HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

GEOMAR

Retrospective analysis of climate response to solar variability

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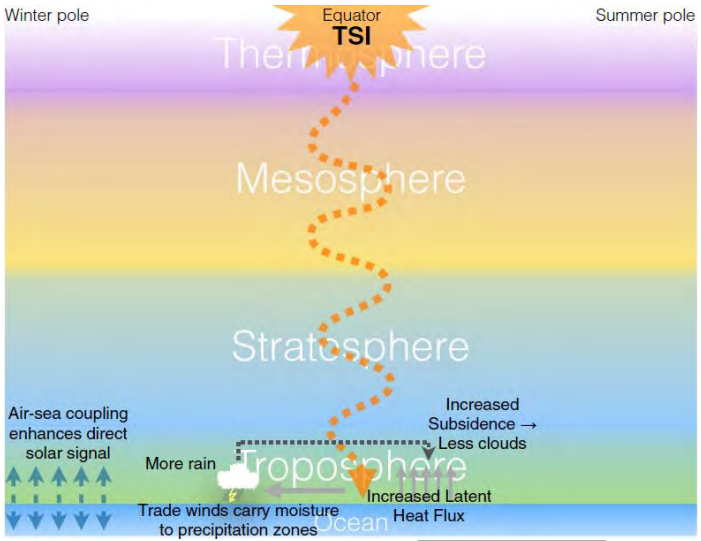
APARC
Atmospheric Processes And their Role in Climate

EPESC – LEADER Science Meeting (15-18 July 2025)

WCRP Lighthouse Activities | Explaining and Predicting Earth System Change (EPESC)

Background

bottom-up VIS/NIR (0.1%)



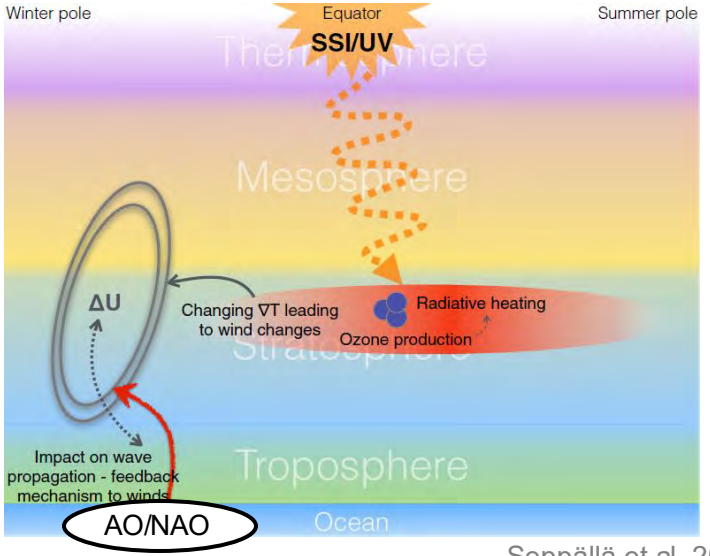
"ENSO-like", phase-locked

Weak warming

(Meehl et al. 2009, Van Loon et al. 2007; Meehl et al. 2009; Huo et al. 2021, 2022)

(Tung and Zhou 2010; Roy 2014)

top-down UV (6-10%)



Seppällä et al. 2014

(Kodera 2002; Gray et al. 2013; Scaife et al. 2014; Thiéblemont et al. 2015; Ineson et al. 2015; Drew et al. 2021; Kuroda et al.2022)

Data and methods

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Large Ensemble Single Forcing MIP (LESFMIP)

Experiment name	Description
hist-GHG	Well-mixed greenhouse-gas-only historical simulations (WMGHGs)
hist-aer	Anthropogenic-aerosol-only historical simulations (BC, OC, SO2, SO4, NOx, NH3, CO, NMVOC)
hist-sol	Solar-only historical simulations (solar irradiance)
hist-volc	Volcanic-only historical simulations (stratospheric aerosol)
hist-totalO3	Ozone-only historical simulations (stratospheric and tropospheric ozone)
hist-lu	Historical simulations with only land use changes

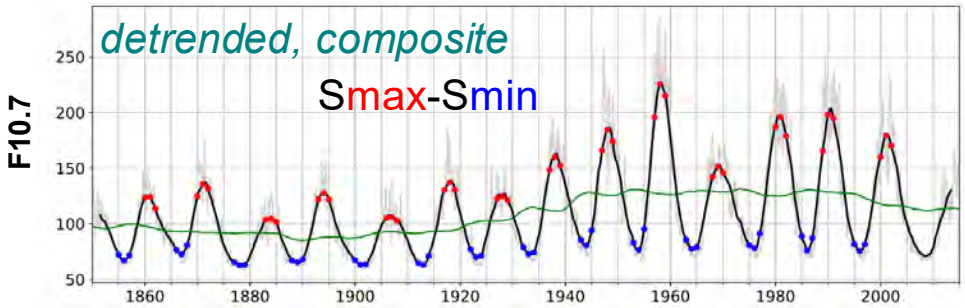
Hist-sol

ACCESS

MIROC6 CanESM5 GISS

NorESM2 **HadGEM3**

MPI-ESM



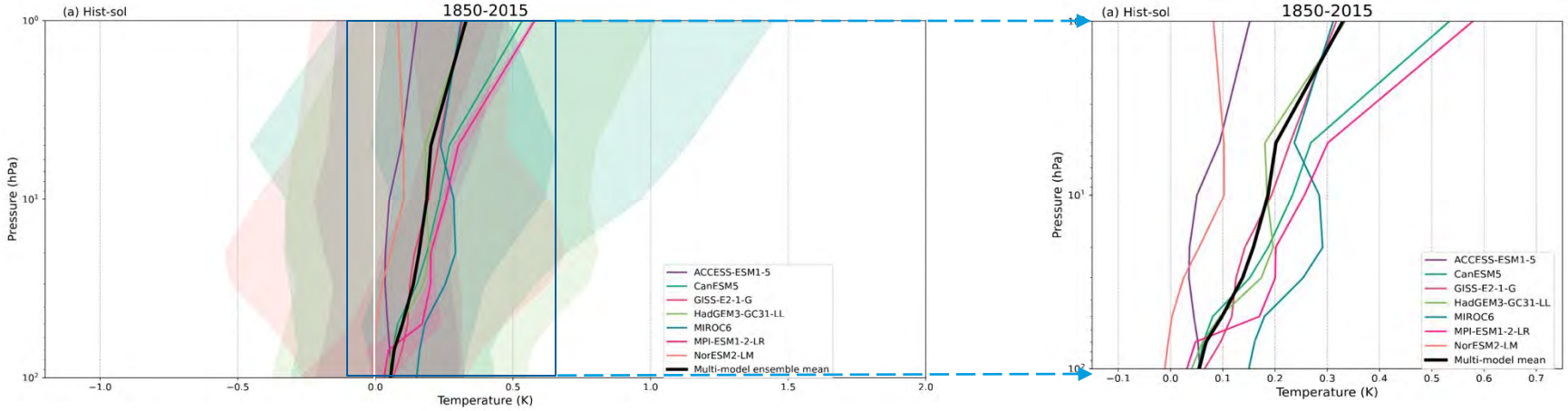
Caveats:

- No isolating strat O3 from trop O3.
- Not all models high-top.
- No interactive chemistry in strat.
- Only 2 spontaneously simulate a QBO.

potential predictability variance fraction (PPVF): $p = \sigma_v^2/\sigma^2$

Solar imprints in the Middle Atmosphere

Annual mean Ta *composite*

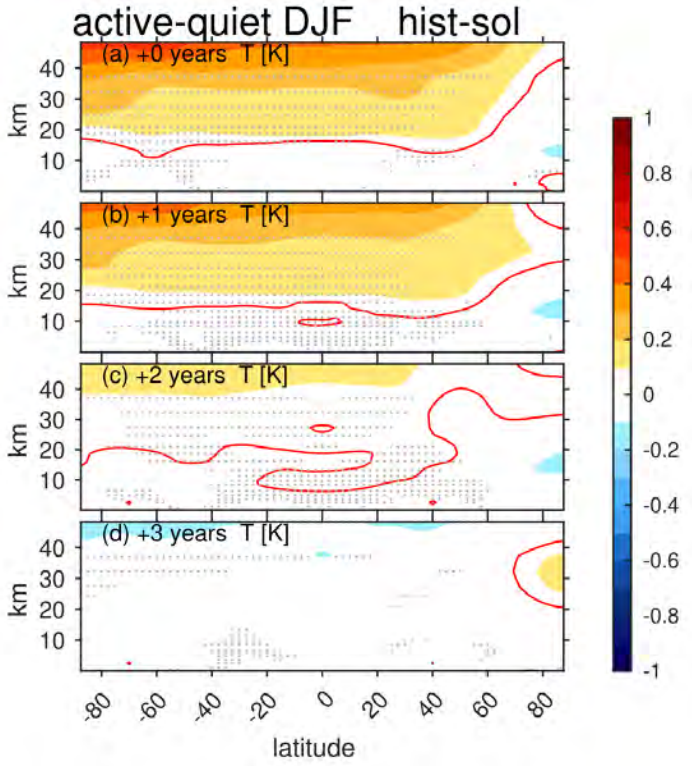


Solar imprints in the Middle Atmosphere

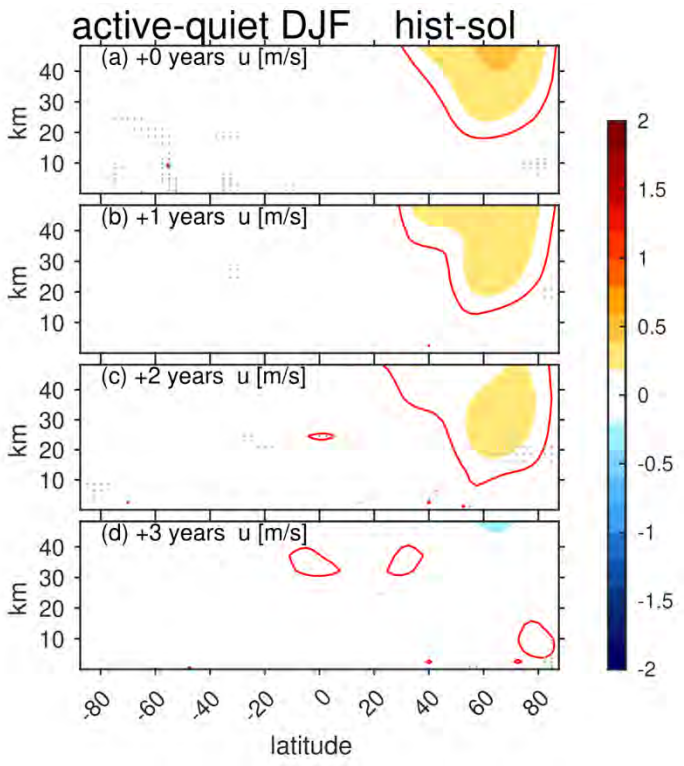
GEOMAR

composite

Zonal mean
T



Zonal mean
U



Solar imprints in the Middle Atmosphere

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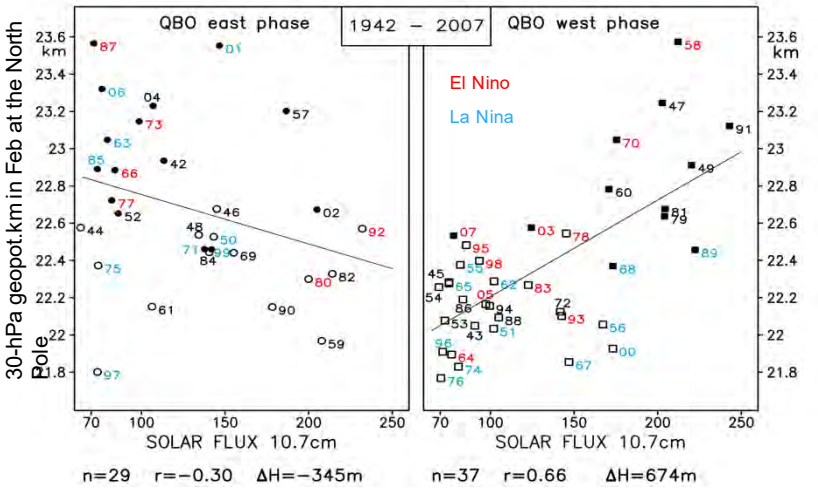
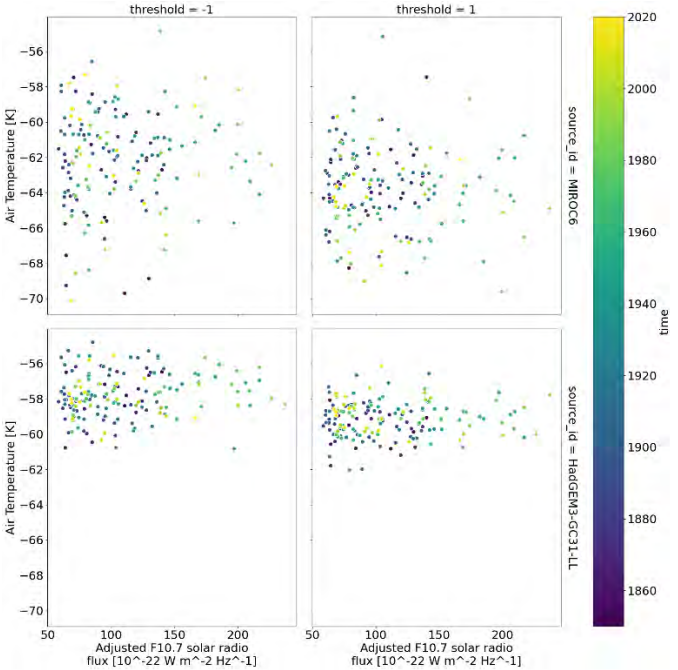
Labitzke's scatter plot on the solar cycle–QBO relationship in the arctic polar region



O years in the east phase of the QBO

□ years in the west phase of the QBO



(Labitzke and Kunze, 2009)

Surface responses to the solar forcing

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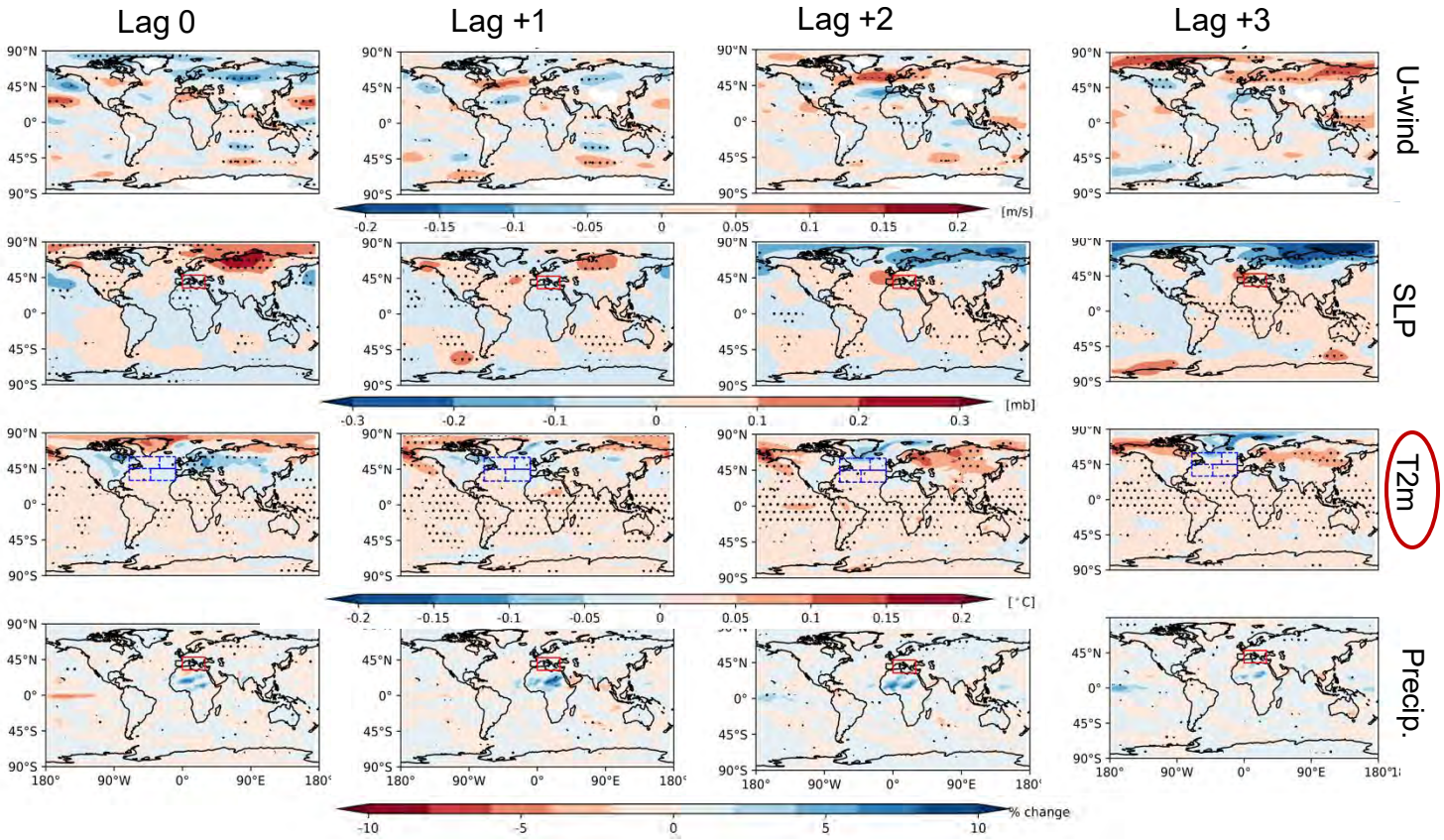

composite

Surface responses to the solar forcing

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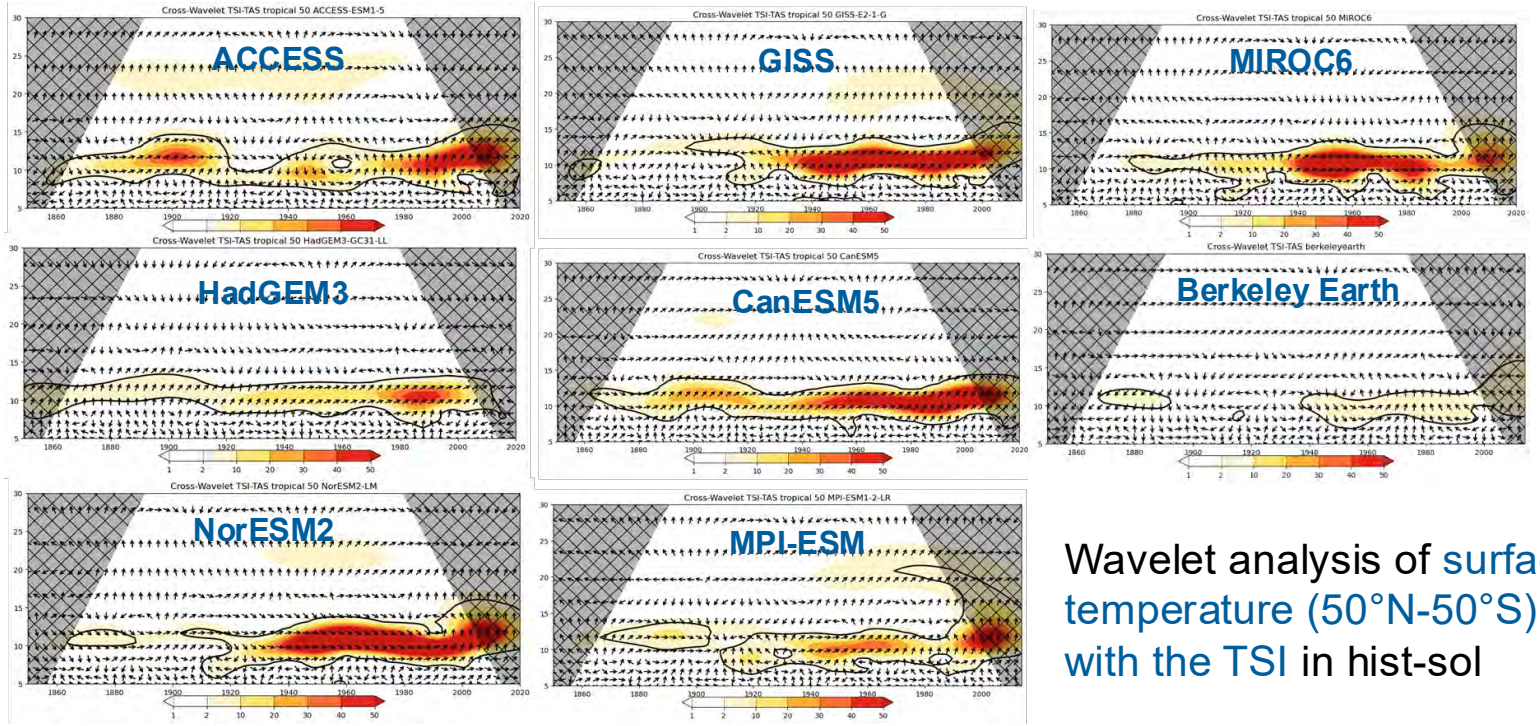
Significant covariance in the late period

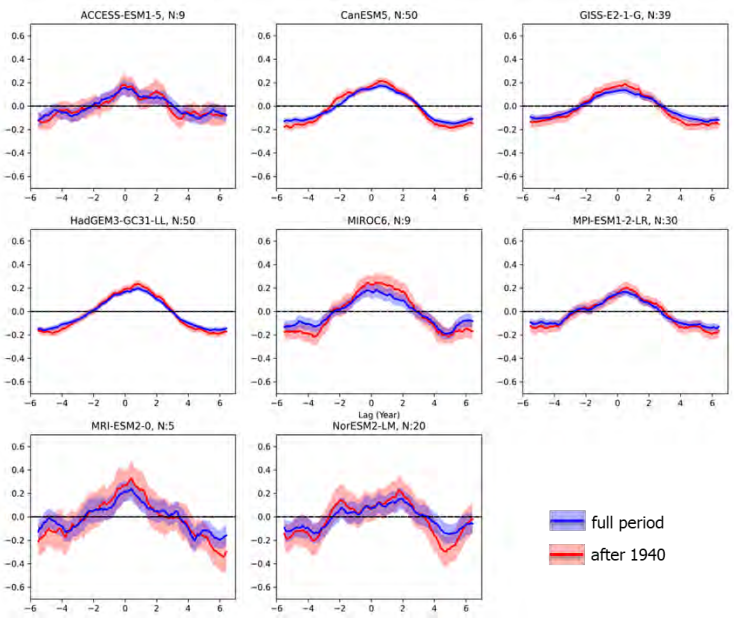


Wavelet analysis of surface temperature (50°N-50°S) with the TSI in hist-sol

Surface responses to the solar forcing

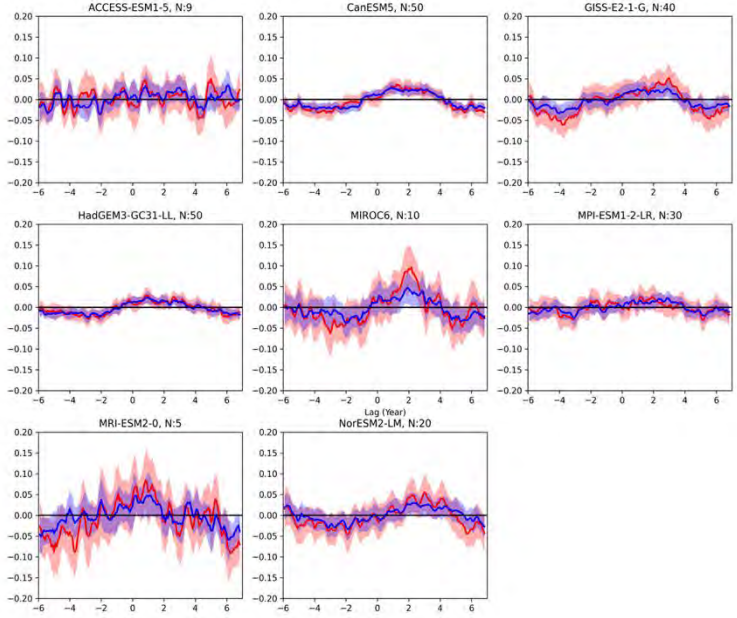
composite

Net SW radiation @TOA



A color band indicates 95% confidence interval of the mean value

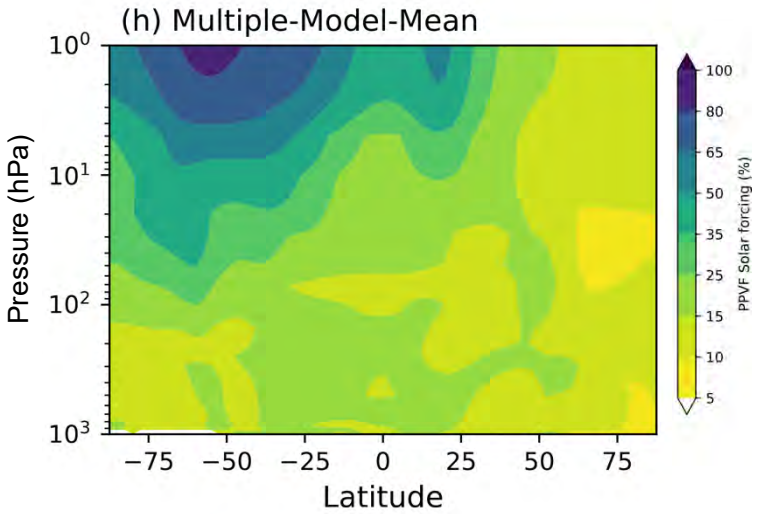
T2m global average



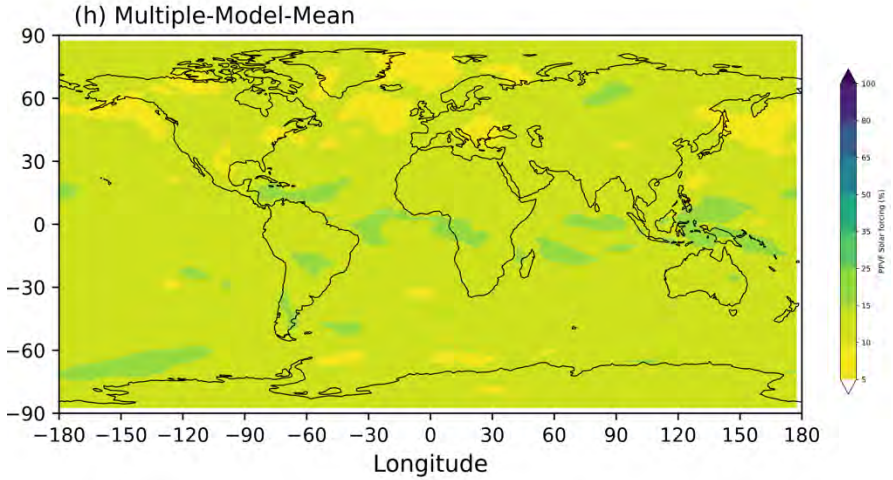
Earth's Energy Imbalance

Contribution to decadal climate predictability

PPVF of Ta

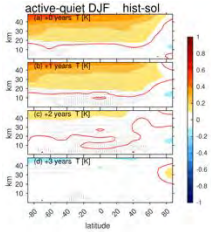


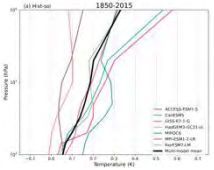
PPVF of Ts

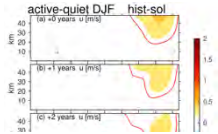


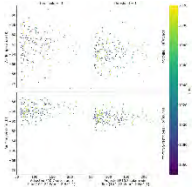
Take home messages

- Robust warm response in the stratosphere to the 11-year solar cycle, but with a large model spread.
- Westerly wind anomalies, not robust, very weak
- No apparent relationship between solar cycle and QBO









- **Lagged** surface responses
  - +NAO/AO
  - robust warm response, be stronger in the central east Pacific at lag +2
  - significant covariance of Ts and TSI in the late period, a stronger warm response

- Solar forcing has a large contribution to the PPVF of Ta in the stratosphere (>50%) and much smaller contribution to the Ts (<15%).

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Thanks for your attention!

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Back up slides

Surface responses to the solar forcing

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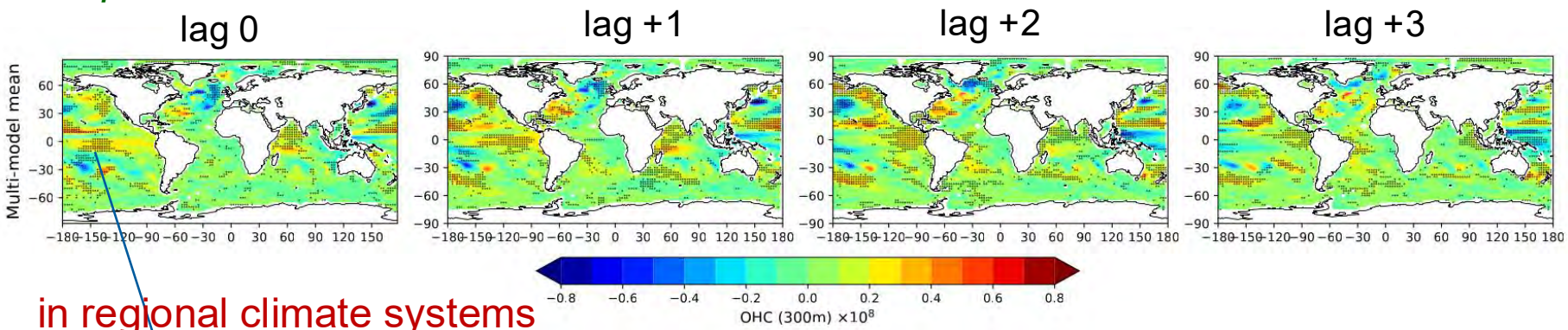
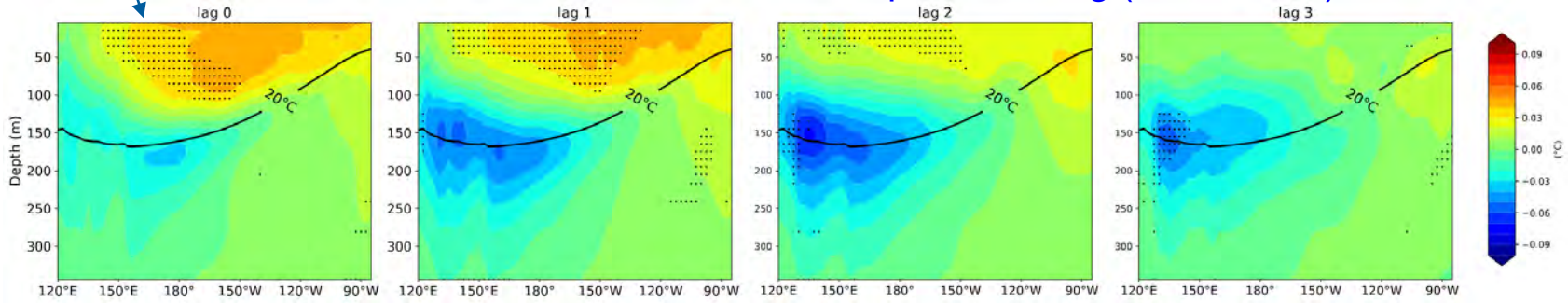
composite

Annual mean OHCa 300m



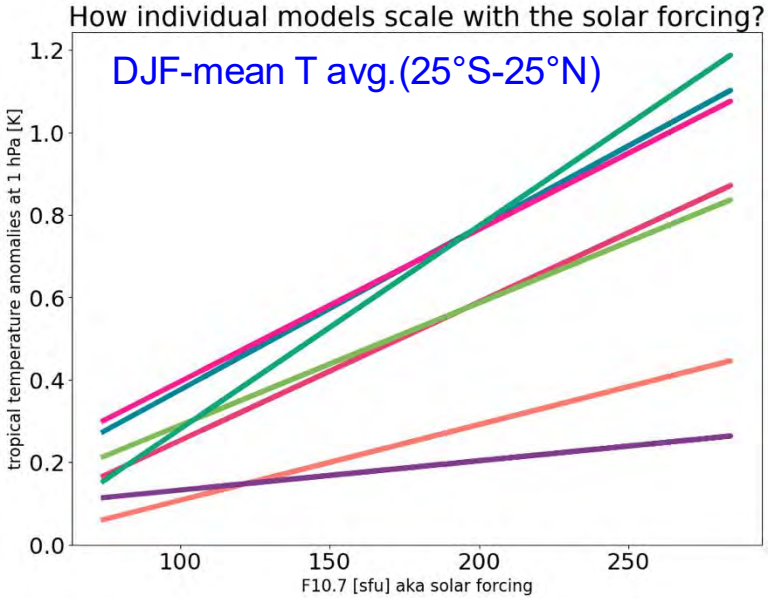
in regional climate systems

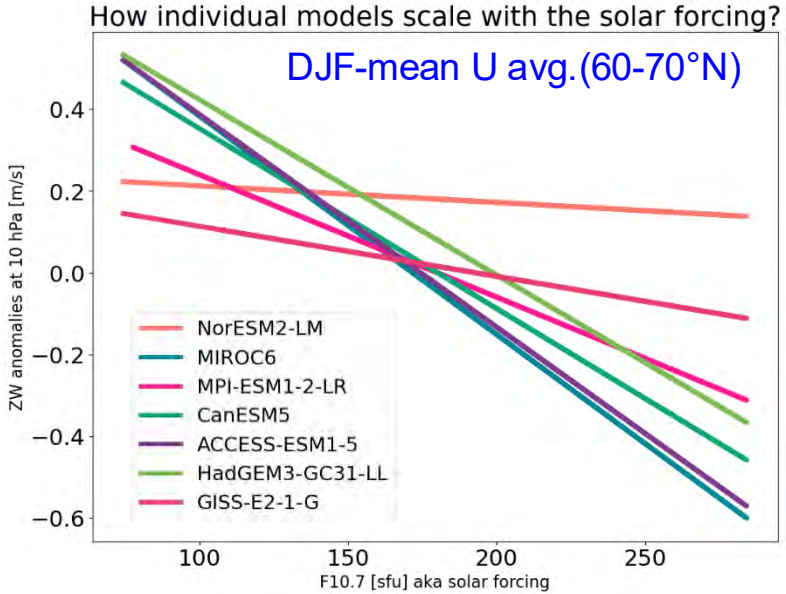
Annual mean subsurface temperature avg (10°S-10°N)



Solar imprints in the Middle Atmosphere

regression





Solar imprints in the Middle Atmosphere

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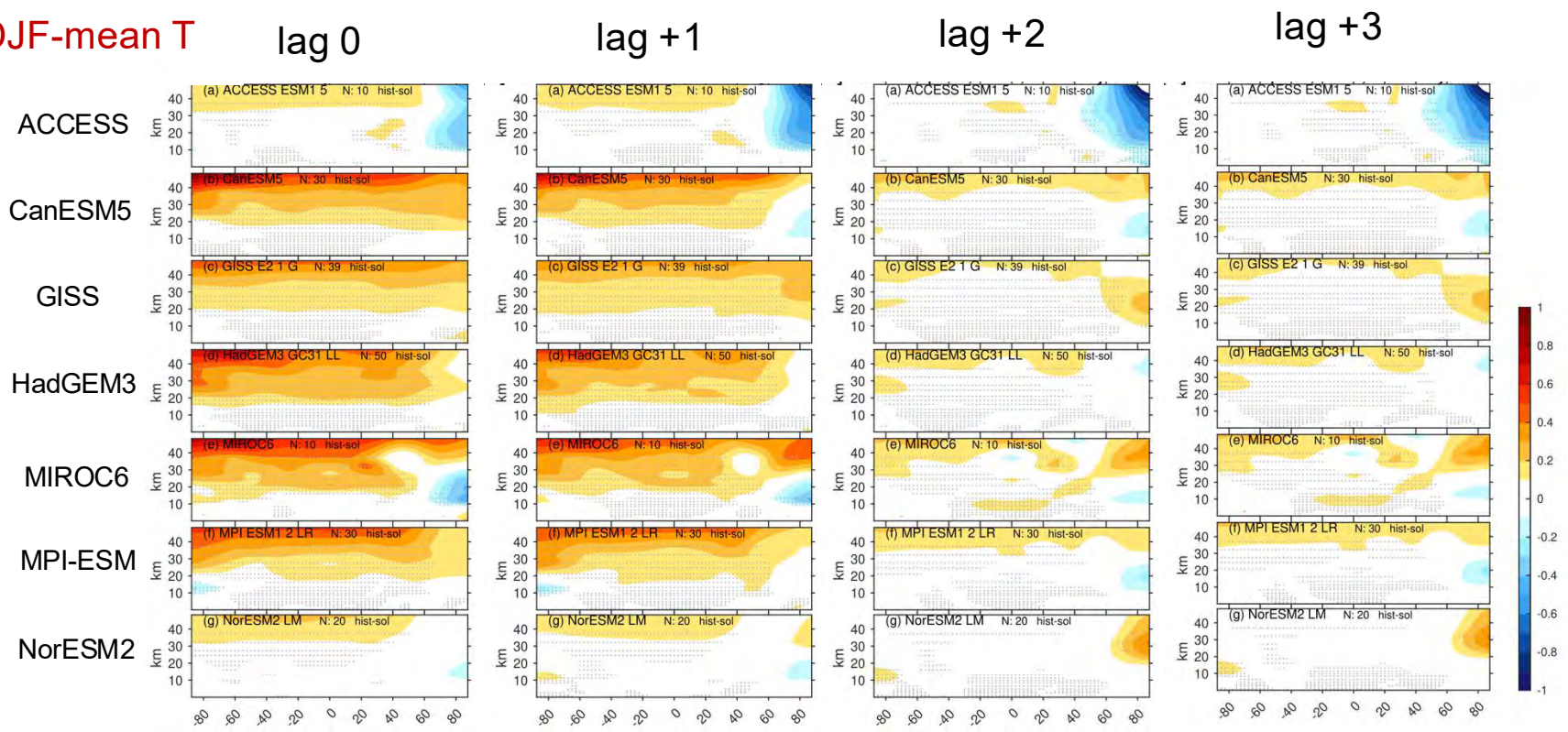
DJF-mean T



Solar imprints in the Middle Atmosphere

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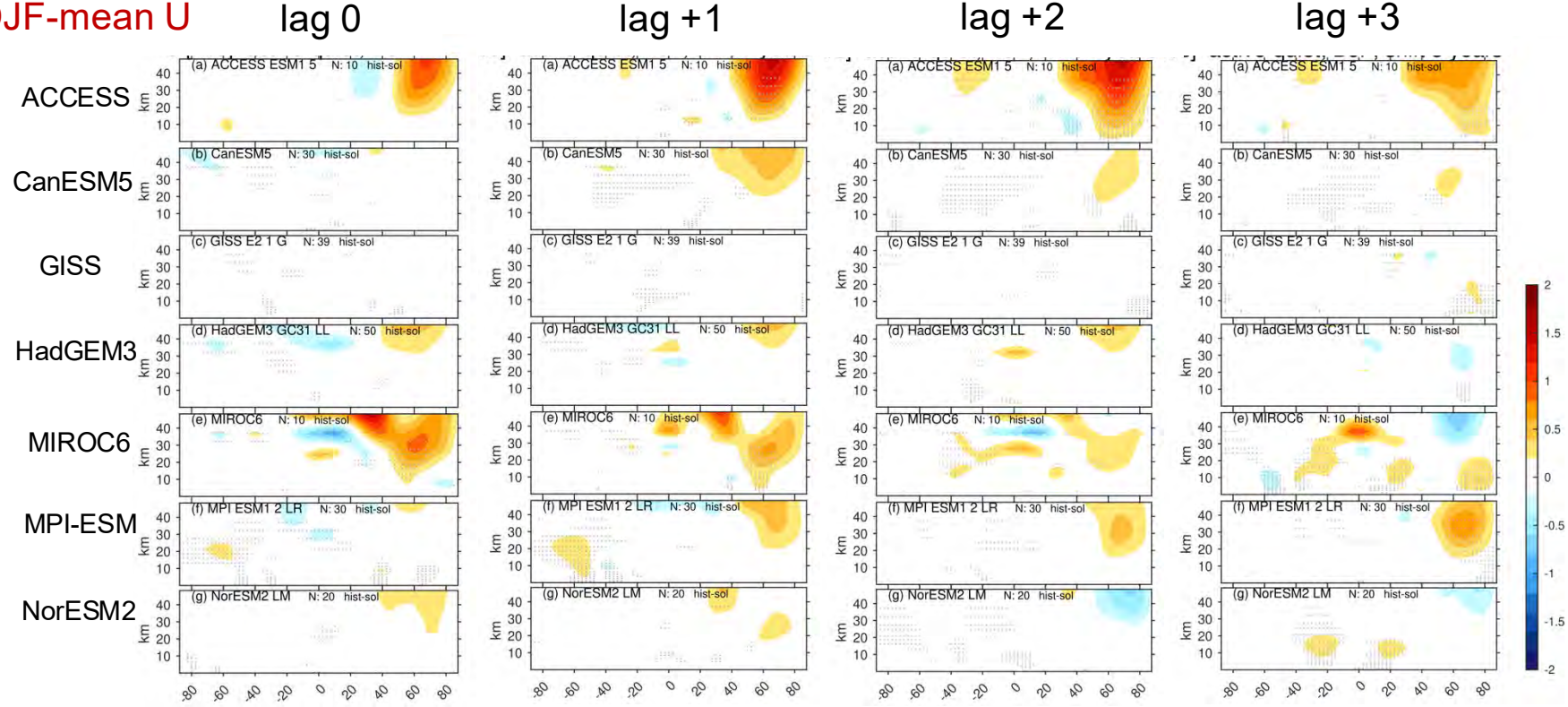
DJF-mean U



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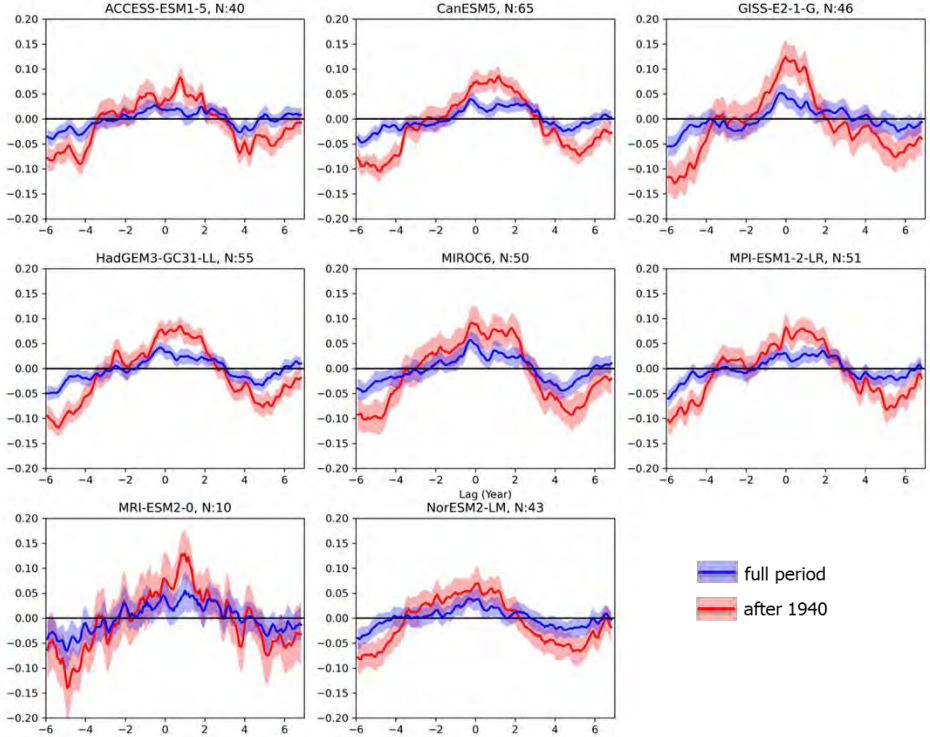
Historical

T2m global average



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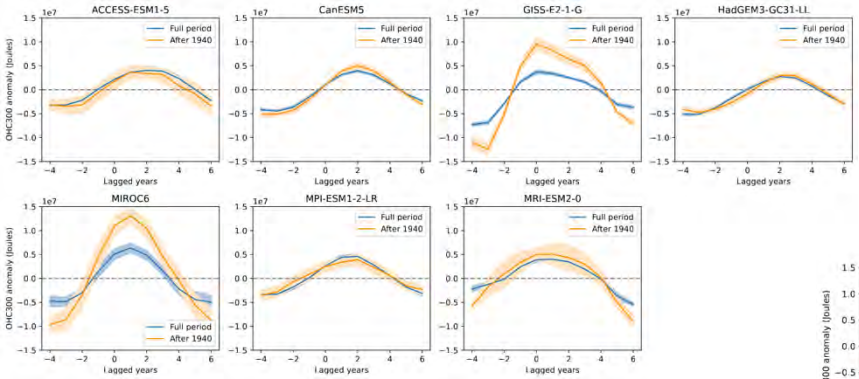
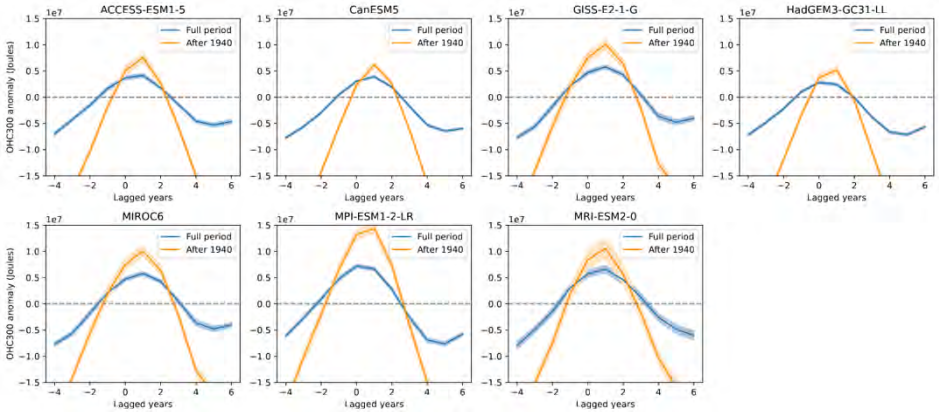
Composite difference of global mean annual mean OHC_300m anomalies (Smax-Smin)

Hist-sol

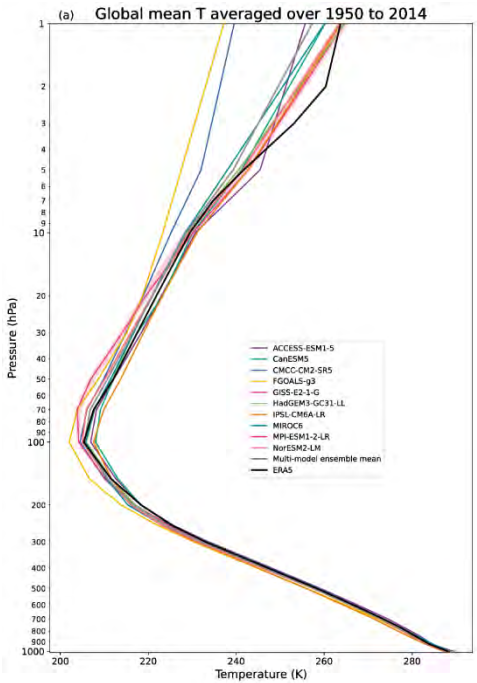


Historial

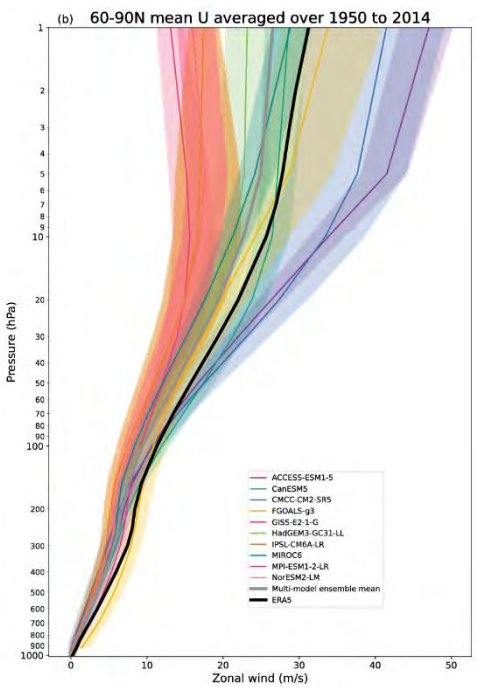


Models' biases

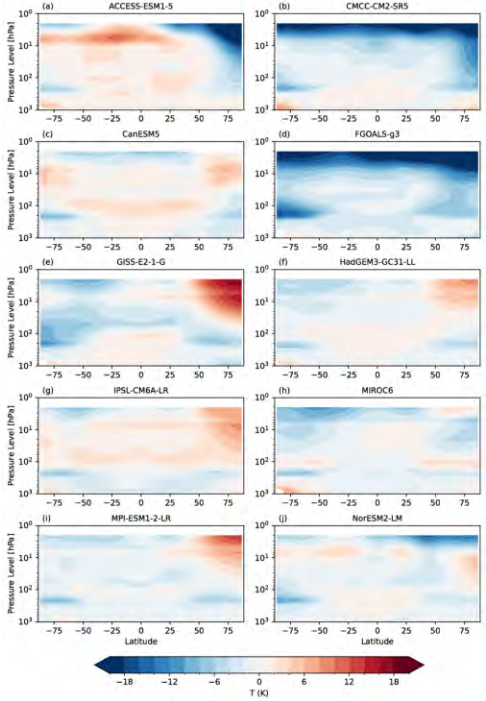
Annual mean global mean Ta



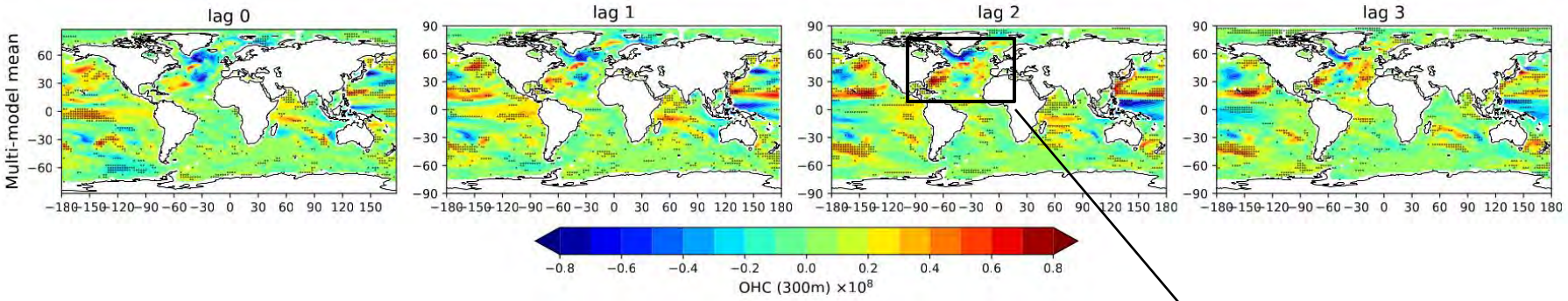
DJF-mean 60-90N averaged Ua



DJF-mean zonal mean Ta (Model-ERA5)

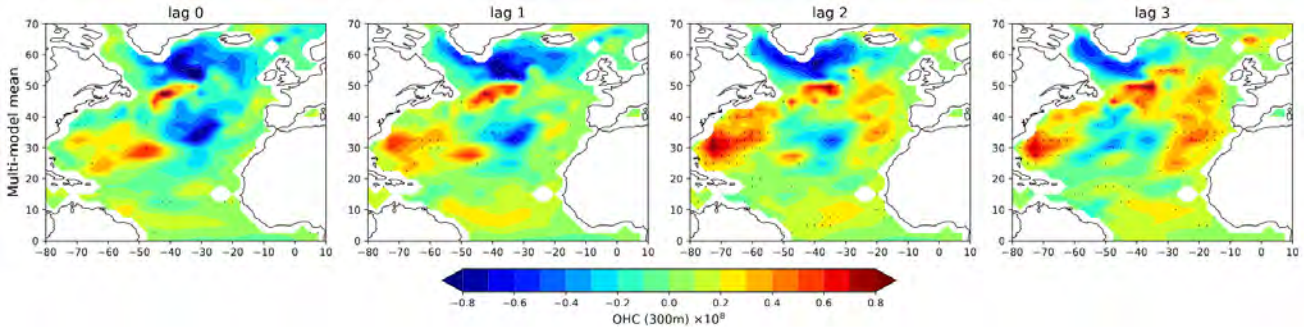


Hist-sol after 1940



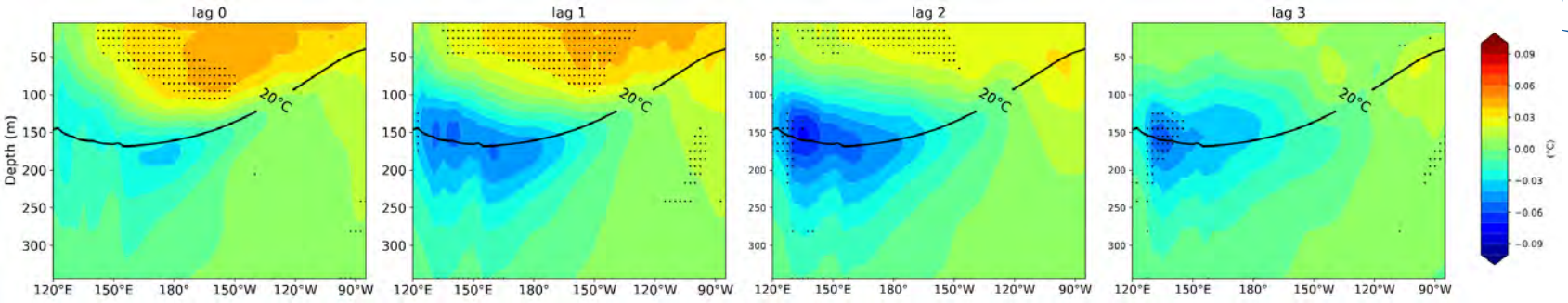
Zoom in of the North Atlantic

A migration of positive OHCa to northward and eastward in the North Atlantic maybe by the ocean current there



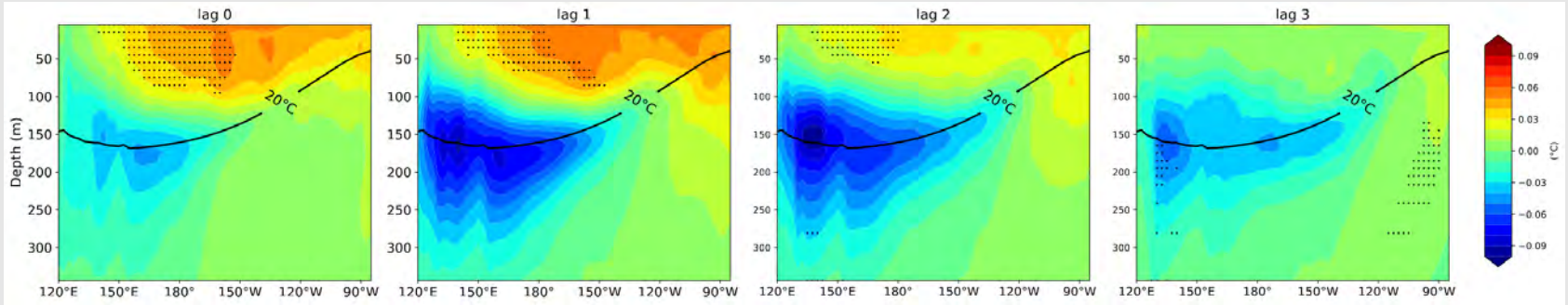
Hist-sol

Multi-model



Hist-sol after 1940

Multi-model

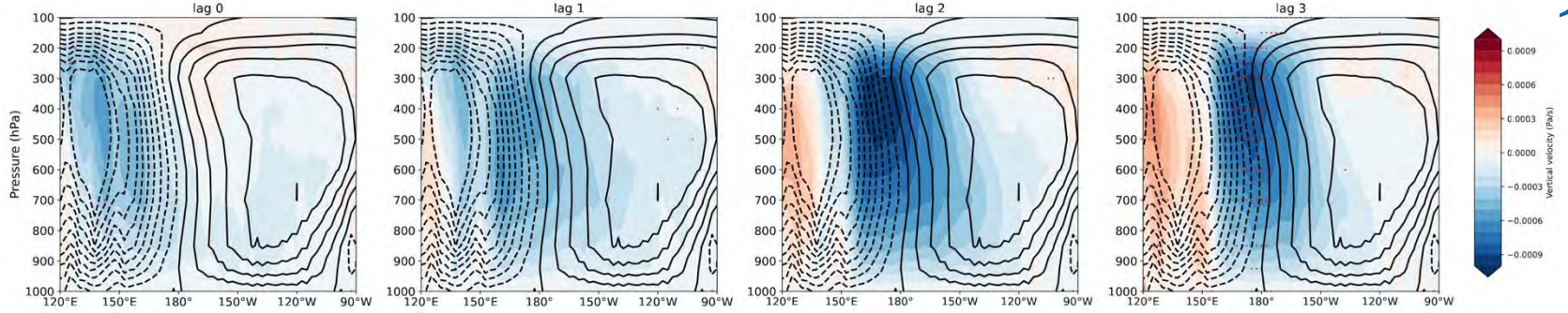


The robust warm response in the tropical Pacific is limited in the mixed layer and hence very less subsurface ocean (meridional) dynamical transport be involved in.

Hist-sol

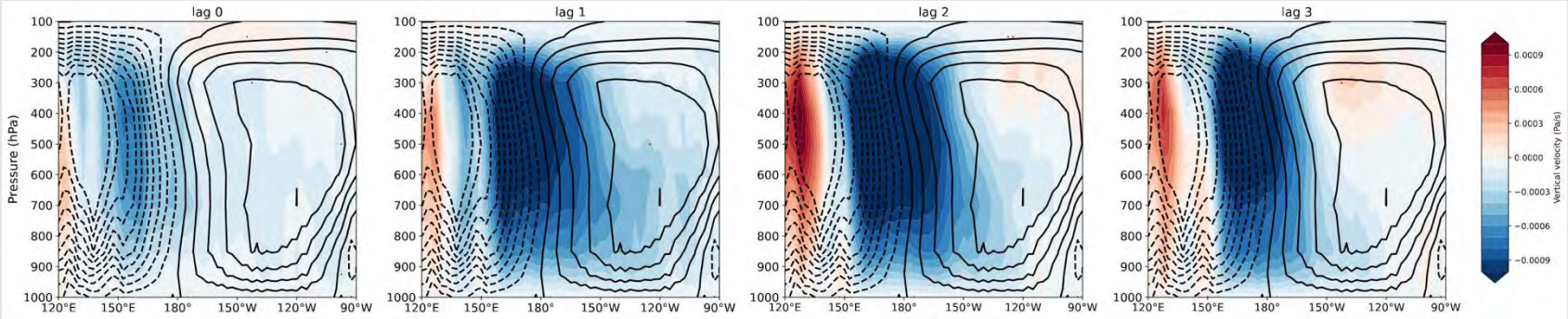
Multi-model mean

Vertical velocity anomalies

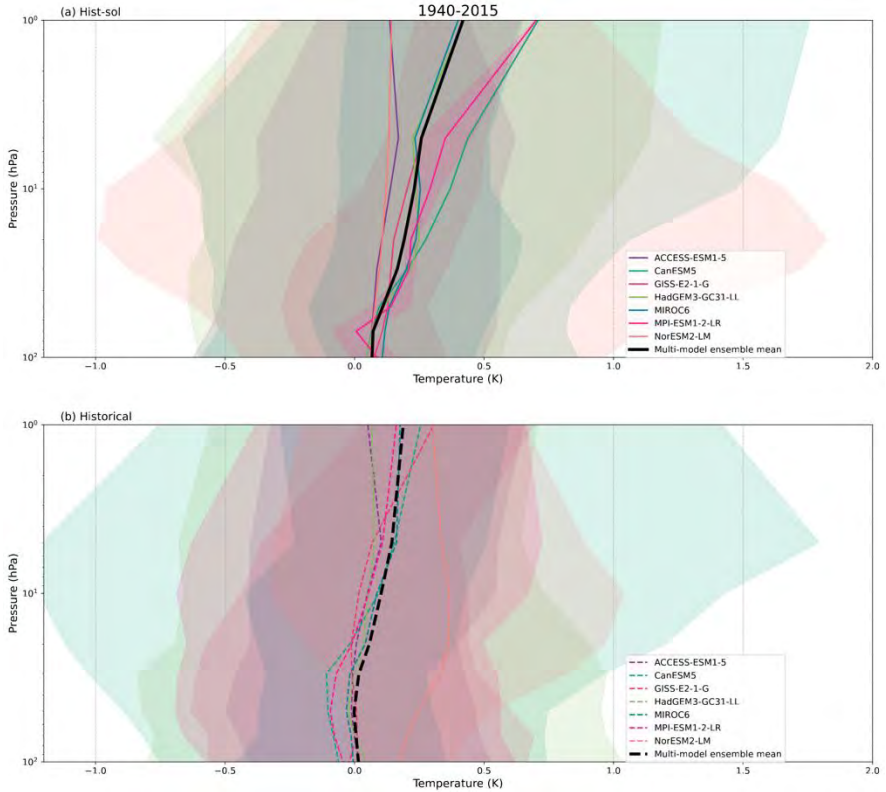


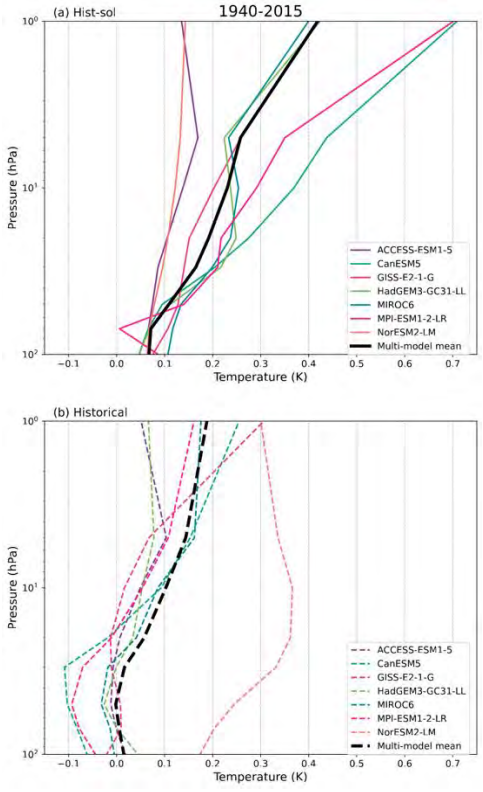
Hist-sol after 1940

Multi-model mean



Hist-sol after 1940





O3 forcing in hist-sol