RC2 with responses

The manuscript fits the scope of the journal well with integration of climate modeling, paleoclimatology, and historical climatology to address the effect of the Huaynaputina (Peru) eruption in 1600 CE on northern hemisphere cooling via the North Atlantic subpolar gyre and ocean-atmospheric feedbacks. The SPG is hypothesized to be the cooling mechanism that led to low temperature anomalies in Europe and Russia in the early 17th century. While the results are not conclusive, the authors have established a research course to investigate the relationship between volcanic eruptions and important climate shifts that have affected humans. The methods and assumptions of the work are clearly outlined and the authors' interpretation of the results is in accord with their analysis. The supplemental materials make the research reproducible with extensive presentation of the historical observations used in the methods. I found the paper well-structured and written with few technical errors.

The cluster of volcanic activity in the late 1500s would seem to make it difficult to determine if the Huaynaputina eruption seeded the SPG slowdown or if the eruption was the final push over a threshold given the background state of the atmosphere after multiple VEI 4 eruptions. Perhaps this is why an SPG shift can occur in some simulations without a volcanic forcing in 1600. However, the combined use of model simulations, paleoclimate reconstruction, and historical climatology helped to better target an initial seed to the SPG slowdown but unfortunately the data are inconclusive at this point. That said, this is a fine contribution demonstrating how these data sources can be integrated to elucidate the mechanism driving climatic change circa 1600.

We thank the reviewer for the generous comments on the manuscript. We agree that the current findings are inconclusive regarding the trigger for the possible SPG mechanism. In the conclusion, we have proposed possible ways the uncertainty could be resolved in future studies, as well as lessons from our experience comparing simulations and data from historical climatology.

Further analysis and discussion of the North Atlantic Oscillation (NAO) and Artic Oscillation (AO) would be helpful to disentangle how the background climate state and internal variability might contribute to an SPG shift. Previous research suggests an interaction between NAO and volcanic eruptions (e.g., Ortega et al. 2015) with a positive NAO emerging after strong volcanic eruptions. NAO+ would lead to stronger westerlies in northern Europe resulting in warmer and wetter winters, meaning the SPG would likely not slowdown. Of course, there are many NAO reconstructions out there to choose from including several recent reconstructions from Ortega et al. 2015, Cook et al. 2019, and Hernandez et al. 2020. The research could benefit from a more comprehensive treatment of NAO/AO.

We thank the reviewer for drawing this issue to our attention. We propose to expand discussion of the NAO/AO between lines 149 and 150. As discussed in Hernández et al. 2020, the precise NAO values are uncertain but both the Ortega et al. 2015 and Trouet et al. 2009 studies indicate roughly average NAO index values in the 1590s, declining in the decade following the 1600 eruption. Thus, the state of the NAO would not appear to be a strong explanation for the cooling before the eruption; nor is there evidence for an NAO+ response following the Huaynaputina eruption, unlike some other tropical eruptions. As recent studies indicate (Bittner et al., 2016; Coupe and Robock, 2021) a post-eruption NAO+ response with Eurasian winter warming appears to be contingent on tropospheric conditions at the time of the eruption rather than an automatic response to stratospheric aerosols.

Sources:

Bittner M, Schmidt H, Timmreck C, Sienz F. Using a large ensemble of simulations to assess the Northern Hemisphere stratospheric dynamical response to tropical volcanic eruptions and its uncertainty. Geophys Res Lett. 2016;43(17):9324–32
Coupe, J, and Robock, A.: The influence of stratospheric soot and sulfate aerosols on the Northern Hemisphere wintertime atmospheric circulation. J. Geophys. Res. Atmos., 126, e2020JD034513, doi:10.1029/2020JD034513, 2021
Hernández, Armand, Celia Martin-Puertas, Paola Moffa-Sánchez, Eduardo Moreno-Chamarro, Pablo Ortega, Simon Blockley, Kim M. Cobb, et al. "Modes of Climate Variability: Synthesis and Review of Proxy-Based Reconstructions through the Holocene." Earth-Science Reviews 209 (2020): 103286. https://doi.org/10.1016/j.earscirev.2020.103286.

L70 - North Atlantic Oscillation (NAO) was not significantly affected by the eruption but it could be foundation to understanding the background state of climate leading into an SPG shift.

L143-48 – Previous research is showing that no volcanic forcing is need to produce SPG shifts depending on the background climate state. Okay, so what was NAO, or the Artic Oscillation (AO), doing when the SPG shift occurred? How would you distinguish intrinsic variability from a volcanic forcing of an SPG shift?

The role of the background state in the onset of the SPG slowdown was previously discussed in the 2017 Moreno-Chamarro et al. studies. We can also include a plot of the NAO index during 1590–1610 in the different ensembles (that is, with and without volcanic forcing and with and without an SPG shift) to illustrate that neither phase dominates either before or after the Huaynaputina eruption.

It is precisely because we were unable to determine a precise set of initial conditions required for the SPG shift (such as a state of the NAO) that we focused our study on identifying the precise timing of climatic and environmental changes associated with the SPG shift. Although timing alone could not definitely determine whether or not the eruption triggered the SPG shift, it could add strong weight to either inference. If climatic and environmental changes associated with the SPG shift had begun several years after the eruption, as found in the simulations, then we could have concluded that the eruption trigger was more probable *a posteriori*. In fact, we found that those changes -- including increased sea ice and winter cooling -- commenced before the eruption. This finding does not eliminate the possibility of an eruption trigger, since the pre-eruption changes could have arisen due to internal variability or other unidentified forcings. However, it makes an eruption trigger less probable *a posteriori*.

L208 – Is the 1550-1590 baseline period suitable to calculate anomalies when it includes multiple eruptions?

The 1550-1590 baseline excludes the largest eruptions of the 1590s and enables accurate comparison with the simulations (including the no-eruption simulations, which remove eruptions after 1593). The reference period may be extended back another 50 years, but it would not significantly change the results.

L229- the reference period here changes from the reference period for the reconstructed anomalies. Please justify the change in reference period. Or is this a typo?

We thank the reader for identifying this mistake. It was probably a typo, but we will plot the data again using the 1550-1590 reference period to be sure.

L275 – there also appears to be a lack of agreement between NTREND and the simulations. Why might this be?

There is also a high degree of disagreement across the ensemble members, which suggests that internal variability strongly shapes the response to the volcanic eruption. Since the observed historical climate would be similar to another "model realization" -- that is, also strongly shaped by internal variability -- we should not expect perfect agreement between the simulations and observations. To highlight the variety of the model responses to the eruption across the ensemble, we could include a panel in the figure with the temperature anomalies in the ensemble mean of the simulations with volcanic forcing, along with a measure of model agreement.

L282- in Figure 6, it appears that the NVOLC reconstruction has much more annual variability and different spectral properties than the simulations. What is causing this discrepancy?

The blue line represents an average of multiple simulations. Following the strong initial post-eruption response in all simulations, this averaging across simulations reduces variability. To compare the amplitude of variability between the reconstruction and any one simulation, the comparison should be between the black line and the range in the background shading, which are similar.

L297-301 – NAO does play a major role in setting winter conditions in Europe. So, what was the state of the NAO during the period of analysis? L308 – Could the shifts in ice break of dates be connected to NAO and AO? Some of the reconstructions of NAO (Cook 2019, Ortega 2015, Hernandez 2020, etc.) show shifts that might correspond to the ice break up regime shifts.

Please see our previous response addressing these concerns. Although NAO reconstructions leave room for uncertainty, current reconstructions indicate NAO index values in a normal range during the 1590s, with a decline after 1600. We will add discussion of the post-eruption negative NAO anomaly as a possible factor in increased sea ice extent and poor sailing conditions during the first decades of the 17th century (in sections 4.4 and 5.2). Jerjeva (2002) has previously found a negative correlation between the winter NAO index and Baltic sea ice.

Reference:

Jevrejeva, Svetlana. "Association Between Ice Conditions in the Baltic Sea along the Estonian Coast and the North Atlantic Oscillation." Hydrology Research 33, no. 4 (2002): 319–30. https://doi.org/10.2166/nh.2002.0011.

L376-385- If additional simulations do not result in determining what the initial seed for SPG slowdown is, what model improvements would be needed to better model what the climate proxies and historical records appear to show?

If a larger ensemble were insufficient to determine an initial seed, then a higher-resolution model or one that could better represent the volcanic forcing (e.g., with updated parametrizations or updated inputs for other external forcings such as solar) might also prove necessary. Furthermore, with higher-resolution reconstructions future studies might specify initial climate conditions in the model world closer to those of the real world.

Technical Edits

L31 – add space between number and m - "4,850m"

L140 – missing hypen "Moreno Chamarro"

We thank the review for reading the manuscript closely. We will make these corrections to the text.