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Natural Hazards and Earth System Sciences
Discussions

Interactive comment on "Modeling volcanic ash aggregation processes and related impacts on the April/May 2010 eruptions of Eyjafjallajökull Volcano with WRF-Chem" *by* Sean D. Egan et al.

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General Comment1: *"Should aggregation uncertainty be considered in an emergency response situation?"*

As mentioned in the paper, aggregation can reduce the total erupted mass substantially, which will reduce the total atmospheric loading of both proximal and distal ash. For example, we reference Van Eaton et al. (2015), who detailed rapid aggregation of proximal ash at the onset of the eruption of Mount Redoubt. This reduces the total amount of both proximal and distal volcanic ash. Aircraft hazard mitigation

involves placing limits on the concentration of volcanic ash that commercial aircraft may encounter. Including volcanic ash aggregation into WRF-Chem, as well as other dispersion models, allows it to capture a more realistic change in the concentration of ash with time, and therefore more realistic volcanic ash concentrations. Therefore, if an Eulerian model is used in an emergency response, it would benefit from the inclusion of this important microphysical process. The text has been updated to reflect this by including the following discussion to the background:

> "Volcanic ash aircraft hazard mitigation typically focuses on limiting commercial aircraft to ash concentration thresholds (Casadevall, 1994). WRF-Chem solves the advection equations such that ash concentration is tracked over time. This ability to track volcanic ash mass, rather than particle number, augments current VATD models and offers another tool to constrain atmospheric ash loading."

General Comment 2: *"Aggregation will only reduce the distal ash concentrations so maybe computational effort should be put into performing ensemble simulations that vary eruption plume height or the meteorological situation."*

This is a valid approach for modeling volcanic ash dispersion which is already in use. Volcanic ash plume models such as the aforementioned FPLUME-1.0 detailed by Folch et al. (2015), for example, run a computationally inexpensive set of calculations that results in parameters which can be input into volcanic ash dispersion models. FPLUME, in addition, includes parameterizations for volcanic ash aggregation, allowing the forecasting of the resulting particle size distribution in long range deterministic and ensemble models.

While this approach is valid and useful for a number of applications, the integration of volcanic ash aggregation into WRF-Chem has distinct benefits. First, WRF-Chem can be used to study a number of physical processes involved with the suspension and transport of volcanic ash in the atmosphere, such as the radiation feedbacks studied by Hirtl et al. (2019) that we mention in the introduction. Including an aggregation option in WRF-Chem allows researchers to include this important microphysical process into the model's treatment of parameterized volcanic ash particle size distributions. Second, volcanic plume models initialize a particle size distribution based on a number of physical processes, to include aggregation. These distributions are then carried forward in the calculations as the proximal plume becomes distal. At this time, the calculations that change the particle size distribution in the distal plume are only based on advection and gravitational settling equations. Aggregation equations allow for another important sink to be considered in the modeling of distal plume ash concentrations.

General Comment 3: *"Can WRF-Chem be run in real-time emergency response situation?"*

WRF-Chem has not yet been used in an emergency response situation, but it is feasible to consider it for such a purpose. With continued increases in computational power, solving for fully coupled, Eulerian solutions has become increasingly cheap. In our studies, a 4 day simulation with 48 hour spin up time using the model parameters detailed in the paper required less than 20 minutes to complete using 512 processing cores. This could augment current Lagrangian particle dispersion models which are able to provide instant results by providing volcanic ash concentrations which take into account not only gravitational settling and wet deposition, but also aggregation processes.

General Comment 4: *"What over head is added by including the representation of aggregation?"*

The added overhead from the aggregation code is minimal. Because the integration has been reduced to a set of simple algebraic computations, the resulting increase in model time is less than 5. These effects scale with domain size and a parametric study could be conducted to show the overall increase in overhead with number of cores and domain size.

Text Comment 1: *"L29: Missing "and" between tools, the study of ash physics"*

These lines have been updated appropriately.

Text Comment 2: *"L30: Could state what the characteristics of the plume are required for modelling."*

These are enumerated later in the text during the model setup, however we updated line 30 to clarify further as follows:

> "Numerical models have been developed to better describe the initial plume characteristics of eruptions, such as plume height, shape, mass loading and particle size distribution, which are all necessary parameters for ash forecasting. "

Text Comment 3: *"L37: Unsure what you mean by plume corner here"*

This terminology has been changed to "edge". The term "corner" stemmed from the use of the model grid cell "corner" that acted as the start and end of the distance calculation.

Text Comment 4: *"L95-102: The text here seems a bit clumsy with section numbers and headings men- tioned Would it be possible to include the equations and* *associated parameters in Table 1 in the main body of text? It would make it easier to follow."*

The equations in Table 1 are mostly referenced in the text to follow, so we are hesitant to move it farther up, but we will discuss with our editor how to best follow up on this comment.

Text Comment 5 and 6: *"L163: This should be equation 6; L180: This should be equation 7"*

These equation references have been corrected.

Text Comment 7: *"L181: Refer to Table 3 so the reader knows the particle sizes that the bins refer to."*

A reference to Table 3 has be added for clarity.

Text Comment 8: *"L205: "radar" missing"*

This word radar has been added after Doppler.

Text Comment 10: *"L216: You refer to 10km2 as high resolution. This maybe true when considering long range dispersion but is it high enough for modelling aggregation near the eruption plume?"*

This study primarily focused on the dispersion of distal volcanic ash. For a study of near vent volcanic ash fallout, one could use a nested domain with a much higher, for example less than 1 square kilometer, resolution. We now address this in the paper by including the following text:

> "As stated, the majority of volcanic ash aggregation occurs proximally, especially when high water vapor concentrations are present in the eruptive column. Future studies of volcanic ash near the vent should consider including a nested, high resolution domain over the source to allow for the study of proximal ash fall. We will add a discussion of this to the conclusions portion of the paper in order to highlight the capability of WRF-Chem to include nested, high resolution domains, and add that the equations used also apply to near vent, proximal aggregation."

Text Comment 11: *"L223: Are 48 hourly meteorological initialisations frequent sufficient?"*

These could be more frequent. The choice of 48 hour re-initialization was chosen to offset the very large lag time that was required by the computation cluster in use. Every time WRF was re-initialized the model first had to checkout processors from the cluster. The cluster we used sometimes would queue these jobs for days before launching. Additionally, the 48 hour re-initialization was used by a study of volcanic ash using WRF-Chem by Hirtl et al. (2019) who observed good results with this interval.

Text Comment 12: *"L244: Why change from 48 hours to 24 hours?"*

The sensitivity study covered only 6 days which allowed for 24 hour re-initializations. We briefly discuss that this choice is to make the sensitivity study "higher fidelity".

Text Comment 13: *"L245: A table outlining the different sensitivity studies would aid the reader here."*

A table has been added to the paper that details these studies. One column lists the parameters varied (total domain mass, each collision kernel, water vapor and the fractal dimension) and the second column lists the method of analysis (change in total domain mass, change in bin mass, etc.).

Text Comment 14: *"L275: How representative is a Df=3.0 of the real world? Does Df vary from volcano to volcano?"*

This is discussed briefly in the text and will be elaborated upon more. For example, we mention that Folch et al. (2010) detail the correlation between Df and the aggregation rate using an aggregation enabled version of Fall3D. We will expand the discussion with their finding that Df=2.99 was realistic in the cases their study covered. Additionally, the sensitivity study shows little difference in the aggregation rate between $D_f = 3.0$ and $D_f = 2.99$.

Text Comment 15: *"L285: Why is the difference between 2.8 and 3.0 highlighted here. Is this unexpected?"*

We are highlighting the change in lifetime seen with varying fractal dimension. Only minimal changes in atmospheric residence time are seen with $D_f < 2.8$. The lifetime decreases substantially for $D_f = 2.8$ and greater. This is also noted in other studies mentioned in the paper where D_f was varied across a range.

Text Comment 16: *"L294: Is this jump that is highlighted unexpected?"*

It is expected, based on the parametric studies included in Costa et al. (2010). Equation 1 in the text reveals the exponential change in the aggregation function with varying values of D_f. This exponential variance is noted in the sensitivity study output.

Text Comment 17: *"L306: What are the implications for the different processes*

being dominant?"

This observation was also noted in Costa et al. (2010) in their parametric study. The main implication is that the contribution from the shear kernel is minimal, and therefore could be disregarded in the calculations.

Text Comment 18: *"L317: The small effect of coupling the aggregation to water emissions seems important. Should this be highlighted more or is it very dependent on the volcano?"*

This study focused primarily on the effects of aggregation in the distal plume. Despite the large amount of water vapor emitted from Eyjafjallajökull during its eruptive phases, the overall contribution to atmospheric water vapor as noted from total precipitable water observations during that time were minimal. A study of the effect of water vapor on proximal ash during the first minutes and hours of the eruption would likely show a greater effect, but the distal plume ends up dry due to the entrainment of dry air by the proximal plume.

Text Comment 19: *"L334: 3.9 should be 8."*

This has been corrected.

Text Comment 20: *"L334/335: Unsure of the use of "cast", "show" would be clearer."*

The wording has been changed as suggested.

Text Comment 21: *"L345: How much computational expense? Do you have plans to do this?"*

Decreasing the grid cell size increases the computational time slightly more than linearly due to the added communication between compute nodes. This is a known drawback to Eulerian models and we do not plan to resolve these with more higher resolution runs.

Text Comment 22: *"L346: What does 9C refer to?"*

This should read Figure 8c. This has been corrected.

Text Comment 23: *"L350: Why do you think that there is such a discrepancy between the observations and WRF-CHEM during this time?"*

We put significant effort into ensuring that this was not an analysis error. The vertical resolution of the model domain is much lower than the horizontal resolution with the most significant spread near the 500mb level. The larger uncertainty in the vertical resulted in differences in the concentration during the transect that were larger than the translational transects, in general. Increasing the vertical resolution of the model increases the computational cost exponentially, as opposed to the near linear increase experienced from increasing horizontal resolution. The text has been updated to include the following discussion:

> "An analysis of the surrounding grid cells in the vertical and horizontal did not contain this peak, however the next vertical grid cell in the positive k contained higher ash concentrations. This analysis, along with analysis of the integrated volcanic ash over the time span of the peak, lead to the conclusion that this the lack of peak concentration in the model is a result of model diffusion."

Text Comment 24: *"L377: 11(d) should be 10(d).*

This has been corrected

Text Comment 25: *"L400: Is wet deposition represented in WRF-CHEM? This can have a large impact on the long-range plume development."*

The volcanic ash settling routine in WRF-Chem does consider wet deposition by increasing the effective radius of the particles, and thus their fall rate, with increasing relative humidity. The following discussion has been added to make this more clear:

> "Without aggregation, the only sinks for volcanic ash are via settling, which is dependent on gravity and water vapor concentration, or via the plume traveling out of the model domain."

Text Comment 26: *"L450: Unsure what is meant by global models here"*

This is in reference to global spectral models, such as the Global Forecast System run by the National Centers for Environmental Prediction and Integrated Forecast System run by the European Center for Medium-Range Weather Forecasts.

Figure Comment 1: *"There seems to be a mismatch between using lower case labels on plots and capital letters in the captions. Please make these consistent."*

These figure labels have been updated as suggested.

Figure Comment 2: *"Figure 5: Think about colouring lines to make it easier for the reader to compare lines with same Df."*

We updated the color schemes with a few different options and will discuss them with the editor to find the best for the final version.

Figure Comment 3: *"Figure 6: The subfigure labels are missing. There seems to be a grey bar between the panels. Reorder the legend to make it easier for the reader (e.g. No aggregation all in same column)"*

These figures have been corrected to include all labels and are separated by column.

Figure Comment 4: *"Figure 7: Rainbow colour scales are not suitable for people who have colour blindness. Please considering using a different colour scale. Unsure what "Note each time output is at 00hr" means."*

We will discuss alternative color schemes with our editor that are more easily seen by those with color deficiencies.

Figure Comment 5: *"Figure 8: As Figure 7 – please consider using a different colour scale."*

We will discuss with the editor our options for different color scales to find the most appropriate for the publication.