Evaluating Climate Model Skill in Simulating Arctic Sea Ice Response to Volcanic Forcing

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Introduction & Motivation

Volcanic eruptions are major natural drivers of climate variability, affecting the Earth from seasonal to multi-decadal timescales [1]. They are considered the most significant natural climate forcing over the past millennia [2]. By injecting large amounts of stratospheric aerosols, eruptions reduce incoming solar radiation and cool the surface for several years post-eruption [1,2].

Arctic sea ice is especially sensitive to volcanic forcing [3]. Aerosol transport to the region can enhance sea ice extent beyond the aerosol lifetime. Volcanic activity, more than solar variability, dominates simulated Arctic sea ice responses to natural forcings [3].

However, the ability of models to capture this response remains uncertain [1,2,3,4]. Improved understanding is critical for assessing model biases and strengthening future projections [5]. The well-observed 1991 Mount Pinatubo eruption is used in the Model Intercomparison Project on the climatic response to Volcanic forcing (**VolMIP**) *volc-pinatubo* experiment designed to evaluate model responses, differences, and uncertainties [4,6]. Volcanic eruptions are thus a valuable natural test of model skill and internal variability [2,4,6].

How well do CMIP6 VolMIP experiments simulate the Arctic sea ice response to the 1991 Mt. Pinatubo eruption?

Data & Methods

Models & Forcing

Models:
- **MPI-ESM1-2-LR** (250km) [7]
- **CanESM5** (100km) [8]

Volcanic forcing:
- VolMIP ***volc-pinatubo-full*** experiment with identical satellite derived aerosol properties applied to each model [6]

Configuration (**RIPF variants**):
- Realisations: 1, 2, 3, 4, 8, 9, 11, 12, 13, 16
- Initialisation: 1
- Physics: MPI = 1, CanESM5 = 2
- Forcing: 1

Branching of models:
- From unperturbed preindustrial (piControl) states
- Captures internal variability via sampling of different ENSO & NAO phases

Baseline & Reference Data

Historical runs:
- Include **all** known natural + anthropogenic forcings

Reference data
- **ERA5 Reanalysis**[1] (merged observation-model dataset)
- Prescribed sea ice from OSI SAF (409a) [9] ([1] land mask applied for lake removal).

Analysis Details

Period: 1991-1997 (post-Pinatubo)

Ensemble: **10 members** per model

Variable:
- Monthly mean sea ice concentration (**siconc**)
- Converted to sea ice extent (**SIE** = area with **≥ 15% ice cover** [10])

Anomalies:

$$Anomaly_m = VolMIP_m - Historical_{m(1980-1990)}$$

where m = calendar month

Results

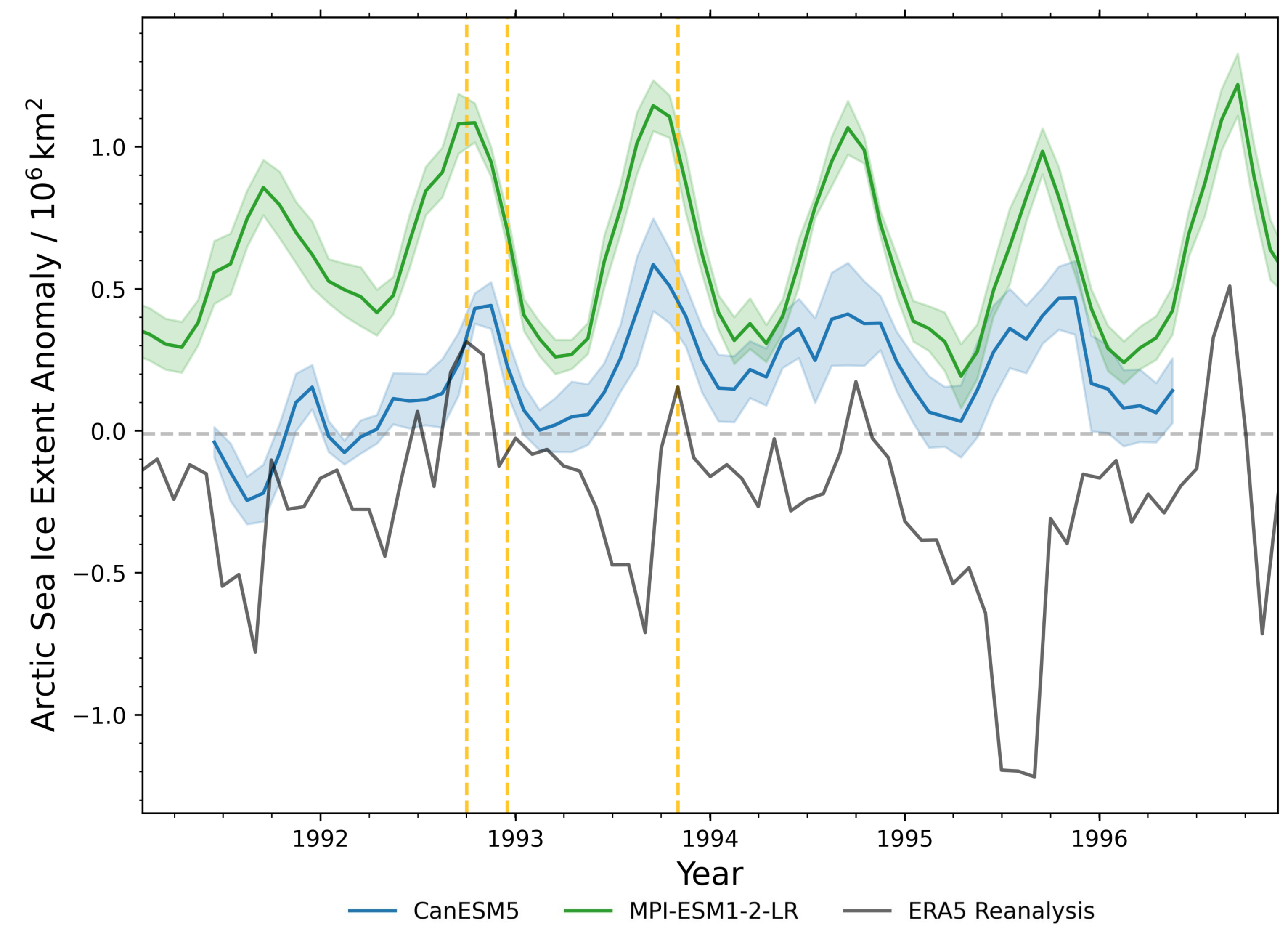

Figure 1 – Monthly Arctic SIE anomalies (10^6 km^2) for CanESM5, MPI-ESM1-2-LR, and ERA5 reanalysis. Shaded envelopes show the ten-member ensemble spread. Peaks are highlighted in yellow (15, 18, and 29, months post-Pinatubo) for further analysis.

- Models reproduce two post-eruption peaks (≈ **15** and **29** months) with consistent overestimates for anomaly magnitude; MPI exhibits large seasonal amplitudes.
- Different timescales are observed to Gagné et al.'s (2017) finding of **18** months for peak SIE anomaly.
- Confirms model dynamic timescales align with reanalysis in VolMIP.

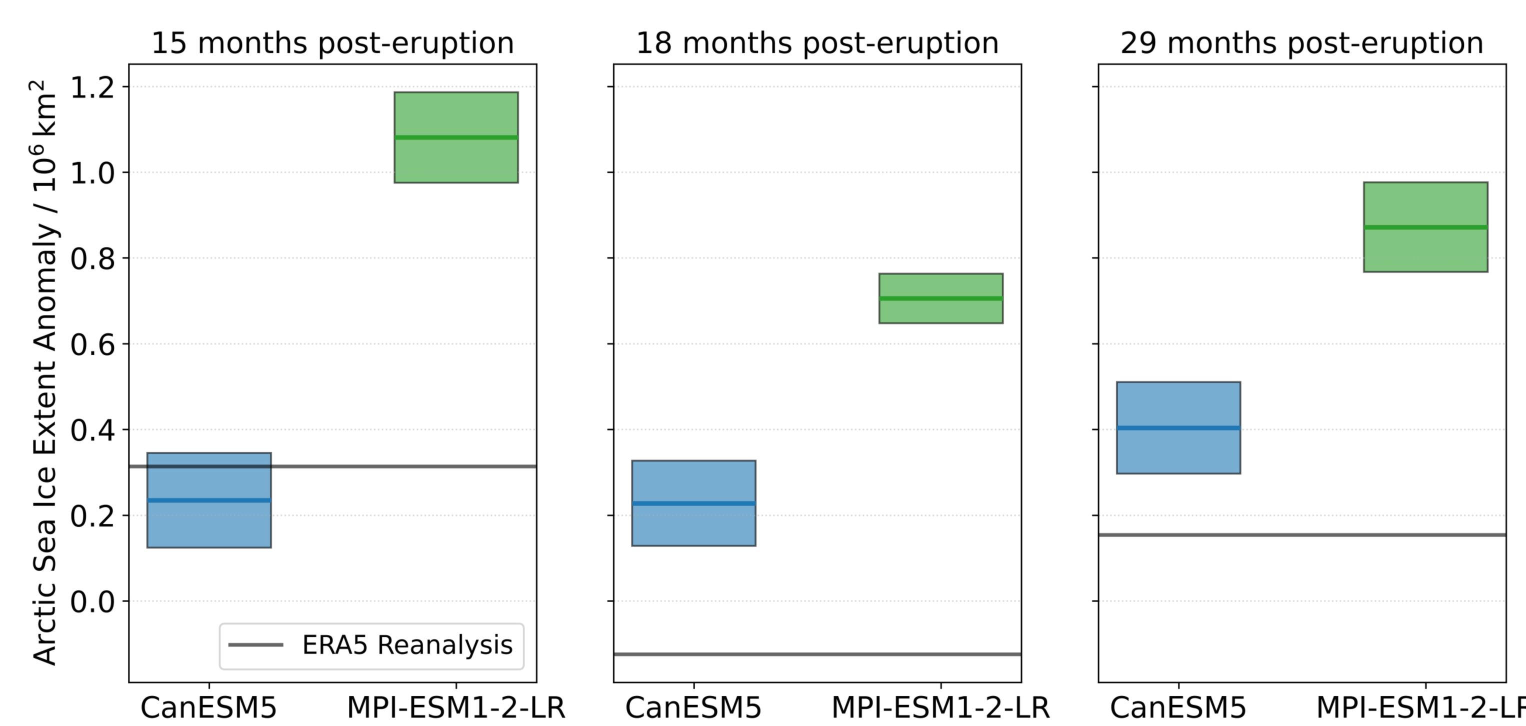

Figure 2 – Distribution of ensemble mean Arctic SIE anomalies (10^6 km^2) at 15 (left), 18 (centre), and 29 (right) months post-eruption. Boxplots show CanESM5 and MPI-ESM1-2-LR spreads with horizontal grey lines marking ERA5 reanalysis values.

- Fig 2. highlights that the magnitude of anomaly is systematically **overestimated** by CanESM5 and MPI to the prescribed aerosol forcing.
- MPI up to > 3x and CanESM5 up to > 2x larger than ERA5.

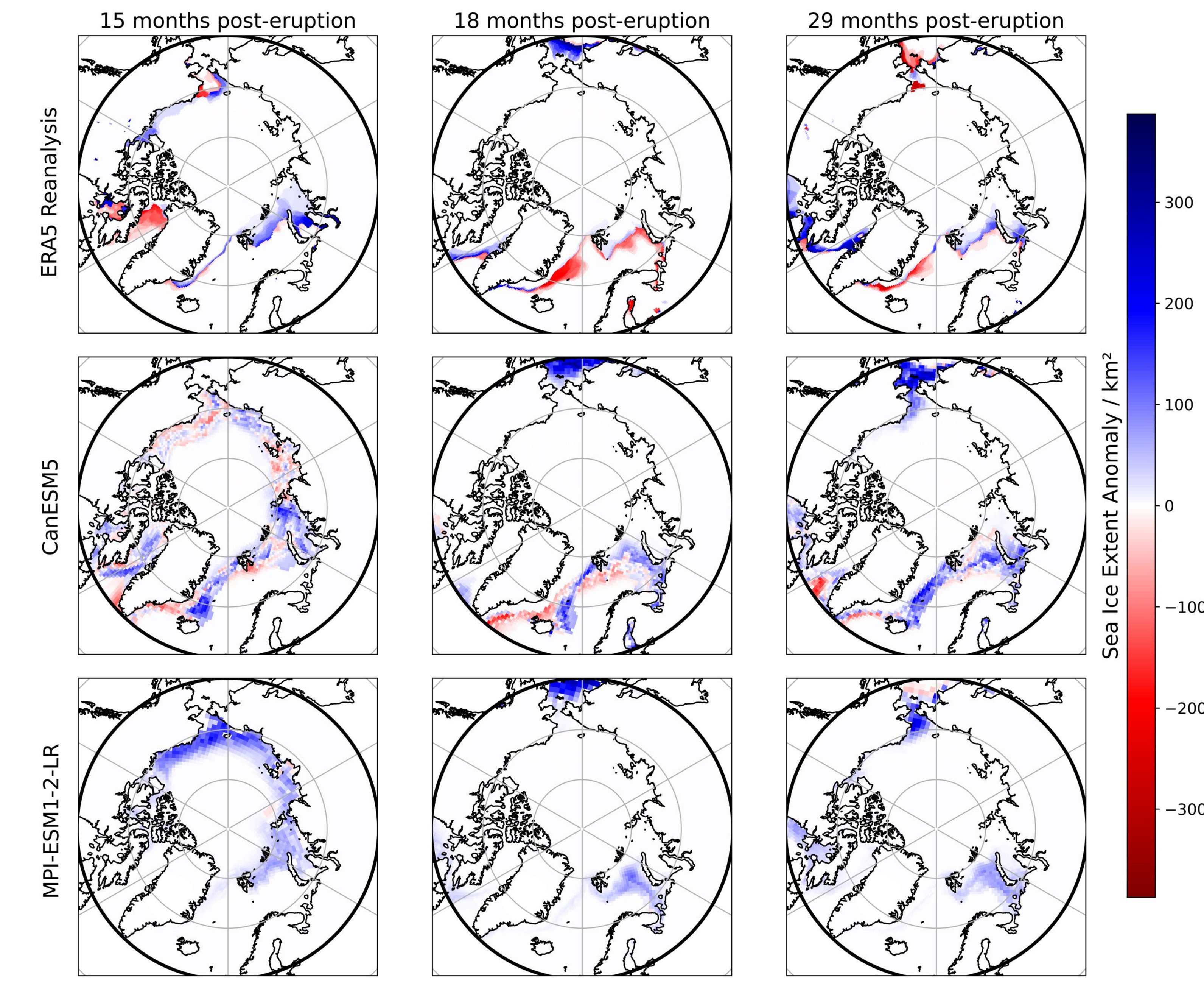

Figure 3 – Spatial maps of ensemble mean Arctic SIE anomalies (km^2) at 15 (left), 18 (centre), and 29 (right) months post-eruption for (top) ERA5, (middle) CanESM5, and (bottom) MPI-ESM1-2-LR. Blue shading indicates positive anomalies (more ice), red shading negative (less ice).

- Models capture general high-latitude increases.
- CanESM5 captures aspects of the ERA5 ice dynamics along Greenland Sea and Baffin Bay. Bering Strait has differences with patterns differing between the model and reanalysis.
- MPI shows increased ice cover lacking specifics shown in ERA5. At 15 months unrealistic increases along the Eurasian shelf break are displayed.
- Models exhibit difficulty in reproducing shifts in SIE anomalies.

Conclusions & Future Work

Implications for Model Skill:
- Strength: the magnitude bias may suggest that either the volcanic aerosol forcing data is **too strong** in VolMIP or that sea ice thermodynamics **overamplify** cooling [cf. 2].
- Pattern: Lack of realistic spatial response (especially in MPI) may point to **missing processes** in ice dynamics, **regional** feedbacks, or **importance** of initial conditions [4].

While CMIP6 VolMIP experiments capture *when* Arctic sea ice response to volcanic forcing, they *overpredict how much* and *misrepresent where* it grows or melts when compared to reanalysis [3,4].

Future directions:
- Compare aerosol forcing schemes to isolate sensitivities.
- Incorporate direct observations to assess possible ERA5 errors.
- Assess other CMIP6 outputs: i.e. ISA-MIP, DCPP.

References

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