

Improved Simulations of Southern Ocean and Tropical Eastern Pacific Trends in High-Resolution Earth System Models

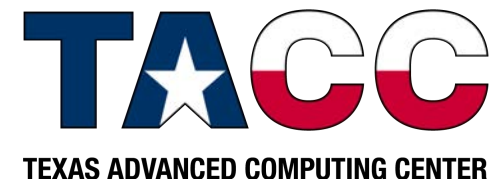
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Qiuying Zhang¹, Gaopeng Xu¹, Pedro DiNezio³, Nan Rosenbloom², Teagan King²*

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US CLIVAR Workshop on Confronting Earth System Model Trends with Observations: The Good, the Bad, and the Ugly
13-15 March 2024, Boulder, Colorado, USA



CESM1.3-HR(0.25° a/l & 0.1° o/i) Climate Simulations

1. CMIP6 HighResMIP Ensemble (See Roberts et al, 2020a, b)
 - Tier 1 - 1950-2014 AMIP (65 years)
 - Tier 2 - 1950 control and 1950-2100 transient (230 years)
 - Tier 3 - 2015-2050 AMIP (35 years)

HighResMIP Set
2. CMIP DECK Set (See Chang et al. 2020)
 - 1850 Pre-industrial control (650 years)
 - 1850 – 2100 historical and future climate simulation under RCP 8.5 (250 years)
 - Ensemble of 9 1920 – 2100 climate simulations under RCP8.5 (9x180 years)
 - Ensemble of 6 2005 – 2100 climate simulations under RCP6.0 (6x95 years)
 - One 2005-2100 climate simulation under RCP4.5 (95 years)
 - One 2005-2100 climate simulation under RCP2.6 (95 years)
 - 1% CO2 simulation (150 years)
 - 4xCO2 simulation (150 years)
 - Ensemble of 3 1950-2015 AMIP (3x65 years)

HR DECK Set
3. Decadal Prediction Ensemble (Yeager et al. 2023)
 - 5 cycles of forced ocean-sea ice (FOSI) simulations from 1958 to 2018 (5x61 years)
 - Ensembles of 5-year, 10-member decadal prediction runs (1970 – 2022) (28x50 years)

HRDP Set

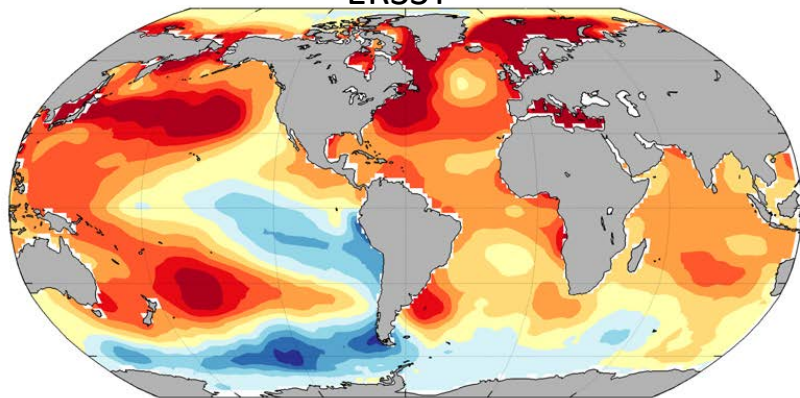
Total simulation years: ~ 6,000 years; Simulation datasets: ~ 6 PB

Cost ratio of HR (~0.25° atm/Ind & 0.1° ocn/ice) to LR (~1°) CESM ~ O(100)

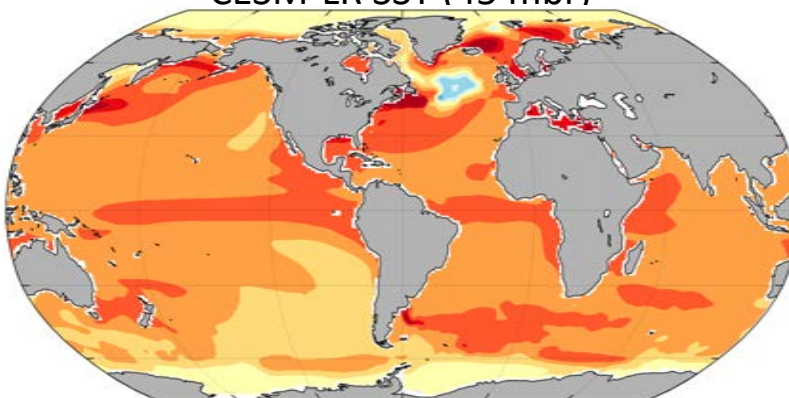
Linear Trend (1980-2022)

(Courtesy of Qiuying Zhang)

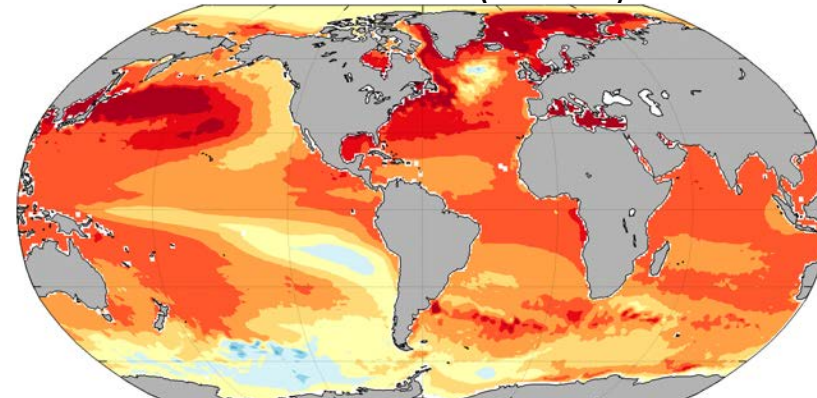
ERSST



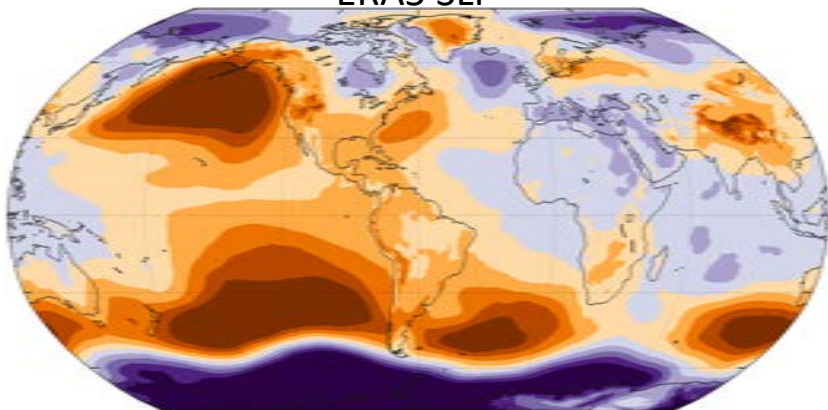
CESM-LR SST (45 mbr)



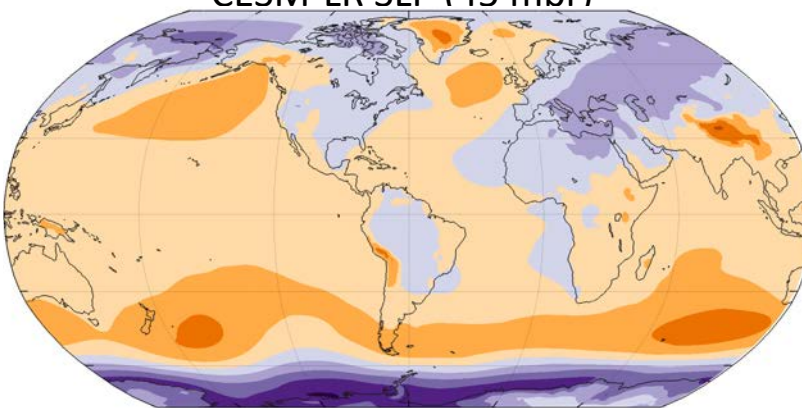
CESM-HR SST (10 mbr)



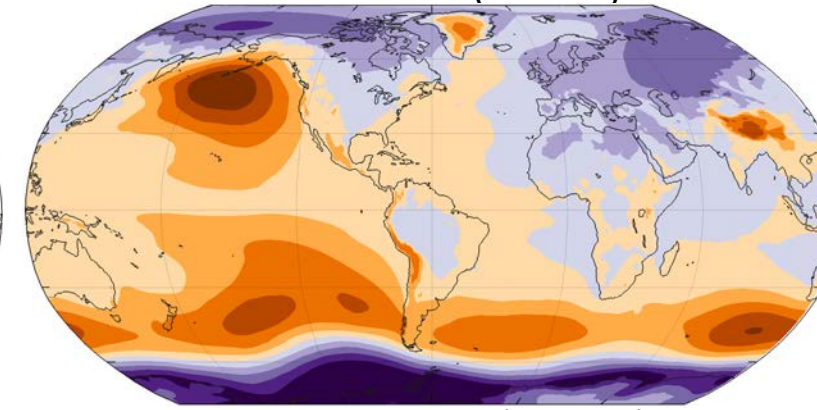
ERA5 SLP



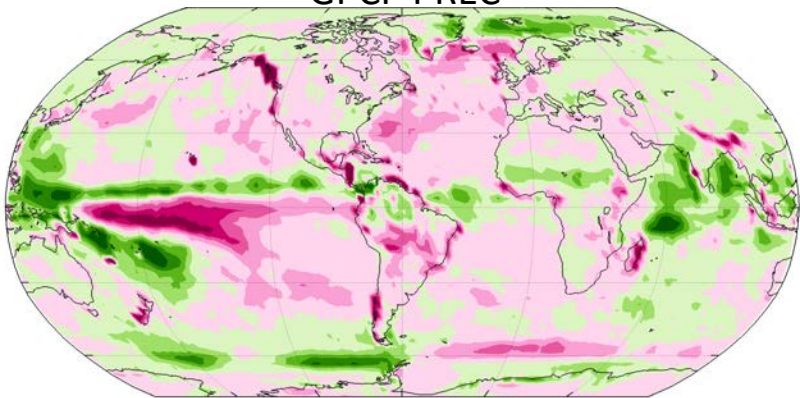
CESM-LR SLP (45 mbr)



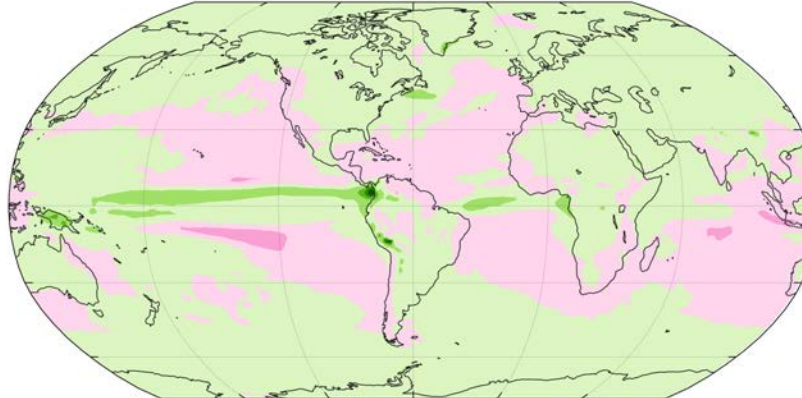
CESM-HR SLP (10 mbr)



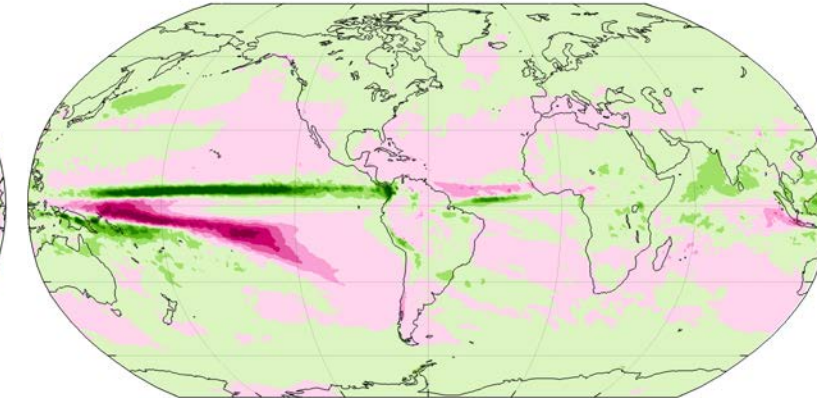
GPCP PREC



CESM-LR PREC (45 mbr)



CESM-HR PREC (10 mbr)



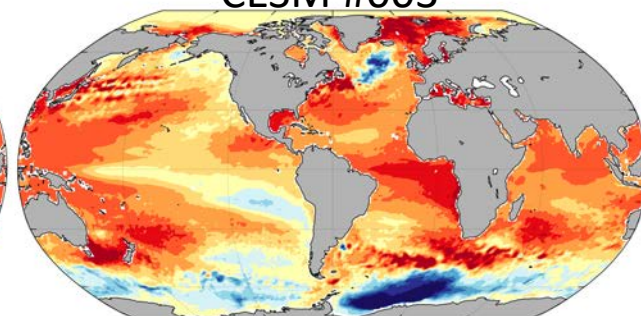
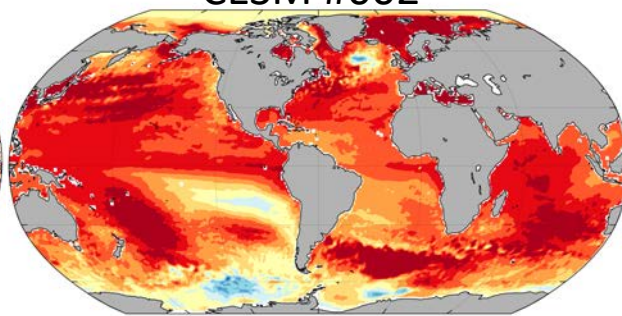
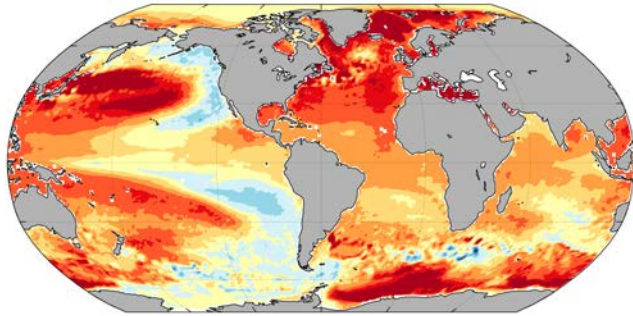
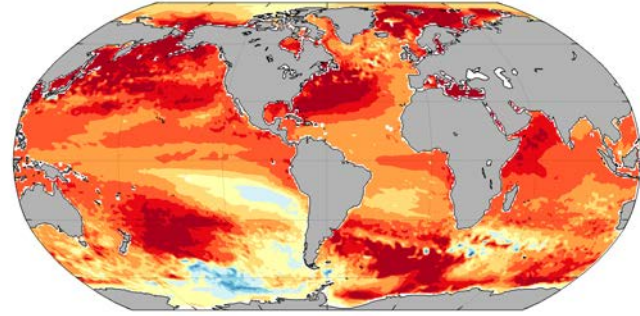
Linear Trend (1980-2022) in Each Ensemble Member

CESM-HRMIP

CESM #001

CESM #002

CESM #003

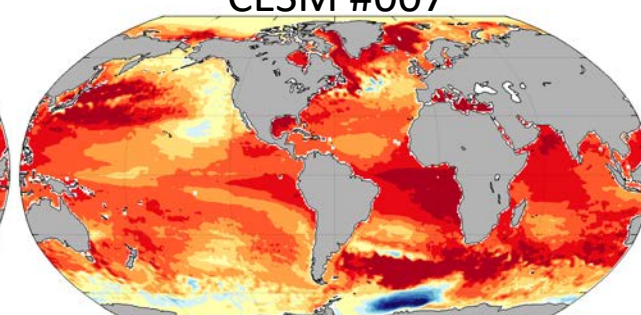
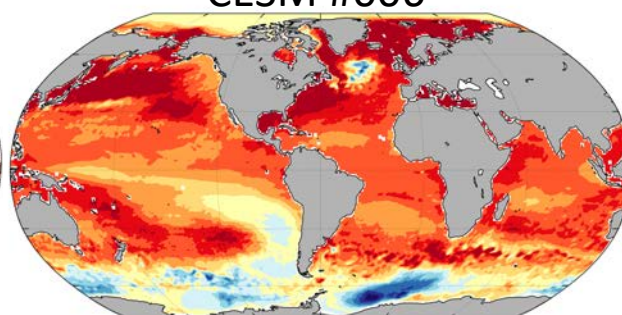
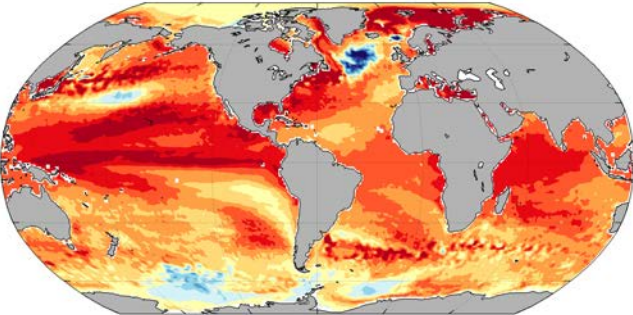
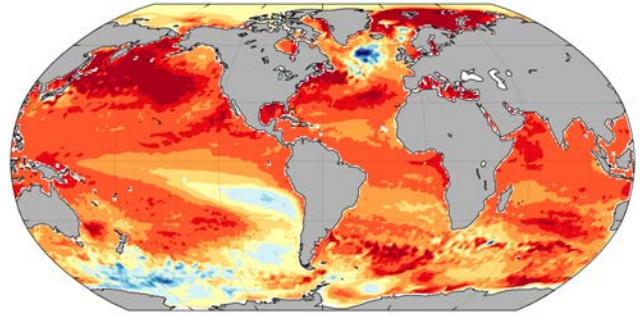


CESM #004

CESM #005

CESM #006

CESM #007

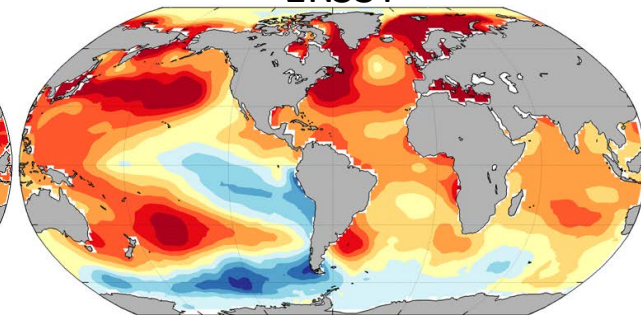
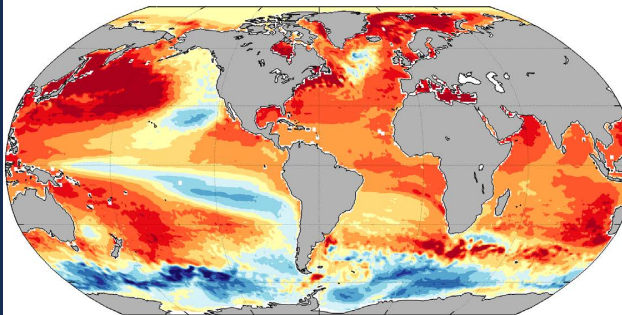
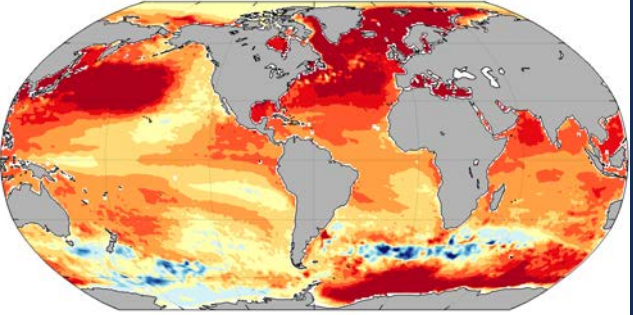
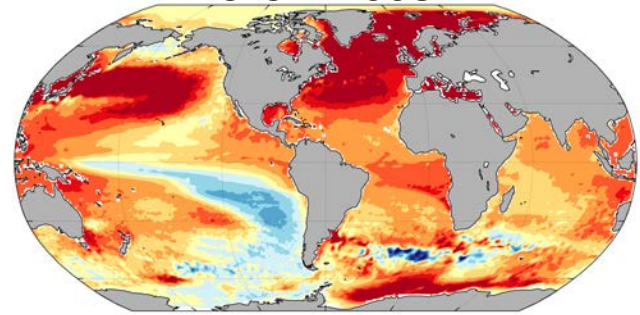


CESM #008

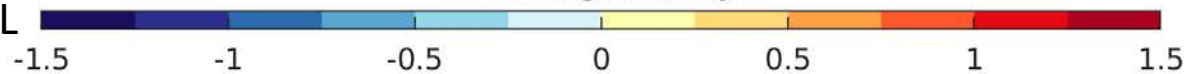
CESM #009

CESM #010

ERSST



SST change [$^{\circ}\text{C}/43\text{yr}$]



After removing linear trend in CTRL

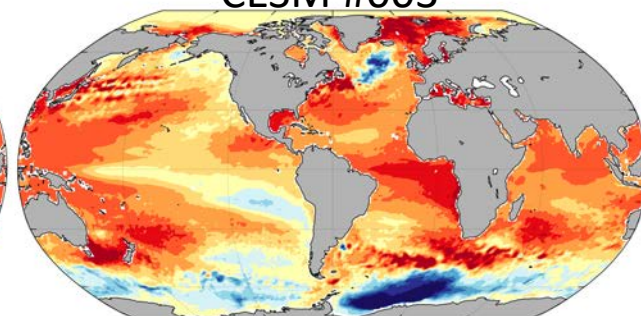
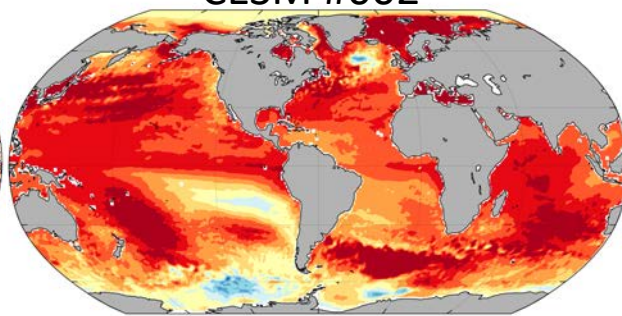
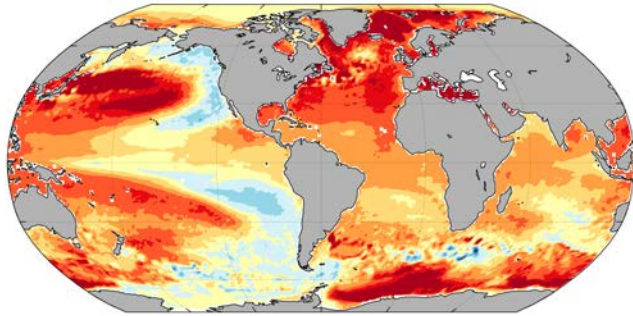
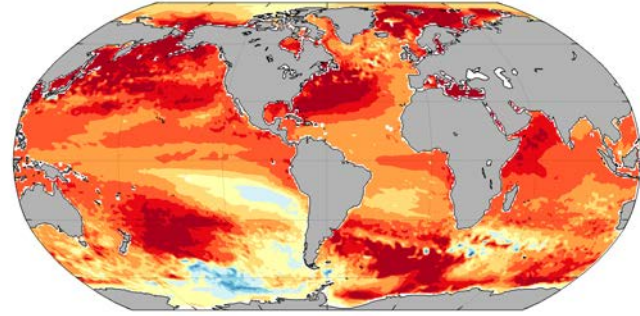
Linear Trend (1980-2022) in Each Ensemble Member

CESM-HRMIP

CESM #001

CESM #002

CESM #003

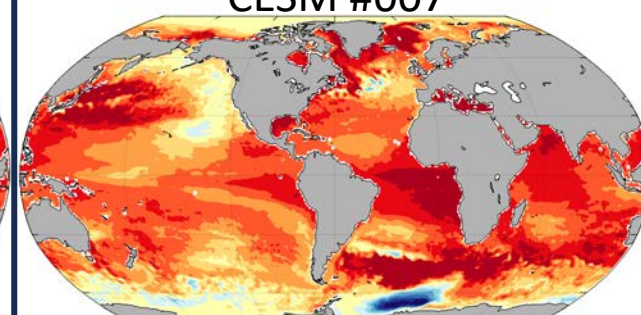
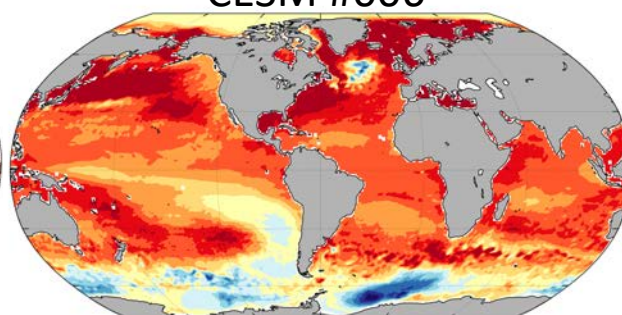
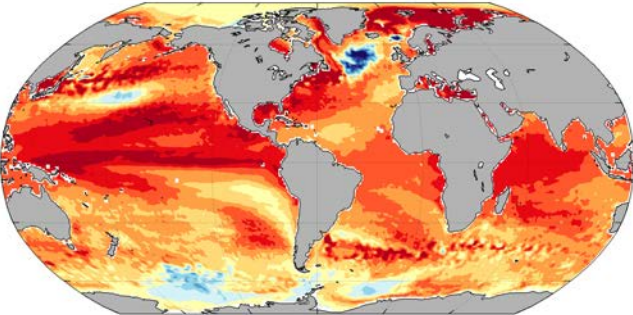
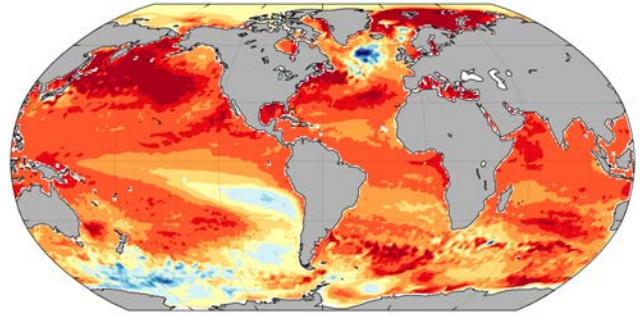


CESM #004

CESM #005

CESM #006

CESM #007

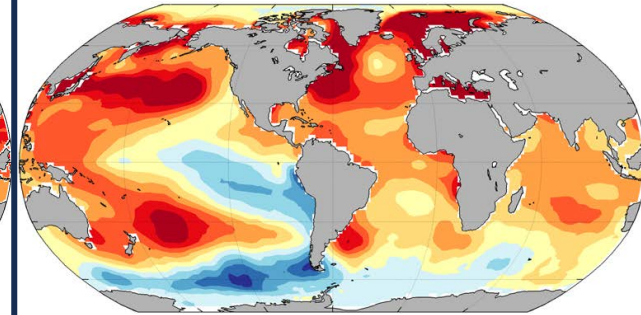
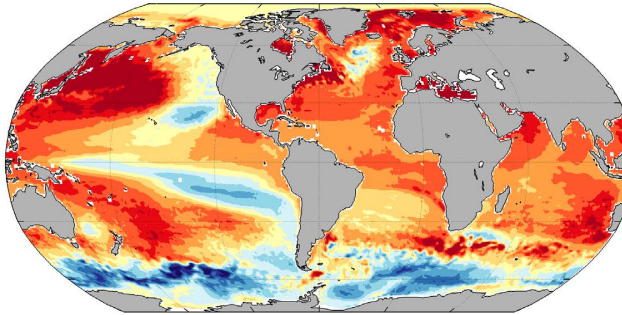
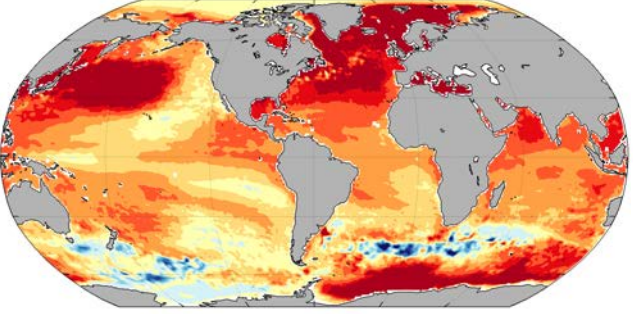
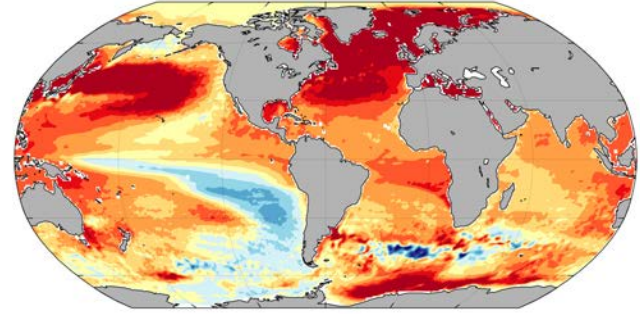


CESM #008

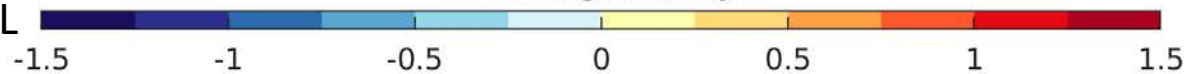
CESM #009

CESM #010

ERSST

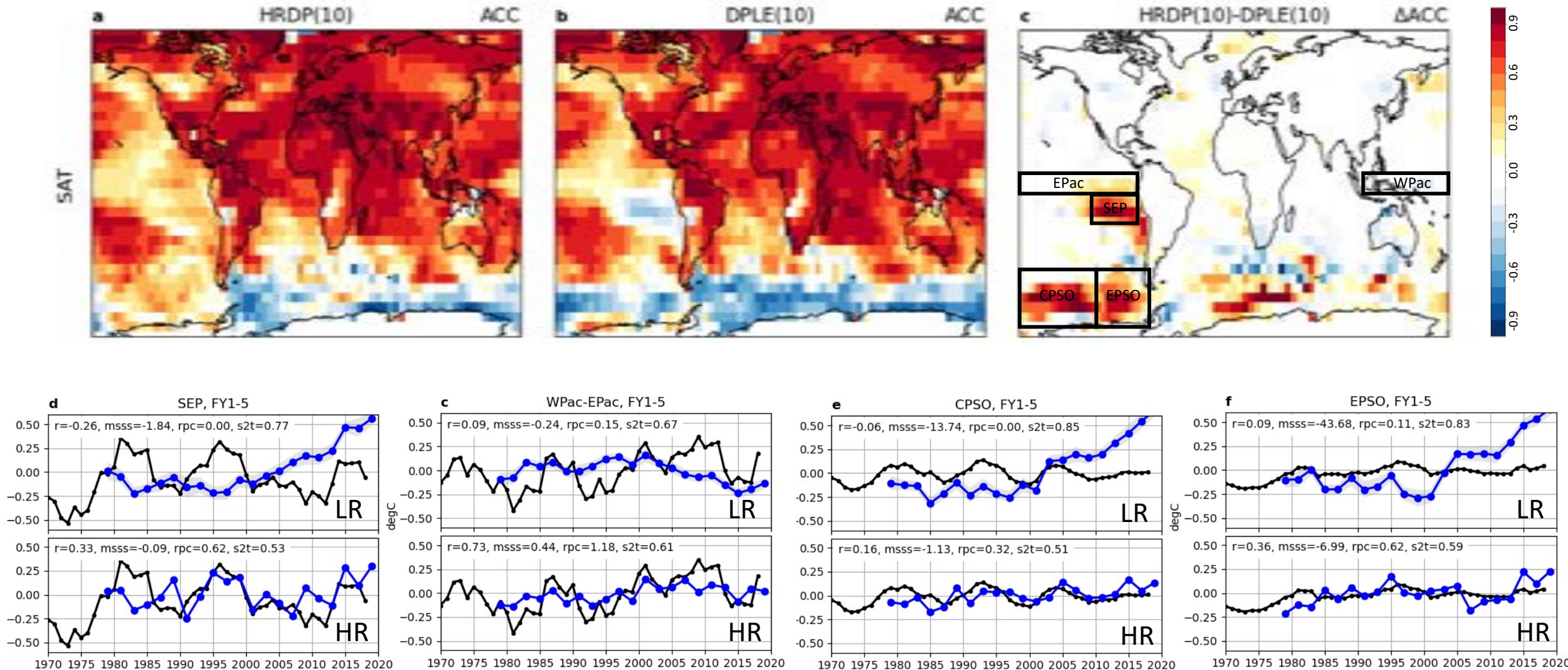


SST change [$^{\circ}\text{C}/43\text{yr}$]



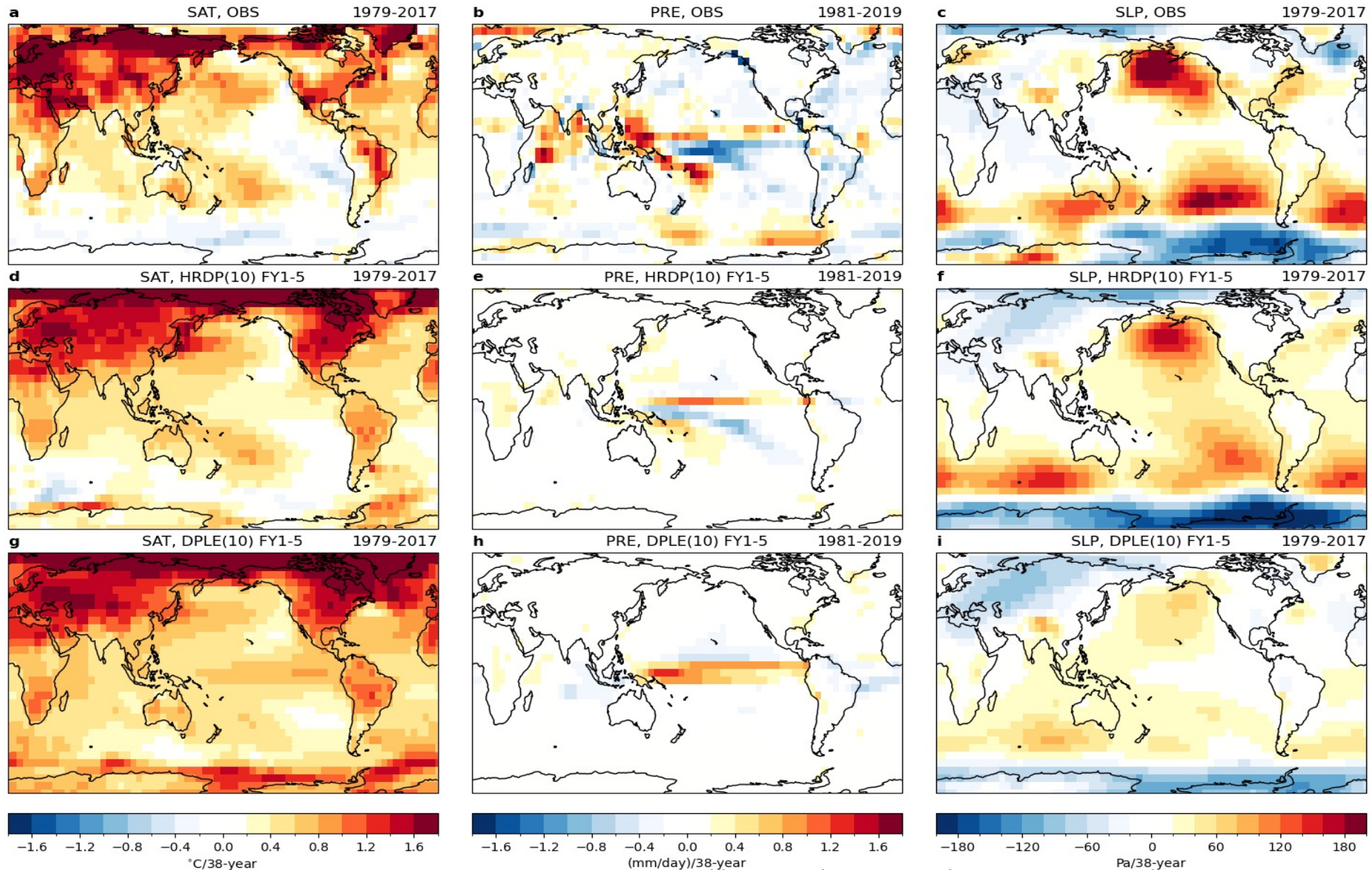
After removing linear trend in CTRL

Multi-Year SAT Prediction in CESM1-HR and -LR



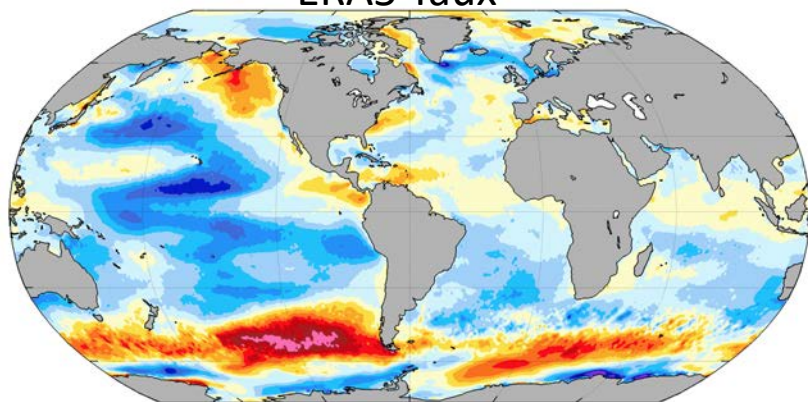
From Yeager et al. (2023), *njp Clim. Atmos.* <https://doi.org/10.21203/rs.3.rs-1792406/v1>

Observed and Predicted Linear Trends

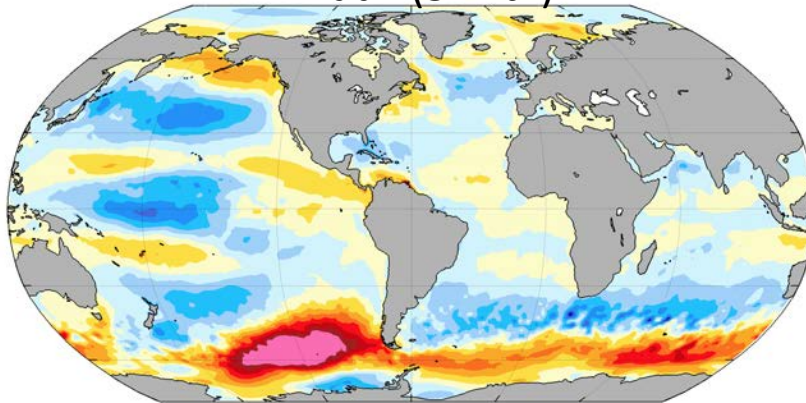


Linear Trend in HR and LR AMIP Simulations (1980-2014)

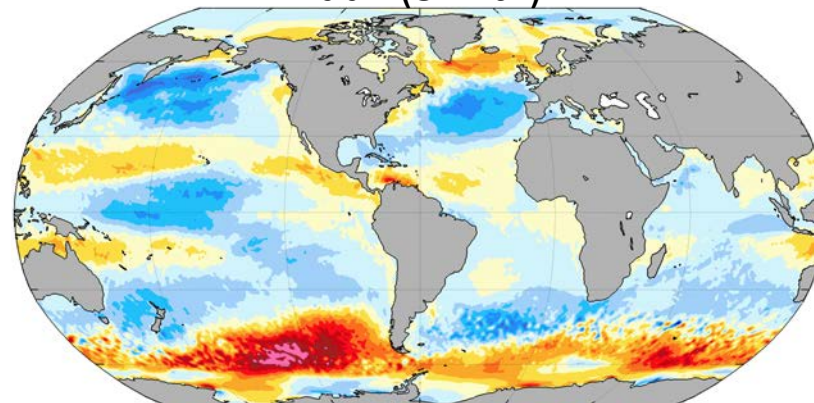
ERA5 Taux



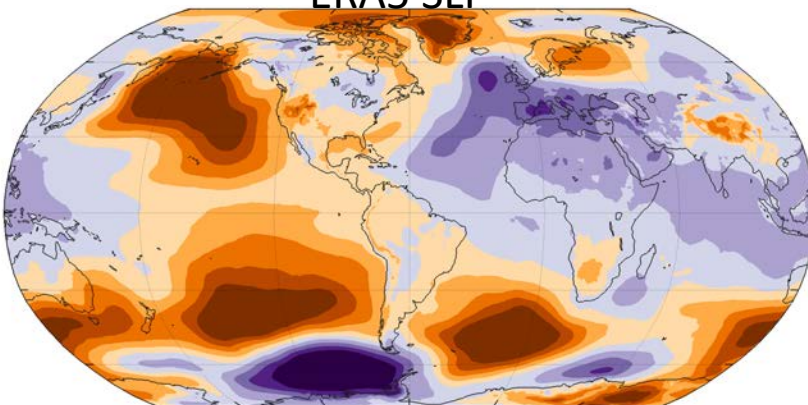
LR Taux (5 mbr)



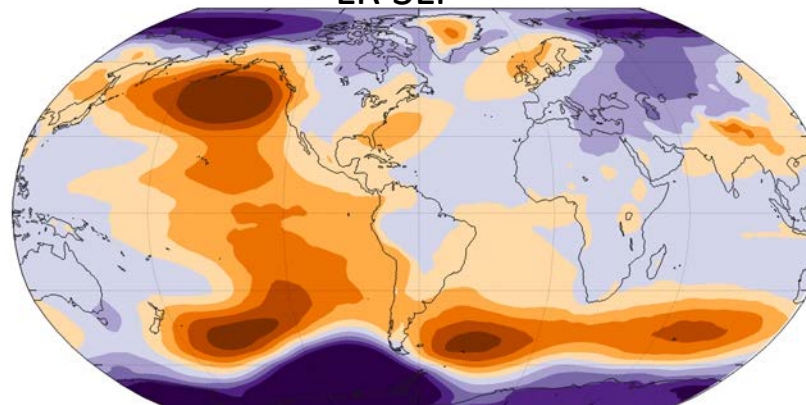
HR Taux (3 mbr)



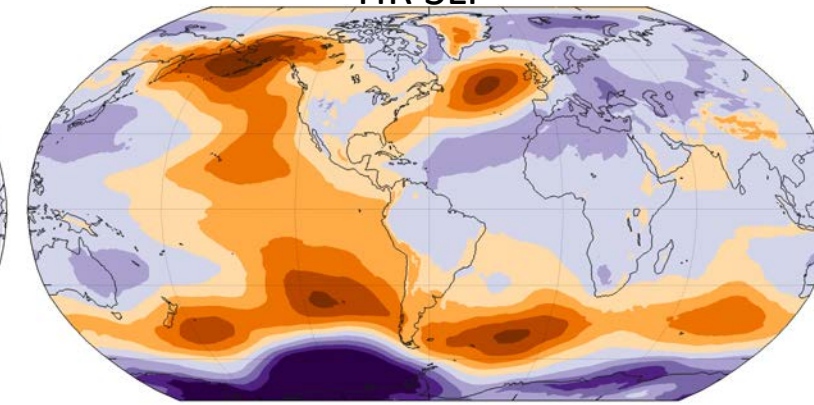
ERA5 SLP



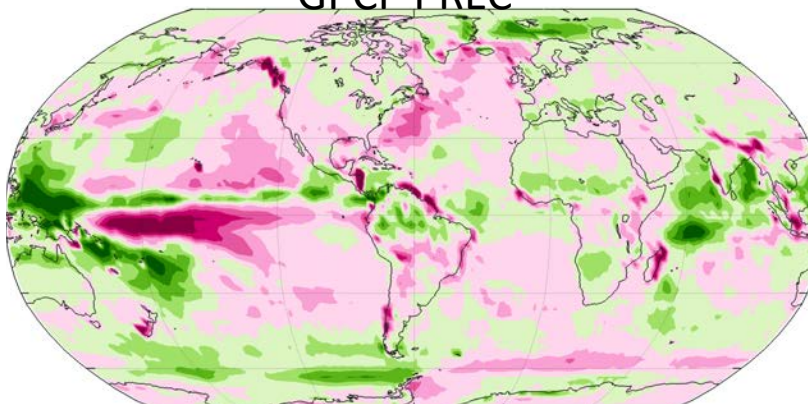
LR SLP



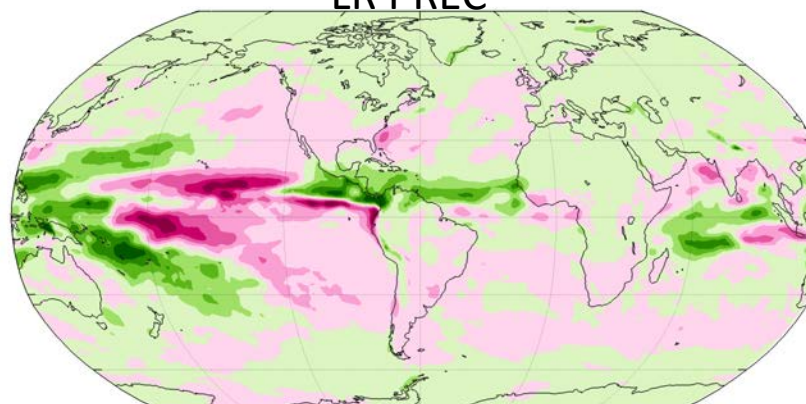
HR SLP



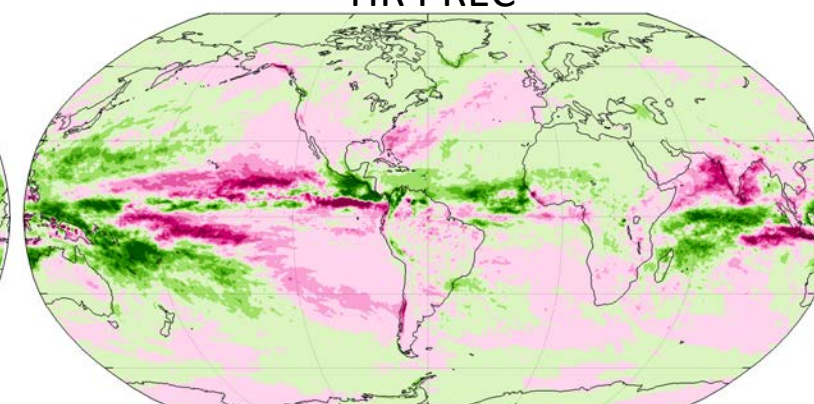
GPCP PREC



LR PREC

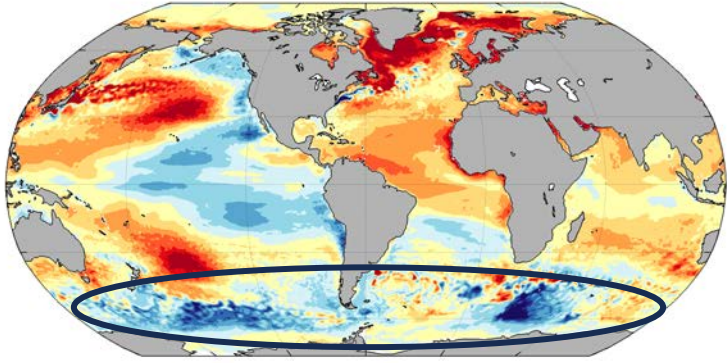


HR PREC

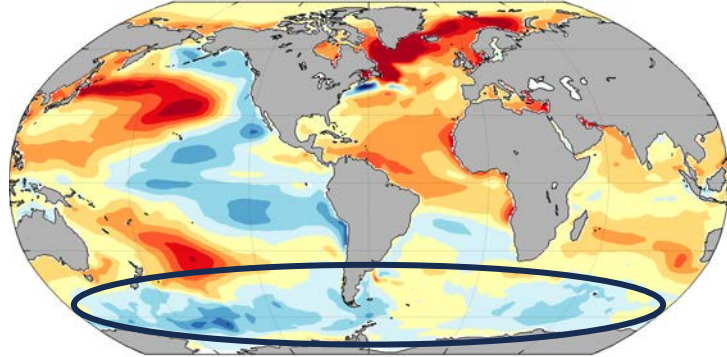


HR and LR Forced Ocean Sea-Ice (FOSI) Simulations

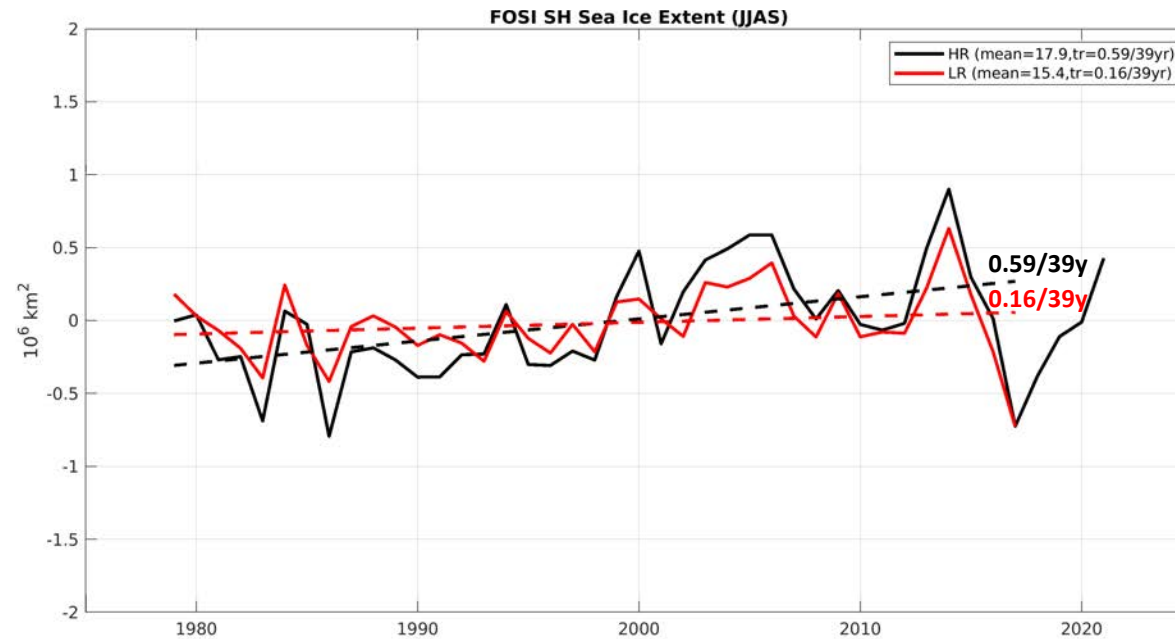
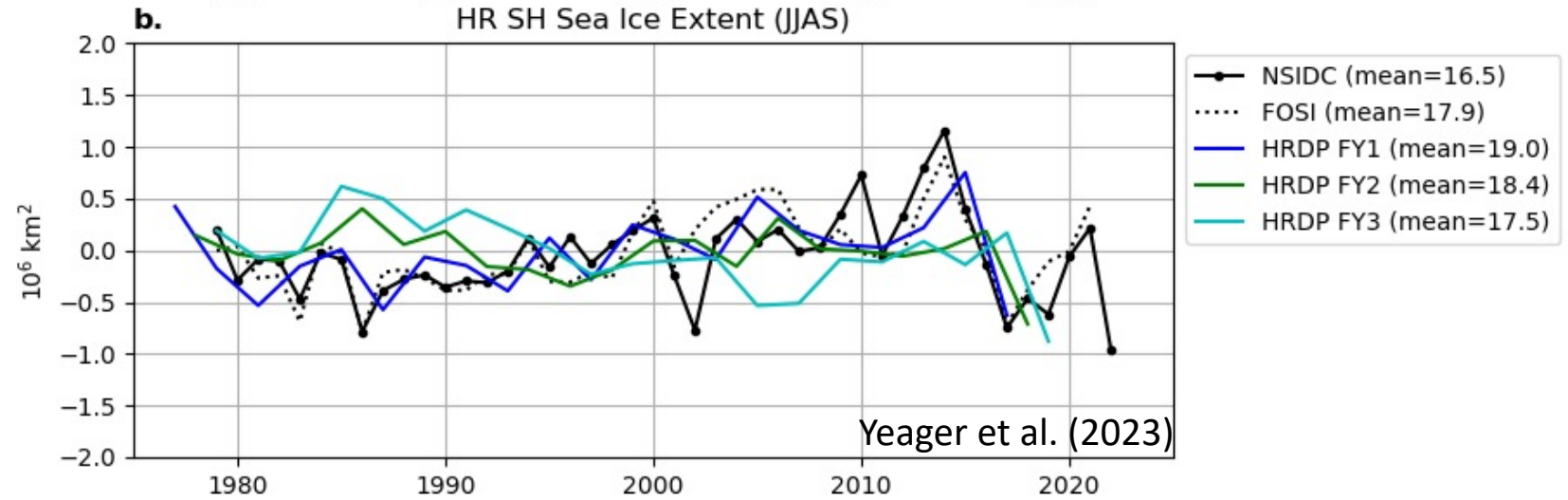
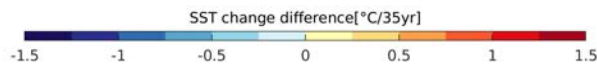
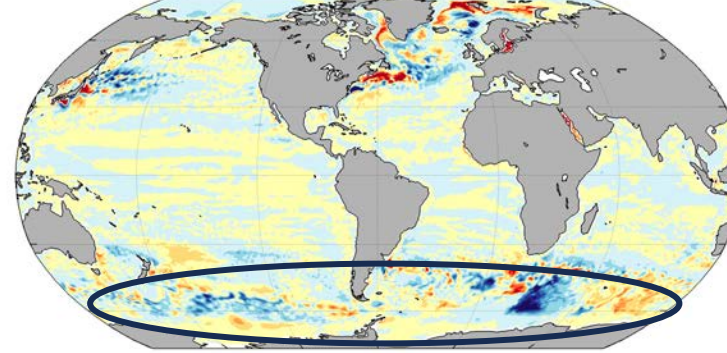
HR FOSI SST Trend



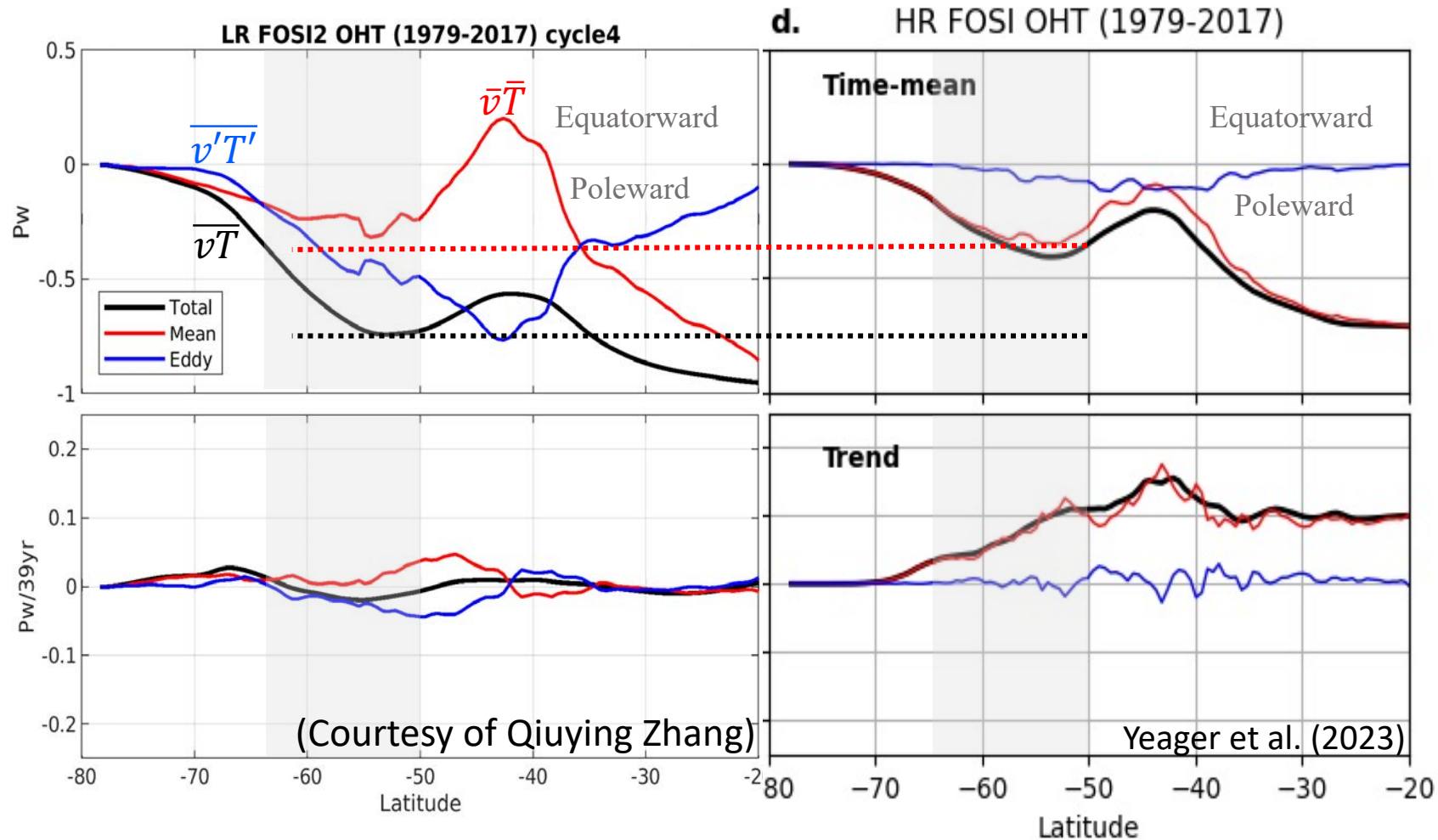
LR FOSI SST Trend



HR-LR FOSI SST Trend



Meridional Ocean Heat Transport in FOSI

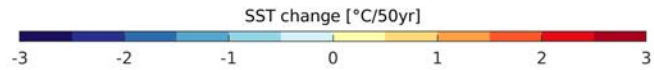
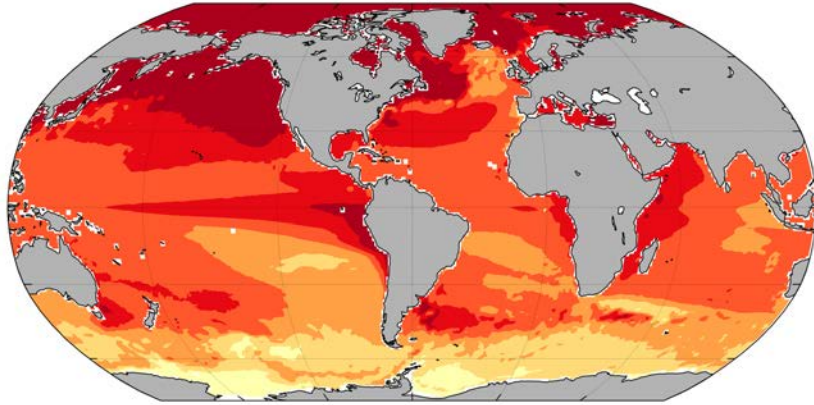


- HR transports less heat poleward than LR
- This OHT difference is primarily due to the difference in eddy heat transport
- HR also shows a much stronger positive trend in OHT

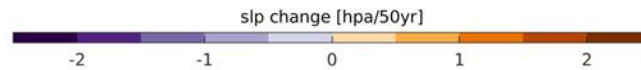
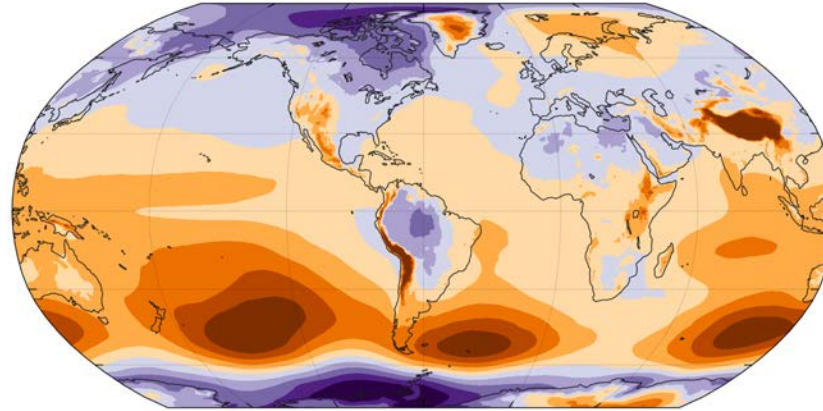
Hypothesis: Explicitly representing ocean eddies in HR is mainly responsible for the improved SO trends!

Future Changes (2051-2100)

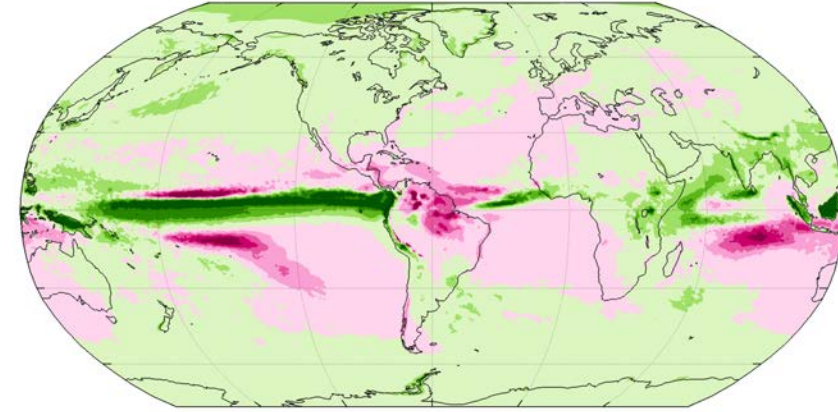
HR SST Trend (2051-2100)



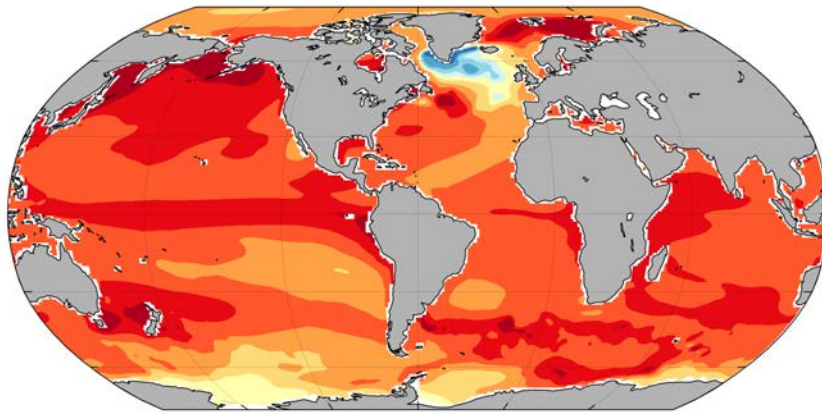
HR SLP Trend (2051-2100)



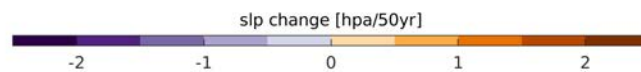
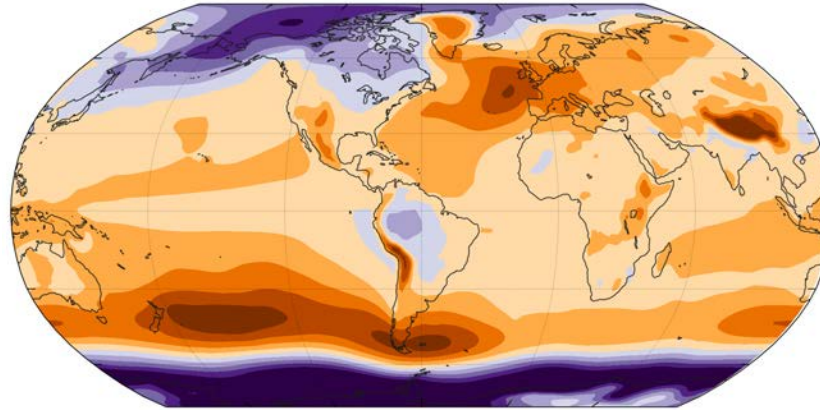
HR PREC Trend (2051-2100)



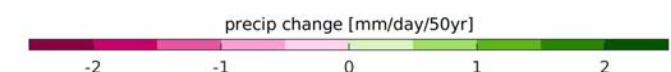
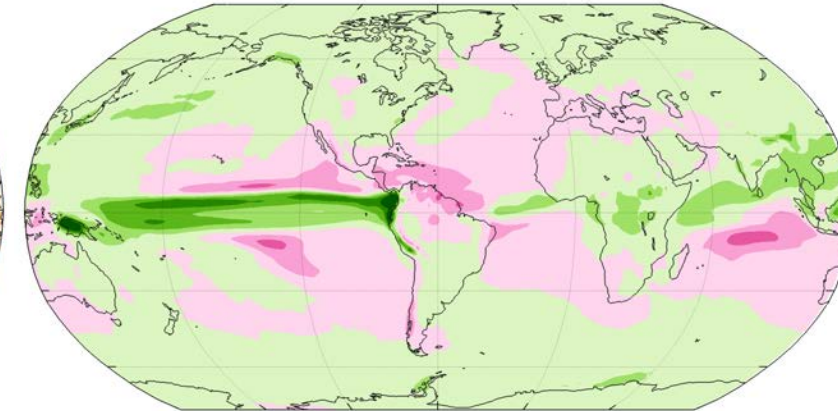
LR SST Trend (2051-2100)



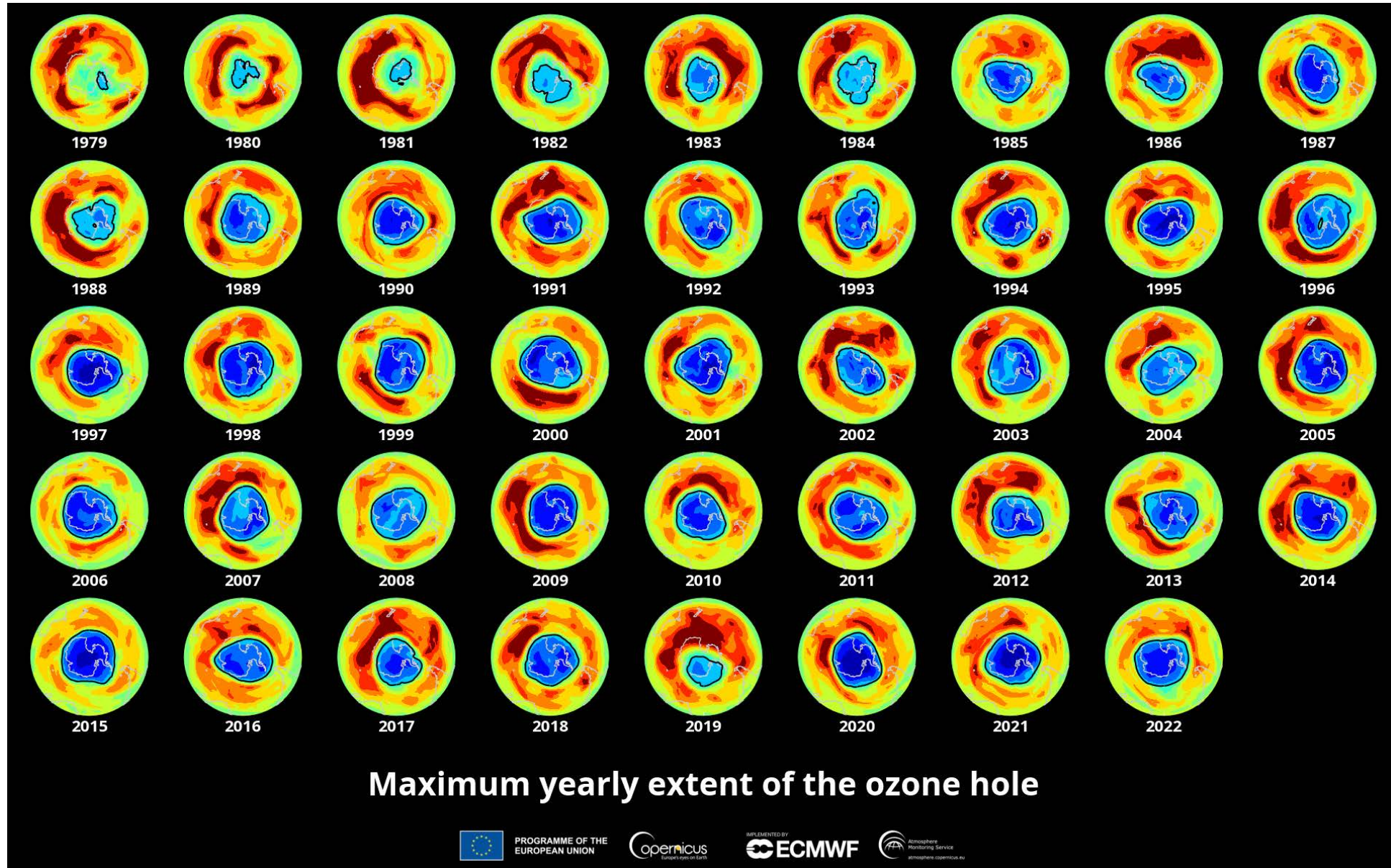
LR SLP Trend (2051-2100)



LR PREC Trend (2051-2100)



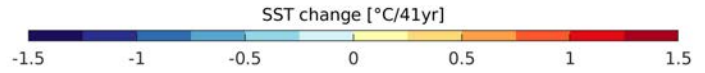
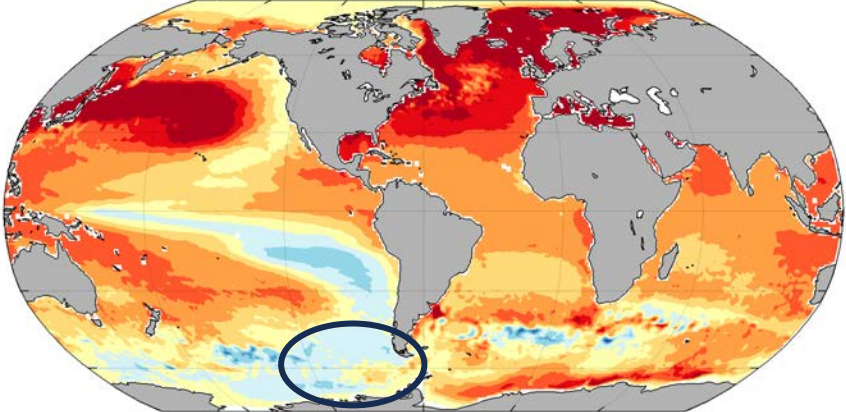
Antarctic Ozone Hole



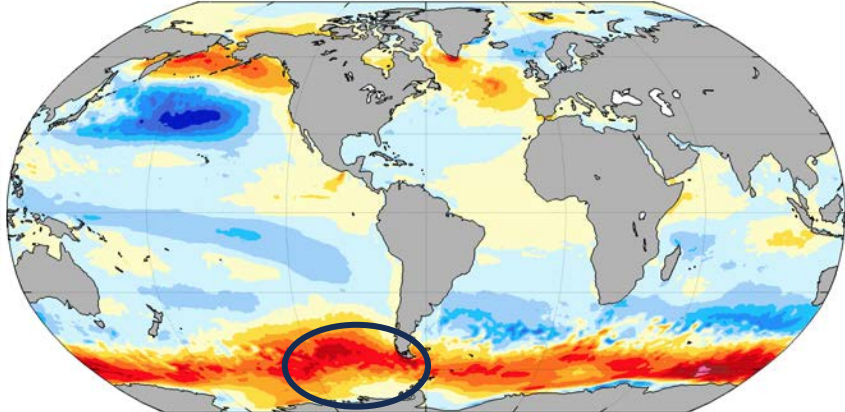
<https://atmosphere.copernicus.eu/three-peculiar-antarctic-ozone-hole-seasons-row-what-we-know>

1980-2020 Trends in CESM-HR with Constant O3 for 1970-2020

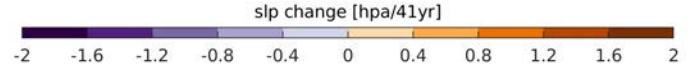
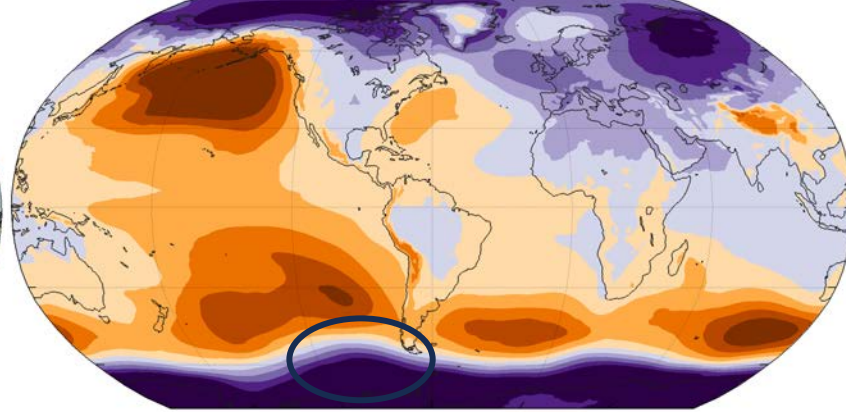
CESM-HR SST Trend (3mbr)



CESM-HR Taux Trend (3mbr)

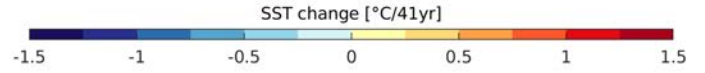
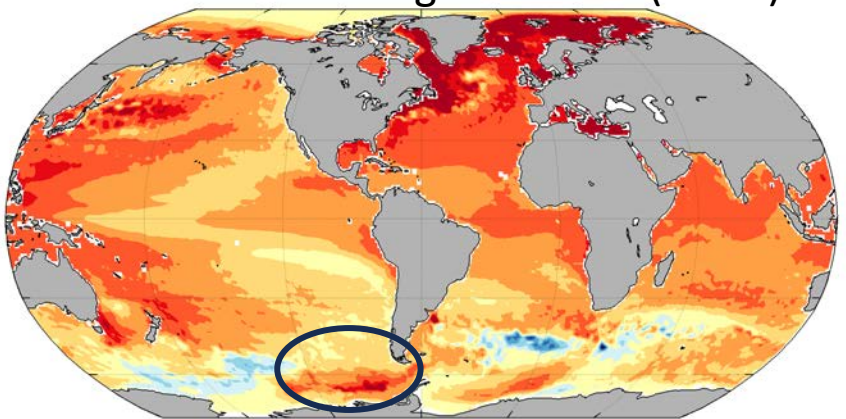


CESM-HR SLP Trend (3mbr)

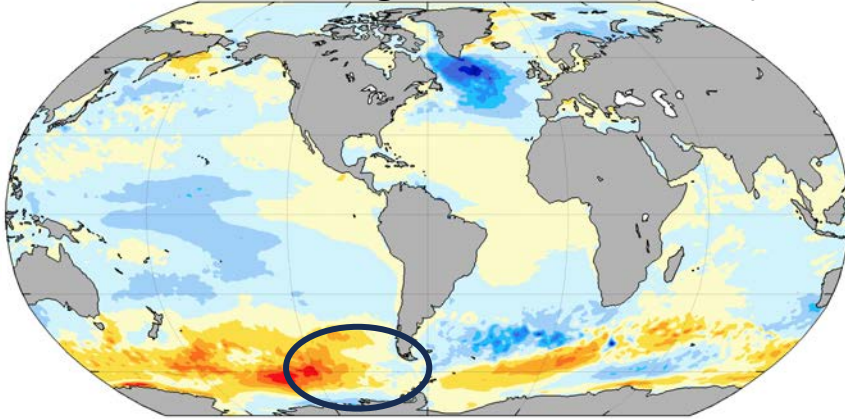


(Courtesy of Qiuying Zhang)

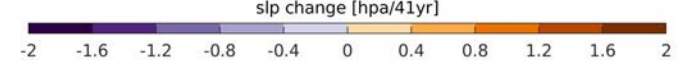
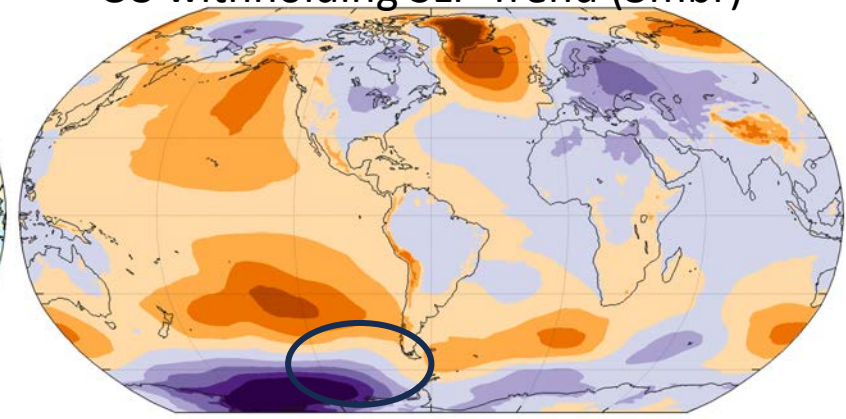
O3 withholding SST Trend (3mbr)



O3 withholding Taux Trend (3mbr)

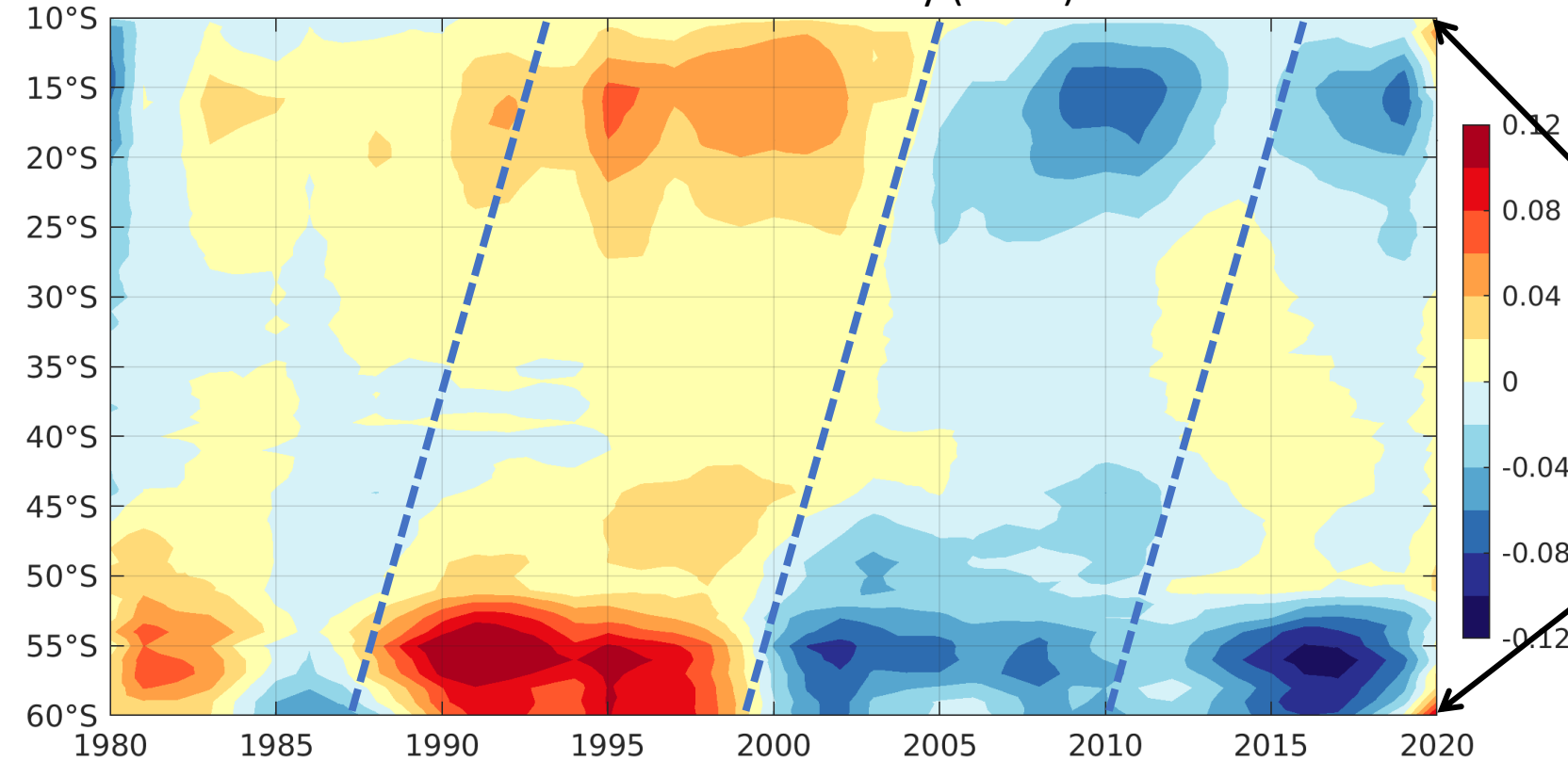


O3 withholding SLP Trend (3mbr)

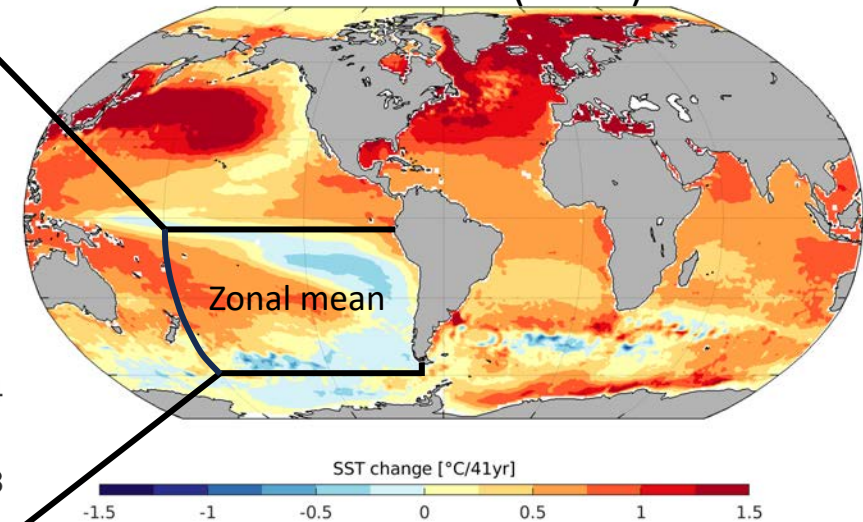


Zonally averaged SST in Southeastern Pacific

Zonal Mean SST Anomaly (6mbr)



CESM-HR SST (6mbr)

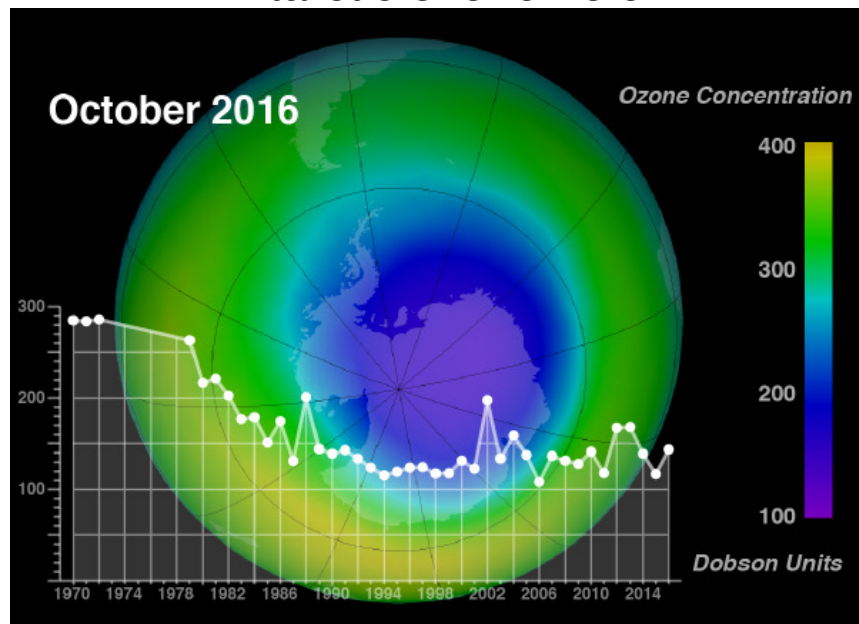


SST change [°C/41yr]

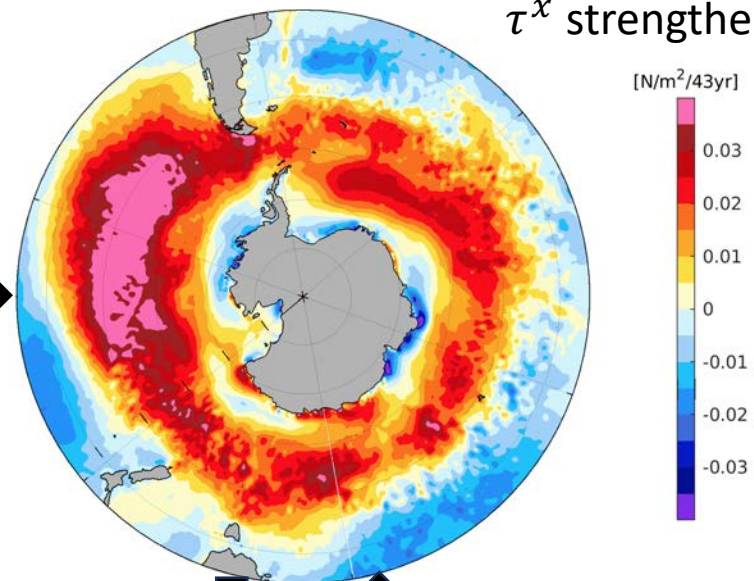


Mechanism (Hartmann 2022)

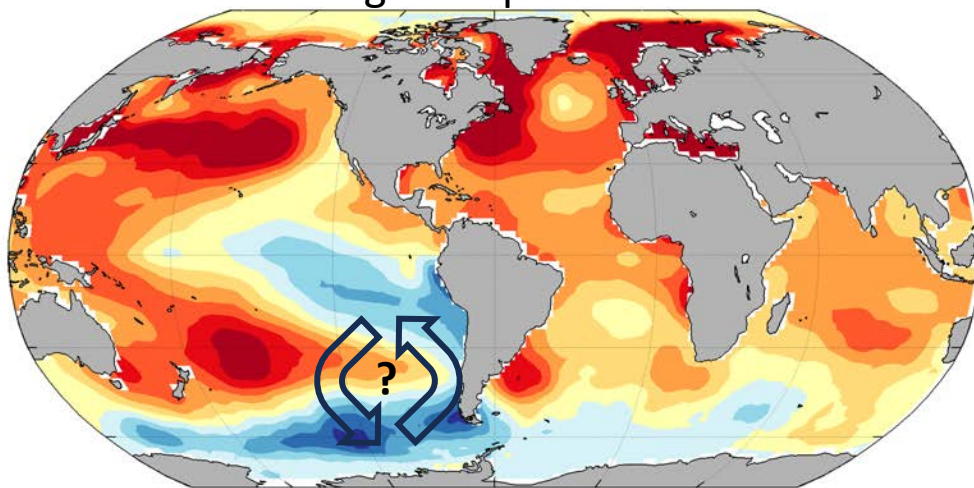
Antarctic ozone hole



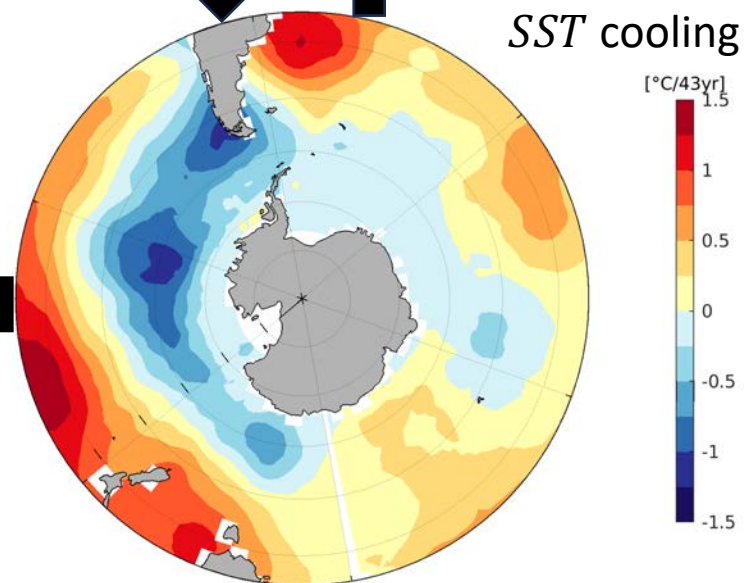
τ^x strengthening



Cooling in tropical Pacific



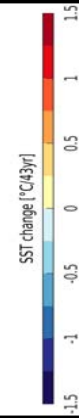
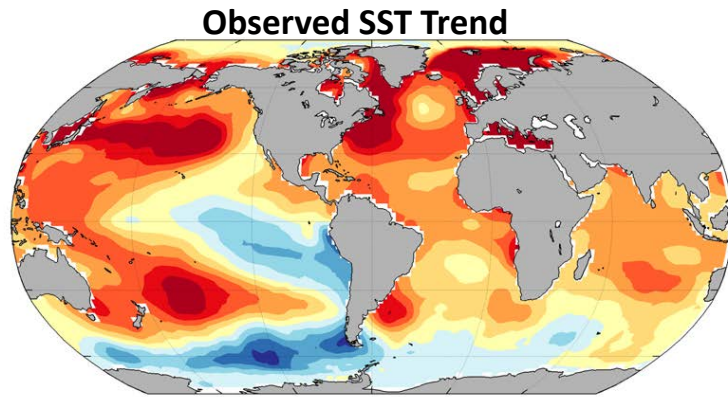
SST cooling in SO



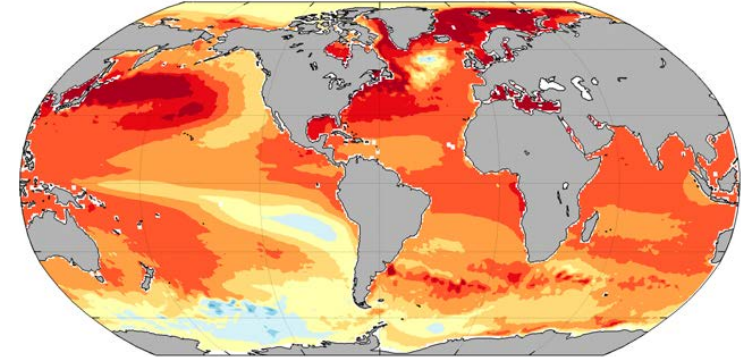
Summary

- **The Good:**

Improved trends in HR simulations

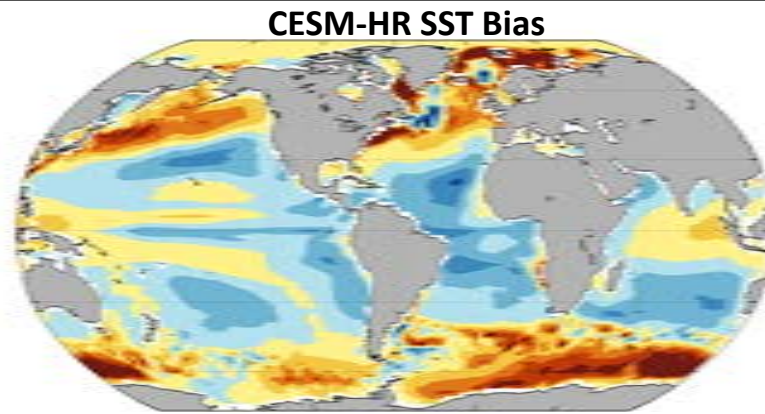


HR-Simulated SST Trend

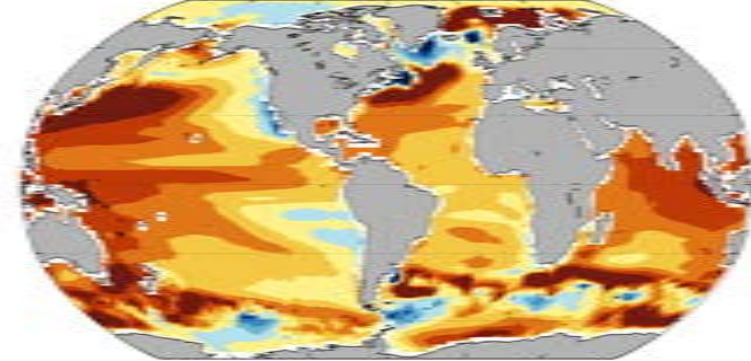


- **The Bad:**

SO warm SST bias worsens



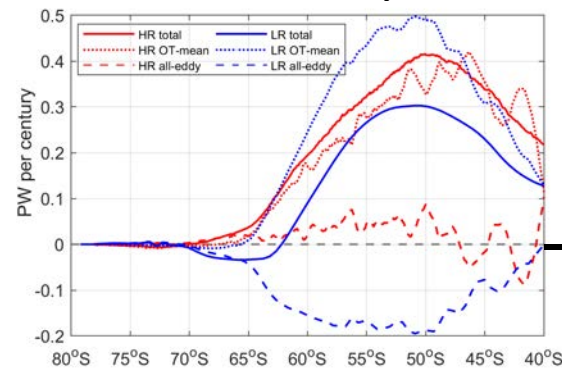
CESM-HR minus CESM-LR



- **The Ugly:**

Inconsistent eddy heat transports

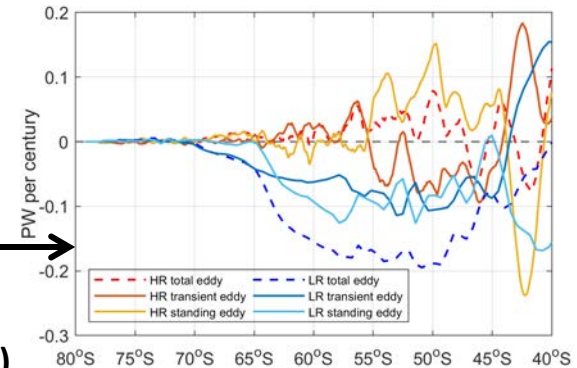
Meridional Heat Transport Trend



Transient eddies + standing eddies

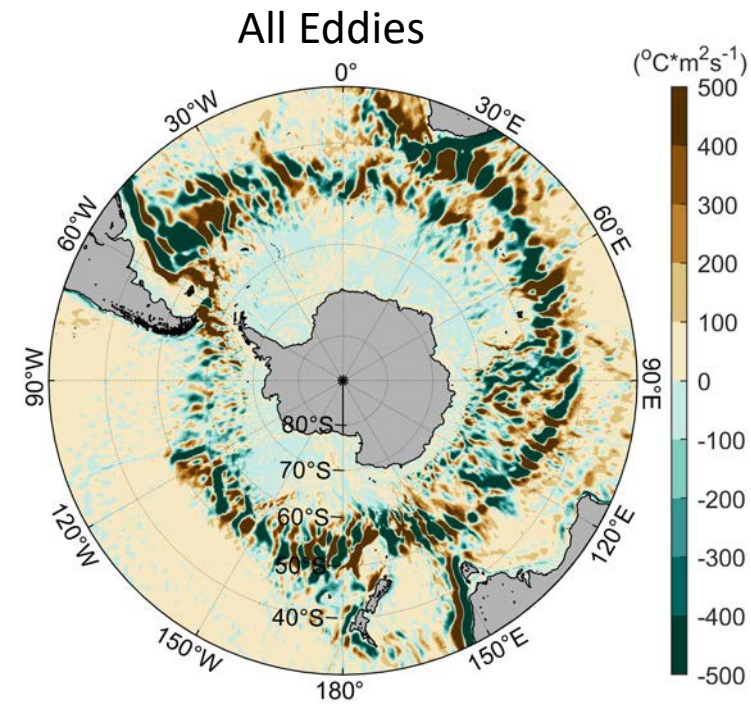
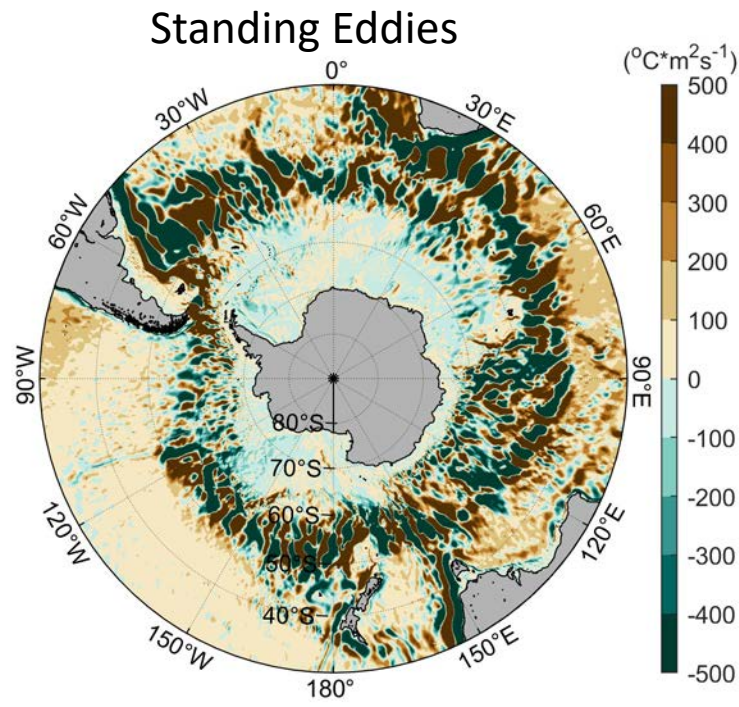
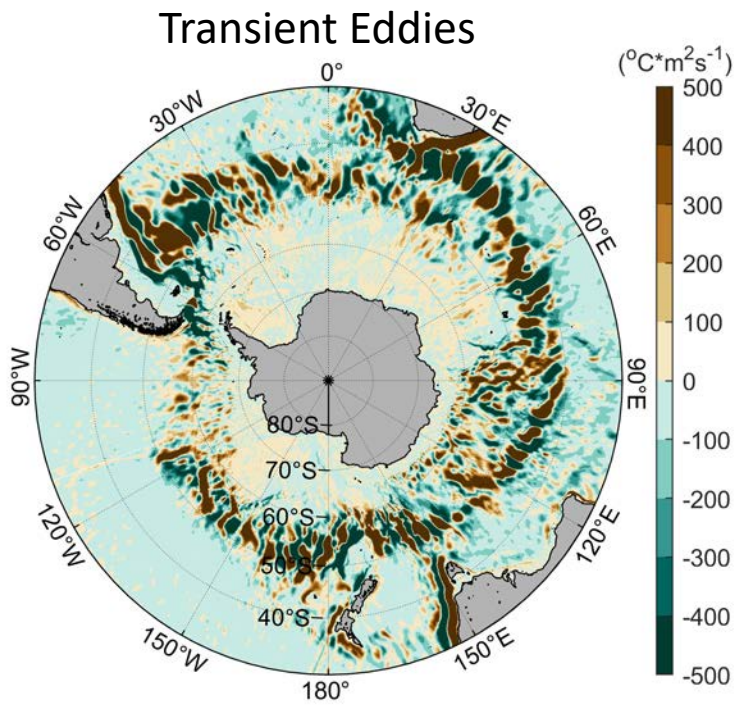
Bryan et al. (2014)
Bishop et al. (2016)
Rackow et al. (2022)

Eddy MHT Trend

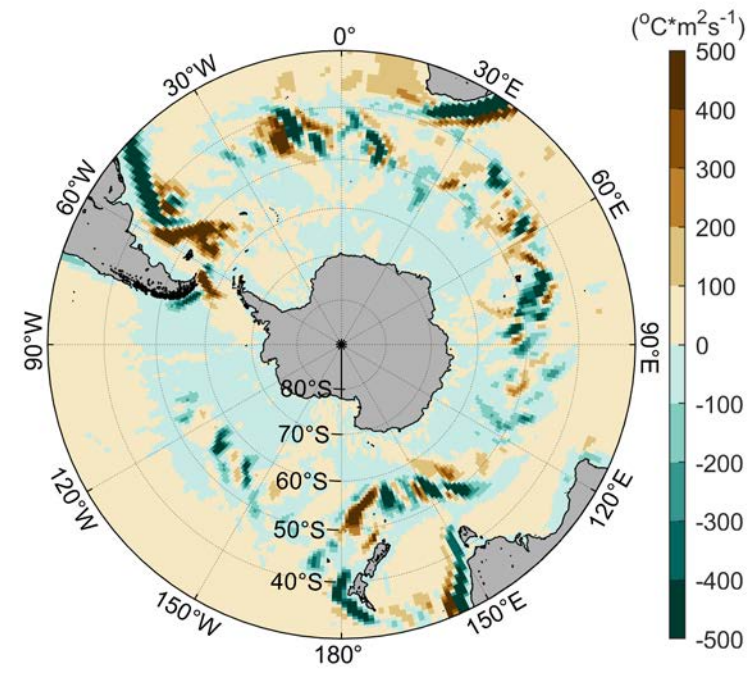
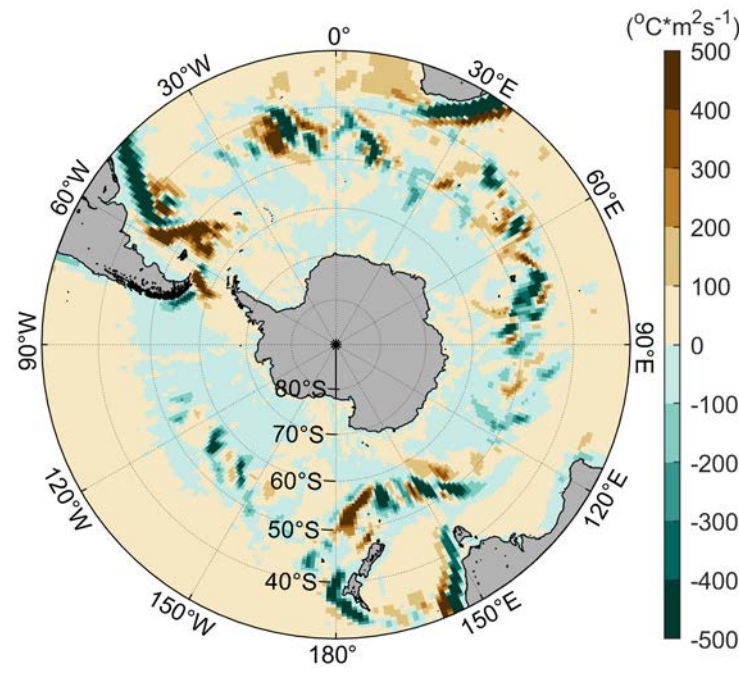
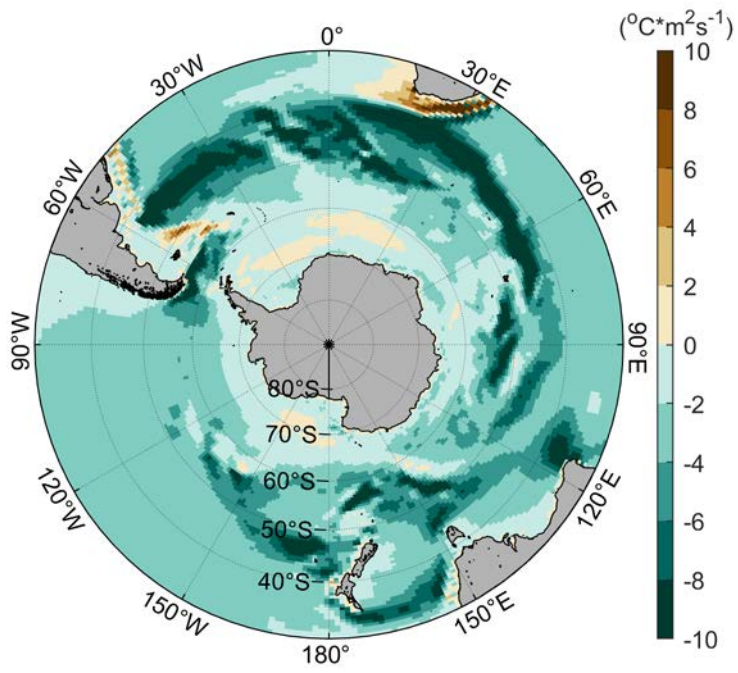


Eddy Heat Transport

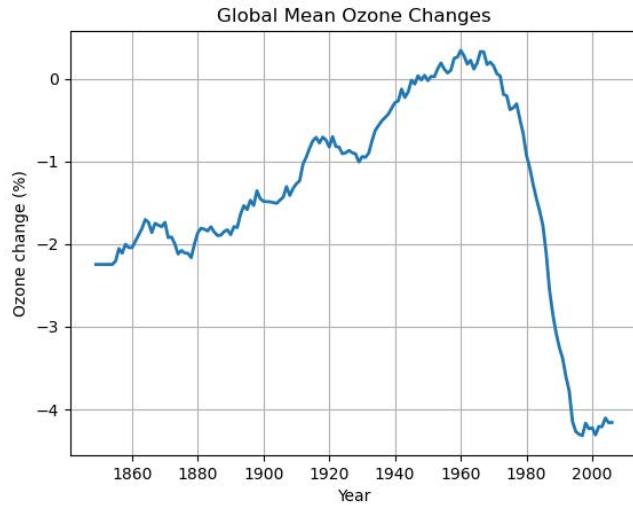
Eddy-Resolving



Non-Eddy-Resolving

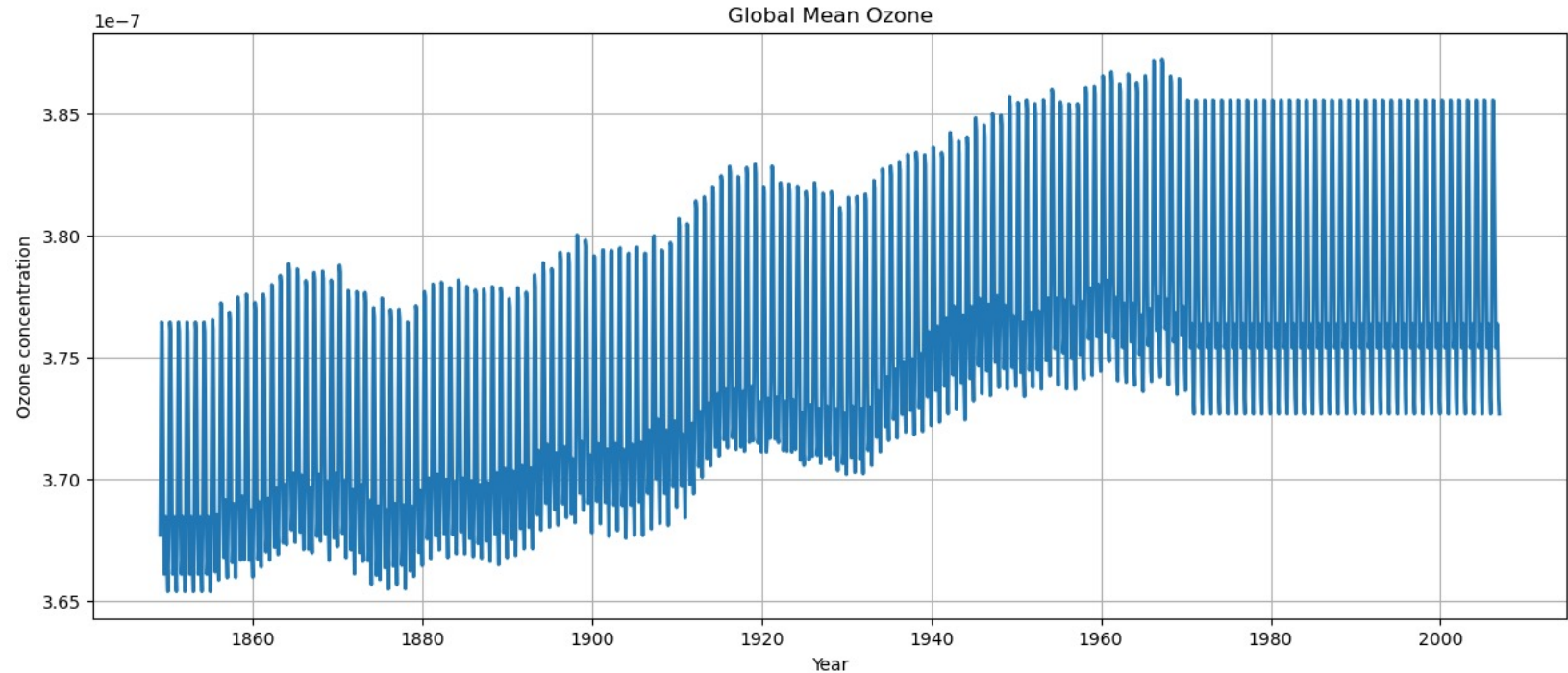


Ozone withholding experiment



- Ozone forcing in CESM-HR

- Ozone forcing in the 3-member ozone withholding experiments



Ozone withholding experiment

- Southern Ocean (SO) has experienced substantial cooling in recent decades
- SO SST trend are poorly simulated by CMIP5 and CMIP6 climate models
- CESM-HR ensemble shows realistic SO cooling trend
- Previous studies have proposed that observed SO cooling is caused by the strengthening of surface westerlies associated with a positive trend of the SAM forced by ozone depletion
- A 3-member ozone withholding CESM-HR ensemble (1970-2020) has been performed in order to test this hypothesis. Ozone is fixed at pre 1970 level.

