Reviewer #1

August 21, 2015

We would like to thank reviewer #1 for his/her review. Our answers and the corresponding changes to the manuscript are given below in a blue text colour.

Using an atmosphere-ocean-chemistry climate model, the authors assess the effects of a generic tropical volcanic eruption on stratospheric ozone and the northern hemispheric polar vortex. With a suite of simulation experiments, they separate the ozone effects of the eruption via eruption-related changes in heterogeneous chemistry and stratospheric dynamics, and the feedback of the induced ozone changes on the temperatures and northern hemispheric polar vortex.

General comments:

- This manuscript presents some new interesting results and confirm the findings of previous studies. In this current version the manuscript largely focuses on results that have already been published, such as the comparison between the effects of a Pinatubo-like eruption on the heterogeneous chemistry and dynamics (PD15_HET Vs PD15_RAD). While a reanalyses of previous studies is always useful, I think that this manuscript would gain novelty by focusing on the comparison between present-day and preindustrial, or among the different magnitude of SO2 injections. To my knowledge such a systematic assessment of tropical eruptions in present-day and preindustrial conditions has not been published. While the figures are present (at least for the PD15 and PI15 cases, but not for the 30Tg and 60Tg experiments), they are often rushed in the description. There are nearly no figures with PI30 and PI30.

Thank you for this comment. Unfortunately, it is not possible to show all figures for all the different cases. For Figure 3 the setup of 2 climate states, 3 forcings, and three processes would results in a figure with 18 panels.
In the revised manuscript we therefore added several figures as supplementary material and reference the figures in the manuscript.

- S1: column ozone anomalies for all experiments (present day, similar to Fig. 3)
- S2: column ozone anomalies for all experiments (preindustrial, similar to Fig. 3)
- S3: Zonal mean DJF ozone and residual circulation anomalies in PD15, PD30, PD60, PI15, PI30, and PI60 (similar to Fig 4).

Furthermore, we have added more information on the comparison present day vs. preindustrial to the revised manuscript. Nevertheless, we decided to keep the results on PD15_HET and PD15_RAD since these experiments allow comparing our results to previous studies, which is important for the interpretations of the other experiments, inparticular for the RAD effects.

The contribution of the chemistry-climate interaction is also interesting, even though I am not sure that the title of Section 3.3 is appropriate. I suggest 'Effects of the coupling between ozone and stratospheric dynamics on the stratosphere'.

Thank you for this comment. We changes the title of Section 3.3 using your suggestion.

Aquila et al. (2013), which is included among the references, is a very similar study but limited to the PD15 experiments. I suggest to include more quantitative comparisons with their results, and to extend the conclusions not covered in their study. For instance, Fig. 3 is very similar to Fig. 7 of Aquila et al. (2013). I suggest adding the same figure for PI15, PD/PI30 and PI/PD 60.

Thank you. A discussion of the similarities and differences to Aquila et al (2013) has been added to the discussion section. Furthermore, we include a figure for PI15, PD/PI30 and PI/PD 60 (similar to the Fig. 4) as supplementary material (S3).

"A comparable case-study for the 1991 Mt. Pinatubo was performed by Aquila et al (2013), with a similar separation between radiative-dynamical and heterogeneous chemical effects on the aerosols. They identified a combination of HET-AER and RAD-DYN processes to be responsible for the ozone anomalies in the SH. In particular they found similar anomalies in the residual mean circulation being responsible for reduced ozone in the tropics and enhanced ozone concentrations at mid-latitudes (compare Figure 4b and their Figure 7). This response, however, is limited to the early phase of the eruptions and in combination with the phase of the Brewer-Dobson circulation the anomaly-pattern is found only in the SH, while in the NH ozone anomalies are mainly affected by HET-AER effects. Our findings suggest a similar response of the residual mean circulation in the NH during boreal winter, and we conclude that a combination of RAD-DYN and HET-AER effects are needed to understand ozone anomalies on both hemispheres. This difference in the response is not yet understood, but may be related to differences in the aerosol forcings. Understanding the response to the RAD-DYN mechanism is of particular importance for volcanic eruptions under preindustrial conditions with low load of ozone depleting halogens, where chemical effects become weak and the response is dominated by radiative-dynamical effects. "

- The manuscript is very confusing in the description of the figures. I have found very difficult to follow which figure the authors are describing, and if they are referring to PD or PI.

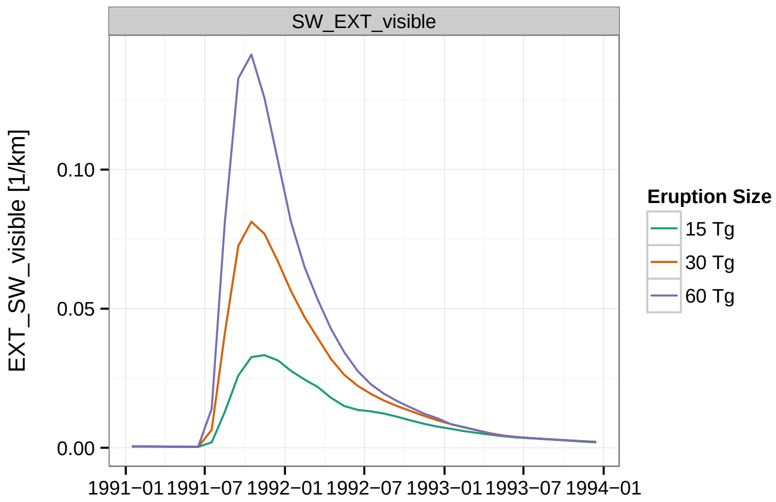

Figure 1: Time series of extintion rates in the visible (440-690nm) at the equator at 54 hPa.

Thank you. In Section 3.1 and 3.2 the describe first changes for the present day climate state and focus on the differences in the preindustrial climate state after that. In the revised manuscript we made the structure clearer by adding subsubsection to these chapters.

- Are aerosol and radiation coupled in AER2D? If not, the dispersal of the aerosol, and therefore the spatial distribution of the forcing, could be totally unrealistic, especially in the case of the 60Tg injections. For instance, a visual comparison of the panels in Fig. 1 suggests that the residence time of the volcanic aerosol is similar for all three injection magnitudes. Is this true, and, if true, is it reasonable? Larger injections should lead to larger particles and faster settling (e.g. English et al., 2012), but also to a larger vertical extent of the volcanic aerosol (Aquila et al., 2014), which would extent the stratospheric lifetime.

Indeed there is no coupling with radiation in AER, which can affect the aerosol distribution. While this is a limitation of our method, the eruptions in this study are idealized, and the radiation-aerosol influence doesn't dominate over the general uncertainties and variations in the transport of the aerosols after an eruption.
The settling effect is present in AER, but is may not be obvious in Fig. 1 of the manuscript. Below (Fig: 1) the extinctions rates in the visible are shown for equatorial latitudes in an altitude of 54 hPa. This figures reveals that about 2 years after the eruption the extinctions are almost independent of the forcing.

Specific comments:

- P14285 L28: PD15 resemble Pinatubo only for the initial conditions (time of the eruption, order of magnitude of the SO2 injected) and GHG scenario, but not in the sense of the initial meteorological conditions and QBO phase (or is the QBO nudged to observations for the period?) nor in the sense of the actual forcing, given that the SAD shown in Fig. 1 does not resemble the one from SAGE observations, which show that the peak of aerosol was south of the equator. I would rather write that the injection amount and timing of the eruptions are compatible to the eruption of Mt. Pinatubo.

Thank you for this comment. We agree that our present day 15 Tg simulation and the real eruption of Mt. Pinatubo differs in a number of aspects. The QBO, however, which is nugged to observations in the model, does not differ from the 1991 eruption. Also the injection amount may not be high in comparison to Pinatubo. We therefore rewrote the description of the experiment and forcing. In Sect. 2.2 (aerosol forcing), we state now:

"Arfeuille et al (2013) found that an injection of 14 Tg of SO_2 (7 Tg of sulphur) produced mid-visible extinctions much higher than observed in the tropical stratosphere after the Pinatubo eruption. As shown by Dhomse et al. (2014), the peak burden of sulphur in the particle phase was around a factor of two lower than the peak sulphur burden in the gas phase, in the range 3.7 to 6.7 Tg of sulphur. The 15 Tg AER simulation shall therefore be regarded as an upper limit for the perturbation that occurred following Pinatubo. Furthermore, some differences in the shape of the AER aerosol forcing and observations for Pinatubo exists."

And in the experiment section (2.3) we replaced the statement that our PD15 experiment closely resembles the Pinatubo eruption by:

"As explained in section 2.2, the PD15 ensemble simulation represents an upper limit for the effects from the Mt. Pinatubo eruption in 1991."

- P14287 L5: what is the significance level?

Thank you, the significance level is 95%. We have added the necessary information to the end of the Section 2.3:

"Significance estimates are based on a two-tailed Student's t-test using the 5 % significance level."

- P14287 L 21: Cite relevant literature for the chemical mechanism (e.g. Tie and Brasseur (1995) or Granier and Brasseur (1992))

Thank you, the references was added.

- P14287 L 25: Is the reduction of N2O5 by 80% a model result or is it from previous published literature? Adding 'not shown' would help clarify, if it is a model result, otherwise please cite the relative reference.

Thank you. It is a model results and we have added '(not shown)' to the corresponding statement.

- P25399 L10: The authors write that the oscillations in column ozone anomalies are due to polar ozone depletion in the northern and southern hemisphere. However, in Fig. 3b no polar depletion is visible in the southern hemisphere, except for the non-significant depletion in August-September at 60S. Is that negative anomaly what the authors refer to?

Thank you for this comment. The oscillation in column ozone shown in Figure 2 are very small for the 15 Tg eruption but become larger for the 30 and 60 Tg forcing. The spatial pattern of the column ozone anomalies for the 30 and 60 Tg eruption, clearly reveals the amplified polar ozone depletion.
We have included the spatial pattern of column ozone anomalies in the supplementary material (Figures S1 and S2) in the revised manuscript.

- P14288 L13: the polar ozone depletion in RAD is said to increase with forcing strength, but this is not shown in any figure.

The increase in polar ozone depletion from PD15_RAD to PD60_RAD is now shown in Figure S1 and S3 (supplementary material).

- P14289 L11: 'In the following' or 'later' (to indicate the following months)?

Thank you, we changes this to "*In the following months...*".

- P 4289 L16: Do the authors mean Fig. 3h or 3d?

We were referring here to the comparison between PD15 and PD60. In particular Fig 3d is meant here, which we are referring now. Thank you for this question.

- P14289 L25 to L28: This is true for the northern hemisphere, while in the southern hemisphere PD15_RAD and PI15_RAD are not very different from each other. If the reason was the reduced polar ozone depletion, shouldn't the difference between PD and PI be even larger in the southern hemisphere?

Thank you for this question. This is again a difference between present day and preindustrial which is very weak in the 15 Tg experiments, but becomes larger for the larger eruptions. This effect is visible in Figure 2, but only for the global mean column ozone anomalies. In the revised manuscript the column ozone anomalies for all experiments are included as supplementary material Figure S1 and S2. A comparison of S1h (PD60_RAD) to S2h (PI60_RAD) reveals the differences in polar ozone depletion between the two climate states.

- P14290 L11: the warming in PD60 is not shown, correct?

The warming for PD60 is shown in Figure 5d. If you were refering to the PD60_HET simulations: temperature anomalies for this experiment are indeed not shown as figures, but the numbers are mentioned in the manuscript.

Why is there a warming at northern high latitudes in PD15_HET, even though not significant?. Is this warming a consistent feature of all ensemble members?

The warming may be related to the NH polar vortex weakening, which is not only present in the ensemble average of PD15_HET but also in the PI15_HET and in the experiments with stronger volcanic forcing. The warming is present in most of the PD15_HET simulations (compare Figure 2, see below). A simple analysis suggest that the relationship between vortex intensity and temperature anomalies in the NH polar stratosphere is robust for the winter season. Figure 3 (see below) displays the relationship between the anomalies in the NH polar vortex intensity (using the u60 index as described in the manuscript) and the temperature anomalies in the polar stratosphere (averaged over the latitudes 75-90N at 40 hPa) for the eight members of the PD15_HET experiment. Both anomalies were calculated relative to the control ensemble average. In the winter after the eruption this relationship is almost linear.
We have added a sentence on the positive temperature anomalies to the revised manuscript:

"The HET-AER effect furthermore causes slight positive temperature anomalies in the NH polar stratosphere (Fig. 5a), which are related to the weakening of the polar vortex. "

- P14290 L16: The black line in Figure 7 is not described anywhere (I suppose it is the average of the reference simulation). Am i suppose to compare the purple line in the upper left panel of Fig. 7 to the black line? If so, u60 is outside of the shaded area only in January and February in the case of PD15.

Thank you. The black line is indeed the control simulations and we add this information to Figure 7. We agree that the u60 index for the HET experiment under present day conditions is significant below the Control in January and February and we will correct this statement in the manuscript. We furthermore, added a monthly mean comparison for January and March to Figure 7 and discuss the differences between the experiments for mid- (January) and late-winter (March) in the results section.

"The weakening of this $\bar{u}60$ index due to the HET-AER effect is mainly a phenomena of the mid to late winter (January, February). In January the vortex intensity reduces to 35±15 m/s in the PD15_HET-AER experiment in comparison to 48±11 m/s in the CTRL experiment (32±18 and 36±11 m/s for the 30 and 60 Tg experiment,respectively. Compare Fig. 7). During spring a slight, but not significant vortex intensification is found for the stronger forced ensemble simulations. In March mean value of the vortex intensity in CTRL is 9±18 m/s, while the vortex in PD15_HET-AER reaches an average of 14±15 m/s (21±19 and 19±13 m/s for the 30 and 60 Tg experiment,respectively). "

- P14290 L25: Is the temperature anomaly in PD30 shown anywhere? If not, how do we know that it is linear? What do the author mean with 'the temperature response seems to saturate' in the PD60 case? Is it because it is not equal to three times the PD15 temperature response? The upper limit of the color scale is not indicated, so it is difficult to understand if the temperature response really saturates.

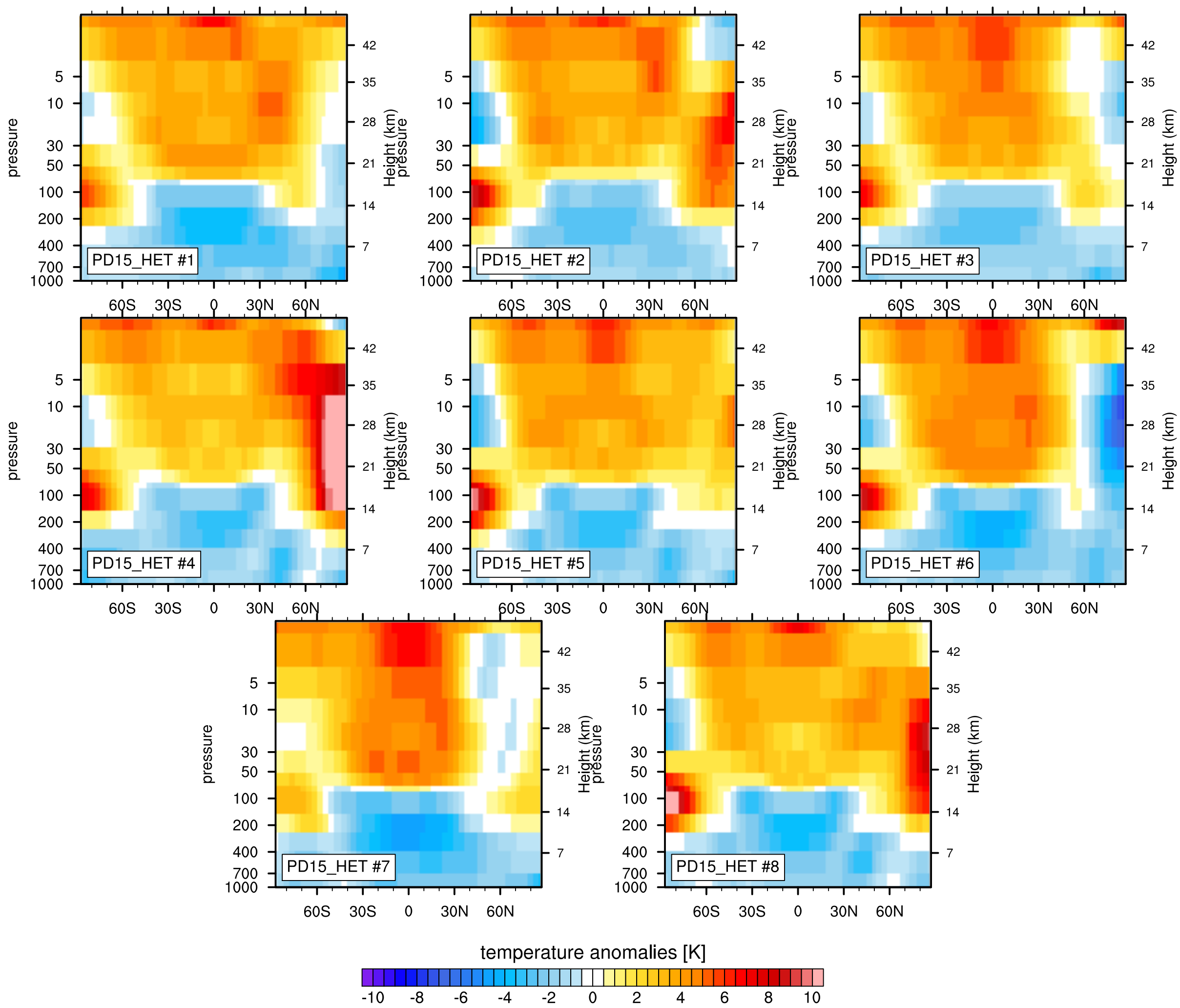

Figure 2: DJF temperature anomaly in the 8 ensemble members from the PD15_HET experiment (similar to Fig.5 of the ACPD manuscript). Anomalies were calculated relative to the ensemble average of the PD control simulations.

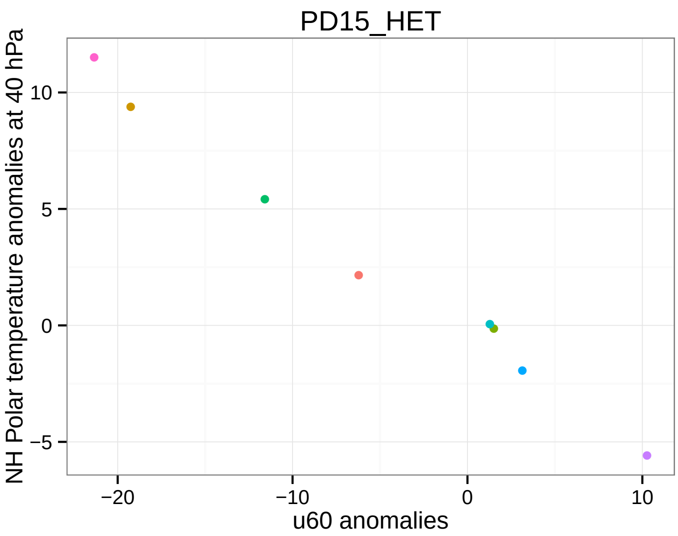

Figure 3: Scatterplot of (x-axis) the NH polar vortex anomalies and (y-axis) temperature anomalies in the polar stratosphere for the first post-eruption DJF season in the individual members of PD15_HET.

The statement of an almost linear temperature increase from PD15 to PD30 is based in the analysis of the model results, but figures for the PD30 temperature anomaly are not shown. In the revised manuscript we give numbers for the maximum temperature anomalies for all forcings:

"As expected, the temperature anomalies increase with rising aerosol mass. At 50 hPa the maximum temperature anomaly, which occurs around December, is 9.5 K for the 15 Tg and increases to 18.2 and 21.7 K for the 30 and 60 Tg eruptions, respectively."

- P14291 L7: To which figure do these lines refer to?

Thank we, we have added references to the Figures to the revised manuscript.

"The amplitude of the temperature change through the HET-AER mechanism is much weaker than the changes caused by the RAD-DYN effect (Fig. 5a). Nevertheless, the temperature reduction causes a significant weakening of the NH polar vortex, but only a slight increase in the vortex intensity is found for the RAD-DYN experiment for the 15 Tg aerosol forcing (Fig. 7)."

- P14291 L111: how does the different patterns of the temperature anomaly exactly translates into a different dynamical response?

Our hypothesis is that the difference between a cooling which is limited to tropical latitudes (HET) and a warming which is present at almost all latitudes, is responsible for the different dynamic response. However, with the current setup, we have no possibility to test this hypothesis. We rewrote this paragraph to make this more clear:

"The difference in the response of the NH polar vortex is not yet fully understood. It may be related to the different patterns of the temperature anomaly. The aerosol induced warming covers all latitudes up to 60 N in the lower and middle stratosphere and reaches even polar latitudes in the upper stratosphere. By contrast, the cooling associated with the HET-AER effect is limited to the SH and up to 30° N due to the seasonal cycle of the Brewer-Dobson circulation."

- P14291 L23: The comparison between Fig. 5c and Fig. 5g is difficult, I would add a third line with difference plots.

Thank you. We have added the temperature differences between present day and preindustrial for the different experiments to Figure 5 and reference them on several occasions in the revised manuscript.

- P14296 L6: a comparison with observations is not very significant, since the forcing itself of Fig. 1 does not look like the observed aerosol distribution. However, I agree that the reason is probably the excessive warming of the lower stratosphere.

Thank you. We are aware of the fact that we can expect some differences between our simulations and the observations caused only the the differences in the forcing. This is why the state at the beginning of this paragraph:

"A direct comparison of our results to observations is difficult given the highly idealised character of our experiments."

Are brominated very-short lived substances included? Oman et al. (2014) shows that it could enhance ozone depletion.

Yes, we have added to the model two brominated very-short lived substances recommended by Liang et al., (2010).

- Liang, Q., R. S. Stolarski, S. R. Kawa, J. E. Nielsen, J. M. Rodriguez, D. R. Blake, E. L. Atlas, and L. E. Ott (2010), Finding the missing stratospheric Bry: A global modeling study of CHBr3 and CH2Br2, Atmos. Chem. Phys., 10, 2269-2286.

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