A review of changes in the coupled Antarctic climate system in models and observations

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1. Review of observed changes
2. Mechanisms for muted Antarctic warming
3. Model-observation discrepancies

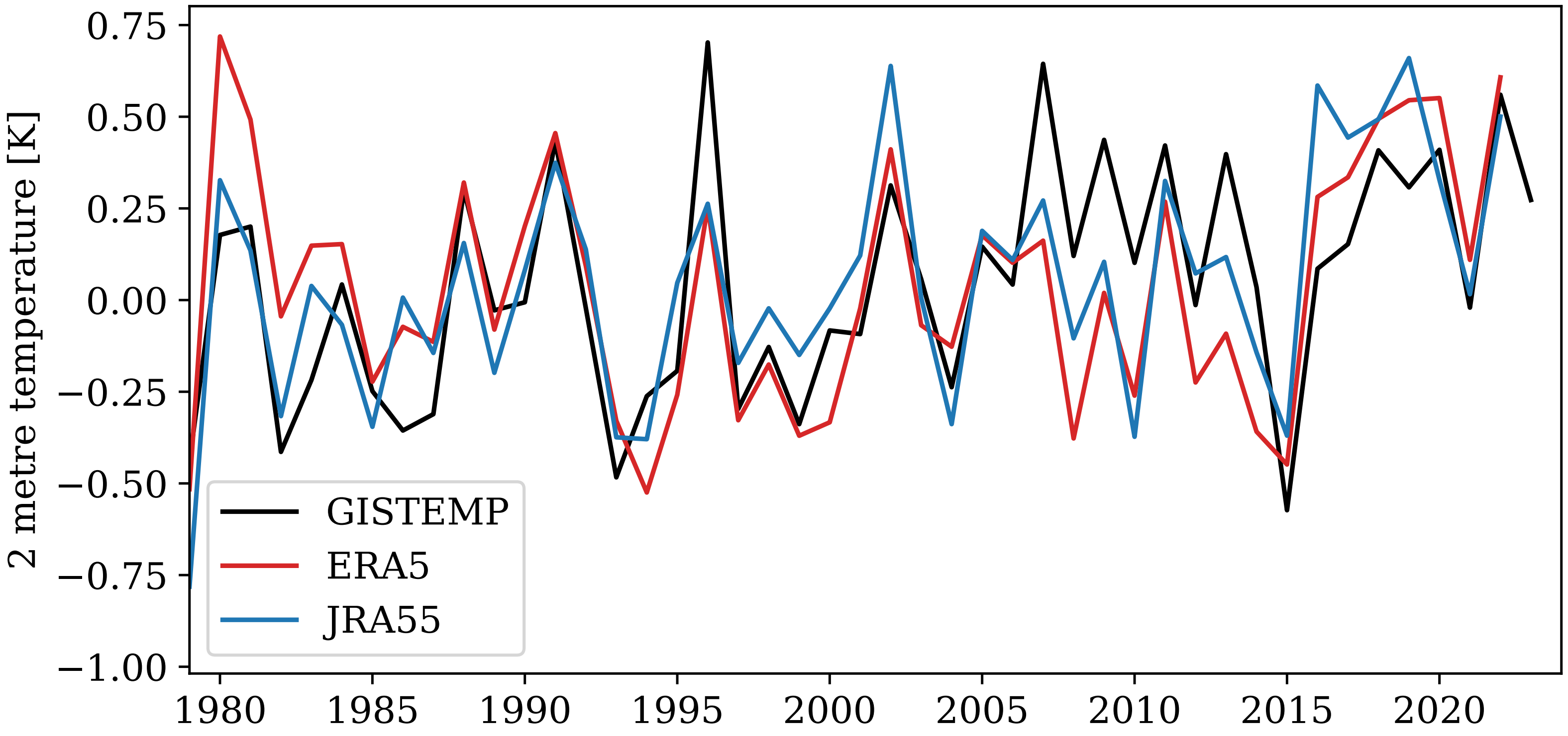
Image generated by Bing with prompt: "schematic of an ice sheet with sunlight bouncing off it and ocean melting the edge"

Review of observed changes

Recent changes in the Antarctic climate system

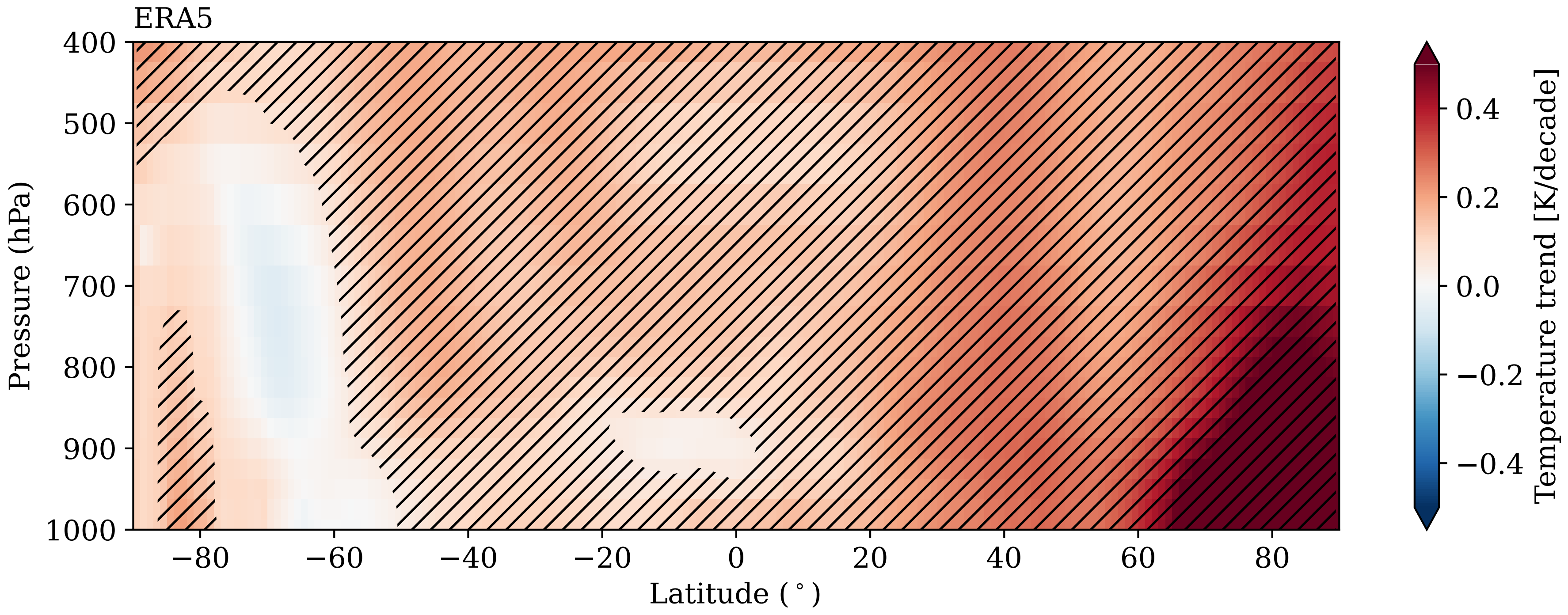
Large variability in near-surface air temperature

- South of 60S

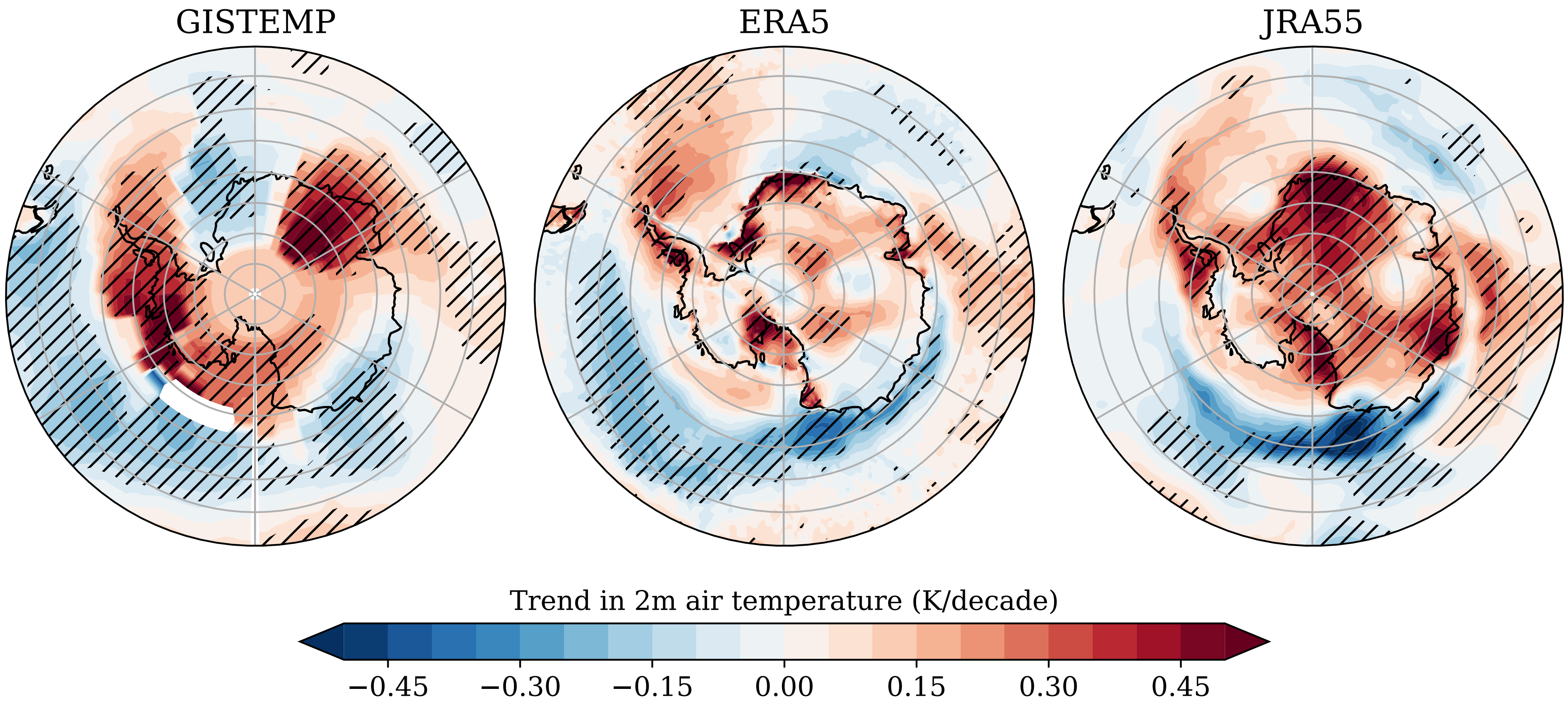


Insignificant warming throughout the lower atmosphere

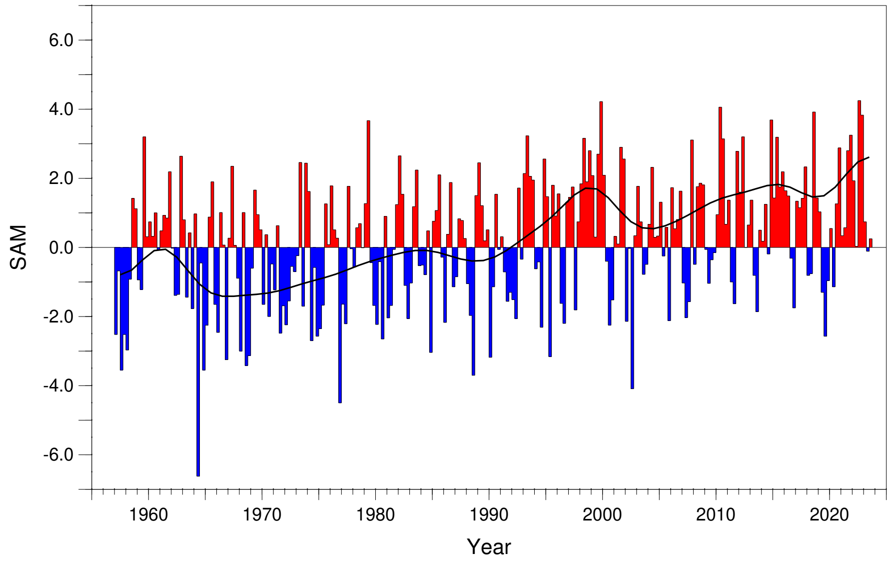
- 1979-2022, hatching marks trends significant at 95%



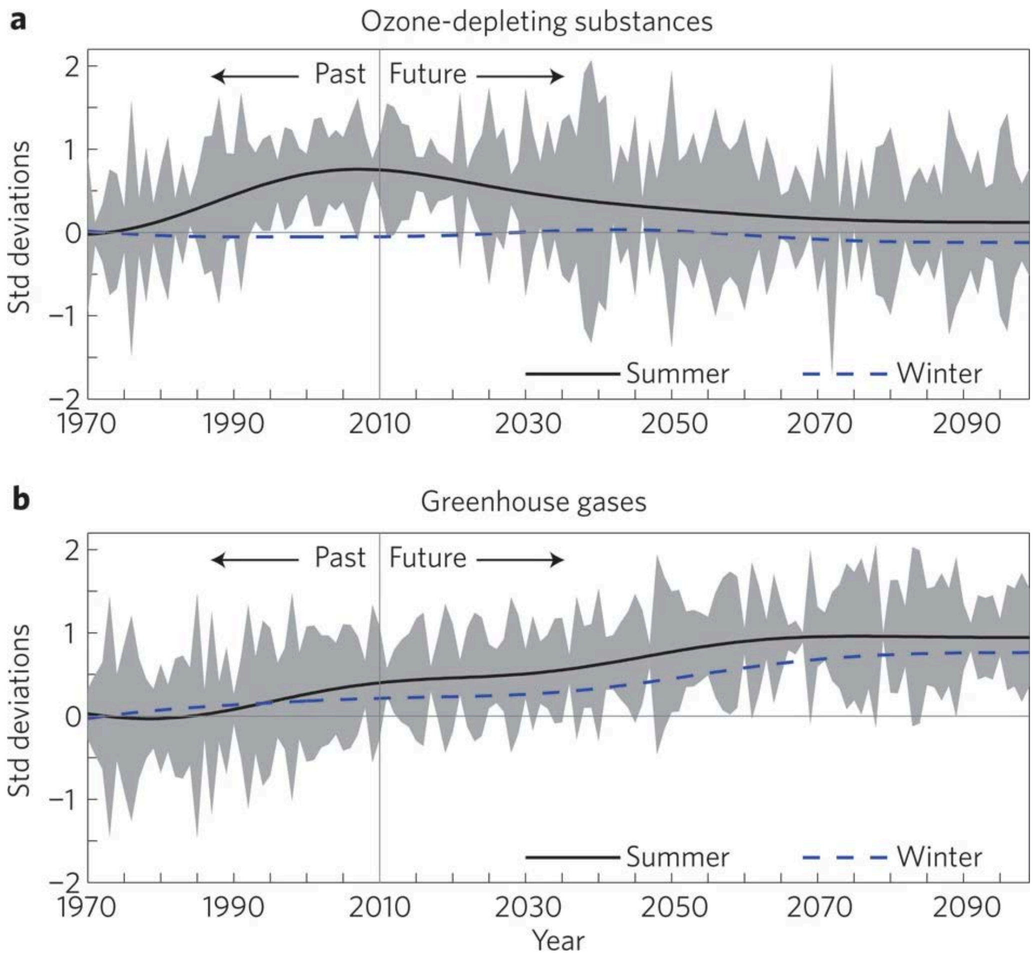
Observational uncertainty in regional air temperature trends



More positive Southern Annular Mode



Marshall (2003) - extended

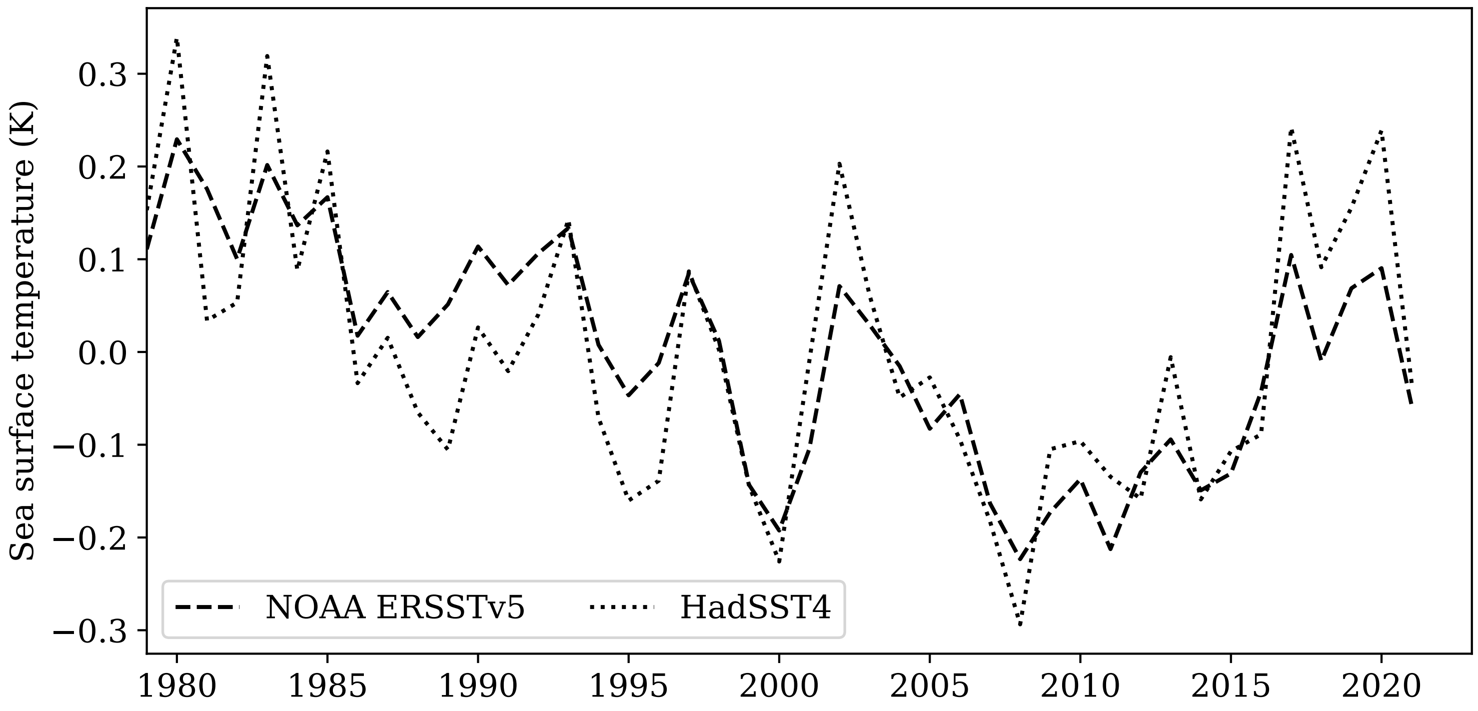


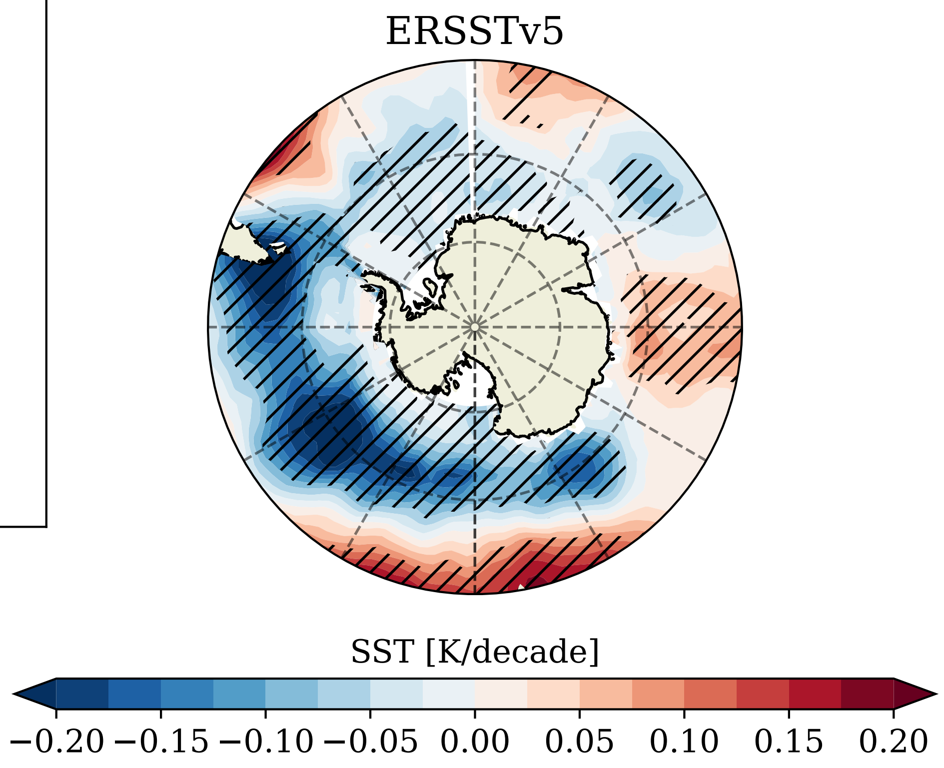
- Amundsen Sea Low has deepened
- Influence of IPO (Meehl et al. 2016)
- Influence of ENSO

Thompson et al. (2011)

Changes in Southern Ocean sea surface temperatures

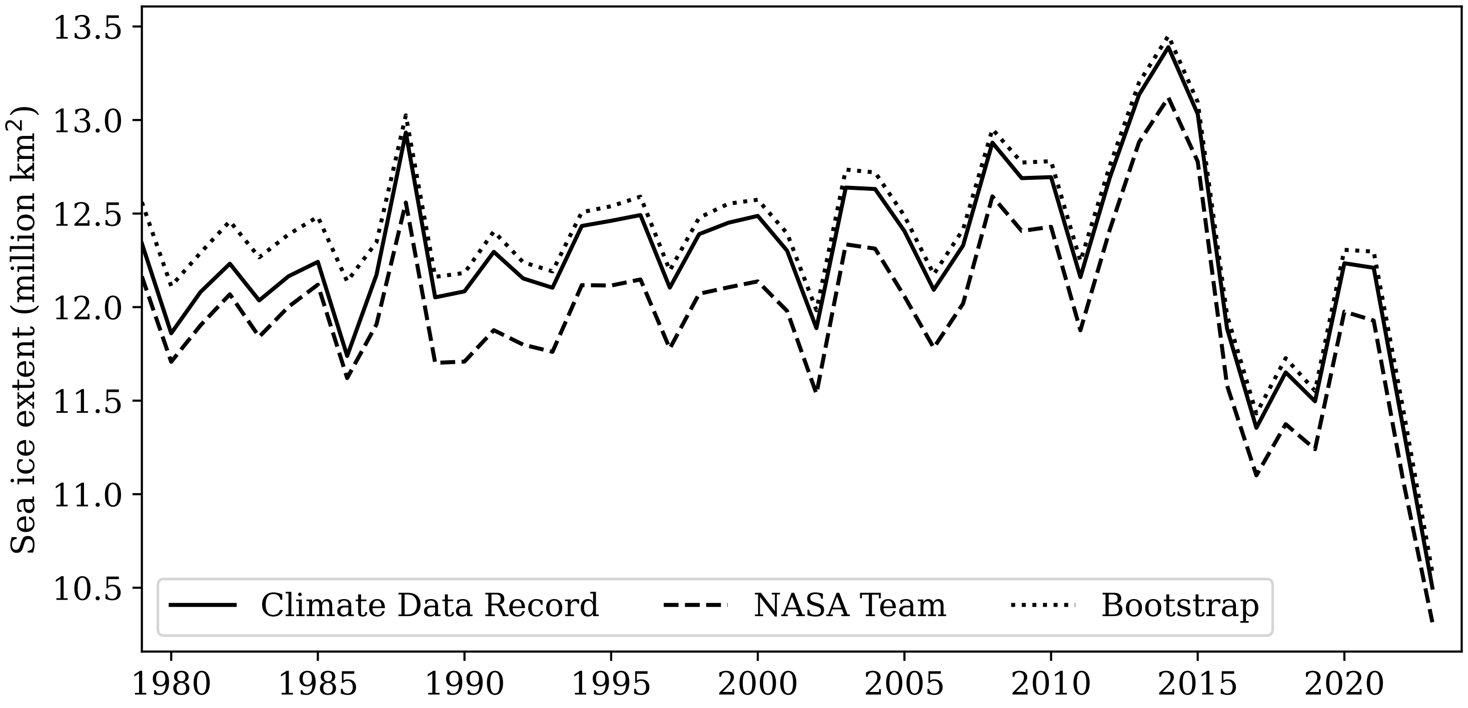
- 50-65S, 1979-2021





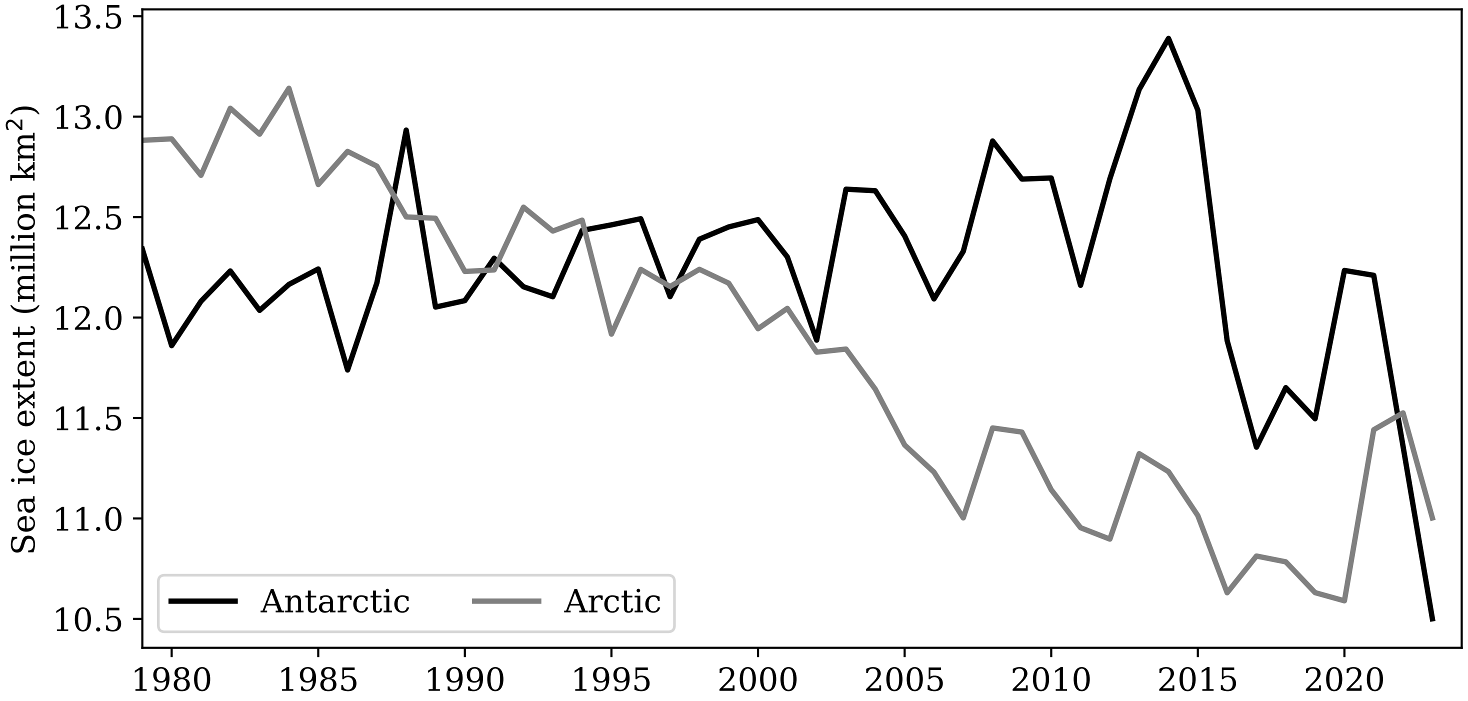
Unexpected changes in Antarctic sea ice

- NSIDC CDR version 4



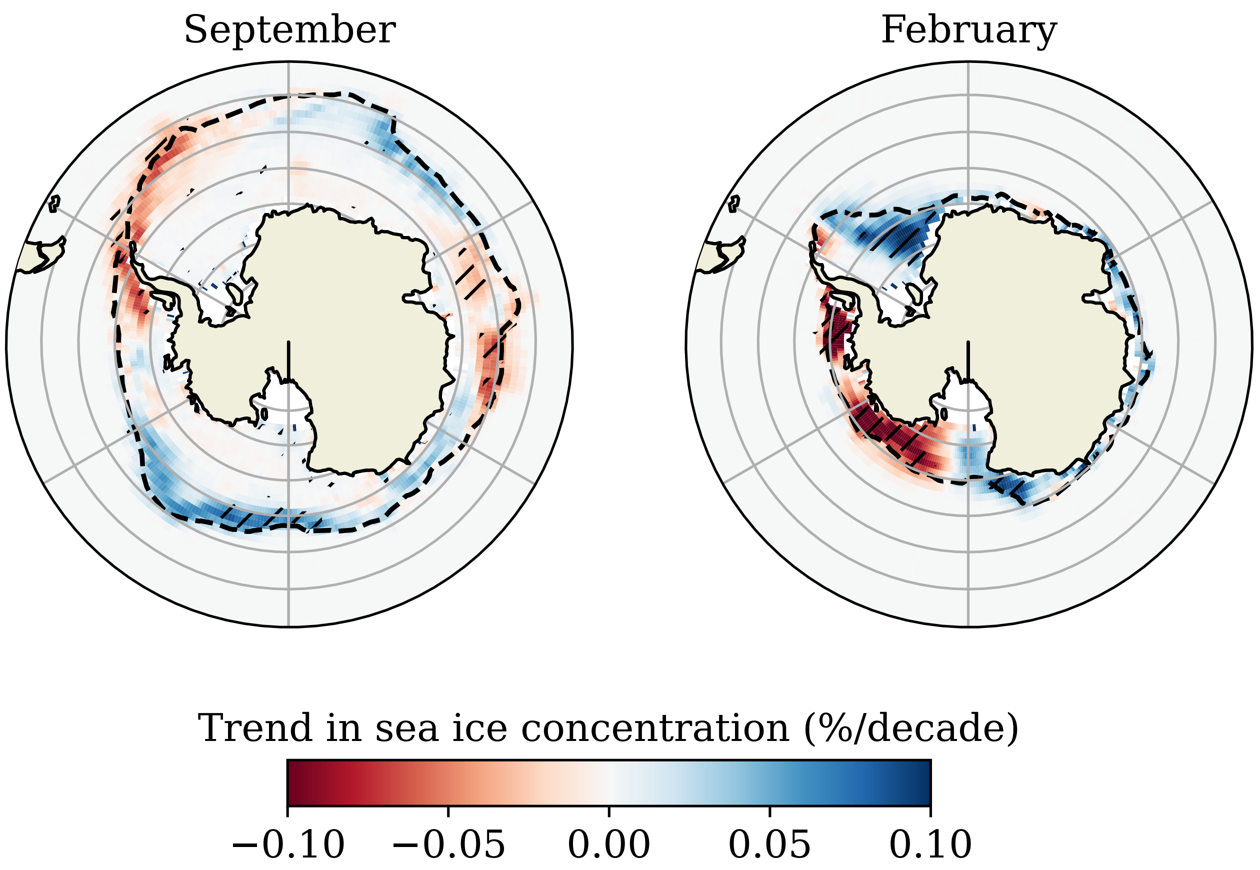
Unexpected changes in Antarctic sea ice

- NSIDC CDR version 4



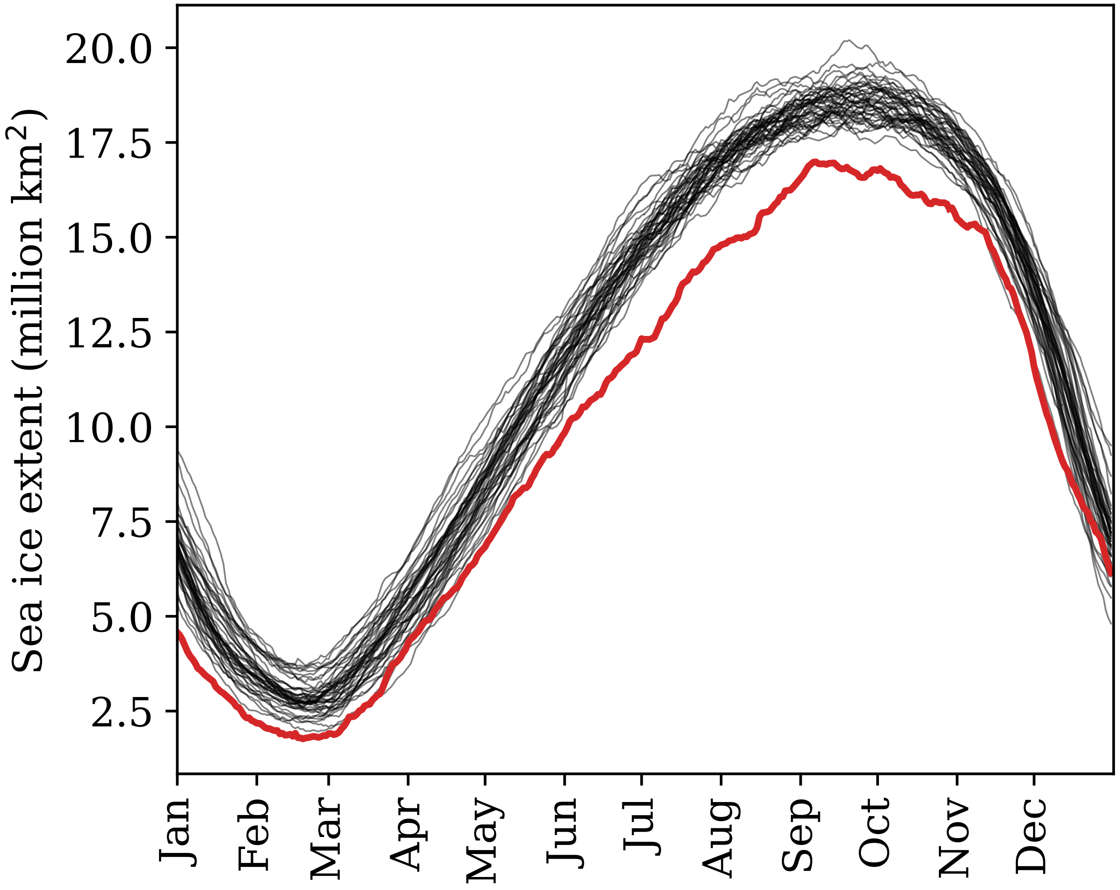
Net result of regionally-opposing trends

- NSIDC CDR version 4
- 1979-2022

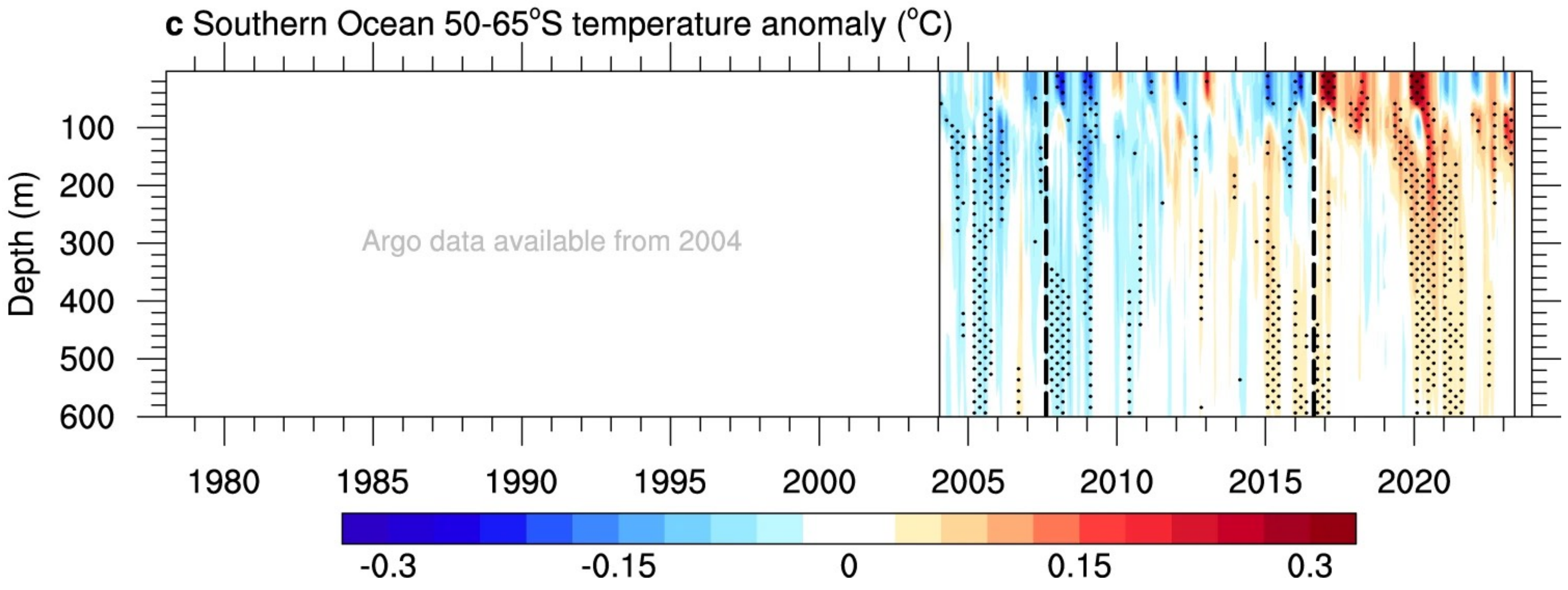


Highly anomalous sea ice behavior in 2023

- NSIDC CDR version 4



Changes in the subsurface ocean - but limited observations

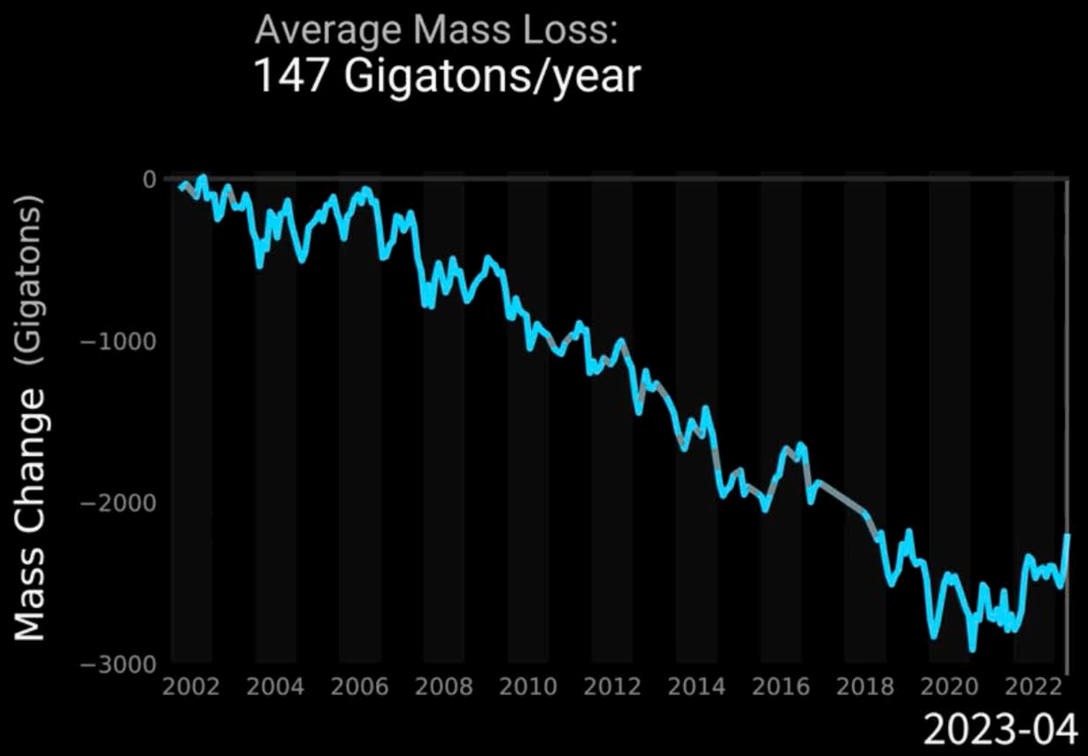


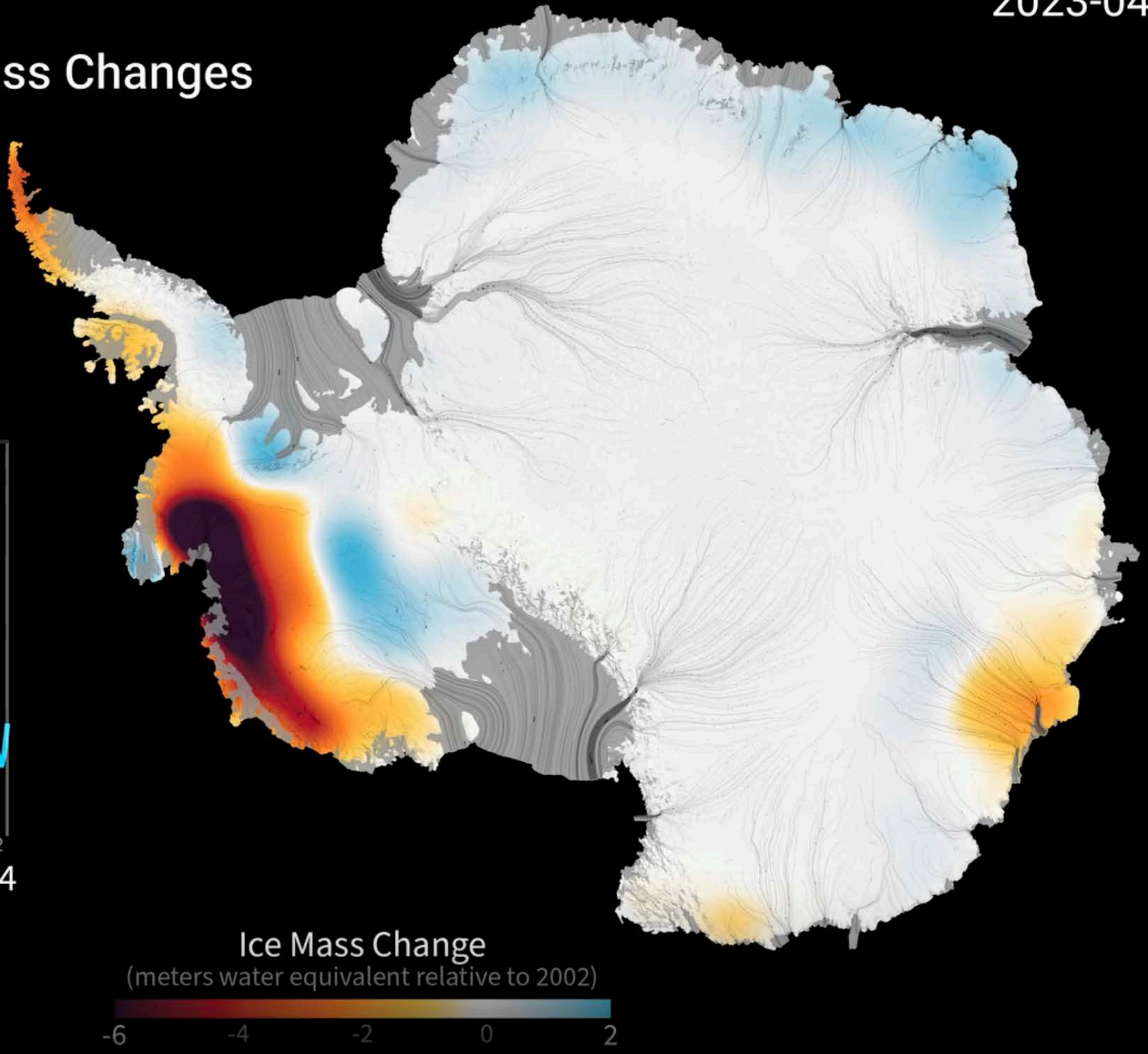
ARGO data - figure from Purich & Doddridge (2023)

- Zhang et al. (2022) - ocean heat played a key role (~50%) in the sustained sea ice lows from 2016 through 2021

GRACE and GRACE-FO Observations of Antarctic Land Ice Mass Changes

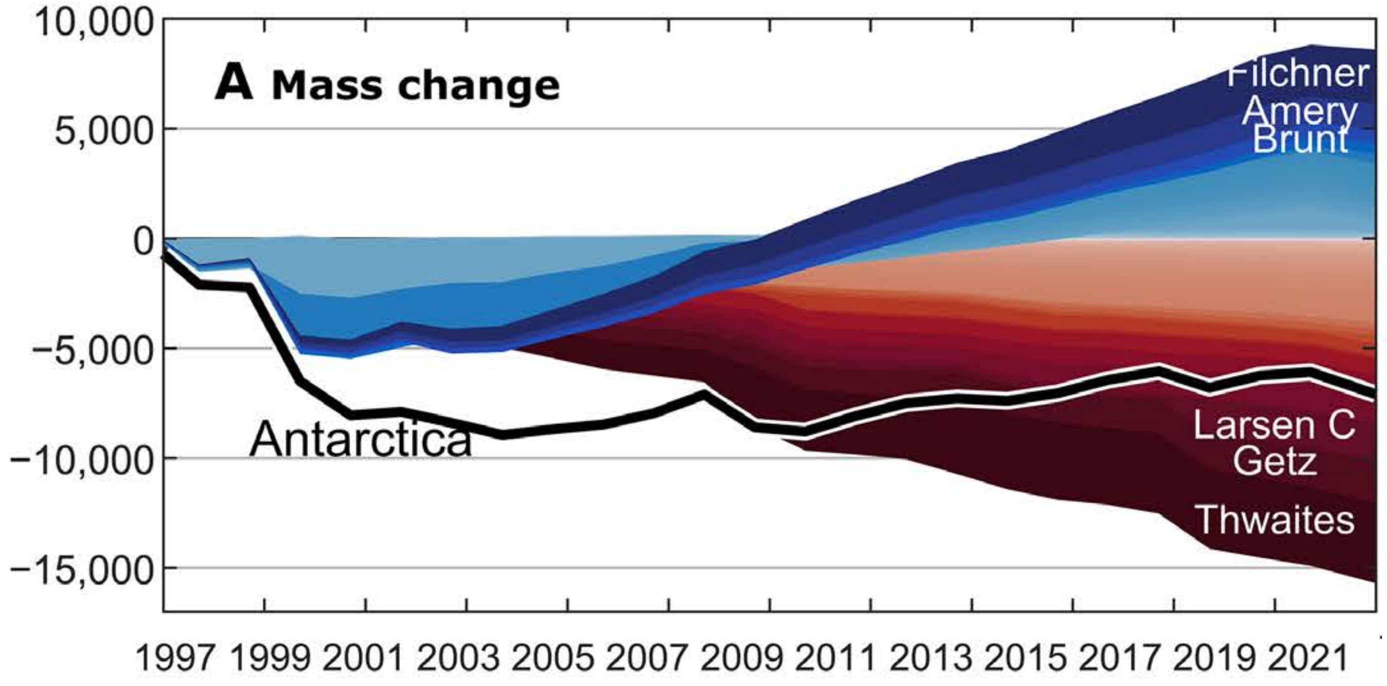
2023-04



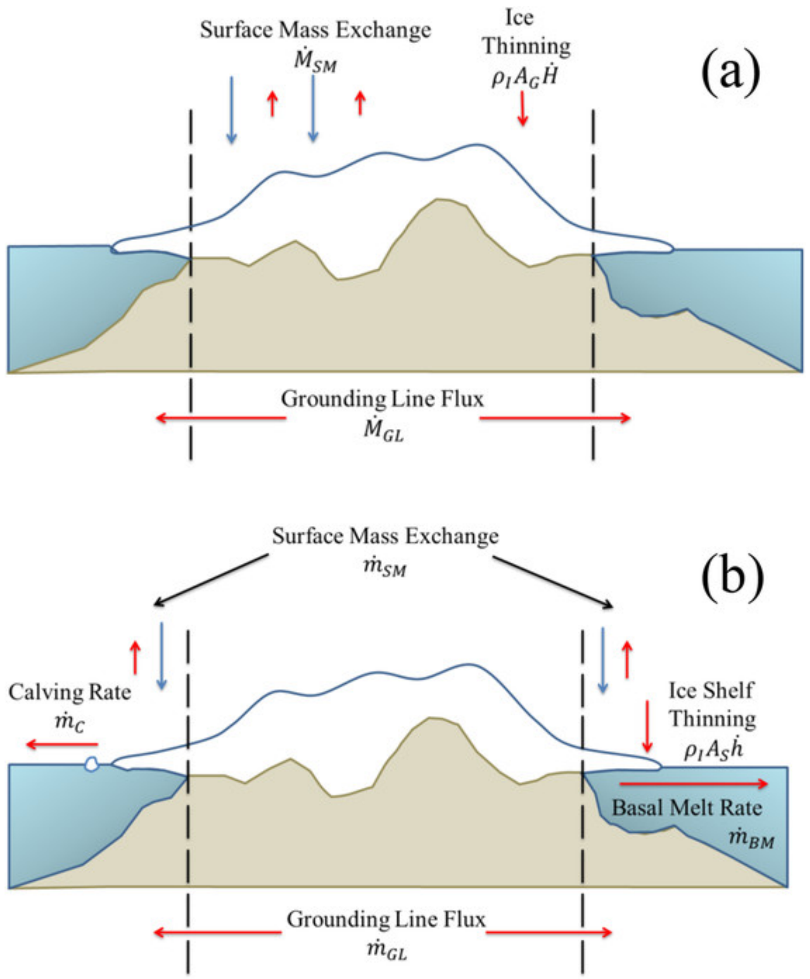


https://grace.jpl.nasa.gov/

Freshwater input to SO - sum of ice sheet, shelf and P-E



Davison et al. (2023)

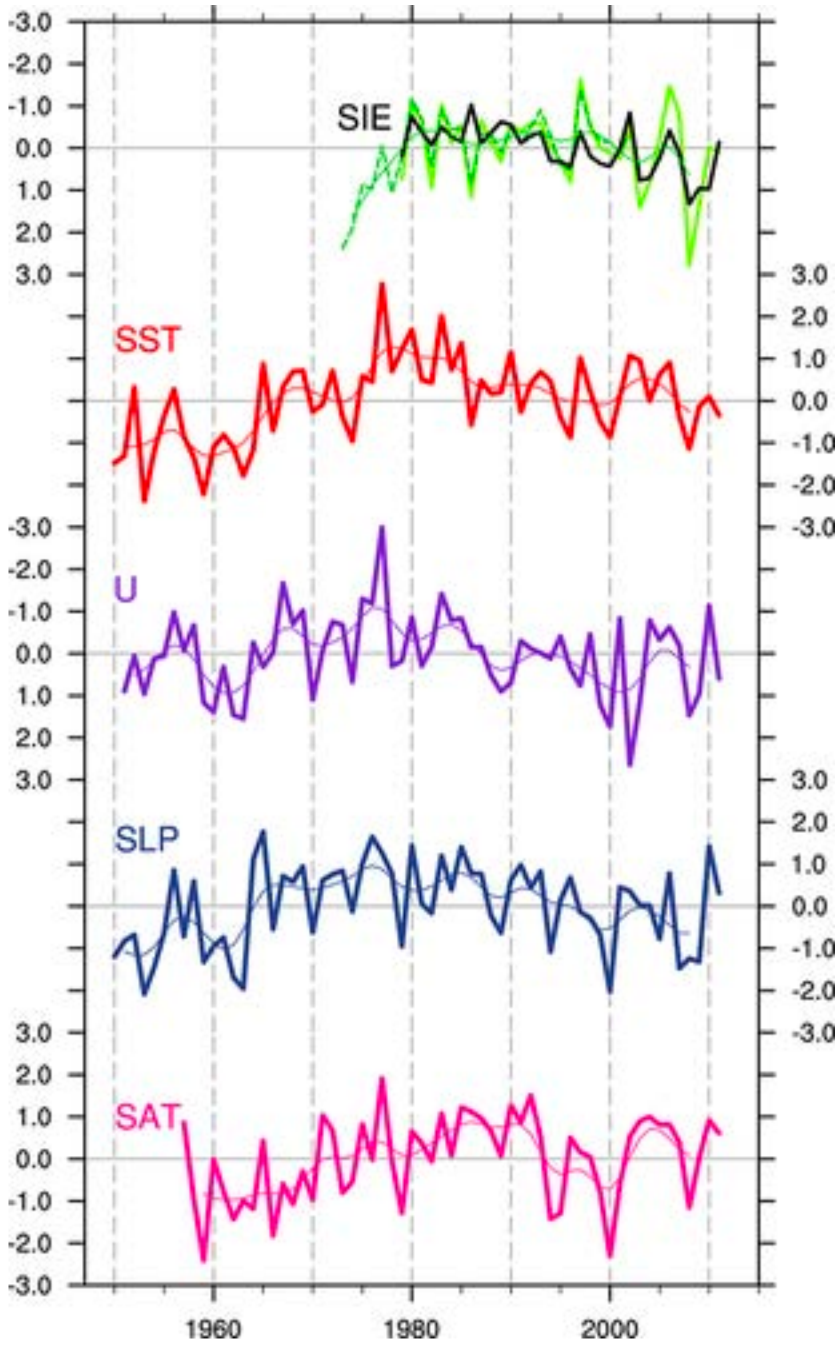


- P-E increases over the Southern Ocean in reanalysis
- Allan (2023), Pauling et al. (2016)

Pauling et al. (2016)

A longer-term perspective

- Fan et al. (2014) - variety of data sets including uninterpolated gridded marine archives, land station data, reanalysis, and satellite products
- Large multi-decadal variability

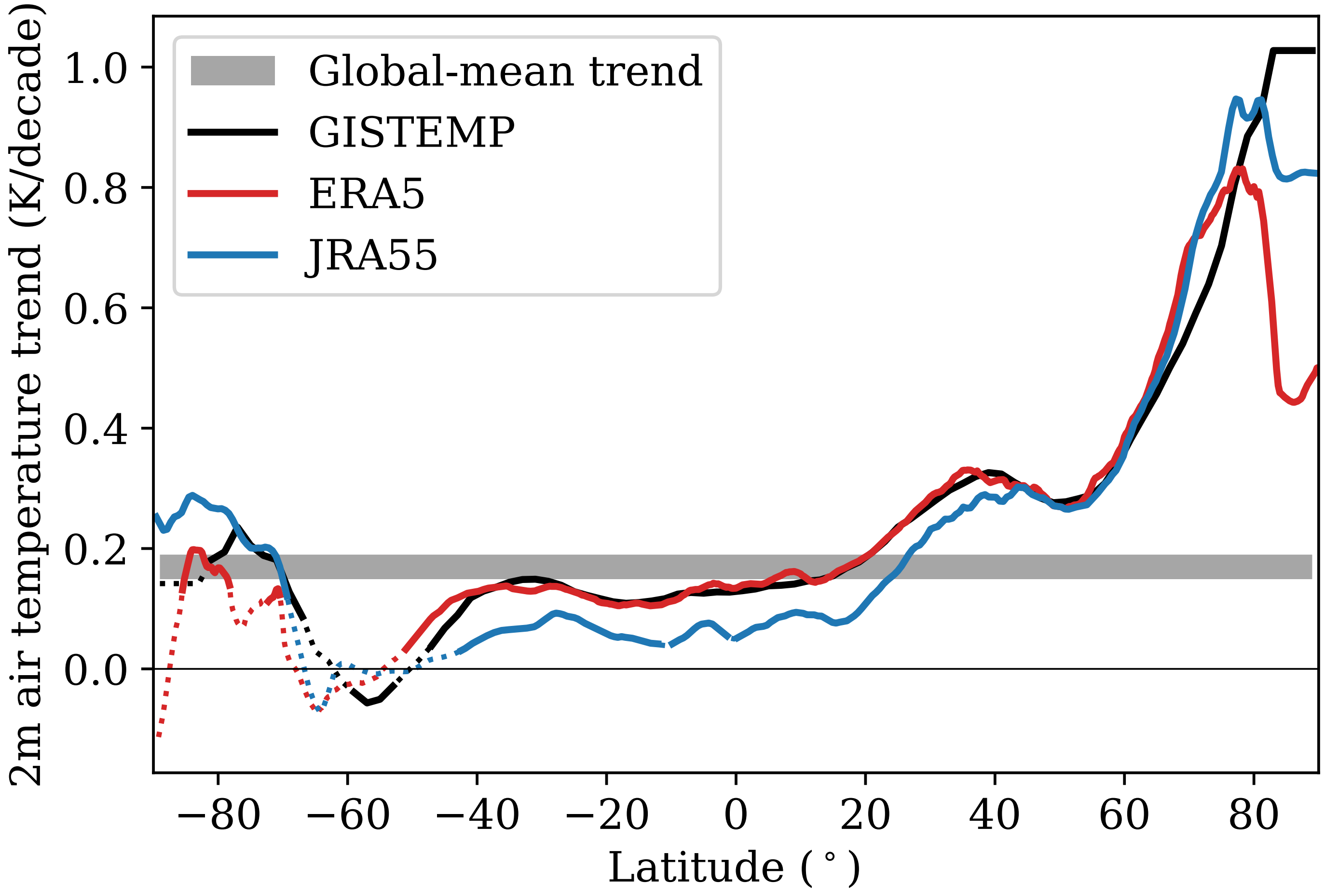


Mechanisms for muted Antarctic warming

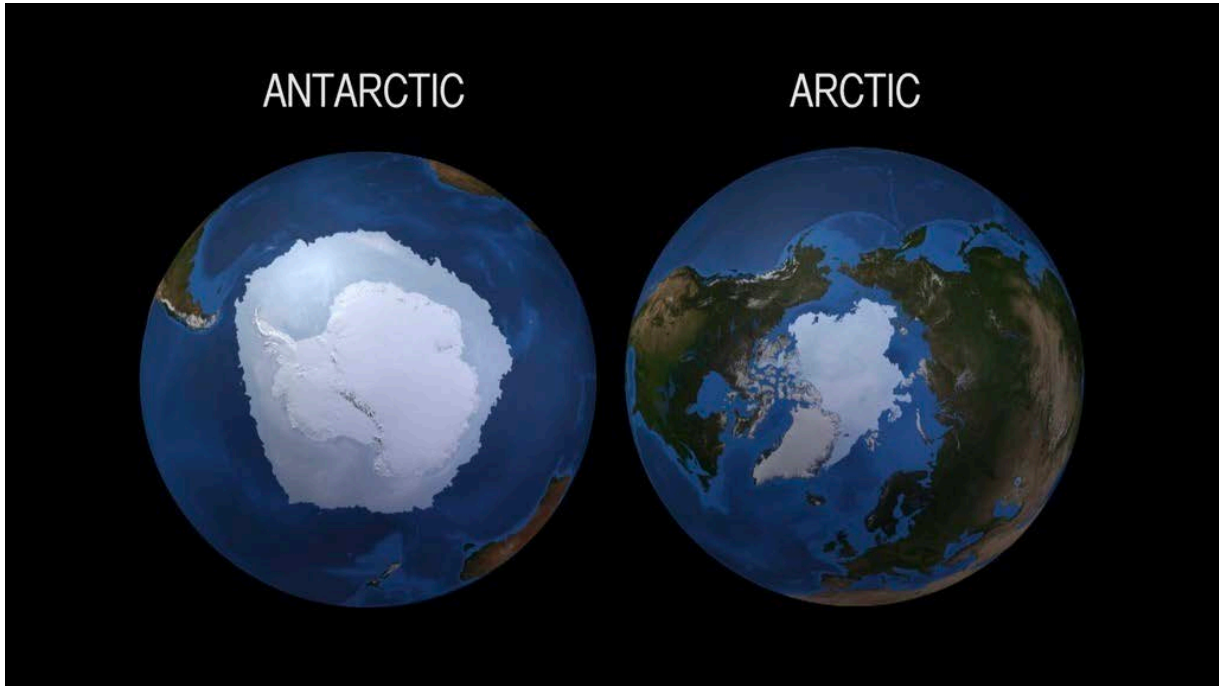
A quick review

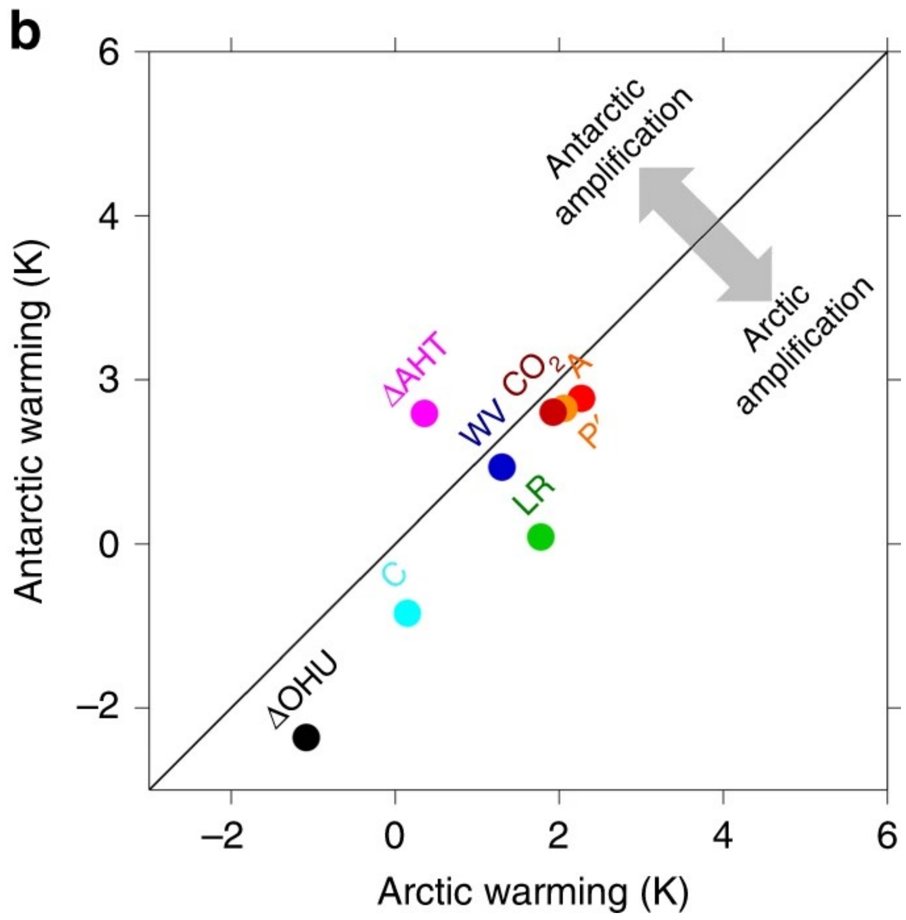
Absence of Antarctic amplification over the satellite era

- 1979-2022



Hemispheric differences





Antarctica is

- Surrounded by ocean
- High! + has an ice sheet

Figure: Goosse et al. (2018) -

Contributions of each feedback and atmospheric forcing to polar amplification. Antarctic (60–90S) relative to Arctic (60–90N) at year 100 of abrupt CO2 quadrupling in climate models involved in CMIP5. The feedbacks are expressed as warming contributions to the total temperature change

Strong ocean uptake in the Southern Ocean

- Near the coast: sinking of dense waters
- Southern Ocean: upwelling of CDW
- Surface heat uptake balanced by anomalous northward heat transport

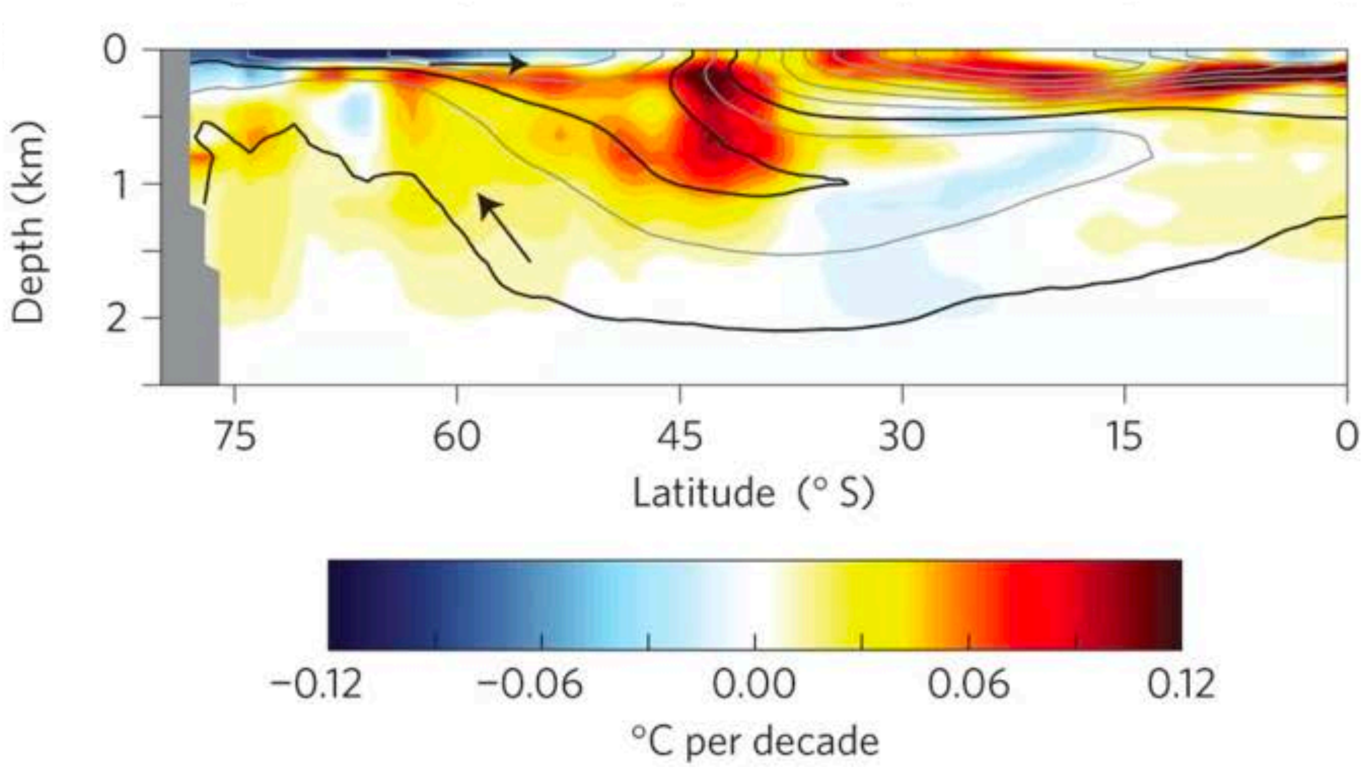


Figure: Armour et al. (2016) -
Zonal-mean ocean potential temperature trend from EN4, with contours of climatological ocean salinity in intervals of 0.15 practical salinity units (psu) (grey lines). Arrows indicate the orientation of the residual-mean MOC along 34.4 and 34.7 psu contours (black lines).

Marshall et al. (2014, 2015)
Armour et al. (2016)
Hu et al. (2022)

Impact of Antarctic topography

- Arctic: stronger climatological inversions support a stronger lapse rate feedback
- Antarctic: weaker
- Flattening Antarctica brings us closer to the Arctic

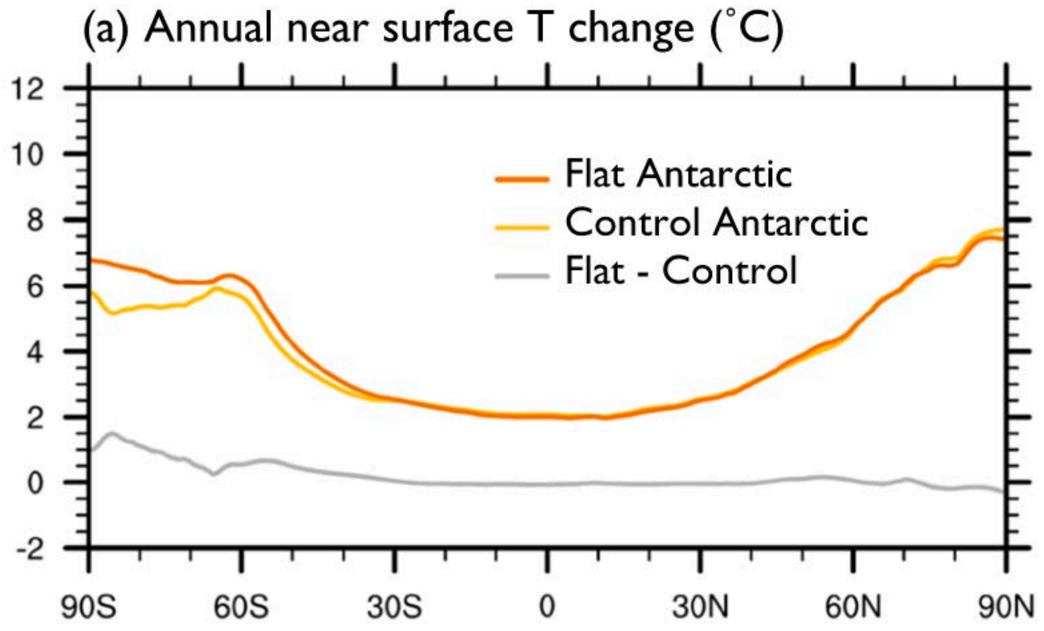


Figure - Hahn et al. 2020. Zonal and annual mean near-surface temperature change (°C) under CO2 doubling in the control (yellow) and flat (orange) Antarctic experiments and their difference (gray).

Salzmann (2017)
Hahn et al. (2020)
Singh and Polvani (2020)

Ozone depletion & winds

- Antarctic atmosphere highly susceptible to ozone depletion
- Strengthening westerlies - associated with DJF SAM
- Ferreira et al. (2015) - two-timescale response: fast cooling followed by slow warming
- Dong et al. (2023) - modest SAM-SST connection in DJF - not sustained on long timescales

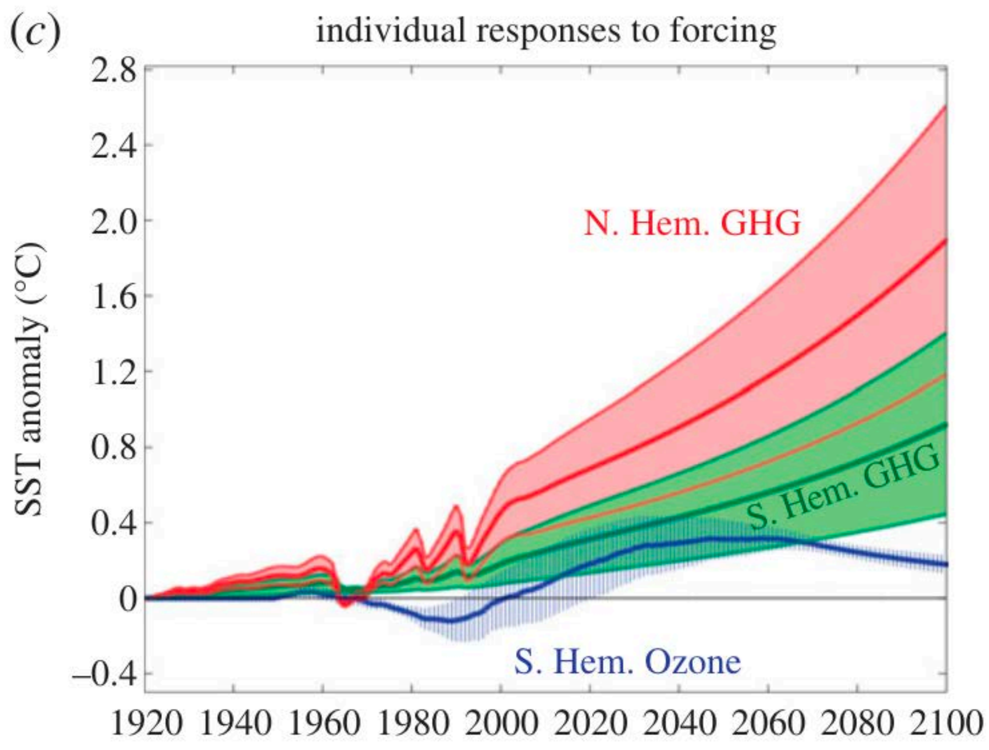
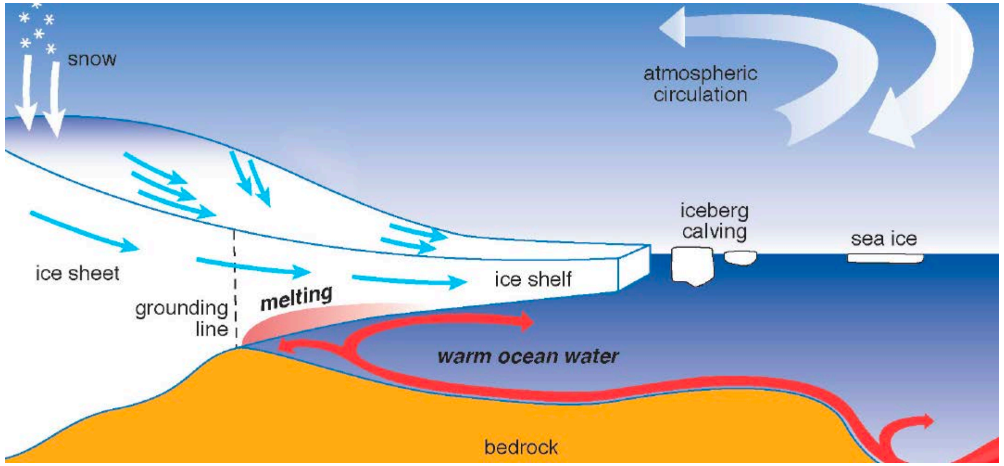


Figure - Marshall et al. (2014) -
Individual convolutions of the GHG and the ozone-hole forcing plotted on the top, with the respective GHG and ozone-hole CRFs plotted in figure 3, yielding estimates and projections of SST anomalies north of 50○ N (Arctic: red due to GHGs) and between 50○ S and 70○ S (Antarctic: green due to GHGs and blue due to ozone-hole forcing).

Interactions with the Antarctic ice sheet



https://nap.nationalacademies.org/read/26617/chapter/3#6

- Many studies highlighted the importance of freshwater forcing - Swart et al. (2023)
- Negative ice shelf—sea ice feedback
- Warm abyssal ocean - Li et al. (2023)
- Dynamical response - Huneke et al. (2023)
- Potential for rapid ice sheet change e.g. MISI
- Not included in CMIP models!

Model-observation discrepancies

Focus on sea ice

Antarctic sea ice in climate models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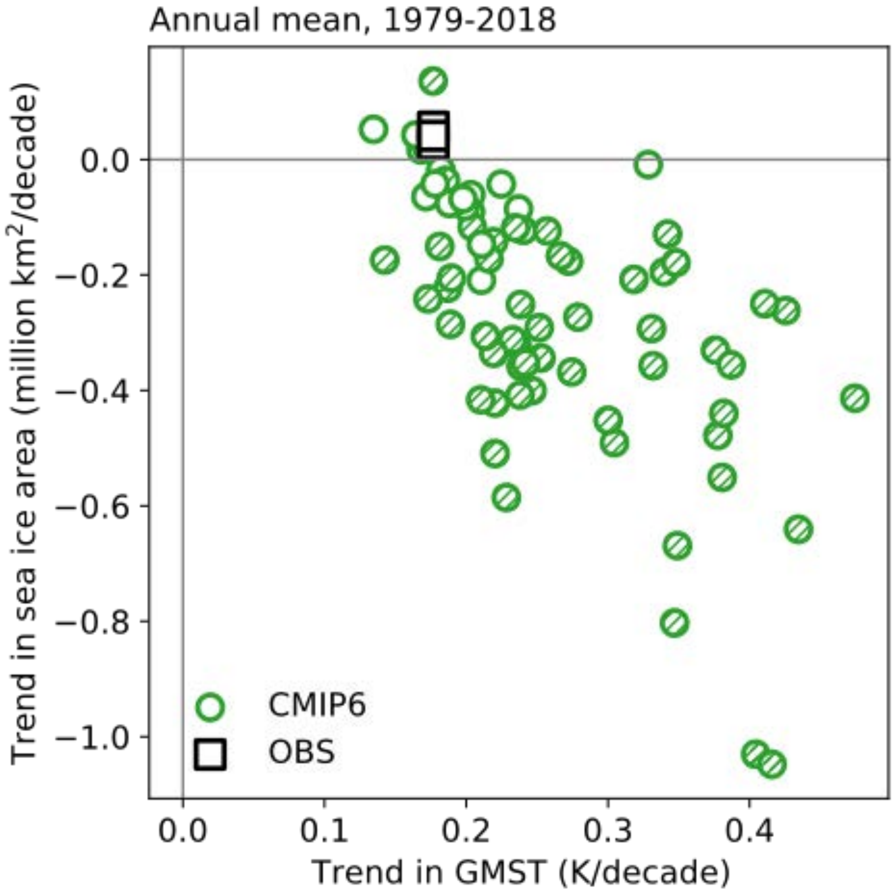
Breaking News | News | World News | Sydney | Melbourne | Brisbane | Malcolm Turnbull | Headlines |

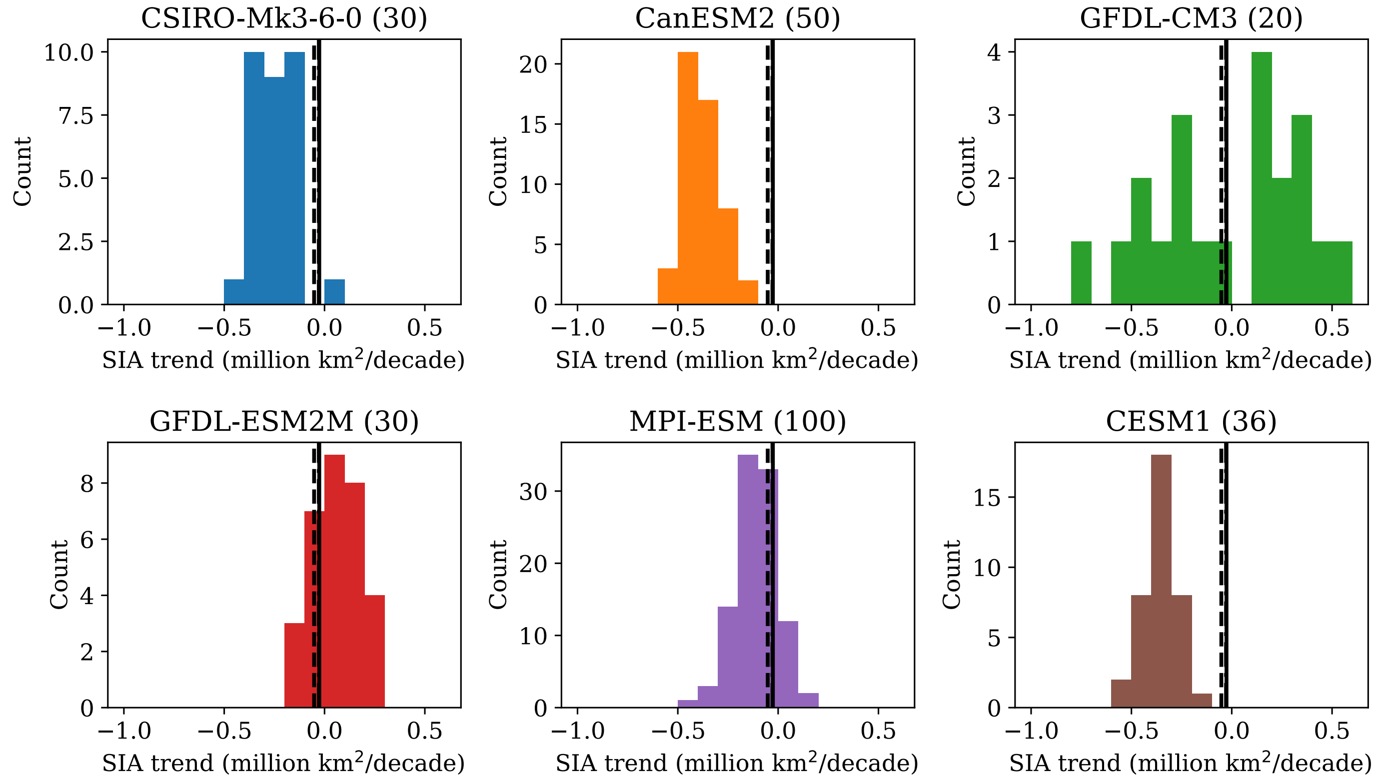
Global warming computer models confounded as Antarctic sea ice hits new record high with 2.1million sq km more than is usual for time of year

- CMIP6 models (historical plus SSP2-4.5)
- Large inter-model spread
- Inter-annual variability similar (or larger than) observations
- Consistently underestimate summer sea ice
- Many simulate strong declines



Roach et al. (2020)

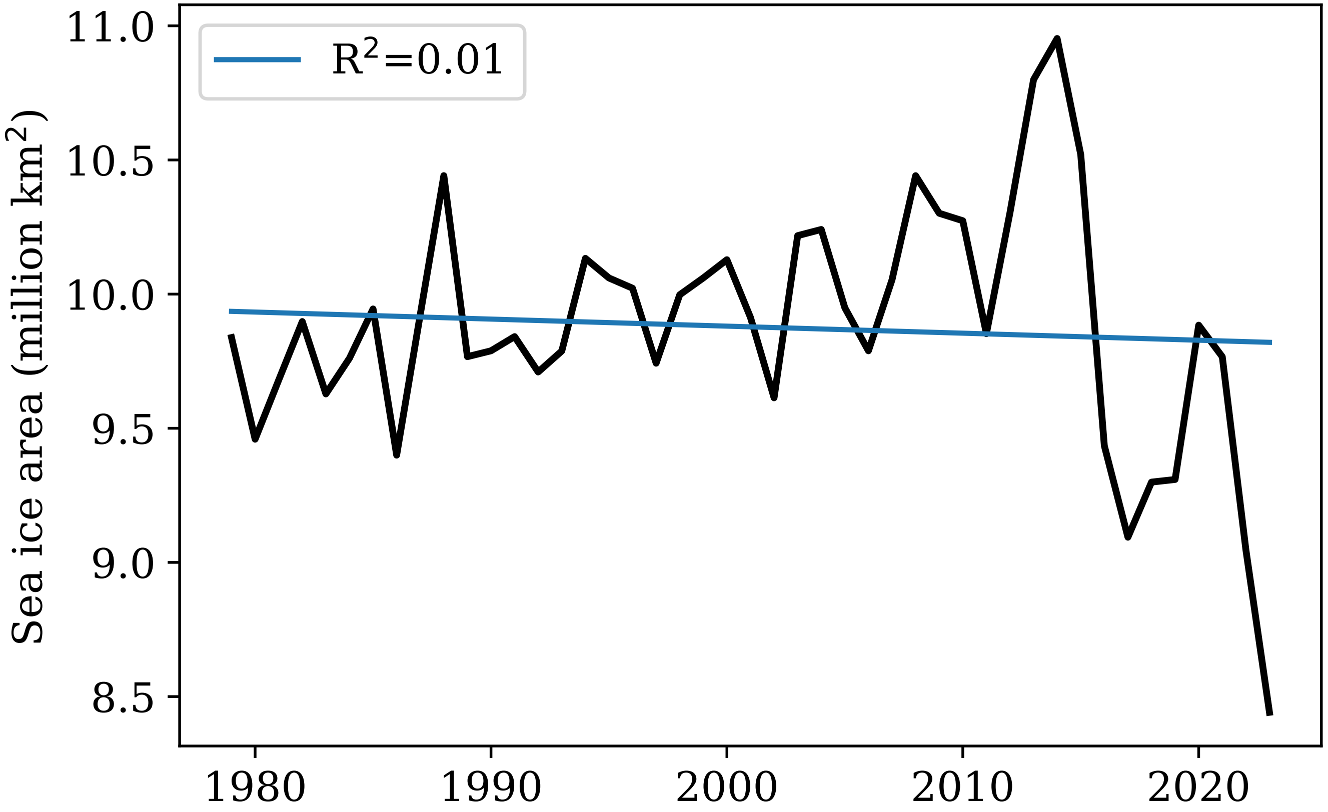
Antarctic sea ice trends in single model large ensembles



- To determine the consistency of each model with observations, need to account for internal variability
- Similar to Chemke and Polvani (2020) but with SIA, more models and longer time period - 1979-2023

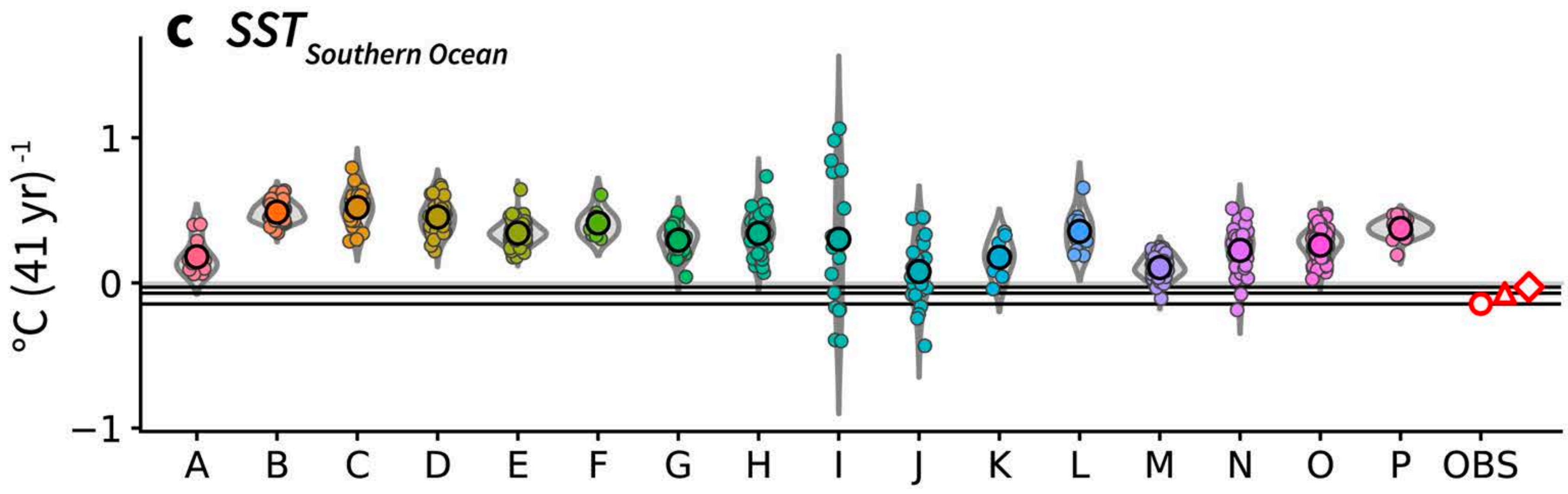
SMILE output processed by Marika Holland

Sensitivity to time period



Southern Ocean SST trends in CMIP6 models

- 1979-2020

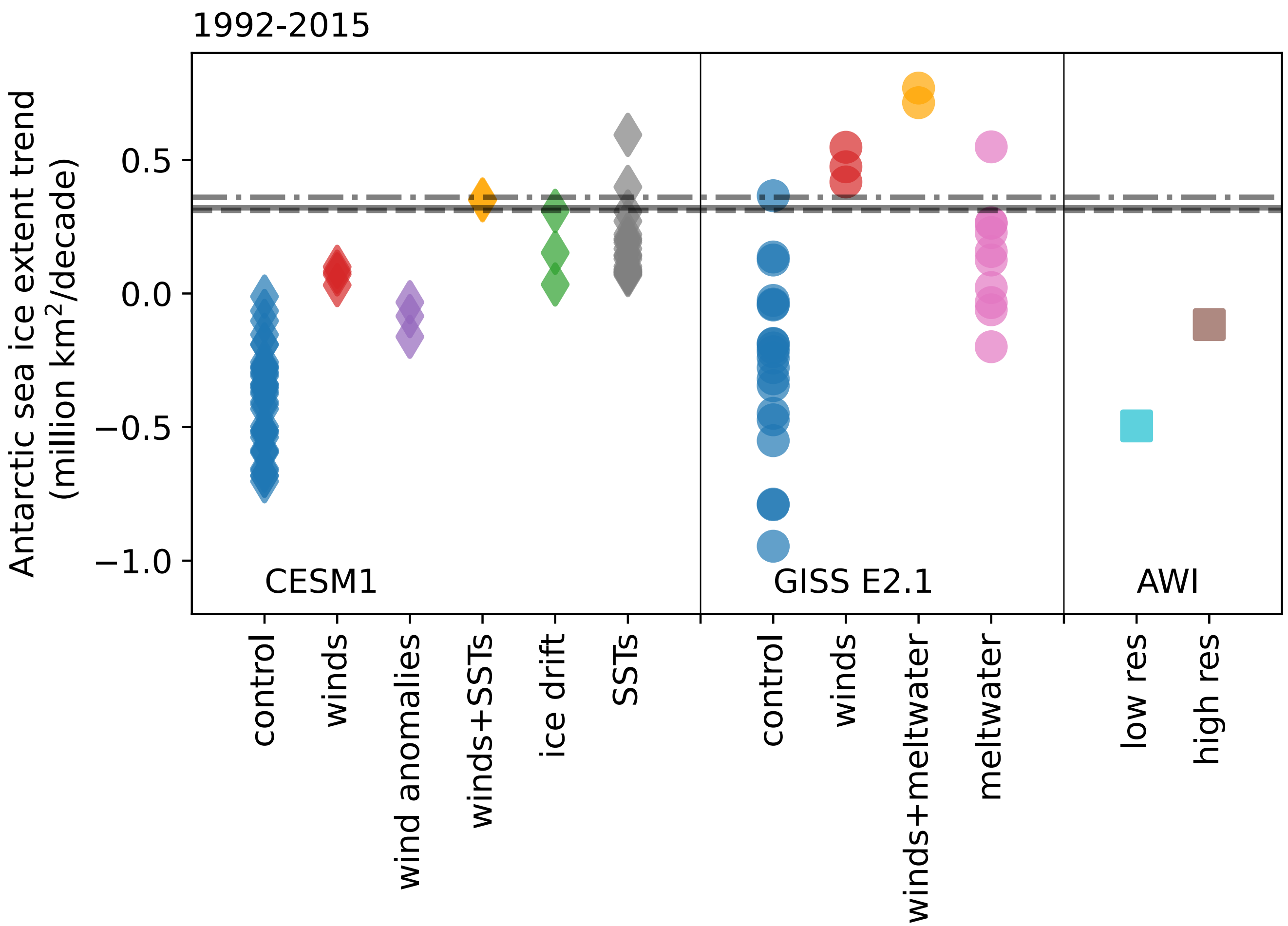


ERSSTv5
AMIPII
COBE
ERA5
JRA55
ERSSTv5, ERA5
ERSSTv5, OBS-mean PSL
OBS-mean SST, ERA5

A: ACCESS-ESM1.5
B: CanESM2
C: CanESM5
D: CESM1
E: CESM2
F: CNRM-CM6.1
G: CSIRO-Mk3.6
H: EC-Earth3
I: GFDL-CM3
J: GFDL-ESM2M
K: GISS-E2.1-G
L: IPSL-CM6A-LR
M: MIROC6
N: MIROC-ES2L
O: MPI-ESM
P: NorCPM1

Wills et al. (2022)

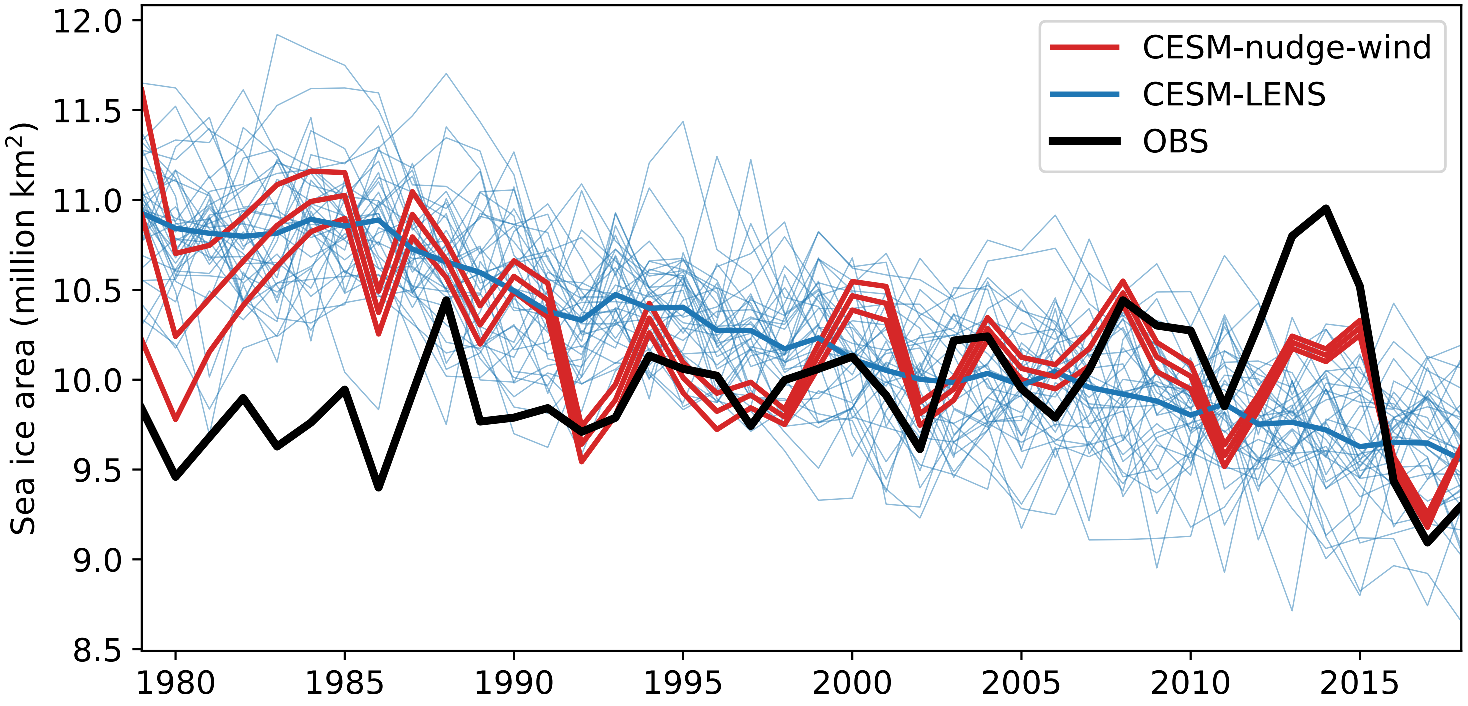
Progress from new experiments in understanding expansion



- Blanchard-Wrigglesworth et al. (2021) - winds, anomalies, winds+SST
- Sun & Eisenman (2021) - ice drift
- Zhang et al. (2020) - SST
- Roach et al. (2023) winds, winds+meltwater
- Schmidt et al. (2023) - meltwater
- Rackow et al. (2022) - low-resolution vs high-resolution

Nudging models to observed winds

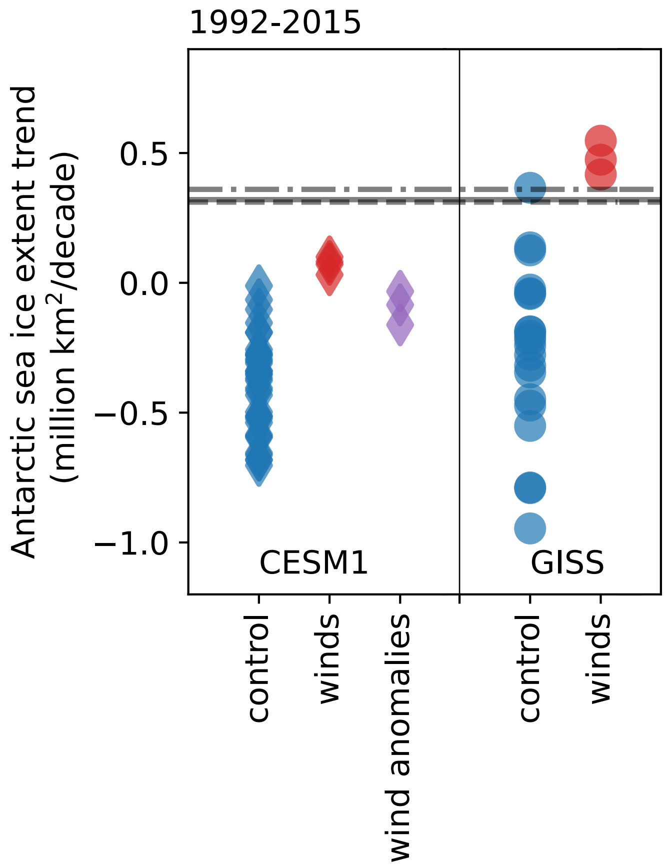
- Constrains models to follow the observed realization of atmospheric internal variability
- Given the observed atmospheric variability, can we capture sea ice trends?



Blanchard-Wrigglesworth et al. (2021)

Nudging models to observed winds

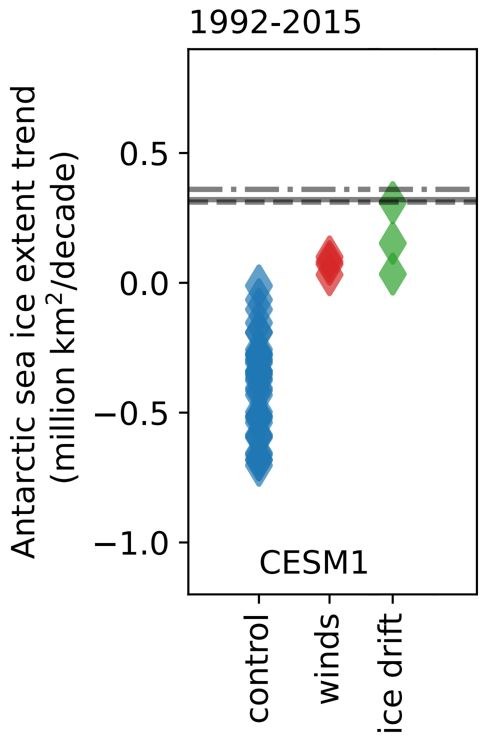
- Given the observed atmospheric variability, can we capture sea ice trends?
  - Depends on model mean state



- CESM1 - control ensemble
- CESM1 - nudged to ERA-Interim winds polewards of 45^{o} - Blanchard-Wrigglesworth et al. (2021)
- CESM1 - nudged to ERA-Interim wind anomalies - Roach et al. (2022)
- GISS - control ensemble
- GISS - nudged to NASA MERRA-2 winds globally - Roach et al. (2023)

Nudging models to observed ice drift

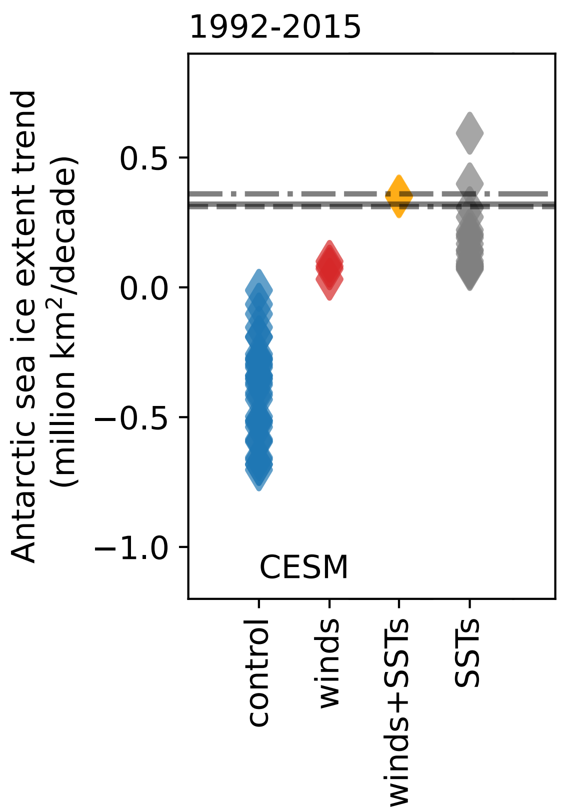
- Given the observed sea ice drift, can we capture sea ice trends?
  - Highlights the importance of dynamical processes



- CESM1 - control ensemble
- CESM1 - nudged to ERA-Interim winds - Blanchard-Wrigglesworth et al. (2021)
- CESM1 - sea ice drift relaxed to NSIDC observations - Sun and Eisenman (2021)

Nudging models to observed SSTs

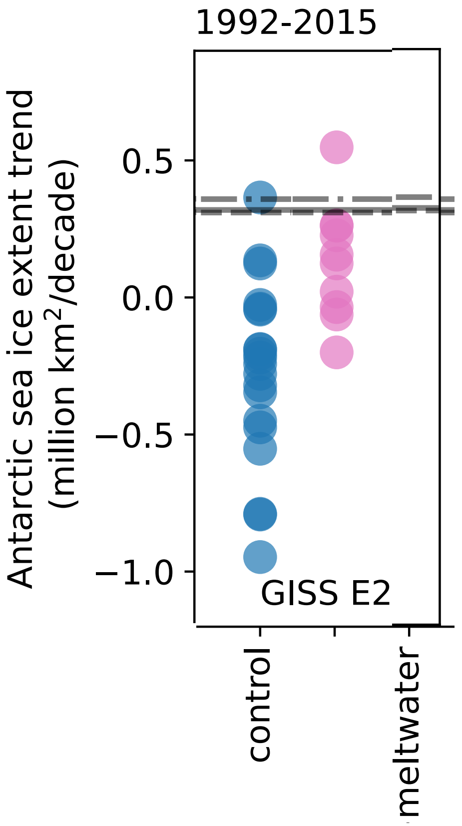
- Many models have strong surface ocean warming in mid-latitudes and SO - correct this
  - Highlights that Southern Ocean SSTs and sea ice are tightly coupled



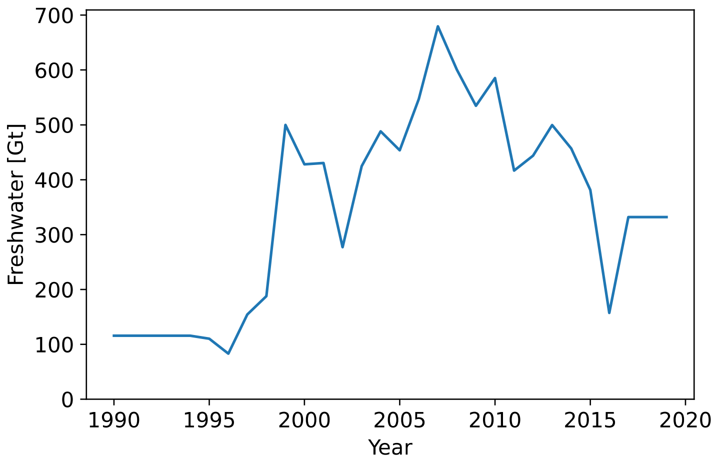
- CESM1 - control ensemble
- CESM1 - nudged to ERA-Interim winds - Blanchard-Wrigglesworth et al. (2021)
- CESM1 - nudged to ERA-Interim winds and observed SSTs 40-56°S - Blanchard-Wrigglesworth et al. (2021)
- CESM1 - nudged to observed SSTs south of 40°S - Zhang et al. (2021)

Adding observational estimates of ice sheet meltwater

- CMIP6 models typically don't include interactive ice sheets
- What's the impact of adding meltwater?



- GISS - control ensemble
- GISS - add interannually-varying observational estimates of AIS meltwater from Slater et al. (2021) - Schmidt et al. (2023)



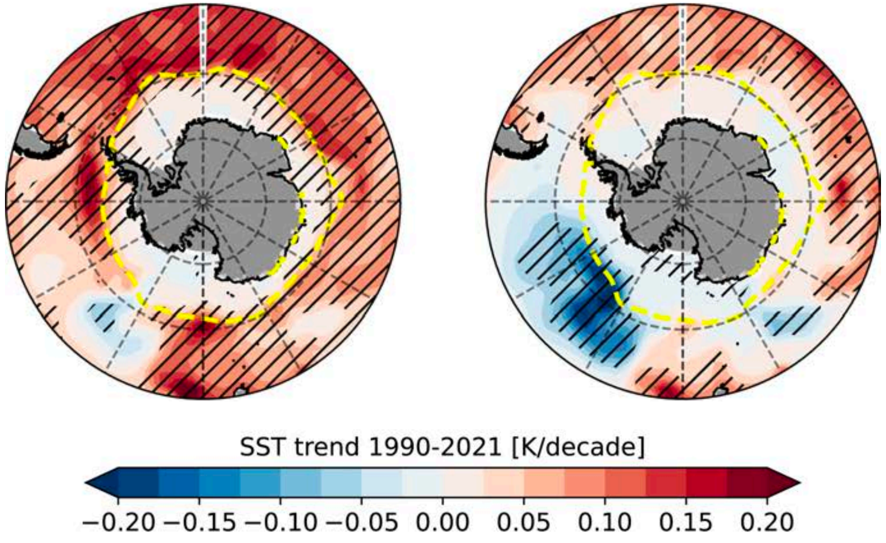
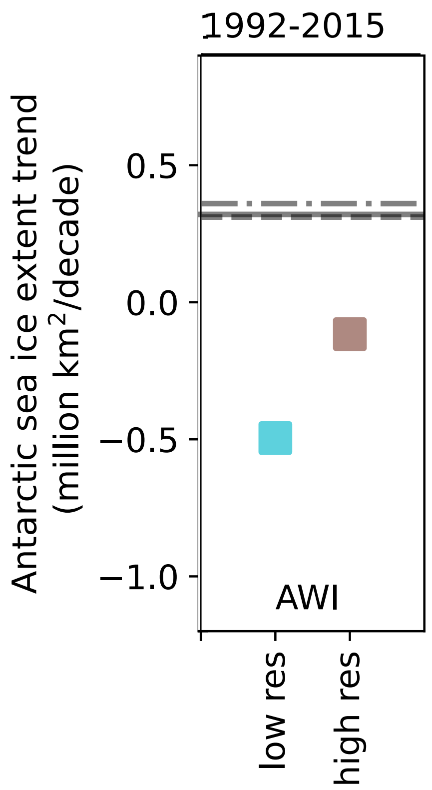


Figure: Roach et al. (2023)

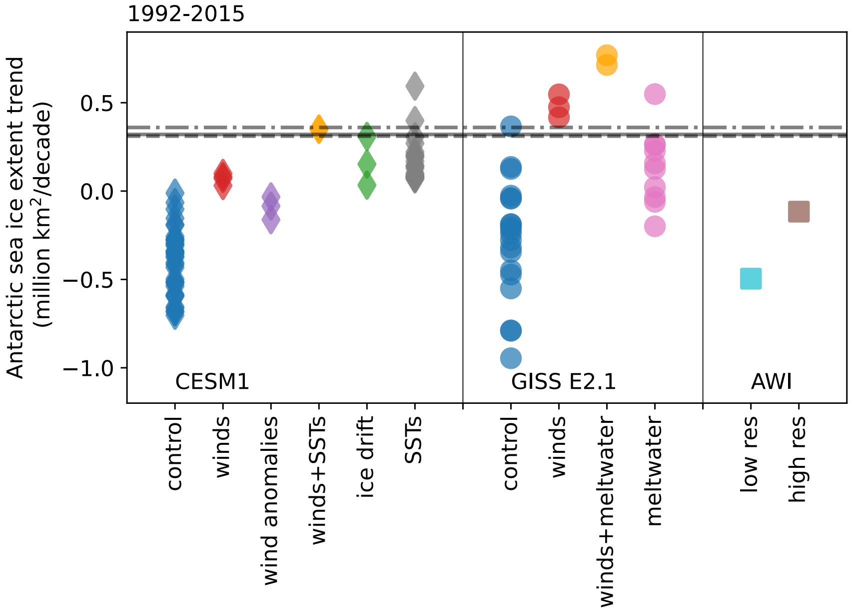
Increasing resolution

- CMIP6 models are non-eddy-permitting - contrast varied resolution - Rackow et al. (2022)
- Eddy-permitting simulations exhibit lower poleward heat transport than non-eddy-permitting simulations in response to external forcing, delaying Antarctic sea-ice decline



- AWI - low resolution - nominal 1º / ~65 km in SO
- AWI - high resolution - ~14km in SO, eddy parametrization switched off

Several factors can improve model agreement with observations

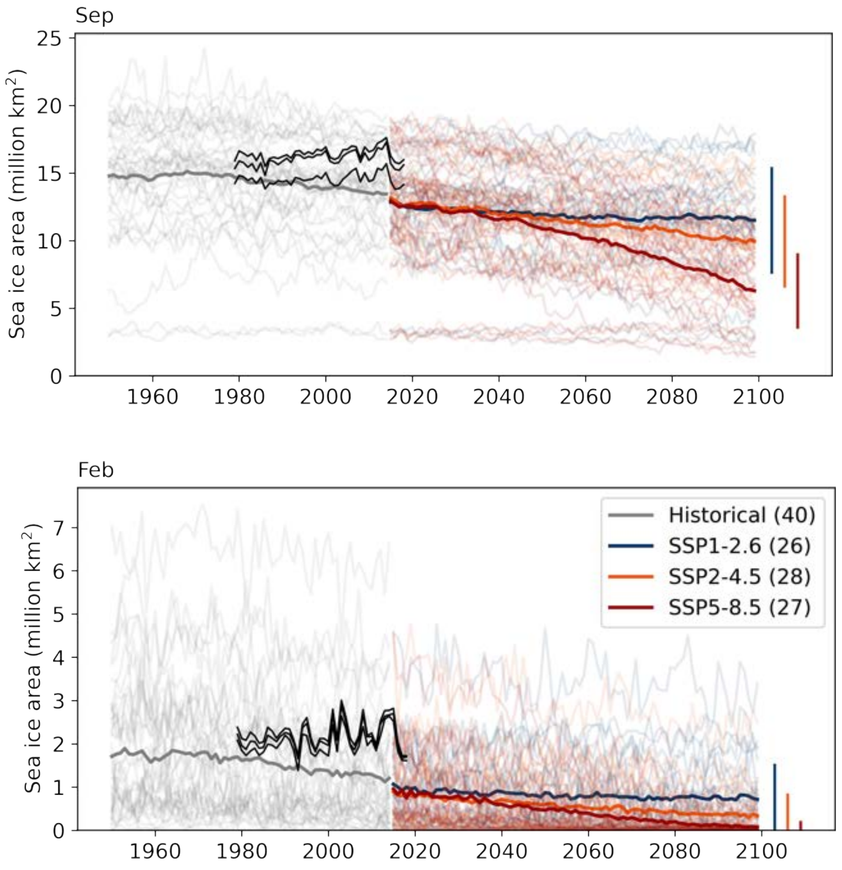


- Highlights that many factors are at play
- Experiments with two factors - some influence of winds, some influence of SST/meltwater
- Ideally, we would compare them all in a common modeling framework

- Possible that observed wind variability is captured in model ensembles (just unlikely)
- But anomaly experiment suggests that mean state winds are biased & this can impact sea ice trends
- Antarctic ice sheet meltwater should be accounted for - but how?
- Impacts of increases in ocean resolution will depend on how eddies are parametrized in each model

Summary

- Observations show changes in the different components of the Antarctic climate system
- Inter-annual and multi-decadal variability is large - satellite record is relatively short
  - Need more, longer records, three-dimensional, more constrained!
- A number of mechanisms driving muted Antarctic warming have been proposed
- However, it's difficult to trust climate models in this region
  - New experiments suggest winds, meltwater, ocean resolution, model thermodynamic biases (clouds?) are likely important
- This means that confidence in attributions of recent observed change in the Antarctic climate system and in projections for the future is low
  - It's difficult to make claims about an emerging state based on CMIP



CMIP6 - Roach et al. (2020)