

Reply to editor

Thanks a lot for the comments to the revised version of our paper. We have changed the manuscript according your suggestions and have listed our replies and changes in blue below. We hope that it is now acceptable for publication.

Editor's comments to the author:

I have read through the reviewer comments, and the revisions the authors have made, and whereas these certainly address each of the points raised, and make appropriate edits to the text and Figures accordingly, in some cases the text added is not specific enough, and requires some improvements.

Also, whilst the revised title the reviewer suggested is generally OK, it omits one of the main values of the study, in documenting and evaluating the updated baseline capability for assimilating total-column-SO₂, now taking in observations from Tropomi. Although the operational volcanic SO₂ plume forecasting system was described quite comprehensively by Flemming and Inness (2013), the initial volcanic forecasting system there was 8 years ago now, and assimilated OMI, GOME-2 and SCIAMCHY SO₂. The updated system described here assimilates Tropomi SO₂, and the manuscript sets out some detailed specifics of the method for combining into the system.

For this reason, the first of my specific comments in the Decision-Stage Topical Editor review is to request a minor revision to the title, adding "column SO₂ and NRT" into the title, to highlight that both the column-SO₂ and the layer-height product aspects are "new" since the original Flemming and Innes (2013) manuscript.

The only other of my major comments (see comment 4) is that section 3.1 of the manuscript "CAM5 model" needs to be extended, to communicate also the important specifics of the atmosphere model being used within the particular version of the Integrated Forecasting System being used in this analysis. Reviewer 1 points out that the experiments are carried out in a different system than the near real time (NRT) CAM5 system used operationally for volcanic forecasting.

I must admit that, from reading the manuscript, this is not apparent, and I was not aware of it when I carried out my initial Topical Editor review. This is an example where the specifics of the broader modelling system used in a study need to be set out clearly, and this being something that partly motivates why GMD required the specific version numbers to be communicated at the outset, in the title of the manuscript/article. The 3rd & 4th of my comments then requests an extra paragraph be added to section 3.1 to set out the specifics of the IFS model used in the experiments -- and also to consider changing the "The CAM5 model" in section 3 title and the subsection 3.1 title to something more specific such as "The ECMWF Integrated Forecasting System" or similar.

The remaining revisions are very minor however, and I expect the authors will be able to make these changes easily -- to then enable the manuscript to progress to publication in the GMD, within the joint ACP/GMD/AMT special issue on the Raikoke eruption.

Note that line numbers below relate to the revised manuscript not the Author-Tracked-Changes manuscript.

Specific comments:

1) Title -- As I mentioned above, in the revised manuscript the authors have completely replaced the original title of the article, following exactly the suggestion of Reviewer 1. The revised title mentions only the assimilation of the SO₂ layer height in the system, and although I agree that is the main focus of the article, since this is (to my knowledge) the first time the ECMWF volcanic SO₂ plume forecasting system has been described with the assimilation of Tropomi SO₂ data, it's important to mention this aspect of the paper also.

Suggest therefore to insert "column SO₂ and NRT" after "S5P/Tropomi", also deleting "data" from the title. Also suggest to insert "forecasting" between "global" and "system".

Suggest also a slight re-wording to improve the grammar and readability -- change "Evaluation of" to "Evaluating the", and "in the " to "into the", changing also "for the" to "", based on case study of the", finally re-ordering "the Raikoke 2019 eruption" to "the 2019 Raikoke eruption" (putting the year before the name of the volcano is the correct way to refer to a specific eruption).

I mean the title then to be "Evaluating the assimilation of S5P/Tropomi column SO₂ and NRT layer height into the CAMS global system, based on case study of the 2019 Raikoke eruption"

2) Title -- this is a follow-on comment, in relation to the GMD policy to request authors state explicitly in the title the specific version number for modeling systems used in the analysis. With the revised title, "the CAMS global system" needs to have a corresponding version number applied. As in my general comments above, I think rather than the "CAMS global system", perhaps better to refer to the "Integrated Forecasting System" -- and then I think providing the IFS cycle number would then satisfy the GMD policy on version numbers.

We have changed the title to:

Evaluating the assimilation of S5P/Tropomi NRT SO₂ columns and layer height data into the CAMS integrated forecasting system (CY47R1), based on a case study of the 2019 Raikoke eruption

3) Titles to Section 3 and section 3.1 -- related to comment 2, and explained in my general comments above, please change "The CAMS system" in the title to section 3 to be more descriptive -- certainly the word "global" is needed -- but as I suggested, maybe the "Integrated Forecasting System" is better in this case? And then the title of sub-section 3.1 also to follow that revision of "CAMS system". In my initial Topical Editor review I suggested the change to "volcanic forecasting system" -- and I note in Flemming and Inness (2013), that initial system was referred to as "volcanic SO₂ plume forecasting system" -- and that would be my preference, for the title of this section 3 and subsection 3.1 at least. Whether the authors feel a change from "CAMS global system" to "CAMS volcanic SO₂ plume forecasting system" is also appropriate I leave to them to decide. Given the GMD policy re: version numbers, perhaps better to have that as Integrated Forecasting System, but perhaps more suitable in this section 3 to re-iterate the "volcanic SO₂ plume forecasting" capability -- with then the specifics of the IFS cycle used etc. then explained in the extra para added to section 3.1 (see comment 4 below).

We have changed the section titles to:

3 CAMS global integrated forecasting and data assimilation system

3.1 CAMS volcanic SO₂ plume forecasting system

4) Add extra paragraph to section 3.1 to briefly describe the specifics of the atmosphere model used.

As in my general comments, please add an extra paragraph here to communicate the specifics of the modelling system used. This can be taken from a description of the specific release cycle of the Integrated Forecasting System that is used in these model experiments. I note that the 2013 Flemming and Innes JGR paper included (section 3.1) quite a detailed description of the Integrated Forecasting System, and resolution of the model experiments etc. Please provide similar (but perhaps briefer, to 1 paragraph) specifics of the IFS model and resolution used in these experiments.

We have added in section 3.1:

The model version used in this paper is based on the IFS model cycle 47R1 (CY47R1, www.ecmwf.int/en/forecasts/documentation-and-support/changes-ecmwf-model), which was the operational CAMS cycle from 6 October 2020 to 18 May 2021. In CY47R1, the CAMS system uses the CAMS-GLOBANTv4.2 anthropogenic emissions (Granier et al., 2019) which include anthropogenic SO₂, as well as a climatology of SO₂ outgassing volcanic emissions based on satellite data (Carn et al., 2016). Further updates relative to the previous version (CY46R1) are

- change to Global Fire Assimilation System (GFAS) v1.4 biomass-burning emissions
- the exclusion of agricultural waste burning from CAMS_GLOB_ANT to avoid double-counting with GFAS
- improved diurnal cycle and vertical profile for anthropogenic emissions
- introduction of Hybrid Linear Ozone (HLO) scheme, a Cariolle-type linear parameterisation of stratospheric ozone chemistry using the multi-year mean of the CAMS reanalysis as mean state
- updated dust source function, which reduces the overestimation of dust in the Sahara, Middle East and other regions, and restores missing dust over Australia
- new sea-salt emission scheme based on Albert et al. (2016), which provides better agreement with measured sea-salt size distribution
- revised coefficients in UV processor, based on ATLAS3 spectrum.

5) Section 2.1 (lines 132-133) -- The 3rd of reviewer 1's comments asks the authors whether there is a "super-obbing" step when the total-column SO₂ data is assimilated, and also whether the data are "thinned", furthermore about specifics of any pre-processing. The authors replied pointing to the text they have already, but for Trompomi that only says "The TROPOMI SO₂ data are averaged to the model resolution (TL511, about 40km) before being used in the CAMS system".

I am not at all clear what is meant by "super-obbing" but the reviewer's question suggests they're requesting more information than simply that the data are averaged. If there is any further "thinning" of the data, or pre-processing in this process, some specific mention should be made of this, or else to state "without any further pre-processing or data thinning" if that is the case.

We have changed the sentence to:

The TROPOMI SO₂ data are super-obbed, i.e. in a pre-processing step area means are created by averaging all data (observation values as well as errors) in a model grid box to the model resolution (TL511, about 40km). These super-observations are then used in the CAMS system without further thinning.

6) Section 2.1 (lines 135-136) -- this sentence was added in response to reviewer 1's 5th comment -- I just take issue with the word "knowledge" here. It's true that the system needs to use a prior SO2 vertical profile -- but perhaps it only needs to be approximate to broadly represent the particular class of eruption. The word "knowledge" suggests a more precise profile for the eruption is needed, but that may well not be the case -- it might not be sensitive to the specifics of the profile used -- it may adjust subsequently to be reasonably accurate even with only an approximate vertical profile.

Suggest to replace "knowledge of a prior SO2 profile" instead to "an assumption for the SO2 vertical profile".

Done.

7) Section 2.1 (lines 136-138) -- Starting a sentence "Because" is poor grammar. Replace with "Since".

Done.

8) Section 3.2.1 (lines 143-144) -- this sentence (beginning "However..") was also added re: reviewer 1's 5th comment. The authors have written "these do not provide any real information". Please re-word this to be specific to what is meant.

We have reordered the sentence and it now reads:

However, as these do not provide information about the real altitude of a specific volcanic plume they are not used in the CAMS system

9) Section 3.2.1 (lines 144-145) -- I am not familiar with the acronym "ATBD" -- please provide the full name here. If the acronym is used later in the manuscript, also add "(ATBD)" -- but otherwise the acronym is not needed.

This is already defined in Section 2.1 "...and further information can be found in Algorithm Theoretical Basis Document (ATBD)..."

10) Section 2.1 (lines 145-146) --- this sentence was added in response to reviewer 1's 4th comment -- I think there needs to be a few extra words added to be more specific than "observation errors as given by the data providers are used". I mean to clarify exactly how they are used and where -- I guess you mean within the 4Dvar data assimilation, right? If so please add a few words after "used" to clarify the specifics of where in the assimilation process those obs-errors are used.

We added that sentence to make clear that we don't modify the observation errors in any way, but use what is given by the data providers. We have now changed the sentence to:

For the TROPOMI data (and also the other SO2 products used in this paper) observation errors as given by the data providers are used within the CAMS data assimilation system.

11) Section 4 (line 306) -- Change "All the satellite data available" to "All the TCSO2 satellite data available".

Done.

12) Section 4 (lines 371-373) -- The authors have added this sentence in response to the 2nd of reviewer 2's comments, but the wording here needs to be improved. Please change "The numerical cost" to the "The CPU cost" or "The computational cost" and ", with the largest increase coming from" changed to ", with ~50% of the increased cost coming from", then enabling also to delete the text "which is about 50% numerically more expensive" from the end of the sentence. I'm assuming this change is consistent with what the authors meant -- but please amend slightly if you meant something different. Main thing is that "numerical cost" needs to be "computational cost" or "CPU cost". Also suggest to insert "stage of the" after "second" and before "minimisation" -- if that's what was meant?

We have changed the sentence to:

The computational cost of one analysis cycle increases by about 20-30% when the spectral resolution of the minimisation is increased in this way, with the largest increase coming from the second minimisation which is about 50% computationally more expensive than at lower resolution.

13) Abstract (lines 29-35) -- the grammar in this new text needs improving -- "which is better than what is obtained" is colloquial English, and not appropriate for a manuscript article. Suggest to delete "what is" from that text, and also add a comma after "the initial eruption". Similarly "forecast skill drops" is colloquial -- change "drops" to "reduces".

We have changed the sentence to:

By assimilating the SO₂ layer height data the CAMS system can predict the overall location of the Raikoke SO₂ plume up to 5 days in advance for about 20 days after the initial eruption, which is better than with the operational CAMS configuration (without prior knowledge of the plume height) where the forecast skill reduces much more for longer forecast lead-times.

14) Introduction (lines 44-45) -- This sentence beginning "In the short term" needs revising -- the sentence is explaining a potential health hazard of SO₂ in the aircraft cabin. I think the term "short term" is referring to the type of exposure, short-term exposure and long-term exposure, and suggest to replace "In the short term, SO₂ in the aircraft cabin" instead with "If sufficient SO₂ is diffused into the aircraft cabin", and replace "is the biggest issue and can lead to" instead to "this could potentially lead to".

We have changed the sentence to:

If sufficient SO₂ is diffused into the aircraft cabin this could potentially lead to respiratory problems for passengers and crew.

15) Introduction (lines 59-60) -- This short sentence states that assimilating volcanic SO₂ in NRT "is difficult". I'm not sure it adds too much though, and needs either to be deleted or to make some specific about which aspect is difficult. I'd recommend the former.

We have removed the sentence.

16) Section 3.2 (lines 233-236) -- This sentence was added in reply to one of Reviewer 2's comments. Change "cost function that measures the differences" to "cost function for the total difference". Also, suggest to delete the word "background" here -- you have "model's background fields" -- but it's the actual model fields that are considered here -- I get that there are specific terms in the assimilation referring to "background fields" etc. -- but when combined with "model" that is

confusing to the more general reader because they might be thinking about the non-volcanic component of the model SO₂. Suggest simply to delete the word "background" here and change "model's" to "model". See for example on line 294 (section 3.2.2) the text states "the model's background SO₂ concentrations" and there it means the non-volcanic part.

Done.

Also, you've written "by adjusting the initial conditions" -- but is that actually what's done in the 4DVAR DA system -- isn't it more to identify the solution that gives that minimum in the cost function? Suggest to delete "by adjusting the initial conditions". Or if I am misunderstanding, please reply to explain this to me.

You misunderstand this. In the current setup of the CAMS and ECMWF 4D-Var the cost function is minimised by adjusting the initial conditions, i.e. we have two representations of the atmospheric state over the 12-hour assimilation windows (the observations and the background (=short range model forecast)) and look for the initial state of the atmosphere at the beginning of the assimilation window that provides the best possible forecast, i.e. for which the cost function is a minimum. CAMS is also developing a prototype 4D-var system where emissions are adjusted in addition to the initial conditions. There we have a larger control vector that includes the initial state and emission scaling factors and that cost function is then minimised with respect to the initial conditions and the emission scaling factors.

17) Section 3.2 (lines 294-295) -- you've added this sentence in response to another of Reviewer 2's comments. But you've written "some vertical variation of the SO₂ loading will be achieved if parts of the plume have different altitudes" . Re-word this to more carefully explain what you're referring to here. I think you mean that volcanic plumes in the troposphere tend to become deformed into multiple layers at different altitudes. Certainly the text "will be achieved" needs to be changed to something different.

Suggest maybe "We note however that some parts of the SO₂ plume are likely to be deformed into multiple layers at different altitudes..." or similar text to explain better what you're communicating here.

We mean that for larger plumes the observations will give different plume altitudes if there are variations within the plume. We have changed the sentence to:

Also, some vertical variation of the SO₂ loading will result from assimilating observations with varying plume altitudes for larger volcanic plumes that are not uniform in height everywhere,...