We would like to thank Dr. Gerasimov and Dr. Khaykin for your helpful comments on our manuscript titled “Long-term (1999–2019) variability of stratospheric aerosol over Mauna Loa, Hawaii, as seen by two co-located lidars and satellite measurements”.

In the case of the comments provided by Dr. Gerasimov, which were included as comments in the manuscript file, we provide our answers together with the page and line number. In the case of the comments provided by Dr. Khaykin, the original comments are in bold, followed by our replies.

An additional file, highlighting the changes introduced in the manuscript, is also included.

**Answer to comments from Dr. Gerasimov (Reviewer #2):**

P2 L16: “form” was replaced by “from”

P2 L34 “datasets” was replaced by “instruments and datasets”

P3 L17 “are used” replaced by “is used”

P3 L34 “help” replaced by “helps”

P5 L26 “range dependency” replaced by “range dependence”

P6 L7 paragraph was relocated after the equations following your suggestion.

P6 L14 “λ = 355,387nm” was replaced by “λ = 355 nm and 387 nm”

P6 L15 sentence was moved after Eq. 3.

Eq. 3 Description of the variables are now included.

P6 L19-20 moved after Eq. 4 as suggested.

P6 23-26 Paragraph removed.

P7 L12 “the ratio of the backscatter and extinction profiles” was replaced by “the ratio of the extinction and backscatter profiles”.

P7 L25 “January 1st 1999 and November 1st 2019” replaced by “1 January 1999 and 1 November 2019”.

P7 L25 “over” was taken out of the sentence to reflect an exact number.

P8 L5 The following sentence was added “In the case of the mid-latitude station located in Tomsk, Russia, a "quiescent" period between 1999 and 2006 was reported (Zuev et al., 2017)”.

P8 L10 “relative” as replaced by “relatively”.

P9 L4 1-sigma variability included as part of the reported value.

P13 L1 We changed the title of the section to “The color ratio of the backscatter coefficient” in order to better reflect its content. We also modified the abstract and replaced Angstrom coefficients by color ratios to improve consistency.

“revealed a color ratio of 0.5 for background aerosols and small volcanic plumes, and 0.8 for a PyroCb plume recorded on September 2017.”

P13 L22 “MLSOL” was replaced by “MLSOL measurements”.

P13 L25 “355 nm and 532 nm” was replaced by “532 nm and 355 nm”.

P13 L30 “the color ratio above the plume is approximately 0.4” was replaced by “the average color ratio above the plume is approximately 0.4”

Fig. 5 caption: “1-sigma variability is indicated by the shaded areas.” was added to the caption.

P14 L2 “measurement” was replaced by “measurements”

P14 L9 “A well defined plume with a peak backscatter coefficient of 0.75 × 10−3 sr−1 km-1 at 18.7 km” was changed to “A well defined plume with a peak backscatter coefficient of 0.75 × 10−3 sr−1 km-1 can be seen at 18.7 km”

Fig. 6 caption: “ratio” was changed by “ratios”.

Fig. 6 caption: the following was added “(see Fig. 5, right plot)”

P16 L7: “are” was replaced by “is”.

P16 L28: “difference” was replaced by “differences”.

P16 L33 Reference to “Fig. 9b” was replaced to a reference to “Fig. 9a”

P17 L1 Reference of the volcanic eruptions were included in Fig. 9.

P18 L8 This is correct. A reference to Fig. 8 was also included.

P20 L3 “show” was replaced by “shows”.

P20 L7 the following sentence was added: “where the mean relative differences between AOD time-series (Xrow,column) are presented.”

P20 L11 “is” was replaced by “has been”.

P21 L6 The sentence was reformulated to include the result of the comparison with Verneier et al., 2011.

P21 L12 The derived lidar ratio was included as requested.

**Answer to comments from Reviewer 2:**

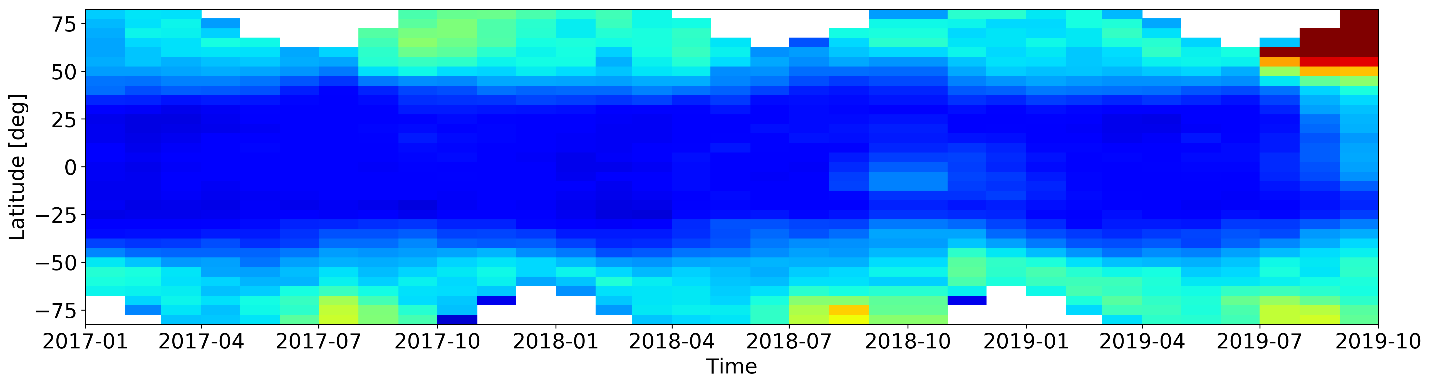
**General remarks**

**1. The attribution of enhanced stratospheric extinctions to the recent volcanic and PyroCb events (Sect. 4.3) is based on very general considerations and may thus be inaccurate. No observational or model-based evidence is provided regarding the detection of smoke from the BC-2017 wildfires at MLO. The authors attribute the SAOD enhancement in late 2019 entirely to Raikoke eruption, whilst totally ignoring the tropical Ulawun eruption that occurred shortly after Raikoke and led to SAOD perturbation of similar magnitude. Please see specific remarks on this matter.**

Thank you for pointing this out. We added further analysis to support our claims regarding the detection of the smoke from the BC-2017 PyroCb during the first days of September 2017 at MLO and included the Ulawun eruption in the analysis of the stratospheric aerosol enhancement observed at MLO during the last months of 2019. Further details on these additions are presented in the “Specific comments” section.

**2. I believe it would be very useful to include time-latitude section of SAOD from e.g. CALIOP L3 dataset, which would facilitate the correct attribution of SA variability observed locally by the MLO lidars.**

We tested your suggestion, but the low spatio/temporal resolution doesn’t provide much help to pinpoint the sources of the plumes observed at MLO during the second half of 2019. For the rest of the cases, the tracing in pretty unambiguous.

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Instead, we decided to include an extinction crossection (latitude/altitude) for a few months after Raikoke/Ulawun eruptions together with the increment registered when compared with background conditions (June 2019). Further discussion on this plot was added as part of the extension of the Raikoke/Ulawun discussion. More details are provided in the “Specific Remarks” section.

**3. Do you perform any sort of cloud screening for lidar data processing? I assume that although rarely, the cirrus clouds may occur as high as 17 km above MLO.**

We perform basic cloud screening based on signal attenuation (i.e. we discard profiles with low SNR). Further screening is unfortunately not possible relying only on MLSOL measurements. In the case of specific events, like the PyroCb plume study, manual screening (based on additional data sources) was conducted to minimize the possibility of misidentifying cirrus clouds as aerosol plumes.

**4. The color maps used to present time-altitude variation of extinction makes it somewhat difficult to read the upper panel in Fig. 1 and very difficult to compare the panels in Fig. 8. Would it be possible to use another color map for these panels, e.g. rainbow type?**

We modified all SR/backscatter/extinction time-altitude plots according to this suggestion.

**5. The intercomparison between monthly-averaged SAOD derived from MLSOL and NOAA lidars reveals important discrepancies, strongly varying with time and reaching 100% during quiescent periods. This bias cannot be explained by the different sampling frequency. I believe, the possible reasons for the observed discrepancies between the two well-established and powerful lidars should be carefully discussed. This is particularly important in the context of synergistic use of the lidars for derivation of the color ratio. Could the color ratio for the 532/1064 nm pair be available from the NOAA lidar?**

There are multiple possible sources for the observed discrepancies, including differences in processing methods, normalization altitude and noise characteristics of each system. Additionally, it is not possible to discard alignment issues that affected the performance of one of the instruments over certain periods of time. Unfortunately, the 1064 nm channel is very noisy, which makes the normalization process difficult and inaccurate. For these reasons, we decided to not include the derived results in this paper. Preliminary results based on the data between 2013/1 thru 2019/7 showed a color ratio of 0.51 +/- 0.30.

**Specific remarks**

**p.4, l.1. Please specify which wavelength does the provided laser power correspond to.**

Corrected. The 40W are produced at 1064nm.

**Fig.1. I wonder if the upper panel could be provided in scattering ratio instead of extinction coefficient, which is reported in Fig. 8 anyway. It would also be useful to slightly expand the time axis in both panels in to order to avoid an impression that SAOD curve is truncated by the axis limits.**

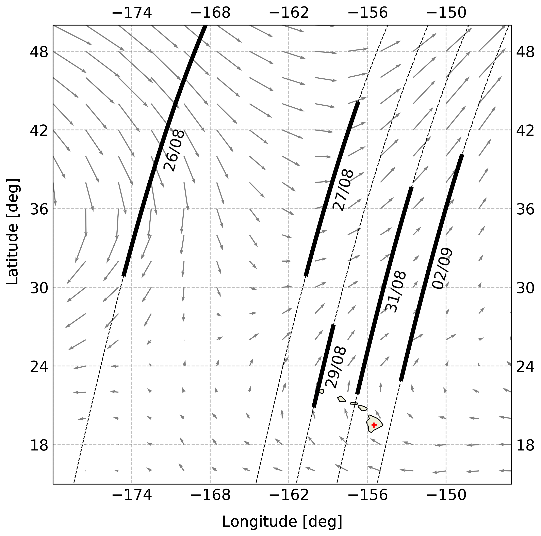
We modified the plot according to the suggestion.

**p.10, l.20-23. The authors claim that BC-2017 smoke plume could have been observed above MLO already on 1st September, which would require a fast equatorward transport of the plume. Could you be more specific how the attribution of the observed backscatter features is supported by CALIOP and backward trajectories? How do you distinguish between the smoke and cirrus cloud?**

Thank you for pointing this out. We identified this plume as smoke from BC-2017 fires based on a multiplicity of sources, including CALIOP L1 data, HYSPLIT back trajectories (not included) and existing publications on the topic.

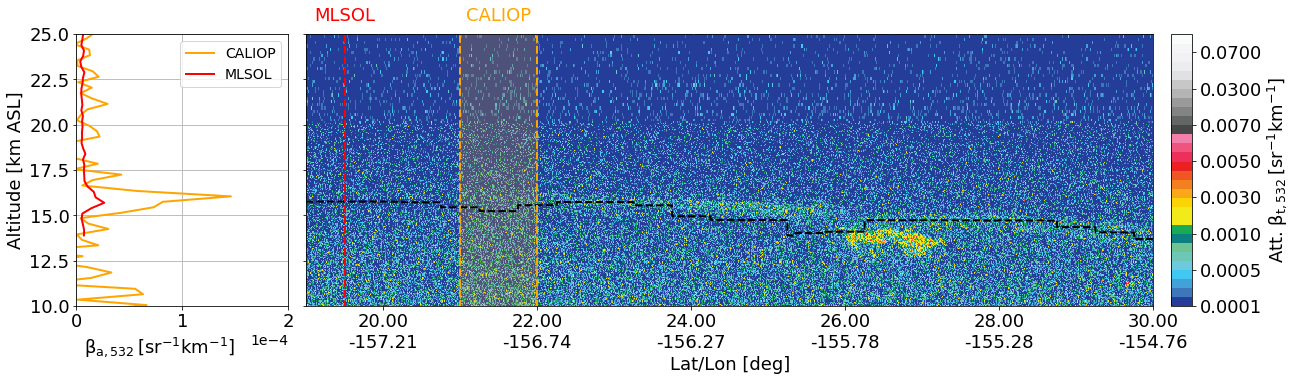
To provide further details on the smoke observations, the following was added to the manuscript:

*In order to relate the origin of this plume to the British Columbia fires and minimize the possibility of a cirrus cloud misclassification, three nighttime CALIOP overpasses around the MLO area between 29 August 2017 and 2 September 2017 were analyzed. For all these overpasses, a thin stratospheric plume at about 15-16 km ASL was observed 150 km north of MLO (Fig. 3). In all cases, the plumes were characterized by a low average depolarization ratio (< 0.1), which is compatible with smoke particles. The rapid equatorward transport of the plume seems in agreement with the wind field reported by the MERRA-2 reanalysis. Additionally, compatible results can be seen in Fig. 3c presented by Kloss et al. (2019), where simulations by the The Chemical Lagrangian Model of the Stratosphere (CLaMS) indicate presence of fire tracers over Hawaii as early as 5 September 2017.*



***Figure 3.*** *Nightime CALIOP tracks (black, dashed) in the MLO (red cross) area analyzed as part of the PyroCb plume tracking. The spatial extension of the stratospheric aerosol plumes detected during the overpasses are highlighted with black thick lines. MERRA-2 winds at 100 hPa are also shown (arrows, black).*

*Among these three CALIOP overpasses, the one corresponding to 31 August 2017 provides the closest temporal and spatial data to what is believed to be the first observation of stratospheric smoke injected by the British Columbia fires at MLO. An overview of the CALIOP total attenuated backscatter measurement during that overpass together with the MLSOL measurements for 1 September 2017 are presented in Fig. 4.*



***Figure 4.*** *Overview of the CALIOP attenuated backscatter measurements during 31 August 2019 overpass in Hawaii area (right panel). The 1 September 2019 MLSOL aerosol backscatter observations (left panel, red) are presented together with the aerosol backscatter retrieval from the CALIOP (left panel, orange) for the southern part of the plume (shaded, orange).*

*Although the plume visible in CALIOP L1 profiles (Fig. 4, right) does not seem to reach the MLO latitude, this could be attributed to several reasons, including the lower sensitivity of CALIOP when compared to MLSOL and the spatiotemporal difference between measurements. In order to provide a quantitative assessment of the plume characteristics observed by CALIOP on 31 August 2017 and compare it with the MLSOL observations during 1 September 2017, an aerosol backscatter profile was derived from the CALIOP L1 total attenuated backscatter averaged over the southern end of the plume (21N to 22N). This conversion includes the correction for molecular and ozone extinction and the subtraction of the molecular backscatter component calculated from co-located MERRA-2 temperature and pressure profiles. The intercomparison (Fig. 4, left), reveals a strong similarity between the plume elevation and thickness measured by CALIOP and MLSOL. On the other side, the backscatter coefficient derived from CALIOP measurements peaks at about 1.5e-4 sr-1 km-1, while the MLSOL measurement on 1 September 2017 has a peak value of about 0.2e-4 sr-1 km-1. In both cases, the backscatter is reported at 532 nm. The MLSOL aerosol backscatter was converted to 532 nm using a color ratio of 0.8 as derived in Sec. 5.1 from co-located MLSOL and NOAA lidar measurements. After the first detection on 1 September 2017, several other plumes were observed by MLSOL over a period of five months, with a maximum average plume center altitude of 19.5 km ASL register during February 2018.*

**p.11, l.1. Do you mean here “slight variations of stratospheric AOD”? What was the maximum altitude of the smoke plumes detected above MLO? For an accurate characterization of the smoke observation by MLO lidars, I would suggest the authors to check the following articles describing the global spatiotemporal evolution of the BC smoke: Khaykin et al., GRL, 2018; Bourassa et al., JGR, 2019; Kloss et al., ACP, 2019.**

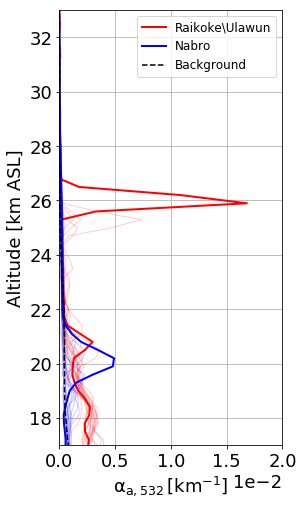
Right, we refer to stratospheric AOD in that sentence. Thanks also for the references, we included them as part of our new extended PyroCb analysis section.

**Fig. 3. It would be very useful to show other examples of aerosol profiles bearing volcanic signals to support the discussion on the altitude variation of the various plumes.**

Fig. 3 (now Fig. 5) was modified according to your suggestions (see next answer). Instead of only one profile, we decided to include all Raikoke/Ulawun profiles and highlight the most prominent one (24 September 2019). In the same way, we included the Nabro eruption profiles and highlighted the most prominent one as a reference.

**p.11, l.6-7. The top altitude of the plume does not seem to exceed 26 km.**

The profile included in the previous version of the manuscript corresponded to 26 September 2019. In the new version of the plot, we included all the profiles with Raikoke/Ulawun plumes and highlighted the profile captured on 24 September 2019, which showed a very thick plume centered around 26 km ASL.

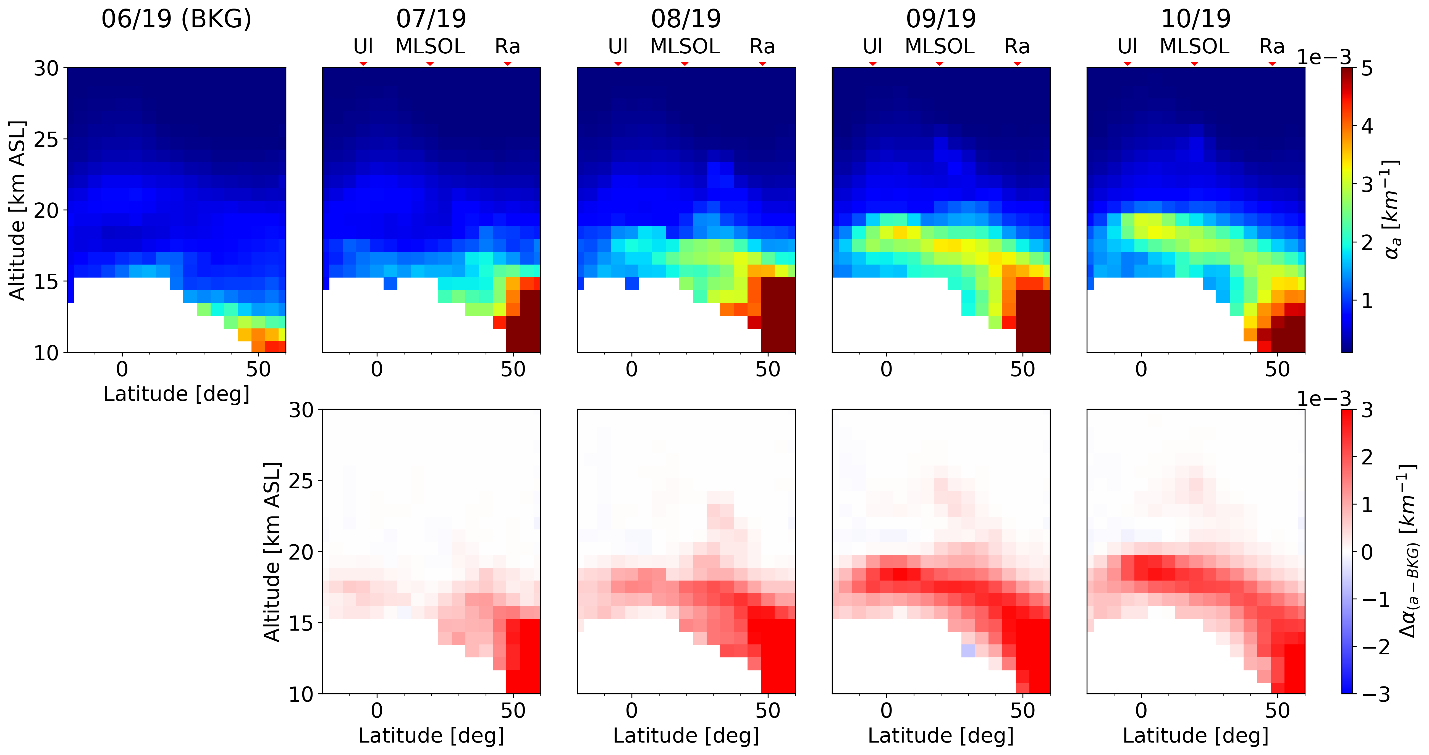


**p.11, l.10-11. The enhancements below 21 km could also be attributed to the Ulawun plume. I really don’t think the Siberian wildfires had any contribution to the tropical stratosphere.**

Thanks for pointing this. At the time of writing this paper, these two eruptions were very recent and the available data was very scattered. We expanded this section based on the new data and available data.

The following was added:

*In order to further investigate whether this plume correspond to the Raikoke eruption, the Ulawun eruption or the large fires that had taken place in Siberia between July and August 2019, CALIOP L3 longitudinally-averaged extinction cross-sections (latitude vs. altitude) from this period are presented in Fig. 7.*

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***Figure 7****. Longitudinally averaged CALIOP L3 extinction cross-sections (latitude-height) between June 2019 and October 2019 (upper panels) are shown together with their difference (lower panels) with respect to the background conditions presented during June 2019*.

*Since no significative stratospheric injection events were registered during the first half of 2019, the extinction cross-section from June 2019 can be considered as background condition for this analysis (Fig. 7, BKG). Starting in July 2019, an enhancement of the aerosol load is clearly visible between the tropopause and 19 km ASL, with a small gap around 15 N. This gap corresponds to the division between the plume of the Ulawun (south) and Raikoke (north) eruptions. By August 2019, this gap is closed as both plumes mixed together, making them indistinguishable. Between 30N and 40N, a fraction of the Raikoke plume is visible rising above the rest of the plume, confirming the back-trajectories presented in Fig. 6. By September 2019, the mixed Ulawun-Raikoke plume reaches 21 km ASL and increases its extinction at low latitudes. The secondary Raikoke plume displaces southward reaching 20N at an altitude of over 25 km ASL. Finally, October 2019 cross-section starts to show a decay in the extinction of the plume, which is compatible with the AOD measurements by MLSOL recorded for that month (Fig. 1).*

**Figure 4 is an excellent demonstration of the equatorward progression of the Raikoke plume, which would hardly be possible using trajectory analysis. Could you provide more detail on how the tracking was done using CALIOP L1 data? The latter should probably be introduced in the datasets section as it is exploited for analysis.**

The following was added to explain the process conducted to track the plume:

*The tracking of the plume was conducted mainly through a manual inspection process of CALIOP L1 profiles considering the main stratospheric circulation patterns. This was possible due to the well-defined shape of the plume and its strong backscattering properties when compared to other previous volcanic plumes.*

The following introduction to CALIOP L1 was included in the Dataset section:

*CALIOP Level 1B*

*The CALIOP Level 1B V4.1 (L1) data product provides half orbit (day or night) calibrated and geolocated single-shot lidar profiles, including 532 nm and 1064 nm attenuated backscatter and depolarization ratio at 532 nm. In this study, since it focuses on thin stratospheric plumes, only nighttime profiles of attenuated backscatter at 532 nm and depolarization are used. Co-located MERRA-2 meteorological profiles including temperature, pressure and ozone concentration are also provided, which in this case are used as part of the aerosol backscatter coefficient retrieval process (Sec. 4.3).*

**p.12., l.9. Please provide an appropriate reference on the Aeolus mission**

The following references were added:

*Stoffelen, A., Pailleux, J., Källén, E., Vaughan, J. M., Isaksen, L., Flamant, P., Wergen, W., Andersson, E., Schyberg, H., Culoma, A., et al.: The atmospheric dynamics mission for global wind field measurement, Bulletin of the American Meteorological Society, 86, 73–88, 2005.*

*Flamant, P., Cuesta, J., Denneulin, M.-L., Dabas, A., and Huber, D.: ADM-Aeolus retrieval algorithms for aerosol and cloud products, Tellus A: Dynamic Meteorology and Oceanography, 60, 273–286, 2008.*

**p.13, l.12-14 and Fig.5 left. I am not sure to understand the point of deriving the color ratio from CALIOP L3 and MLSOL if the former argued to yield systematically higher values compared to MLSOL and SAGEIII. I don’t think these results are worth mentioning at all.**

Although the CALIOP L3 show some disagreement with the other datasets, it is still unclear which one is right and which one is wrong. For this reason, we would like to leave this comparison for future reference.

**p.14, l.5-8. Please specify the wavelength for which the lidar ratios are provided**

In both cases, the lidar ratios are reported at 355 nm. This was added to the manuscript.

**Figure 6. I suppose that the backscatter profiles from the two lidars are provided at their native wavelengths. This is controversial with the statement in p.13, l.18. Please clarify.**

Fig. 6 is presented in the native wavelength of the lidars. The sentence was change to:

*Along this work, when the backscatter coefficient derived from MLSOL measurements at 355 nm is required to be converted to 532 nm (e.g. Sec. 3.2), a smoothed version of the average of the two color ratio profiles derived from the NOAA lidar and MLSOL measurements is used.*

**p.15, l.1-3. “This difference is partly due…” This sentence is difficult to understand and furthermore I am not sure that this small wavelength difference would matter. Please clarify.**

That sentence was removed from the new manuscript, as the difference between the lidar ratio used by CALIOP L3 (50 sr) and GloSSAC (53 sr) is more likely a result of the different technique used for the retrieval than from the small wavelength difference.

**p.16., l.7. There is no mention regarding the Angstrom exponent of -1.6 in Sect. 5.**

This mistake was corrected in the manuscript. Instead of referring to Sec. 5, we added a citation to Jager et al., 2002.

**p.16, l.22. The word “slight” is hardly applicable to the differences reported in Fig.9d, which, at the first glance, vary between -50..50%. Please provide quantitative estimates of the differences and ideally a discussion on their possible sources.**

The word slight was removed, as it certainly not applicable in this case. A quantitative overview of the differences is provided in Fig. 10 (Fig. 13 in the new manuscript).

**p.18,l.3. I don’t think that the differences between long-term averages of MLSOL and NOAA extinction profiles could at all be attributed to the different sampling.**

We decided to remove that sentence and replace it by:

*Although in the case of MLSOL and NOAA lidar this absolute difference likely originates from different retrieval approaches, including noise subtraction and normalization, systematic errors caused by misalignment cannot be ruled out. The relative impact of these error sources is currently under investigation.*

**p.20, l.6-7. This sentence should belong to the data availability statement. Normally, all the data assets should be publicly available at the time of writing. While waiting for archival at NDACC, the reprocessed MLSOL data could already be made publicly available through a file-sharing service.**

Datasets not already available, are available on request.

**p.20, l.12. “…based on alternative methodologies.” The ascent rates derived from MLSOL measurements are compared to only one study by Minschwaner et al. (2016). What about comparison with ascent rates derived directly from aerosol by Vernier et al., ACP, 2011?**

The following was added to the discussion “…and double the ascent rate derived from CALIOP measurements of the Soufriere Hills plume (Vernier et al., 2011)”.

**p.21, l.14, l.19. Comparison of the obtained results with published studies should be discussed in the main body of the article, it does not belong to conclusions.**

No comparisons are presented in the Conclusion section that haven’t been introduced before. The title of the section was changed to ‘Summary and conclusions’ to better represent the content.

**p.22, l.21-22. Please provide the proper links to all data sets used in the study.**

Links to CALIOP, SAGE, GloSSAC and MERRA-2 were included.

**Technical corrections**

The following corrections were introduced to the manuscript.

**p.7, l.25. Replace “periods” by “sessions”**

**p.8, l.2. Suggested correction: “Several studies focusing on midlatitude refer to the time period between…”**

**p.8, l.9. « Ulawun »**

**p.10, l.17 « On 12 August… »**

**p.12, l.8 « latter »**

**p.12, l.9 “derived using Raman lidar…”**

**p.13, l.30. “stratospheric”. Replace “during” by “after”.**

**p.14, l.1 replace “high receiver aperture” by “large receiver”**

**p.14, l.4-5. “A well defined plume…was found at…”**

In this case **p.14, l.10. “Intercomparison of…”**, we change the title from

“Intercomparison with NOAA lidar and satellite-based datasets” to “Intercomparison between MLSOL, NOAA lidar and satellite-based datasets”