# Internal Variability Explains Much of the Observed–Model Discrepancy in Spring Arctic Amplification

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Polar Climate Working Group

February 6, 2026

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Photo: Sandra Angers-Blondin

# Models rarely capture observed spring Arctic Amplification (AA)
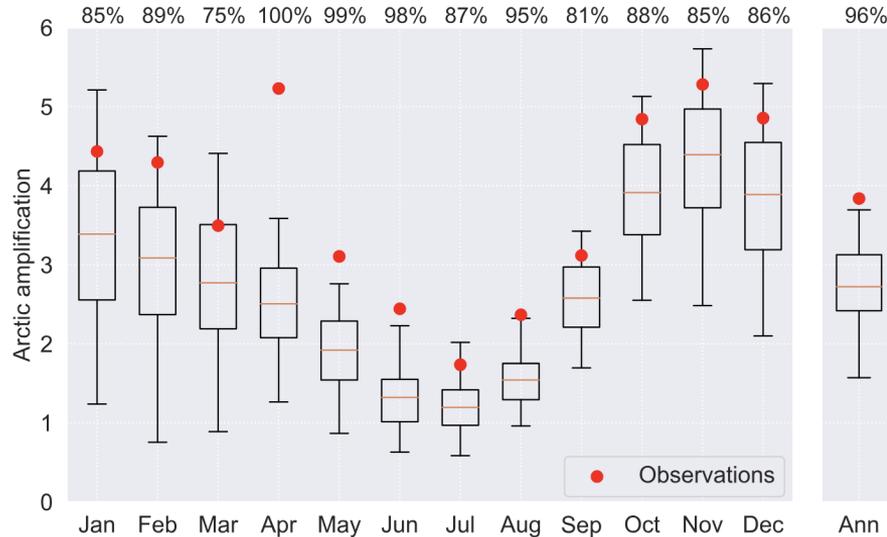


Rantanen et al. 2022

There is a large difference between models and observations in the spring, especially in April.

The observed April SAT trend lies within the CMIP6 intermodel spread, suggesting the difference could potentially be due to internal variability.

Sweeney et al. (2023) reconciled the difference in annual-mean AA using machine learning.

Screen and Simmonds 2012, Hahn et al. 2021, Ye and Messori 2021, Chylek et al. 2022, Previdi et al. 2022, Rantanen et al. 2022, Sweeney et al. 2023, Zhou et al. 2024

# Significant observed-model spatial differences in spring

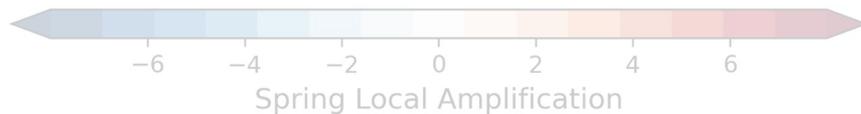Based on observations, the Arctic has warmed ~4x faster than the global mean compared to only ~3x faster for models.



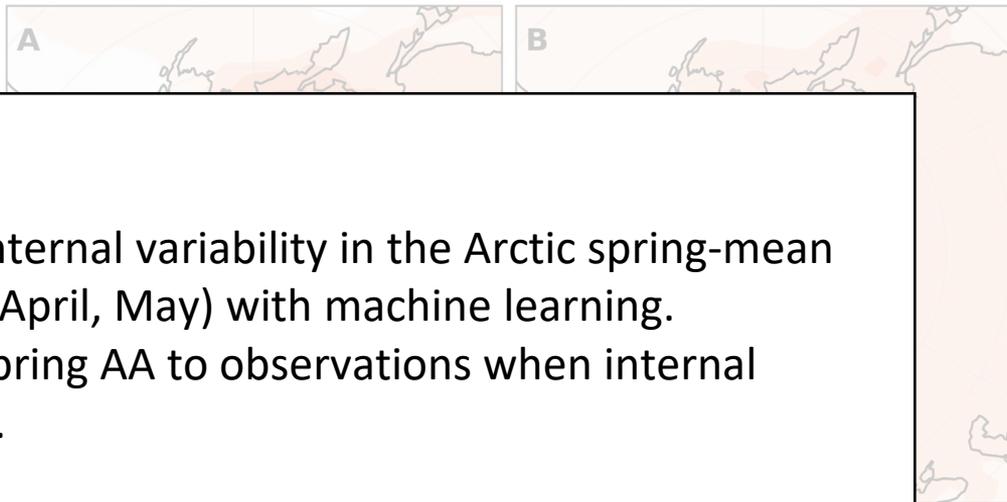Spring Obs Mean: 4.2     Spring CMIP6 MMM: 2.7

Spring Local Amplification
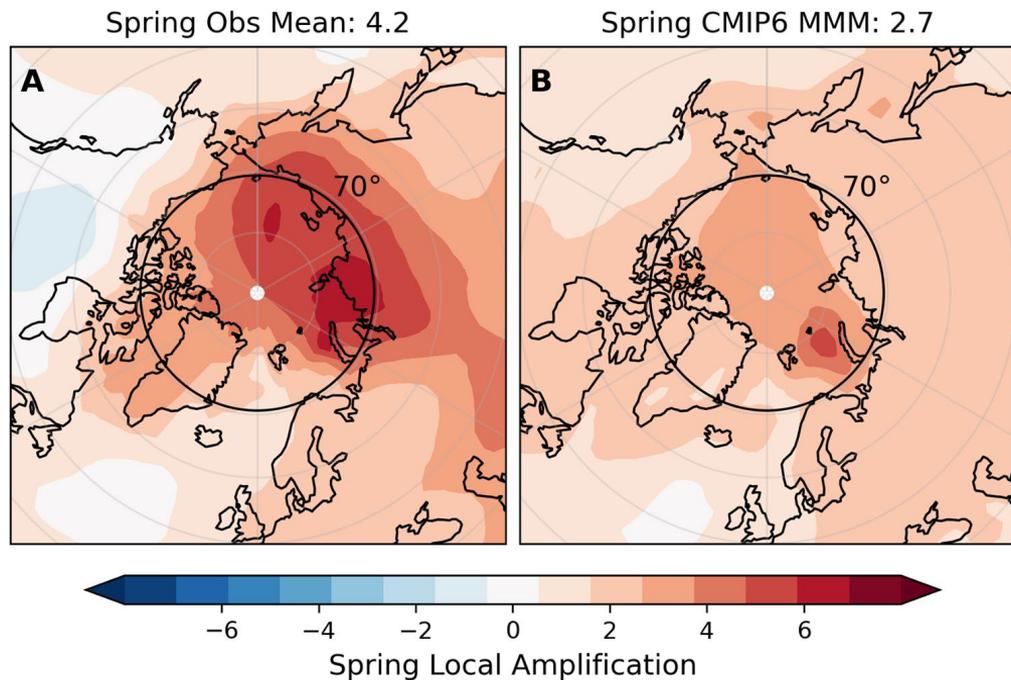
Gale et al. (2025, submitted)

# Significant observed-model spatial differences in spring

Spring Obs Mean: 4.2

Spring CMIP6 MMM: 2.7

A

B

Based on
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global m
faster fo

Goals:
- Quantify the role of internal variability in the Arctic spring-mean and monthly (March, April, May) with machine learning.
- Compare simulated spring AA to observations when internal variability is removed.

−6    −4    −2    0    2    4    6

Spring Local Amplification

Gale et al. (2025, submitted)

# Observations and Training Data

Observations/Reanalysis (1980–2022, 2.5°x 2.5°):
- ✓ Four 2m surface air temperature (SAT) datasets: NOAAv6, GISTv4, HadCRUTv5, BerkeleyEarth
- ✓ Three sea level pressure (SLP) datasets: MERRA-2, ERA5, JRA-55

Models (2.5°x 2.5°):
- ✓ 12 large ensembles (>10 members, historical and extended with SSP3-7.0 or SSP5-8.5)
- ✓ 43-year SAT and SLP trend maps
- ✓ 43-year simulated internally and externally generated trends

| Model Name | Ensemble Members | Period |
|---|---|---|
| CESM2 | 50 | 1855-2047 |
| CESM2_SMBB | 50 | 1855-2047 |
| E3SMv2 | 21 | 1855-2047 |
| ACCESS-ESM1-5 | 25 | 1855-2047 |
| MPI-ESM1-2-LR | 10 | 1855-2047 |
| IPSL-CM61-LR | 11 | 1855-2047 |
| MIROC6 | 50 | 1855-2047 |
| CanESM5 | 25 | 1855-2047 |
| GISS-E2-1-G | 12 | 1855-2012 |
| GISS-E2-1-H | 10 | 1855-2012 |
| MPI-ESM1-2-HR | 10 | 1855-2012 |
| NorCPM1 | 29 | 1855-2012 |
| OthersAllEM | 79 | 1855-2012 |

Huang et al. 2024, Lenssen et al. 2019, Morice et al. 2021, Rohde and Hausfather 2020
Gelaro et al. 2017, Hersbach et al. 2020, Kobayashi et al. 2015
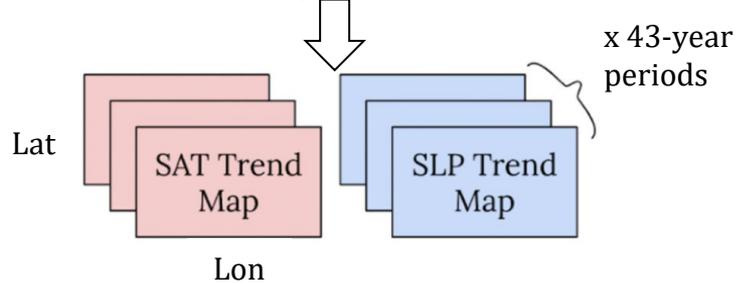Eyring et al. 2016, Fasullo et al. 2022, Golaz et al. 2022

Gale et al. (2025, submitted)

# Convolutional Neural Network (CNN) Approach

**Training data**:
43-year SAT & SLP trend maps (predictors)
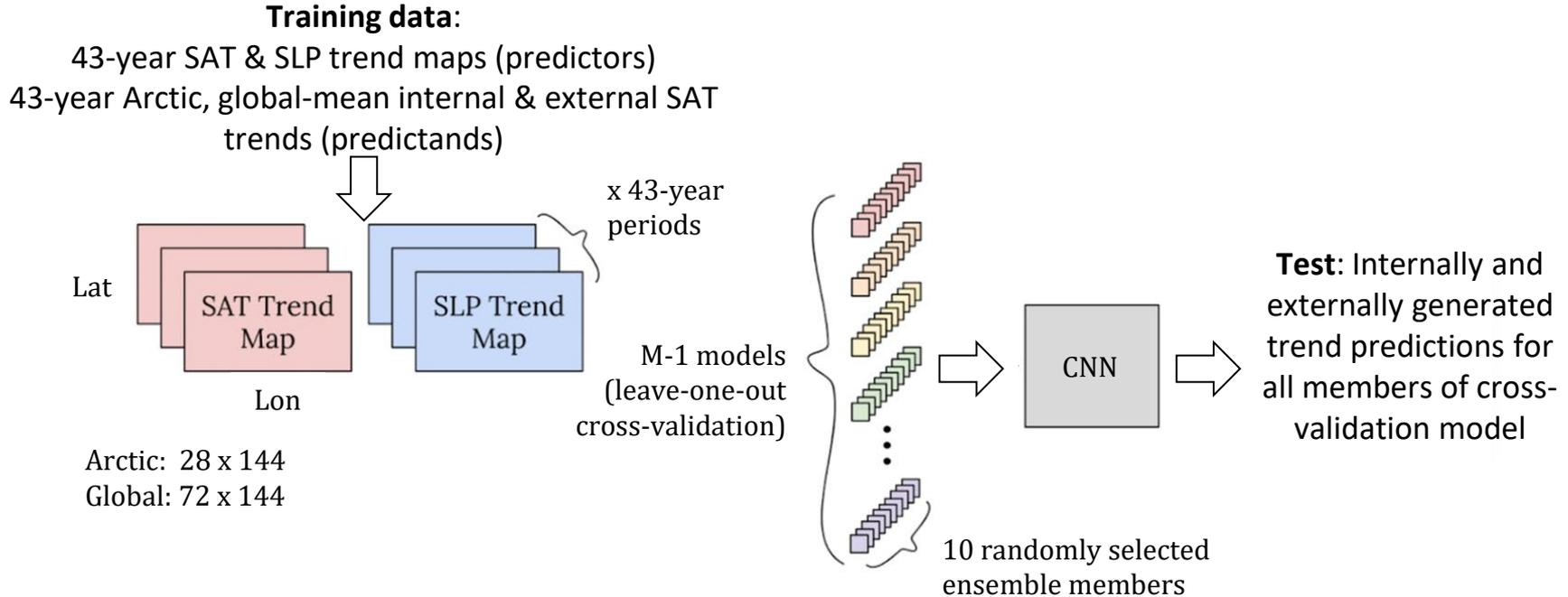43-year Arctic, global-mean internal & external SAT
trends (predictands)

x 43-year
periods

Lat

SAT Trend
Map

SLP Trend
Map

Lon

Arctic:  28 x 144
Global: 72 x 144

Sweeney et al. 2023, Gale et al. (2025, submitted)

# Convolutional Neural Network (CNN) Approach



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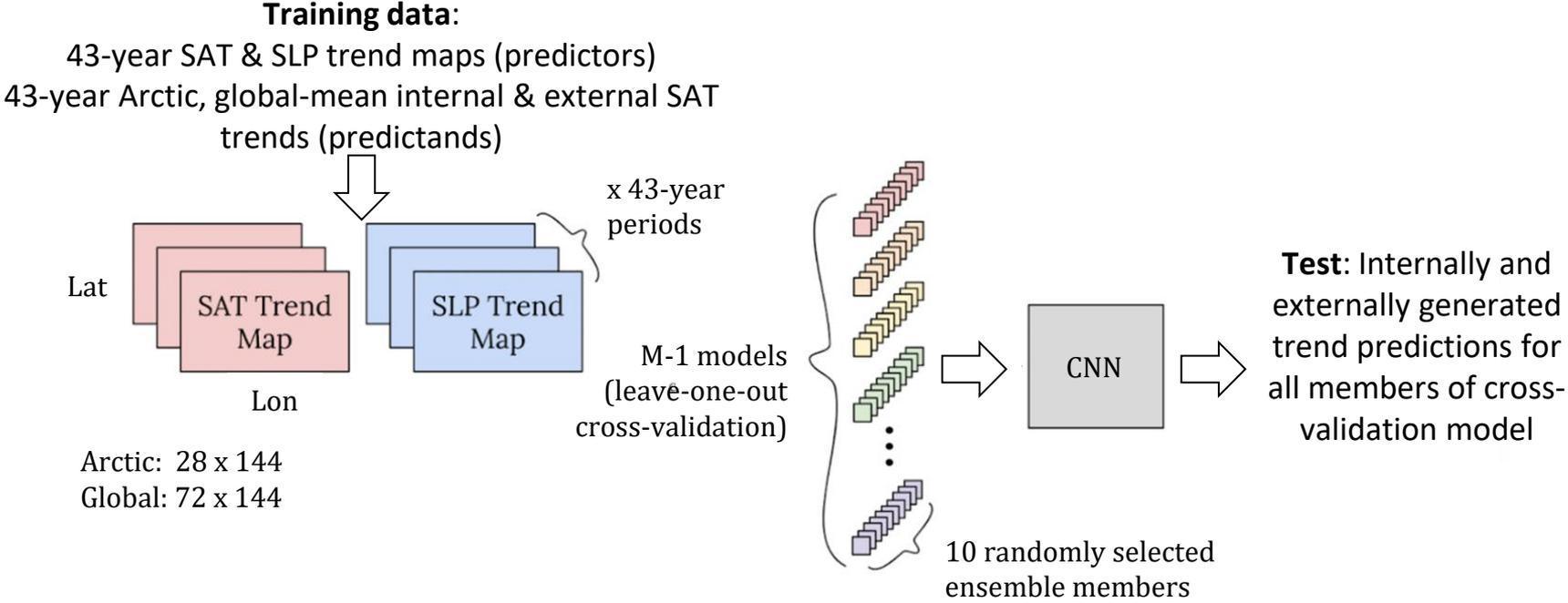43-year Arctic, global-mean internal & external SAT trends (predictands)

Lat

SAT Trend Map

SLP Trend Map

Lon

Arctic: 28 x 144
Global: 72 x 144

x 43-year periods

M-1 models (leave-one-out cross-validation)

10 randomly selected ensemble members

CNN

**Test**: Internally and externally generated trend predictions for all members of cross-validation model

Sweeney et al. 2023, Gale et al. (2025, submitted)

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**Test**: Internally and externally generated trend predictions for all members of cross-validation model

Last step: Apply to observed SAT and SLP trend maps

# Removing internal variability reconciles springtime difference
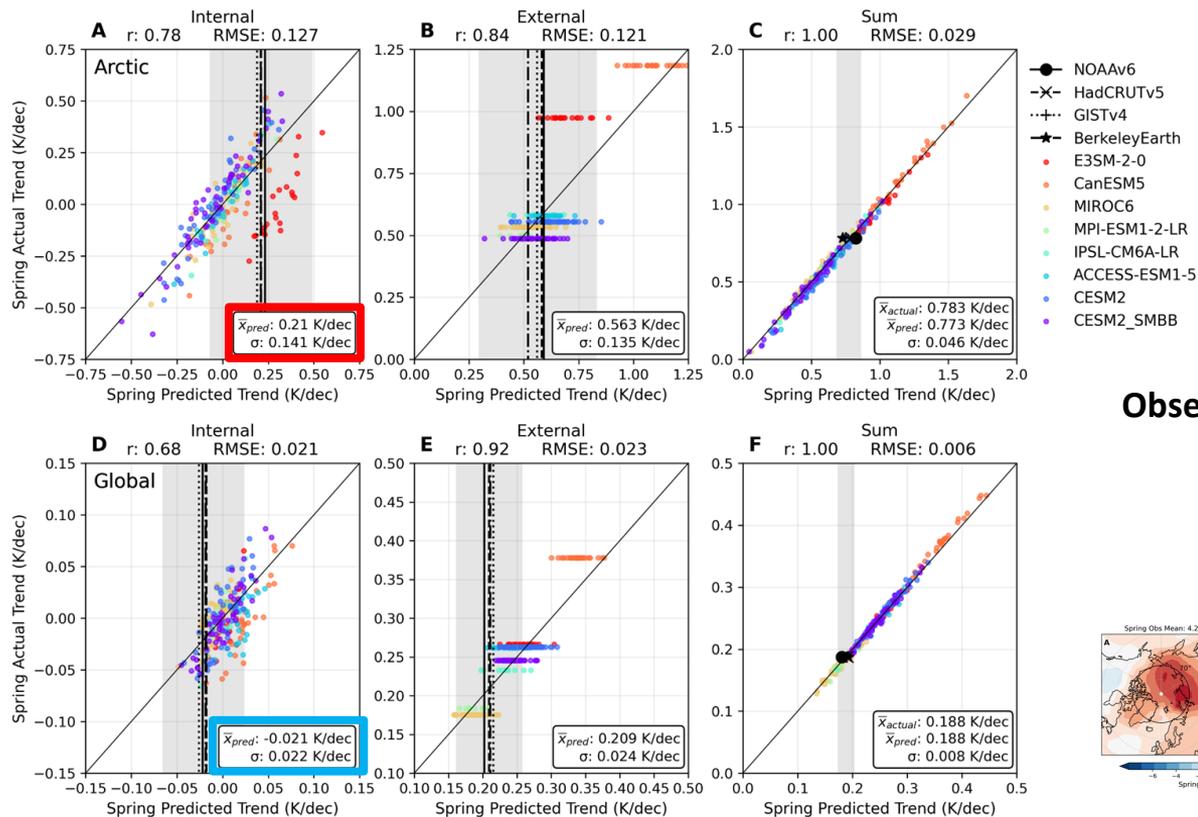


Estimated observed internal Arctic trend: 0.210 K/dec

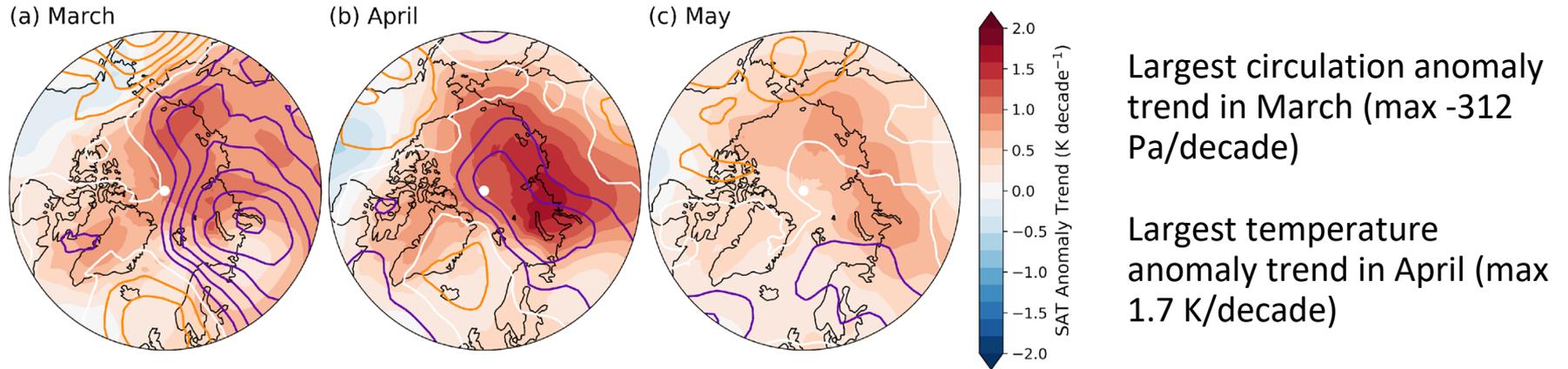Estimated observed internal global trend: -0.021 K/dec

**Observed Externally Forced Spring AA:**

$$\frac{0.783 - 0.21}{0.188 - (-0.021)} = \mathbf{2.7}$$
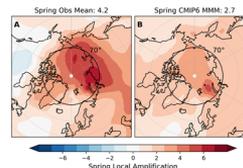
Observed Mean AA: 4.2
CMIP6 MMM AA: 2.7

Gale et al. (2025, submitted)

# Breakdown reveals monthly variations in observed trends



(a) March  (b) April  (c) May

Gale et al. (2026, to be submitted)

SAT Anomaly Trend (K decade$^{-1}$)

Largest circulation anomaly trend in March (max -312 Pa/decade)

Largest temperature anomaly trend in April (max 1.7 K/decade)

*SLP line contours at 50 Pa/dec intervals, purple = negative, orange = positive, white = zero*

# MMM doesn't show large regional SAT trends variations as in obs.

The observed ('total') SAT trend shows more variability
- Slight cooling in North America
- Warming across continental Siberia, particularly in April

MMM generally shows more uniform warming signal across the Arctic
- More concentrated warming over the Barents Sea
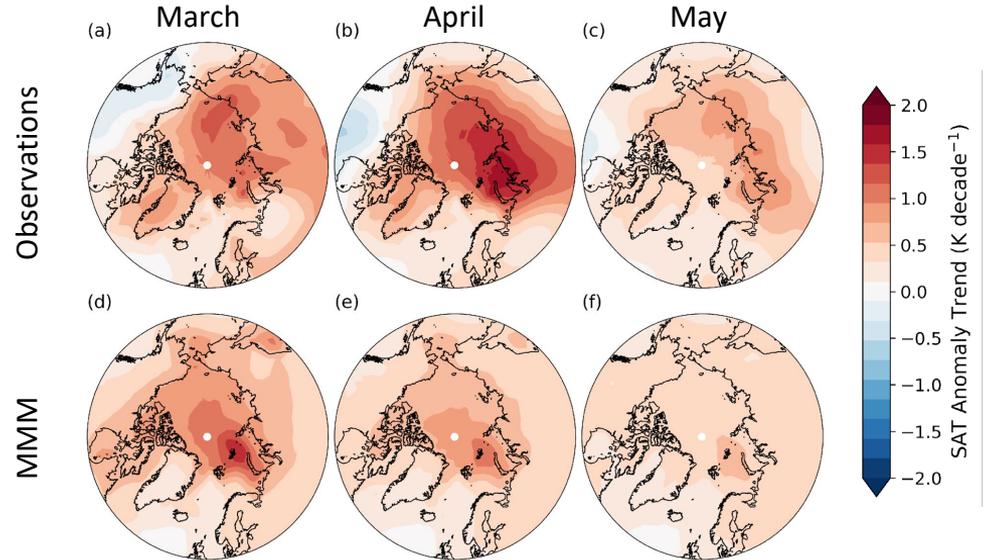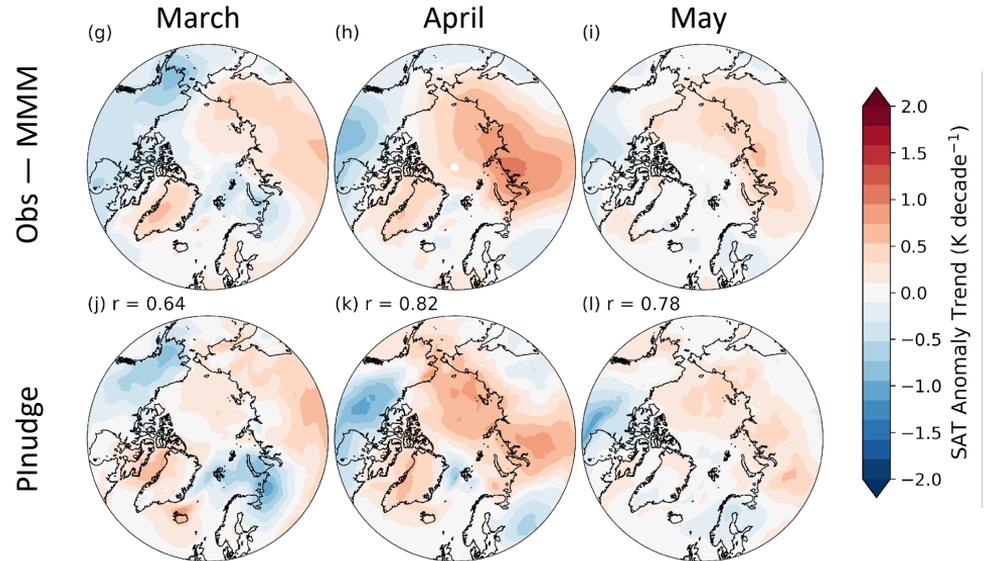


Gale et al. (2026, to be submitted)

# Comparing the difference with wind-nudged runs

Wind-nudged runs (Gilbert et al. 2025)
- Ensemble CESM2 pre-industrial control nudged to ERA5 winds (u, v) at 850 hPa and above from 60N to 90N
- Isolate the influence of observed winds on Arctic climate

High pattern correlations from poleward of 60N
- Circulation is critical for April warming pattern and magnitude
- Internally-driven warming is clearly tied to wind-driven warming



Gale et al. (2026, to be submitted)
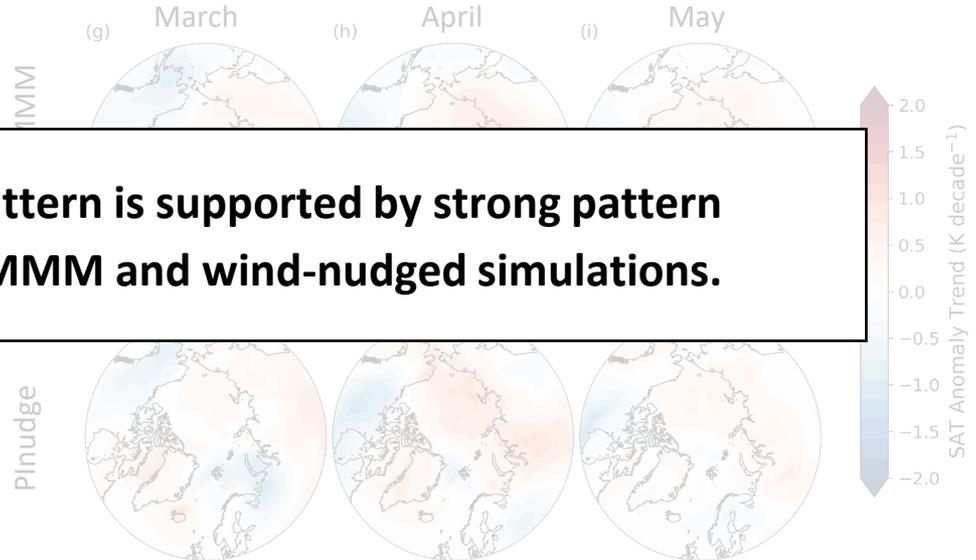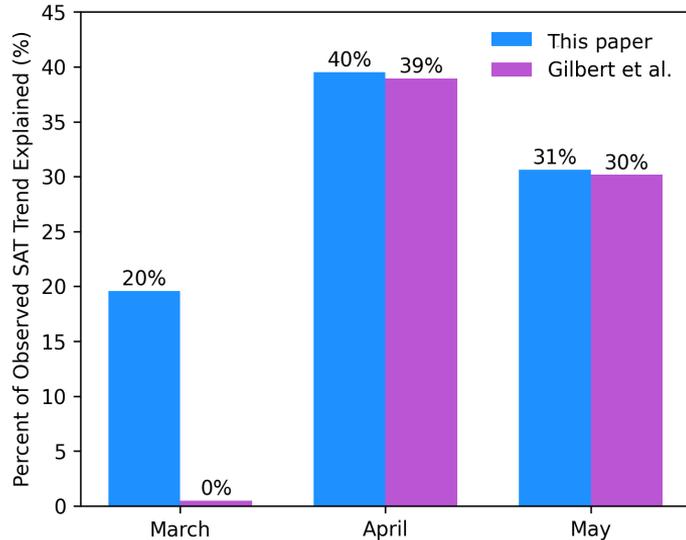
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**MMM (forced) SAT trend pattern is supported by strong pattern correlations between Obs−MMM and wind-nudged simulations.**

High pattern correlations from poleward of 60N
- Circulation is critical for April warming pattern and magnitude
- Internally-driven warming is clearly tied to wind-driven warming



March    April    May

MMM

Plnudge

SAT Anomaly Trend (K decade$^{-1}$)

2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0

Gale et al. (2026, to be submitted)

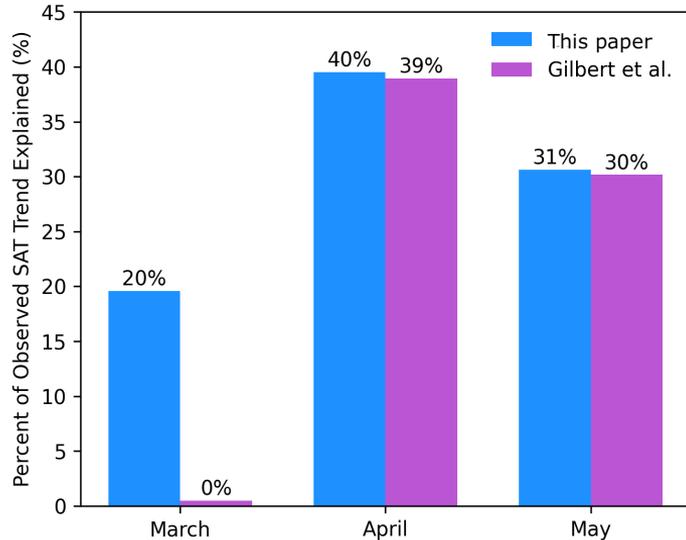# Monthly attributions of internal variability agree among methods



Gale et al. (2026, to be submitted)

- Divide estimate of internal variability by total observed monthly Arctic-mean temperature trend
- Good agreement between CNN and PInudge methods for April and May
- Potential offset of warming and cooling trends in March in PInudge means wind contribution is nearly zero compared to CNN
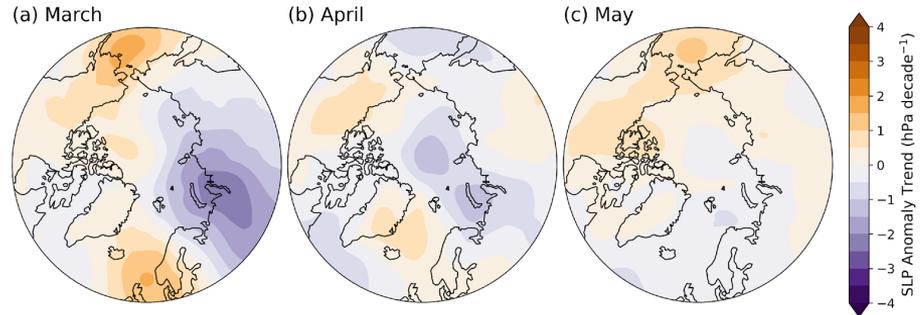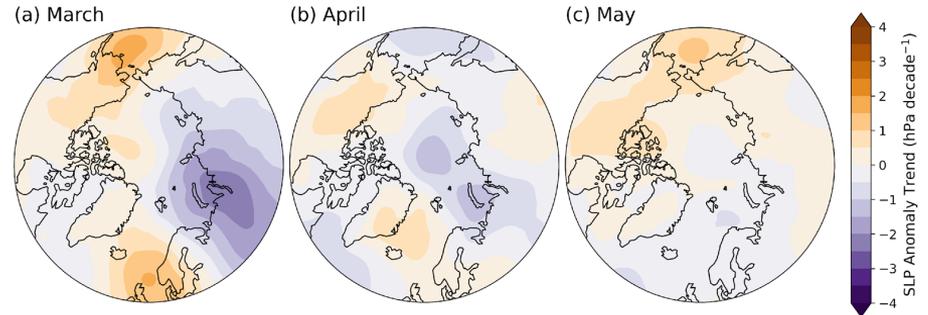


*SLP output from PInudge*

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*SLP output from PInudge*

# Takeaways

1. In observations, internal variability enhances Arctic Amplification 27% in the spring (40% in April), supported by independent CNN, dynamical adjustment, and wind-nudged methods.

1. Removing internal variability reconciles the difference between modeled and observed springtime AA.

1. High pattern correlations between Obs—MMM and wind-nudged simulations provide confidence in the forced Arctic warming pattern.
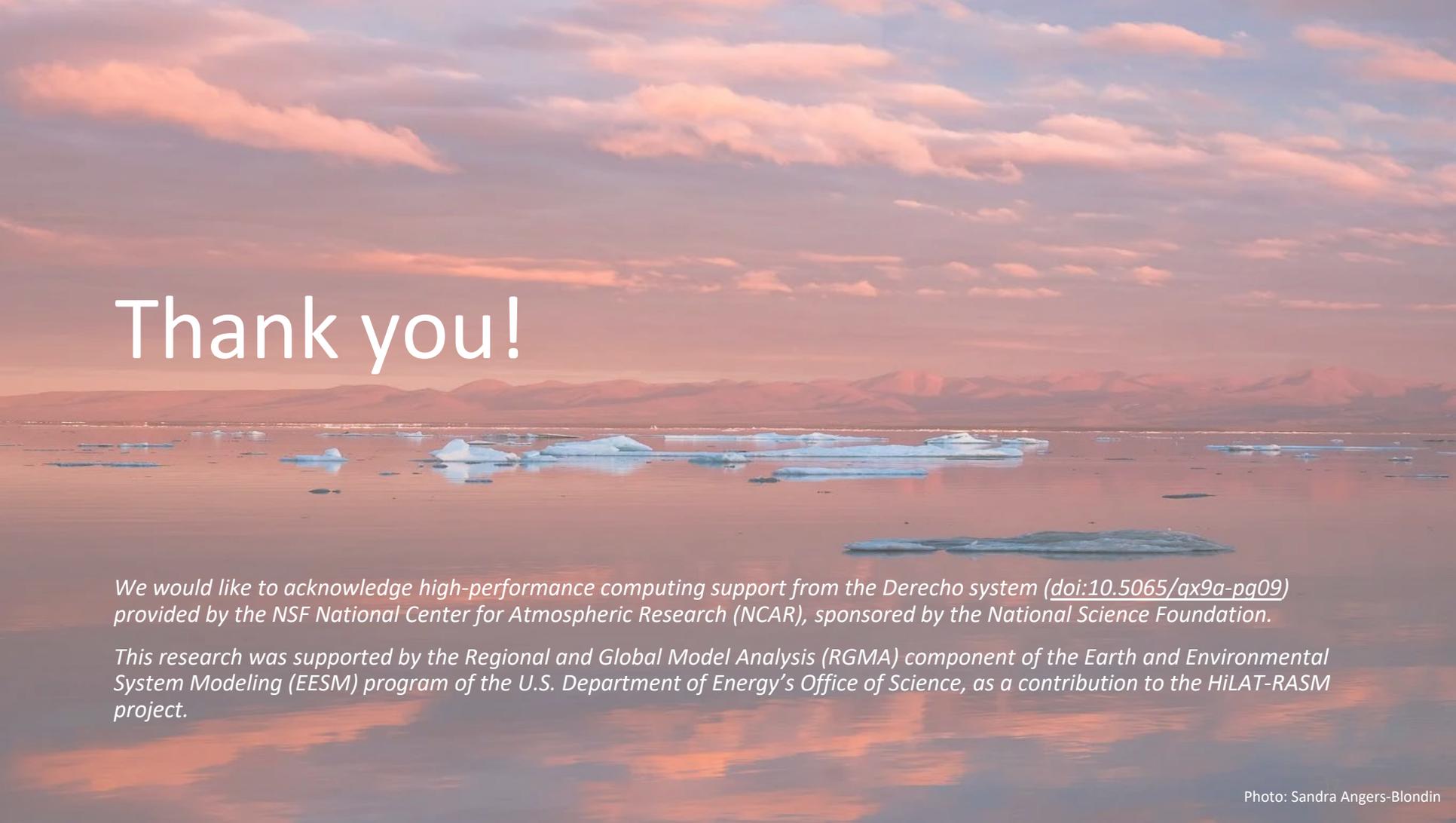
# Thank you!

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