

Review of manuscript by Ulrike Niemeier et al. for Climate of the Past journal
"Simulation of ash clouds after a Laacher See-type eruption"

This manuscript presents a very interesting analysis of interactive stratospheric aerosol simulations of the volcanic ash and sulphuric acid aerosol cloud from the VEI6 Laacher See eruption (Germany, 13,000 years ago,) comparing to tephra deposits across central and northern Europe.

The interactive stratospheric aerosol modelling is novel in resolving both components of the volcanic cloud, and in assessing how the radiative effects from the ash, primarily via absorption of solar radiation, change the wind flow, and the onward dispersion of the cloud in the initial weeks after the eruption.

There are some important findings in the study, and the science is certainly within scope of the Climate of the Past journal, and the manuscript will be publishable, but requires first some substantial improvements to better communicate the results with also some changes of emphasis in their interpretation.

Whilst the conclusions section was well-written, I found several parts of the manuscript were quite poorly worded, with the Abstract also needing sharpening up. As a consequence I have listed below a large number of minor specific revisions that need to be addressed to improve the explanation of the results before being ready for publication.

And whereas the interactive stratospheric aerosol modelling is a clear strength of the article, and presents a genuine advance to understand the impacts of the ash on the sulphate cloud that causes the climate impacts, the Abstract did not sufficiently explain the rationale to assess this, and mistakenly stated "southerly" when southward was meant, in the clockwise rotation of the predominantly eastward transport found in the experiments and the tephra deposits.

Another concern I have is that the Results section seems to attribute the rotation of the cloud entirely to the heating effect from the volcanic ash. Although clearly the volcanic cloud has important radiative effects, it's clear that even in the control run, the flow pattern changes markedly through the weeks in May (shown in Figures 1a to 1d), with the volcanic cloud then being transported already with this "rotation".

Also, the word "rotation" seems non-geoscientific somehow -- it's not really a rotation in the same way as the coriolos force. I'd argue it is more of a horizontal wind shear effect from the change in the flow pattern (and hence the direction the plume is transported). I suggest the authors consider changing the terminology, although in general I guess that is consistent. See also comment 41 that also in other places the authors seem to mean recirculation rather than rotation.

The last sentence of the Abstract includes somewhat hyperbolic or non-scientific wording and overall the article feels like it has not been properly checked across the author team.

There are really a lot of places (see Main minor revisions) where the text is poorly worded, too vague and not scientifically descriptive enough to explain the basis of the model runs. The study is really very interesting, and I'm sure the authors can make the required revisions -- which are mostly minor but important re-wordings. But because of the large number of these "Main minor revisions", I am having to recommend major revisions in my review (but I am happy to review the article again once the revisions have been made).

I have continued to write a long list of comments, but still have further comments on paper. But the authors need to review the writing of the results section, and I strongly suggest they try to improve the wording themselves before submitting the revised version.

Main minor revisions

1) Abstract, line 6 -- the phrase "informed out experimental set-up" sounds too technical and isn't it true to say it is the tephra deposits (from Figure 2b) that provide the primary constraint for the model experiments? I'm suggesting then to be clearer and rather than "This evidence", state explicitly that the tephra is the main constraint. So after the more general sentence that includes also the paleo-ecological and archaeological evidence, to make this sentence specifically about the tephra deposits. I mean replace "This evidence has informed our experimental setup" with "LSE tephra deposits across northern and central Europe have provided the primary observational constraint for simulated ash deposition as a validation test for the interactive simulations. Or similar wording to this.

2) Abstract, lines 7 and 8

This sentence in the Abstract explaining the experiments are at different injection altitudes and emissions strengths does not need to provide the specific pressure values for the chosen injection altitudes, and the amounts of SO₂ emitted. And doing so makes the sentence clunky and difficult to read. Suggest to delete "(30, 60 and, 100 hPa)" and "(1.5, 15 and 100Tg SO₂)" For the different injection heights, just say "at different altitudes within the lower stratosphere" and for the emissions amounts just say the best-estimate amounts of 20 Tg SO₂ and 200Tg of fine ash, because the lower and higher are just sensitivity runs for much larger and much lower amounts. Nine of the 11 simulations use that 20 Tg of SO₂ and 5 of the 7 runs including ash use that 200 Tg of ash amount -- so it's only necessary to state that value here.

Suggest to add "across two eruptive phases in May and June" and re-word the sentence to something like:

"The interactive stratospheric aerosol model experiments are based around a central estimate for the LSE aerosol cloud of 20 Tg of SO₂ and 200 Tg of fine-ash, across 2 eruptive phases in May and June (of 10-hour and 3-hour duration), sensitivity experiments injecting to different altitudes within the lower stratosphere.

I suggest also to add a 3rd sentence explaining about the modelling rationale to assess the role the ultra-fine ash plays in modifying the dispersion of the volcanic sulphur. I mean something like:

"Additional sensitivity experiments assess how the solar-absorptive heating from the 150 Tg of sub-micron ash emitted in the 1st eruptive phase changed the LSE cloud's dispersion.

3) Abstract, line 9 -- The phrase "it proved difficult" is not really appropriate in an Abstract. And in this case, it's not really necessary to represent exactly the meteorological conditions. I wonder whether it's maybe more that you're accepting it won't represent the climate conditions, but that the experiments are designed to represent the approximate meteorological regime.

Suggest to re-word this sentence to "Whilst our simulations are based on present-day conditions, and we do not seek to replicate the meteorological [or climate?] conditions that prevailed 13,000 years ago, we consider our experiment design to be a reasonable approximation of the transport pathways in the mid-latitude stratosphere at this time of year."

And then continue with a new sentence providing the remainder of the sentence you have there, but delete the word "novel" and "crucial" which might be considered too much like hyperbole. Suggest re-wording slightly to something more objective such as: "The simulations show how the heating effect from the emitted fine-ash plays an important role in the subsequent dispersion of the volcanic cloud (both the sulphate and the ash)"

4) Abstract line 15 -- "throw new light" -- it's not possible to throw light.

I think you mean "shed light" but again this is too subjective for a journal article. Also "awakened" seems out-of-place -- It reads like a copy and paste from a popular science journal or proposal... Please re-word to something more scientific and objective, such as: "The simulations provide insight into the impacts from the Laacher See eruption, and more generally for dispersion of mid-latitude volcanic clouds in the stratosphere."

5) Introduction, lines 49-50 -- This sentence seems to be starting to introduce the interactive stratospheric aerosol modelling -- and there needs to be at least 1 paragraph here (or somewhere in the Introduction) that explains about interactive stratospheric aerosol modelling studies of volcanic ash and sulphur -- the authors' own Niemeier et al. (2009) study is not even mentioned at all in the Abstract.

Since the paper is mainly applying an interactive stratospheric aerosol model to simulate the volcanic aerosol cloud, the Introduction needs to have a paragraph or 2 explaining about modelling studies of similar very large magnitude volcanic aerosol clouds, perhaps one on the interactive stratopsheric aerosol models, and one on either modern observations from Pinatubo & El Chichon or on the impacts from climate model studies. E.g. cite the articles by Vernier et al. (2016), and ash modelling from mid-latitude eruptions such as 2008 Kasatochi (e.g. Langmann et al., 2010) or more recent articles modelling the ash dispersion from 2019 Raikoke (e.g. Muser et al., 2020).

The paragraph at the start of Results Section 3 (from lines 180 to 184) seemed to be giving some Introduction to findings from ash modelling but that should be in the Introduction not in the Results section.

6) Page 4, line 98 -- "For our simulations only natural sulfur emissions are taken into account". I'm inferring that this sentence is explaining anthropogenic sulfur emissions are not included, but it's not clear from the wording whether it might alternatively mean there are no other natural emissions (e.g. biogenic VOCs). And does the sentence mean DMS is included or not? And what about passively degassing volcanoes? Re-word to state more clearly what is not included that sometimes is. "For these simulations, no anthropogenic sulphur was included, only surface DMS emissions and tropospheric volcanic SO₂ from passively degassing volcanoes" and give the reference for the inventory used or other paper that did the same and explained the method (e.g. as in xxx et al. 20yy). The next sentence says "This model" -- so are the anthropogenic emissions the same in all these simulations even though the 2009 paper is for 1991 Pinatubo whereas this is for 13,000 years ago? Please provide more info here to explain what is different from those other volcanic studies and that other things are the same. The Niemeier and Timmreck does not emit volcanic ash -- only the Neimeier (2009) does. So these are clarily different models (or at least different configurations). The vertical resolution is here a lot higher and the version of the atmosphere model different, right? Please state this, as it's then good to point out where these simulations might be more realistic. The Niemeier et al. (2009) model only had 39 vertical levels for example.

7) Page 4, line 104 -- "This might play a role for determining the specific day of the eruption as discussed in Section 2.2.2". That sentence really doesn't make sense for a number of reasons. Firstly, it is under-playing the significance of the previous sentence. You've acknowledged that the different Arctic sea-ice cover is likely to have changed the stratospheric circulation and dynamics. Even without that issue, there'd still be the different meteorological variability between what actually happened when the eruption occurred and the year these simulations are representing. It's more that the climate situation, and the timing of the disturbed meteorological situation at vortex break-up would likely be different. Also, the current wording "might play a role in determining the specific day of the eruption" is just the process you've followed to get the model to represent this situation. Please re-word this sentence to be more appropriate for the Climate of the Past audience rather than framing it simply as a model set-up issue.

8) Page 4, line 108 -- Change "We focus here on a Laacher See-type eruption which could produce.." to something more scientific such as "The approach when setting up the model experiment, was to focus on ensuring the transport of the ash in the simulations captured the observed two-lobed pattern in the tephra deposits." And suggest to make within that same sentence (at the end) the point about the two eruption phases. That then makes more clear to the reader the link between the timing of the 2 eruption phases and the 2 observed lobes in the tephra deposits." Suggest to delete "Hence we consider in our simulations two eruption phases", and instead say this as an extension to the previous sentence -- I mean extend "pattern in the tephra deposits" to "captured the observed pattern in the tephra deposits, the SO₂ and ash emitted within 2 distinct eruption phases." Then you can start the next sentence as follows to continue this point: "Firstly, a ten-hour-long eruption explosive phase, when the majority of the ash and sulphur were emitted, corresponding to the LLST, ash transported in the north-eastward lobe. And secondly, a shorter and less-substantial three-hour-long phase, corresponding to the MLST-C eruption phase, when the volcanic plume deposited ash in the southward direction."

9) Page 4, line 113 -- This sentence needs to be better worded. It's such an important part of the manuscript that sets out the basis of the modelling results and the authors should have taken much more care over this part of the manuscript. The current wording seems out of order, and the placing of the "released into the stratosphere" straight after "two historic ash lobes" is odd -- I realise this isn't meant but the wording is clunky and since the lobes are associated with the surface, they may not of course reflect the flow pattern in the stratosphere. Also, the word "difficult" is a poor choice -- although I realise whether something is difficult or easy affects the behavioural choices people make, the wording is unscientific in this physical science context. And of course if we all made easy choices scientific progress would be slow (in my opinion). That said, I'm simply suggesting to re-word "is difficult" to "is poorly constrained" or similar. I suggest to put the 150 Tg ash emission in this 1st sentence, and then explain the justification of the choice afterwards, re-wording this 1st sentence as below and deleting the last 2 sentences (that information then communicated up-front in the 1st sentence).

"Only very limited information exists to determine how much fine-ash was emitted in the Laacher See model experiments, and our best-estimate fine-ash emission of 150 Tg in phase one is based on the eruption rate of 4×10^8 kg/s given in Textor et al. (2003), based on the 10-hour duration and approximately 1% of the mass emitted was fine ash.

10) Page 5, lines 144-145 -- This initial sentence needs to be clearer this is referring to very large magnitude eruptions (on the scale of Pinatubo), and the word "mid-latitude" needs to be specified in the re-wording of the sentence. . Also, suggest to add ", in the first weeks after the eruption" to spell out exactly what is meant by "initial dispersion" of the cloud. Also, the Jones et al. (2016) study is referring to the Pinatubo cloud's dispersion within the tropical stratosphere, which is different from the mid-latitude stratosphere case considered here. The Toohey et al. (2019) reference is fine, because that is specifically discussing mid-latitude volcanic clouds, but a different 2nd paper needs to be cited here -- I suggest replacing the Jones et al. (2016) cite instead with Marshall et al. (2019), since this JGR paper (which you have already cited in the references) explores the aerosol clouds from both tropical and mid-latitude eruptions. Please re-word this sentence to be more specific here.

11) Page 5, line 145 -- The terms "Ash deposition pattern" and "long-range transport of volcanic ash" in this sentence are not sufficiently well defined. From the sentence after this, it sounds like you are referring to the very localised ash deposition within the proximal tephra deposits, rather than the fine-ash deposition at further distances. But the localised tephra deposits are probably determined more by the dynamical behaviour of the plume rather

than the flow pattern in the stratosphere. The distinction between localised ash fallout and long-range transport of ultra-fine ash needs to be made clear here. Suggest extending this current sentence instead to two sentences, then giving space to clarify there is a difference between the coarse ash particle deposition local to the site and the stratospheric flow pattern which determines the longer range transport. Although I realise that the tephra deposits have been the basis for establishing the deposition, and that is a reasonable basis given the very long length-scale of the tephra deposits, it still needs to be stated the role of the plume-scale processes for partially determining the ash deposition, but that you are arguing (and I agree) that in this case of such a very large magnitude eruption, the stratospheric flow becomes the most important driver.

12) Page 5 lines 146-150 -- The wording of this sentence needs to be improved. In particular, to explain better how it can be concluded this season of the eruption, and what is meant by the environs being of a "non-analogue nature". It is not clear to me what the authors are trying to explain here, and this sentence is an example of the many places in the manuscript where it feels like this manuscript has been submitted before it has been properly checked and the text improved to a high enough standard. Perhaps they mean the local environment is very different than today's, i.e. they meant "not analogous" rather than "non-analogue". But the meaning of those phrases in English are quite different and in any case not well explained. Suggest to discuss clearly within the author team how best to state this difference and then be able to justify the difference will only be second order compared to the main circulation drivers of the volcanic plume. Or something like that, probably with also some re-wording of the sentences after this one.

13) Page 5 lines 151-154 -- Again this wording is poorly worded -- "that matches an empirically known one" is not good wording and needs to be changed. The sentence can simply state that the model experiments are not intended to match exactly to the Laacher See tephra, but to approximate the main magnitudes of the ash emissions in the two eruption phases, and the change in flow pattern that the two lobes indicated likely occurred between the two phases. Delete "This is not possible for ancient eruptions." And I think the authors' phrase "is a prior lead" is confused with "a priori estimate" or similar. But again, I think "a priori" is not the right phrase -- I'd suggest "primary constraint" or similar. Please re-word that sentence also accordingly.

14) Page 6, Table 1 -- Suggest to change the labels of these experiments to make it easier for the reader to connect up the sensitivity simulations. The LS8 and LS9 are the no-ash equivalent runs of the LS1 and LS3 runs (respectively) -- and it will help the reader follow what is explained if you include already in the label that connectivity -- e.g. by labelling them "LS1-no-ash" and "LS3-no-ash". and LS10 and LS11 runs then labelled as LS1-no-ash-8day and LS1-no-ash-15day, so it's then clear immediately what those model runs are assessing.

15) Page 6, Table 1 -- The fine-ash number-emission values given in column 3 of Table 1 will not be meaningful to most readers of the paper, and it's clear from the ratio of these values to the total mass emission, that the same emission size must be used in all 7 model experiments that emit ash. Having those numbers alongside the mass emitted also makes the Table difficult to scan, and since the size is the same in all runs, the number-emission value can be given within an extra sentence in the caption, that initially states the emissions size used. I mean add sentence something like "In all 7 simulations that emit fine-ash, the same emission size distribution is used, with a geometric mean radius of xxx nm and standard deviation of y.z (particles emitted into the accumulation insoluble mode)" -- or similar. And then "With this emission size distribution, the 150 Tg of ash emitted in LSE1, LSE2 and LSE3 translates to a number-emission of 2.2×10^{23} ."

16) Page 6, line 160 -- More details of the control simulation need to be

provided here. Was this a TimeSlice run with periodic boundary conditions to repeat a particular year's conditions? Also, for how many years was the control run spun-up prior to the analysis of which year's May meteorology provides the required transition in the flow pattern for the two-lobed ash deposition signature seen in the tephra deposits. An indication should also be given as to how many years were considered to select this particular year for the main experiments. Was it only found in 1 year in 10 or a more common meteorological situation than that.

17) Page 7, caption to Figure 1 -- This Figure illustrates really nicely the change in the flow pattern that then achieves the two-lobe ash deposition pattern seen in the tephra deposits. However, the caption here is much too brief, and should communicate better the situation in these 1-week-separated snapshots of the flow pattern during the transition. The 4 panels in the Figure are labelled a), b), c) and d), and the caption should re-iterate to the reader the prevailing flow-direction in the region of the volcanic emission. Suggest a sentence such as "Shown are 1-week separated snapshots of the flow pattern through the 1st eruptive phase (LLST) with westward flow in disrupted to be eastwards over most of Europe on May 9th (panel b) and then temporarily Southward on May 15th (panel c), then returning to eastward flow on May 22nd (panel d)." Or something like this. The wording of the 2nd half of the 1st sentence also seems out-of-order somehow, suggest to insert "on selected days in May" before "of the control", deleting "at different days in May" at the end of the sentence, also deleting the "at 48 hPa" at the end of the sentence, and inserting "48 hPa" between "zonal" and "wind". Also moving "over Europe" to be after "Streamlines".

18) Page 7, line 180 -- I agree with the statement in the 1st sentence of the Results section, but at the very least a citation to a paper that has shown this is required here. As per my Main Minor Revision 5), the Introduction requires a paragraph explaining previous interactive ash modelling results (including the lead author's) and I suggest here to add to that paragraph also mention of the in-situ sampling of ash particles in the stratosphere from major volcanic aerosol clouds: Agung (e.g. Mossop, 1964, Mossop, 1965), El Chichon (e.g. Woods and Chuan, 1983; Gooding et al., 1983; Chuan and Woods, 1984; Rose and Durant, 2009) and Pinatubo (e.g. Pueschel et al., 1994). The 2nd and 3rd sentences here are also not Results and can be part of the added para in the Introduction.

19) Page 7, line 186 -- Again, I agree with the statement in this 1st sentence of section 3.1.1, but a reference should be cited for this, and again this should be in the Introduction section rather than the Results.

20) Page 8, line 190 -- The wording "LSE1 shows the main deposition closest to the Baltic Sea of all simulations" needs to be re-worded. And I suggest to append the re-worded version of this sentence as an extension to the previous sentence, i.e. re-word from "all simulations (Figure 2). LSE1 shows the main deposition closest to the Baltic Sea in all simulations" with "all simulations (Figure 2), with LSE1 showing best agreement with the LLST tephra lobe." Or similar.

21) Page 8, lines 192-193 -- Re-word these 2 very short sentences --- you're analysing in these 2 cases much smaller volcanic clouds (factor-10 less ash and SO₂ in LSE4) and then a much larger case, almost on the scale of Toba or so, and this needs to be explained to the reader as you are presenting the results. I mean to re-word to something like "The LSE4 and LSE5 cases are designed to illustrate how the radiative effects of a very large volcanic cloud effect the dispersion, the contrast between LSE1 and LSE4 giving the impact from the best-estimate LSE magnitude (15Tg SO₂ and 150Tg ash) to a much smaller volcanic cloud at 1.5 Tg SO₂ and 15Tg ash, then LSE5 representing a very large volcanic cloud at 1000 Tg of ash and 100 Tg of SO₂." I realise that this information is given in the Table, but the reader needs to be reminded of the nature of these experiments as the results are being presented.

22) Page 8, lines 213-214 -- The sentence begins "The deposition pattern of ash..." but you need to state "model simulated" or similar so it's clear you mean that predicted by the model experiments. More importantly, this issue of the ash showing "a turn towards south in all cases" needs to be clarified. As you've shown in Figure 1, even in the control run the flow pattern is already turning to the south for a brief period. And although I get that you're contrasting this among the different simulations, this initial sentence suggests it's entirely to do with the ash radiative effects. Your results do show the effect, but you need to note initially that the flow situation already does have a brief turn to the south in the control run.

Minor specific revisions

1) Abstract, lines 1 and 3 -- The acronym "LSE" needs to be introduced at first use, and suggest simply to add "(LSE)" before "was one of the largest" on Abstract line 1.

2) Abstract, line 4 -- the word "mirror" within "that mirror the empirically known ash transport" needs to be changed as it's too precise a term. Suggest to replace "that mirror" with "and show can reproduce quite well".

3) Abstract, lines 5-6 -- shorten the last part of this sentence -- you've introduced the acronym "LSE" already, and already stated the eruption occurred in the Late Pleistocene, and I suggest to replace "Late Pleistocene eruption of the Laacher See volcano" with "13 ka LSE". or "13 ka Laacher See eruption".

4) Abstract, line 12 -- "adds a southerly component" is too simplistic a description, and that's an error I think -- where you say "southerly" you actually mean "southward". Suggest instead to reword to "acts to effectively rotate the flow in a clockwise direction, with eastward flow changing to be more southward."

5) Abstract, line 14 -- change "Greenlandic ice cores" to "Greenland ice cores".

6) Introduction, line 20 -- The terms "VEI" and "M" have not been introduced, and it's a strange choice of 1st sentence to launch straight into those indices for the eruption. Suggest to replace "VEI=6/M=6.2" explosive" with "very large magnitude explosive"

7) Page 3, line 65 -- re-word "ash- and aerosol-driven" -- ash is an aerosol particle. I think by "aerosol-driven" you mean sulphate-driven? Please re-word accordingly.

8) Page 3, line 79 -- insert "volcanic aerosol" before "simulations for this study", so that it's clear immediately the model is simulating the volcanic aerosol cloud.

9) Page 3, line 79 -- the word "GCM" has not been explained -- this acronym could be introduced in the extra para or 2 I'm requesting in the Introduction to provide some explanation of previous studies of ash/volcanic modeling/obs (see main minor revision 5)

10) Page 3, line 80 -- replace "a grid size of about" with "a lat-lon grid spacing of".

11) Page 3, lines 81-82 -- the word "evolution" seems somehow not quite right here, suggest to replace "evolution of a volcanic cloud" with "progression of a volcanic cloud's aerosol properties" or similar.

- 12) Page 3, line 82 -- Suggest to insert "an adapted version of" before "the prognostic aerosol aerosol microphysical model" -- this is a non-standard version that has been adapted to include ash, right? (e.g. with the geometric standard deviation of 1.8 and optical properties)?
- 13) Page 3, line 86 -- It needs to be stated here that fixed oxidant fields are used (assuming that is the case) and that the SO₂ oxidation does not slow down for the large volcanic SO₂ emission as the OH is used up.
- 14) Page 3, lines 89-90 -- insert "geometric" before "standard deviation" and "mean radius" so it's clear these are geometric mean not arithmetic mean.
- 15) Page 3, line 90 -- I don't understand what you mean here re: wet radius -- so does the ash take up water in the same way as in soluble modes in M7? What hygroscopicity is assumed for the ash? And this value of wet radius must be specific to a particular Relative Humidity or assumed volume-fraction for the water uptake in the stratosphere? Please add a sentence to the manuscript to explain briefly how this is done in the model.
- 16) Page 3, line 91 -- the term "direct effect" is out-of-date -- replace "The radiative direct effect" with "aerosol-radiation radiative effect" following the terminology in AR5.
- 17) Page 4, line 93 -- Change "We calculate the aerosol radiative forcing" -- it's the model that calculates this as it is running (online). And you mean the instantaneous forcing, right? In which case suggest to re-word to "The model diagnoses the instantaneous aerosol radiative forcing each timestep, via double-call to the radiation, once with aerosol (the advancing call) and once without (an extra "diagnostic call").
- 18) Page 4, line 94 -- insert "both heat the stratosphere, and thereby" before "dynamically influence" and suggest to change "via temperature change" to "via circulation change" since the "heat" already communicates that the temperature will change, and the circulation change gives more insight into the subsequent effects/responses.
- 19) Page 4, line 107 -- Change "whom we follow here for setting the basic eruption parameter ranges" to "whose eruption chronology we follow here for setting the basic emission parameter ranges". It's the "emission parameter" or "source parameter" rather than "eruption parameter", and its a chronology of the eruption -- that's where the term "eruption" should be used.
- 20) Page 4, line 114 -- with the re-wording of the 1st sentence in comment 9 of the "Main minor revisions", suggest to make this 2nd sentence continue this explanation, re-worded to instead begin "The 1% as fine ash is an estimate, with only very limited size information on the distal tephra from Laacher See (see Riede and Bazely, 2009)".
- 21) Page 4, line 116 -- Typo -- "Volcanic Explositivity Index" --> "Volcanic Explosivity Index".
- 22) Page 4, lines 118-119 -- suggest to delete the sentence "Yet, the amount of fine ash that reached the stratosphere is likely much smaller" -- that's implied in the subsequent sentence, and with the 1% figure already cited (based on the suggested re-wording in Main Minor Revision 9), the reader will already realise this is the case.
- 23) Page 4, line 119 -- Replace "Pinatubo simulations (Niemeier et al., 2009).." with "When simulating the Pinatubo volcanic aerosol cloud, Niemeier et al. (2009) used the 1% figure to determining the fine ash mass to the stratosphere, and given the large uncertainties, we consider it a reasonable approximation also for the Laacher See eruption cloud.

24) Page 5, line 156 -- Please provide a reference for the statement in this sentence re: the change in the zonal winds in the 50-60N latitude range. The landmark Lamb (1970) paper discusses the meteorological regimes in relation to volcanic cloud dispersion, and although 50 years old, and focussing mainly on the North Atlantic circulation, in relation to the British Isles, I wonder if this or another citing a paper discussing Central Europe flow regimes should be cited in relation to this discussion.

25) page 6, line 158 -- replace "can be more complex" with "can lead to greater southward transport" if that is what is meant -- with also "due to more disturbed meteorological situation" or similar.

26) Page 6, line 160 -- change "without volcanic eruption" to "without any volcanic emission" to remind the reader the model is simulating the volcanic aerosol cloud interactively.

27) Page 6, line 161 -- change "conditions at the LSE" to "conditions at the time of the 13 ka LSE" or similar (to be more specific re: the particular eruption"

28) Page 6, line 164 -- insert "the" before model initialisation" and add afterwards "(and the volcanic ash and SO2 emission)" to communicate better it's specifically in relation to when the eruption cloud is generated in the model.

29) Page 7, line 172 -- insert "volcanic emissions during" after "a day for the" and replace "for the MLST-C eruption phase" with "for the 2nd eruptive phase (MLST-C)".

30) Page 7, lines 173-174 -- replace "a date for the MLST-C phase with transport to be" with "a date when the volcanic aerosol cloud from the 2nd eruptive phase (MLST-C) would be transported to".

31) Page 7, lines 174-175 -- Replace "The results that best match the simulated ash to those known empirically..." with "The meteorological situation during the 2nd eruptive phase that gave best agreement to the MLST-C tephra deposit..." or similar. And insert "a volcanic emission on" before "June 20th". And then replace "This day was then used" with "This emission timing was then chosen".

32) Page 7, line 176-177 -- Insert "as a result of the ash radiative effects" after the open-brackets of "(Figure A1)", adding a comma before "Figure A1)". And re-word "could only be reproduced" with "was only reproduced" (that more accurately represents what was done, since presumably other ensemble members approximating this situation could be chosen from a continued control run...).

33) Page 8, line 191 -- reword "lower altitudes, the maximum deposition occurs farther to the east" with "lower altitudes, the model predicting ash deposition much further to the east."

34) Page 8, line 192 -- Delete "is more narrow" and reword "but longer with a more pronounced eastward spread" to "but with a longer and narrower eastward spread".

35) Page 9, caption to Figure 2. This panel b) is really important to see the two tephra deposits, but the colour scale chosen is hard to distinguish (for my eyes at least) with the grey dots, black dots and red dots. It's also stated that the LLST deposits are shown in brown but that looks red to me rather than brown. Suggest trying different colours and achieve best contrast so that it's immediately clear to the reader which tephra deposit is which.

36) Page 9, line 215 -- Again, the reader needs to be reminded of the magnitude of the volcanic cloud you're explaining here -- the Baines & Sparks (2005) paper is for a super-eruption -- so if that is what you're discussing then you

should insert "For a super-eruption, " at the start of the sentence and suggest to change "heated air" to "the heating effect from the volcanic ash" to again be explaining more clearly to the reader the effect you're discussing.

37) Page 9, line 217 -- Re-word "a right turn" -- I think you mean "clockwise rotation" and suggest to add "(towards the South for prevailing eastward flow)" or similar.

38) Page 10, Figure 3 -- change "12 h" to "12 UT" in each Figure and add "12 UT on" between "at" and "the 1st" in the 1st line of the caption.

39) Page 10, line 223 -- "simulation" --> "simulations".

40) Page 10, line 225 -- Add "the higher altitude volcanic cloud in" (or similar) before "LSE1 stays closer" to better communicate the results. Also re-word "is less strongly transported with the wind" --- do you mean the wind speed is less? Or is this less strongly perturbing the flow pattern in the control? Please explain.

41) Page 10, line 226 -- Again, the wording here needs to communicate what is different about LSE3 -- it's basically that the volcanic cloud is closer to the tropopause -- or even at around that altitude. Change "The fast easterly transport of of ash" to "The lower altitude volcanic cloud in LSE3, at around the altitude of the tropopause" (or "only slightly above the tropopause" or similar) and then continue "... is rapidly transported by the strongly eastward wind at that altitude" or similar, and re-writing the subsequent sentence as "with the lifting of the cloud in subsequent days...". This "rotating cloud" needs to be changed to "recirculating cloud" in all cases -- the word "rotating" is not really appropriate.

References

Chuan, R. L. and Woods, D. C. (1984) "Temporal variations in characteristics of the El Chichon stratospheric cloud" *Geofisica Internazionale*, vol. 23-3, pp. 335-349.

Gooding, J. L., Clanton, U. S., Gabel, E. M. and Warren, J. L. (1983) "El Chichon volcanic ash in the stratosphere: particle abundances and size distribution after the 1982 eruption" *Geophys. Res. Lett.*, vol. 10, no. 11, pp. 1033-1036.

Lamb, H. H. (1970): "Volcanic dust in the atmosphere; with a chronology and assessment of its meteorological significance" *Phil. Trans. Roy. Soc. A*, vol. 266, pp. 425--533.

Langmann, B., Zaksek, K. and Hort, M. (2010): "Atmospheric distribution and removal of volcanic ash after the eruption of Kasatochi volcano" *J. Geophys. Res.*, vol. 115, D00L06, doi:10.1029/2009JD013298.

Mossop, S. C. (1964): "Volcanic dust collected at an altitude of 20km" *Nature*, vol. 203, pp. 824--827.

Mossop, S. C. (1965): "Stratospheric particles at 20km altitude" *Geochimica et Cosmochimica Acta*, vol. 29, pp. 201--207.

Muser, O. M., Hoshyaripour, G. A., Bruckert, J., Horvath, A. et al. (2020): "Particle aging and aerosol-radiation interaction affect volcanic plume dispersion: Evidence from Raikoke eruption 2019" Accepted for publication in *Atmos. Chem. Phys.*: <https://doi.org/10.5194/acp-2020-370>

Niemeier, U., Timmreck, C., Graf, H.-F. et al. (2009): "Initial fate of fine ash and sulfur from large volcanic eruptions" *Atmos. Chem. Phys.*, 9, 9043-9057.

Pueschel, R. F., Russell, P. B., Allen, D. A., Ferry, G. V. et al. (1994) "Physical and optical properties of the Pinatubo volcanic aerosol: Aircraft observations with impacts and a Sun-tracking photometer" *J. Geophys. Res.*, vol. 99, no. D6, pp. 12,915--12,922.

Rose, W. I. and Durant, A. J. (2009) "El Chichon volcano, April 4, 1982: volcanic cloud history and fine ash fallout", *Nat. Hazards*, vol. 51, pp. 363-374.

Vernier, J.-P., Fairlie, T. D., Deshler, T. et al. (2016) "In situ and space-based observations of the Kelud volcanic plume: The persistence of ash in the lower stratosphere" *J. Geophys. Res. Atmos.*, vol. 121, pp. 11,104-11,118, doi:10.1002/2016JD025344.

Woods, D. C. and Chuan, R. L. (1983) "Size-specific composition of aerosols in the El Chichon volcanic cloud" *Geophys. Res. Lett.*, vol. 10, no. 11, pp. 1041-1044.