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Atmospheric Chemistry and Physics Discussions

# *Interactive comment on* “Determination of time- and height-resolved volcanic ash emissions for quantitative ash dispersion modeling: the 2010 Eyjafjallajökull eruption” *by* A. Stohl et al.

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We thank referee 1 for the constructive comments on our paper. Below, we repeat these comments in italics and add our answers in normal font. We would also like to point out that many of the reviewer’s comments are on remote sensing aspects. We agree that these are very important for determining quantitative ash concentrations. However, the innovation in the paper is mainly on the inverse modelling to determine the ash source strengths. As we do not wish to distract attention from this main purpose of the paper, we kept the description of the remote sensing aspects relatively short and would like to keep this short also in the revised version of the paper. The



cited papers on remote sensing of volcanic ash contain much more information on the satellite retrieval methods used.

*1). It is unclear how the uncertainty (estimated to be 10 K) in the ash cloud temperature and surface temperature are accounted for in the source term inversion process. Lidar measurements show that the Eyjafjallajökull ash cloud height varied considerably and the North Atlantic is quite cloudy, making clear sky regions difficult to find, which greatly impacts the ability to accurately determine the surface temperature. Given that the satellite retrieval of mass loading used in the source term inversion process requires accurate surface temperature and cloud temperature information, the paper should contain more information on how the plus/minus 10K uncertainty in Ts and Tc is accounted for in the inversion scheme. I assume this error is accounted for in the observation error covariance matrix, but how is it combined with the baseline mass loading uncertainty of 40-60%?*

The surface and cloud top temperature do not need to be determined accurately in the retrieval of ash cloud properties. These are like boundary conditions in the retrieval process and must be specified, but their overall impact on the retrieval of effective particle radius is small but larger for the infrared optical depth. It is possible to allow these to be free parameters and estimate them in the retrieval process and this is something that we are investigating. The main effect of these parameters on the retrieval comes from what is termed the "thermal contrast" (the temperature difference between surface and cloud top). When this is small the retrieval is less reliable. Note that we do not explicitly retrieve cloud height from the satellite data and hence do not need an accurate cloud top temperature. We are also looking at using the assumed temperature field combined with the estimated cloud top height from the inversion to estimate the cloud top temperature and then iterate to obtain better satellite retrievals. We have included a comment on this in the revision. Estimating clear regions is in fact quite easy because the domain chosen is quite large and the chance of finding a clear pixel in the whole region is almost a certainty. However, this clear pixel may not be in the vicinity of the ash cloud and this does introduce error. The error related to this is not considered explicitly in the inversion but assumed to be part of the overall observation error.

*2). How was the ash detection threshold of -0.8 K determined? Would this threshold hold up over other regions of the world?*

The threshold was determined by trial-and-error and is possibly conservative. It will vary from place to place and on time (it depends on atmospheric conditions and path-length) and so is not easily transferable to other locales and other sensors. In theory the threshold should be 0 K but never is in practice.

*3). What sort of re-sampling scheme is used to re-map the satellite data to a 0.25 degree by 0.25 degree grid, averaging, nearest neighbor?*

Resampling was done by summing up mass loadings in all pixels that fall within the 0.25x0.25 grid cell and dividing by the area. Retrievals were performed at the resolution of the SEVIRI sensor pixels, which are much smaller than the 0.25x0.25 grid cells.

*4). The IASI ash retrieval methodology was 'calibrated' using the SEVIRI retrievals. Why even use IASI, if the IASI mass loading information is being severely constrained by the lower spectral resolution SEVIRI results?*

IASI has better sensitivity to ash (due mostly to its much better spectral resolution) and does not rely on a temperature threshold. Its spatial structure can be different to that of SEVIRI and retrieved spatial ash cloud fields often appear less noisy than the SEVIRI fields but the IASI retrievals were not done in a rigorous manner and needed to be "normalised" for use in the inversion. A better approach (but also needing more research and time) would be to provide IASI retrievals independently and with an error field. This is also part of on-going research.

*5). It was assumed that 10% of the erupted mass was fine ash. Is there a theoretical basis for this assumption?*

No. We know that the fraction is small and depends on the eruptive style. Rose et al



(2000) report that between 0.04 and 2.6% of the erupted mass in volcanic eruptions may be in the fine ash range. The fraction cannot only be variable but also depends on how exactly "fine" ash is defined (i.e., the respective size range), and also how the total erupted mass flux is derived. In our case, this is the mass of tephra erupted into the atmosphere. The difficulty in quantifying the mass flux of fine ash with volcanological methods is actually an important motivation for our study.

*6). It is unclear how this methodology can be used operationally. The source term inversion methodology seems to require a long time series of a priori source term information and satellite data for a given eruption. Is it being assumed that the a posteriori source term determined from one eruption (e.g. the April 14 - May 24 Eyjafjallajökull eruption) is valid for future eruptions of Eyjafjallajökull? If a volcano with no eruptions in the satellite era erupts, how would this methodology be employed to immediately help operational forecasts?*

The inversion scheme would not be used like this, but rather in an incremental manner by introducing satellite data as it becomes available. Remember that SEVIRI data are available every 15 minutes and could be used in early stages of the eruption. The source term could be determined from the on-set of the eruption until the time the latest real-time satellite data are available. The accuracy of the inversion would increase with time as more satellite data become available. There would be no way to forecast the ash mass flux with this method. However, for forecasting the dispersion of the ash that is already in the atmosphere, this would not be needed. As a first approximation of future activity, one would also use the latest available ash mass flux, which would still be a better extrapolation than the assumptions made today. Notice that, in a real-time environment, the method would be applied ahead of every planned ash dispersion forecast (e.g., every 3 hours or every 6 hours) to determine the ash flux as an input to the forecast. In principle, the methodology could also be used with other real-time data, including ground-based and satellite lidar measurements. The method is fast enough to be suitable for such a real-time application, even though it would require more computational resources than what is needed for the forecast alone.

*7). How do satellite false alarms and missed detection impact the source term inversion? Could an area of false alarms with a moderate to high retrieved mass loading significantly impact the inversion?*

We have been careful to eliminate as many "false" ash detections from the satellite data as possible. Without having an objective measure of a false detection, the removal process has been somewhat subjective, which is undesirable. The conservative threshold of -0.8 K helps to eliminate most potential false detections but inevitably some still exist. There should be no regions of false detection with a moderate to high mass loading. False detections occur where the temperature difference lies close to the threshold and these correspond to low mass laodings. In cases where the temperature difference is low over optically thick cloud (very few of these cases are observed), a low temperature threshold test was applied.

If false or missed detections occur for scattered pixels only, they appear as noise for the inversion and would not lead to dramatically or systematically wrong ash emission mass fluxes. In case that large parts of a volcanic cloud are missed by the satellite data retrieval or non-real ash clouds are erroneously generated by it, the story would be different. However, this is unlikely.

*8). From April 21 to May 4, meteorological clouds generally obscured the volcanic ash cloud. Under these conditions, how exactly does the satellite data constrain the source term inversion?*

From April 21 to May 4 ash emissions were low according to independent observations, the inversion results and the satellite retrievals. While the relative errors of the ash emissions may be high during such a period, this does not matter much since the absolute emissions are low.

*9). The paper should contain more information about potential limitations of the source*



*term inversion method. For instance, how would this method work in an atmosphere with weak vertical wind shear (e.g. the tropics)?*

We will try to give more information on this in the revised version of the paper. In a region with low vertical shear of the horizontal wind, it would take longer for specific dispersion patterns to develop, which allow to separate emissions at different altitudes. This might reduce the effective vertical resolution of the method. On the other hand, low vertical shear also means higher total column loadings, which makes it less likely that ash pixels are below the detection threshold of the satellite retrievals, which is beneficial. As the pixel size of the satellite data is very small, one could also regrid them to a finer inversion grid and, thus, resolve finer structures of the ash cloud. This, in turn, would increase the effective vertical resolution of the method (at least if the meteorological data, especially the winds, are accurate enough) and, thus, compensate for the smaller wind shear.

Reference:

Rose, W. I., Bluth, G. J. S. and Ernst, G. G. J., 2000, Integrating retrievals of volcanic cloud characteristics from satel- lite remote sensors: A summary. Philos. Trans. R. Soc., Lon- don A No.358, 1585-1 606

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