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Comment on acp-2021-973

Anonymous Referee #2

Referee comment on "Quantifying the impact of meteorological uncertainty on emission estimates and the risk to aviation using source inversion for the Raikoke 2019 eruption" by Natalie J. Harvey et al., Atmos. Chem. Phys. Discuss.,
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Referee comment for acp-2021-973, Quantifying the impact of meteorological uncertainty on emission estimates and volcanic ash forecasts of the Raikoke 2019 eruption by Natalie J. Harvey, Helen F. Dacre, Cameron Saint, Andrew Prata, Helen N. Webster, and Roy G. Grainger

Harvey et al. present uncertainty estimations of volcanic ash emissions and their dispersion based on ensemble simulations with perturbed meteorology during the 2019 Raikoke eruption. These simulations were performed by using the Met Office Global and Regional Ensemble Prediction System (MOGREPS-G) to generate meteorological ensemble forecasts to drive volcanic ash dispersion simulations within NAME (Numerical Atmospheric-dispersion Modelling Environment). To quantify ash emission estimates from satellite retrievals, the InTEM (Inversion Technique for Emissions Modelling) has been applied. Volcanic ash observations are retrieved from the infrared imager of the geostationary Himawari-8 satellite. The ensemble results discuss the differences between prior and posterior simulations, ensemble spread, and ensemble mean in terms of emissions as well as the horizontal and vertical dispersion of ash. Further, ash concentration risk maps are provided and discussed with respect to be used for aviation advice.

Even though the manuscript fits well into the scope of ACP and highlights many important aspects with respect to volcanic emission optimisation, volcanic ash satellite retrievals and dispersion forecast uncertainty assessments, there are several points that need further elaboration and better discussions. Please find below the remarks, which need to be addressed before the manuscript can be accepted for publication.

Major points of discussion:

The title "Quantifying the impact of meteorological uncertainty on emission estimates and

volcanic ash forecasts of the Raikoke 2019 eruption” does only reflect parts of the work that has been presented in the manuscript. The forecast improvement due to the inversion derived emissions compared to the prior emissions estimate as well as the risk assessment for ash encounters of air traffic are significant contributions to this study but not represented in the title. Please consider adapting the title such that it reflects the whole manuscript.

Within the abstract, there is no hint on the model system used nor the satellite data sets being used for the inversion. The ensemble setup as well as the satellite data are an essential part of the study and should be named in the abstract. The same applies to the short summary of the aim of the paper (lines 32-40), where no tools are mentioned. Here, the essential information that the ensemble of ash dispersion simulations is based on perturbations in the meteorological forecast is missing.

In line 101 to 103, the authors state that “ensembles can provide improved volcanic ash forecasts”. However per definition, ensemble simulations describe a method where a computer model is run a number of times with diverse perturbations. An improvement of volcanic ash forecasts cannot be expected by just applying ensemble forecasting. Please clarify this contradiction.

There are two different volcanic ash retrievals described and used in this study. However, the similarities and differences could be elaborated in more detail. When describing the ORAC retrieval method, the term of fine ash is firstly introduced in the manuscript (line 161). Is there a difference in the retrieved particle sizes compared to the Met Office algorithm? Please also elaborate if only the ORAC algorithm is able to retrieve volcanic ash properties over day and night (stated in line 167) or if it is also valid for the MetOffice retrieval. Overall, the purpose of using two Himawari-8 retrieved volcanic ash data sets could be described clearer from the beginning (MetOffice data used for the inversion and ORAC used for validation of inversion results). This is especially important when referring to the ORAC retrieval being independent satellite retrievals (line 289). Please elaborate to what extent they are independent, when building upon the same satellite, exploiting identical spectral range measurements, deriving the same retrieval quantity for identical time steps.

Even though the model setups and inversion method are successively introduced and explained with many details, it is hard to extract the main configurations used for performing the analysis being discussed in the results section. Therefore, there is an urgent need to include a paragraph explaining the different simulation time horizons, the corresponding eruption times as well as the time window of used retrieval data (with a clear distinction between retrieval data used for the inversion and for evaluation of results). What is the temporal resolution of the VATDM simulations? For example, the sentence extending from line 291-293 includes important information that should have been presented earlier.

Minor comments that need to be addressed:

- In the abstract (line 18) and discussion (line 409), it is stated that the area deemed to be highest risk to aviation is reduced by 51 % comparing posterior to prior emission scenarios. However, in the section 5 this reduction is discussed to be 49 % (line 374).
- As the uncertainties in eruption sources parameters and dispersion model parameters are not investigated within this study, their discussion takes a prominent amount of the abstract. I therefore suggest removing the sentence "The posterior inversion emission estimates are also sensitive to uncertainty in other eruption source parameters (e.g., the ash density and size distribution) and internal dispersion model parameters (e.g., parameters relating to the turbulence parameterisation).", and moving the sentence "Extending the ensemble inversion methodology to account for uncertainty in these parameters would give a more complete picture of the emission uncertainty, further increasing confidence in these estimates." to the end of the conclusion.
- In line 98, the authors state "similar agreement at short lead times". It remains unclear to what the similar agreement refers to. Is it an observation-model agreement or a similar agreement to results of more than 12 hours lead times? Further, the definition of "short lead times" would improve the discussion at this point.
- Please provide detailed references on MOGREPS-G (line 126). Is MOGREPS-G an ensemble generation system, which builds on a specific or any meteorological model, or is it a meteorological ensemble model system?
- The information provided in line 128 on the initialisation of forecasts 4 times per day and 7 days extent is probably related to operational forecasts. However, this is not relevant for this study, because only 12 UTC initialised forecasts are used. Instead, please provide more information on the meteorological simulations used: Are these meteorological forecasts or reanalysis? From which data are the forecasts initialised?
- In lines 143-144, the channels used to identify ash contaminated satellite pixels are discussed. Even the authors state that the retrieval algorithm is based on Frances et al. (2012), mentioning that the ash identification is based on the reverse absorption technique might be valuable. Please also explain if ash identification is applicable to pixels being dominated by meteorological clouds and how meteorological clouds are identified.
- Please discuss if and how differently classified pixels (clear sky, unclassified, meteorological clouds, ash) are treated in the inversion algorithm. Are meteorological cloud pixels classified as unclassified or does unclassified relates the retrieval failures?
- Please justify the selection of 50 % and 90 % in line 157. How do the 90 % build up of fractions containing ash or clear sky? How are for example ash column values calculated if 50 % of the pixels contain ash and 50 % of the pixels are unclassified?
- Are the cloud-top pressures discussed in line 181 related to the troposphere/stratosphere model configuration? Then, the new paragraph should start one sentence earlier with "The troposphere/stratosphere model configurations are run by ...". Otherwise, please explain how these cloud-top pressures relate to the 800 hPa cloud top in line 176.
- Chapter 2 seems a bit mixed up. First describing all modelling related systems (MOGREPS-G and NAME), before introducing the retrieval algorithms and finally the inversion system would improve the guidance through methods and data.
- Please explain if the prior source term (section 2.4.1) is also restricted to chosen model inversion resolution (4km height levels and 3-hourly time steps).
- Are emissions or ash concentrations constrained to positive values (cf. line 227)?
- It would be helpful to see the quadratic cost function (mentioned in line 229) to understand how emission profiles and dispersed volcanic ash states are contributing to the costs and what quantity is ultimately optimised by the inversion algorithm.
- In section 3, the initial eruptive plume height of the Raikoke eruption is discussed. However, is there any information on the temporal evolution of the plume height? This could be also interesting with respect to section 4 – Results, where emission plume heights are discussed.
- In figures 1 and 3, colormaps extend from 10^5 g/s to 10^8 g/s. Are emissions lower than

10⁵ g/s visualised here? If not, please also include these emissions or explain where this lower limit of emissions comes from. Is this a limitation defined by the inversion algorithm?

- In lines 252-253, the authors claim, "Four members (e.g., member 13) have continuous emission of ash between 4-12 km above vent level (avl) whereas the other 14 members have times when there is no emission of ash at this height range.". However, ensemble member 13 is not part of the four members being characterized by continuous emissions between 4-12 km. And for the other 14 members, there are surely emissions at this height range, yet, not continuous.
- Please explain what is meant in line 263 by "There is also a range, 4459–5314, in the number of unique observations which impact the inversion between ensemble members.". What do the numbers refer to (a quantity of observations or a numbering of observations)? How does the ensemble meteorology sort out observations in the inversion process?
- For all figures illustrating the horizontal dispersion of ash (fig. 5a-d, 6a-d, 7, and 8), it would be helpful to have some geographical orientation here. Please add longitude and latitude information to the figures.
- Figure 5 and 6 need adjustments in their colormaps to fit the values mentioned in the discussion. The extreme values of the prior emission ensemble are not represented by the selected colormap limits. Further, it would be helpful to know, if the selected cross sections are following a selected line of longitude or if the cross sections are irregular due to the selected projection. What is the reason that some error bars of the Met Office algorithm extend to the x-axis (in panel e))? What is the lower limit of the y-axis?
- In lines 316-317, the authors describe that "Between 45-50 °N, the posterior ensemble spread encompasses the Met Office retrievals within their retrieval uncertainty." Isn't this an overfit of the inversion algorithm? Please discuss in more detail about the interpretation of this extreme fit, the choice of the prior emission error and the observation errors used for the inversion.
- "In this case the cross section intersects the simulated ash plume in 3 locations - 45-46°N, 49-51°N and 53-59°N." cannot be followed, as figure 6 reveals volcanic ash continuously extending between 43-60°N. Please clarify. Further use "---" in latex for the dash before the list of locations such it does not appear as a minus.
- It would be interesting to learn something about the detection limit of volcanic ash with Himawari retrievals, e.g., where discussing the detected ash of figures 5 and 6 (e.g. line 326).
- There are multiple points that should be revised in figure 7: First, please adjust the colormap limits such that the illustrated ash values are better discriminated. I.e. use 3.49 g/m³ as the maximum of the color scales in a)-f). Please also adjust the limits of the difference plots according to the maximum/minimum difference. Secondly, ash concentrations in g/m³ seem to be unrealistic. Having maximum ash concentrations of 3.3 million micrograms per cubic meter cannot be correct. Such values also do not fit to the green contour lines nor to the minimum concentrations shown. Please check the stated unit and adjust the figure as well as the text. Thirdly, changing the order of the last two sentences of figure 7's caption would improve the line of reasoning.

Technical corrections:

- Please make sure that all abbreviations used are introduced when used for the first time (e.g. line 131 – NAME, line 158 – InTEM) and that abbreviations are consistently used throughout the manuscript (i.e. in some cases, it just says VATD instead of

VATDM).

- There are many sentences where commas would be appropriate to support readability.
- There is no subsection 2.2.1 needed since it is the only subsection to section 2.2.
- Please indicate, which two channels are used for the effective absorption optical depth ratio (line 148-149).
- Please explain where the value of "10" is coming from in line 172.
- Line 178: Please elaborate what "nearby" means at this point. Is it meant as nearby to the Raikoke volcano, nearby the ash cloud or something else?
- At this stage of Prata et al. in preparation cited in lines 184-185, please remove this sentence from the manuscript and add it again if the cited publication is published during the ongoing review process.
- Are there any references on the algorithms used for "free tropospheric turbulence, sedimentation, dry deposition and wet deposition" (line 189)?
- Is there any reference for the ash density of 2300 kg m^{-3} (line 190)?
- Please state what observations the plume height estimate relies on in line 208.
- Please note that the release rates discussed in lines 219-220 refer to a first guess and are different to the prior source term.
- Line 236: What does the "peak value" relate to? The ensemble distribution?
- Does 21-24 June refer to the ash retrievals used in the inversion? If so, this is in contradiction to section 2.4.3. Please clarify.
- Please check if the statement "especially below 4 km avl where ash is only emitted for one 3 hour period at the start of the eruption." is valid or if this finding is related to the choice of colormap having a lower limit at 10^5 g/s .
- Lines 273-274: There is no need of the "Note"-sentence in parentheses.
- Figure 4: Is the fraction of total ash emitted in the three atmospheric levels dependent of the ensemble meteorology when applying the prior emission profile to ensemble simulations?
- Line 280: Please change "other parts" to "lower regions".
- Line 281: Please state that de Leeuw et al. (2020) also relates to the Raikoke eruption.
- In lines 304-305, the authors state to show a difference in figure 6. However, the figure does not contain difference plots. Further, there is no reference to the illustrated prior ash cloud. Please rephrase this sentence to make clear what is shown in figure 6.
- Please explain what "matching ensemble" means (e.g. caption fig. 5 or line 332).
- In line 315, it is stated that "Between $46.5\text{--}48.5^\circ \text{ N}$, the posterior ensemble spread falls within the uncertainty of the ORAC retrievals.". Contrarily, figure 5 shows an ORAC retrieved column loading at 48° N , which does not match the posterior ensemble spread.
- Line 318: Please state what "mean magnitude" is meant here. Is it the magnitude of the cross-section evolution ensemble mean volcanic ash column mass loading?
- Please be more precise when discussion latitude ranges of figure 6e. In line 326, Himawari retrievals used in the inversion (thus MetOffice retrievals only) detect ash between $49\text{--}52^\circ \text{ N}$.
- Please add "by comparing the different ensemble members" to the sentence "At this time, the ash plume structure at all three levels is qualitatively very similar." (in line 338).
- Line 337: Please correct "the maximum over" to "the maximum of".
- Please clarify what fraction of ensemble members is used in line 360. Do you use the ensemble mean, the ensemble minimum or does the fraction consists of selected ensemble members?
- Line 396: Please connect "over estimated" to "overestimated".