount of clouds and aerosols in actual atmosphere. After removing elements identified as 'no signal', surface, and sub-surface, aerosols and clouds occupied 4.43 - 4.52% and 5.35 - 6.15% of the cells; clear-skies account for the remainder. The horizontal cloud coverage between 60°N and 60°S for the tested periods in April and September 2015 are 68.7% and 71.3%, respectively.

The RXS is expanded to 100 km on both sides of it by constructing profiles along 40 parallel tracks every 5 km. Figure 1 shows an example of a CALIPSO track passing the African coast on 23 April 2015 between 5°S and 15°N. For better visualization, only 4 extended tracks are shown on both sides of the CALIPSO track, each separated by 25 km. The clear arrays on the extended tracks are made transparent.

Height-resolved global AOD maps (averaged for a 2° × 2° lat/long grid) based on the two selected periods are shown in Fig. 2. In the near-surface layer, 2 km above ground level (AGL), in April, relatively high aerosol loadings are found in the cross-Atlantic African dust transport, Saudi Arabia, and India. In September, dust dynamics are much weaker but much biomass burning is apparent in the Brazilian Amazon and Southern Africa. This seasonal trend of dust and smoke is more obvious in the layer 2-4 km AGL. Aerosol in this layer aloft are expected to be undergoing long-range transport. In April, the thickest dust layers are found slightly inland of the western coast of Africa, around 12.5°N, 5.5°E, and in the centre of Saudi Arabia around 24.5°N, 42.5°E. The shift of AOD distribution between surface layer and layer above is logical, and indicates the movement of dust layers as the aerosol loadings are transported towards the oceans. In September, this contrast is harder to observe as the dust dynamic is weaker, but similar trends are found in the biomass burning regions. In addition, persistent high aerosol loadings in both 0-2 km and 2-4 km AGL are found in India and the east coast of China with mixed sources of natural aerosols and pollutants. The results could be affected by the local topography. Marine aerosols are confined largely to the near-surface layer, with some vertical transport in Southeast Asia in September due to the Asian monsoon. The observed pattern is mostly consistent with other studies in terms of global distribution and seasonal variations (Martins et al., 2018; Liu

et al., 2012; Chen et al., 2018). Height-resolved global AOD maps (averaged for a $2^{\circ} \times 2^{\circ}$ lat/long grid) based on the two selected periods are shown in Fig. 2. In the near-surface layer, 2 km above ground level (AGL), in April, relatively high aerosol loadings are found in the cross-Atlantic African dust transport, Saudi Arabia, and India. In September, dust dynamics are much weaker but much biomass burning is apparent in the Brazilian Amazon and Southern Africa. This trend of dust and smoke is more obvious in the layer 2–4 km AGL. In addition, persistent high aerosol loadings are found in India and the east coast of China with mixed sources of natural aerosols and pollutants. Marine aerosols are confined largely to the near-surface layer, with some vertical transport in Southeast Asia in September due to the Asian monsoon. The observed pattern is mostly consistent with other studies in terms of global distribution and seasonal variations (Martins et al., 2018; Liu et al., 2012; Chen et al., 2018).

In comparison, globally-averaged AOD from RXS-expand is 0.0027 larger than observations made by CALIPSO in April, and 0.0028 larger in September. Both positive and negative differences in regions with high aerosol loadings, but none of the regions exhibit consistent high or low biases. Therefore, these insignificant differences are likely caused by random errors in the algorithm in conjunction with CALIPSO's unbiased sampling, and suggest that aerosol distributions constructed using SRM method do not change the global aerosol mass as inferred directly from CALIPSO data.

4.2 Reconstruction of RXS-nadir

To evaluate the reliability of its result, RXS cross-sections were reconstructed for *dead zones* set to 30 km and 100 km, which should give an approximate evaluation of the chances of successfully constructing scenes nearby and well removed from the RXS. Detailed analysis of matching rate between reconstructed RXS and RXS-nadir is summarized in Table 3.

During each 16-day cycle, there were about 600,000 CALIPSO observations made in the selection range. With *dead zone* set to 30 km, about 95% of them, as recipients, are matched up with selected donors. The remaining 5% are not matched because no suitable donors are found in the range with conditions described in Section 3. This ratio increases with the distance of *dead zone*, because the number of potential donors that meets the requirement of surface type and solar angles decreases with increasing distance between donor and recipient. When *dead zone* is set to 100 km, only about 71% of recipients are matched with a donor. The following analysis focuses on the portion of recipients matched up with donors, unless mentioned otherwise.

Overall, at 30 km, the reconstruction based on SRM method correctly matches 92.04% of air columns in April, and 92.55% in September. At 100 km, SRM method correctly matches 88.57% of air columns in April, and 89.68% in September. To investigate the reasons behind imperfect reconstruction, the correctly reconstructed arrays and incorrectly reconstructed arrays are analysed separately (see Table 3).

The same analysis is also performed with the TBM reconstruction in which 96.87% of air column is correctly reconstructed in April, and 92.55% in September at 30 km. At 100 km, 93.95% of air column is correctly reconstructed in April, and 94.76% in September. As discussed in Section 3.2, the difference between TBM reconstruction and perfect reconstruction (i.e. 100% correct reconstruction of nadir profiles) indicates the errors caused by selection from limited numbers of donors.

On the other hand, differences between TBM reconstruction and SRM reconstruction indicate that the SRM method still needs improvement. In comparison, over 50% of the mismatches by TBM reconstruction come from clear arrays; higher than that from SRM reconstruction. The fraction of no signal (5-9%) in the mismatch of ~~the~~ TBM reconstruction is much lower than that of SRM reconstruction. This ~~is result~~ed partly from the procedure of ~~the~~ TBM method which tends to choose donors
5 with less arrays of no signal. The fractions of mismatch of clouds and aerosols are not significantly different between the methods.

Since the analysis of the entire air column is easily overwhelmed by clear arrays, the matching rate with respect to aerosols is calculated. The ratio is obtained as the number of correctly reconstructed aerosol arrays divided by ~~the~~ total number of aerosol arrays in the original profile (both correctly and incorrectly matched in ~~the~~ reconstructed profile), and other arrays
10 mismatch as aerosols in ~~the~~ reconstructed profile. ~~Global results combined for April and September are shown in Fig.3. The empty zones were caused by missing data due to CALIPSO nadir observations, and lack of information over special topography.~~

The average matching rate with respect to aerosols across the globe is 68.18% at 30_km, and 62.33% at 100_km. The matching rate is higher over land than over ocean, possibly because there are more aerosols over land. The matching rate also shows a general trend with latitude. At 30_km, the average matching rate is 73.78% between 14 °24 °N, 71.79% between 14 °
15 24 °S, and 66.92% between 4 °N - 4 °S. At 100_km, the average matching rate is 67.43% between 14 °24 °N, 66.18% between 14 °24 °S, and 59.91% between 4 °N — 4 °S. This is linked to the persistent high cloud fraction in the Intertropical Convergence Zone: as clouds attenuate CALIPSO's signal, the ratio of mismatching in the reconstruction increases.

In addition, the matching rate is strongly affected by the number of observed pixels (containing aerosols) in the grid, especially at high latitudes. Figure.4_3 contains a box plot analysis which indicates that sample variance is high for grids
20 lacking sufficient data points (Fig.43). The boxes are separated by the number of pixels in 1 °x_1 °grid. Boundaries of each box represent the 25th and 75th percentiles of the sample data in the grid, the central red line marks medians, the length of whiskers corresponds to approximately +/-2.7 σ and 99.3 percent coverage assuming the data are distributed normally. At both distances, the matching rate of aerosol increases steadily while the span of data decreases with the number of pixels in the grid. For grids with more than 20 pixels over the two CALIPSO cycle, the average matching rate of aerosol is 75.32% at
25 30_km, and 68.52% at 100_km. ~~In reality, t~~This could be explained by the fact that in regions where aerosols occur more frequently (thus have more pixels observed), suitable donors are easier to find.

4.3 Case study

With the complete datasets of CALIPOP profiles, MODIS radiances and geolocation fields, construction based on the SRM method can be applied worldwide. It is applied here to aerosols along the east coast of Asia (117 °E—132 °E, 26 °—41 °N) for
30 a 3-month period (MAM) in 2015. SRM method's AOD estimates are compared to AErosol RObotic NETWORK (AERONET) values inferred from ground-based sun-photometers on a day-by-day basis.

The east coast of Asia represents one of the most complicated aerosol regions as it includes transported natural dust, anthropogenic dust, black carbon (BC) and organic carbon (OC) from biomass burning, as well as mixtures of BC, OC and

sulfates from urban pollution (Logan et al., 2013;Huang et al., 2015b). Analysis of multiple AERONET sites in East Asia during the 2001-2010 period showed that the area is dominated by mineral dust during spring months, likely transported from the Gobi and Taklamakan Deserts (Eck et al., 2005;Huang et al., 2008;Logan et al., 2013). The dominance of these outflowing aerosols continues to be observed as far away as Japan (Ikeda et al., 2014; Uchino et al., 2017).

5 Figure-5-4 shows seasonal distributions of AOD in the area. Data are binned in a $0.25^\circ \times 0.25^\circ$ lat/long grid. A couple locations with seasonal-mean AOD > 0.5 occur on the main land of China, surrounding the Bohai Sea, and the Sea of Japan. Large AOD across the Bohai Sea and near the island of Japan indicate mass-transportation of aerosols during this season. A region of small AOD (< 0.1) exists to the east of Shanghai, which might be caused by frequent failures of satellite retrievals at the Yangtze River Delta and the Yellow Sea due to turbidity of local water. Regional distribution based on MODIS AOD
10 products shows certain similarity, but is higher in general. Note that the extreme high values (AOD > 1) over the Yellow Sea and inside the Bohai Bay (i.e., the same area where RXS-expand shows small AOD values), result from few measurements; 10 times less than other cells. The small sample sizes from both CALIPSO and MODIS suggest the large difference here is due to difficult to handle local surface conditions.

To better analyse the source of aerosols, the area was divided into three regions along two CALIPSO ground-tracks (Fig.
15 54). Region A mainly includes land inside China. Region B includes inshore coastal waters between China and the Korean peninsula, as well as part of the East China and Yellow Seas. It also includes the most populated area of South Korea. Region C includes the remaining area of the Korean peninsula, Kyushu island of Japan, and surrounding waters.

Vertical distributions of aerosol subtypes for these regions are shown in Fig. 65. In Region A, the average extinction profile indicates aerosol layers between 1-2 km, near 3.7 km, and above 5 km. The two lower layers are dominated by polluted
20 dust, while the upper one is mainly clean dust. Occurrence of polluted continental aerosols and polluted dust suggests local aerosol production. The increase of smoke near 2.8 km suggests some transportation of biomass burning aerosols, possibly due to spring agricultural practices and indoor heating. Average-The average extinction profile for Region B is smaller than that for Region A. These aerosols are dominated by polluted dust below 2 km, and clean dust above. The distribution of polluted dust and dust could be explained as transported from Region A with decrease in altitude. There might be some
25 transport of polluted continental aerosols or dusty marine aerosols, but no transport of smoke is observed. In Region C, the average extinction profile shows few aerosols above 2 km except a thin layer at 5.5 km. Near surface layer is composed of dust, dusty marine, clean marine, and polluted continental aerosols. The fraction of clean marine is highest among the three regions, possibly due to large ocean area and major harbours in Busan and Kyushu. The upper layer of dust and polluted dust is questionable at first glance. Detailed analysis showed that the regional AOD, with especially large values near Japan, is
30 caused by high values on April 17, 2015. Two days before, in the afternoon of April 15, 2015, China recorded the most severe dust storm since 2002 across Beijing, known as the “4.15 Dust Storm”. Large values of AOD near Japan might be due to the influence of this major aerosol transport event, while the middle layer might be missed due to limited viewing by CALIPSO. In fact, a small region of relatively high AOD near Japan is also shown in Fig. 5-4 for MODIS.

In the three-month period, the Asian dust and aerosol lidar observation network (AD-Net) site at Seoul, Korea (37.5N,127.0E) provided measurements of atmospheric profiles that we were able to compare with those constructed in the surrounding area using the SRM method. Seoul station has a standard lidar system in AD-Net, which is a two-wavelength (1064 nm, 532 nm) polarization sensitive (532 nm) Mie-scattering lidar, plus a 532 nm Raman (Shimizu et al., 2004). Based
5 on the ground track, the A-Train sensors made overpass near the station for a total of 6 days during that spring. However, 4 out of these 6 days were heavily cloudy. For the remaining 2 days, 7 March and 24 April, the comparisons among ground-based lidar profiles, CALIPSO profiles at shortest distance and RXS-expand profiles averaged 25 km around the location of Seoul station are shown Fig. 6.

The CALIPSO measurements used for comparisons are level 1.5 data products of attenuated backscatter profiles, which
10 clouds, overcast, surface, subsurface, and totally attenuated samples have been removed before being averaged to a 20 km horizontal resolution. In this case, RXS-expand profiles are based on the same products. The ground-based measurements used for comparison are the 532 nm attenuated aerosol backscatter coefficient products, averaged within 2 hr before and after the satellite overpass with 15 min time resolution.

For the aerosol layer 0-4 km above the ground, the relative error between CALIPSO profiles and ground station profiles
15 are on average 21.6% on 7 March, and 18.7% on 24 April. The distances between station and ground track are 51.0 km on the first day, and 50.1 km on the second. Between RXS-expand profiles and ground station profiles, the average relative errors are 27.9% and 23.4%, respectively. The results from the comparisons agreed in general. Previous studies found that there were considerable disagreement between CALIPSO measurements and ground-based lidar measurements; in most studies, the differences were found to be around 20% (Mamouri et al., 2009; Wu et al., 2011; Kim et al., 2008; Chiang et al., 2011).

In the same period, five AERONET sites in the selected region recorded 20 comparable measurements between RXS-
20 expand and AERONET, with the CALIPSO ground-track passing within 100 km of AERONET sites (see Fig.7). AERONET AOD at 500nm were constrained to ± 2 hours of CALIPSO's passing. The RXS-expand AOD at 532nm is averaged using the 10 pixels closest to each AERONET site. Comparisons were made between RXS-expand AOD and AERONET AOD, as well as RXS-nadir AOD and AERONET AOD. Among these collocated measurements, 17 measurements (85%) show better
25 agreements between AERONET and RXS-expand values of AOD. One outlier (grey circle) was found for Baengnyeong on May 21st. Measurements from Baengnyeong have a larger span than the other sites in general, which might be explained by strong sea winds across the Bohai Sea which often change direction and speed and may lead to large variations in aerosol transport. Removing the outlier, the correlation between RXS-expand AOD and AERONET AOD is $R = 0.88$, whereas for RXS-nadir AOD and AERONET AOD it is $R = 0.80$. Still, however, both are less than $R = 0.95$ between MODIS AOD and
30 AERONET AOD.

5 Summary

Three-dimensional aerosol structure is constructed across the globe using vertical profiles from CALIPSO and MODIS radiances. Based on matching and substituting nadir pixels (*donors*) into off-nadir pixels (*recipients*) with similar radiances, the atmosphere's vertical structure is expanded up to 100 km on both sides of the ground-track. The construction results fill gaps between CALIPSO ground-tracks and increase the frequency of observations for some areas by as much as once in 8 days as opposed to CALIPSO's 16 days. Consequently, the construction algorithm approximates aerosol vertical structure at locations never measured by CALIPSO; this has the potential to alter-improve our understanding of regional distributions of aerosols. Increasing the number of observations can also help reduce the CALIPSO-centric selection bias by allowing for the study of aerosols over short time periods and small regions.

Reconstruction of nadir profiles verifies the overall performance of using the SRM method to construct 3D cloud-aerosol structure as a function of distance from ground-track. By mimicking off-nadir distance with a *dead zone* along ground-track profiles, reconstruction of nadir profiles shows that at 30 km from the RXS the SRM method correctly matches 92% of cells in April and September 2015. At 100 km, these rates drop to ~89%. Comparison to TBM reconstruction suggests that the limited number of columns available from the active sensor is responsible for ~3% of mismatches at 30 km and ~6% at 100 km. Differences between profiles reconstructed using SRM and TBM methods come mostly from profiles whose lidar signals are totally attenuated. Otherwise, the fraction of mismatching of aerosols or clouds is similar. With a sufficient number of observations, the average matching rate of aerosol could reach 75% at 30 km, and 68% at 100 km.

The construction algorithm was applied to the east coast of Asia where heavy aerosol loadings are frequent. The expansion of RXS successfully provided regional distributions of aerosols in spring 2015. Analysis of vertical distributions of each aerosol subtype showed that regional west-east transportation was dominated by dust and polluted dust. Comparison of atmospheric profiles against AD-Net lidar station shows agreement with constructed profiles and CALIPSO measurements at similar level. Comparison of column AOD against ground-based AERONET values shows better agreement with expanded RXS relative to CALIPSO observations. The correlation increases from $R = 0.80$ to $R = 0.88$.

The construction of 3D aerosol structure based on the SRM method appears as though it could be a ~~powerful~~ important tool to analyse global and regional aerosol properties. Though the matching rate is well-off ~~not~~ perfect, improvements to the algorithm seem likely. The method in this work is not intended to get a precise quantification of aerosol profile, but to provide an estimate of the column's vertical structure. We did expect, to some extent, the estimation could be improved through calculations with constrains such as the column AOD measured by passive sensor at the exact location of the recipient pixel, which will need a lot more work in the future. In addition, sSince lacking of more suitable pixels is responsible for about half of the mismatching results, we are looking forward to launching more satellites with active and passive sensors, and possibly combining data from multiple satellite systems.

Data availability: NASA EOSDIS Land Processes Distributed Active Archive Centre (LP DAAC) provided MODIS data (available at: https://lpdaac.usgs.gov/data_access/data_pool, LP DAAC, 2019). NASA Langley Research Centre (LaRC) provided CALIPSO data (available at: <https://subset.larc.nasa.gov/calipso/>, LaRC, 2019).

Author contribution: Sijie Chen designed the experiments and Chonghui Cheng helped carried them out. Professor Barker developed the scene construction method utilized in this work and gave suggestions during the progress. Dr. Dong is responsible for resources and funding acquisition. Ju Ke, Shuaibo Wang and Zhuofan Zheng helped data analysis. Professor Liu supervised the project and the preparation of the manuscript with contributions from all co-authors.

The authors declare that they have no conflict of interest.

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Table 1. Contingency tables for the comparison of the reconstructed profile using SRM method to CALIPSO VFM product.

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| Agree | Recipient | Donor | Disagree | Recipient | Donor |
|---------------------|-----------|-------|---------------------------|-----------|--------|
| Agree _{cr} | 1 | 1 | Disagree _{cr-cd} | 1 | 2 |
| | | | Disagree _{cr-ae} | 1 | 3 or 4 |
| Agree _{cd} | 2 | 2 | Disagree _{cd-cr} | 2 | 1 |
| | | | Disagree _{cd-ae} | 2 | 3 or 4 |
| Agree _{ae} | 3 | 3 | Disagree _{ae-cr} | 3 or 4 | 1 |
| Agree _{ae} | 4 | 4 | Disagree _{ar-cd} | 3 or 4 | 2 |
| | | | Disagree _{suf} | 1 - 4 | 5 or 6 |
| | | | Disagree _{nosig} | 1 - 4 | 7 |

The bits are interpreted as clear air (1), cloud (2), tropospheric aerosol (3), stratospheric aerosol (4), surface (5), subsurface (6), or no signal (7).

Table 2. Summary of Atmosphere condition from 10 to 24 April, and from 14 to 29 September 2015.

| | Aerosol (st) | Aerosol(tr) | Clear | Cloud | No signal | Surf/Subsurf |
|-------------------|--------------|--------------|----------------|--------------|----------------|--------------|
| 20.2 km – 30.1 km | 0.14% | – | 99.84 – 99.85% | 0.01 – 0.02% | – | – |
| 8.2 km – 20.2 km | 0.038% | 0.24 – 0.28% | 91.87 – 93.71% | 4.77 – 6.41% | 1.24 – 1.31% | – |
| -0.5 km – 8.2 km | – | 7.08 – 7.12% | 63.42 – 65.32% | 5.48 – 5.68% | 16.48 – 18.13% | 5.64% |

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Table 3. Summary of comparison between observed nadir profiles and reconstruct nadir profiles.

带格式的: 字体: 非加粗

| Dead Zone 30 km | | | | | | | | | | |
|-----------------------------|--------|--------|-------|---------|----------|--------|--------|---------|---------|-------|
| | Match | Clear | Cloud | Aerosol | Mismatch | Clear | Cloud | Aerosol | No Sig* | Surf* |
| 10-24 April 2015 | | | | | | | | | | |
| Actual | 522200 | 480846 | 24057 | 17297 | 45160 | 14920 | 11665 | 6688 | 11197 | 689 |
| | 100% | 92.08% | 4.61% | 3.31% | 100% | 33.04% | 25.83% | 14.81% | 24.79% | 1.53% |
| Theo | 549580 | 496553 | 31243 | 21784 | 17780 | 9298 | 4804 | 2291 | 1086 | 301 |
| | 100% | 90.35% | 5.68% | 3.96% | 100% | 52.30% | 27.02% | 12.88% | 6.11% | 1.69% |
| 14-29 September 2015 | | | | | | | | | | |
| Actual | 514340 | 478282 | 19329 | 16729 | 41380 | 13770 | 10336 | 6522 | 10018 | 733 |
| | 100% | 92.99% | 3.76% | 3.25% | 100% | 33.28% | 24.98% | 15.76% | 24.21% | 1.77% |
| Theo | 540220 | 493044 | 25818 | 21357 | 15500 | 8274 | 3944 | 2082 | 885 | 316 |
| | 100% | 91.27% | 4.78% | 3.95% | 100% | 53.38% | 25.44% | 13.43% | 5.71% | 2.04% |
| Dead Zone 100 km | | | | | | | | | | |
| | Match | Clear | Cloud | Aerosol | Mismatch | Clear | Cloud | Aerosol | No Sig | Surf |
| 10-24 April 2015 | | | | | | | | | | |
| Actual | 368330 | 342896 | 12891 | 12543 | 47540 | 16977 | 11378 | 7875 | 10374 | 937 |
| | 100% | 93.09% | 3.50% | 3.41% | 100% | 35.71% | 23.93% | 16.56% | 21.82% | 1.97% |
| Theo | 390690 | 357283 | 17358 | 16049 | 25180 | 13367 | 5247 | 3981 | 2066 | 520 |
| | 100% | 91.45% | 4.44% | 4.11% | 100% | 53.09% | 20.84% | 15.81% | 8.20% | 2.07% |
| 14-29 September 2015 | | | | | | | | | | |
| Actual | 382520 | 359847 | 10101 | 12572 | 44020 | 15379 | 9725 | 7793 | 10112 | 1011 |
| | 100% | 94.07% | 2.64% | 3.29% | 100% | 34.94% | 22.09% | 17.70% | 22.97% | 2.30% |
| Theo | 404170 | 373653 | 14077 | 16441 | 22370 | 11711 | 4117 | 3987 | 2017 | 538 |
| | 100% | 92.45% | 3.48% | 4.07% | 100% | 52.35% | 18.40% | 17.82% | 9.02% | 2.41% |

*'No Sig' stands for 'no signal' and 'Surf' stands for 'surface and subsurface' portions of the measured columns.

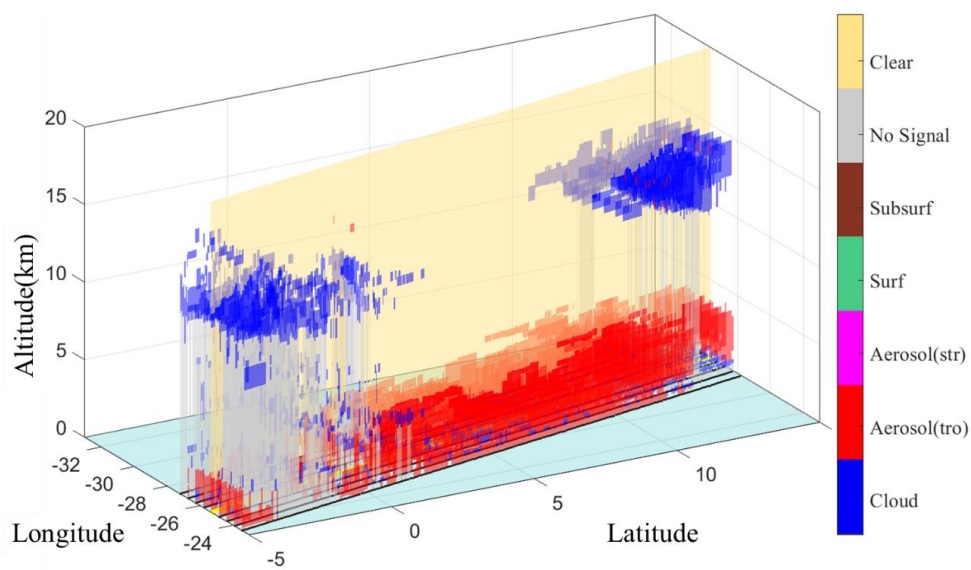


Figure 1 Demonstration of the expansion of the active–passive retrieved cross-section (RXS), which runs through the centre, for a transect near Africa-Atlantic coast between 15 °N and 5 °S on 23 April 2015.

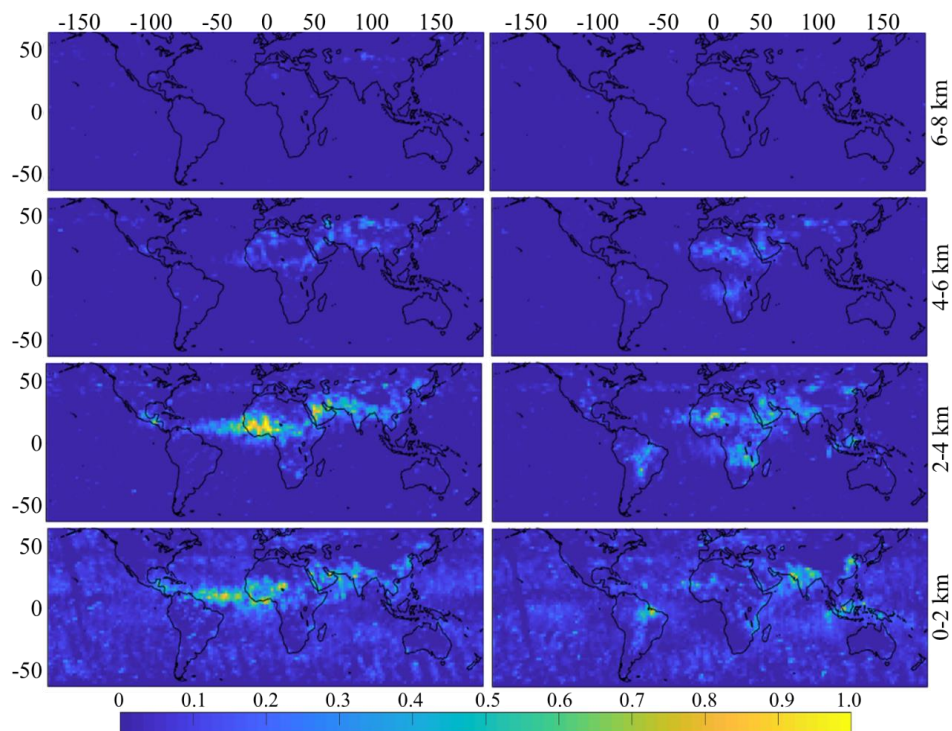


Figure 2 Height-resolved global distributions of aerosol optical depth (AOD) based on construction of RXS expanded 100 km on both sides of CALIPSO's ground-track. Left column is for the April dataset and the right column is for September . Data are binned on a 2°lat/long grid.

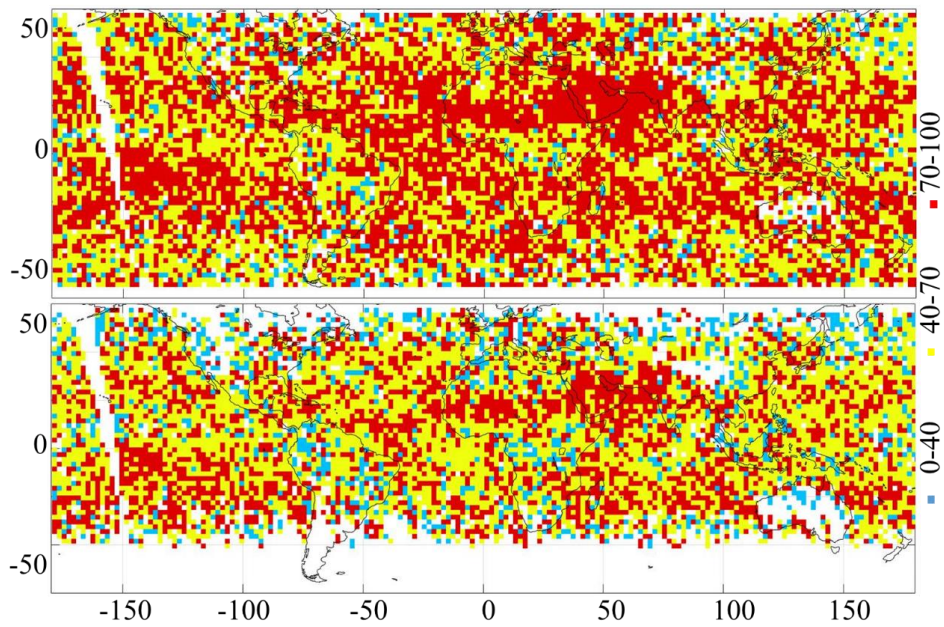


Figure 3 Matching rate of aerosols based on reconstruction of nadir profile with 30km dead zone (top) and 100km dead zone (bottom). Data are binned in a 2° lat/long grid. Each grid is coloured according to average matching rate of pixels in the grid: Red = 70-100%, Yellow = 40-70%; Blue = 0-40%.

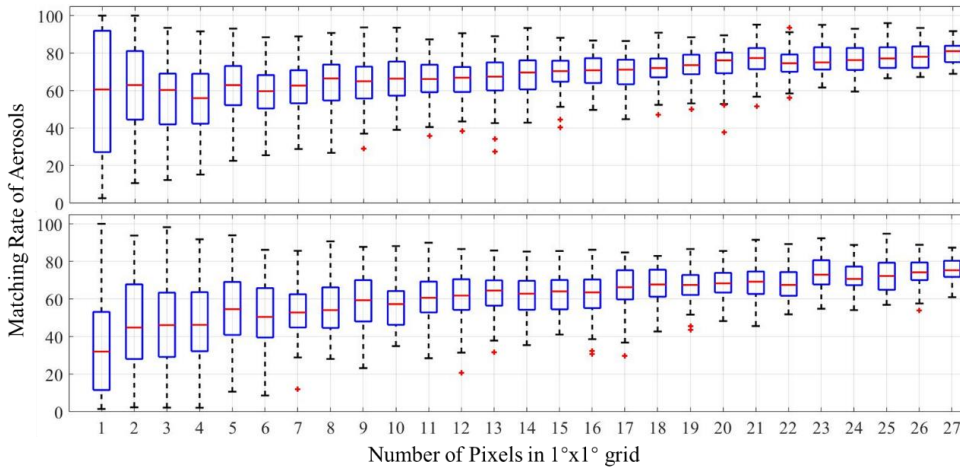


Figure 4-3 Matching rates of aerosols as a function of number of samples in 1° grid cells for reconstructions of nadir profiles with 30 km dead zone (top) and 100 km dead zone (bottom). Boundaries of each box represent the 25th and 75th percentiles of the sample data in the grid, red lines indicate medians, and whiskers correspond to approximately $\pm 2.7\sigma$ (99.3 percent coverage assuming data are distributed normally). Points marked with '+' are extreme outliers.

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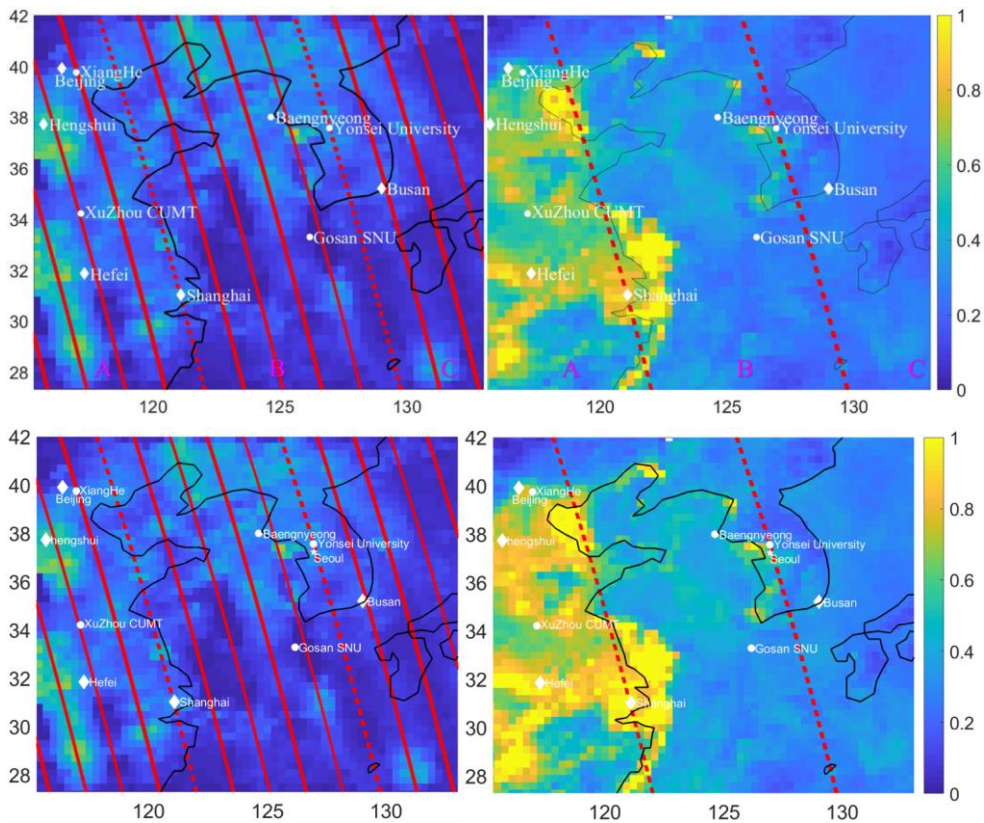


Figure 5.4 Seasonal distribution of aerosol optical depth (AOD) between 117°E – 132°E , 26° – 41°N for March to May, 2015 based on RXS-expand (left) and MODIS (right). Lines mark CALIPSO ground-tracks. Dotted tracks are used as the boundaries for the analysis of aerosol subtypes in Fig. 65. White circles mark AERONET sites. Star marks the AD-Net site at Seoul. Diamonds mark some major cities.

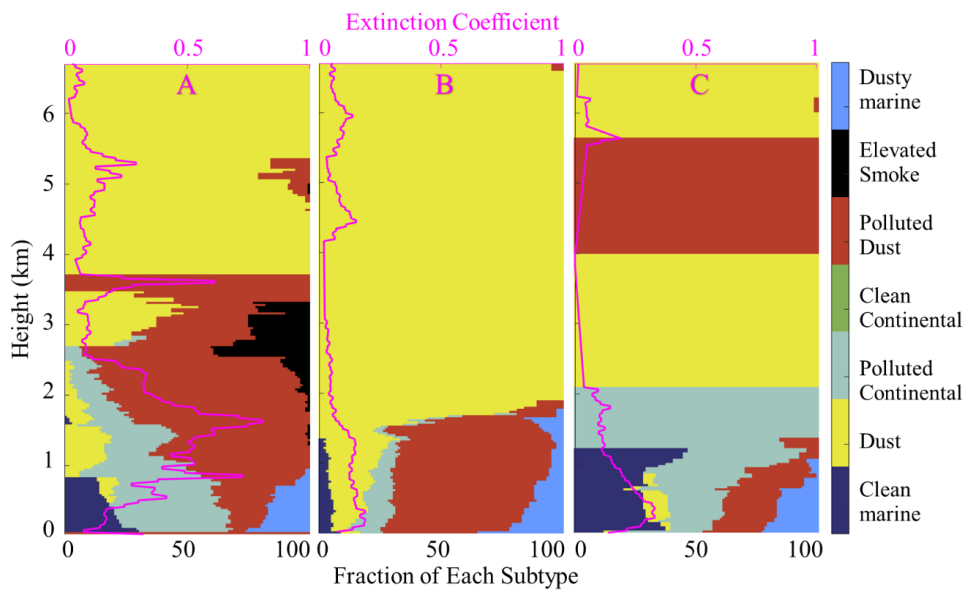


Figure 6-5 Vertical distributions of each aerosol subtypes in region A, B, and C (see Fig. 5). Pink lines show profiles of average aerosol extinction coefficient (km^{-1}). The fraction is calculated as the occurrence of each subtype divided by the total occurrence of aerosols in each region.

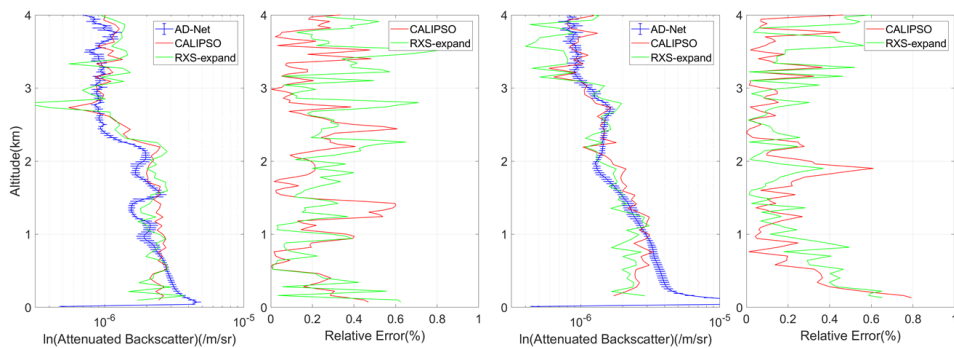


Figure 6 Comparisons among ground-based lidar profiles of 532 nm attenuated backscatter coefficient products (units: $\text{m}^{-1}\text{sr}^{-1}$, averaged 2 hours within satellite overpass), CALIPSO profiles at shortest distance and RXS-expand profiles averaged 25 km around the location of Seoul station. The two plots on the left are from 7 March 2015, and the two plots on the right are from 24 April 2015.

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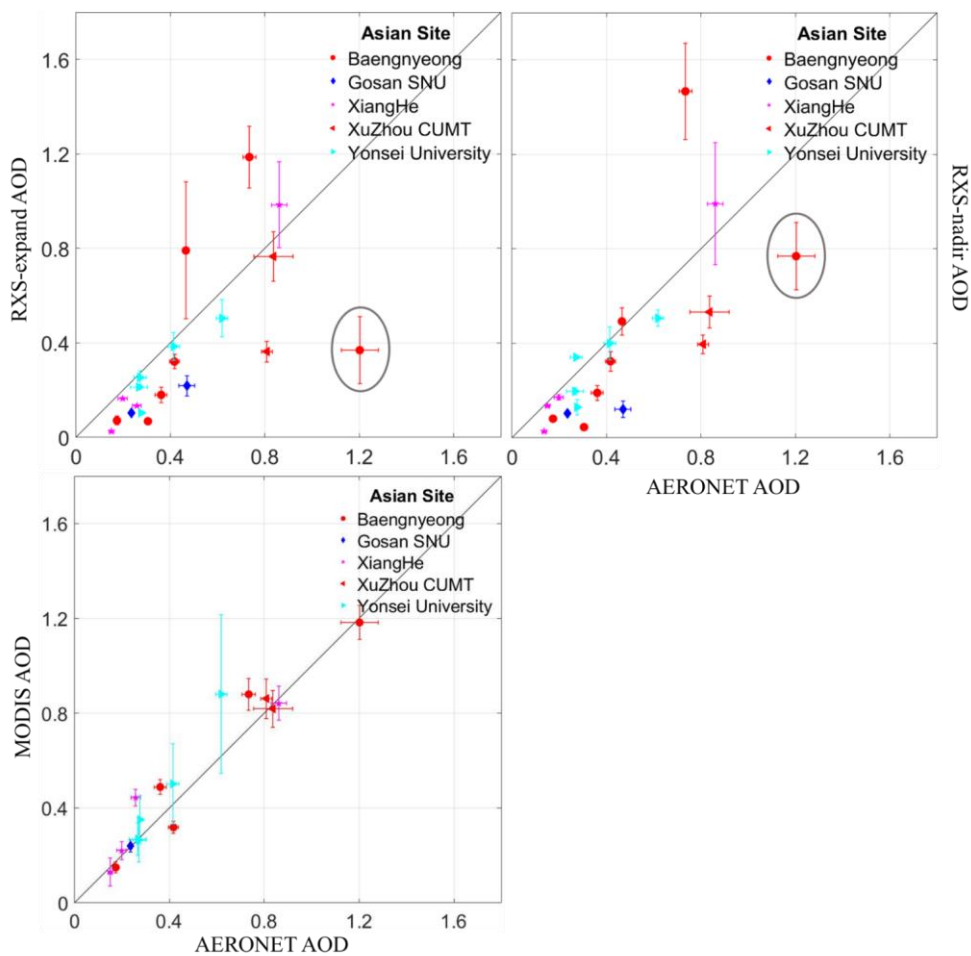


Figure 7 Comparison of collocated measurements of RXS-expand and AERONET (upper left), RXS-nadir and AERONET (upper right), and MODIS and AERONET (lower left). Error bars in y-direction indicate standard deviations of RXS-expand, RXS-nadir or MODIS measurements within 50 km of the site, and in the x-direction AERONET measurements within ± 2 hour of CALIPSO's passing. Grey circles mark a notable outlier.