

Polar warming would have emerged a decade earlier without major volcanic eruptions

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Abstract

Volcanic eruptions in the 20th century—Agung (1963), El Chichón (1982), and Pinatubo (1991)—released SO₂ which formed sulphuric acid aerosol that temporarily cooled the polar regions. Using CMIP6 simulations, HadCRUT5 temperature data, and MERRA2 reanalysis and aerosol datasets, this study shows that these eruptions delayed the emergence of polar warming by nearly a decade. Arctic surface air temperature (SAT) anomalies would have been up to **0.5°C warmer** without these eruptions. The **Arctic minimum temperatures (Tmin) warmed faster than maximum temperatures (Tmax)**, while the Antarctic response was weaker, buffered by oceanic and atmospheric dynamics. **Volcanic cooling persisted 4–5 years following each eruption**, highlighting the regulatory role of natural aerosols. This has implications for geoengineering strategies.

Introduction & Methods

The Arctic is warming three to four times faster than the global average (Arctic Amplification). While volcanic eruptions inject SO₂ into the stratosphere, forming sulphuric acid aerosols which scatter sunlight and cool the planet, this study seeks to answer the question: how much has volcanic eruptions delayed polar warming?

Models: CMIP6/DCPP ensemble simulations (historical vs. volcanic only vs. no-volcano).

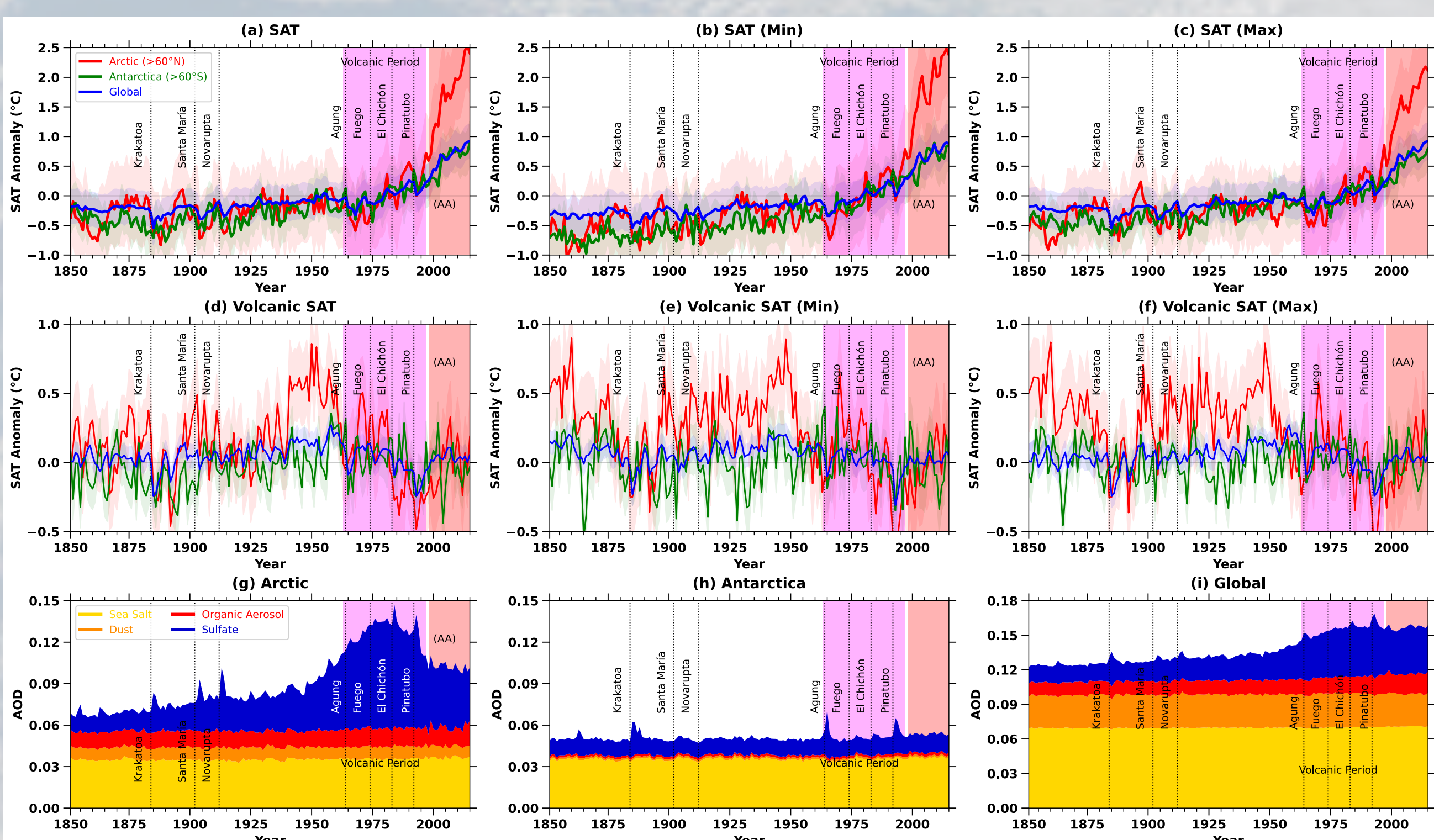
Data used: HadCRUT5 (temperature), MERRA2 (AOD).

Regions of interest: Arctic (>60°N), Antarctic (>60°S).

Climate Metrics: Mean SAT, Tmin, Tmax anomalies.

Period of study: 1850–2015, focusing on 1964–1996 (period of major 20C eruptions).

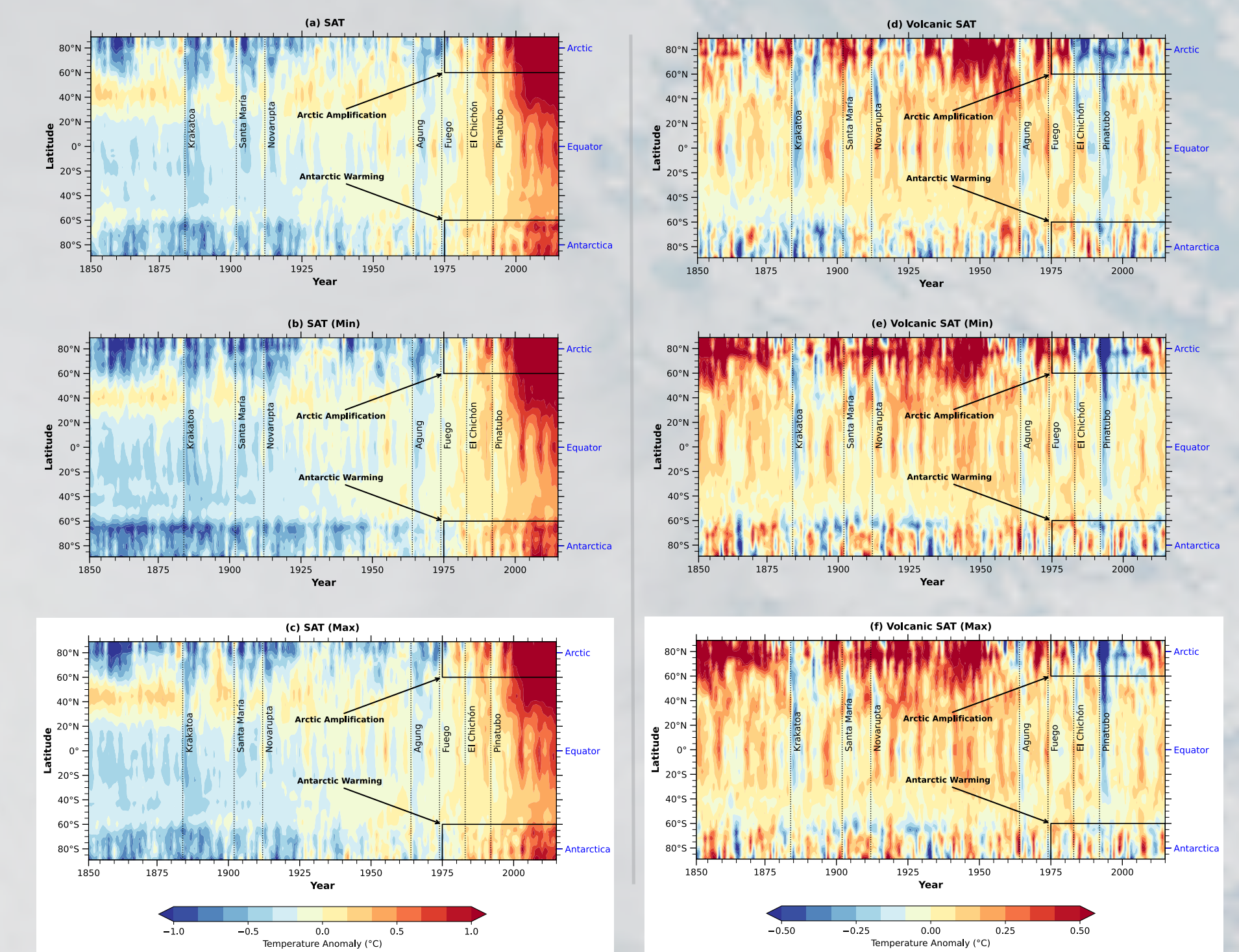
Polar response to historical eruptions



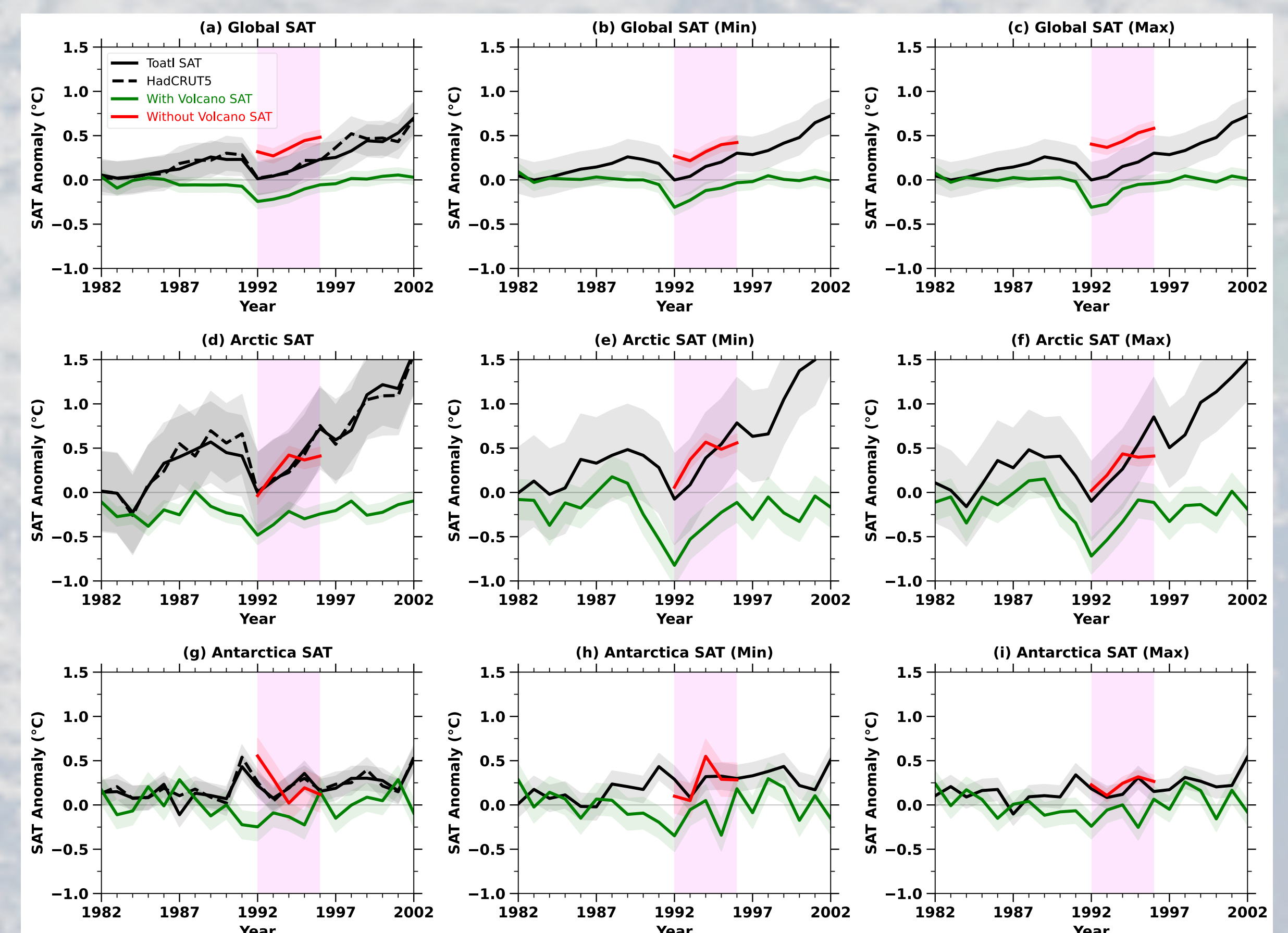
Temporal changes in SAT and AOD. (a–c) Annual anomalies of SAT, Tmin, and Tmax from all-forcing simulations for global, Arctic, and Antarctic regions. (d–f) Same as (a–c) but for volcanic-only forcing. Anomalies are relative to the volcanically influenced period (1964–1996), which includes the Agung, Fuego, El Chichón, and Pinatubo eruptions. Arctic, Antarctic, and global series are shown in red, green, and blue. (g–i) Stacked AOD components showing that elevated AOD coincides with reduced SAT, Tmin, and Tmax following major eruptions.

Onset delay of polar warming

Zonally averaged SAT anomalies. (a–c) Annual zonal anomalies of SAT, Tmin, and Tmax from all-forcing runs; (d–f) same for volcanic-only runs. Anomalies are relative to the volcanically influenced period (1964–1996), showing latitudinal contrasts in warming and volcanic cooling.

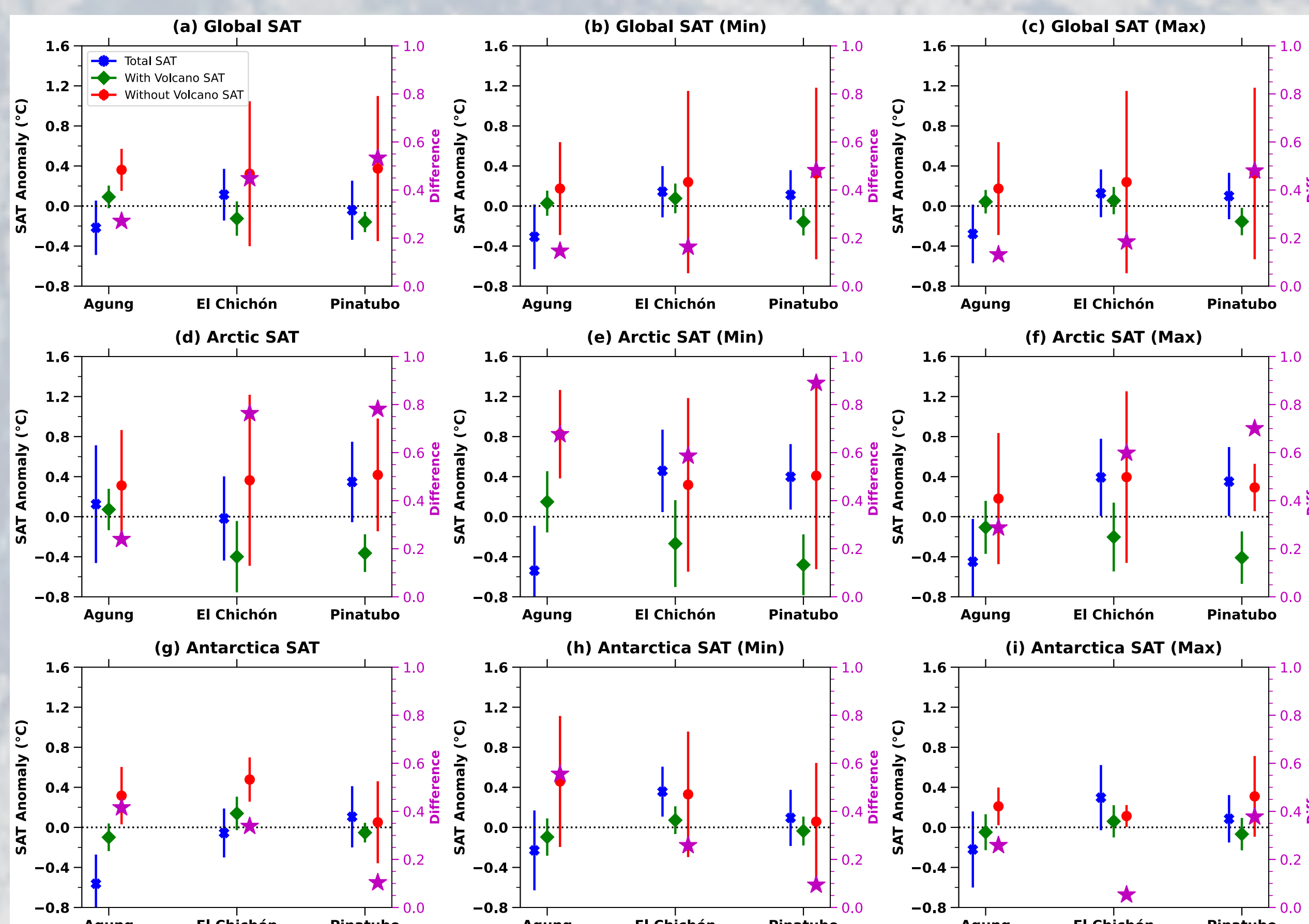


Implications for future change



Temporal evolution of SAT, Tmin, and Tmax anomalies with and without volcanic forcing during the Pinatubo eruption. (a–c) global, (d–f) arctic, and (g–i) Antarctic regions. Anomalies are relative to the volcanically influenced period (1964–1996). CMIP6 multi-model means are shown for total (black), with-volcano (green), and no-volcano (red) runs, with HadCRUT5 observations (dotted black). The figure highlights the transient cooling from Pinatubo across all regions.

Polar response to eruptions



Mean SAT, Tmin, and Tmax anomalies (±1 SD) with and without volcanic eruptions for global, Arctic, and Antarctic regions. (a–c) Global, (d–f) Arctic, and (g–i) Antarctic results from CMIP6 multi-model means. Anomalies are differences between four-year post-eruption averages (Agung, El Chichón, Pinatubo) and the volcanic reference period (1964–1996). Blue, green, and red denote total, with-volcano, and no-volcano SAT; maroon stars show their differences.

Discussion

- Volcanic eruptions significantly modulate polar climate variability.
- Volcanic aerosols delayed Arctic warming by almost a decade.
- Tmin is more sensitive than Tmax to aerosol forcing (nighttime radiative cooling).
- The Arctic's strong response underscores the importance of natural aerosols in climate dynamics, however, cooling is short-lived and spatially uneven
- Effects resemble solar geoengineering proposals (e.g., stratospheric aerosol injection).

Acknowledgments

All the CMIP6 model datasets are available at <https://esgf-data.dkrz.de/search/CMIP6-dkrz/>. Observational data from HadCRUT5 is available at <https://crudata.uea.ac.uk/cru/data/temperature/>. MERRA2 data is available at <https://gmao.gsfc.nasa.gov/reanalysis/merra-2/>. This study was supported by the NERC National Centre for Atmospheric Science, National Centre for Earth Observation; with co-funding from NE/Y000048/1