Drivers of model-observation discrepancies in Southern Ocean SSTs and Antarctic sea ice trends

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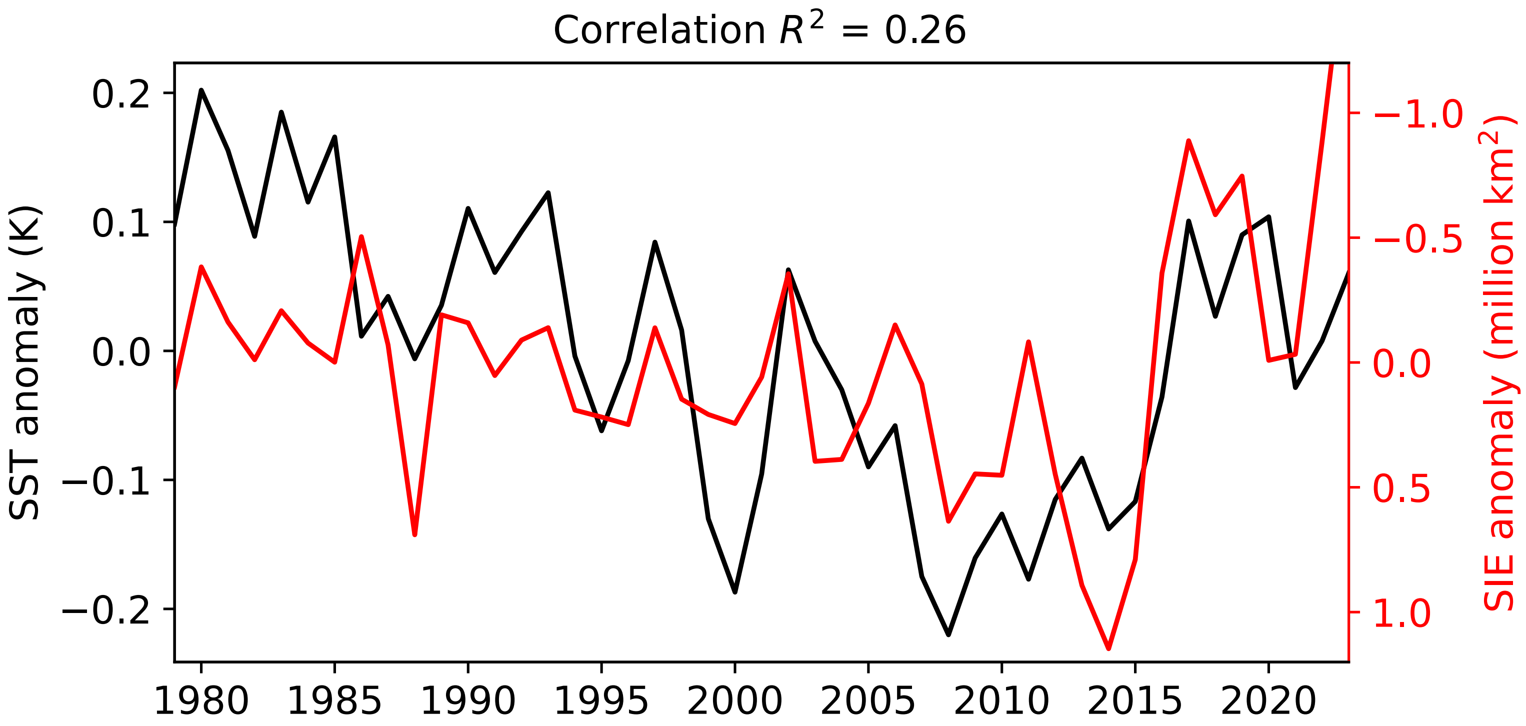
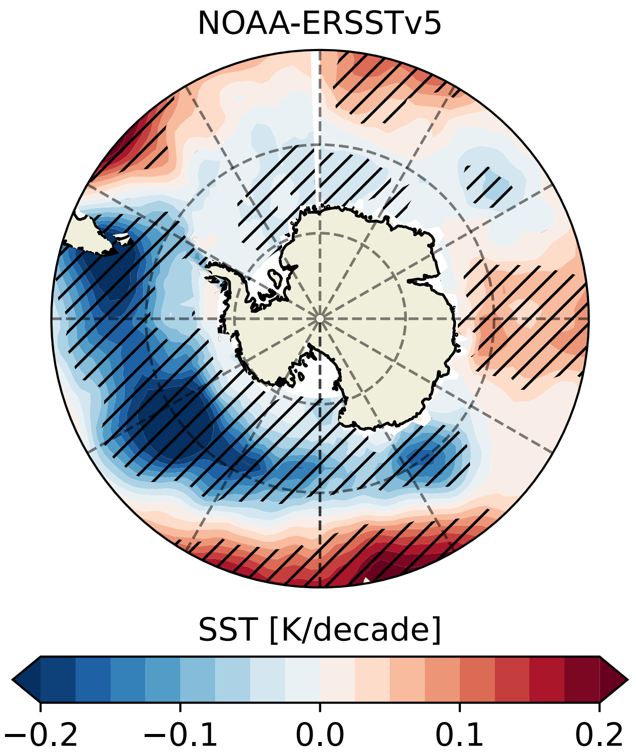
CLIVAR workshop - Confronting Earth System Model Trends with Observations: The Good, the Bad, and the Ugly - March 2024

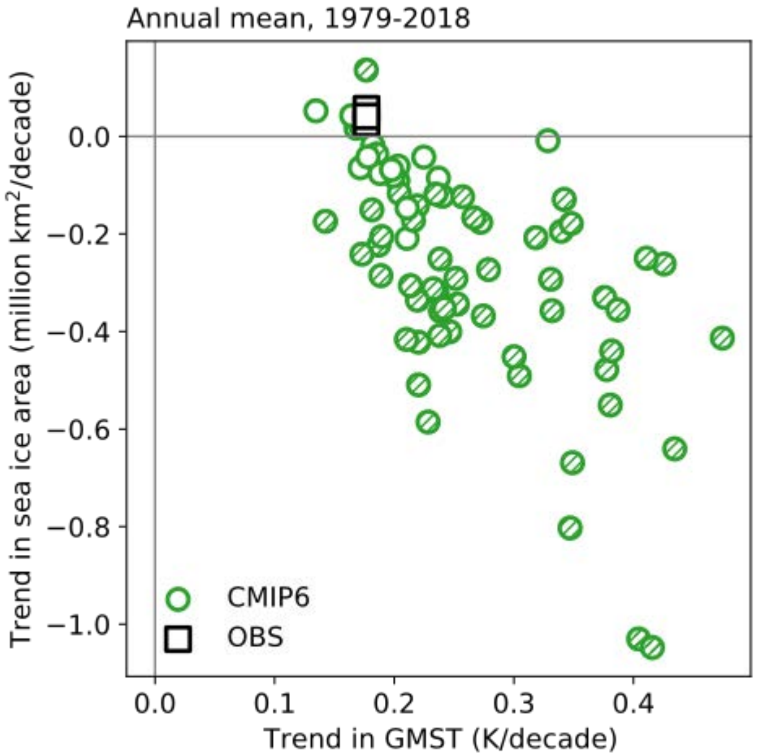
Unexpected changes in Southern Ocean SSTs and sea ice



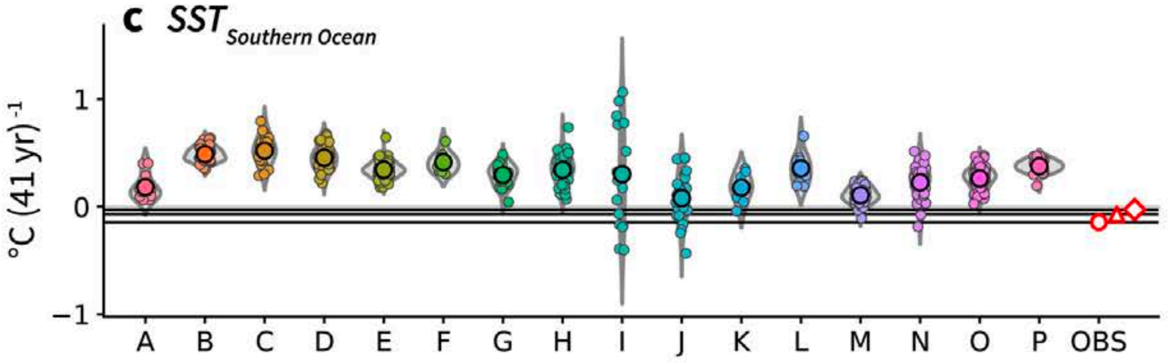


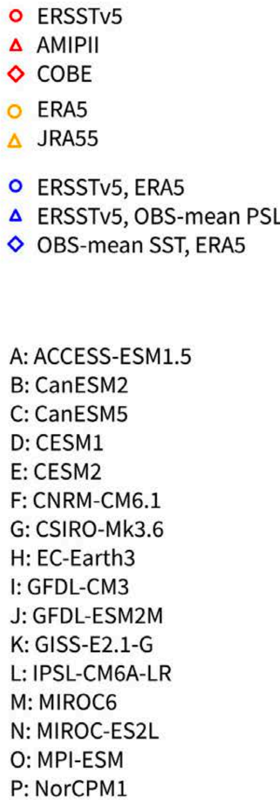
Cooling and sea ice expansion rarely captured in CMIP6

Antarctic sea ice and GMST trends



Southern Ocean SST trends (1979-2022)





Roach et al. (2020)

Wills et al. (2022)

Proposed drivers for the cooling and sea ice expansion

1. Changes in atmospheric circulation (*e.g. Ferreira et al. 2015, Kostov et al., 2018; Meehl et al. 2016, Blanchard-Wrigglesworth et al., 2021; Chung et al., 2022*)

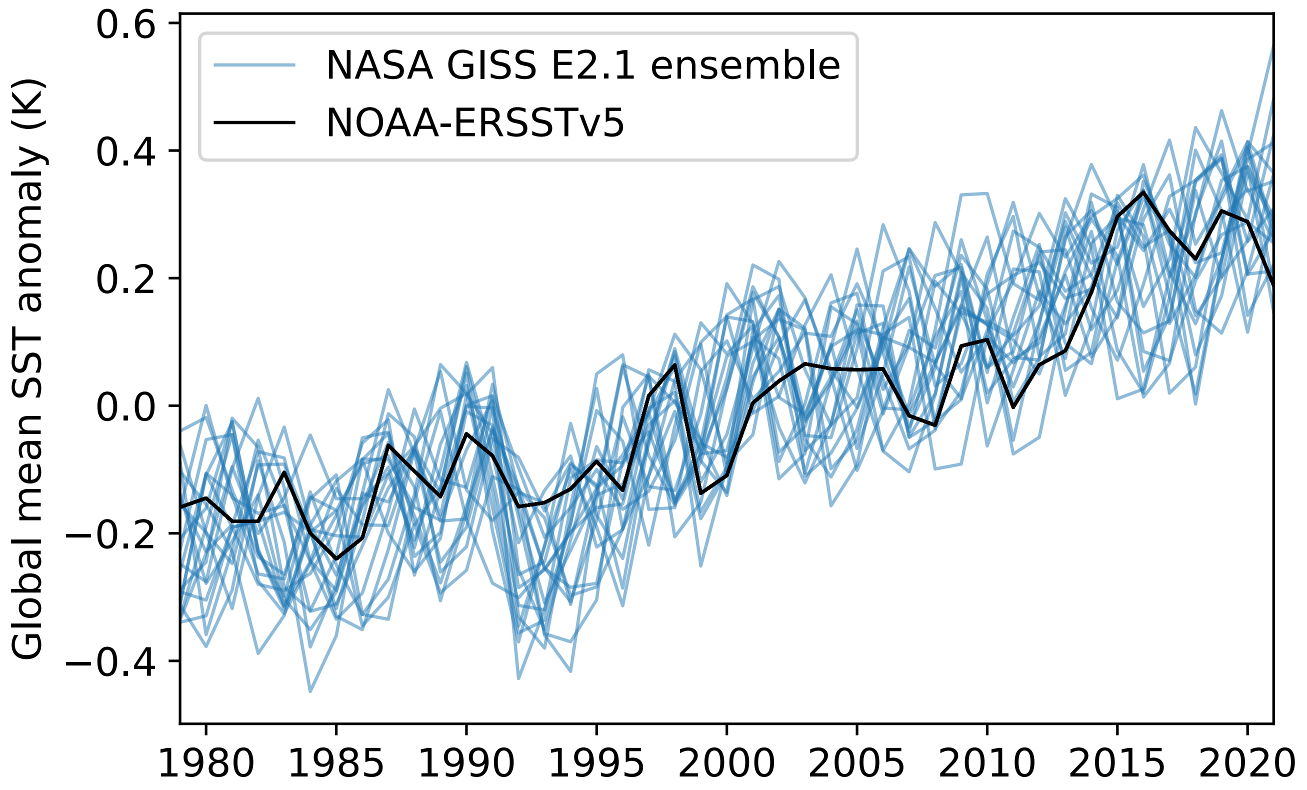
    - SAM has strengthened and shifted polewards due to greenhouse gases and ozone depletion, ASL has also deepened, influence of IPO

2. Increases in freshwater fluxes (*e.g. Pauling et al., 2016, 2017; Rye et al., 2020; Dong et al., 2022, Swart et al. 2023*)

    - Net mass loss from ice sheets and ice shelves is generally increasing and influences the ocean via changes in salinity and stratification, as well as P minus E

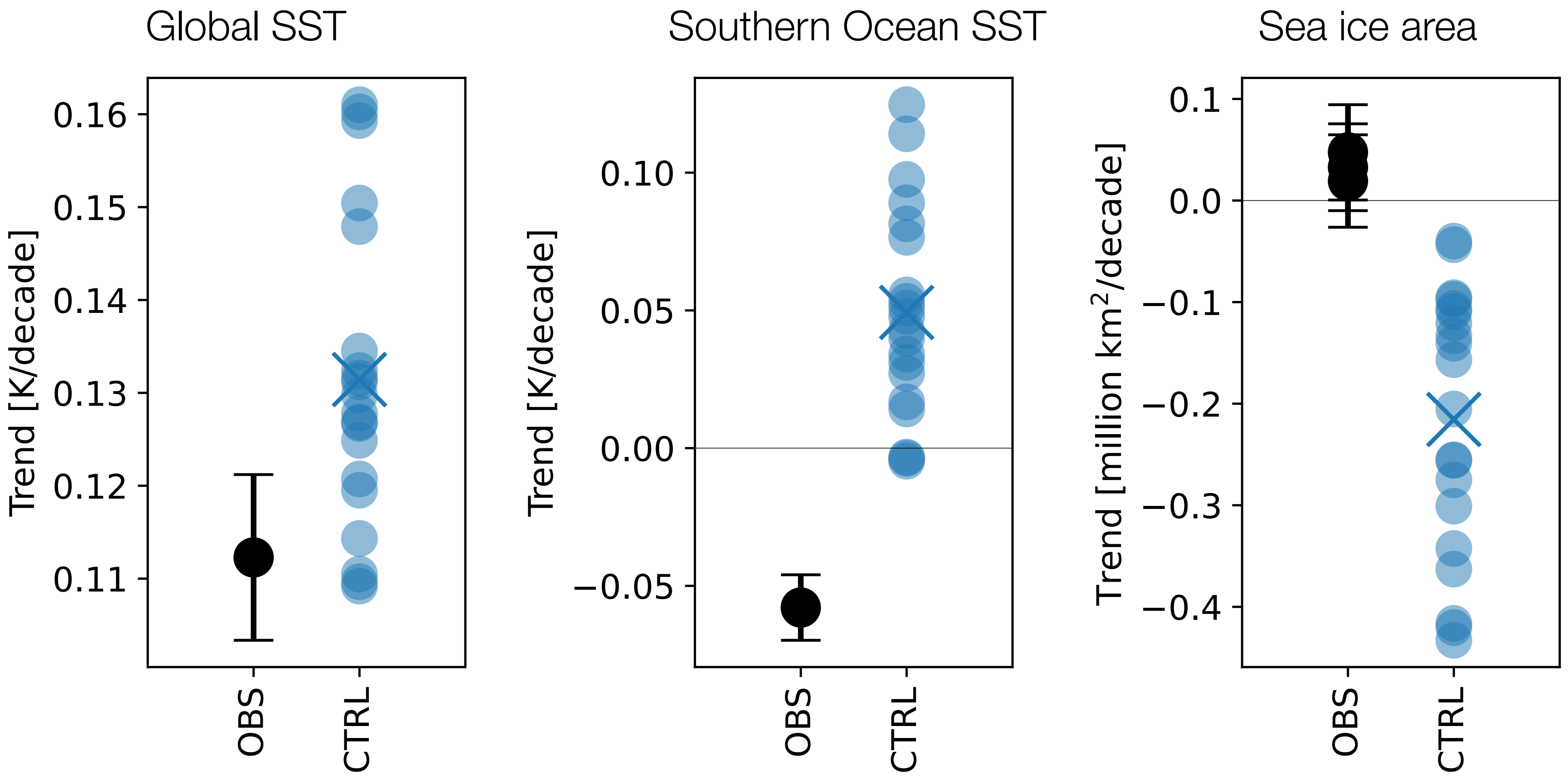
NASA GISS E2.1 climate model

- Atmospheric component 2x2.5deg lat x lon, 40 vertical layers
- Ocean component 1x1.25deg lat x lon, 40 vertical layers.
- Sea ice component - 2 mass layers with 2 thermal layers in each mass layer, viscous-plastic rheology, ‘brine-pocket' parameterization, no ITD
- Land ice is represented by a simple two-layer model topped by snow cover (‘excess’ discharged to ocean)



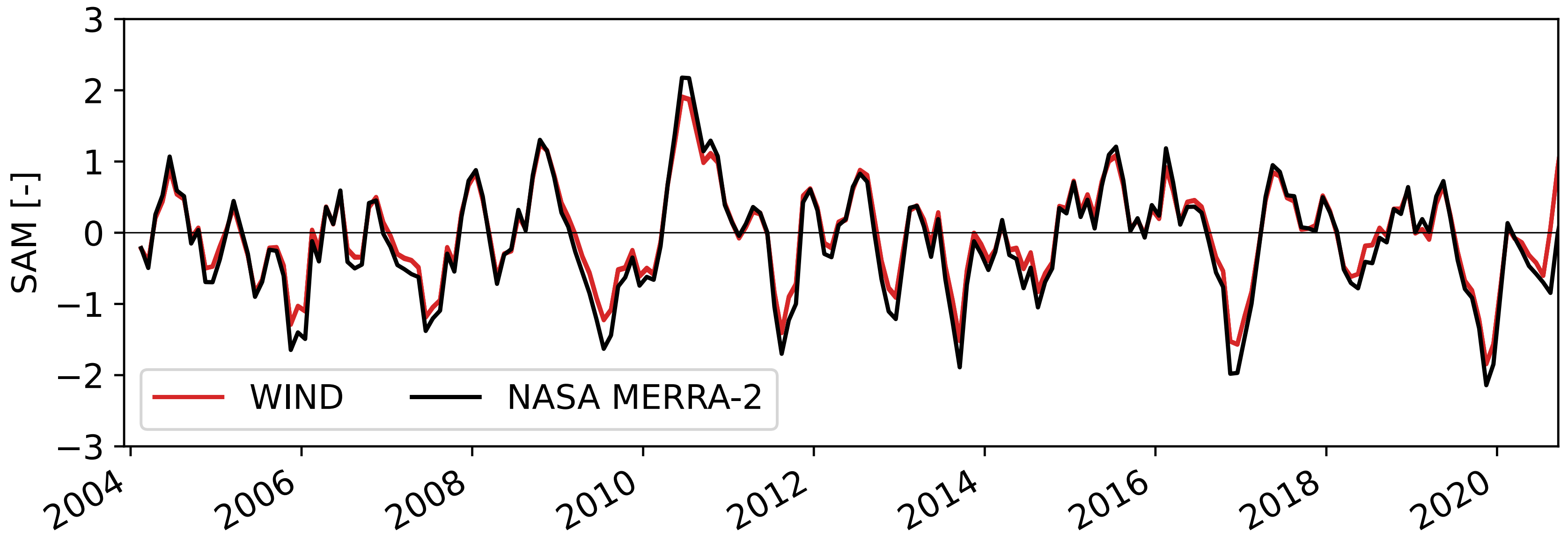
Kelley et al. (2022)

NASA GISS E2.1 climate model (1990-2021)



Step 1: Apply wind-nudging towards NASA MERRA-2

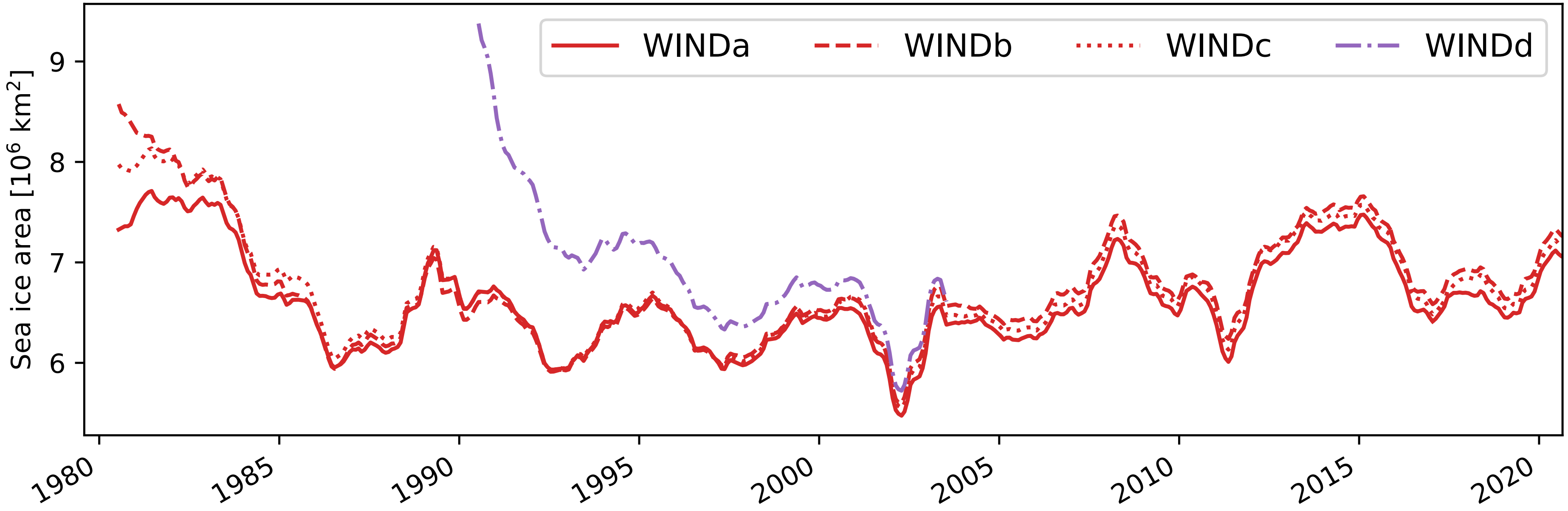
- A powerful tool to understand coupled model biases (e.g. Blanchard-Wrigglesworth et al. 2021, Roach & Blanchard-Wrigglesworth 2022, Roach et al. 2022)
- Add a term to the model equations to relax towards reanalysis U and V winds every timestep (globally, all atmospheric levels)



Roach et al. (2023)

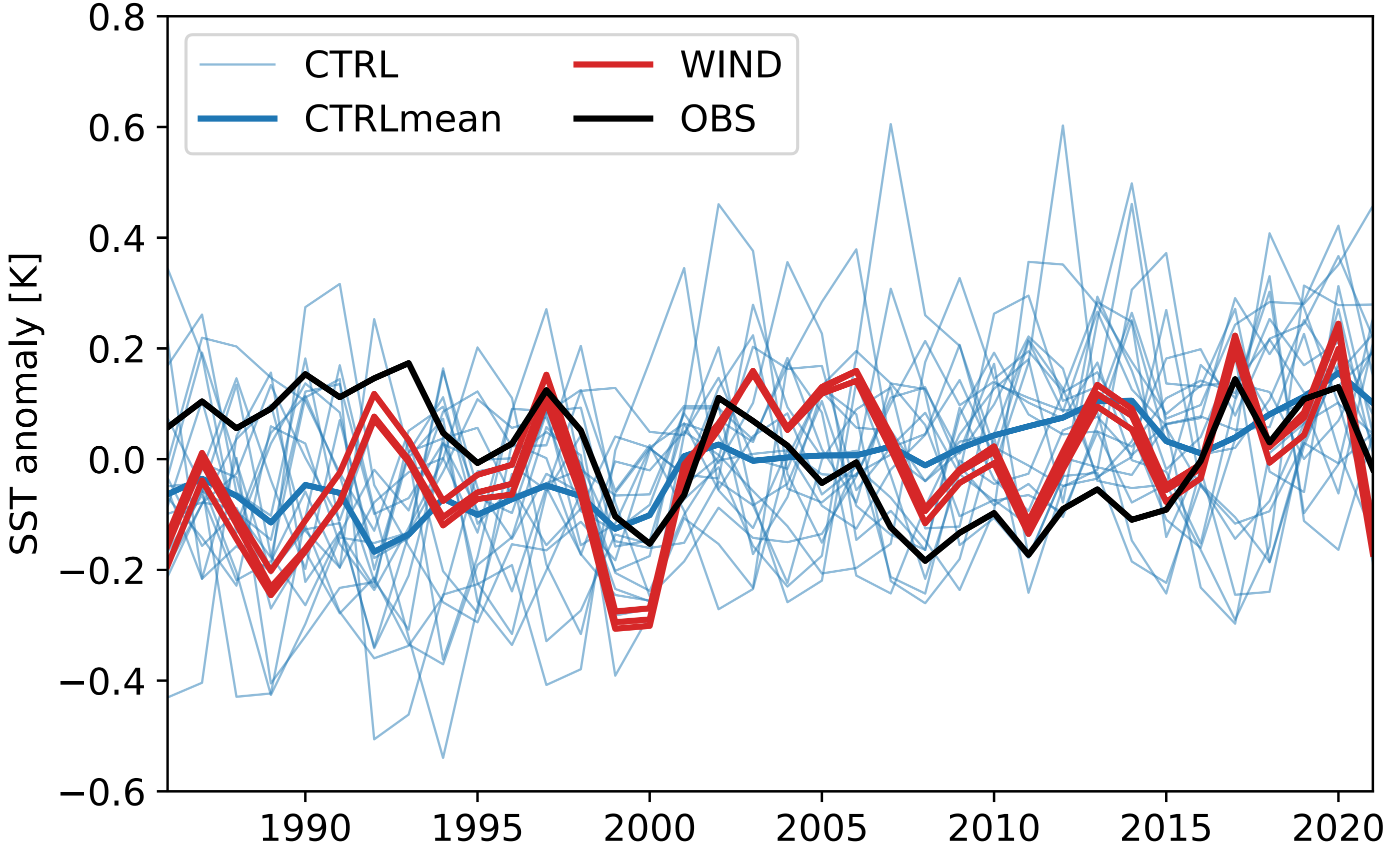
Step 1: Apply wind-nudging towards NASA MERRA-2

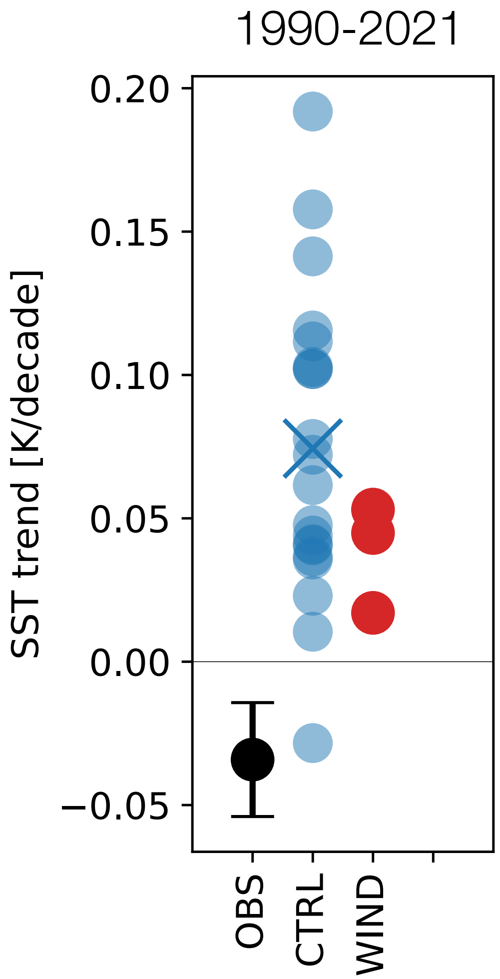
- Limits initial condition uncertainty due to the large-scale atmospheric circulation
- Three ensemble members starting from high, medium and low sea ice conditions
- Allow 10 year spin-up - focus on 1990-2021



Roach et al. (2023)

Influence of winds on Southern Ocean SSTs

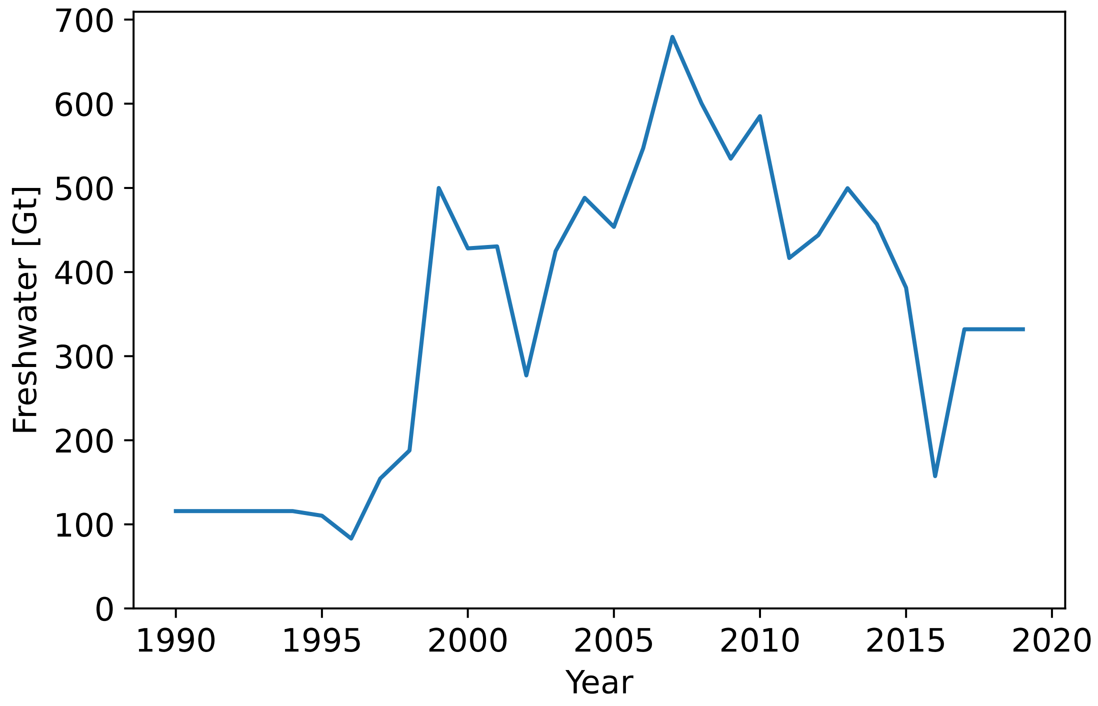


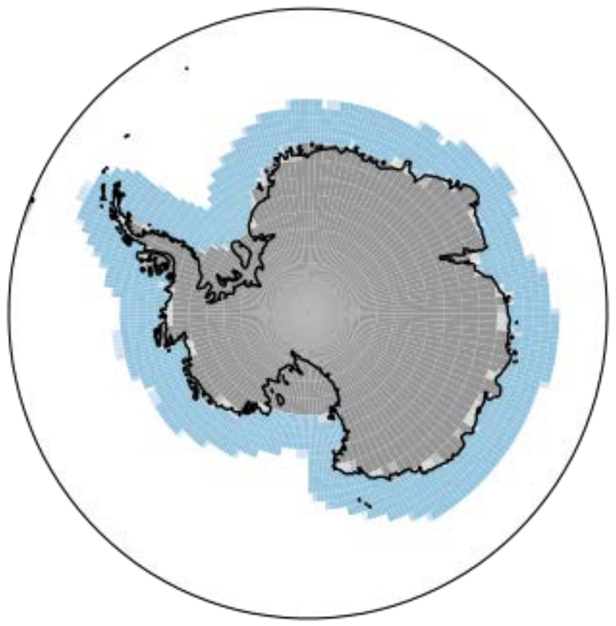


Roach et al. (2023)

Step 2: Add anomalous meltwater based on observations

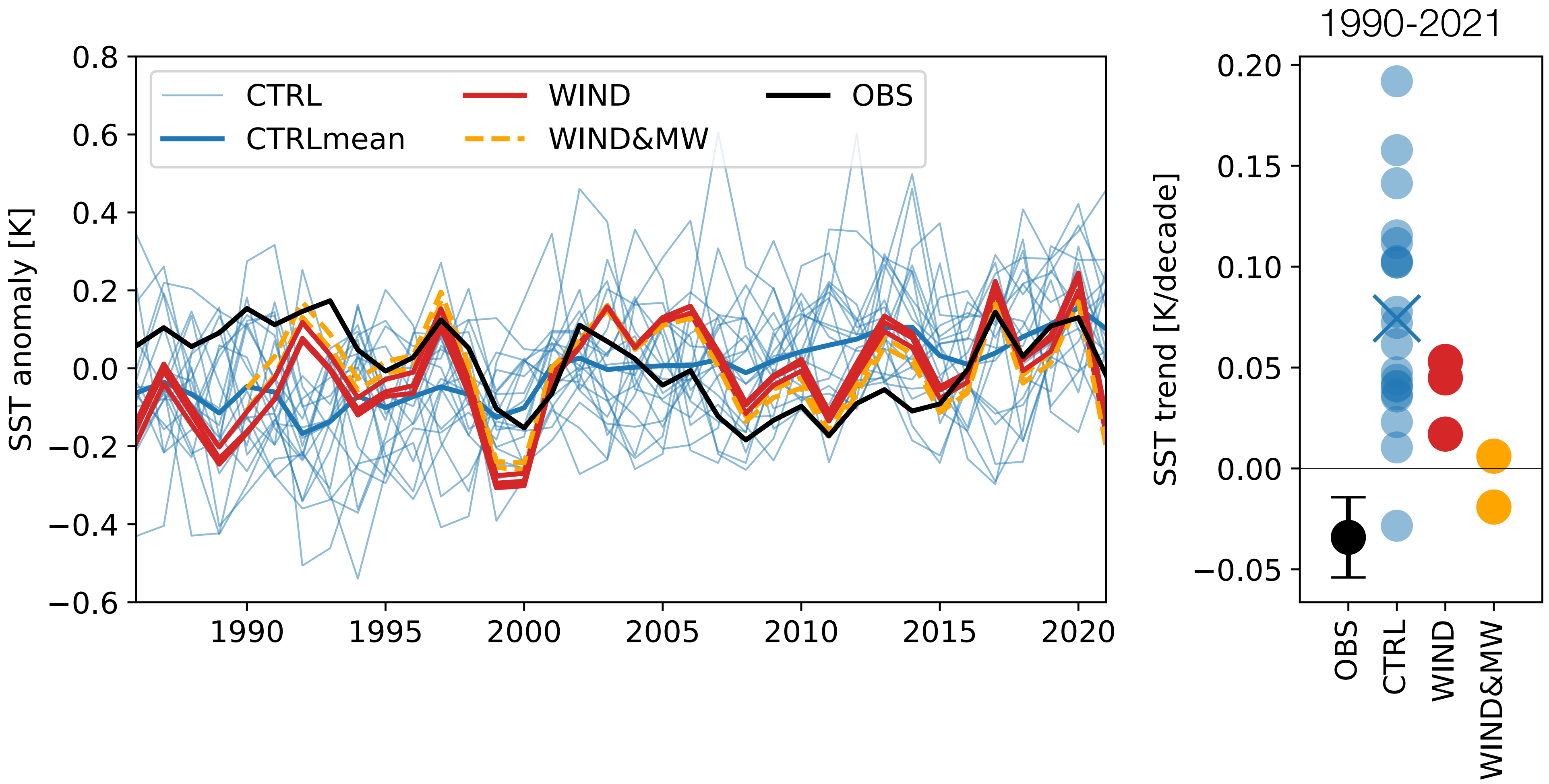
- Interannually-varying observation-based estimates from Slater et al. (2021) over 1990-2021





Roach et al. (2023)

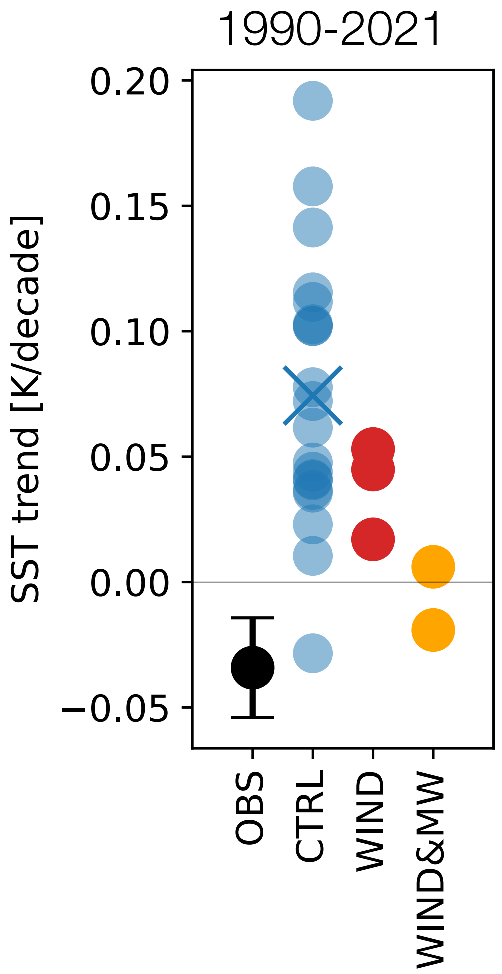
Influence of winds and meltwater together on SO SSTs



Roach et al. (2023)

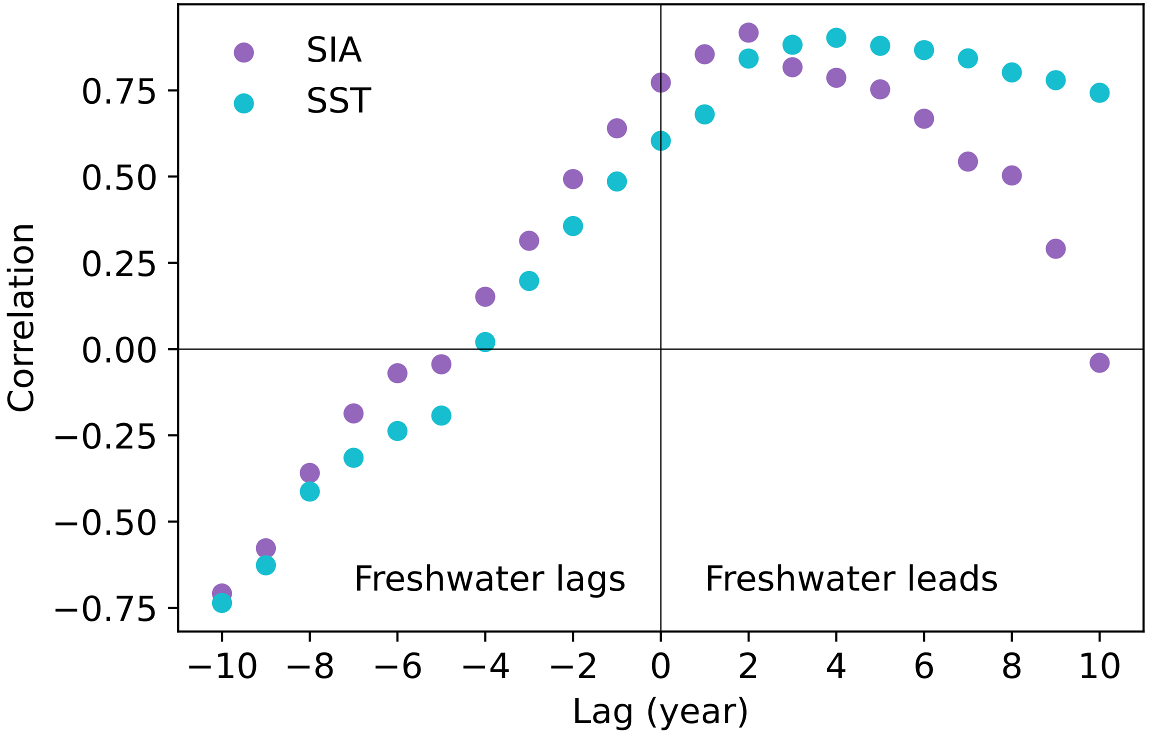
Influence of winds and meltwater together on SO SSTs

- Both winds and meltwater each cause Southern Ocean cooling of approximately 0.04K/decade
- Both factors are important!



Roach et al. (2023)

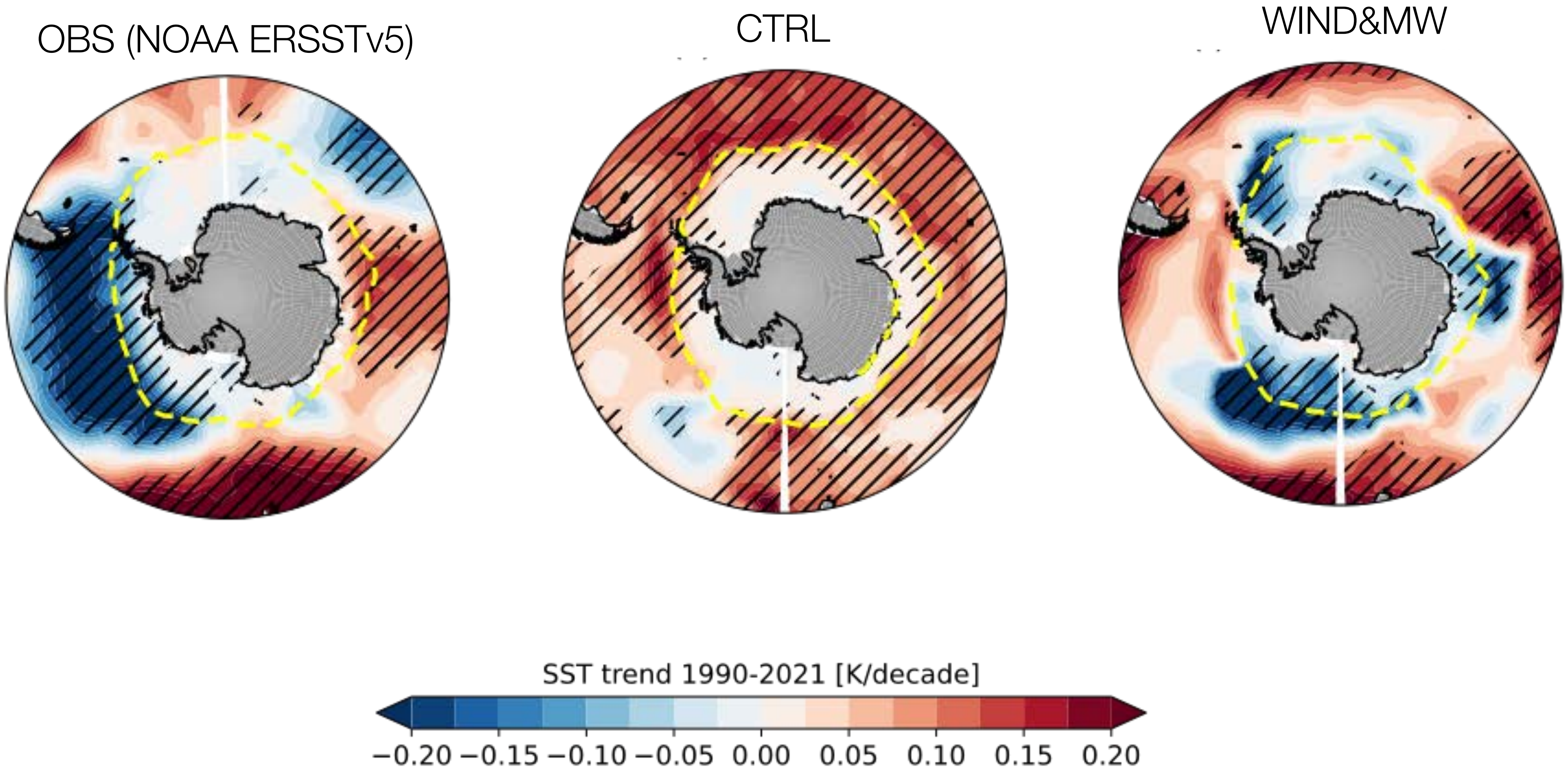
Timescales of response to meltwater



- SST response peaks at 4 years
- 0.14K Southern Ocean cooling per 1000 Gt of anomalous meltwater forcing
- Sea ice response peaks at 2 years
- 0.6 million km^2 of sea ice expansion per 1000 Gt of meltwater

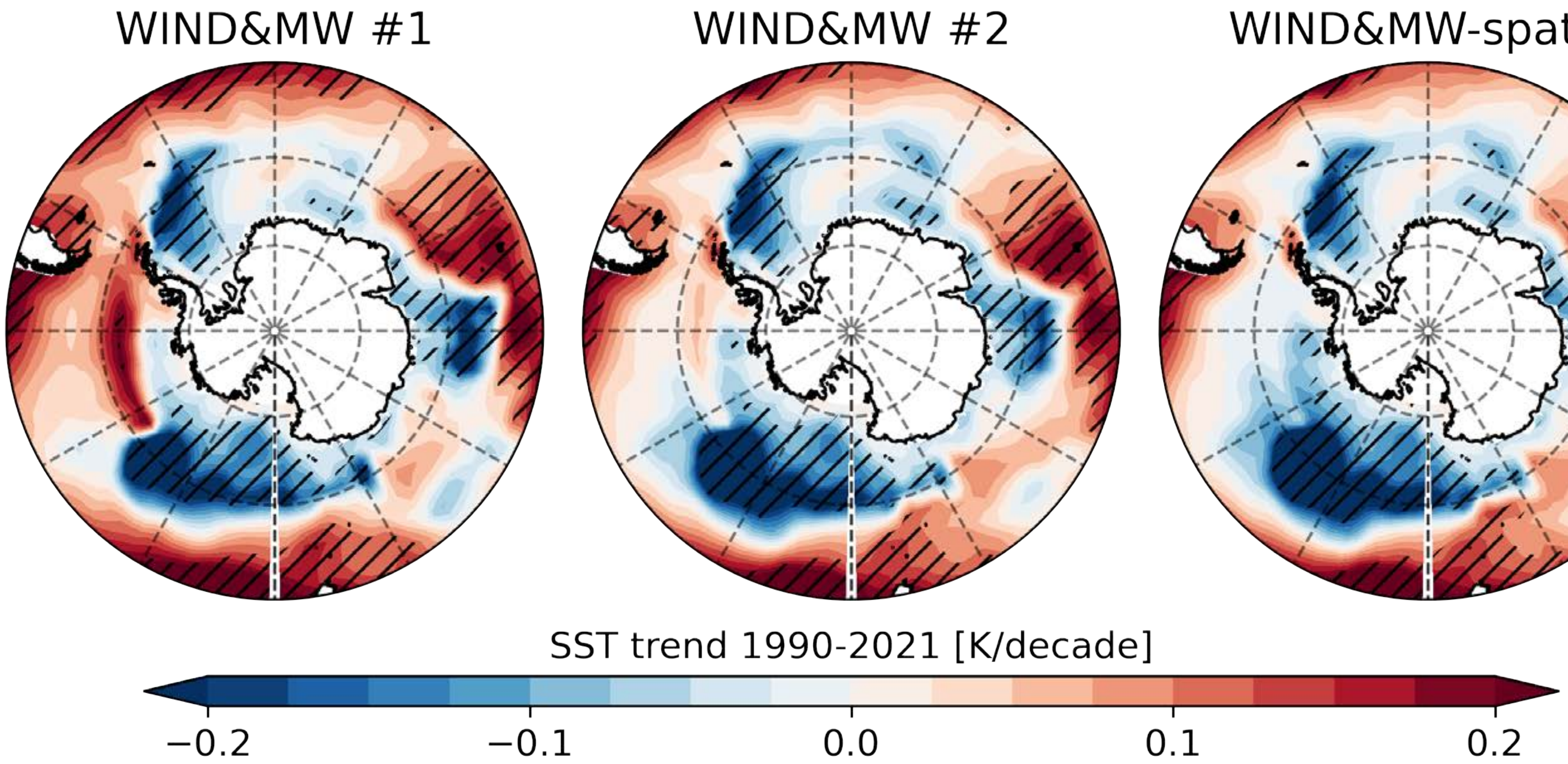
Roach et al. (2023)

Spatial patterns in SST trends



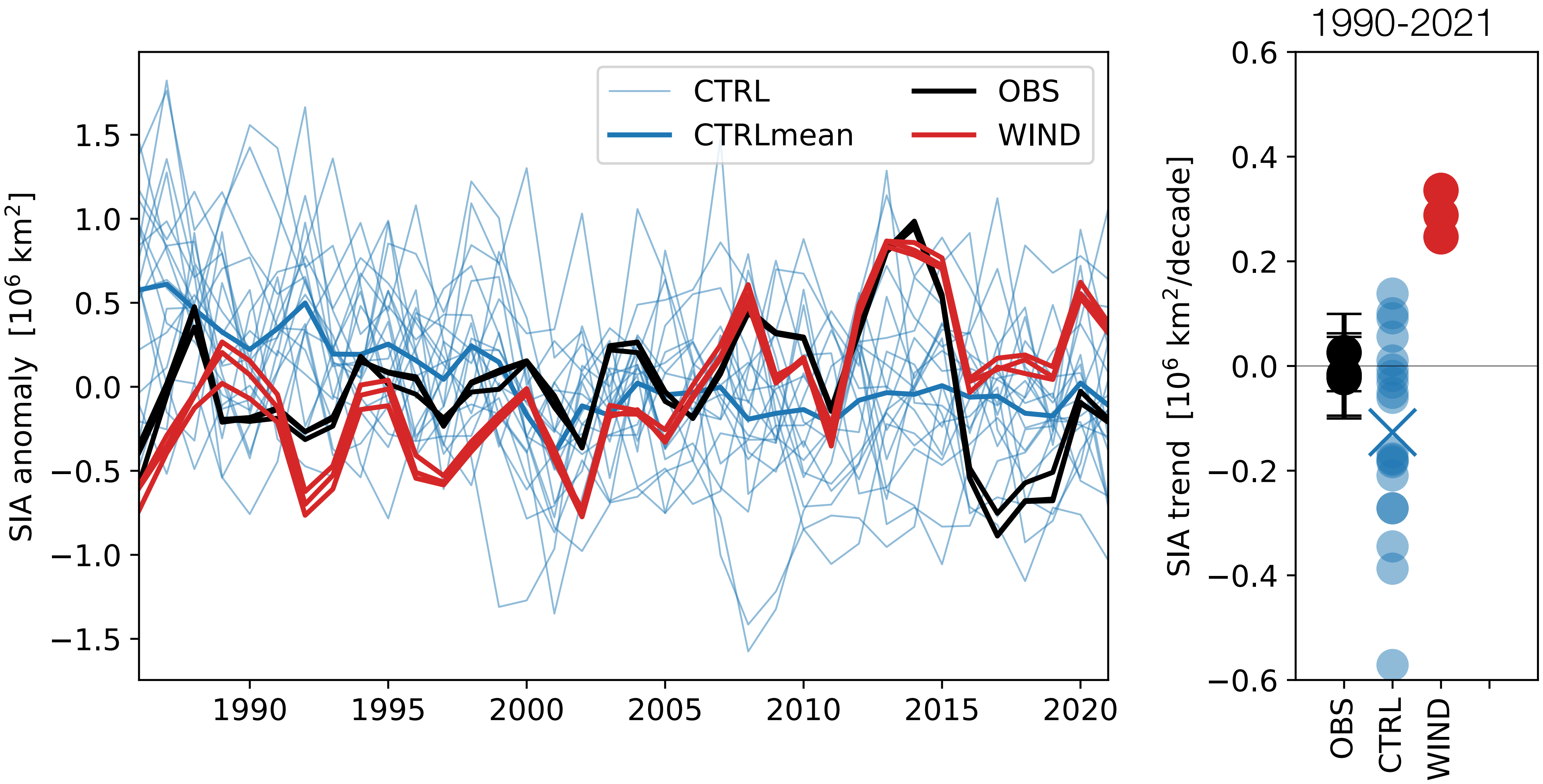
Roach et al. (2023)

Minimal contribution of spatial variations in meltwater



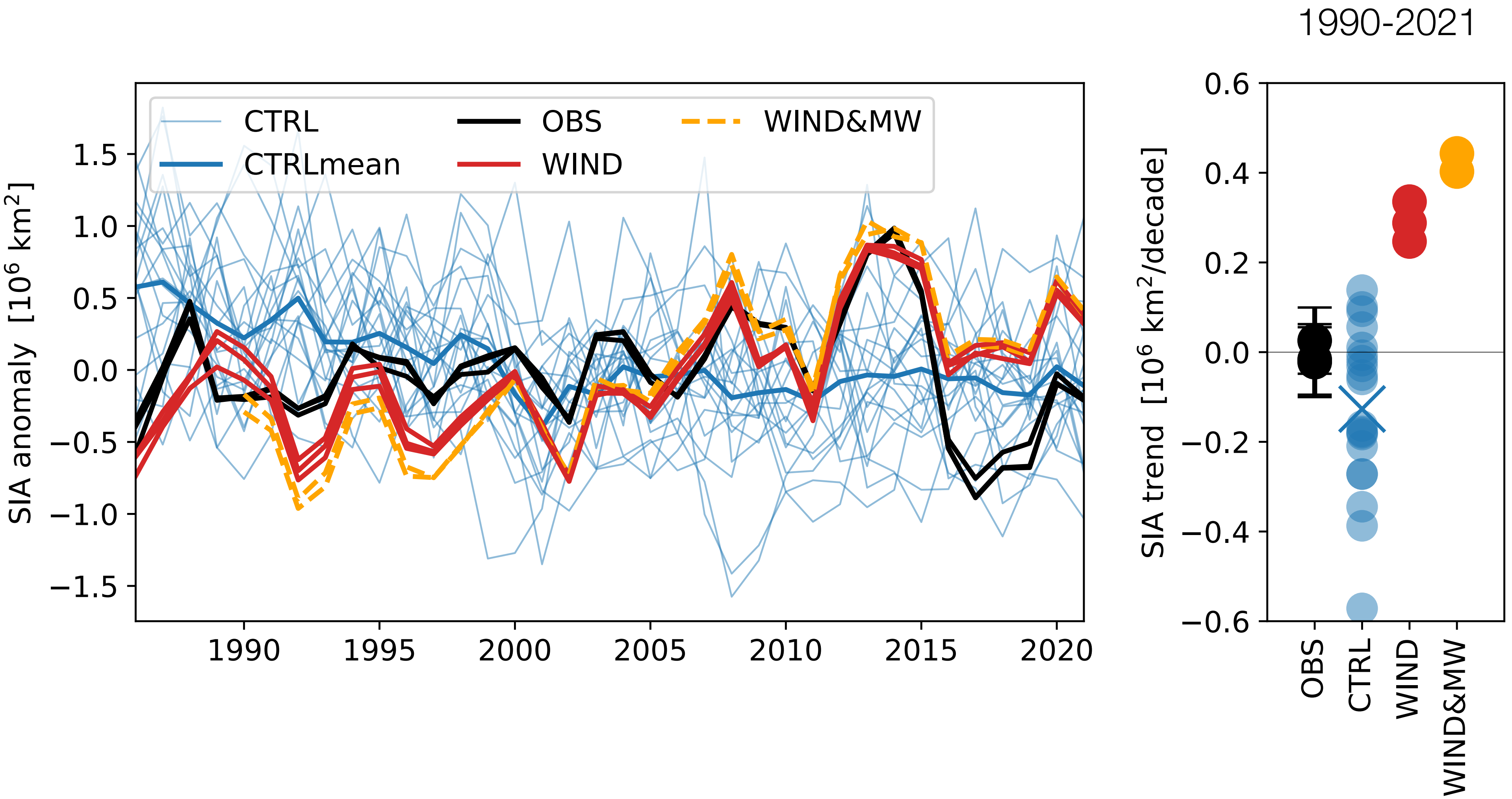
- Add 70% of the meltwater to the West Antarctic region, with 15% from East Antarctic and 15% from the Peninsula

Influence of winds on Antarctic sea ice



Roach et al. (2023)

Influence of winds and meltwater on Antarctic sea ice



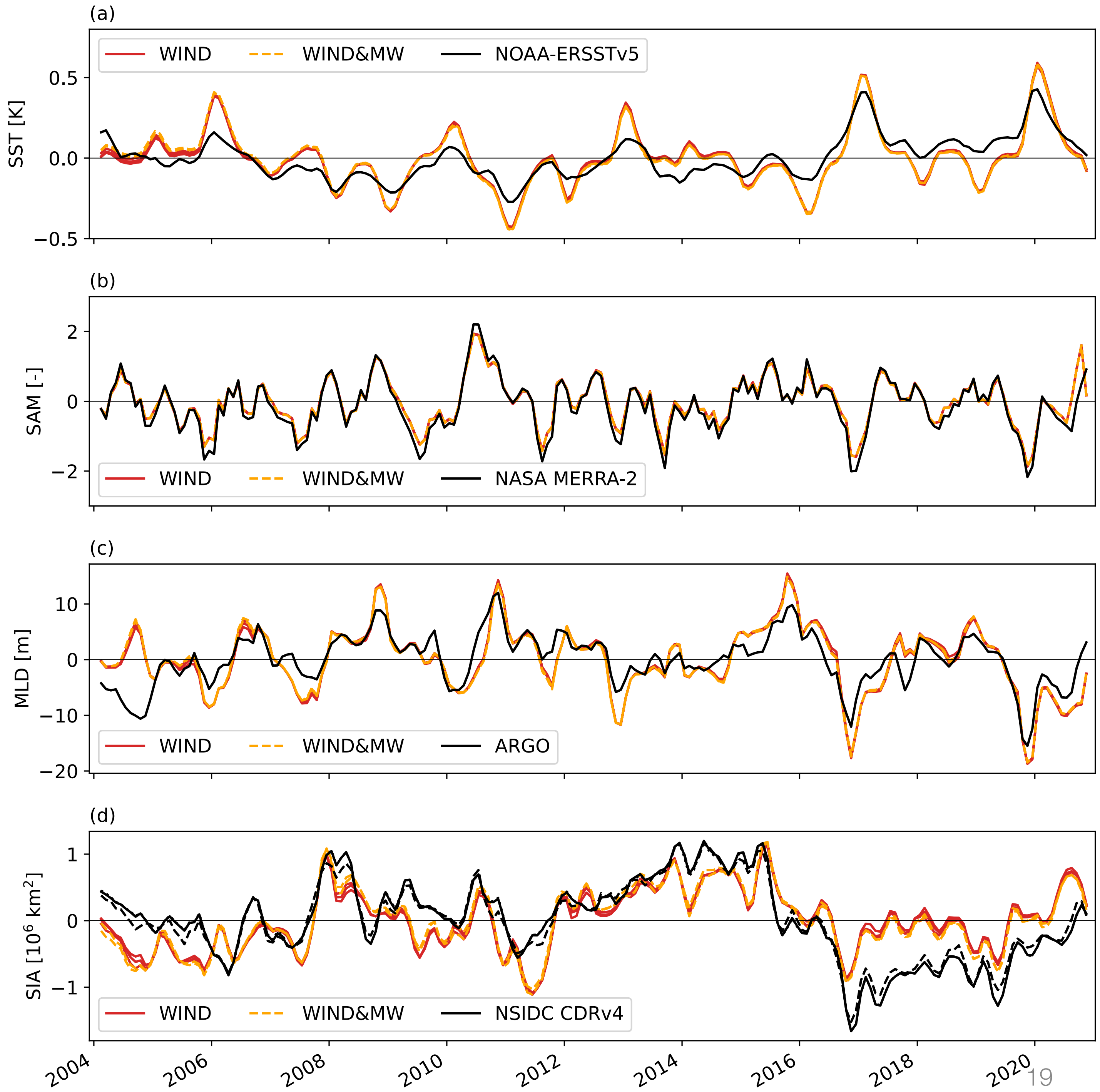
Roach et al. (2023)

Summary

- We nudge winds to observations and add estimates of observed freshwater from ice sheet and ice shelf melt in a coupled climate model
- Southern Ocean sea surface temperature trends and variability better match observations, with both winds and meltwater being important
- The constrained model simulates strong Antarctic sea ice expansion and only partially captures recent sea ice lows
- Comparison to previous studies highlights the importance of model mean state and that many different factors are at play in this complex system

Roach, L. A., Mankoff, K., Romanou, A., Blanchard-Wrigglesworth, E., Haine, T. W. N., Schmidt, G. A.. Winds and meltwater together lead to Southern Ocean surface cooling and sea ice expansion (2023). *Geophysical Research Letters,* 50, e2023GL105948. https://doi.org/10.1029/2023GL105948

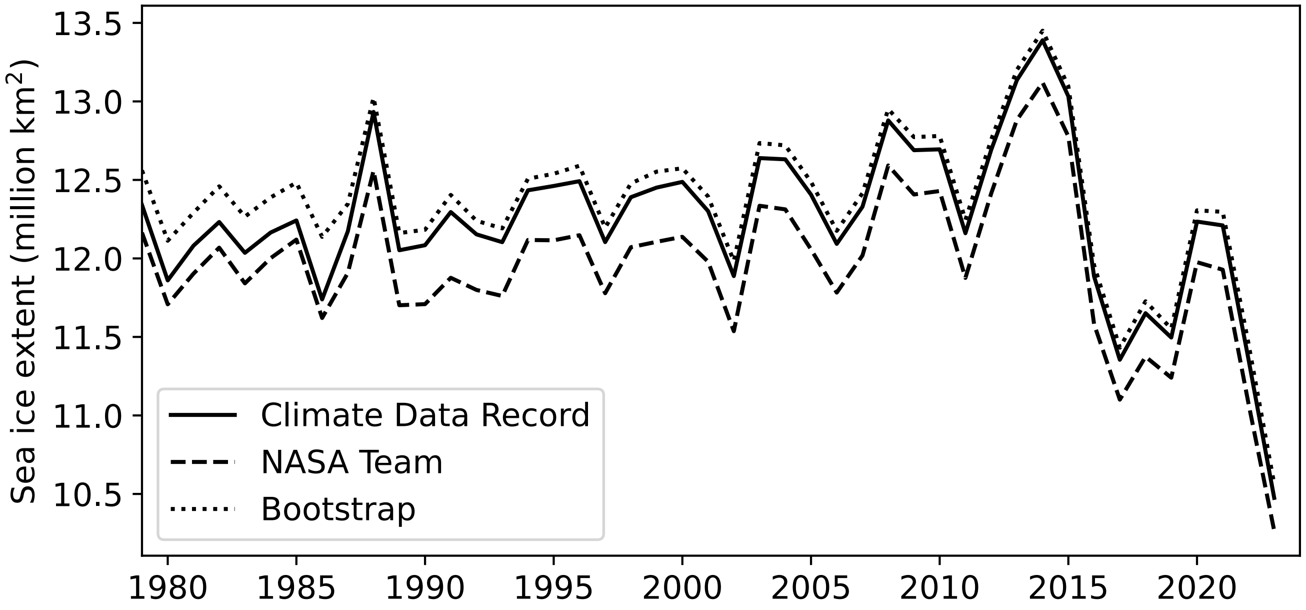
- NASA GISS E2.1 captures Southern Ocean SST, wind and mixed layer depth variability
- But overestimates sea ice expansion and underestimate the recent sea ice lows!
- Setting freshwater to zero after 2014 has minimal influence
- Biases in coupling, subsurface ocean?

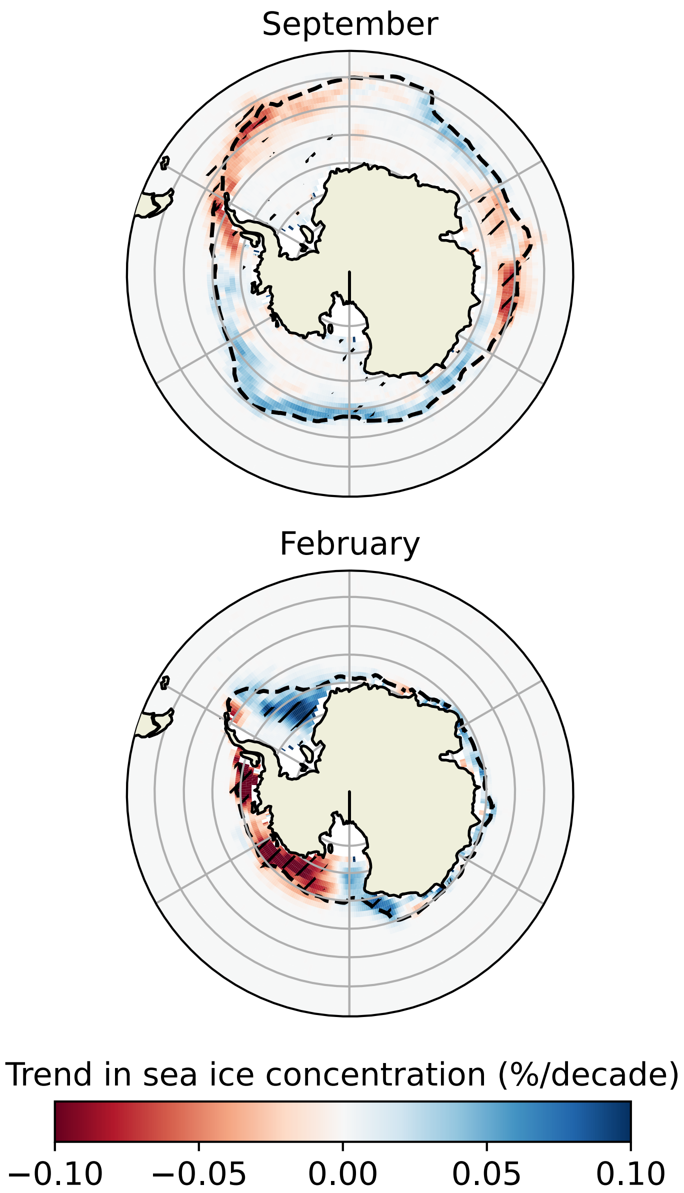


Roach et al. (2023)

Unexpected changes in Antarctic sea ice

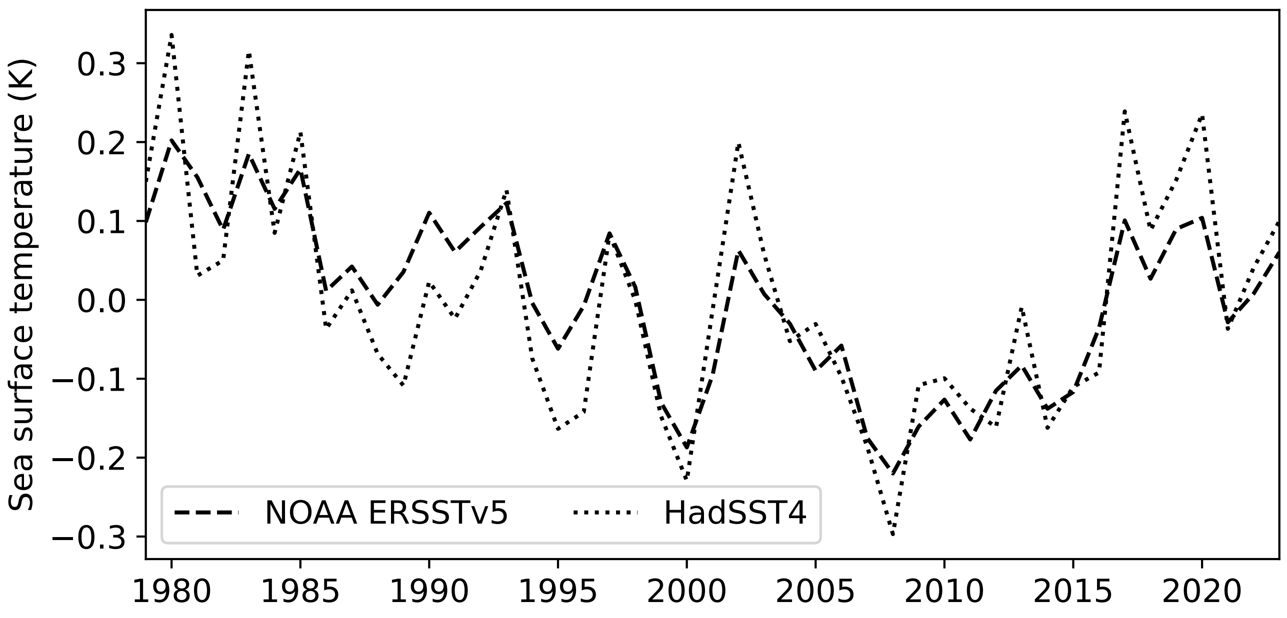
- NSIDC CDR version 4

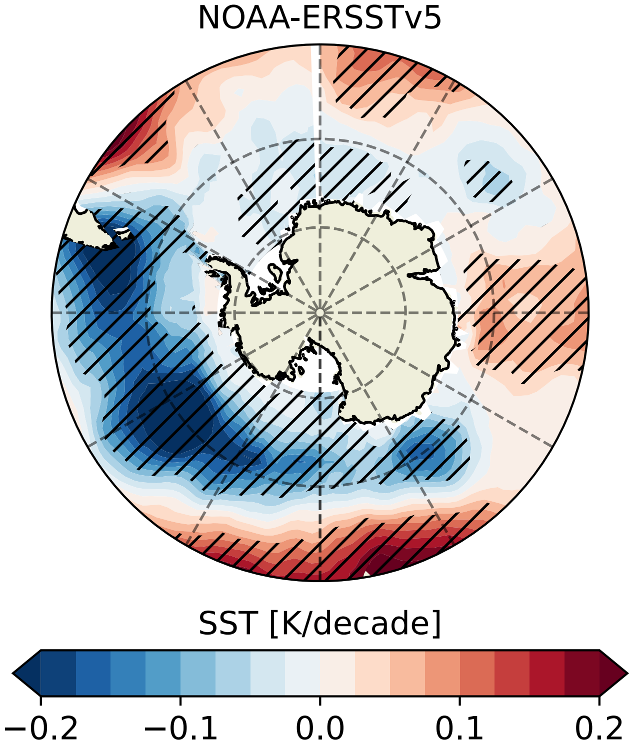




Changes in Southern Ocean sea surface temperatures

- 50-65S, 1979-2023

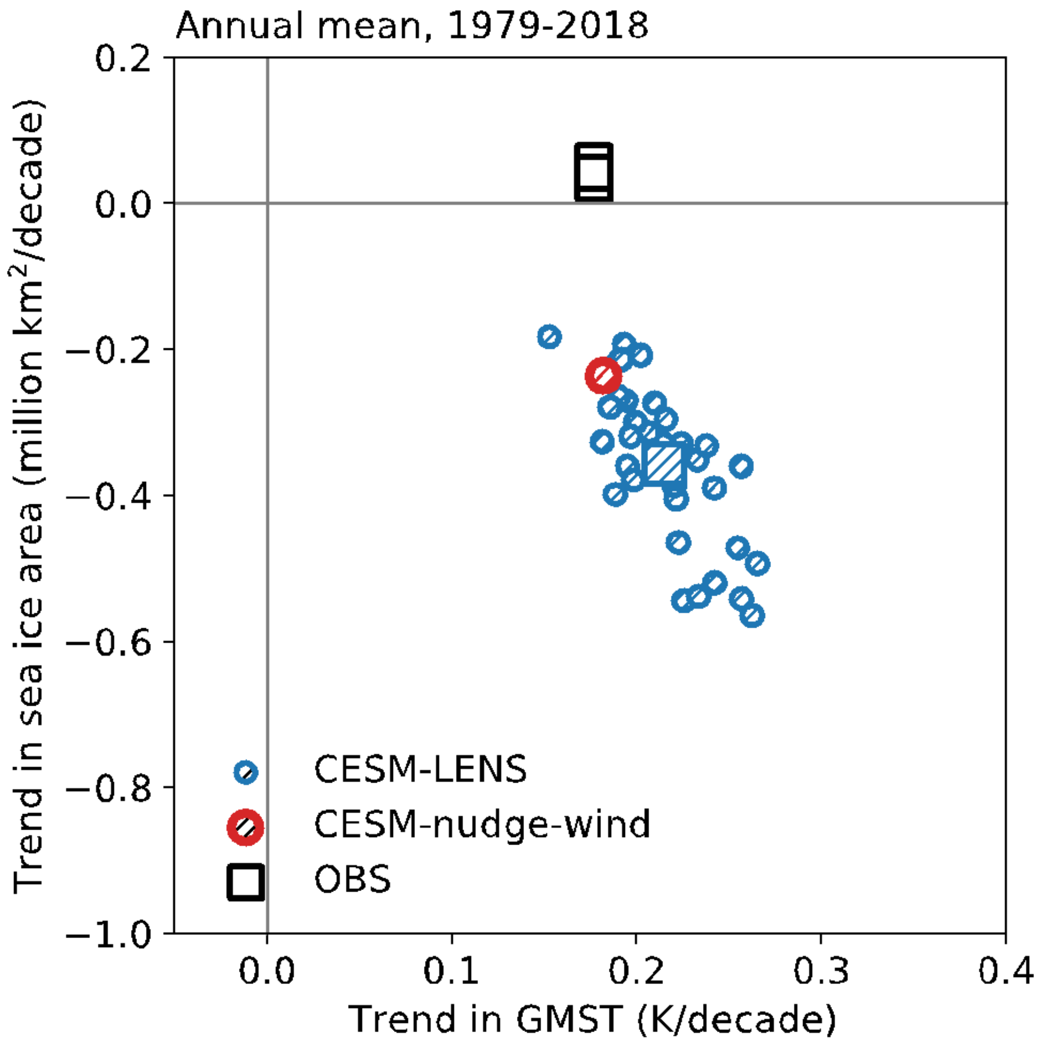




Wind-nudging in CESM1

*Similar experimental design, but nudging only polewards of 45º , above BL and towards ERA Interim

Observed wind variability explains around a third of the difference between observations and the LENS mean

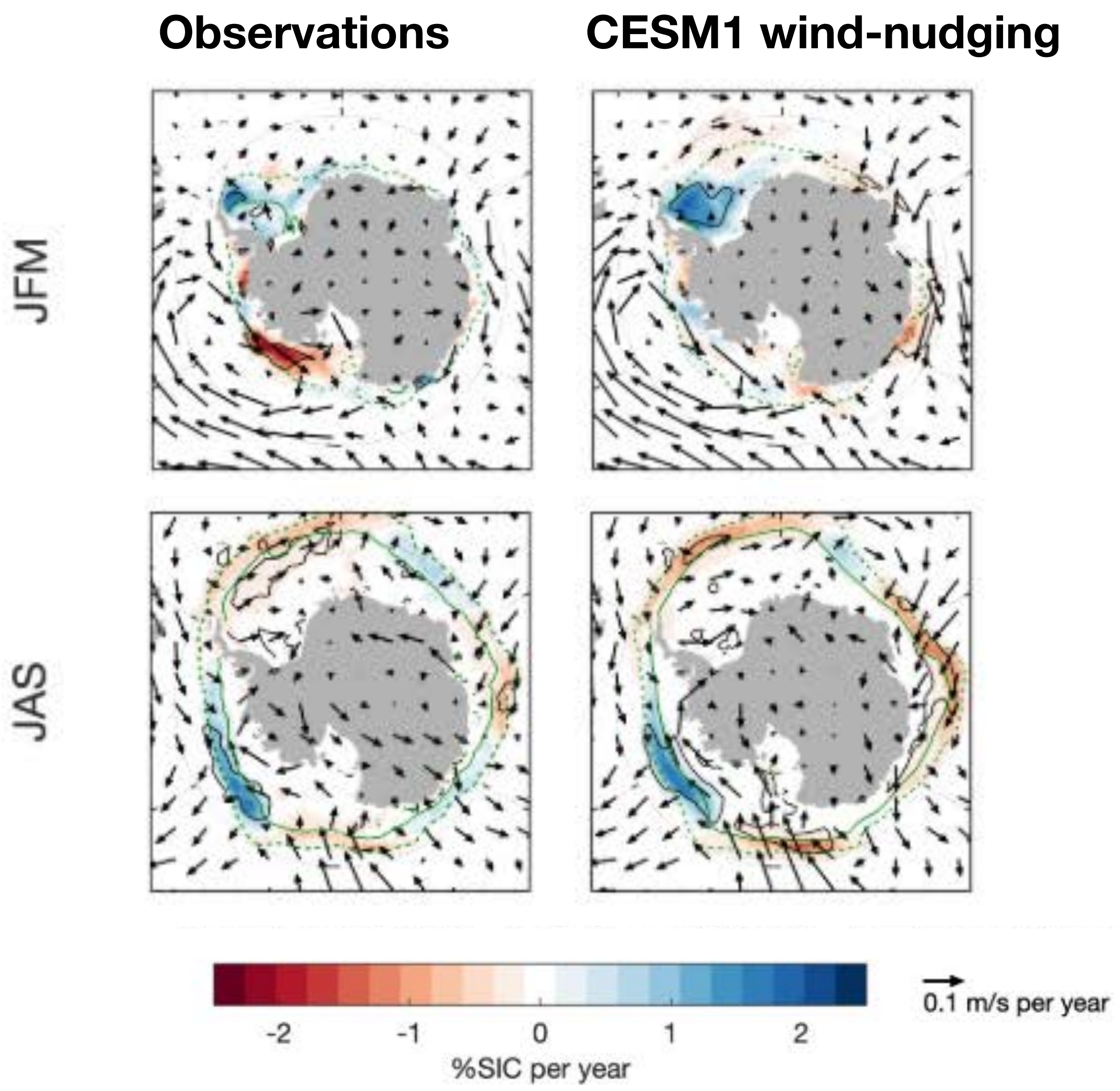


Blanchard-Wrigglesworth, Roach et al. (2021)

Wind-nudging in CESM1

Observed wind variability explains around a third of the difference between observations and the LENS mean

Capture spatial patterns in sea ice concentration trends



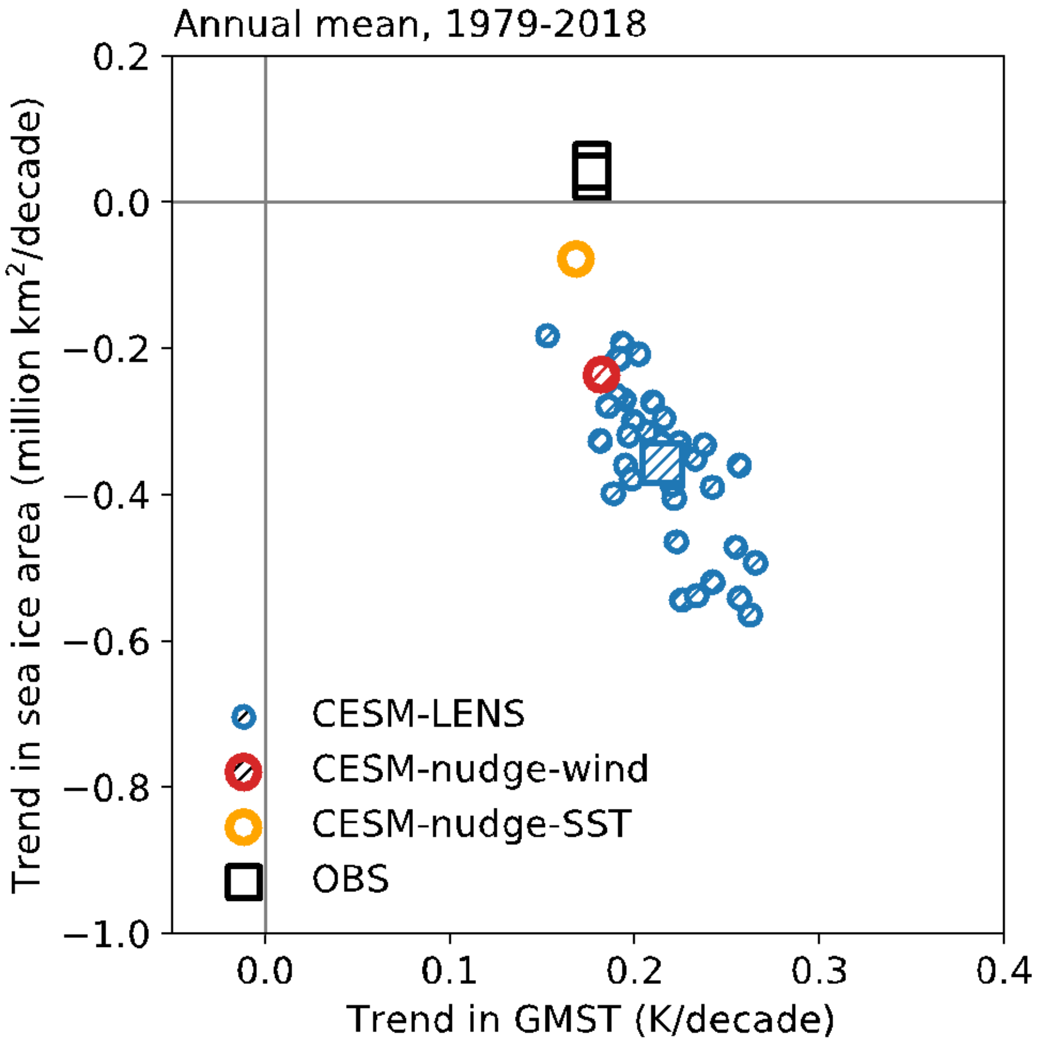
Blanchard-Wrigglesworth, Roach et al. (2021)

Wind-nudging in CESM1

Observed wind variability explains around a third of the difference between observations and the LENS mean

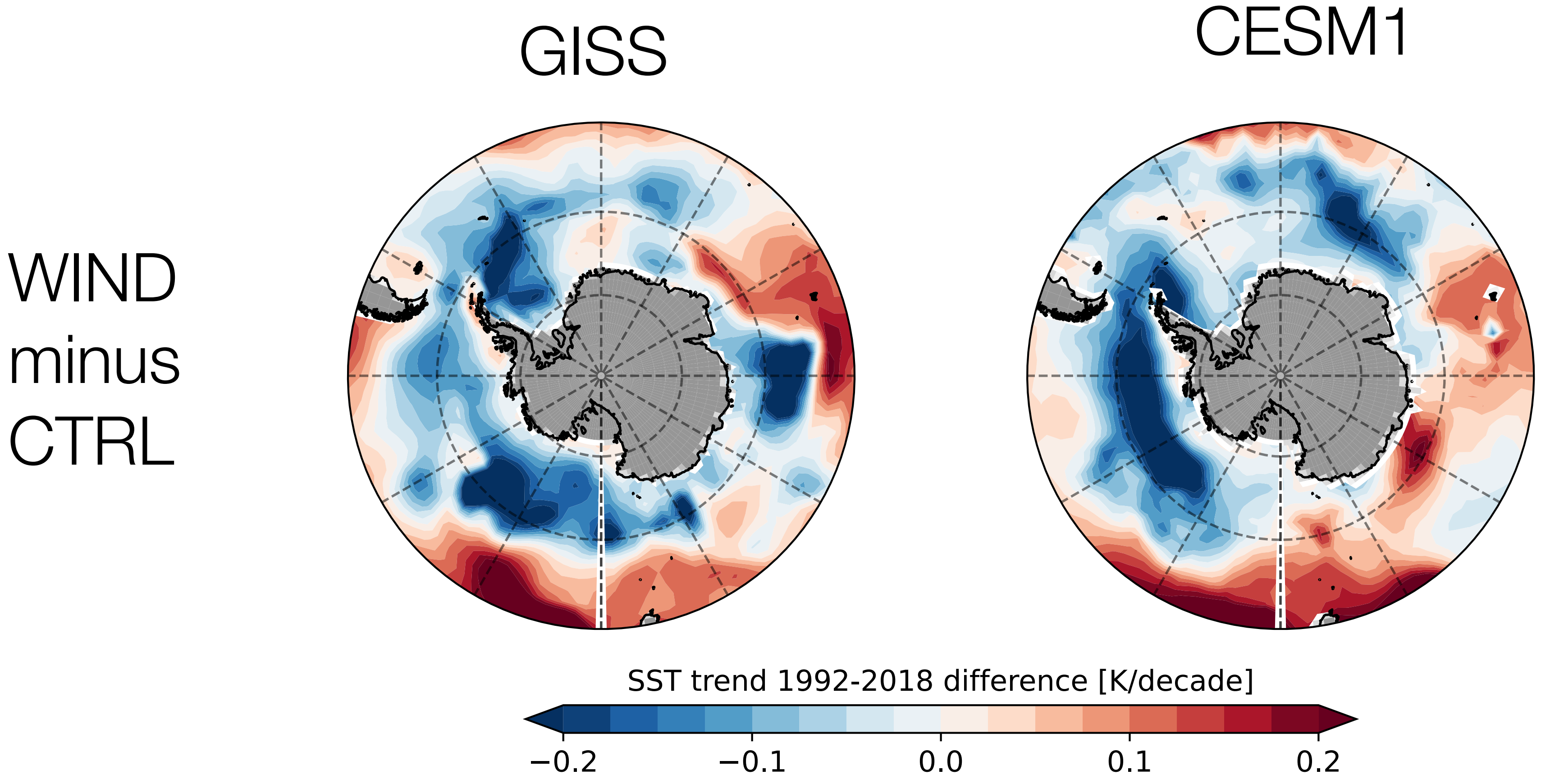
Capture spatial patterns in sea ice concentration trends

Relaxation to mid-latitude SSTs required to recover ~70% of model-observation difference



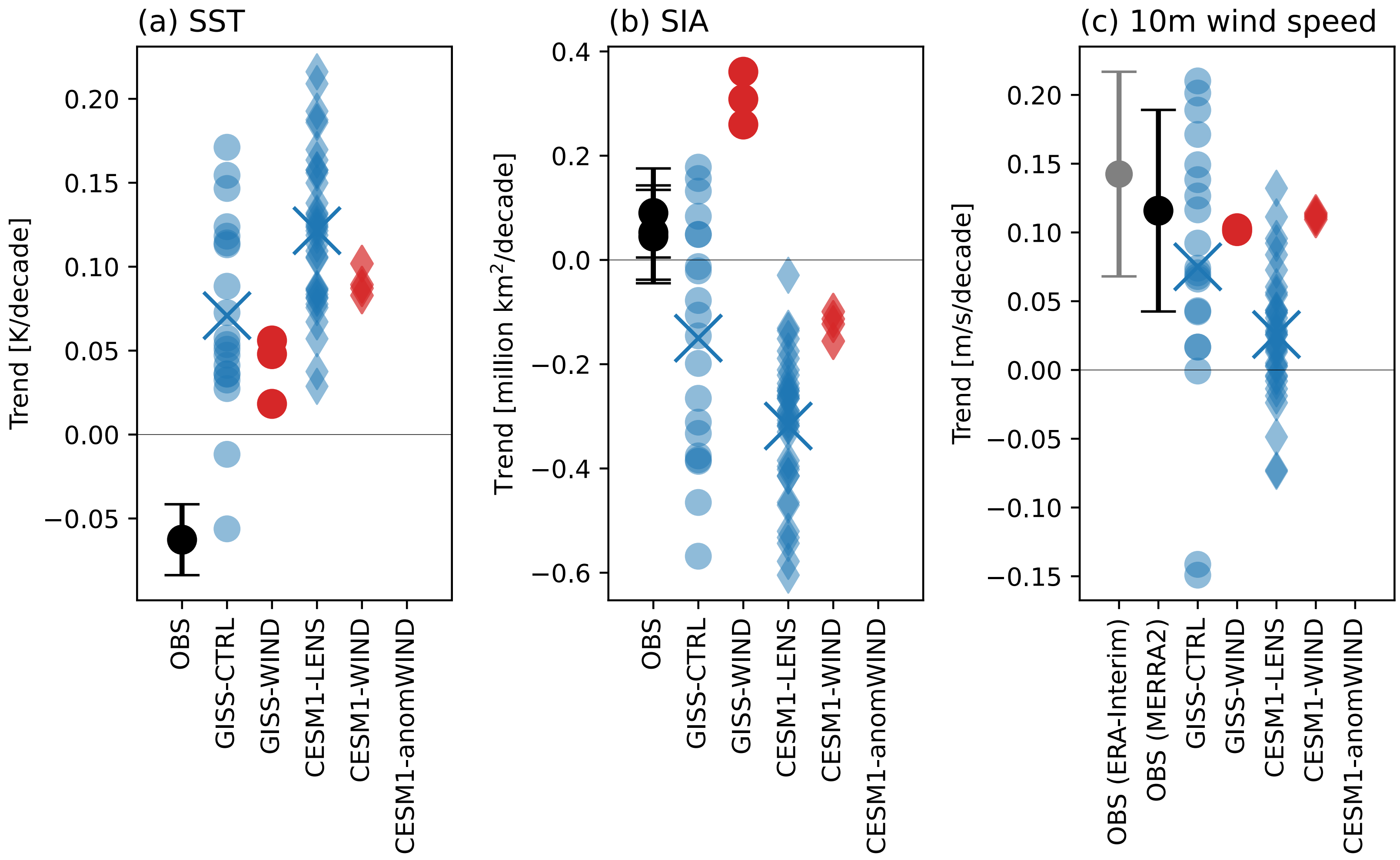
Blanchard-Wrigglesworth, Roach et al. (2021)

Wind-nudging in GISS vs CESM1 - impact on SST trends



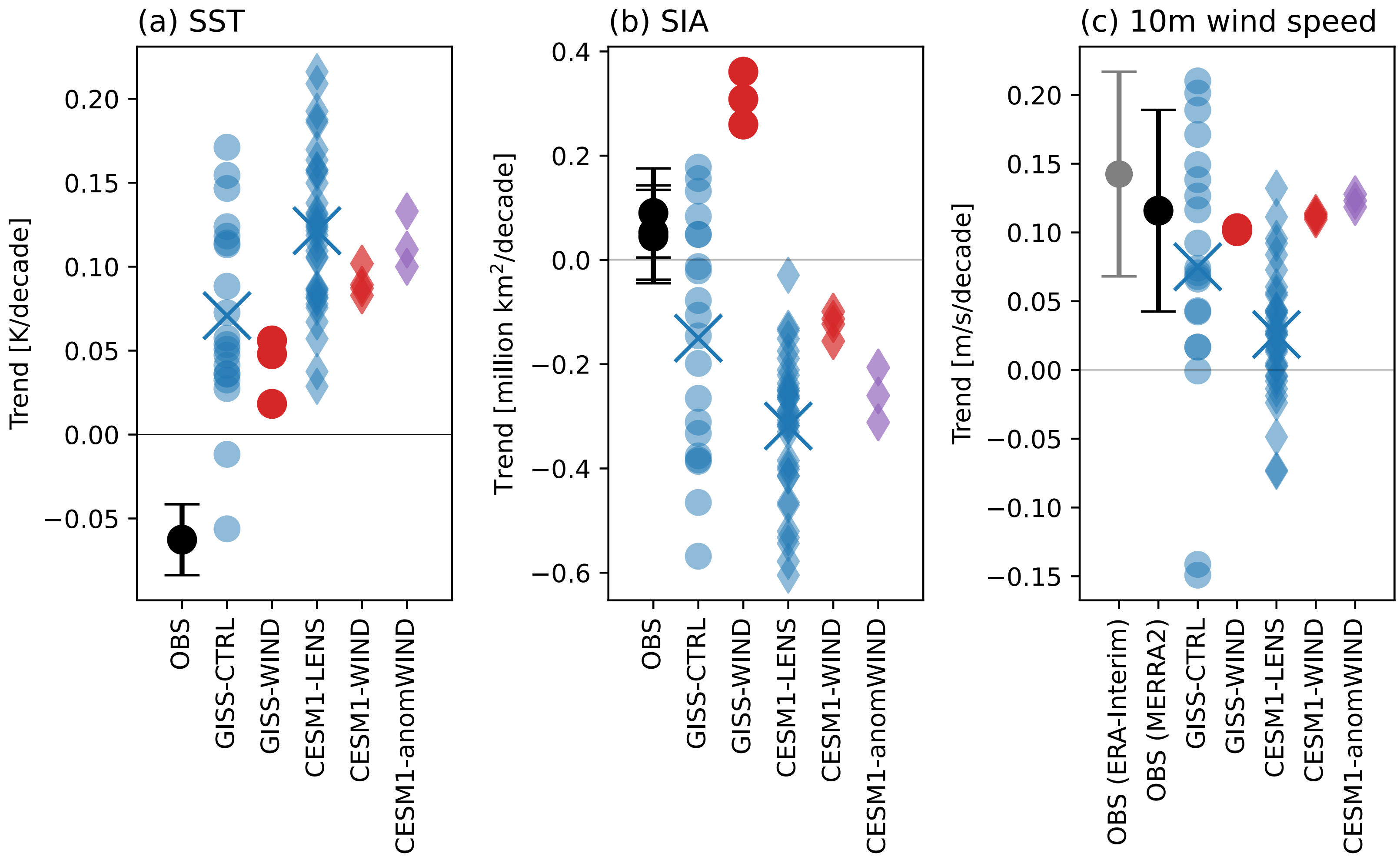
Blanchard-Wrigglesworth et al. (2021), Roach et al. (2023)

Wind-nudging in CESM1 vs GISS



Blanchard-Wrigglesworth et al. (2021), Roach et al. (2022), Roach et al. (2023)

Wind-nudging in CESM1 vs GISS



CESM1 nudged to reanalysis wind anomalies - removes influence of observed wind mean state

Changes are due to a combination of changes in wind anomalies and wind mean state

Blanchard-Wrigglesworth et al. (2021), Roach et al. (2022), Roach et al. (2023)