Dear Editor,

We thank both referees for taking their time to read the paper and extensively comment on the paper. It was well worth considering their suggestions and they have definitely improved the paper. We have prepared a detailed response to both referee comments.

However, there remains one important issue that we could not fully address, and for which an editorial decision or suggestion is needed and which we completely reiterate here:

Referee #1 notes that … another concern is the reliance and interpretation of the 'VADUGS' algorithm. The authors refer to a conference talk, which in general is fine, but as some of the conclusions reached rely on an understanding of this algorithm and its uncertainties a reference to a published article describing it is necessary (in my opinion). If it is not published elsewhere, then a section describing the algorithm should be added if it is to be used in the comparison of the TROPOMI data.

- *This is a sensitive and difficult point. We currently do not have the capacity nor the time to extensively describe VADUGS, which in essence would be a DLR task, as VADUGS is their algorithm.*

  Originally we expected that VADUGS – which has been an operational algorithm at DLR since 2013 – would be described in a separate paper independent of the EUNADICS-AV project by DLR and by the time our paper was submitted. Due to several staffing changes at DLR (including the DLR co-author moving to EUMETSAT) this has not yet happened.

  However, we would argue that the paper actually does not rely that much on VADUGS but rather mostly on HIMAWARI-8 IR ΔBT differences, which is identical for any volcanic ash retrieval algorithm. We do use he retrieved VADUGS heights (but not ash amounts, not effective radius), but only in a qualitive sense.

  As the reliance on specific and quantitative VADUGS results is limited, the lack of official VADUGS description should not have to be considered as overly important.

  However, so this is to decide by the editor. And we reiterate that unfortunately there is little we can do to resolve this point by providing a full reference to the VADUGS algorithm.

Sincerely yours, also on behalf of my co-authors,

Jos de Laat

Response to referee #1

Specific comments

My major concern is with the relationships drawn between the brightness temperature difference (ΔBT), Absorbing Aerosol Index (AAI) and SO2 total column amounts (i.e. Fig. 5). By eye, it looks like there is no correlation at all. However, it's difficult to tell as no statistical metrics are given. I suggest adding a statistical metric (perhaps a correlation coefficient if the relationship is expected to be linear) to demonstrate that there's a notable relationship (as the authors claim). Further comment on this is provided in the Technical corrections section.

- *there is indeed no clear relation between* ΔBT*, AAI, and SO2, which is an important aspect of the paper. If anything, our results suggest that the relation is complex because the observations were made shortly after the eruption, and the presence of ash and condensed water. We find indications that the presence of ash and condensed water causes a possible shielding effect, i.e. TROPOMI only observes some aspects of the volcanic plume, while the presence of condensed water also hampers the IR* ΔBT *detection of volcanic ash (a known problem, but nevertheless problematic if these type of measurements are to be used in for example aviation applications).*

  with the help of the referee comments and changes we made we think this should be clearer, see further in the responses to the referee comments.

Another concern is the reliance and interpretation of the 'VADUGS' algorithm. The authors refer to a conference talk, which in general is fine, but as some of the conclusions reached rely on an understanding of this algorithm and its uncertainties a reference to a published article describing it is necessary (in my opinion). If it is not published elsewhere, then a section describing the algorithm should be added if it is to be used in the comparison of the TROPOMI data.

- *This is a sensitive and difficult point. We currently do not have the capacity nor the time to extensively describe VADUGS, which in essence would be a DLR task, as VADUGS is their algorithm.*

  Originally we expected that VADUGS – which has been an operational algorithm at DLR since 2013 – would be described in a separate paper independent of the EUNADICS-AV project by DLR and by the time our paper was submitted. Due to several staffing changes at DLR (including the DLR co-author moving to EUMETSAT) this has not yet happened.

  However, we would argue that the paper actually does not rely that much on VADUGS but rather mostly on HIMAWARI-8 IR ΔBT differences, which is identical for any volcanic ash retrieval algorithm. We do use he retrieved VADUGS heights (but not ash amounts, not effective radius), but only in a qualitive sense.

  As the reliance on specific and quantitative VADUGS results is limited, the lack of official VADUGS description should not have to be considered as overly important.

  However, so this is to decide by the editor. And we reiterate that unfortunately there is little we can do to resolve this point by providing a full reference to the VADUGS algorithm.

Another issue is the interpretation of the CALIOP data. The CALIOP pass clearly showed a feature that reached 18 km (asl). This is not mentioned anywhere. In addition, the feature (on average) reached cloud-top heights of 16 km (the authors cite a height of 15 km). It is important to get this right as this paper could be a nice reference for the eruption height of the 19 February 2018 Sinabung cloud in the future.

- *we have added the observation that there also appears to be (some) ash up to 18 km, and explained why this layer likely is also of volcanic origin as there are no indications from HIMAWARI-8 that there are other high altitude clouds at those locations at that time. This does not impact the findings of the analysis, as this layer coincides with the thinner part of the volcanic plume for which we argued the TROPOMI height retrievals are less accurate as TROPOMI "sees" partly through the cloud.*

In general, the authors use the terms ash plume, volcanic cloud, volcanic ash, volcanic ash plume, aerosols etc interchangeably to refer to the eruption cloud (and in some cases to refer to components of the volcanic cloud that were ice-rich). I suggest that the authors define these terms early on in the manuscript. This will avoid confusion, especially when discussing the microphysical make-up of the volcanic cloud. One suggestion could be to use the generic term 'volcanic cloud' to refer to a cloud of volcanic origin and use the terms ice-rich, ash-rich and SO2-rich to refer to regions of the volcanic cloud that exhibit these spectral signatures.

- *we have changed all references to "volcanic ash plume" into "volcanic ash cloud", all references to "volcanic ash height" into "volcanic ash cloud height". This leaves essentially two expressions: "volcanic ash cloud (height)", which refers to the volcanic eruption cloud phenomon, and "volcanic ash", which refers to the physical quantity. We checked the document to ensure that "volcanic ash" is only used when we refer to volcanic ash as the physical quantity.*

Technical corrections

Title: Please be consistent with the use of 'Himawari'. In the text and section headings, the authors use all capital letters in some cases (it is not an acronym). I suggest using 'Himawari-8' throughout the manuscript instead of just 'Himawari' as this is the platform that is used for the analysis (there is a Himawari-9 now, so the distinction is important).

- *All references to HIMAWARI have been replaced with HIMAWARI-8 (incl. figure captions)*

P1L18: 'Evaluation of corresponding Himawari geostationary height retrievals based on InfraRed (IR) brightness temperature differences...' - This statement doesn't seem correct to me. It's the evaluation of the brightness temperature differences (not the height retrieval) that indicates whether the volcanic cloud contains ash or ice/water particles. I suggest changing to 'Evaluation of Himawari-8 geostationary InfraRed (IR) brightness temperature differences...'.

- *Changed lines 19-21 to:*

  "Evaluation of corresponding HIMAWARI-8 geostationary InfraRed (IR) brightness temperature differences (ΔBT) - a signature for detection of volcanic ash in geostationary satellite data and widely used as input for quantitative volcanic ash retrievals - reveals that for this particular eruption the ΔBT volcanic ash signature changes to a ΔBT ice crystal signature for the part …"

P3L78,L80: Please check the citation style for Smithsonian reports. I don't know which report the authors are referencing. The citation styles used in these two lines are different and I only see one reference to the Smithsonian Institute in the References section. I suggest using their guidelines (i.e. 'Cite this Report' link) for referencing reports.

- *Deleted the reference in the reference list, changed the "ïn-text" reference to:*

  "[https://volcano.si.edu/volcano.cfm?vn=261080; Eruptive History]"

P3L85: '13:30' is this local time (LT) or UTC?

- *changed to*

  "The TROPOMI equator crossing local time of 13:30"

P5L145: 'attenuated backscatter imagery' - Please be more specific. Is this the level 1 version 4, 532 nm total attenuated backscatter product (L1-Standard-V4-10)? There were several recent changes to the CALIPSO lidar calibration from version 3 to 4. Also an up-to-date reference could be added (a series of papers on the new version are published in AMT).

- *Results presented are CALIPSO v3.40 data. For the qualitative use of the TAB data product (actual TAB values) in this study and the purpose of this study, differences in the TAB between both product versions are marginal/negligible. We found it very hard to find differences in a comparison of figure 1 between both v3.40 and v4.10. The choice for v3.40 data was pragmatic as data files at the time for v3.40 were earlier available than data files for v4.10*

- *changed sentence to:*

> " … we use total attenuated backscatter data from one CALIPSO orbit (data version 3.40) in a qualitative approach, *i.e.* detection of cloud and aerosol layers and their heights."

P5L158: 'local time of 06:25 UTC' - Is this local time or UTC?

- *'local' here refers to the geographical location, as measurement times change during a TROPOMI orbit. This is indeed confusing, so we changed the sentence to:*

  "with TROPOMI measurements within the figure area made at approximately 06:25 UTC"

P6L164: 'Cook et al. (2014)'. Could add references to Moxnes et al. (2014) and Prata et al. (2017), which both specifically investigate the separation mechanisms of volcanic ash and SO2

- *references added*

P6L166-168: I would consider moving the VIIRS and NOAA/CIMSS volcanic ash retrieval Supplementary Figures into the main manuscript. The true colour VIIRS image is important for context and interpretation of the TROPOMI height retrievals (presented in Fig. 1). Also, use of NOAA/CIMSS retrievals (which are referred to for the cloud height in this sentence) should be stated with the correct references (i.e. Pavolonis et al. 2015a, b)

- *this is a point of contention: originally the VIIRS and NOAA/CIMSS retrievals actually were in the main paper. However, as (1) the paper is already rich in figures and (2) the main topic of the paper is evaluating TROPOMI and HIMAWARI-8 volcanic ash heights, we decided at the finalizing stage of writing to move the VIIRS/NOAA/CIMSS results to the SI.*

  Furthermore, in essence the VIIRS/NOAA/CIMSS results are based on the same type of measurements (broad band IR) and the same retrieval approaches (split-channel) as the HIMAWARI- data. However, data files of the VIIRS/NOAA/CIMSS results are not publicly available and accessible, which would allow for direct comparison. Hence, use of results that are only available as imagery, not as data, and we prefer not to rely just on imagery in the main body of the paper.

  Unless it is really crucial for the paper – which believe it is not - we would prefer to keep the VIIRS and NOAA/CIMSS figures in the SI.

- *references have been adjusted as suggested*

P6L171: 'Systematically higher' - This implies FRESCO cloud heights are always higher than the O22CLD heights. Based on Fig. 3, this looks to be the case from 3-5 degrees latitude. However, from 2-3 degrees latitude it looks like O22CLD is higher than FRESCO. So, I wouldn't call this systematic. Perhaps it would be simpler to state 'In general, FRESCO cloud heights are higher than the O22CLD heights'. Or something similar. A correlation plot could also be added to show the bias of FRESCO/ROCINN vs. O22CLD cloud heights.

- *changed sentence as suggested*

- *For general interest: we did a check: for the region of the plot, and for 88% of clouds with CTH > 5 km, FRESCO CTH are higher than O2O2 CTH. For a wider geographical area (entire orbit), this drops to 60%. However, when instead considering clouds with CTH > 10 km for the* *wider area, this fraction increases again, even further for larger cloud fractions (0-25-50-75% cloud fraction 67-71-76-87%). For ROCINN, these numbers are even better (89-91-93-97%).*

P6L176: ‘up to 15 km altitude’ - Please provide a reference for this. Also, how strict is this limit? In Fig. 3, I see cloud heights higher than 15 km. Also, is this above sea level? Please make this clear in the text.

- *changed to:*

  “up to approximately 17 km altitude (~100 hPa) [Wang et al., 2012]”

- *This is a typo, it should read “25 km”, which is a hard-coded limit for FRESCO CTH. However, a more realistic limit – and hence why we overlooked it, is that in reality FRESCO has – by virtue of its oxygen absorption – an acceptable sensitivity up to approximately 100 hPa or approximately 17 km altitude. Research papers on both FRESCO validation as well as FRESCO methodological uncertainties indicate suggest an uncertainty range of 25-50 hPa. Furthermore, there is limited information about the quality of FRESCO CTH above 15 km there are few validation opportunities. Clouds with clouds top heights at 15 km or above are rare, even more so optically thick clouds for which the FRESCO “centroid altitude” lies at 15 km or above. However, with increased possibilities for measuring clouds above 15 km altitude (more & better satellites), as well as interest in high altitude clouds above 15 km altitude, this will be a valuable future research topic.*

P6L183: Please provide a colour scale/legend with Fig. 2 to show which AAI values correspond to which colour.

- *a color scale was added*

P6L183: Interpretation of the CALIOP data. Based on Fig. 2, it looks like the main feature has cloud-top heights of around 16 km (15 km is stated in the manuscript). There is also a clear feature at 18 km (detected by the AAI). This is not mentioned at all and should be addressed in the manuscript.

- *changed to “approximately 16 km”*

- *added a short discussion about this 18 km plume later in section 3.4 in relation to Figure 4.*

  “There is also a layer detected in CALIPSO at 18 km around 3°N, which likely is also volcanic as the HIMAWARI-8 BT does not provide any indication of other high clouds while there are negative ΔBTs near the CALIPSO track at 3°N, indicative of the presence of volcanic ash.”

P6L188-189: There is poor agreement between FRESCO and CALIOP from 3-4 degrees latitude, which should be stated here.

- *changed to:*

  “Between 3° and 4° latitude, the agreement is poor as the FRESCO”

P7L193: CALIOP’s feature mask - Please state which version of the feature mask is being interpreted. There were changes made from V3 to V4. I looked at the VFM V4 for this pass and I can see some small parts of the feature classified as dust aerosol but the majority is cloud.

- *added, it is v3.4*

P7L194: ‘clearly the attenuation is not complete.’ - I’m not sure it is that clear. This interpretation would be more justified if the VFM was plotted on the same scale as Fig. 2 and inserted as a second panel.

- *correct, although even for CALIPSO v4.10 the nearly all cloud pixels for this scene are flagged as “cloud”. We changed the sentence to:*

  “does not identify hardly any of these backscatter signals as aerosol (for CALIOP v4.10 an occasional cloud pixel is flagged as aerosol):”

P7L196: Comparison of FRESCO and ROCINN – is this only for AAI > 0? Please clarify.

- *The R2 = 0.98 is based on all clouds regardless of AAI value. Sentence changed to:*

  “FRESCO cloud heights between 0.5 and 14 km regardless of corresponding AAI value”

P7L200-201: ‘and all data products increasing heights in the volcanic cloud going from south to north.’ - This is simply not true. The heights increase from 2-4 degrees latitude and then decrease from 4-6 degrees latitude. Please clarify in the text.

- *This is sloppy formulation from our side, the point we wanted to make – and the change we made - is:*

  “… with the largest heights between 4° and 5° latitude, consistent with the CALIOP observation that backscatter signals between 3° and 4° latitude are weaker than between 4° and 5° latitude”

P7L209-210: ‘The eruption dynamics may thus have additional effects on the ash plume displacement, but this cannot be investigated based on the available satellite data.’ - This statement requires further justification and clarification about why the available satellite data cannot be used to study the eruption dynamics. For example, Himawari-8 provides excellent observations (every 10 minutes) of the volcanic cloud’s evolution and dynamics (as the authors discuss in Section 3.4).

- *What would be needed for properly understanding the eruption dynamics are time series of its 3D structure (time-lon-lat-height), like in a model, but which clearly cannot be observed or reconstructed from satellite observations. Satellites thus only provide a partial view of the entire eruption plume.*

  Changed the description to:

  “The eruption dynamics may thus have additional effects on the ash plume displacement, for which time series of the complete 3-dimensional view of the eruption plume would be preferred. The current available satellite data only provide a 2-dimensional view of the eruption plume from above (geostationary, Polar orbiting), with information about changes over time in case of the geostationary satellites and with some but limited information about cloud and aerosol height. CALIOP measurements only provide one 2-dimensional cross-section through the eruption plume, without any information about changes over time.”

P7L212: Change ‘is’ to ‘was’.

- *changed*

P7L216: Positive ΔBTs are also indicative of clouds composed of water droplets (not just ice). Please clarify in the text.

- *changed to:*

  "with negative ΔBT potentially indicating volcanic ash, and positive ΔBTs indicative of the presence of nontrivial liquid water of ice content [Pavolonis et al., 2006]."

P7L218-219: 'one associated also with a high cloud height, and another one further south with much lower cloud heights' - what cloud heights are being referred to here? The VADUGS algorithm in Fig. 4 only appears to show a high altitude cloud.

- *some reddish colors within the contours, potentially indicating volcanic ash, collocated with high clouds (whites), while other reddish colors collocated with low clouds (blues). To describe exactly what we note, we changes the sentence to:*

  "one associated also with a high cloud height (white cloud colors), and another one further south with much lower cloud heights, likely low-altitude outflow or pyroclastic flows (blue cloud colors).

P7L221: 'dense high ice clouds' - What do the authors mean by 'dense' here? Optically thick ice clouds would show a near zero ΔBT, not a strongly positive ΔBT.

- *dense refers to the observations that initially the high cirrus is not transparent (see also SI figures S 2A/2B). It is not critical, so we modified the text in combination with the next comment.*

P7L221: 'purple region' - I actually see this as blue. Maybe call it an 'ice-rich cloud'?

- *see also previous comment, sentences were changed, the color purple now only refers to the ΔBTs:*

  "large positive ΔBTs (purple), indicative of high ice clouds, which continues to grow and expand northward."

P7L222-224: Figure 5 - I found this figure difficult to interpret. At this line in the manuscript the authors refer to the 'HIMAWARI VADUGS ΔBTs'. How are VADUGS ΔBTs different to a simple 11-12 micron ΔBT? In Fig. 5 they just look like ΔBTs. The authors also state that 'When focusing on AAI and SO2 values, it appears that larger ΔBT values occur for smaller AAI values (< 2) and SO2 (< 20 DU)' - For the lower left plot in Fig. 5, I can see numerous data points that have positive ΔBT (0-10 K) for large (2-6) positive AAI values (contradictory to what the authors claim) and I find it very hard to interpret any relationship whatsoever in this panel. In Fig. 5 lower right panel, again, it's hard to see any relationship because there are positive and negative ΔBT values that correspond to a whole range of SO2 values (5-100 DU).

There are several ways Fig. 5 could be improved: First, I would only plot the data that falls within the contours plotted in the upper left panel of Fig. 5 as this clearly contains the volcanic cloud (what are these contours by the way? They are not mentioned in the Fig. 5 caption). This would remove the black dots (I assume?), which at the moment are distracting. Second, some kind of statistical metric could be used to indicate that there is indeed a relationship between AAI, ΔBT and SO2. If the relationship is not linear then maybe some kind of curve fit (exponential for lower right panel?) will help the reader interpret the relationships.

- *'HIMAWARI VADUGS ΔBTs' should read 'HIMAWARI ΔBTs'.*

- *The point of the comparison between ΔBT on the one hand and the AAI and SO2 on the other hand is to check if there was any relation between both. Based on passed literature showing that the magnitude of ΔBT is not related to ash optical depth (Figure 2 of [Prata & Prata, 2012] provides a nice illustration of this point), the "naive" assumption would be that ΔBT then should also not show a clear relation with the AAI and SO2. Which is doesn't, as the largest AAI and SO2 values occur for smaller ΔBTs. This is in a way a "negative" result, lack of a relationship between two parameters, but we felt that it was important to show this, as it highlights our point that there is added value in combining IR ΔBT with UV/VIS AAI and SO2.*

  We added the following sentence to this section:

  "Overall, we find little evidence of large AAI values and large SO_2values associated with large ΔBTs. Rather, their relation is complex."

- *In addition, we also added the following to the discussion & conclusion section (added section underlined here):*

  "… synergistically combining different satellite data products like the AAI and SO_2. Furthermore, ΔBT appears not to be a good indicator of either large AAI values or large SO_2 columns. This is not surprising as ΔBT is not a good indicator for ash optical depth [*e.g.* Prata and Prata, 2012; Pavolonis et al., 2016]. Our results therefore highlight that there is added value in combining IR ΔBT with UV/VIS AAI and SO_2. Satellite measurements … "

- *The solid and dotted contours denote outline of TROPOMI > 10 DU SO_2 columns and TROPOMI AAI > 0 value. This information is provided in the figure caption of figure 4, which the figure caption of figure 5 refers to. We added the same explanation to the caption of figure 5.*

- *Figure 5 is modified with now only showing 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. Color bars have been added. 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."

P7L224: 'The larger ΔBT are also associated with optically more dense clouds (see VIIRS imagery in the SI and comparison of TROPOMI with CALIPSO).' - This statement needs to be further clarified. It's not physically possible for an optically thick cloud to have a large ΔBT in the infrared. When clouds become optically thick they behave as grey bodies (little spectral variation across thermal infrared wavelengths) and so a difference in brightness temperature between 11 and 12 micron should be close to zero. However, I think what the authors are observing is a relationship between high reflectance at visible wavelengths (white clouds in VIIRS imagery) and large ΔBTs, but it's not clear in the way that it's stated.

- *We agree, the comparison* with ΔBT and SO_2 */AAI requires careful wording. The main points we want to make is that the relationship between all three parameters is complex, and that we find indications of possible shielding effects (thick ash/ice shielding part of the underlying ash/*SO_2 *column). We modified this section as follows:*

  "Figure 5 shows a comparison of TROPOMI AAI and SO_2 data with regridded HIMAWARI-8 ΔBTs (upper left plot). When focusing on AAI and SO_2 values, it appears that larger ΔBT values occur for smaller AAI values (< 2) and SO_2 columns (< 20 DU). The largest positive ΔBT are associated with optically thicker/less transparent water and ice clouds (see also VIIRS imagery in the SI and comparison of TROPOMI with CALIPSO). The lack of larger AAI and SO_2 values for larger positive ΔBT values therefore may reflect some kind of shielding of the volcanic ash and SO_2 by the iced upper levels of the volcanic ash cloud. SO_2 may have been converted into sulphate as the SO depletion rate (e-folding time), which, although uncertain, has been estimated to be as small as 5-30 minutes [Oppenheimer et al., 1998; McGonigle et al., 2004], scavenged by ice [Rose et al., 2000], or via ice nucleation of volcanic ash particles [Durant et al., 2008]. For negative ΔBTs – indicative of volcanic ash – we also find little evidence of a distinctive relation between either the AAI and SO_2 with ΔBTs. This may similarly reflect a shielding effect, as the largest ΔBTs do not occur for the largest aerosol concentrations [*e.g.* Prata and Prata, 2012; Pavolonis et al., 2016]."

P8L225-227: This could be due to scavenging of SO2 by ice (Rose et al., 2000). It could also be due to ice nucleation of volcanic ash particles (Durant et al., 2008). In terms of the conversion of SO2 to sulphate, is there a reference that could be added here? i.e. how long does it typically take for SO2 to convert to sulphate in the upper troposphere? And does this conversion rate make sense given the time of observation and time since eruption?

- *Mechanisms and references included in the text (see previous question for text modifications). The SO2-to-sulphate conversion time scale (e-folding time) is highly uncertain but can has been estimated as small as 5-30 minutes. Both remarks – including references – have also been added (again, see previous question for the new text).*

P8L245-248: 'Comparison with geostationary IR volcanic ash height' - Which retrieval is this statement referring to? Is this the VADUGS volcanic ash cloud height retrieval? It's the comparison with CALIOP that demonstrates TROPOMI height algorithms may underestimate heights for semi-transparent ash clouds. Please clarify this.

- *Should be CALIOP, not geostationary IR. This has been changed.*

P8L251-252: The 'shielding' effect - This is rather speculative and could be due to a number of different reasons (see previous comments on P8L225-227). Also, is this shielding of SO2 or ash or both? I think to substantiate this claim, evidence of SO2/ash existing underneath the cloud-top should be provided.

- *As explained, the lack of a distinctive relation between ΔBTs (both positive and negative) on the one hand and AAI and SO2 on the other hand we interpret as indications for shielding effects, see further the answer to P7L224. There does not exist other data to substantiate this claim. However, with the mentioning of other processes like SO2 conversion, depletion, scavenging, and nucleation, it should be clear to the reader that the analysis is by far definitive with regarding to the presence of a shielding effect.*

P9L257-258: ‘the retrieval algorithm’ - which retrieval algorithm is being referred to here? Please clarify.

- *Should read “IR volcanic ash retrieval algorithms”, changed accordingly.*

P9L266-268: ‘TROPOMI cloud heights can be used for determining aerosol heights for AAI values greater than 4’ - How was this conclusion reached? What is the significance of AAI > 4. As stated in the previous sentence, the TROPOMI cloud heights do not perform well for semi-transparent clouds regardless of their AAI value. This statement requires further clarification. Also ’column values > 1 DU’ is TROPOMI’s signal-to-noise really this good? Please provide a reference.

- *preamble: although the AAI is not a quantitative parameter, in general there is – all else being equal - a clear correlation between the AAI and the AOD. The problem here is the “all else being equal”: the AAI value depends on many parameters, like aerosol type, aerosol height, solar zenith angle, viewing angle, albedo below the aerosol layer (which includes clouds), and some more [de Graaf et al., 2005].*

  A large AAI value will – generally speaking – indicate thick aerosol layers. Both user experience and theoretical calculations suggest – again, generally speaking – that AAI values larger than 2 (two) indicate significant amounts of aerosols. To be on the safe side and because the main interest is also to have non-transparent aerosol layers, we increased the AAI threshold to 4 (four). According to de Graaf et al. [2005], for aerosol layers with AAI values > 4, the AOD generally will be (much) larger than one (AOD of 1 = 1/e or 36.7% of the light is not scattered by the aerosol layer). At such scattering levels, aerosol layers become opaque.

  We added the following sentence:

  “This AAI threshold value of 4 may be conservative but ensures that the aerosol layer very likely is opaque, as generally the associated aerosol optical depth will be (much) larger than on [de Graaf et al., 2005].”

- *TROPOMI SO2 accuracy is estimated to be at least 1 DU, but likely even better, see Theys et al. [2017]. Reference added.*

P11L323-325: Please fix reference formatting here. Also link provided to Stein Zweers (2016) results in a ’Page not found’ error.

- *changed (document recently officially accepted by ESA, so the filename changed)*

P16L411: Check style for figure labels e.g. ‘A+E’ should be ‘(a) and (e)’.

- *checked and updated*

P19L415: VADUGS cloud heights are on the right column of Fig. 4 not left and the ΔBTs are on the left.

- *changed*

P19L427: Change ‘derived’ to ‘shown’.

- *changed*

P19L427: What is the ΔBT bias correction? This needs to be explained and defined in the manuscript.

- *This refers to a typical value of the atmospheric correction of geostationary infrared brightness temperatures for this part of the world, but I do not know why this remark – stemming from an email exchange - has managed to seep into the paper. This can be removed.*

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]."

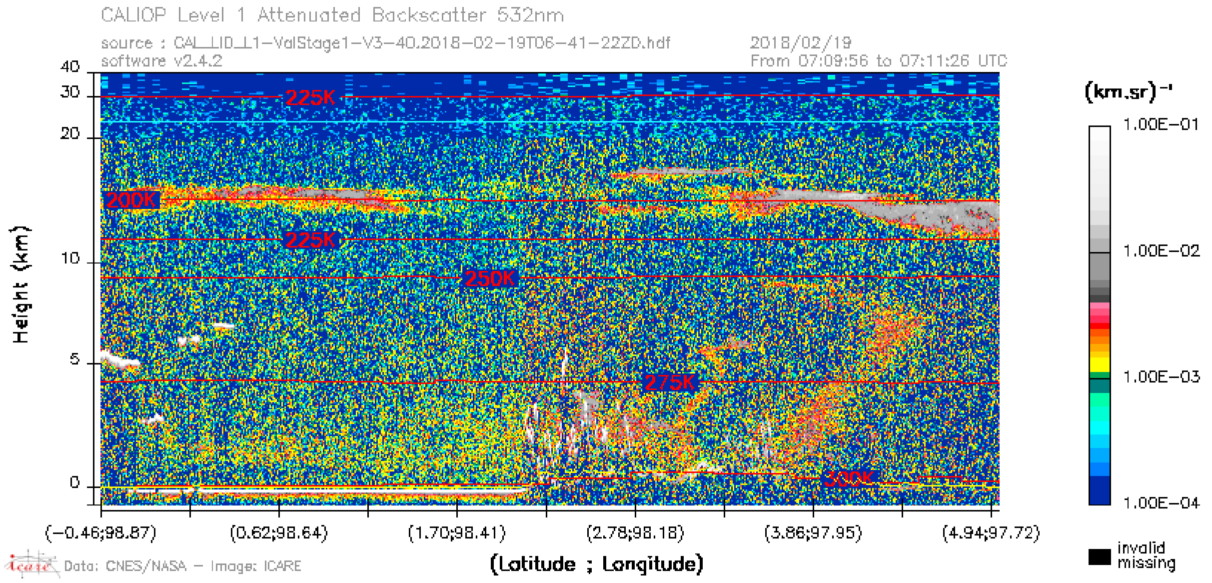
P5, Sect. 2.5: I suggest to add more information on CALIOP, references and a description of what the 'attenuated backscatter imagery' displays, i.e. what it is sensitive to, etc. I also propose to also add the VFM, which shows the type of absorption feature as well as the BTD which gives information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

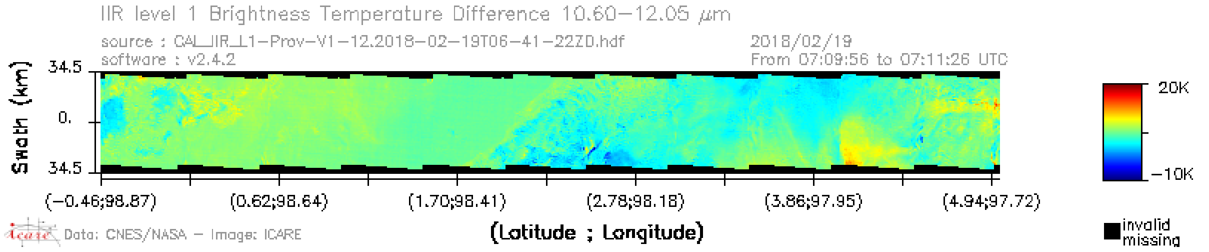
- *we added the following to section 1.5*

  "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*

Analysis of properties of the 19 February 2018 volcanic eruption of Mount Sinabung in S5P/TROPOMI and ~~Himawari~~HIMAWARI-8 satellite data

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Formatted: English (United States)

Abstract. This study presents an analysis of TROPOMI cloud heights as a proxy for volcanic plume heights in the presence of absorbing aerosols and sulfur dioxide for the 19 February 2018 eruption plume of the Sinabung volcano on Sumatra, Indonesia.

Comparison with CALIPSO satellite data shows that all three TROPOMI cloud height data products based on oxygen absorption which are considered here (FRESCO, ROCINN, O22CLD) provide volcanic ash cloud heights comparable to heights measured by CALIPSO for optically thick volcanic ash clouds. FRESCO and ROCINN heights are very similar with only differences for FRESCO cloud top heights above 14 km altitude. O22CLD cloud top heights unsurprisingly fall below those of FRESCO and ROCINN, as the O22CLD retrieval is less sensitive to cloud top heights above 10 km altitude. For optically thin volcanic ash clouds, *i.e.* when Earth's surface or clouds at lower altitudes shine through the volcanic ash cloud, retrieved heights fall below the volcanic ash cloud heights derived from CALIPSO data.

Evaluation of corresponding ~~Himawari~~HIMAWARI-8 geostationary ~~volcanic ash height retrievals based on~~ InfraRed (IR) brightness temperature differences (ΔBT) - a signature for detection of volcanic ash clouds in geostationary satellite data and widely used as input for quantitative volcanic ash cloud retrievals - reveals that for this particular eruption the ΔBT volcanic ash signature ~~– widely used for detection of volcanic ash in geostationary satellite data –~~ changes to a ΔBT ice crystal signature for the part of the ash plume reaching the upper troposphere beyond 10 km altitude several hours after the start of the eruption and which TROPOMI clearly characterizes as volcanic (SO_2 > 1 DU and AAI > 4 or more conservatively SO_2 > 10). The presence of ice in volcanic ash clouds is known to prevent the detection of volcanic ash clouds based on broadband geostationary satellite data. TROPOMI does not suffer from this effect, and can provide valuable and accurate information about volcanic ash clouds and ash top heights in cases where commonly used geostationary IR measurements of volcanic ash clouds fail.

1 Introduction

Monitoring airborne volcanic ash is of crucial importance for aviation planning, as volcanic ash is an environmental hazard that can cause damage to avionics systems, abrasion of exposed airframe parts, engine damage, and even engine failure

[Prata and Rose, 2015]. From early 1980s onwards there have been several well-documented damaging encounters of (jet) aircraft with volcanic ash ~~plumes~~clouds. Since then, aviation authorities have set up working groups and task forces to develop guidelines, procedures, and rules, on what to do in case of known or predicted volcanic ash [i.e. ICAO, 2012]. The advance of satellite remote sensing techniques in the early 2000s allowed for real-time global monitoring of volcanic eruptions and airborne volcanic ash and sulfur dioxide (SO_2), like the Support to Aviation Control Service - SACS [http://sacs.aeronomie.be; Brenot et al., 2014] or the NOAA/CIMSS Volcanic Cloud Monitoring platform [https://volcano.ssec.wisc.edu/]. Nevertheless, in 2010, an eruption of the Icelandic volcano Eyjafjallajökull resulted in the closure of most of the European air space, stranding more than 8.5 million people and profoundly affecting commerce [Alexander, 2013]. The total economic damage was estimated at 2.2 billion $US [Oxford Economics, 2010]. In the aftermath of the 2010 eruption of Eyjafjallajökull, aviation authorities were quick to realize that aviation guidelines for volcanic ash avoidance were too strict. Since then, guidelines have been updated [ICAO, 2012], allowing for more flexibility for aircraft to maneuver around volcanic ash clouds and giving airliners more responsibility. Furthermore, it was also recommended to further develop global real-time volcanic eruption and volcanic ash cloud monitoring services. Ongoing programs by ICAO and WMO continue to work on improving volcanic ash cloud satellite data products that can be used for real-time monitoring of volcanic eruptions and volcanic ash clouds, as well as for tactical and strategic flight planning [ICAO, 2012; WMO SCOPE, 2015, 2018].

However, despite the clear need for constant monitoring of volcanic eruptions and volcanic ash clouds, and despite the availability of a wide variety of satellite remote sensing data products to meet that particular need, a centralized facility to access and analyze all available remote sensing data on volcanic eruptions and volcanic ash clouds is still lacking. This strongly hampers integration of that information into aviation operations. As a consequence, volcanic eruptions continue to pose a larger than necessary risk for aviation.

In order to fill this information gap, the European Union funded the EUNADICS-AV project by the European Union's Horizon 2020 research program for "Societal challenges - smart, green and integrated transport". The main objective of EUNADICS-AV is "to close the significant gap in European-wide data and information availability during airborne hazards". Volcanic ~~clouds~~ ash clouds are one of those airborne hazards. An important aspect of EUNADICS-AV is to verify how well various satellite instrument are capable of monitoring volcanic eruptions and volcanic ~~clouds~~ash clouds, and how to integrate various satellite data products on board a variety of satellites. This requires integrated analyses of volcanic ~~clouds~~ ash clouds with the current suite of satellites and remote sensing data.

For more than a decade, satellite instruments ~~like~~ such as SCIAMACHY, OMI, GOME-2, OMPS, AIRS, and IASI, have been used to monitor volcanic eruptions in support of aviation. Measurements of SO_2 and the absorbing aerosol index (AAI) are currently provided in near-real-time (within 3 hours after the satellite spectral measurements) to the aviation community via the SACS web-portal, which builds on the TEMIS project, which in 2003 provided the first web-based service that allowed to browse and download atmospheric satellite data products, also funded by ESA.

On 13 October 2017, ESA successfully launched the TROPOMI instrument as the single payload of ESA’s S5P satellite [Veefkind et al., 2012]. TROPOMI is a grating spectrometer that measures Earth reflected radiances in the ultraviolet, visible, near infrared (NIR), and shortwave infrared (SWIR) parts of the spectrum, building on the legacy provided by the satellite instruments OMI and SCIAMACHY. Already a few weeks after launch, TROPOMI started to provide promising high spatial resolution measurements (down to 3.5×7 km^2) of SO$_2$, the AAI, and cloud heights from various retrieval algorithms (FRESCO, O22CLD, ROCINN).

Compared to its predecessors, TROPOMI provides measurements with a better signal-to-noise ratio and much better spatial resolution (factor 10 or more, depending on the satellite that is compared with). This allows for a much better and more detailed characterization of volcanic ~~clouds~~ash and SO$_2$ plumes. Furthermore, due to a better spatial resolution and better instrumental signal-to-noise, TROPOMI is expected to provide improved height retrievals~~s~~ of volcanic ash clouds and volcanic SO$_2$~~clouds~~, ~~an~~ important parameter ~~for volcanic cloud~~ monitoring purposes [WMO SCOPE, 2015].

On 19 February 2018, 08:53 local time, the Indonesian volcano Mount Sinabung on Sumatra generated a dark gray plume with a high volume of ash that quickly rose to an estimated 15-17 km above sea level, according to the Darwin Volcanic Ash Advisory Center (VAAC). Ash plumes were identified in satellite images, recorded by webcams and smartphones, and widely shared on social media, also because of the time of the eruption (early morning) and the clear skies at that time. The event was possibly the largest since the beginning of the current episode of unrest at Sinabung, which started in September 2013 [https://volcano.si.edu/volcano.cfm?vn=261080; Eruptive History~~Smithsonian Institute, 2019~~].

Mount Sinabung is located in Karo Regency, North Sumatra Province (03°10′ North, 98°23.5′ East, with a height of 2460 m a.s.l. [Hendrasto et al., 2012; Primulyana et al. 2017; Smithsonian Institute, Global Volcanism Program, 2019]. The stratovolcano had been dormant for more than 1200 years before it became active again in 2010, and especially since 2013 small eruptions have occurred regularly.

The 19 February 2018 Sinabung eruption provides one of the first possibilities to study the quality of TROPOMI data for volcanic cloud monitoring, also because there was a fortunate overpass of the CALIOP instrument on the ~~Calipso~~ CALIPSO satellite. CALIPSO~~, which~~ 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 13:30 local solar time, within seconds to minutes of each other along the same or a very similar orbital “track”. ~~.~~The TROPOMI equator crossing time ~~of 13:30~~ is comparable to those of satellites in the A-train constellation.

In this paper, we evaluate satellite measurements of the 19 February 2018 Sinabung eruption with a particular focus on determining volcanic ash cloud heights ~~from~~ combining TROPOMI AAI data with TROPOMI cloud height data. We also characterize the volcanic eruption plume in TROPOMI data, as well as compare TROPOMI data with geostationary HIMAWARI-8 satellite infrared data that are widely used for volcanic ash cloud detection. TROPOMI-based volcanic ash cloud heights are also compared with measurements from the CALIPSO satellite overpass.

2. Data

2.1 TROPOMI AAI

The AAI is a well-established data product that has been produced for several different satellite instruments spanning a period of more than 30 years. The AAI was first calculated as a correction for the presence of aerosols in column ozone measurements made by the TOMS instruments [Herman et al., 1997; Torres et al., 1998], because it was observed that ozone values were too high in typical regions of aerosol emission and transport. The AAI is based on spectral contrast in the ultraviolet (UV) spectral range for a given wavelength pair, where the difference between the observed reflectance and the modeled clear-sky reflectance results in a residual value. When this residual is positive it indicates the presence of UV-absorbing aerosols, like dust, smoke, or volcanic ash. Clouds yield near-zero residual values and negative residual values can be indicative of the presence of non-absorbing aerosols (e.g. sulphate), as shown by sensitivity studies of the AAI [e.g. de Graaf et al., 2005, Penning de Vries et al., 2009]. Unlike satellite-based aerosol optical thickness measurements, the AAI can also be calculated in the presence of clouds, so that daily global coverage is possible. This is ideal for tracking the evolution of episodic aerosol plumes from dust outbreaks, volcanic eruptions, and biomass burning. For this study, we use the TROPOMI AAI data for the wavelength pair 340-380 nm. For more details about the TROPOMI AAI retrieval algorithm, see Stein-Zweers [2016].

2.2 TROPOMI SO_2

Since the late 1970s, a large number of UV-visible satellite instruments have been used for monitoring anthropogenic and volcanic SO_2 emissions. In some cases, operational SO_2 retrieval streams have also been developed aiming to deliver SO_2 vertical column densities (VCD) in near real-time (NRT), i.e. typically with a delay of less than 3 hours.

The TROPOMI SO_2 retrieval algorithm is based on the DOAS technique [BIRA, 2016; Theys et al., 2017]. In brief, the log-ratio of the observed UV-visible spectrum, of radiation backscattered from the atmosphere, and an observed reference spectrum (solar or earthshine spectrum) is used to derive a slant column density (SCD), which represents the SO_2 concentration integrated along the mean light path through the atmosphere. This is done by fitting absorption cross-sections of SO_2 to the measured reflectance in a given spectral interval. In a second step, slant columns are corrected for possible biases. Finally, the slant columns are converted into vertical columns by means of air mass factors (AMF) obtained from radiative transfer calculations, accounting for the viewing geometry, clouds, surface properties, total ozone, and SO_2 vertical profile shapes. 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 data product.

2.3 TROPOMI cloud information

TROPOMI provides information about cloud properties by use of oxygen absorption in either the O_2A-band around 760 nm or the O_2-O_2 band around 477 nm [Veefkind et al., 2016]. In this study, we use the TROPOMI operational ROCINN cloud height [Loyola et al., 2018; Cloud as Reflecting Boundaries or CRB model] and FRESCO cloud height [Wang et al., 2008, Wang et al., 2012], both based on the O2-A-band, as well as off-line cloud height from the O22CLD algorithm based using the O_2-O_2– band [Veefkind et al., 2016]. Note that TROPOMI operational cloud fractions are derived from the OCRA algorithm [Loyola et al., 2018]. Both the FRESCO cloud height and the O_2-O_2- cloud height are based on a Lambertian cloud model. Therefore, the retrieved cloud height is the cloud mid-level rather than the cloud top [Wang et al., 2008, Sneep et al., 2012]. Note that because the current TROPOMI surface albedo databases – which rely on OMI data - are not fully representative for the TROPOMI spatial resolution and/or wavelengths, which results in inaccurate or unrealistic cloud retrievals which are flagged as missing data. It is expected that the coming years a surface albedo database will be developed based on the TROPOMI measurements itself, which should solve these retrieval artefacts.

2.4 ~~HIMAWARI~~HIMAWARI-8 AHI

The Advanced HIMAWARI-8 Imager (AHI) is a geostationary satellite imager with 16 broad-band spectral channels from the visible to infrared portion of the electromagnetic spectrum between 0.46 μm and 13.3 μm. The sub-satellite spatial resolution of AHI is 1 km for all-but-one VIS channels and 2 km for IR channels. The ~~HIMAWARI~~HIMAWARI-8 AHI is a multipurpose imager that provides full-disk scans of Earth every 10 minutes from a geostationary orbit at 140.7°E. The imagery can be used for a variety of applications, including general environmental monitoring (e.g. cloud-tracked winds) and numerical weather prediction [Bessho et al. 2016]. For the detection of volcanic ash clouds, results from an ad-hoc version of the VADUGS algorithm are used [Graf et al., 2015]. The VADUGS algorithm is a neural-network based on a large number of radiative transfer simulations of geostationary infrared brightness temperatures, and retrieves the column mass loading (kg/m^2) and the top altitude of volcanic ash ~~layers~~clouds. VADUGS was initially developed for SEVIRI/MSG, it has been adapted to ~~HIMAWARI~~HIMAWARI-8 for the purpose of this paper. VADUGS uses the 10.8-12.0 μm channel brightness temperature difference (ΔBT) for geostationary IR volcanic ash clouds retrieval algorithms. The use of this particular ΔBT is common practice [Prata, 1989], with negative ΔBT potentially indicating volcanic ash, and positive ΔBTs indicative of the presence of nontrivial liquid water or ice content [Pavolonis et al., 2006].

2.5 CALIOP

The CALIOP lidar on board of the CALIPSO platform delivers global cloud and aerosol information. The vertical resolution of atmospheric profiles is high with 30-300m, but the horizontal sampling is poor, as the satellite is in a low-altitude earth orbit with a 16- day repeated cycle and the horizontal resolution is only 330 m to 5 km [Winker et al., 2007, 2009]. In this study, we use 532 nm total attenuated backscatter (TAB) ~~imagery~~ data from one CALIPSO orbit (data version 3.40) in a qualitative approach, *i.e.* detection of cloud and aerosol layers and their heights. 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.

3. Results

3.1 Brief description of the spatiotemporal evolution of the volcanic ash cloud

The analysis of ~~HIMAWARI~~HIMAWARI-8 AHI IR brightness temperatures and IR-based volcanic ash cloud heights from CIMSS (Supplementary Information SI figure S1) shows that 19 February 2018 Sinabung eruption consisted of two distinct ash plumes. The initial eruption quickly reached the upper tropical troposphere (14-16 km altitude), after which the volcanic ash cloud was transported in a north/northwesterly direction. These heights are consistent with results the recently introduced new TROPOMI SO_2 height data product [Hedelt et al., 2019]. Approximately two hours after the start of the eruption the satellite data shows lower-altitude volcanic ash cloud ΔBT signatures (up to 6-8 km altitude) emerging from under the high altitude volcanic ash cloud at both the northwest and southeast end of the high altitude ~~plume~~volcanic ash cloud. As these lower altitude plumes also move more or less in opposite direction, they more likely reflect remnants of surface pyroclastic flows and/or the eruption column collapse that are also seen in the time-lapse webcam video footage on the internet (https://youtu.be/v45J5BO_ge0).

3.2 TROPOMI

Figure 1A shows the TROPOMI FRESCO cloud height and ~~cloud fraction~~ROCINN cloud pressure, along with the TROPOMI AAI, and the AAI = 0 contour and the SO_2 = 10 Dobson Unit (DU) contour, with TROPOMI measurements within the figure area made at approximately 06:25 UTC~~, which coincides with an approximate local time of 06:25 UTC~~, and 4.5 hours after the start of the eruption. By then, the volcanic plume has dispersed over an area with an approximate diameter of 200 km, while some parts of the volcanic ash cloud have sufficiently thinned so that cumulus clouds lower down in the atmosphere can be identified in VIIRS imagery (see SI figure S2; note that TROPOMI flies in a so-called loose formation with VIIRS, with a temporal separation between both of less than 5 minutes). The AAI and SO_2 contours agree well with the ~~extent~~ cloud structure associated with ~~of~~ the volcanic plume, indicating there has not been a spatial separation between ~~aerosols~~ volcanic ash and SO_2, which is known to sometimes happen in volcanic eruptions [Cooke et al., 2014; Moxnes et al., 2014; Prata et al., 2017]. Guided by the AAI and SO_2 contour lines, the ash cloud can be identified in the FRESCO cloud height and ROCINN cloud – in particular for cloud tops above 10 km ~~-~~– as well as in the ROCINN and O22CLD scene pressures (figure 1B), but not in the FRESCO cloud fraction (figure 1B), probably because of light absorption by ash. Comparing the cloud height with the VIIRS reflectances (SI figure S2), the volcanic plume altitudes occur where the ash cloud is sufficiently optically thick to not show the underlying surface and clouds.

All cloud height products show the same spatial structure with the highest clouds in the northern half of the ash plume. The FRESCO and ROCINN cloud heights are rather similar. However, there are also clear differences. ~~The~~ In general, FRESCO cloud heights are ~~systematically~~ higher than the O22CLD cloud heights (figure 1B). The O22CLD data product is based on absorption of the O_2-O_2 ~~–~~complex, and is less sensitive to high altitude clouds as concentrations of the O_2-O_2 complex decrease strongly above approximately 10 km altitude [Acarreta et al., 2004]. The O22CLD algorithm is therefore computationally limited to a maximum cloud top pressures of 150 hPa (~13) km. FRESCO and ROCINN are based on absorption of O_2, whose concentrations decrease much slower above 10 km altitude. The FRESCO and ROCINN cloud heights can therefore be used up to approximately 17~~5~~ km altitude (~100 hPa) [Wang et al., 2012]. The lower cloud height of O22CLD vs FRESCO/ROCINN is thus most likely due to the lower sensitivity of O22CLD for high clouds. 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.

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3.3 CALIOP

Although the 19 February 2018 Sinabung eruption was small in spatial extent and rather short-lived, by mere accident there was a perfect overpass with the CALIOP instrument in the A-train constellation (see Figure 1). The CALIOP track goes straight through the core of the volcanic ash cloud and across the north-south gradient in cloud tops.

Figure 2 shows the CALIOP backscatter signal at 532 nm overlaid with the TROPOMI FRESCO cloud heights, which are color coded according to the corresponding AAI values. 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. The CALIOP data clearly shows a cloud/ash layer around 15 km altitude, but also two cloud/ash structures extending from the ground up to approximately 10 km altitude, with an increase in height going from south to north. There is also a layer detected in CALIPSO at 18 km around 3°N, which likely is also volcanic as the HIMAWARI-8 BT does not provide any indication of other high clouds while there are negative ΔBTs near the CALIPSO track at 3°N, indicative of the presence of volcanic ash.

There is a good agreement between the location of enhanced TROPOMI AAI values, FRESCO cloud height, and the altitude of high backscatter signal in the CALIOP data. The maximum cloud height in FRESCO agrees with the maximum backscatter height in CALIOP between 4° and 5° latitude. Between 3° and 4° latitude, the agreement is poor as the FRESCO cloud height fall right in between the CALIOP backscatter data ~~around~~ between 13-18~~15~~ km altitude and those close to the surface. The CALIOP data also suggests that backscatter signals between 3° and 4° latitude are weaker than between 4° and 5° latitude, which might indicate less dense ash or clouds. For a semi-transparent cloud/ash plume it could be expected that FRESCO cloud heights are lower than the actual height of the cloud/ash plume due the presence of bright clouds nearer to the surface. Note that CALIOP's own feature mask ~~-~~does not identify ~~any~~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].

Figure 3 shows the corresponding cloud heights from the O22CLD and ROCINN algorithms. The ROCINN cloud height is very similar to the FRESCO cloud height (R^2 = 0.98 for FRESCO cloud heights between 0.5 and 14 km regardless of corresponding AAI value). The only difference occurs for FRESCO cloud heights > 14 km where the ROCINN cloud height appears to be nearly constant. For the O22CLD data the maximum heights are on average lower than the FRESCO/ROCINN cloud heights. The lower cloud height of the O22CLD product is likely related to the reduced sensitivity of O22CLD for clouds above approximately 10 km altitude. Nevertheless, all products clearly indicate volcanic cloud heights of 10 km and higher, with the largest heights between 4° and 5° latitude, consistent with the CALIOP observation that backscatter signals between 3° and 4° latitude are weaker than between 4° and 5° latitude~~and all data products increasing heights in the volcanic cloud going from south to north~~.

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Although the CALIOP overpass is perfect in space, the time difference between TROPOMI and CALIOP of approximately 45 minutes is not insignificant. It is therefore unlikely that TROPOMI and CALIOP ash layers and structures exactly match. The flow direction of the volcanic ash ~~plume~~ cloud was northwards, which means that CALIOP should also be displaced north compared to TROPOMI. A rough estimate of northward cloud motion based on the geostationary satellite data indicates that the displacement may be approximately 0.5°/hour, which makes it not unreasonable to assume that some of the discrepancies between TROPOMI and CALIOP could also be related to the differences in observation time. Furthermore, volcanic eruption plumes have their own dynamics, with for example pyroclastic flows near the surface which appear to travel partly in the opposite direction of the background flow. The eruption dynamics may thus have additional effects on the ash plume displacement, for which time series of the complete 3-dimensional view of the eruption plume would be preferred. ~~but this cannot be investigated based on the a~~The current available satellite data only provide a 2-dimensional view of the eruption plume from above (geostationary, Polar orbiting), with information about changes over time in case of the geostationary satellites and with some but limited information about cloud and aerosol height. CALIOP measurements only provide one 2-dimensional cross-section through the eruption plume, without any information about changes over time.

3.4 ~~HIMAWARI~~HIMAWARI-8

The temporal evolution of the ash plume wa~~i~~s further investigated using ~~Himawari~~HIMAWARI-8 geostationary IR observations. Figure 4 shows the ~~HIMAWARI~~HIMAWARI-8 10.8-12.0 μm channel ~~brightness temperature differences~~ (ΔBT) as observed between 02:30 UTC and 07:30 UTC in hourly intervals, including the TROPOMI SO_2/AAI contours shown in Figure 1. ~~The 10.8-12.0 μm channel ΔBT is the basis for geostationary IR volcanic ash retrieval algorithms [Prata, 1989], with negative ΔBT potentially indicating volcanic ash, and positive ΔBTs indicative of the presence of ice.~~

During the first few hours (02:30-03:30), the ash plume is clearly visible both in the ΔBTs (reddish colors) and cloud heights (whites). At 03:30 UTC, two distinct clouds have emerged with fairly negative ΔBTs: one associated also with a high cloud height (white cloud colors), and another one further south with much lower cloud heights, likely low-altitude outflow or pyroclastic flows (blue cloud colors). From 04:30 UTC onwards, a third region becomes visible with high cloud heights and large positive ΔBTs (purple), ~~more reminiscent~~indicative of ~~dense~~ high ice clouds~~. This ‘purple’ region~~, which continues to grow and expand northward~~.~~.

Figure 5 shows a comparison of TROPOMI AAI and SO_2 data with regridded ~~HIMAWARI~~HIMAWARI-8 ~~VADUGS~~ ΔBTs (upper left plot). When focusing on AAI and SO_2 values, it appears that larger ΔBT values occur for smaller AAI values (< 2) and SO_2 columns (< 20 DU). The largest~~r~~ positive ΔBT are ~~also~~ associated with optically ~~more dense~~thicker/less transparent water and ice clouds (see also VIIRS imagery in the SI and comparison of TROPOMI with CALIPSO). The lack of larger AAI and SO_2 values for larger positive ΔBT values therefore may reflect some kind of shielding of the volcanic ash and SO_2 by the iced upper levels of the volcanic ash cloud.~~,~~ ~~or~~ SO_2 may have been converted into sulphate as the SO depletion rate (e-folding time), which, although uncertain, has been estimated to be as small as 5-30 minutes [Oppenheimer et al., 1998; McGonigle et al., 2004], scavenged~~.~~ by ice [Rose et al., 2000], or via ice nucleation of volcanic ash particles [Durant et al., 2008]. For negative ΔBTs – indicative of volcanic ash clouds – we also find little evidence of a distinctive relation between either the AAI and SO_2 with ΔBTs. This may similarly reflect a shielding effect, as the largest ΔBTs do not occur for the largest aerosol concentrations [*e.g.* Prata and Prata, 2012; Pavolonis et al., 2016].

The emergence of an IR ice/water cloud signature within the volcanic ash cloud is consistent with analysis of available video footage and pictures on social media that show signs of condensation within the ash clouds soon after the start of the eruption. This is indicative of a moist troposphere in this area, which is further supported by the widespread development of (late) afternoon thunderstorms on 19 February throughout Sumatra. The eruption thus caused an increase in high altitude water vapor, either by moisture contained in the eruption itself or by the rapid vertical motions within the eruption column. The results presented here support the notion that the IR volcanic ash cloud ΔBT signature disappears when condensed water vapor or ice forms in a volcanic ash cloud, which are known to significantly hamper IR volcanic ash cloud retrievals [Francis et al., 2012; Pavolonis et al., 2015a, 2015b~~3~~; Zhu et al., 2017].

4. Discussion and conclusions

Analysis of measurements from the ~~recently launched~~ polar orbiting TROPOMI satellite - with unprecedented spatial resolution and accuracy – of the volcanic eruption of Mount Sinabung on Sumatra on 19 February 2018, has revealed that the combination of TROPOMI AAI and TROPOMI SO_2 allows for accurate identification of the volcanic ash ~~plume~~ cloud location. In addition, under the condition that the ash plume is sufficiently thick so that clouds and the Earth surface below the ash cloud are not visible, TROPOMI cloud heights also provide accurate information about the volcanic ash cloud heights. The TROPOMI FRESCO and ROCINN cloud heights agree with CALIOP cloud top measurements for optically thick volcanic ash clouds. In passing we note that the unprecedented spatial resolution of TROPOMI allows for detection of much smaller eruptions than is currently possible with polar orbiting satellite instruments like OMPS, GOME-2, and OMI. Also note that it could be argued that it would be better to use the TROPOMI SO_2 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.

Comparison with CALIOP ~~geostationary IR volcanic ash~~ aerosol and cloud heights provides clear indications that ash height estimates using cloud heights and AAI values from UV/VIS satellites like TROPOMI may underestimate actual ash heights in case of semi-transparent volcanic ash clouds, especially in the presence of high concentrations of water vapour and for very high altitude volcanic ash clouds. For optically thin(ner) volcanic ash clouds the TROPOMI cloud heights are a weighted mean of the ash height and heights of other clouds or the surface, and may therefore be less useful for volcanic ash cloud height monitoring purposes. Some discrepancies between TROPOMI and CALIPSO may be related due to misalignment in observation times of both satellite instruments (~ 45 minutes). In addition, indications were found of shielding of ~~the~~ volcanic ash ~~plume~~ by this ice/water near top of the volcanic ash cloud.

There are also clear indications in the geostationary IR data of the formation of water/ice near the top of the volcanic ash cloud. The analysis of geostationary satellite data for this particular case revealed that under conditions of volcanic ash mixed with ice of condensed water, the geostationary IR volcanic ash cloud ΔBT signature is lost and geostationary volcanic ash cloud retrievals cannot identify crucial parts of the ash plume. It is worth mentioning that the temporal resolution inherent to the geostationary orbit allows the observation of the onset and evolution of the plume, even in adverse conditions for ~~the~~ IR volcanic ash cloud retrieval algorithm.

Polar orbiting satellites like TROPOMI thus may be better able to detect volcanic ~~clouds~~ ash when condensed ice/water is present in volcanic plumes, in particular when synergistically combining different satellite data products like the AAI and SO_2. Furthermore, ΔBT appears not to be a good indicator of either large AAI values or large SO_2 columns. This is not surprising as ΔBT is not a good indicator for ash optical depth [*e.g.,* Prata and Prata, 2012; Pavolonis et al., 2016]. Our results therefore highlight that there is added value in combining IR ΔBT with UV/VIS AAI and SO_2. Satellite measurements like those from TROPOMI measurements thus can add significant value to geostationary IR volcanic ash cloud retrievals. Furthermore, in case of sufficiently dense ash ~~volcanic clouds~~, the cloud height data products provide accurate volcanic ash cloud heights, an important piece of information for aviation. For semi-transparent volcanic ash clouds, where the cloud top height retrievals become sensitive to other reflective surfaces below the transparent volcanic ash clouds, detection of accurate volcanic ash cloud heights is limited.

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Hence, for AAI values larger than 4, TROPOMI cloud heights can be used for determining aerosol heights ~~for AAI values larger than 4~~, and in case also SO_2 is detected such measurements should be interpreted as also containing volcanic ash (column values > 1 DU [Theys et al., 2017]). For more conservative estimates SO_2 column values > 10 could be considered. This AAI threshold value of 4 may be conservative but ensures that the aerosol layer very likely is opaque, as generally the associated aerosol optical depth will be (much) larger than on [de Graaf et al., 2005].. The combination of UV/VIS cloud heights, AAI and SO_2 could also be used for other UV/VIS satellites like GOME-2, OMPS, and OMI. These results highlight the importance of the integrated use of multiple (satellite) data sources for the detection and characterization of volcanic ash clouds, in particular for aviation purposes. This has been recognized by the European Union and is being further developed within the H2020 project EUNADICS-AV (http://www.eunadics.eu).

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Glossary

AAI	- Absorbing Aerosol Index
AIRS	- Atmospheric InfraRed Sounder
AMF	- Air Mass Factor
AHI	- Advanced Himawari Imager
BIRA	- Belgian Institute for Space Aeronomy
ΔBT	- Brightness Temperature Difference
CALIOP	- Cloud-Aerosol Lidar with Orthogonal Polarization
CALIPSO	- Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations
CIMSS	- Cooperative Institute for Meteorological Satellite Studies
DOAS	- Differential Optical Absorption Spectroscopy
DU	- Dobson Unit
ESA	- European Space Agency
EUNADICS-AV	- European Natural Airborne Disaster Information and Coordination System for AViation
FRESCO	- Fast Retrieval Scheme for Clouds from the Oxygen A-band
GOME-2	- Global Ozone Monitoring Experiment 2
ICAO	- International Civil Aviation Organization
IASI	- Infrared atmospheric sounding interferometer
IR	- InfraRed
NOAA	- National Oceanic and Atmospheric Administration
NRT	- Near Real Time
OCRA	- Optical Cloud Recognition Algorithm
OMI	- Ozone Monitoring Instrument
OMPS	- Ozone Mapping Profiler Suite
O22CLD	- ~~O_2-O_2~~ O_2-O_2- cloud
ROCINN	- Retrieval Of Cloud Information using Neural Networks
SACS	- Support for Aviation Control Service
SCD	- Slant Column Density
SCIAMACHY	- SCanning Imaging Absorption SpectroMeter for Atmospheric ChartographY
SCOPE	- Sustained, Coordinated Processing of Environmental satellite data for nowcasting
SI	- Supplementary Information
SO_2	- Sulfur dioxide
SUOMI-NPP	- Suomi National Polar-orbiting Partnership
S5P	- Sentinel-5 Precursor

TAB - Total Attenuated Backscatter
TEMIS - Tropospheric Emission Monitoring Internet Service
TOMS - Total Ozone Mapping Spectrometer
TROPOMI - TROPOspheric Monitoring Instrument
UTC - Universal Time Coordinate
UV - UltraViolet
VAAC - Volcanic Ash Advisory Center
VADUGS - Volcanic Ash Detection Using Geostationary Satellites.
VCD - Vertical Column Density
VIS - Visible
VIIRS - Visible Infrared Imaging Radiometer Suite
WMO - World Meteorological Organization

Figures

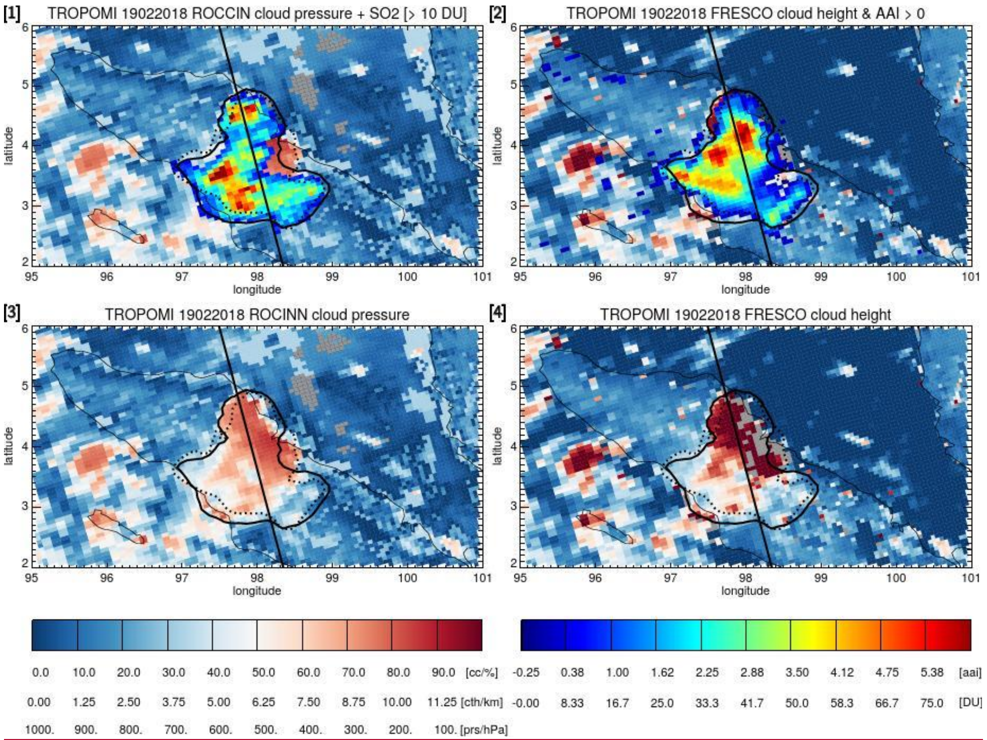


Figure 1A. TROPOMI cloud ~~heights~~pressure (ROCINN, panels [1] + [3]), ~~cloud fraction~~ and TROPOMI FRESCO cloud heights (panels [2] + [4]). TROPOMI SO_2 (panel [1~~A~~]) and the AAI (panel [2~~B~~]) for the overpass of the 19 February 2018 Sinabung eruption. The straight line denotes the path of the CALIPSO overpass, the solid line shape denotes the outline of > 10 DU SO_2 columns, the dotted line shape denotes the AAI > 0 value. ~~ROCINN cloud height is shown in panels A+E, FRESCO cloud heights in panels B+C, FRESCO cloud fraction in panel D, and O22CLD cloud heights in panel F.~~ Note that for FRESCO and ROCINN cloud heights certain pixels are greyed out ("no data"), related to yet unresolved retrieval artefacts.

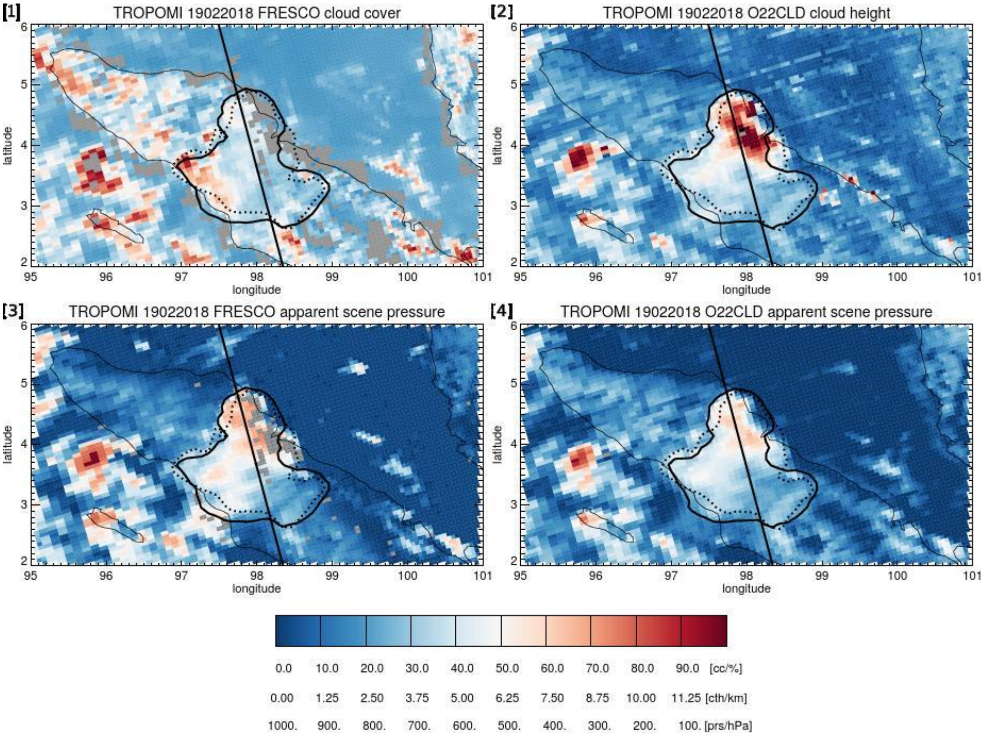
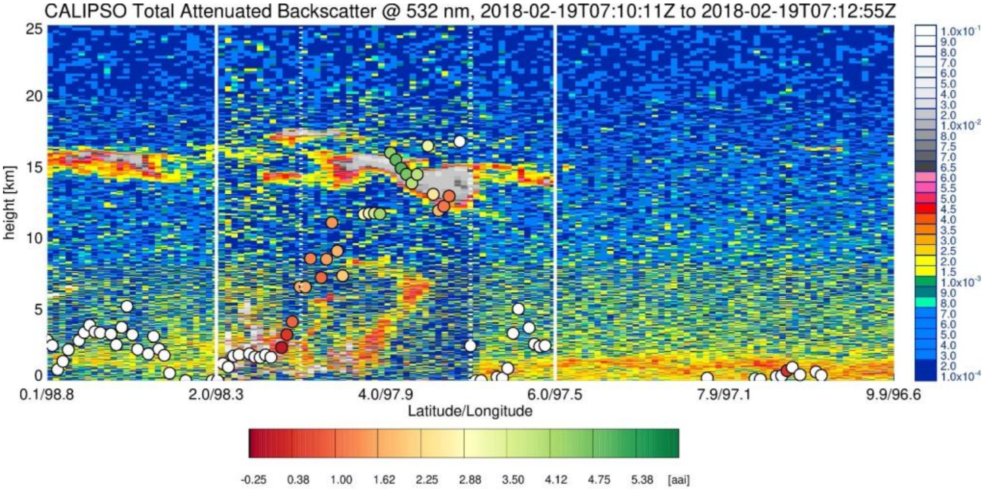


Figure 1B. As figure 1A but for TROPOMI FRESCO cloud cover (panel [1]), O22CLD cloud height (panel [2]), FRESCO apparent scene pressure (panel [3]) and O22CLD apparent scene pressure (panel [4].



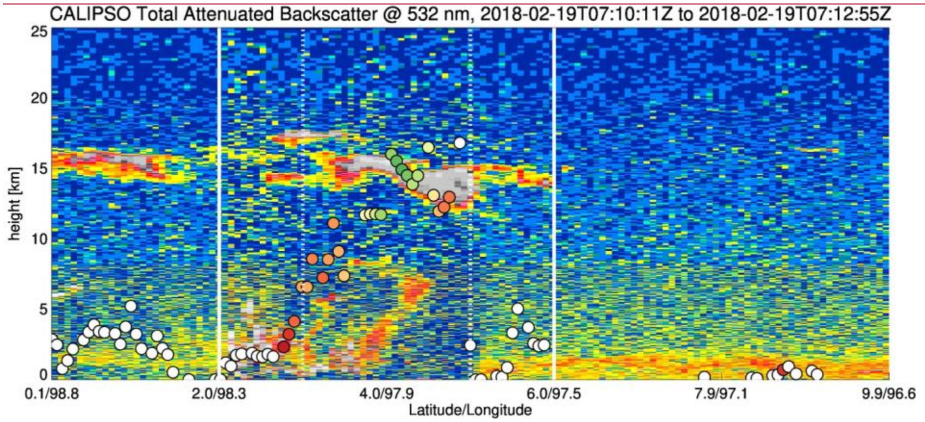
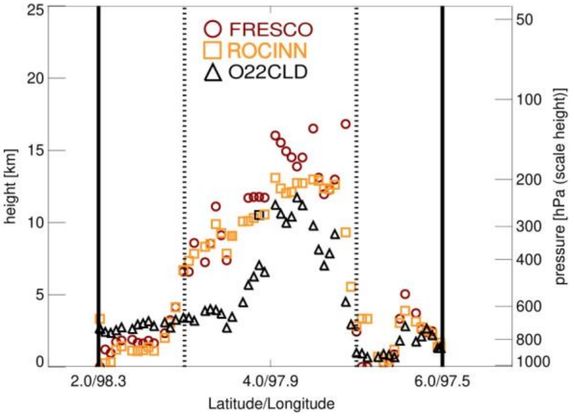


Figure 2. CALIOP total attenuated backscatter profile for the Sinabung eruption on 19 February 2018 along the track indicated in Figure 1. The circles denote the TROPOMI FRESCO cloud heights, color coded according to the TROPOMI AAI values as in figure 1. White dots indicate AAI values < 0.



510 **Figure 3.** TROPOMI cloud heights from the FRESCO, ROCINN and O22CLD algorithms. The solid vertical lines denote the 2°N and 6°N latitudes, the dotted vertical lines the 3° and 5° latitudes. The FRESCO data is identical to the FRESCO data shown figure 2.

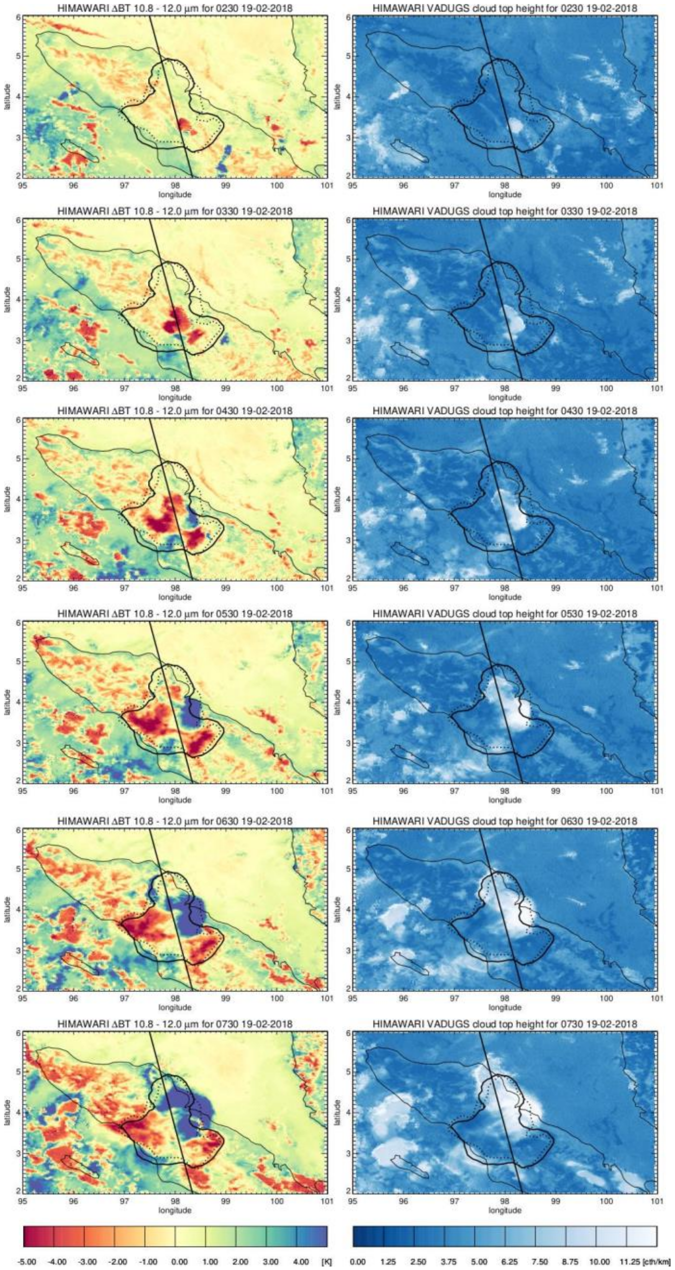
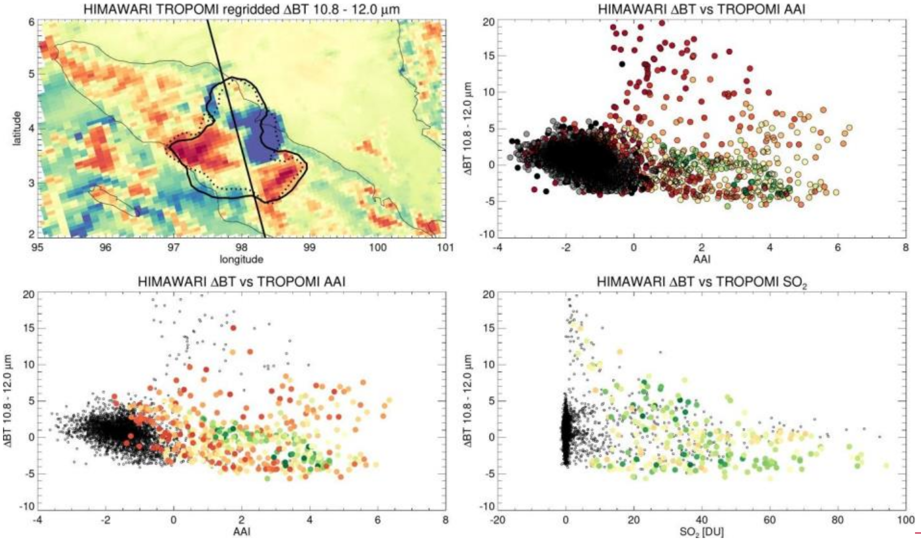

HIMAWARI ΔBT 10.8 - 12.0 μm for 0230 19-02-2018
HIMAWARI VADUGS cloud top height for 0230 19-02-2018
HIMAWARI ΔBT 10.8 - 12.0 μm for 0330 19-02-2018
HIMAWARI VADUGS cloud top height for 0330 19-02-2018
HIMAWARI ΔBT 10.8 - 12.0 μm for 0430 19-02-2018
HIMAWARI VADUGS cloud top height for 0430 19-02-2018
HIMAWARI ΔBT 10.8 - 12.0 μm for 0530 19-02-2018
HIMAWARI VADUGS cloud top height for 0530 19-02-2018
HIMAWARI ΔBT 10.8 - 12.0 μm for 0630 19-02-2018
HIMAWARI VADUGS cloud top height for 0630 19-02-2018
HIMAWARI ΔBT 10.8 - 12.0 μm for 0730 19-02-2018
HIMAWARI VADUGS cloud top height for 0730 19-02-2018
latitude
longitude
2
3
4
5
6
95
96
97
98
99
100
101
-5.00 -4.00 -3.00 -2.00 -1.00 0.00 1.00 2.00 3.00 4.00 [K]
0.00 1.25 2.50 3.75 5.00 6.25 7.50 8.75 10.00 11.25 [cth/km]

Figure 4. ~~HIMAWARI~~HIMAWARI-8 VADUGS cloud heights (~~left~~right) and 10.8-12.0 μm ΔBTs (~~right~~left) for every hour between 02:30 and 07:30 UTC. The line denotes the CALIPSO overpass track. The solid and dotted contours denote outline of TROPOMI > 10 DU SO_2 columns and TROPOMI AAI > 0 value, as ~~derived~~ shown in Figure 1.~~ Note that for the HIMAWARI ΔBTs a bias correction of +5K is applied.~~


HIMAWARI TROPOMI regridded ΔBT 10.8 - 12.0 μm
latitude
longitude
HIMAWARI ΔBT vs TROPOMI AAI
ΔBT 10.8 - 12.0 μm
AAI
HIMAWARI ΔBT vs TROPOMI AAI
ΔBT 10.8 - 12.0 μm
AAI
HIMAWARI ΔBT vs TROPOMI SO2
ΔBT 10.8 - 12.0 μm
SO2 [DU]

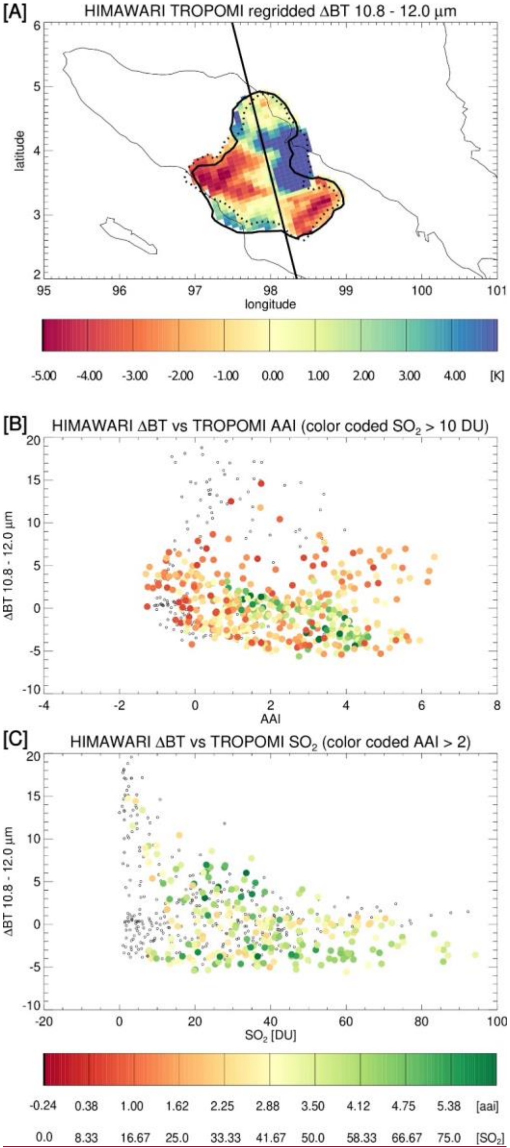

[A]
HIMAWARI TROPOMI regridded ΔBT 10.8 - 12.0 µm
latitude
longitude
2
3
4
5
6
95
96
97
98
99
100
101
-5.00
-4.00
-3.00
-2.00
-1.00
0.00
1.00
2.00
3.00
4.00
[K]
[B]
HIMAWARI ΔBT vs TROPOMI AAI (color coded SO2 > 10 DU)
ΔBT 10.8 - 12.0 µm
AAI
-10
-5
0
5
10
15
20
-4
-2
0
2
4
6
8
[C]
HIMAWARI ΔBT vs TROPOMI SO2 (color coded AAI > 2)
ΔBT 10.8 - 12.0 µm
SO2 [DU]
-10
-5
0
5
10
15
20
-20
0
20
40
60
80
100
-0.24
0.38
1.00
1.62
2.25
2.88
3.50
4.12
4.75
5.38
[aai]
0.0
8.33
16.67
25.0
33.33
41.67
50.0
58.33
66.67
75.0
[SO2]

Figure 5. **[A]** ~~HIMAWARI~~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~~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 shown in Figure 1. The color coding of the dots in the AAI scatterplots is indicative of the corresponding SO_2 value (> 10 DU) ~~upper right plot: SO_2 > 0 DU, lower left plot: SO_2 > 10 DU; with green = small, red = large~~), and the color coding in the SO_2 scatterplot is indicative of the AAI value (AAI > 2~~0 with green = small, orange = large~~), see also the lower color bar. ~~. The upper right plot is thus similar to the lower left plot but only pixels with SO_2 > 10 are color coded.~~ These color codings were added for qualitatively identifying possible relationships between ΔBT and AAI or SO_2 within the volcanic ash ~~plume~~cloud.

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