Climatic Impacts of Tropical Volcanic Eruptions over Eurasia and MENA in MIROC6 High-Top Simulations

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1. Summary
We used the Earth Simulator (ES) to conduct MIROC6 high-top coupled climate simulations examining how tropical volcanic eruptions (e.g., the Pinatubo eruption) modulate large-scale atmospheric circulation and regional climate, with a particular focus on the Middle East and North Africa (MENA) and Eurasia. Building upon our recent publication (Dogar et al., 2025), we investigated the mechanisms linking volcanic forcing, ENSO, and NAO and their combined effects on surface temperature, precipitation, and stratosphere–troposphere coupling. Our results confirm that volcanic-induced NAO variability is the primary driver of post-eruption winter cooling over MENA and warming over high-latitude Eurasia, while ENSO primarily amplifies the response. Additionally, summer responses reveal weakened ITCZ convection, tropical warming, and northern-Hemisphere mid-latitude cooling—features that MIROC6 captures effectively due to its high-top configuration. Ongoing ES experiments extend this work to multiple tropical eruption types and their hemispheric scenarios, focusing on polar vortex dynamics and ITCZ responses.

2. Research Background and Objectives
Large tropical eruptions inject stratospheric sulfate aerosols that alter the meridional temperature gradient and strengthen the polar vortex, contributing to a positive NAO-like phase. Observational and modeling studies show notable MENA cooling and Eurasian warming after major eruptions such as El Chichón (1982) and Pinatubo (1991). Attribution, however, is made complex by concurrent ENSO variability (Polvani et al., 2019).
The objectives of this research were to:

1. Summarize results from our recently published MIROC6 volcanic-ENSO–NAO analysis, performed on the Earth Simulator.
2. Extend these simulations to multiple volcanic scenarios, including Pinatubo, El Chichón, and Agung, with both northern-hemisphere and hypothetical southern-hemisphere eruptions.
3. Evaluate stratosphere–troposphere coupling, including polar vortex strengthening and NAO/ITCZ responses.
4. Assess how eruption latitude influences hemispheric climate asymmetry, focusing on Eurasia and MENA.

3. Methodology
We used the MIROC6 high-top coupled climate model (90 vertical levels) on the Earth Simulator. Completed experiments included a baseline climatological evaluation using ERA5 for DJF temperature, precipitation, and NAO-related patterns (Figs. 1–2), followed by volcanic sensitivity experiments initialized from three ENSO states (El Niño, Neutral, La Niña). For each ENSO condition, eight ensemble members were integrated from 1991–2002 under enhanced volcanic forcing (three times the 1991 Pinatubo aerosol loading), together with corresponding control simulations. Volcanic impacts were quantified using composite anomalies (volcanic minus non-volcanic runs) and compared with observational, reanalysis products and CMIP6 simulations (Fig. 3), demonstrating that MIROC6 performs realistically for both climatological patterns and volcanic responses.

For FY2025 and FY2026, extended simulations include northern-hemisphere eruptions (Pinatubo, El Chichón, Agung, each scaled to 3× intensity) and their southern-hemisphere counterparts (Pinatubo-SH, El Chichón-SH, Agung-SH). All experiments are initialized from the same three ENSO states with eight-member ensembles. This experimental design allows systematic assessment of polar vortex responses, NAO/SAM modulation, ITCZ north–south displacement, and broader hemispheric asymmetries in post-eruption climate variability.

4. Major Results

During winter (DJF), all volcanic simulations produced pronounced cooling over MENA and warming across high-latitude Eurasia, accompanied by a robust positive NAO pattern that appeared consistently across all ENSO states. ENSO mainly amplified these anomalies, with El Niño–initialized runs showing the strongest signals, although Neutral and La Niña states also produced clear responses (Dogar et al., 2025). Stratospheric diagnostics further showed an intensified polar vortex, reflected in strengthened westerlies around 50–60°N.

In summer (JJA), the simulations showed widespread mid-latitude cooling over northern MENA and southern Europe, together with approximately 1°C warming in convective regions of the ITCZ. Reduced precipitation and cloud cover indicated a southward shift of the ITCZ, associated with weakened Hadley-cell ascent and diminished moisture transport into MENA. Comparisons with UDEL, ERA5, and CMIP6 confirmed that MIROC6 reproduces the spatial structure of volcanic cooling and ITCZ displacement realistically, with enhanced forcing yielding stronger but dynamically consistent responses (Fig. 3).

5. Ongoing ES Experiments and Expected Outcomes

Our ongoing ES simulations investigate how northern- versus southern-hemisphere eruptions (Pinatubo, El Chichón, Agung at 3× intensity) influence stratospheric warming, polar vortex behavior, and NAO/SAM variability. "Mirror" southern-hemisphere eruptions allow assessment of hemispheric symmetry in vortex and annular-mode responses. These simulations also examine ITCZ sensitivity, including north–south displacement, tropical–extratropical gradient changes, and cross-equatorial energy transport under asymmetric forcing. The outcomes are expected to clarify hemisphere-dependent volcanic impacts on the polar vortex and NAO/SAM, improve understanding of ITCZ displacement mechanisms, and contribute to a follow-up manuscript planned for 2026.

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References

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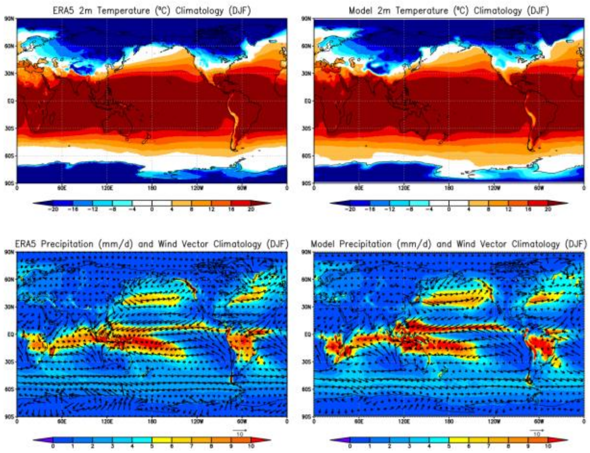

Figure 1: The Climatological patterns from ERA5 (left) and MIROC6 model (right panel) for 2m-surface temperature (top) and precipitation with associated UV wind vectors (bottom).

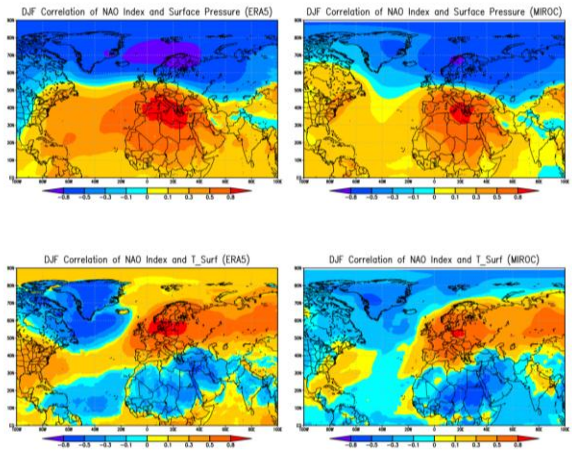

Figure 2: The correlation patterns from ERA5 (left) and MIROC6 model (right panel) between NAO-index and surface pressure (top) and NAO-index and surface temperature (bottom).

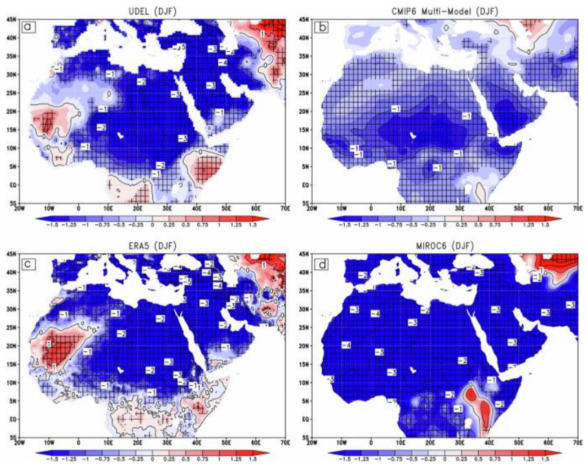

Figure 3: The Near-surface air temperature anomalies during the first post-eruption winter.