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Interactive comment on "The initial dispersal and radiative forcing of a Northern Hemisphere mid latitude super volcano: a Yellowstone case study" *by* C. Timmreck and H.-F. Graf

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All of the referees' comments have been considered in the paper. One reviewer (D. Stevenson) made suggestions concerning the English. We went carefully over the text and included all suggestions for improving the English. In the following, we will briefly answer to specific points.

- Reply to specific comments

  1. *Theoretical study of super volcano*
     Steve Self suggested to be not so specific that our study is a specific "Yellow-

stone study" rather to describe more general a theoretical study of a super volcano. That it is good point. We have changed the title into "The initial dispersal and radiative forcing of a Northern Hemisphere mid-latitude super volcano: a model study" and modified the text, in particular the introduction and experimental set up accordingly.

2. *100 times Pinatubo*

   Super eruptions are defined to be those eruptions yielding in excess of 10^{15} kg of products (>150 times the mass of the 1991 eruption of Mt. Pinatubo) with a volcanic explosivity index (VEI) of 8 or larger (Mason et al., 2004). 10^{15} kg of products includes all injected material: volatile gases (mainly SO_2 and H_2O) and ash particles.

   We have assumed in our paper a 100 times the amount of Pinatubo SO_2 emission and not of the magma released. The chosen injected mass of SO_2 might be at the lower end of the range for super eruptions but it is in the estimated range of the Younger Toba Tuff eruption 74kyr BP. Estimates of the sulfuric acid aerosol yield for the Toba eruption, the largest known Quaternary eruption, are 2300 -4700 Mt (Oppenheimer,2001). Hundred times Pinatubo (1700 MT $SO_2 - >$ 2603 MT

   $H_2SO_4 - >$ 3470 MT H_2SO_4/H_2O (75%)) would be in the middle of the estimated range. We now mention this in the introduction.

   D. Stevenson suggested to speculate about the possible range of SO_2 emissions of the Yellowstone eruption and the uncertainty on this. We do not include a discussion about this because first: the SO_2 amount of a future Yellowstone eruption is highly uncertain, and second: we do not describe a specific Yellowstone super eruption but a generic mid-latitude Northern Hemisphere one, see point above.

3. *preliminary in many aspects*

   We agree with D. Stevenson that the study is preliminary. The simulation of

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a super eruption is however a quite difficult task due to the various complex interactions between chemical, microphysical and dynamical processes. To understand the various feedback mechanisms it is important to take them step by step, see also point “indication of possible impacts”.

We have tried to state our simplifications and possible implications more clearly in the revised manuscript and discuss the most important ones in the text below.

4. *12 months*

   We have deliberately restricted our study to one year with the focus on the initial dispersal and the radiative forcing. For a longer simulation period it is expected that the various climate feedbacks (response of the ocean and biosphere) would become more and more important. We have also not considered the feedback on the OH concentration, see discussion point below, which also becomes quite important for a longer simulation period. Of course if the focus of the study would lie on the climate response of a super volcano 12 months would certainly not be enough, nor would single simulations be.

5. *aerosol bulk approach*

   We apologize for not being very clear at this point. In the current model version the H_2O/H_2SO_4 aerosol is considered by a bulk approach and a simple parameterization for the aerosol size distribution. It is assumed as a first-order approximation that the volcanic aerosol size distribution is log-normal and mono-modal, although observations after the Mount Pinatubo eruption (e.g. Deshler et al., 1993), as well as model simulations (e.g., Zhao et al., 1995), indicate that the volcanic aerosol size distribution is bimodal. Our approximation however, for modes that overlap, is accurate enough compared to other model uncertainties (Russel et al., 1996).

   To keep track of the time evolution of the aerosol size distribution, we calcu-

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late the aerosol mode radius r_m from the effective radius r_e. The standard deviation of the size distribution σ=1.86 is kept constant in time and space because the aerosol radiative properties are only weakly dependent on σ (Stenchikov et al., 1998). The effective radius is derived from the aerosol volume V according to an empirical formula, which has been derived from 744 aerosol size distribution measurements made at Laramie Wyoming (Grainger et al., 1995):

$$r_e = 0.357 * V^{0.249} \quad (1)$$

The aerosol volume itself V is calculated from the online computed aerosol mass M and the density ρ and sulphuric acid mass fraction W for every grid box at every time step. We also take into account the loss of the particles due to gravitational sedimentation at every time step and at every grid box. Thus, we keep track of the time evolution of the volcanic aerosol even though in a very simple way. This is a first approach which later has to be replaced by a microphysical model.

6. *feedback of chemical processes*

   The sulphate aerosol is coupled with the radiation and the chemistry scheme. In the chemistry scheme the volcanic aerosol is considered in the calculation of heterogeneous reactions on the surface of the sulphate aerosol particles and in the calculation of the actinic flux. We have clarified this in the text.

7. *SO2 + OH Dehydration of the stratosphere*

   Both reviewers point out the importance of the dehydration to the stratosphere and the extension of the SO_2 cloud due to reduced OH levels. Simulations by Bekki (1995) and Pinto et al (1998) have demonstrated that for extremely large volcanic eruptions the stratospheric OH concentration can be significantly reduced by the SO_2 oxidation, leading to a prolonged SO_2 life time and a dehydration of the stratosphere.

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We have neglected the feedback of the OH concentration (it is mentioned in the model set up) because it needs a fully coupled microphysical-chemical model which we do not have at the moment, but which is on the way.

This is of course a rough approximation but the most important effect of this feedback mechanism is a long lived SO_2 cloud and therefore a sustainable source of condensable sulfuric acid. As a consequence the volcanic aerosol life time would be prolonged. For a typical Pinatubo eruption the stratosphere is at it's background level after 4-5 years. For a super eruption one could expect that the volcanic aerosol remains about a decade in the atmosphere, see e.g Bekki et al. (1996). The effect would therefore be important for the simulation of longer time periods. This was one of the reasons why we restricted our simulation to one year.

However it is not quite clear how important these effects will in fact be, as neither Bekki nor Pinto include an additional source of volcanic released water vapor. H_2O is the most prevalent volcanic gas contributing between 50 and 90 Vol.%. Nevertheless the amount of water vapor released in the stratosphere after a volcanic eruption is quite unknown. The contribution to the global H_2O inventory for a Pinatubo sized eruption is negligible in comparison to it's atmospheric concentration but this might not be the case for a super eruption. Model studies by Glaze et al. (1997) have shown that volcanic eruptions can lead to the direct injection of water vapor into the lower stratosphere, so that the stratospheric dehydration might not be so severe as predicted. The role of water vapor in a volcanically perturbed stratosphere is an open question which requires a chemical-microphsical model considering all chemical microphysical and radiative feedbacks.

8. *prolongation of aerosol life time*

   A long lived SO_2 cloud will be a sustainable source of condensable sulfuric acid over a long time. The concentration of sulfuric acid will be not so high as for the reference case (with no OH feedback), so the particles will grow much

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slower and the particles won't fall out of the stratosphere so quickly. Thus in our openion the aerosol life time is dependent on the H_2SO_4 concentration via condensational growth and therefore indirectly dependent on the oxidant level.

9. *fixed SST*

   We focus here on the initial dispersal and the radiative forcing of the volcanic cloud in the first months after the eruption. Keeping SST fixed leads to an underestimation of surface climate effects, but these are dominated by radiation anomalies during the first year. Since we concentrate on transport and radiation in the stratosphere, SST effects are suggested to be of minor importance initially.

   In addition, we consider in our simulation the instantaneous radiative forcing by calling the radiation code twice in the model. Radiative heating and net radiative fluxes are estimated at every time step from the difference between the radiation calculations with and without volcanic aerosol. Stenchikov et al (1998) found the instantaneous aerosol radiative forcing (vertical structure of the aerosol net heating rates) is insensitive to climate variations except in the regions with changed dense clouds. To estimate the climate effect of volcanic eruptions one should of course discuss the adjusted radiative forcing, i.e the radiative forcing after the stratosphere is allowed to adjust radiatively to the perturbation. However to calculate the adjusted radiative forcing ensemble model runs with a fully coupled atmosphere-ocean OGCM are necessary which are beyond the scope of this paper.

10. *implications of radiative heating*

    We get an unusual temperature response in the mid stratosphere, which results in large positive flux anomalies in the tropics at the top of the atmosphere of more than 16 W/m^2 in the first months after the eruption. However, at the surface the flux anomalies are negative with peak values of less than

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-32 W/m^2. Therefore strong tropospheric cooling and strong stratospheric warming is expected what is typical for large volcanic eruptions. The dynamical response in the stratosphere is forced by the strong stratospheric temperature gradient leading to a strengthing of the polar vortex, see point dynamical response. The cooling above the volcanic cloud in the first months after the eruption in the middle and upper stratosphere is suggested to result from enhanced infrared irradiance by the very dense aerosol plus adiabatic cooling induced by the heating below. At the current state it remains unclear if the Northern Hemisphere winter warming pattern at the surface will show up since radiative and dynamic effects counteract. Our results do not show surface warming after a super eruption since the cooling tendencies due to reduction in shortwave radiation still are stronger than the long wave warming tendencies. However, it seems that radiatively the cooling is weakened. Final results can only be gained if sea surface temperature is coupled since this will strongly change the longwave irradiance over a large part of the globe. In any case radiation acts non-linearily to aerosol load and this is mentioned in the manuscript.

11. *Influence of interactive treatment on tracer transport*
    Certainly this is a well established point for tropical eruptions but it has not been discussed for Northern Hemisphere midlatitudes eruptions so far. In addition we think it is still an important issue which one should address in particular as in most aerosol chemistry studies the aerosol is prescribed. This might be sufficient for Pinatubo case studies due to the large amount of observations but it is a coarse assumption for other volcano studies.
12. *circulation response*
    We would be happy to discuss the circulation response in more detail, but an adequate discussion of circulation changes requires a statistical ensemble of perturbed and unperturbed simulations with variable SSTs, see point above. Thus, we abandoned a discussion about that in the original paper.

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Nevertheless, it is possible to look to gph and wind anomalies between the perturbed and the unperturbed run, similar to what we did for the temperature anomalies (Figure 7). We see for YESTJUN and YESTDEC that the strong temperature gradient in the stratosphere leads to a strengthing of the polar vortex and to changes in tropospheric circulation (Figure 8). The result is similar to what one knows from large tropical eruptions, e.g. Mt. Pinatubo (e.g Graf et al, 1993, Timmreck et al 1999, Stenchikov et al, 2002;2004). This is now mentioned in the manuscript. A detailed discussion will be made in a follow up study with an AOGCM.

13. *chemical impact*

Our results are only of limited validity because we neglect the input of volcanic water vapor in the stratosphere and the feedback on the OH concentration, see discussion above. This is a point which has been raised by the other two reviewers and which was the reason to focus on transport and radiative impact.

Of course we looked into changes of trace gases. The new Figure 9 shows an altitude-height cross section of the average simulated tropical (30°S-30°N) changes in chemical concentrations between the disturbed and the undisturbed run for YESTJUN. Similar results are found for YESTDEC (not shown).

The results in general look similar to what is known for trace gas changes after the Pinatubo eruption (Al Saadi, 2001; Rozanov et al., 2002; Timmreck et al., 2003) but the deviations are much stronger Aerosol induced heating leads to an uplifting of the trace gases which can clearly be seen in the upper stratospheric increase in the CH_4 concentration of up to 75% and in the increase in NO_x above 40 km, The strong loss in NO_x of more than 50% in the lower stratosphere is mainly a result of heterogeneous chemistry. Heterogeneous reactions on the surface of the aerosol particles lead to a conversion of NO_x to HNO_3 and to chlorine activation (increase of ClO_x). The con-

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centration of ClO_x increases by more than 250 % in the aerosol containing layers and below, The tropical averaged O_3 mixing ratio decreases in our simulation between 20 km-30 km due to heterogeneous chemistry and upward transport (up to -20%), and increases above 30 km (up to 10 %) due to a decrease in NO_x. This agrees qualitatively with other model studies (e.g. Rozanov et al, 2002) and with measurements of tropical ozone profiles after Pinatubo (e.g. Grant et al, 1994). While for the Pinatubo simulation we found only slight increases below 20 km in the simulated O_3 mixing ratio, the increase in O_3 is over 60% in our super volcano simulation in the first months after the eruption. This is probably due to changes in the photolysis rates. It should again be emphazised that in the first months after the eruption, the high SO_2 concentration has a significant impact on stratospheric OH and O_3 (Bekki, 1995). This effect is not taken into account in the present simulation and could modify the results in particular for O_3 concentration.

14. *definition of super/large volcano*

    Clarified in the text.

15. *Yellowstone different from Laacher See*

    These two mid-latitude eruptions differ in two important aspects. The first one is the geographical location: The Laacher See is situated in Western Germany while our super volcano is located at Yellowstone on the North American continent. The latter one is, as shown in the paper, strongly influenced by the stratospheric Aleutian high, which drives the volcanic cloud towards the equator in the summer months. The second aspect is the amount of SO_2 released, 1700 Mt for “Yellowstone” compared to 15 Mt for Laacher See. This leads to a stronger radiative forcing in the super volcano case with heating rates about four times higher than for the Laacher See eruption. The radiative effects have a big impact on the global dispersal of the clouds with enhanced cross-equatorial transport.

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16. *Maximum cooling of 1.6 K/day*

    It is a local maximum of less then 1.6 K/day (exactly -2.2 K/day). In Figure 3 values less than -3.2 K/day are black and values less than -1.6K/day are dark blue. When you blow up the figure you can see it more clearly.

17. *hemispheric average*

    Clarified in the text.

18. *seasonal dependent transport*

    The seasonally dependent transport patterns of the volcanic cloud are certainly not unexpected, but this effect has not been discussed so far. We have changed the sentence. June and December are typical months for Northern Hemisphere summer and winter circulation.

19. *Indication of possible impacts*

    We have revised the manuscript indicating more possible impacts on the earth-system. However any existing feedbacks can not be realistically estimated by thought experiments. It is therefore quite difficult to set up a ranking of possible feedbacks as D. Stevenson suggested. A possible ranking of effects would be:

    – initially: radiative effects of SO_2 converted to sulphate aerosol in the stratosphere, also ash in the stratosphere and deposited at the surface. Effects on snow cover.
    – later: ocean response, first SST, then circulation driven by temperature and salinity and atmospheric dynamics.
    – still later: changes in vegetation and biogeochemical cycles (uptake/emission from ocean, permafrost, vegetation etc.)

20. *reference to vegetation model*

    We mention the vegetation model explictely because long lasting climate effects of a super volcano cannot be assessed without it. We agree that at

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first other feedback processes, which are partially already included have to be studied before the impact on vegetation should be taken into account, see also the ranking list of effects (point above).

21. *Figure captions*
    All captions have been revised.
22. *Figure 1*
    We apologize for this error. It is now clarified. We also indicate the location of the Yellowstone volcano by a cross instead of showing a picture with the initial distribution.
23. *Figures 2*
    Figure 2 is revised because we discovered an inconcistency in the calculation of the optical depth. The pattern is not changed much but the values are now roughly a factor of two smaller in comparison to the original ones. The other results are not effected by this inconsistency, because we calculate the optical depth off line form the model output.
24. *Figures 3 4*
    The isobaric grid structure is improved
25. *Figures 5 6*
    The figures are now colored. In the original paper the shading indicates the negative values.

Thank you, for your helpful comments.

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