HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

GEOMAR

A Pacemaker Role of the 11-year Solar Cycle in the Tropical Pacific Decadal Variability

SPACE CLIMATE SYMPOSIUM 8
(Sep 19-22, 2022)

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Ziniu Xiao, Liang Zhao, Katja Matthes, Sebastian Wahl

SPACE CLIMATE
CLIMATE IN SPACE AND ON EARTH

Mechanisms of solar influence on climate

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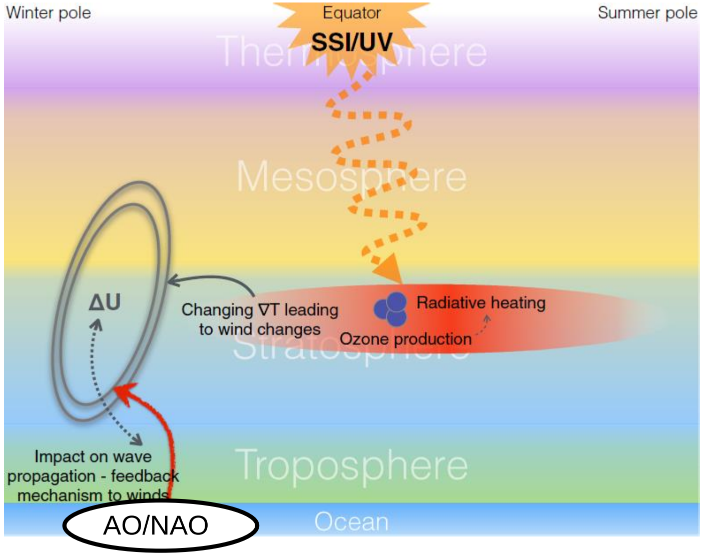
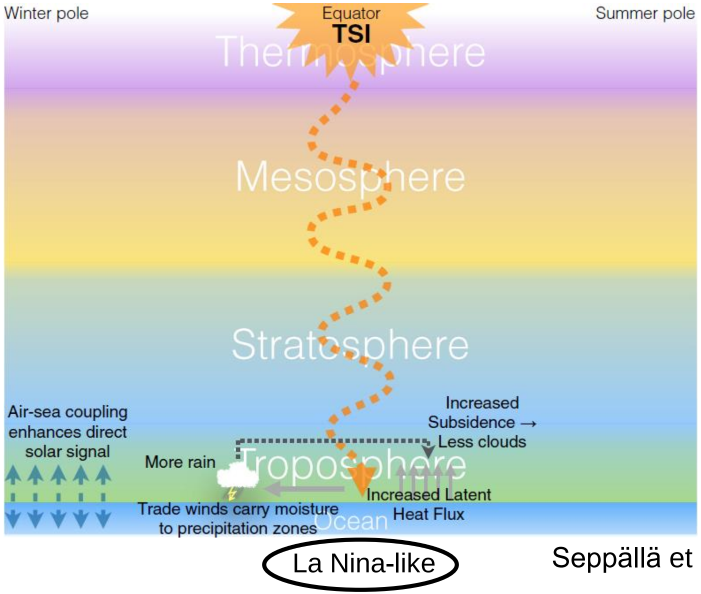
top-down UV (6-10%)



(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)

bottom-up VIS/NIR (0.1%)

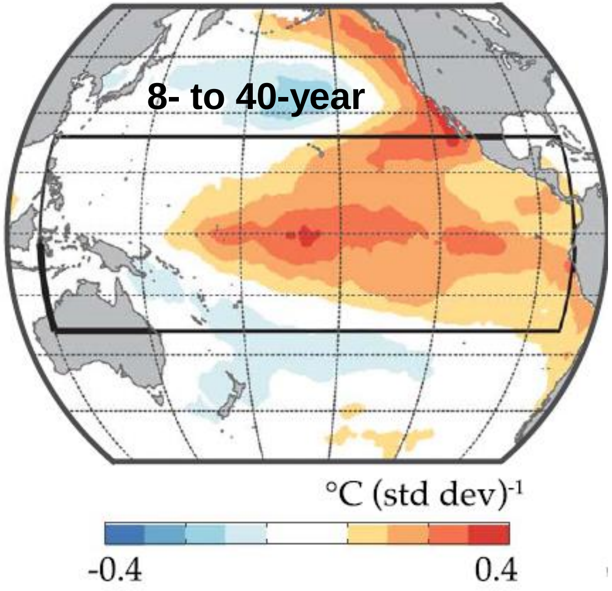


Seppälä et al. 2014

(Meehl et al., 2008; 2009)

Background

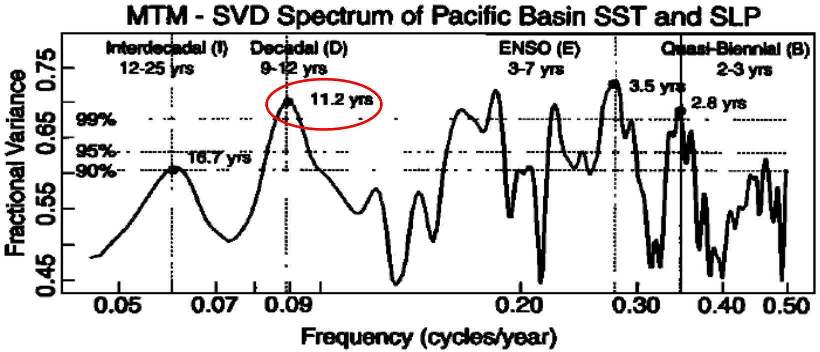
Tropical Pacific decadal variability (TPDV)



(Power et al. 2021)

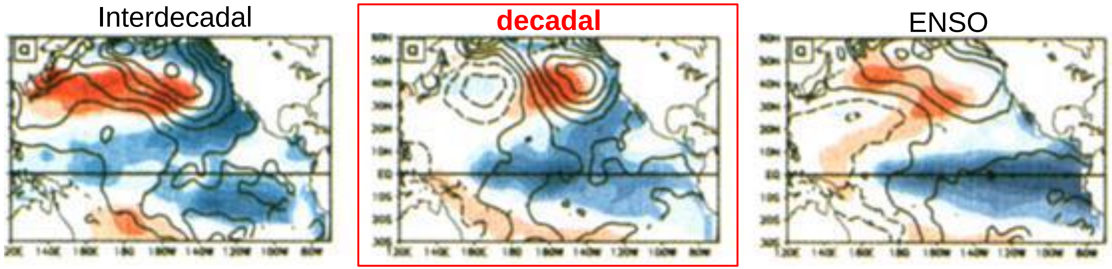
- Internal TPDV
- External TPDV:

Anthropogenic sources (e.g., GHGs, aerosols), volcanic eruptions, **11-year solar cycle** (Meehl et al., 2009)



1900-1991

(Tourre et al. 2001)

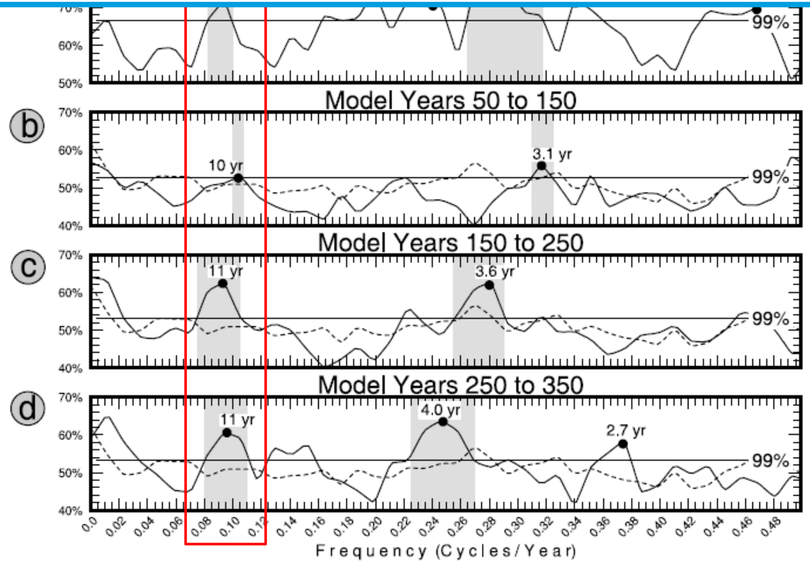


Background

Fast Ocean- Atmosphere Model (FOAM)

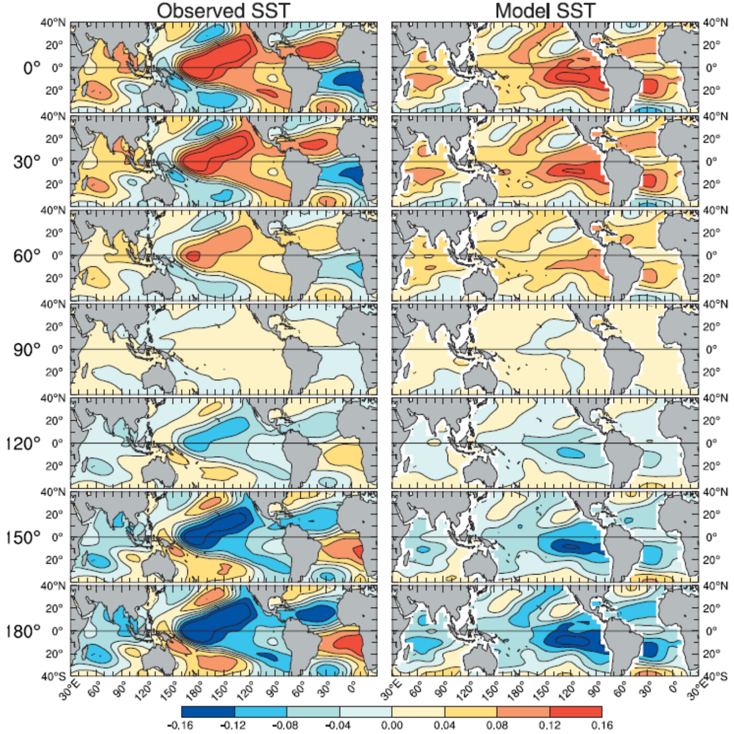
- 11-year-period cosine signal of amplitude **2.0 W/m²** to the solar constant in the model. (model troposphere and upper ocean) (White and Liu et al., 2008)

→ **Without** this idealized 11-year solar forcing, the FOAM simulates **only the ENSO**.



~0.4 W/m² for globe averaged
~0.5 W/m² for tropics averaged

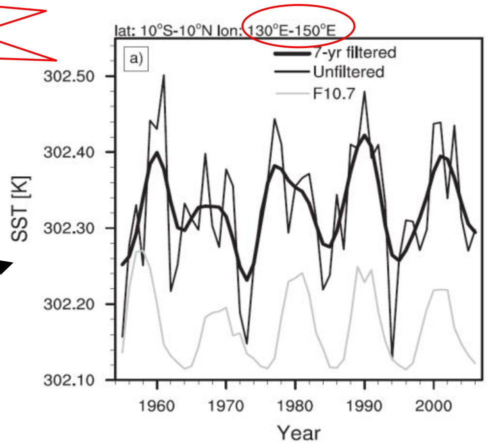
Quasidecadal Oscillation (9- to13-yr)



Background

Diverse results!

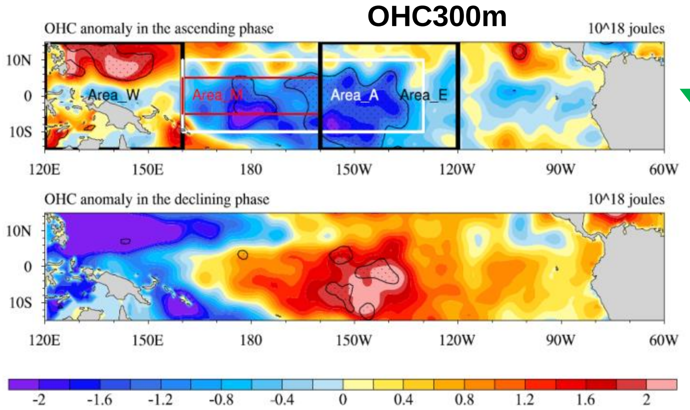
- **ENSO-like** (Van Loon et al., 2007; Meehl et al, 2009)
- **Not ENSO-like**, weak warming in the in the tropical central and eastern Pacific (Tung and Zhou, 2010; Roy, 2014)
- **In-phase oscillation** (White and Liu, 2008; Misios and Schmidt, 2012)

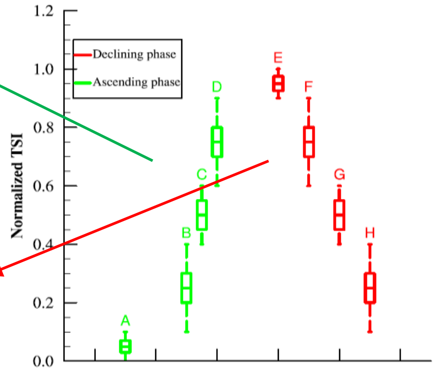


(Misios et al., 2012)

- Decadal variability of upper ocean heat content anomaly (OHC_700m) is significantly related to the 11-year solar cycle (Wang et al., 2015, Huo et al., 2016)

Mechanisms?





(Huo and Xiao., 2016)

Results:

1. **Lagged Responses of the Tropical Pacific to the 11-year Solar Cycle Forcing (Obs. & CMIP5 MME)**

   Huo, W., Z. Xiao, X. Wang and L. Zhao, 2021, J. Meteorol. Res., doi: 10.1007/s13351-021-0137-8.2.

2. **Modulations of the 11-year Solar Cycle on El Niño Modoki (Obs. & FOCI)**

   Huo, W. and Z. Xiao, 2017, J. Atmos. Sol.-Terr. Phys., doi: dx.doi.org/10.1016/j.jastp.2017.05.008.

3. **Phase-locking Decadal Covariations in the Tropical Pacific to the 11-year Solar Cycle Forcing (Obs. & CESM-WACCM)**

   Huo, W., Z. Xiao, and L. Zhao, 2022, J. Clim. (accepted)

Result 1:

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1. Lagged Responses of the Tropical Pacific to the 11-year Solar Cycle Forcing (Obs. & CMIP5 MME)

Huo, W., Z. Xiao, X. Wang and L. Zhao, 2021, J. Meteorol. Res., doi: 10.1007/s13351-021-0137-8.2.

Observational /reanalysis datasets:

- ERSST v5
- EN v4.2.1
- NCEP/NCAR reanalysis 1

CMD: (Camp and Tung, 2007)
Composite difference between solar max and min

CMIP5 models used in this study

historical-Nat & pi-Control

Model	Institute	HR (lat × lon)	1861–2005 Time	Ens.	Pattern Correlation Coefficients
CanESM2	CCCMA (Canada)	64×128	1850–2012	5	0.60
CSIRO-Mk3.6.0	CSIRO-QCCCE (Australia)	96×192	1850–2012	10	0.73
FGOALS-g2	IAP-THU (China)	60×128	1850–2009	3	0.47
GFDL-CM3	NOAA GFDL (USA)	90×144	1860–2005	3	0.59
GFDL-ESM2M	NOAA GFDL (USA)	90×144	1861–2005	1	0.67
HadGEM2-ES	MOHC (UK)	144×192	1859–2005	4	0.71
MIROC-ESM-CHEN	MIROC (Japan)	64×128	1850–2005	1	0.61

Result 1: Responses in the Tropical Pacific

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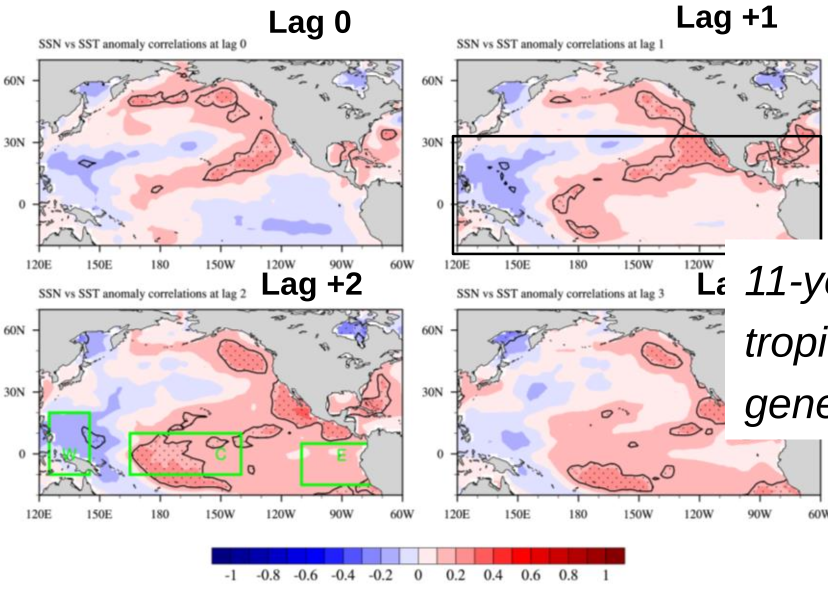
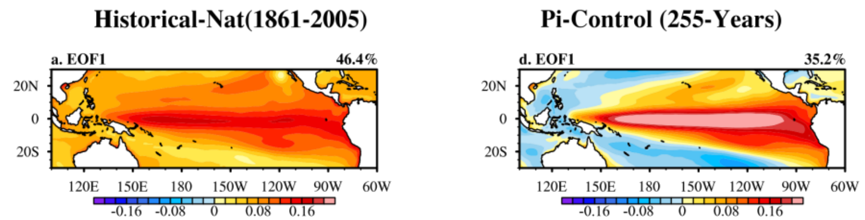
Obs.

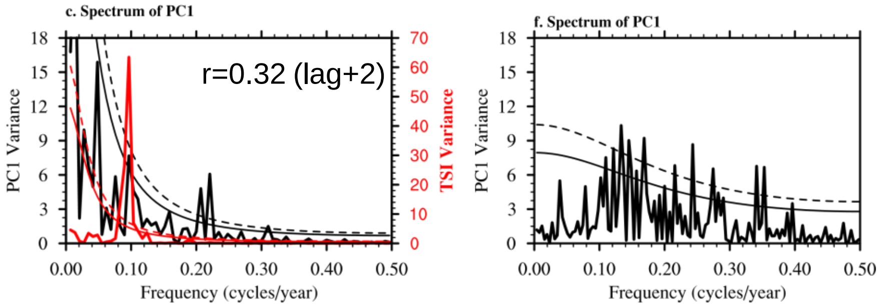


Lagged correlation map between SSN and SSTa

CMIP5_MME



11-year solar cycle has a footprint in the EOF1 of the tropical Pacific SST and is independent of the internally generated ENSO cycle.



Result 1: Responses in the Tropical Pacific

CMD_SSTa

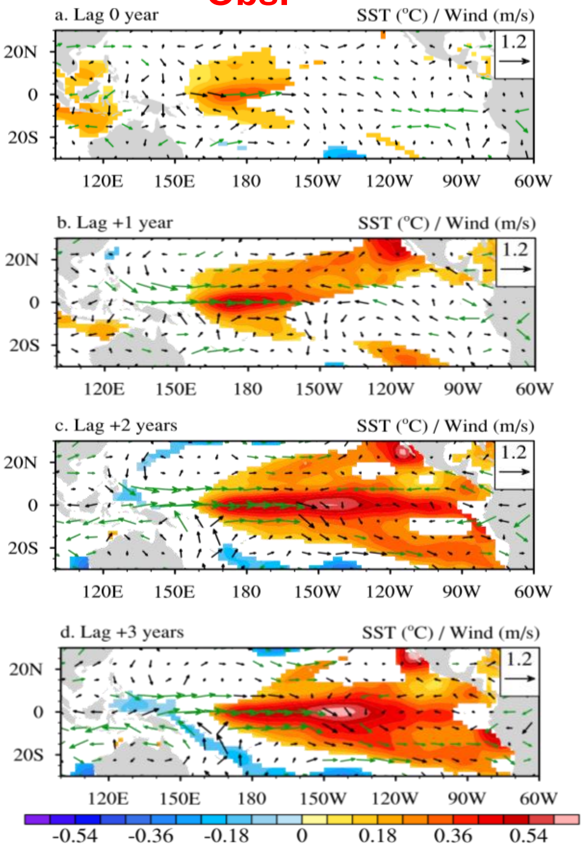
Lag 0

Lag +1

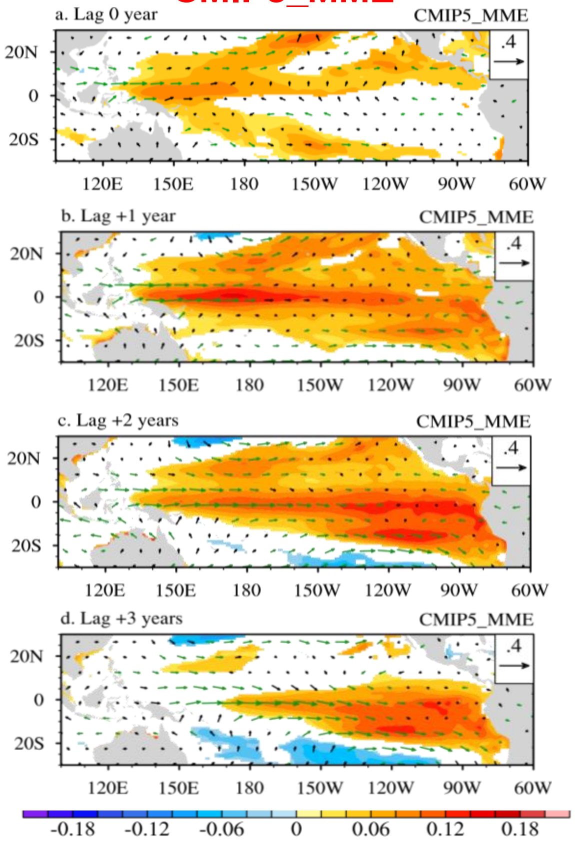
Lag +2

Lag +3

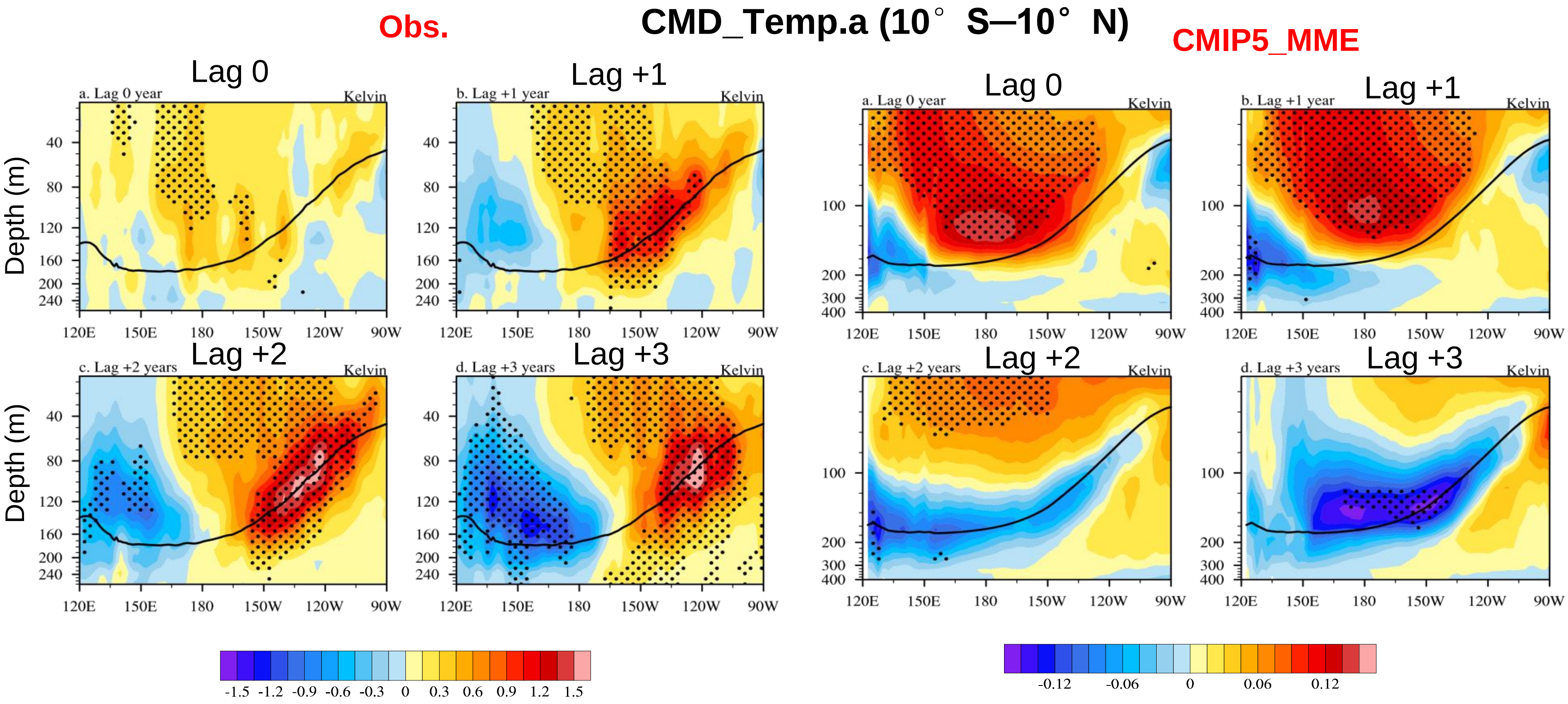
Obs.



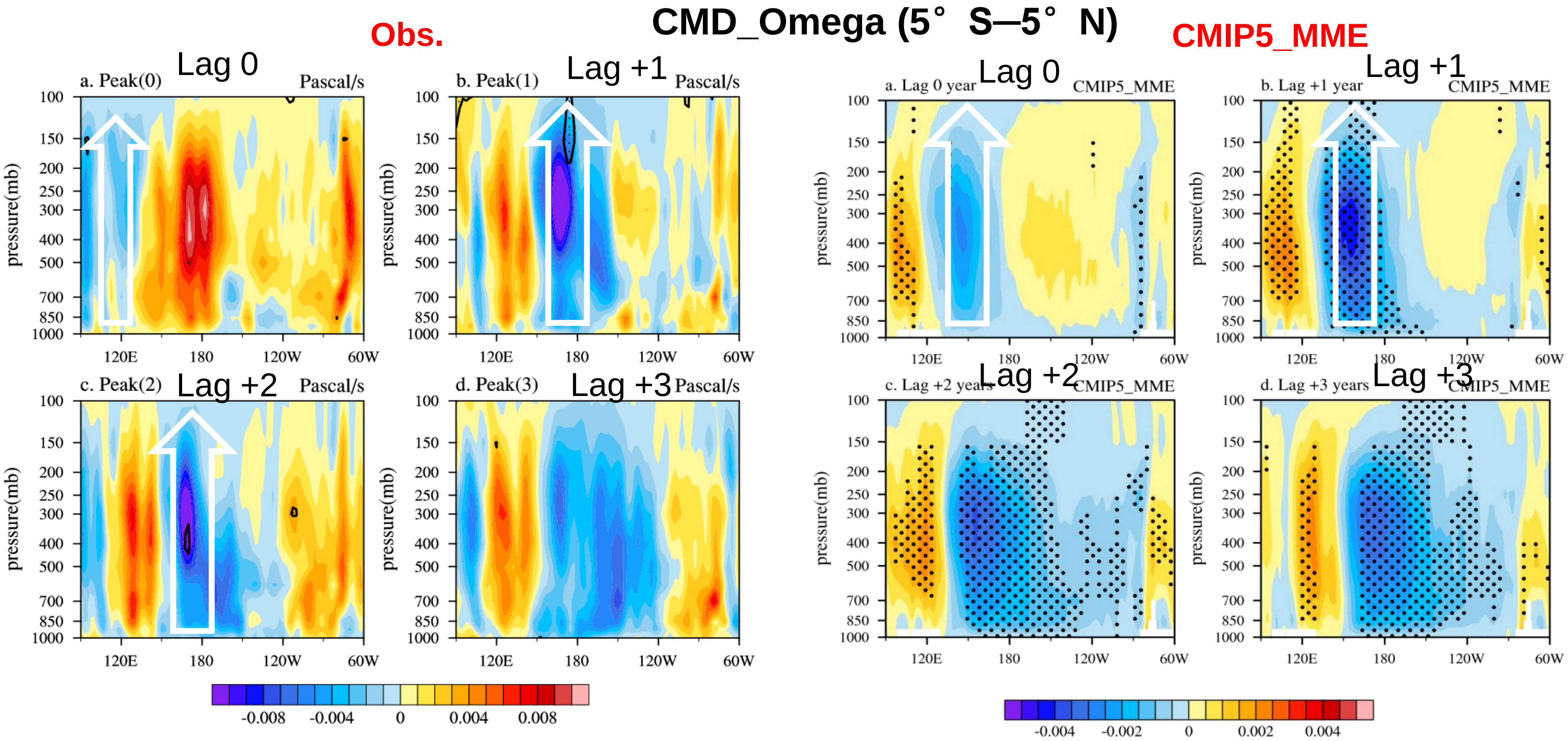
CMIP5_MME



Result 1: Responses in the Tropical Pacific



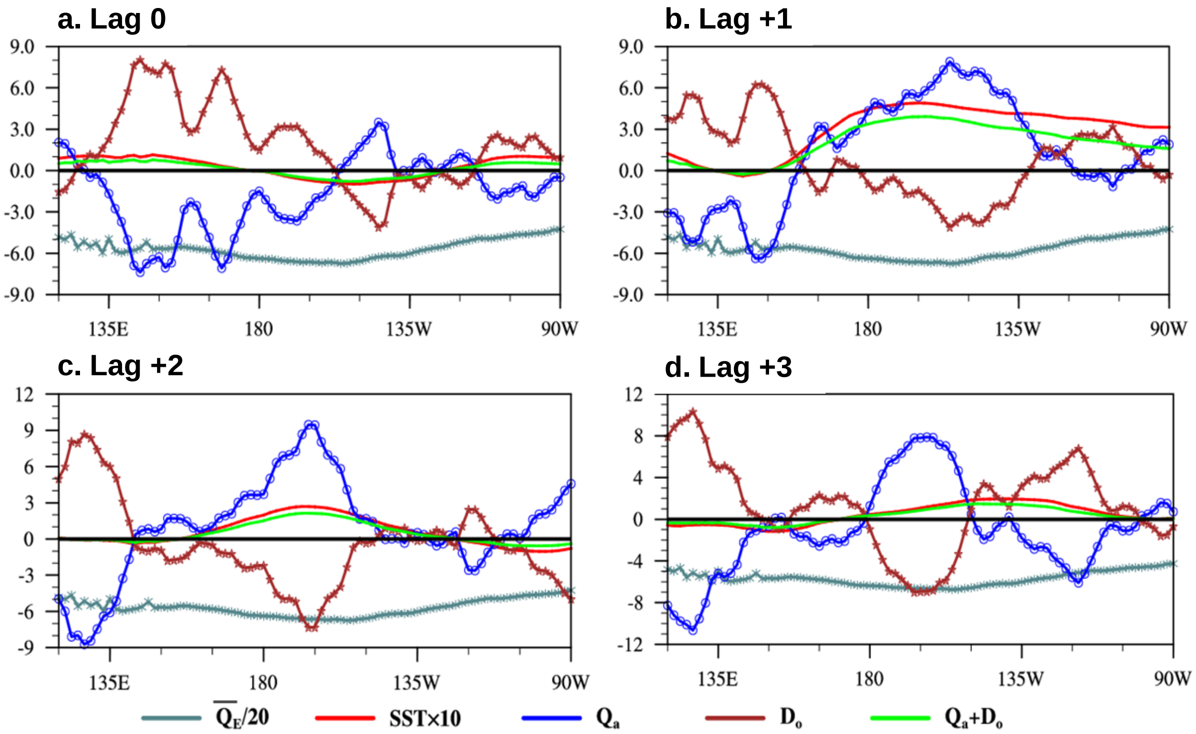
Result 1: Responses in the Tropical Pacific



Result 1: Major Contributors to the Warming in CP

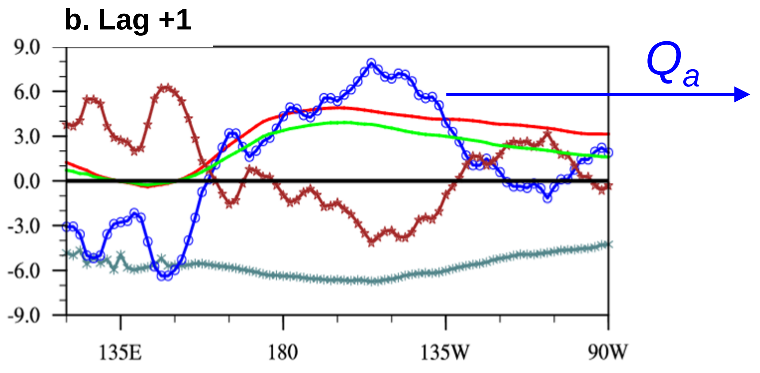
Ocean mixed layer heat budget analysis → $T' = \frac{D_o + Q_a}{\alpha \overline{Q_E}}$

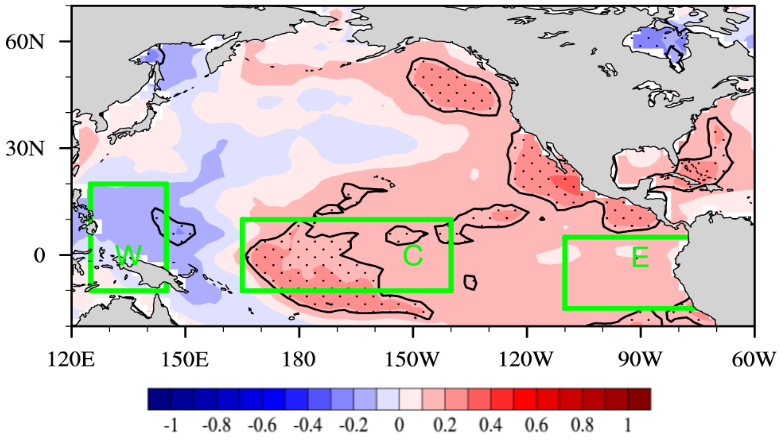
Obs.

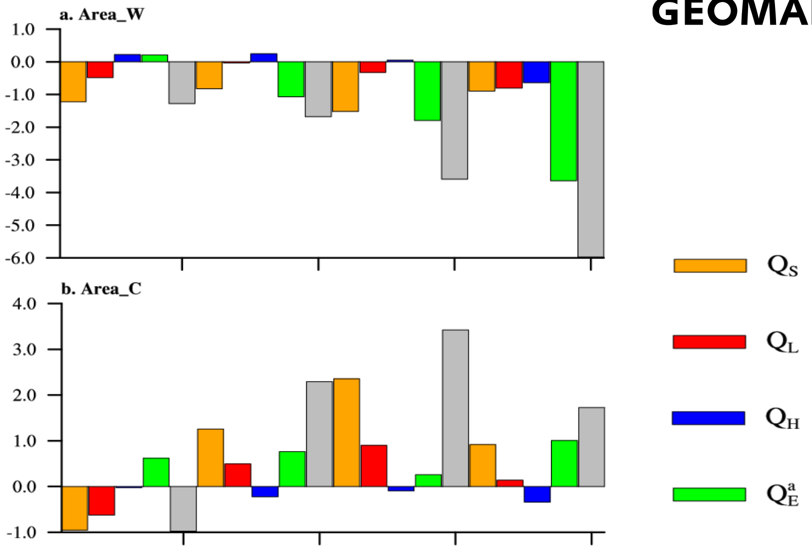


Atmospheric forcing
Q_a *plays a crucial role in the warming response of the central Pacific*

Result 1: Major Contributors to the Warming in CP





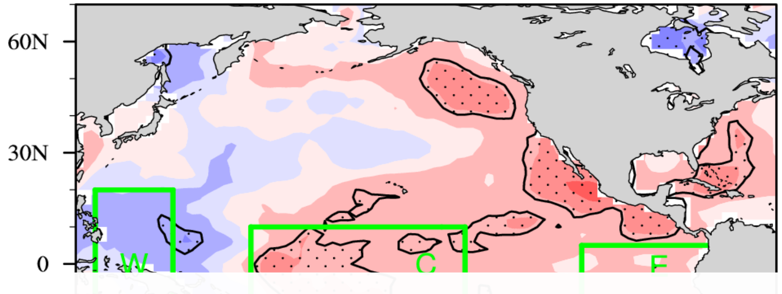


*The **radiative fluxes (Q_S and Q_L)** emerge as the main factors for the warming response in central equatorial Pacific*

lag 0 lag +1 lag +2 lag +3

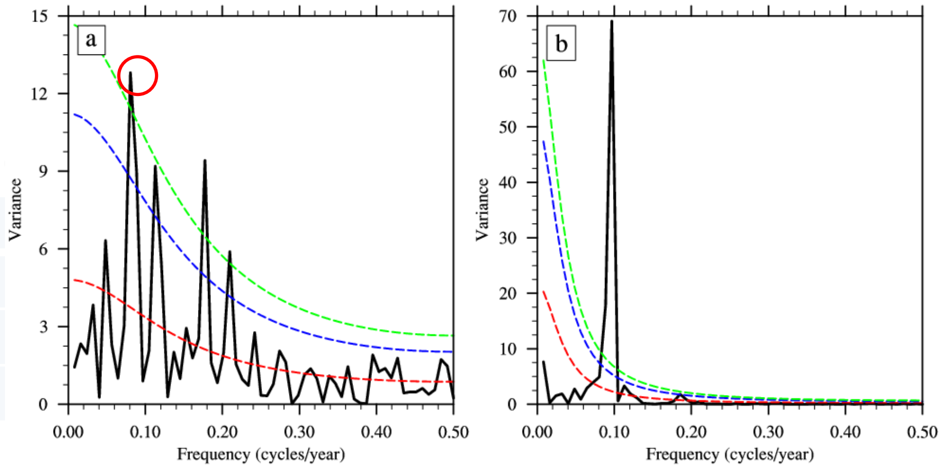
Result 2: Modulation on El Niño Modoki

Obs.



El Niño Modoki index (**EMI**) (Ashok et al., 2007)：

$$\boldsymbol{EMI} = \overline{SST_c} - \frac{(\overline{SST_W} + \overline{SST_E})}{2}$$



Quasi-decadal period

Result 2: Modulation on El Niño Modoki

FOCI: 1850-2014, 18. Ens.

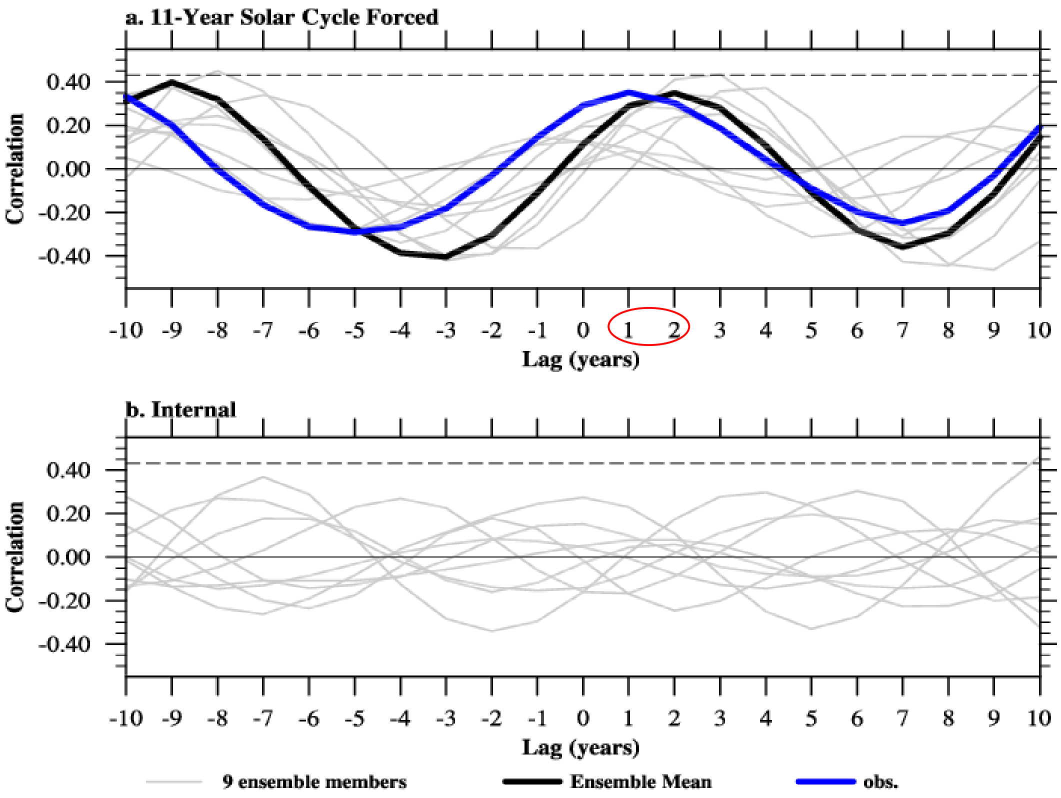
1. Full
2. Low- frequency

Full-Ens.lowf

Strong epoch (1931-2014)

Synchronization!

Cross cor: TSI / EMI_DJF



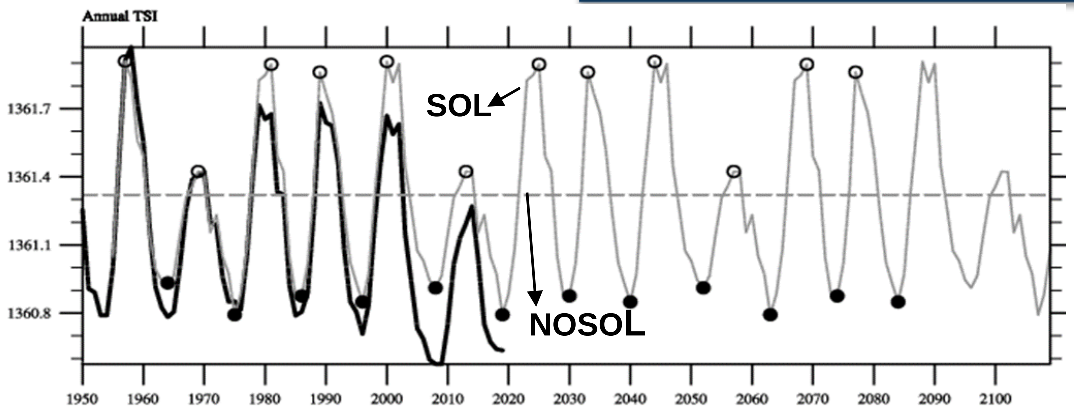
Result 3:

3. Phase-locking Decadal Covariations in the Tropical Pacific to the 11-year Solar Cycle Forcing (Obs. & CESM-WACCM)

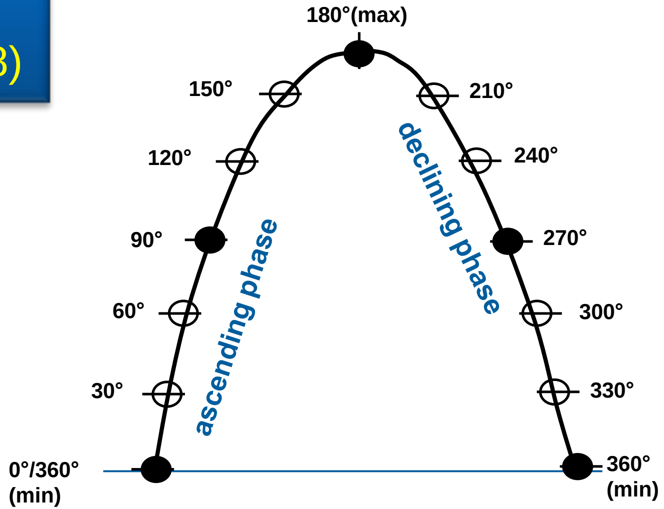
Huo, W., Z. Xiao, and L. Zhao, 2022, J. Clim. (accepted)

Sensitivity experiments:
- SOL (1955-2099)
- NOSOL (avg.1965-2008)

CESM1(WACCM) (Marsh et al. 2013)



Phases of the 11-year solar cycle



Result 3: Phase-locked Decadal Covariations

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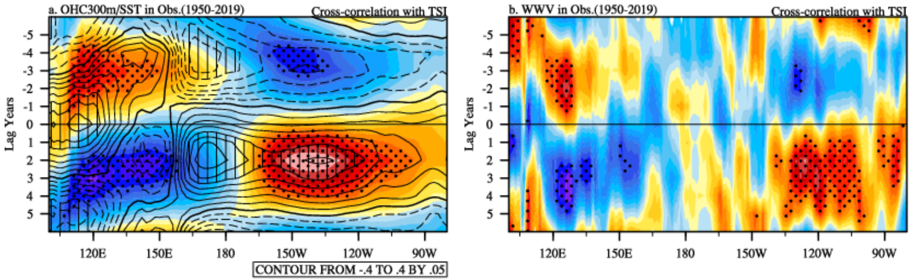
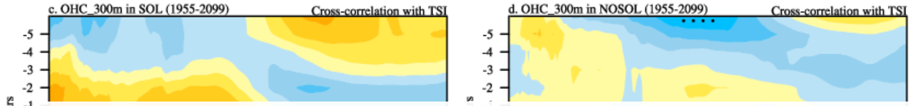
Upper ocean thermal state

Obs. OHCa (SSTa) &TSI WWVa &TSI



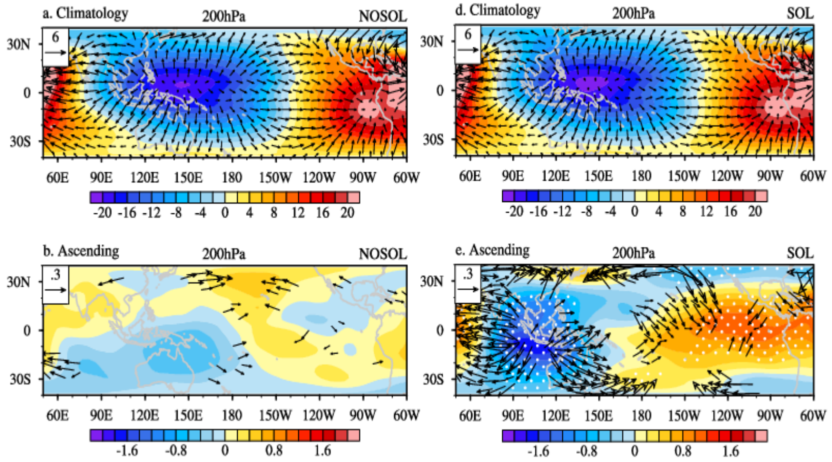
SOL OHCa &TSI **NOSOL** OHCa &TSI



Pacific Walker circulation

divergent winds and velocity potential @200hPa

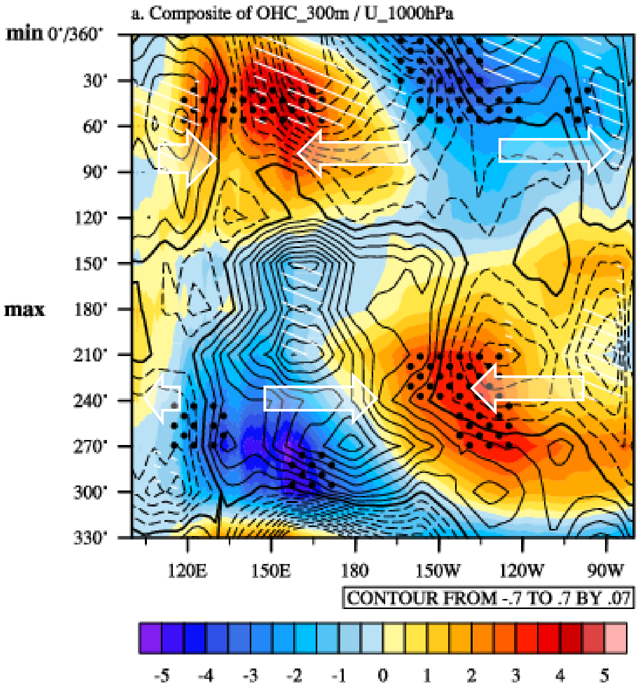
NOSOL **SOL**



Phase-locked decadal covariations** in the tropical Pacific climate system to the 11-year solar cycle: **La Nina (El Nino)-like + PWC westward (eastward) shifting in solar ascending (declining) phase .

Result 3: Processes Related to the Decadal Covariations

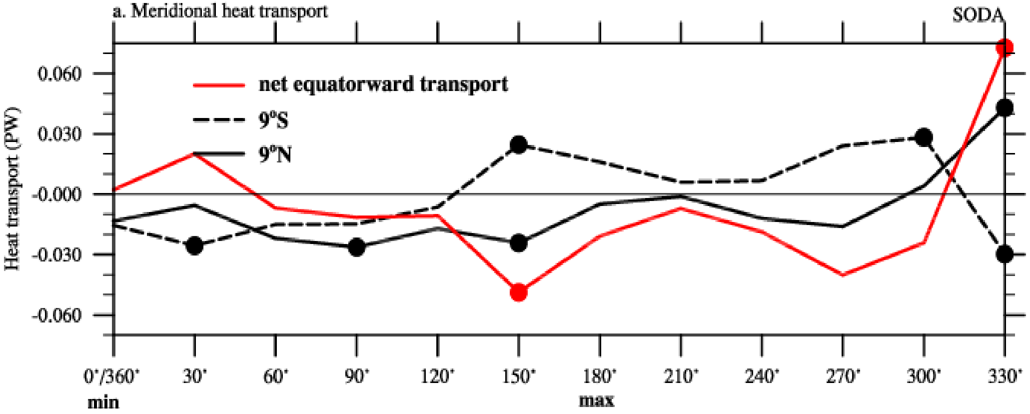
Obs. **OHCa / U1000hPa**



U1000hPa provides a + feedback to Pacific OH

Meridional heat transport by the Pacific STCs

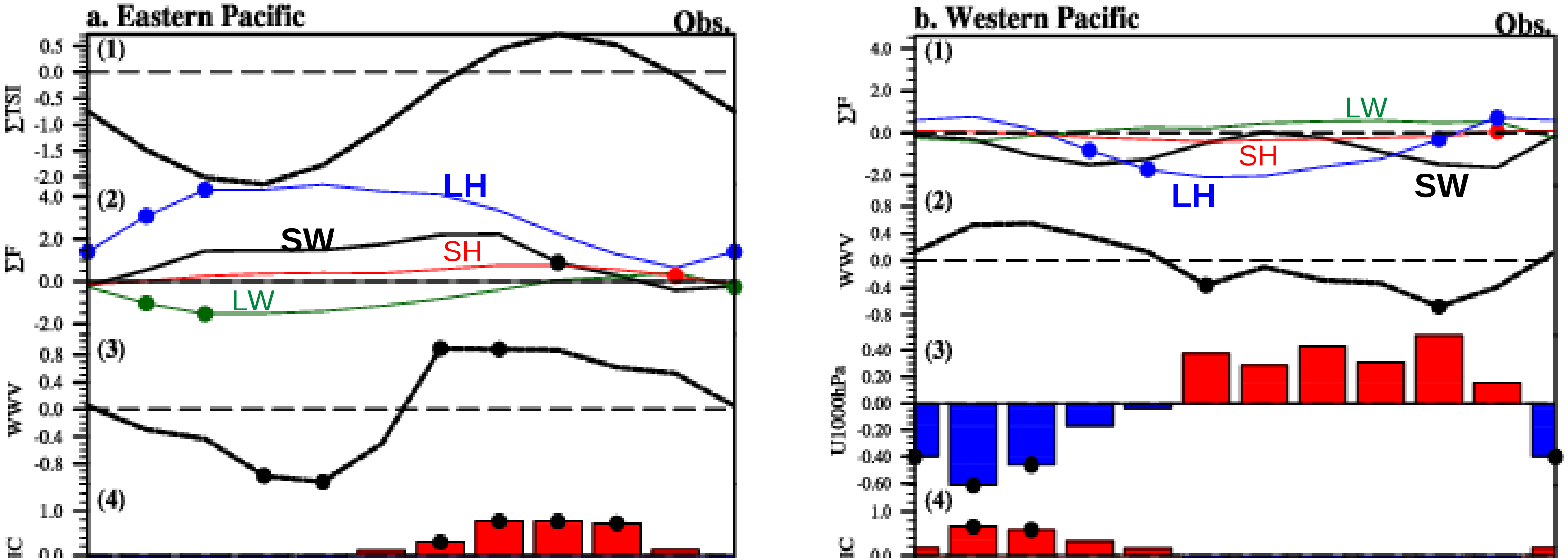
(Unit: PW, 1PW=10^{15}W)



MHT provides a + (-) contribution to western (eastern) Pacific OHCa

Result 3: Accumulative TSI in OHCa

Obs.

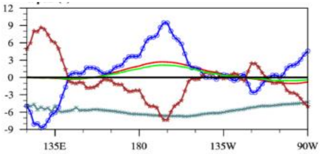


*The **extra solar heating effect** (compared to the TSI minimum) can be gradually accumulated in the eastern Pacific OHCa and be released quickly once this heat source disappears (back to the TSI minimum).*

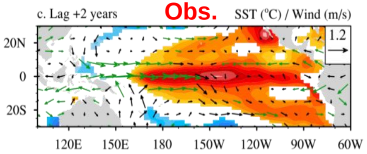
Take Home Messages:

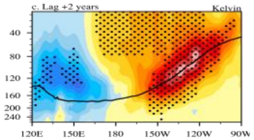
1. **Lagged Responses of the Tropical Pacific to the 11-year Solar Cycle Forcing**
   Huo, et al., 2021, doi: 10.1007/s13351-021-0137-8.2.

✓ ***Atmospheric forcings (radiation fluxes)*** *play a crucial role in the warming response of the central Pacific*



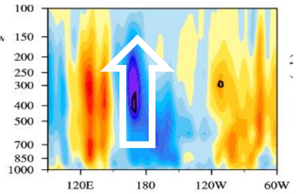
✓ ***Lagged warm*** *response (El Niño –like)*





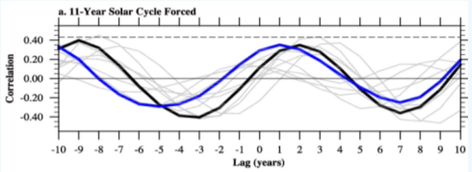
Lag +2 yrs

✓ *An anomalous updraft arises over the western equatorial Pacific and* ***shifts eastwards***



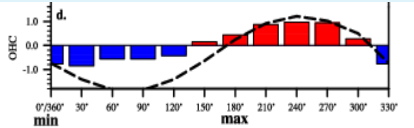
2. **Modulations of the 11-year Solar Cycle on El Niño Modoki** *Huo, W. and Z. Xiao, 2017, doi: dx.doi.org/10.1016/j.jastp.2017.05.008.*

✓ *The 11-year solar cycle* ***synchronizes*** *the El Niño Modoki*

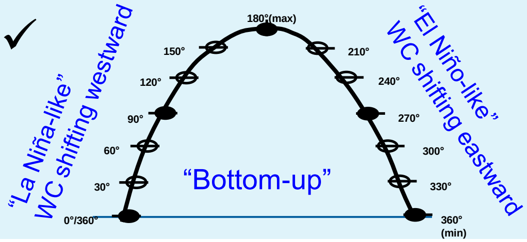


3. **Phase-locking decadal covariations in the tropical Pacific to 11-year solar cycle** *Huo, et al., 2022, JC*

✓ ***Accumulative solar irradiation*** *in the OHC (above 300m)*



✓



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Many thanks for your attention!

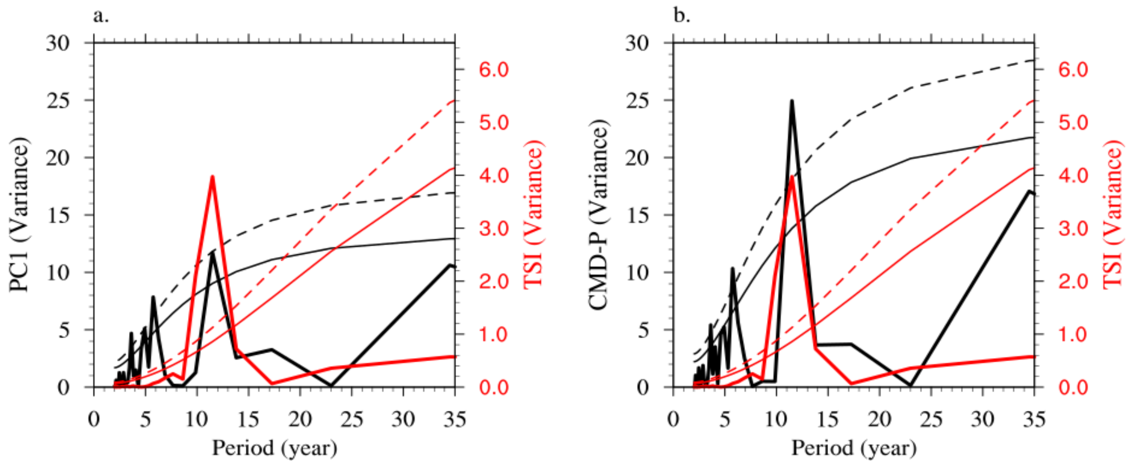
Model and Experiments

- **CESM1(WACCM4)** (Marsh et al., 2013)
- spatial resolution: 1.9°lat x 2.5°lon, 66 layers up to ~145km
- MOZART3 chemistry (Kinnison et al. 2007)
- Representation of solar irradiance effects:
  - coarse SW radiation (for z<65km) (19 bands in UV-NIR)
  - high resolution photolysis scheme (100 bands in UV-NIR)
- Representation of auroral effects:
  - direct impact on ionization rates, depending on Kp-index
- Apart form solar forcing, all other external forcings are same as CMIP5

- **Experiments set up**:
- SOL
- NOSOL

Table 1. Three big volcanic eruptions in the 1955-2000 and aliasing of the solar activity

Volcanic eruptions	**Mt Agung March 1963**	**El Chichón April 1982**	**Pinatubo June 1991**
Solar activity	Minimum	2 years after Maximum	Maximum



Outlook

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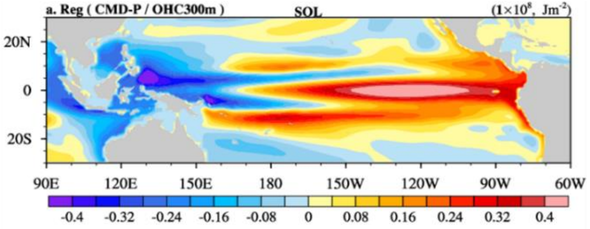
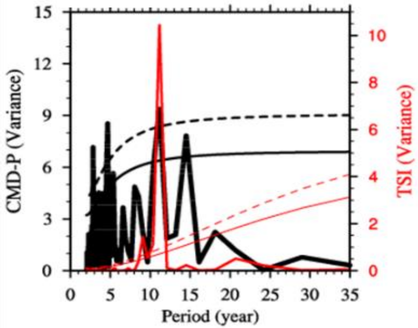
SOL

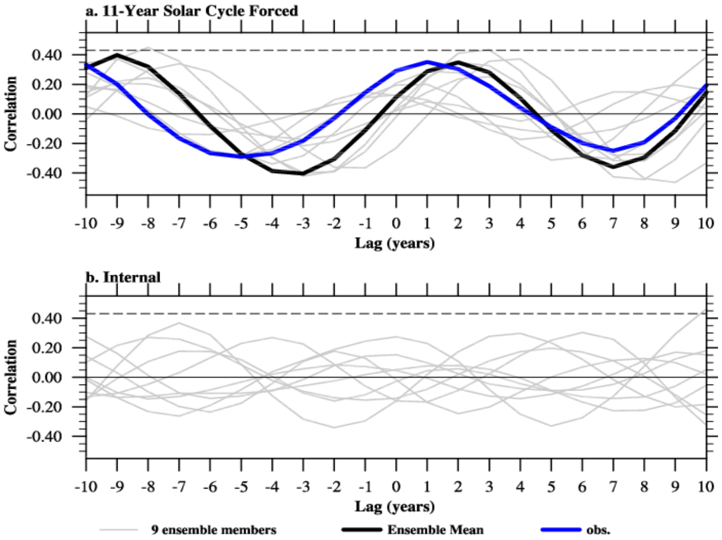
CESM-WACCM

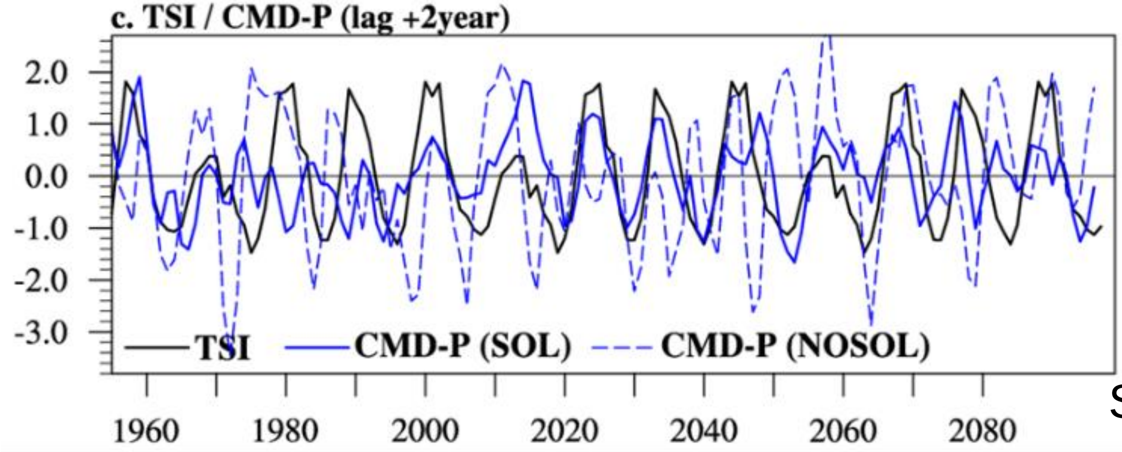


d. SOL



FOCI





Solar cycle works as a pacemaker
→ synchronizes natural mode

CMD: SST_DJF

in strong epoch

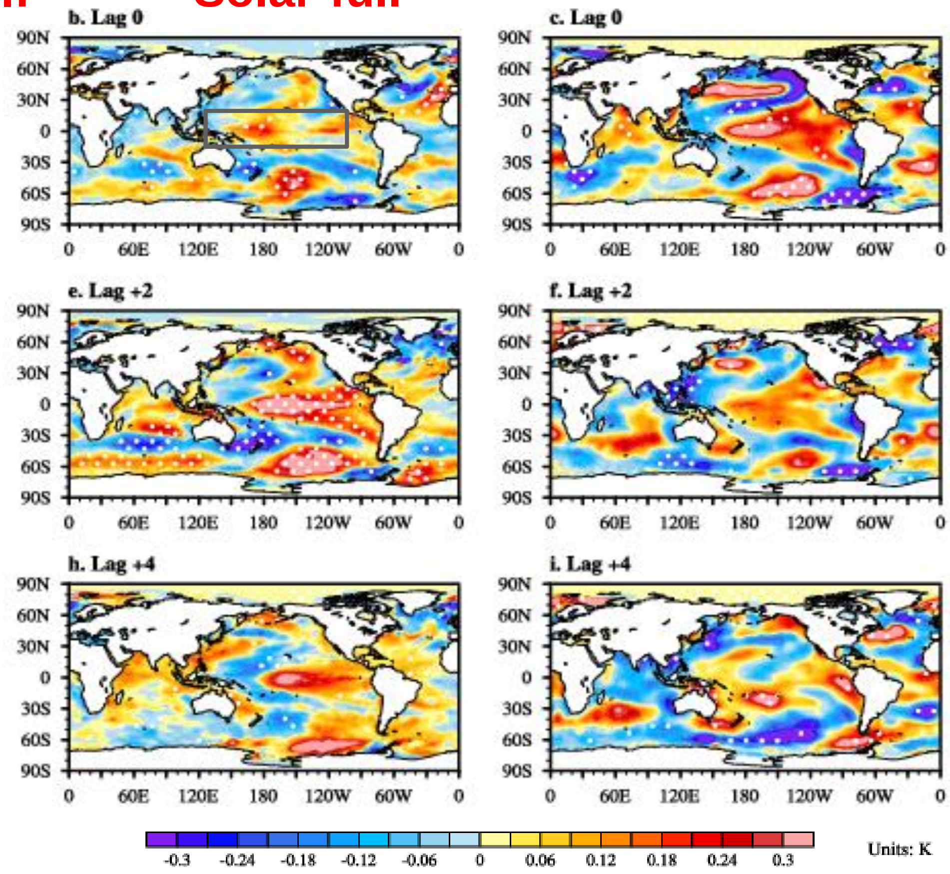
(1931-2014)

FOCI: **Solar-full** **Obs.**

Lag 0

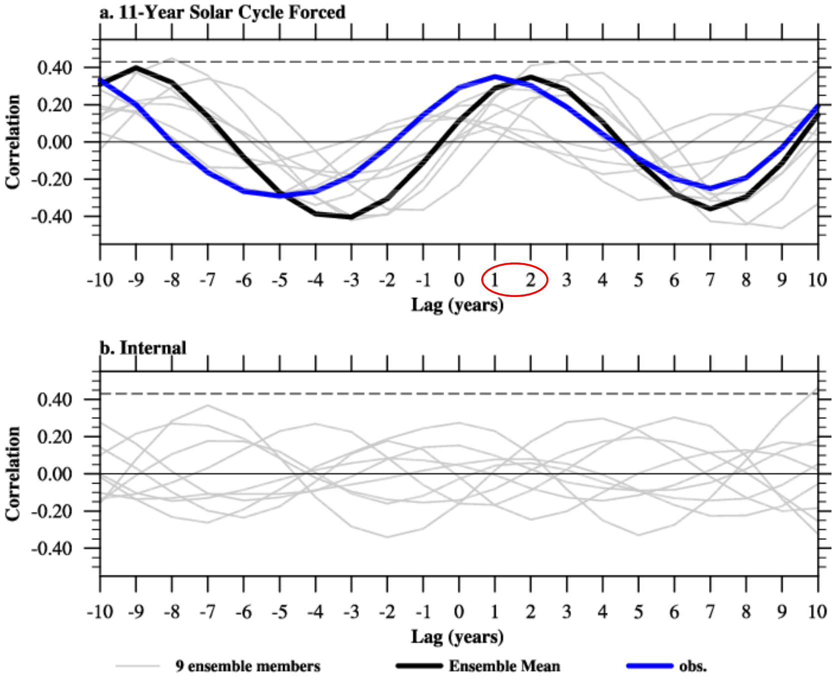
Lag +2

Lag +4

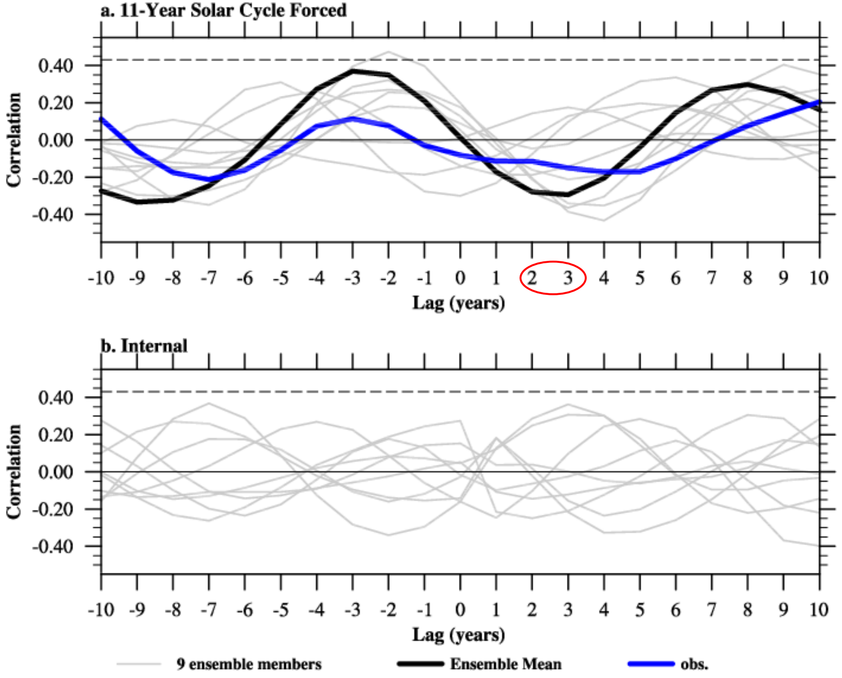


Cross cor: EMI_DJF / F10.7_DJF

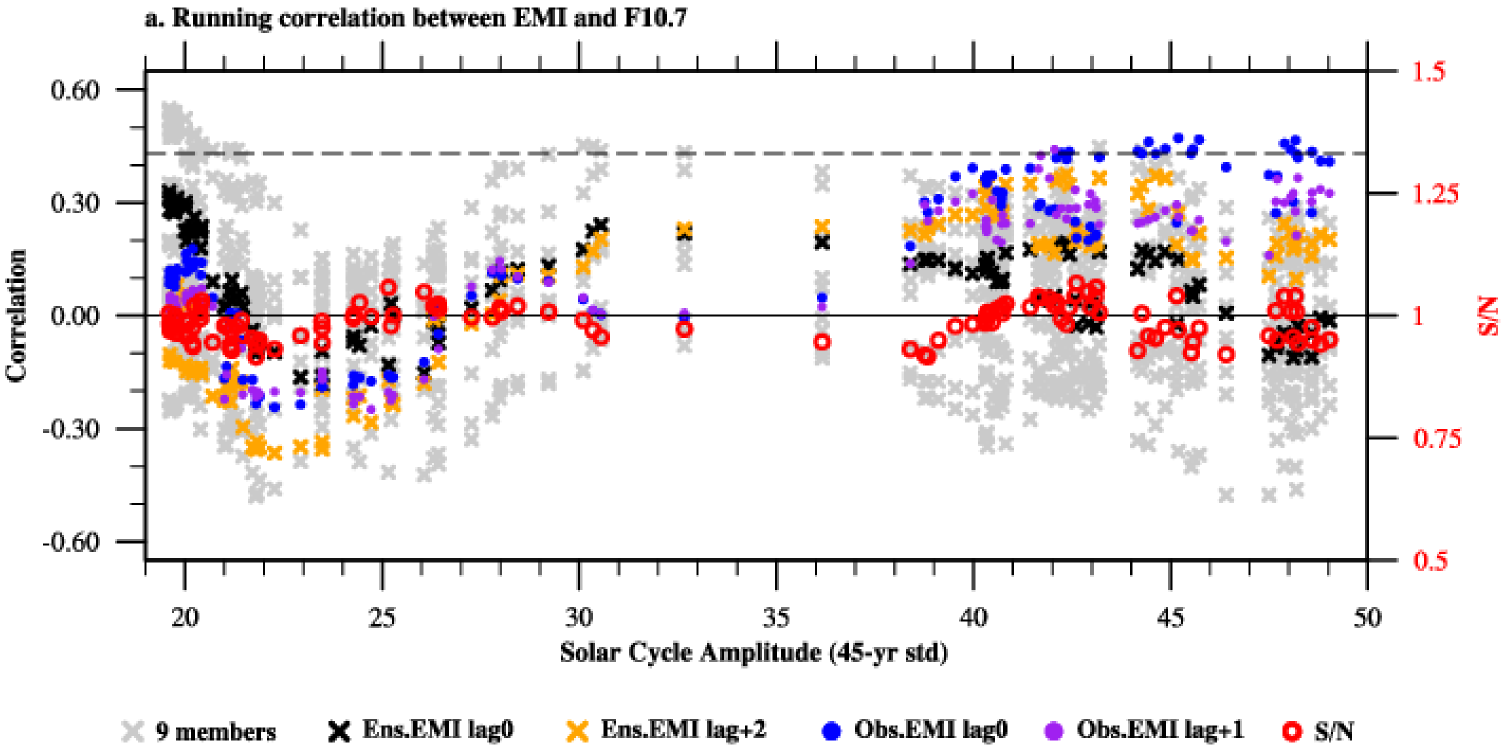
Strong epoch



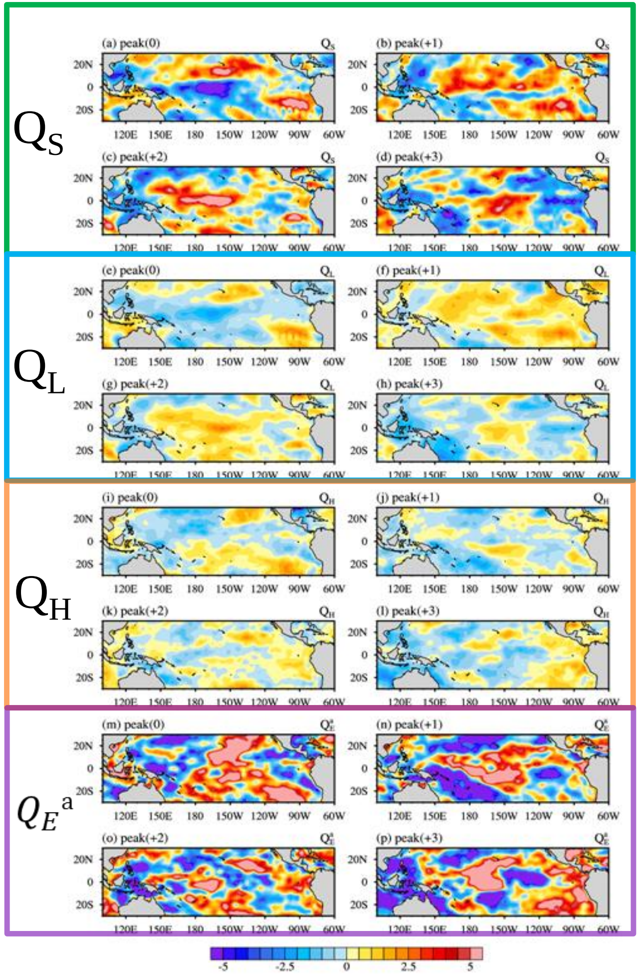
Weak epoch



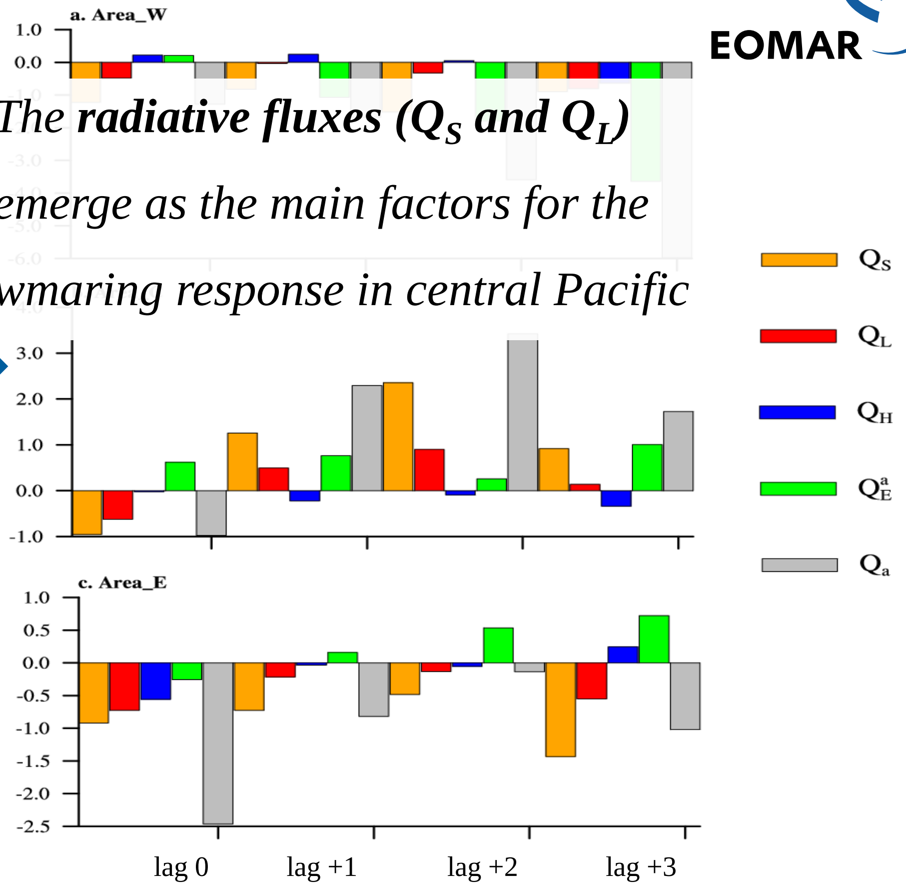
Running cor: TSI / EMI_DJF



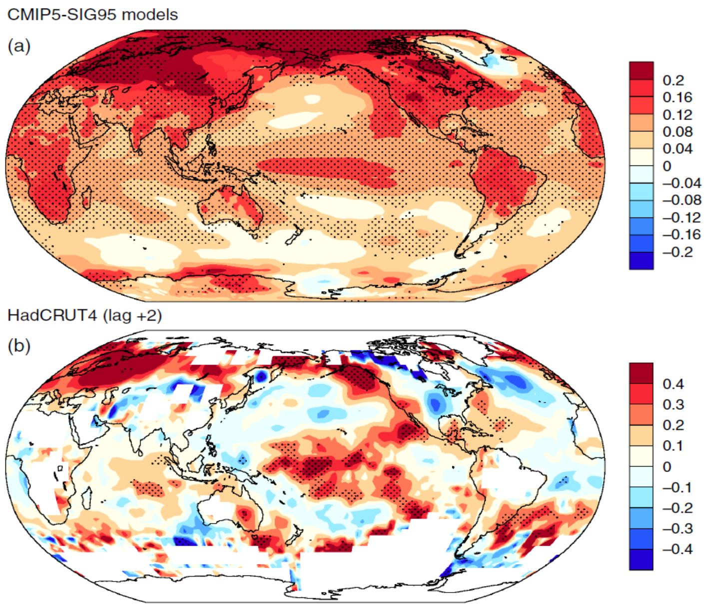
Obs.

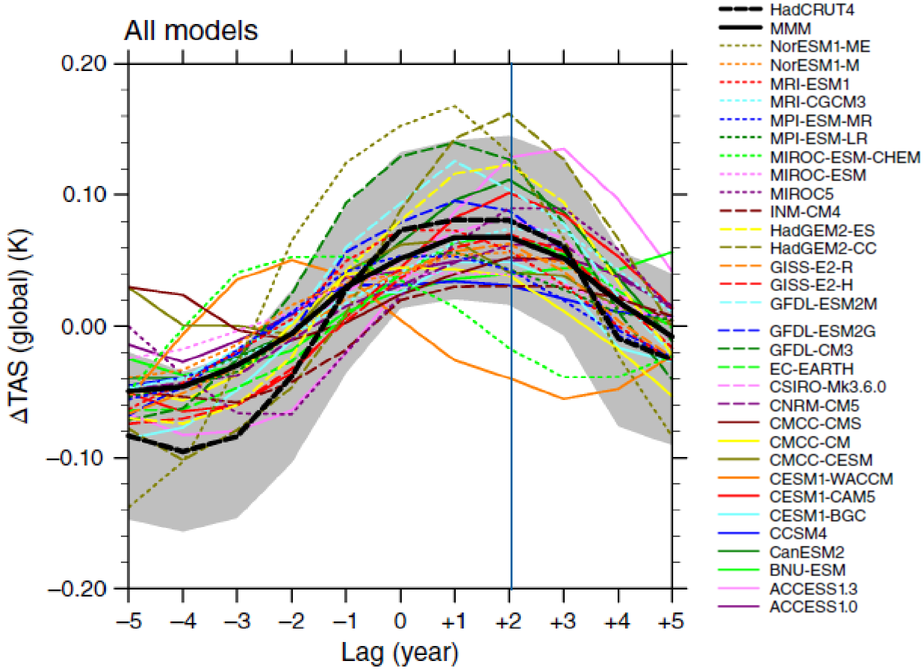


*The **radiative fluxes (Q_S and Q_L)** emerge as the main factors for the wmaring response in central Pacific*



Background



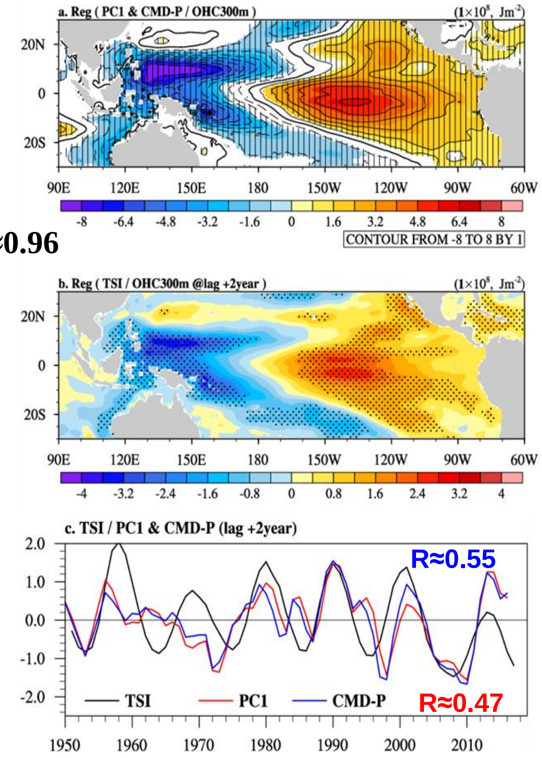


(Misios et al, 2015)

Results: Phase-locking Decadal Covariations

OBS

R≈0.96



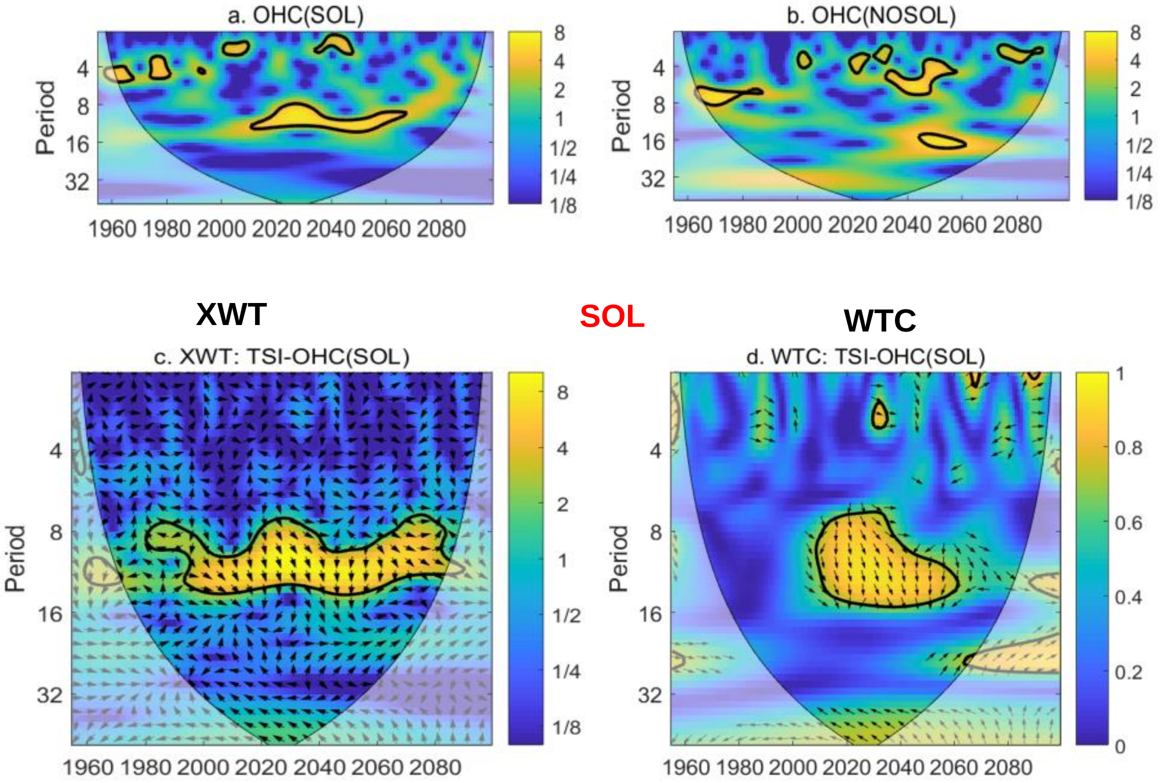
SOL

NOSOL

XWT

SOL

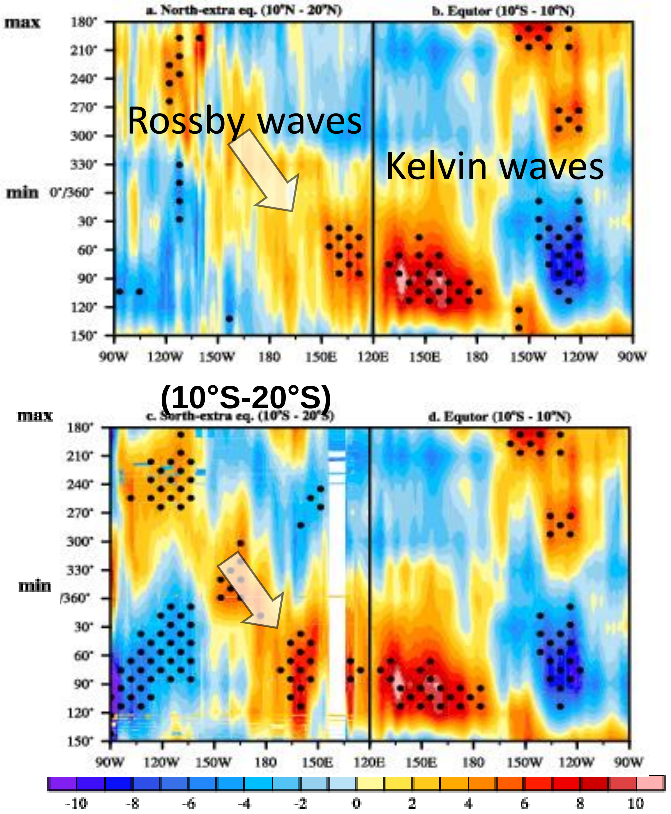
WTC



Mechanisms: Contribution of oceanic processes

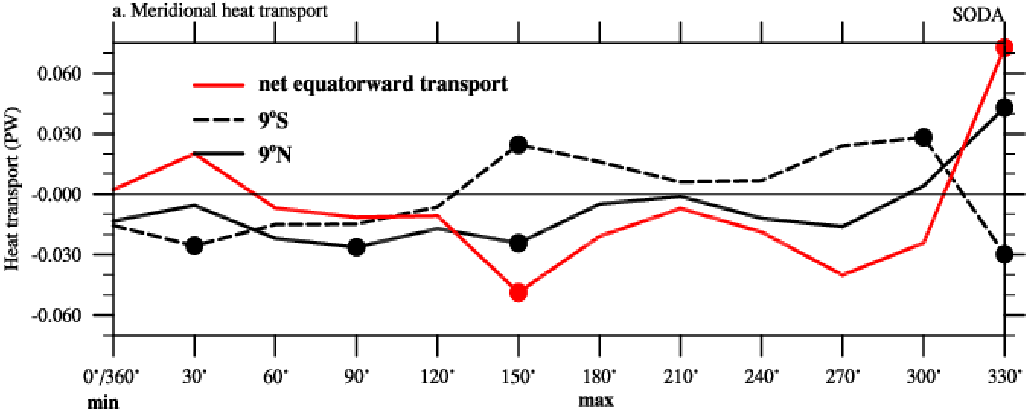
GEOMAR

OBS **(10°N-20°N)** **depth of 20℃ isotherm**



Meridional heat transport by the Pacific STCs

(Unit: PW, 1PW=10^{15}W)



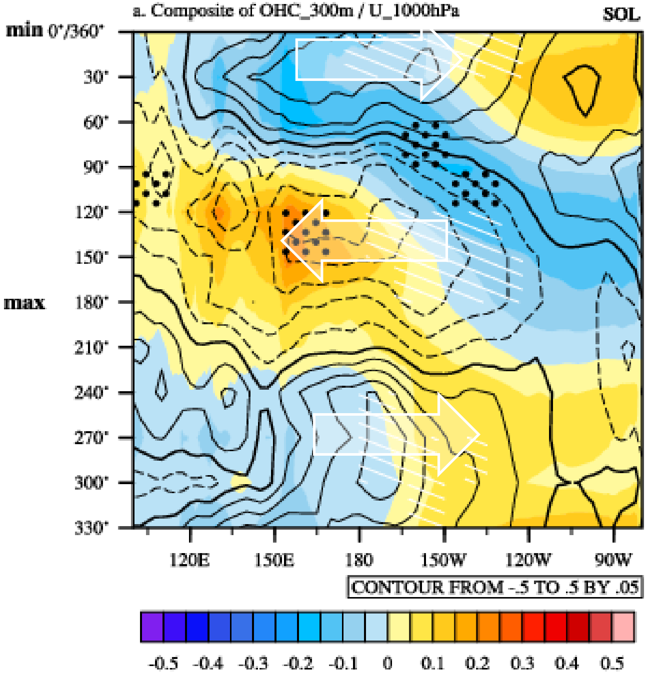
Lagged negative feedbacks

→ TPDV phase transition

Result 3: Phase-locked Decadal Covariations

SOL

OHCa / U1000hPa



MHT by the Pacific STCs