Investigating the Climatic Impacts of Volcanic Eruptions over Eurasia and MENA Using the MIROC6 Coupled Climate Model

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1. Summary
Tropical volcanic eruptions are significant drivers of climate variability, inducing North Atlantic Oscillation (NAO)-like circulation changes that are known to trigger high-latitude Eurasian winter warming and amplified cooling in the Middle East and North Africa (MENA). However, recent studies have raised concerns about the consistency of this post-eruption NAO-like pattern and its regional effects on Eurasia and MENA. To address this gap, this study utilizes the high-top MIROC6 coupled model to investigate the roles of NAO and ENSO in shaping these regional climate dynamics following tropical volcanic events. Findings reveal that winter responses are primarily NAO-driven, with El Niño-like conditions amplifying cooling but not initiating it. Summer responses, including tropical warming and drying and high-latitude cooling, underscore ENSO's pivotal role. These results validate MIROC6's effectiveness in simulating volcanic impacts and provide critical insights for interpreting climate models and informing post-eruption climate policies.

2. Introduction
Tropical volcanic eruptions significantly impact the global climate, particularly through the injection of sulfur dioxide (SO_2) into the stratosphere, altering solar radiation and atmospheric circulation. Previous studies have shown that such eruptions induce positive NAO phase that causes warming in high-latitude regions and cooling in MENA. However, there is debate regarding whether this cooling is due to volcanic-induced NAO or the influence of co-occurring ENSO conditions (Dogar et al., 2023; 2024; Polvani et al., 2019; Qin et al., 2024; Polvani and Camargo, 2020; Coupe and Robock, 2021). Our study uses the MIROC6 model to better investigate the role of NAO and ENSO in driving these climate responses, particularly in MENA, a region sensitive to both volcanic and natural variability.
In this study, we aim to investigate the response of ENSO and NAO variability to tropical volcanic eruptions, with a specific focus on the amplified high-latitude winter warming over Eurasia and winter cooling over the MENA region. Using the high-top MIROC6 coupled ocean-atmosphere model, our research seeks to address the following key questions:

1. How accurately does the MIROC6 coupled model simulate the indirect volcanic impacts of post-eruption changes in ENSO and NAO in the MENA region?
2. What is the primary driver of post-eruption low-latitude amplified winter cooling and summer tropical convective belt warming and drying in the MENA region?

3. Methodology
This study utilizes the MIROC6 coupled model to investigate the post-volcanic climatic impacts on winter (DJF) and summer (JAS) seasons in the MENA region. We performed a long control run for 100 years from which we selected stable ENSO conditions (El Niño, La Niña, Neutral) to initialize our volcanic (i.e., three times the intensity of the 1991 Pinatubo eruption) and corresponding control runs. Before analyzing these runs, we tested the model climatology for the winter season using the aforementioned MIROC6 long control run. The results of the model climatology are promising (Figure 1 and Figure 2), indicating that MIROC6, a high-top model essential for simulating stratospheric dynamics following volcanic eruptions, could be used effectively to understand the impacts of ENSO-

preconditioned variability over high-latitude Eurasia and low-to-mid-latitude MENA.

4. Preliminary Results and Expected Outcomes

The preliminary findings from model volcanic-sensitivity runs suggest that the primary driver of post-volcanic winter cooling over high-latitude Eurasia and low-to-mid-latitude MENA is the NAO, with ENSO conditions amplifying the cooling but not triggering it. Summer warming and high-latitude cooling are influenced by ENSO-related variability, highlighting the complex interplay between volcanic activity, ENSO, and the NAO in the region. These findings provide new insights into the mechanisms behind volcanic impacts on regional climate, emphasizing the importance of high-top coupled models in understanding these interactions. Our study underscores the need for further research into the combined effects of volcanic eruptions and ENSO/NAO variability on Eurasia and MENA's climate. The above content was submitted to npj Climate and Atmospheric Science.

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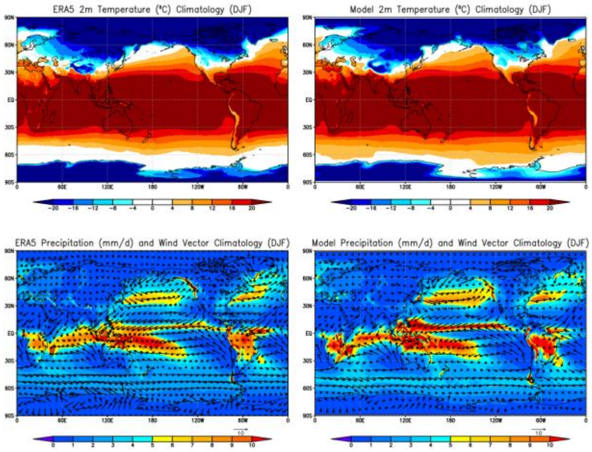

Figure 1: The Climatological patterns from ERA5 (left) and MIROC6 model (right panel) for 2m-surface temperature (top) and precipitation with associated UV wind vectors (bottom).

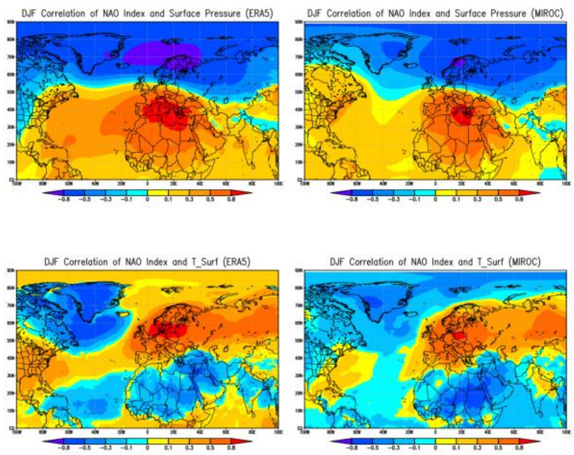

Figure 2: The correlation patterns from ERA5 (left) and MIROC6 model (right panel) between NAO-index and surface pressure (top) and NAO-index and surface temperature (bottom).