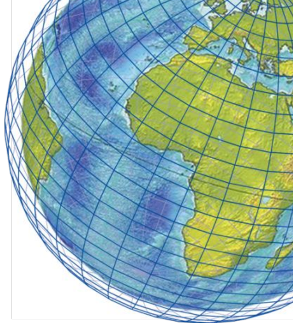

2023 CESM Workshop - CVCWG

Origins of Uncertainty in Projections of Summer North Pacific High

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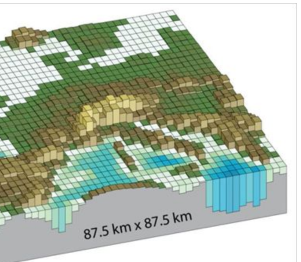
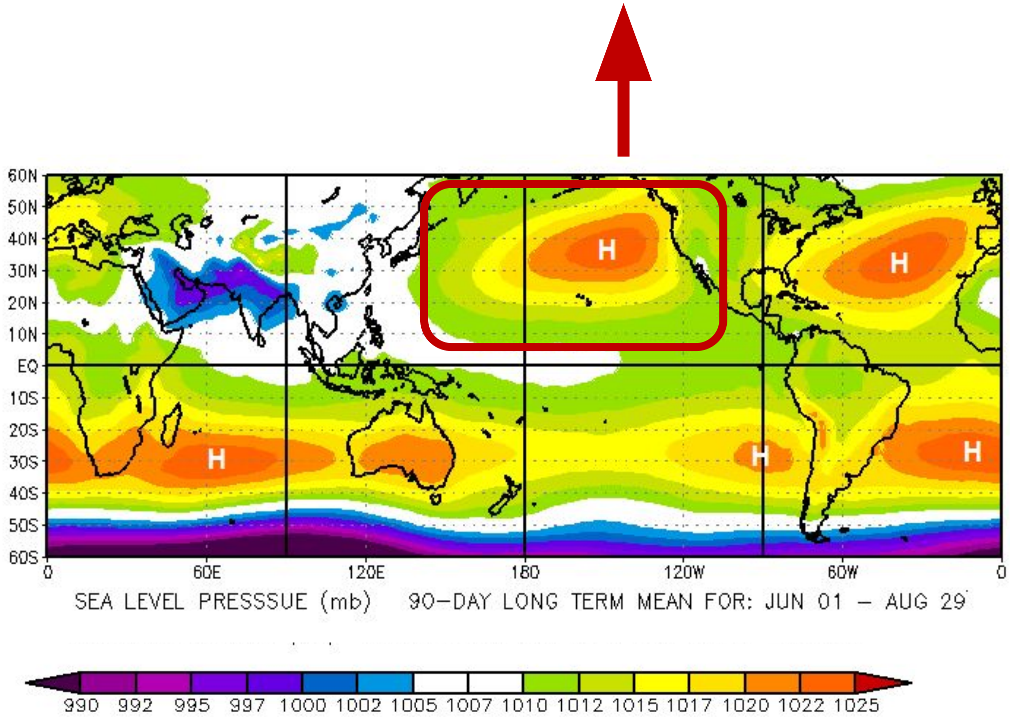
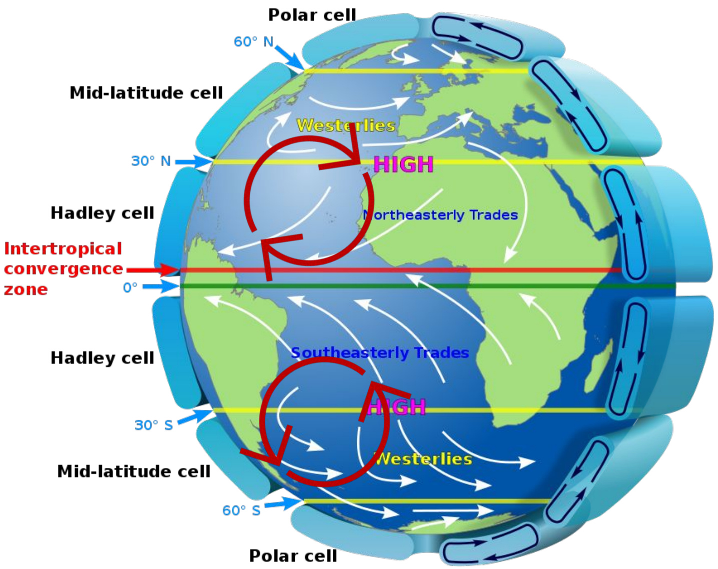


Introduction

What is summer NPSH?

North Pacific Subtropical High (NPSH)





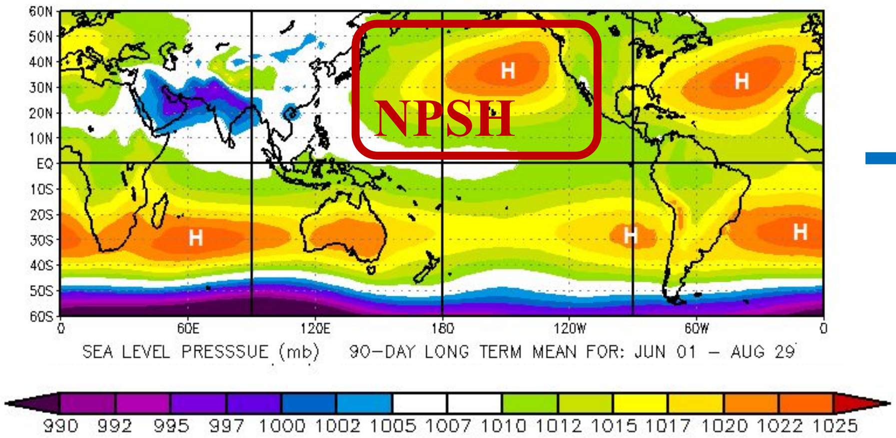
Boreal summer Sea level pressure (Pa)

Credit: ESRL

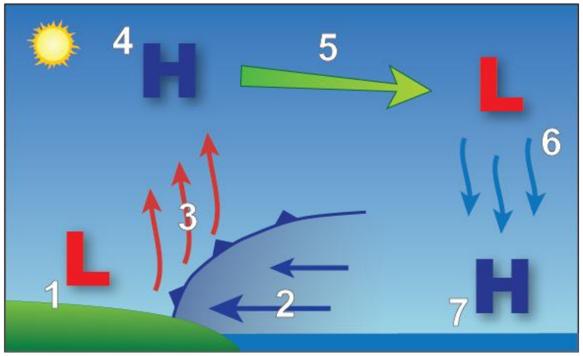
Credit: Wikipedia

Introduction

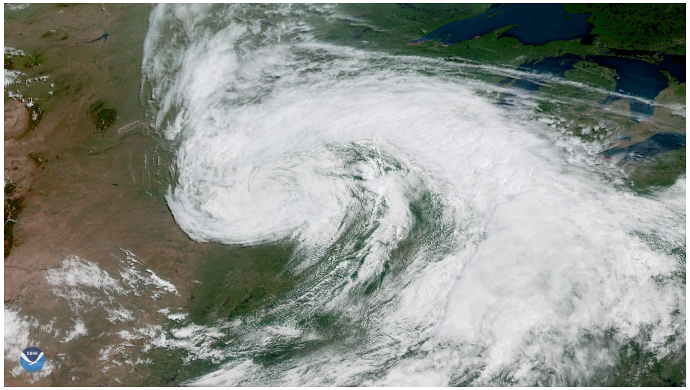
What maintains summer NPSH?



Land-sea thermal contrast

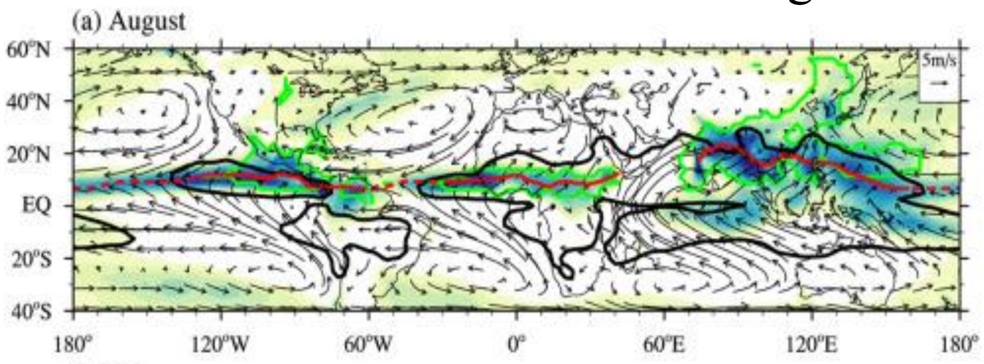


Extra-tropical transient eddy fluxes



Main driver

Summer monsoon heating



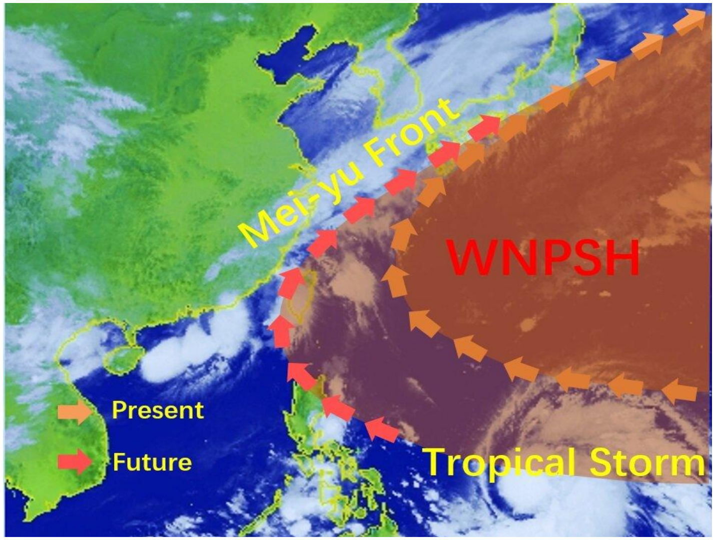
(Wills, 2019, Wang et al, 2017)

Introduction

Why do we care about summer NPSH?

- The variability in summer NPSH has a significant impact on the monsoon and typhoon over the East Asia

Debris in Tacloban, Philippines after Typhoon Haiyan



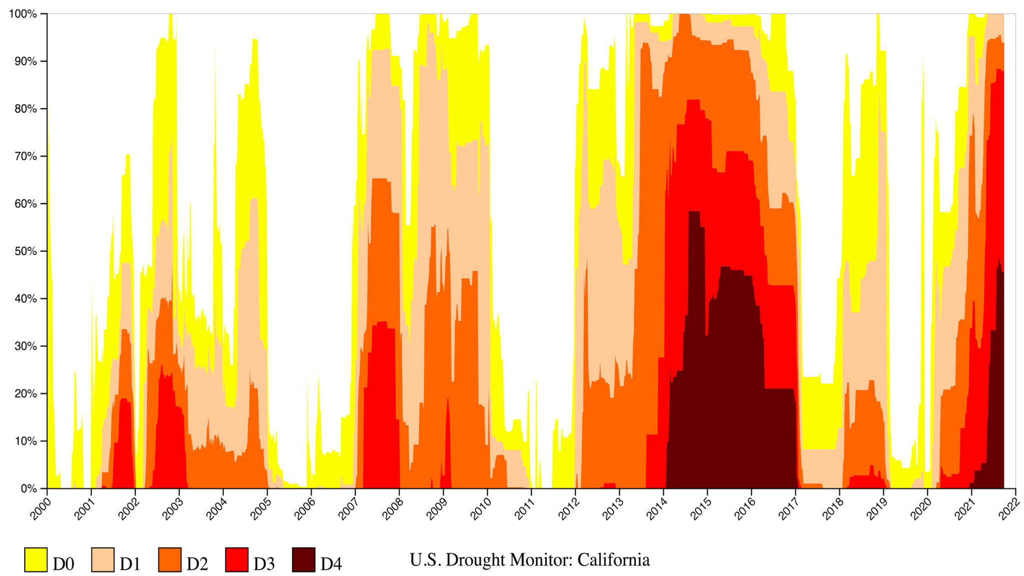
The western North Pacific Subtropical High (WNPSH) might extend further westward in the future

Potentially more typhoons and floods

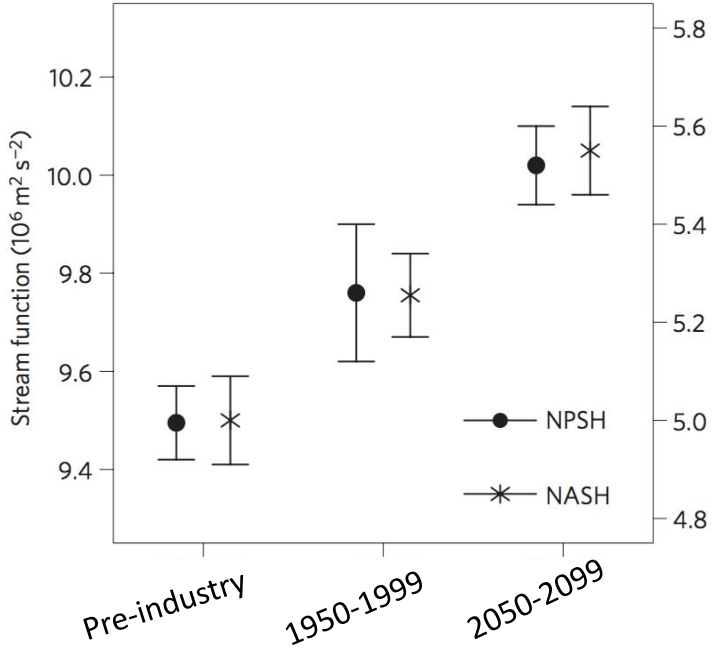
Credit: Xiaolong Chen

Introduction Why do we care about summer NPSH?

- Future changes of the NPSH could intensify the drought over California



California drought index



Model projection of summer NPSH intensity

Potentially more wildfires

Credit: https://www.drought.gov/states/california

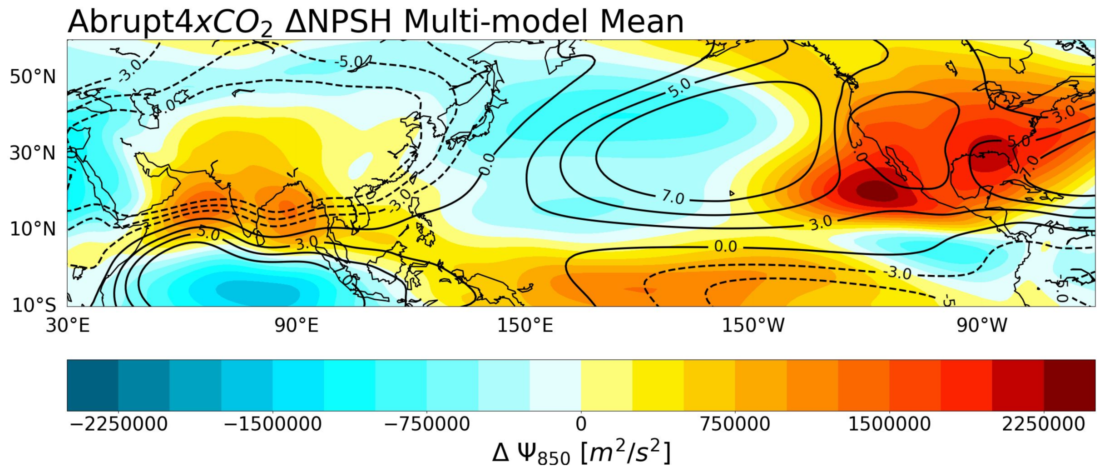
(Li et al, 2012)

Results

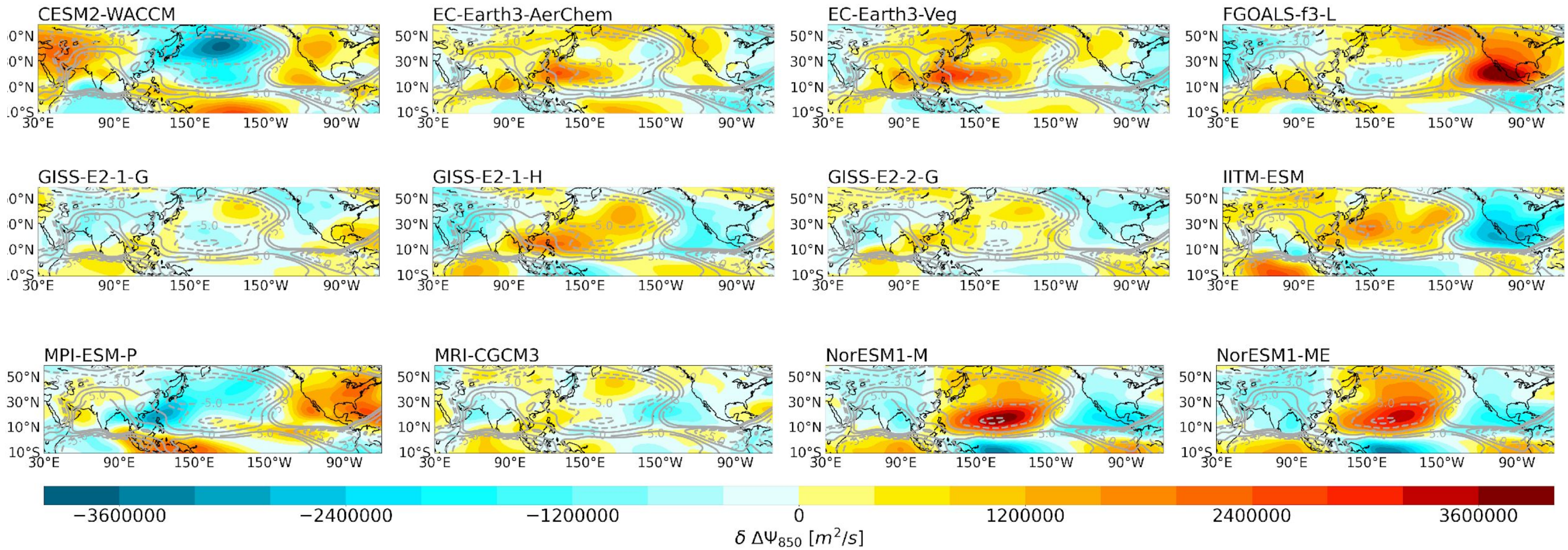
Model uncertainty in summer NPSH projection

Response of summer NPSH in coupled climate models under abrupt4×CO_2 scenario

Multi-model mean (MMM) changes in NPSH from 46 CMIP5 and CMIP6 models



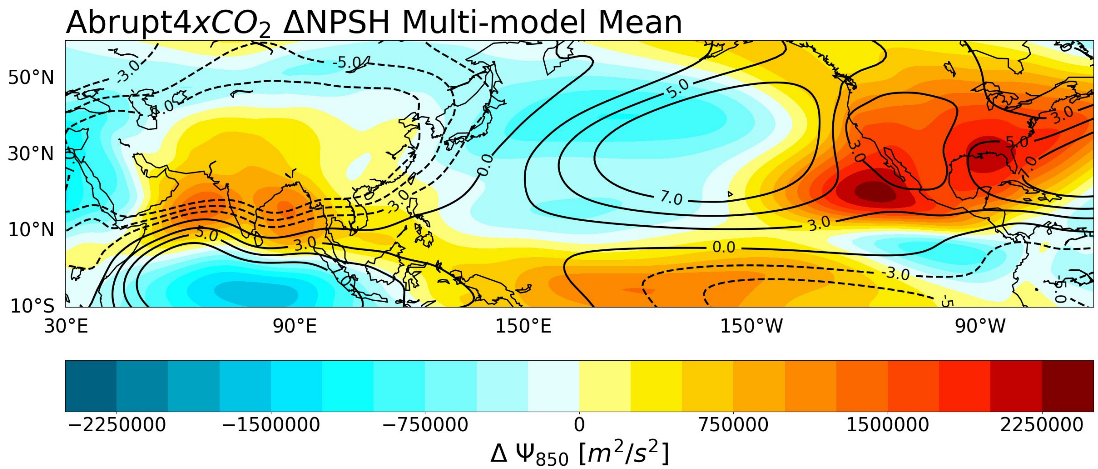
Deviation from the multi-model mean

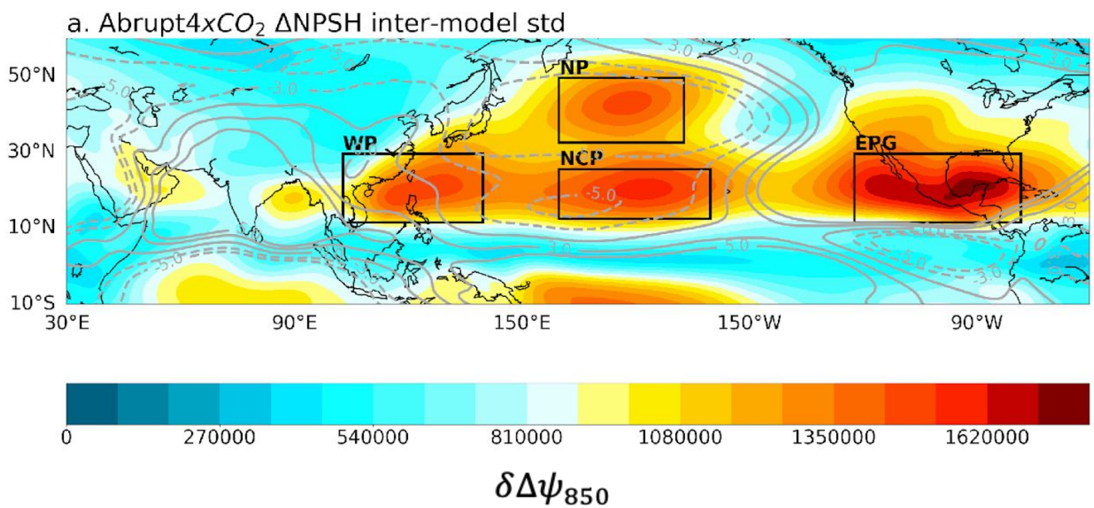


Results

Model uncertainty in summer NPSH projection

Response of summer NPSH in coupled climate models under abrupt4×CO_2 scenario





Shading: MMM (top) and inte-rmodel std (bottom) of 850-hPa eddy streamfunction

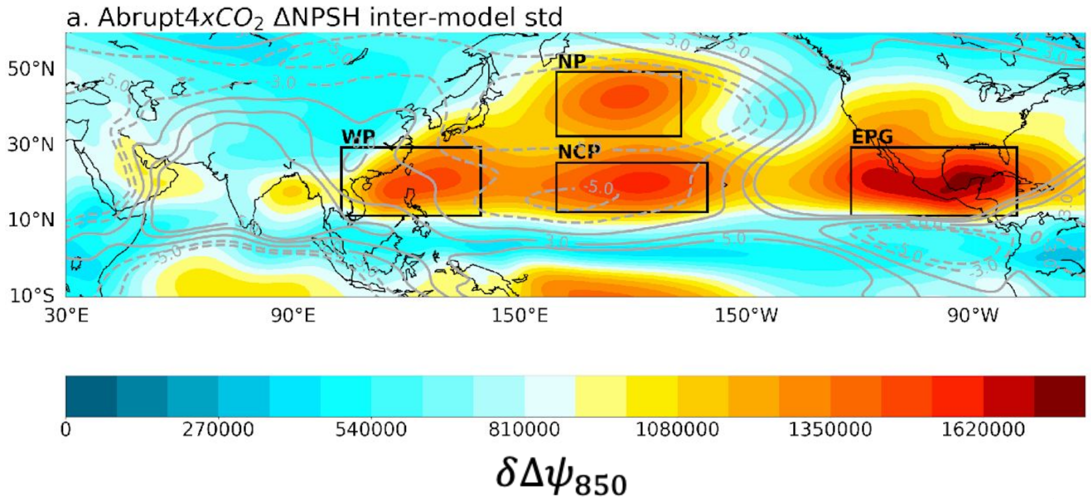
Contours: climatological mean (intervals: 10^6 m^2/s^2)

- The multi-model mean changes of NPSH under high CO_2 scenario from models are comparable to its inter-model standard deviation

- Four regions of high inter-model variability are identified: the western Pacific, the eastern Pacific and Gulf of Mexico, the North Pacific and the central North Pacific

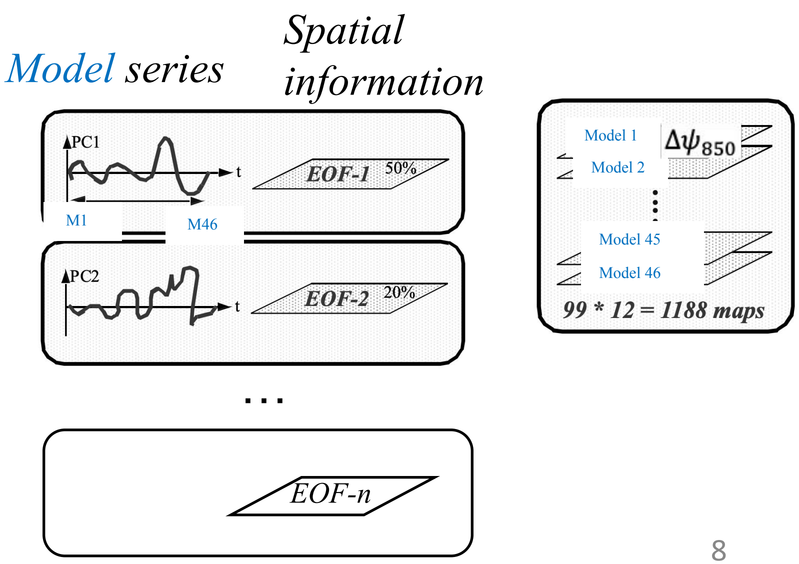
Methods **Model uncertainty in summer NPSH projection**

How to evaluate the spatial structure of model uncertainty?



Inter-model EOF analysis (IEOF):

$$\delta X\,(m, s) = \sum_{1}^{n} PC_{m,i} \cdot IEOF_{i,s}$$

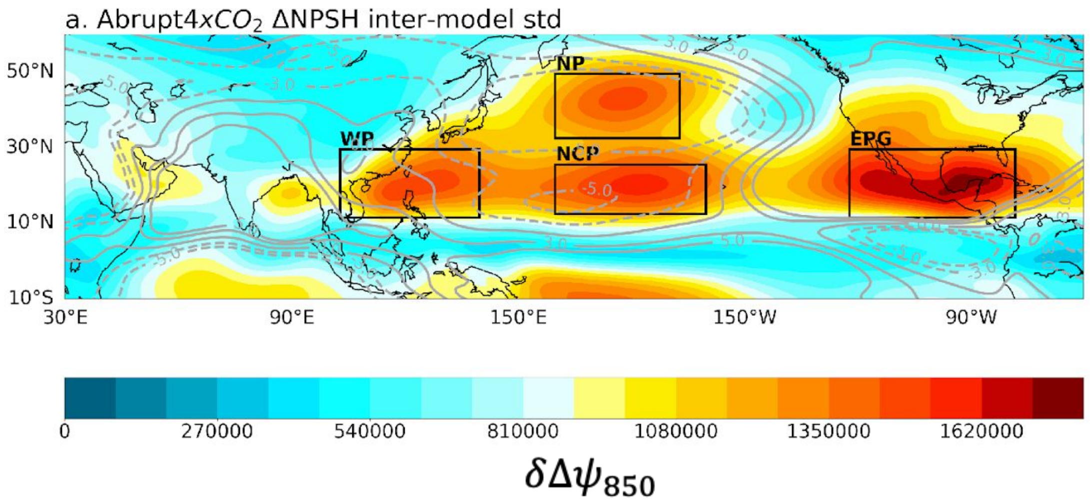


δ: deviation from the multi-model mean
m: number of models
s: number of grid points

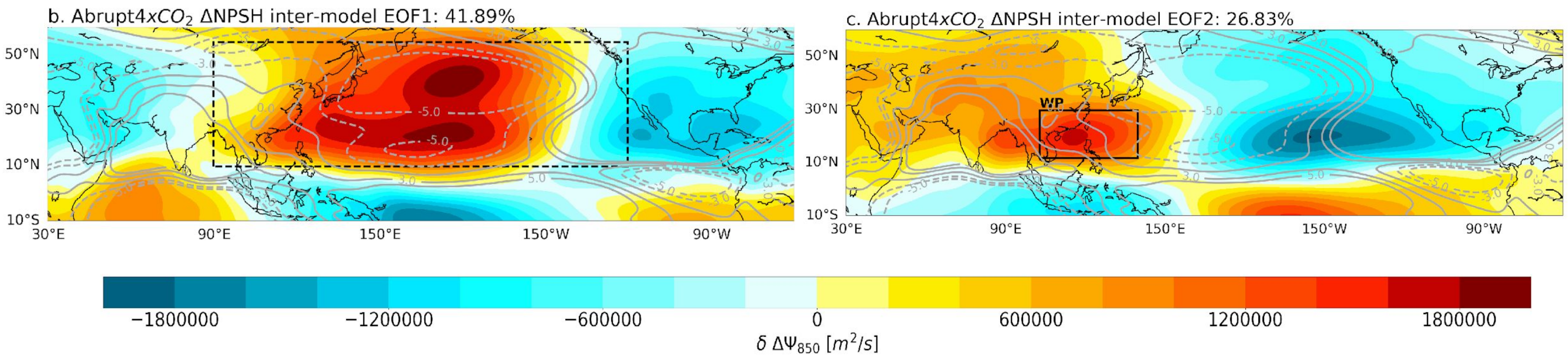
Methods

Model uncertainty in summer NPSH projection

How to evaluate the spatial structure of model uncertainty?



First two leading IEOFs of $\Delta NPSH$ from abrupt4xCO_2 :



Methods

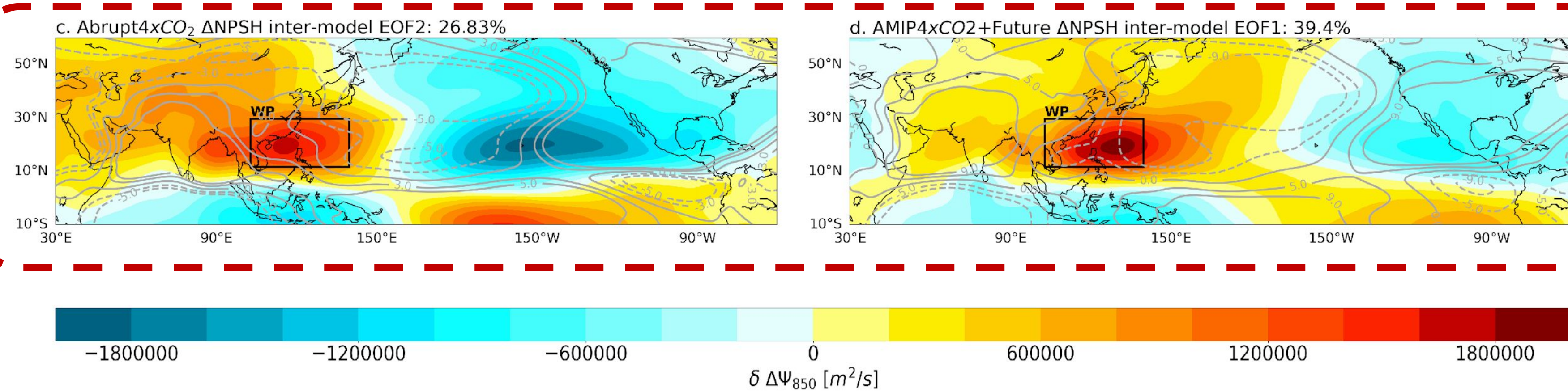
Model uncertainty in summer NPSH projection

Can we simply the question by using AGCM?

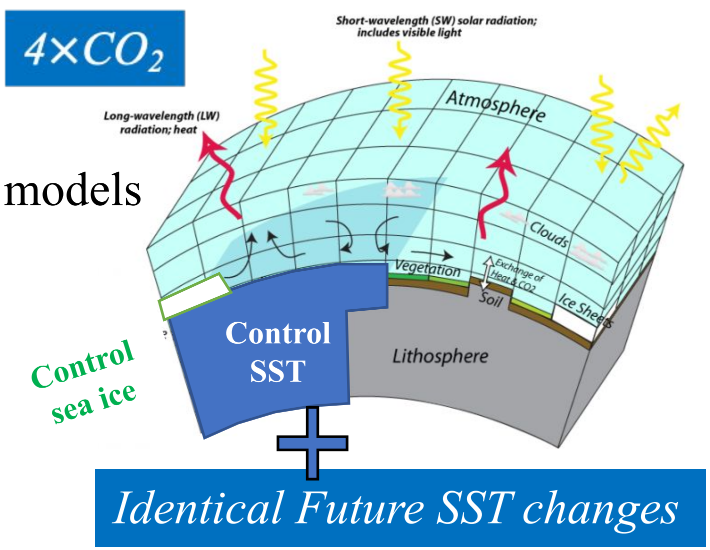
? Possibly due to **non-SST** related factors

IEOF2 of $\Delta NPSH$ from abrupt4xCO_2:

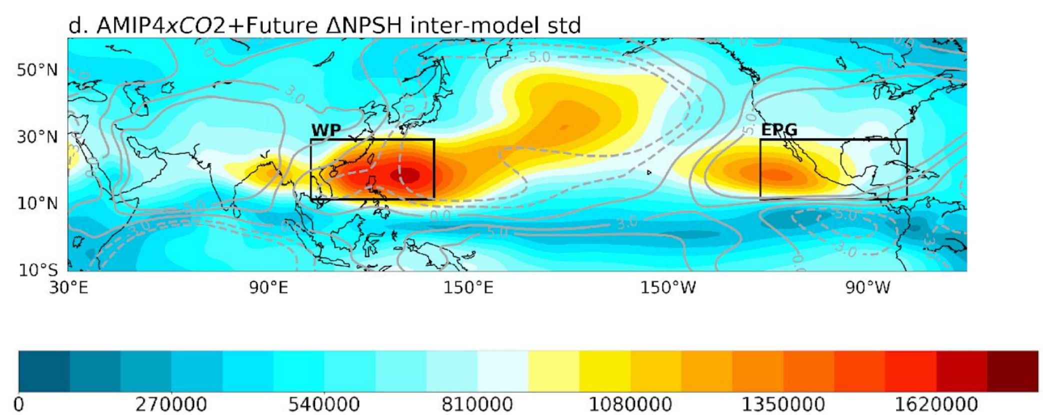
IEOF1 of $\Delta NPSH$ from AMIP4xCO_2+Future:



15 models



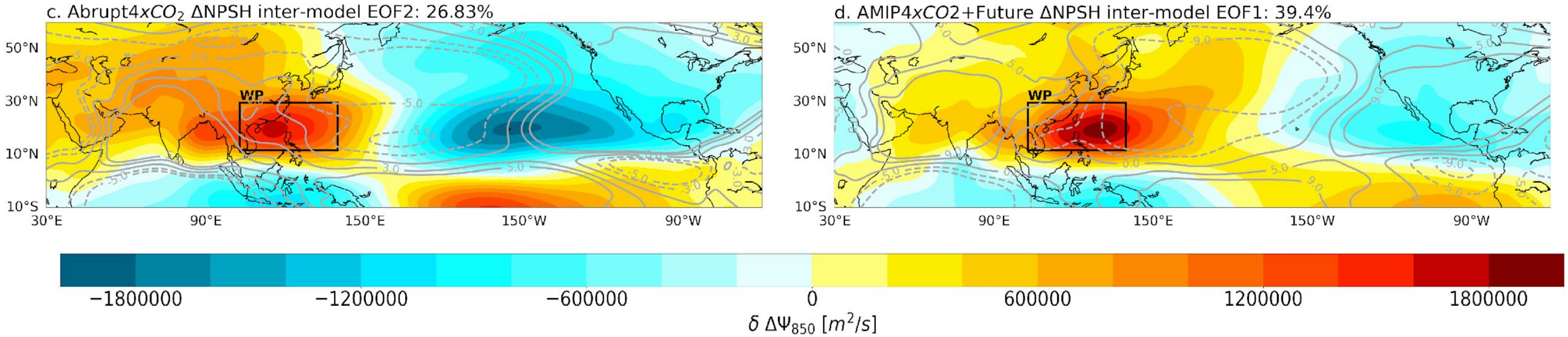
Inter-model std of $\Delta NPSH$ from AMIP4xCO_2+Future



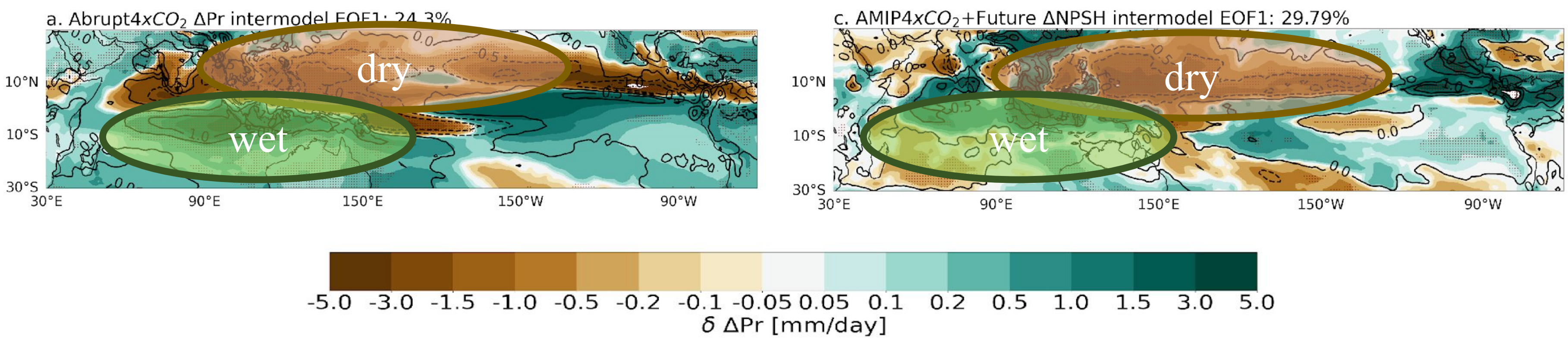
Results **Non-SST related inter-model spread of ΔNPSH**

• Statistical relationship with tropical Δprecipitation inter-model spread

IEOF2 of $\Delta NPSH$ from abrupt4xCO_2: IEOF1 of $\Delta NPSH$ from AMIP4xCO_2+Future:



IEOF1 of $\Delta Prceip$ from abrupt4xCO_2: IEOF1 of $\Delta Precip$ from AMIP4xCO_2+Future:



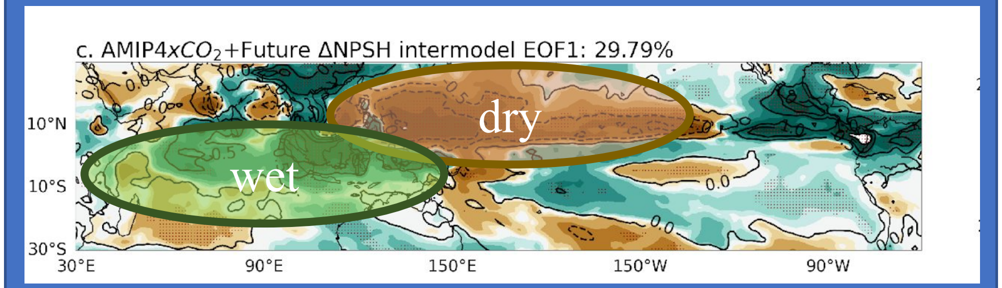
Contours: $\Delta Precip$ regressed onto inter-model PC of $\Delta NPSH$

Methods **Non-SST related inter-model spread of ΔNPSH**

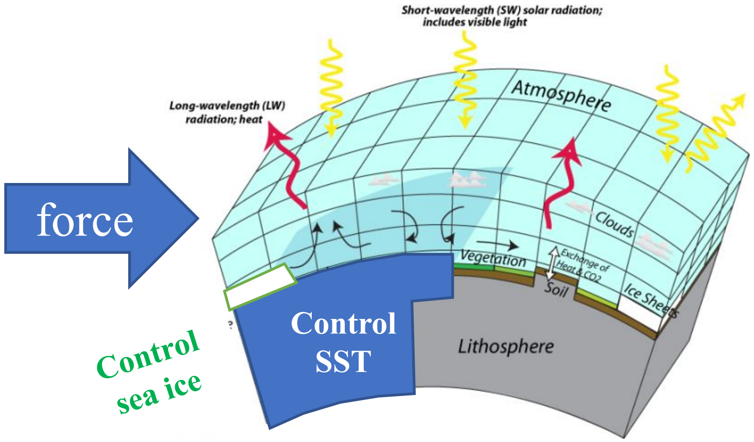
Non-SST related diabatic heating experiment

IEOF1 of $\Delta Precip$ from AMIP4xCO_2+Future:

AGCM: CESM1-CAM5



Diabatic heating anomalies



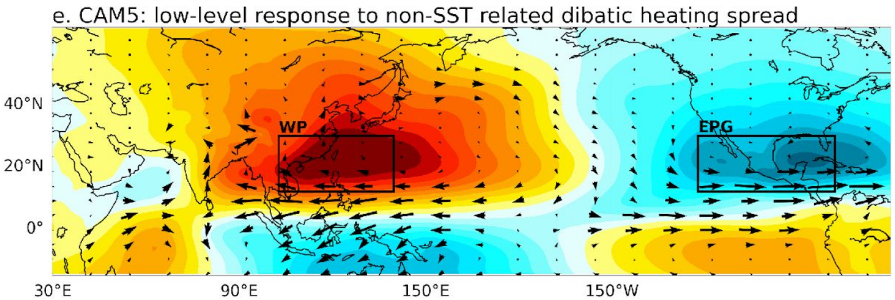
- Prescribe the leading inter-model uncertainty mode of tropical **diabatic heating inter-model spread** from AMIP output to CAM5
- An "iterative approach" is used when prescribe diabatic heating to account for the moist processes in CAM5
- Each iteration contains 5 ensembles to minimize the influence of internal variability

Results

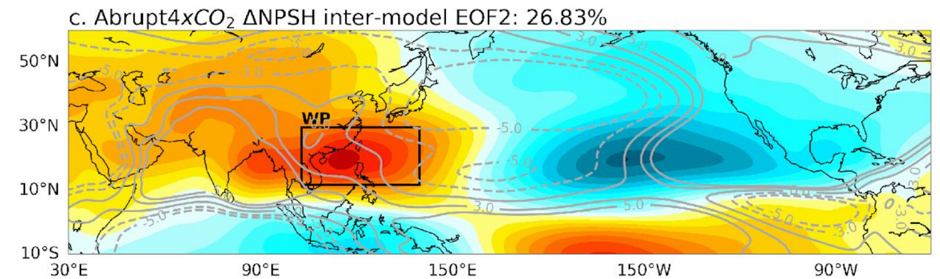
Non-SST related inter-model spread of ΔNPSH

- Non-SST related diabatic heating inter-model spread drives IEOF2 of $\Delta NPSH$

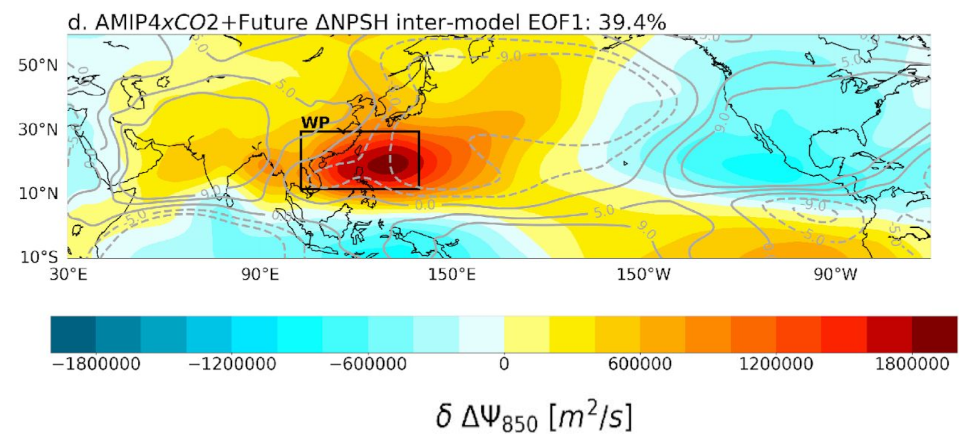
Low-level circulation response



IEOF2 of $\Delta NPSH$ from abrupt4xCO_2:



IEOF1 of $\Delta NPSH$ from AMIP4xCO_2+Future:



- The circulation anomaly maxima over the WP and the EPG are consistent with statistical results

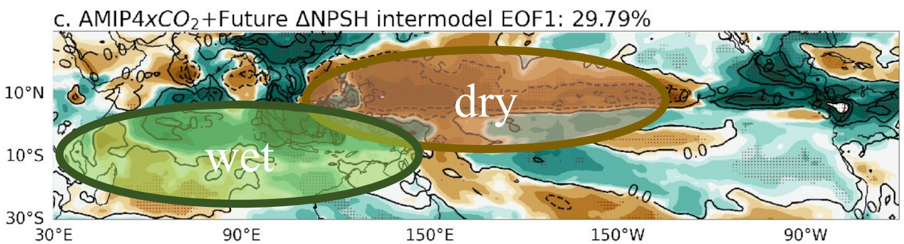
- High inter-model ΔNPSH variance at the WP results from the model of tropical precipitation inter-model spread that is unrelated to SST

Results

Non-SST related inter-model spread of ΔNPSH

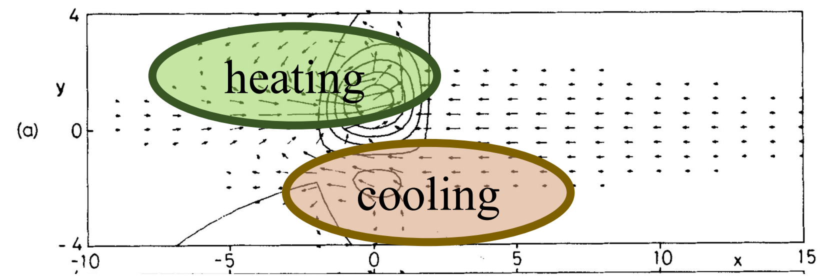
- Non-SST related diabatic heating inter-model spread drives IEOF2 of Δ$NPSH$

IEOF1 of Δ$Precip$ from AMIP4xCO_2+Future:

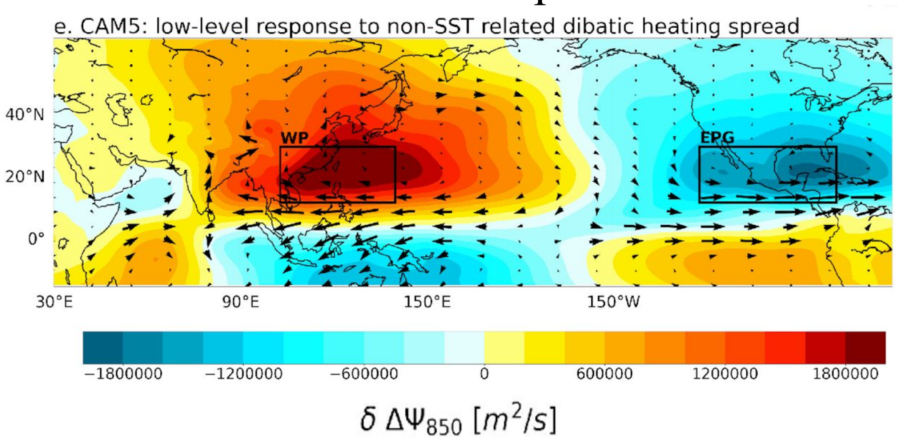


Matsuno-Gill response *(Gill, 1998)*

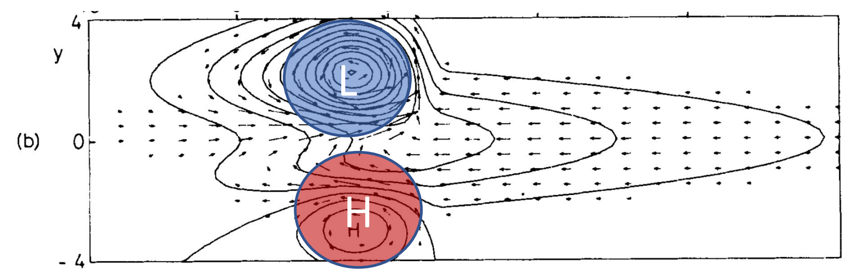
Asymmetric Heating



Low-level circulation response



Low-level circulation

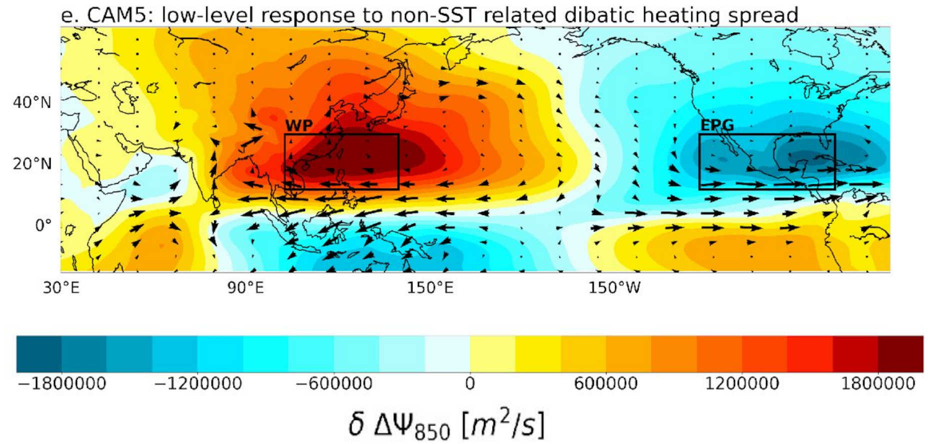


- The dry-north-wet-south diabatic heating in the northeastern Indian and western Pacific induces a Matsuno-Gill type response

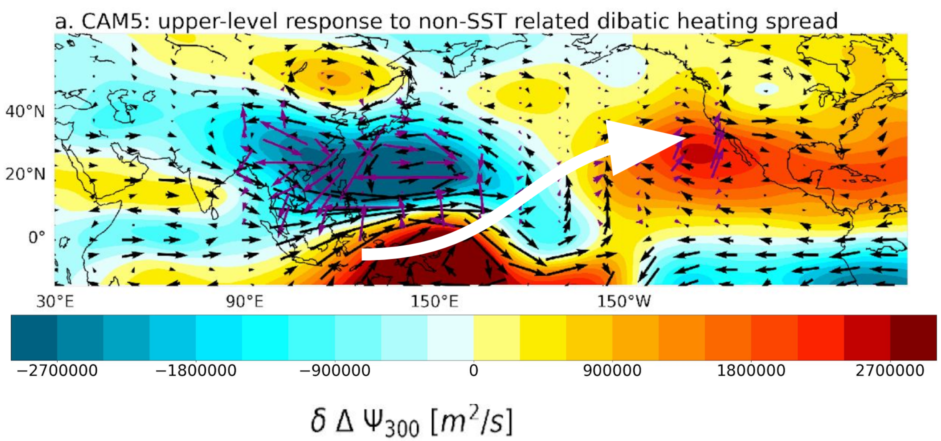
Non-SST related inter-model spread of ΔNPSH

- Non-SST related diabatic heating drives IEOF2 of $\Delta NPSH$

Low-level circulation response



Upper-level circulation response



- The baroclinic structure of circulation locates at around 15°N-20°N
- The barotropic structure locates at around 45°N-55°N
- The tropical diabatic heating affect the North Pacific and North American circulation via Rossby wave train

Purple arrows: Takaya-Nakamura Flux (identify wave source and sink)

$$W = \frac{1}{2|\bar{U}|}\begin{bmatrix} \bar{u}(\psi_x'^2 - \psi'\psi_{xx}') + \bar{v}(\psi_x'\psi_y' - \psi'\psi_{xy}') \\ \bar{u}(\psi_x'\psi_y' - \psi'\psi_{xy}') + \bar{v}\left(\psi_y'^2 - \psi'\psi_{yy}'\right) \end{bmatrix}$$

(Takara and Nakamura, 1997)

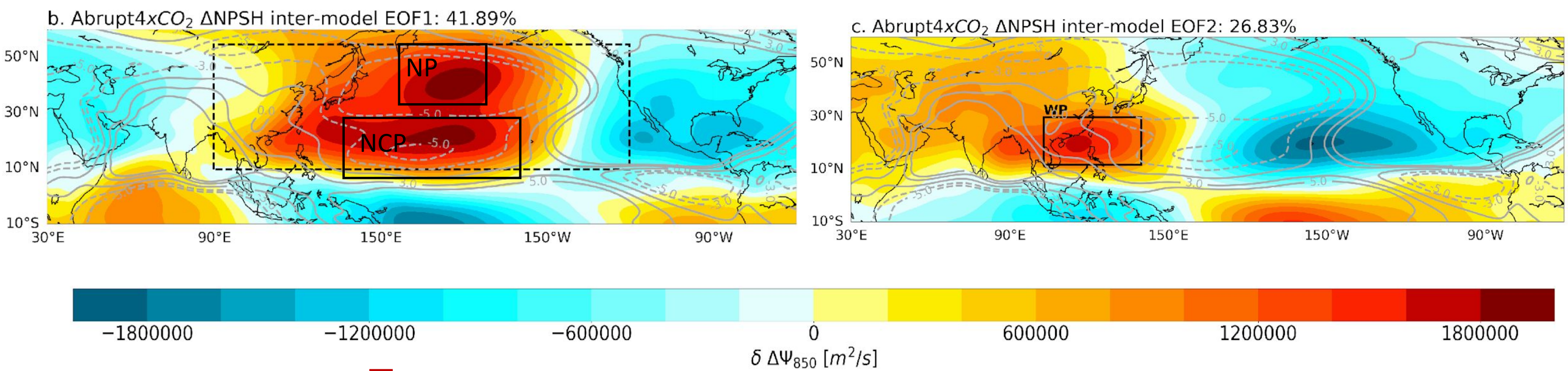
Results

Model uncertainty in summer NPSH projection

• What cause inter-model uncertainty of $\Delta NPSH$?

IEOF1 of $\Delta NPSH$ from abrupt4xCO_2:

IEOF2 of $\Delta NPSH$ from abrupt4xCO_2:



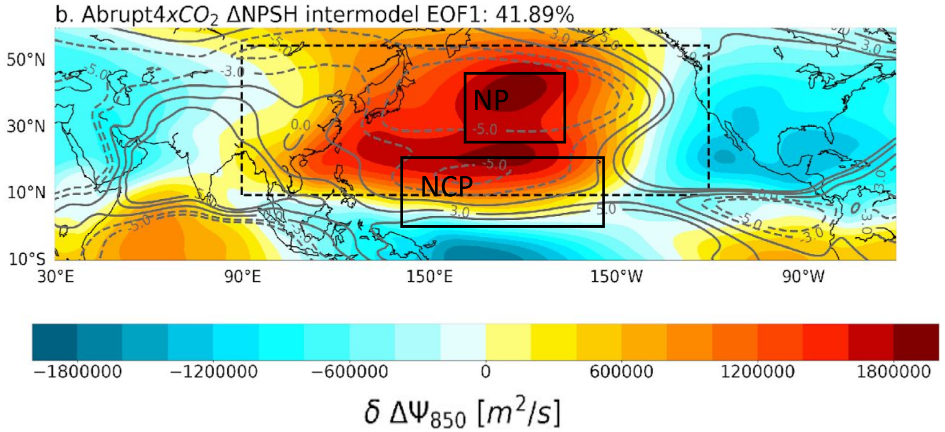
Possibly due to **SST** related factors

Due to **non-SST** related inter-model spread of changes in tropical precipitation

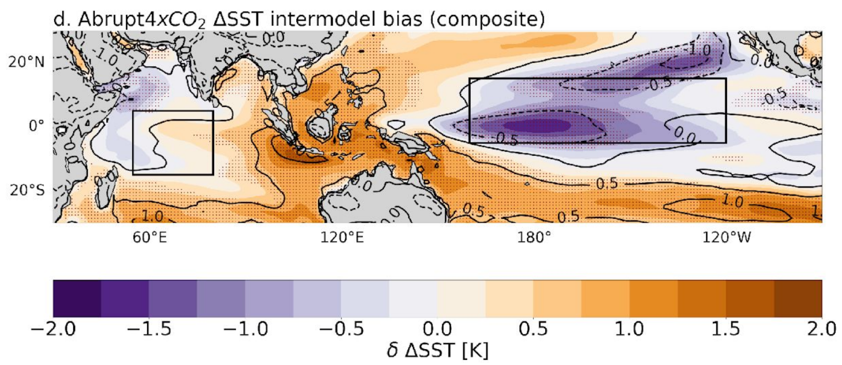
Results

SST related inter-model spread of ΔNPSH

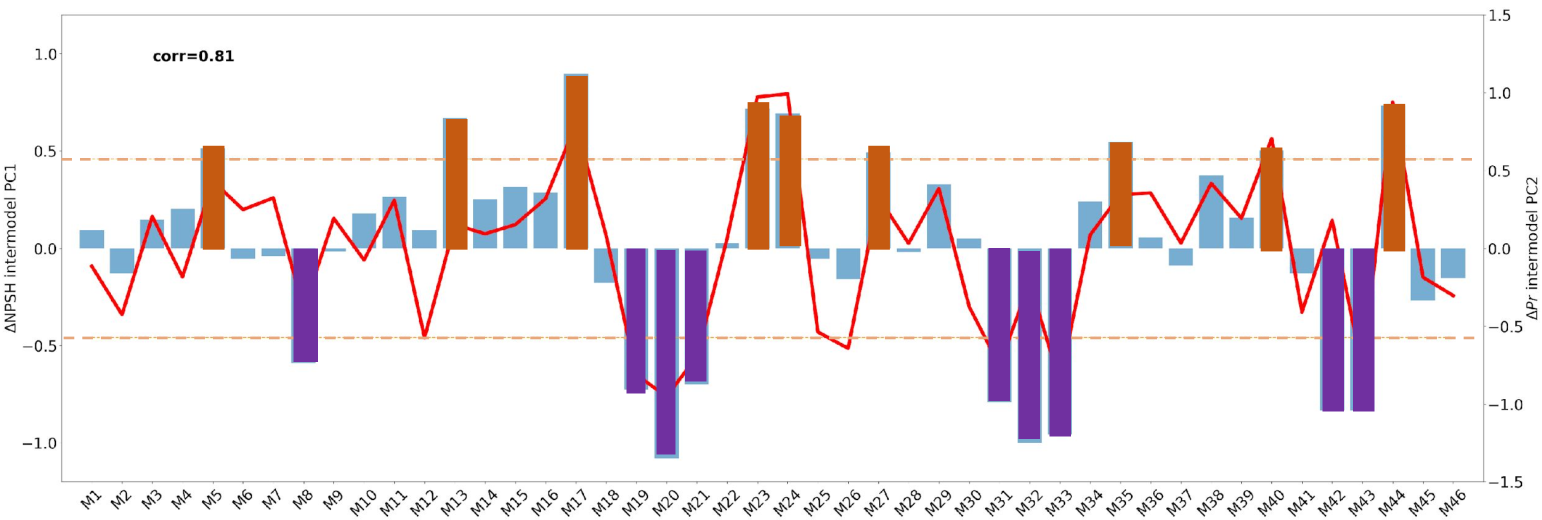
IEOF1 of Δ*NPSH* from abrupt4xCO_2:



Inter-model spread of Δ*SST* by composing positive and negative models:



Inter-model PC1 of Δ*NPSH* from abrupt4xCO_2:

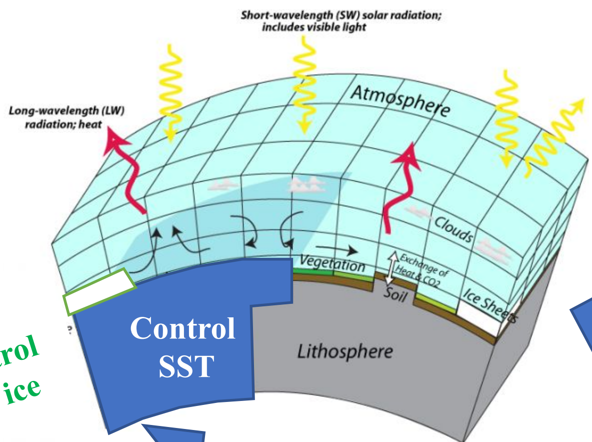


Contours:
Δ*SST* regressed onto inter-model PC2 of Δ*Precip*

Methods

SST related inter-model spread of ΔNPSH

SST related diabatic heating experiments

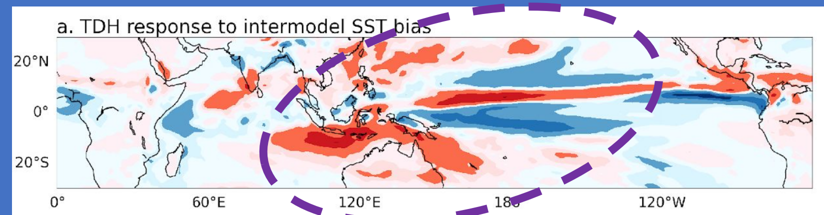


Control SST

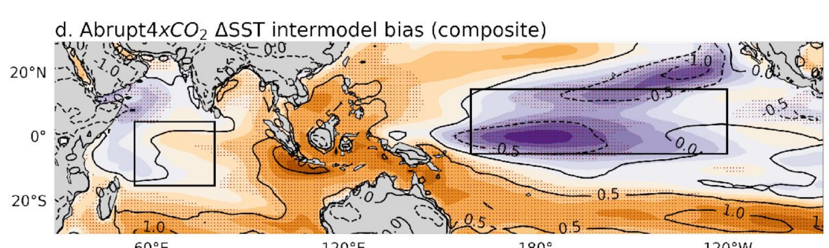
Control sea ice

force

produces



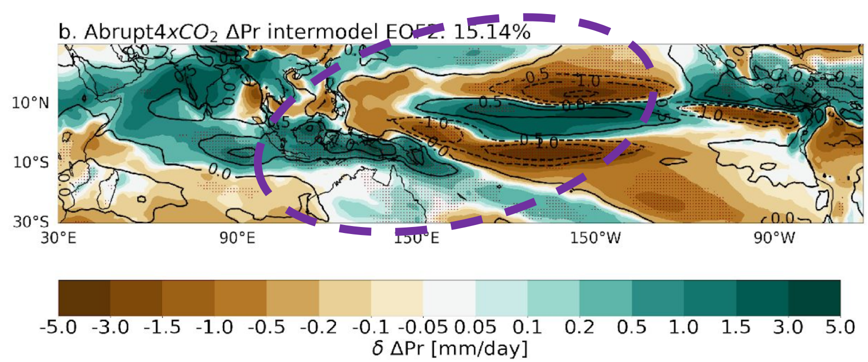
Diabatic heating anomalies



SST anomalies

Step 1: Prescribe the leading inter-model uncertainty mode of tropical ΔSST to CAM5

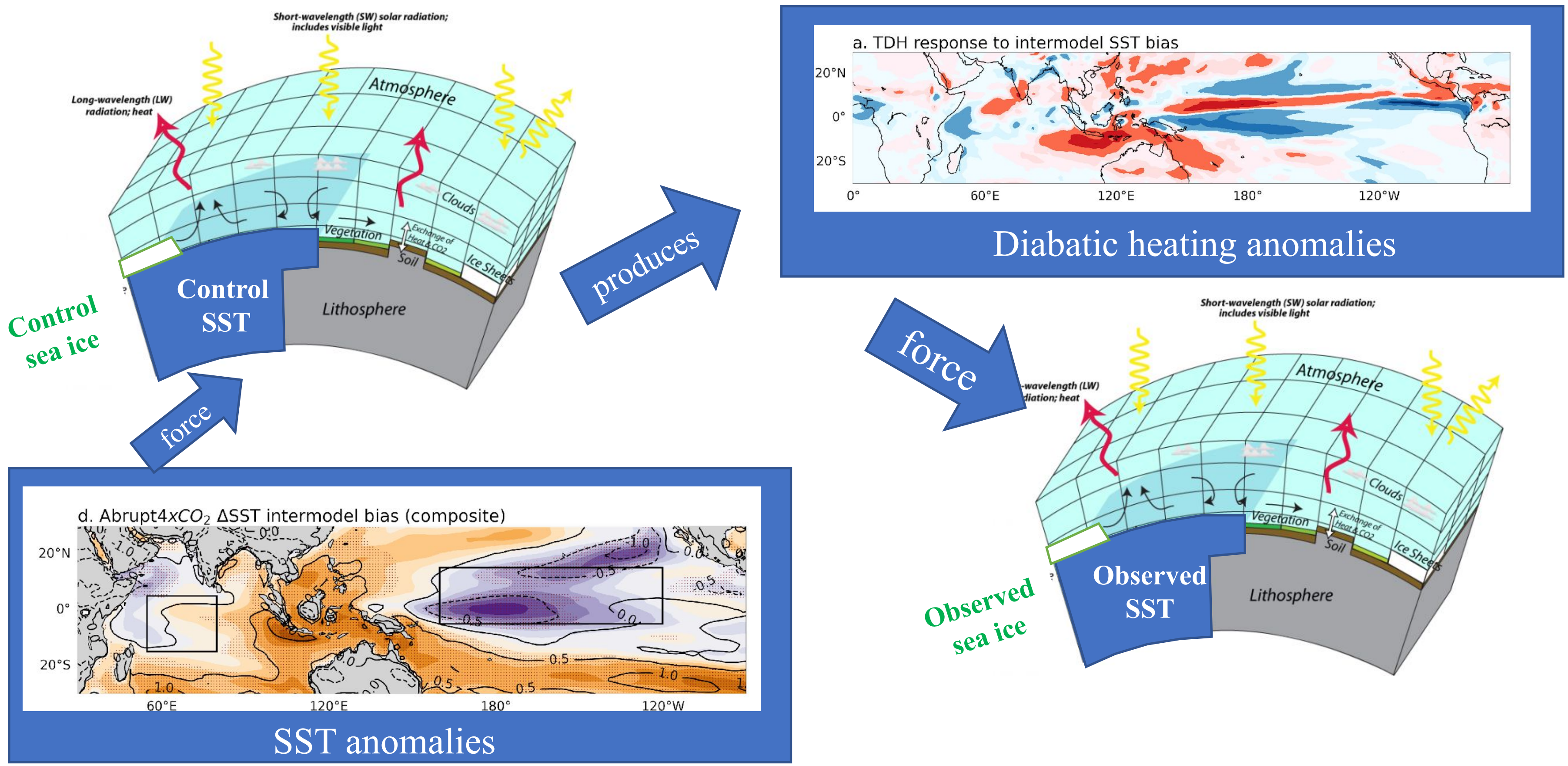
Δ*Precip* inter-model spread associated with IEOF1 Δ*NPSH* from coupled abrupt4xCO_2 :



Methods

SST related inter-model spread of ΔNPSH

SST related diabatic heating experiments



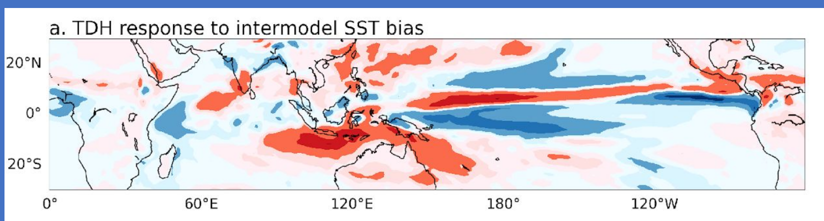
Step 1: Prescribe the leading inter-model uncertainty mode of tropical ΔSST to CAM5

Step 2: Prescribe the diabatic heating generated in step 1 to CAM5

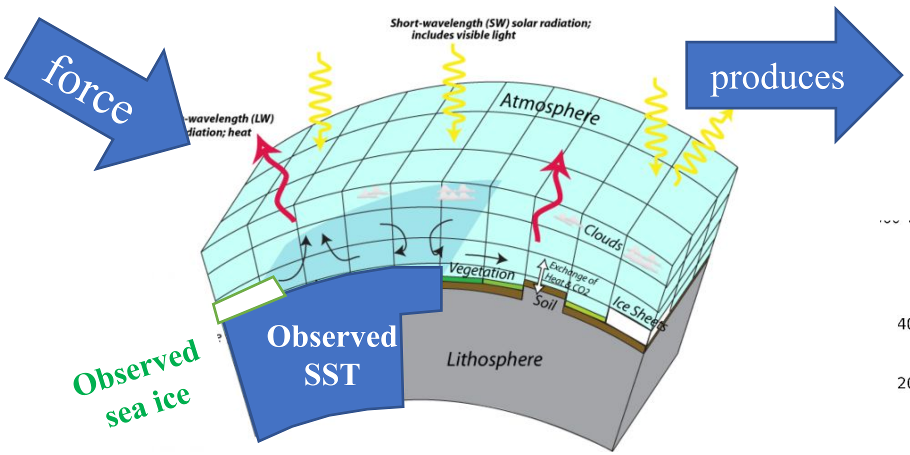
Results

SST related inter-model spread of ΔNPSH

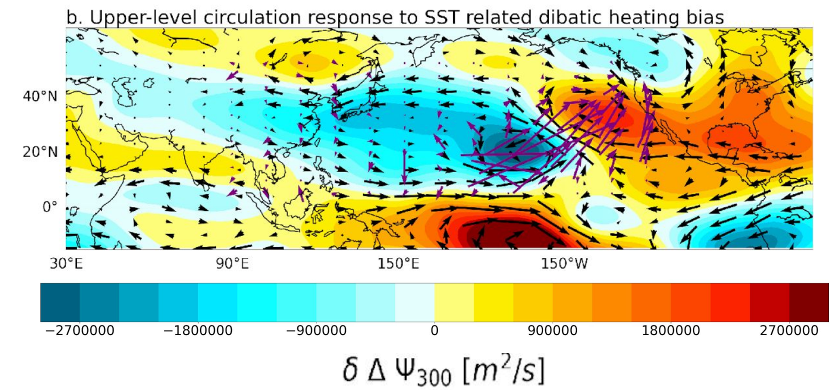
- The SST-induced diabatic heating inter-model spread drives IEOF1 of $\Delta NPSH$



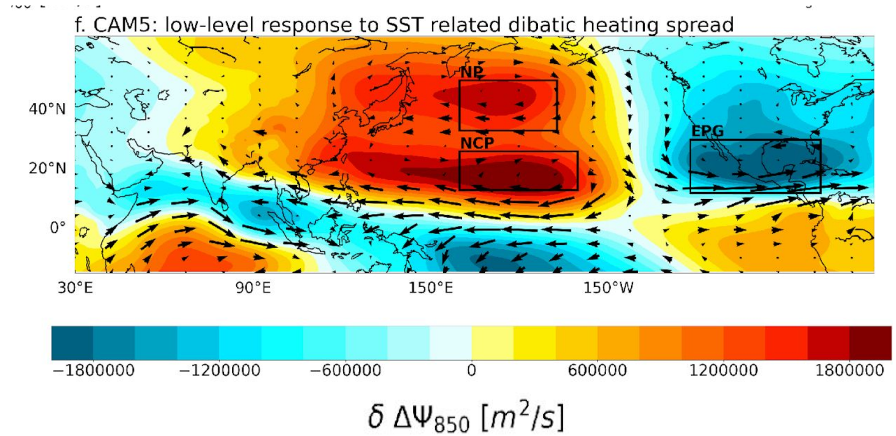
Diabatic heating anomalies



Upper-level circulation response



Low-level circulation response



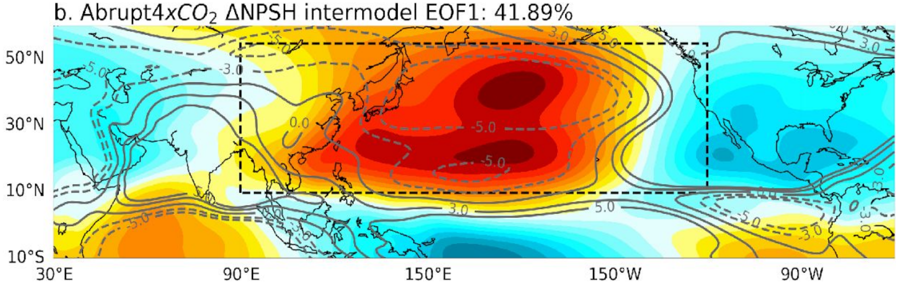
- The Matsuno-Gill circulation response shifts eastward

Results

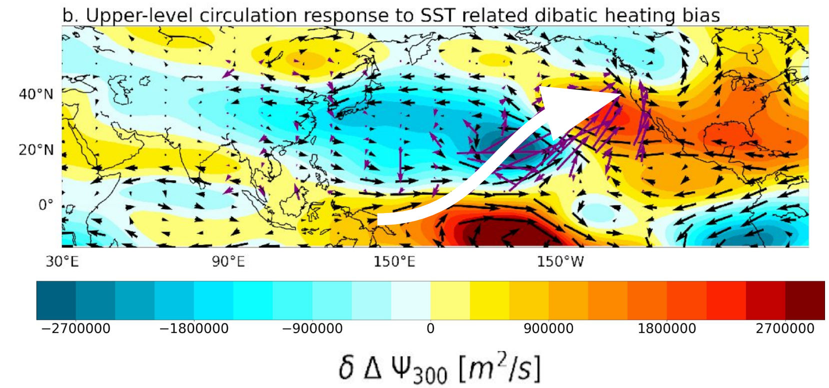
SST related inter-model spread of ΔNPSH

IEOF1 of $\Delta NPSH$ from abrupt4xCO_2:

IEOF1 of $\Delta NPSH$ from abrupt4xCO_2:

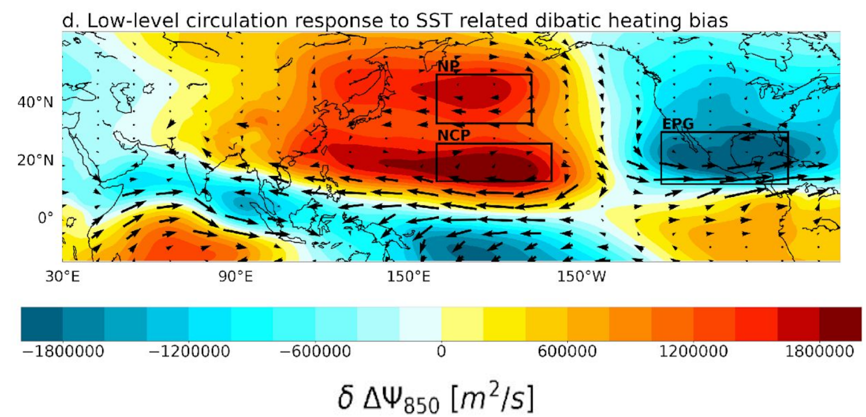


Upper-level circulation response



- The circulation anomaly maxima over the NP and the NCP regions are consistent with statistical results

Low-level circulation response



- The upper troposphere wave propagation is similar to the experiment forced with non-SST related TDH inter-model spread but shifts to the east
- The Matsuno-Gill circulation response shifts eastward

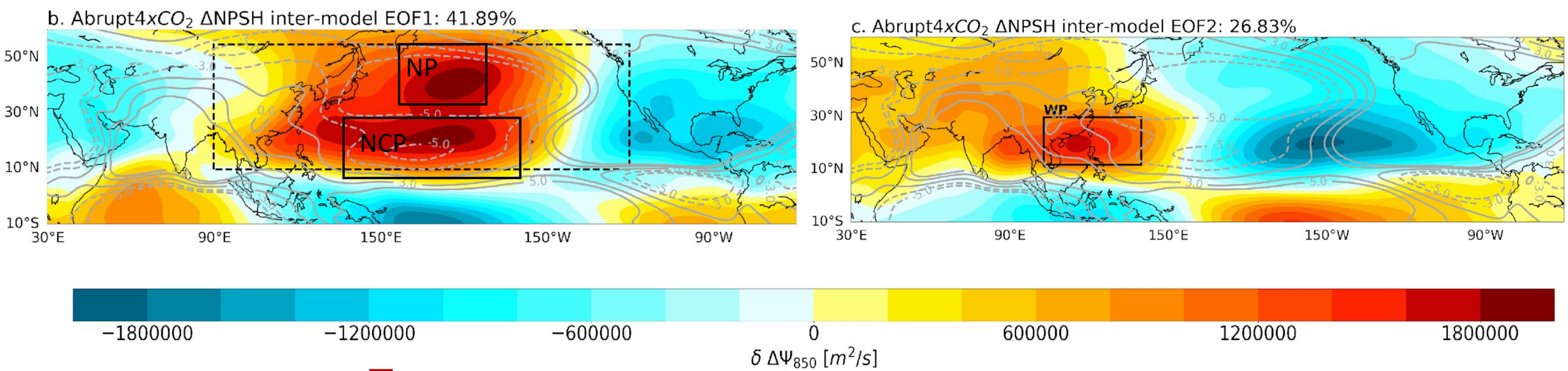
Results

Model uncertainty in summer NPSH projection

- **What cause inter-model uncertainty of $\Delta NPSH$?**

IEOF1 of $\Delta NPSH$ from abrupt4xCO_2:

IEOF2 of $\Delta NPSH$ from abrupt4xCO_2:

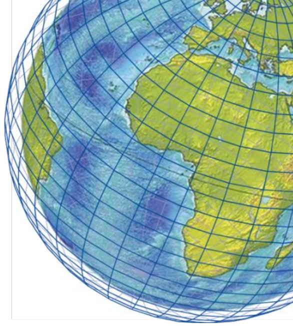


Due to **SST-driven** inter-model spread of changes in tropical precipitation

Due to **non-SST** related inter-model spread of changes in tropical precipitation

Summary

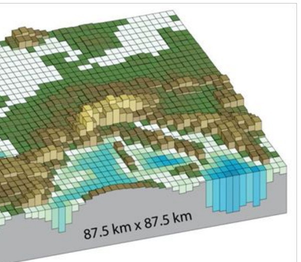
- State-of-the-art models show large diversity in the future projection of summer NPSH
- The source of this uncertainty originates from the tropics
- Model spread in tropical SST affects the NPSH through the production of anomalous precipitation
- Model spread in tropical precipitation that is independent of SST also contributes to the uncertainty of the NPSH projection



2023 Graduate EAS Symposium

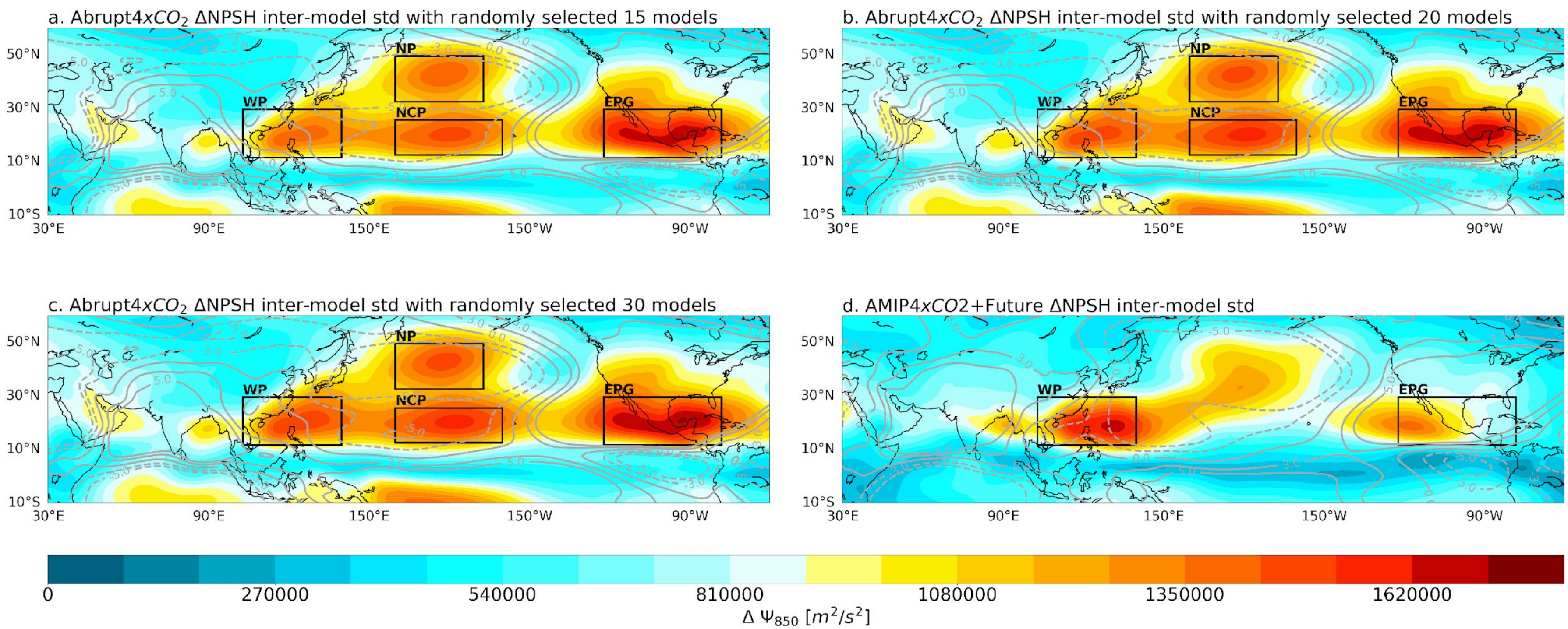
Q & A

Contact me: kezhou.lu@eas.gatech.edu



Extra Plots

Robustness of inter-model analysis



Extra Plots Relationship with extra-tropics

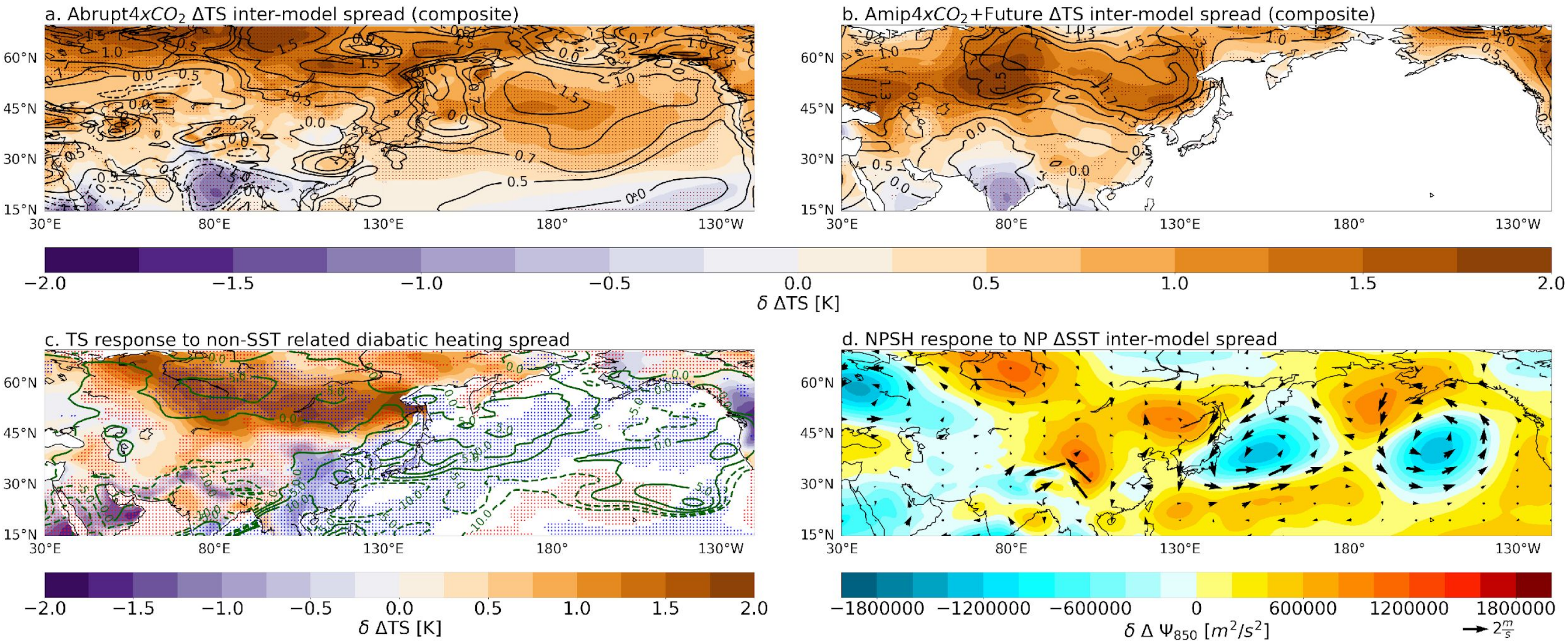
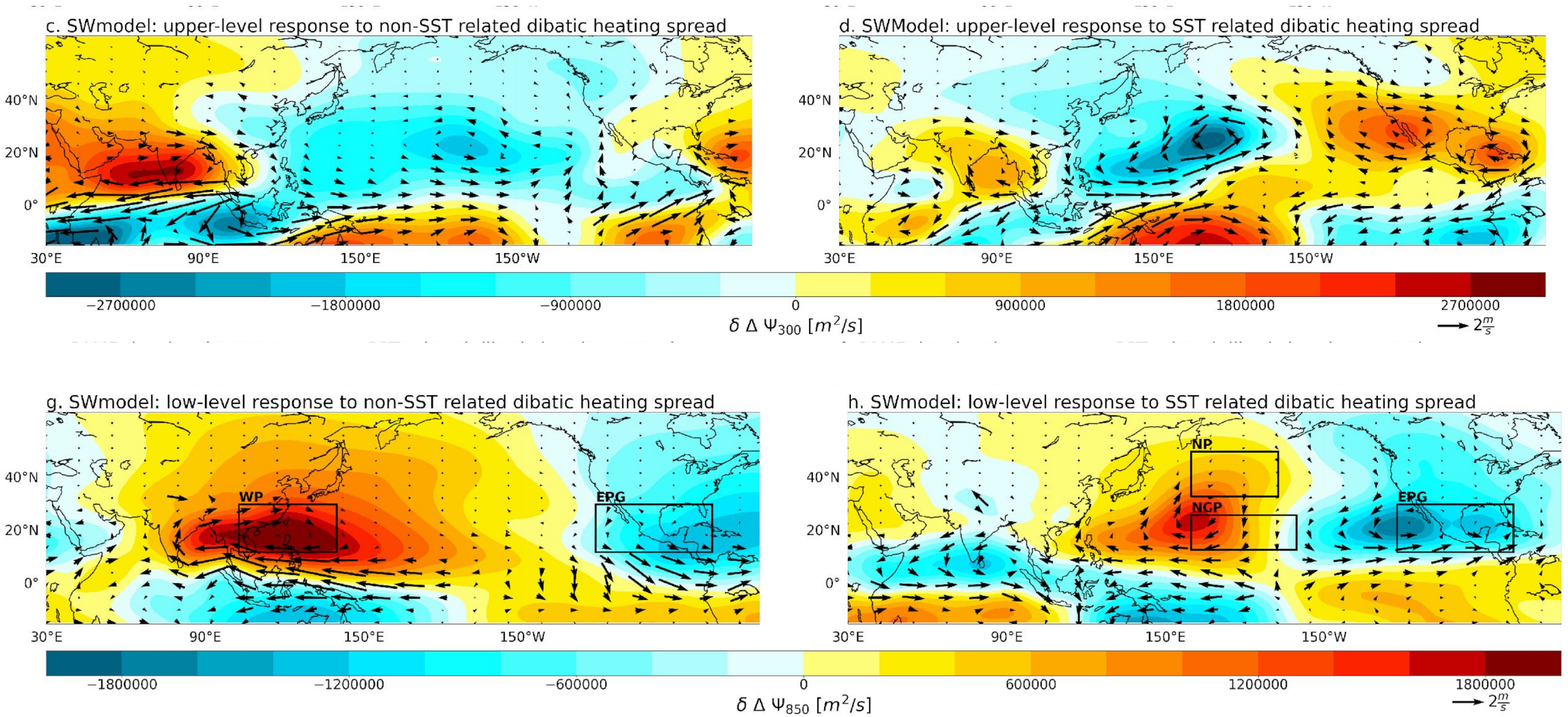


Figure 4. Relationship between inter-model uncertainty of ΔNPSH and extra-tropical land ΔTS and the North Pacific ΔSST. **a** Inter-model uncertainty of ΔTS by composite analysis (shadings; K) and TS anomalies associated with inter-model PC2 of $\Delta\Psi_{850}$ (contours; K). **b** Similar to **a** but with IEOF1 of land TS and associated land TS anomalies regressed onto PC1 of $\Delta\Psi_{850}$ under the AMIP4xCO_2+Future scenario. Regions with statistically significant correlations are marked with stipples in **a** and **b**. **c** Response of land TS (shadings; K), net surface shortwave radiation (thick green contours; W/m^2), and low cloud fraction (blue and red scatters where blue indicates a significant low cloud reduction and vice versa) to SST independent inter-model tropical diabatic heating spread in CAM5. **d** Response of eddy streamfunction at 850 hPa(shadings; m^2/s) and horizontal winds (vectors; m/s) to inter-model spread of ΔSST over North Pacific.

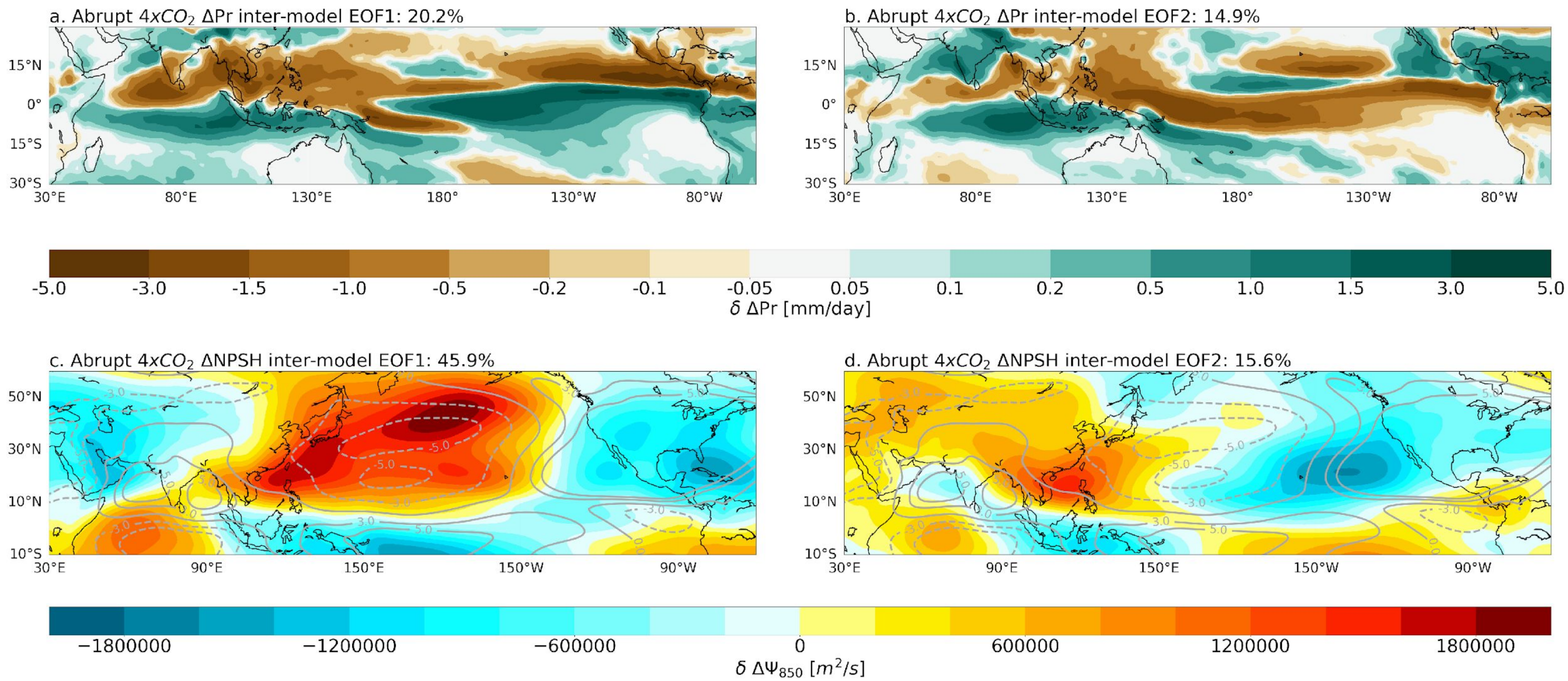
Extra Plots

Stationary wave model results



Extra Plots

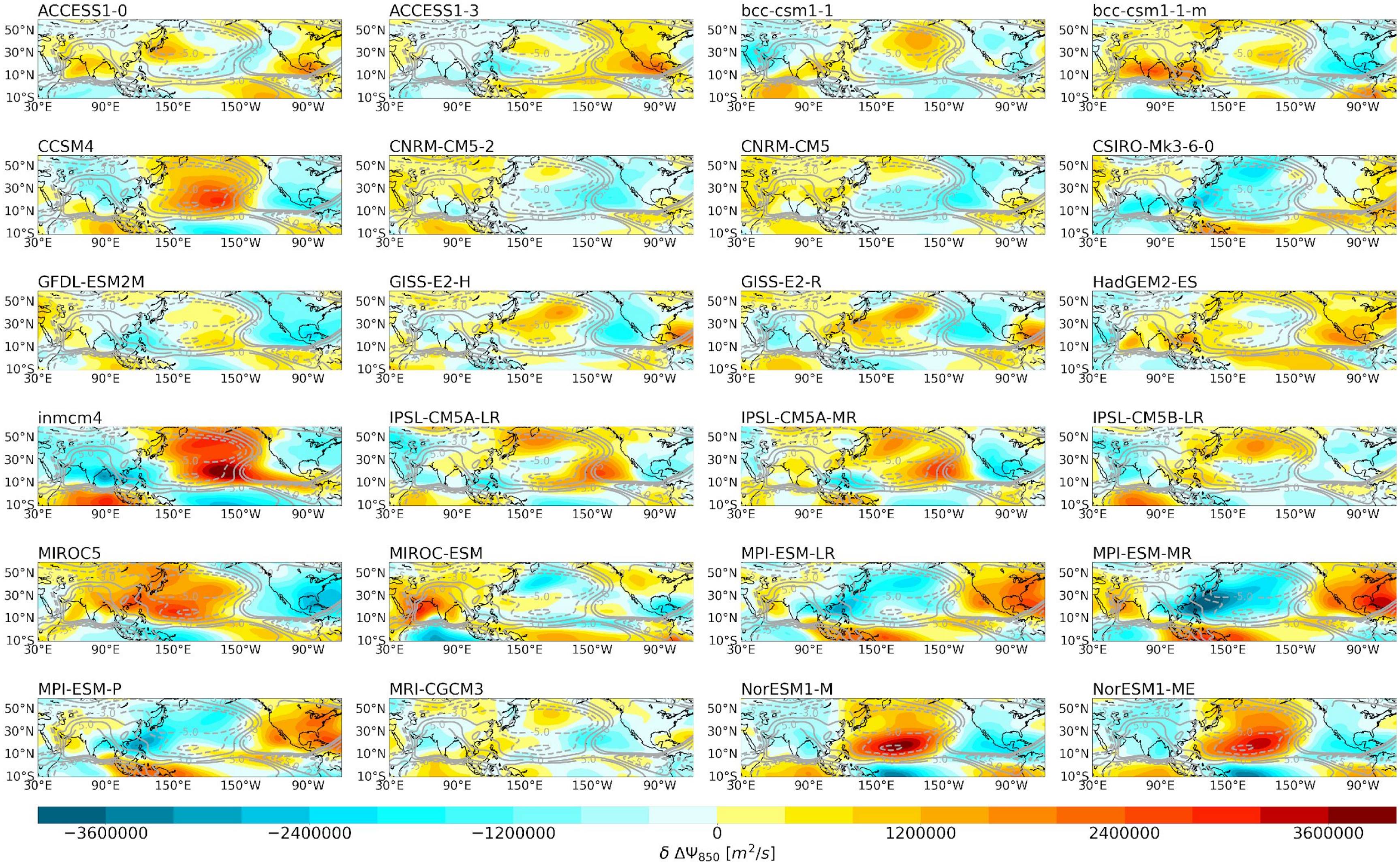
CMIP models with AMIP outputs



Extra Plots

Deviation form the multi-model mean

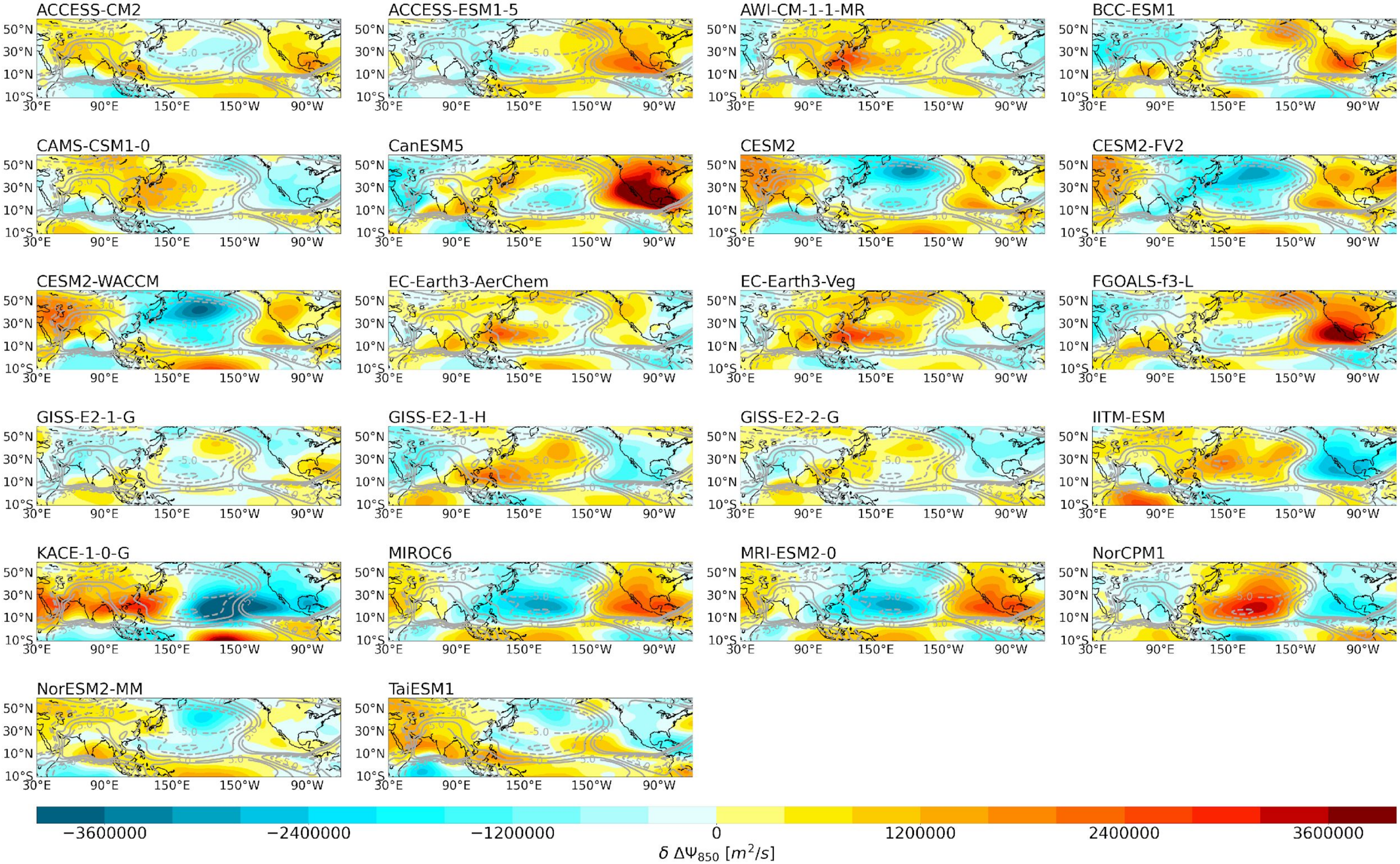
CMIP5-abrupt4xCO2



Extra Plots

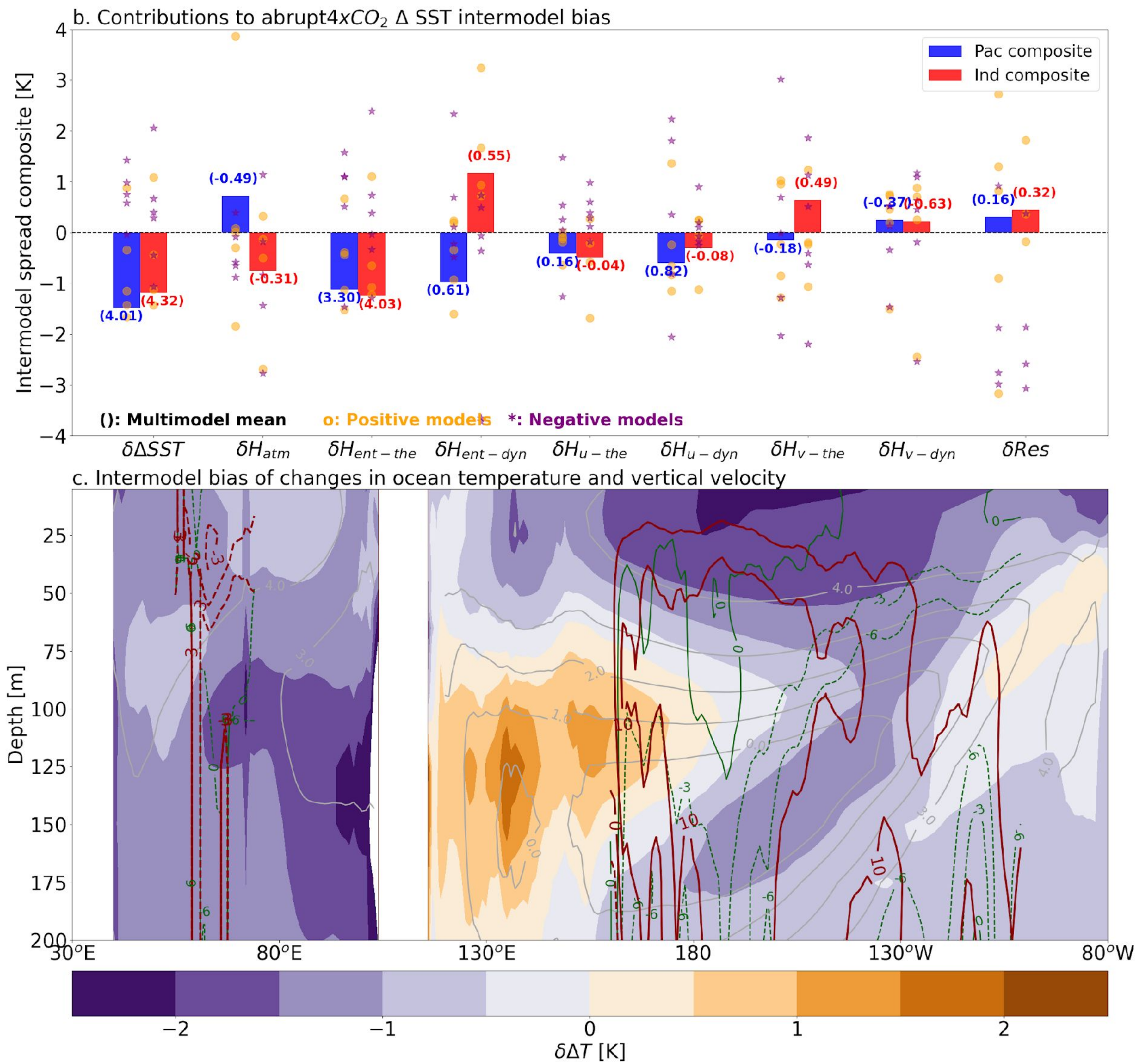
Deviation form the multi-model mean

CMIP6-abrupt4xCO2



Extra Plots

Cause of SST inter-model spread



Models simulate less weakening of upwelling velocity and less shoaling of thermocline also project a stronger NPSH compared to the multimodel mean

Table S1: Summary of CMIP5 and CMIP6 simulations (Models with AMIP output available are highlighted)

CMIP5			
No.	Model Name	Resolution (atmosphere)	Resolution (ocean)
1	ACCESS1-0	$1.875° EW \times 1.25° NS$, 38 levels	Tripolar $1° EW \times 1° NS$, 50 levels
2	ACCESS1-3	$1.875° EW \times 1.25° NS$, 38 levels	Tripolar $1° EW \times 1° NS$, 50 levels
3	bcc-csm1-1	T42, 26 levels	Tripolar $1° EW \times 1° NS$, 40 levels
4	bcc-csm1-1-m	T106, 26 levels	Tripolar $1° EW \times 1° NS$, 40 levels
5	CCSM4	$0.9° EW \times 1.25° NS$, 30 levels	Tripolar gx1v6, 60 levels
6	CNRM-CM5-2	TL127, 31 levels	Tripolar $1° EW \times 1° NS$, 42 levels
7	CNRM-CM5	TL127, 31 levels	Tripolar $1° EW \times 1° NS$, 42 levels
8	CSIRO-Mk3-6-0	T63, 18 levels	$1.875° EW \times 0.9375° NS$, 31 levels
9	GFDL-ESM2M (GFDL-CM4)	M45, 24 levels ($1° EW \times 1° NS$, 33 levels)	Tripolar 360x200, 50 levels
10	GISS-E2-H	$2.5° EW \times 2° NS$, 40 levels	Tripolar $1° EW \times 1° NS$, 26 levels
11	GISS-E2-R	$2.5° EW \times 2° NS$, 40 levels	$1.25° EW \times 1° NS$, 32 levels
12	HadGESM2-ES (HadGEM2-A)	N96, 38 levels	$1° EW \times 1° NS$, 40 levels
13	inmcm4	$2° EW \times 1.5° NS$, 21 levels	$1° EW \times 0.5° NS$, 40 levels
14	IPSL-CM5A-LR	$3.85° EW \times 1.875° NS$, 39 levels	$2° EW \times 2° NS$, 31 levels
15	IPSL-CM5A-MR	$2.5° EW \times 1.25° NS$, 39 levels	$2° EW \times 2° NS$, 31 levels
16	IPSL-CM5B-LR	$3.85° EW \times 1.875° NS$, 39 levels	$2° EW \times 2° NS$, 31 levels
17	MIROC5	T85, 40 levels	$1° EW \times 1° NS$, 50 levels
18	MIROC-ESM	T85, 40 levels	$1.4° EW \times 1° NS$, 44 levels
19	MPI-ESM-LR	T63, 47 levels	GR15, 40 levels
20	MPI-ESM-MR	T63. 95 levels	TP04. 40 levels
21	MPI-ESM-P	T63, 47 levels	GR15, 40 levels
22	MRI-CGCM3	TL159, 48 levels	$1° EW \times 0.5° NS$, 51 levels
23	NorESM1-M	f19, 26 levels	Tripolar gx1v6, 53 levels
24	NorESM1-ME	TL159, 48 levels	$1° EW \times 0.5° NS$, 51 levels

CMIP6			
No.	Model Name	Resolution (atmosphere)	Resolution (ocean)
25	ACCESS-CM2	N96, 85 levels	Tripolar $1° EW \times 1° NS$, 50 levels
26	ACCESS-ESM1-5	N96, 85 levels	Tripolar $1° EW \times 1° NS$, 50 levels
27	AWI-CM-1-1-MR	T127, 95 levels	Unstructured grid in the horizontal, 46 levels
28	BCC-ESM1	T42, 26 levels	$1° EW \times 0.8° NS$, 40 levels
29	CAMS-CSM1-0	T106, 31 levels	Tripolar $1° EW \times 1° NS$, 50 levels
30	CanESM5	T63, 49 levels	Tripolar $1° EW \times 1° NS$, 41 levels
31	CESM2	$1.25° EW \times 0.9° NS$, 32 levels	Tripolar gx1v7, 60 levels
32	CESM2-FV2	$2.5° EW \times 1.9° NS$, 32 levels	Tripolar gx1v7, 60 levels
33	CESM2-WACCM	$1.25° EW \times 0.9° NS$, 70 levels	Tripolar gx1v7, 60 levels
34	EC-Earth3-AerChem	TL255, 91 levels	Tripolar $1° EW \times 1° NS$, 75 levels
35	EC-Earth3-Veg	TL255, 91 levels	Tripolar $1° EW \times 1° NS$, 75 levels
36	FGOALS-f3-L	c96, 32 levels	Tripolar $1° EW \times 1° NS$, 30 levels
37	GISS-E2-1-G	$2.5° EW \times 2° NS$, 40 levels	$1° EW \times 1° NS$, 32 levels
38	GISS-E2-1-H	$2.5° EW \times 2° NS$, 40 levels	$1° EW \times 1° NS$, 32 levels
39	GISS-E2-2-G	$2.5° EW \times 2° NS$, 40 levels	$1° EW \times 1° NS$, 32 levels
40	IITM-ESM	T62, 64 levels	Tripolar $1° EW \times 1° NS$, 50 levels
41	KACE-1-0-G	N96, 85 levels	Tripolar $1° EW \times 1° NS$, 50 levels
42	MIROC6	T85, 81 levels	Tripolar $1° EW \times 1° NS$, 63 levels
43	MRI-ESM2-0	TL195, 80 levels	$1° EW \times 0.5° NS$, 61 levels
44	NorCPM1	$2.5° EW \times 1.9° NS$, 26 levels	$1° EW \times 1° NS$, 53 levels
45	NorESM2-MM	$1° EW \times 1° NS$, 32 levels	$1° EW \times 1° NS$, 70 levels
46	TaiESM1	$1.25° EW \times 0.9° NS$, 30 levels	Triploar gx1v6, 60 levels