Southern Annular Mode response to volcanic eruptions: implications for ice core proxies

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1. Introduction

Large tropical volcanic eruptions have been observed[1] to have a significant influence on the large-scale circulation patterns of the Northern Hemisphere (NH), through mechanisms related to the radiative effects of stratospheric volcanic sulfate aerosols. Such atmospheric anomalies can be described as perturbations to the Northern Annular Mode, a mode of variability that is characterized by large scale shifts of mass between the polar and middle latitudes[2].

In the Southern Hemisphere, comparable perturbations to the Southern Annular Mode (SAM) after tropical eruptions have not yet been observed[3]. Here, with a coupled aerosol general circulation model, we investigate:

1. How strong must a tropical eruption be to produce a significant SAM response?
2. What characterizes a volcanically perturbed SAM state?
3. How could a volcanically perturbed SAM impact Antarctic ice core proxies?

2. Model simulations

Volcanic simulations were performed with the MAECHAM5-HAM general circulation model (T42/L39) including detailed aerosol microphysics[4]. Eruptions are simulated by injecting SO_2 into the lower stratosphere (30 hPa). The model then simulates the full lifecycle of the volcanic aerosols, including oxidation of SO_2 to H_2SO_4, aerosol formation and growth, sedimentation, and the removal processes wet and dry deposition. The model is run in a free-running climate mode, with modern day external forcings, including climatological SSTs. Eruptions with a wide range of stratospheric SO_2 injection magnitudes are simulated, with eruptions in January and July[5]. All eruptions are situated at 14°N, 91°W, the site of the Los Chocoyos (~84ka BP) eruption, the largest eruption (~700 Tg SO_2) in the Central American Volcanic Arc (CAVA) timeseries of the last 200ka (Metzner et al., submitted manuscript). Simulations of the Los Chocoyos eruption are referred to as the E700 experiment.

3. Atmospheric dynamics

A direct result of the injection of volcanic aerosols is heating of the lower stratosphere through the absorption of long wave radiation emitted by the Earth's surface.

- In our E700 simulations, the creation of volcanic aerosols leads to strong temperature anomalies in the tropical lower stratosphere, of magnitudes >20 K (Fig. 1).
- This heating leads to a stronger equator to pole temperature gradient, which in turn leads, through the thermal wind balance, to stronger zonal winds.
- The zonal wind anomalies are strongest in the stratosphere, but significant anomalies (>10 m/s) extend down to the surface, especially in the SH.

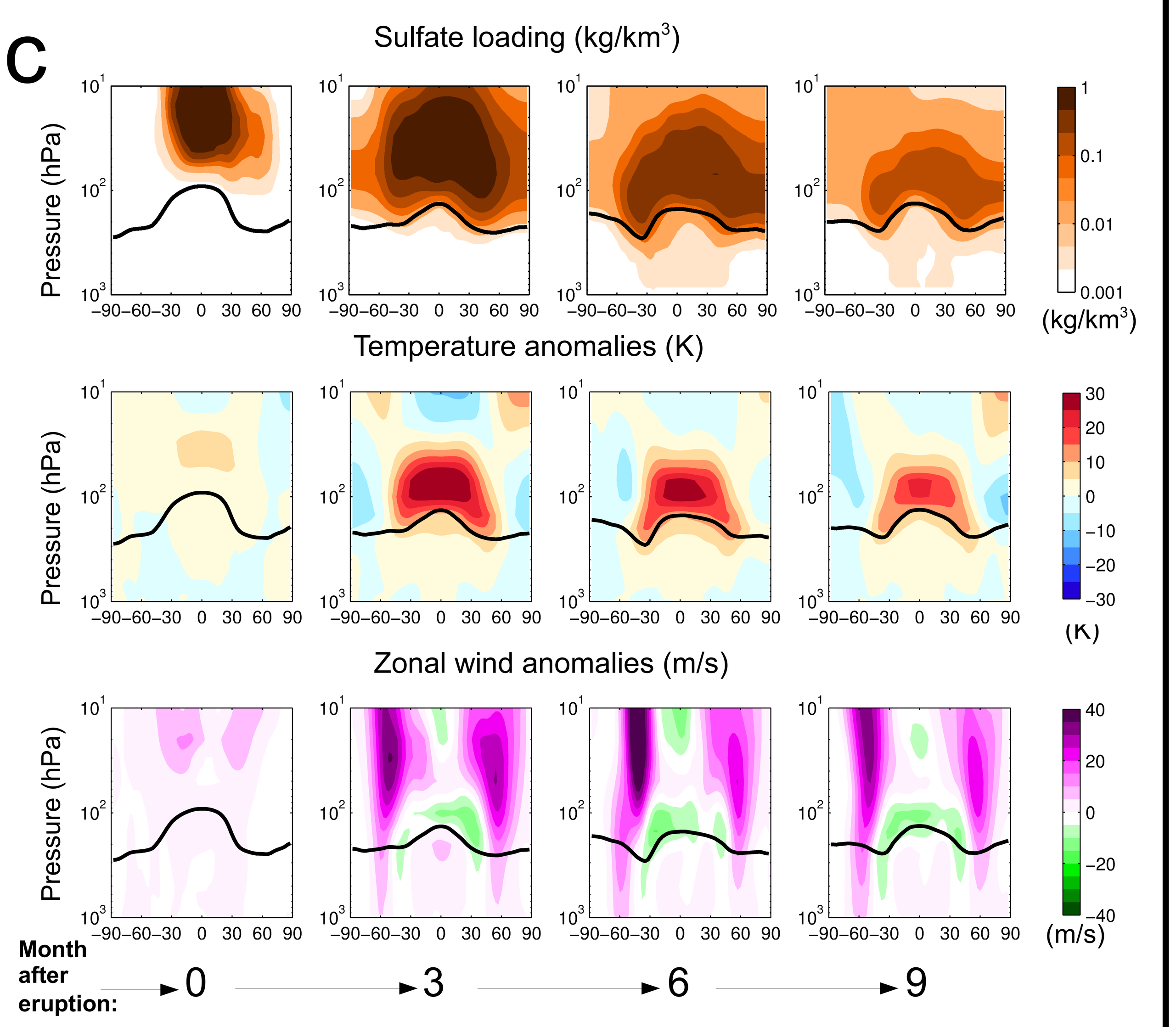


Figure 1: Post-eruption monthly mean, zonal mean sulfate loading (top), temperature anomalies (middle), and zonal wind anomalies (bottom) for the E700 January eruption experiment.

4. Southern Annular Mode response

The SAM Index can be defined as the difference in the normalized monthly zonal mean pressure anomalies between 40° and 65°S[6].

In our volcanic simulations:

- Following very strong eruptions (e.g., E700, Fig. 2) the SAM index is clearly skewed toward positive values, with significant anomalies occurring in the first year, and a tendency towards positive values lasting up to 4 years.
- The strength of the first-year mean SAM response is directly related to the magnitude of the stratospheric SO_2 injection (Fig. 3).
- Significant SAM response, defined as a SAM anomaly that is greater than twice the standard deviation of the SAM of a 20 year control run, is produced in the stratosphere for a eruption with >15 Tg SO_2 injection. At the surface, where the natural variability is larger, one requires an eruption of >90 Tg SO_2 to produce a significant response.

Meteorological anomalies (e.g., for E700, Fig. 4) show a clear picture of extreme impact of volcanically induced SAM.

- Sea level pressure anomalies show a classic positive SAM structure, with relatively zonally symmetric anomalies.
- Westerly wind anomalies over the Southern ocean are strongest at ~60ºS.
- Significant easterly wind anomalies present at ~40ºS.
- Precipitation anomalies follow a banded structure, with a dry Antarctic continent, wet Antarctic peninsula and Southern Ocean, a dry band around ~45ºS including tip of South America, and a dry Australia.

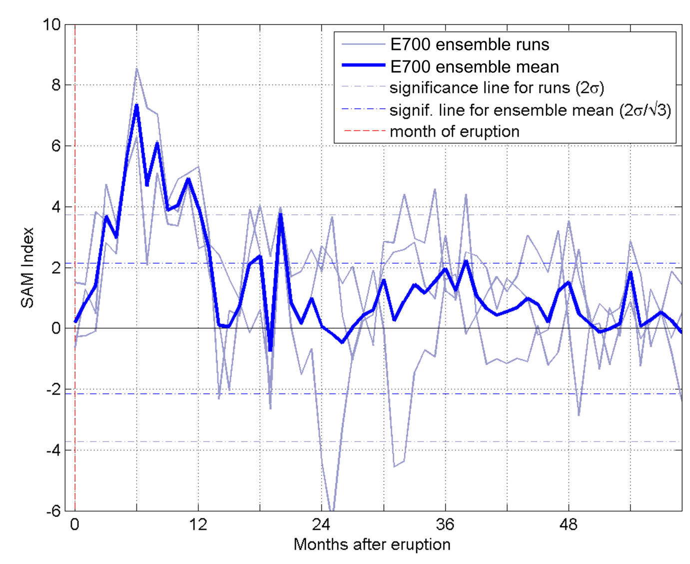


Figure 2: Post-eruption SAM index evolution, for 3 E700 January eruption simulations, and the ensemble mean.

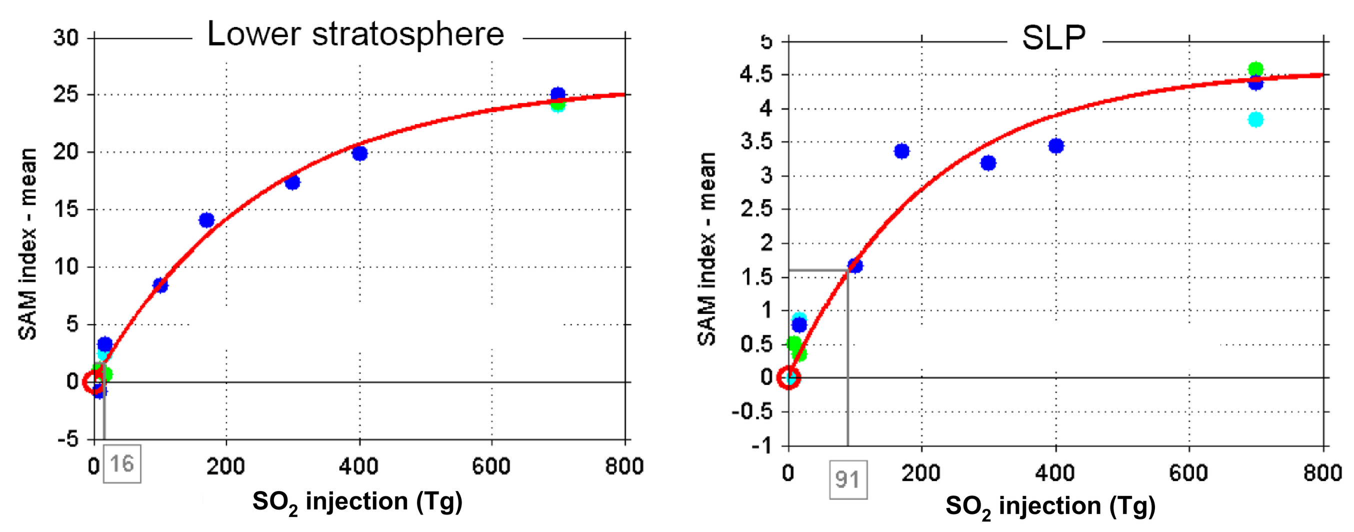


Figure 3: Post-eruption year 1 mean SAM index for January eruption simulations of different SO_2 injection magnitude, in terms of 50 hPa geopotential height (lower stratosphere, left) and sea level pressure (right).

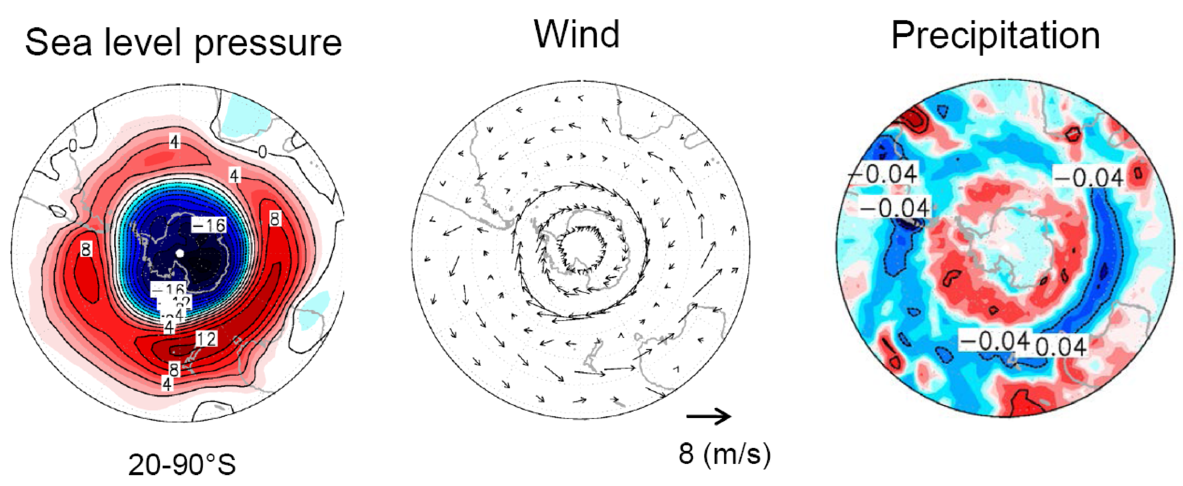


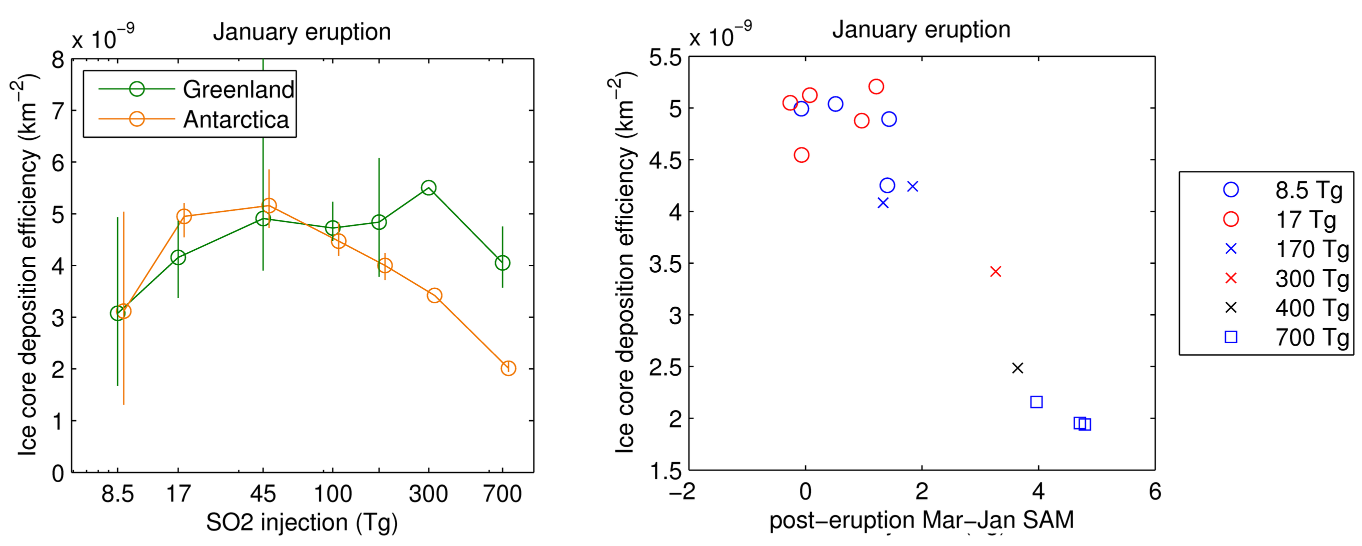
Figure 4: First post-eruption winter meteorological anomalies for the E700 January eruption experiment.

5. Antarctic sulfate deposition

Reconstructions of paleo-volcanic aerosol loading, used in paleo-climate modeling, are based on ice core sulfate records. Ice core sulfate levels are used to infer stratospheric aerosol loading, through a scaling factor, itself based on deposition of material from nuclear bomb tests and modern eruptions[7]. This method assumes linearity, but could changes in atmospheric dynamics brought about by the volcanic aerosols affect the deposition to ice cores?

We define an “ice core deposition efficiency” as the average sulfate deposition to the Antarctic (and Greenland) land masses divided by the hemispheric sulfate mass burden.

- For eruptions larger than 45 Tg SO_2 injection, Antarctic deposition efficiency decreases with increasing eruption magnitude (Fig. 5, left).
- For such eruption magnitudes, Antarctic deposition efficiency is negatively correlated with post-eruption SAM anomaly (Fig. 5, right). Thus, the strong westerly winds at the Antarctic coastline, and the related decrease in Antarctic continental precipitation lead to a relative decrease in sulfate deposition to the Antarctic ice sheets for strong eruptions.
- Compared to Greenland ice sheets, Antarctic ice sheets are a much less efficient sink of volcanic sulfate for large eruptions (Fig. 6).



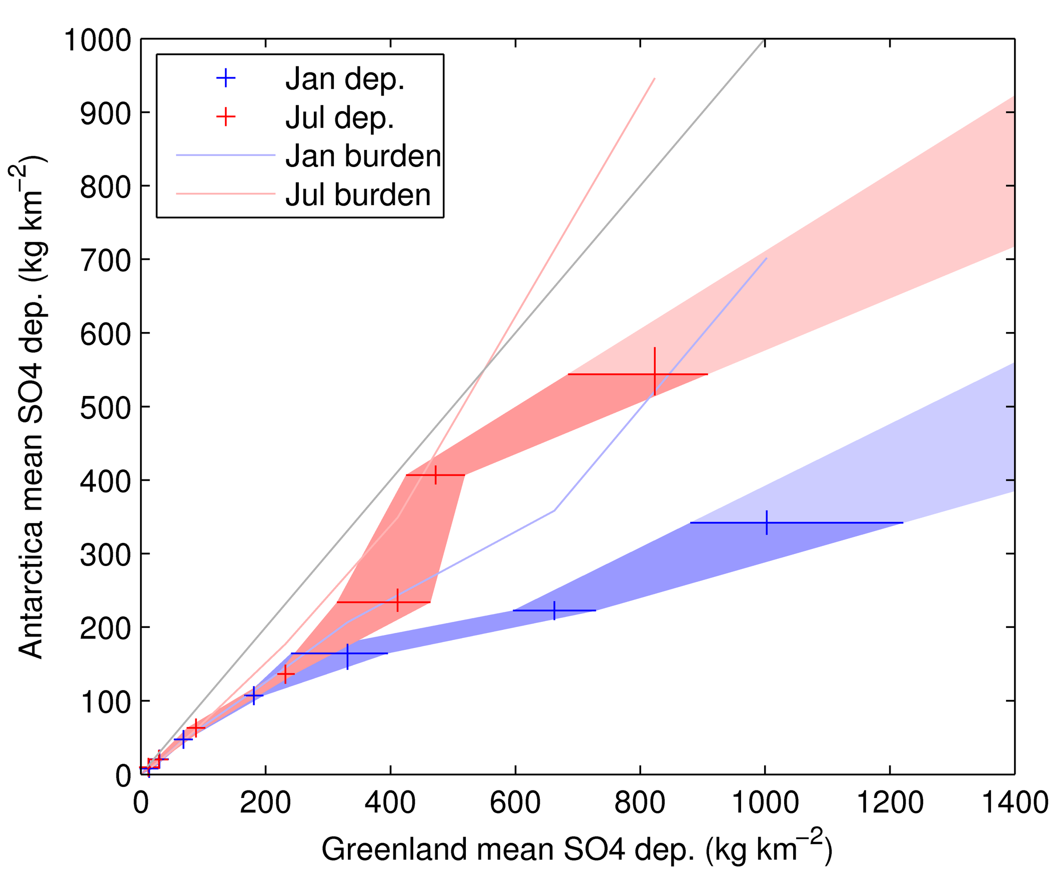


Figure 6 (above): Sulfate deposition to the Antarctic vs. Greenland ice sheets, for January (blue crosses and shading) and July (red crosses and shading) eruptions. Relative ratio of hemispheric atmospheric sulfate burden shown by red and blue lines.

Figure 5 (to left): Ice core deposition efficiency, as a function of SO_2 injection magnitude (left) and post-eruption SAM index (right).

6. Conclusions

Tropical volcanic eruptions can have strong impacts on surface conditions in the SH, which can be well described as perturbations to the SAM.

- Eruptions with SO_2 injection magnitudes of around the size of the 1991 Mt. Pinatubo eruption have significant impacts on stratospheric dynamics, but it requires a stronger eruption (4-5 times) to have a significant impact on the surface SAM.
- Eruptions of sufficient stratospheric sulfur injection magnitude lead to classic positive SAM-like response, with low pressure over Antarctica, strong westerly wind anomalies over the Southern Ocean, and banded precipitation anomalies.

The deposition of sulfate to the Antarctic polar ice sheet is strongly dependent on eruption magnitude.

- Sulfate deposition to Antarctica is strongly diminished for very large amounts of stratospheric SO_2 injection, and is a symptom of SAM perturbations.
- Due to the SAM influence on ice sheet deposition, sulfate deposition to Antarctica for extremely large eruptions (e.g., Toba, ~73 ka BP) could be less than a third that to Greenland.
- Proper reconstruction of volcanic timeseries from ice-core sulfate records should account for the effects of anomalous atmospheric dynamics brought about by aerosol heating after explosive tropical eruptions.

7. References

1. Stenchikov G. Arctic Oscillation response to the 1991 Mount Pinatubo eruption: Effects of volcanic aerosols and ozone depletion. Journal of Geophysical Research. 2002.
2. Thompson DWJ, Wallace JM. Annular Modes in the Extratropical Circulation. Part I: Month-to-Month Variability*. Journal of Climate. 2000.
3. Robock A, Adams T, Moore M, Oman L, Stenchikov G. Southern Hemisphere atmospheric circulation effects of the 1991 Mount Pinatubo eruption. Geophysical Research Letters. 2007.
4. Niemeier U, Timmreck C, Graf H-F, et al. Initial fate of fine ash and sulfur from large volcanic eruptions. Atmospheric Chemistry and Physics. 2009.
5. Toohey M, Krüger K, Niemeier U, Timmreck C. The influence of eruption season on the global aerosol evolution and radiative impact of tropical volcanic eruptions. Submitted to Atmospheric Chemistry and Physics. 2011.
6. Gong D, Wang S. Definition of Antarctic Oscillation index. Geophysical Research Letters. 1999.
7. Gao C, Robock A, Ammann C. Volcanic forcing of climate over the past 1500 years: An improved ice core-based index for climate models. Journal of Geophysical Research. 2008.