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Atmospheric Chemistry and Physics Discussions

Interactive comment on "The 2019 Raikoke volcanic eruption: Part 1 Dispersion model simulations and satellite retrievals of volcanic sulfur dioxide" *by* Johannes de Leeuw et al.

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General comments

In this contribution, de Leeuw et al. present satellite observations and dispersion model simulations of the SO2 cloud produced by the 2019 Raikoke (Russia) eruption. The paper mainly uses TROPOMI retrievals to validate NAME SO2 simulations. IASI SO2 height retrievals are also used to assess the SO2 simulations in the vertical and the VolRes team's assessment of the Raikoke eruption is used to constrain the source term (i.e. vertical profile of SO2). The paper is well written and

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the figures are excellent. The paper advances our understanding of what the important processes are for large eruptions that inject SO2 at altitudes close to and above the tropopause. Some insights into the NAME SO2 chemistry scheme are given and estimates of the total mass of SO2 injected into the troposphere and stratosphere are provided. Discussion of the e-folding times for the Raikoke event is also presented. This information is particularly important for climate modellers and stratospheric dynamicists as well as VAACs that in the future may be required to provide SO2 forecasts for volcanic eruptions. I recommend publication after addressing some minor revisions suggested below.

Specific comments

One theme I noticed throughout the paper was the use of the term 'SO2 concentration' when describing the satellite retrievals. I don't think this is technically correct as the satellite retrievals represent total column densities (VCDs or mass per metre squared). I've highlighted some lines where I think this needs correcting (see Technical corrections below). It is, however, correct to talk about concentrations (mass per metre cubed) when describing the NAME simulations. I think providing units in parentheses would clear up any confusion when discussing these quantities.

In terms of the model setups, one potential issue is the SO2 emission source duration. I see that the authors decided to simulate a constant SO2 emission from 21 June at 18 UTC to 22 June at 3 UTC. However, there's evidence (from Himawari-8) that there were emissions continuing until 22 June at 10 UTC. Therefore, some justification as to why the emission was stopped at 3 UTC is warranted. With regard to the StratProfile simulation and resulting improvements in model skill. This doesn't surprise me too much as the way this profile was derived was based on a fit to the TROPOMI retrievals. Therefore, it should be expected that the simulations would show a better agreement to the TROPOMI retrievals. It would be very interesting to see how the

different model setups (i.e. StratProfile, StratProfile$_{rd}$, VolRes1.5, VolRes2.0) compare to the IASI SO2 retrievals because the TROPOMI and IASI retrievals have different sensitivities. For example, TROPOMI might 'see' SO2 closer to the surface than IASI due to the presence of water vapour or a low thermal contrast. As you compare total column SO2 (VCDs) this difference is not taken into account by the SAL and FSS. I appreciate that comparison against IASI would require a significant amount of extra work and the paper is already rather long; however, adding some discussion on this issue would help the reader appreciate that there are subtleties to be considered when comparing model simulations to satellite retrievals of SO2 from different sensors.

Discussion of the Raikoke SO2 e-folding times. I think it would be worth mentioning e-folding times of similar eruptions to give the Raikoke event some context. For example, Sarychev 2009 erupted at a very similar latitude (also during the NH summer) and there are several papers that discuss e-folding times. Another obvious choice for comparison is Kasatochi 2008.

Technical corrections/suggestions

Abstract:
I noticed nothing is said about the SAL-metric in the abstract. It might be worth adding some mention of its use as it's used as a validation metric alongside the FSS.

L11: 'high-concentration regions'. Are the authors referring to vertical column densities here or actual concentrations? This needs to be clarified. For example, Fig. 3 shows VCDs, but Fig. 4 show concentrations.

L11-12: 'NAME shows skill'. Please specify what you mean here by 'skill'. Is it FSS$>$0.5?

L14: ‘high-concentration’. Are you talking about ‘concentration’ or VCD?

L24: ‘high-resolution’. What do you mean by high resolution here? Spatial, temporal, spectral? Please clarify.

L45: ‘dormant since 1924’. Add reference. Is this from GVP?

L46: ‘erupting until about 0300 UTC’. I’m not sure this is correct. Looking at the Himawari-8 data there are at least two significant explosive eruptions after this time which are contributing SO2 into the plume. Upon close inspection of the Himawari-8 data it looks like eruptive activity is discernible until 1000 UTC. This needs checking as the SO2 simulation results will be affected if the source is stopped at 0300 UTC vs. 1000 UTC.

L49: More examples of satellite observations of the SO2 plume produced by Raikoke have now been published. I provide them here as they may serve as useful references for the authors to consider in their revisions:

Hyman, D. M. and Pavolonis, M. J.: Probabilistic retrieval of volcanic SO2; layer height and partial column density using the Cross-track Infrared Sounder (CrIS), Atmospheric Measurement Techniques, 13(11), 5891–5921, doi:10.5194/amt-13-5891-2020, 2020.

Prata, A. T., Mingari, L., Folch, A., Macedonio, G., and Costa, A.: FALL3D-8.0: a computational model for atmospheric transport and deposition of particles, aerosols and radionuclides – Part 2: model applications, Geosci. Model Dev. Discuss., https://doi.org/10.5194/gmd-2020-166, in review, 2020.

L61: Carn et al. (2009) is another useful reference suggesting the use of SO2

detection as an aviation hazard mitigation tool: Carn, S. A., Krueger, A. J., Krotkov, N. A., Yang, K. and Evans, K.: Tracking volcanic sulfur dioxide clouds for aviation hazard mitigation, Natural Hazards, 51(2), 325–343, doi:10.1007/s11069-008-9228-4, 2009.

L67: Change 'VAACS' to 'VAACs'.

L80: '...measures atmospheric SO2 concentration...'. I suggest changing to '...measures atmospheric SO2 total column densities...'. The TROPOMI product does not provide concentrations (kg m^{-3}).

L80: Suggest changing 'unprecedented resolution' to 'unprecedented spatial resolution for UV measurements'.

L97: Change 'sections' to 'section'.

L102: 'SAL-score'. Spell 'SAL' out here as it's the first time in the text this acronym appears.

L129: Change 'TROPOMI VCD data ... is' to 'TROPOMI VCD data ... are'.

L130: 'above ground level'. Is this correct? Aren't the retrievals relative to sea level?

L132: Comparison of the 7 km TROPOMI product doesn't affect the interpretation or overall conclusions. This is somewhat surprising. As, later on, the authors suggest that the height of the SO2 is critical in governing its dispersion. I would have expected a SO2 retrieval assuming a 7 km vs 15 km layer to be significant. This needs some clarification.

L141: Change 'nothern hemisphere' to 'NH' as defined earlier. I would also check all the references to northern hemisphere for consistency if this abbreviation is going to be used.

L142-148: Discussion of factors affecting the SO2 retrievals. What about band saturation issues? Is TROPOMI capable of measuring $>$1000 DU?

L155: 'different set of assumptions in the retrieval algorithm (e.g. plume height)'. Doesn't TROPOMI also assume a plume height? How is this a different assumption?

Section 2.3: It might be worth emphasising that NAME is a Lagrangian model as later on in the manuscript you talk about releasing 10 million air parcels.

L175: Change 'Global analysis' to 'global analysis'.

L184: Change 'Each NWP' to 'Each NWP model'.

L192: Use of r here to represent a random number. Note that later on r is re-defined as the rainfall rate. The symbol might be worth changing to avoid any confusion.

L200: 'SO2 concentrations'. Are we now talking about kg m^{-3} or VCD?

L209: 'After multiplying each grid cell value by the area of the grid cell and summing the resulting mass in each column we obtain the VCDs estimate from NAME'. Please specify the units here. For example, what is the unit of each grid cell value? Is it kg m^{-3}? If so, I can't see how multiplying by the area gives you VCD (i.e. kg m^{-2}). Wouldn't you need to integrate vertically? I.e. kg m^{-3} to kg m^{-2}?

L211: ‘which is the detection threshold used for TROPOMI, see section 2.1’. To avoid confusion with the detection threshold of the TROPOMI product (1 DU, that you discuss later) it might be better to say ‘which is the detection threshold used for TROPOMI in the present study, see section 2.1’.

L225-229: Check subscripts in chemical reactions.

L239: ‘SO2 air concentration’. Please provide units.

L246: ‘mass flux’. Is mass flux the correct term here? Usually we talk about the mass eruption rate or mass flow rate (units of kg s^{-1}) when referring to ESPs. Mass flux implies units of kg s^{-1} m $^{-2}$. Please check this and in other parts of the manuscript where a mass flux is mentioned.

L252: Mass released between ‘21 June 18 UTC and 22 June 03 UTC’. Is this correct? As mentioned above, explosive activity was observable beyond 03 UTC and didn’t appear to subside until about 10 UTC. How was this end time decided?

L259: ‘agl’. I noticed that ‘above ground level’ is referred to throughout the manuscript. Are you sure this isn’t ‘above sea level’? i.e. is terrain elevation accounted for in NAME? Also, I thought that the IASI height retrievals are relative to sea level.

L279: ‘large amount of ash’. What do you mean by ‘large’? Can you provide evidence for this? Perhaps you could refer to the Part 2 paper here.

L316: ‘Fractional Skill Score’. Use FSS if you’ve already defined the acronym. Check this in other places of the manuscript.

L336: ‘mass concentrations’ or mass loadings? Or VCDs?

L338: ‘varying mass densities’. What are the units here?

Figure 5. This is a great illustrative example of how the SAL-score works. Good job.

L369: ‘within the domain’. What is the size of the domain used for the SO2 simulations?

L406: ‘TROPOMI retrievals’. So all results presented are for the 15 km agl TROPOMI retrievals? It might be worth highlighting this at the beginning of the results section.

L434: Change ‘has skill’ to ‘has skill (FSS> 0.5)’.

Figure 10. Which SO2 DU threshold is used here? Please state this in the Figure caption.

L478: ‘larger total SO2 mass than the TROPOMI retrievals’. Couldn’t this also be due to the spatial coverage of TROPOMI (as you’re comparing individual overpasses here)?

L499: Discussion on the differences between StratProfile and StratProfile$_{rd}$ (i.e. Fig. 10c and d). It would be nice to see some S values quoted here or maybe include a table to help understand how large the change in S was when reducing the diffusion parameter by 75%. If you decide to include a table then I suggest reporting values for S, A, L and SAL at key time steps.

Figure 11b. It’s difficult to see changes in the SO4 mass deposition. If you want to plot it on the same figure panel then I suggest adding a second y-axis and reducing its range.

L512: Factors affecting TROPOMI estimates of mass. What about band saturation due to high SO2 loads?

L563: 'StratProfile ... compares best with TROPOMI'. What about the StratProfile$_{rd}$? It appears to show better agreement than StratProfile based on Figure 10.

L576: 'able to reasonably accurate simulate'. I'm not sure what this means. Please rephrase.

L597: Discussion on varying input parameters. Did you consider a variation in column height with time? The Raikoke eruption was characterised by a series of explosive eruptions (or 'pulses') that varied in height. Some discussion acknowledging this seems appropriate to add here.

L653: Discussion on Harvey et al. (2018). They were also looking at ash, not SO2, so presumably the impact of the diffusion parameter would be different for that reason as well.

L662: 'high-resolution'. Spatial? Spectral? Temporal? Please clarify.

L698: Change 'In future' to 'In the future'.

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