Interactive comment on “A multi-sensor satellite-based archive of the largest SO_2 volcanic eruptions since 2006” by Pierre-Yves Tournigand et al.

Anonymous Referee #2

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We would like to thank the anonymous reviewer for the insightful and constructive comments, which helped us to improve our manuscript. We appreciate the valuable comments and try to address the issues raised as best as possible.

Reviewer Comments
Manuscript ESSD-2020-109, Tournigand et al., A multi-sensor satellite-based archive of the largest SO2 volcanic eruptions since 2006

The authors describe a new data archive that combines synoptic maps of SO2 plumes, derived from UV and TIR radiance measurements, with estimates of plume heights and thickness derived from lidar profiles and radio occultation (RO). This archive will prove to be of great value to studies of gas emissions for the selected eruptions, as accurate knowledge of the height and thickness of plumes is critical to the estimation of gas concentrations. The authors have done a great service by collocating the RO products with the UV, TIR, and lidar data products, thus facilitating the incorporation of RO products into future analyses of the combined data record.

Reviewer: Unfortunately, this manuscript falls short as a description of the new data archive and show-case for the potential applications of the combined data records. With few exceptions, the descriptions of the data products are too sparse to be of much use to anyone but the most experienced remote sensing specialists. The exceptions to the sparse descriptions are focused on the RO products and, to a lesser extent, lidar profiles. Despite the attention paid to the RO data processing, the authors fail to discuss the basic relationships between the RO signals and volcanic plume phenomena. For example, what are the bending angles and bending angle anomalies (Sections 3.5, 4.1.2, and 4.1.3) and what do these anomalies tell us about volcanic plumes? Similarly, what is the relation between the RO refractivity and plume heights?
Reply:
GNSS RO is an active limb sounding technique which uses the signals transmitted by a GNSS satellite and received by a Low Earth Orbit satellite, where the atmosphere is vertically scanned due to the relative motion of the two satellites. A ray crossing the atmosphere is refracted, i.e. bent, according to Snell's law due to the vertical gradient of atmospheric density. The effect of the atmosphere is represented by a bending angle, from which refractivity and density is retrieved. Refractivity in the neutral atmosphere depends mainly on temperature, pressure, and water vapour pressure. In other words, the bending angle is a function of the density of the atmosphere which depends on temperature, pressure and humidity.
Depending on the type of volcanic eruptions, the presence of volcanic clouds can modify the vertical structure of the atmosphere in different ways. Some eruptions eject large amounts of ash and SO_2 affecting the density of the atmosphere in the region of the cloud, some other eruptions are rich in water vapour. Some eruptions, specifically explosive volcanic eruptions, can also impact atmospheric temperature due to radiative effects. The vertical bending angle anomaly profile shows the perturbation given by the presence of the volcanic cloud since it is computed by subtracting the climatological bending angle profile of the area from the actual bending angle profile co-located with the cloud. The anomaly is thus associated with the perturbation that the volcanic cloud produces in the atmosphere. The largest discontinuities in the vertical bending angle anomaly profile are evident at the height corresponding to the volcanic cloud top. We made this clearer in the revised manuscript text at the beginning of section 2.5:

"The Global Navigation Satellite Systems (GNSS) Radio Occultation (RO) is an active limb sounding technique which uses radio signals transmitted by a GNSS satellite and received by a Low Earth Orbit satellite, where the atmosphere is vertically scanned due to the relative motion of the two satellites. The signal, travelling through the atmosphere, is refracted and bent due to the vertical gradient of atmospheric density. The effect of the atmosphere is represented by a bending angle, from which refractivity and density is retrieved. Refractivity in the neutral atmosphere depends mainly on temperature, pressure, and water vapour pressure. Information about the vertical structure of the troposphere and stratosphere is provided (Kursinski et al., 1997). ….
We also provide the bending angle anomaly which is proven to be an efficient parameter to reveal the impact of the VC on the atmospheric structure (Biondi et al., 2017; Cigala et al., 2019; Stocker et al., 2019) because perturbations in the vertical structure are seen as in the bending angle profile as anomalous peaks, specifically at the volcanic cloud top. …"

Reviewer: The processing of the CALIOP (lidar) data is discussed in the context of the RO data (Section 4.2.1), and the shortcomings outlined above affect the CALIOP discussion as well. The procedure for removing "unnecessary" information from the CALIOP images is confusing. How do the authors determine the "zones of interest" upon which to focus their processing? The practice of discarding CALIOP data corresponding to altitudes below 10 km seems short-sighted. If the RO data products are noisy for such altitudes, then shouldn't the lidar data for low altitude (< 10 km) clouds be all the more important? Since the authors never explain the significance of the RO bending anomaly, relative to volcanic plume heights, it is difficult to appreciate why the low-altitude lidar data should be discarded.
Reply: The zone of interest in CALIOP image is determined using the latitude and longitude of the collocated RO profile and by selecting a window around those values as explained line 292. This part of the text may have been unclear and we rephrased it as:

"*The first step of the cloud top detection procedure consists of cropping the CALIOP backscatter image according to the collocated RO profile position at +/-14° in latitude and +/-80° in longitude. The objective of this first step is to focus the processing on a restricted zone around the position of the collocated RO profile in order to save computational time*".

The CALIOP data are not provided within this archive due to the large file dimension and the quick and easy way to download them from the NASA portal. What we provide here is the CALIOP filename allowing to quickly retrieve the original data within which it is possible to get all the different parameters including the total attenuated backscatter (at 532 and 1064 nm) and depolarization ratio. However, we provide the complete RO profile (from the surface to 60 km). We thus never provide in this archive data arbitrarily incomplete.
We only cropped the CALIOP backscatter images at 10 km during the procedure of cloud top determination. This choice was made for several reasons. First, all the volcanic clouds in this study reached a maximum altitude higher than 10 km. Second, below 10 km the water vapour content and the presence of meteorological clouds is much more pronounced and it tends to disturb the cloud top identification. The confusion may have come from unclear explanations, we thus rephrased them. Again, this selection is just part of the cloud top detection algorithm, but the full RO profile is provided in the archive and the CALIOP information is kept also for the cases for which we do not detect any cloud top with the RO. Last but not least, CALIOP classification algorithm do not include the volcanic ash type below the tropopause level (Kim et al. 2018) so it is difficult to distinguish the volcanic ash from other aerosol types in the lower troposphere. The manuscript has been now updated as:

"*Below 10 km altitude, the RO bending angle anomaly is noisy due to the presence of moisture. Thus we only included in this archive volcanic clouds with a top altitude above 10 km. The following step in the volcanic cloud top determination is then to remove image information below 10 km which also removes a significant part of meteorological clouds increasing the volcanic cloud top altitude detection accuracy*".

We also added a new sentence in the section 2.4 of the manuscript stating

“*The CALIOP does not allow SO_2 measurements or estimation (it provides estimations of dust, elevated smoke, volcanic ash and sulfate), however, the selected CALIOP backscatter is collocated with the SO_2 estimation from AIRS, IASI and GOME-2. Moreover, The CALIOP classification algorithm do not include the volcanic ash type below the tropopause level (Kim et al. 2018) making difficult to distinguish the volcanic ash from other aerosol types in the lower troposphere.*”

- Kim, M. H., Omar, A. H., Tackett, J. L., Vaughan, M. A., Winker, D. M., Trepte, C. R., ... & Kar, J. (2018). The CALIPSO version 4 automated aerosol classification and lidar ratio selection algorithm. Atmospheric measurement techniques, 11(11), 6107.

Reviewer: Similarly, the cloud aspect ratio is not explained, and the threshold value of 0.09 is not justified. What is the significance of a low aspect ratio? What are typical aspect ratios of volcanic plumes vs. meteorological clouds? Finally, the authors do not include CALIOP depolarization ratios in the archive. The CALIOP Aerosol Type (included in the Archive) does not identify volcanic ash or sulfates uniquely, while the depolarization ratios document variations in the size and aspect of particles within volcanic plumes.
Reply: Low aspect ratio means a thin cloud. Analysing our dataset, within all the RO timely collocated with CALIOP backscatter (with the constraints explained in the previous point) It turns out that volcanic clouds are thinner than meteorological clouds. We have computed the aspect ratio for all the clouds (defined as volcanic by CALIOP) exactly collocated in space with the ROs and in a strict time range of 2 hours finding out that all the clouds within these constraints show an aspect ratio lower than 0.09. On the other side, the meteorological clouds usually show an aspect ratio higher than 0.1 except for a few cases. At the end of section 4.2.1 we now added the sentence

“*Based on all the collocations between CALIOP and the GNSS RO, a statistical analysis of volcanic clouds defined by the CALIOP cloud mask and collocated with the RO within 2 hours, has shown that the volcanic clouds are usually thinner than meteorological clouds with an aspect ratio lower than 0.09. According to this result, the final stage of the algorithm consists of distinguishing clusters corresponding to volcanic features from the ones corresponding to meteorological clouds setting the higher limit of the aspect ratio to 0.09. Finally, the remaining clusters’ top altitudes are measured and an average value calculated and saved in the archive as an estimate of the volcanic cloud top altitude.*”

As also reported in the previous reply, the CALIOP data are not provided within this archive due to the large file dimension and the quick and easy way to download them from the NASA portal. What we provide here is the CALIOP filename allowing to quickly retrieve the original data within which it is possible to get all the different parameters including the total attenuated backscatter (at 532 and 1064 nm) and depolarization ratio.

Reviewer: In an effort to justify the creation of the archive, the authors make a number of problematic statements. The statement that “… not any archive is available at the moment to be used as background for future studies“ (Line 17) is not true, as the authors demonstrate by citing the existing LaMEVE (Lines 68-70), OMI (Lines 92-93), and TOMS/OMI MSVOLSO2L4 (Lines 95-96) archives. In addition, the authors acknowledge the GVN archive at many locations in the text. The new archive may be the first to include RO data, but the potential contributions of RO to volcanology (see my previous comments) have never been discussed. Consequently, the unique nature of the new archive is not obvious.
Reply: It is true that other archives collecting data about volcanic ash clouds and SO2 clouds exists. However, these archives are focusing on one volcano and/or data from one instrument, and/or on ancillary information (e.g. LaMEVE). This archive brings together quantitative data on volcanic clouds for the first time from several major eruptions observed through several instruments and for the very first time including GNSS RO data. We agree with reviewer 2 on the fact that our statement was not phrased correctly and would have been potentially confusing for the reader. We modified the text accordingly:

Line 16: "*Several papers have been published focusing on single eruptive events, but no archive available at the moment combines quantitative data from as many instruments*".

Line 75: "*although these types of database are generally limited to ancillary information, a specific volcano, a specific time window or a specific instrument (e.g. de Moor et al., 2017)*".

Reviewer: The authors claim that papers describing individual eruption events "make it difficult to compare" the data sets (Lines 74-75) is disingenuous. The authors neglect to mention that the studies cited in this paragraph (Lines 74-90) The authors present no evidence for the claim that the volcanic clouds generated by the Merapi, Tolbachik, Kelut, and Calbuco eruptions were not studied "in depth" (Lines 87 – 90) What is the definition of "in depth?" The Calbuso eruption clouds, in particular, have been studied extensively, as this eruption had an impact of the evolution of the southern ozone hole.
The first statement line 74-75 was indeed potentially too strong and actually not really necessary. We elected to remove it. The term "in depth" was probably not appropriate. We choose to rephrase this sentence:

"*The Calbuco 2015 eruption (Marzano et al., 2018; Lopes et al., 2019) was widely studied especially in connection to its impact on the Antartic ozone hole (Ivy et al., 2017; Stone et al., 2017; Zhu et al., 2018; Zuev et al., 2018). The rest of the volcanic clouds, such as the ones produced by Merapi 2010 (Picquout et al., 2013), Tolbachik 2012 (Telling et al., 2015), and Kelut 2014 (Kristiansen et al., 2015; Vernier et al., 2016) also received some attention from the scientific community*".

- Ivy, D. J., Solomon, S., Kinnison, D., Mills, M. J., Schmidt, A., & Neely, R. R. (2017). The influence of the Calbuco eruption on the 2015 Antarctic ozone hole in a fully coupled chemistry-climate model. Geophysical Research Letters, 44(5), 2556-2561.
- Stone, K. A., Solomon, S., Kinnison, D. E., Pitts, M. C., Poole, L. R., Mills, M. J., ... & Vernier, J. P. (2017). Observing the impact of Calbuco volcanic aerosols on South Polar ozone depletion in 2015. Journal of Geophysical Research: Atmospheres, 122(21), 11-862.
- Zhu, Y., Toon, O. B., Kinnison, D., Harvey, V. L., Mills, M. J., Bardeen, C. G., ... & Jégou, F. (2018). Stratospheric aerosols, polar stratospheric clouds, and polar ozone depletion after the Mount Calbuco eruption in 2015. Journal of Geophysical Research: Atmospheres, 123(21), 12-308.
- Zuev, V. V., Savelieva, E. S., & Parezheva, T. V. (2018). Study of the Possible Impact of the Calbuco Volcano Eruption on the Abnormal Destruction of Stratospheric Ozone over the Antarctic in Spring 2015. Atmospheric and Oceanic Optics, 31(6), 665-669.

Reviewer: The authors need to include at least one example of unique contribution of the new archive to plume studies. Figure 2 shows the locations of data points, but not the unique contributions to the study of plumes enabled by the new archive. For example, what are the levels of agreement between the UV- and TIR-based SO2 retrievals? What are the variations in SO2 retrievals relative to atmospheric conditions (principally temperature and humidity) and plume altitude? What are the levels of agreement between the IASI, CALIOP, and RO-based plume altitude estimates? Which altitude estimates have the highest level of confidence? Examples of the potential contribution of the new archive to plume studies would help with the troublesome justifications for the new archive. The contributions would become readily apparent, eliminating the need for the current unsupported statements.
Reply: The current paper introduces a new data archive that combines several satellite data-sets for recent eruptions and, for the first time, includes radio occultation data. Some limited inter-comparisons of the data are already published in the literature (Brenot et al., 2014; Carn et al., 2015; Theys et al., 2013), so here we concentrate on describing the archive. A future paper is planned that demonstrates how to use the data for some specific cases. The validation of SO_2 from GOME-2 and IASI is also part of the EUMETSAT Satellite Application Facility on Atmospheric Composition and Monitoring (AC SAF) activity. The objective of this paper is to present the organisation of an archive grouping data from different instruments, but not to discuss the efficiency of each retrieval algorithm used by each instrument.

Table1 shows the agreement between IASI, CALIOP and RO-based plume altitudes. The average discrepancies between IASI and CALIOP, IASI and RO and CALIOP and RO are respectively 2.0 km, 1.7 km and 0.8 km. Consequently, we have the lowest confidence in IASI data.

We agree with the reviewer 2 that some examples of unique contribution of the archive is needed. So we added a new section to the manuscript titled "Results", where we summarize the content of the archive and we show with some examples (and citations to previous works) how the dataset can be used. Also a new figure (related to the section Results) has been added to the manuscript. the Figure 3 shows an example of dataset usefulness: The archive allows the user to collocate the different sensors (maps on the right), to check the vertical structure of the cloud (aerosol types from CALIOP), to analyse the effect that the cloud has in the atmospheric structure in terms of density (bending angle anomaly), humidity and temperature and to compare the different cloud top estimations.

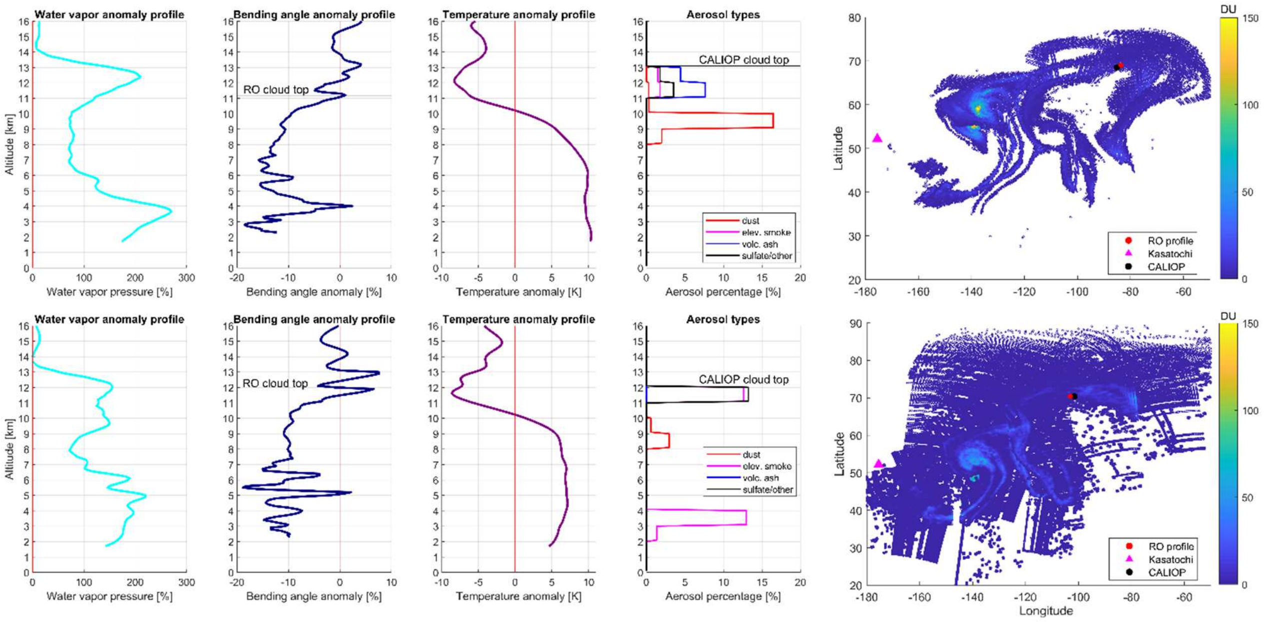

Figure 3. RO profiles corresponding to the CALIOP aerosol types profile co-located with the SO_2 estimation from IASI (top panels, 12/08/2008) and AIRS (bottom panel, 11/08/2008).

- Brenot, H., Theys, N., Clarisse, L., van Geffen, J., van Gent, J., Van Roozendael, M., et al.: Support to Aviation Control Service (SACS): an online service for near-real-time satellite monitoring of volcanic plumes, in: Natural Hazards and Earth System Sciences, 14(5), 1099–1123. https://doi.org/10.5194/nhess-14-1099-2014, 2014.
- Carn, S. A., K. Yang, A. J. Prata, and N. A. Krotkov (2015), Extending the long-term record of volcanic SO2 emissions with the Ozone Mapping and Profiler Suite nadir mapper, Geophys. Res. Lett., 42, doi:10.1002/2014GL062437.
- Theys, N., Campion, R., Clarisse, L., Brenot, H., van Gent, J., Dils, B., Corradini, S., Merucci, L., Coheur, P.-F., Van Roozendael, M., Hurtmans, D., Clerbaux, C., Tait, S., and Ferrucci, F.: Volcanic SO2 fluxes derived from satellite data: a survey using OMI, GOME-2, IASI and MODIS, Atmos. Chem. Phys., 13, 5945–5968, https://doi.org/10.5194/acp-13-5945-2013, 2013.