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Atmospheric Chemistry and Physics
Discussions

Interactive comment on “Atmospheric processes affecting the separation of volcanic ash and SO_2 in volcanic eruptions: Inferences from the May 2011 Grímsvötn eruption” *by* Fred Prata et al.

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1 Summary

The paper reports on the dispersal of volcanic ash and sulphur dioxide from the May 2011 eruption of Grímsvötn volcano, Iceland. It demonstrates that most of the the ash, which was mainly present in the lowest 4 km of the plume, was transported southwards and then east to Europe; the sulphur dioxide travelled northwards at higher altitudes. Various satellite data were used. Infrared and LiDAR measured the altitude of the ash cloud. Ash concentration and grainsize were retrieved from infrared data. Infrared and ultraviolet data were used to retrieve concentration and erupted mass of SO2.

Dispersion modelling found that smaller mass eruption rates than would be calculated based on the plume height gave a better match to satellite observations. A model of plume physics demonstrates that addition of meltwater resulted in a large region where liquid water was present. This could promote aggregation and premature deposition of fine ash. The study concludes that forecasts of ash concentration and our general understanding of volcanic cloud behaviour would be improved if volcanic ash and SO2 were modelled as independent components.

2 Contribution

Understanding the separation of volcanic ash from sulphur dioxide is important to the wider understanding of volcanic plume processes and the hazards presented by airborne volcanic ash. Such separation is most common in lava-producing eruptions. This paper provides a striking example of separation during an explosive eruption where much extremely fine ash was produced. As such, it is a very interesting contribution.

The satellite methods used are all well-established, as was the tool used for modelling dispersion of volcanic ash. The modelling of aggregation within the plume is a new application of an existing volcanic plume model.

The main conclusion, that most of the volcanic ash was transported in a different direction from the sulphur dioxide gas is well supported by the data. However, there are other statements that are not well supported and should be dropped. These include:

- "separation of material ... is inevitable ... in presence of wind shear"
- that "column collapse" was the reason for the low level of the ash-rich plume
- that the ash cloud "was not significant enough to cause a hazard to aviation"

Instead, I think that the following conclusions deserve more emphasis.

- Modelling of plume physics shows that addition of meltwater leads to a large region in the plume where water is present in the liquid phase. This promotes aggregation of ash and premature deposition of finer particles, leading to low concentrations of ash in the upper part of the plume.
- The separation of gas and ash was a consequence of *both* aggregation *and* wind shear.
- The Mastin equation, which relates discharge rate to the fourth power of the plume height and which is based on data from ’dry’ plumes, is not appropriate when eruptions take place through water or ice.
- Satellite data are very useful in evaluating dispersion model predictions and this eruption highlights a situation where refining dispersion model source parameters using inversion techniques could have resulted in improved predictions.

3 Suitability for publication

The main findings of the paper represent an important case study and should be published. However, there are areas where major revisions are required before the paper is suitable for publication.

4 Areas for revision

4.1 Missing reference

The authors should discuss their results in the context of findings of Stevenson et al (2013), who measured deposition in the UK of ash from the Grímsvötn 2011 eruption. The most relevant findings were that:

- The majority of ash deposition was in Scotland on 24-25 May (in agreement with modelling results and satellite observations presented here).
- Air mass trajectories showed that material from the lowest 4 km of the plume was transported southwards, while material higher up was transported northwords (in agreement with modelling results and satellite observations presented here).
- Ash deposited in Scotland had a median grainsize of 19-23 microns and a maximum of 80 microns (significantly higher than suggested by the effective radius values presented here).
- Pollen traps in Scotland collected tiny (3-5 micron length) ash particles that fell within rain drops on 27 May. Trajectory analysis showed that these came from the upper part of the plume and had travelled via Greenland. Thus, there was at least some ash present in the material that went north. (Raising the question of why it was not detected in the IR retrievals or why the particles appear spherical to Caliop LiDAR).

4.2 Discussion of physical volcanology and plume ’collapse’

The discussion of physical volcanology is speculative and contains some errors. The figure shows Grímsvötn as a conical peak, when the eruption took place in a caldera lake, and shows the SO2 and ash clouds moving in the same direction. The text uses out-dated terminology (e.g. pyroclastic flows instead of pyroclastic density currents) and contains factually incorrect statements e.g. that the meltwater 'added' energy to the plume (it absorbs it from the magma during vaporisation and releases it again at altitude when it condenses).

I think that this section should be trimmed by removing the discussions of collapse mechanism, which are not informed by new data from this study. The focus on aggregates, which are explained by the subsequent modelling section, should be sharpened.

Nevertheless, I also recommend that the authors cite Jude Eton et al (2012), which describes the plume and the deposits from the 2004 eruption at Grímsvötn. I have worked on the 2011 deposits in the field (as has Thordarson) and they are very similar and indicate that the same processes took place. The paper contains very instructive photographs of ground-hugging, laterally-emplaced density currents that were sourced from the eruption column that do not require 'collapse' of the plume.

4.3 Uncertainty estimates for ash retrievals (Figure 7)

On Page 16, the authors state that "the error in estimating fine ash mass from infrared retrievals has been investigated by Wen and Rose (1994) and Prata and Prata (2012), who suggest errors of 40-50%". I would suggest that this is strongly underestimated.

There are two lines of evidence within this study that suggest this.

Firstly, the authors state repeatedly that much of the ash cloud is covered by meteorological cloud. This will prevent detection in those regions and is a large source of uncertainty. Therefore, any estimates should be treated as minima and the symmetrical error bars in Figure 7 are not appropriate. The upper bars should be much longer.

Secondly, the three different measurement techniques (SEVIRI, MODIS, IASI) produce results that disagree by more than the size of the error bars. If two measurements

of the same feature disagree, then either the measurements are wrong or the errors have been underestimated. The reasons for disagreement are not fully investigated, but it is suggested that IASI has higher readings because it works better when the ash is overlaid by meteorological cloud. This suggests that SEVIRI and MODIS have systematically underestimated the mass loading and so again, the upper error bars should be extended. This also means that mass loading estimates based on SEVIRI or MODIS data for other eruptions where clouds were present, e.g. Eyjafjallajökull 2010, were also underestimated.

There are also two extra sources of error that have been highlighted since the references cited made the estimate of 40-50%.

Firstly, the 40-50% figure assumes that the particles are dense spheres. Prata and Prata (2012) cite Wen and Rose (1994) and Gu (2005) [who, in turn cites Gu et al 2003] as the source of this estimate. Wen and Rose only considered the effect of varying the size distribution and particle composition. Gu et al add variations in surface and cloud temperatures. They also include a shape factor, however their study looks at desert sand and not volcanic ash.

The dense spheres assumption is not met by volcanic ash. The authors demonstrate this with CALIOP data, which show high volume-depolarization ratios for clouds rich in volcanic ash. Deviation from this assumption increases the uncertainty. Kylling et al (2013) demonstrated that if the particles are vesicular spheriods, then the mass loadings are underestimated by up to 40%. In fact, the grains are bubbles and plates and shards (see pictures in Stevenson et al., 2013), so the deviation is even greater.

Secondly, satellite retrieval algorithms have been shown to systematically underestimate the grainsize and the mass loading of ash clouds, even where the dense spheres assumption is met. Stevenson et al. (2015) used simulated satellite images to show that algorithms prefer solutions with low concentrations of smaller particles (which exhibit a strong brightness temperature difference effect) to ones with high concentrations of larger particles (which exhibit a weak BTD effect). Clouds with many large particles do not exhibit a BTD effect, so they are indistinguishable from meteorological clouds and are not included in mass loading estimates. Stevenson et al. (2015) suggest that over 50% of the mass can be missed in this way.

There is evidence of such underestimation in this study. Figures S4 and S5 include effective radius estimates generated from SEVIRI and MODIS data. There are no values higher than 8 microns, which corresponds to a number size distribution with a modal diameter of 5 microns and a 95th percentile of 15 microns. This is significantly lower that measured values from ash deposited in Scotland (median length 19-23 microns, 95th percentile 42-51 microns). On the other hand, the corresponding mass size distribution has 95th percentile of 64 microns. This discrepancy should be discussed.

4.4 Discussion of the failure to detect ash grains in the upper plume

Pollen sensor data demonstrates that there was some ash in the upper plume (Stevenson et al., 2013). This is corroborated by reports of ashfall in northern Iceland described in the paper. It is also to be expected, unless the aggregation process was 100% effective.

Some discussion should be included about why it was not detected by the satellites. Reasons may include:

- The ash grains were not spheres, but shards. Although they are 3-5 microns in diameter, they are a tiny fraction of micron thick and may not exhibit a strong differential absorption.
- The low Earth surface temperature of Arctic sea ice and the Greenland ice sheet may limit the potential for brightness temperature differences.
- The ash grains may have been coated by ice.

- The ash concentration may have been too low.

5 Other modifications

5.1 Plume height time series

I think that the paper would be improved by replacing Figure 3 with a time series of plume height data. Four sources of plume height measurements are mentioned in the paper, radar, cloud shadow, IR brightness temperature for volcanic ash, and IR brightness temperature for SO2 (which appears to be a new technique). It would be very instructive to present a time-series graph of plume height using the various methods. This would allow the evolution of the eruption to be understood and so the height-estimation methods to be compared.

6 Line-by-line comments (page:line)

- 2:20 - Magma composition is important factor in separation. Basaltic magmas (e.g. BárÃřarbunga 2014) have low viscosity and fragment into coarse particles that easily separate from gas. Silicic magmas (e.g. Mt St Helens 1980, Chaiten), or basaltic eruptions through water (e.g. Grímsvötn), fragment into smaller particles. Some of these particals are essentially aerosol and only separate from the gas through aggregation.
- 5:20 - Good to emphasise the importance of getting the correct height.
- 7:20 - What is the explanation for the difference in height estimate between radar and that satellite measurements?

- 8:table1 - Add columns for spectral range e.g IR, UV and whether active or passive.
- 9:figure3 - A time series plot would be really nice here.
- 10:5 - Much of this information should be in the figure caption.
- 11:figure5 - (a) add direction of travel arrow to overpass. Which bands are compared in BTD? (d) what is the peak at 5 km? it is as large as the SO2 signal over Greenland. What do the black lines represent?
- 12:5 - The non-spherical particles measured here contradict an important assumption in the ash retrievals and dispersion models. The implications of this should be discussed.
- 14:5 - The definition of fine ash is discipline specific. Ash <63 microns is 'extremely fine' to a volcanologist.
- 14:12 - Define exactly what mass means e.g. sum of all detected, ash-containing pixels?
- 14:figure7 - The error bars appear to be +/-20-25%. This is an underestimate.
- 15:5 - Be explicit about what the different assumptions between IASI and SEVIRI retrievals are, including references.
- 16:9 - The 'Separation of the dispersing volcanic cloud' section is poorly named. It mainly describes cloud top height measurements, so the contents should be moved to that section of the paper.
- 16:15 - Which wavenumbers, which models. Give reference(s).
- 16:17 - Give examples of other causes of positive BTD (with references) and explain why they are 'generally unusual'.

- 16:27 - What are the altitudes of the sounding level peak contributions?
- 18:13 - A pyroclastic flow is typically used to mean a dense current supported by particle-particle collisions moving on the ground. These can travel in all directions depending on topography, including upwind. The more modern and generic term 'pyroclastic density current' includes low density currents supported by a turbulent gas phase. Their travel direction may be influenced by wind. Lenses of different-sized grains in the deposits from G2011, which correspond to dunes or ripples, are evidence that this took place.
- 18:figure10 - The vertical column is shown as the source of a gravity current moving along the ground. What is the source of particles at 4 km altitude that are carried to the UK? Note that images from G2004 in Jude-Eton et al show particles raining downwards from bent over plume then spreading horizontally across the glacier surface in a dilute pyroclastic density current.
- 19:1 - How can a low-level ash layer 'persist' for 24 hours before moving south or east? Surely it would sediment out or be advected away during that time?
- 19:5 - The term 'collapse' here evokes images of total column collapse and dense pyroclastic density currents moving in all directions (e.g. the Pinatubo eruption in 1991). This did not happen at Grímsvötn in 2011.
- 19:10 - The presence of hail is an indication of the removal of water from the plume. The ash itself, particularly the fine grainsize, is the evidence for the rapid removal of ash.
- 19:16 - I prefer the idea of the column sloughing to it collapsing. What is the altitude of this skirt? Does it reach from the ground to 4 km or does it disperse above the ground level.
- 20:5 - The radar measurements should be in the plume height section.

- 20:10 - Be explicit about how the observations rule out ash separation at the source or in the laterally intruding cloud.
- 22:figure13 - Mark a 'Region of wet aggregation' on each of the subplots based on subplot (b).
- 23:11 - Separation of material is not inevitable. Extremely fine ash produced by explosive eruptions is suspended in turbulent air. Separation only occurs if particles aggregate. The composition of the magma and the size distribution of tephra at the vent are crucial. All eruptions are not equal.
- 23:23 - The plume model does not reproduce the observations, it provides evidence for liquid water in the plume that would enhance aggregation.
- 24:figure14 - This chart only shows the presence of ash, and does not mention concentration. It shows the ash-rich plume moving south. It shows the SO2-rich plume, which also contained some ash, moving northwards. This is in agreement with the results presented in this paper.
- 24:1 - Provide a reference for concentrations in Europe. Prata and Prata (2012) present ground-based PM10 data from 6 locations in Norway and Scotland. These cannot be generalised to the atmosphere, nor to a wider area.
- 24:4 - This wording suggests that there was nowhere that the ash was sufficiently concentrated to be a hazard to aircraft. This is not true. The south coast of Iceland during the eruption was clearly hazardous. It is important to specify a location and time. The satellite retrievals presented in figure S5 show total column loadings of around 1.8 g/m^2 to the west of Scotland on 23 May. Assuming that the plume was 1 km thick, this corresponds to 1.8 mg/m^3. Taking into account the uncertainties in the method that mean these retrievals represent minimum values, then it is probable that there were locations where the concentration exceeded

the 2.0 mg/m^3 limit for Zone of Medium Contamination that aircraft require special permission to enter.

- 24:15 - See also recent work by Julia Eychenne on the Mt St Helens pyroclastic density currents as a source of ash plumes.
- 25:2 - I would also argue that the fourth-power law is inappropriate for eruptions through water or ice.
- 25:14 - Is hemispheric spread likely? I thought that circulation patterns moved air to the poles and Grímsvötn is already close to the Arctic.
- 25:15 - Can you put the mass released into context with other eruptions that did effect climate?
- 27:equation1 - What is sgn?
- 27:26 - The sensitivity of fall velocity to the drag coefficient is discussed. The particle density will also vary greatly. Volcanic glass is 2 to 3 times more dense that water, and dry aggregates contain large propotions of void space. This may have a greater impact on fall velocity.
- 28:1 - Why did you use radar plume height data when the rest of the paper disagrees with it?
- 28:16 - It would be excellent to get particle size data for the grains within the hailstones from Arason et al (2013) and compare with the predictions. Is it possible to contact them?
- S1:6 - Why only model up to 10 km when the plume went higher?
- S2:2 - What is the geometric standard deviation of the distribution?

- S2:5 - Give more information about the bi-Gaussian vertical distribution. What were the levels, what proportion of mass was assigned to each, why were those values chosen?
- S7:figureS4 - What is the geometric standard deviation assumed?
- S8:figureS5 - What is the geometric standard deviation assumed?

7 References

- Gu Y (2005) Advantageous GOES IR results for ash mapping at high latitudes: Cleveland eruptions 2001. Geophysical Research Letters. doi: 10.1029/2004GL021651
- Gu Y, Rose WI, Bluth GJS (2003) Retrieval of mass and sizes of particles in sandstorms using two MODIS IR bands: A case study of April 7, 2001 sandstorm in China: RETRIEVAL OF MASS AND SIZES OF PARTICLES IN SANDSTORMS. Geophysical Research Letters. doi: 10.1029/2003GL017405
- Jude-Eton T, Thordarson T, Gudmundsson M, Oddsson B (2012) Dynamics, stratigraphy and proximal dispersal of supraglacial tephra during the ice-confined 2004 eruption at Grímsvötn Volcano, Iceland. Bulletin of Volcanology 1–26. doi: 10.1007/s00445-012-0583-3
- Kylling A, Kahnert M, Lindqvist H, Nousiainen T (2013) Volcanic ash infrared signature: realistic ash particle shapes compared to spherical ash particles. Atmos Meas Tech Discuss 6:8937–8958. doi: 10.5194/amtd-6-8937-2013
- Prata AJ, Prata AT (2012) Eyjafjallajökull volcanic ash concentrations determined using Spin Enhanced Visible and Infrared Imager measurements. J Geophys Res 117:24 PP. doi: 2012 10.1029/2011JD016800

- Stevenson JA, Loughlin SC, Font A, et al (2013) UK monitoring and deposition of tephra from the May 2011 eruption of Grímsvötn, Iceland. Journal of Applied Volcanology 2:3. doi: 10.1186/2191-5040-2-3
- Stevenson JA, Millington SC, Beckett FM, et al (2015) Big grains go far: understanding the discrepancy between tephrochronology and satellite infrared measurements of volcanic ash. Atmos Meas Tech 8:2069–2091. doi: 10.5194/amt-8-2069-2015
- Wen S, Rose WI (1994) Retrieval of sizes and total masses of particles in volcanic clouds using AVHRR bands 4 and 5. J Geophys Res 99:PP. 5421-5431. doi: 10.1029/93JD03340

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