# The Interplay between Solar and Volcanic Cooling in the Early 19th Century

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## The early 19th Century

The early 19th century (~1800-1830 CE) is found to be the coldest period over the past 500 years and is mainly caused by multiple volcanic eruptions (mainly 1809 and 1815 eruption) and a grand solar minimum (Dalton Minimum, ~1790-1820 CE). A cluster of strong tropical volcanic eruptions that includes the 1815 Mt. Tambora eruption, an unidentified eruption estimated occurred in ~ 1809, and a series of eruptions in the 1820s and 1830s.

## Early 19th century cooling: how solar and volcanic cooling interplay with each others?

- Does the MPI-ESM model **simulate reasonable** climate impacts from solar and volcanic forcing?
- What are the **relative climate impacts** from solar and volcanic forcing?
- Can the solar and volcanic cooling be **linearly combined**? If not, where are the nonlinearity and where do they come from?

## Methodology

Model (as past1000 run in PMIP4[1]): MPI-ESM1.2[2] with T63L47,top level @ 80 km) (atmosphere), GR15 (256x220), 64 levels (ocean)

Experiments:

- **Basic** ensemble: A 10-member ensemble with SATIRE[3,4] solar forcing reconstruction without volcanic eruptions.
- **PMOD** ensemble: A 10-member ensemble with PMOD[5] solar forcing (weaker solar radiation) reconstruction without volcanic eruptions.
- **Volcano** ensemble: A 10-member ensemble with SATIRE solar forcing reconstruction and with volcanic eruptions[6].
- **Volcano&PMOD** ensemble: A 10-member ensemble with PMOD solar forcing reconstruction and with volcanic eruptions.

## Well-simulated solar and volcanic cooling in MPI-ESM

**Thermal Mechanism (bottom-up)**

Reduced solar radiance → Surface cooling due to reduced incoming radiation

Volcanic aerosol → Surface cooling due to reduced incoming radiation

→ **Changes in surface Oceans, Arctic Sea ice, and atmospheric circulation**

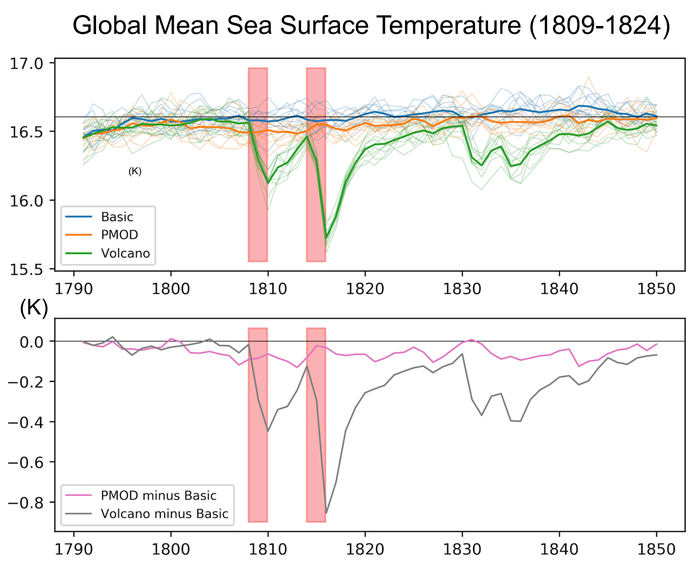


Figure 1: (a) Ensemble means of global mean sea surface temperature and (b) anomalies from 1791-1850.

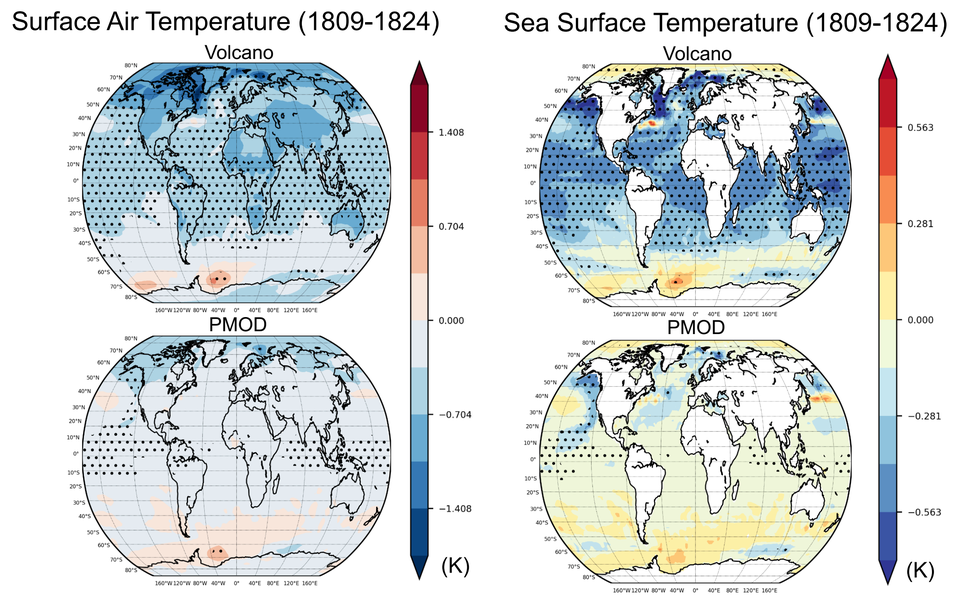


Figure 2: Ensemble mean of surface air temperature and sea surface temperature anomalies of Volcano and PMOD experiments during 1809-1824. The anomalies are calculated respect to ensemble mean of Basic experiments.

**Dynamical Mechanism (top-down)**

Reduced solar radiance → Stratosphere cooling due to absorbing less radiation → **Weaker polar vortex with smaller temperature gradient**

Volcanic aerosol → Stratosphere warming due to radiation absorbed by aerosol → **Stronger polar vortex with larger temperature gradient**

→ **Impacts on troposphere and surface ocean**

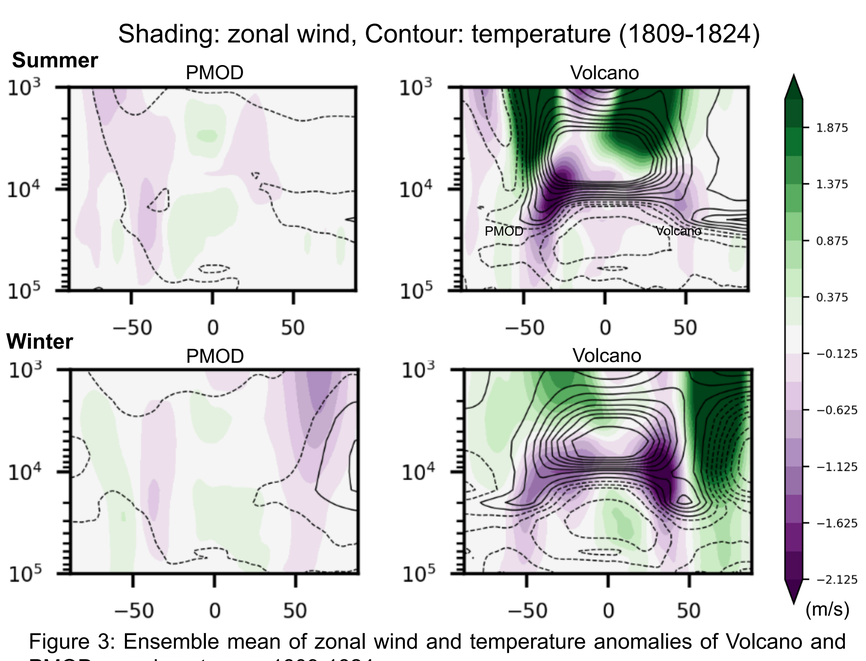


Figure 3: Ensemble mean of zonal wind and temperature anomalies of Volcano and PMOD experiments over 1809-1824.

## Conclusion and Future Work

- The strong variations in solar irradiation of PMOD do **not** have a comparable impacts to volcanic (Tambora) forcing in MPI-ESM.
- Solar and volcanic impacts **are not linearly additive** after 5 years, especially at the **surface atmosphere and polar regions**.
- What is the **source** of those nonlinearity, Arctic sea ice, polar vortex or others?
- Do we need **more ensembles** to better understand the polar responses from solar and volcanic forcing?

## Solar and volcanic cooling cannot be linearly added in MPI-ESM

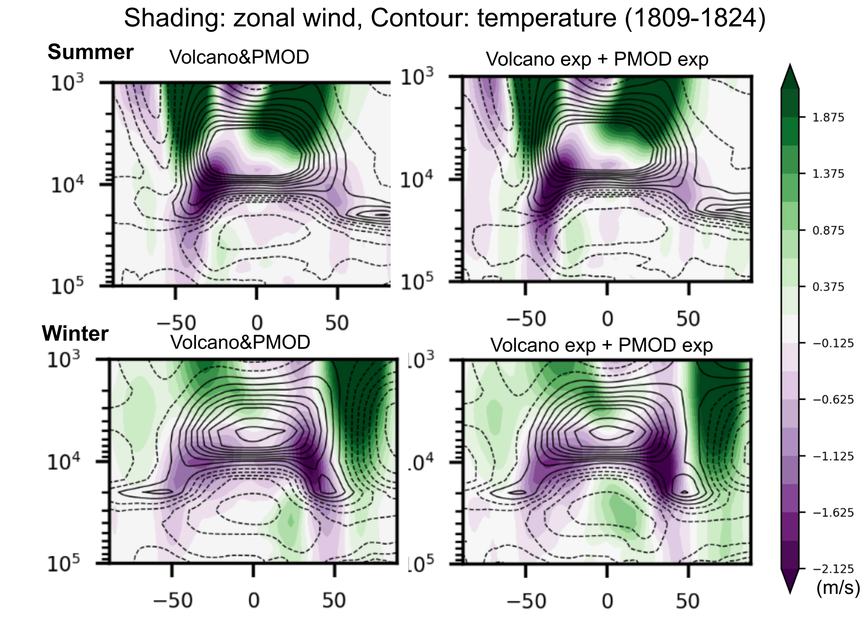


Figure 4: Ensemble mean of zonal wind and temperature anomalies of Volcano&PMOD experiment and Volcano plus PMOD experiment over 1809-1824.

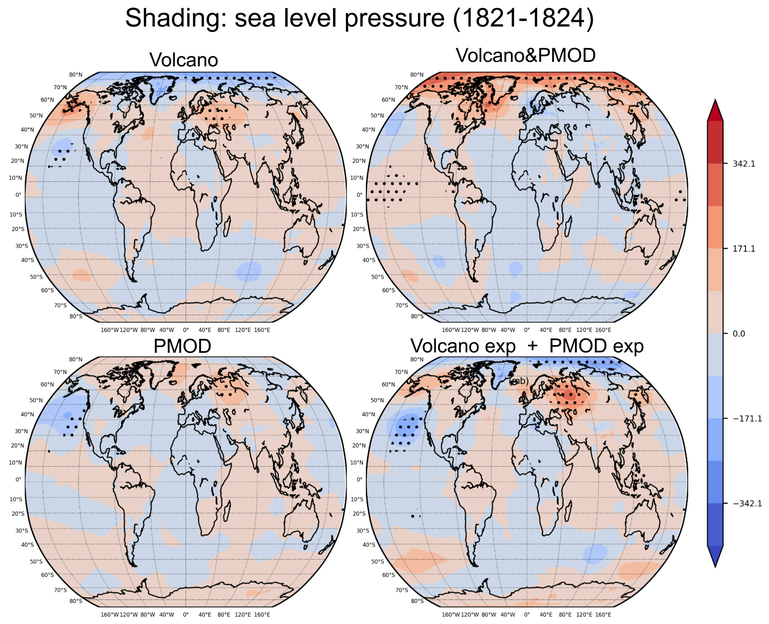


Figure 5: Ensemble mean of sea level pressure of all experiments over 1821-1824.

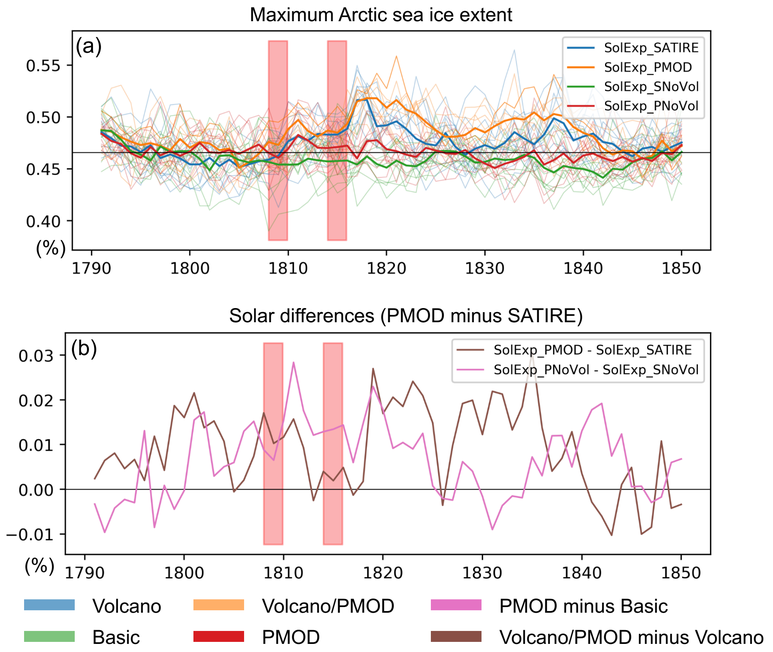


Figure 5: (a) Maximum Arctic sea ice extent over 1791-1850 for all four ensembles. The think lines are the ensemble mean. (b) Maximum Arctic sea ice extent for Solar difference.

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