NCAR High Altitude Observatory
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Climate Responses Under an Extreme Quiet Sun Scenario

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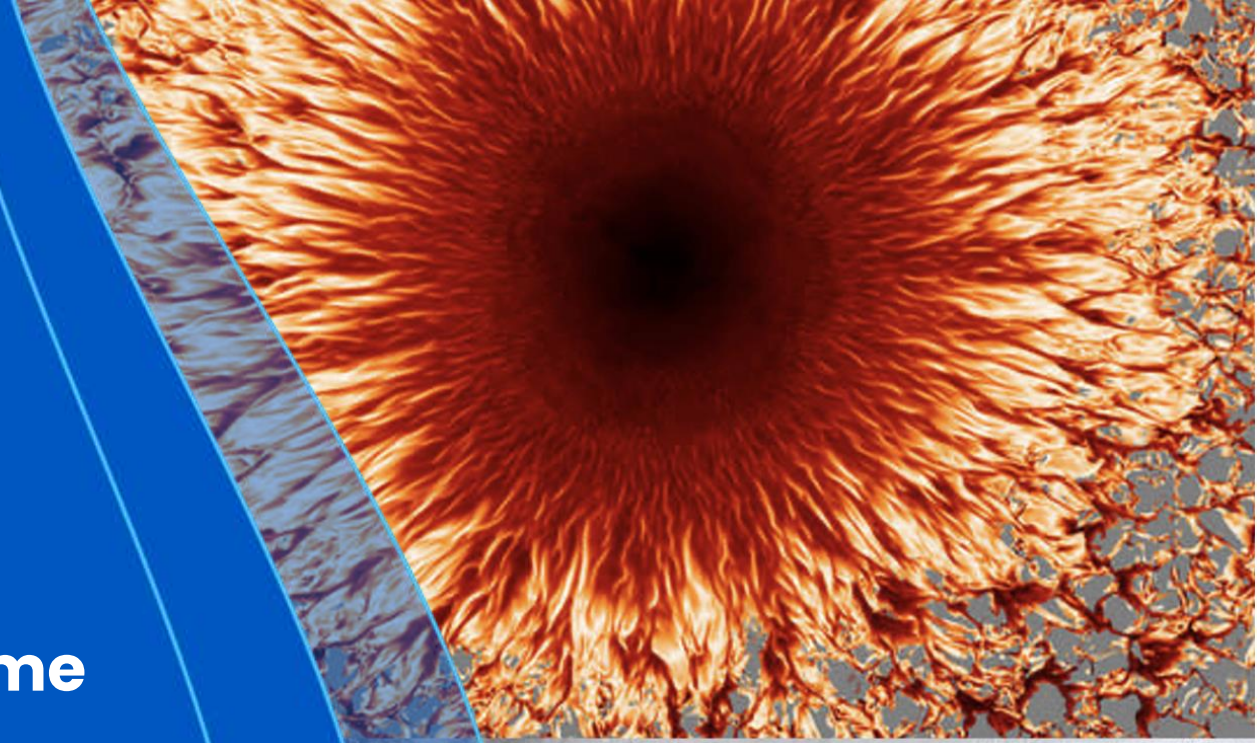
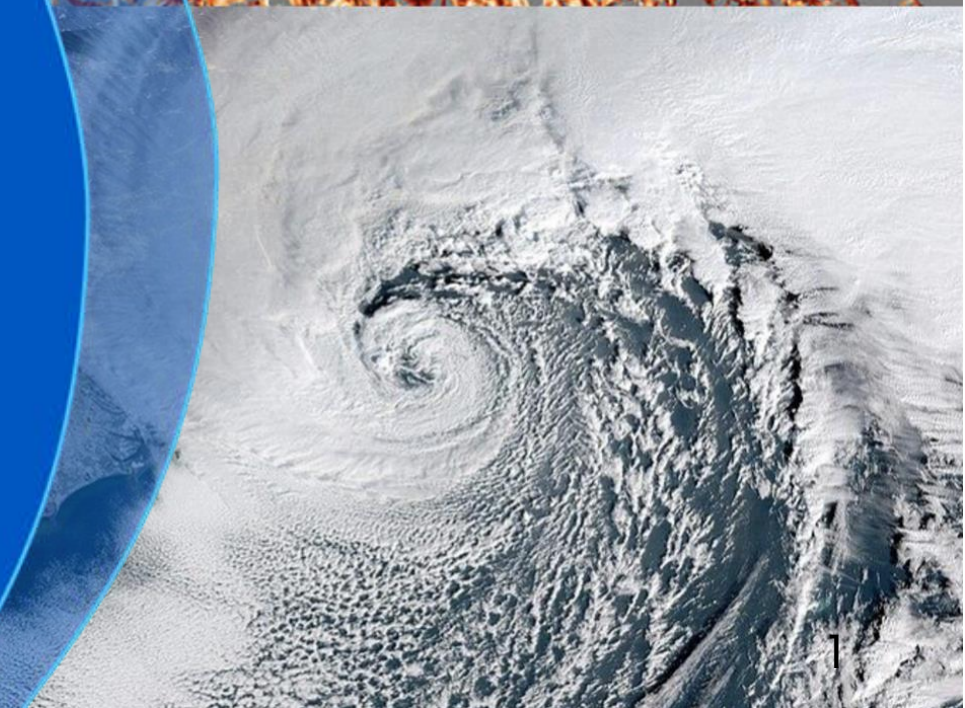
1. NSF NCAR HAO, 2. NSF NCAR CGD





NASA 5th Eddy Cross-Disciplinary Symposium
Boulder, Colorado

Outline

- Motivation, Challenges and Goal of the Study
- Methodology: Model, numerical experiments, and analysis method
- Results and analysis
  - Surface/troposphere/ocean responses on regional scales and driving mechanism.
  - Middle atmosphere responses and bottom-up/top-down driving.
  - Hemispheric differences.
- Summary

Liu, H.-L., Rempel, M., Danabasoglu, G., Solomon, S. C., & McInerney, J. M. (2023). Climate responses under an extreme quiet sun scenario. *Journal of Geophysical Research: Atmospheres*, 128, doi: 10.1029/2022JD037626

Motivation

- 2011 SORCE Science Meeting: Symposium on the Decadal Variability of Earth's Climate, Solar Irradiance, and Sun-like Stars
  - What can we learn about decadal climate response and climate sensitivity using the solar cycle as a well-specified external radiative forcing?
  - What is the current understanding of the amplitude of solar spectral variability and the response of the Earth's atmosphere and climate system?
  - How does total solar irradiance vary over the solar cycle and what are the implications for climate modeling to recent refinements in its magnitude?
  - How do comparisons with Sun-like stars improve our understanding of solar variability?
  - How can solar and climate models be advanced to better reproduce decadal variability and improve forecast capabilities?

Challenges and Uncertainties

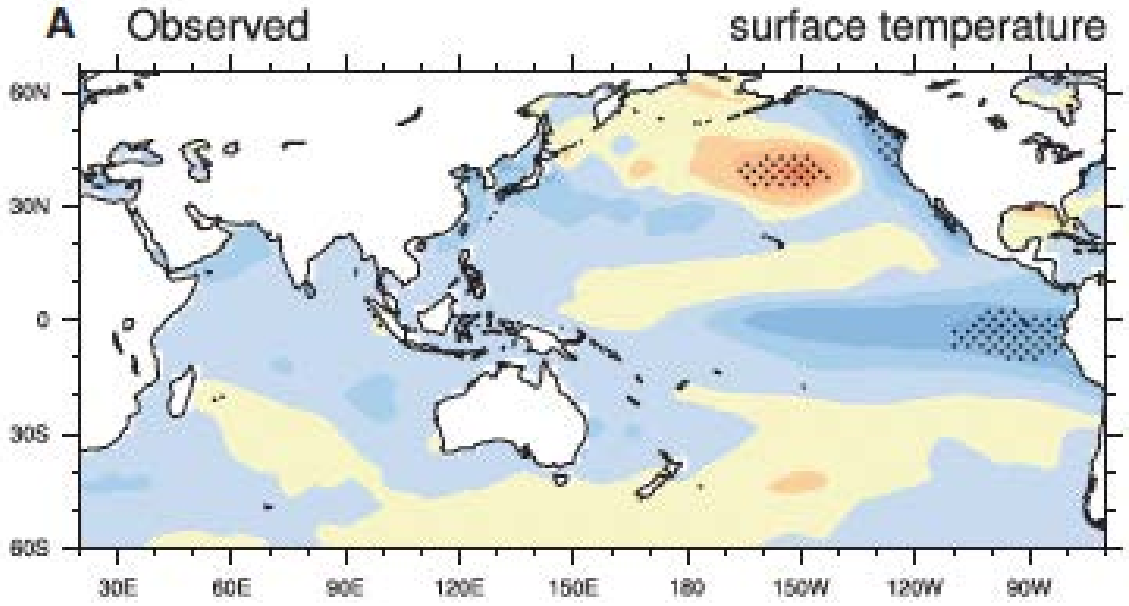
- **Uncertainties in TSI reconstruction of Grand Minimum.**
- **Solar signal in the tropospheric climate is small compared with the large climate variability (small SNR).**
- Solar variability is large in stratosphere and above, but the downward impact is unclear.
- Relying mainly on statistics and difficult to examine processes through which solar forcing affects climate.
- Conflicting results from various climate modeling studies.
- Questionable significance tests: False discovery rate in Student T test in auto-correlated system.

TSI Reconstructions of Grand Minimum

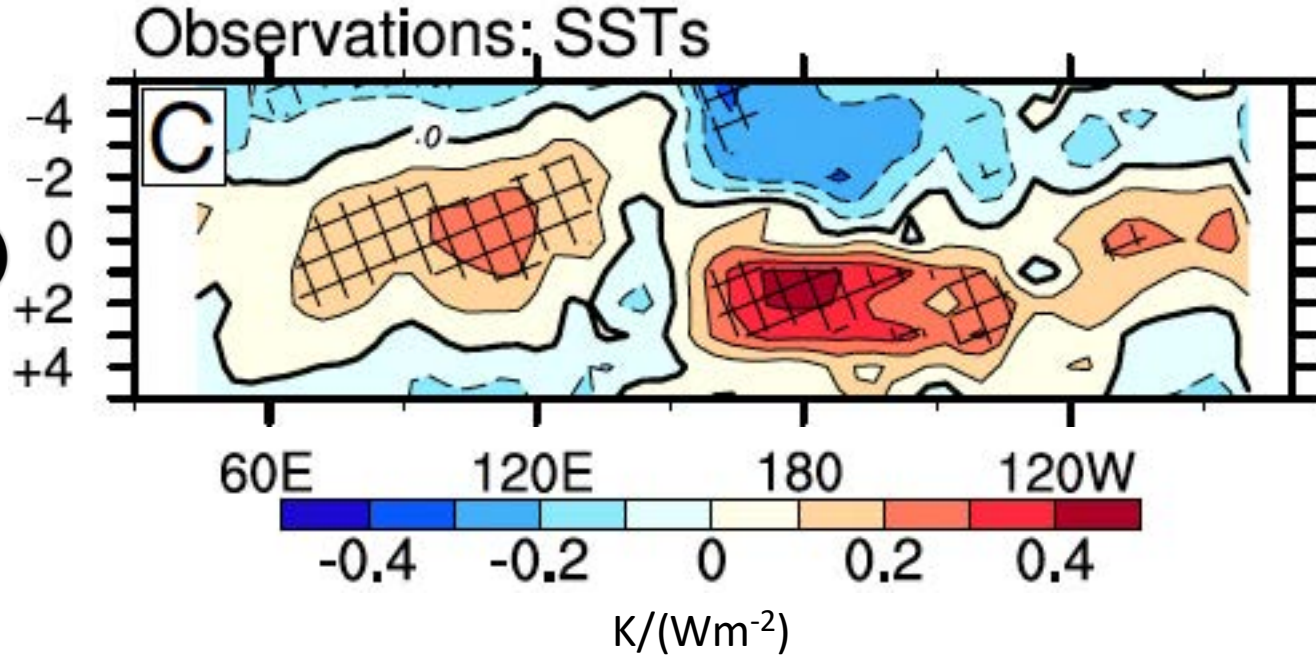
Name	TSI [W m^{-2}]	ΔTSI from REF [W m^{-2}]	Reference
REF	1361	/	Prša et al. (2016)
MIN1	1360.66	-0.34	Schrijver et al. (2011)
MIN2	1360.07	-0.93	Lean (2018)
MIN3	1359.3	-1.7	/
MIN4	1359.2	-1.8	/
MIN5	1359.1	-1.9	/
MIN6	1359	-2	/
MIN7	1358.9	-2.1	/
MIN8	1358.8	-2.2	Penza et al. (2024)
MIN9	1358.7	-2.3	/
MIN10	1358.6	-2.4	/
MIN11	1358.5	-2.5	Penza et al. (2022)
MIN12	1355	-6	Shapiro et al. (2011)

Lucaferri et al. (under revision)

Regional Solar Signal: Equatorial Responses?

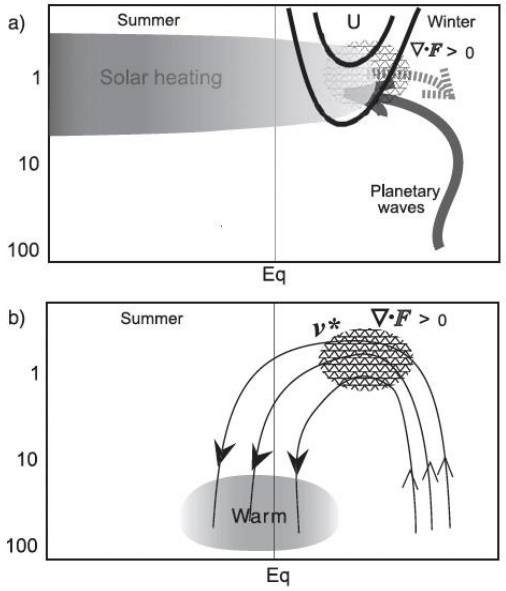


Enhanced Walker circulation under solar maximum conditions.
Meehl et al, 2009

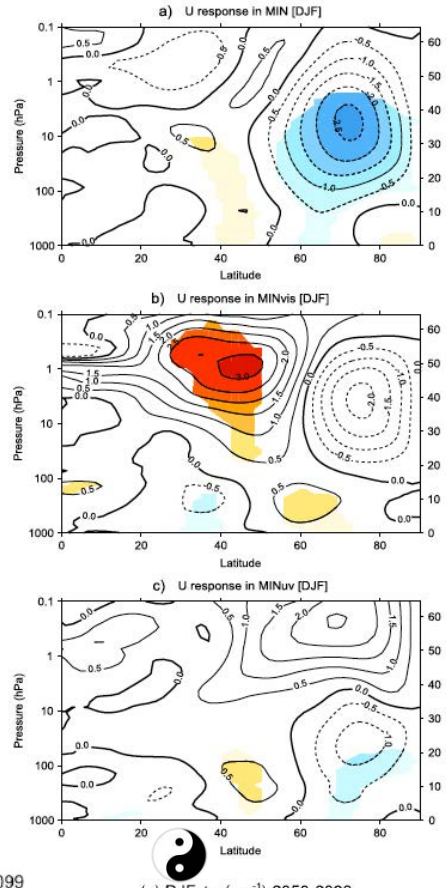


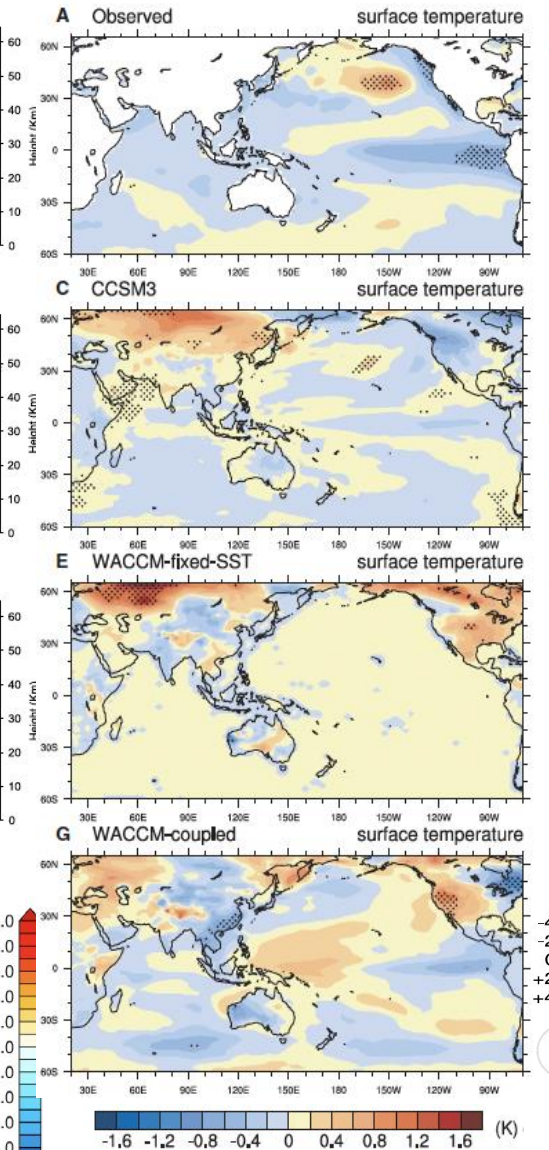
Slower Walker circulation under solar maximum conditions.
Misios et al., 2019

Bottom-up + Top-Down: Enhance Regional Responses?

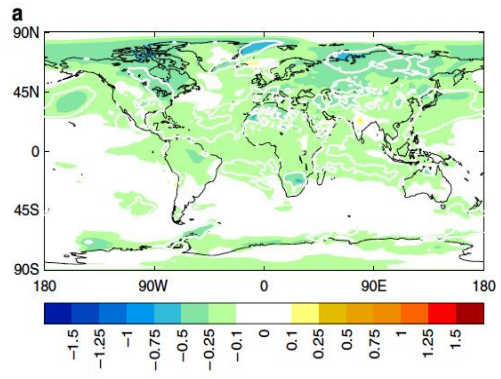


Kodera&Kuroda, 2002

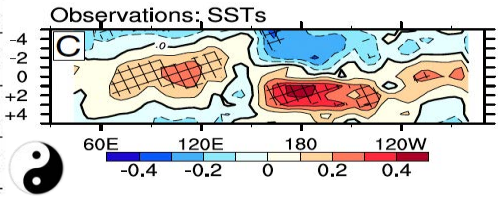




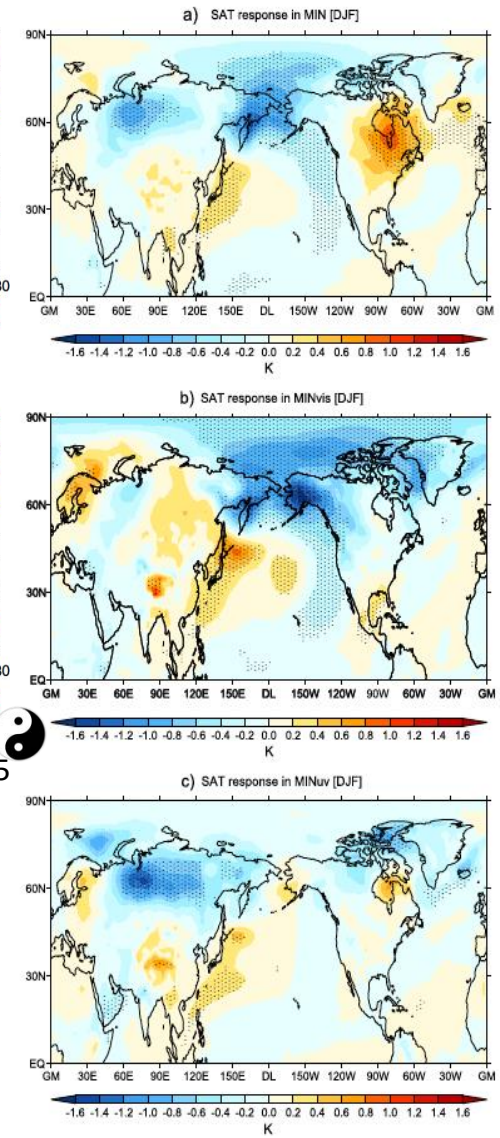
Meehl et al., 2009



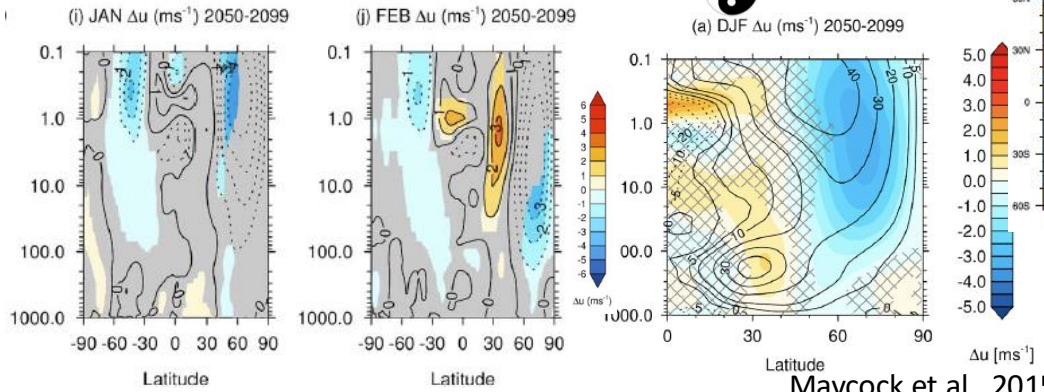
Ineson et al., 2015



Misios et al., 2019

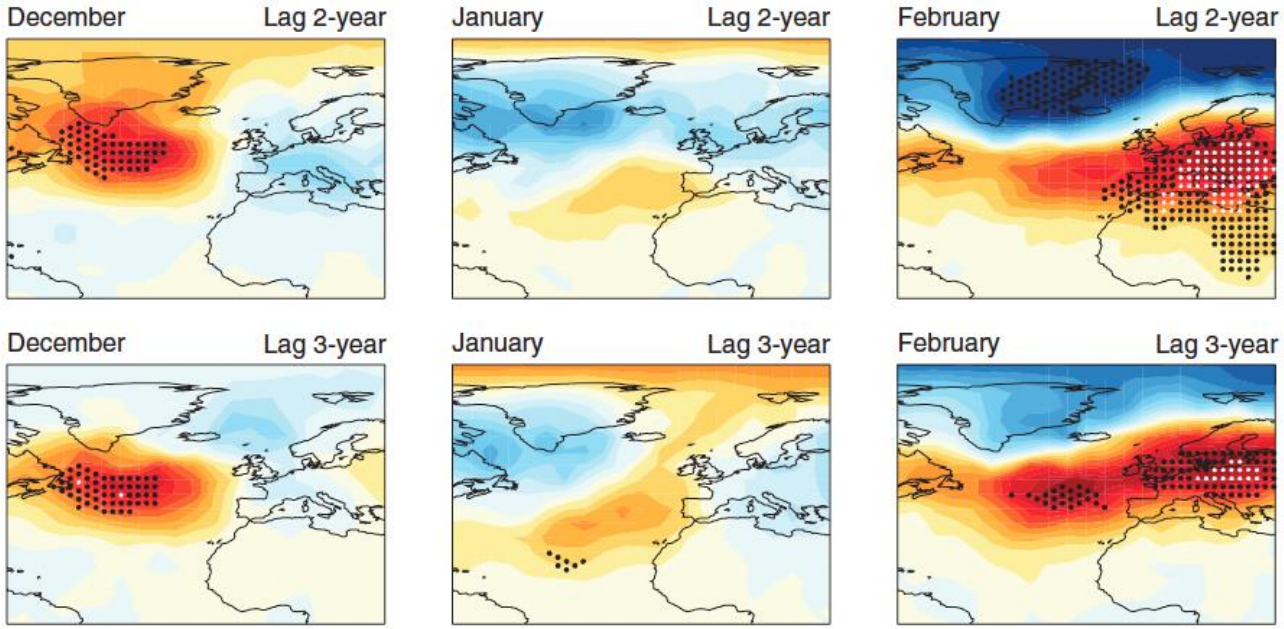


Chiodo et al., 2016

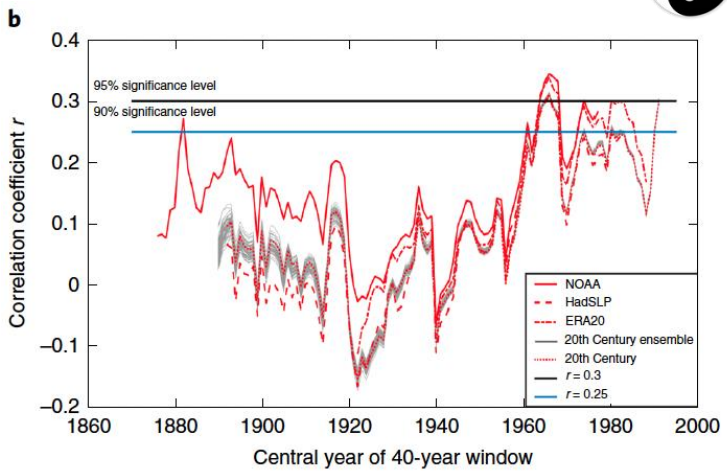


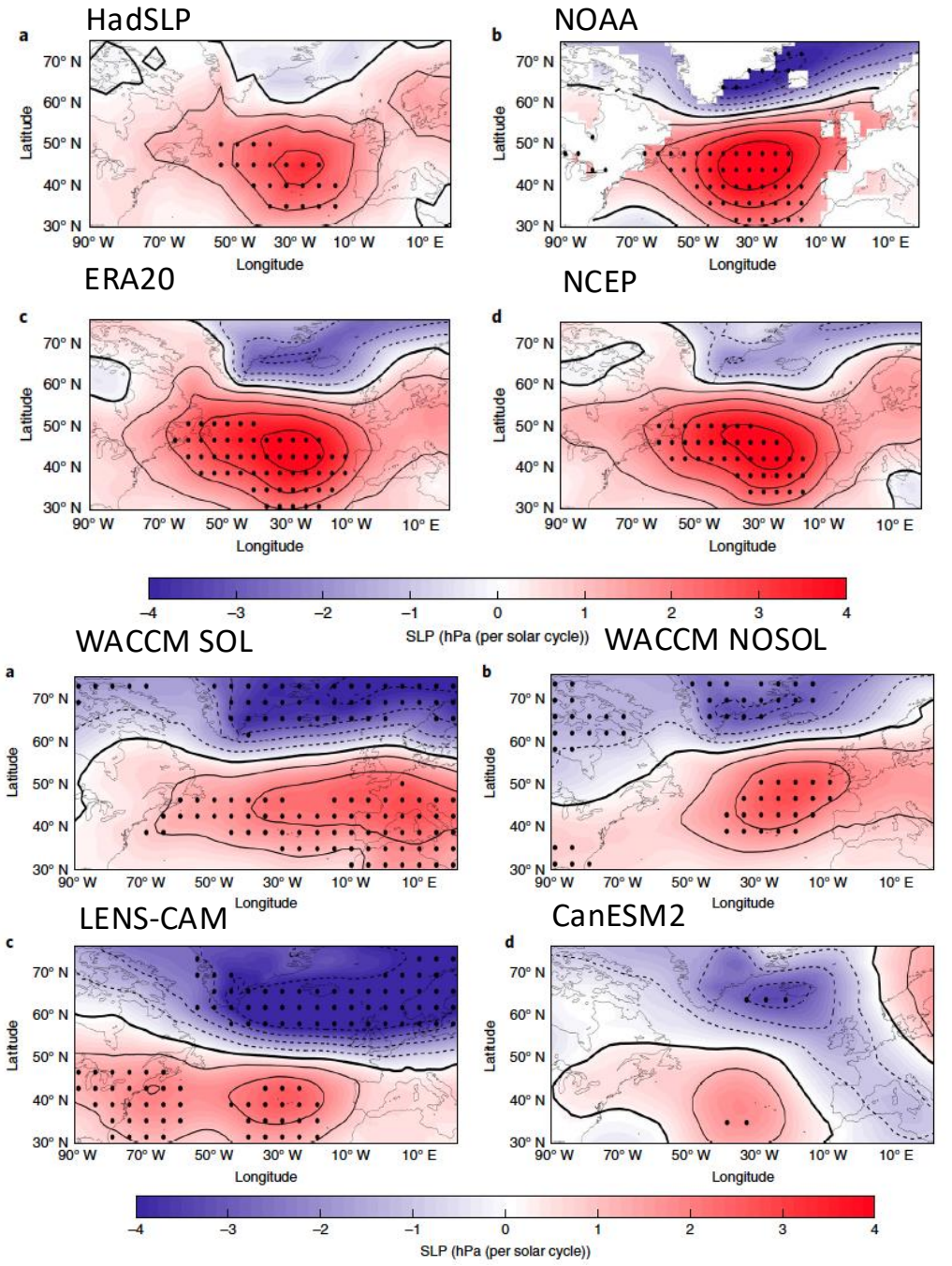
Maycock et al., 2015

Regional Solar Signal: NAO?



Gray et al., 2016





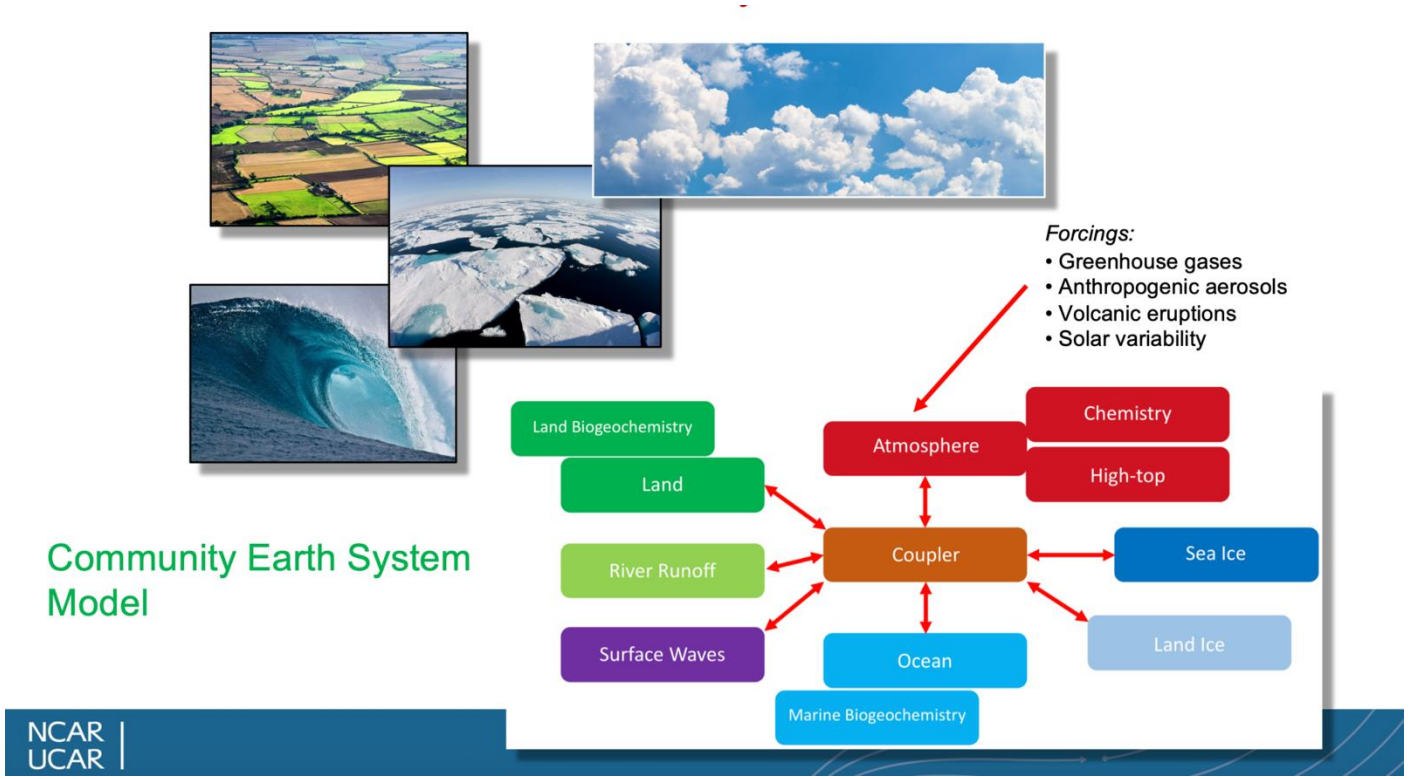
Chiodo et al, 2019

Goal of This Study

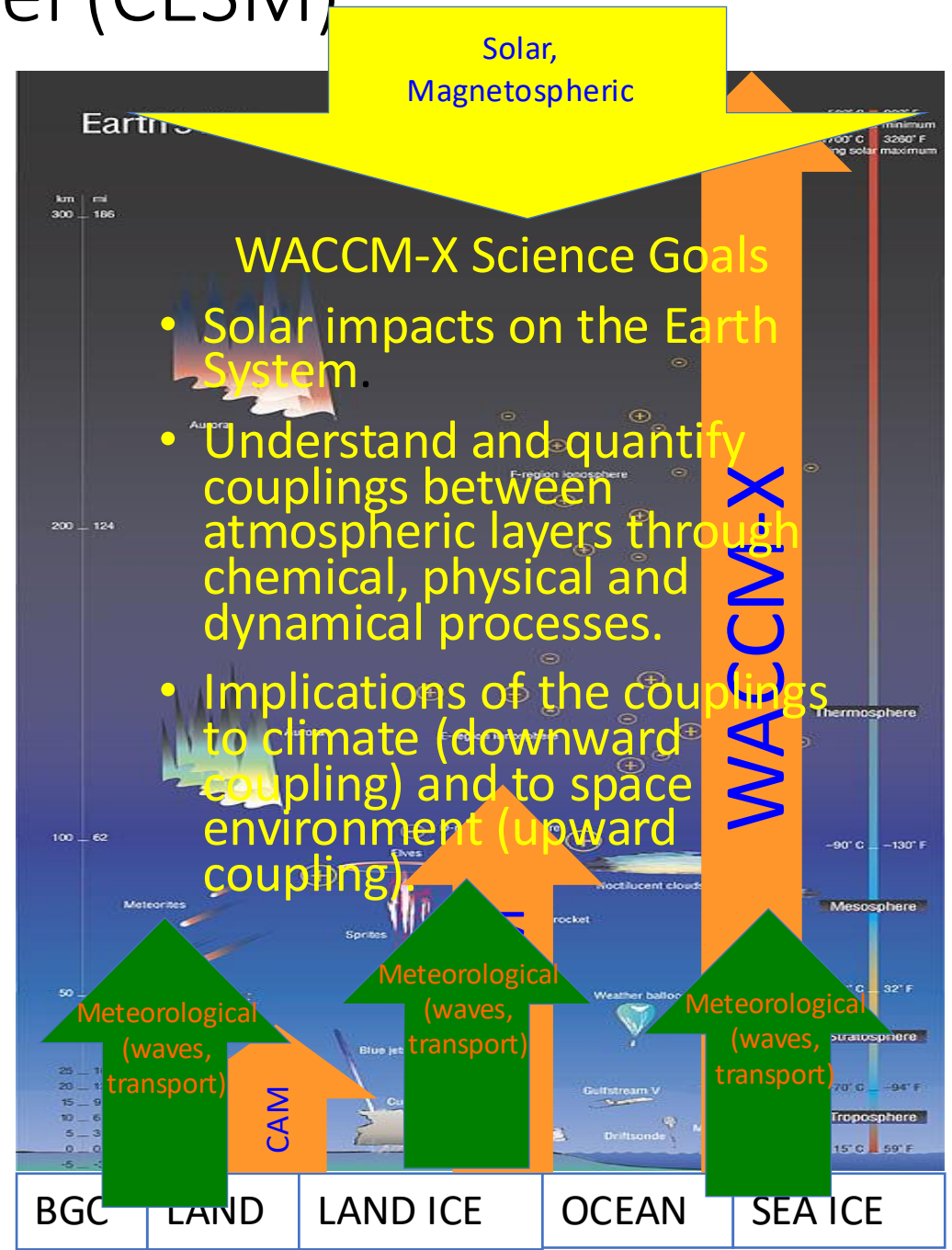
- Adapt an extreme quiet Sun (EQS) scenario to drive a fully coupled climate model (CESM-WACCM).
- Maximize the solar signal (by minimizing the solar forcing) as allowed by current understanding of solar physics.
- Enable better understanding of mechanisms responsible for climate responses, including the relative significance of bottom-up vs top-down mechanisms.

NASA LWS Grant for Sun-Climate Study: NNX16AB82G

NCAR Community Earth System Model (CESM)



CAM: Community Atmosphere Model
WACCM: Whole Atmosphere Community Climate Model
WACCM-X: WACCM with thermosphere/ionosphere extension



Key WACCM-X Capabilities

- Physics-based whole atmosphere general circulation model (0-700km)
- Solves dynamics, radiative transfer, photolysis and energetics
- Fully interactive chemistry, including ion chemistry.
- Ionospheric electrodynamics using fully interactive dynamo.
- Ion transport in the E and *F*-regions.

Model physics

- Solar inputs from F107/EUVAC or FISM for solar flares.
- Solar spectral irradiance (SSI) specification (NNLSSI record).
- Magnetospheric inputs using empirical (Heelis/Weimer) or specifications (AMIE, GAMERA).
- Energetic particle precipitation specification (EEP, SPE).
- Meteorology can be constrained by reanalysis (MERRA2, GEOS5, or ERA).

Drivers

- High-resolution capability to resolve mesoscales.
- Whole atmosphere data assimilation (DA) for specification and forecast.
- Run on request at NASA CCMC (Community Coordinated Modeling Center).

CESM Whole Atmosphere Community Climate Model

- WACCM configuration used, not focusing on the downward impact of thermosphere/ionosphere.
- Interactive chemistry package from the troposphere to the lower thermosphere.
- Fully coupled ocean component Parallel Ocean Program (POP) model.
- Resolution: 1.9^{o}x2.5^{o} 66 levels (atmosphere); 1^{o} (ocean).
- 200 year simulations under each constant solar conditions (no solar cycle, no forced QBO in simulations).

Solar Forcing

- Nominal solar maximum and minimum.
- Extreme quiet Sun (EQS) scenario derived from finite domain MURaM quiet Sun simulation (Rempel, 2020).
  - The lowest TSI/SSI level from the non-magnetic/hydrodynamics (HD) reference case.
- Additional simulations with only visible/IR or UV using EQS values

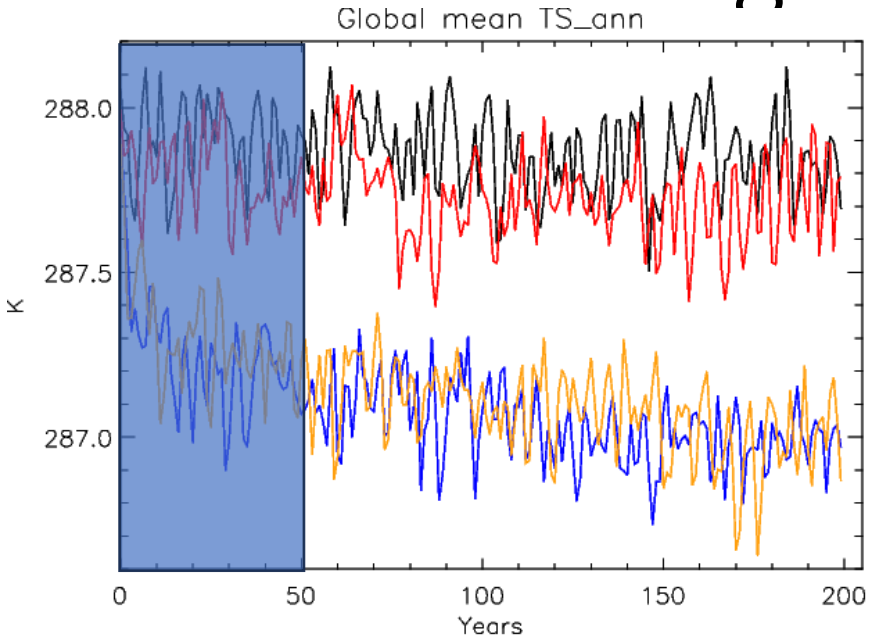
Solar Forcing Used for Driving CESM/ WACCM Simulations	Nominal solar maximum (Smax)	Nominal solar minimum (Smin)	Non-magnetic, hydrodynamic (HD) reference	SSI(Smin) ($\lambda \leq 320$nm)+ SSI(HD) ($\lambda > 320$nm) (HDVIR)	SSI(HD) ($\lambda \leq 320$nm)+ SSI(Smin) ($\lambda > 320$nm) (HDUV)
TSI (Wm^{-2})	1361.93	1360.43	1350.08	1350.84	1359.76

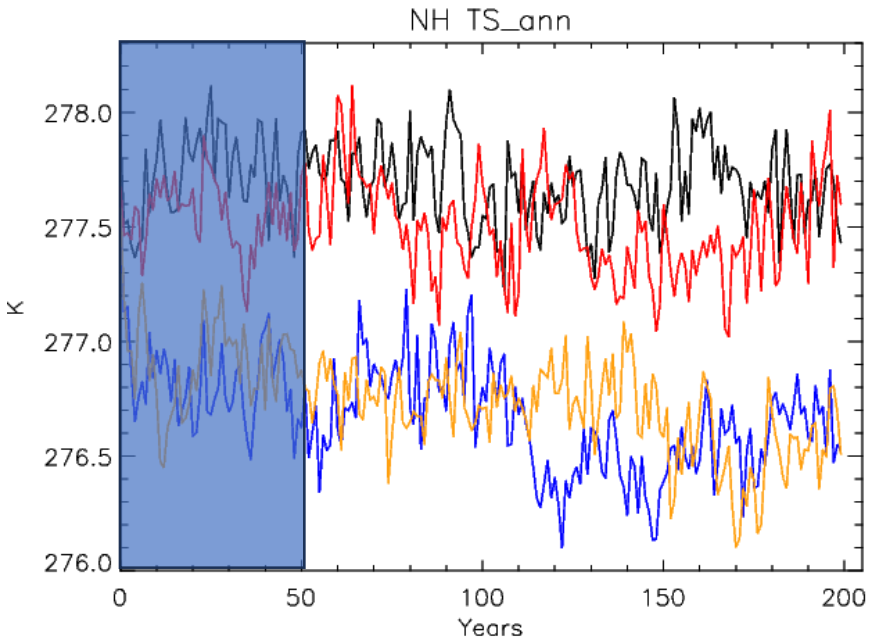
Numerical Experiments and Analysis Method

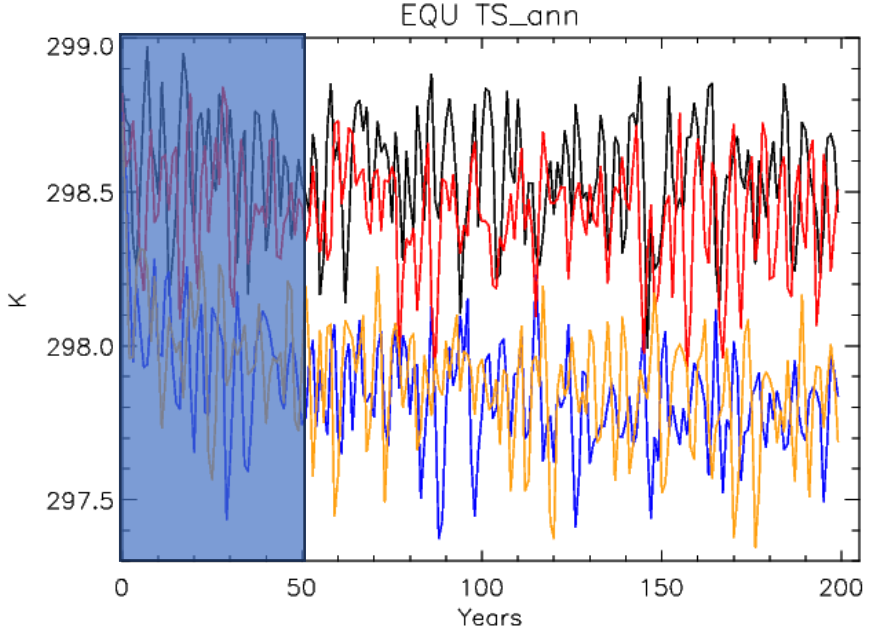
- CESM/WACCM Numerical experiments (200 years for each configuration)
  - Nominal solar max
  - Nominal solar min
  - SSI/TSI from HD solar simulation (0.86% lower than solar max)
    - <320 nm nominal solar min; >320 nm HD (HDVIR)
    - <320 nm HD; >320 nm nominal solar min (HDUV)
- 50-200 years used for the analysis.
- Grid-by-grid Student T-test: Could lead to high false discovery rate (FDR) (Wilks, 2016).
- Applying test method to control FDR (Ventura et al., 2004).

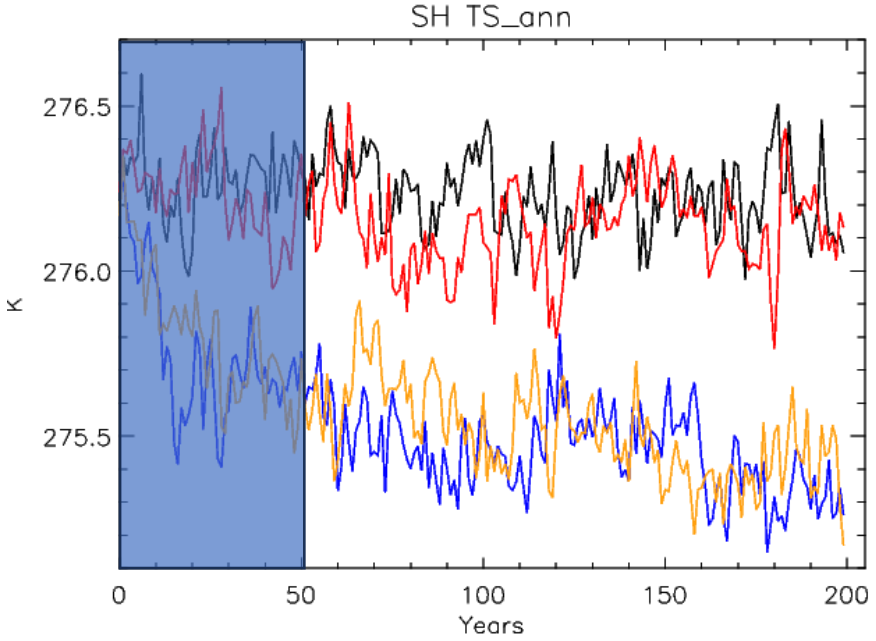
Surface, Troposphere and Ocean Responses

Annual Average TS Time Series





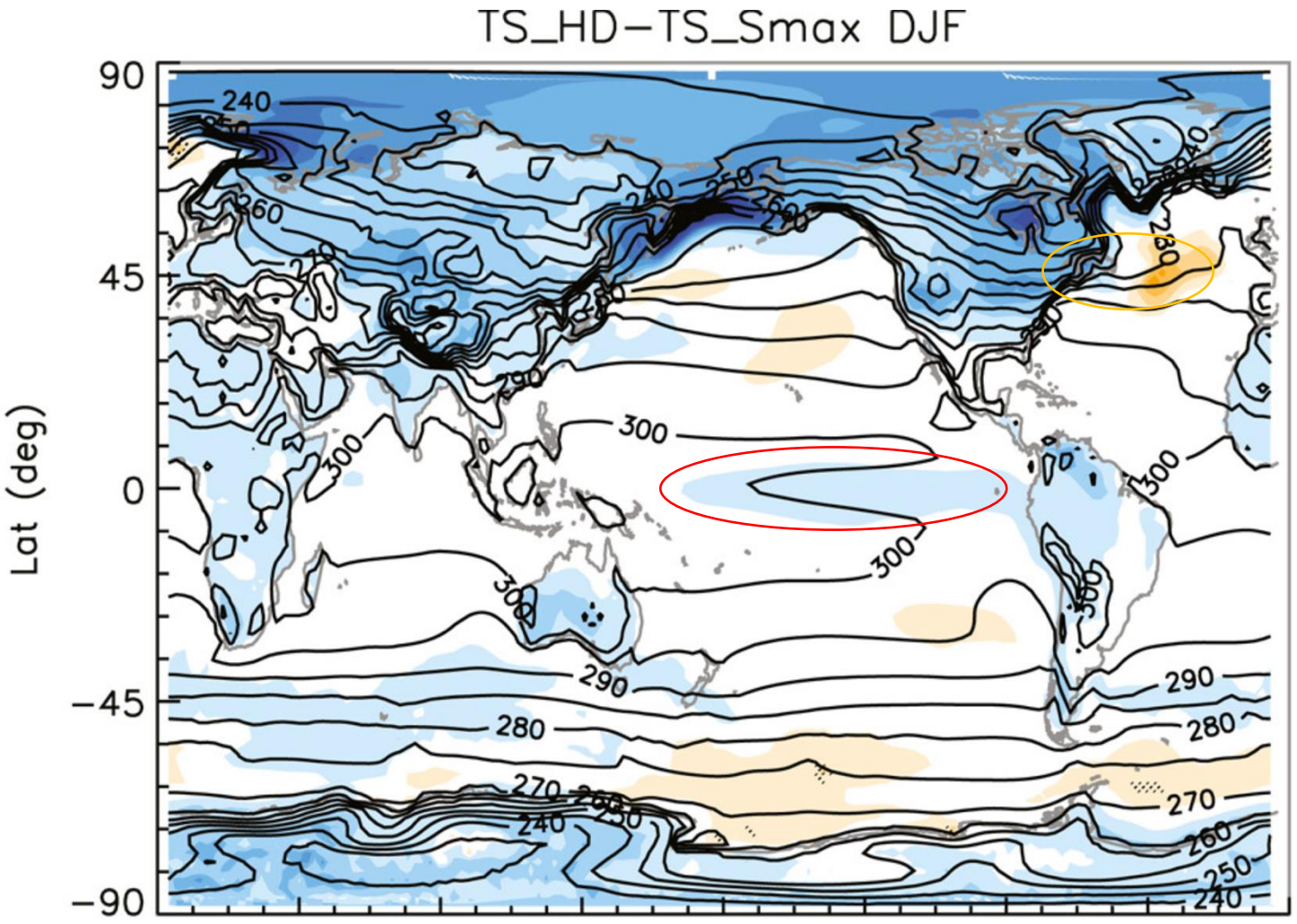


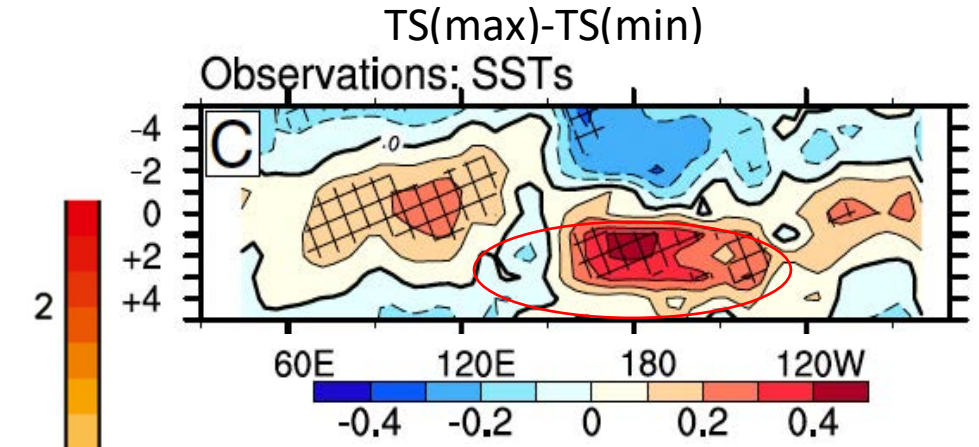


Smax
HDUV
HDVIR
HD: EQS

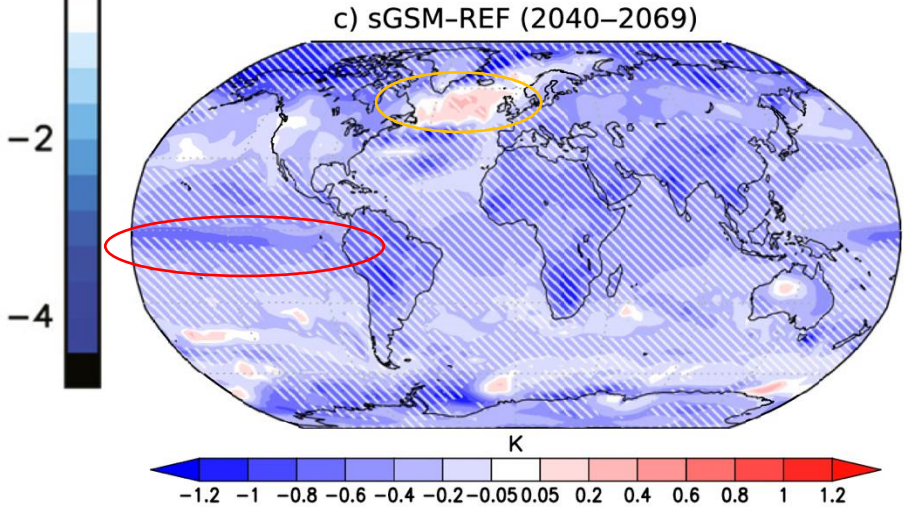
~0.07 K/(W m^{-2})

Surface Temperature: Comparison with Earlier Studies





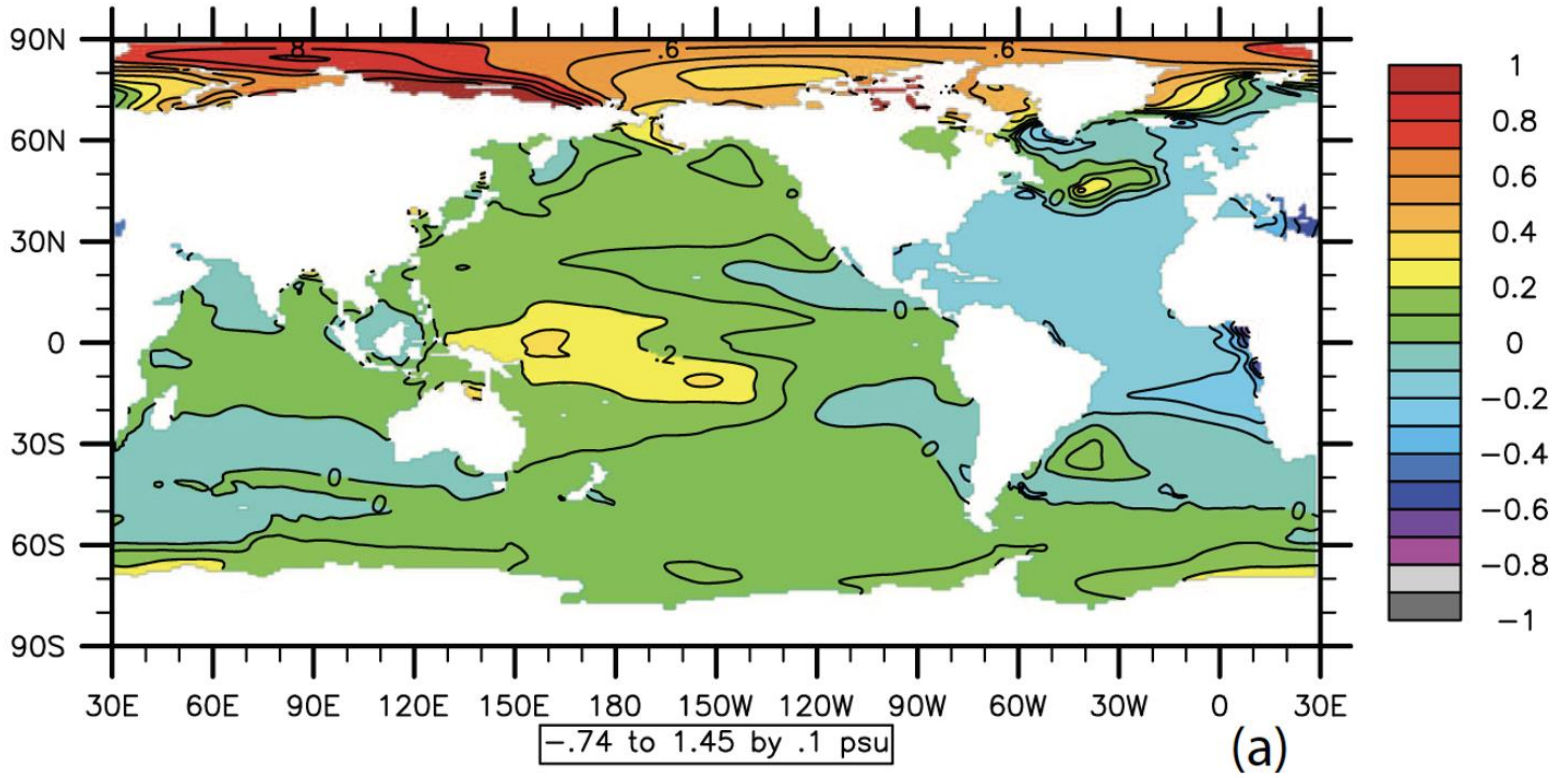
Misios et al., 2019



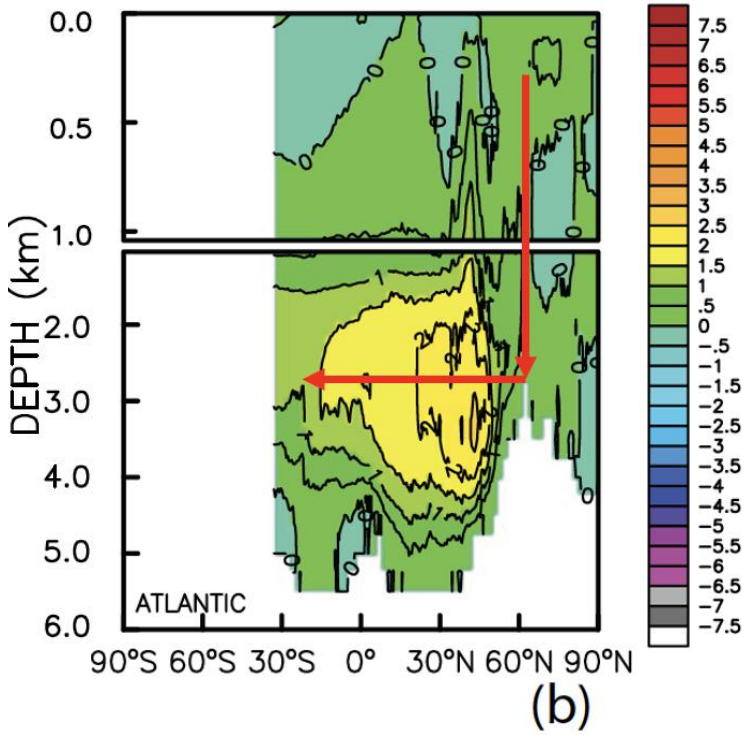
Spiegl and Langematz, 2020

Ocean Response: HD-Smax (DJF)

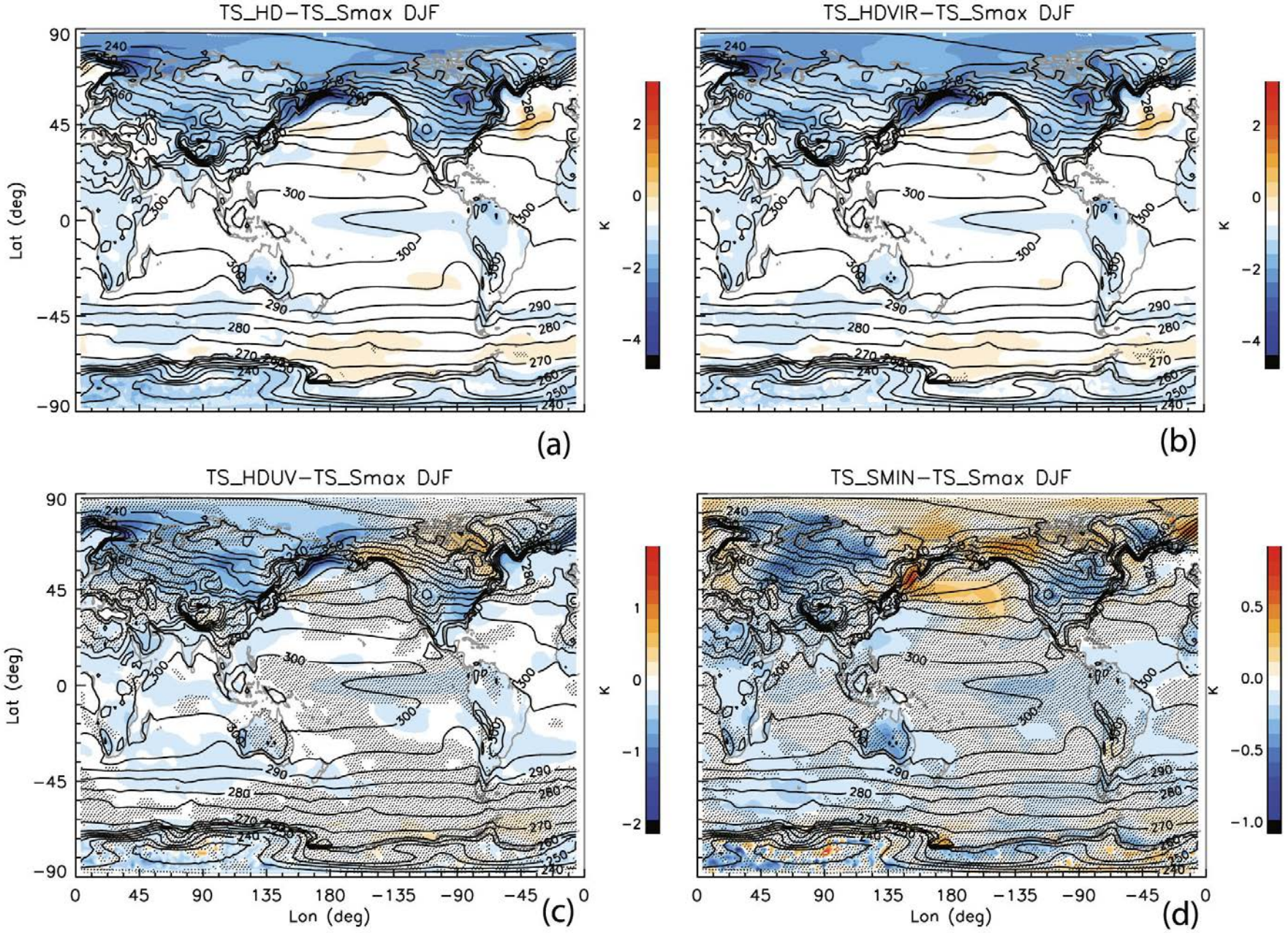
Salinity



AMOC



Surface Temperature DJF: Bottom-up (HDVIR) and Top-down (HDUV)



HDVIR and HDUV in phase:

- Eastern Pacific cooling
- Top-down weaker than bottom-up

HDVIR and HDUV out of phase:

- Ts pattern over land > 50N

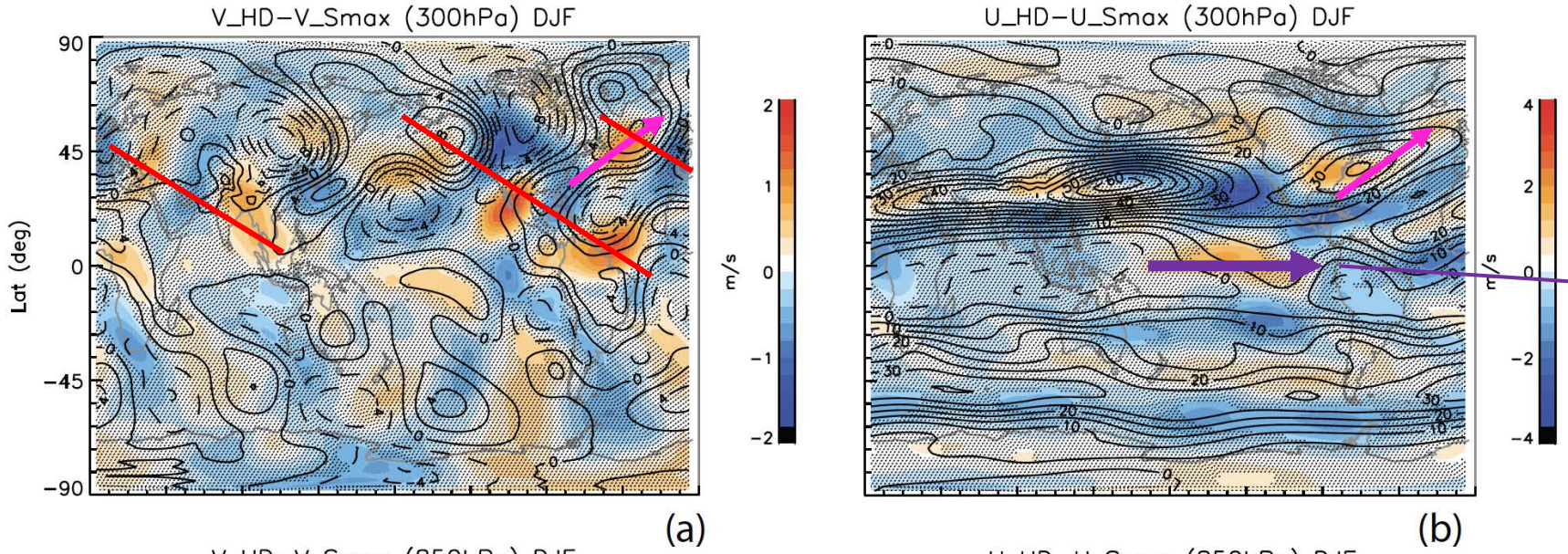
Features in Smin and HDUV similar to HD/HDVIR, but may not appear statistically significant.

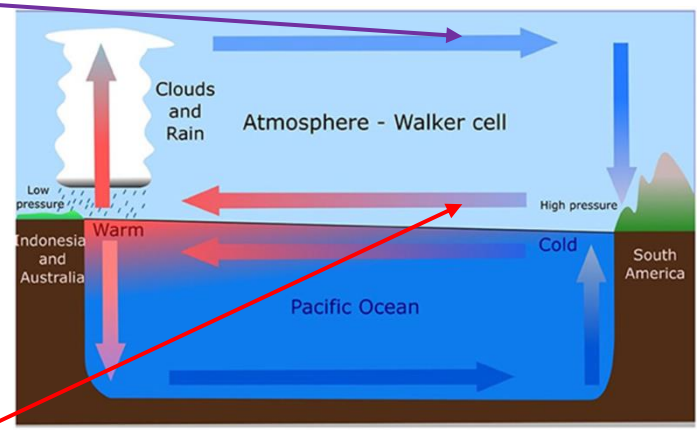
- Land cooling except N.N. America
- Eastern Pacific cooling

Regional Changes of Tropospheric Winds (DJF)

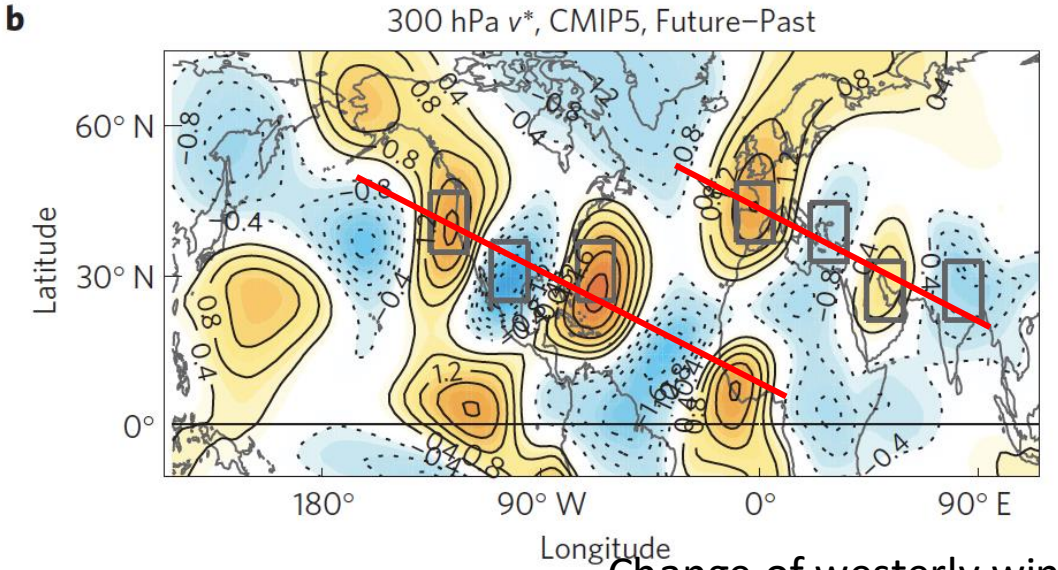
300 hPa (10 km)

850 hPa (near surface)

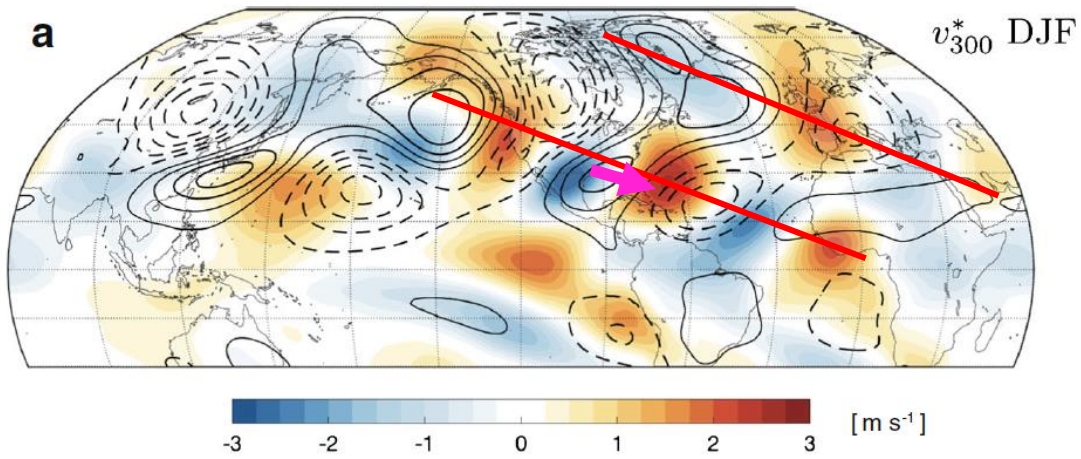




Cause of Tropospheric Wind Change

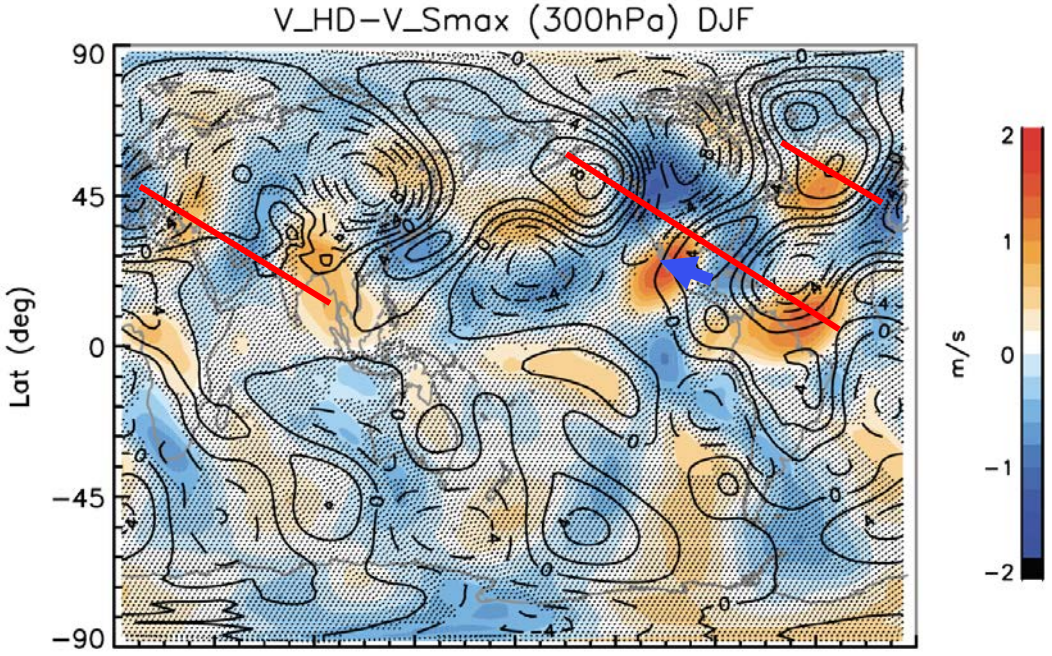


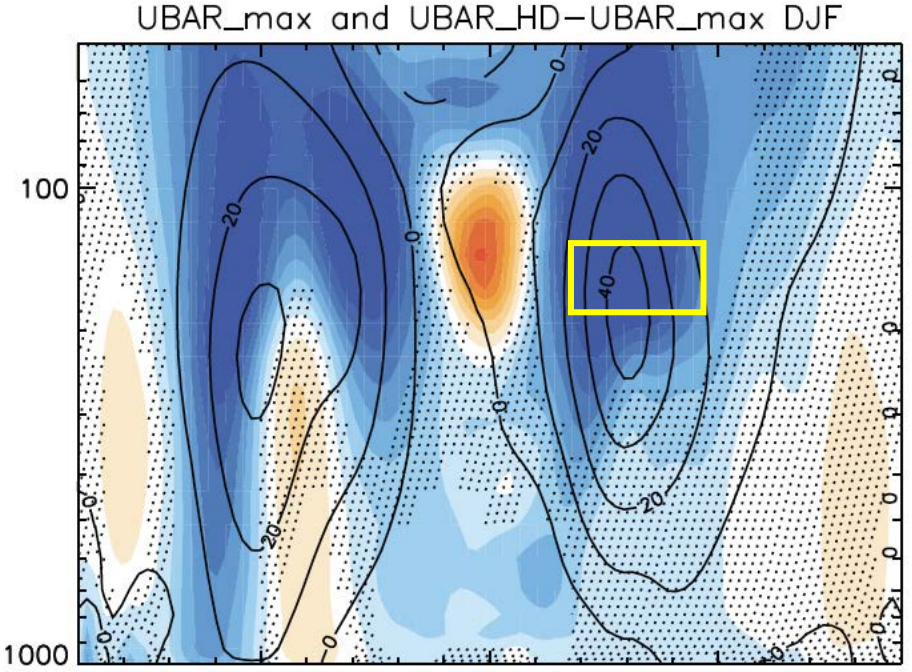
Simpson et al. 2016



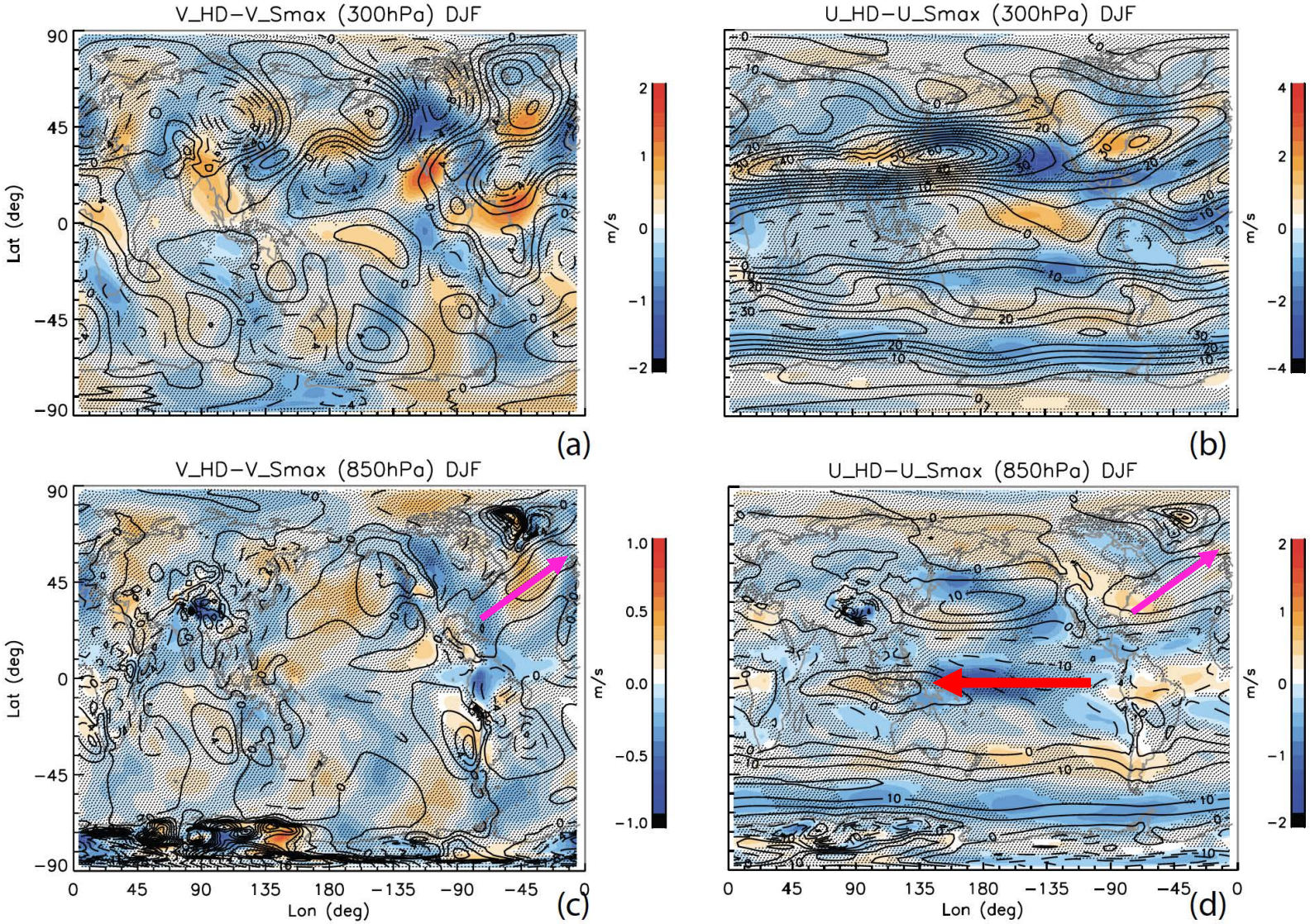
Wills et al. 2019

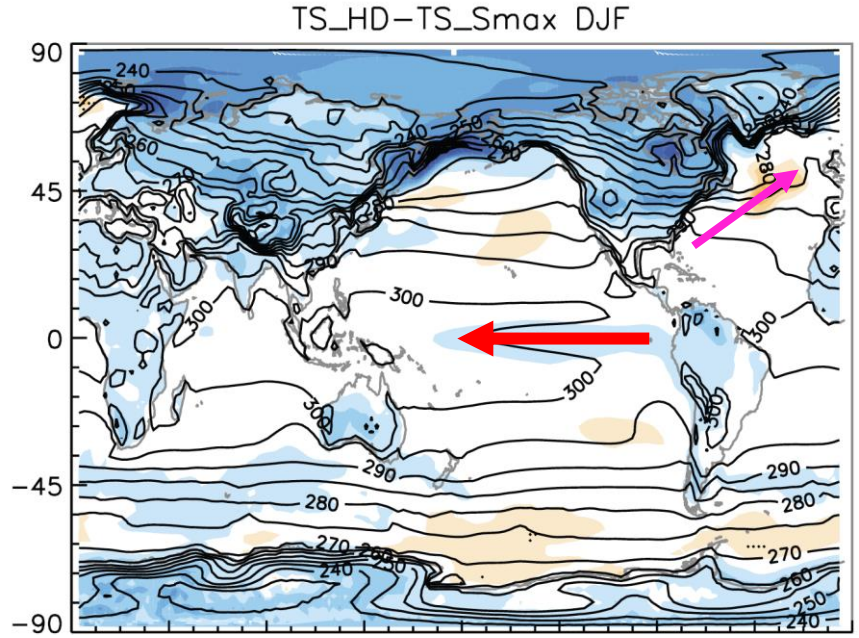
Change of westerly wind in the sub-tropical upper troposphere

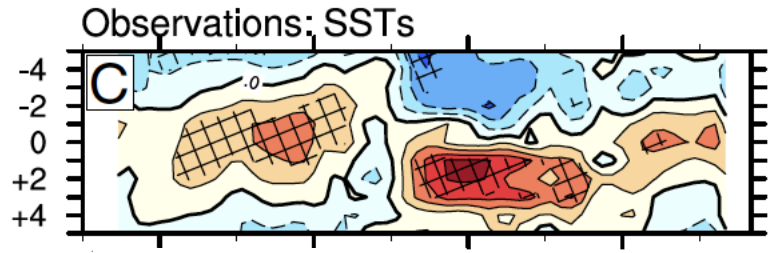




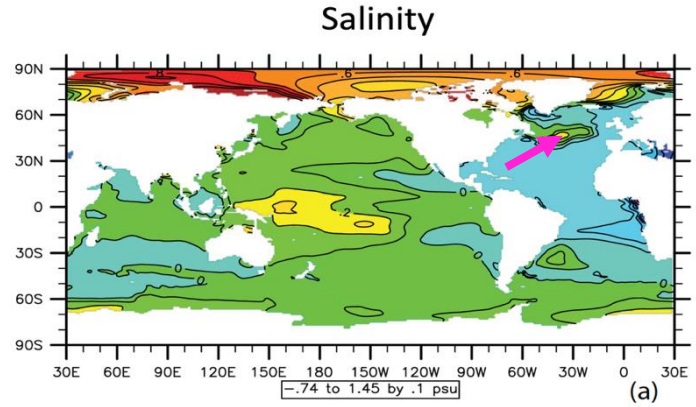
Wind and surface temperature changes







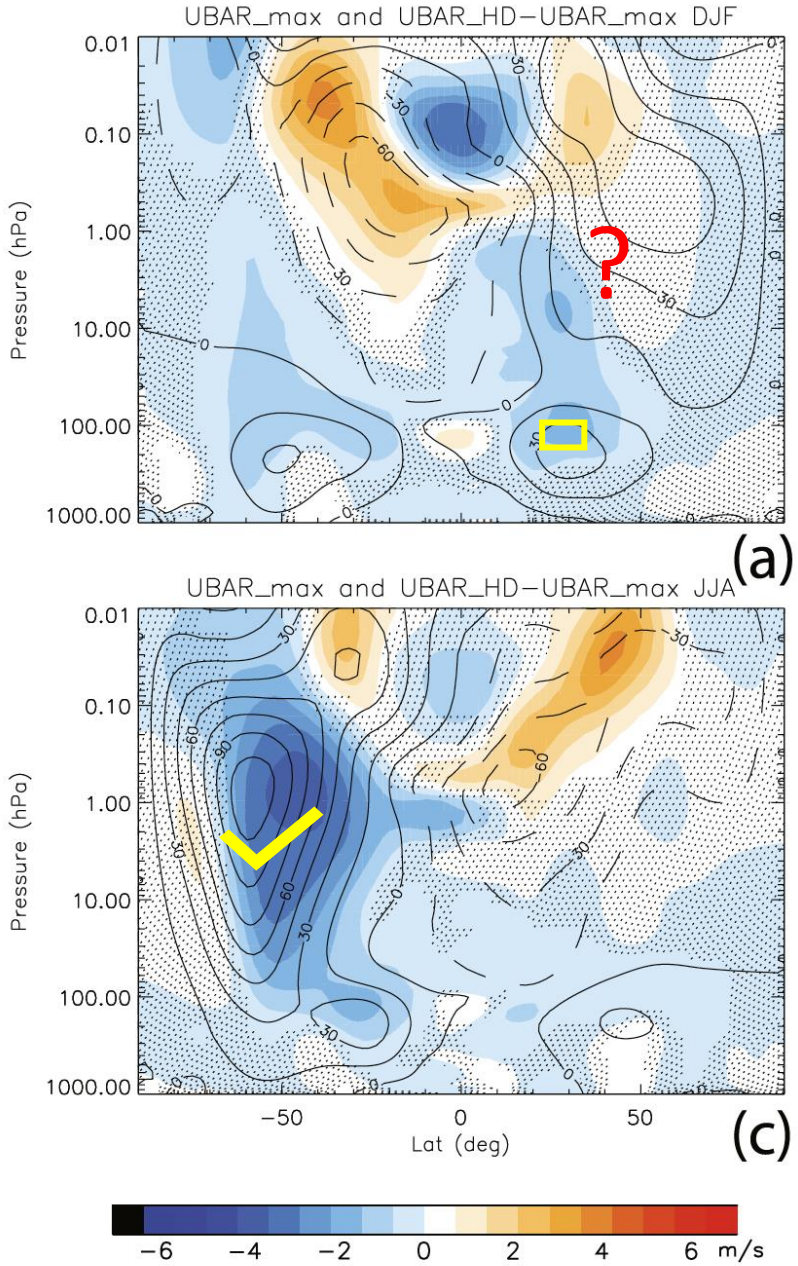
Misios et al., 2019



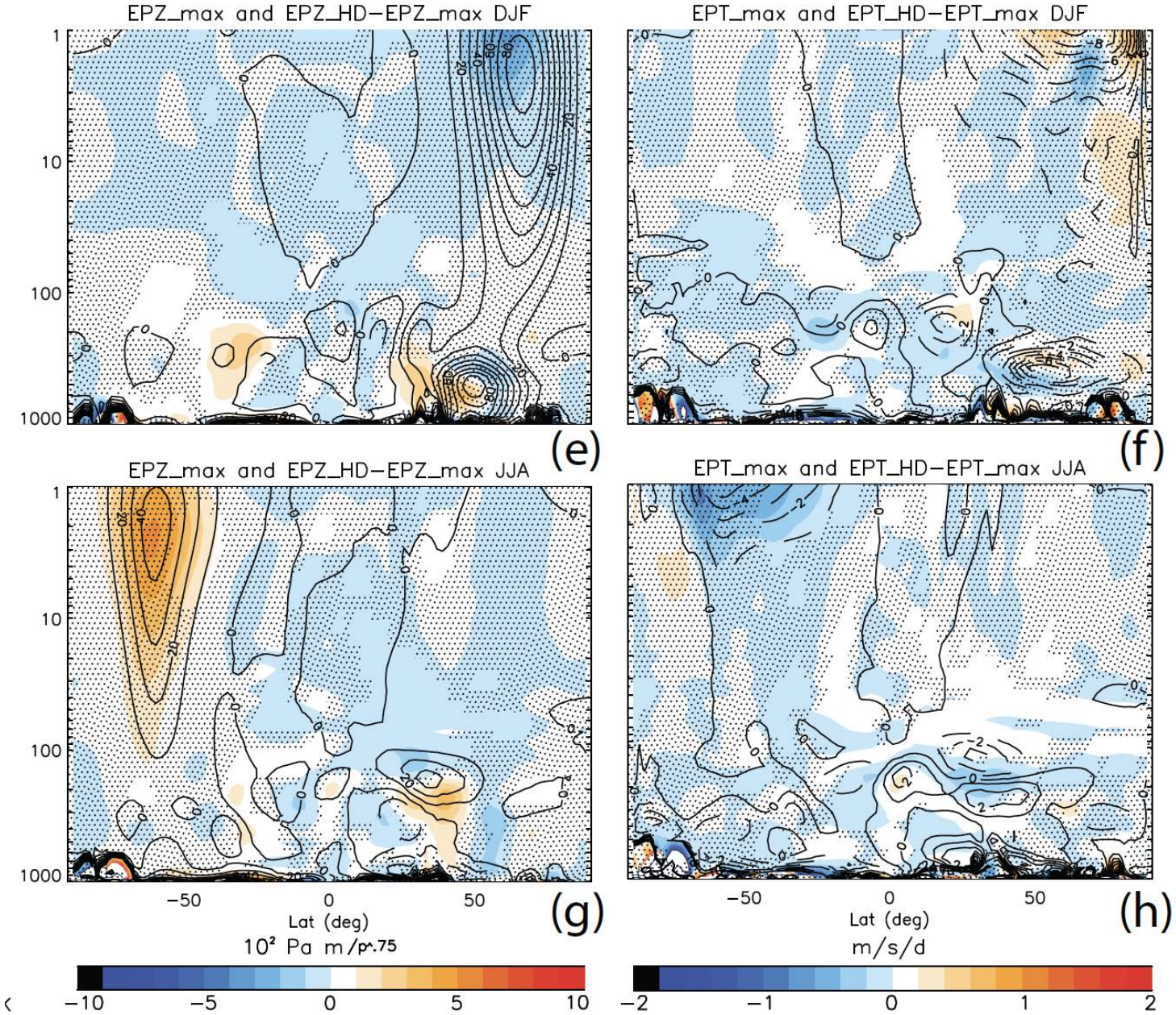
Middle Atmosphere Responses

Mean wind and temperature change in stratosphere/troposphere

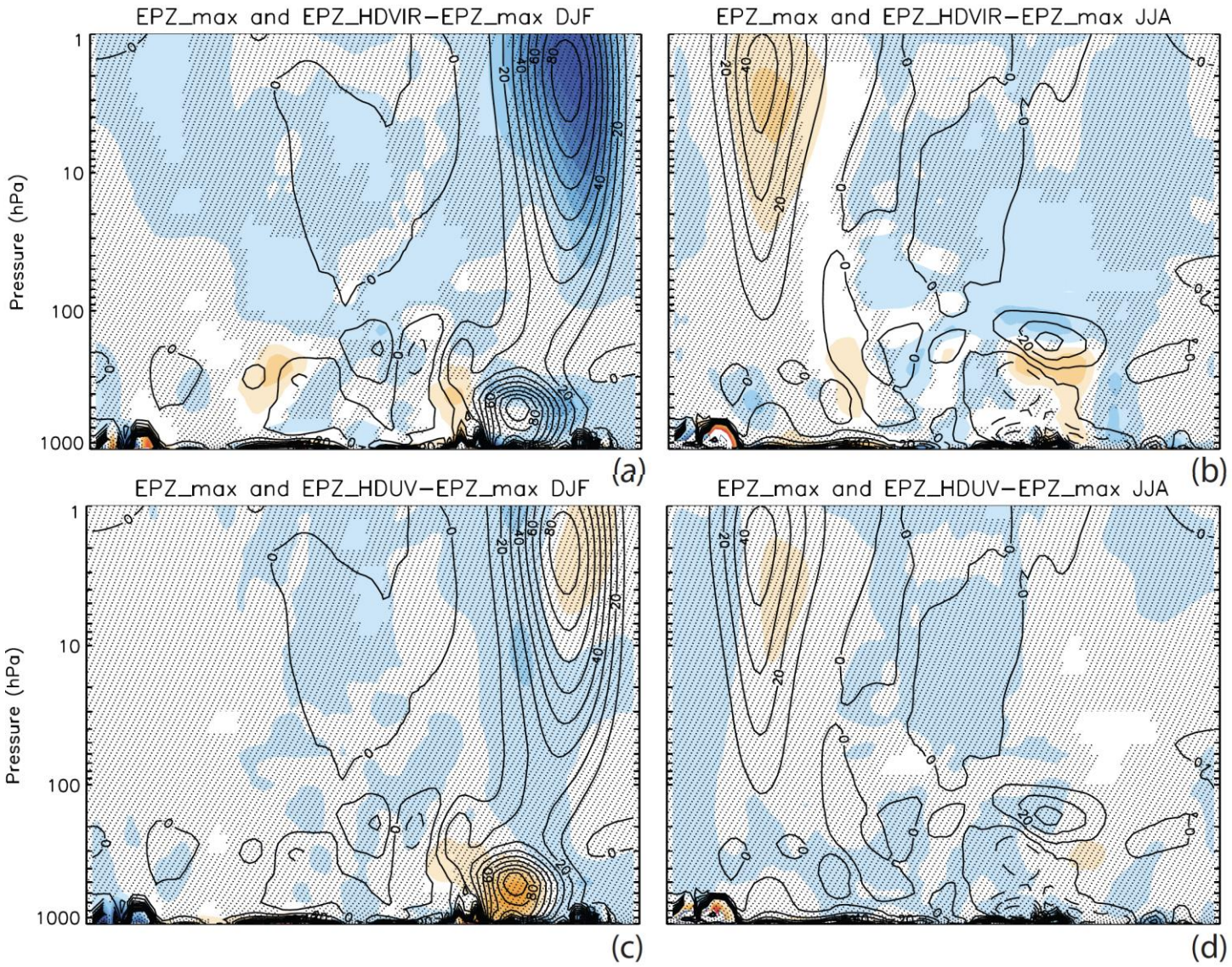
Agreeing with Kodera and Kuroda (2002)?

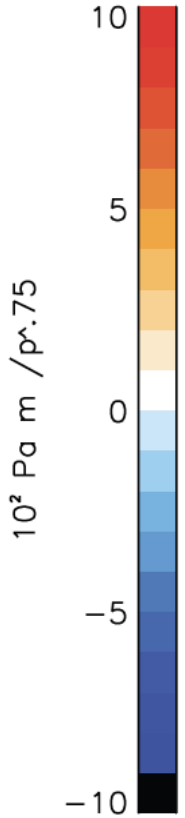


Planetary Wave Responses: EP Fluxes (DJF and JJA)



PW Responses to VIR and UV changes

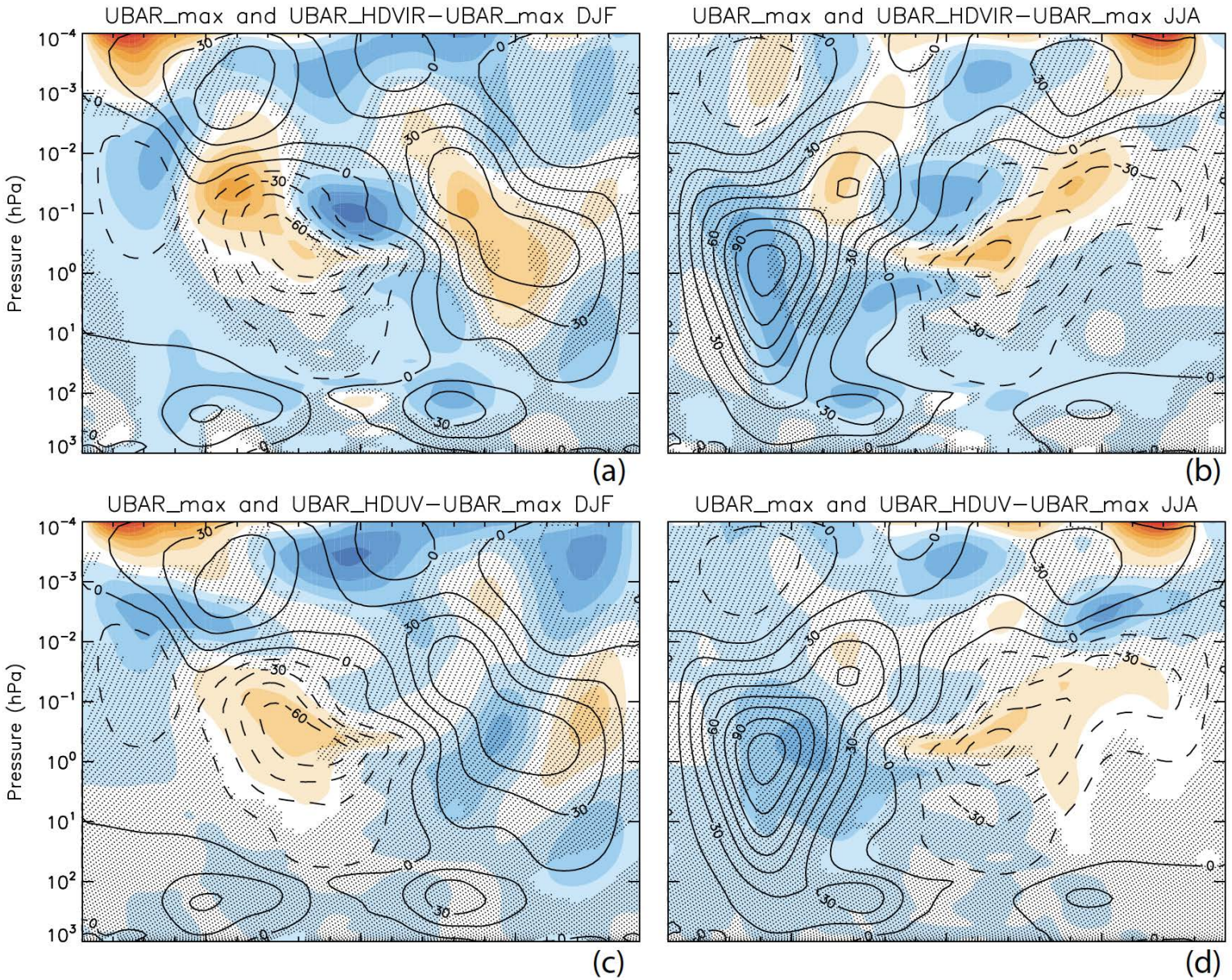




VIR/tropospheric change: Asymmetric

UV/stratospheric change: Symmetryic

Mean Zonal Wind Responses to VIR and UV Changes



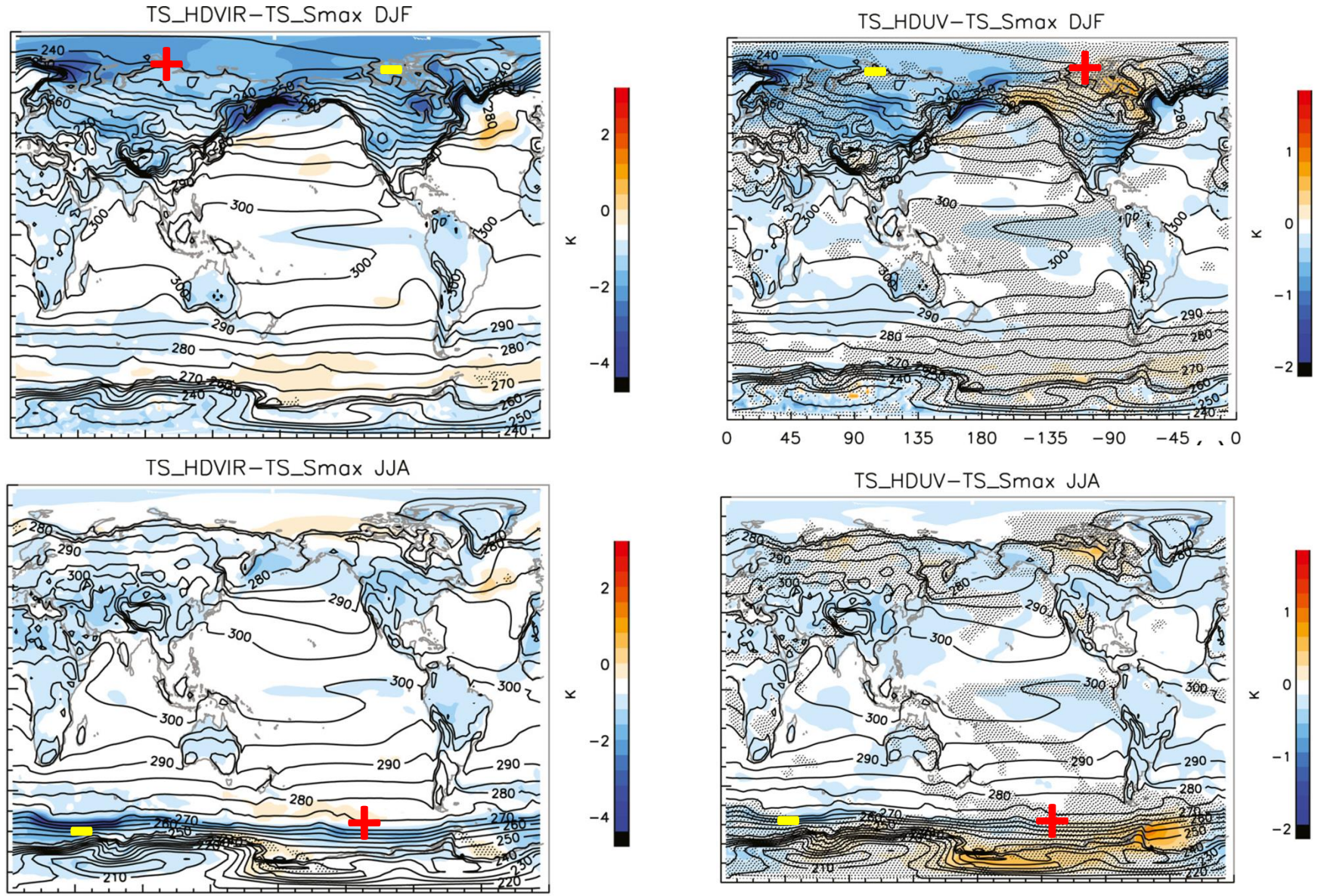
Hemispheric Asymmetry: PW and Surface Responses

HDVIR

HDUV

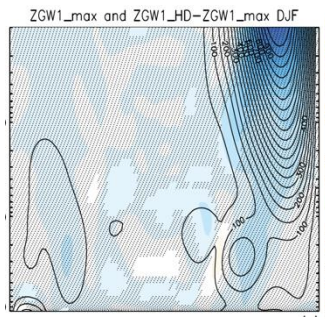
DJF

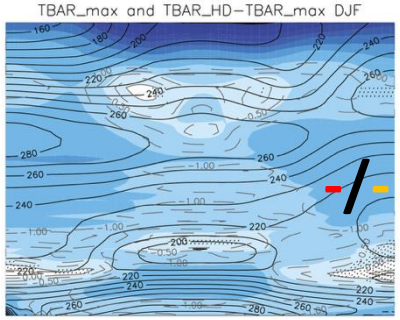
JJA

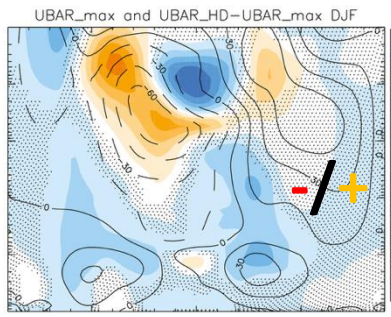


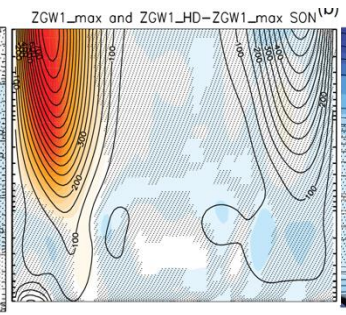
Changes under Quasi-equilibrium Conditions (Min vs Max year 50-200)

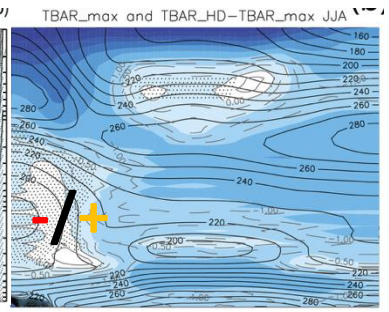
	PW(NH)	T(NH)	U(NH)	PW(SH)	T(SH)	U(SH)
Radiative		Cooling	Slower		Cooling	Slower
Dynamics	Weaker (BD Weaker)	Cooling	Faster	Stronger (BD Stronger)	Warming	Slower
Net		Strong Cooling	Variable		Variable	Much Slower
Tropo/Ocean		Cooling (Arctic)				Slower

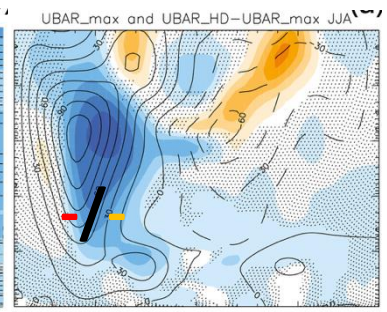












Summary

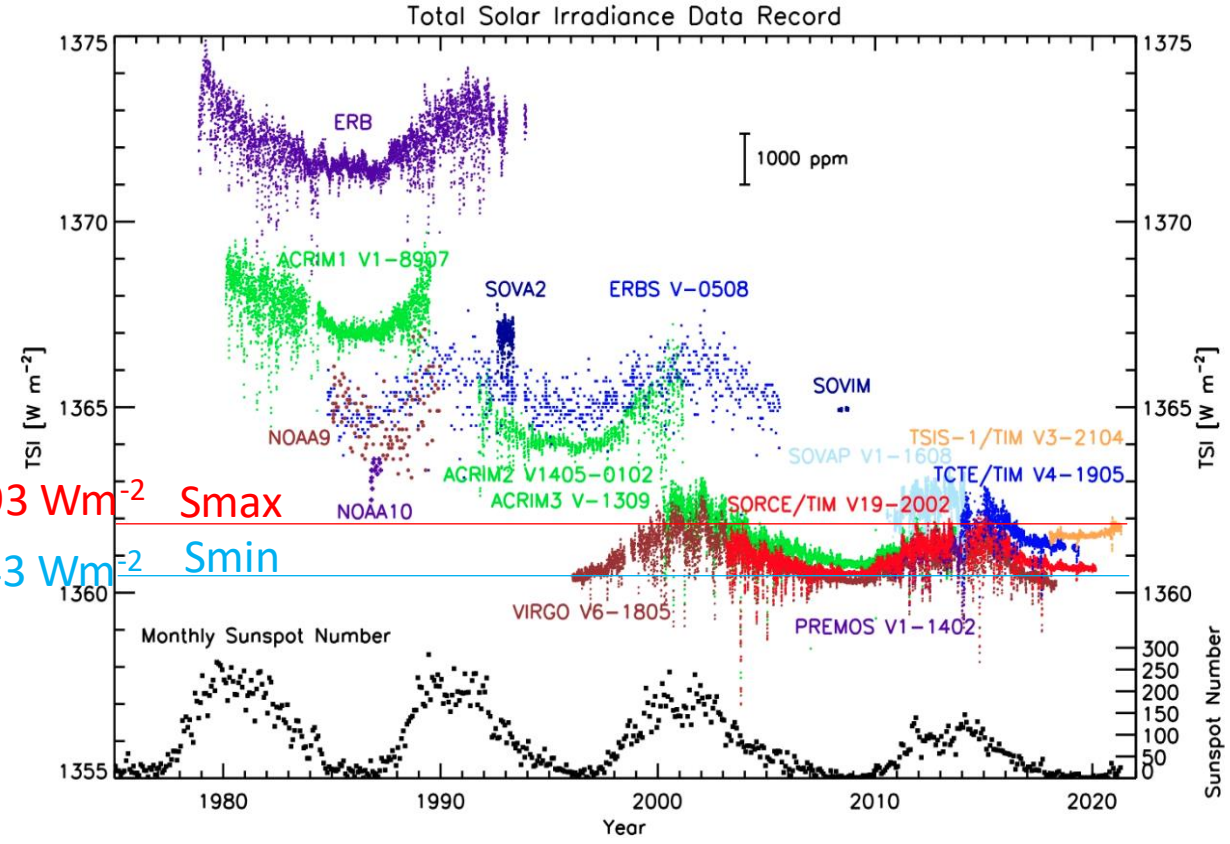
- Extreme quiet scenario enables better quantification of climate responses to solar forcing.
- Regional surface features: Intermediate scale stationary planetary wave.
  - Sensitively controlled by extratropical zonal wind in the upper troposphere.
  - In turn affected by both tropospheric and stratospheric diabatic heating.
  - Patterns similar to patterns caused by anthropogenic climate change.
- Robust responses in the coupled middle atmosphere, troposphere, and ocean system, with significant hemispheric differences.
  - Different stationary planetary wave responses in two hemispheres.
  - Interplay between radiative and dynamical changes.
  - Top-down and bottom-up can be in phase, but former is weaker than latter.
- Simulations under EQS conditions reveal patterns of responses ”hidden” under weaker solar forcing changes.

Future Studies

- Impact on the precipitation.
- Impact on leading climate modes (NAM, SAM)
- Model resolution dependence (especially regarding regional climate)
- Identify ”hidden” solar signals using responses to EQS.
- Use EQS criteria for inter-model comparisons of solar signals.
- AMOC impact: >500 years
- Applications for geoengineering studies.

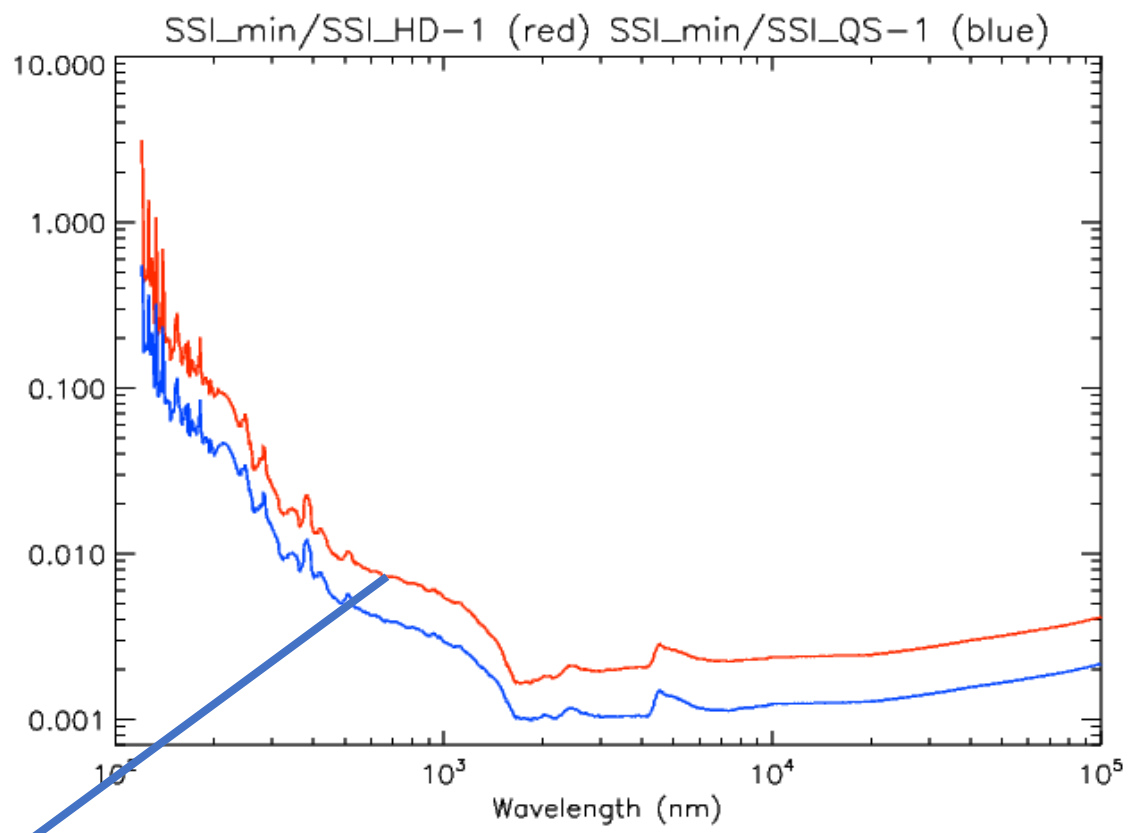
Backup Slides

TSI and SSI compared to Current Solar Conditions



1361.93 Wm^{-2} Smax

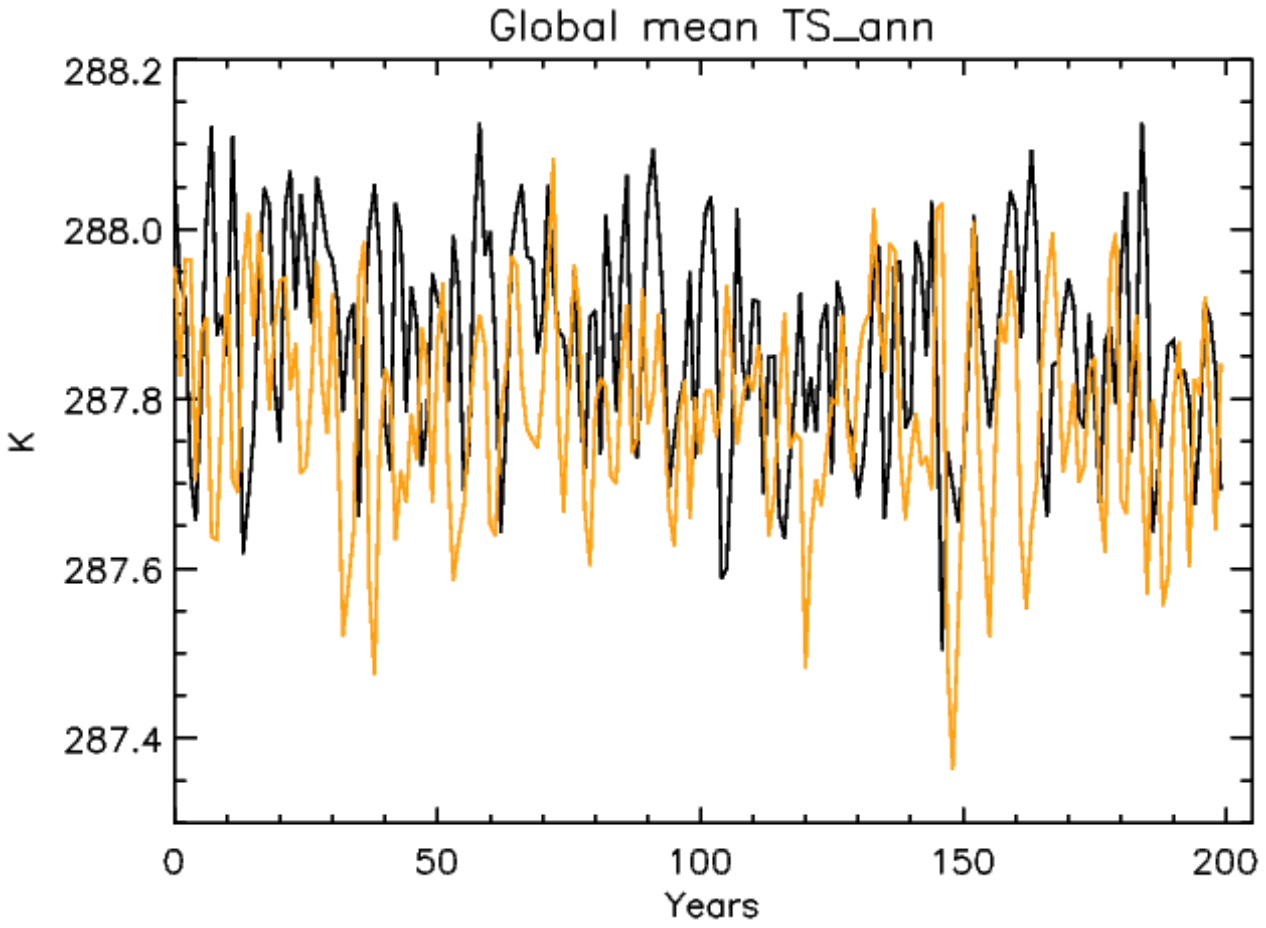
1360.43 Wm^{-2} Smin



Kopp, 2021

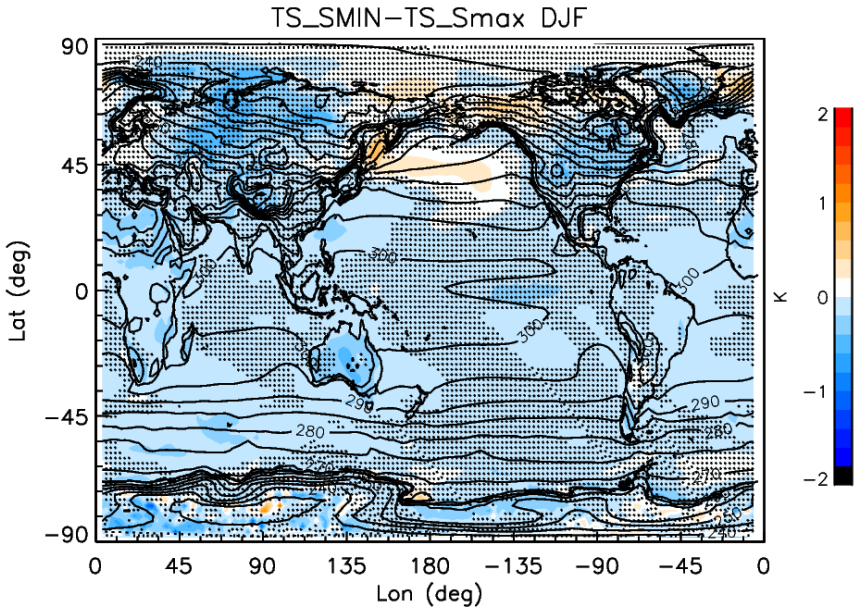
1350.08 Wm^{-2} HD

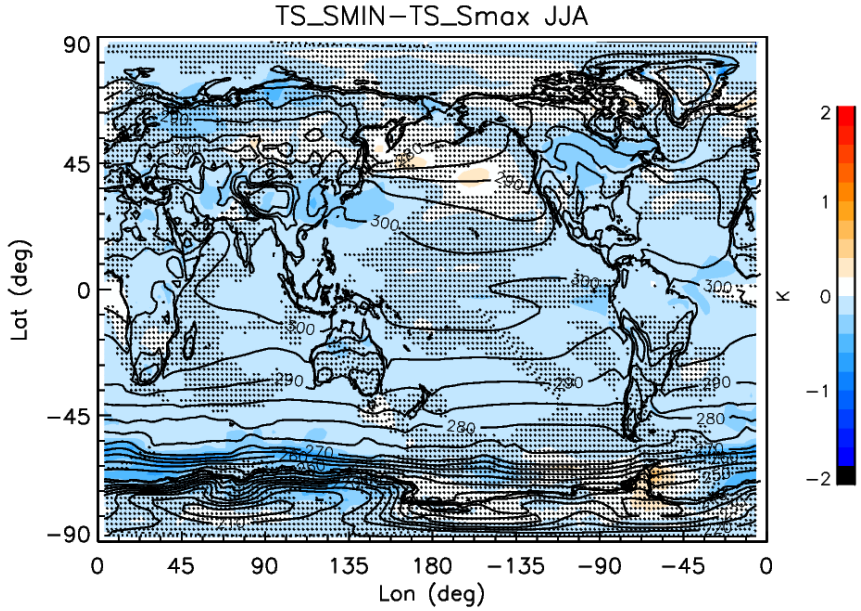
Solar Signal in Surface Temperature?



Constant solar maximum (SOLIN: 340.483 W/m^2)

Constant solar minimum (SOLIN: 340.107 W/m^2)





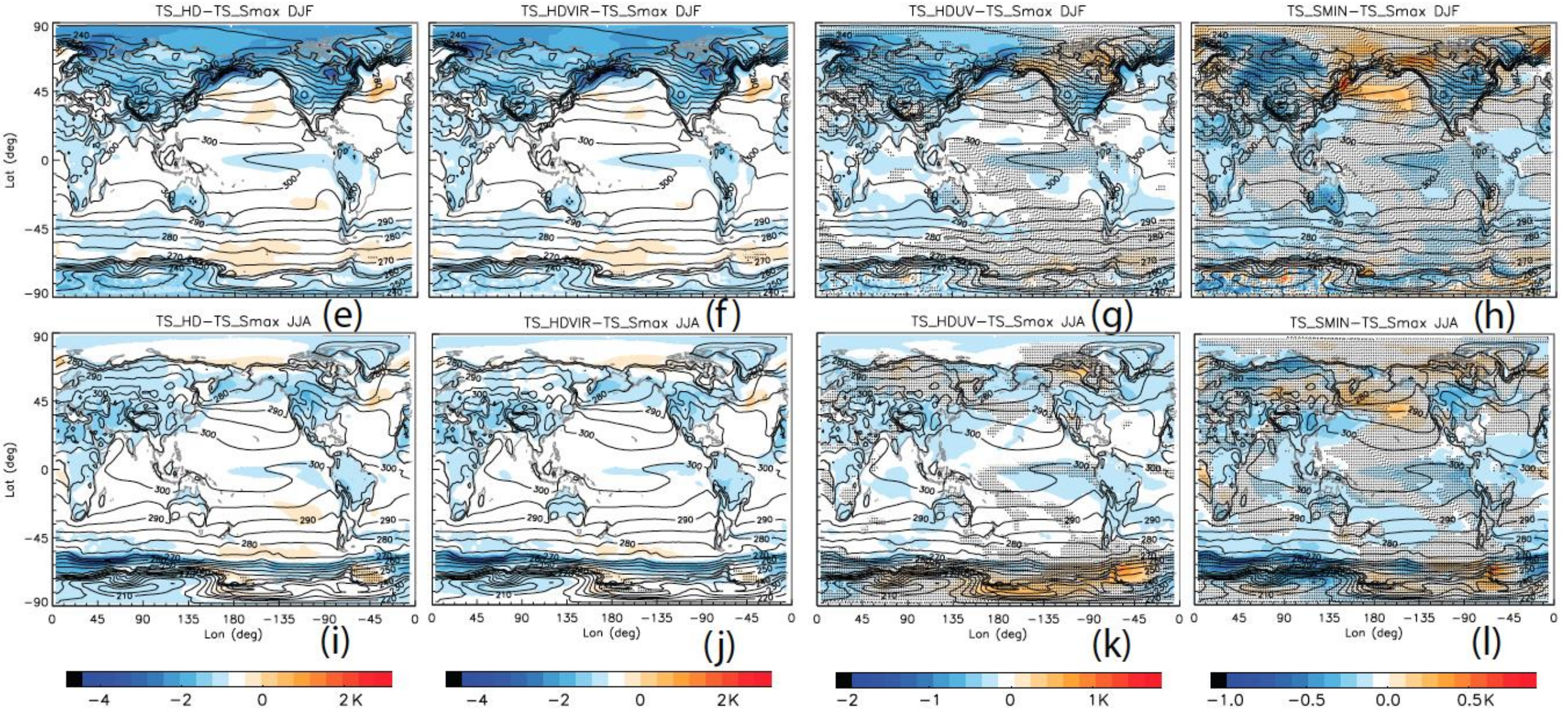
Stippled: Statistically insiginficant

Climate Sensitivity: Surface Temperature

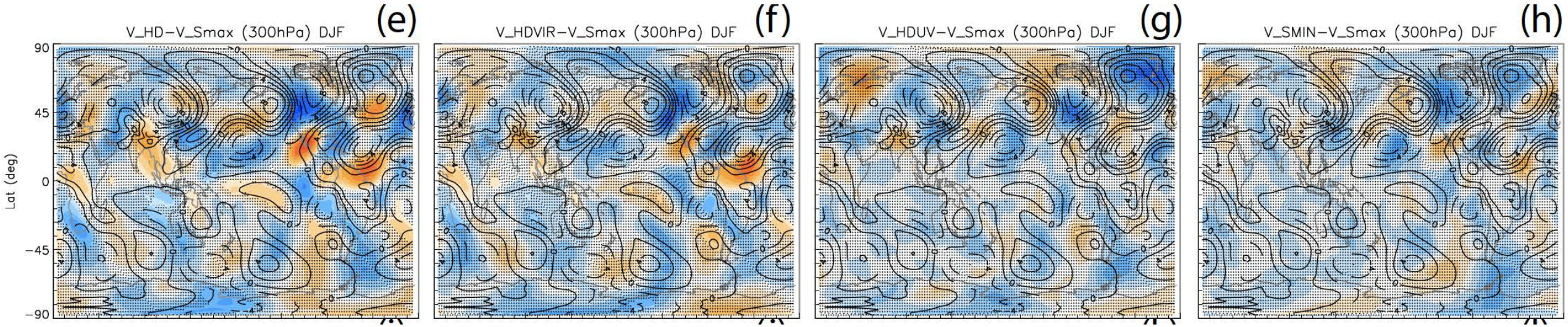
Solar Forcing Used for Driving CESM/ WACCM Simulations	Nominal solar maximum (Smax)	Nominal solar minimum (Smin)	Non-magnetic, hydrodynamic (HD) reference	SSI(Smin) ($\lambda \leq 320$nm)+ SSI(HD) ($\lambda > 320$nm) (HDVIR)	SSI(HD) ($\lambda \leq 320$nm)+ SSI(Smin) ($\lambda > 320$nm) (HDUV)
TSI (Wm^{-2})	1361.93	1360.43	1350.08	1350.84	1359.76
Ts (K)	287.87	287.78	287.04	287.08	287.72
Climate Sensitivity ($K(Wm^{-2})^{-1}$)		0.0578	0.0705	0.0712	0.0691

0.07-0.08 K/(W m^{-2}): White et al., 1997; Gray et al., 2010

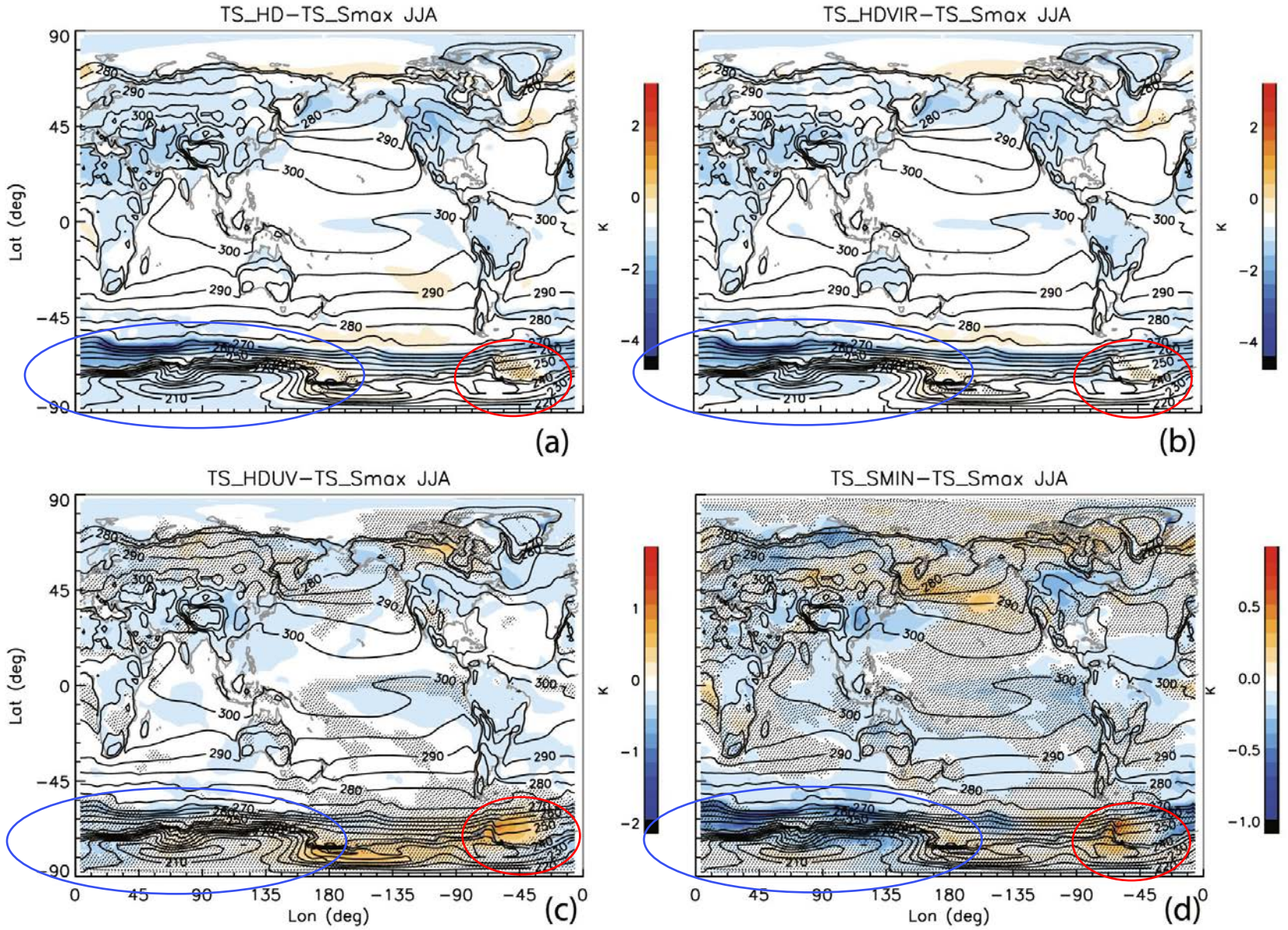
Surface Temperature: HD/HDVIS/HDUV (50-200 yrs)



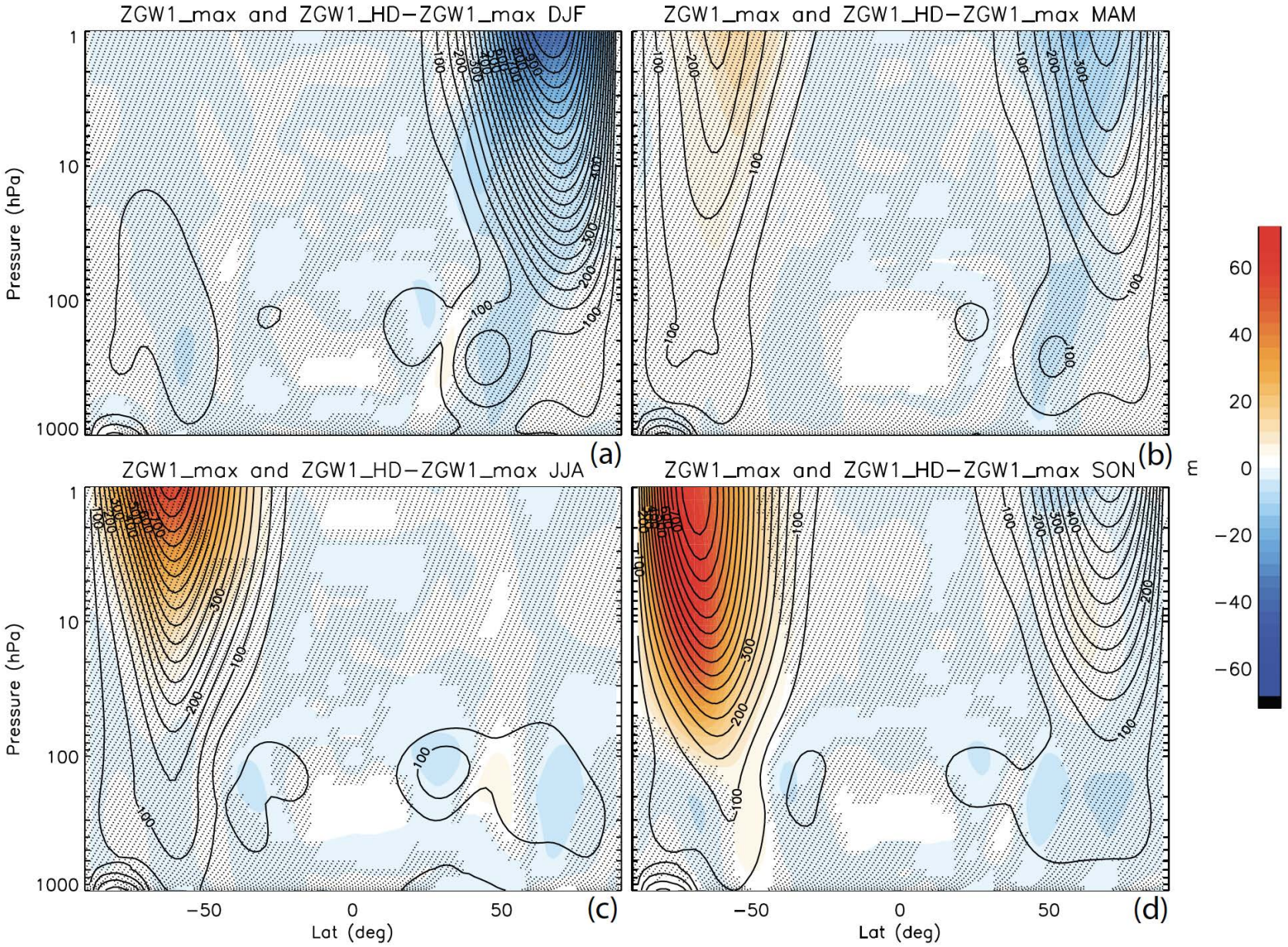
Meridional Wind Responses to Different Solar Forcing



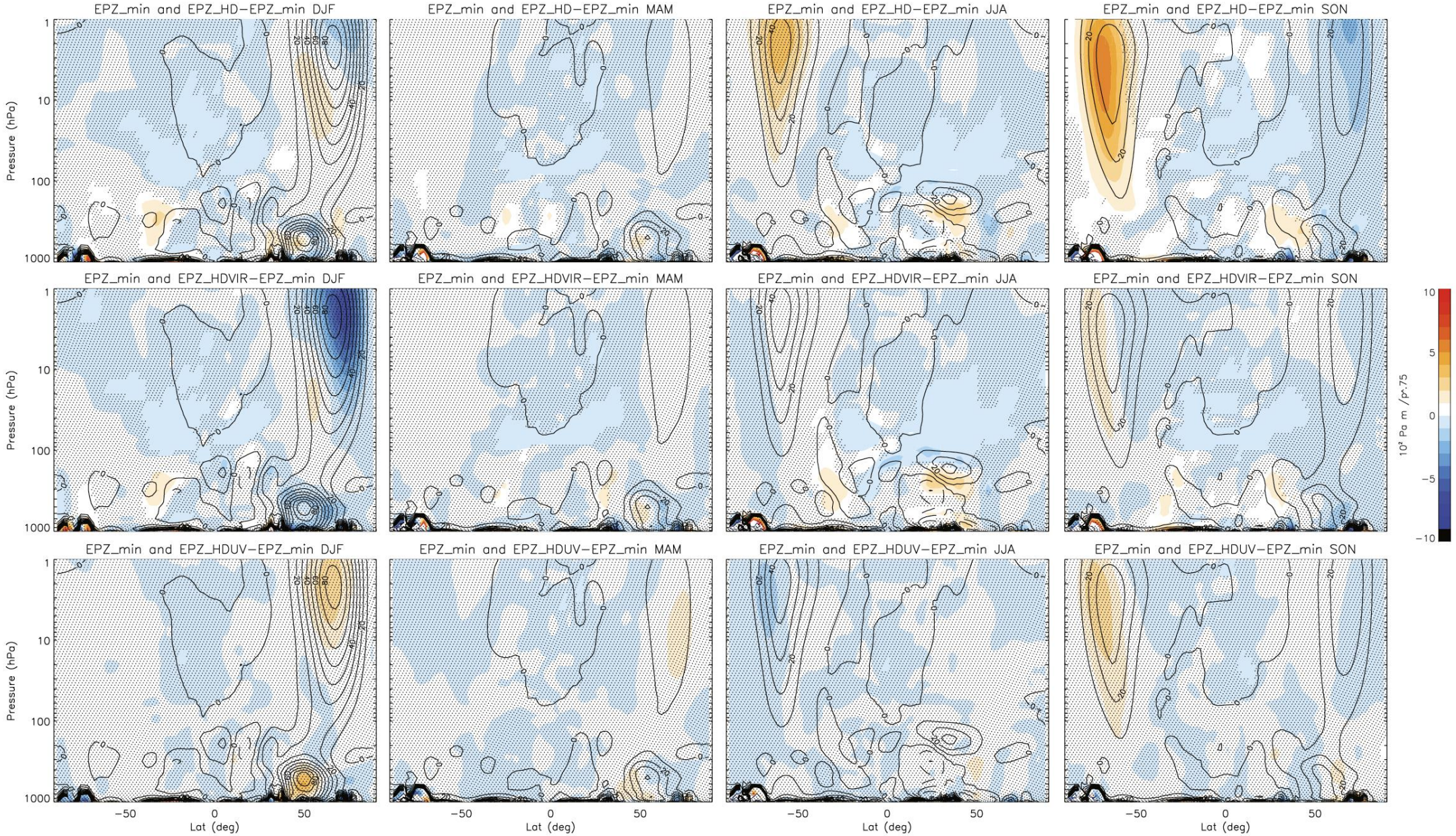
Surface Temperature: HD/HDVIR/HDUV JJA (50-200 yrs)



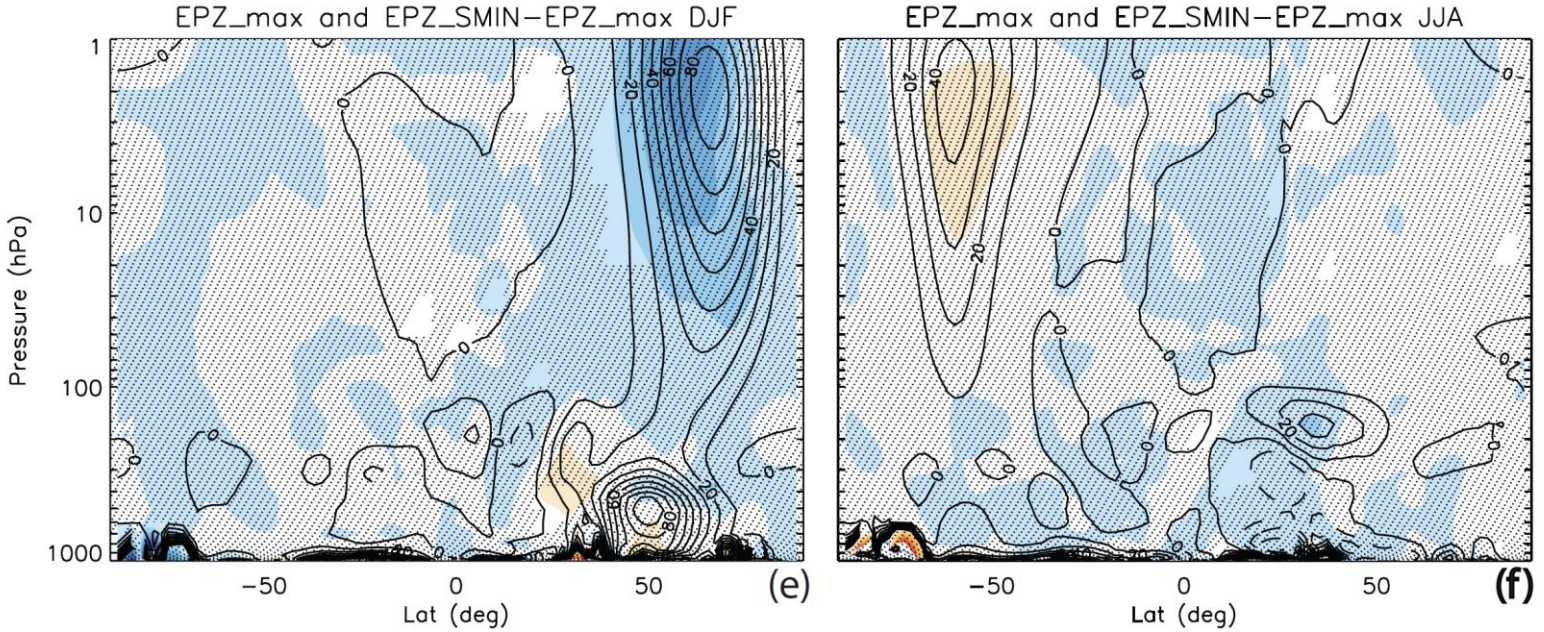
Planetary wave activity changes

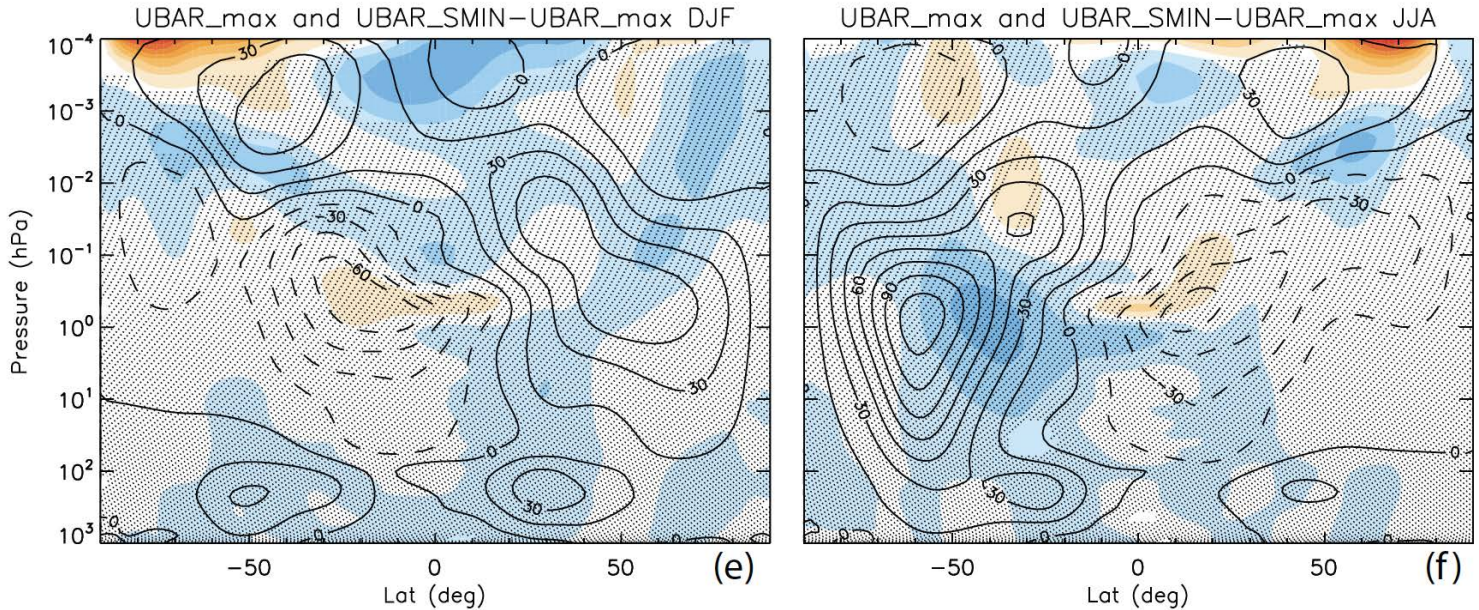


VIR and UV Signals in EPz: Seasonal Variation

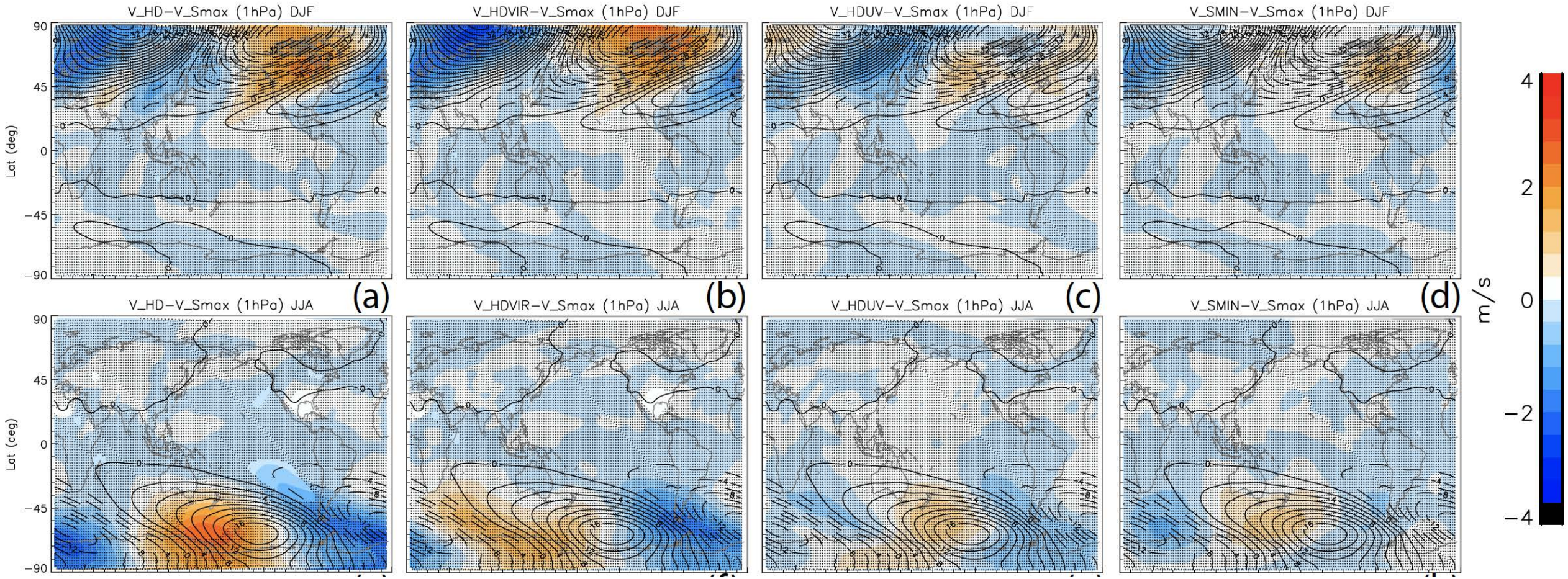


Responses to Nominal Solar Min

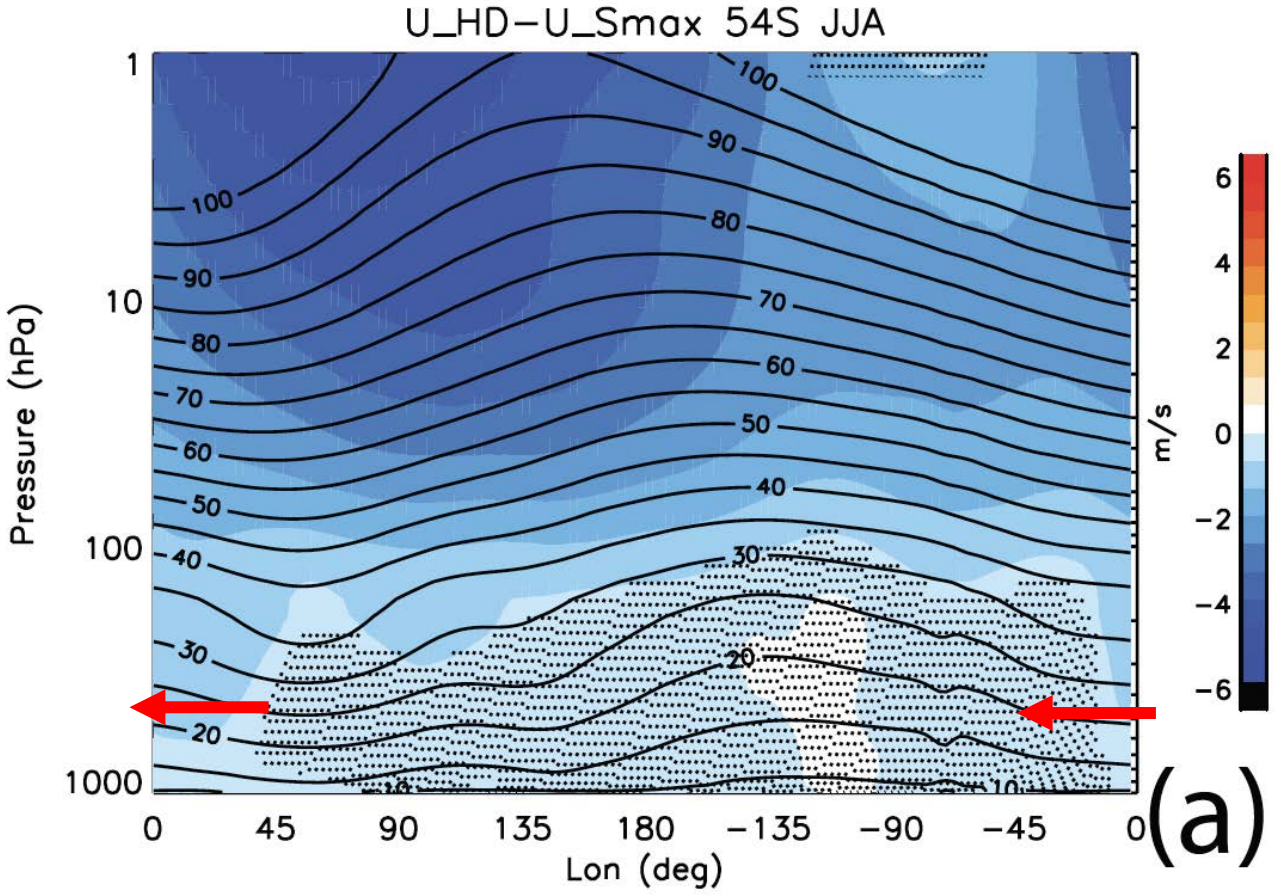


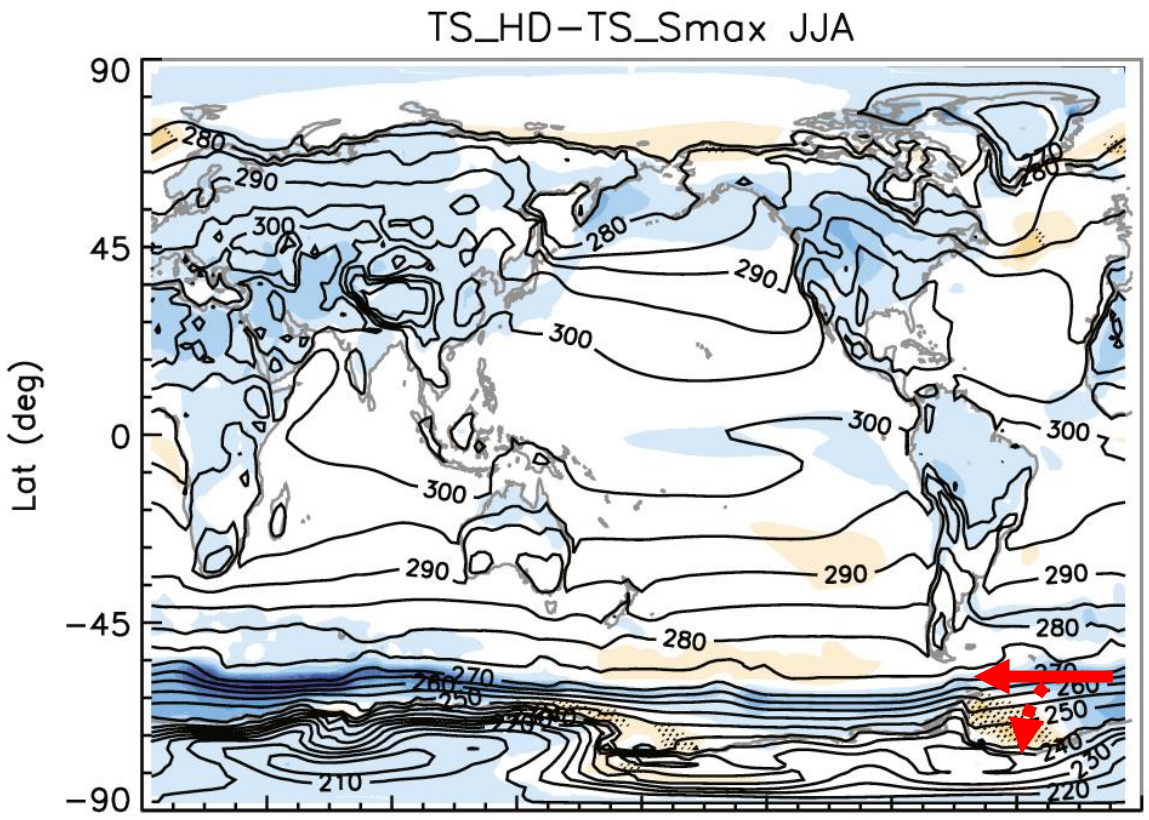


Stratospheric PW Responses to Different Solar Forcing

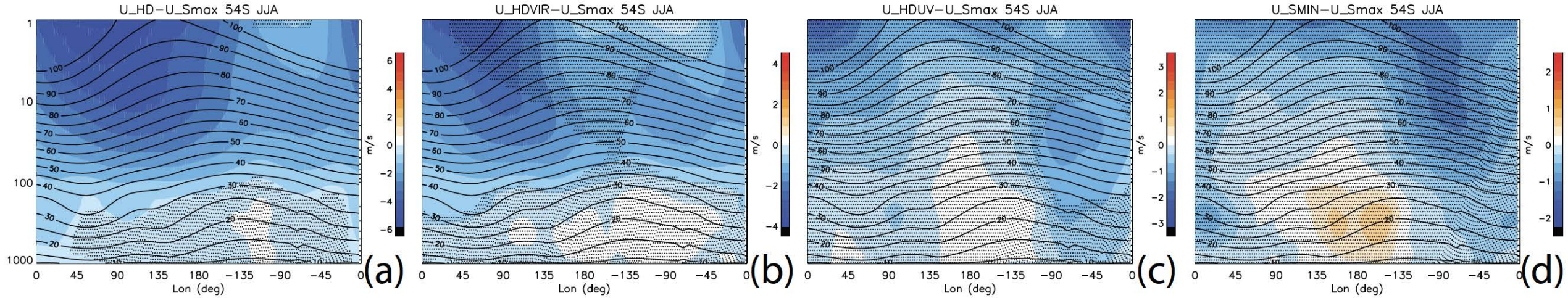


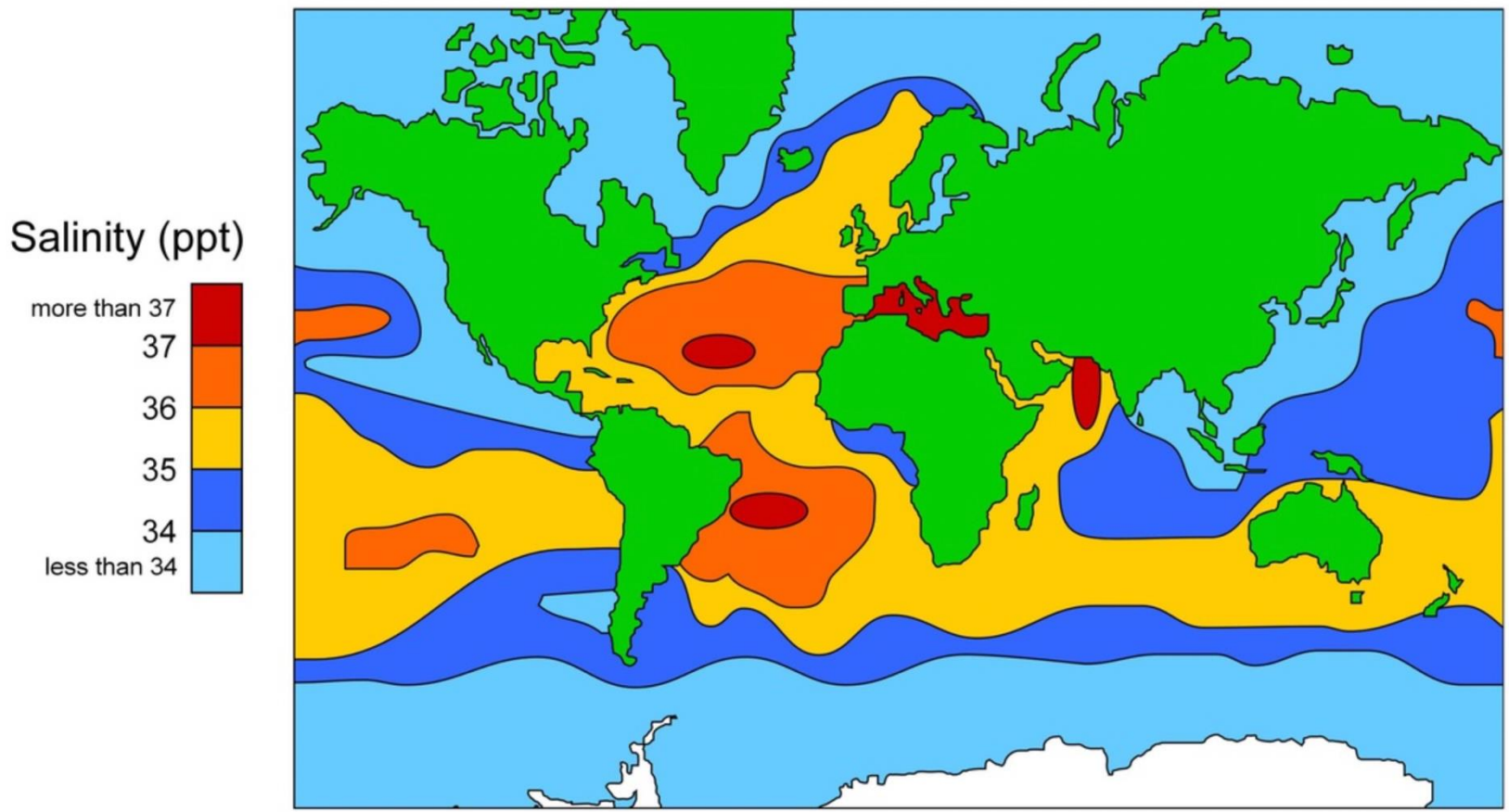
Zonal wind change in SH



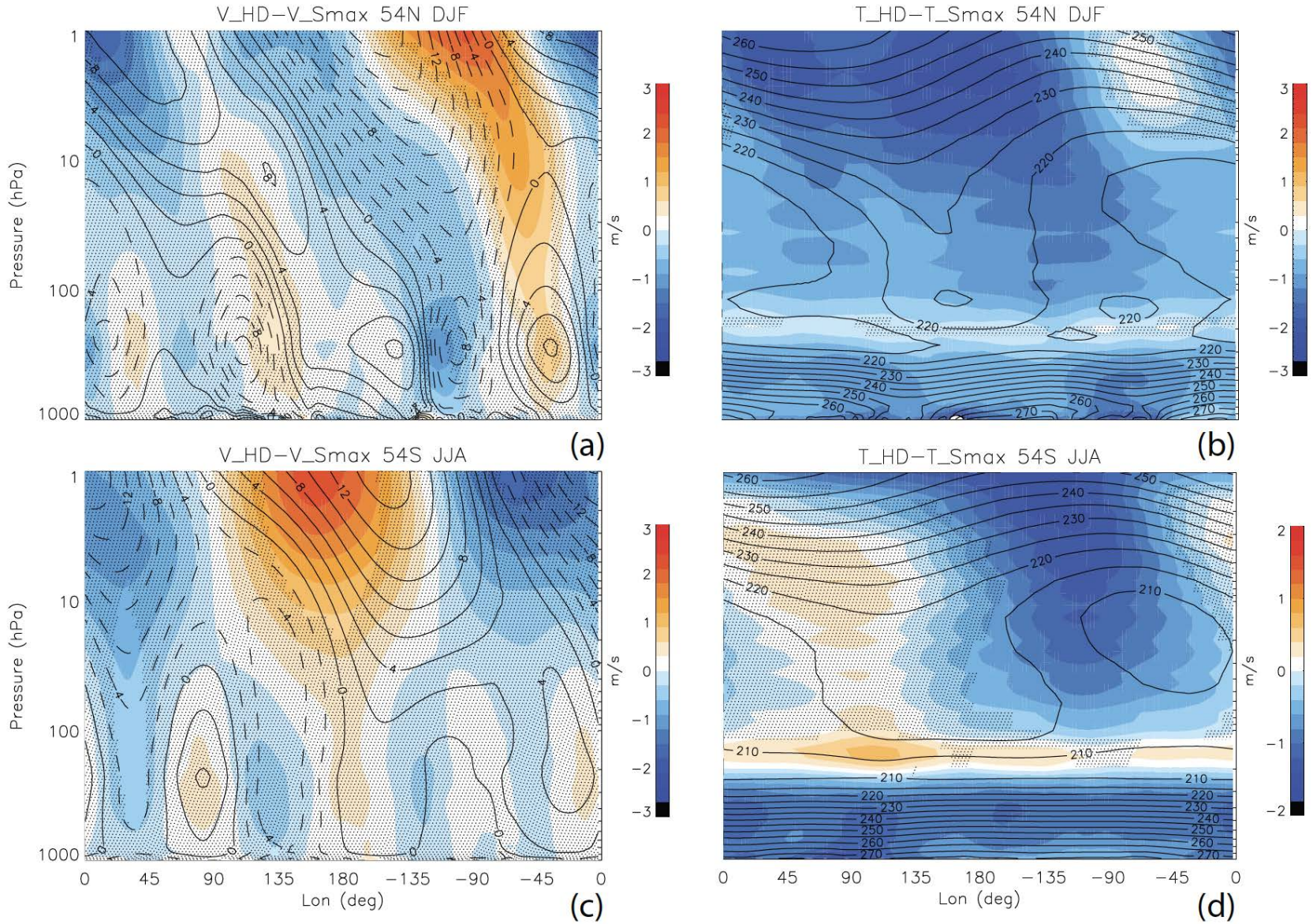


Zonal Wind Change

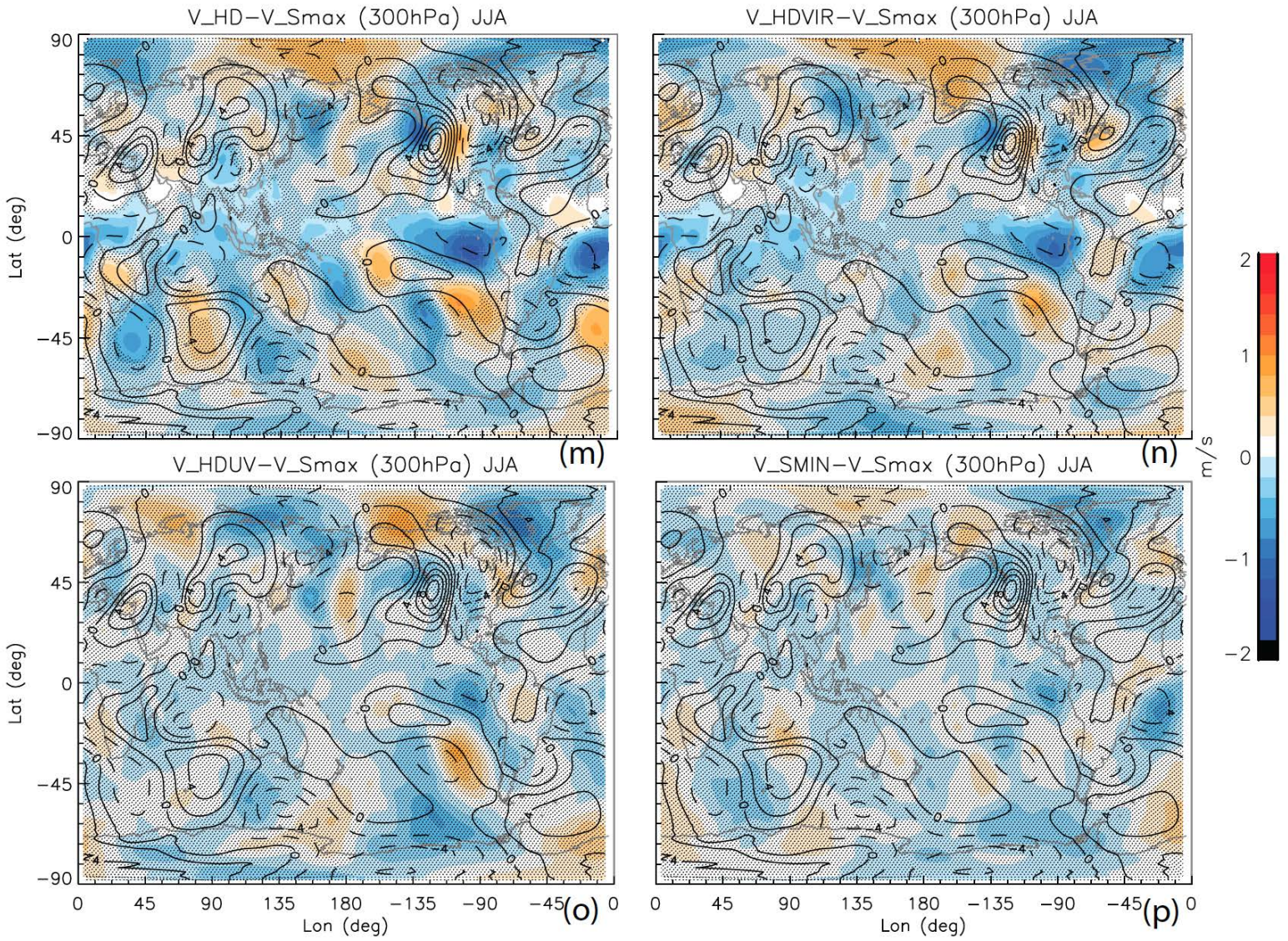



Salinity (ppt)
more than 37
37
36
35
34
less than 34

Meridional and Temperature Responses in NH/SH



Change of Intermediate Scale PW: Austral Winter



Global Feedback Parameter

Table 1

Community Earth System Model/Whole Atmosphere Community Climate Model Simulations and the Solar Forcing Used, the Corresponding Total Solar Irradiance, the Global Mean Surface Temperature (T_s) Averaged Over the Whole Simulation Period (Smax) and the Last 150 Years of the Simulations (HD, HDVIR, HDUV, and Smin), and the Global Feedback Parameter Based on All 200 Years of Simulations

Solar forcing used for driving CESM/WACCM simulations	Nominal solar maximum (Smax)	Nominal solar minimum (Smin)	Non-magnetic, hydrodynamic (HD) reference	SSI(Smin) ($\lambda \leq 320$ nm) + SSI(HD) ($\lambda > 320$ nm) (HDVIR)	SSI(HD) ($\lambda \leq 320$ nm) + SSI(Smin) ($\lambda > 320$ nm) (HDUV)
TSI (Wm^{-2})	1361.93	1360.43	1350.08	1350.84	1359.76
*T*s (K)	287.87	287.78	287.04	287.08	287.72
Global feedback parameter ($Wm^{-2}K^{-1}$)		1.68 (0.22)	1.64 (0.17)	1.62 (0.17)	1.75 (0.22)