

Reply to reviewer 2:

Comments of reviewer 2 are provided in *italic blue*, our corresponding replies are in black, and the text to be revised or added in the manuscript is highlighted in *red*.

Understanding the differing responses to tropical and Northern Hemisphere volcanic forcing is crucial. This knowledge not only aids us in making informed predictions regarding potential future eruptions but also serves as a valuable analogy for stratospheric aerosol injection. This paper provides a thorough comparison between multiple reconstructions and simulations. The consistency observed in both reconstructions and simulations reveals positive NAO anomalies and Eurasian warming following tropical volcanic eruptions. However, significant discrepancies emerge in the case of Northern Hemisphere eruptions. These findings are intriguing, and I believe this paper could be published in Climate of the Past following major revisions.

Response:

Thank you for the positive comment on our manuscript. Below, we provide our point-by-point responses.

My primary concern lies in the definition of the eruption year. The impact of a volcanic eruption on climate is contingent upon when and where its stratospheric aerosols evolve. Specifically, tropical to mid-latitude lower stratospheric aerosols absorb shortwave radiation, leading to warming, which in turn increases the meridional temperature gradient and enhances the polar vortex. The role of ozone deflection is not adequately represented in these PMIP models when explaining the enhanced polar vortex following tropical eruptions. For instance, consider the Samalas eruption, which is identified as occurring in 1258 in the GRA dataset, while it is recorded as 1257 in both the CEA and eVolv2k datasets. This discrepancy means that comparisons made for the winter NAO refer to the 58/59 winter in GRA, whereas they refer to the 57/58 winter in CEA and eVolv2k. In Fig. 4c, we can see that the middle-latitude lower tropospheric aerosol forcing is significantly large in GRA six months prior to the 58/59 winter, while it only appears one or two months before the 57/58 winter in CEA and eVolv2k. This suggests that the aerosol warming effect did not have sufficient time to exert its influence in the latter case. Moreover, for many historical eruptions, pinpointing the exact eruption month can be challenging. Therefore, I recommend defining the eruption year based on the maximum annual aerosol production in simulations and making subsequent comparisons accordingly.

Response:

Thank you for raising this important point and for suggesting a revised definition of the eruption year. We agree that the timing of maximum aerosol forcing provides a more robust criterion for identifying eruption events, and we have therefore re-examined our analysis accordingly.

Using this revised definition, we find that the main differences compared to our original analysis appear in the superposed epoch analysis (Figure 3) and in the interpretation of

individual events (Figure 5). For example, in the updated Figure 3 (attached below), the significant responses occur in year 0 relative to peak forcing year (the year of maximum annual aerosol production), corresponding to the first DJF winter of that year. Specifically, we note that most events reach their maximum aerosol production in the year following the onset of the eruption. For those few events peaking in the same year as the onset, the forcing data are typically assigned with onset in January, which requires shifting the reference to the following winter to ensure sufficient time for their climatic influence to develop. Consequently, the eruption year +1 coincides with the maximum forcing year in most cases. This explains why the composite anomalies and corresponding spatial patterns of all selected eruptions (e.g., Figures 1, 2, 6, and 7, not shown here in our reply) remain nearly unchanged compared with the original version.

Therefore, to incorporate the suggestion of this comment without making the manuscript overly complex, we propose to retain Table 2 showing the starting year of the eruption for supporting the comparison in Figure 4. In the meanwhile, we will add a supplementary Table S1 listing the year of maximum forcing used for other analysis. We will also update the Methods section to clarify this definition and revise the relevant figures accordingly. We hope this will address your concern while keeping the manuscript concise.

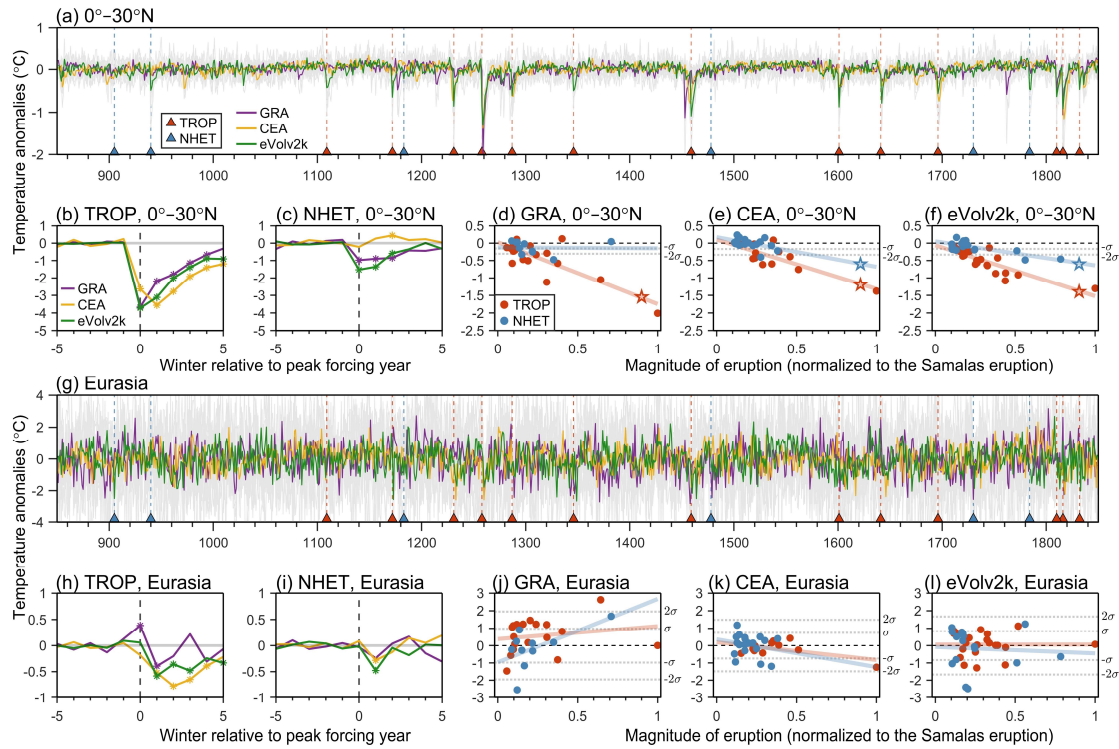


Figure 3. Winter near-surface air temperature responses to TROP and NHET eruptions in the last millennium simulations. (a) Time series of winter near-surface air temperature (T2m, unit: °C) anomalies over the tropical region (0°–30°N) for multi-model means forced by GRA, CEA, eVolv2k datasets. Grey shading denotes the spread among individual model simulations. Red and blue triangles indicate TROP and NHET eruptions with magnitudes greater than the 1991 Pinatubo eruption defined in the eVolv2k dataset, respectively. (b-c) Results of superposed epoch analysis for tropical T2m over 0°–30°N after TROP and NHET eruptions, with data statistically significant at the 95% confidence level marked with asterisk. (d-f) T2m anomalies over 0°–30°N in the first winter following each eruption with respect to the average of five preceding years. The solid lines represent the linear regression of T2m anomalies against the magnitude of eruptions, with star symbols indicating that linear trends are statistically significant at the 95% confidence level using F-test. (g-l) are as (a-f) but for the regional T2m over northern Eurasia (55°N–70°N, 10°E–120°E).

Abstract: The results of this paper are not sufficiently summarized and emphasized in the abstract. It is crucial to clarify the nature of the NAO response observed following tropical and Northern Hemisphere eruptions, as well as to outline the consistencies and discrepancies between the models and reconstructions. We can confidently conclude that tropical eruptions tend to enhance the NAO positive phase. However, there is no consistent conclusion regarding the effects of Northern Hemisphere eruptions.

Response:

Thank you for bringing it up. We agree that the abstract can be improved. We will revise it as follows:

Abstract. Large tropical (TROP) volcanic eruptions can influence North Atlantic climate by inducing a positive shift of the North Atlantic Oscillation (NAO), typically resulting in winter warming across northern Eurasia. However, these changes remain highly uncertain, as they may coincide with strong internal variability in Northern Hemisphere wintertime climate. In contrast, Northern Hemisphere extratropical (NHET) eruptions are proposed to have opposite impacts, but they have been comparatively less studied, and large uncertainties remain regarding the ability of climate models to capture volcanic responses. This study examines winter North Atlantic climate responses to TROP and NHET eruptions by comparing temperature and atmospheric circulation patterns from last millennium simulations with multiple proxy-based reconstructions. We find distinct differences in NAO-related climate changes in reconstructions, with TROP eruptions followed by a shift towards positive NAO and NHET eruptions associated with a negative NAO. In comparison, modelled responses exhibit a wide spread with strong dependence on the choice of volcanic forcing dataset. Notably, simulations using the latest volcanic forcing data show improved agreement with reconstructions, particularly for TROP eruptions. This model-proxy agreement provides a useful basis for investigating the mechanisms that drive positive NAO responses after TROP eruptions. However, the simulated impacts of NHET eruptions are less consistent and remain unclear. These results highlight the importance of improved volcanic forcing datasets, refined paleoclimate reconstructions, and robust statistical approaches to better constrain uncertainties in assessing volcanic impacts on North Atlantic climate.

Section 2.2: To compare reconstructions and simulations, the criteria for event selection were similar to those used in previous work (Liu et al. 2022 Nature communications).

Response:

We will include this point in Section 2.2:

Similar to previous model-proxy comparison work on volcanic impacts (Liu et al., 2022), we select eruptions in the PMIP last millennium simulations according to the volcanic aerosol datasets used to force the models, as three different datasets are employed across the 15 simulations. For the proxy-based reconstructions, eruptions are identified from the volcanic forcing reconstruction of Sigl et al. (2015), which is derived from Greenland and Antarctic ice cores [...]

Lines 245: The composite aerosol forcing for these three datasets, as shown in Figs. 4c and 4d, is valuable for understanding the differing responses observed in the simulations.

Response:

Thank you for bringing it up. We will add more descriptions about Figs. 4c and 4d in this paragraph to clarify the differences in the representation of the Samalas and Laki eruptions across the three datasets, with particular attention to the aspects highlighted in your primary concern. We will also add the following text regarding this point in Discussion Section 4.3:

[...] The temporal evolution and spatial distribution of volcanic forcing for the selected eruptions differ markedly among the GRA, CEA, and eVolv2k datasets (Fig. 4), and these differences are critical because the climatic impact of an eruption depends on when and where its stratospheric aerosols evolve. For many eruptions without a recorded eruption month, the events are defined as occurring in April in the GRA dataset, but in January in the CEA and eVolv2k datasets. Such discrepancies in the timing and duration of peak forcing complicate the comparison of winter signals, as it becomes difficult to ensure both sufficient time for the eruptions to exert their impacts and an accurate capture of the peak climate anomalies. This challenge is particularly pronounced for NHET eruptions, which are often less well documented and identified than TROP eruptions due to their smaller magnitudes and more geographically restricted impacts on the Northern Hemisphere. As a result, the simulated impacts of NHET eruptions are less consistent across models compared to those of TROP eruptions [...]