Manuscript ID: acp-2020-982
Title: Measurement Report: Lidar measurements of stratospheric aerosol following the Raikoke and Ulawun volcanic eruptions

Reply to Reviewer 1. Reviewer's comments in black, our comments in blue, new or amended text in red.

We thank Vladislav Gerasimov for his helpful comments on the paper.

Comment 1:
The manuscript contains several assumptions (even in the Abstract) that can be easily checked using forward or backward trajectory analysis. The first assumption is related with aerosol layers detected in the UTLS over Capel Dewi prior to the arrival of the Raikoke plume. For example:
Citation 1 (Abstract, page 1, lines 6–7): "Small amounts of aerosol were measured prior to the arrival of the volcanic cloud, probably from pyroconvection over Canada."
Citation 2 (Results, page 5, lines 92–93): "These are most likely due to pyroconvection, but it is not possible to rule out the arrival of volcanic aerosol over Europe at this time."
Citation 3 contains the second assumption about aerosol layers detected in the stratosphere over Capel Dewi on 3 July 2019 and an assertion of unambiguous detection of volcanic ash on 13 July 2019 (Abstract, page 1, lines 7–8): "Volcanic ash may have first arrived as a thin layer at 14 km late on 3 July, and was certainly detected from 13 July onwards, eventually extending up to 20.5 km."
See also (Conclusions, page 8, line 141): "The first unambiguous observation of volcanic aerosol at Capel Dewi was therefore the night of 13-14 July."
I do not insist, but I invite the authors to perform a trajectory analysis that will help to check the assumptions and prove the assertion for at least these two measurement dates (3 and 13 July 2019) like it was done, for example, by Vaughan et al. (2018), Fromm et al. (2010), Gerasimov et al. (2019), and Zuev et al. (2019). The trajectory analysis results can be added to the manuscript as "Supplement."

We thank the reviewer for this suggestion. In fact, we did a trajectory analysis very similar to that published by Grebennikov et al (2020) in our initial analysis of this event. Unfortunately we found that the trajectories were very sensitive to initial conditions, and do not consider them accurate enough to include in this paper. Instead, we take advantage of the material in the supplement of de Leeuw et al (2020) to provide a more rigorous estimate of the spread of the volcanic cloud, with this text in section 3 (we also add a reference to Kloss et al (2020) for the spread of pyroconvection smoke in late June and early July):

The Hysplit model calculates air parcel trajectories based on 3-D advection by winds from an operational analysis model, and its predictions become increasingly sensitive to initial conditions as time goes on (e.g. Vaughan et al. (2018)). An alternative approach to simulating the spread of the aerosol cloud was presented by de Leeuw et al. (2020), using the UK Met Office's NAME dispersion model. This model is based on the global winds from the Met Office Unified Model analyses and includes chemical reactions for converting SO_2 to sulphate, as well as mixing through turbulence and subgridscale dynamics. Its simulations of SO_2 were found to agree well with the TROPOMI satellite for the three weeks after the eruption. de Leeuw et al. (2020) provide video files of model simulations as supplements to their paper, one of which shows the spread of volcanic aerosol across the Northern Hemisphere after the eruption. Up to the end of June the cloud was confined to North

America and eastern Asia. Between 1 and 4 July there are hints that small amounts of aerosol were reaching Europe, with a more prominent filament reaching Scotland by the 7th. The main aerosol cloud in this simulation reached the southern UK on 10 July. These conclusions are consistent with the CLAMS model simulations presented by Kloss et al. (2020) (their fig.5), suggesting that lidar observations over Europe might detect volcanic aerosol from 1 July onwards, and would definitely do so after the 10th. The analysis of OMPS satellite data by Kloss et al. (2020) showed small amounts of stratospheric aerosol over Europe 110 between 24 June and 6 July 2019 (their Fig. 3b), which they attribute using CLAMS modelling calculations to plumes from pyroconvection in Alberta.

Comment 2
Another assumption in the manuscript ("It is likely that aerosol from the eruption of Ulawun in Papua New Guinea on 26 June 2019 mixed with the Raikoke aerosol over the months following the eruptions, so that the residual aerosol in 2020 contained contributions from both sources." (Conclusions, page 8, lines 144–146)) was proved by Chouza et al. (2020) (Fig. 7, page 6830). Therefore, the aerosol layers that were detected by the Capel Dewi lidar after August 2019 should contain volcanic plumes from both eruptions.

Final sentence in conclusions now reads:
'It is likely that aerosol from the eruption of Ulawun in Papua New Guinea on 26 June 2019 mixed with the Raikoke aerosol over the months following the eruptions, so that the residual aerosol from August 2019 onward (Chouza et al., 2020) contained contributions from both sources.'

Comment 3
When we submitted the paper (in August) the Chouza et al paper was the only one we could find reporting lidar observations of Raikoke. We now include a paragraph on Grebennikov et al (2020) in the Introduction:
Lidar measurements of the volcanic aerosol cloud at 355 and 532 nm for four Russian stations were presented for the second half of 2019 by Grebennikov et al. (2020). These stations ranged in longitude from Obninsk at 36.6°E to Petropavlovsk-Kamchatsky at 158.65°E, and observed volcanic aerosol from late July onwards, reaching up to 18-20 km. A maximum integrated backscatter above 13 km of $> 10^{-3}$ was found in August, corresponding to aerosol optical depth of around 0.045.

Comment 4
The authors did not provide direct links to the CALIOP profiles and trajectories for the dates mentioned in the manuscript. This makes it difficult to read the article and to compare the CALIOP data with the authors' lidar measurements. I would recommend authors to provide a list of these links with the corresponding dates, for example, in the "Supplement."
A reference to the CALIPSO web page from which images may be browsed is given on the fifth line of section 3. It is an easy task to navigate from these to any desired image, if the time and date is known. An http reference has been added to the caption of fig 5 which shows a caliop image.

Technical comments

a. Title. We have added 2019 to the title
b. Abstract. Both reviewers asked for changes to the abstract, and we have mostly incorporated those of reviewer 2. For consistency we have removed the co-ordinates

of Capel Dewi from the Abstract and give all the coordinates in the main text, where the Ulawun eruption is also described. A sentence is included to describe the simulations of the spread of the aerosol cloud by de Leeuw etal (2020) and Kloss et al (2020). We also removed the ‘probably’ for the pyroconvection.

c. Mann and Vernier reference replaced by Crafford and Venzke, 2019).
d. Reference to Science article changed
e. ‘Specificate please the month’: following sentence added at the end of the Introduction: All the measurements were taken during the hours of darkness when there was no cloud cover over the site; in all there were 34 nights’ measurements between 27 June 2019 and 30 May 2020.
f. Westward corrected – now reads eastward (sect 3 l.1)
g. We have not provided the direct link to the CALIOP image as explained above
h. L.108 knots changed to ms^{-1}
i. L. 114 – 2019 added and figure caption made consistent with text (thanks to the reviewer for spotting that mistake!)
j. Pyroconvection over Canada: sentence removed from conclusions and replaced by: Small patches of volcanic aerosol may have reached the UK in first few days of July, but were indistinguishable from the elevated aerosol background in the lower stratosphere at that time.
k. Trajectories: the reviewer has far greater faith in the accuracy of trajectory calculations than we do, so we have taken the published model simulations as our guide for the spread of the aerosol.