Response to referee #2

P3, L66: Missing word '(down to 2.5x7km2) of SO2'

- *changed*

P3, L70. The term "volcanic clouds" is mis-leading, since it can refer to clouds of ash, particles, trace-gases. Here you are clearly referring to volcanic ash clouds. You use this term very often throughout the text. Please describe at each occasion what you mean.

- *systematically changed "volcanic cloud" to "volcanic ash", "volcanic ash plumes" or "volcanic ash and SO_2 plumes", depending on the context.*

P3, L84: Calipso -> CALIPSO P3, L85. Maybe add a short explanation about what the 'A-train constellation' is.

- *changed to:*

  "CALIPSO is part of the A-train constellation, which consists of several Earth-observing satellites that closely follow one another, crossing the equator in an ascending (northbound) direction at about 1:30 PM local solar time, within seconds to minutes of each other along the same or a very similar orbital "track"."

P3, L85. It is "13:30h local time"

- *changed*

P4,L118: Add here that the SO2 product provides four different SO2 VCDs for different SO2 vertical profile shapes, since they are not known at the time of the measurement. For the rest of the paper it would be also good to know, which SO2 VCD you have chosen. Here you might also refer to the paper of Hedelt et al. 2019, who has also studied the Sinabung eruption and retrieved SO2 plume heights for this.

- *we added the following:*

  "The TROPOMI SO_2 data product provides four different SO_2 VCDs for different SO_2 vertical profile shapes, since they are not known at the time of the measurement. For this paper, we use the standard SO_2 VCD product."

- *We also added to section 3.1:*

  "These heights are consistent with results the recently introduced new TROPOMI SO_2 height data product [Hedelt et al., 2019]."

- *we also added to the summary and discussion in relation to the use of the standard SO2 data product rather than for example the 15 km SO2 data product the following:*

  "Also note that it could be argued that it would be better to use the TROPOMI SO2 15 km data product, as 15 km is more consistent with the volcanic plume height. However, this 15 km data product assumes a "nice and tidy" SO_2 plume without any contamination, let alone the complexity of a fresh, optically very thick eruption plume and the presence of condensed water, in combination with indications of a shielding effect. Furthermore, the main focus of this paper is ash heights rather than SO_2, which is mostly used as a proxy for a volcanic plume, although investigating the accuracy and precision of satellite SO_2 VCD observations in fresh volcanic plumes would be valuable, in particular with soon to be launched geostationary hyperspectral satellites."

P4, L123: Add a reference for the O22CLD algorithm (either paper or ATBD)

- *reference to Veefkind et al. [2016] added*

P4, L129. Consider also adding information about the cloud fraction from OCRA

- *added the following:*

  "Note that TROPOMI operational cloud fractions are derived from the OCRA algorithm [Loyola et al., 2018]."

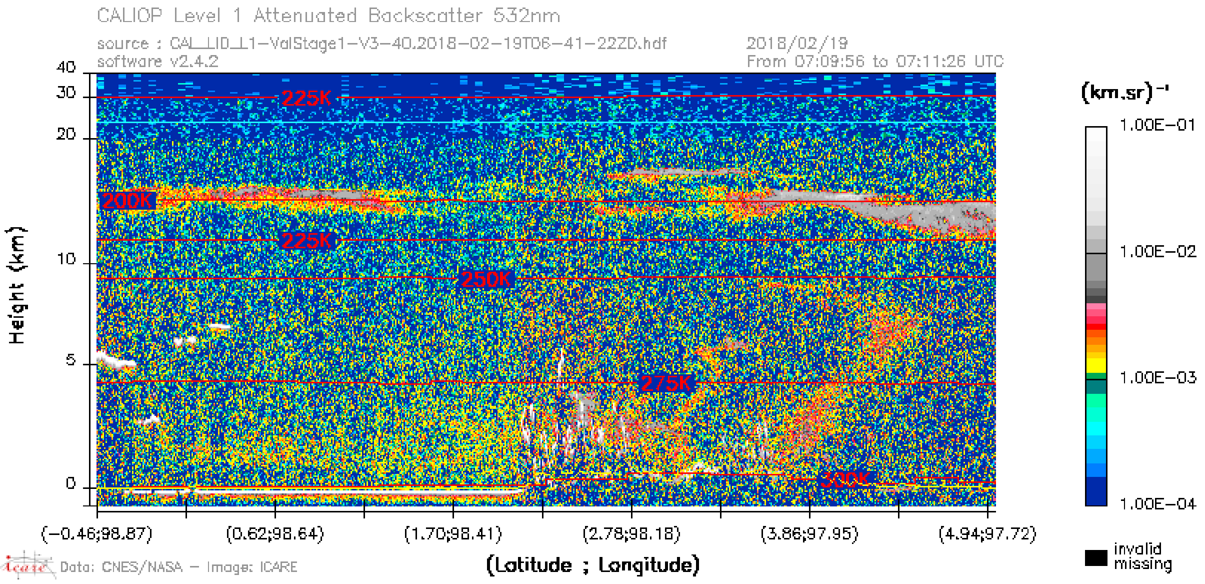
P5, Sect. 2.5: I suggest to add more information on CALIOP, references and a description of what the 'attenuated backscatter imagery' displays, i.e. what it is sensitive to, etc. I also propose to also add the VFM, which shows the type of absorption feature as well as the BTD which gives information about the type of absorption.

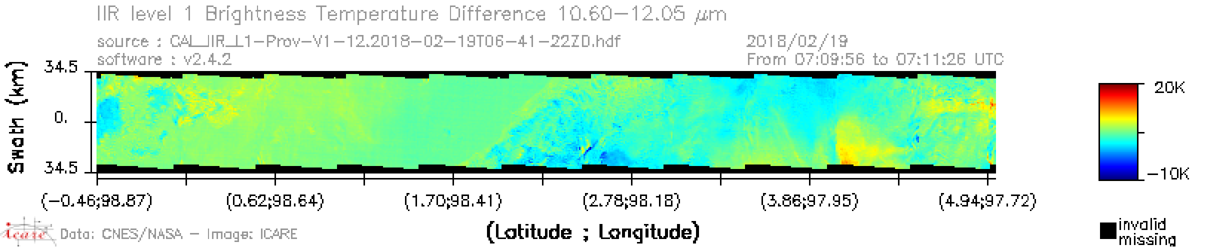
- *we added the following to section 1.5*

  "The TAB signal strength is color coded such that blues correspond to molecular scattering and weak aerosol scattering, aerosols generally show up as yellow/red/orange. Stronger cloud signals are plotted in gray scales, while weaker cloud returns are similar in strength to strong aerosol returns and coded in yellows and reds. The TAB in sensitive to atmospheric particles: both water and ice droplets as well as various types of aerosols."

- *with regard to the VFM, we added halfway section 3.3 a reference to Hedelt et al. [2019] who present and analyze the VFM for the same CALIPSO orbit, and conclude that the volcanic cloud "contains high concentrations of water droplets".*

- *we further investigated the corresponding CALIPSO DBT (10-12 micron; see below), but found the small swath of the CALIPSO DBT difficult to interpret without the context provided by for example HIMAWARI-8 time series in conjunction with the various TROPOMI data products. Since we already extensively show and discuss HIMAWARI-8 DBT, there does not appear to be much added value in the small-swath CALIPSO DBT plot.*





http://www.icare.univ-lille1.fr/calipso/browse/calipso_browse.php?event=change_orbit_segment&segment=20&y_offset=648

P6, L163 You write the 'extend of the volcanic plume', but by means of what? SO2 VCD or AAI or? Please specify.

- *changed to:*

  "The AAI and SO_2 contours agree well with the cloud structure associated with the volcanic plume , …"

P6, L166: Here it would be interesting to see what is the TROPOMI OCRA cloud fraction.

- *the FRESCO cloud fraction (figure 1, panel [D]) shows that there is little cloud fraction structure resembling the volcanic plume, which is also the reason we only continue to use cloud heights/pressures.*

P6, L170 Please describe the 'clear differences' between FRESCO and ROCINN

- *added the following:*

  "Differences between FRESCO and ROCINN for the volcanic plume are small, most notably the lack of saturated pixels in ROCINN (greys in FRESCO), possible due to the neural network filling in the gaps with nearby cloud information or interpolating between cloud pixels."

P6, L183 I suggest to rephrase the sentence, since the CALIOP data only shows an attenuation by clouds. As you write later on, there is no *CLEAR* detection of an ash layer

- *currently these layers are characterized in the text as "cloud/ash" layers to reflect the ambiguity about CALIPSO not always being able to discriminate between clouds particles and aerosols. We honestly think this should be sufficient. Hedelt et al. [2019] does not even make this reservation. Instead, they directly conclude that this must be and ash/aerosol layer – only supported by the VFM identification of a few aerosol pixels, where most pixels suggest it is a cloud (which they then attribute to water/ice within the volcanic plume).*

P6, L187: Add the CALIPSO overpass time here, such that the reader gets an idea about the overpass time difference btw TROPOMI & CALIPSO

- *added the following to the first paragraph of the section:*

  "The CALIOP overpass time of this area is between 07:09:56 and 07:11:26 UTC, the TROPOMI overpass time is between 06:24:23 and 06:26:00 UTC, a time difference of approximately 45 minutes."

P7, L193. The VFM classifies the volcanic cloud as 'cloud' and sometimes 'ash'. This is because fresh volcanic plumes are typically rich in water vapor (especially for tropical eruptions). The volcanic clouds also contain high concentrations of water droplets. Therefore, the classification in the CALIPSO VFM sometimes fails to pick up the volcanic ash or sulfate aerosol because of competing clouds. Another interesting feature which could be analyzed in this paper is the brightness temperature difference from CALIPSO which clearly shows the ash in the data

- *as shown above, although there are clear BTD signatures in the CALIPSO imager data CALIPSO, there appears little added value to what HIMAWARI shows.*

- *We added the following sentence:*

  "The lack of aerosol masking in the feature mask most likely is related to liquid water or ice contaminating the volcanic ash [Hedelt et al., 2019]."

P7 L214-216. The description of the BTD should appear in Sect. 2.4

- *moved to section 2.4*

P8 L237: TROPOMI was launched in 2017. Given that we now have 2019, I wouldn't call it 'recently launched'.

- *removed*

P8 L225-226 Since the ash and SO2 cloud are co-located there is certainly also an effect of the ash on the SO2 VCD retrieval (and not only shielding). Might be interesting to study the effect of ash on the SO2 VCD

- *we added a recommendation of investigating SO2 retrievals in fresh volcanic plumes to the summary and discussion section*

Figures

Figure 1 is clearly overloaded. Although it is interesting to see all results in one single figure, it is really hard to understand all plots. I would suggest to break down the figure into several figures (i.e. show FRESCO/OCRA/O22CLD cloud heights separately in a figure, as well as FRESCO/OCRA CF and SO2/ AAI) before showing combined plots.

- *we have split figure 1 in two separate ones (1A and 1B, both with our panels). 1A shows the ROCINN CP and the FRESCO CTH, with and without the SO2 and AAI overlaid. This highlights the correspondence between the AAI, SO2, and the cloud height/pressure. 1B shows the FRESCO cloud fraction and apparent scene pressure, and the O22CLD cloud height and apparent scene pressure. This illustrates that the FRESCO cloud fraction does not show spatial structures consistent with the volcanic plume, but that the FRESCO scene pressure and the O22CLD cloud height and scene pressure also show similar structures. In all plots the same SO2 and AAI contours are added for visual guidance. Combined, 1A and 1B provide a consistent view of the various cloud altitude products.*

Figure 2: Clearly a colorbar for the attenuation backscatter is missing. Also please add the AAI colorbar to this figure and not only refer to it. Please consider to show also the VFM, showing some ash classification in the cloud

- *see also our response to Referee #1, P5, Sect. 2.5:*

  with regard to the VFM, we added halfway section 3.3 a reference to Hedelt et al. [2019] who present and analyze the VFM for the same CALIPSO orbit, and conclude that the volcanic cloud "contains high concentrations of water droplets".

  This whole section now reads:

  "Note that CALIOP's own feature mask does not identify hardly any of these backscatter signals as aerosol (for CALIOP v4.10 an occasional cloud pixel is flagged as aerosol, see Hedelt et al., [2019]): the high-altitude structures are flagged as regular clouds, and the below-cloud structure as "totally attenuated", even though clearly the attenuation is not complete. The lack of aerosol masking in the feature mask most likely is related to liquid water or ice contaminating the volcanic ash [Hedelt et al., 2019]."

- *attenuation backscatter color bar has been added to figure 2*

Figure5: I would rearrange the plots and show the HIMAWARI vs AAI plots next to each other and clearly indicate the SO2 threshold in the plot title. A color bar for each sub plot would also be very helpful. Have you tried to display these results in a 3D scatter plot, with x=SO2, y=AAI and z=BTD? Furthermore, why did you show the scatterplots for AAI < -0.25 – they are not part of the volcanic ash cloud, as your AAI contours also indicate. For the SO2 plot I suggest using a logarithmic scale. I also suggest showing horizontal/vertical lines at x=0 and y=0

in conjunction with comments by Referee #1, we modified Figure 5 which now only shows three panels (3x1 rather than 2x2), with in the spatial regridded ΔBTs only the ΔBTs within the SO_2 /AAI contours (see here below for explanation of the contours). The lower two plots have remained, but with only data from within the SO2+AAI contours.

There remain some AAI values < 0.0 because we combine the SO2 and AAI contours to define the eruption plume outline, the AAI and SO2 contours do not exactly overlap, and the contours - by construction – represent a smooth outline which not exactly follows the SO2 and AAI threshold values. Nevertheless, by only using data within the contours the number of pixels with AAI < 0.0 is limited.

The negative AAI values are found at the eruption plume edge and in the region where the DBT values are positive, indicative of snow/ice rather than volcanic ash. Negative AAI values can be related to water/ice clouds, which can produce zero or negative AAI values [de Graaf et al., 2005; 10.1029/2004JD005178], which is consistent with the presence of negative AAI values despite this still clearly being part of the volcanic plume as derived from following the volcanic plume development and dispersion in the HIMAWARI-8 data.

A color bar for plot (B) and (C) has been added below the plot, which, combined with the rearrangement from 2x2 to 3x1 should help make the plot easier to view/read/interpret.

The figure caption now reads:

"**Figure 5. (A)** HIMAWARI-8 ΔBTs for 19 February 2018 06:30 UTC (see also Figure 4) regridded to the TROPOMI measurement grid of that day, and correlations between the HIMAWARI-8 ΔBTs and TROPOMI **(B)** AAI and **(C)** SO_2. The solid and dotted contours denote outline of TROPOMI > 10 DU SO_2 columns and TROPOMI AAI > 0 value, as also shown in figure 4 and derived from Figure 1. The color coding of the dots in the AAI scatterplots is indicative of the corresponding SO_2 value (> 10 DU) , and the color coding in the SO_2 scatterplot is indicative of the AAI value (AAI > 2), see also the lower color bar. These color codings were added for qualitatively identifying possible relationships between ΔBT and AAI or SO_2 within the volcanic ash plume."

Figures S1, S2a, S2b: Would it be possible to indicate the location of the volcano on the maps?

- *volcano location indicated with red triangle*

Figures S2: Would it be possible to add the AAI/SO2 contours to the maps?

- *contours of SO2 and AAI as in figure 1 added to figures S2A/S2B*