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Second Review
of the manuscript "Northern Hemisphere continental Winter-warming following the 1991 Mt. Pinatubo eruption: Reconciling models and observations" by L. Polvani et al.

I believe the paper raises a legitimate question about the nature and reality of a Winter warming response to volcanic forcing, but, with all respect to the authors, I do not believe they present convincing arguments to support their results, at least in the way they formulated them.

General Comments

The evidence of the development of a positive NAO/AO (further referred as AO) anomaly or Winter warming, in response to explosive equatorial volcanic eruptions, was first reported in the 1990s, and is based on compositing multiple observed volcanic events (e.g., Robock and Mao, 1992; Fisher et al., 2007). However, the AR4 and AR5 models tend to produce a weaker ensemble mean Winter warming than in observation composites (Stenchikov et al., 2006; Driscoll et al., 2012). Therefore, the dilemma is whether models are deficient, or Winter warming is spurious. The authors claim they solve this puzzle based solely on model output and observations for only one Winter, following the 1991 Pinatubo eruption.

We know that up-to-date models generate large uncertainties in reproducing circulation changes (e.g., Deser et al., 2012; Shepherd, 2014). The AO response to volcanic forcing, real or not, is an interesting example of dynamic perturbation caused by imposed radiative forcing. According to (Deser et al., 2012; Shepherd, 2014) it is not surprising that the models cannot capture it well.

A positive AO anomaly, after a volcanic eruption, can be generated by a number of stratospheric and tropospheric mechanisms (Stenchikov et al., 2002; Stenchikov, 2016). The stratospheric mechanism involves the strengthening of a NH Polar Vortex, which is relatively well-reproduced by the models, in general, and in this study particularly, and the downward propagation of a signal (Baldwin and Dunkerton, 1999), which is not well-captured by the models (Stenchikov et al., 2006; Driscoll et al., 2012).

Due to high variability, an individual Winter warming event is difficult to identify empirically (e.g., stand-alone 1991/92 Winter warming is not statistically significant). The conventional approach to reconcile model results and observations is to match a simulated ensemble mean and a statistically significant composited observed anomaly. Robock and Mao (1992) and Fisher et al. (2007) have composited several post-eruption events to obtain a statistically significant AO response; Stenchikov et al. (2006) and Driscoll et al. (2012) have composited model outputs. They all have to composite eruptions of different magnitudes. I do not think it is an unforgivable sin, assuming that the authors in this study compare the responses in the models where the SW flux, reflected by volcanic aerosols, differs by 50%, which is probably more than the difference between the NH radiative forcing of El Chichon and the forcing of Pinatubo.

In the current study, the authors choose to compare the "climate-type" large model ensembles with only one observed event: the Winter-warming response in the first year after the 1991 Pinatubo eruption. The Winter warming in 1991/92 is not typical because it is not associated with the strong NH polar vortex, as in the most post-volcanic years in observation. The asymmetry between 1991/92 and 1992/93 Winters caused by different phases of QBO is discussed in details by Stenchikov et al. (2004), based on a "large" 24-member ensemble, and using 40-layer stratosphere-resolving model. In addition, a Central Pacific El Nino of 1991/92 contributed into peculiarity of the chosen case-study (Predybaylo et al., 2017; Dogar et al., 2017). In the current study, none of those factors (QBO, El Nino) are accounted for in the simulations or, alternatively, their effects were not removed from observations, which as discussed in (Kirchner et al., 1999; Santer et al., 2001; Lehner et al., 2016) is nevertheless important.

Obviously, a simulated ensemble average cannot match the one natural realization, which is not statistically significant, as it comprises both the forced response and the natural variability. The authors stated in their response to the reviewer:
"Our key finding, after analyzing three large ensembles, is that the observed warming falls well within the distribution of the model members. From this, we conclude that the models capture the observations."
Basically, the authors claim that, if the observed response for one season falls within the spread of model ensemble responses (i.e., there are a few ensemble members that show Winter warming), this fact validates the model. This is an overstatement. If a model is valid, then the observed response has to fall within the spread of model responses, but the opposite is not necessarily correct.

In summary , the actual results of the study do not support the authors' ambitious claim, as stated in the paper. The authors show that the models perturbed by the Pinatubo-like radiative forcing, due to a strong variability in high NH latitudes of the troposphere and the stratosphere, did not produce a statistically significant positive AO anomaly. It remains unclear if this would be right for the real physical system, or if it is the result of the model or experimental setup deficiencies. A comparison with the observed anomaly, for only one Winter following the 1991 Pinatubo eruption, does not sound convincing to me.

The models themselves do not perfectly simulate the Pinatubo impact. They generate volcanic radiative forcing with at least 50% uncertainty and overheat the equatorial lower stratosphere almost twice the amount in comparison with observations. The effects of QBO and ENSO on the Winter warming of 1991/92 are supposed to diminish in the model ensemble mean, but are not removed from observations; the ensemble sizes, at least for WACCAM –(the only stratosphere-resolving model used for the analysis) are relatively small. Clearly, the models presented in this study and the method itself have some significant drawbacks. The conclusions are overstated and are at odds with empirical reconstructions (Robock and Mao, 1992; Fisher et al., 2007; Wunderlich and Mitchell, 2017) that are simply verbally dismissed. The results of the study are incorrectly interpreted. The conclusions should be made consistent with the actual results of the study, before submission for publication in ACP.

Specific Comments

P1, L5: This is an overstatement; the strengthening of the NH polar vortex is often reproduced in the model simulations.

P1, L8: Which climate model is highly accurate? What does this mean? How did you prove it?

P1, L20: I believe most of these effects were previously discussed.

P2, L24: This is an inaccurate statement. Winter warming is associated with a positive phase of AO, and could occur independently of a volcanic impact.

P5, L16: English et al. (2013) did not account for the aerosol radiative feedback.

P7, L18: with this **in** mind

P7, L25: Stenchikov et al., **2006**

P7, L25-26: The statement made by the authors is inaccurate. Stenchikov et al. (2006) and Driscoll et al. (2012) compared observed and simulated anomalies composited for a few eruptions since 1850. They found that the simulated composited Winter warming is weaker than in observations.

P7, L30-35: Probably most, if not all, AR4 and AR5 models have ensemble members showing 1991/92 Winter warming, and therefore satisfy this suggested weakened criterion.

P8, L16: I do not think the authors, in their experiments, can claim "that the models are perfectly capable of capturing the post-Pinatubo Winter anomalies in the NH", based on the fact that a few ensemble members do this. E.g., the ensemble members that demonstrate Winter warming might do it for wrong reasons, as the models do not account for some important factors such as the Easterly QBO phase, El Nino in the Winter of 1991/92; models overheat the lower stratosphere and have 50% uncertainty in radiative forcing.

P9, L6: It would be fair to mention that, for some ensemble members, the zonal wind anomaly exceeds 10 m/s.

P9, L10-18: One possible explanation would be that WACCM does not capture the propagation of AO from the stratosphere to the troposphere, as in observations (Baldwin and Durkenton, 1999). Was WACCM tested in this way?

The vertical propagation of planetary waves is a threshold process (Charney and Drazin, 1961), so even small zonal wind changes might matter. The exact value of a threshold velocity obtained in (Charney and Drazin, 1961) might not be perfectly right in the real world, as it was obtained for idealized conditions. But a fundamental conclusion that a planetary wave propagation process is threshold should hold.

P10, L15-19: It is a sampling problem with only one post-Pinatubo season chosen. Multiple cases have to be considered to judge which mechanism works more frequently.

P10, L22: addre**sss**

P11, L20-30: Not all previous studies were conducted using models with a poorly resolved stratosphere. Stenchikov et al. (2002, 2004) used the 40-level GFDL stratosphere resolving model.

References

Baldwin, M. and T. Dunkerton (1999), Propagation of the Arctic Oscillation from the stratosphere to the troposphere, J. Geopys. Res., V. 104, No. D24, pp 30,937-30,946.

Deser C., R. Knutti, S. Solomon, A. Phillips (2012), Communication of the role of natural variability in future North American climate, Nature Climate Change, 2, DOI: 10.1038/NCLIMATE1562.

Dogar, M., G. Stenchikov, S. Osipov, B Wyman, M. Zhao (2017), Sensitivity of the Regional Climate in the Middle East and North Africa to Volcanic Perturbations, J. Geophys. Res. Atmos., 122, doi:10.1002/2017JD026783.

Driscoll, S, A. Bozzo, L.J. Gray, A.Robock, G.Stenchikov (2012), CMIP5 Simulations of Climate Following Volcanic Eruptions, J. Geophys. Res, 117, D17105, 26 pp., doi:10.1029/2012JD017607.

Fischer, E. M., J. Luterbacher, E. Zorita, S. F. B. Tett, C. Casty, H. Wanner (2007), European climate response to tropical volcanic eruptions over the last half millennium, Geophys. Res. Lett., V. 34, L05707, doi:10.1029/2006GL027992.

Kirchner, I., G. Stenchikov, H. Graf, A. Robock, J. Antuña, (1999), Climate Model Simulation of Winter warming and Summer Cooling Following the 1991 Mount Pinatubo Volcanic Eruption, J. Geophys. Res., 104, 19,039-19,055

Lehner, F., A. P. Schurer, G. C. Hegerl, C. Deser, and T. L. Frölicher (2016), The importance of ENSO phase during volcanic eruptions for detection and attribution, Geophys. Res. Lett., 43, 2851–2858, doi:10.1002/2016GL067935

Predybaylo, E., G. Stenchikov, A. Wittenberg, F. Zeng (2017), Impact of a Pinatubo-Size Volcanic Eruption on ENSO, J. Geophys. Res. Atmos., 122, 925-947, doi:10.1002/2016JD025796.

Robock, A. and Mao, J. (1992), Winter warming from large volcanic eruptions, Geophysical Research Letters, 19, 2405–2408.

Santer, B. D., et al. (2001), Accounting for the effect of volcanoes and ENSO in comparisons of modeled and observed temperature trends, J. Geophys. Res., 106, 28,033–28,059, doi:10.1029/2000JD000189.

Shepherd, T. (2014), Atmospheric circulation as a source of uncertainty in climate change projections, Nature Geosciences, 7, 703-708, DOI: 10.1038/NGEO2253.

Stenchikov, G., A. Robock, V. Ramaswamy, M. D. Schwarzkopf, K. Hamilton, S. Ramachandran (2002), Arctic oscillation response to the 1991 Mount Pinatubo eruption: Effect of volcanic aerosols and ozone depletion, J. Geophys. Res., 107 (D24), 4803, doi:10.1029/2002JD002090.

Stenchikov, G., K. Hamilton, A. Robock, V. Ramaswamy, and M. D. Schwarzkopf (2004), Arctic Oscillation response to the 1991 Pinatubo Eruption in the SKYHI GCM with a realistic Quasi-Biennial Oscillation, J. Geophys. Res., 109, D03112, doi:10.1029/2003JD003699.

Stenchikov, G., K. Hamilton, R. J. Stouffer, A. Robock, V. Ramaswamy, B. Santer, and H.-F. Graf (2006), Arctic Oscillation response to Volcanic Eruptions in the IPCC AR4 Climate Models, J. Geophys. Res., 111, D07107, doi:10.1029/2005JD006286.

Stenchikov, G. (2016), The Role of Volcanic Activity in Climate and Global Change, in: T.M. Letcher (Ed.), Climate Change: Observed Impacts on Planet Earth, Second Edition, Elsevier, 2016, pp. 419–447, ISBN: 978-0-444-63524-2.

Wunderlich, F. and D. Mitchell (2017), Revisiting the observed surface climate response to large volcanic eruptions, Atmos. Chem. Phys., 17, 485-499, https://doi.org/10.5194/acp-17-485-2017, doi:10.5194/acp-17-485-2017.