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Evaluation of anthropogenic aerosol forcing and multidecadal internal variability contributing to mid-20th century Arctic cooling — CMIP6/DAMIP multimodel analysis

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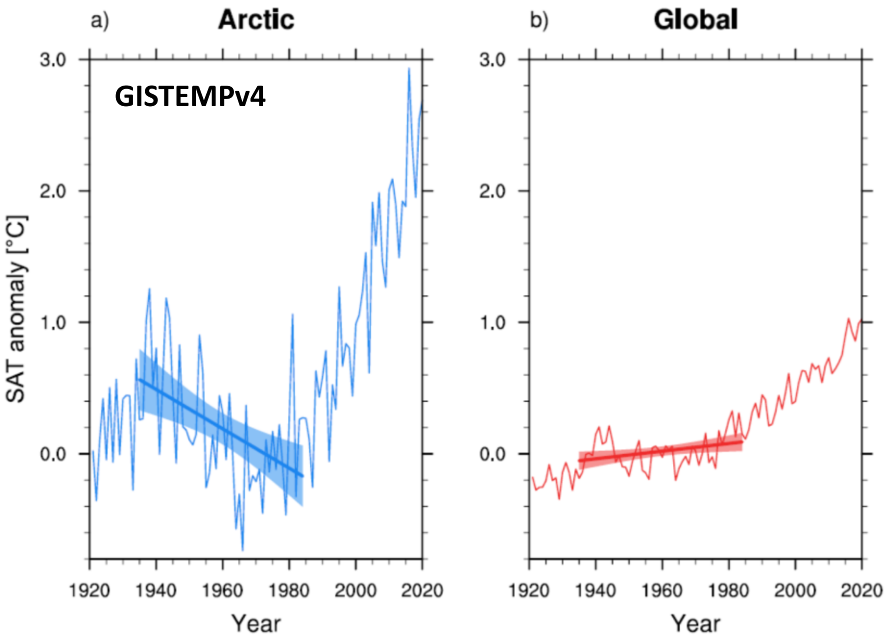
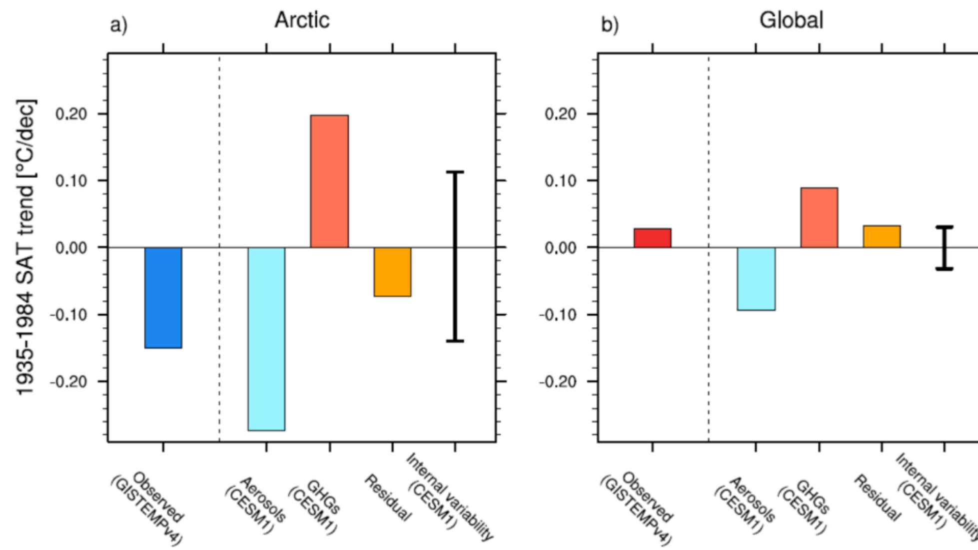
Introduction





England et al. (2021), GRL

Aerosols：HIST (all forcing)－aerosols (aerosol forcings were held at 1920)
GHGs：HIST (all forcing)－ GHGs (GHG forcings were held at 1920)
Residual：Internal variability：Observation－Aerosols－GHGs
Internal variability：Range of 2nd and 39th members after removing forced responses

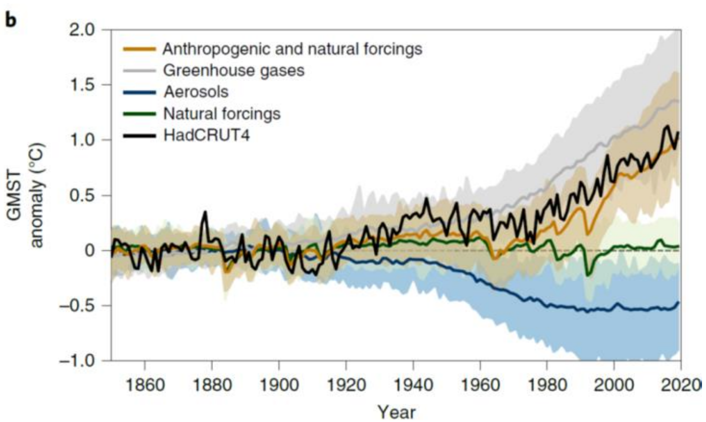
Observations show slight increase trend in global mean surface air temperature (SAT) during 1935-1984 and a cooling trend in Arctic mean SAT during the same period.

Substantial contributions from aerosols and internal climate variability to the mid-20th century Arctic cooling using a single model from the Coupled Model Intercomparison Project (CMIP) Phase 5.

Purpose of this study

※DAMIP：Detection and Attribution Model Intercomparison Project (Gillett et al. 2016; 2021)
was conducted as a part of CMIP6 to assess how **external anthropogenic and natural forcings** have influenced historical climate changes since the Industrial Revolution.

Global SAT anomaly



Gillett et al. (2021, Nat. Clim. Change)

Compared to 1850s, greenhouse gases and aerosols contributed changes of 1.2 to 1.9 ℃ and −0.7 to −0.1 ℃, respectively, and natural forcings contributed negligibly.

To quantify contributions to the Arctic cooling during 1940–1970 from greenhouse gases, aerosols, natural forcings, and multidecadal internal variabilities using CMIP6/DAMIP models.

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DAMIP models and outline of the experiments

We used 35 CMIP6 model including 13 DAMIP model listed below.

Table S1

List of DAMIP models, their spatial resolutions, and numbers of ensemble members for each experiment. Total integrated year of CNTLs for each DAMIP models.

Model name	Atmospheric resolutions	Ensemble members				Period of CNTLs (years)	Numbers of cooling epochs
		HIST	GHG	AER	NAT		
ACCESS-ESM1-5	192 × 145 (1.875° × 1.25°)	5	3	3	3	900	4
BCC-CSM2-MR	320 × 160 (1.125° × 1.125°)	4	3	3	3	600	2
CanESM5	128 × 64 (2.8° × 2.8°)	51	50	30	50	1000	5
CESM2	288 × 192 1.25° × 0.94°	11	3	2	3	1200	6
CNRM-CM6-1	256 × 128 (1.4° × 1.4°)	30	10	10	10	500	1
FGOALS-g3	180 × 80 (2° × 2.25°)	3	2	3	3	700	3
GFDL-ESM4	288 × 180 (1.25° × 1°)	3	1	1	1	500	2
GISS-E2-1-G	144 × 90 (2.5° × 2°)	22	10	10	16	851	4
HadGEM3-GC31-LL	192 × 144 (1.875° × 1.25°)	4	4	4	4	500	1
IPSL-CM6A-LR	144 × 143 (2.5° × 1.25°)	32	10	9	10	1200	3
MIROC6	256 × 128 (1.4° × 1.4°)	10	3	10	50	800	3
MRI-ESM2-0	320 × 160 (1.125° × 1.125°)	10	5	5	5	701	2
NorESM2-LM	144 × 96 (2.5° × 1.9°)	3	3	3	3	501	2

All cooling epochs are sampled using surface air temperature data of CNTL for 13 DAMIP models by a statistical method (see Subsect. 2.2).

CNTL：all forcings were held at preindustrial levels

HIST：All forcing combined

GHG：well-mixed greenhouse-gas-only

AER：anthropogenic-aerosol-only

NAT： natural solar irradiance forcing- and volcanic forcing-only

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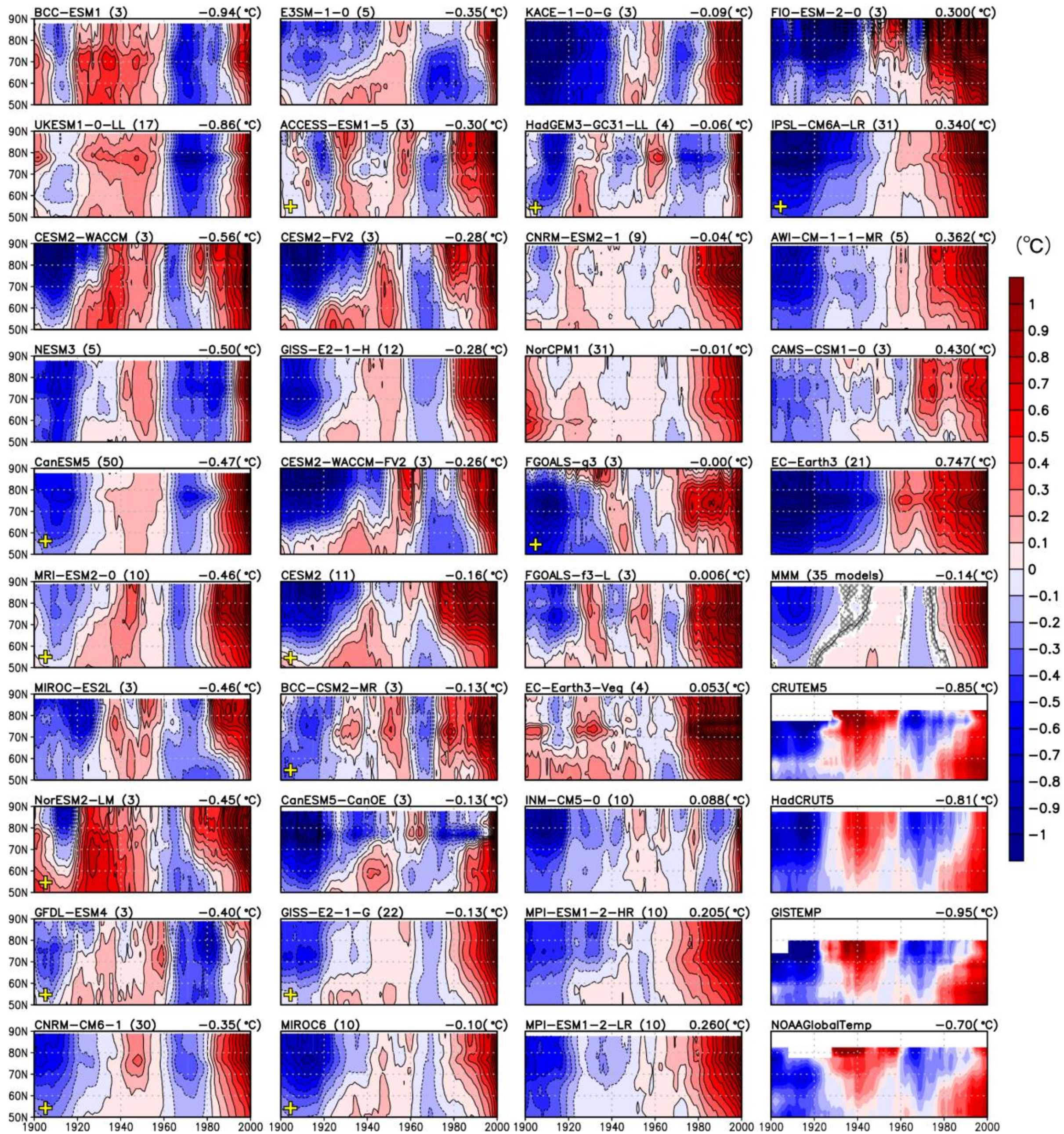
Historical Arctic SAT change in 35 CMIP6 models



Twenty of the 35 CMIP6 models showed an Arctic surface cooling stronger than −0.1℃ during the mid-20th century.

→ Suggesting contribution from external forcings the mid-20th Arctic cooling

Large intermodel difference

→ Suggesting contribution from multidecadal internal variability to the mid-20th Arctic cooling

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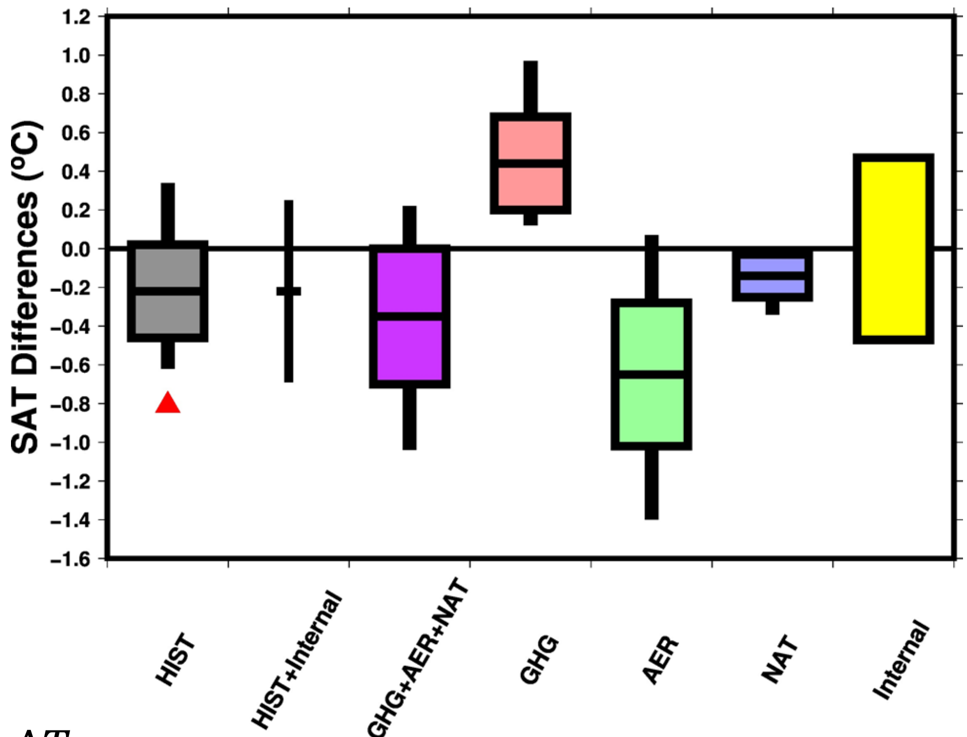
Contributions from forcings and internal variability



Exp.	30-yr SAT_{10y} differences
HIST	−0.22℃ (±0.24℃)
GHG	**0.44℃ (±0.22℃)**
AER	**−0.65℃ (±0.37℃)**
NAT	**−0.14℃ (±0.11℃)**
Obs	−0.81℃
MMM(HIST)±σ(HIST)—Internal	**−0.93℃〜−0.45℃**

$$\Delta T_{RF} = \frac{1}{13}\sum_{j=1}^{13}\left(\frac{1}{K}\sum_{k=1}^{K}\left(\bar{T}_{10yr,1970,j,k} - \bar{T}_{10\mathrm{yr},1940,j,k}\right)\right)$$

Major contributions from multidecadal internal variability and anthropogenic aerosol forcings to the observed Arctic cooling during 1940–1970.

Multidecadal Internal variability

$$V_I = \frac{1}{13}\sum_{j=1}^{13} v_j = \frac{1}{13}\sum_{j=1}^{13}\left(\sqrt{\frac{1}{N-40}\sum_{t=36}^{N-4}\left(\bar{T}_{j,t} - \bar{T}_{j,t-30}\right)^2}\right)$$

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Summary

- **Most CMIP6 models reproduced a portion of the multidecadal surface cooling trend observed during 1940–1970 in the Arctic, which can be attributed to external forcings.**
- **Anthropogenic aerosol forcing and multidecadal internal variability are the two major factors contributing to the mid-20th century Arctic cooling around 1970.**
- **As anthropogenic sulfur emissions and sulfate aerosols will decrease in any future scenarios of shared socioeconomic pathways (Gidden et al., 2019), Arctic warming will continue over the near-term future even under strong cooling fluctuations generated by internal variability.**

Exp.	**30-yr SAT differences**
HIST	－0.22℃ (±0.24℃)
GHG	0.44℃ (±0.22℃)
AER	**－0.65℃ (±0.37℃)**
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MMM(HIST)±σ(HIST)—Internal	**－0.93℃～－0.45℃**

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Contributions of Anthropogenic Aerosol Forcing and Multidecadal Internal Variability to Mid-20th Century Arctic Cooling—CMIP6/DAMIP Multimodel Analysis

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Thank you for your attention.

Key Points:

- Most Coupled Model Intercomparison Project Phase 6/Detection and Attribution Model Intercomparison Project models represent the observed multidecadal surface cooling trend during the mid-20th century (1940–1970) in the Arctic
- Anthropogenic aerosol forcing and multidecadal internal variability are the major components contributing to the 1940–1970 Arctic cooling
- We identify a spatial pattern of pan-Arctic multidecadal cooling due to internal variability that [illegible] the 1940–1970 cooling pattern

Abstract In the Arctic, observed decadal mean surface air temperatures (SATs) were 0.70°C–0.95°C lower around 1970 than those around 1940. The 35-multimodel ensemble mean of historical simulations in the Coupled Model Intercomparison Project Phase 6 (CMIP6) exhibited Arctic surface cooling trend in 1940–1970, which could be attributed to external forcings. Multimodel ensemble means of CMIP6 Detection and Attribution Model Intercomparison Project historical simulations exhibited Arctic surface cooling of −0.22°C (±0.24°C) in 1970 versus 1940 and showed that anthropogenic aerosol forcings contributed to a cooling of −0.65°C (±0.37°C), which was partially offset by a warming of 0.44°C (±0.22°C) due to well-mixed greenhouse gases. In addition to the anthropogenic aerosol forcings, multidecadal internal variability with a magnitude of 0.47°C was the component primarily contributing to the observed Arctic cooling. We identified a spatial pattern of pan-Arctic multidecadal cooling due to the internal variability that resembles the 1940–1970 cooling pattern.

Plain Language Summary Instrumental records show Arctic surface cooling during the mid-20th century (1940–1970) followed by ongoing rapid warming since 1970. Long-term global warming has been extensively researched and has been primarily ascribed to anthropogenic greenhouse gas forcing. However, the factors contributing to the mid-20th century Arctic surface cooling remain poorly constrained. In this work, multimodel analyses using state-of-the-art climate models suggest that external factors may have contributed to the high-latitude surface cooling observed in 1940–1970. Further analysis shows that both increased anthropogenic aerosols and multidecadal internal variability provide major contributions to the 1940–1970 Arctic surface cooling. By analyzing surface cooling via unforced long-term climate simulations, we identified a spatial pattern of pan-Arctic multidecadal cooling, similar to the observed cooling pattern in the Arctic during 1940–1970.

Supporting Information:
Supporting Information may be found in the online version of this article.

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1. Introduction

[illegible] the past [illegible] observed surface air temperatures (SATs) in the Arctic have exhibited substantial multidecadal variations: early-20th-century warming, mid-20th-century cooling, and subsequent ongoing enhanced warming (e.g., Aizawa et al., 2021; Bengtsson et al., 2004; Chylek et al., 2009; Gillett et al., 2008; Johannessen et al., 2004; Serreze & Francis, 2006; Shindell & Faluvegi, 2009; M. Wang et al., 2007). Anthropogenic green-

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