The Southern Annular Mode (SAM) and Southern Ocean SST:

consistency & discrepancy between models & observations across timescales

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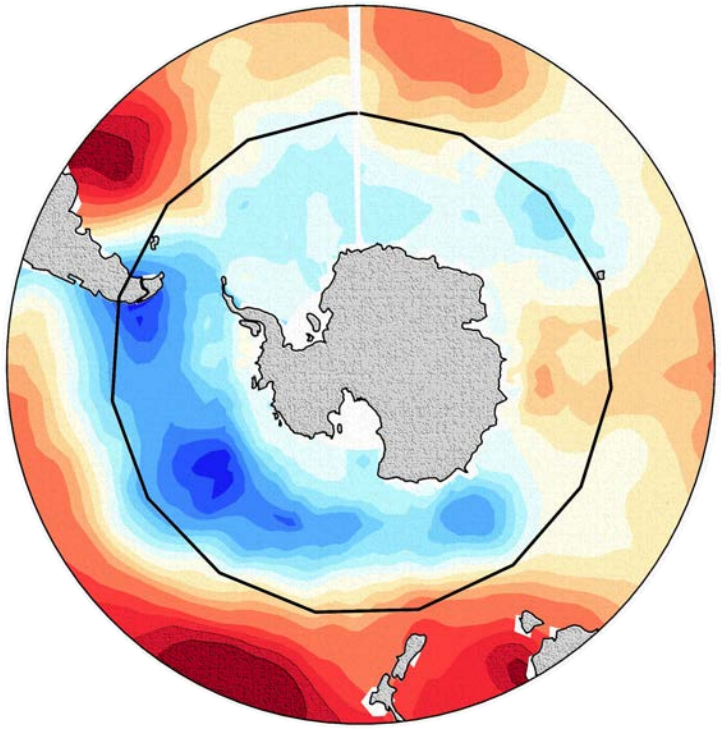
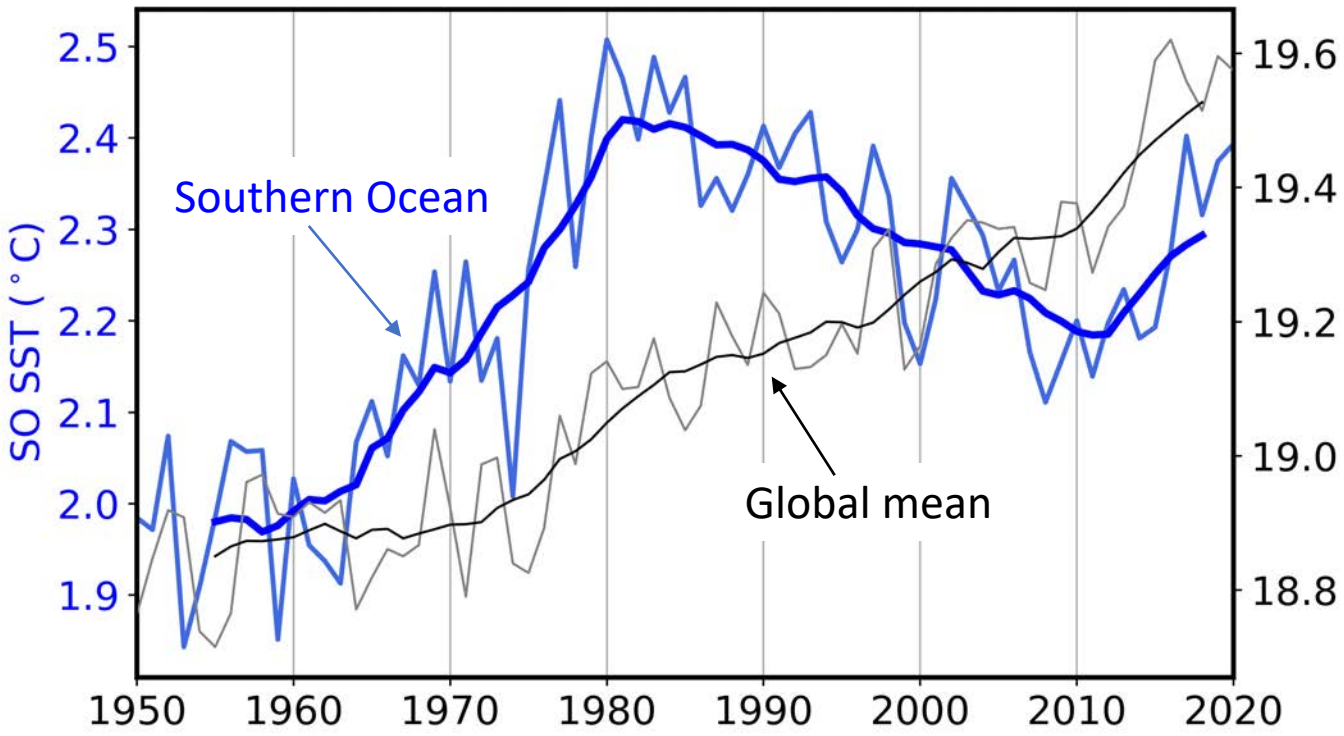
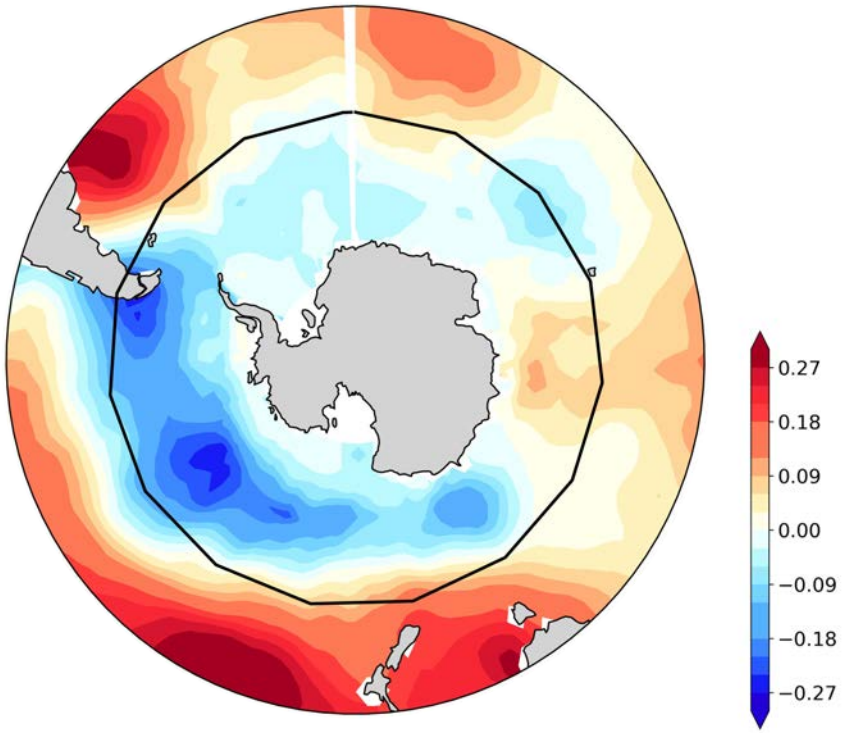


Observed multi-decadal SO SST cooling trend

Global and SO (annual-mean) SST

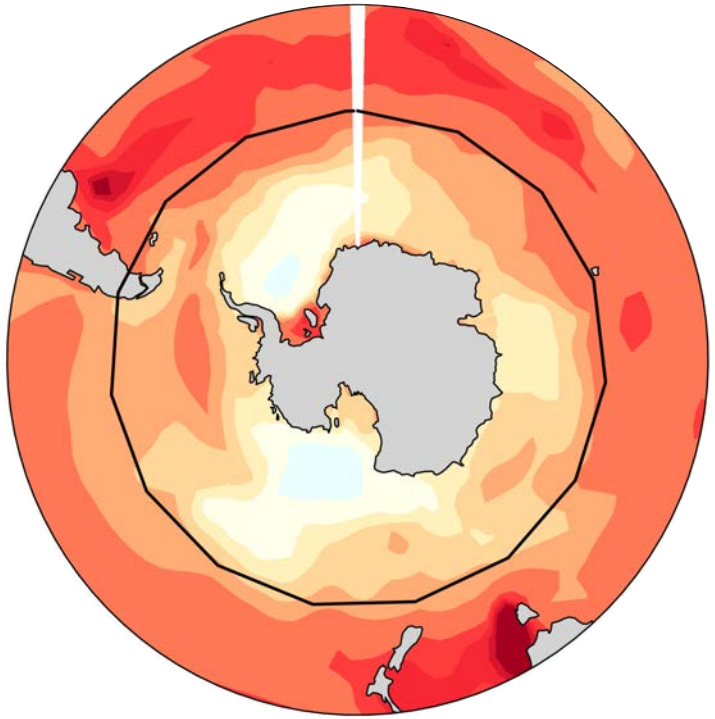


ERSSTv5 SST trend (1979-2022)



GCMs fail to simulate the SO cooling

CMIP multi-model mean
SST trend (1979-2022)



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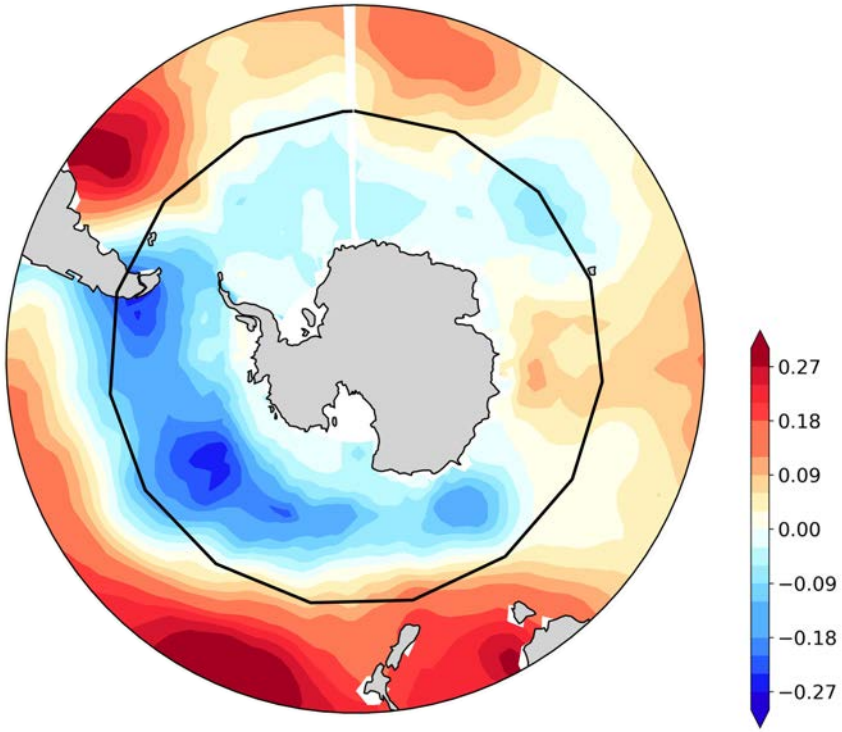
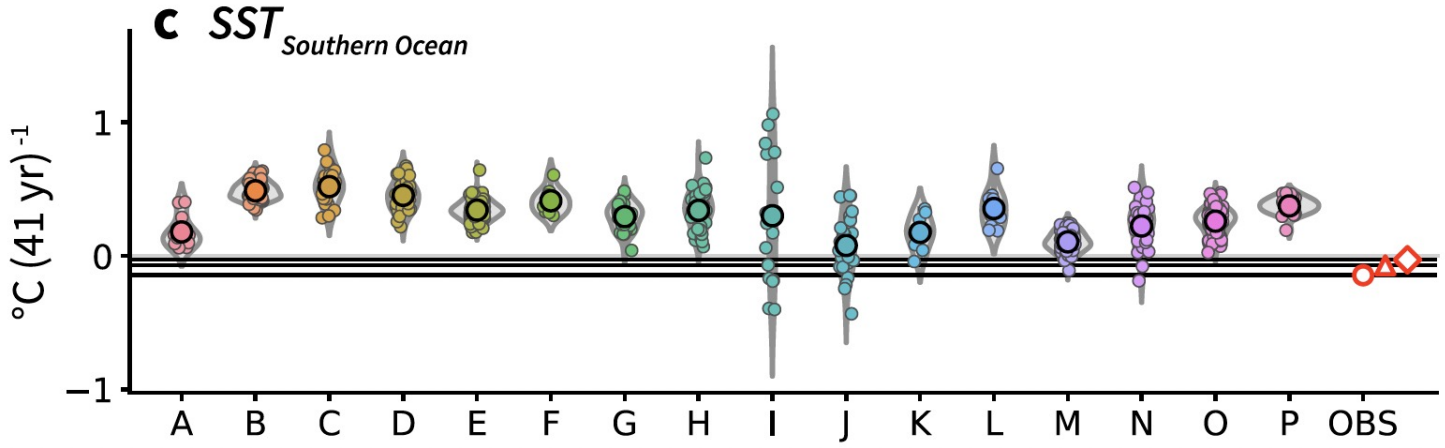


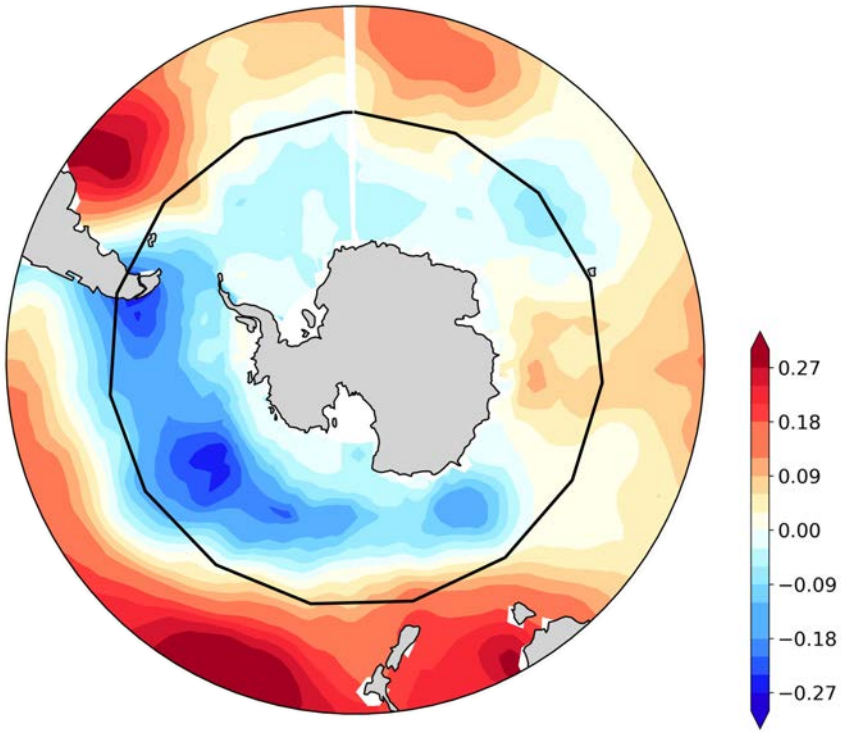
GCMs fail to simulate the SO cooling

CMIP5/6 large ensembles



Wills et al. 2022

ERSSTv5 SST trend (1979-2022)

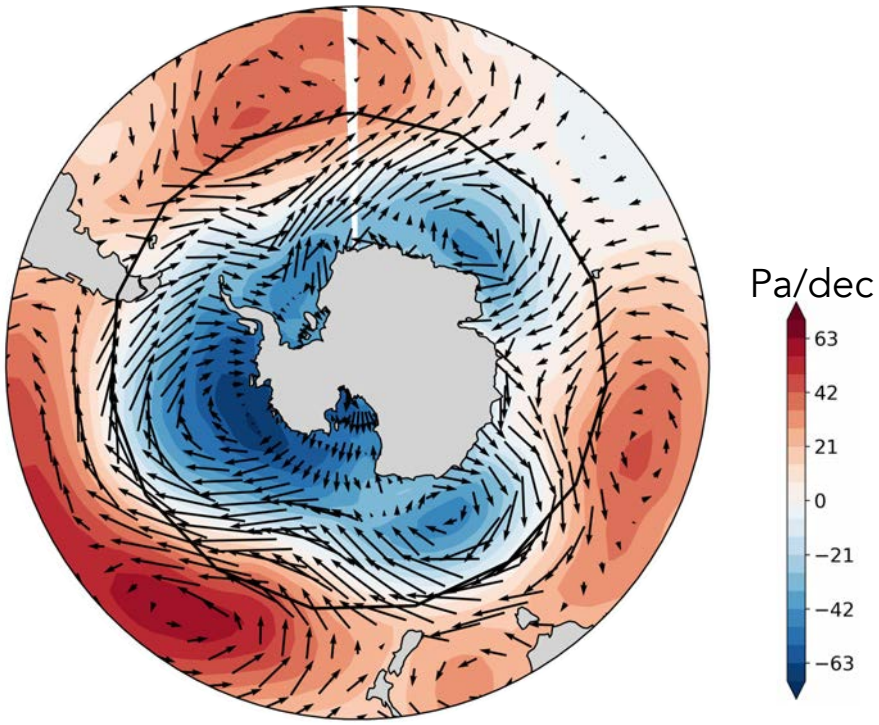


What caused the observed SO cooling?
Why do GCMs generally fail to simulate that?

Proposed contribution from the SAM

- Positive SAM trend in DJF since 1950s, associated with strengthened SO westerlies (primarily caused by ozone depletion and GHG)
  Banerjee et al. 2020; Polvani et al. 2011

ERA5 SLP/UV850 trend (1979-2022)



Proposed contribution from the SAM

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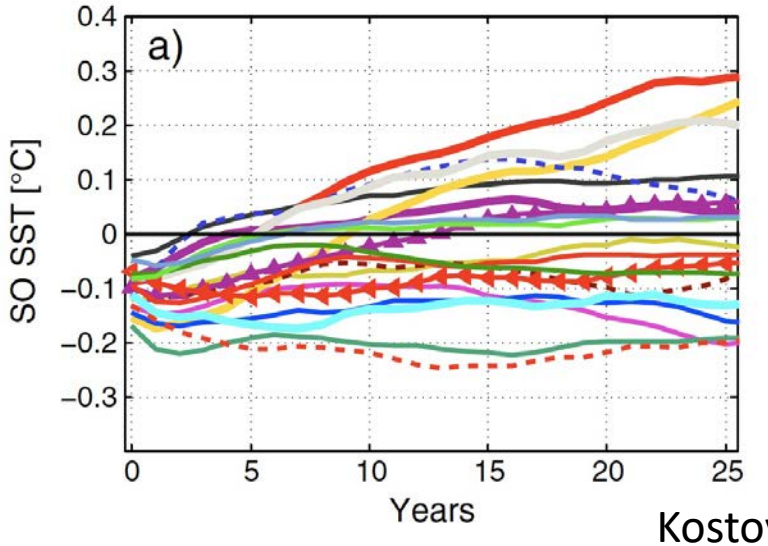
- Abrupt forcing/step-function simulations show a fast SST cooling response to positive SAM



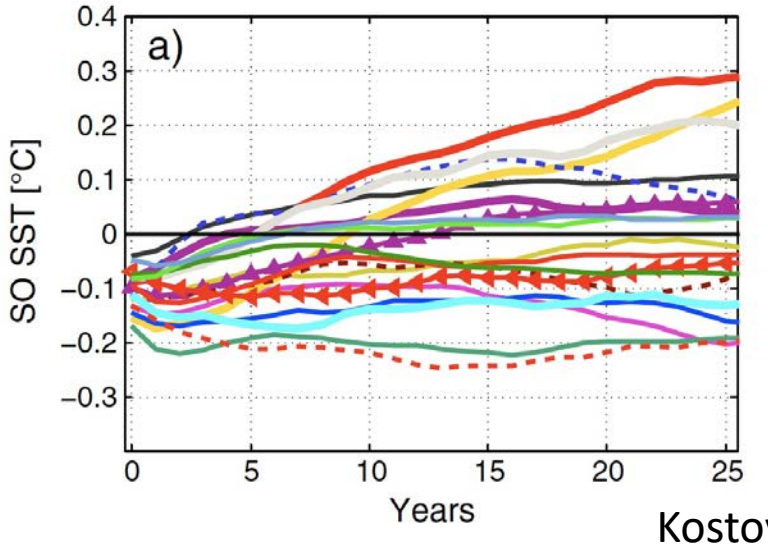
Kostov et al. 2018

Proposed contribution from the SAM

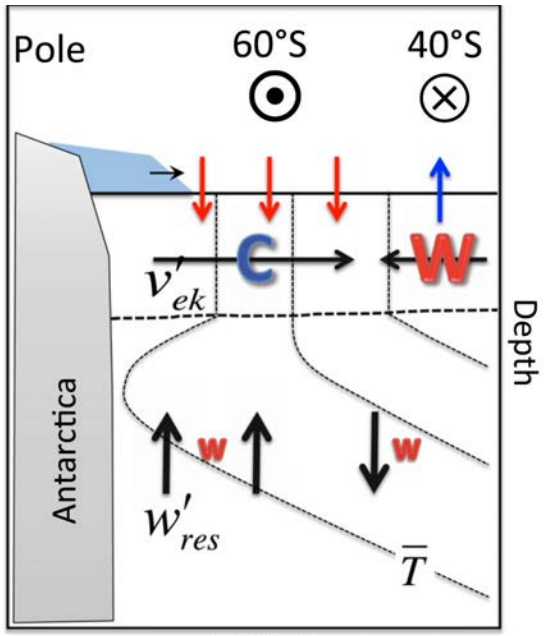
- Positive SAM trend in DJF since 1950s, associated with strengthened SO westerlies (primarily caused by ozone depletion and GHG)
  Banerjee et al. 2020; Polvani et al. 2011

- Abrupt forcing/step-function simulations show a fast SST cooling response to positive SAM, driven by enhanced northward Ekman heat transport
  (+ Seviour et al. 2017; 2019)

The observed SO cooling trend reflects the fast-timescale SST response to the positive SAM?



Kostov et al. 2018



Ferreira et al. 2014

Question 1: Model-observation comparison

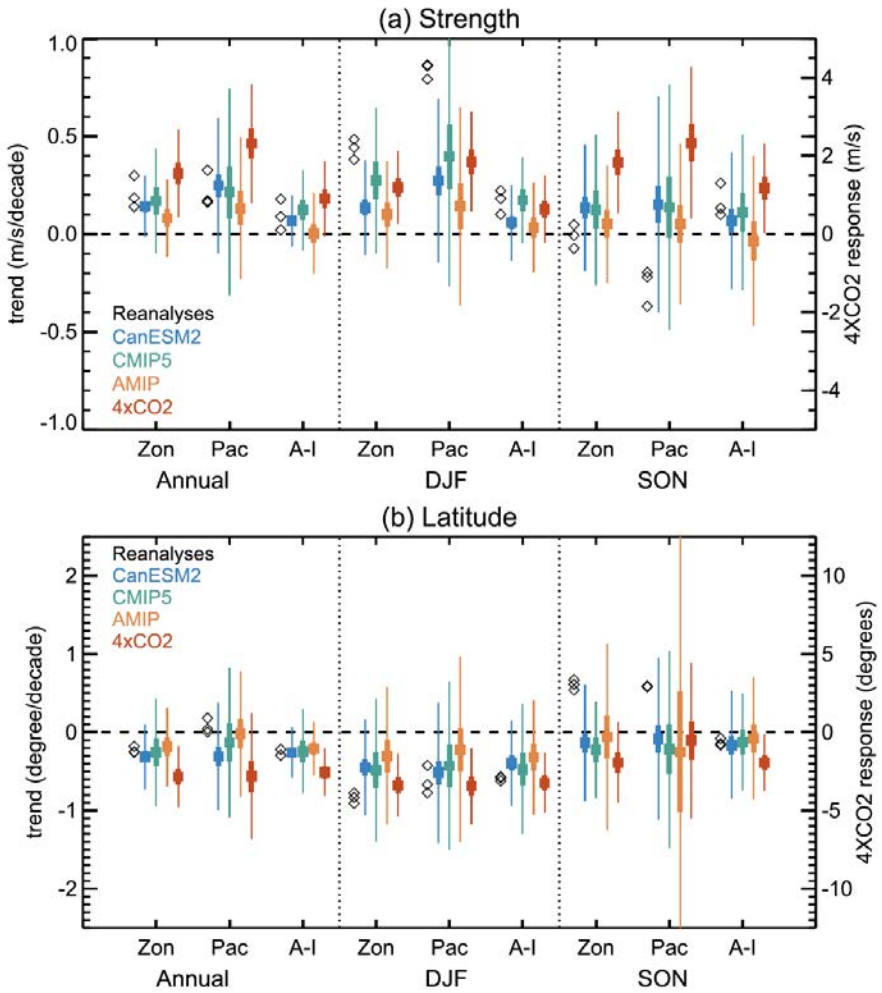
Assuming
the observed SO cooling trend is indeed (at least partly) caused by the fast-timescale SST response to the positive SAM

$$SST(t) = \frac{dSST}{dSAM} SAM(t)$$

- How do GCMs simulate the SAM-modulated SST variability compared to obs?
- Do model biases in the SST trends come from biases in dSST/dSAM?

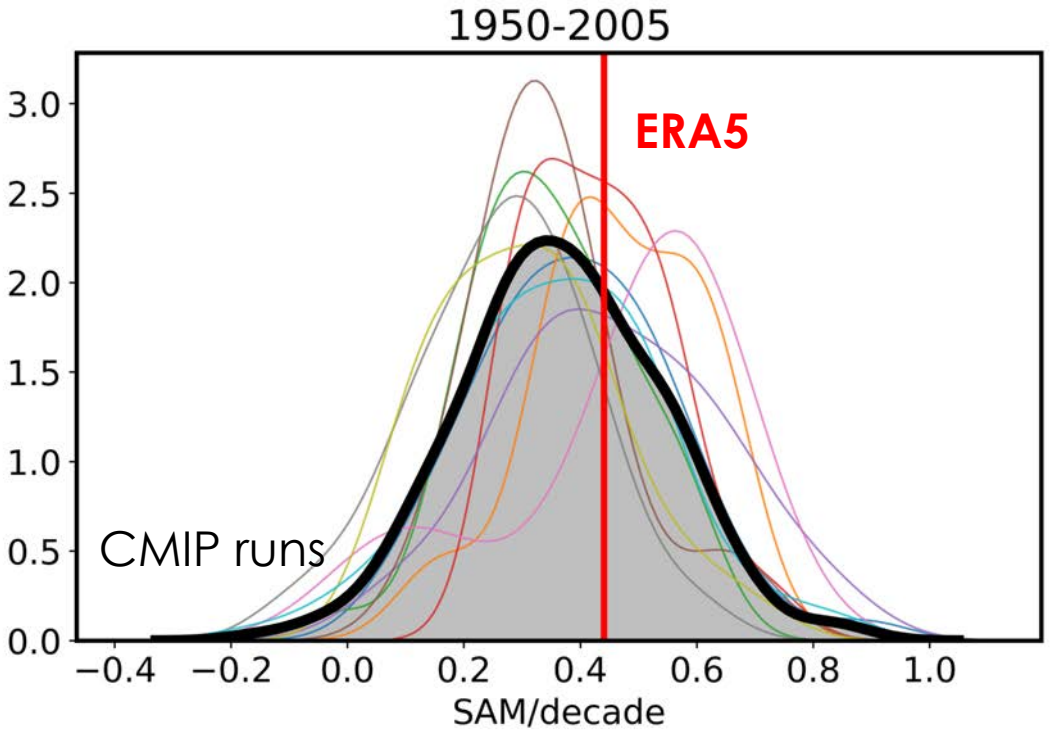
Models generally capture the observed SAM trend

1980-2005



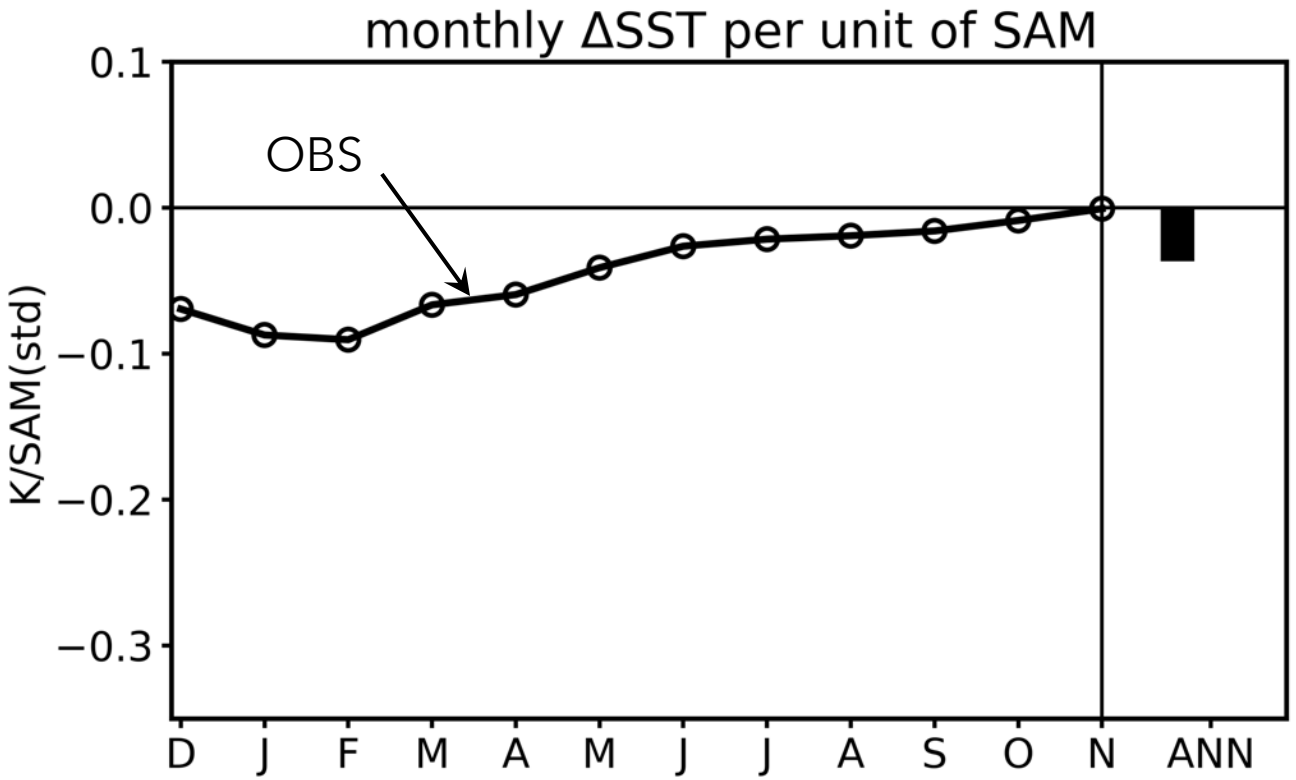
Waugh et al. 2020 GRL

10 CMIP large ensembles
DJF SAM trends



dSST/dSAM sensitivity

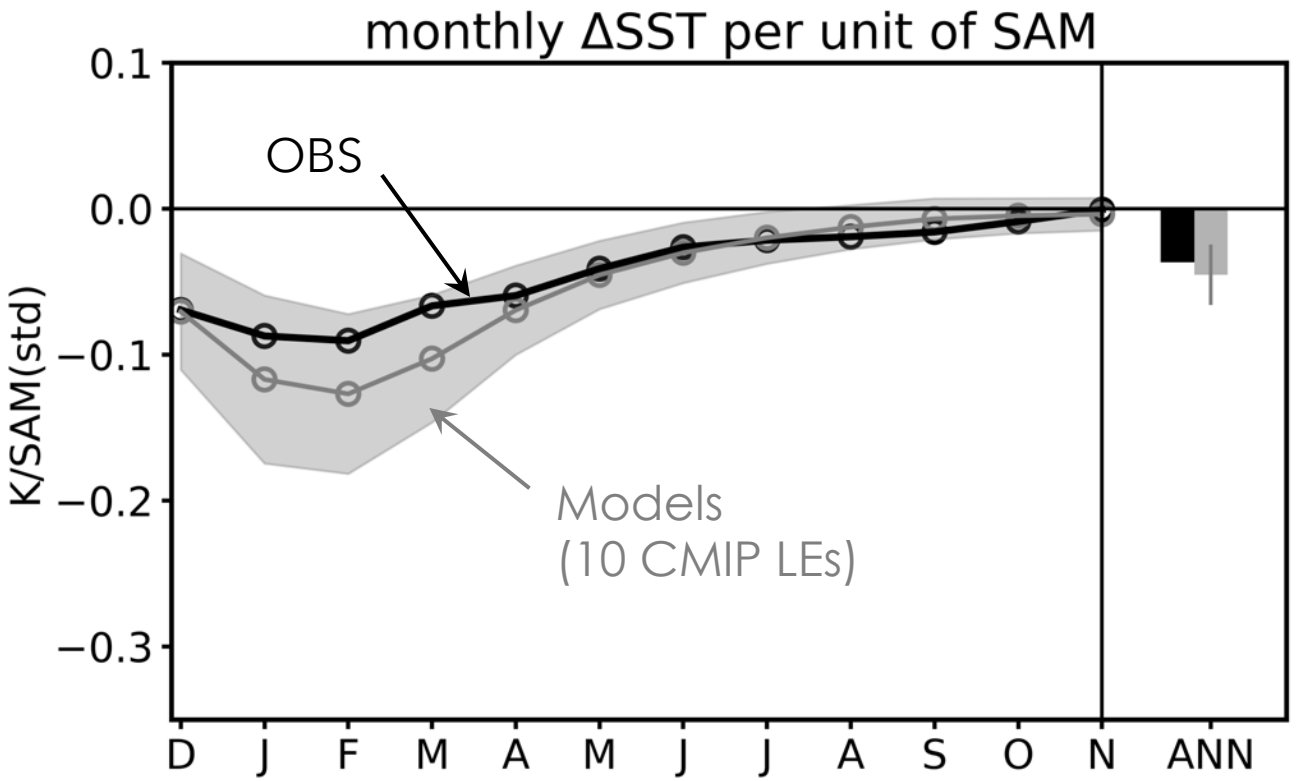
- 1950-2022 detrended SAM index (SLP gradient) in DJF and monthly SST (50°-70°S)



- Observed SST cooling following a unit of DJF SAM anomaly
- pronounced at seasonal timescales; the SAM-driven SST cooling doesn't survive over a year

dSST/dSAM sensitivity

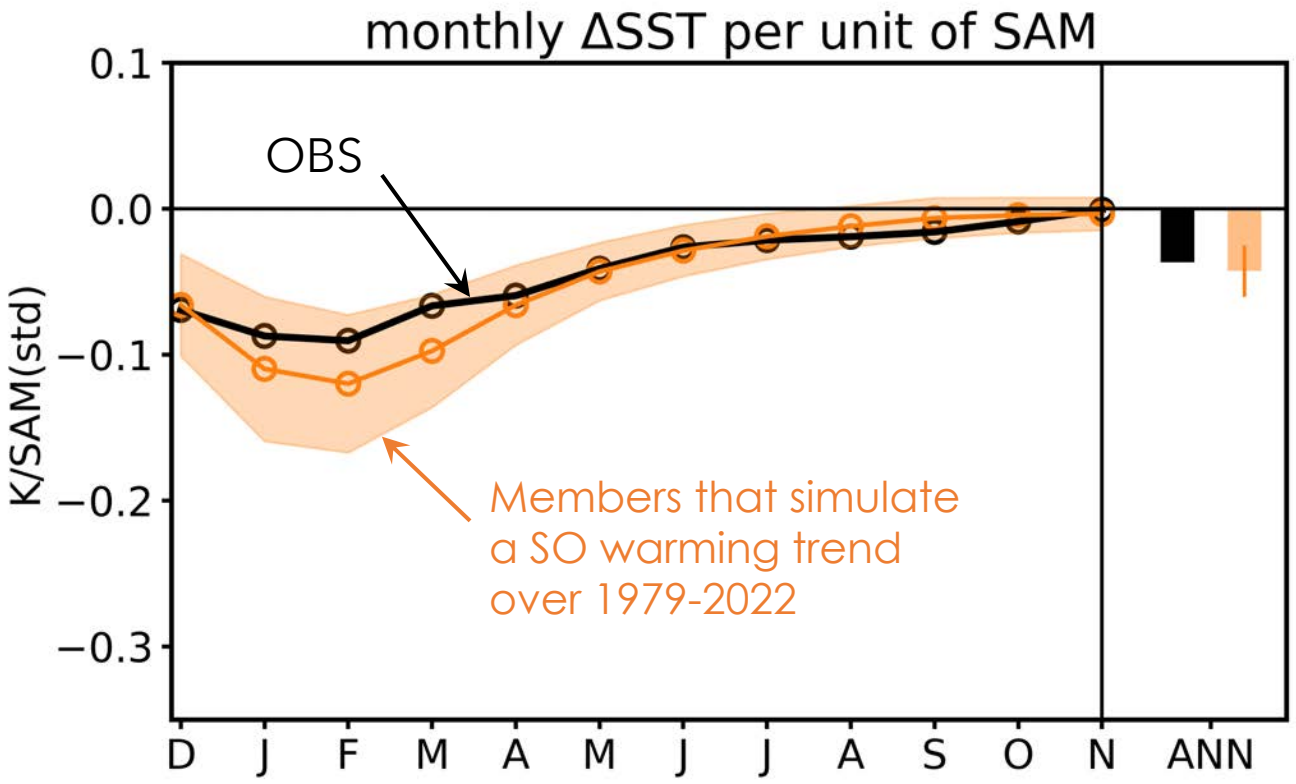
- 1950-2022 detrended SAM index (SLP gradient) in DJF and monthly SST (50°-70°S)



- GCMs in general well reproduce the seasonal-to-interannual SAM modulation of SST

dSST/dSAM sensitivity

- 1950-2022 detrended SAM index (SLP gradient) in DJF and monthly SST (50°-70°S)



- GCMs in general well reproduce the seasonal-to-interannual SAM modulation of SST, including those who fail to simulate the recent SO cooling trend

Question 1: Model-observation comparison

Assuming
the observed SO cooling trend is indeed (at least partly) caused by the fast-timescale SST response to the positive SAM

$$SST(t) = \frac{dSST}{dSAM} SAM(t)$$

- How do GCMs simulate the SAM-modulated SST variability compared to obs?
  Yes, generally

- Do model biases in the SST trends come from biases in dSST/dSAM?
  Correctly simulating the seasonal-to-interannual SAM modulation of SO SST does not guarantee model performance on multi-decadal SST trends

Question 1: Model-observation comparison

Is this true?

the observed SO cooling trend is indeed (at least partly) caused by the fast-timescale SST response to the positive SAM

$$SST(t) = \frac{dSST}{dSAM} SAM(t)$$

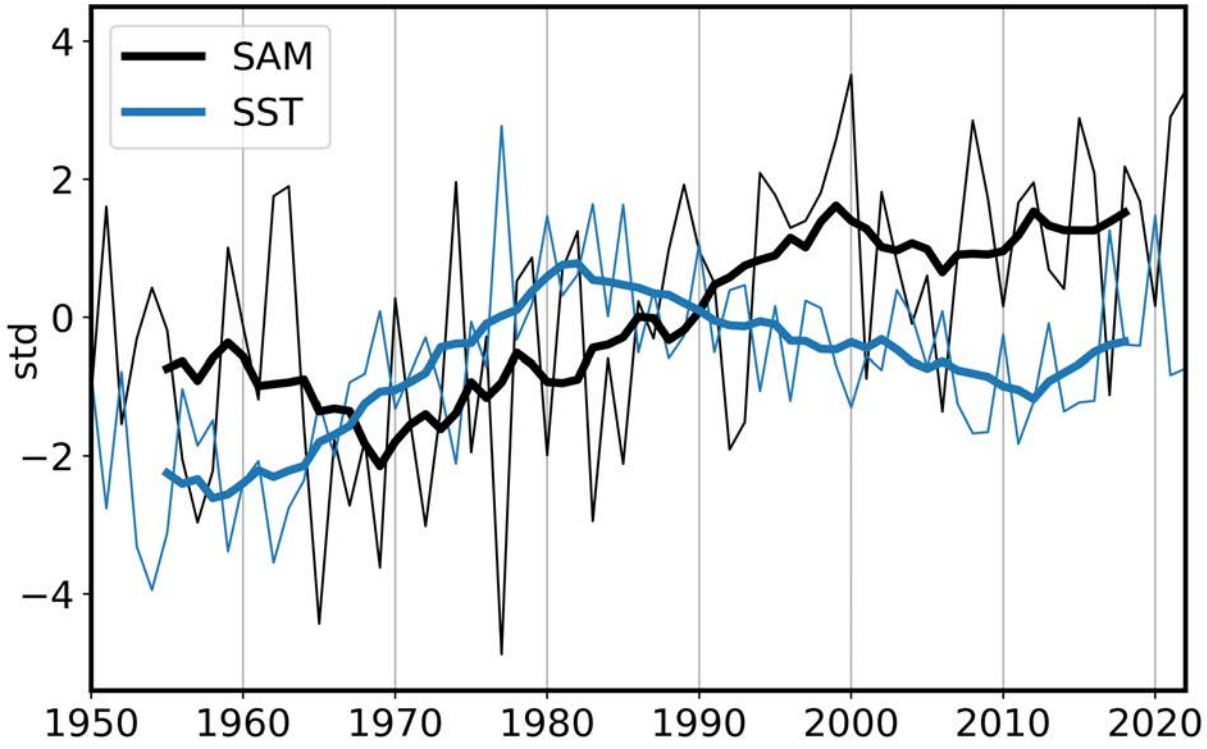
Question 2: Re-examine observation

To what extent does the fast (interannual) time-scale SAM modulation of SST contribute to the SO multi-decadal cooling trends?

$$SST(t) \xleftarrow{?} SST_{SAM}(t) = \frac{dSST}{dSAM} SAM(t)$$

Could apply simple linear regressions, but…

Normalized DJF SST and SAM in obs



Thick lines: 10yr running means

- Both the SAM and SST have mixed temporal variability
- The low-frequency variabilities of the SAM and SST do not align with each other (already some hints!)
- No information about the spatial patterns

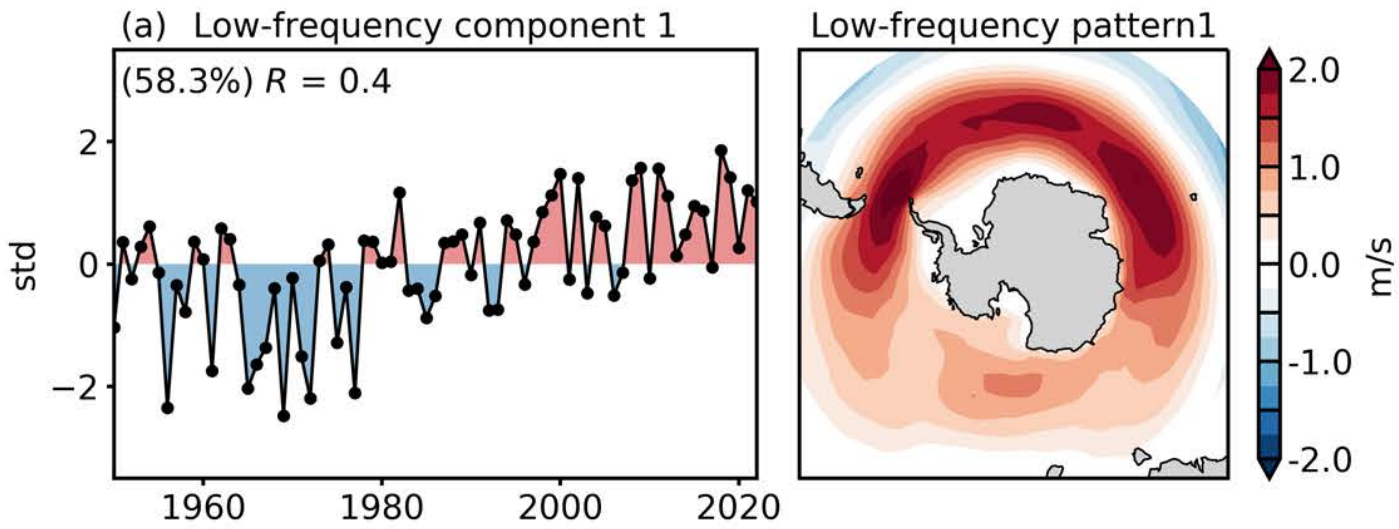
Low-frequency component analysis (LFCA)

- Similar to EOF, an approach to extract modes of variability.
- It ranks the modes based on the ratio of low-pass filtered (low-frequency) to total variance, such that it isolates **leading modes of *low-frequency variability***
- E.g., Wills et al. 2018; 2022

- Apply LFCA to ERA5 U850 for 1950-2022
- DJF-only, Southern Ocean (40-80S) only
- 15-yr cut-off low-pass filtered to isolate low-frequency variability
- Retain 5 EOFs, account for 77% of the total variance

LFCA-based modes of Reanalysis U850

The first leading mode of U850
(**low-frequency** dominant)

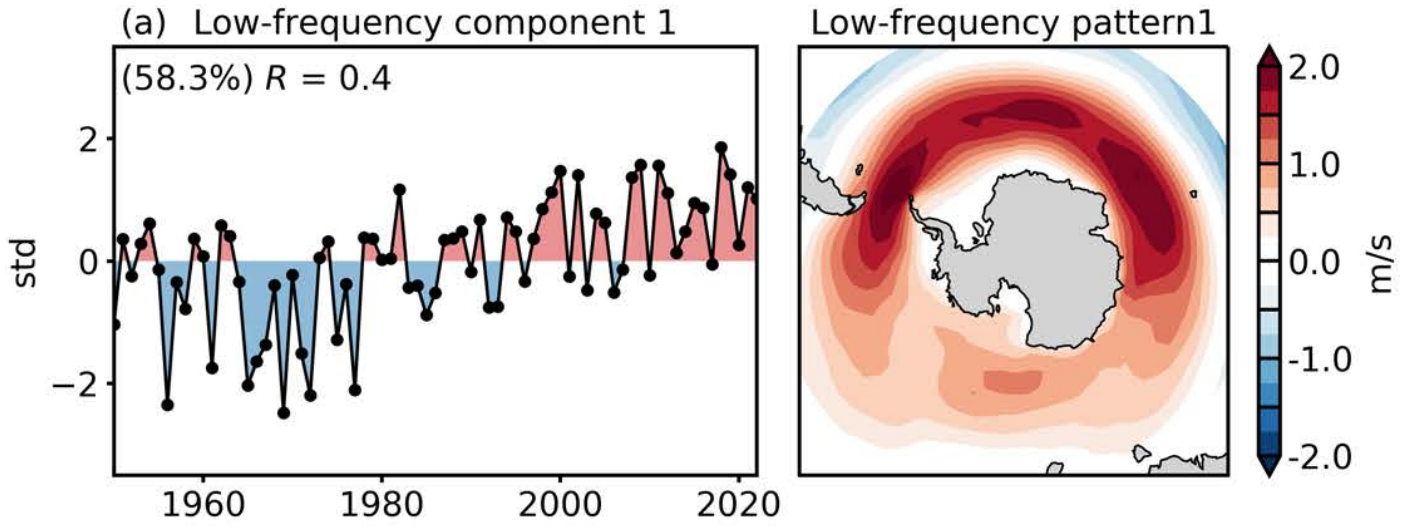


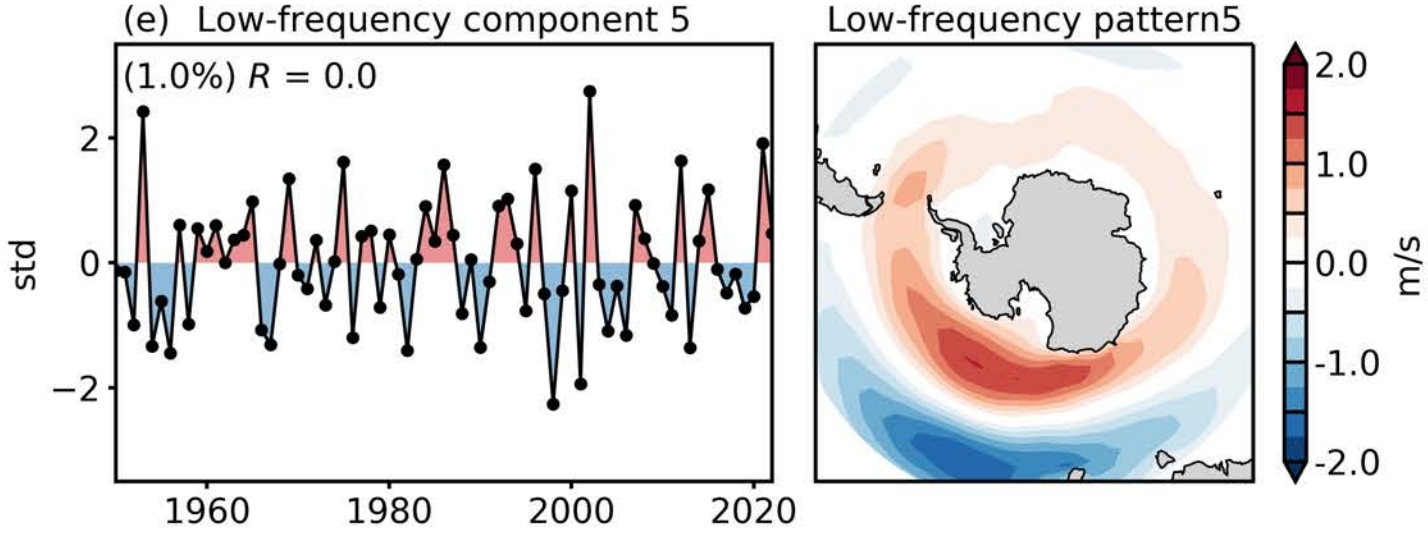
LFCA-based modes of Reanalysis U850

The first leading mode of U850 (**low-frequency** dominant)

Using the leading three modes can fully reproduce the total U850 trends over recent decades

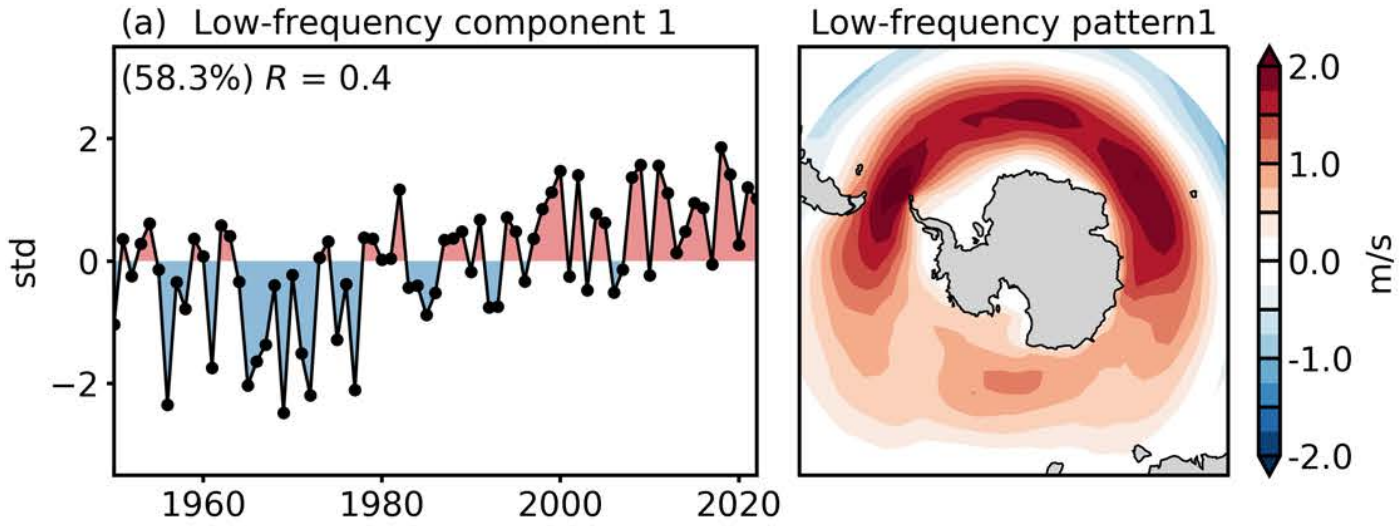
The last mode of U850 (**high-frequency** dominant)





SST regressions onto U850 PCs

Consider using the PCs as alternatives to the zonal-mean SAM index



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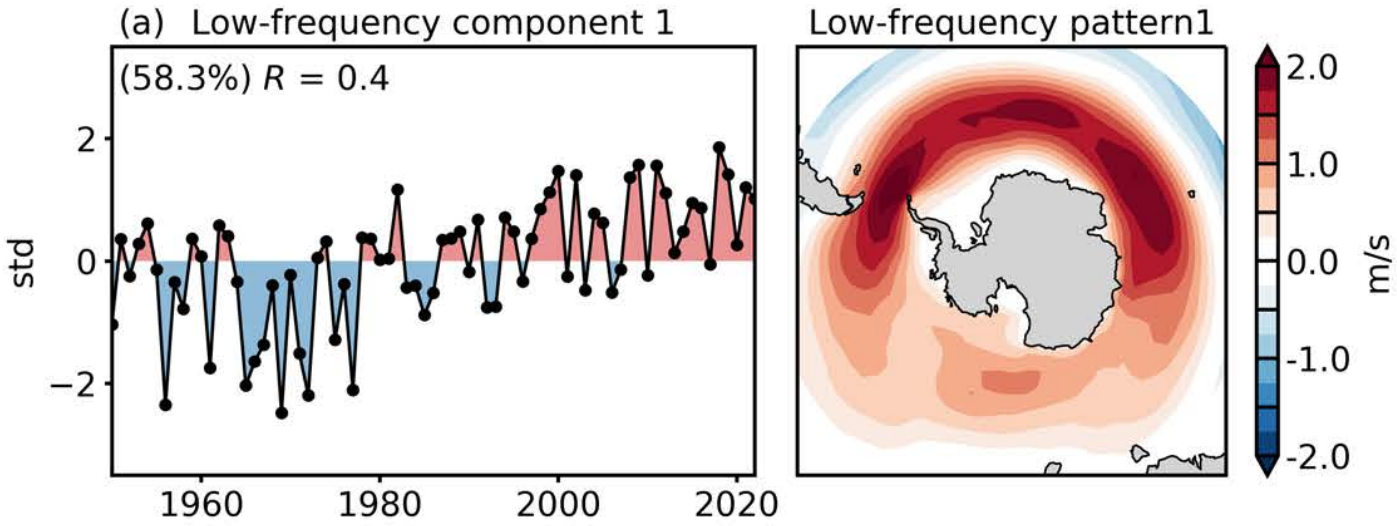
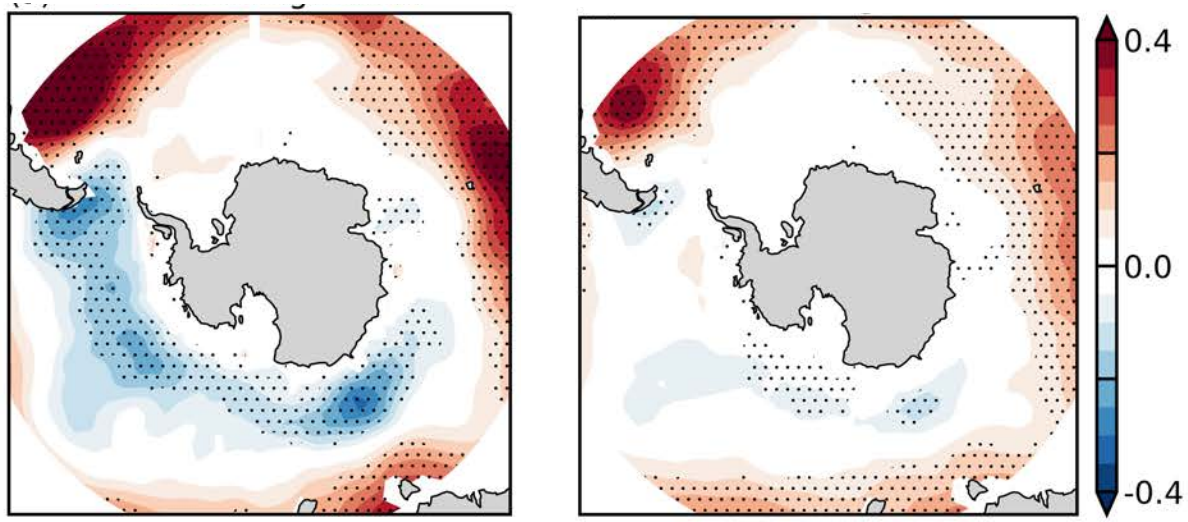


Regressing SST onto PC1

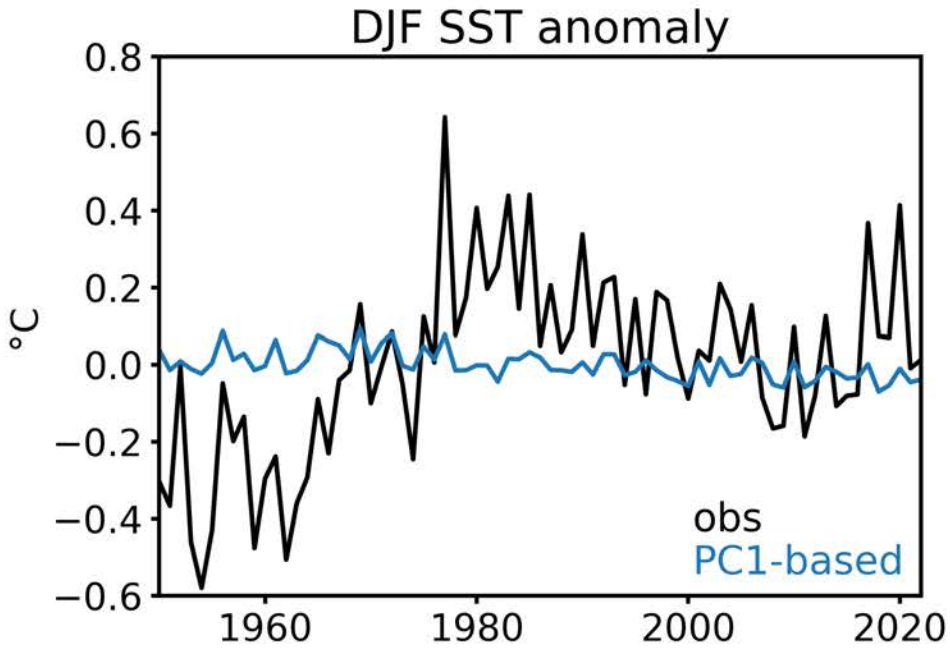
consistent with the observed negative dSST/dSAM

DJF SST regression

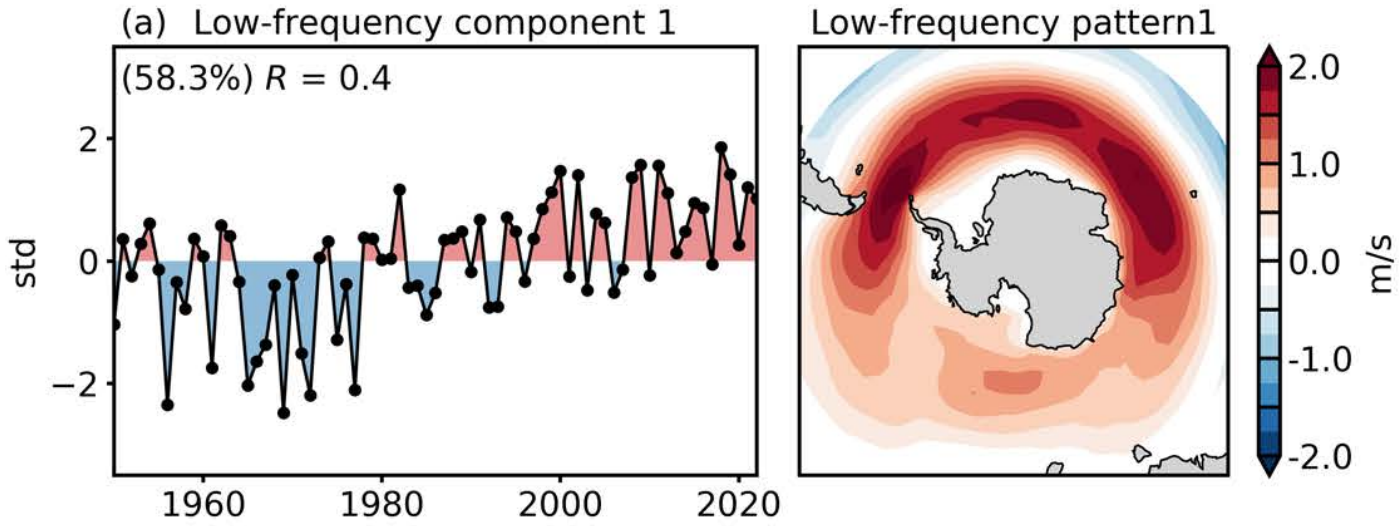
ANN SST regression

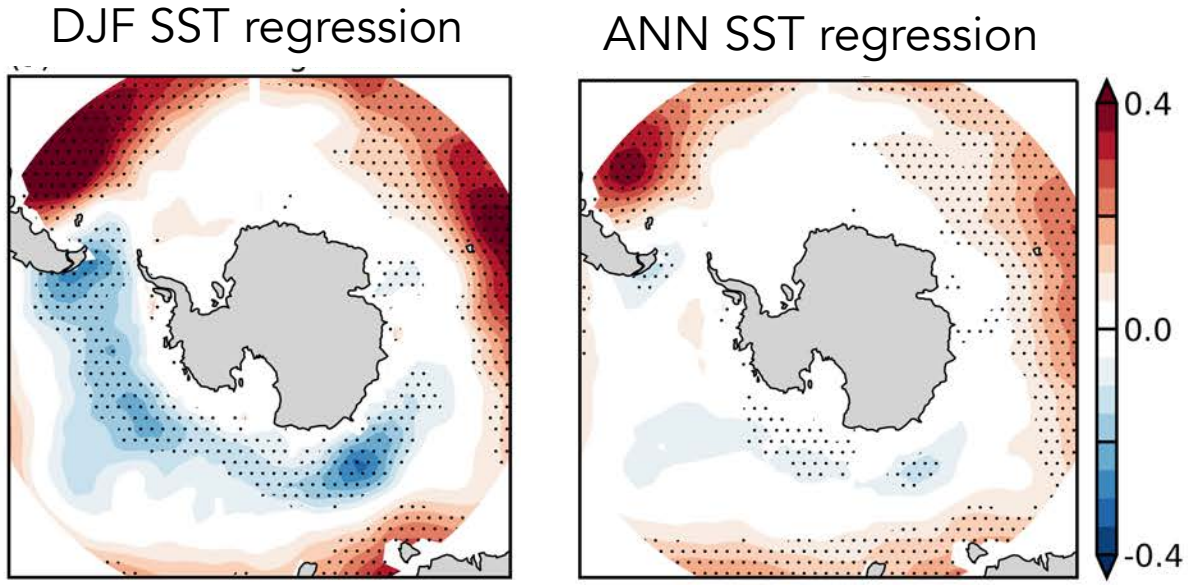


U850 PCs-associated SST variability

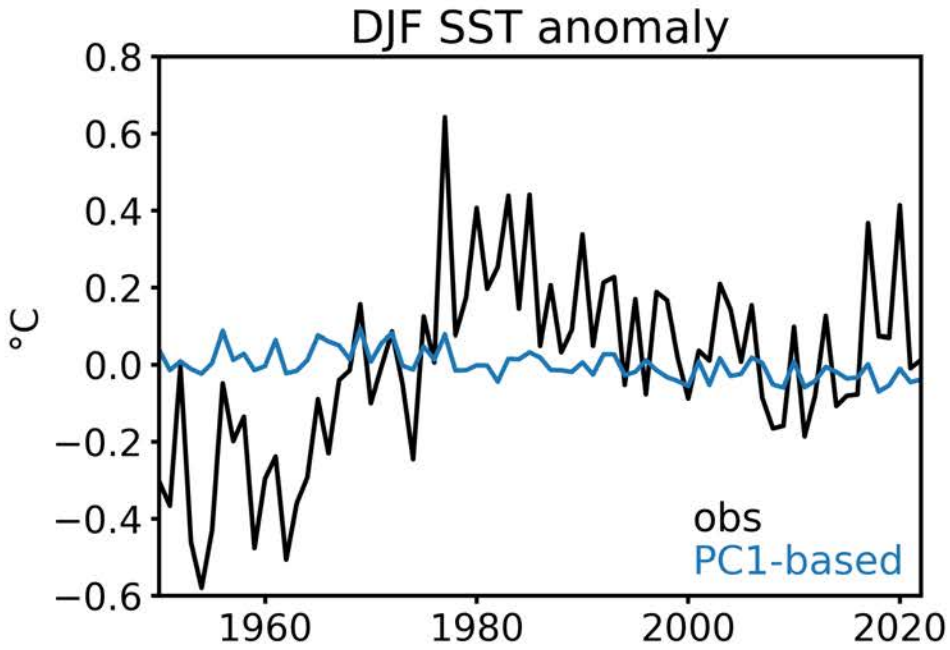


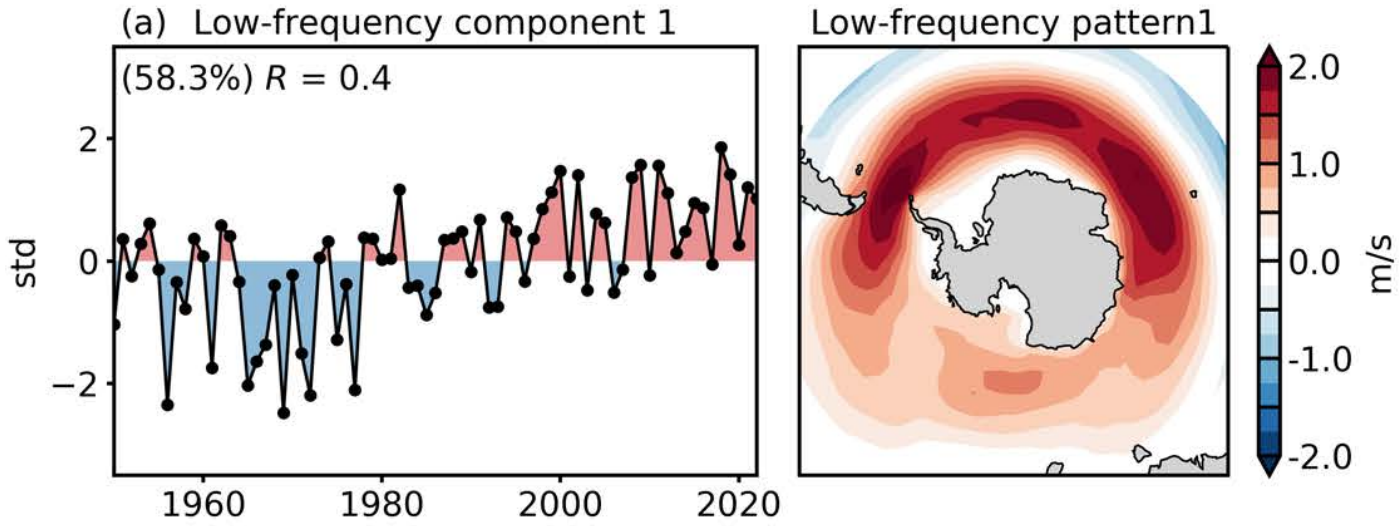
PC1-associated SST contributes little to the actual low-frequency SST variability

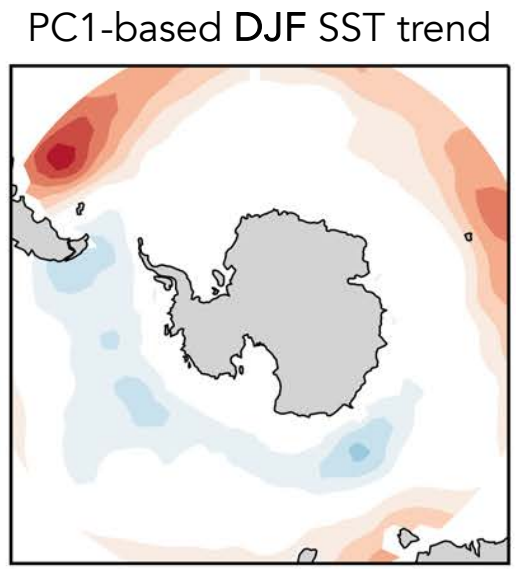


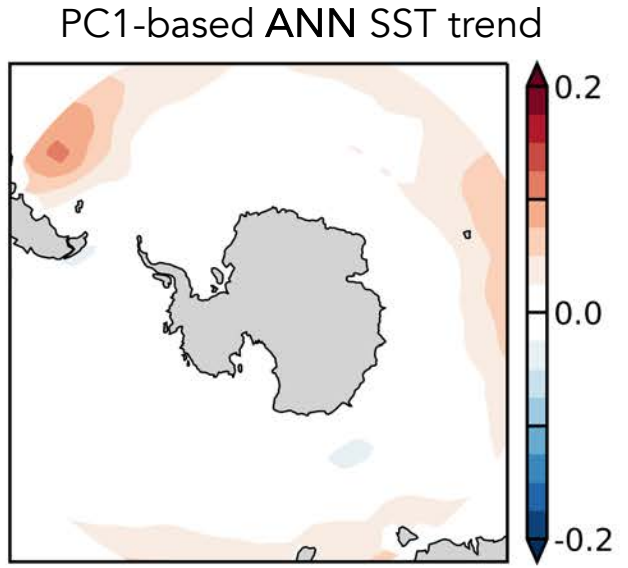


U850 PCs-associated SST variability

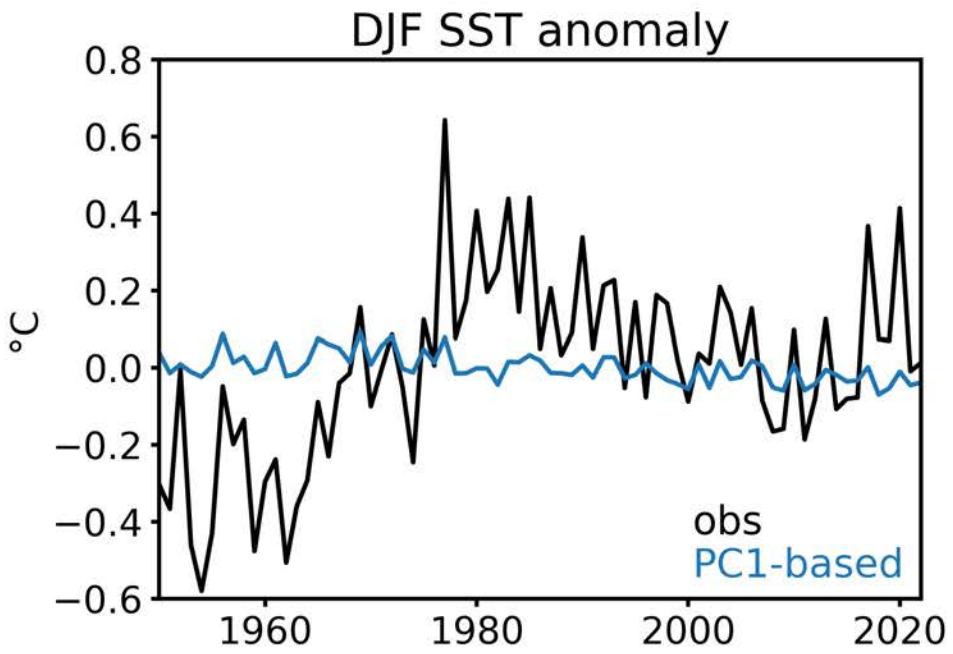




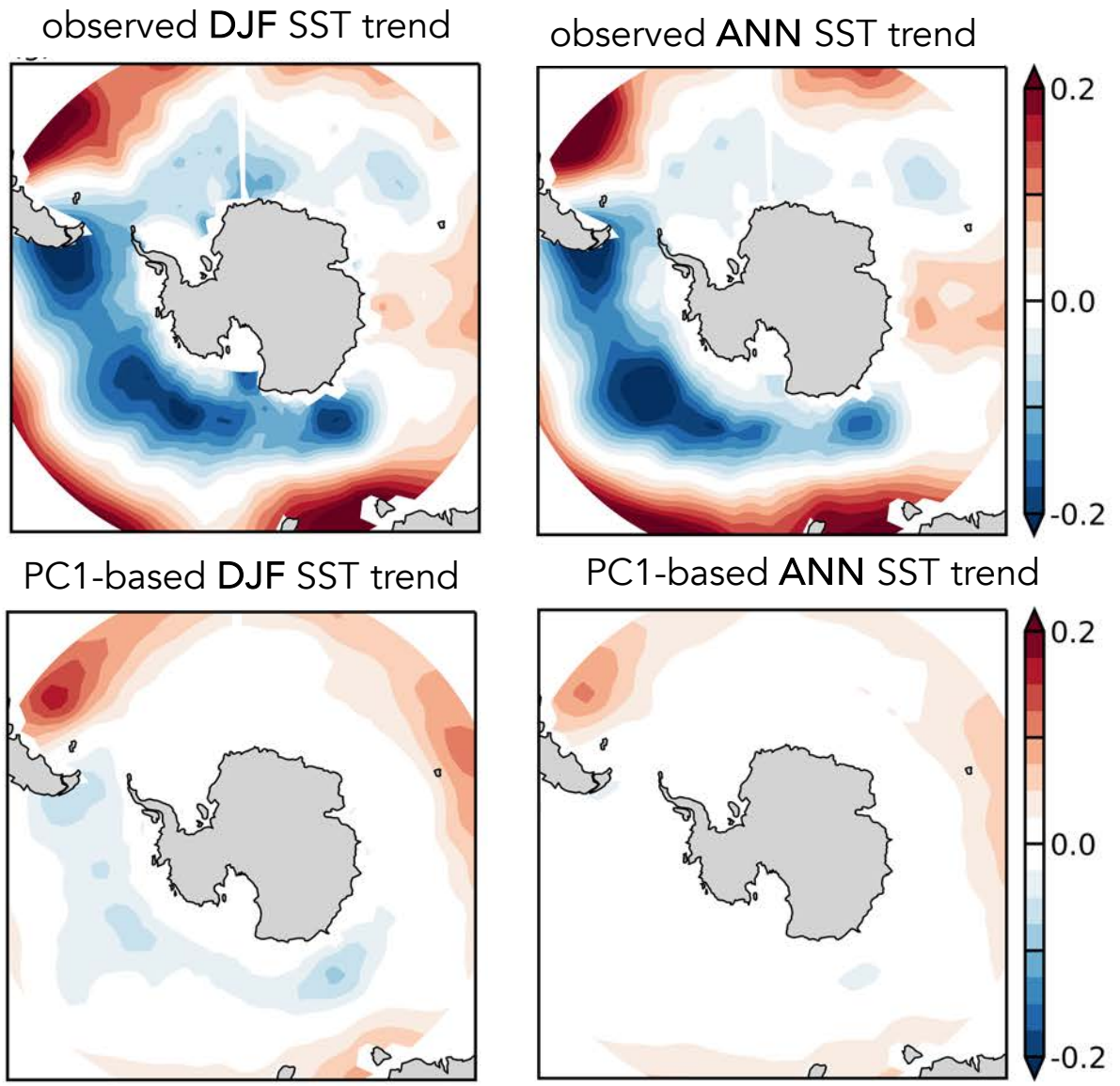




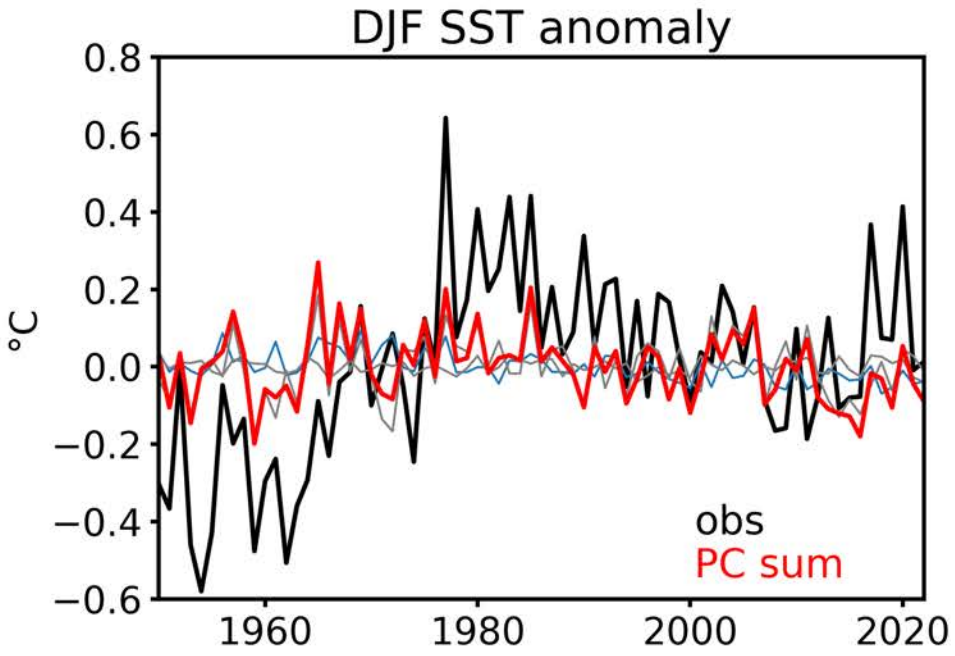
U850 PCs-associated SST trends



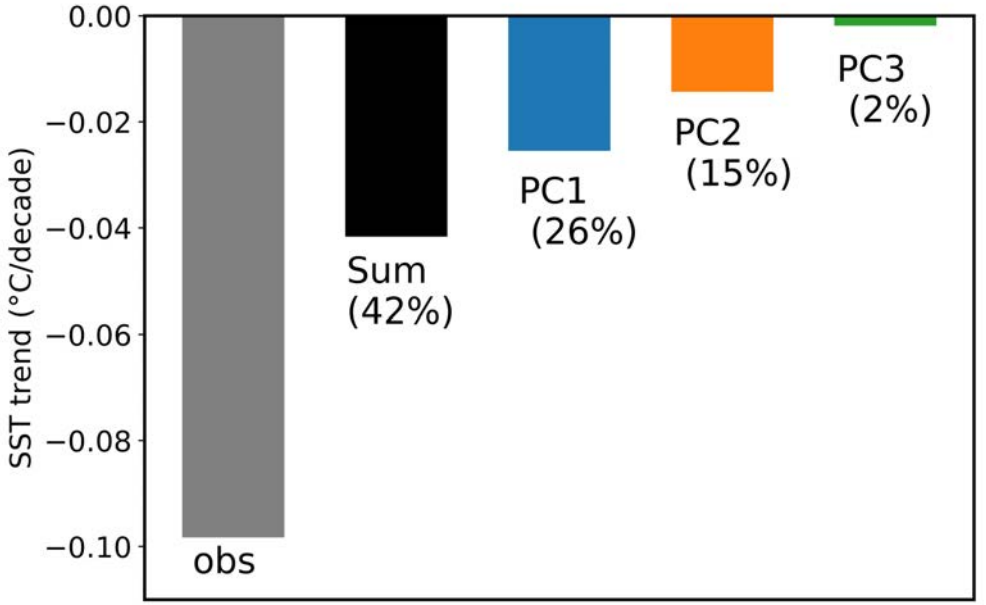
PC1-associated SST contributes little to the actual low-frequency SST variability and multidecadal SST trends



U850 PCs-associated SST trends

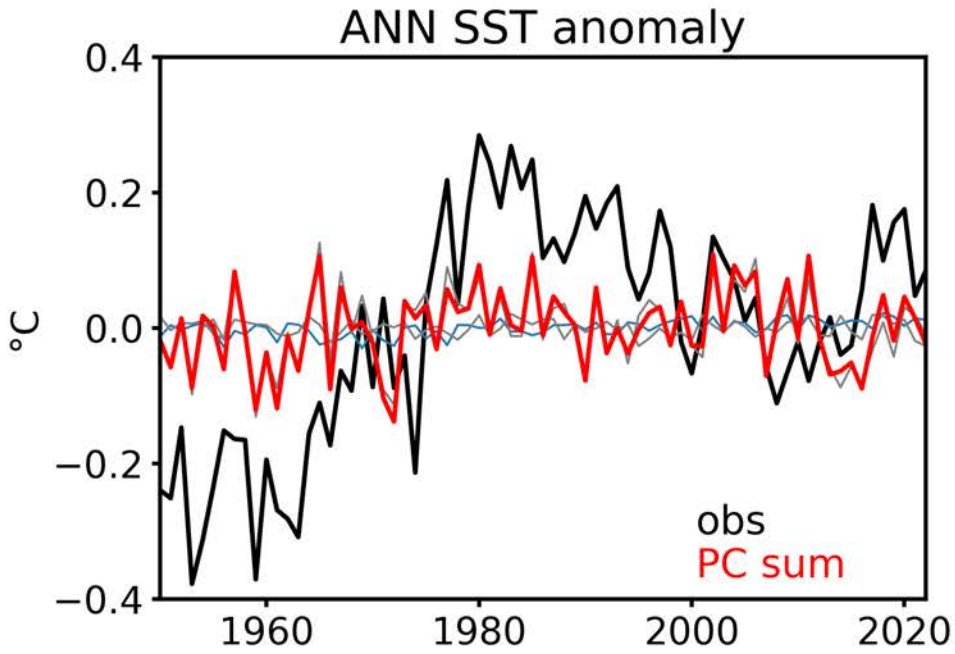


DJF SST trend over 1979-2022 in the Pacific sector

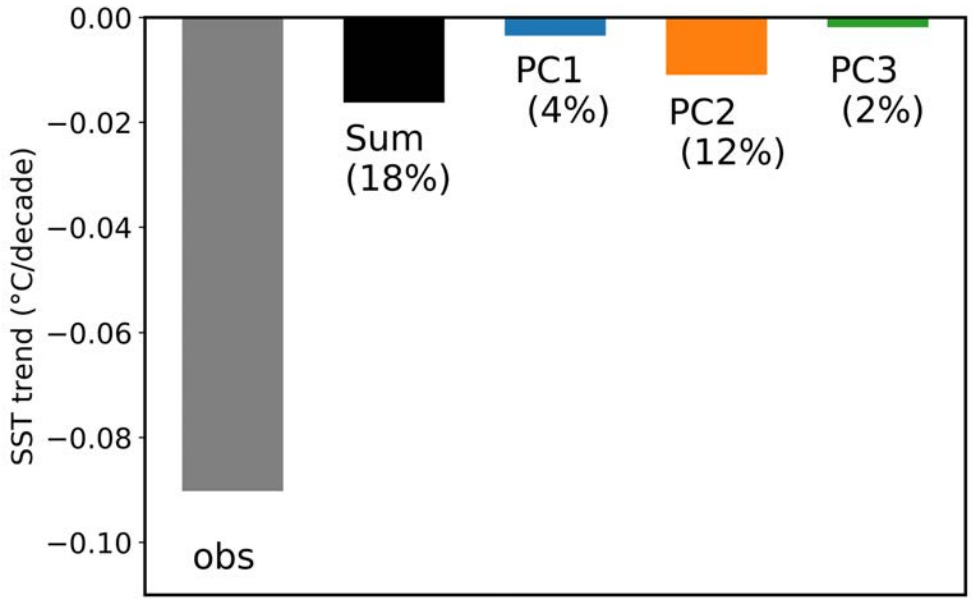


The collective contribution from the leading three U850 modes only explains 40% of the observed SST trend in DJF

U850 PCs-associated SST trends



ANN SST trend over 1979-2022 in the Pacific sector



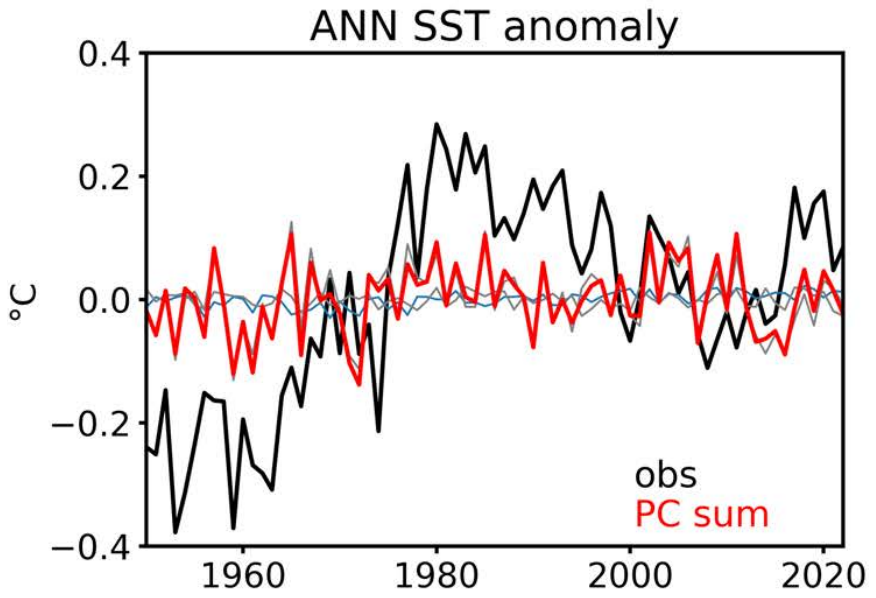
The collective contribution from the leading three U850 modes only explains <20% of the observed SST trend in ANN

Question 2: Re-examine observation

To what extent does the fast (interannual) time-scale SAM modulation of SST contribute to the SO multi-decadal cooling trends?

- The seasonal-interannual wind modulation of SO SST does not account for much of the multi-decadal SST trends

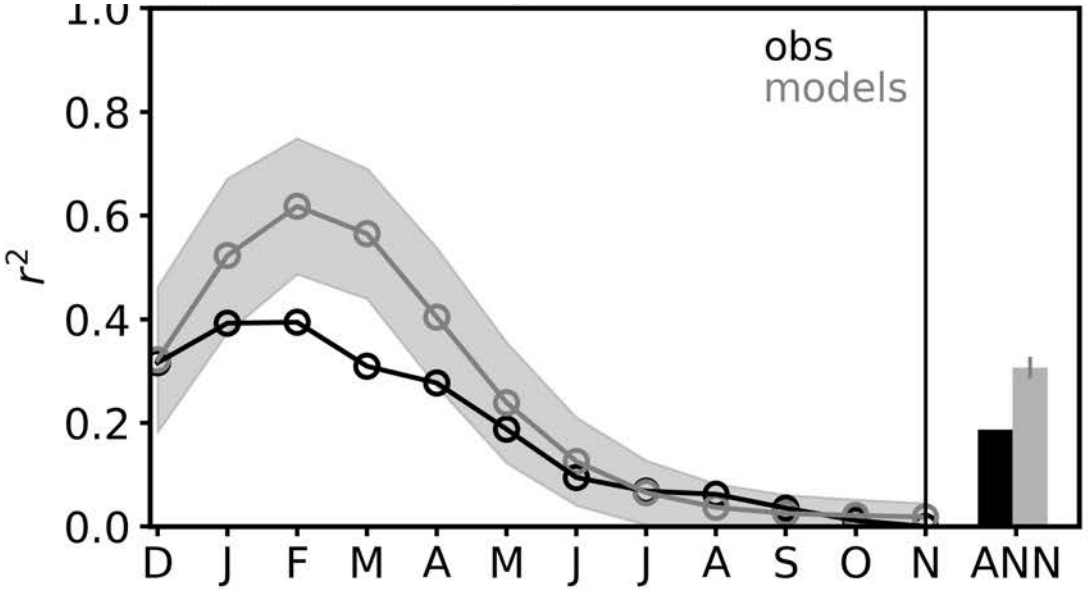
- The SAM-induced wind strengthening is unlikely the main cause of the observed multi-decadal SO SST trend



Some physical intuition

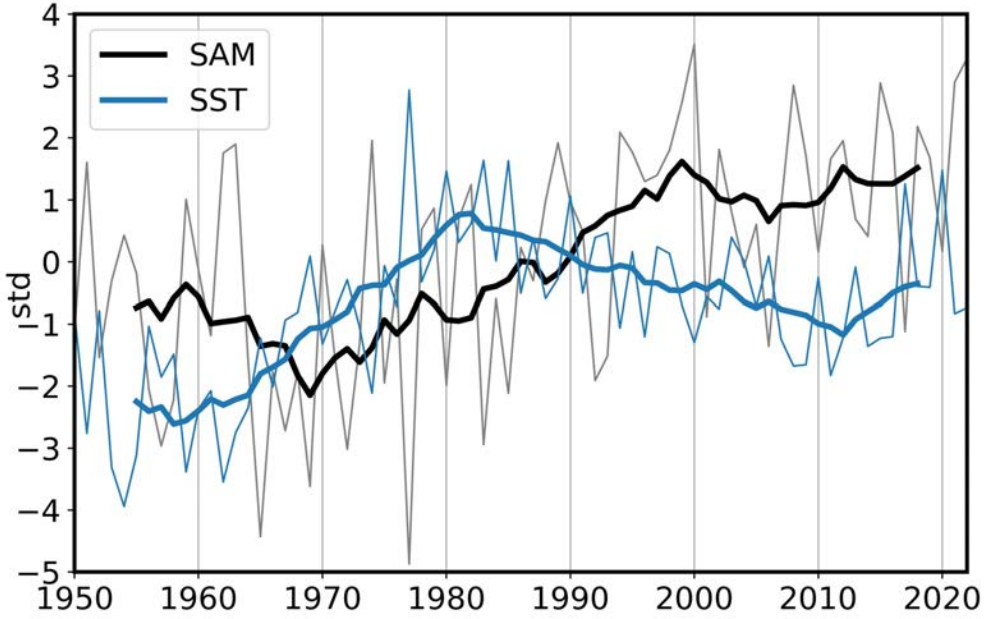
$$SST(t) \gg SST_{SAM}(t) = \frac{dSST}{dSAM} SAM(t)$$

r^2 of monthly dSST/dSAM



Too-weak modulation of SST by the SAM

Observed DJF SAM(t) & SST (t)



Low-frequency variabilities in the SAM and SST don't align with each other

Summary

Using the conventional SAM index

Part 1. SAM modulation of SST in obs and models

- Observations: the SAM drives SST cooling only at seasonal to interannual timescales
- Models: well reproduce the observed SAM modulation of SO SST

Using the low-frequency component analysis

Part 2. Observed contribution of winds to SST trends

- The wind-associated SST cooling does not account for much of the long-term SST trends
- **The SAM-induced wind strengthening is unlikely the main cause of the observed multi-decadal SO SST trend**

Dong, Y., Polvani, L. M., & Bonan, D. B. (2023). Recent multi-decadal Southern Ocean surface cooling unlikely caused by Southern Annular Mode trends. *GRL*.

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NOAA C&GC postdoc fellowship program