

State-Dependent Stratospheric and Surface Climate Responses to Pinatubo-like Volcanic Forcing: Insights from VolMIP

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Introduction:

Whether major volcanic eruptions are capable of modulating, and potentially even shifting, the North Atlantic Oscillation (NAO) phase has been a long-standing question. The postulated dominant stratosphere-troposphere pathway for this modulation starts with the aerosol-driven heating of the tropical lower stratosphere, which leads subsequently to a strengthening of the meridional temperature gradient and the stratospheric polar vortex (SPV). This in turn favors a positive NAO, and thereby also anomalous advection of maritime air into the continental interiors leading to a warming response especially over Eurasia during the first one or two post-eruption winters. This post volcanic wintertime warming mechanism has been challenged in several recent studies. These argue, that the observed post-eruption surface warming is indistinguishable from the large internal variability of the northern hemispheric (NH) SPV strength.

Northern Atlantic Oscillation (NAO):

The NAO is recognized as the dominant mode of atmospheric and climate variability in the mid/high latitudes in the Northern hemisphere (NH), particularly during boreal winter. A positive NAO phase (NAO+; typically associated with a stronger SPV) during winter leads, among other things, to warmer air masses and more precipitation over north-western Europe. In a negative phase (NAO-) these effects are reversed.

NAO state surface temperature anomalies (K) DJF in Control

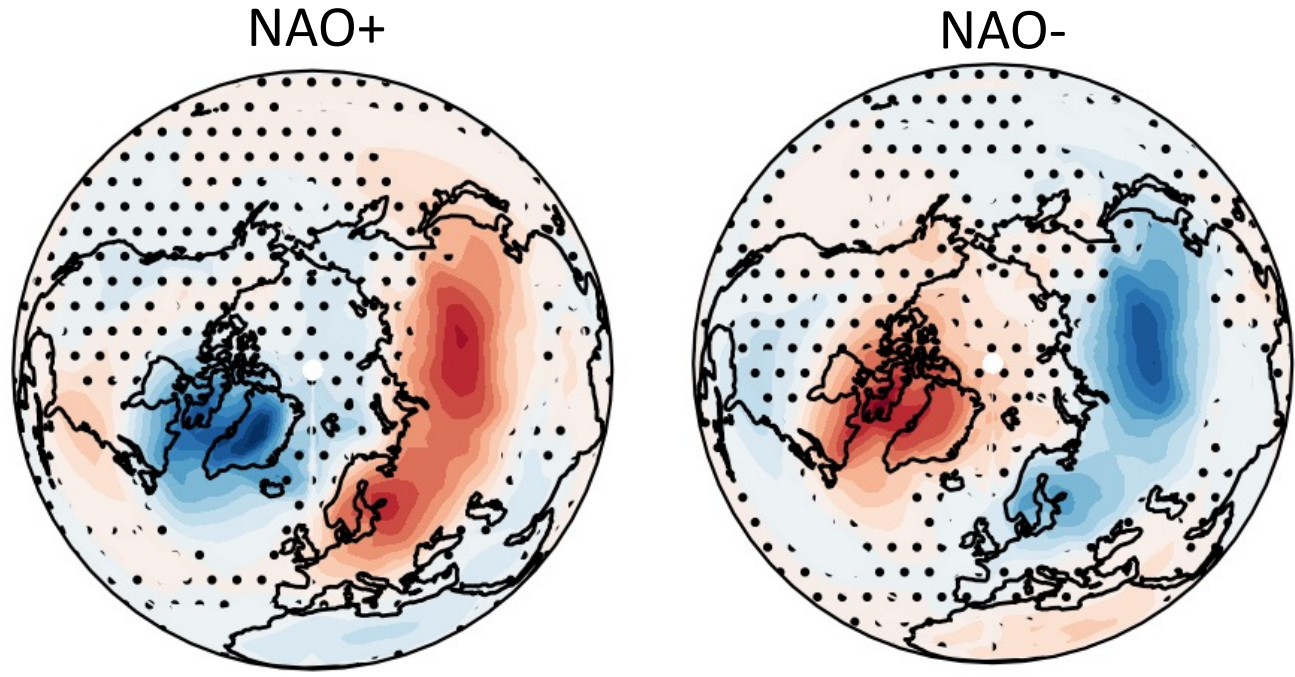


Figure 1: Winter surface temperature anomaly patterns emerging in Control simulations for NAO+ and NAO- in the multi-model mean. Significance (not stippled) is defined as 75% of models agreeing on the sign of the temperature anomaly.

Control NAO state vs ΔU (60N-70N, 10hPa)

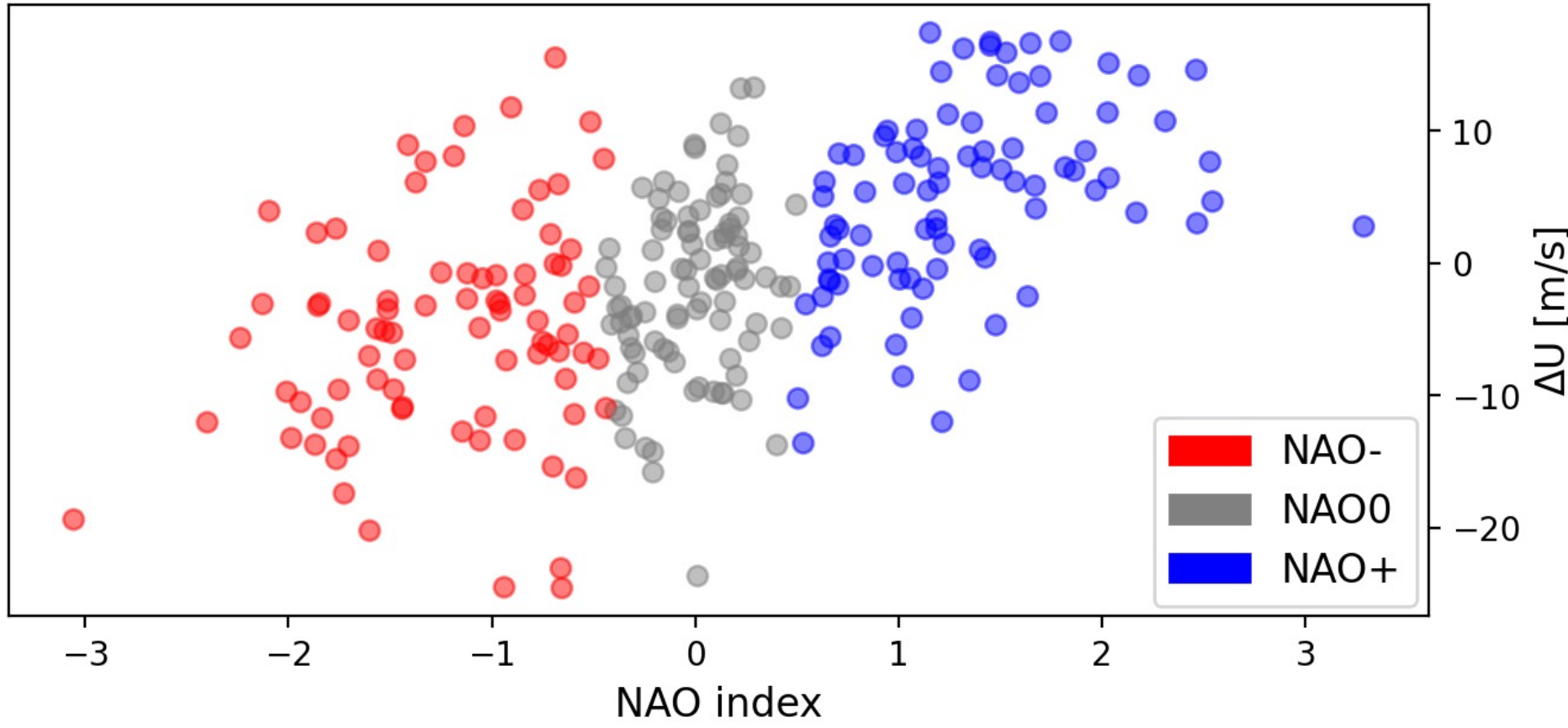


Figure 2: Multi-model perspective on the relationship of NAO with polar vortex strength represented by mid-latitude stratospheric zonal wind anomalies for Control simulations.

(1) Does a significant modulation or even shift in the NAO phase emerge after major volcanic eruptions?

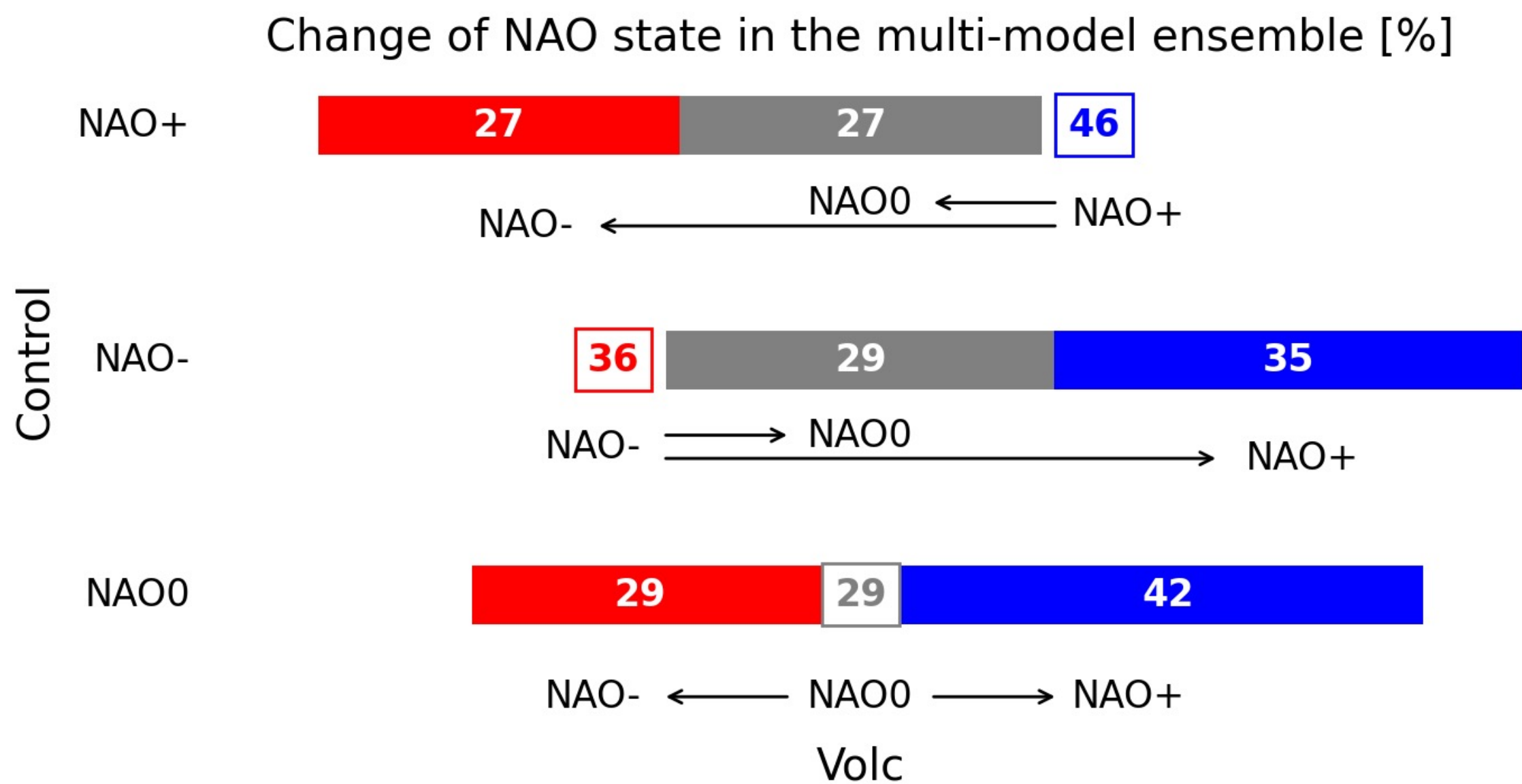


Figure 3: Multi-model perspective on the relative change of each NAO phase in the first post-eruption winter within Control to Volc ensemble pairs. Fraction of Volc simulations with NAO remaining in the NAO phase of Control are given in open squares, and fractions of Volc simulations changing phase (indicated by arrows) are shown in coloured bars scaled to fraction.

Methods and Data:

We analyze a series of targeted pre-industrial simulations performed within the Model Intercomparison Project on the climatic response to Volcanic forcing (VolMIP; Zanchettin et al, 2016), which were designed and carried out in alignment with the protocol of the sixth phase of the Coupled Model Intercomparison Project (CMIP6). Monthly mean output of 6 models from the *pinatubo-full* experiment within VolMIP were used which provided at least 25 ensemble members (see Table 1). The simulations are branched off from the piControl simulation (unperturbed pre-industrial climate conditions, hereinafter Control) based on equally distributed states of ENSO (cold/neutral/warm states) and of the NAO (negative/neutral/positive states). Following the VolMIP protocol, we calculate NAO indices as the pressure difference between spatial averages over (20-55° N; 90° W-60° E) and (55-90° N; 90° W-60° E). Anomalies of individual variables are built for each model separately using a climatology from the full piControl, accounting for seasonality. Significance of (multi-)model distributions is tested using the Kolmogorov-Smirnov test at the 95% level.

Model	NAO	Control	Volc
CanESM5	-1	13	19
	0	15	7
	1	12	14
GISS-E2-1-G	-1	35	27
	0	46	42
	1	40	52
IPSL-CM6A-LR	-1	10	7
	0	7	5
	1	8	13
MIROC-ES2L	-1	6	8
	0	8	9
	1	11	8
MPI-ESM1-2-LR	-1	10	8
	0	7	7
	1	8	10
UKESM1-0-LL	-1	9	6
	0	9	8
	1	7	11

Table 1: Number of ensemble members per model and NAO phase in Control and Volc.

(2) Can a stratospheric impact of the volcanic eruption be clearly identified from the tropics to the Arctic?

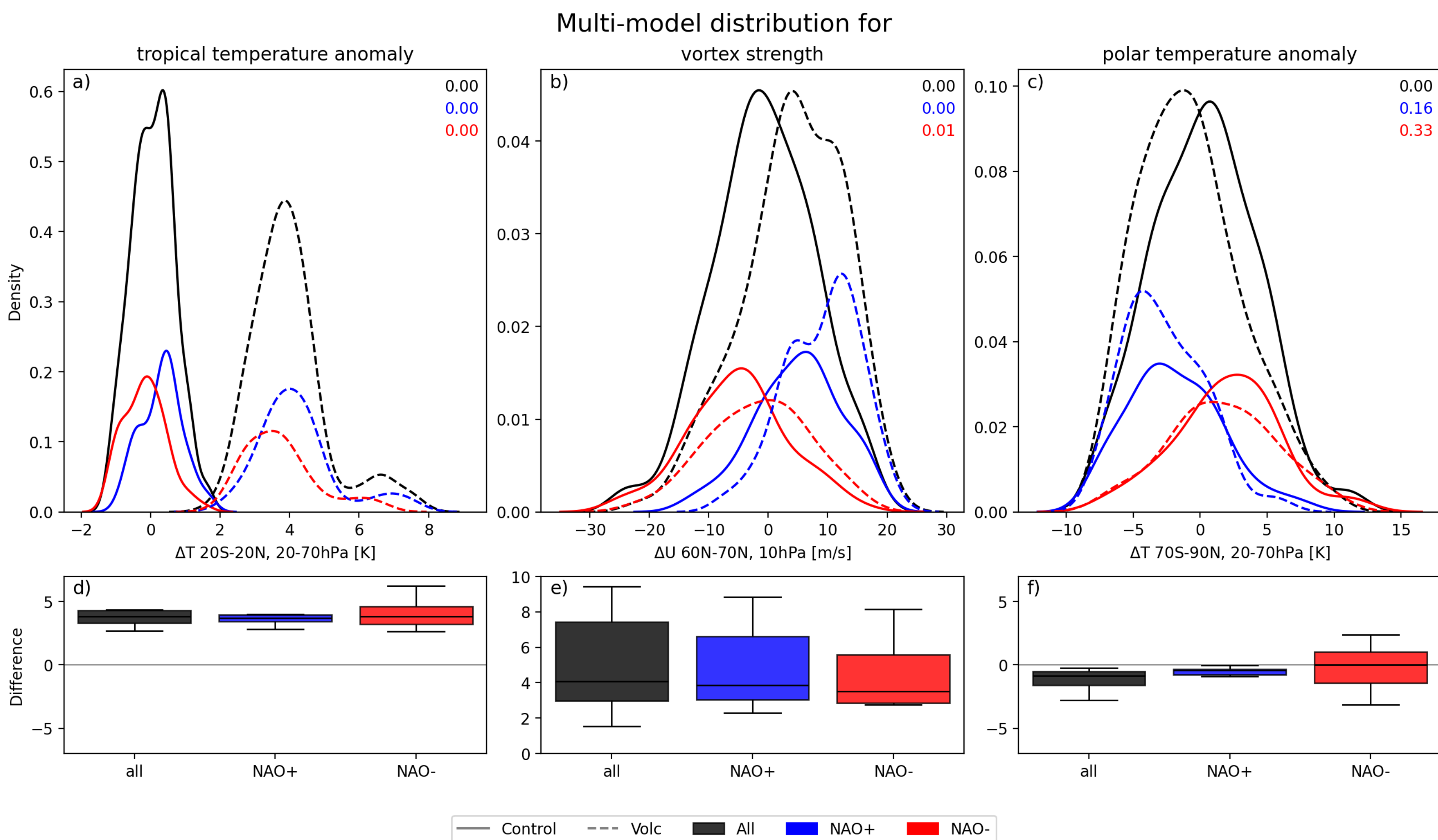


Figure 4: Multi-model distribution of a) tropical stratospheric temperature, b) polar stratospheric vortex strength, and c) polar stratospheric temperature in the first post-eruption winter for Control (solid) and Volc (dashed) ensembles. Panels d) - e) show the distribution of model specific mean differences between Volc and Control for variables in a) - c), respectively. p-values indicating significance of differences of Control and Volc distributions are provided panels a) - c) (top right).

Our key findings:

- A clean sampling of the dynamical background state is necessary to separate imprints of volcanic forcing from internal variability
- A robust strengthening of the stratospheric polar vortex emerges under Pinatubo-like forcing independent of the dynamical background state
- No significant modulation of the North Atlantic Oscillation and thus no Eurasian warming emerges in the first post-eruption winter

(3) Does a robust wintertime surface warming signal emerge in Eurasia after the eruption?

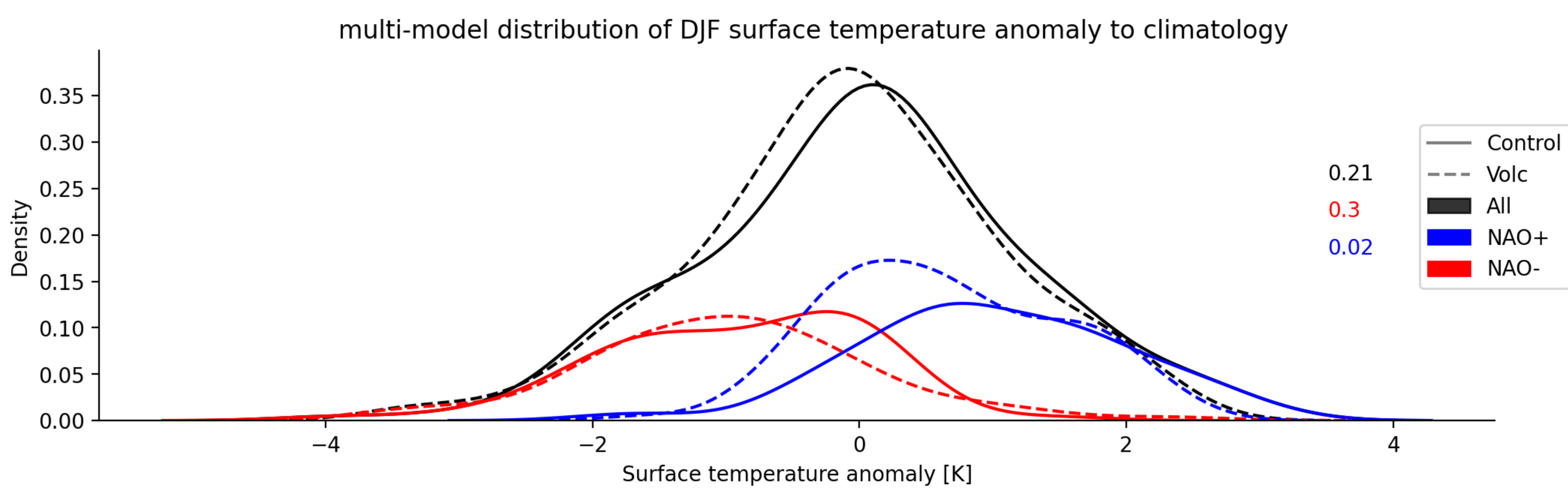


Figure 5: Multi-model distribution of Eurasian temperature anomalies for Control (solid) and Volc (dashed) in the full ensemble and subset by NAO computed over 40-70°N and 0-150°E following Polvani & Camargo, 2020.

Conclusions:

- the significance (insignificance) of atmospheric and surface responses is robust in the multi-model mean but varies in strength (and sometimes robustness) among the individual VolMIP models
- significance hinges on ensemble size, thus, significance may strengthen (or appear) as signal-to-noise ratios might change with substantially larger ensemble size
- in this study the focus was given on a Pinatubo-like forcing and dynamical and surface impacts may change if a larger volcanic forcing is applied
- VolMIP considers pre-industrial climate conditions and responses might differ under other climate states, a question worthy to potentially explore in future MIPs.

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