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Global ocean warming and Southern Ocean hotspots: roles of external forcings and internal variability

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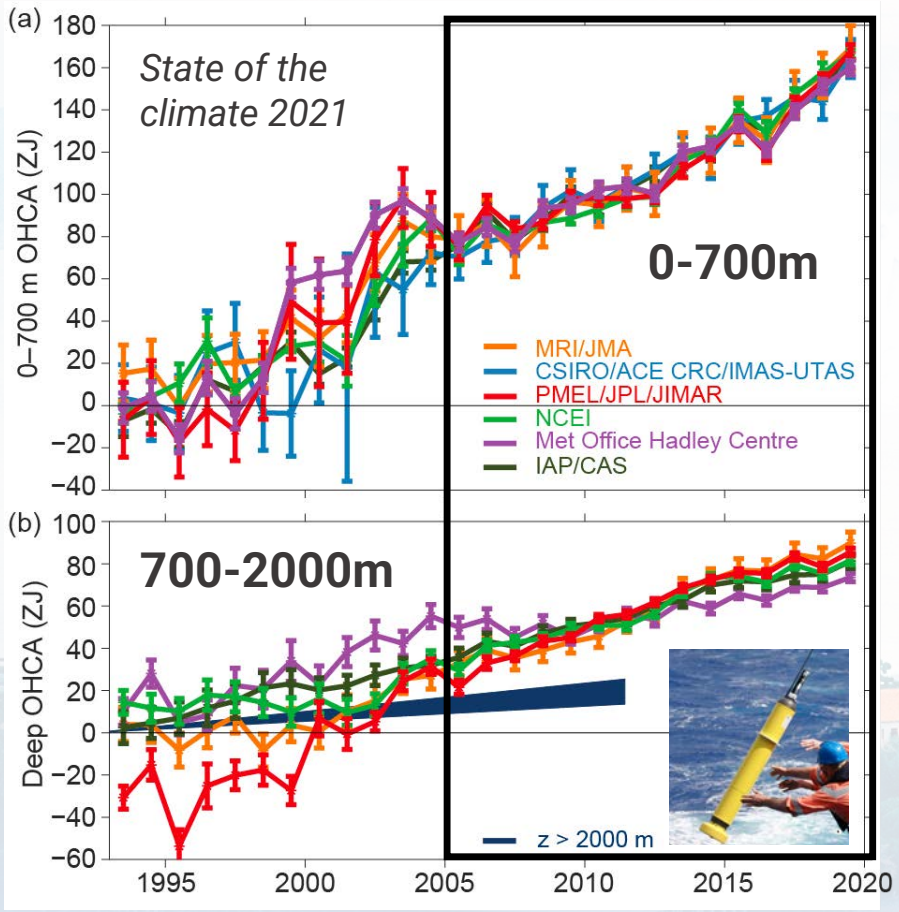
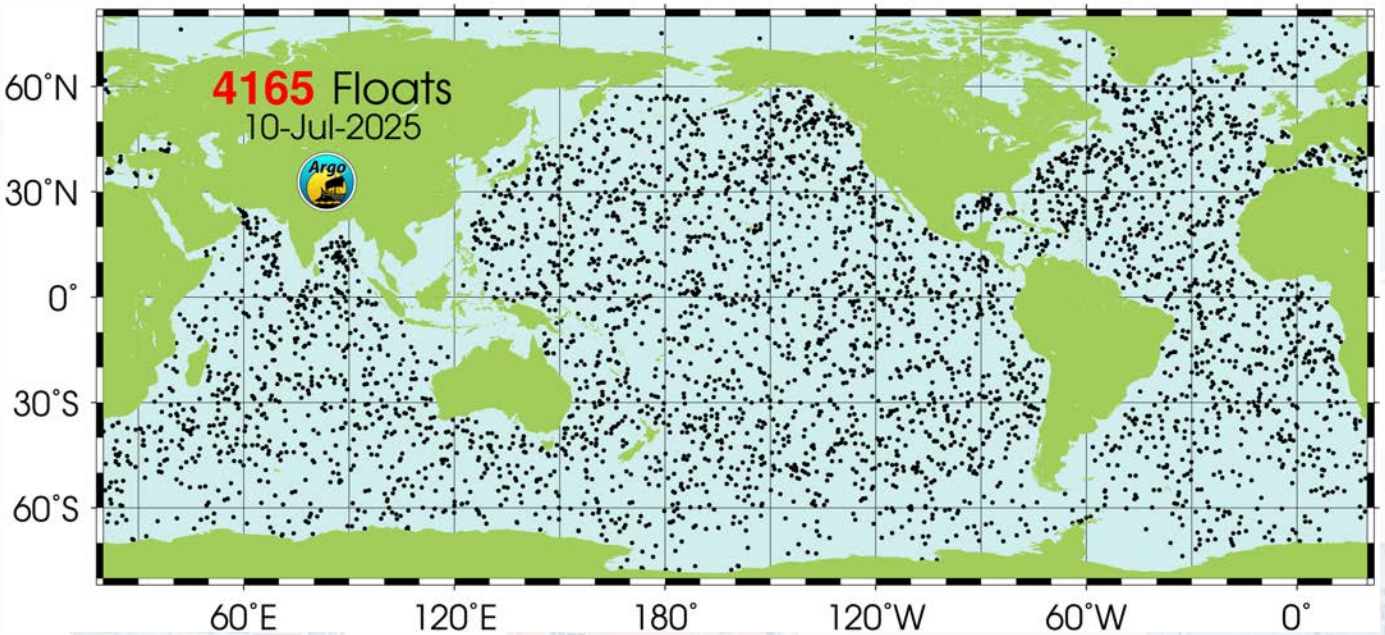
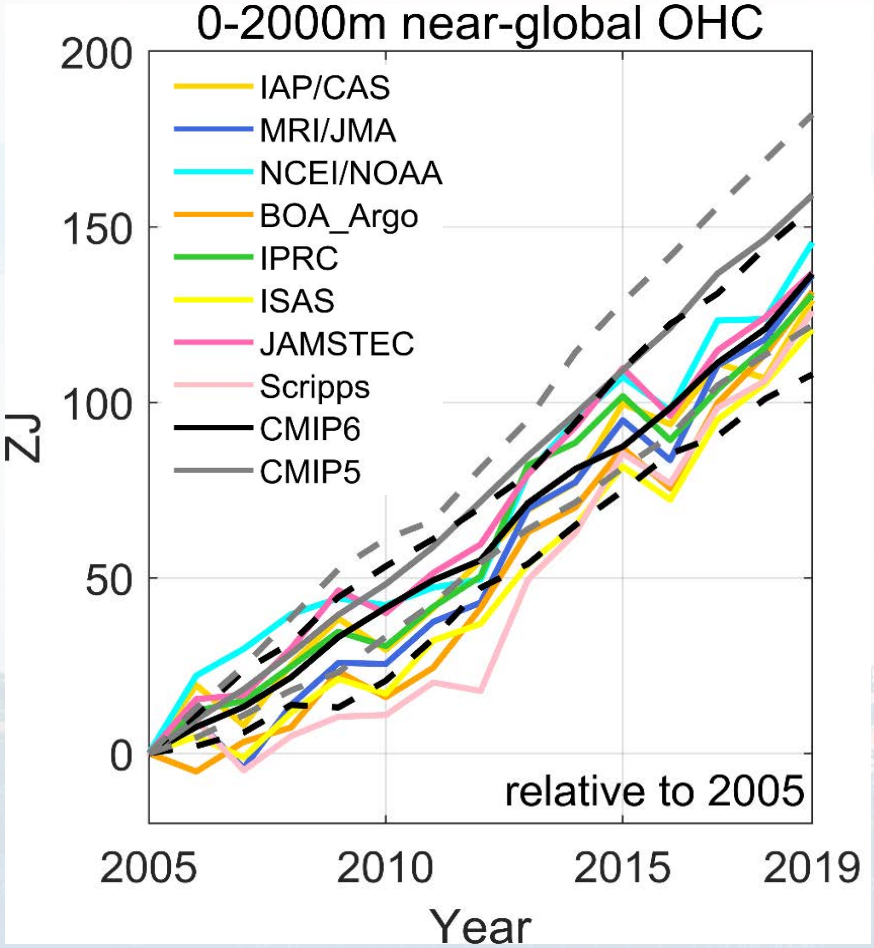
Observational record of global ocean warming

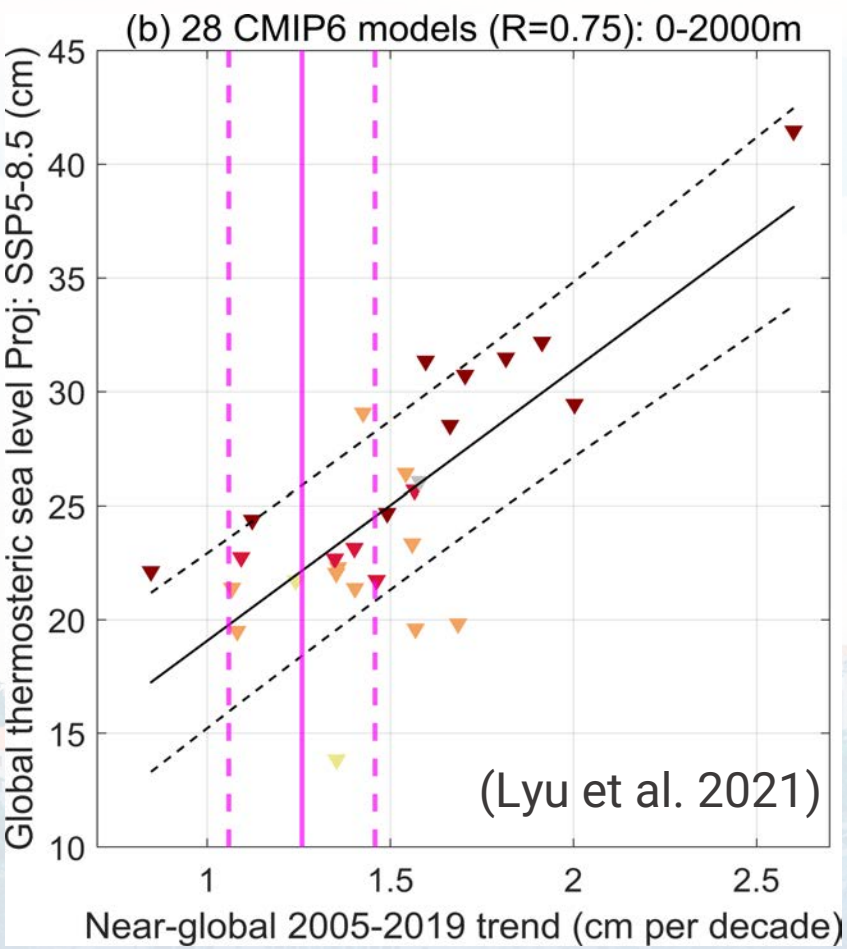




Global ocean heat content time series: much greater consistency since ~2005 with near-global coverage of Argo floats

Can climate models reproduce the observed global ocean warming rate during the Argo period?

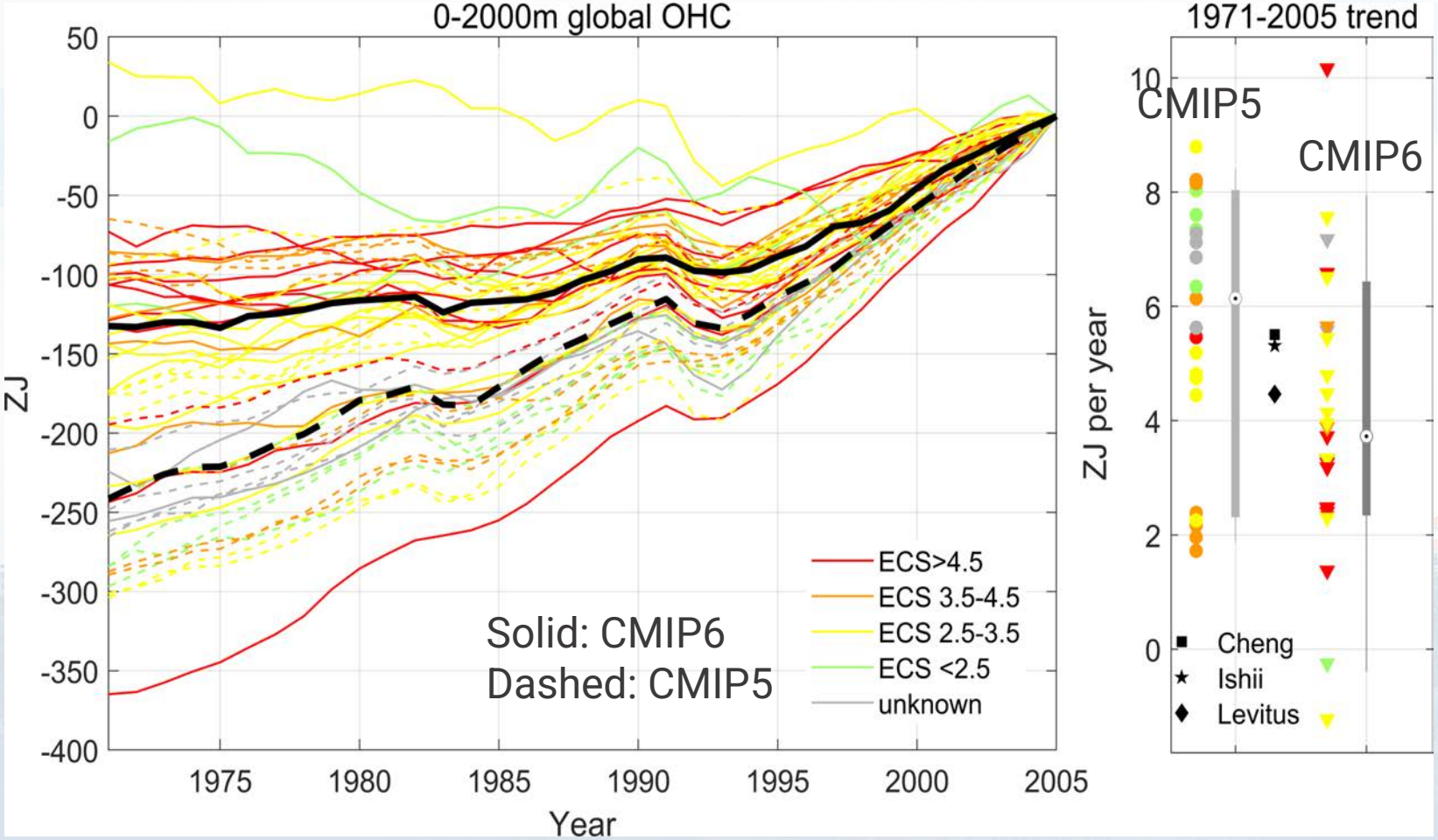




Upper 2000m global ocean heat content changes over 2005-2019: obs and model comparison

- CMIP6 MMM is close to observational trend while **CMIP5 overestimates due to the lack of 21st century volcanic forcing**
- **Upper-tail projections from high climate sensitivity CMIP6 models are very unlikely** as they tend to overestimate the Argo-period warming

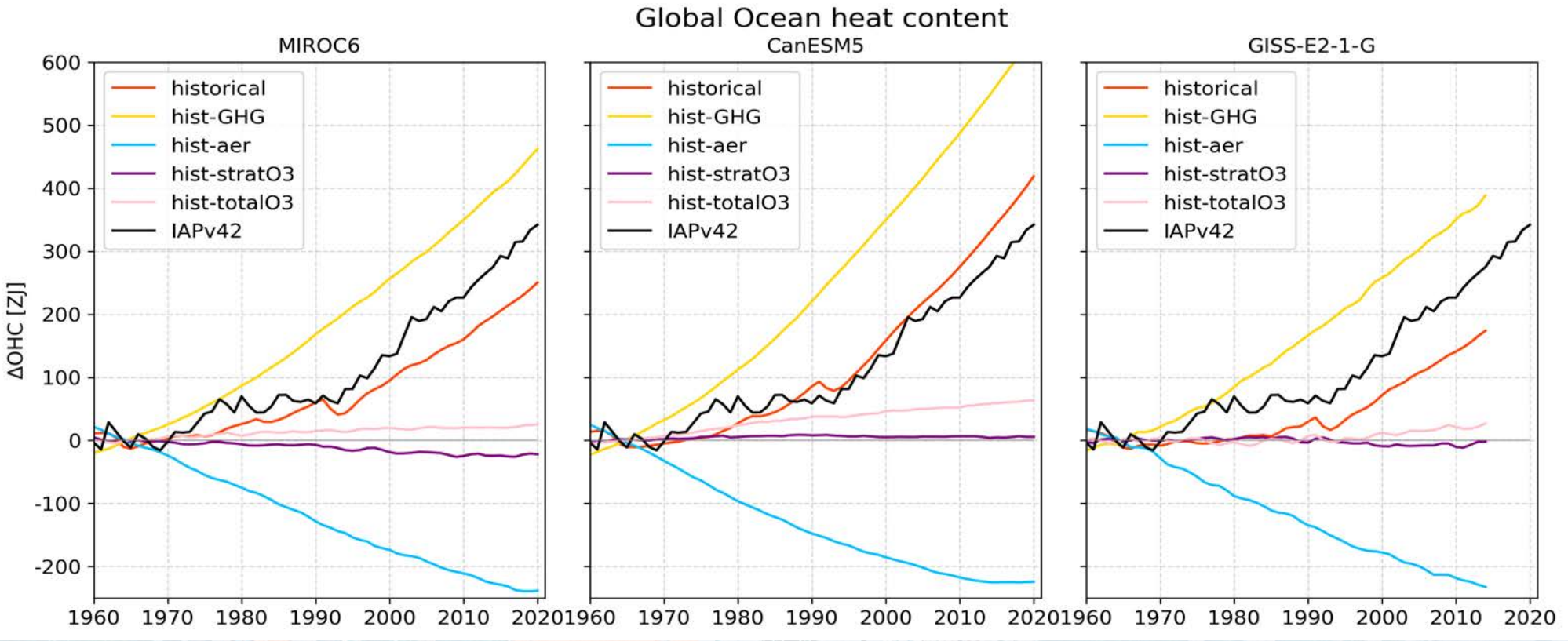
Can climate models reproduce the observed global ocean warming rate during the pre-Argo period?



Upper 2000m global ocean heat content changes over 1971-2005

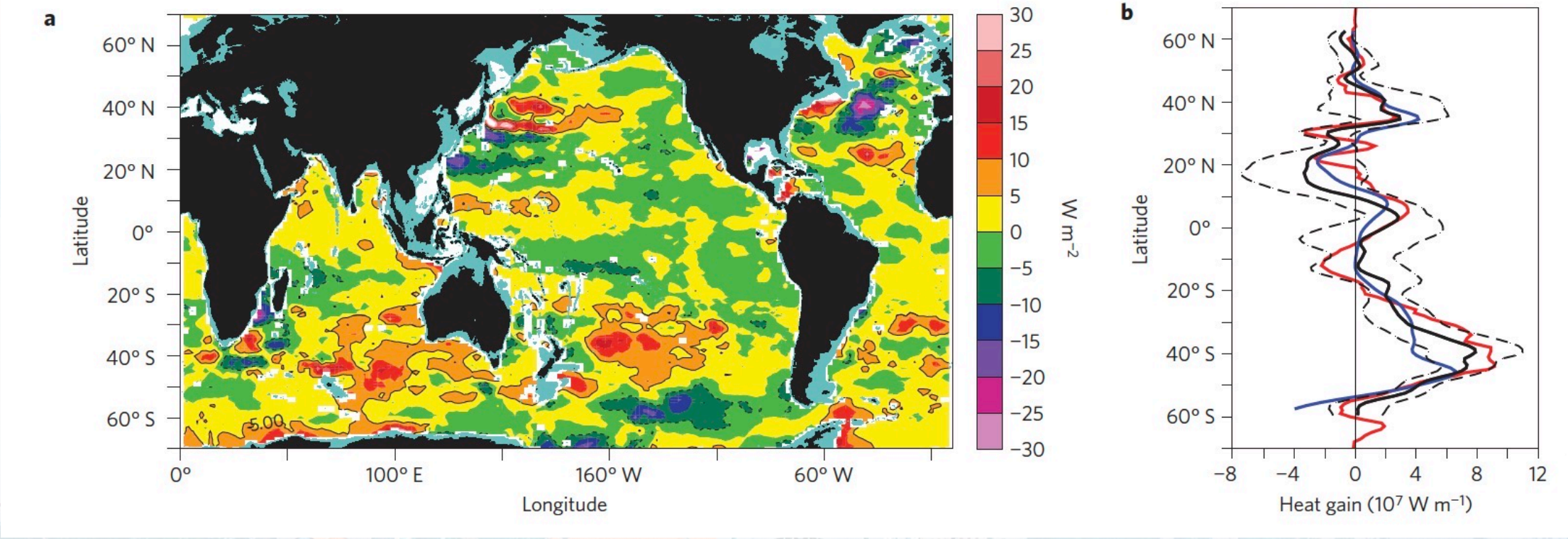
- While CMIP5 MMM is close to observational trend, the **CMIP6 MMM significantly underestimates the warming rate over 1971-2005**
- Especially, **most high climate sensitivity models show the least warming trends** over this period, in stark contrast to the Argo period

Preliminary analysis of single forcing experiments



- Model-dependent and time-evolving partial **offset between GHG and aerosol**;
- Unlike global surface temperature, the global ocean heat content shows **delayed response to the stabilized aerosol forcing**, with slowdown in aerosol cooling only until very recently
- Non-negligible global ocean warming effect from **tropospheric ozone forcing**

Ocean warming is NOT spatially uniform

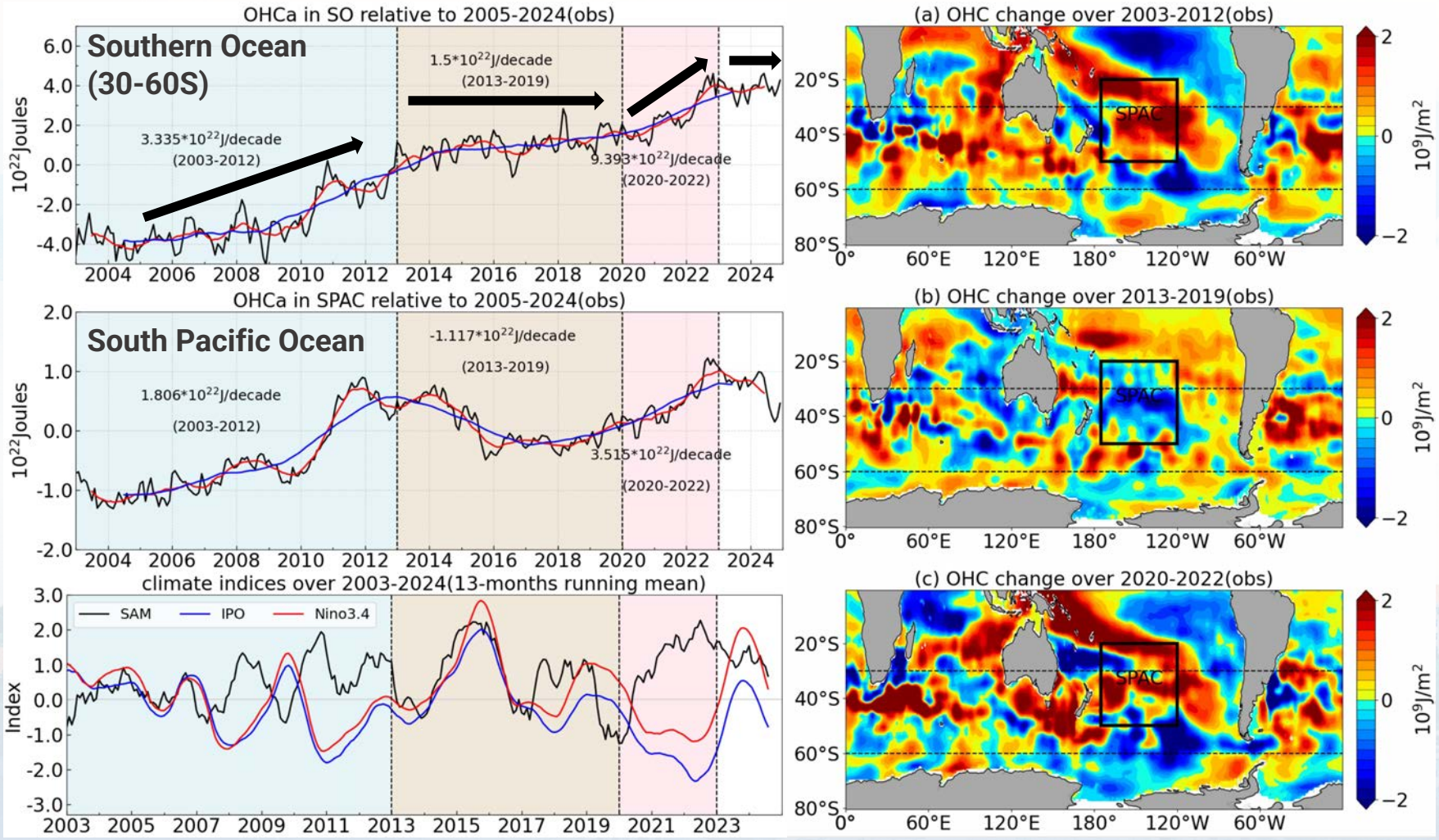


Upper 2000m depth integrated ocean heat content change **over 2006-2013** (Roemmich et al. 2015)

Most (67~98%) of the ocean warming occurred in the Southern Hemisphere extratropical Ocean:

consistent with stronger aerosol forcing in the NH? ocean dynamics?

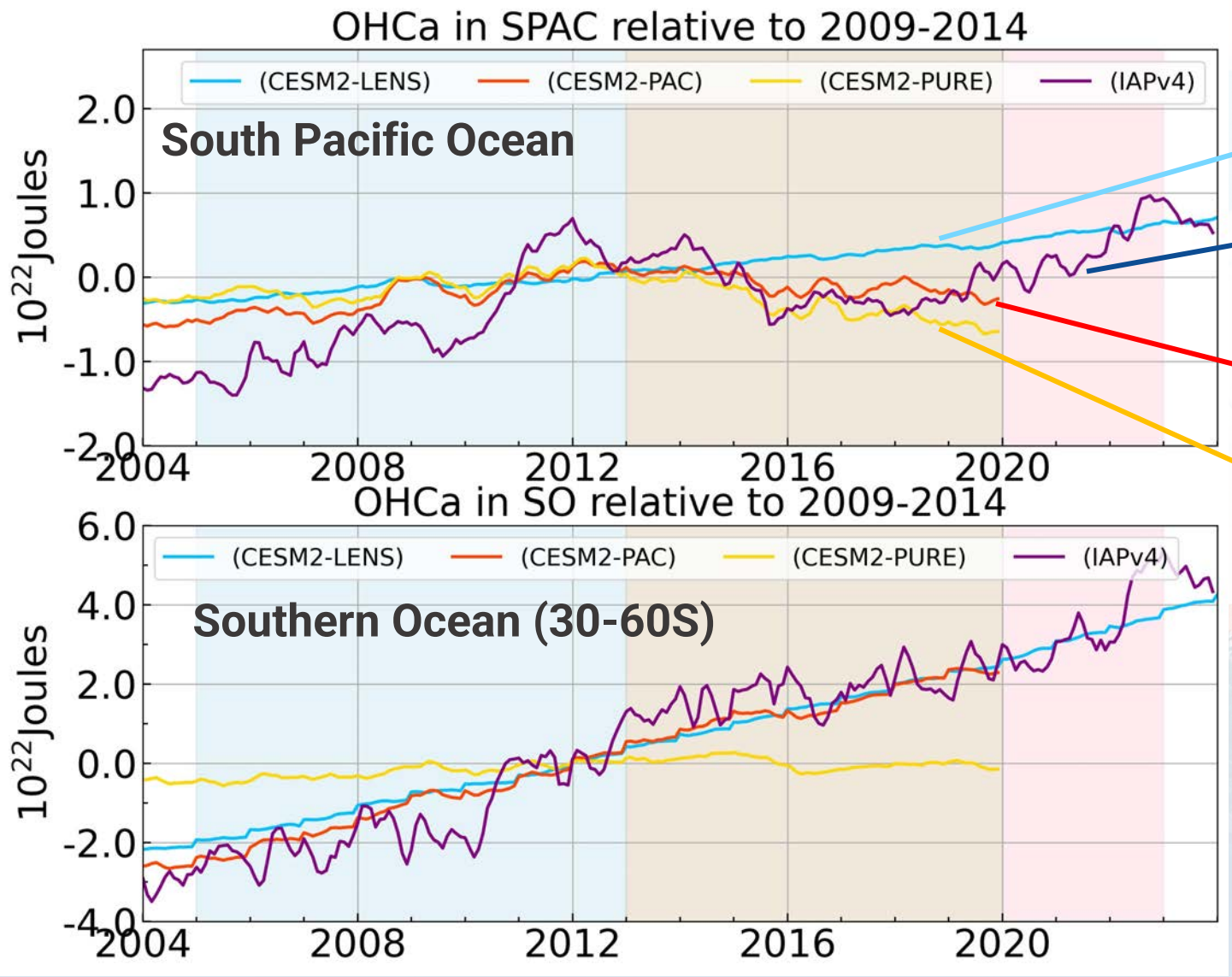
Updated Argo record reveals substantial variations



Upper 2000m depth integrated ocean heat content changes
(good consistency between IAP, ishii, EN4, Scripps Argo)

- The Southern Ocean warming and the South Pacific Ocean hotspot experienced several shifts in the warming rate;
- **Rapid warming** occurred before 2013 and over 2020-2022, accompanied by **positive SAM trend and La Niña-like change**

Roles of tropical teleconnection – evidence from CESM2 large ensemble and pacific pacemaker experiments



CESM2 large ensemble average

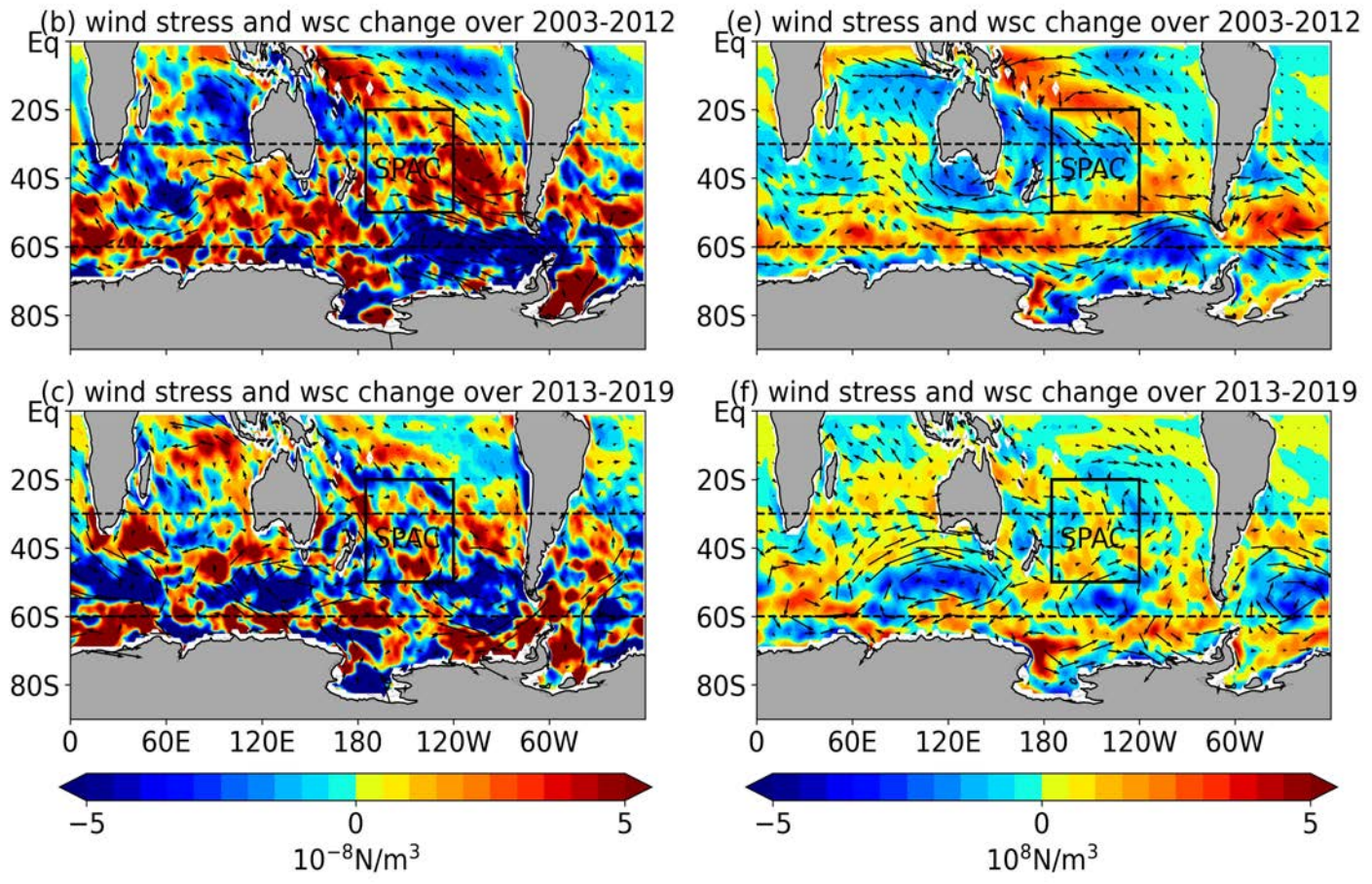
Observations

CESM2 tropical Pacific pacemaker ensemble average (updated until 2019)

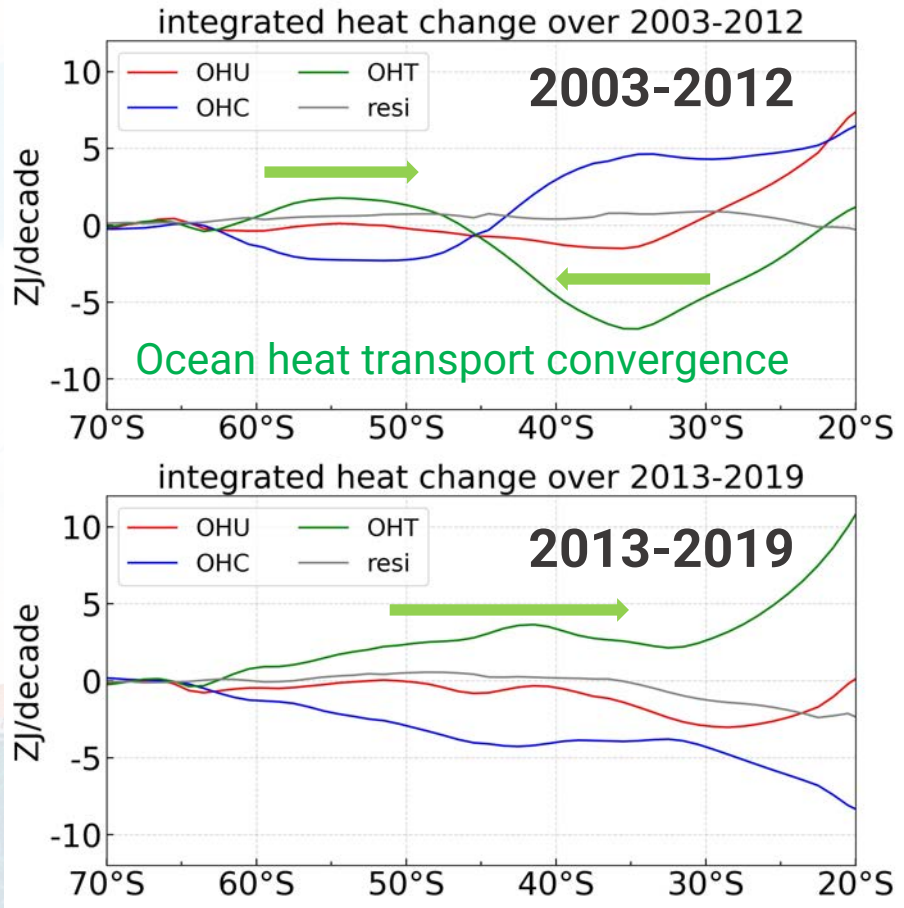
Difference between LENS and Pacific pacemaker

Accounts for ~ half of the Southern Ocean warming slowdown before/after 2013

Mechanisms for TP teleconnection impacts on the Southern Ocean warming



Wind stress and curl changes from (left) JRA-55 and (right) PAC minus LENS



Ocean heat uptake, transport, and storage budget based on PAC minus LENS

Summary

- **High climate sensitivity models** tend to **overestimate global ocean heat content increase over the Argo period** since 2005 – a (most) useful constraint for future projections.
- However, most of them significantly **underestimate the warming over 1971-2005**, indicating a possibility that their responses to aerosol forcing are also too strong (further evidence is needed from LESFMIP and D&A effort would help to constrain model responses).

- The Argo record since 2005 witnessed **several interannual-to-decadal shifts in the Southern Ocean warming rate.**
- Evidence from CESM large ensemble and pacific pacemaker experiments confirms **the important role of tropical Pacific teleconnections,** mainly through the anomalous meridional ocean heat transport related to gyre circulation spin up/down.