Decadal variations of tropical Pacific climate & ENSO: Model representation & key questions

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Tropical Pacific
Decadal Variability (TPDV)

CMIP5 models: Diverse PDO SST patterns

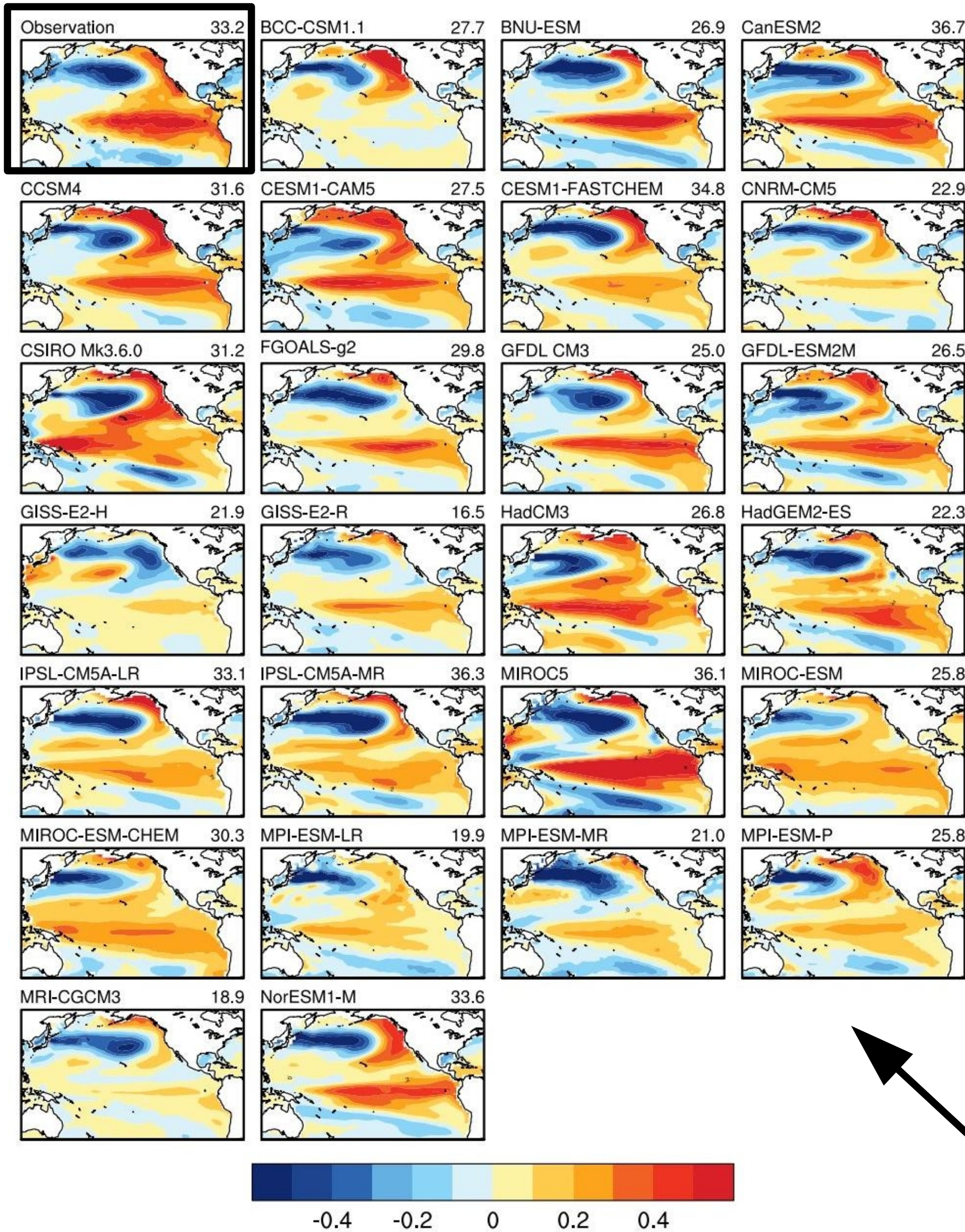


Figure 1. Observed and simulated regression distributions of SST on the PDO index (units: °C).

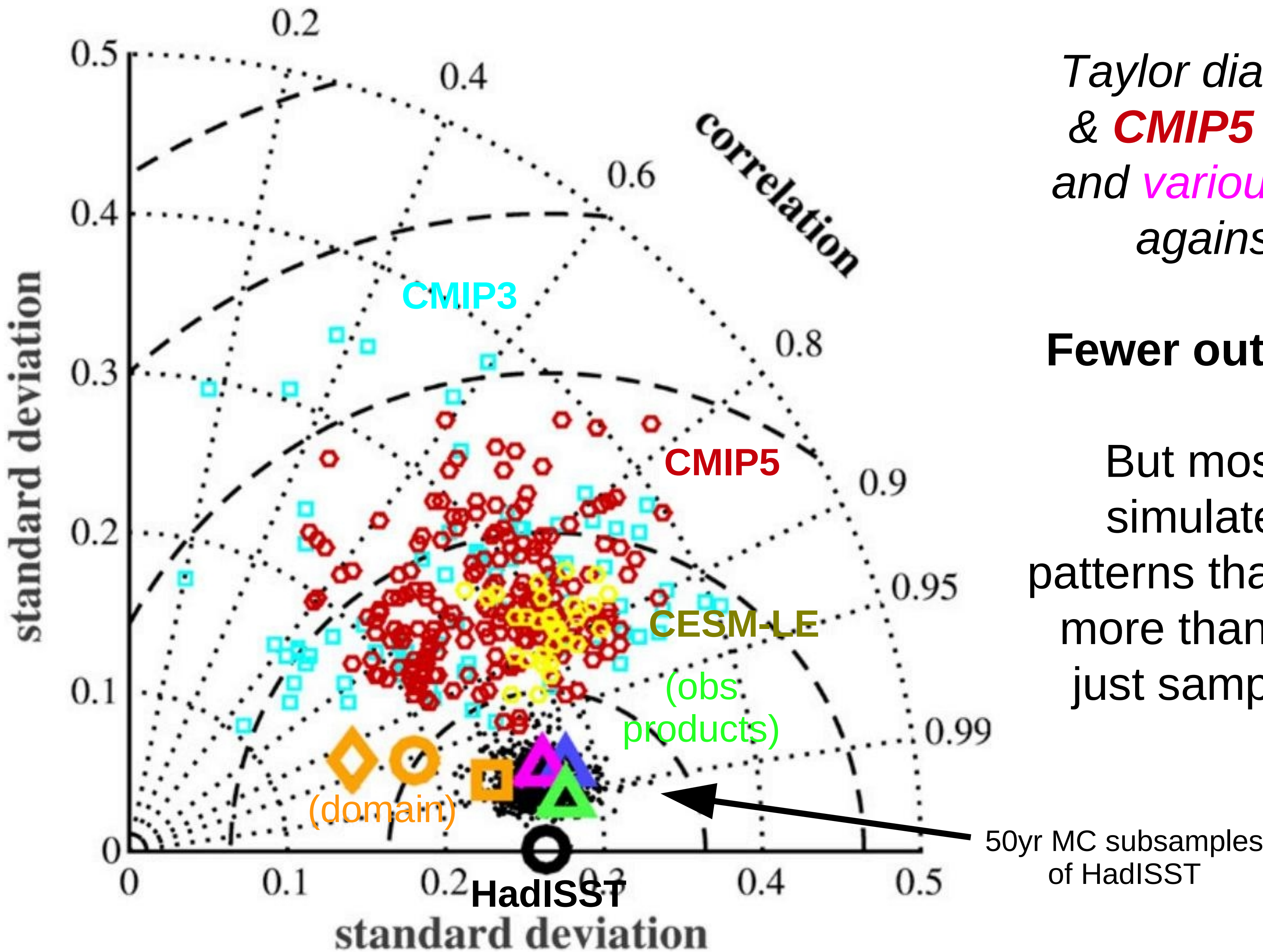
Wang & Miao (AOSL 2018)
see also: Lyu et al. (IJC 2015)

Most models capture something like the observed pattern in the tropical & southern Pacific.

But the overall **amplitude**, and **tropical-extratropical connections**, differ among models.

SST regressed on 9yr running mean of PC1 of non-GW NPac (20N:70N) SST.

Simulated PDO SST patterns have improved



Taylor diagram of ***CMIP3*** *&* ***CMIP5*** *historical runs, and various obs products, against HadISST.*

Fewer outliers in CMIP5.

But most models still simulate SST spatial patterns that differ from obs, more than expected from just sampling variability.

Newman et al. (JC 2016)
see also: Lyu et al. (IJC 2015)

PDO: SST regressed on PC1 of non-GW NPac SST (20N:70N).

Simulated IPO SST patterns have improved

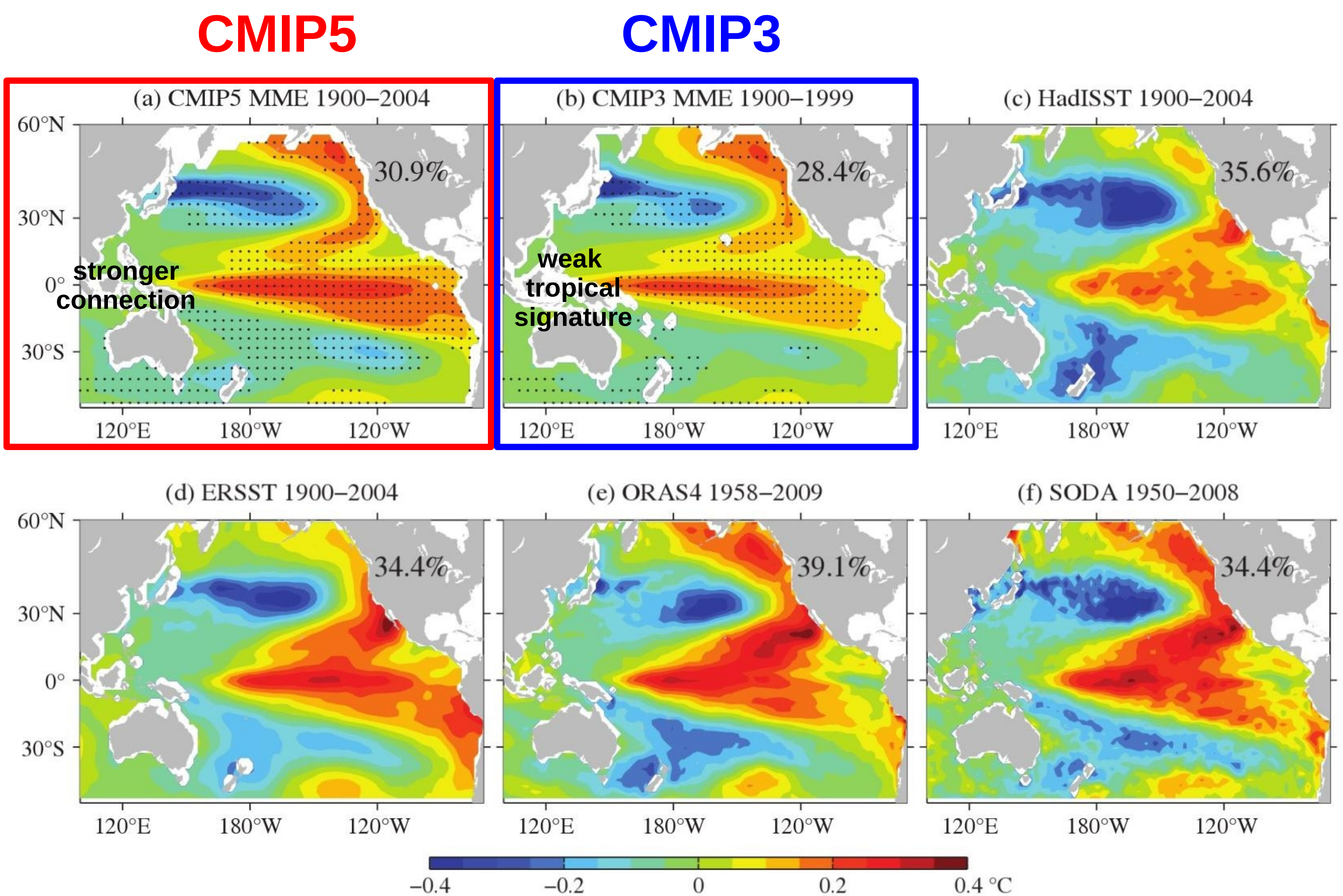


Figure 1. Interdecadal SST patterns (°C) from different products, obtained by applying the EOF analysis to the low-pass filtered SST anomalies in the Pacific. The percentage in each panel represents the percentage of variance explained by the IPO-like mode. In (a) and (b), the multi-model ensemble (MME) mean patterns and percentages are shown for CMIP5 and CMIP3, respectively. Stippling indicates where the amplitude of the MME mean is larger than the inter-model standard deviation and thus models tend to agree with each other.

Lyu et al. (IJC 2015)

IPO SSH patterns remain a challenge to simulate

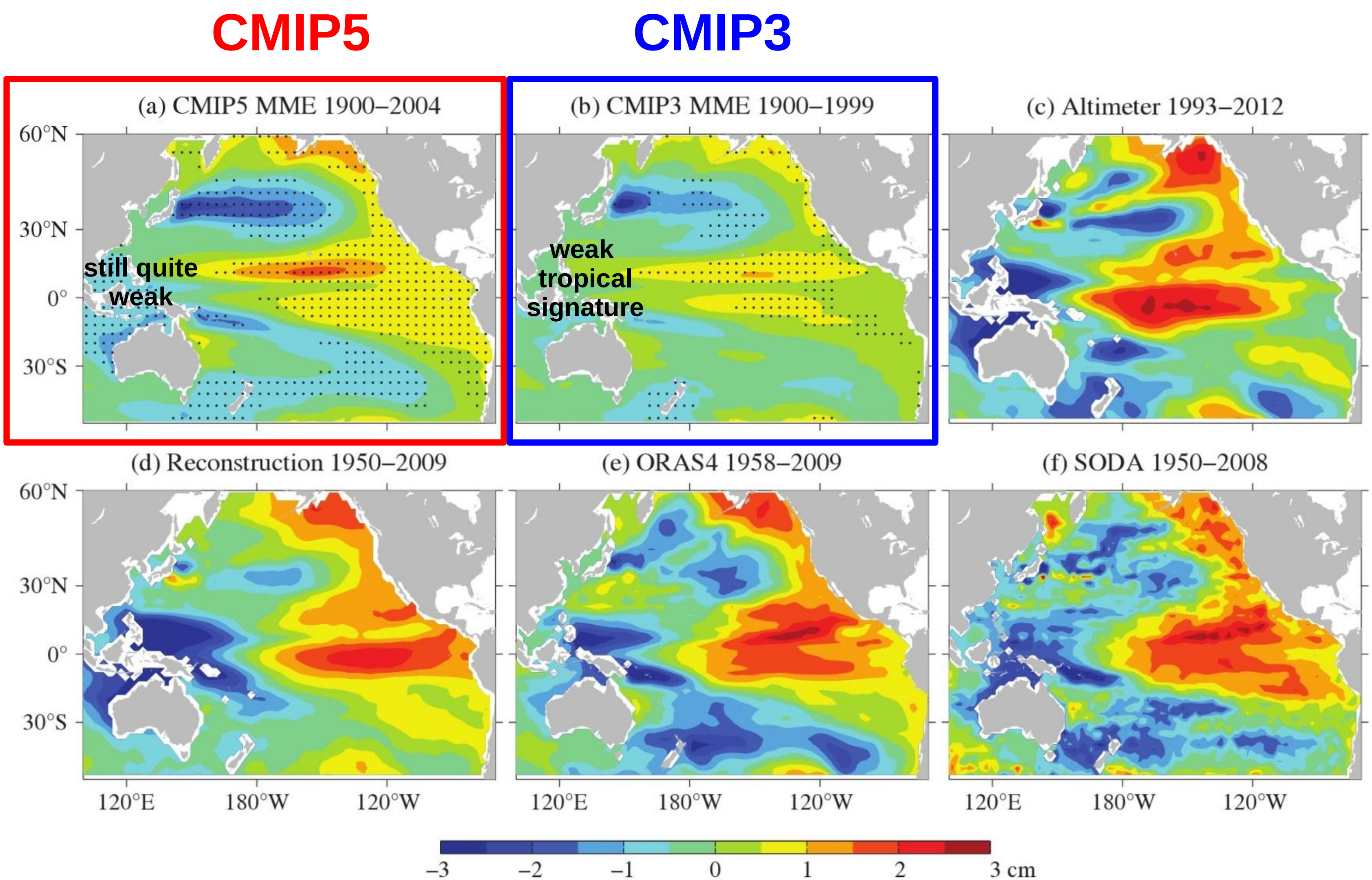


Figure 4. Interdecadal sea level patterns (cm) from different products, obtained by regressing sea level data onto the IPO index. In (a) and (b), the multi-model ensemble (MME) mean patterns are shown for CMIP5 and CMIP3, respectively. Stippling indicates where the amplitude of the MME mean is larger than the inter-model standard deviation and thus models tend to agree with each other.

Lyu et al. (IJC 2015)

TPDV SLP/wind pattern biases → SSH pattern biases

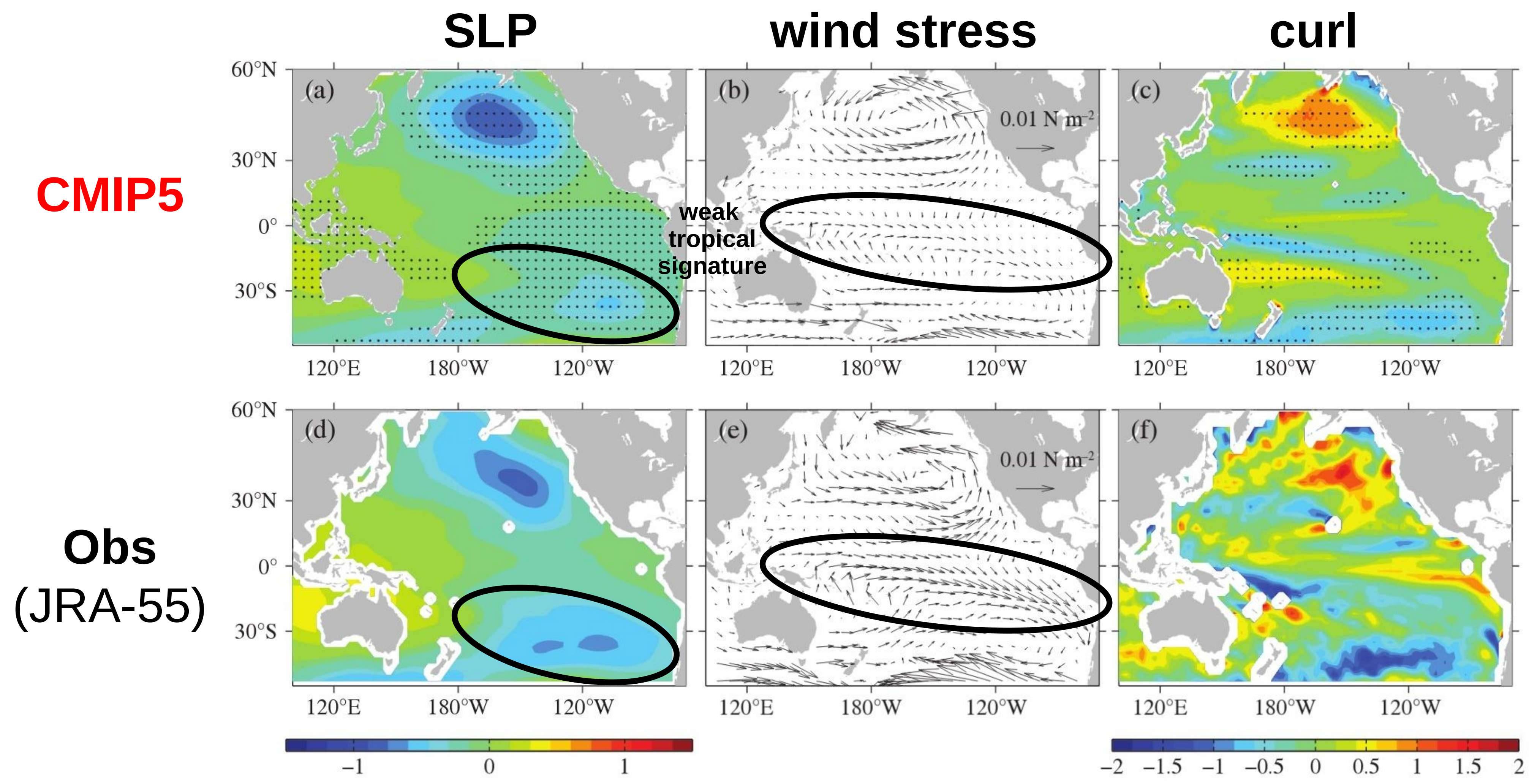


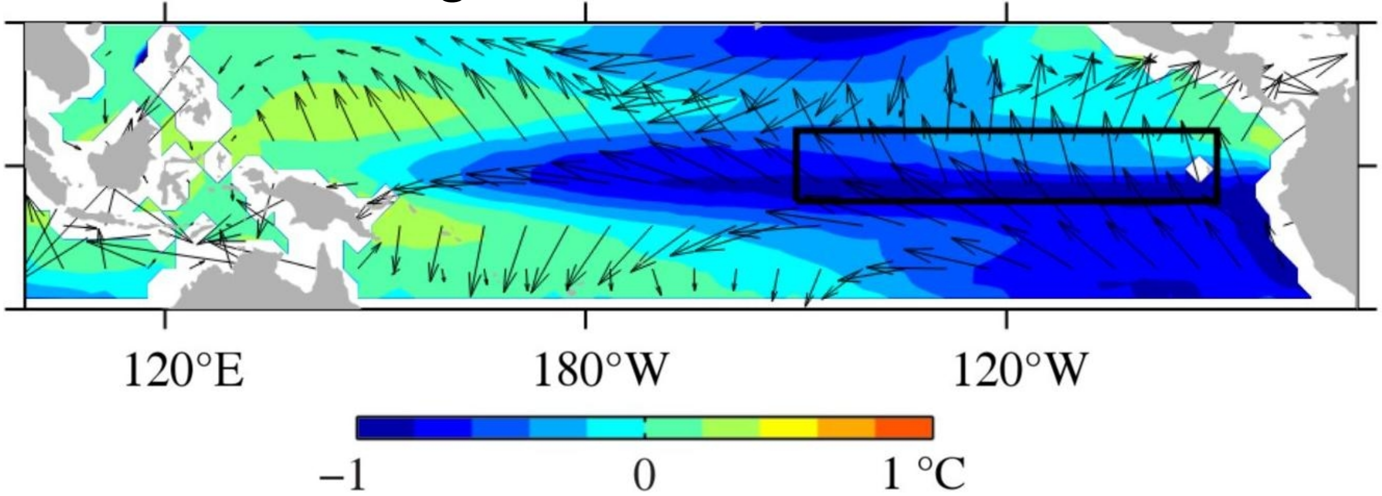
Figure 8. The CMIP5 multi-model ensemble (MME) mean of interdecadal variability patterns for (a) sea level pressure (hPa), (b) wind stress (N m^{-2}) and (c) wind stress curl (10^{-8} N m^{-3}), derived from the average of regressed patterns onto the IPO index in individual models. In (a) and (c), stippling indicates where the amplitude of the MME mean is larger than the inter-model standard deviation. (d–f) Regression patterns using the atmospheric reanalysis data from JRA-55 and the IPO index calculated from HadISST.

Lyu et al. (IJC 2015)

CMIP5: Tropical IPO SSTA pattern is linked to mean state

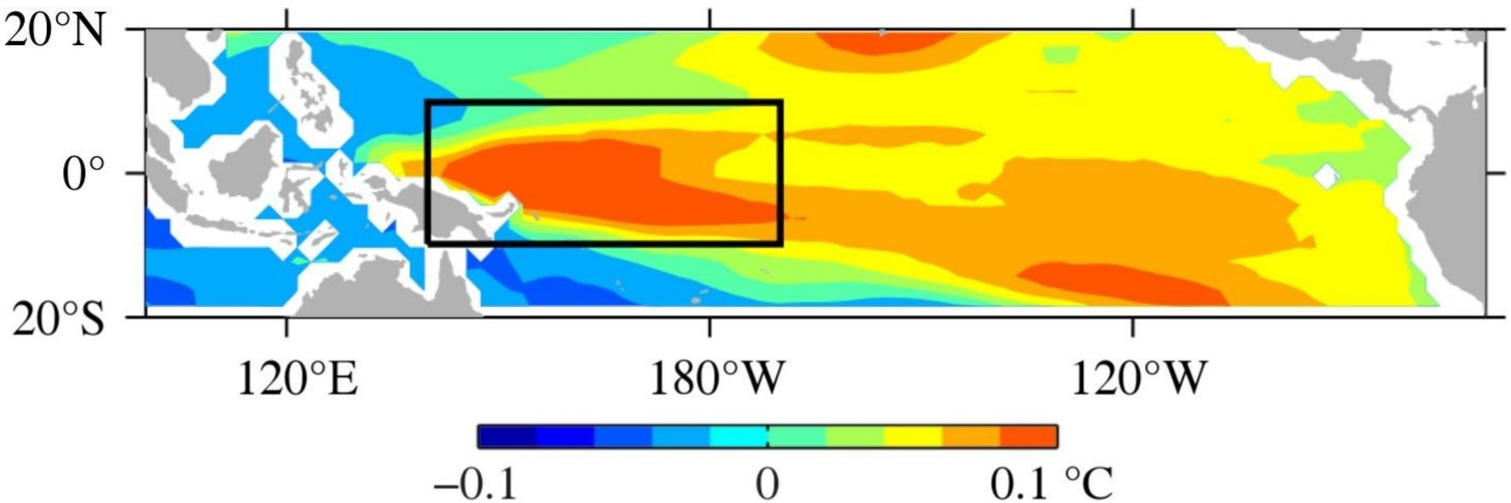
Leading SVD mode of intermodel covariance between **background mean** and **IPO anomaly** SST patterns.

Climatological SST & wind difference



Models with **colder mean ECTs** simulate tropical IPO SSTAs that are **farther westward & poleward**.

IPO SSTA pattern difference



Lyu et al. (IJC 2015)

IPO = PC1 of 7yr-LPF detrended SST (100°E-70°W, 50°S-60°N)

Intrinsic Decadal Modulation of ENSO

Epochs of extreme ENSO behavior

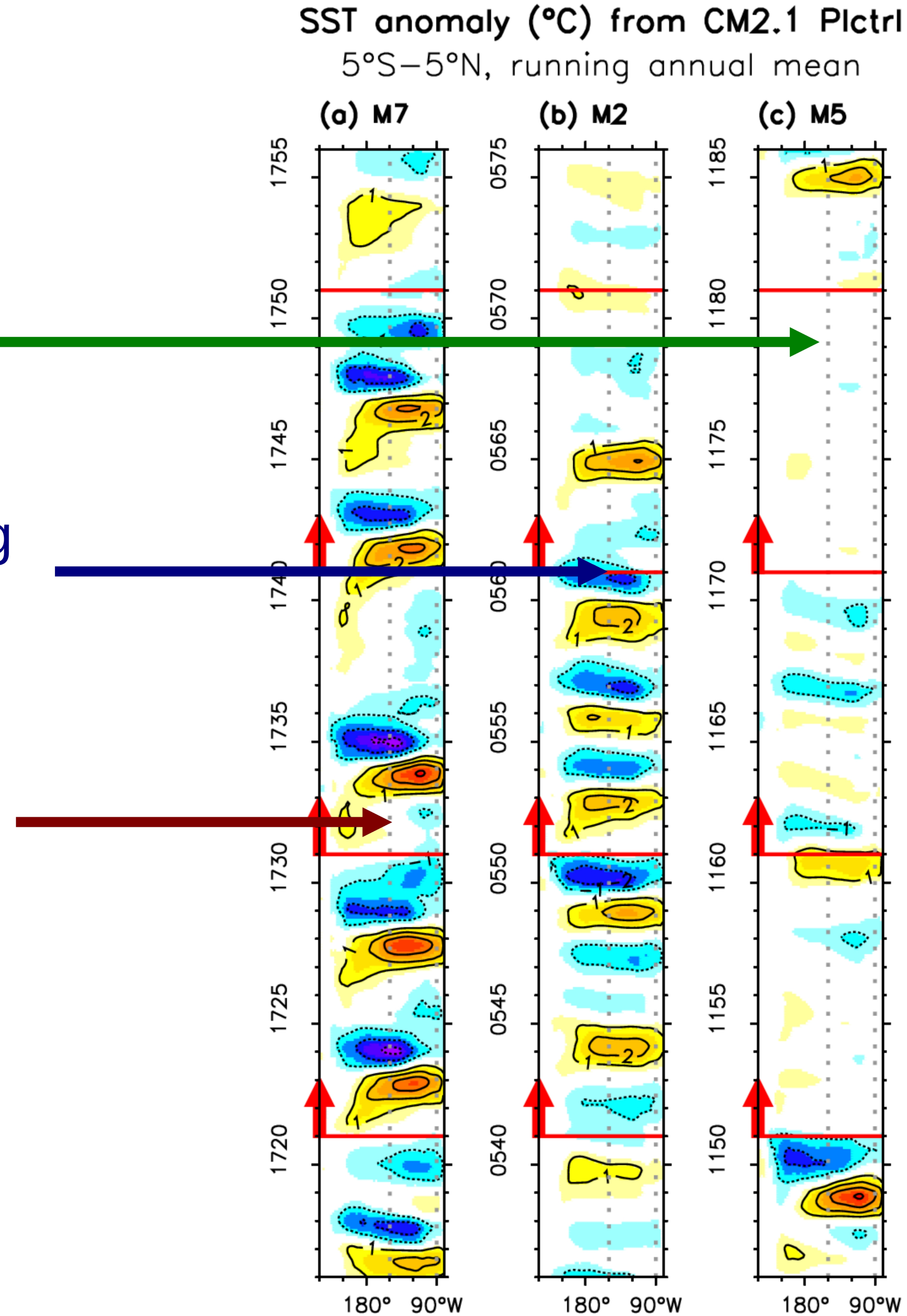
weak, biennial, "Modoki"
(early 1990s & 2000s)

regular, westward propagating
(1960s & 70s)

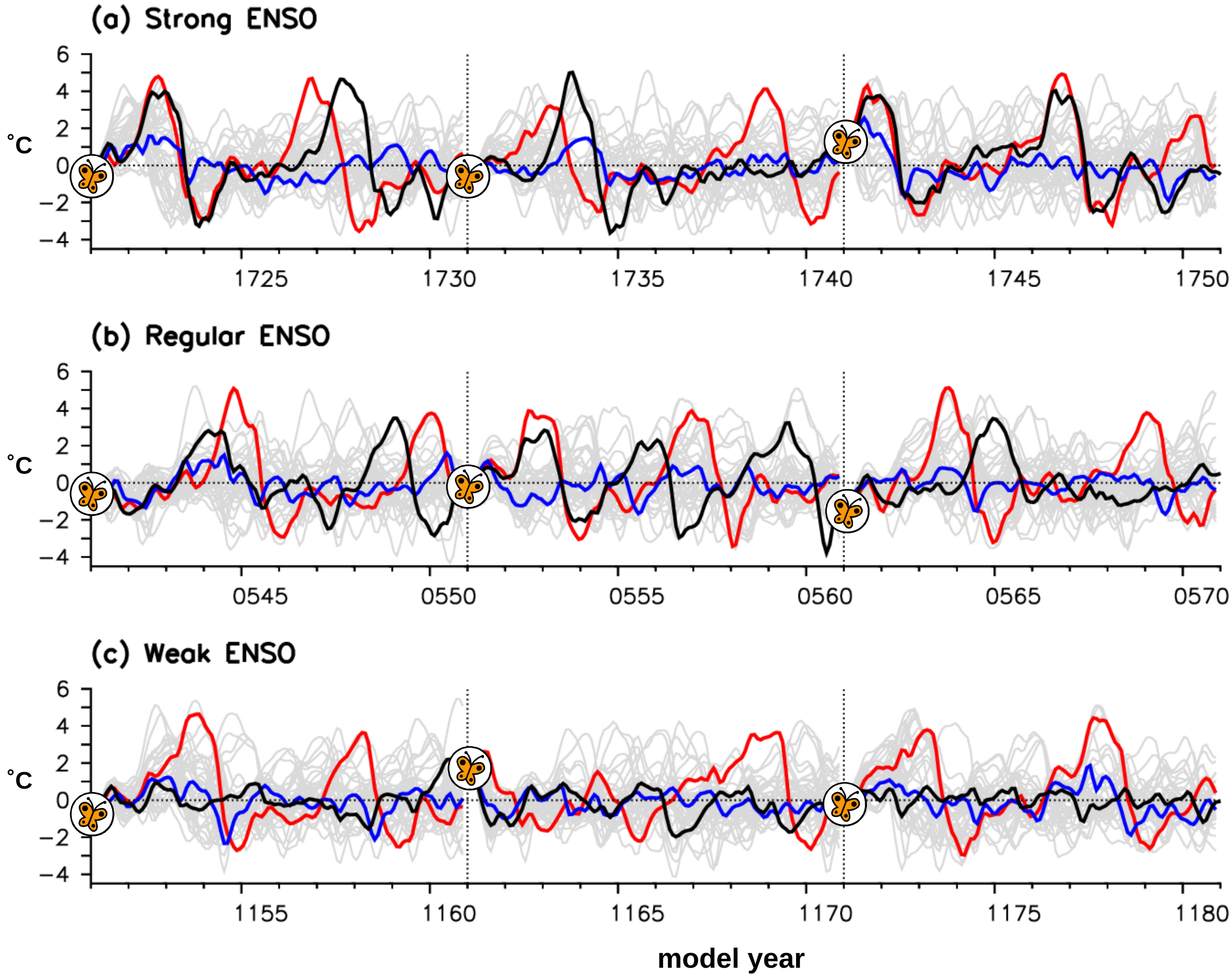
strong, skewed, long period, eastward propagating
(1980s & late 1990s)

All from a simulation with **unchanging** forcings.

Wittenberg et al. (J. Climate, 2014)



ENSO modulation: Is it decadally predictable?



NINO3 SSTA, for extreme-ENSO epochs simulated by CM2.1

External forcings **held fixed** at 1860 values.

Add a tiny perturbation...

"Perfect-model" reforecasts:

weakest,

strongest,

all 40 members

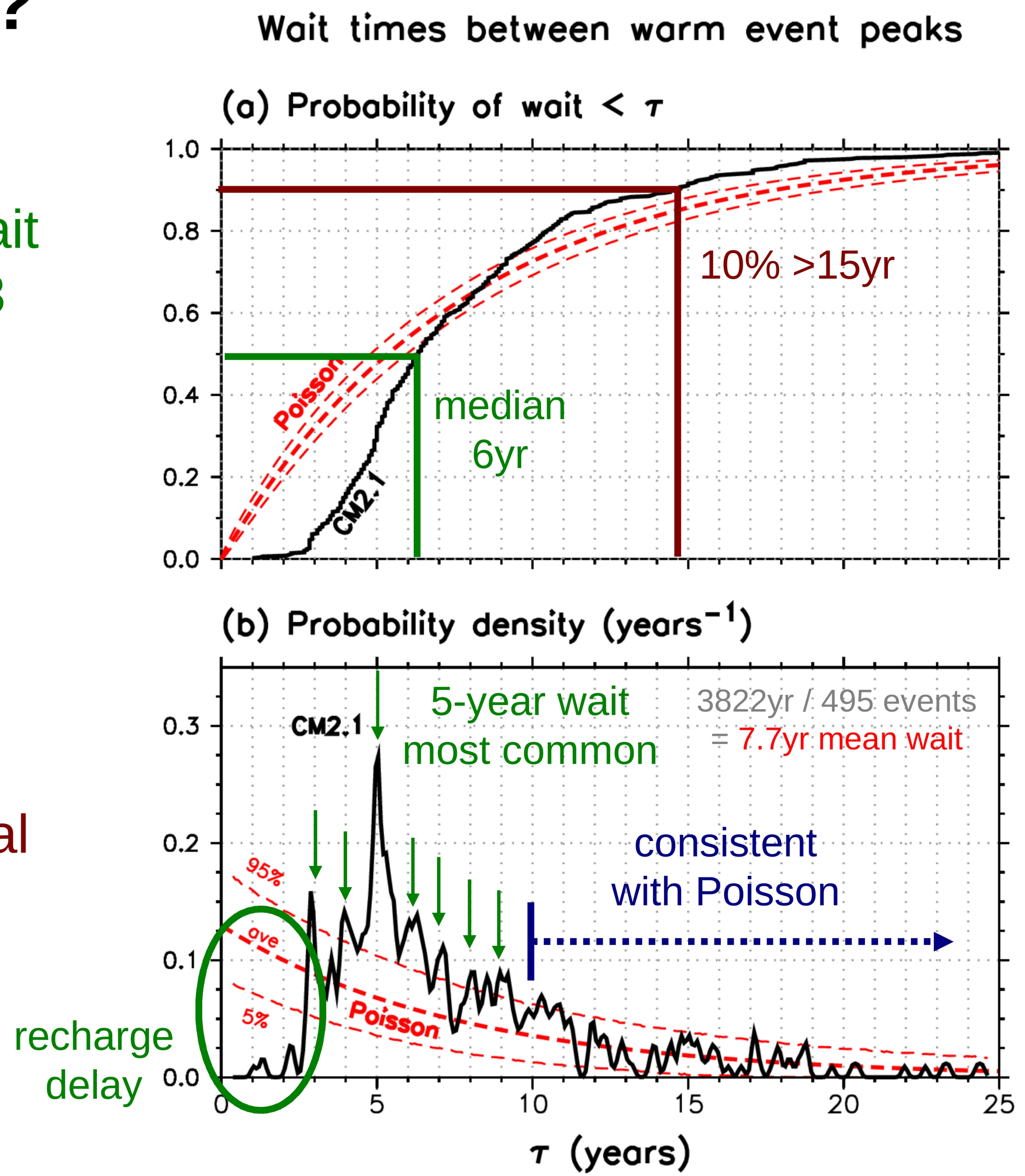
Wittenberg et al. (J. Climate, 2014)

Long-term memory?

Distribution of inter-event wait times suggests that NINO3 SSTA *might* have some memory beyond 5 years.

But beyond 10 years?

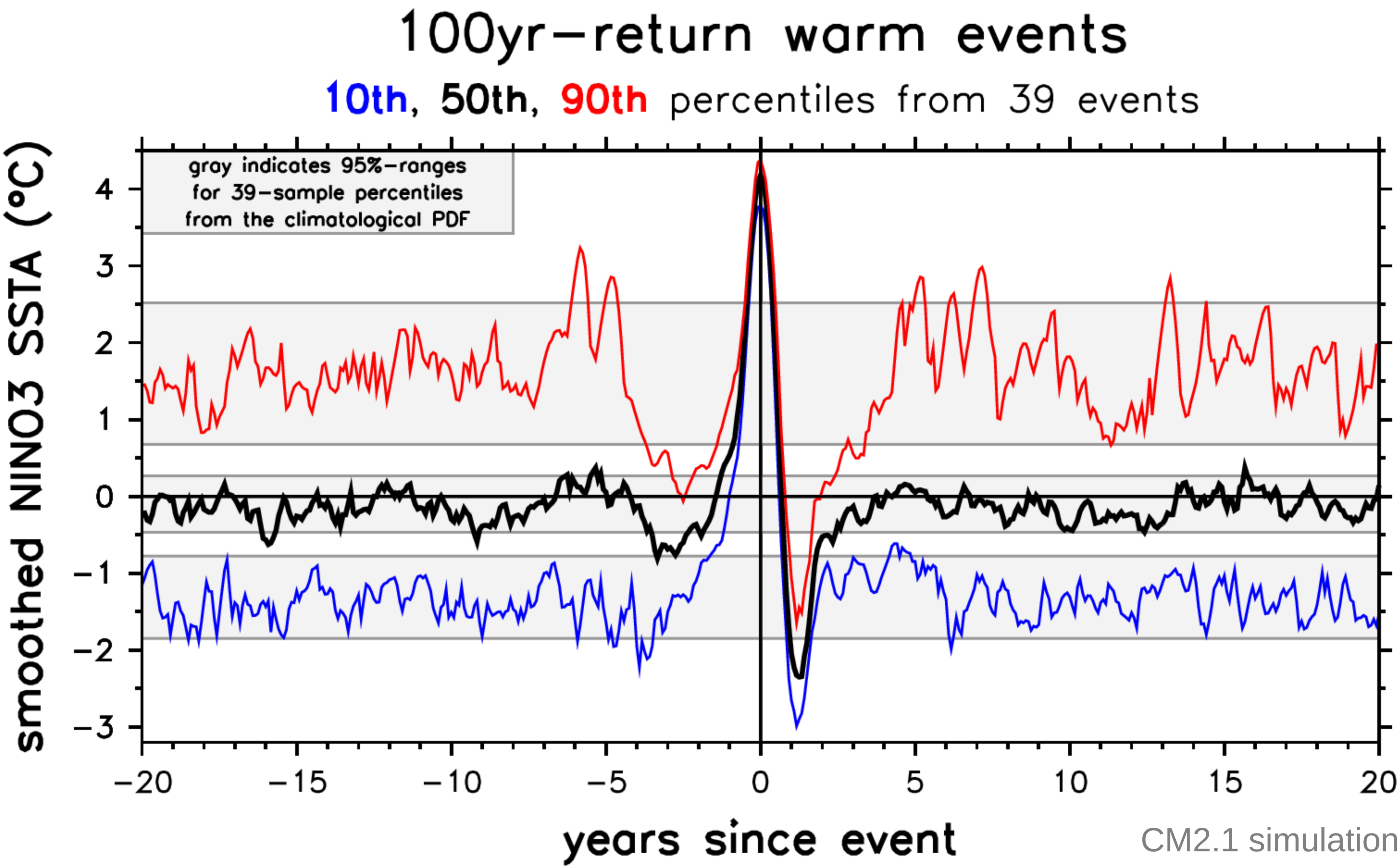
Even a *purely* memoryless ENSO would give occasional waits of 20 years or more, as seen in CM2.1.



Wittenberg (GRL 2009)

Best hope for long-term ENSO predictability?

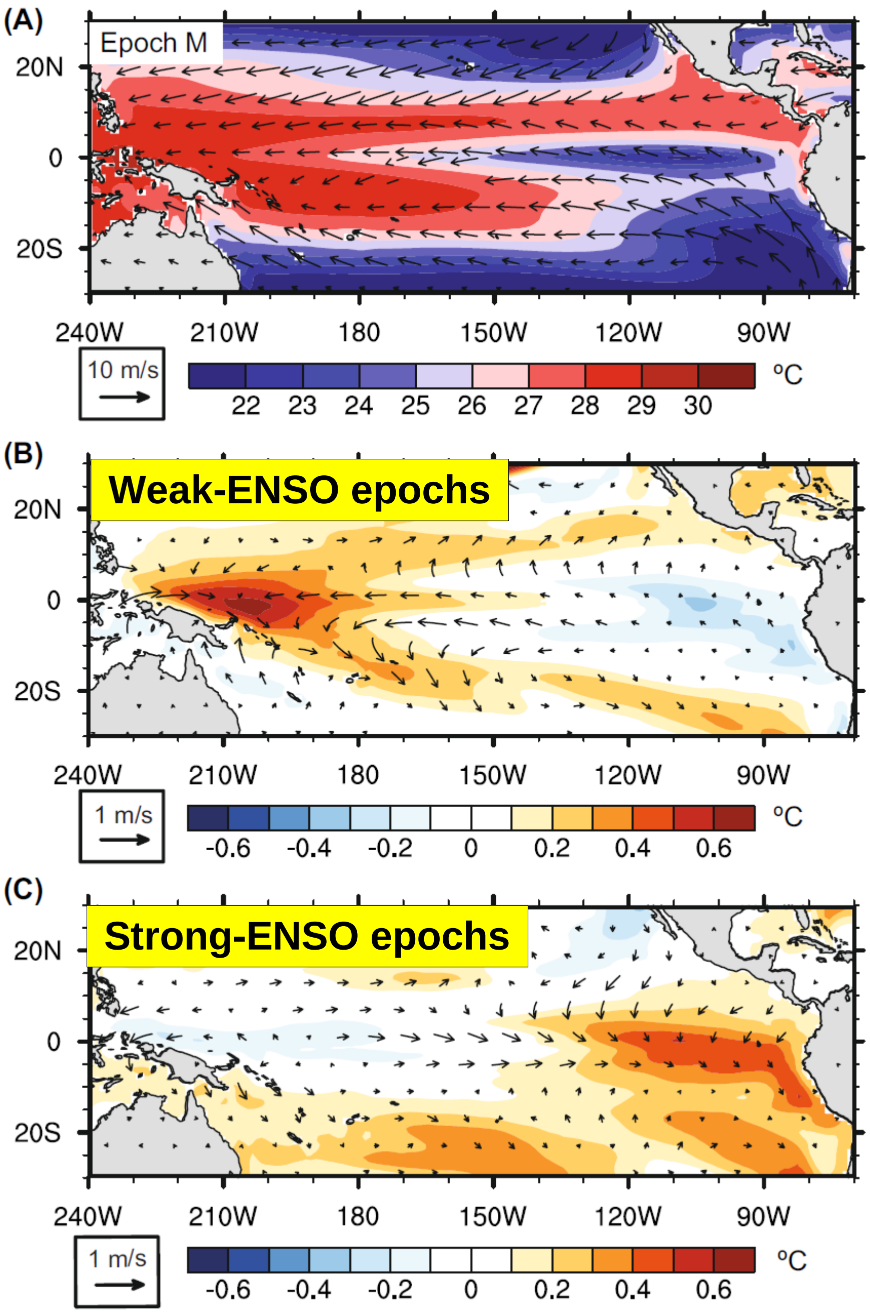
NINO3 memory might last 5yr, following strong warm events.



CM2.1 simulation

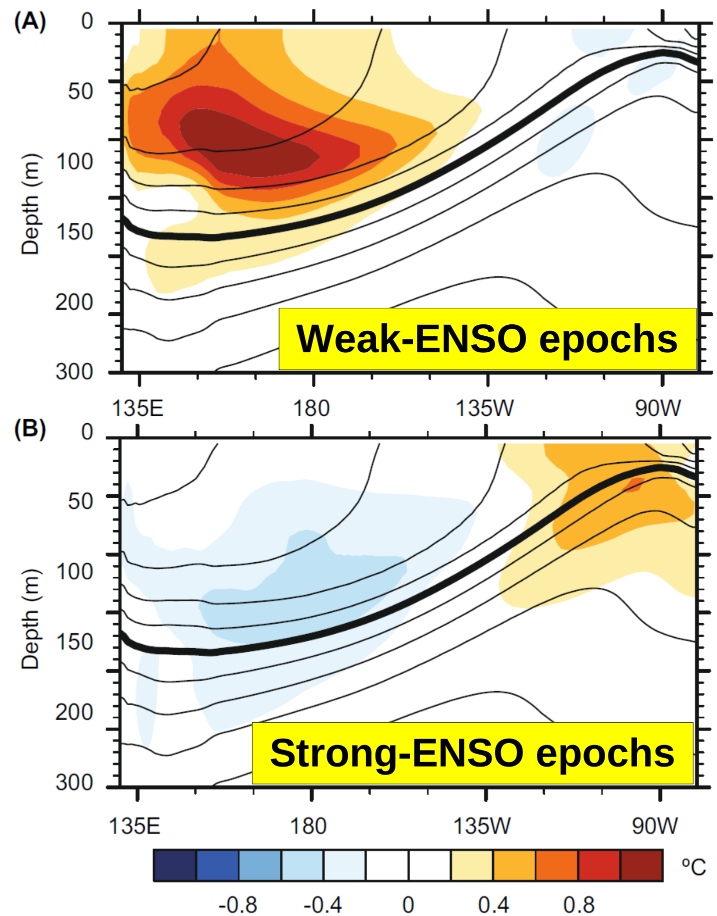
ENSO/Decadal interactions

ENSO's decadal-mean residual



Atwood et al. (Climate Dyn., 2017)

also Ogata et al. (2013), Schopf & Burgman (2006), Burgman et al. (2008)



SST patterns of ENSO and TPDV (CMIP3 models)

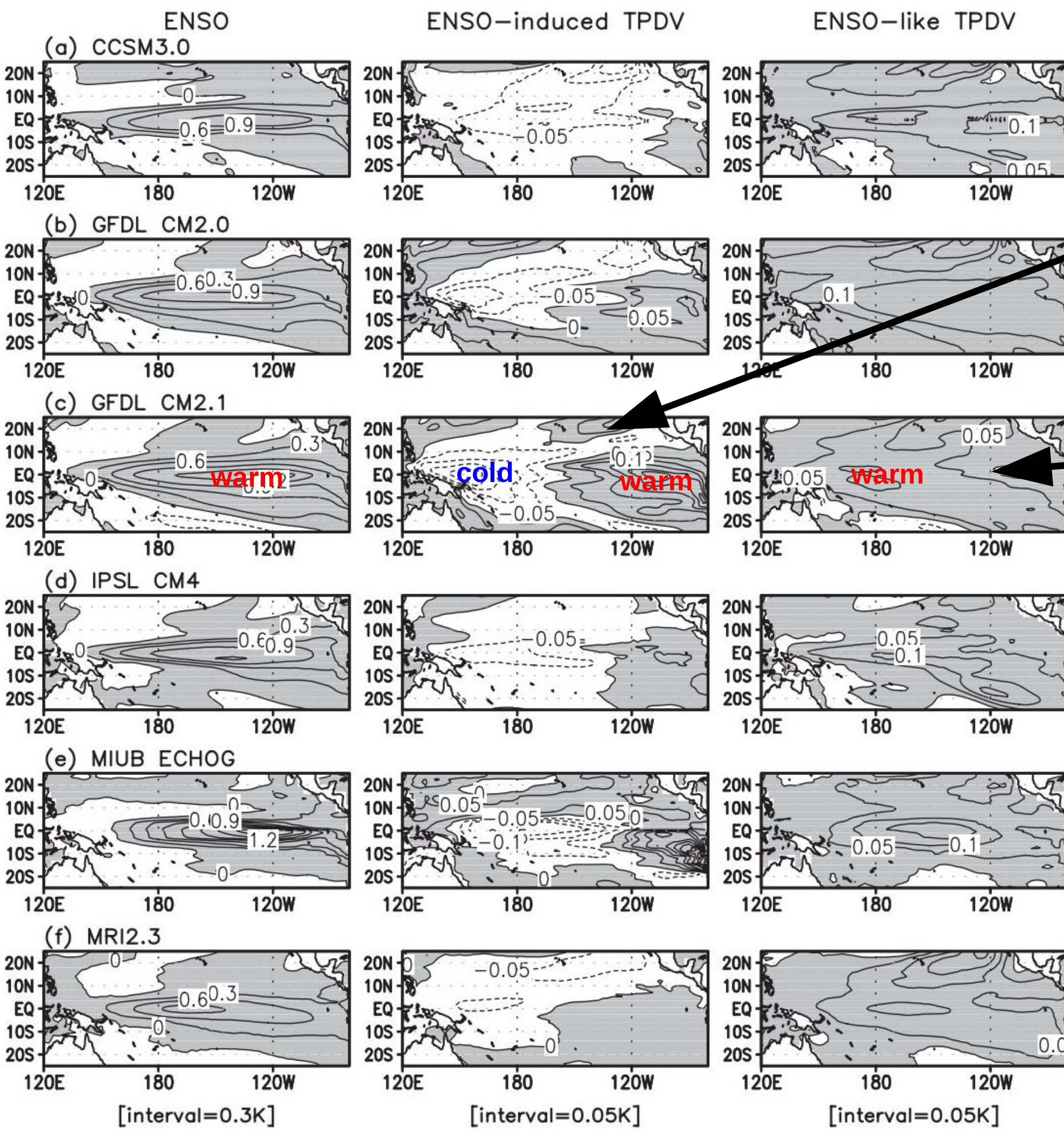


FIG. 3. Regressed map of SST associated with the EOF PC time series of ENSO, ENSO-induced TPDV, and ENSO-like TPDV modes (K).

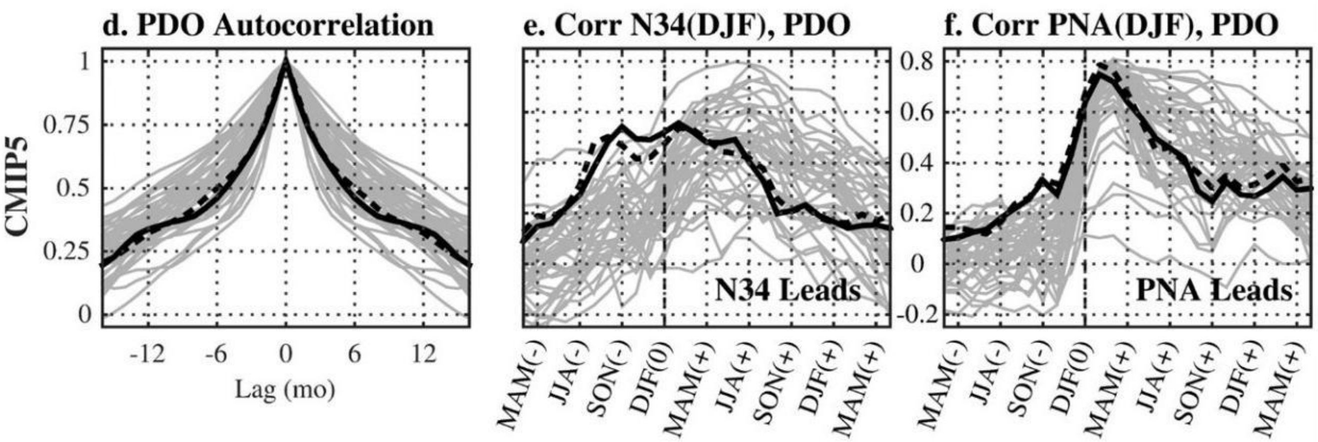
Active-ENSO epochs + ENSO asymmetry → **decadal ENSO residual** is cold west & warm east.

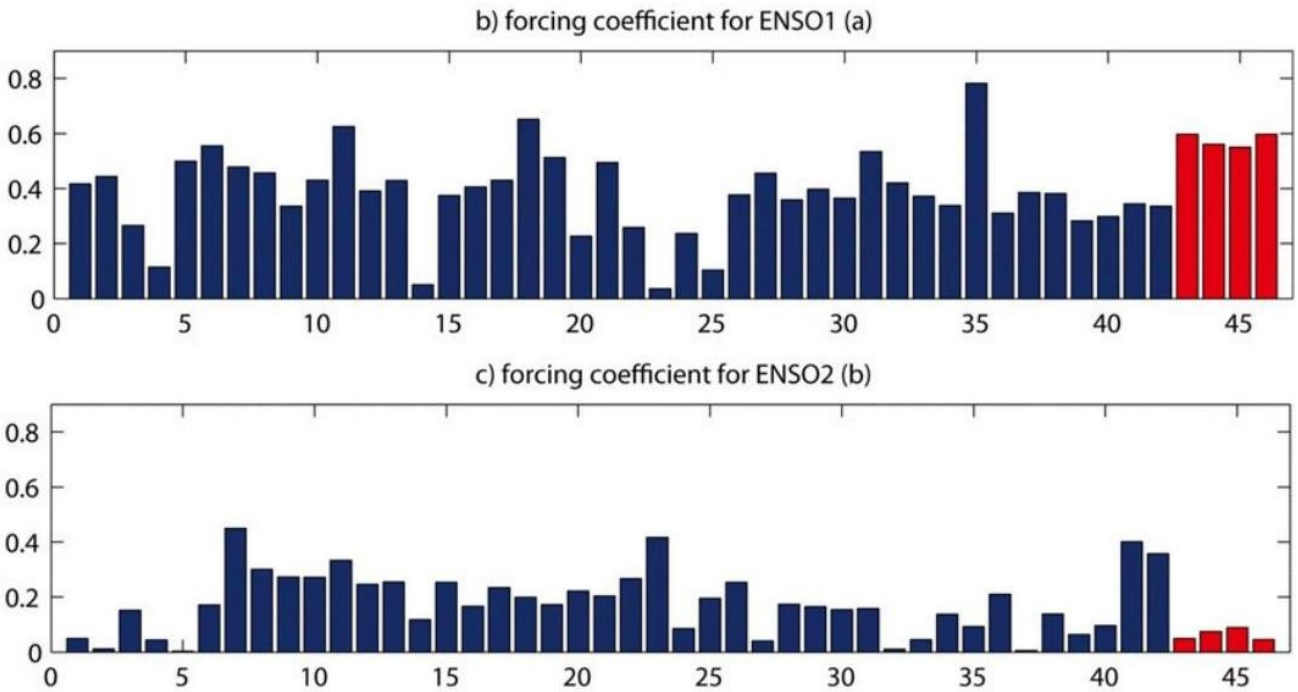
Distinct from decadal **recharge/discharge mode** that is uncorrelated with ENSO modulation. (But similar spectral peaks.)

Models with **stronger ENSOs** show more **ENSO diversity & skewness**, and more **ENSO-induced TPDV**.

Choi et al. (JC 2013)

PDO persistence and ENSO/PNA relationships





Newman et al. (JC 2016)

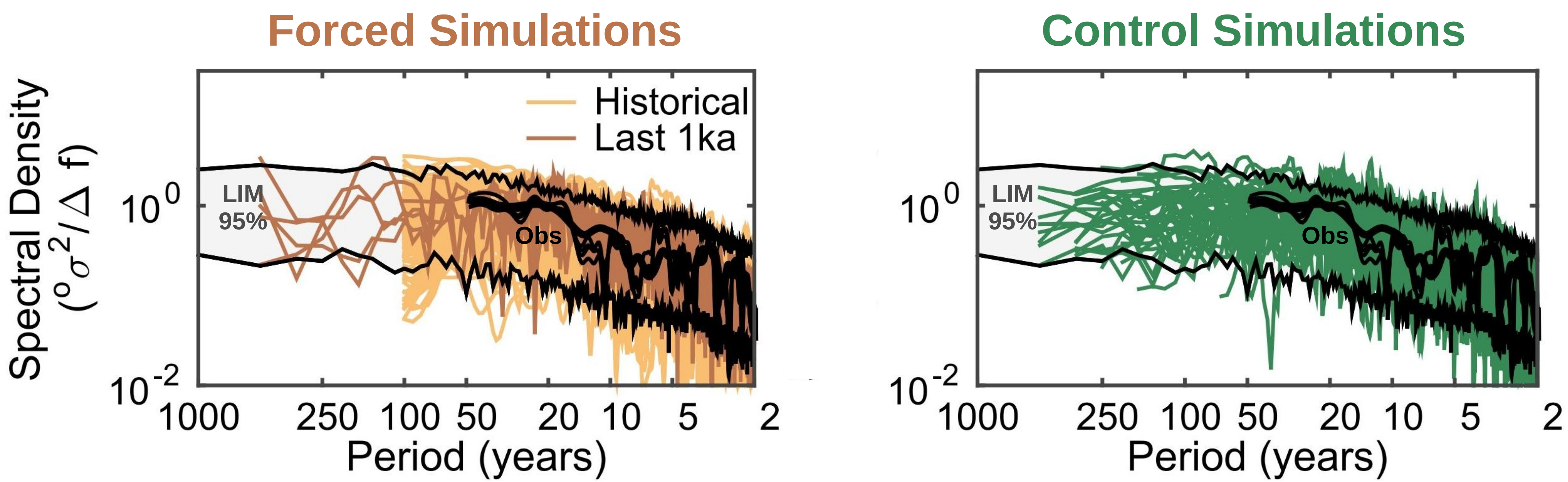
CMIP5 PDOs remain **too persistent**.

PDO lags ENSO too much. Links to NINO3.4 & PNA are too weak in DJF, too strong in JJASON.

Obs PDO is forced mainly by ENSO PC1.

CMIP5 PDOs are additionally forced by ENSO PC2, due to displaced teleconnection patterns.

CMIP5 PDO spectra



Obs 95% confidence intervals are from 140 different 1750-yr runs of a LIM fit to HadISST (1901-2014).

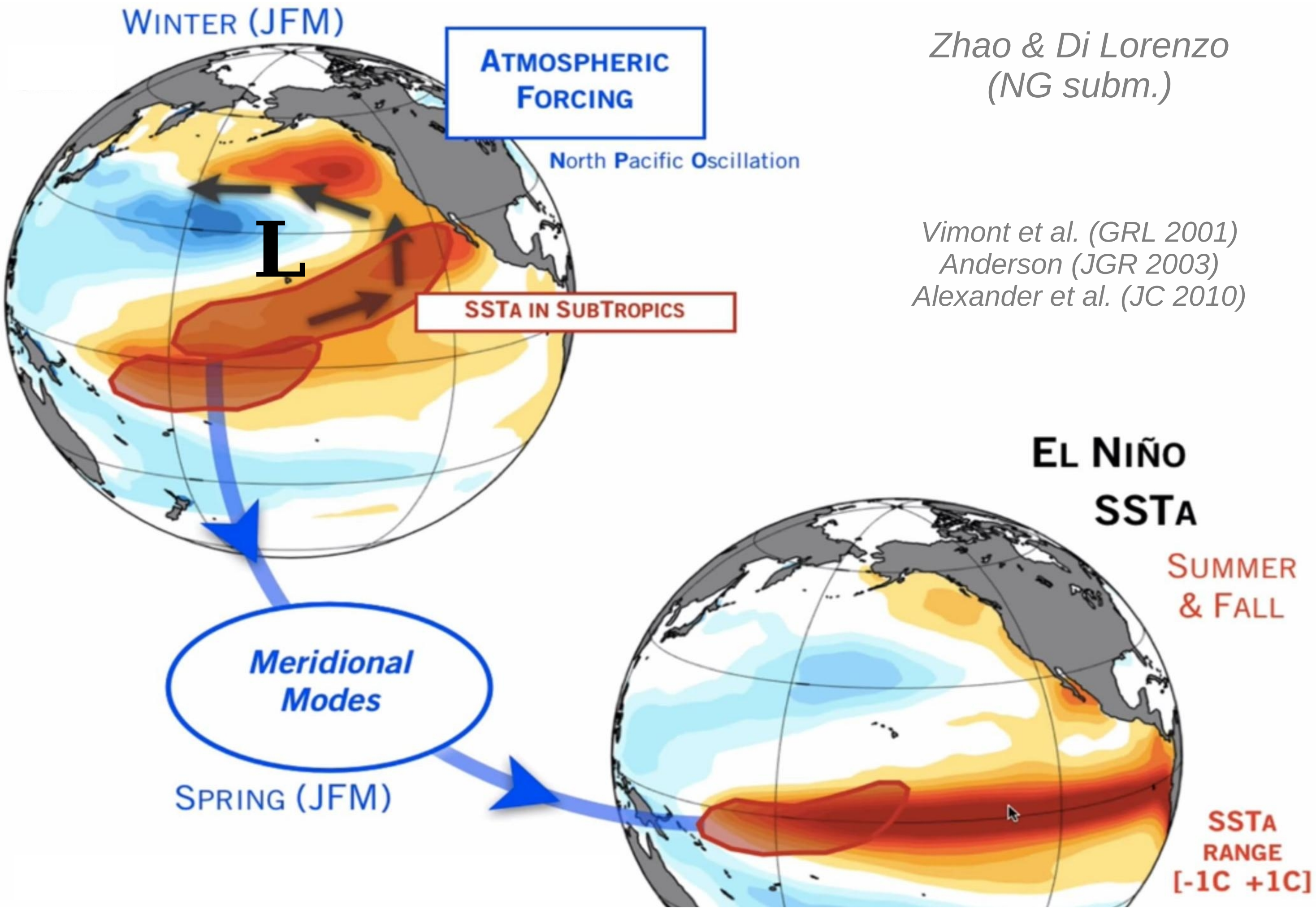
Historical & control run spectra are hard to distinguish from obs.

So is the PDO largely **unforced?**

Or is there **compensation** in the models, between too *little* ENSO-reddening and too *much* extratropical persistence?

Newman et al. (JC 2016)

Pacific Meridional Mode (PMM): An ENSO precursor



Zhao & Di Lorenzo (NG subm.)

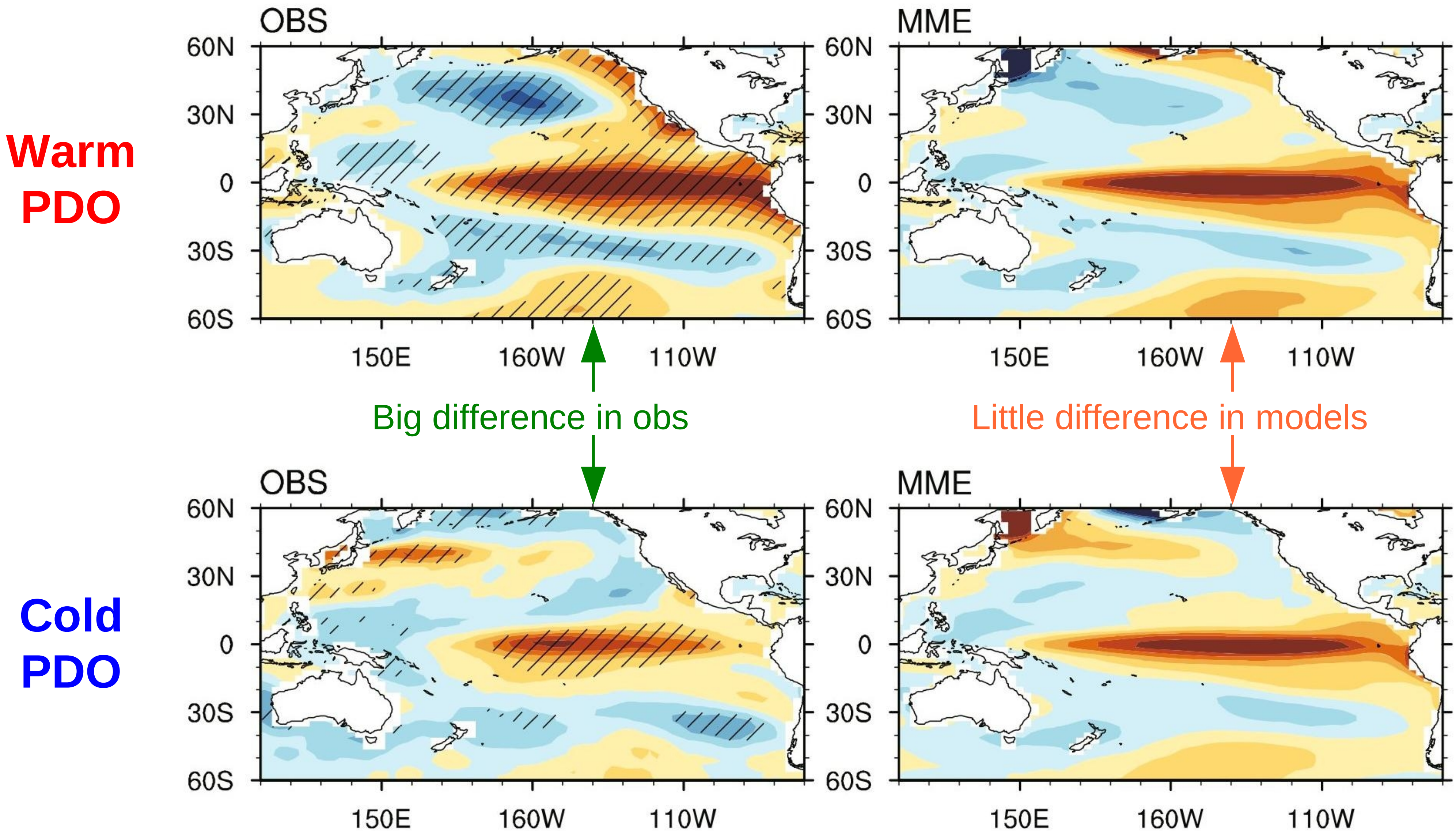
Vimont et al. (GRL 2001)
Anderson (JGR 2003)
Alexander et al. (JC 2010)

Mediated by off-equatorial winds & evaporation (**WES feedback**).
Propagates **equatorward & westward** to affect WWEs & ENSO.

CMIP5 models that **capture this link**, tend to have **more TPDV** (Furtado et al., AGU 2012).

PDO & El Niño flavors/skewness:

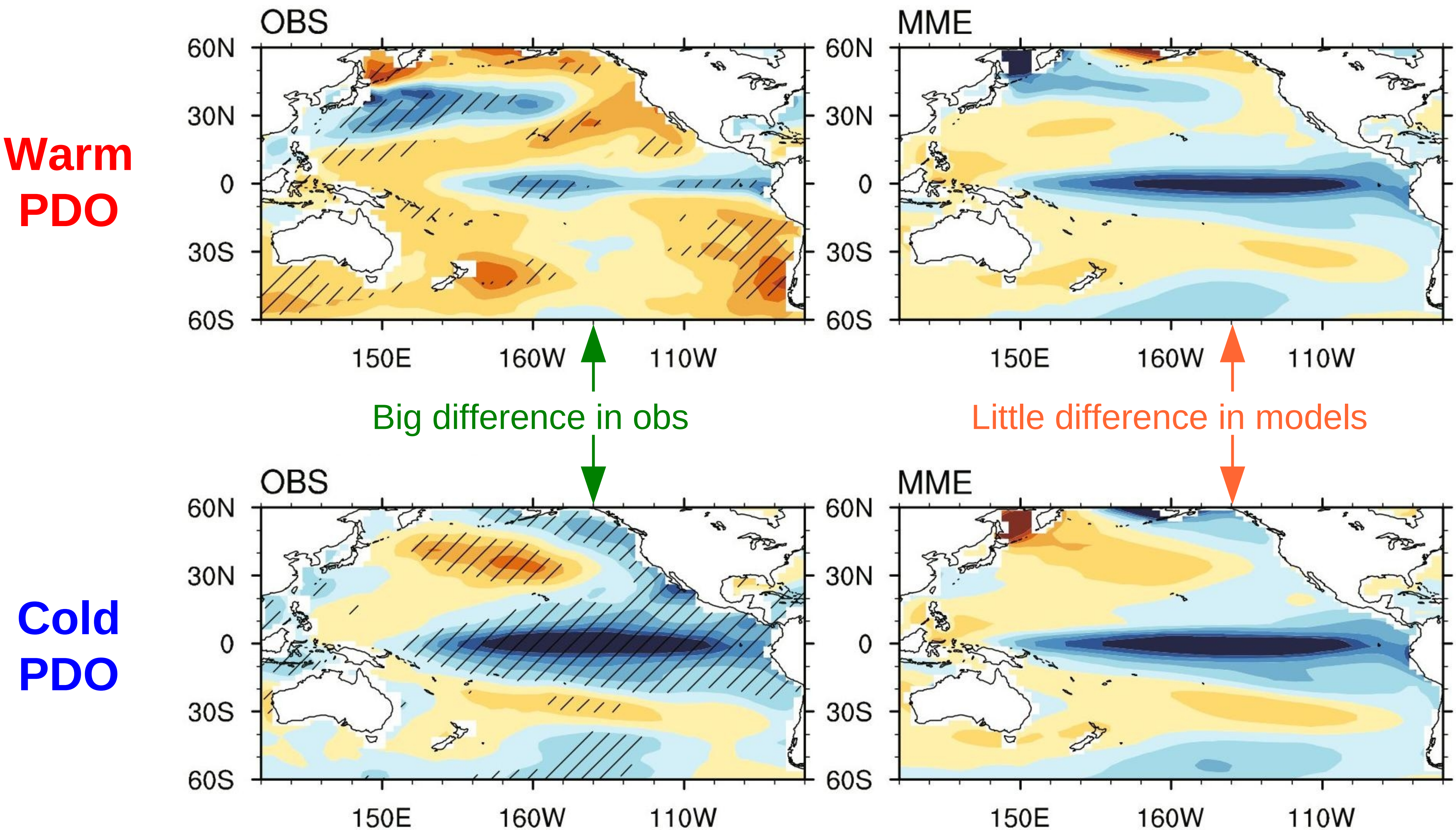
Too weakly related in CMIP5 models



Lin et al. (AAS 2018)

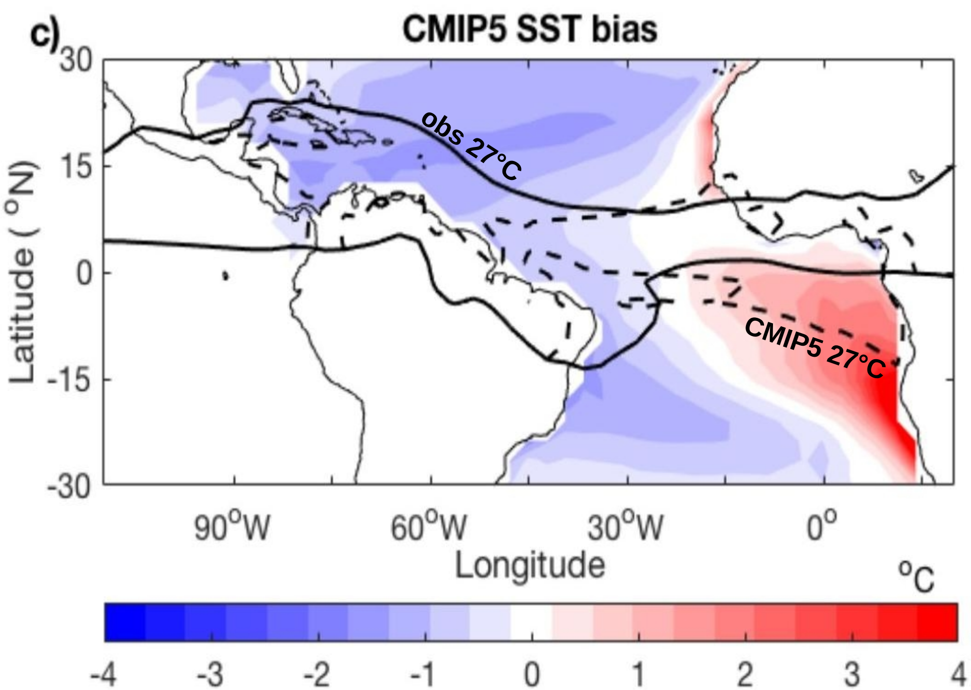
PDO & La Niña flavors/skewness:

Too weakly related in CMIP5 models



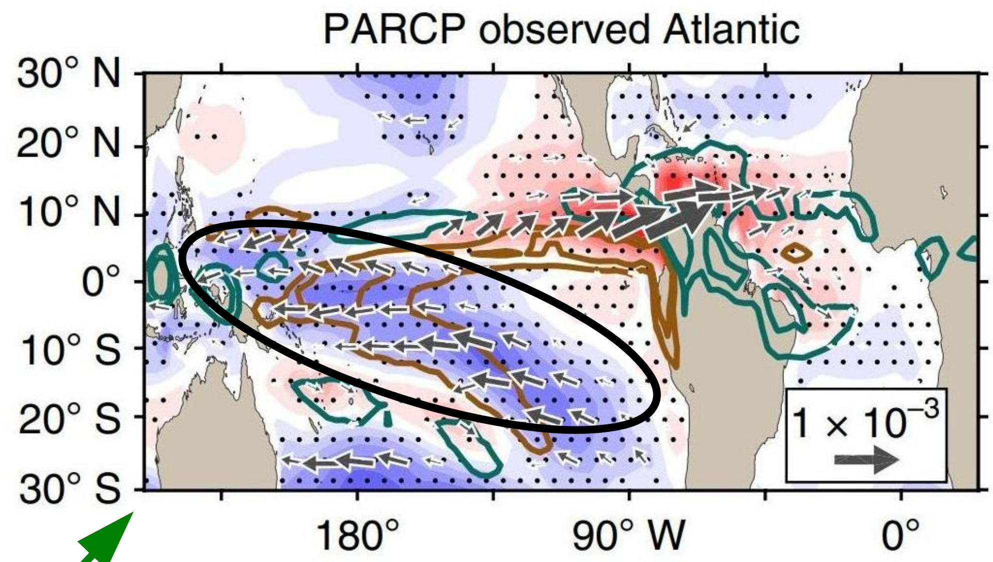
Lin et al. (AAS 2018)

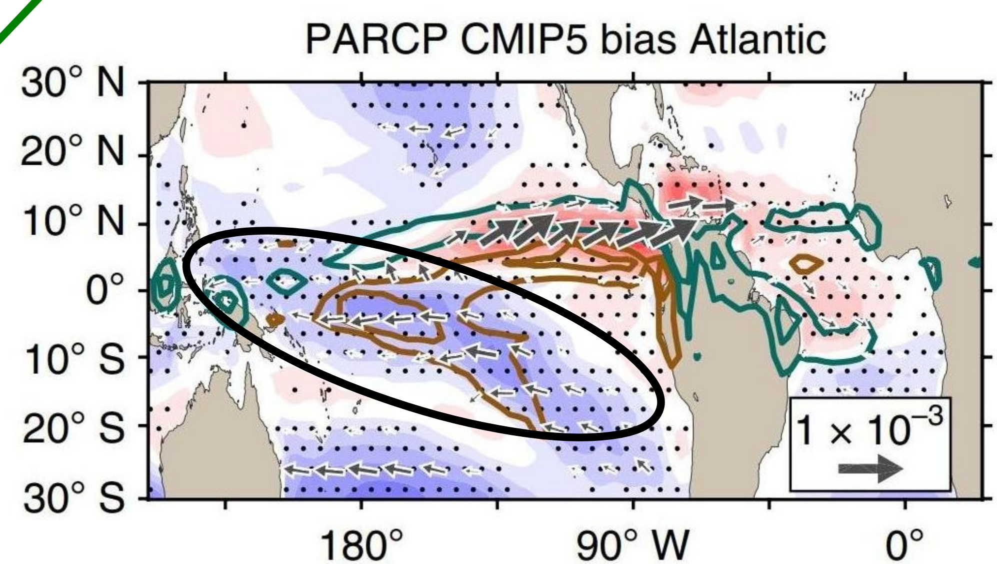
Atlantic SST biases affect Atlantic → Pacific connections



Obs **Atlantic warming** → poleward & westward shift of WPac convection → **easterly τ_x response** in Pacific.

But add CMIP5 Atlantic **SST bias** → convection responds farther east → **weakens** Pacific τ_x response.



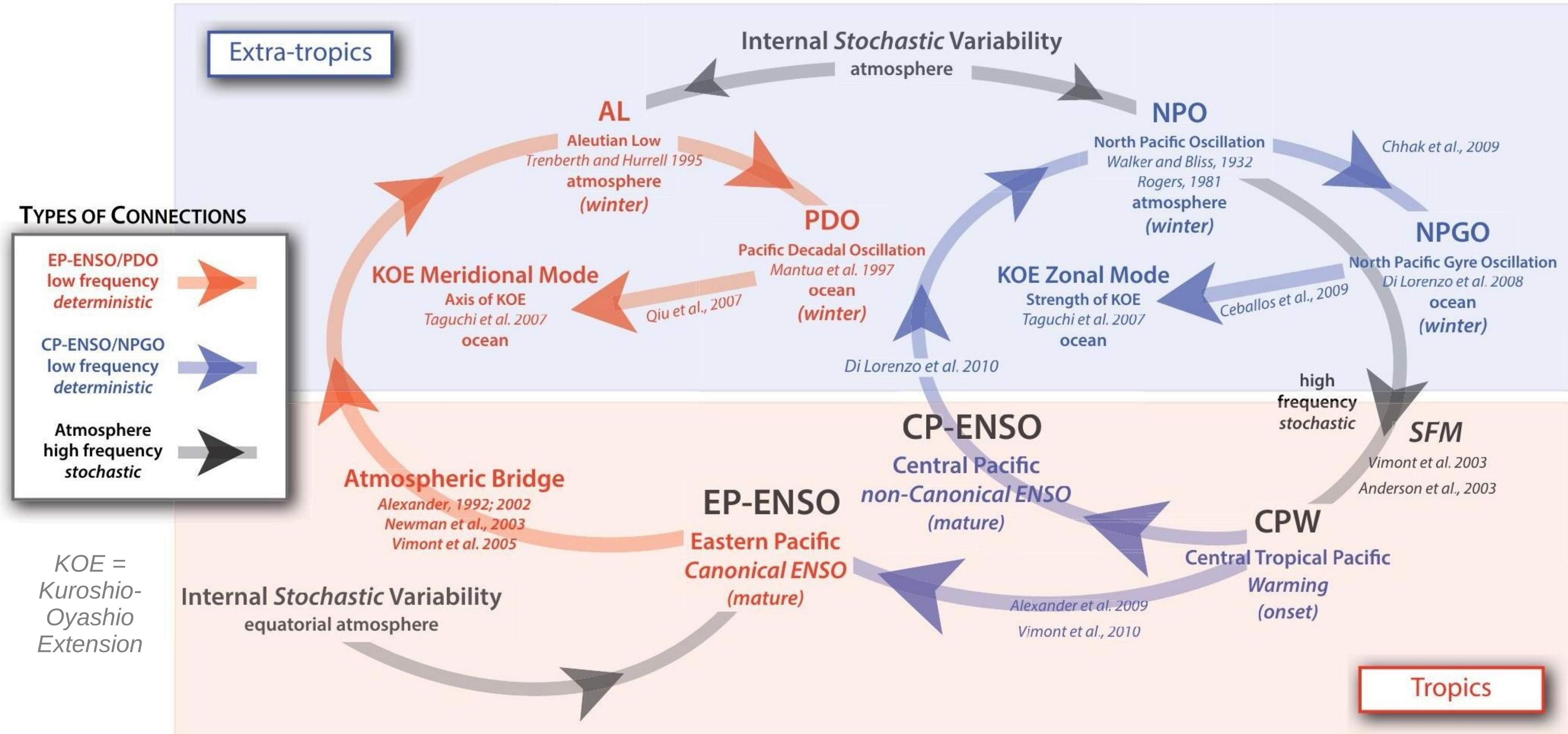


McGregor et al. (NCC 2018)

AGCM + Pacific slab OML + prescribed Atlantic SST warming (1992-2011)

Pacific decadal interactions with ENSO

Di Lorenzo et al. (Oceanogr. 2013)



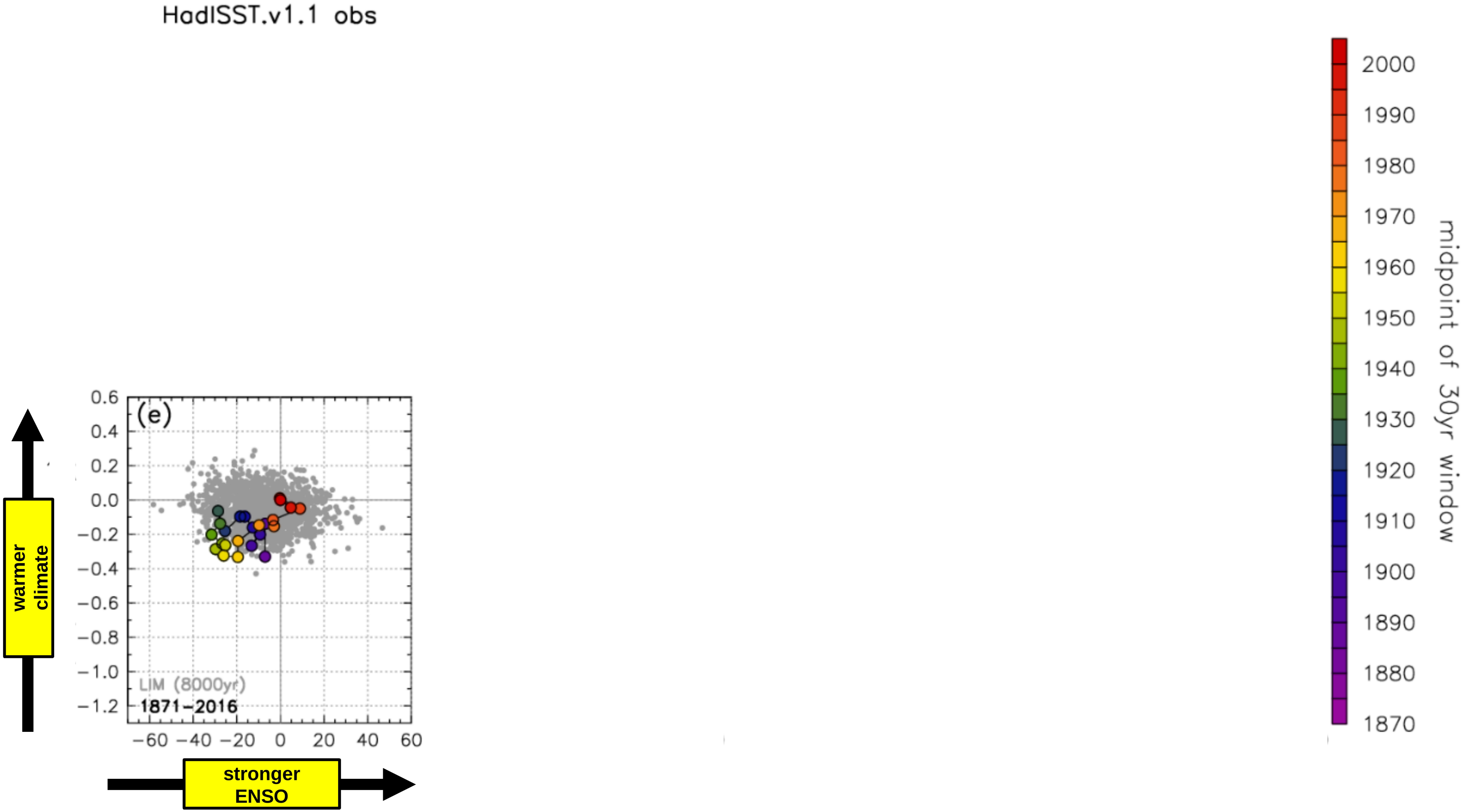
KOE = Kuroshio-Oyashio Extension

Random **ENSO modulation** + ML/RW **reddening** at higher latitudes.
PDO & NPGO might **interact** with ENSO flavors.
Are these **open** or **closed** loops? Do these links imply **predictability**?

Past & future changes
in TPDV & ENSO modulation

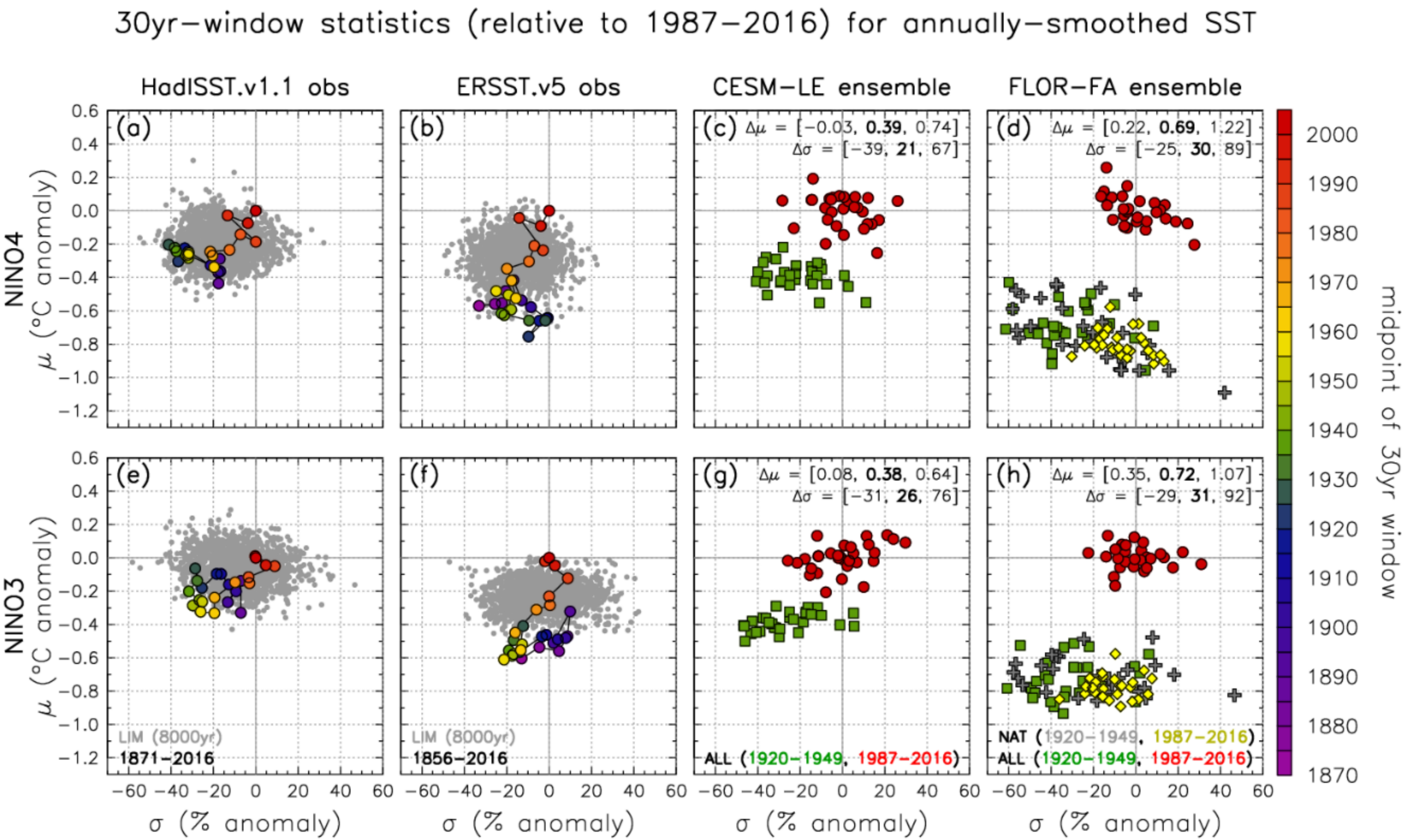
Observed & simulated mean/ENSO SST changes

30yr−window statistics (relative to 1987−2016) for annually−smoothed SST



Newman, Wittenberg, et al. (BAMS 2017)

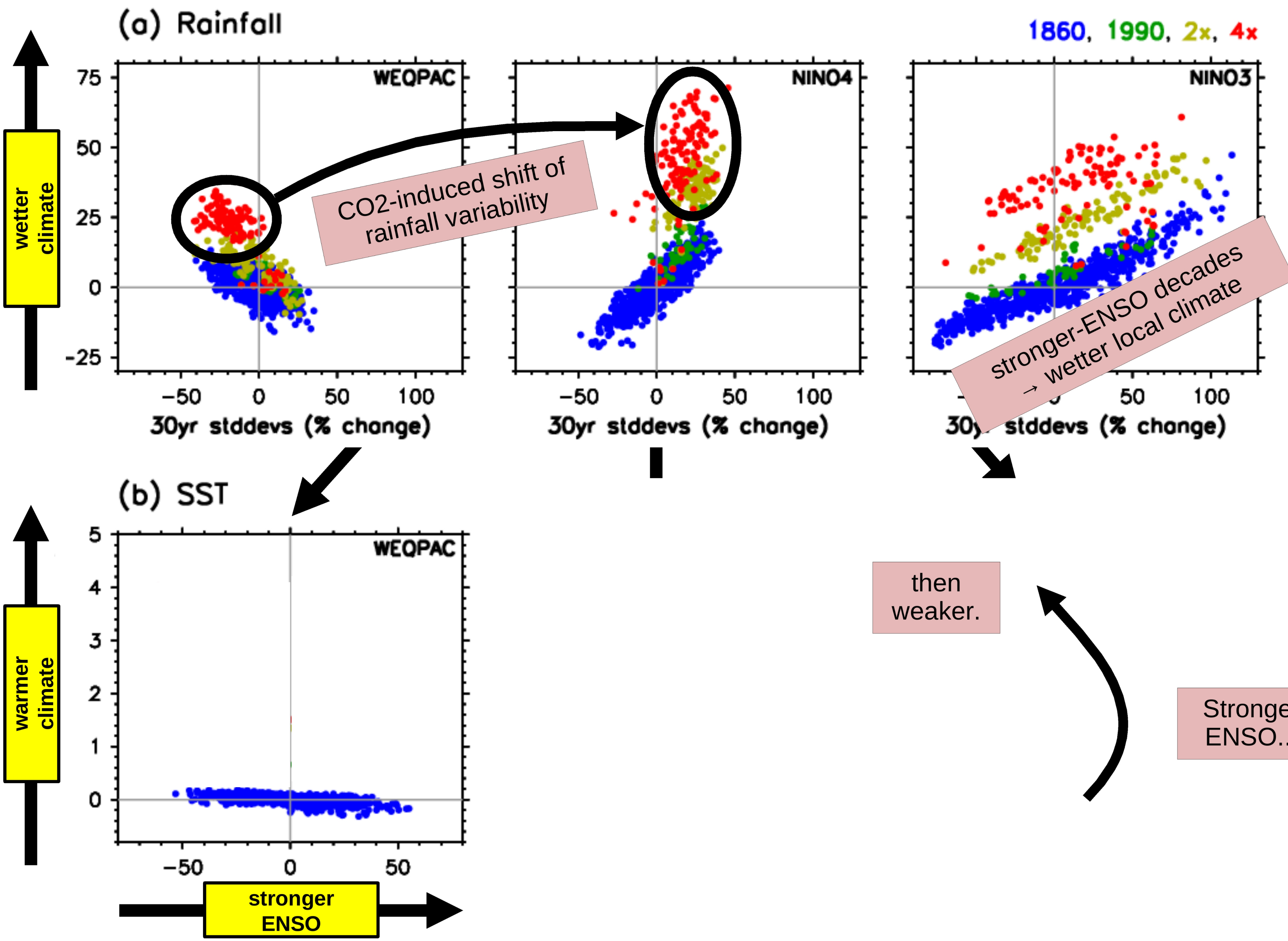
Observed & simulated mean/ENSO SST changes



Mean change is marginally detectable. ENSO change, less so.

Newman, Wittenberg, et al. (BAMS 2017)

ENSO response to increasing CO_2



Simulations show interplay of intrinsic ENSO modulation, decadal variation, nonlinear sensitivity, and regional responses to increasing CO_2

Vecchi & Wittenberg (2010)

Collins et al. (2010)

Xie et al. (2010)

DiNezio et al. (2012)

Watanabe & Wittenberg (2012)

Watanabe et al. (2012)

Ogata et al. (2013)

Power et al. (2013)

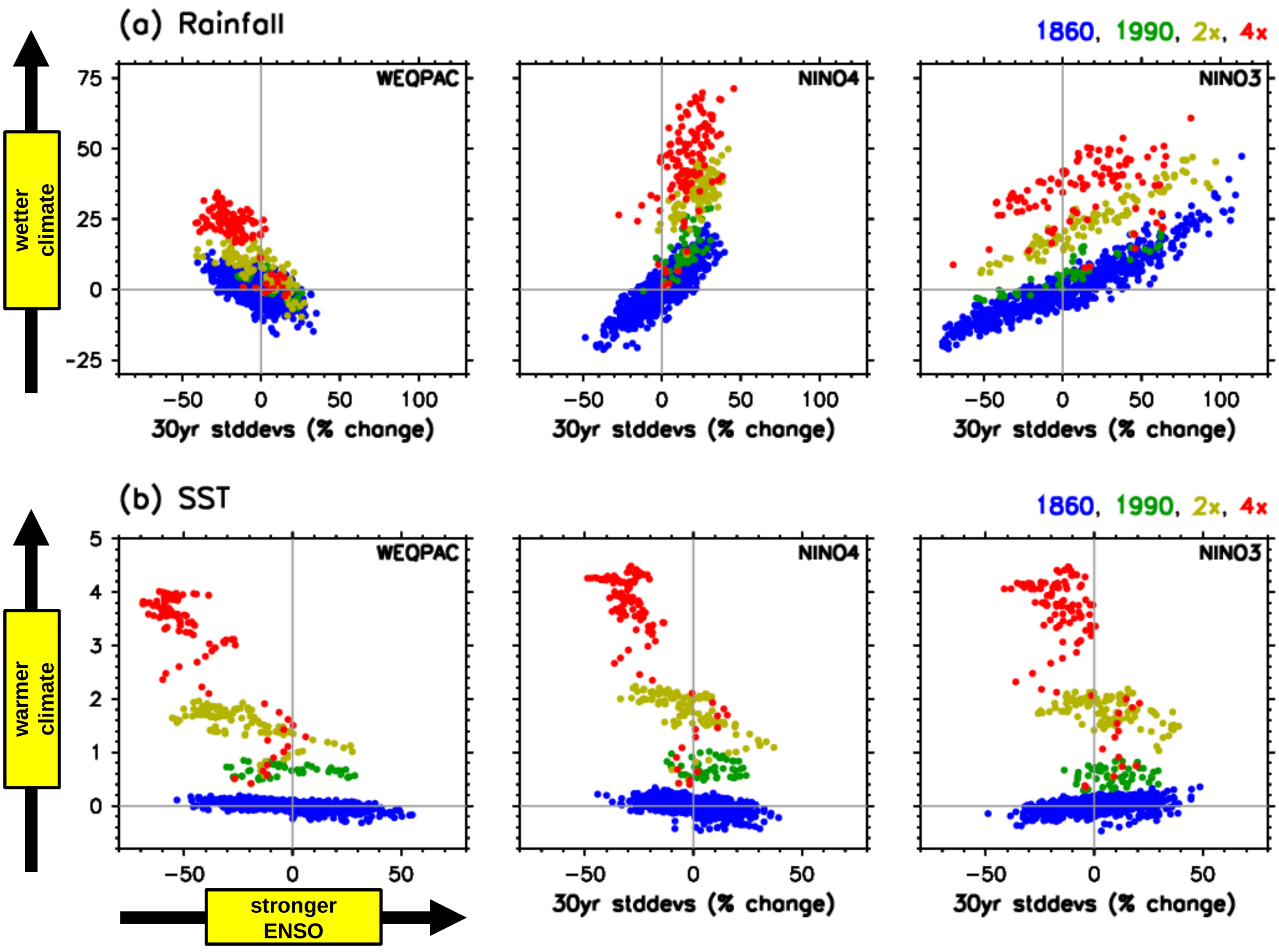
Cai et al. (2014)

Atwood et al. (2017)

Wittenberg (U.S. CLIVAR Variations, 2015)

CM2.1 simulation

ENSO response to increasing CO_2



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Wittenberg (U.S. CLIVAR Variations, 2015)

CM2.1 simulation

Summary of Model Results (1 of 2)

1. Simulated decadal-scale variations (PDO, IPO, ...)

a. **Amplitudes & patterns** have improved, but remain diverse in models

b. **Tropical/extratropical connections** remain too weak

- Model PDOs have excessive persistence, lag ENSO too much
- Weak PMM & tropical wind stress signature; weak impact of PDO on ENSO flavors
- Excessive projection of ENSO-PC2 onto PDO
- Excessive persistence + weak tropical forcing: Amplitude compensation?

c. **Mean-state biases** alter remote interactions

- Weaken **EqPac cold bias** → improves IPO SSTAs in tropics (eastward/equatorward shift)
- Remove **Atlantic SST bias**: improves Atlantic→Pacific causal link (both intrinsic & forced)

2. Interdecadal ENSO modulation

a. Large **intrinsic component**

- Amplitude, spectrum, pattern, mechanisms
- May be fundamentally unpredictable on decadal scales
- Interannual memory + Poisson statistics → multidecadal modulation
- "El Nino of the century" → little evidence of decadal impact on ENSO

b. Residual of **strong-ENSO epochs**: Cold west, warm east

c. Models with **strong ENSOs** get more diversity, nonlinearity, ENSO-induced TPDV

Summary of Model Results (2 of 2)

3. Historical changes

a. Large uncertainties in obs SST products → hard to evaluate model trends

b. Models produce clear **anthropogenic warming** at equator

c. **Amplification** of ENSO SSTAs

- hard to detect in short obs records
- clear in large ensembles (CESM & FLOR)
- both anthro + natural forcings may matter

4. Future changes

a. Differing **regional** responses to mean + ENSO changes

b. **Unprecedented** climate regimes & extremes

c. **Transient** amplification of SSTAs in eastern equatorial Pacific?

d. Eastward/equatorward **shift & amplification of rainfall variability**

e. Might be masked for decades by intrinsic modulation

Key Questions (1 of 2)

1. Model biases

a. What are the most **common** model biases in mean/TPDV/ENSO?
b. What **causes** these biases, and how do they **interact**?
c. Are **existing obs** sufficient to constrain model dynamics & phenomena?
- How long must our obs records & simulations be, to robustly detect differences?
- What should we be observing now, to detect future changes & improve models?
- How can we improve historical & paleo reanalyses?

d. When a model does something right, is it for the **right reasons**?
- Cancelling errors affect model sensitivities, frustrate future development

e. In the near term: How can we **cope** with model biases?
- Flux adjustments, pattern corrections, dynamic corrections, emergent constraints

f. In the longer term: How can we **accelerate** model improvement?

2. Model diversity

a. Why do models show **diverse** TPDV/EDV behavior?
b. What are the most/least robust future **projections** from models?
c. **Emergent constraints**
- What can we learn from diverse biased models about the real world?
- Does a realistic historical simulation imply realistic sensitivity to future change?
- Do inter-model spreads adequately represent the uncertainty?

d. How might **future CGCMs** behave differently?
- TIWs, convective/cloud feedbacks, coastal resolution

e. Do we have a sufficient toolbox of **conceptual & intermediate models**?

Key Questions (2 of 2)

3. Utilizing the models

a. How do TPDV/EDV interact with **remote regions**?
- Atlantic & Indian oceans, subtropics, extratropics
- atmospheric bridges & oceanic tunnels
- reddening processes: subduction & re-emergence of extratropical heat; ocean Rossby waves
- ENSO modulation, asymmetry, rectification

b. What are the fundamental **limits of predictability**?
- Is ENSO modulation decadally predictable?
- Do tropical/extratropical interactions impart decadal predictability?

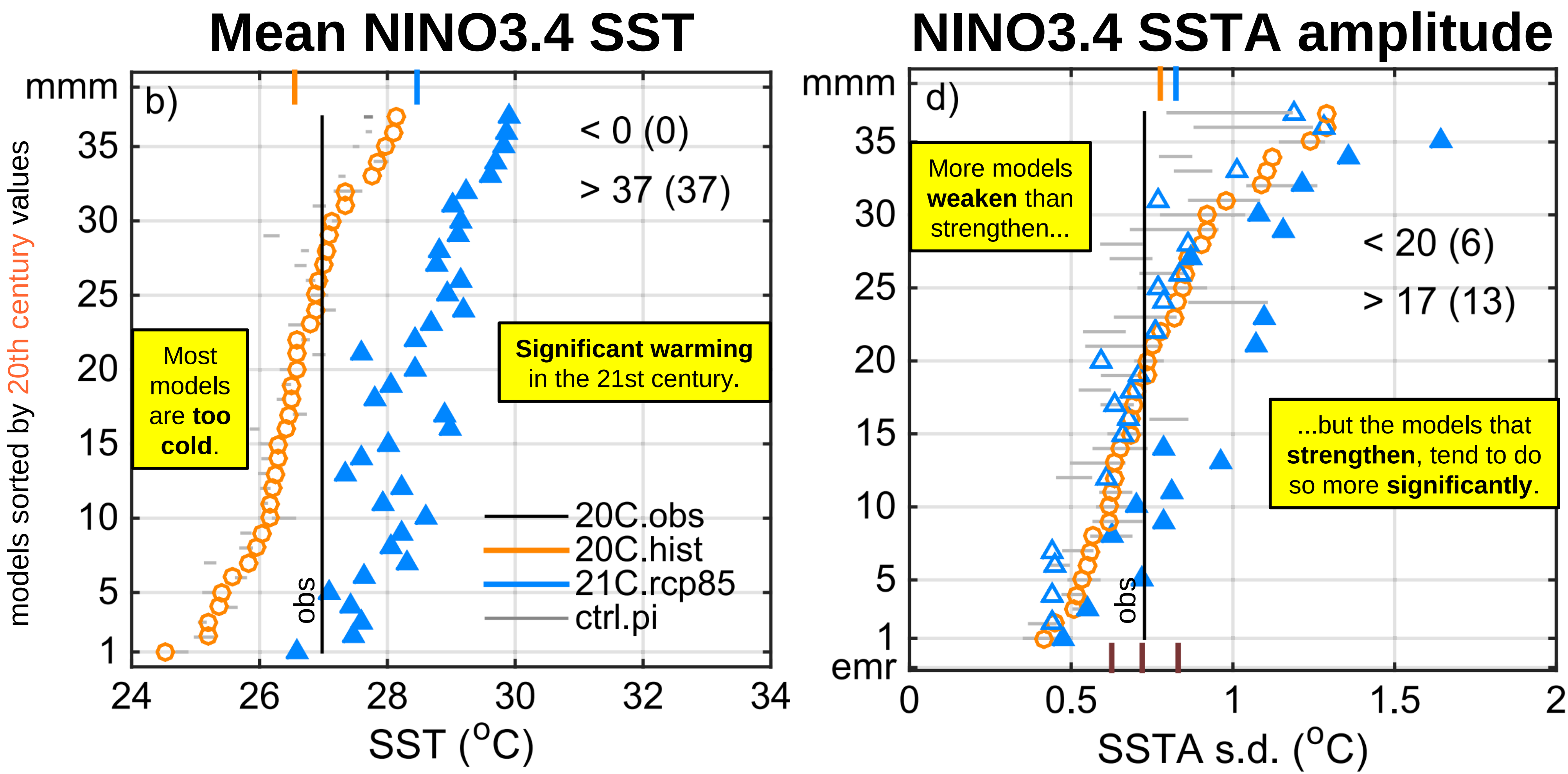
c. How & why have TPDV/EDV evolved in the **past**?

d. How will TPDV/EDV change in the **future**?
- When will we start to notice changes?
- How do we best communicate future risks to stakeholders?

e. What experiments & analysis should we be doing?
- Large ensembles, long runs, perturbed physics, partial coupling, ...
- Dynamical model hierarchies, statistical emulators, automated metrics, …
- Would further community coordination help?

Reserve Slides

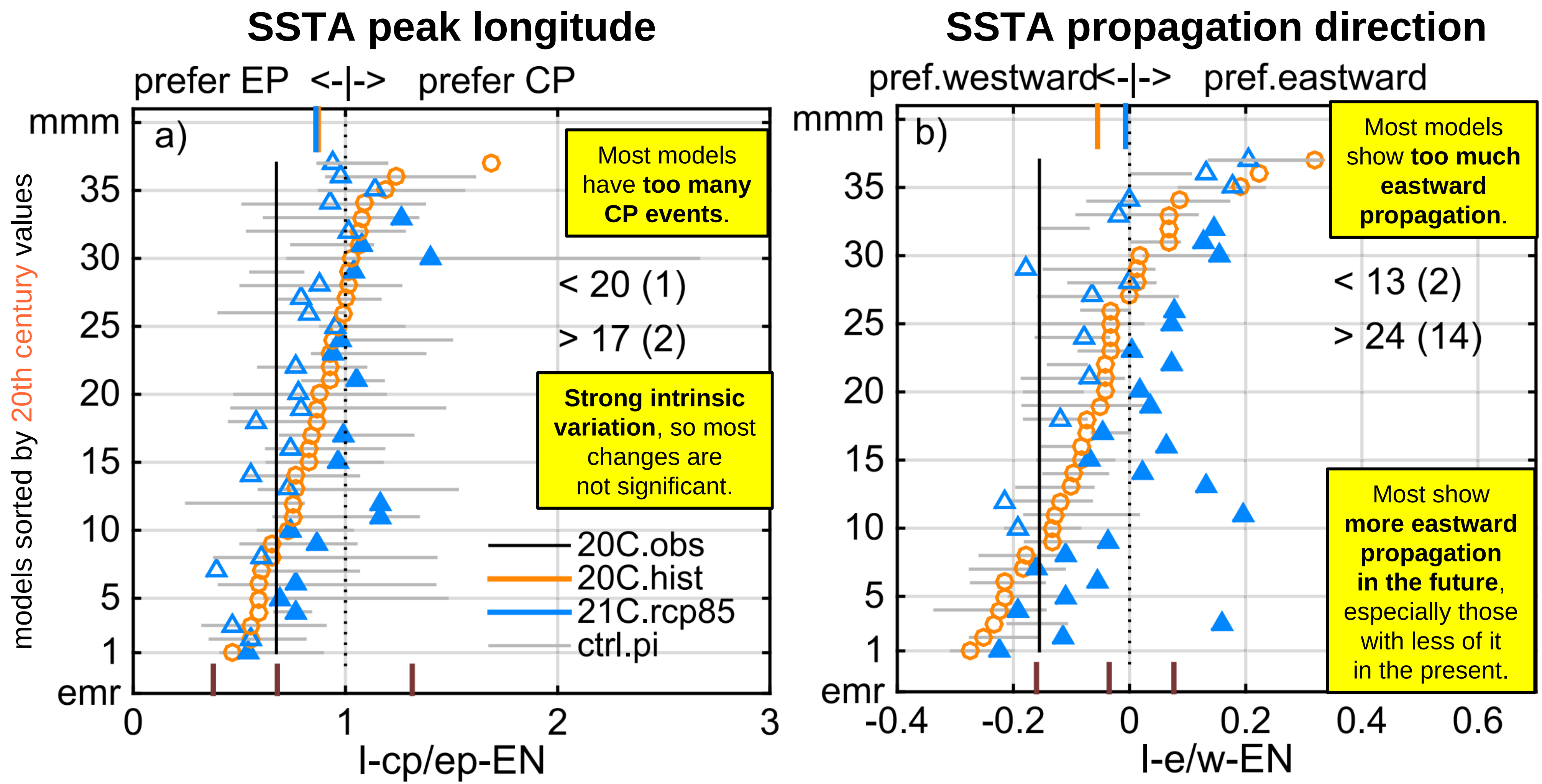
CMIP5 projections (PI, 1900-99, 2000-99)



All the models show **significant mean warming** in the 21st century.
But **ENSO SSTAs** weaken in some models, strengthen in others.

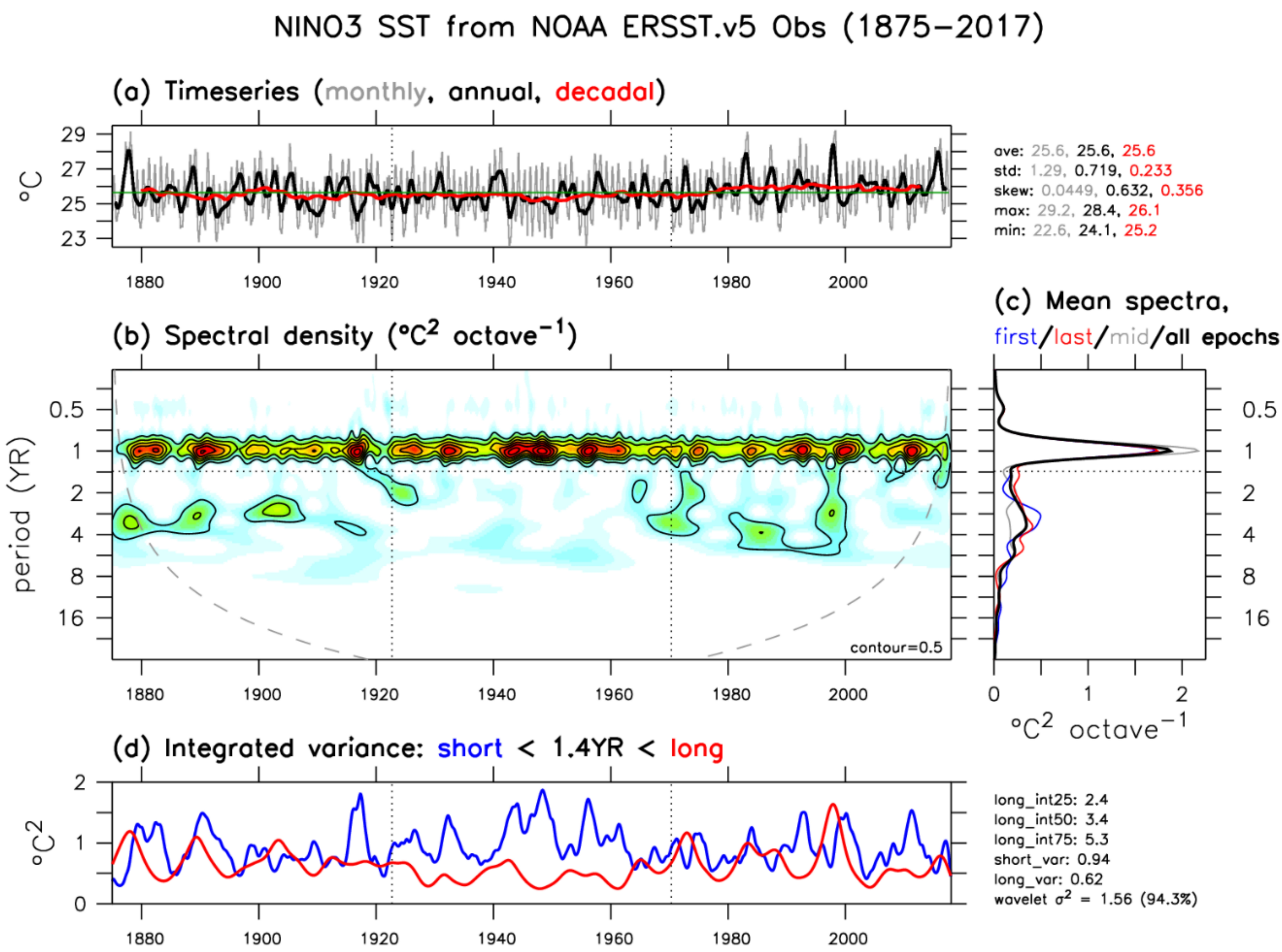
Chen et al. (JC 2017)

CMIP5 projections (PI, 1900-99, 2000-99)



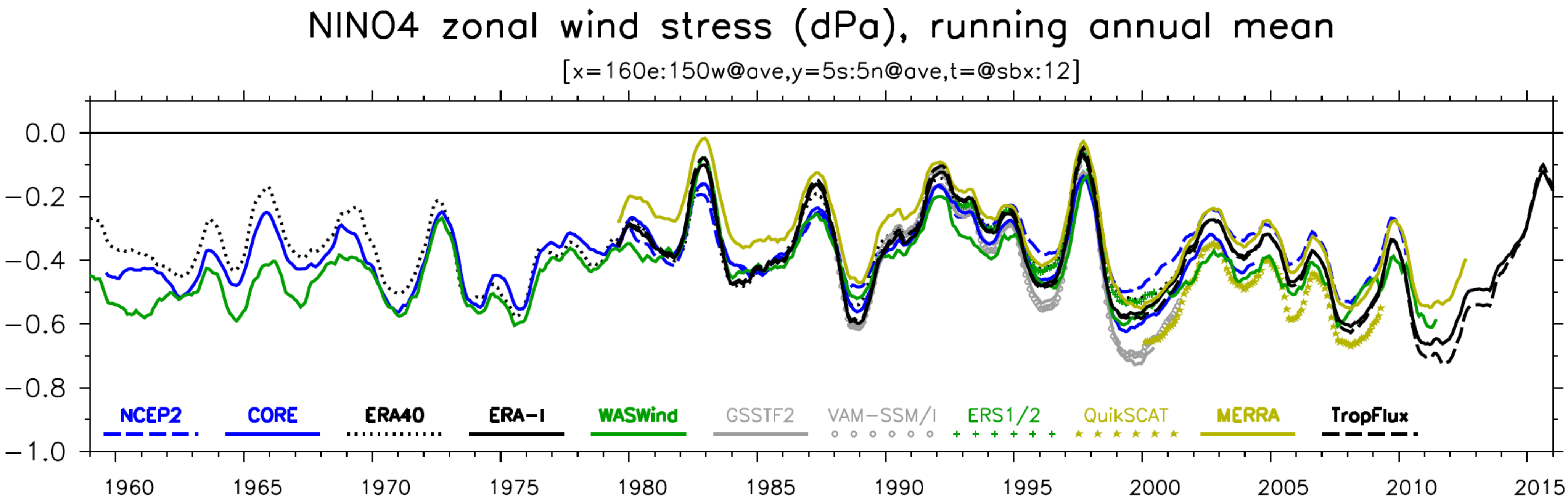
No consensus on whether EP or CP El Niños will be more likely in the future.
But projected ENSO SSTAs do show **more eastward propagation**.

Chen et al. (JC 2017)



NINO3 SST from NOAA ERSST.v5 Obs (1875–2017)
(a) Timeseries (monthly, annual, decadal)
°C
ave: 25.6, 25.6, 25.6
std: 1.29, 0.719, 0.233
skew: 0.0449, 0.632, 0.356
max: 29.2, 28.4, 26.1
min: 22.6, 24.1, 25.2
(b) Spectral density (°C^2 octave^{-1})
period (YR)
contour=0.5
(c) Mean spectra, first/last/mid/all epochs
°C^2 octave^{-1}
(d) Integrated variance: short < 1.4YR < long
°C^2
long_int25: 2.4
long_int50: 3.4
long_int75: 5.3
short_var: 0.94
long_var: 0.62
wavelet σ^2 = 1.56 (94.3%)

Diverse wind stress estimates



Updated from Wittenberg (JC 2004). See also: Wen et al. (CD 2017), McGregor et al. (JGRO 2017).

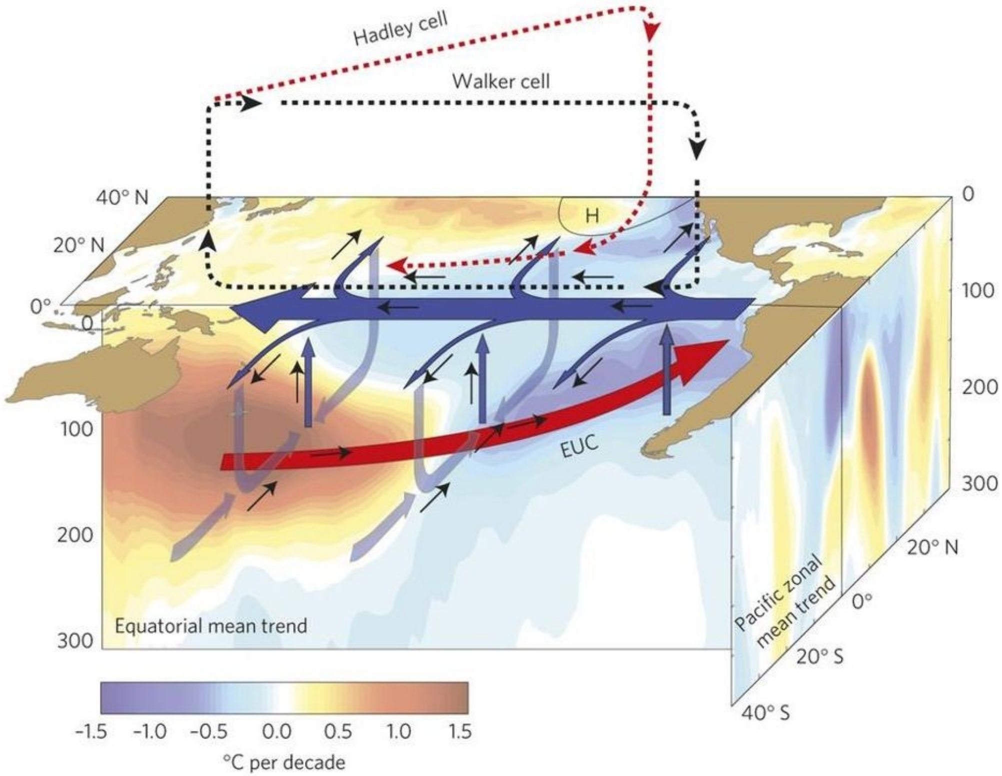
Multiple issues in comparing mooring/satellite/reanalysis winds & stresses:

- **surface currents** (relative wind; 15 m vs. true surface currents)
- **buoy motion** (gustiness – horizontal & vertical)
- **representativeness** (continuous single-point vs. intermittent swath; aliasing)
- scatterometer **rain contamination** (sampling/gustiness biases)
- **bulk formula** (drag coefficient, height correction)
- background wind product (model/**reanalysis biases**)
- **changing obs network** (false trends)

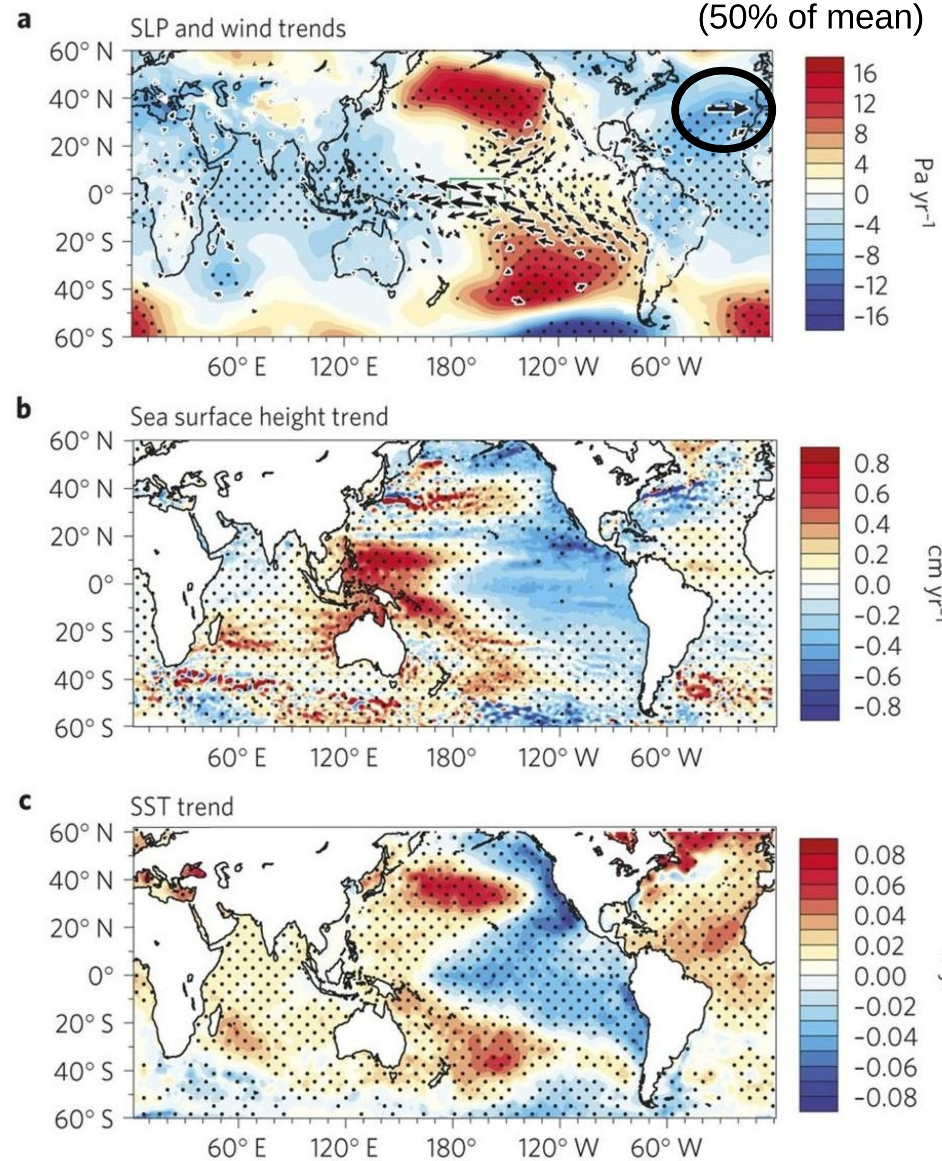
Stress differences strongly affect OGCM response (Chiodi & Harrison, JC 2017).

La Niña-like multidecadal “hiatus” (1992-2011)

stress changed
by ~3 cPa
(50% of mean)



Colour shading shows observed temperature trends (°C per decade) during 1992–2011 at the sea surface (Northern Hemisphere only), zonally averaged in the latitude-depth sense (as per Supplementary Fig. 6) and along the equatorial Pacific in the longitude-depth plane (averaged between 5° N–5° S). Peak warming in the western Pacific thermocline is 2.0 °C per decade in the reanalysis data and 2.2 °C per decade in the model. The mean and anomalous circulation in the Pacific Ocean is shown by bold and thin arrows, respectively, indicating an overall acceleration of the Pacific Ocean shallow overturning cells, the equatorial surface currents and the Equatorial Undercurrent (EUC). The accelerated atmospheric circulation in the Pacific is indicated by the dashed arrows; including the Walker cell (black dashed) and the Hadley cell (red dashed; Northern Hemisphere only). Anomalously high SLP in the North Pacific is indicated by the symbol ‘H’. An equivalent accelerated Hadley cell in the Southern Hemisphere is omitted for clarity.



a, Observed trends in surface wind stress (N $m^{-2} yr^{-1}$) shown as vectors with observed trends in atmospheric SLP overlaid in colour shading (Pa yr^{-1}). The maximum vector is 0.003 N $m^{-2} yr^{-1}$ and only vector trends that are significant at the 95% confidence level are shown. The green rectangle is the region computed in Fig. 1b. **b**, Observed trends in sea surface height (cm yr^{-1}) from satellite altimetry. **c**,**d**, Observed trends in SST (**c**) and surface layer air temperature (**d**), respectively (°C yr^{-1}). In all panels, stippling indicates where the trends are significant at the 95% confidence level given the linear regression standard error over the entire period of 1992–2011.

Decadal variations in trade winds matter,
and they have off-equatorial x/y structure.

Can satellites + assimilation reliably
compensate for a thinner TMA?

England et al. (NCC 2014)

Pacific Decadal Variability (PDV): ENSO and the PMM

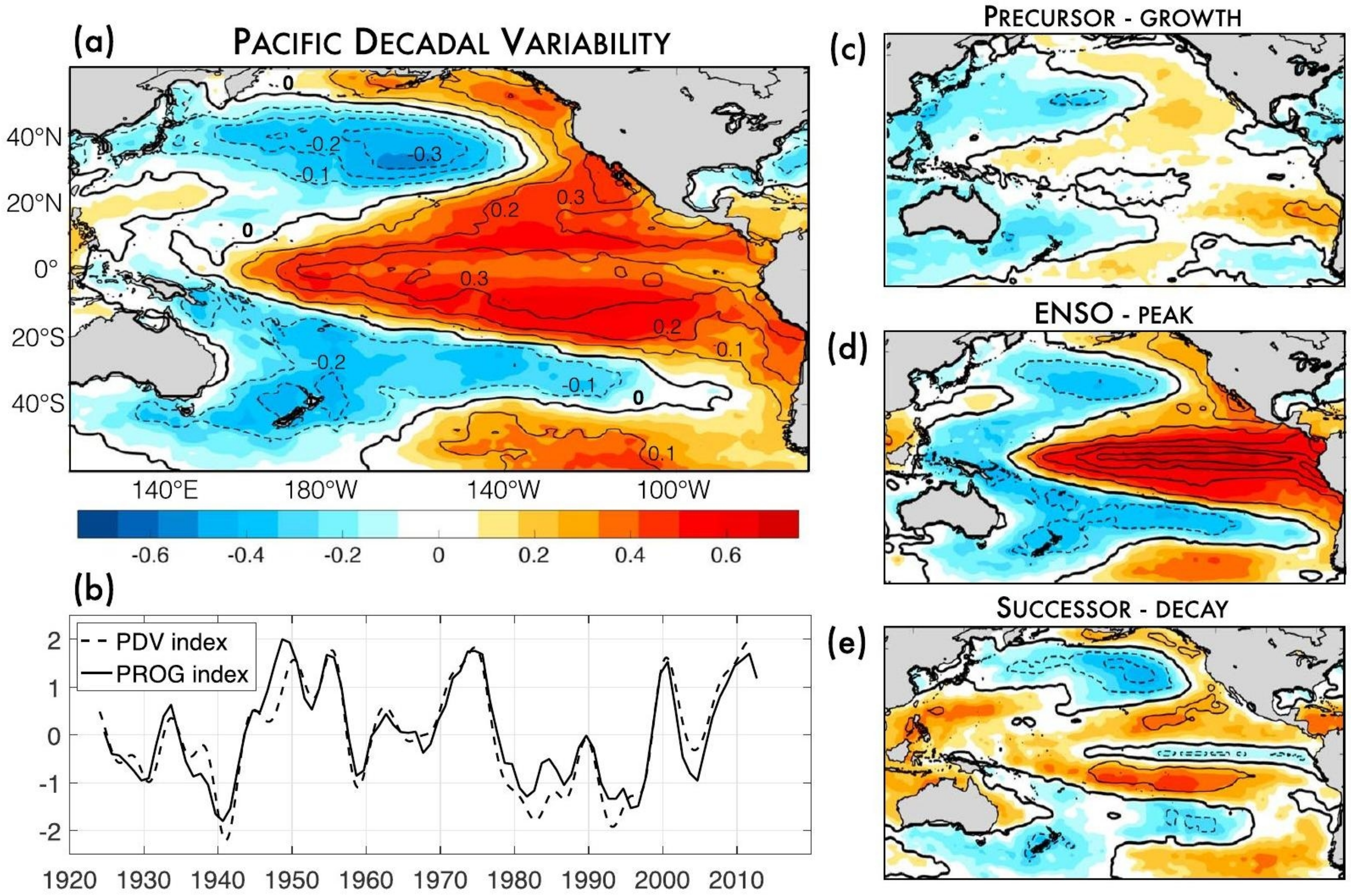
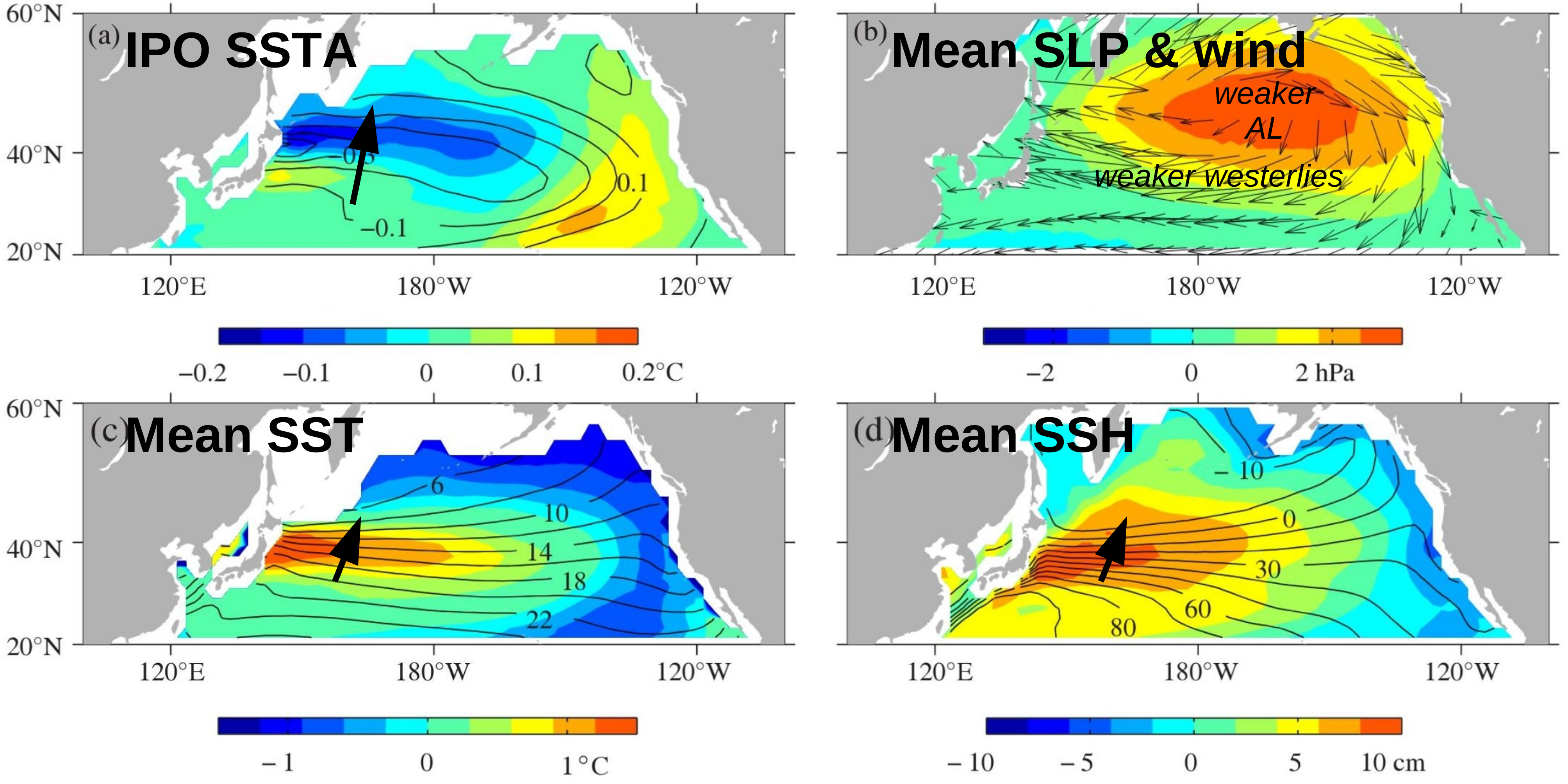


Figure 1. Pacific decadal variability. (a) Correlation and regression maps of the PDV index (i.e., leading PC of 8 year low-passed SST over the Pacific domain) onto 8 year low-passed Pacific SST. Color shading represents the correlation coefficient while the contours represent the regression coefficient. Contour interval 0.1°C per standard deviation of the PDV index. Negative contours are dashed; the zero contour is thickened. (b) The PDV index shown together with the 8 year low-passed PROG index (see text for the definition of the PROG index). As in Figure 1a but at different lags and using unfiltered SSTs and ENSO index (defined as the PC1 of SST anomalies between 20°S and 20°N). When SSTs precede ENSO of 1 year, (c) the precursor, when there is no lag between ENSO and SSTs, (d) the peak, and when ENSO leads the SSTs of 1 year, (e) the successor.

Liguori & Di Lorenzo (GRL 2018)

PDV can affect ENSO via the PMM.
ENSO can imprint on extratropics & PDV.

CMIP5: Midlatitude IPO SSTA pattern is linked to mean state



Models with **northward-shifted PDO SSTAs** in the NW Pacific, also tend to have climatologies with a **weaker Aleutian Low**, weaker midlat westerlies, and **northward-shifted SST & SSH gradients**.

Lyu et al. (IJC 2015)

ENSO flavors relate to the PDO

Warm PDO

Cold PDO

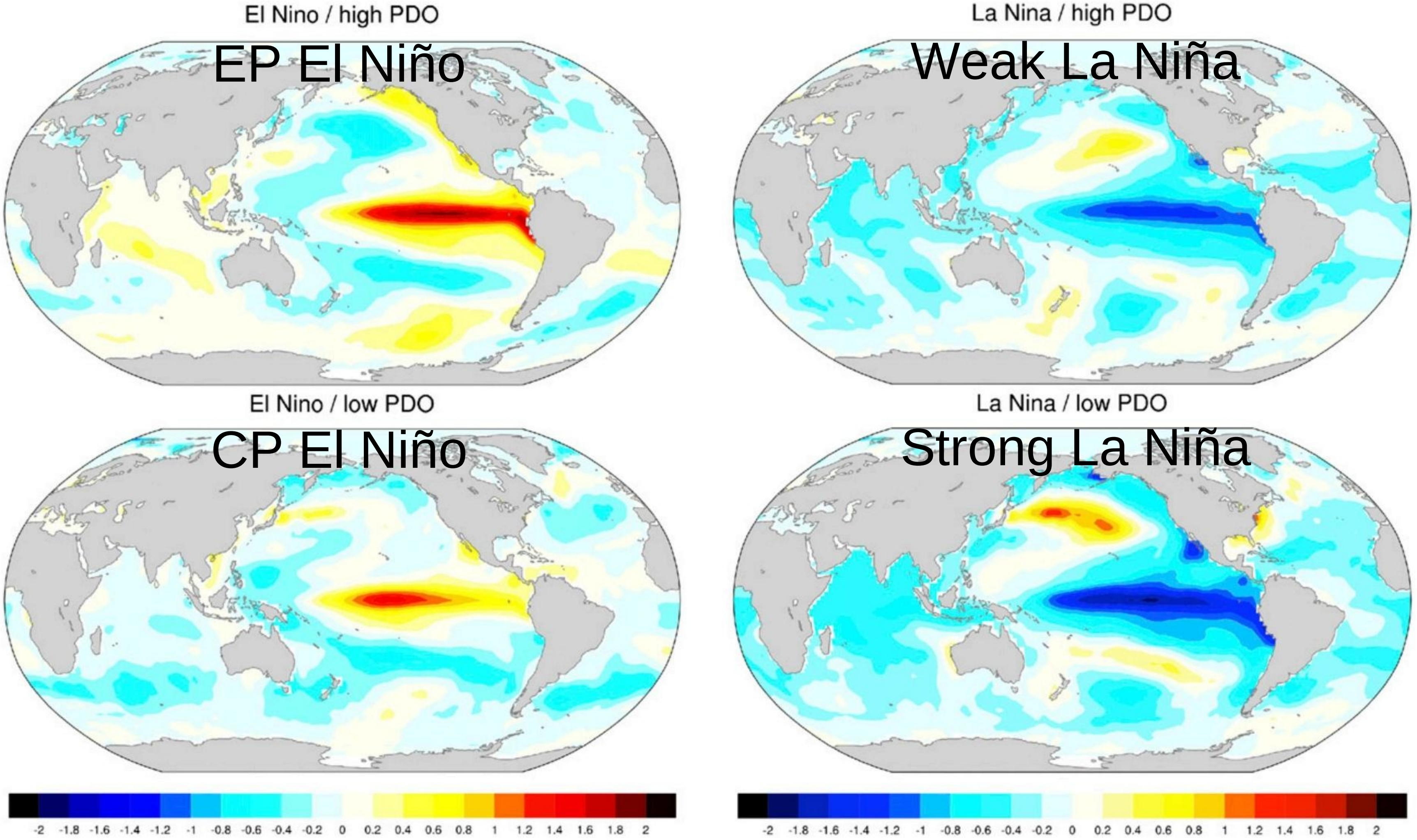
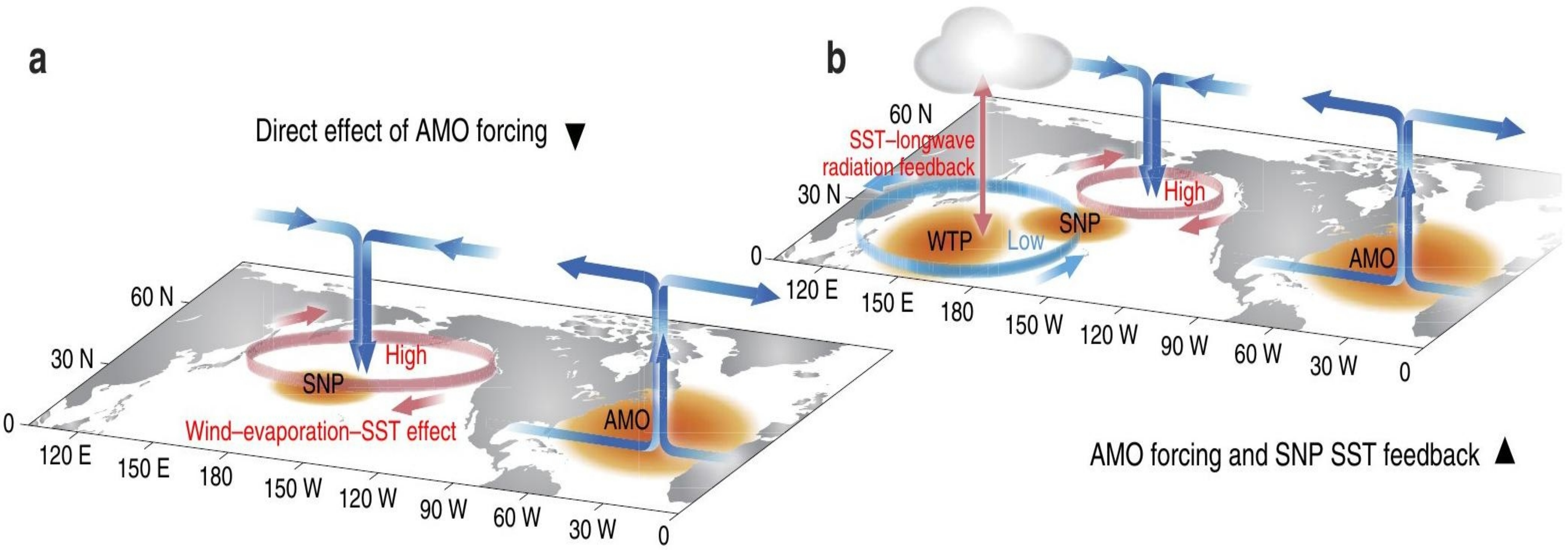


FIG. 13. NDJFM SST ENSO composites separated by high and low PDO values, determined over the years 1948–2008 from the ERSST.v3b SST dataset. Shown are composites of the top quintile (El Niño) of the ENSO index segregated by the (top left) top and (bottom left) the bottom halves of the PDO indices for the 12 cases, and the bottom quintile (La Niña) of the ENSO index segregated by the (top right) top and (bottom right) the bottom halves of the PDO indices for the 12 cases. Each half of the quintile is determined by ranking the PDO values of the quintile years. Contour interval is 0.2°C.

Newman et al. (JC 2016)

Atlantic/Pacific decadal interactions

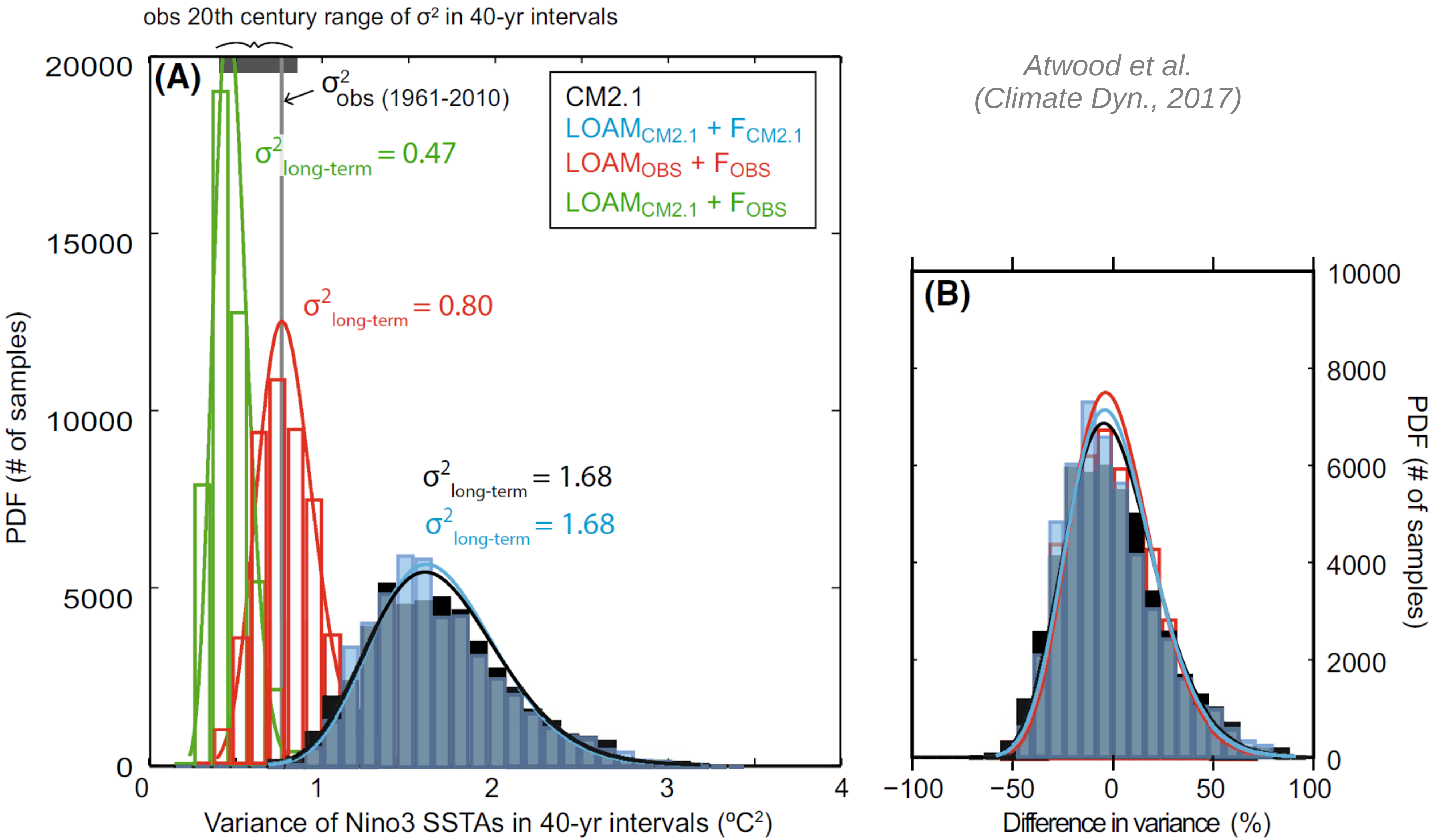
Sun et al. (Nat. Commun. 2017)

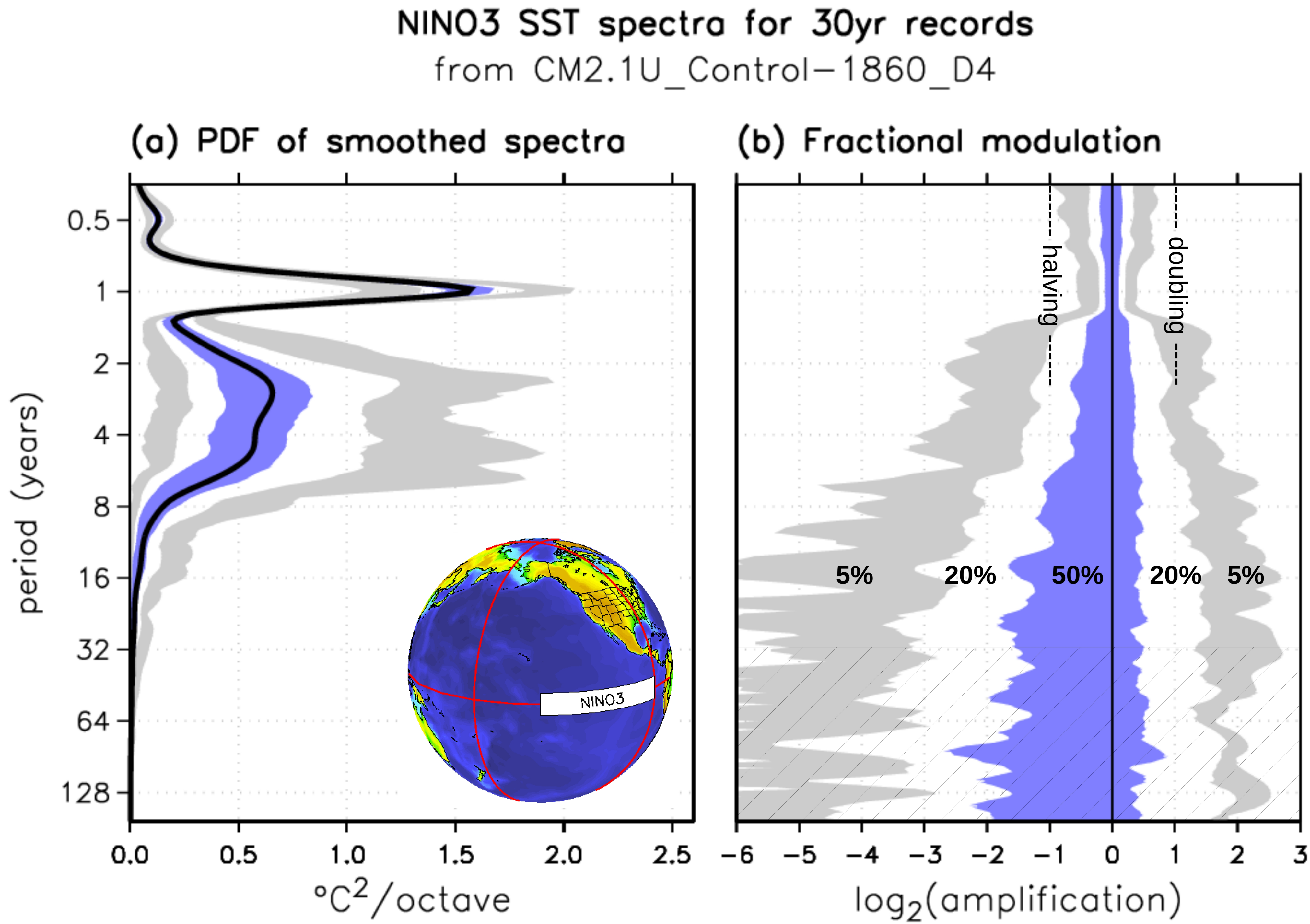


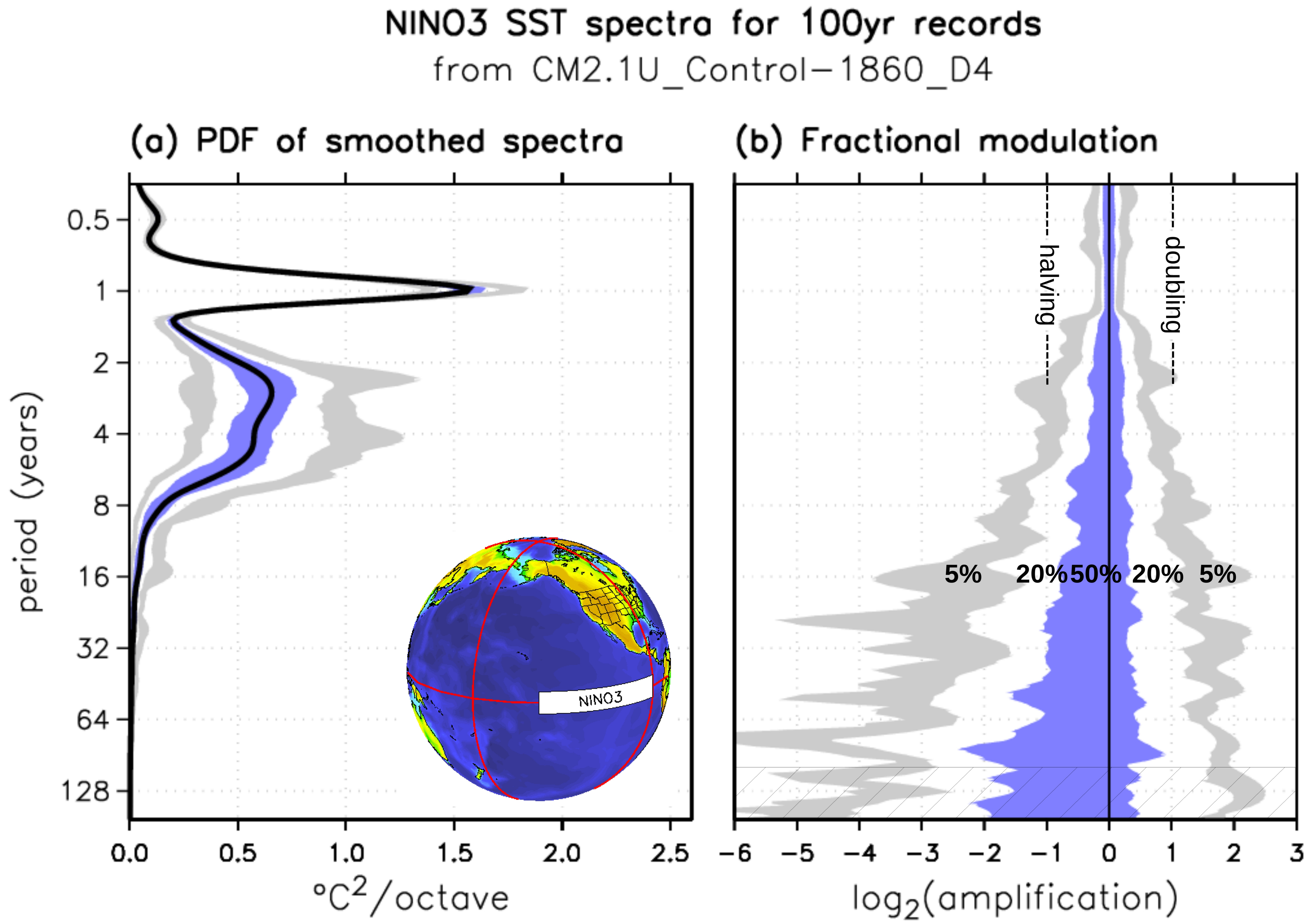
Tropical Atlantic (AMO) imprints on N. Pacific. Signal spreads equatorward via off-equatorial WES & cloud feedbacks.

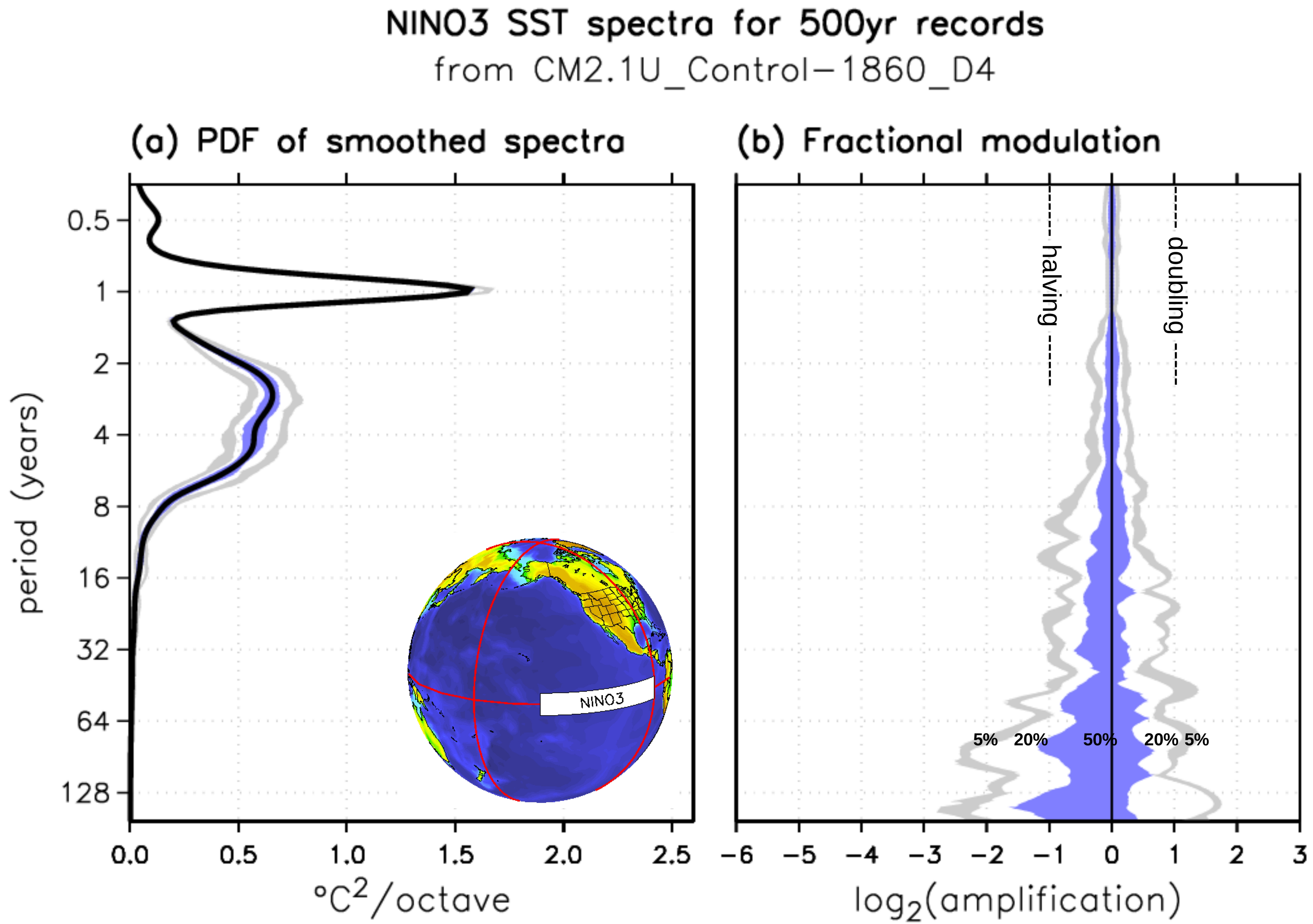
ENSO modulation

Atwood et al.
(Climate Dyn., 2017)

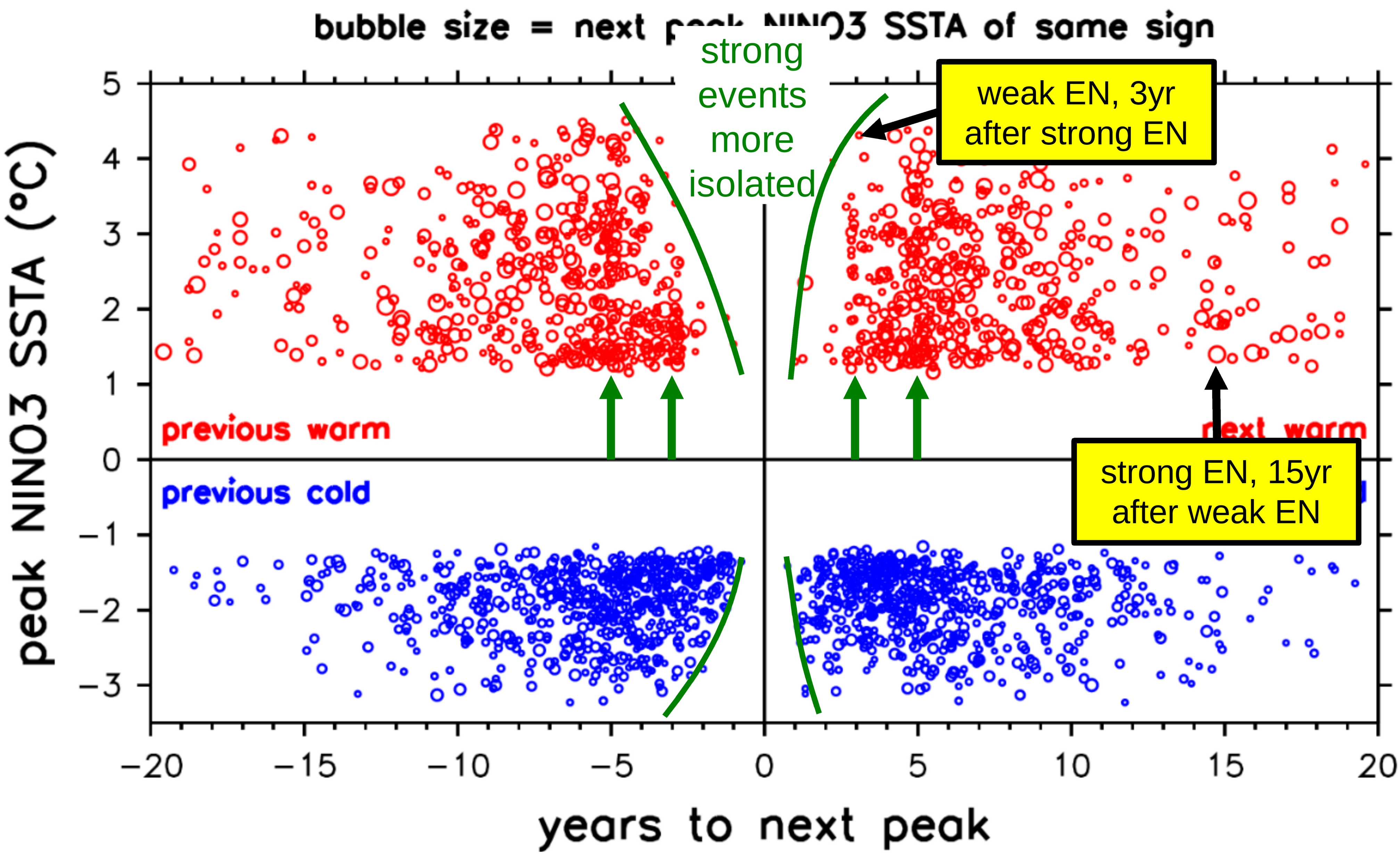



NINO3 SST spectra for 30yr records
from CM2.1U_Control−1860_D4
(a) PDF of smoothed spectra
(b) Fractional modulation
period (years)
0.5
1
2
4
8
16
32
64
128
0.0
0.5
1.0
1.5
2.0
2.5
°C²/octave
NINO3
−6
−5
−4
−3
−2
−1
0
1
2
3
log₂(amplification)
halving
doubling
5%
20%
50%
20%
5%


NINO3 SST spectra for 100yr records
from CM2.1U_Control−1860_D4
(a) PDF of smoothed spectra
(b) Fractional modulation
period (years)
0.5
1
2
4
8
16
32
64
128
0.0
0.5
1.0
1.5
2.0
2.5
°C²/octave
NINO3
halving
doubling
5%
20%
50%
20%
5%
−6
−5
−4
−3
−2
−1
0
1
2
3
log₂(amplification)

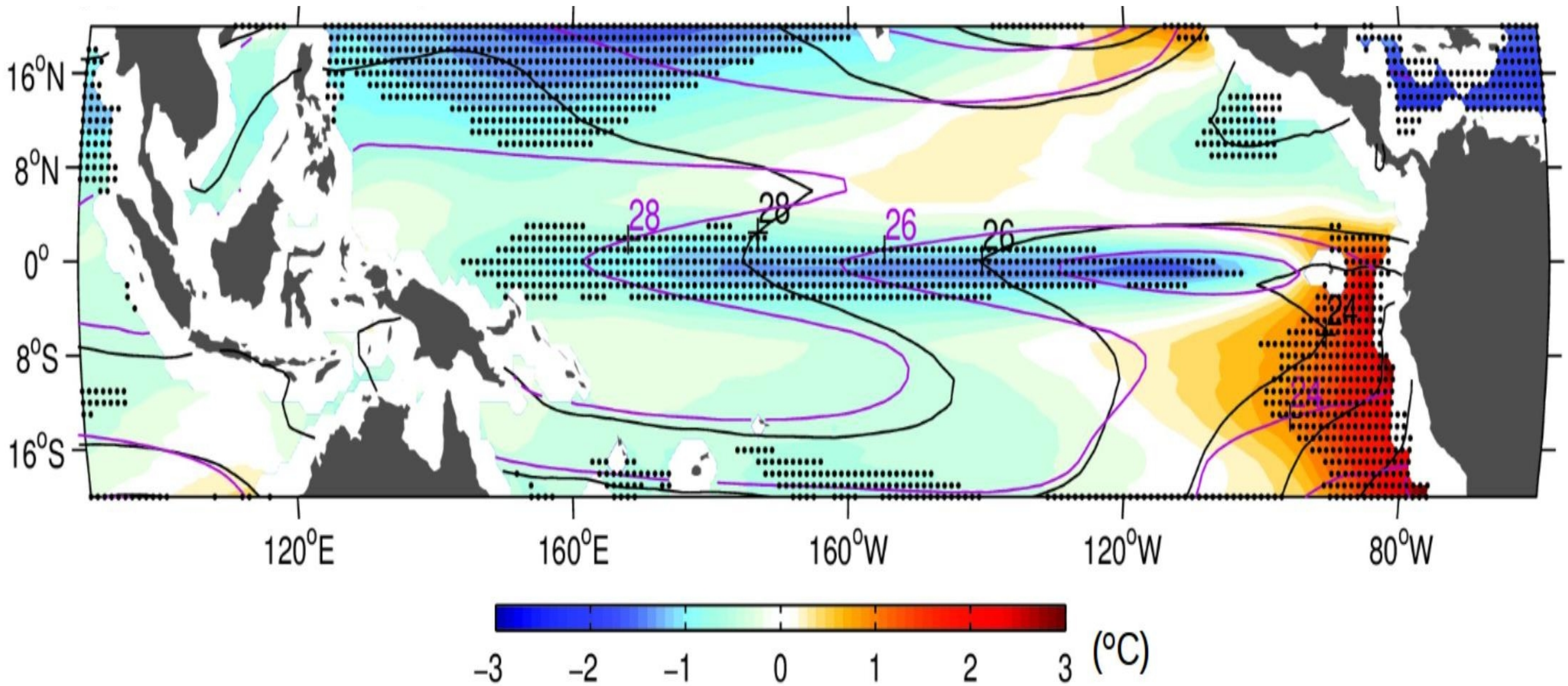

NINO3 SST spectra for 500yr records
from CM2.1U_Control-1860_D4
(a) PDF of smoothed spectra
(b) Fractional modulation
period (years)
0.5
1
2
4
8
16
32
64
128
0.0
0.5
1.0
1.5
2.0
2.5
°C2/octave
NINO3
halving
doubling
5%
20%
50%
20% 5%
−6
−5
−4
−3
−2
−1
0
1
2
3
log2(amplification)

ENSO events and their nearest neighbors



CM2.1 simulation

CMIP5 multi-model SST bias

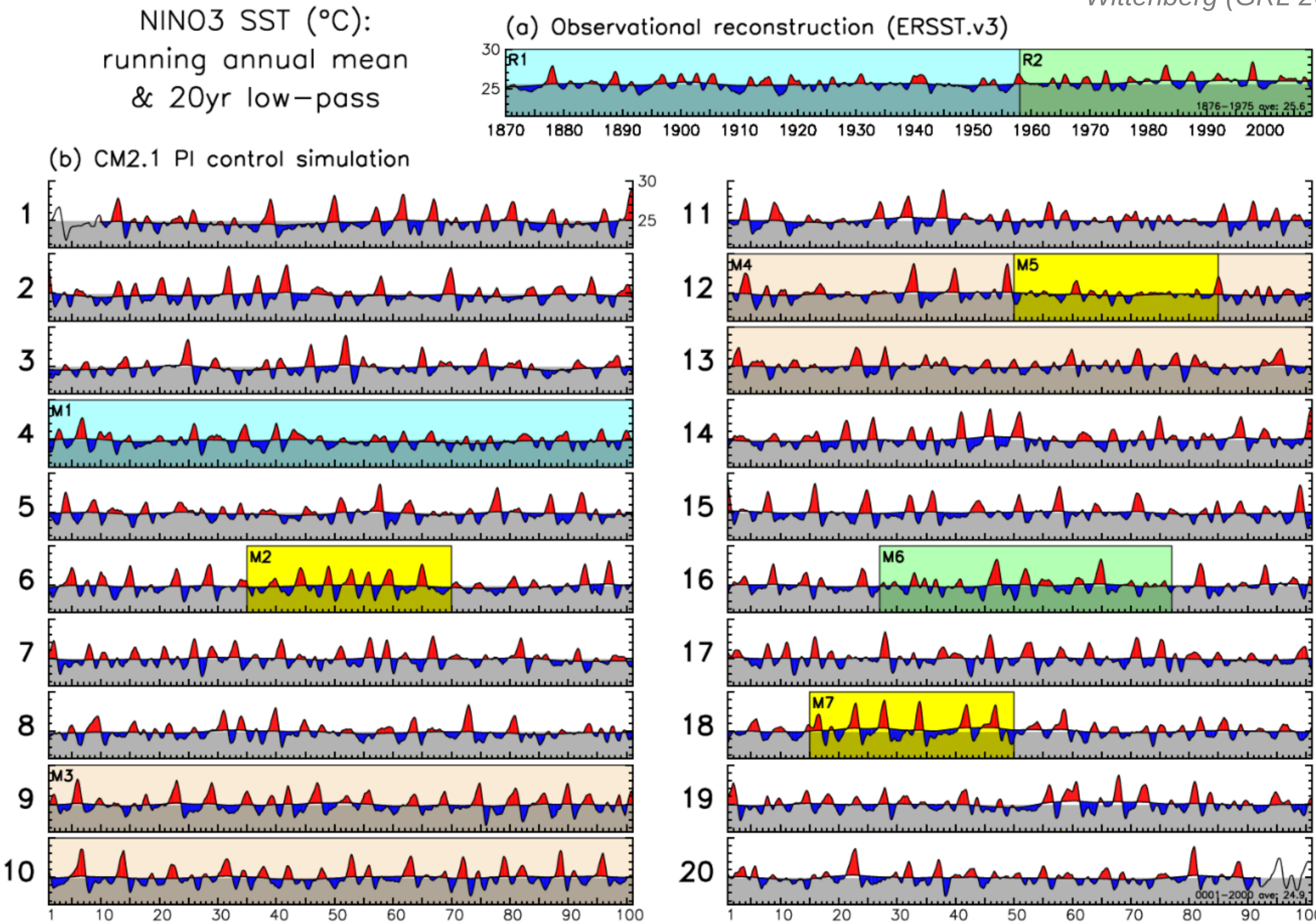


20-model mean for CMIP5 historical runs, relative to ERSST.v5.
SST contours are for obs (black) and models (purple).
Stippling: at least 90% of models have bias of same sign.

Santoso et al. (BAMS 2019)

ENSO modulation in a 2000-year control simulation

Wittenberg (GRL 2009)



Decadal variations in El Niño structure

Composite El Niño DJF anomalies, averaged over 9 reanalysis products.

Note the zonal structure in the **off-equatorial** wind stress anomalies.

1980-99

2000-10

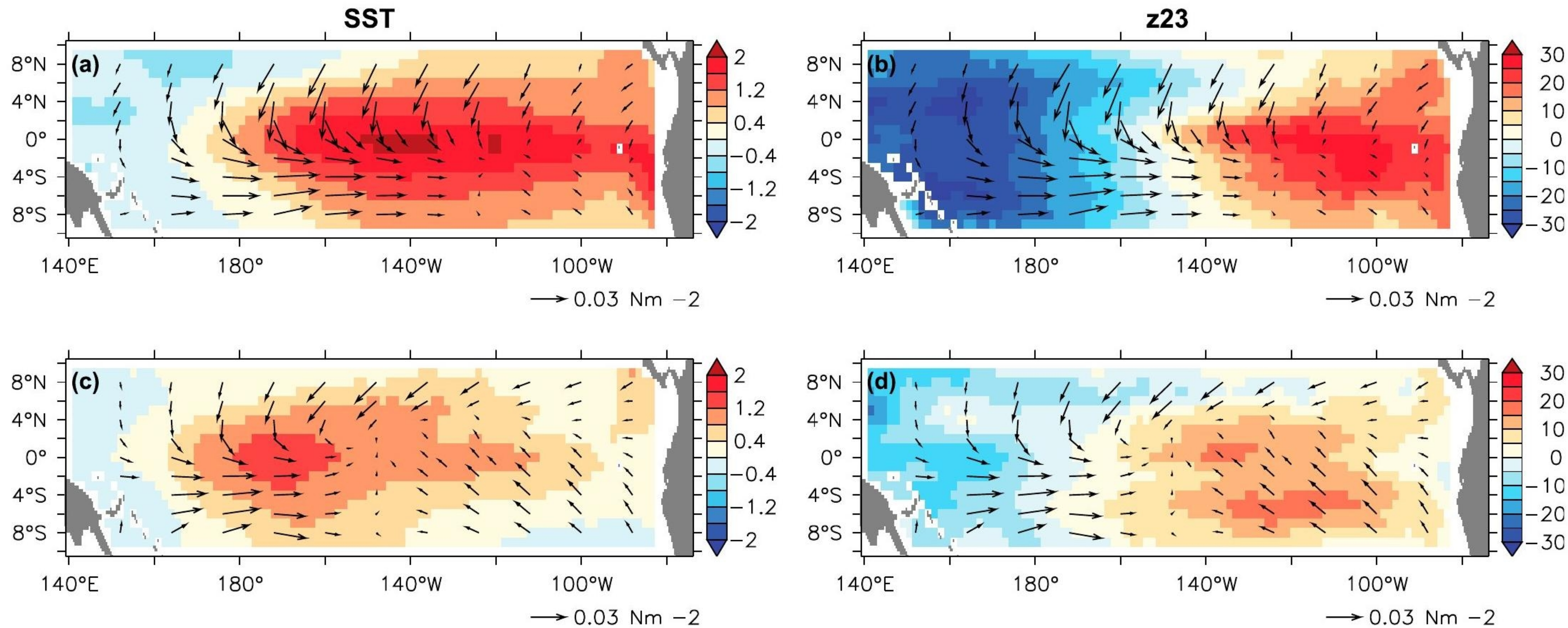


FIG. 2. Ensemble mean composites from the eight reanalysis products of (a),(c) El Niño year December–February (DJF) SST anomalies (°C) and (b),(d) depth of the 23°C isotherm (z23) anomalies (m) with wind stress anomalies (N m^{-2}) overlaid for the corresponding time period; (a),(b) 1980–99 and (c),(d) 2000–10.

Lübbecke & McPhaden (JC 2014)