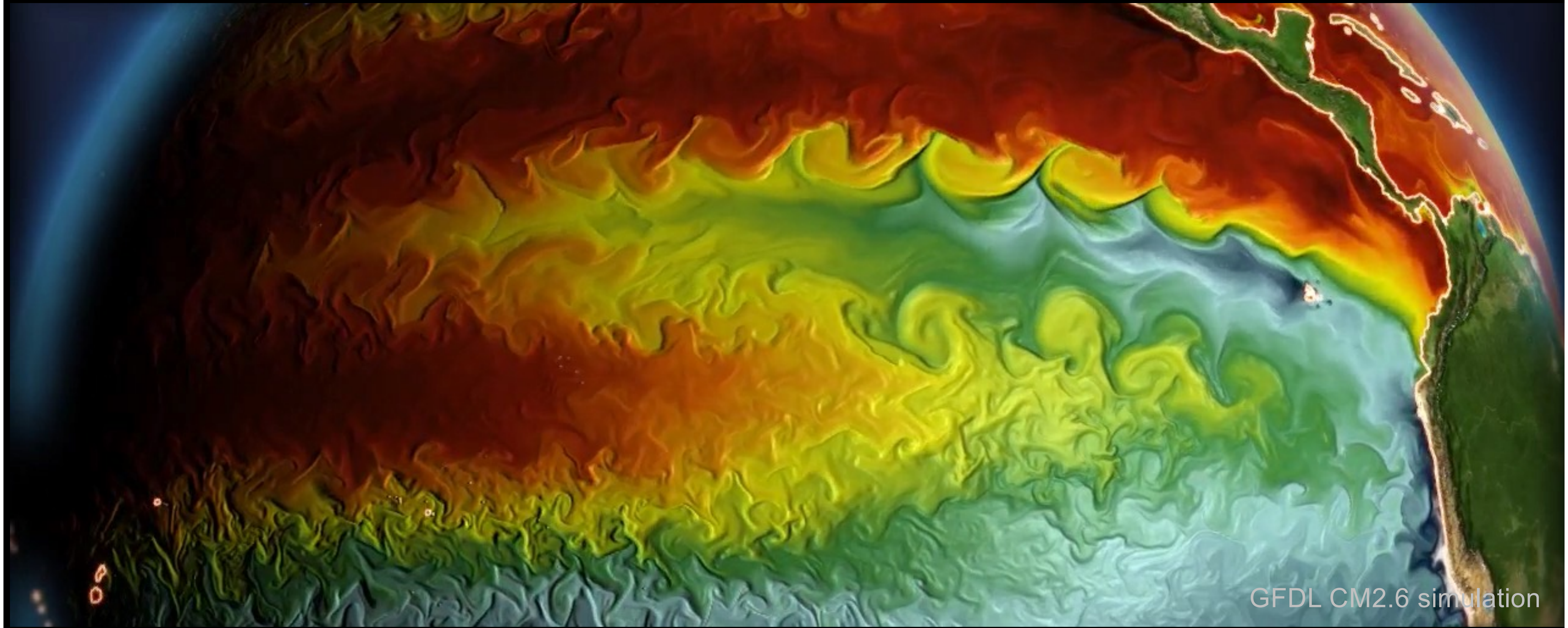
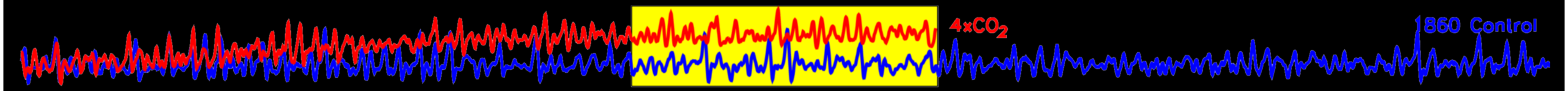
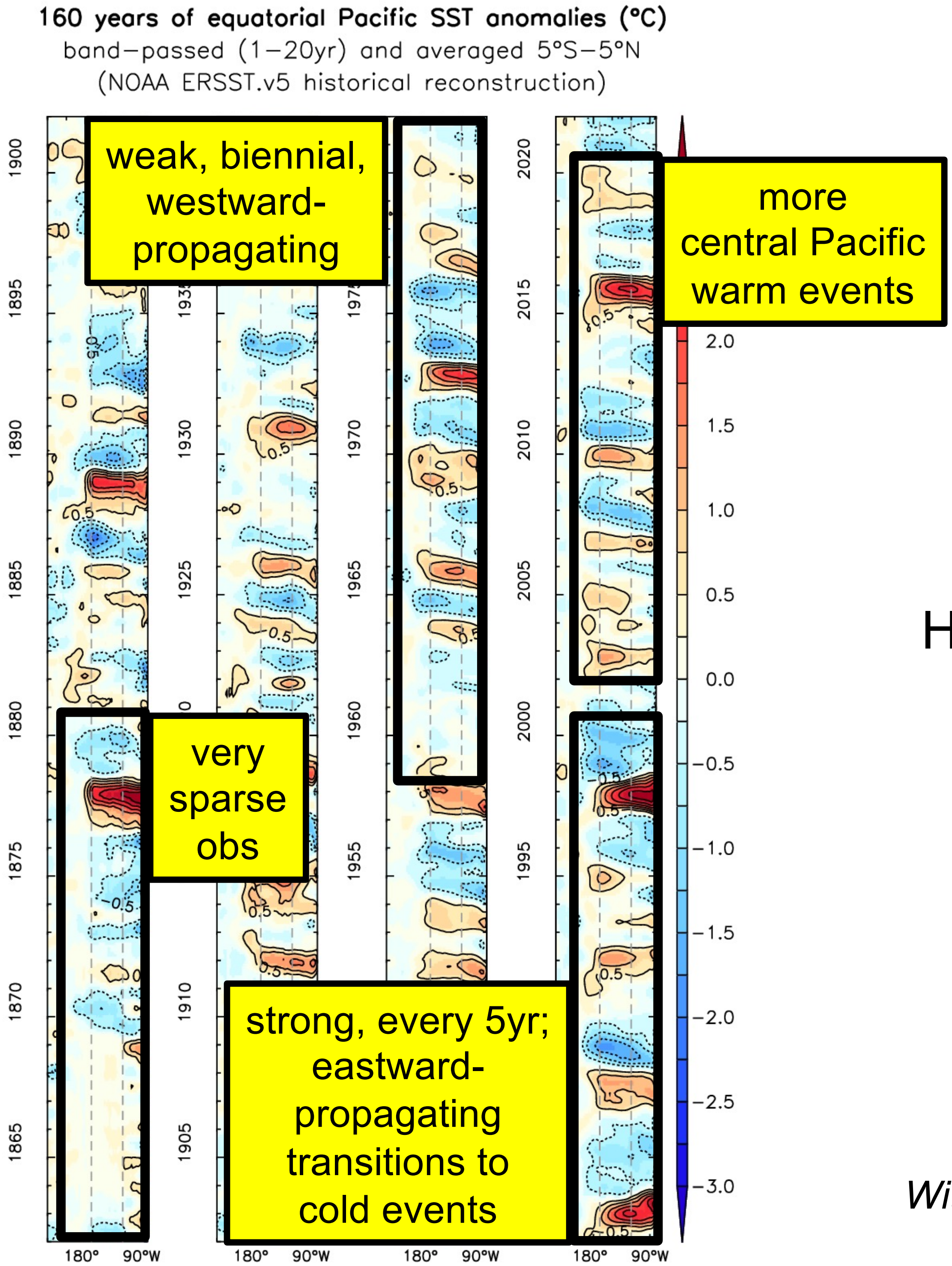
Multi-Decadal Modulation of ENSO





Andrew T. Wittenberg
NOAA GFDL, Princeton, NJ, USA

1: Observed ENSO modulation



Observed Equatorial Pacific SSTAs (K)

ENSO's behavior varies from decade to decade.

Have we observed everything that ENSO can do?

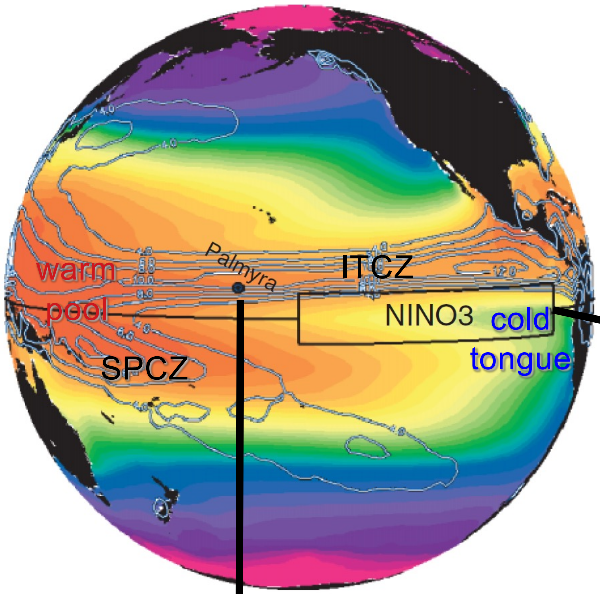
Is ENSO changing?

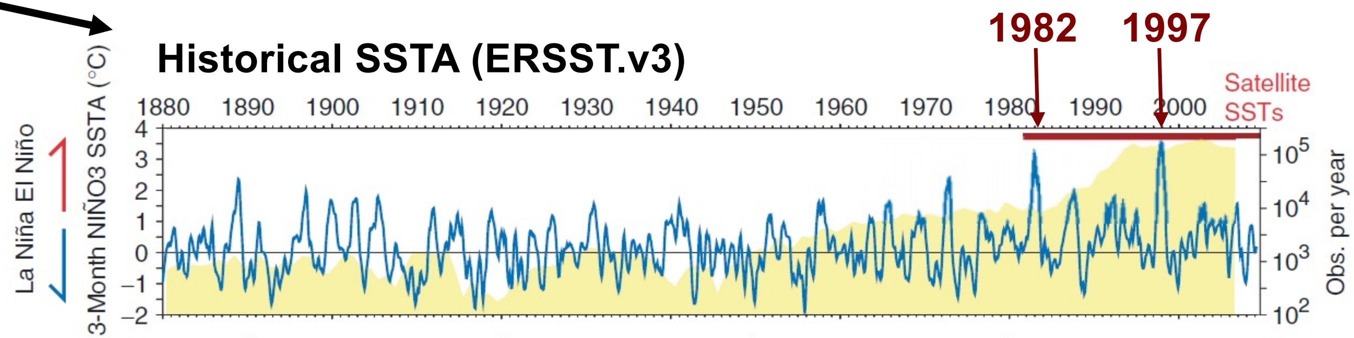
Updated from:

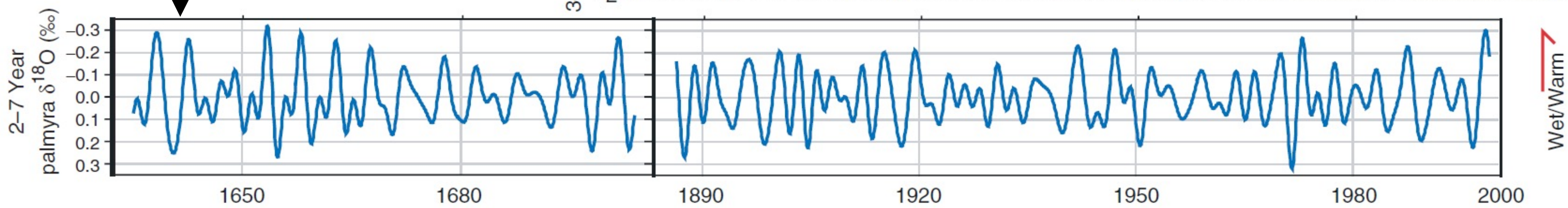
Wittenberg (US CLIVAR Variations, 2015)

Tropical Pacific Climate & ENSO Modulation

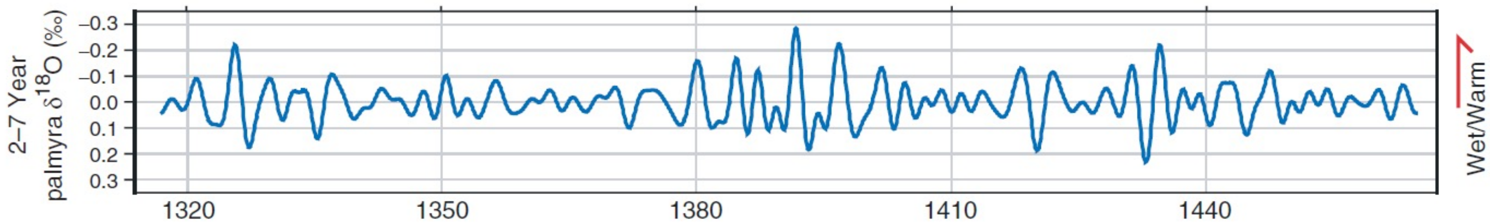
Vecchi & Wittenberg (WIREsCC 2010)
https://doi.org/10.1002/wcc.33



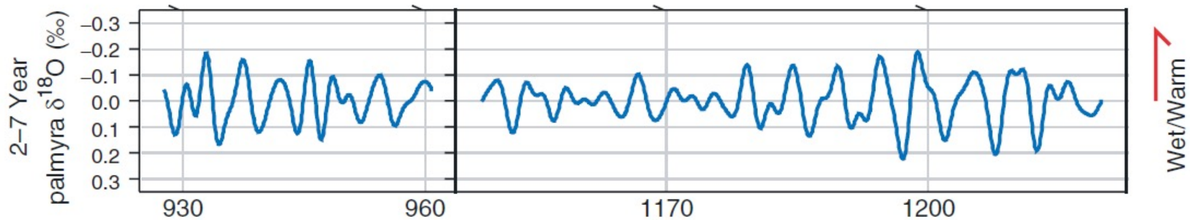




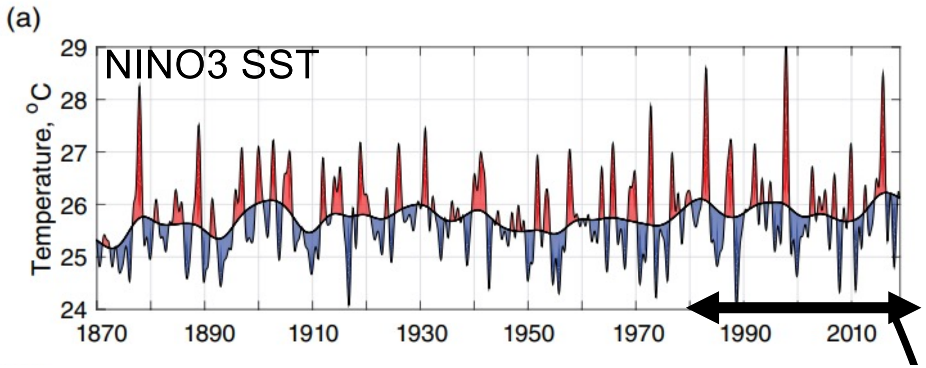
Palmyra corals (Cobb et al., Nature 2003)



Multiproxy reconstructions:
e.g. Li et al. (NCC 2011);
Emile-Geay et al.
(J. Climate, 2013ab);
McGregor et al. (CP 2013)



ENSO waxes & wanes. It has strengthened recently — why?
ENSO also obscures detection of slower climate changes (decadal, global warming).



Observed Equatorial Pacific SSTA & Rainfall

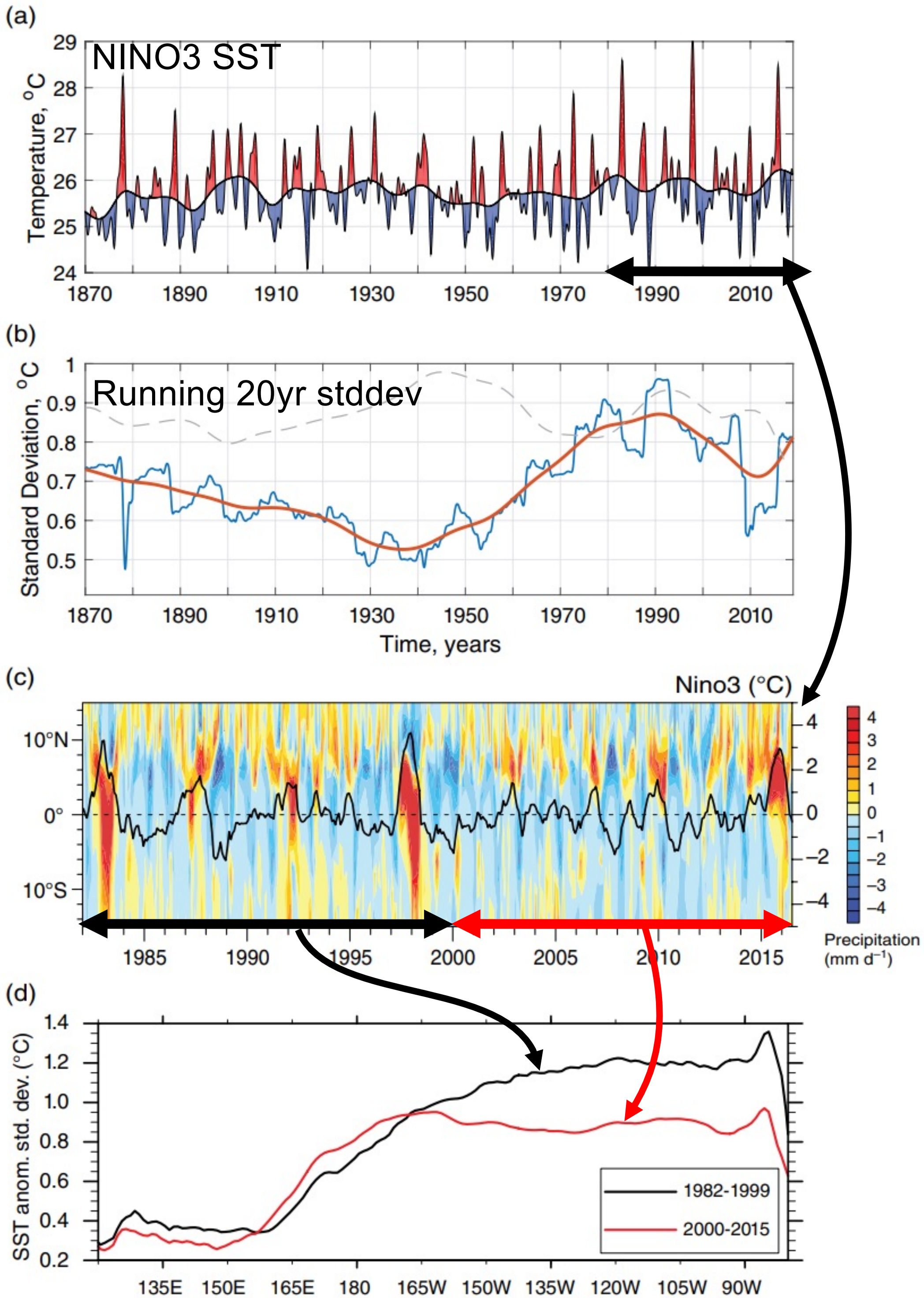
Strong ENSO near end of instrumental record.

Since 1998: a muted equatorward shift of ITCZ rain during warm events,

and weaker SSTAs in the east.

Fedorov et al. (AGU 2020)

https://doi.org/10.1002/9781119548164.ch8



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Multidecadal variations in El Niño structure

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

After 1999: **SSTAs weaker & farther west; weaker wind response; less thermocline tilt.**

1980-99

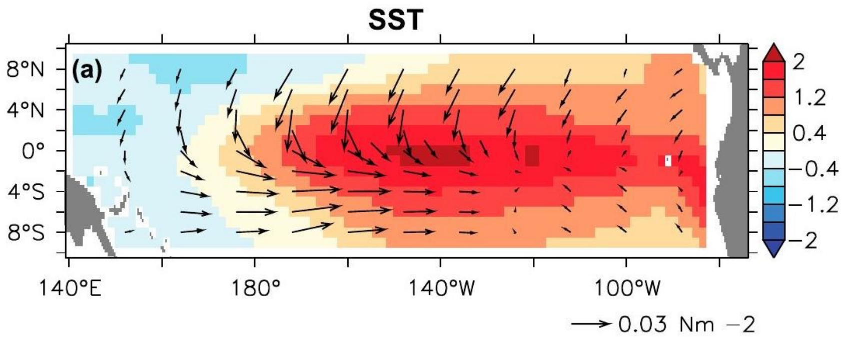
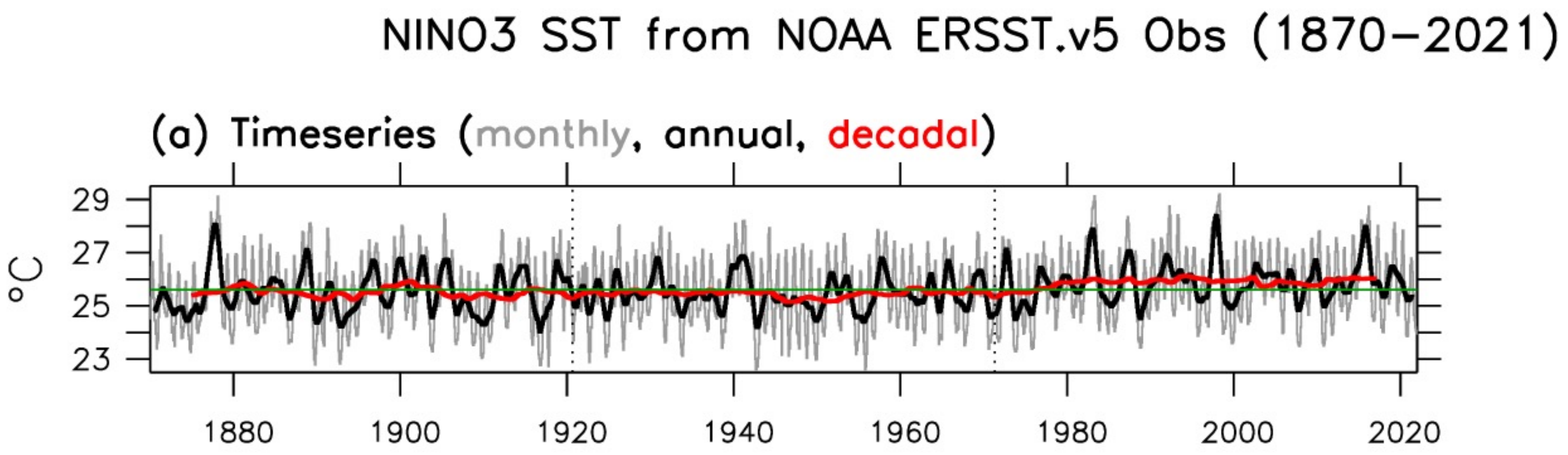
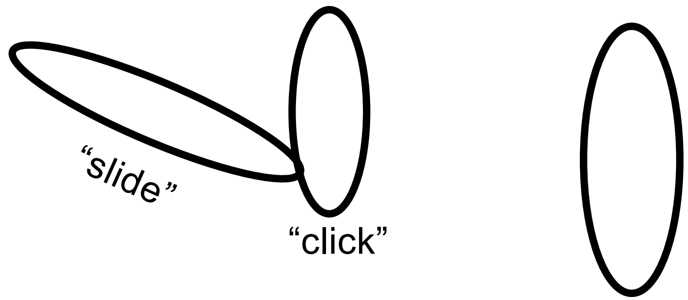


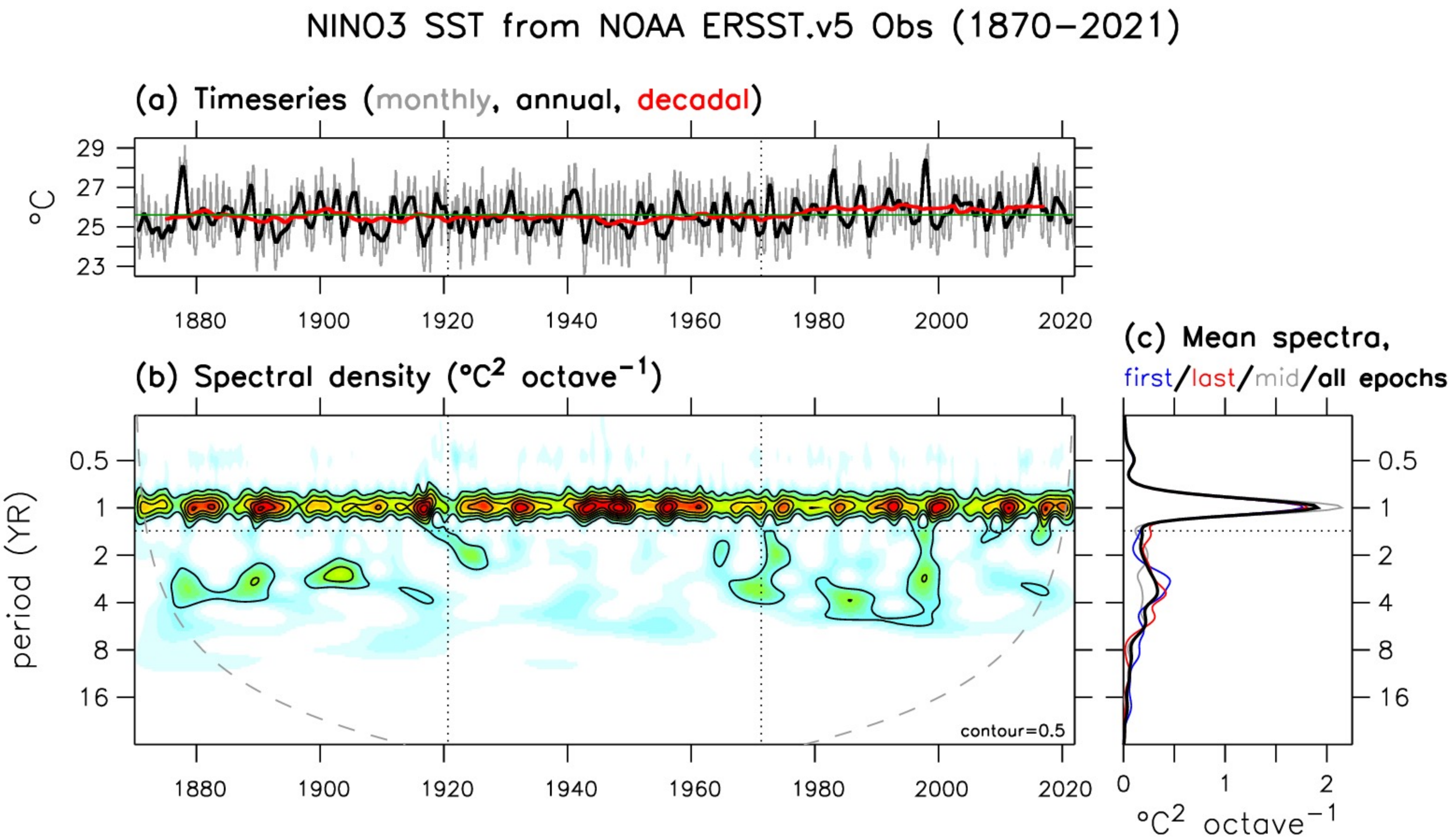
FIG. 2. Ensemble mean composites from the eight reanalysis products of (a),(c) El Niño year December–February (DJF) SST anomalies (°C) and (b),(d) depth of the 23°C isotherm (z23) anomalies (m) with wind stress anomalies (N m^{-2}) overlaid for the corresponding time period; (a),(b) 1980–99 and (c),(d)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

Lübbecke & McPhaden (JC 2014); also Dieppois et al. (NCEE 2021)





ENSO has a **broad spectrum** – due to both its **episodic** nature, and **variations** in its dominant time scales.



ENSO has a **broad spectrum** – due to both its **episodic** nature, and **variations** in its dominant time scales.

2: ENSO modulation in models

Where models can help

1. They **integrate** sets of hypotheses.
   - ENSO arises from **interactions** of feedbacks, some nonlinear.
   - **Quantitative** solutions ("devil in the details").

2. Enable **data assimilation** to integrate diverse, sparse obs.
   - Helps us to **reconstruct** past climate variations.
   - **Confront** models/hypotheses with measurements → "increments"

3. Enable seasonal-to-decadal **forecasts** & future **projections**.
   - "Alternate futures," with quantified **uncertainties** arising from intrinsic variability.

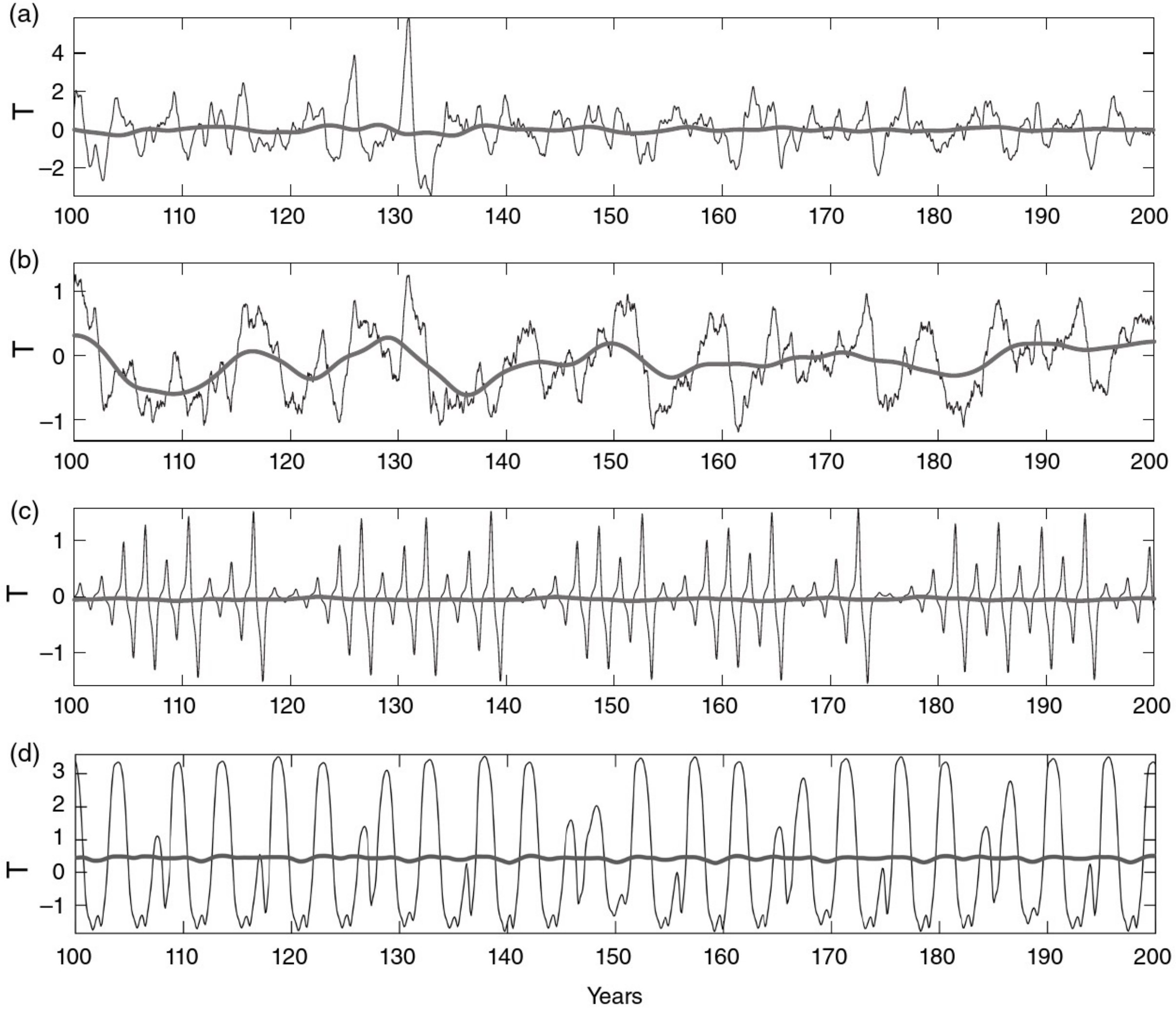
4. Aid **detection & attribution** of past climate changes.
   - "Alternate pasts," with suppressed **forcings & feedbacks**.

5. Provide a **detailed** look at "Earth-like" climate systems.
   - Long runs, large ensembles → **statistical significance**.
   - **Comprehensive** & continuous view of every modelled variable.

6. Used properly, they can aid **understanding**.
   - **Test** & cull hypotheses; **predict** emergent phenomena; **target** new observations.

Idealized models of ENSO

Decadal modulation doesn't *require* external forcings.



RO + multiplicative noise

Levine et al. (2016)

DO w/ nonlin growth rate

Choi et al. (2013)

Chaotic linear oscillator

Mu et al. (2007)

CZ model

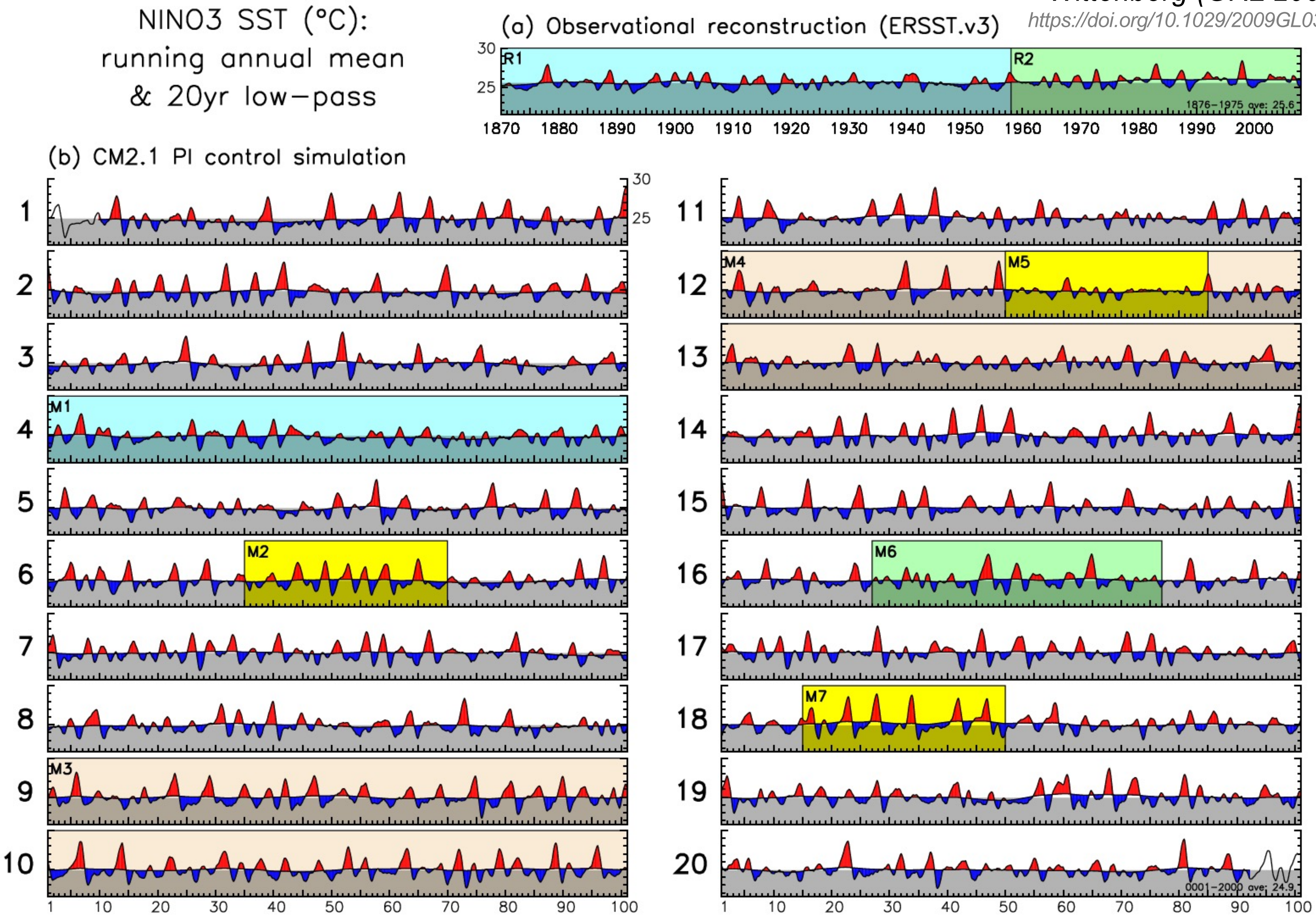
Bejarano & Jin (2008)

Fedorov et al. (AGU 2020)

https://doi.org/10.1002/9781119548164.ch8

ENSO modulation in a 2000-year CGCM simulation

Wittenberg (GRL 2009)
https://doi.org/10.1029/2009GL038710

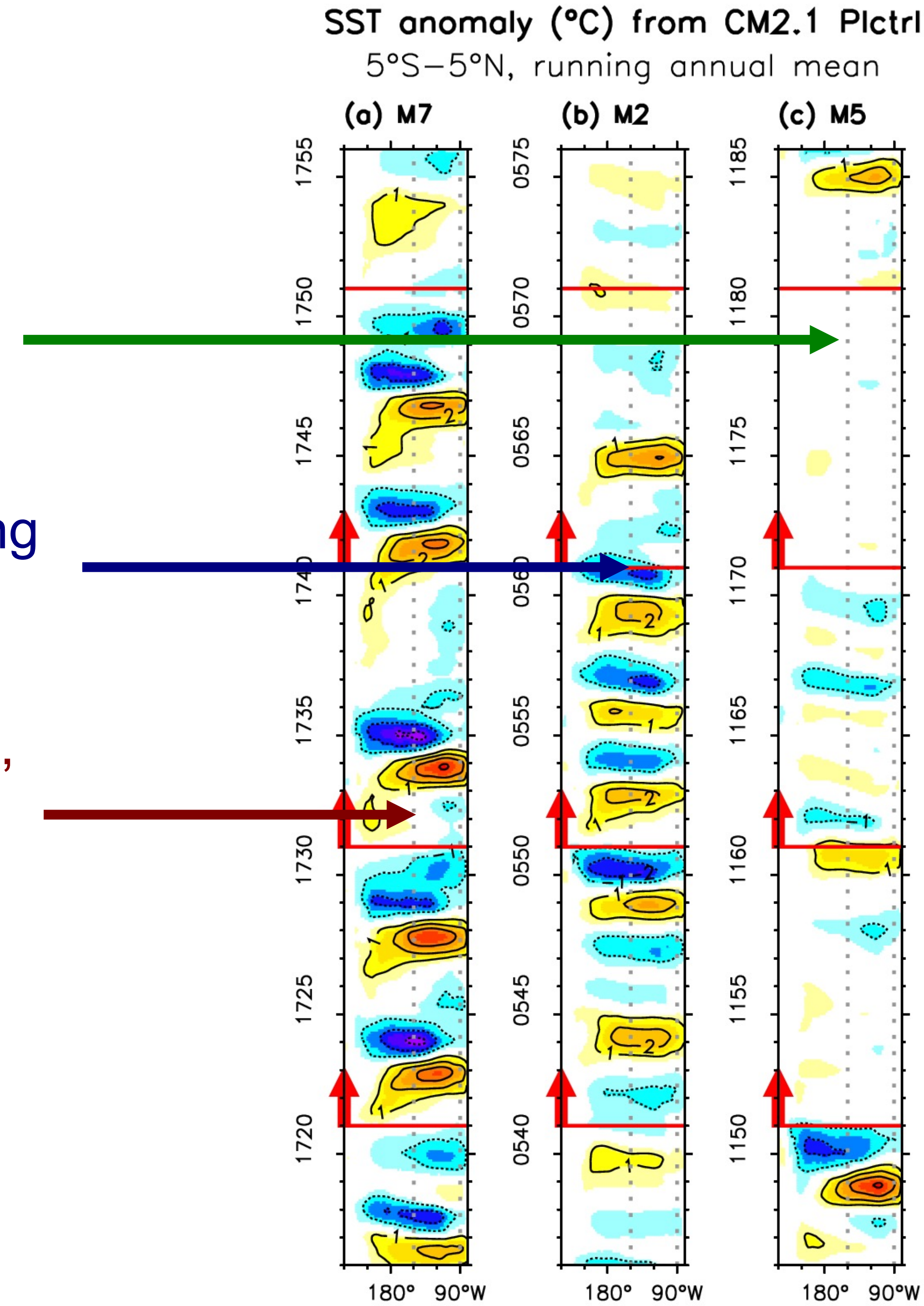


Epochs of unusual ENSO behavior

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

regular, westward propagating
(1960s & 70s)

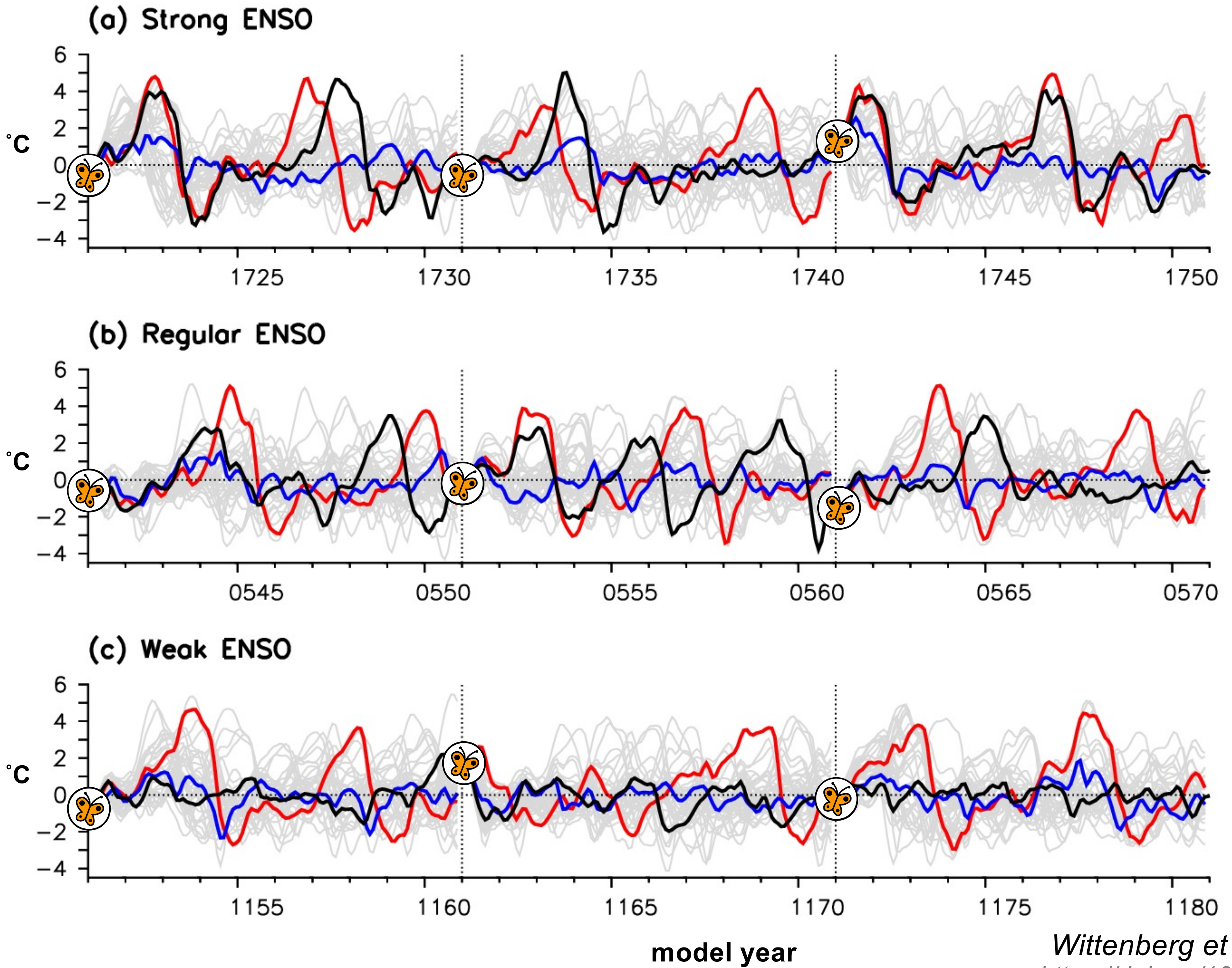
strong, skewed, long period, eastward propagating
(1980s & late 1990s)



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

Wittenberg et al. (J. Climate, 2014)
https://doi.org/10.1175/JCLI-D-13-00577.1

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

CM2.1's intrinsically-generated extreme-ENSO epochs are fundamentally **unpredictable.**

Wittenberg et al. (J. Climate, 2014)

https://doi.org/10.1175/JCLI-D-13-00577.1

Long-term memory?

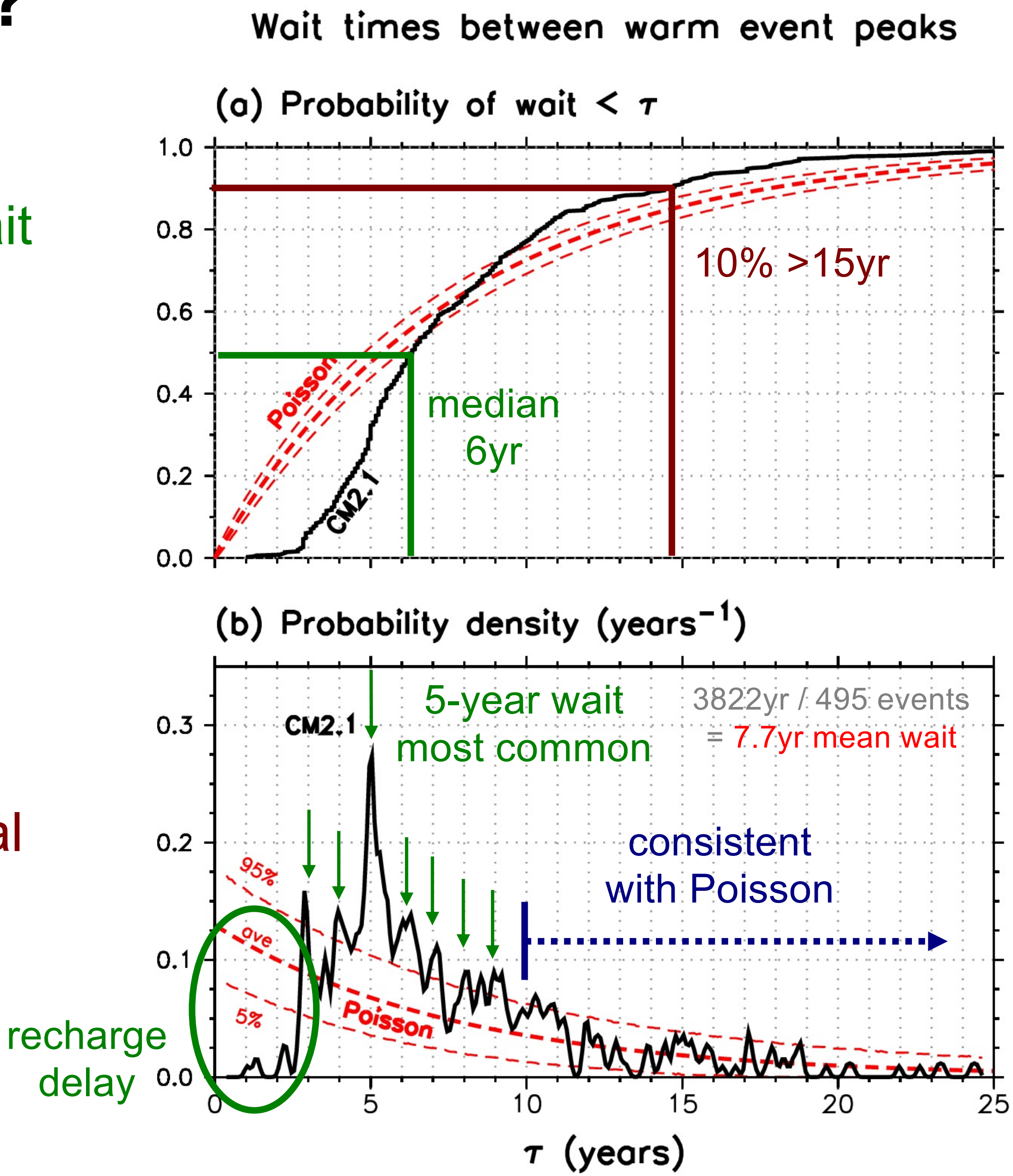
Distribution of inter-event wait times suggests that NINO3 SSTA *might* have some memory beyond 5 years.

But beyond 10 years?

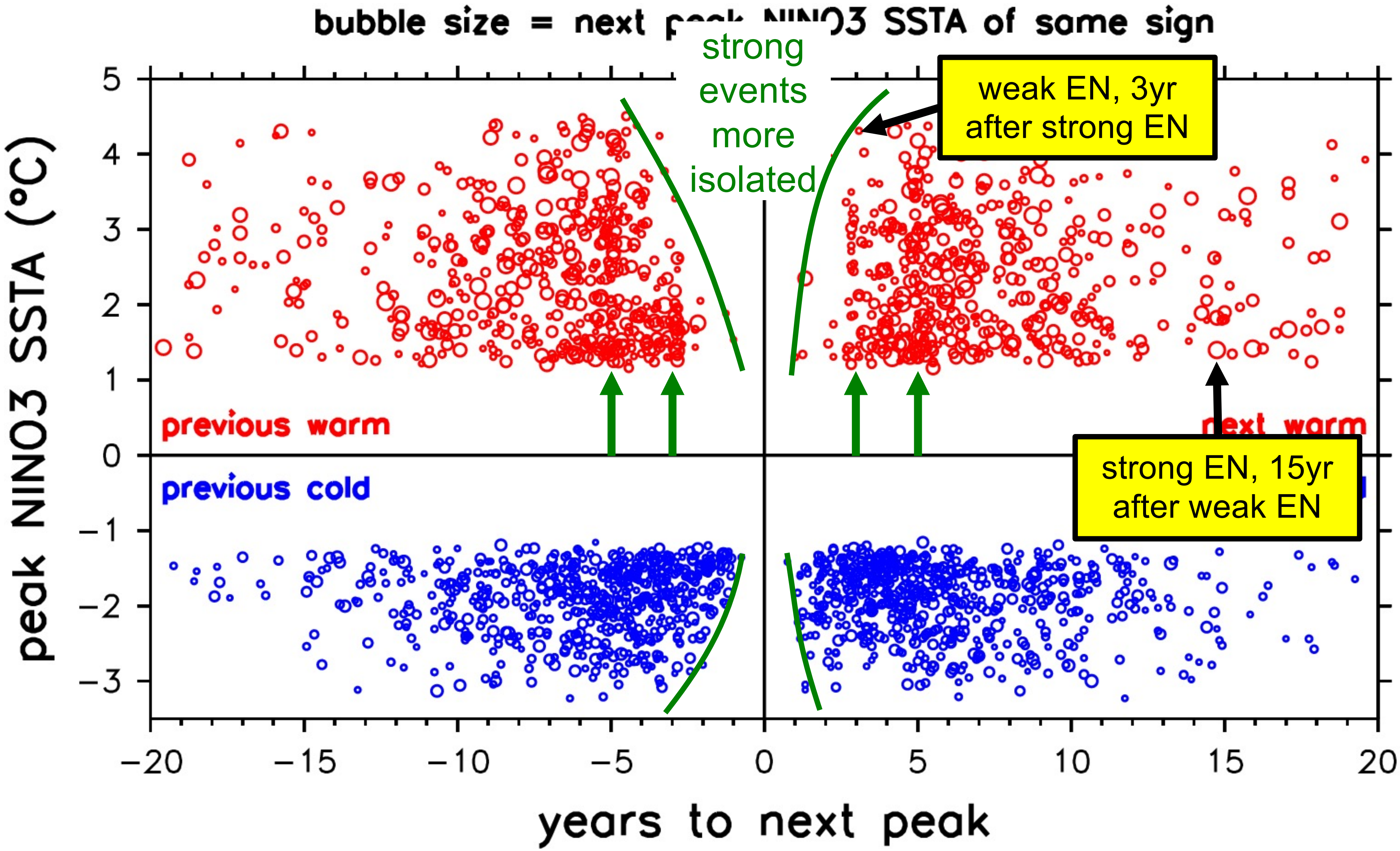
Even a *purely memoryless* ENSO would give occasional waits of 20 years or more, as seen in CM2.1.

Wittenberg (GRL 2009)

https://doi.org/10.1029/2009GL038710



ENSO events and their nearest neighbors

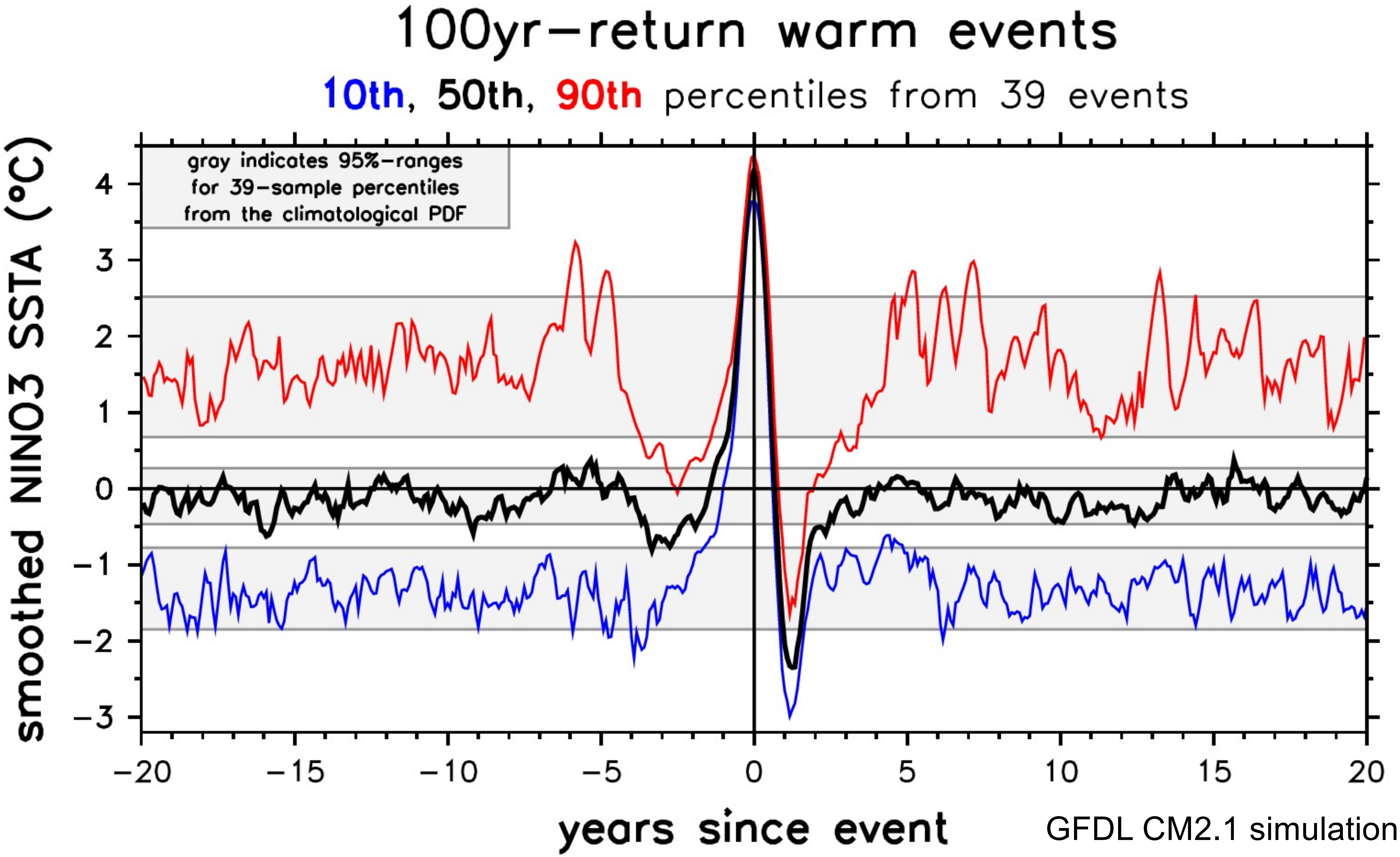


GFDL CM2.1 simulation

Best hope for long-term ENSO predictability?

(e.g. Gonzalez & Goddard, CD 2016; DiNezio et al., CD 2017; Thomas et al., JC 2018)

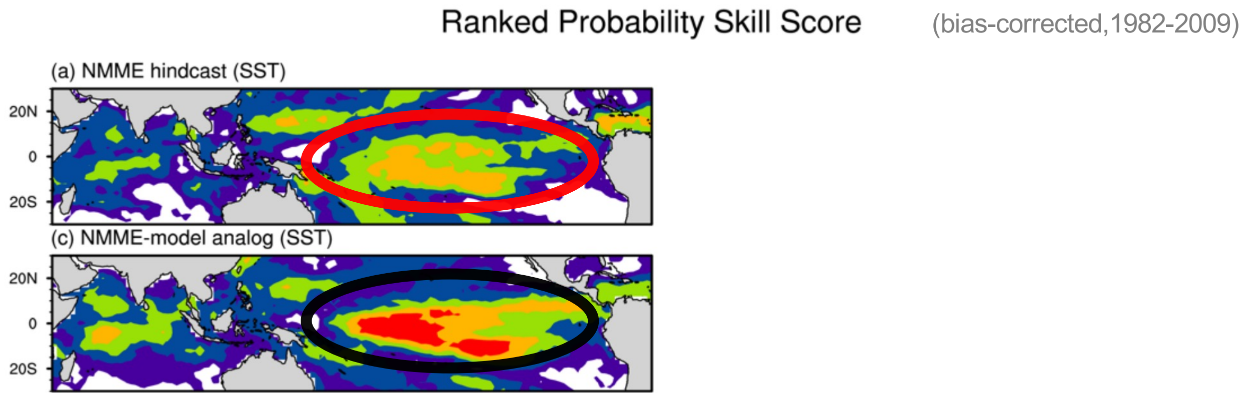
NINO3 memory might last 5yr, following strong warm events.

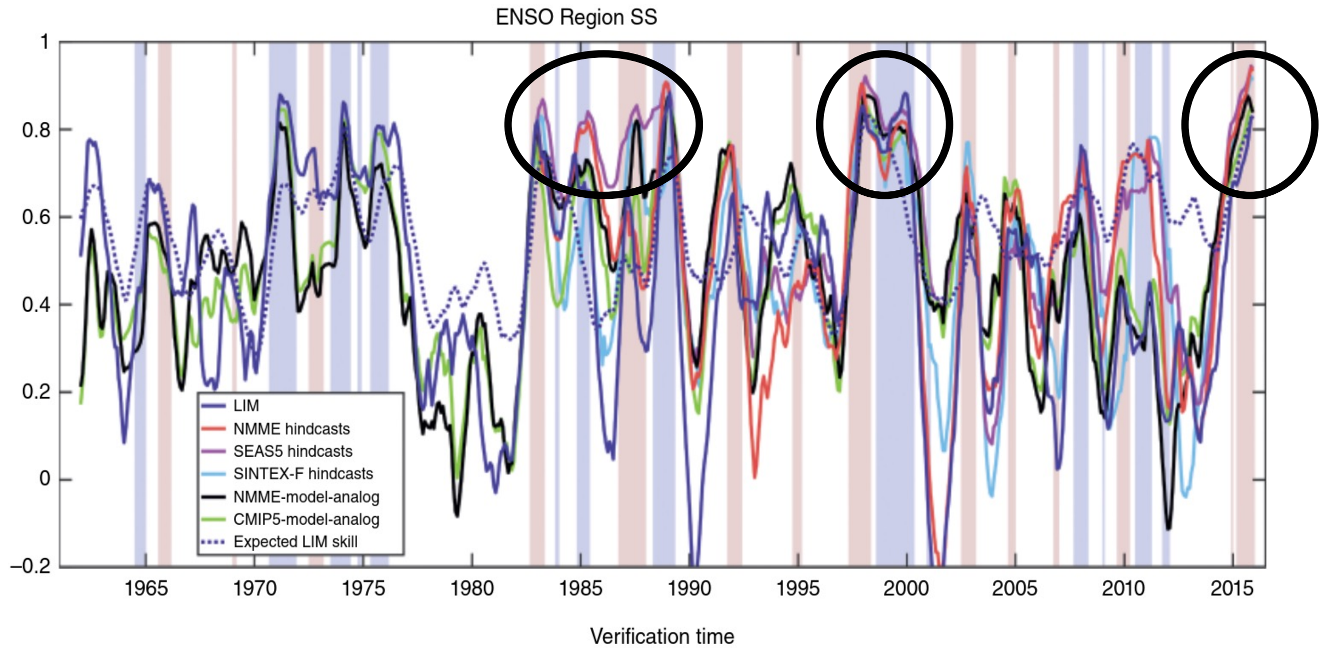


GFDL CM2.1 simulation

Modulation of ENSO predictability

*Existing **long model control runs** are like "libraries" of ENSO behavior.*
*Find **analogs** of obs SST & SSH → trace how those states evolved in control runs.*





*→ Like a forecast with **no initialization shock**.*

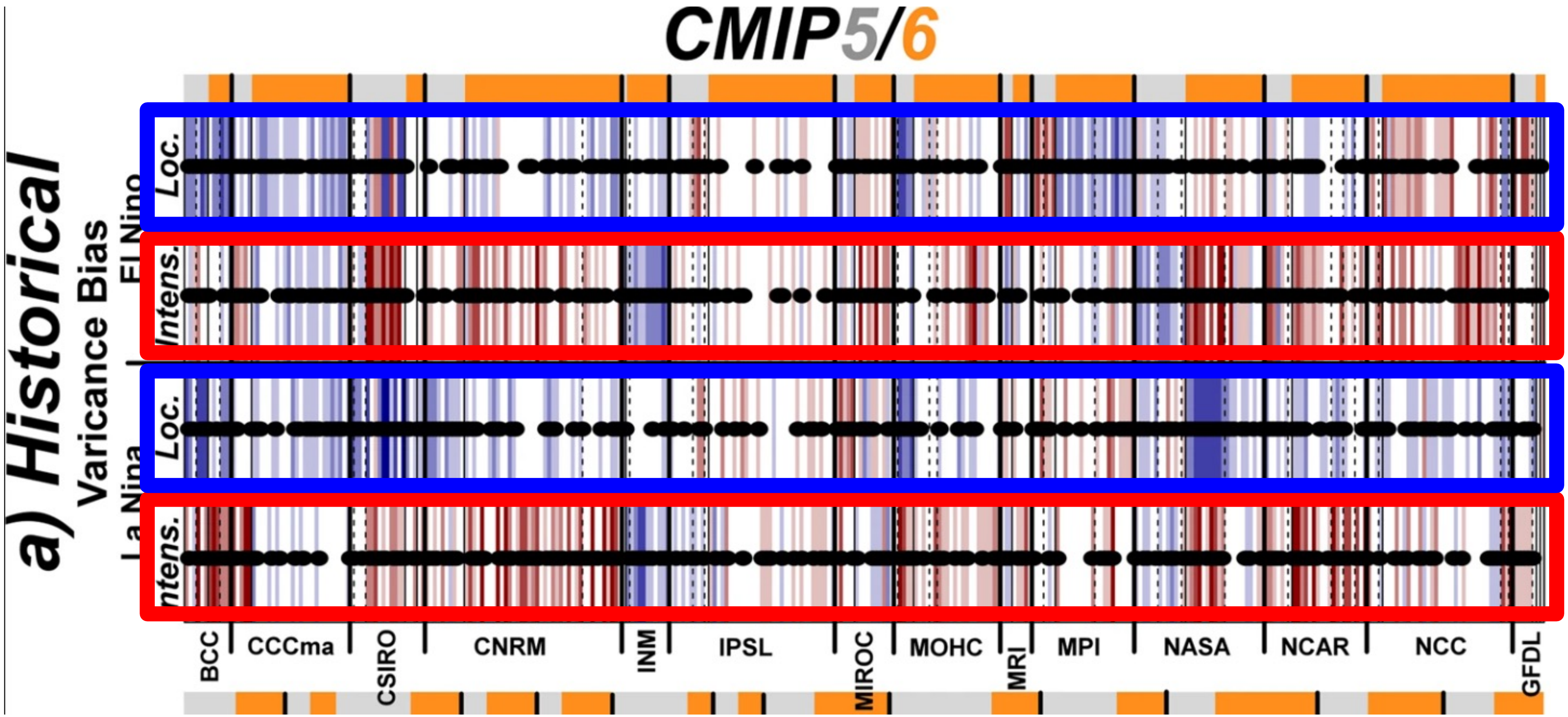
At 6-month leads in the tropics, **analogs** from the NMME control runs beat the same models' **initialized forecasts**!

Permits rapid assessment of secular variations in **predictability**.

Epochs with **stronger ENSO** and **longer persistence** → better prediction skill.

Ding et al. (JC 2018; GRL 2019)
L'Heureux et al. (AGU 2020)
Karamperidou et al. (CD 2014)
Weisheimer et al. (GRL 2022)

Simulated modulation of ENSO intensity & longitude



Compared to obs, many CGCMs have **more amplitude modulation** and **less longitude modulation** of the EN/LN SSTA peaks.

Dieppois et al. (NCEE 2021): https://doi.org/10.1038/s43247-021-00285-6

Summary, 1 & 2: ENSO modulation in obs & models

1. ENSO's behavior varies from decade to decade

- **Amplitude, spectra, patterns, evolution, mechanisms, teleconnections, predictability**
- Appears in both **obs** (e.g. 1978 & 1998 shifts) and **models**
- **Broad spectrum** due to ENSO's **episodic** nature, and **variations** of dominant time scales

2. Much of ENSO's historical modulation could have been *intrinsic*

- Modulation can arise in models with **no changes** in external forcings
- This intrinsic component of modulation may be **decadally unpredictable**
- Interannual memory (recharge) + **Poisson statistics** → multidecadal modulation

3. Modulation complicates model evaluation & climate change detection

- Need **long obs records, long simulations, large ensembles** for robustness
- Obs might not yet have spanned all possible ENSO behaviors
- Unprecedented "**surprises**" have been common — and may continue

4. Epochs with strong/persistent ENSO tend to boost prediction skill

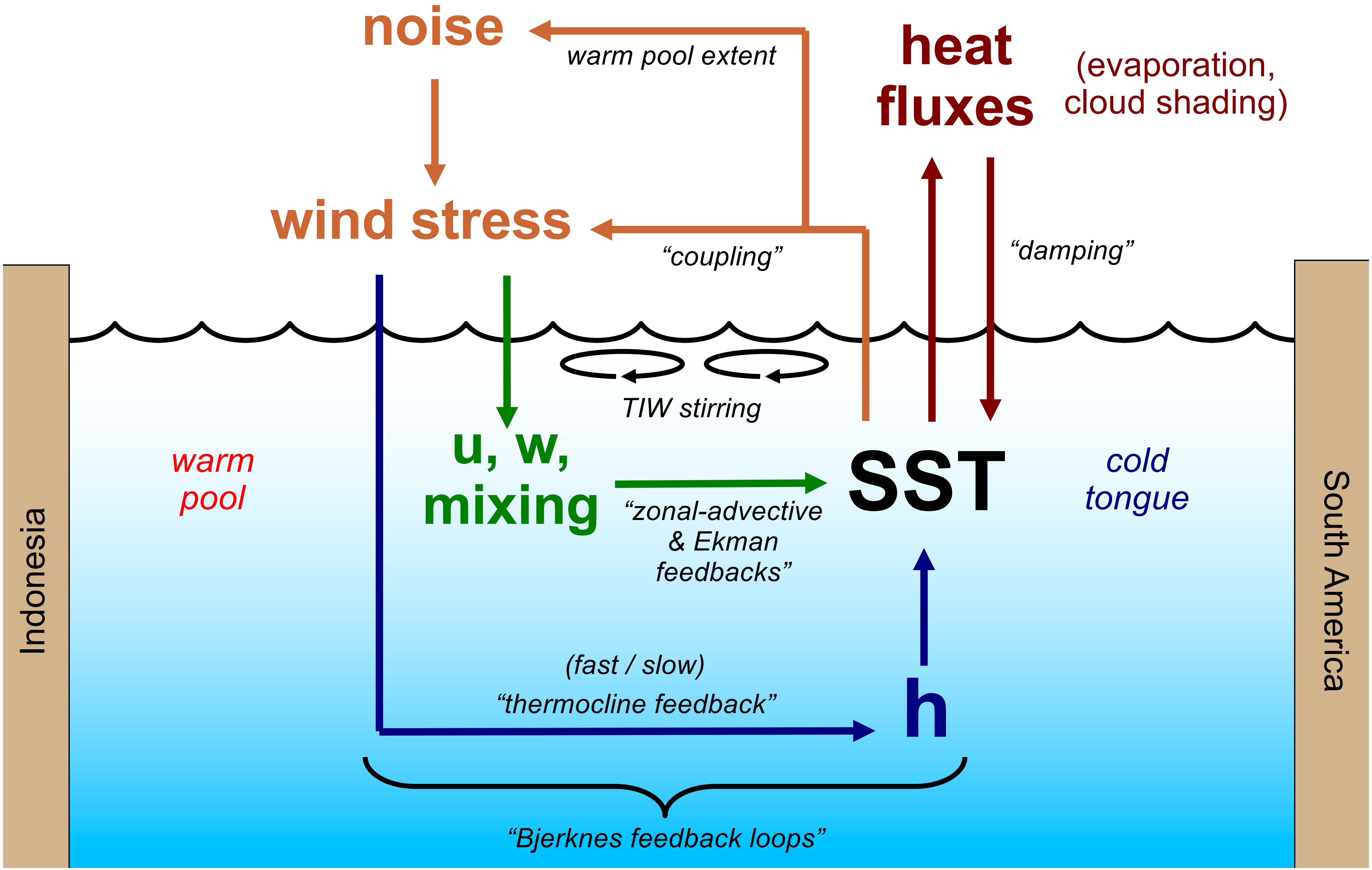
- Due to stronger **recharge/discharge** that imparts multi-year memory
- Strong ENSO events (especially strong El Niños) tend to be more isolated
- No evidence yet for strong *decadal* memory/predictability of ENSO

What *causes* ENSO modulation?

3: ENSO feedbacks & nonlinearites

Keys to understanding
ENSO modulation & its impacts.

Key ENSO feedbacks



Mixed-layer temperature anomaly equation

weaker in future?

$$
\begin{aligned}
T'_t = & -u'\overline{T}_x - \overline{u}T'_x - (u'T'_x)' \\
& -v'\overline{T}_y - \overline{v}T'_y - (v'T'_y)' \\
& -w'\overline{T}_z - \overline{w}T'_z - (w'T'_z)' \\
& +\text{eddy} + Q'_{\text{sfc}}
\end{aligned}
$$

stronger in future

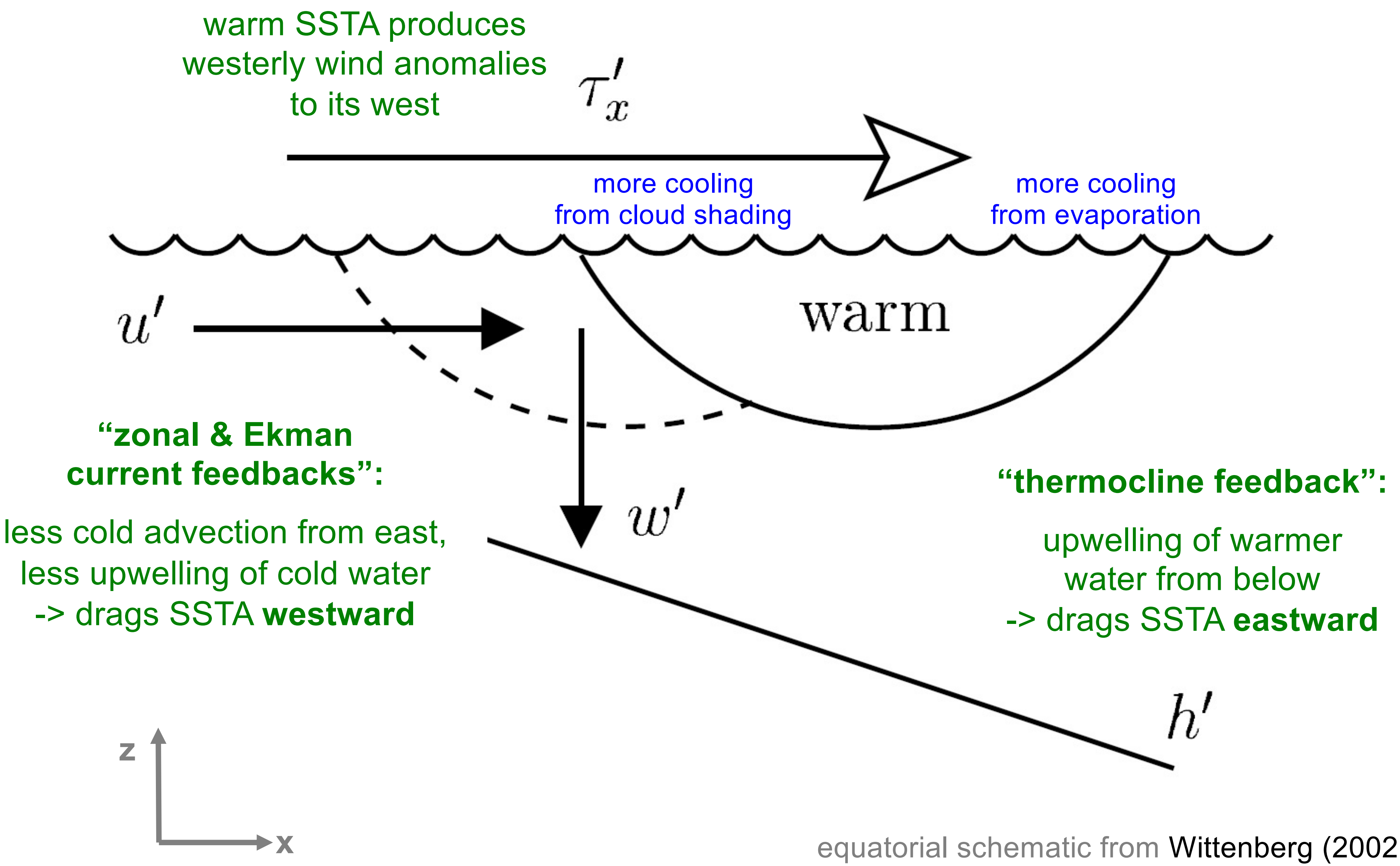
stronger in future?

dominant terms near equator

Key to understanding the influence of **climate change** on ENSO.

Feedbacks depend on background zonal & meridional asymmetries.

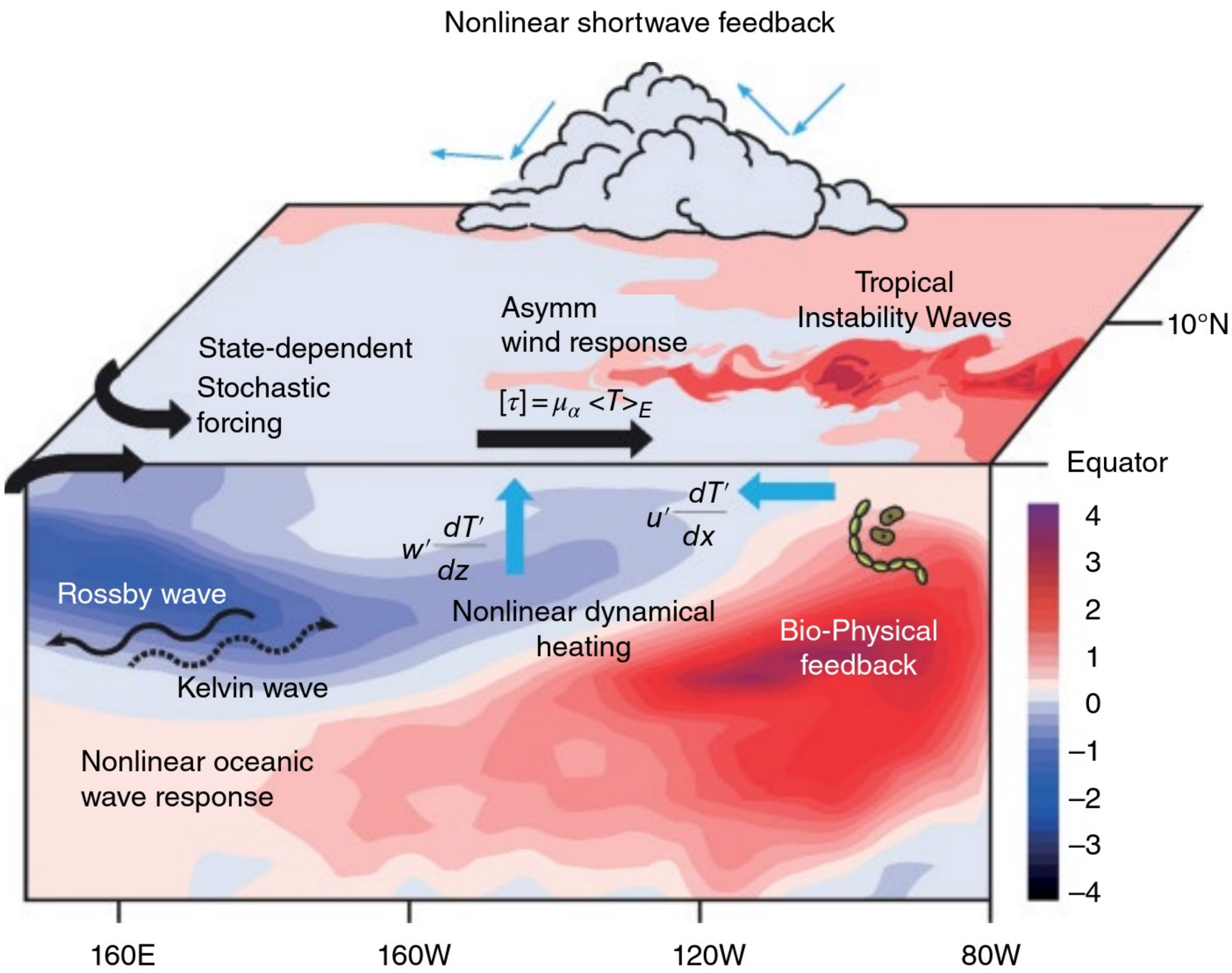
SST mode (Neelin, JAS 1991)



equatorial schematic from Wittenberg (2002)
https://extranet.gfdl.noaa.gov/~atw/research/thesis

Key ENSO nonlinearities

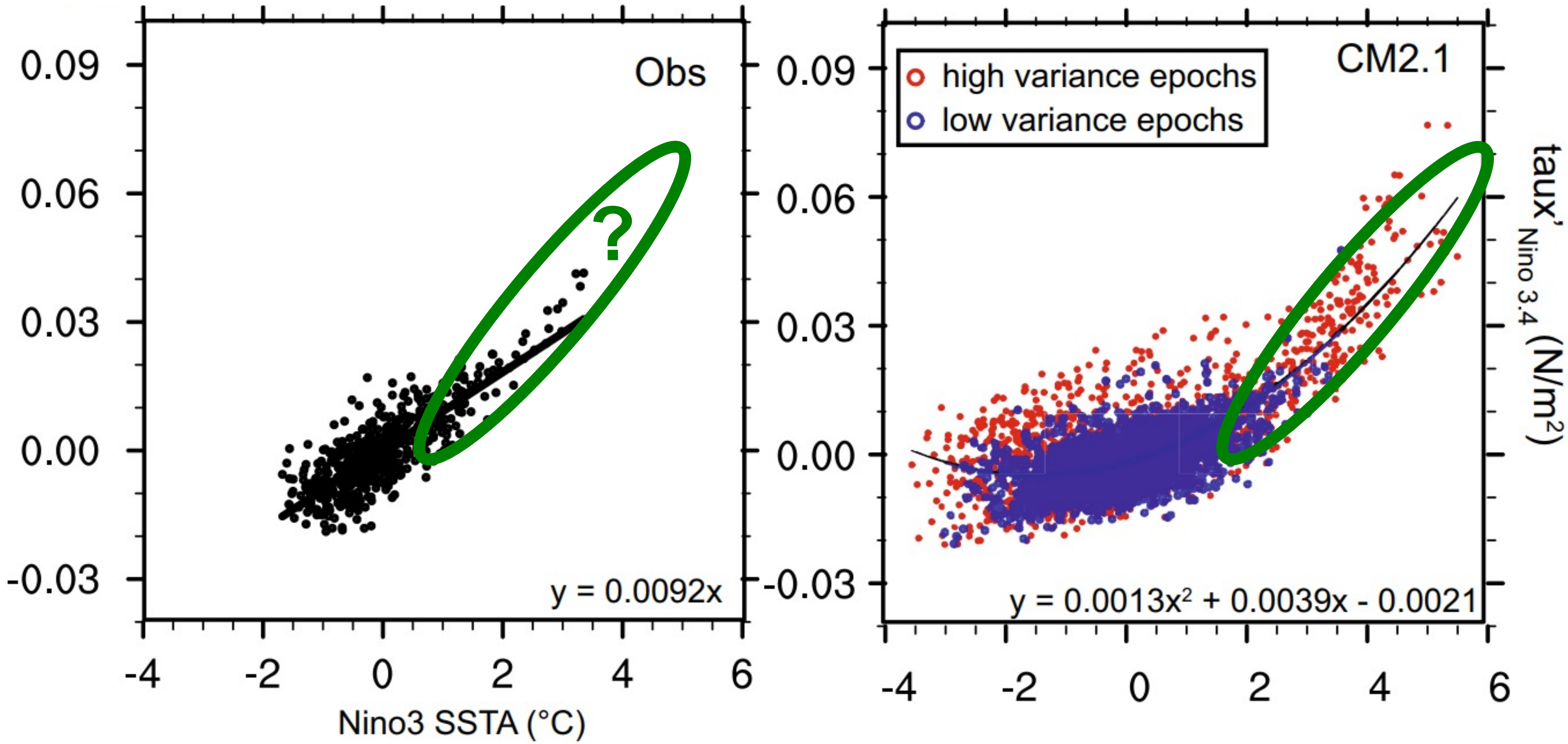
Lead to ENSO asymmetry & irregularity, interactions across time scales, and feedbacks from & onto the background climate.



An et al. (AGU 2020): https://doi.org/10.1002/9781119548164.ch7

Key ENSO nonlinearities

Active epochs → stronger SSTAs → more nonlinear wind response.
Contributes to ENSO asymmetry & modulation in CM2.1.



Atwood et al. (CD 2017): https://doi.org/10.1007/s00382-016-3477-9

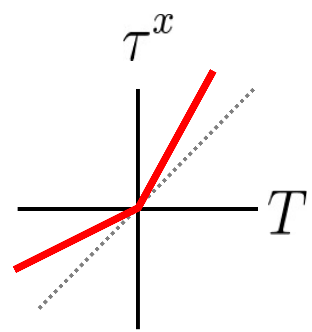
Wind nonlinearity → asymmmetry

Choi et al. (J. Climate, 2013)

https://doi.org/10.1175/JCLI-D-13-00045.1

stronger wind response during warm events

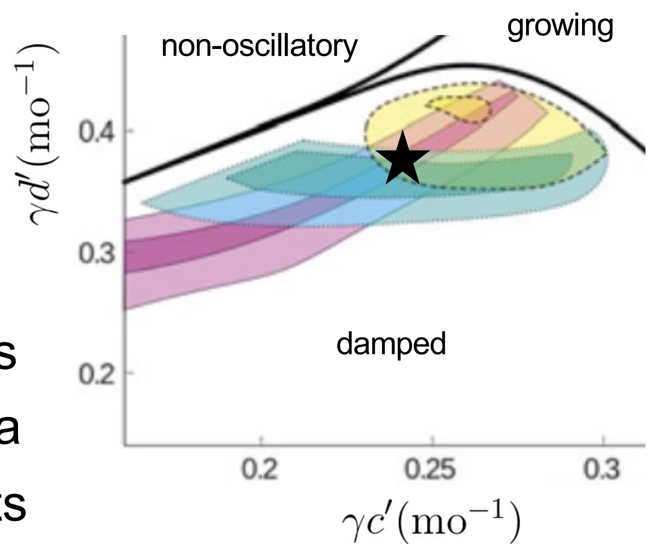
$$\tau^x = \gamma\,(T + r|T|) + \text{noise}$$



$$\dot{T}(t) = -bT(t) + c'\tau^x(t - t_1) - d'\tau^x(t - t_2)$$

local damping — local growth — delayed remote feedback

$$\dot{T}(t) \approx \tilde{c}\tau^x(t) - d'\tau^x(t - t_2)$$



Reproduces observed asymmetries in

- **Amplitude:** warm events stronger than cold events
- **Transition:** warm→cold more likely than vice versa
- **Duration:** cold events last longer than warm events

Stronger coupling during El Niño → stronger growth, faster transition & overshoot

Weaker coupling during La Niña → milder, slower, susceptible to noise

Summary 3: ENSO feedbacks & nonlinearities

1. Keys to understanding sources & sensitivities of modulation

- Control ENSO's stability, irregularity, diversity, propagation, and sensitivities
- Vary with location/regime, season, ENSO phase, and background climate

2. Competing feedback loops

- Growth from **thermocline**, **zonal-advective**, and **Ekman** feedbacks
- Damping from **surface fluxes**, **recharge/discharge**, **TIWs**
- Thermocline feedback drags SSTAs **eastward**; most others drag SSTAs **westward**

3. Nonlinearities → asymmetries, irregularity, rectification

- Control ENSO's asymmetries, and interactions across time scales
- Convection, clouds, nonlinear dynamical heating, TIWs
- Stronger equatorial wind response to warm events than cold events
- **Strong-ENSO epochs** tend to show more nonlinearity

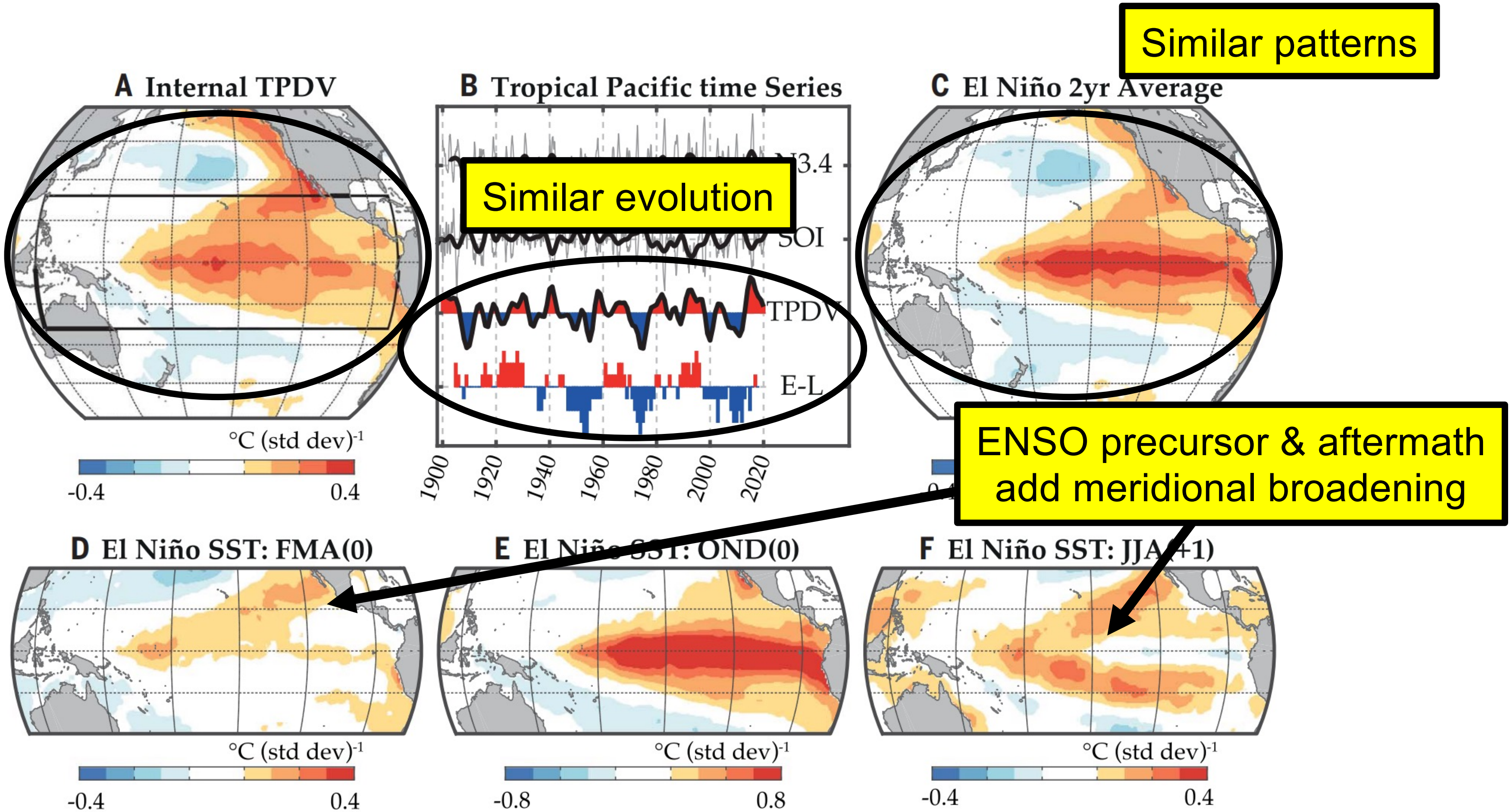
4. Noise

- **State-dependent WWEs**: amplify as warm pool shifts east (boreal spring & El Niño onset)
- Can energize damped modes, leading to transient superposition & growth
- Can smooth out sensitivities to parameters & background climate

4: Role of ENSO modulation in decadal climate

Observed Tropical Pacific Decadal Variability (TPDV)

Null hypothesis: TPDV is a residual of random ENSO events.
When **more ENs than LNs** → warm decadal pattern.
EN/LN **asymmetry** & **diversity** also contribute to decadal residual.



Power et al. (Science 2021): https://doi.org/10.1126/science.aay9165
after Liguori & Di Lorenzo (GRL 2018): https://doi.org/10.1002/2017GL076548
Also: Newman et al. (JC 2003)

ENSO flavors/asymmetry relate to TPDV

Warm PDO

Cold PDO

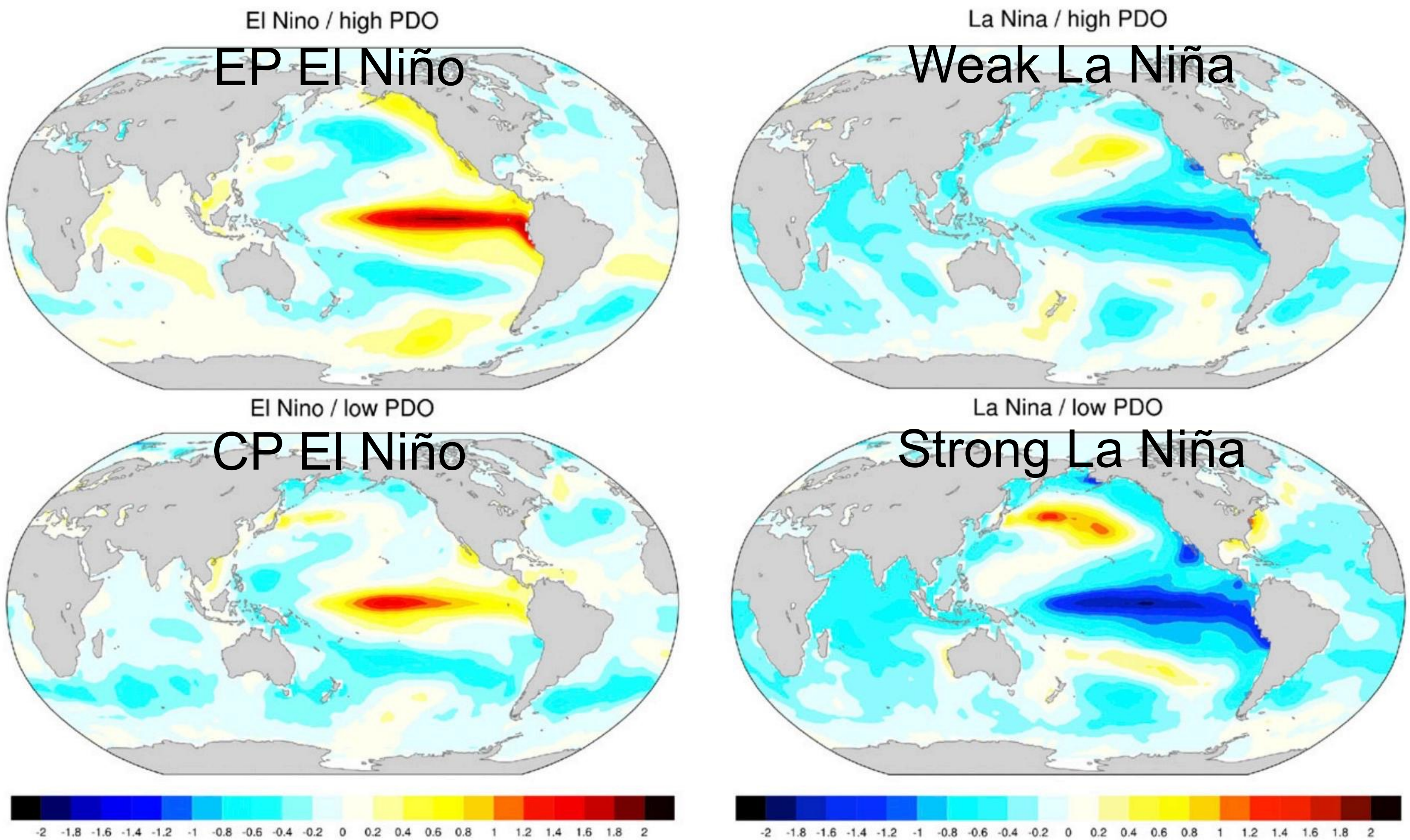
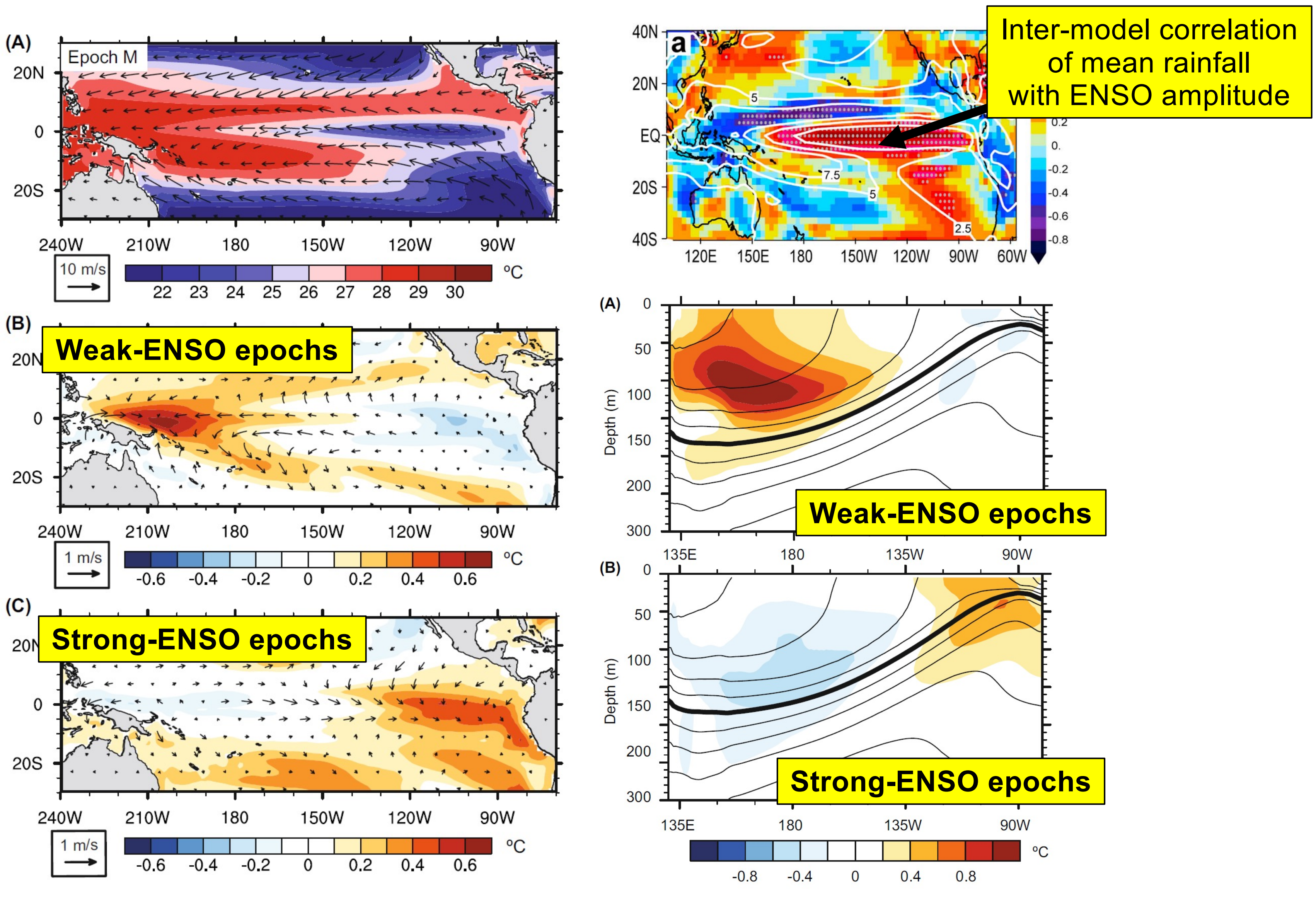


FIG. 13. NDJFM SST ENSO composites separated by high and low PDO values, determined over the years 1948–2008 from the ERSST.v3b SST dataset. Shown are composites of the top quintile (El Niño) of the ENSO index segregated by the (top left) top and (bottom left) the bottom halves of the PDO indices for 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); *also Sun & Yu (JC 2009)*

ENSO's decadal-mean residual



Atwood et al. (Climate Dyn., 2017); Watanabe et al. (GRL 2012)

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

SST patterns of ENSO and TPDV (CMIP3 models)

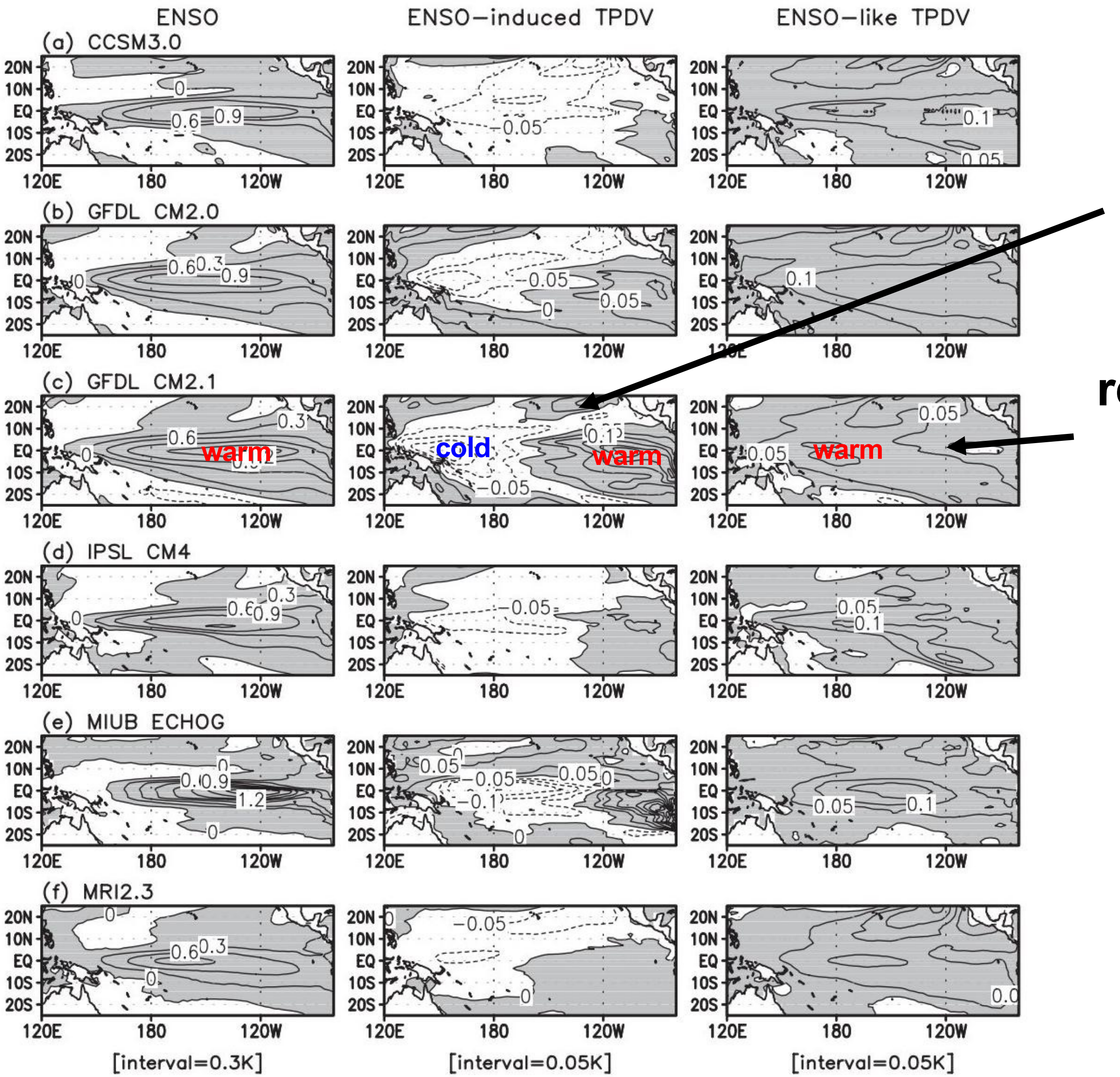


FIG. 3. Regressed map of SST associated with the EOF PC time series of ENSO, ENSO-induced TPDV, and ENSO-like TPDV modes (K).

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**.

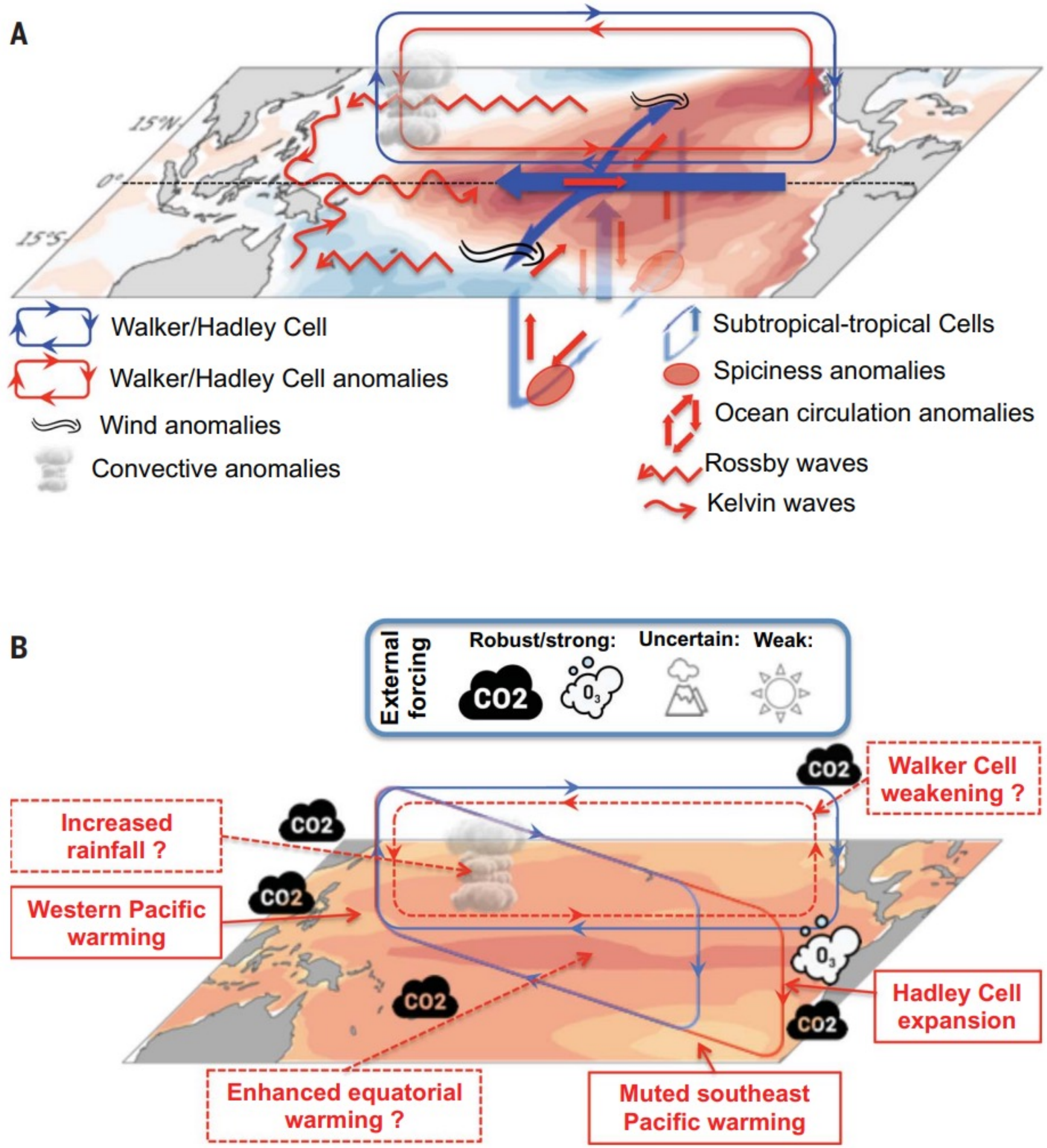
Choi et al. (JC 2013)

also: Yeh & Kirtman (JGRO 2004), Rodgers et al. (JC 2004), Choi et al. (CD 2011)

Internal & external drivers of TPDV

Overturning subtropical cells, off-equatorial wind stress curl & Rossby waves, spiciness subducted in the subtropics – all interact with the equatorial Pacific background climate and ENSO.

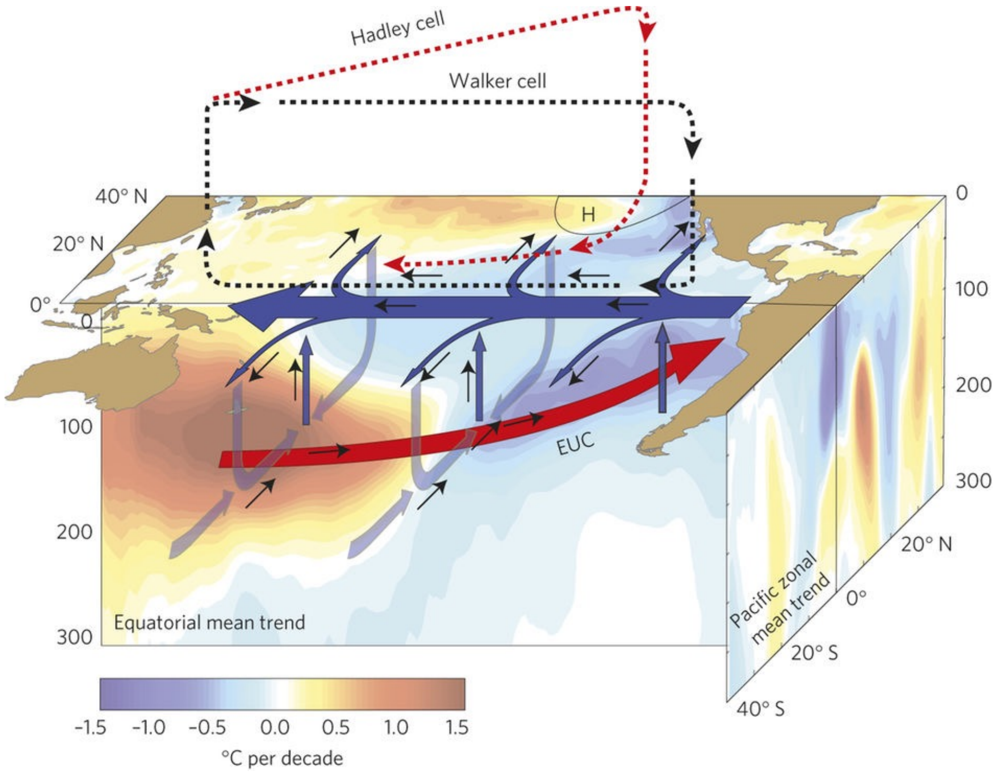
Natural (volcanic, solar) & anthropogenic (GHG, aerosol) forcings can also drive changes in Pacific atmos/ocean circulation & temperature gradients.



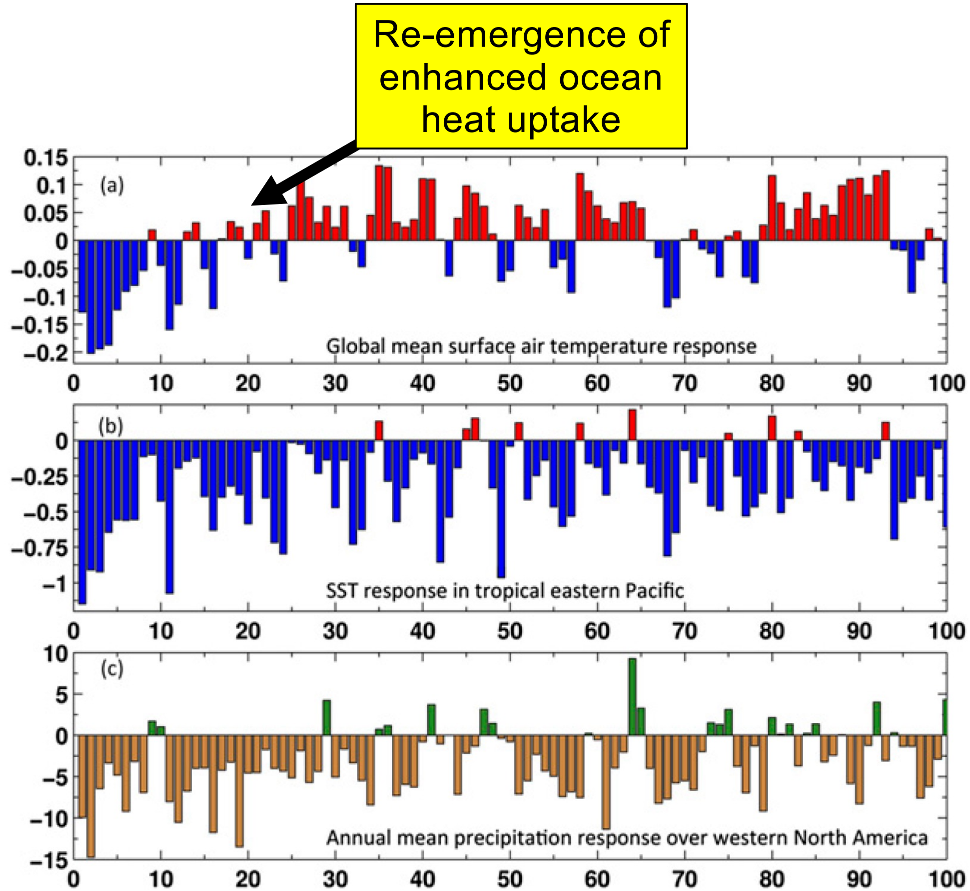
Power et al. (Science 2021)

https://doi.org/10.1126/science.aay9165

Pacific trends affect global climate



England et al. (2014)



Delworth et al. (2015)

Stronger trade winds can drive transient global cooling (**hiatus**), greater **ocean heat uptake**, **drought** over the western U.S.

Kosaka & Xie (2013); England et al. (2014); Delworth et al. (2015)

Summary 4: Role of ENSO in decadal climate

1. ENSO modulation + asymmetry → residual decadal signal

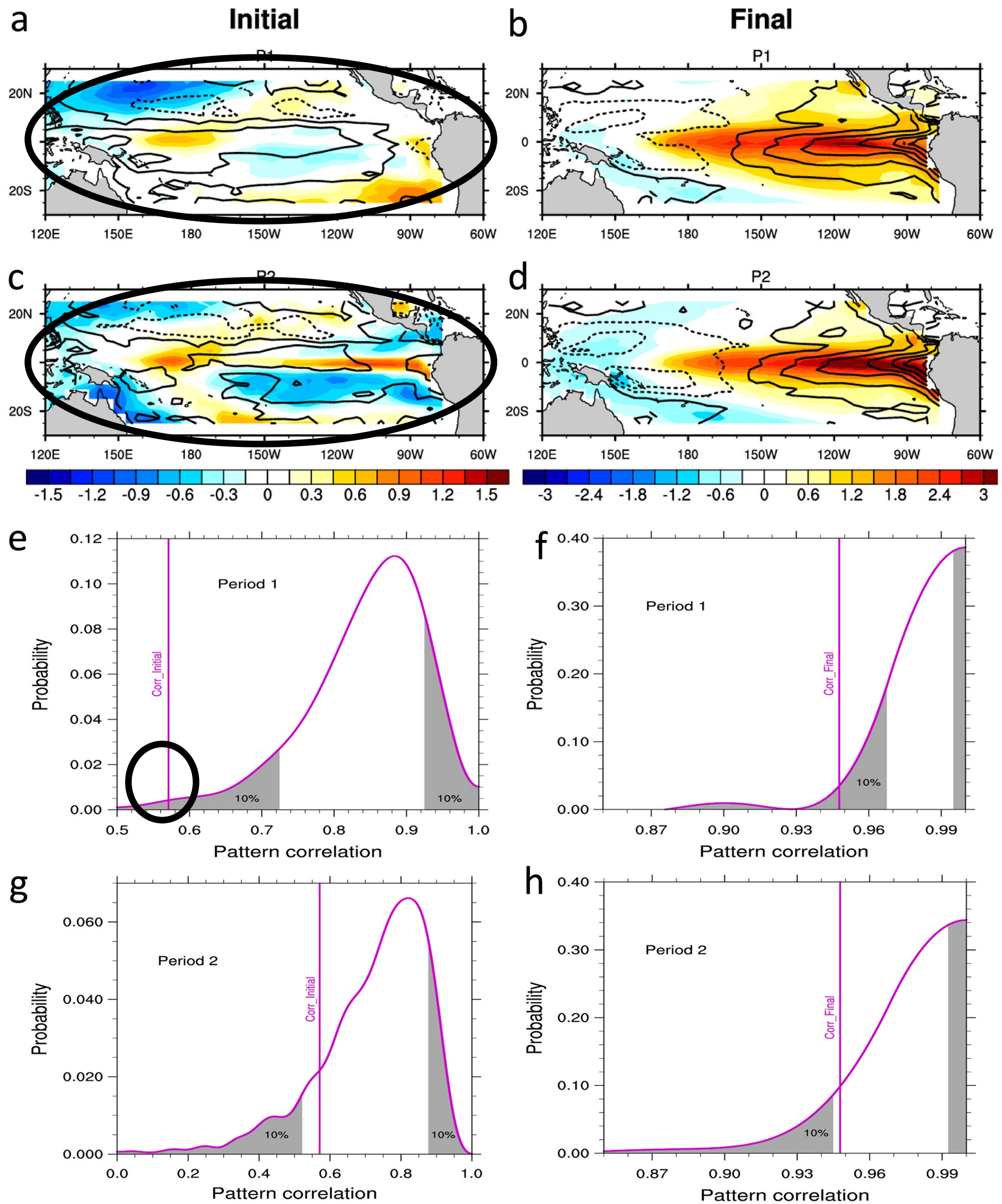
- "Null hypothesis" for TPDV
- Random **excess of ENs**, or **strong ENSO + asymmetry** → warm decadal SST in east Pacific (opposite occurs when fewer/weaker El Niños)
- Epochs/models with stronger, more diverse & skewed ENSO → more ENSO-induced TPDV
- Together with decadal recharge/discharge mode → intrinsic/unforced TPDV

2. TPDV events have multiple impacts

- E.g. stronger trade winds, thermocline tilt, STC overturning, equatorial heat discharge
- Stronger global ocean heat uptake, pause in global warming
- Hydrologic impacts (e.g. drought over western North America)

5: ENSO / decadal interactions

Changing ENSO dynamics?



LIM indicates statistically-significant **change in event initiation**, after 1978.

Linear dynamics from the *former* epoch probably wouldn't have generated the *latter* – though the reverse isn't ruled out.

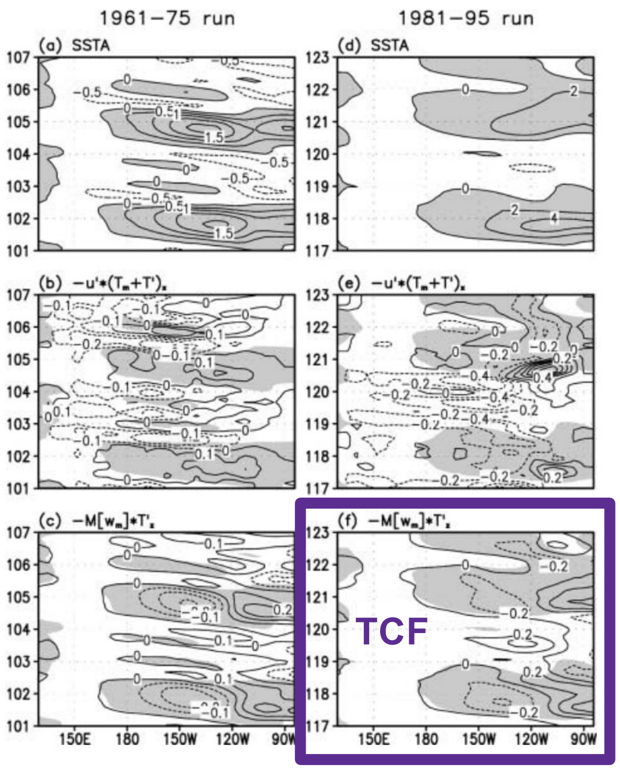
Is nature randomly sampling a different *part* of a stationary *nonlinear* ENSO attractor?

Or is the *attractor* changing?

Capotondi & Sardeshmukh (GRL 2017)

https://doi.org/10.1002/2017GL074515

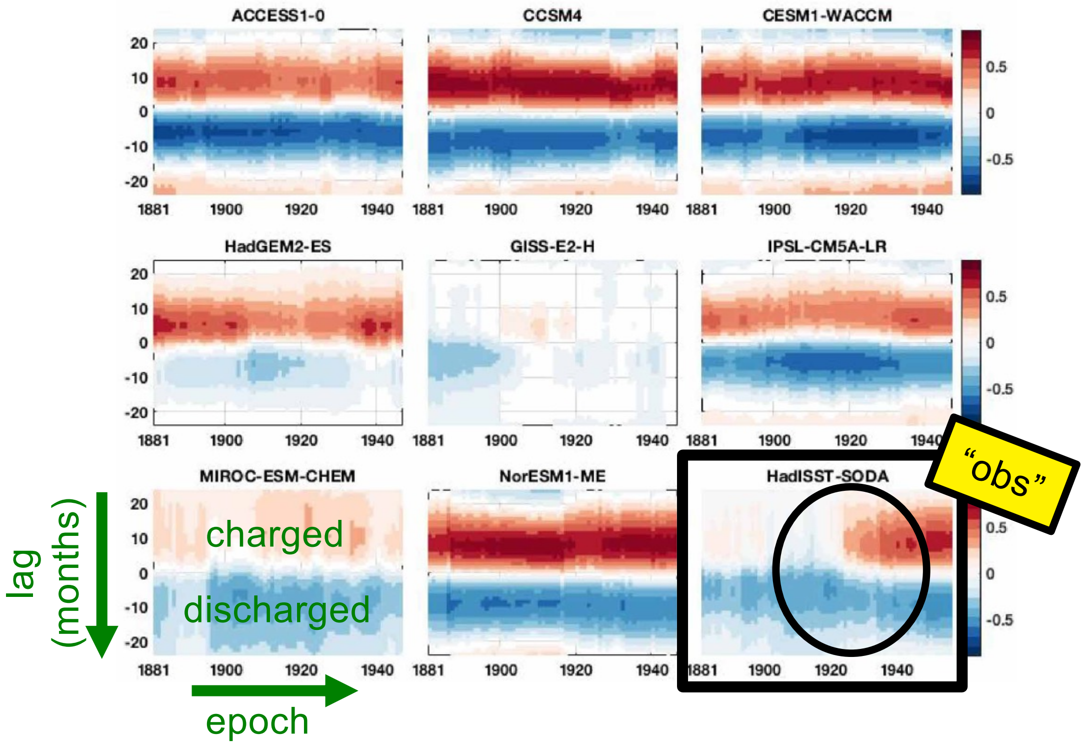
ENSO changes after the 1970s Pacific climate shift



Wang & An (CD 2002)

https://doi.org/10.1007/s00382-001-0189-5

Sliding 30yr lag-correl of NINO3 SST with equatorial-mean *h*



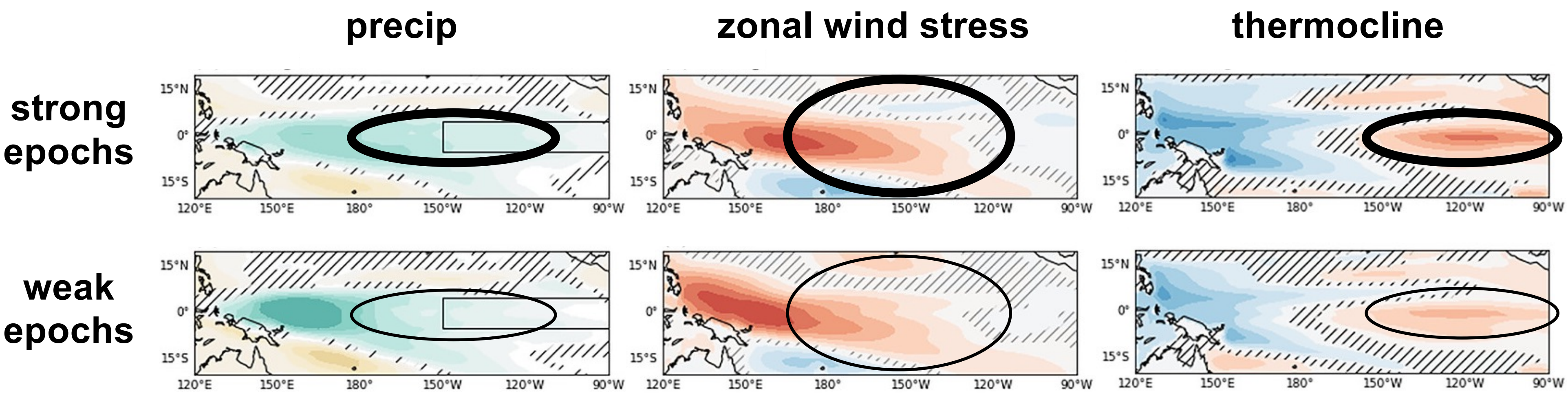
Crespo et al. (ERL 2022)

https://doi.org/10.1088/1748-9326/ac72a3

Impose late-1970s climate shift in intermediate/conceptual models:
Weaker trades → weaker dTbar/dx → **eastward shift of tau_x'** response
→ **stronger thermocline feedback (TCF) & recharge/discharge**
→ **stronger ENSO**, longer period, more eastward SSTA propagation.

Fewer such shifts in CGCMs; a *cause* or *effect* of their **weak TPDV**?

Simulations: Strong-ENSO epochs show distinct feedbacks



(GFDL CM2.1 simulation)

Strong epochs: **eastward shift & y-narrowing of tau_x response**

→ **stronger thermocline tilt** response to tau_x

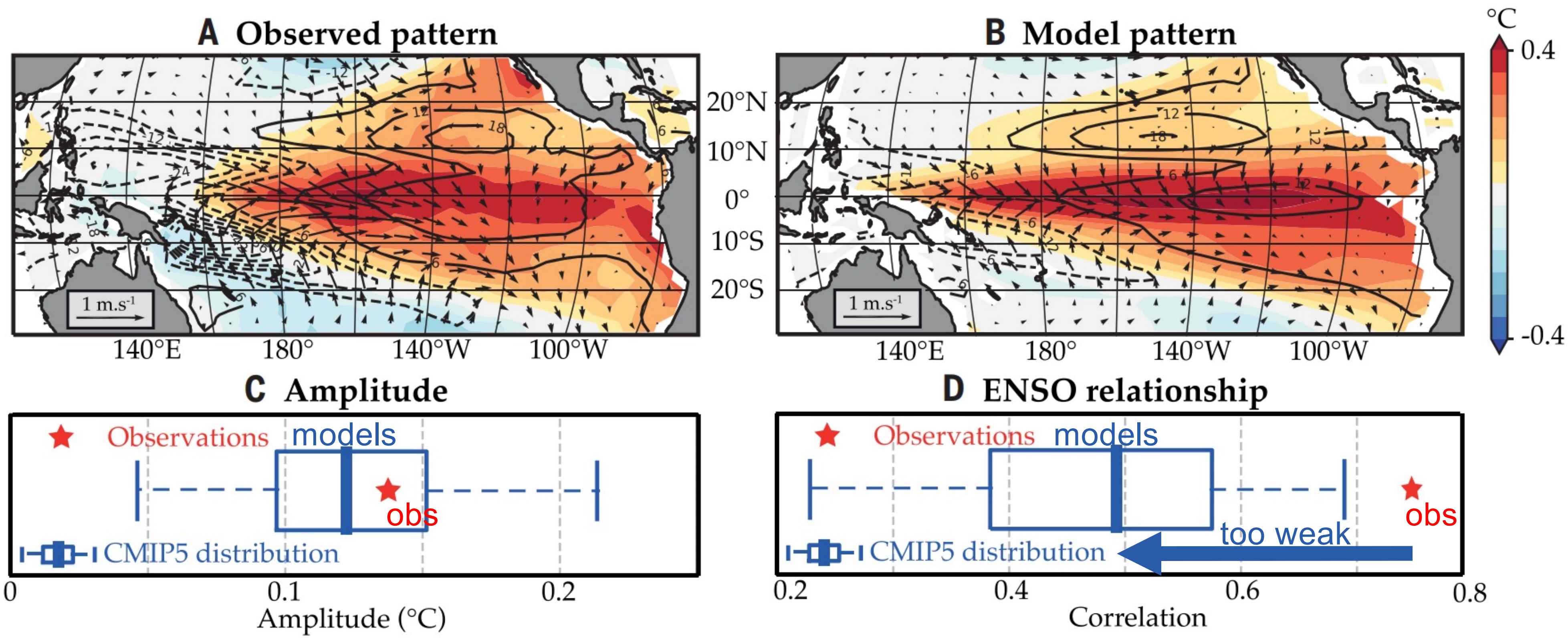
→ **stronger thermocline feedback** (& delayed feedback) in EEqPac

Weaker background dT/dx → weaker trades → weaker STCs
→ narrower SSTAs & tau_x → feedback on ENSO amplitude?

Kim & Kug (JC 2022): https://doi.org/10.1175/JCLI-D-21-0181.1

Simulated TPDV

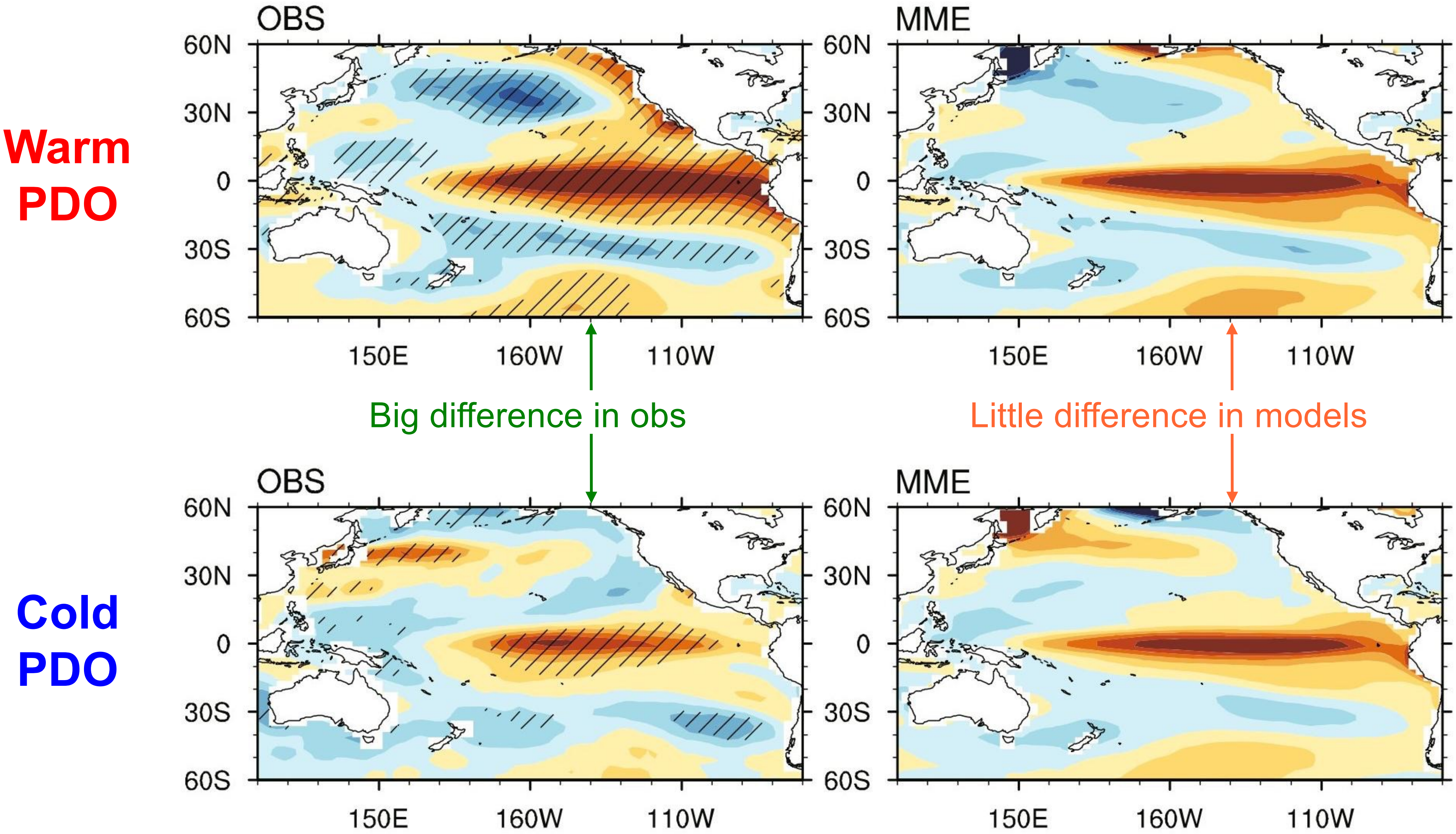
CMIP-simulated warming is too far west; weak tradewind/tilt response.



Wide range of simulated TPDV amplitudes & links to ENSO.
Many have biennial ENSO, weak persistence → weak ENSO/TPDV link.

Power et al. (Science 2021): https://doi.org/10.1126/science.aay9165

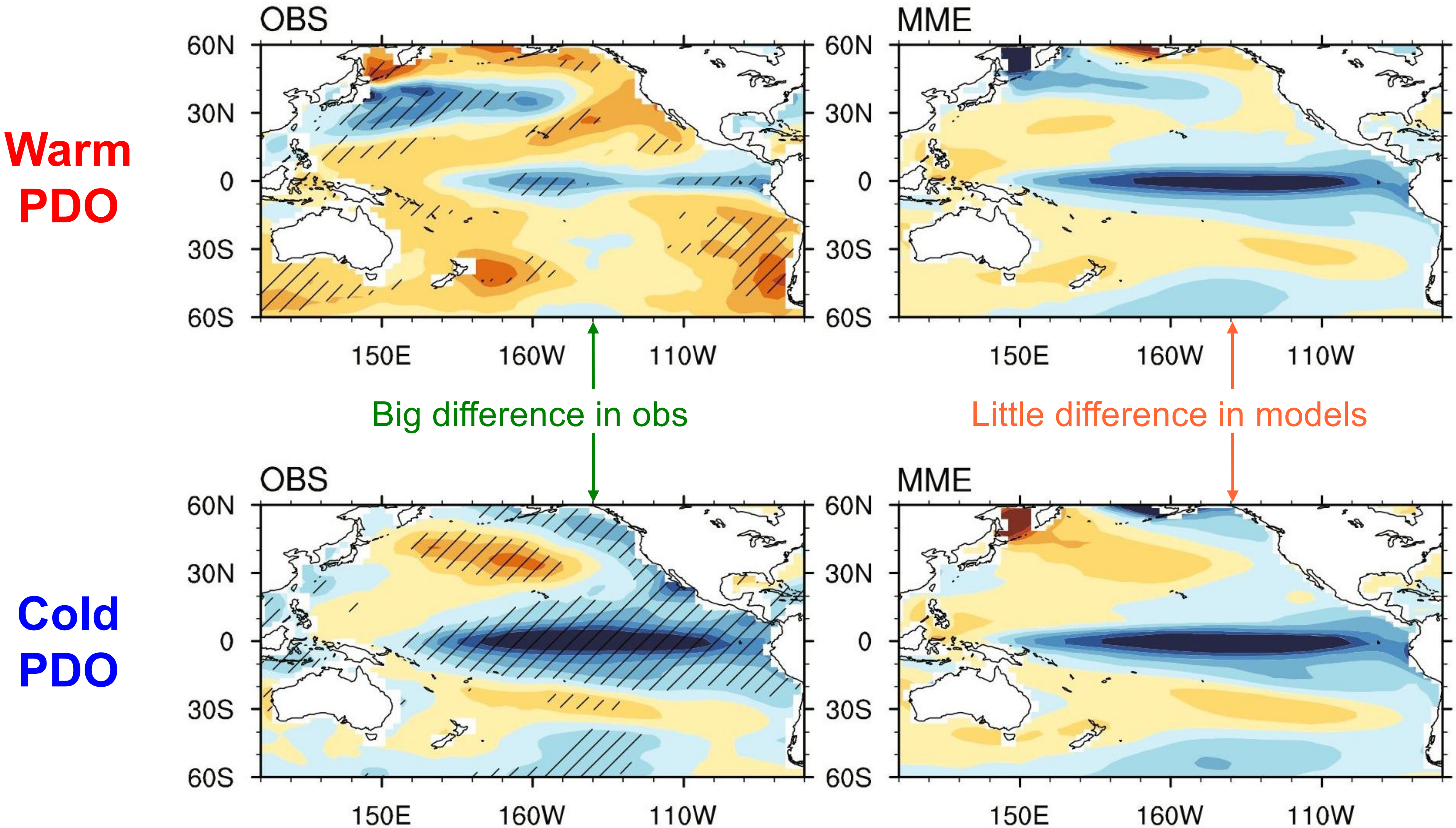
PDO & El Niño flavors/skewness:
Too weakly related in CMIP5 models



Lin et al. (AAS 2018)

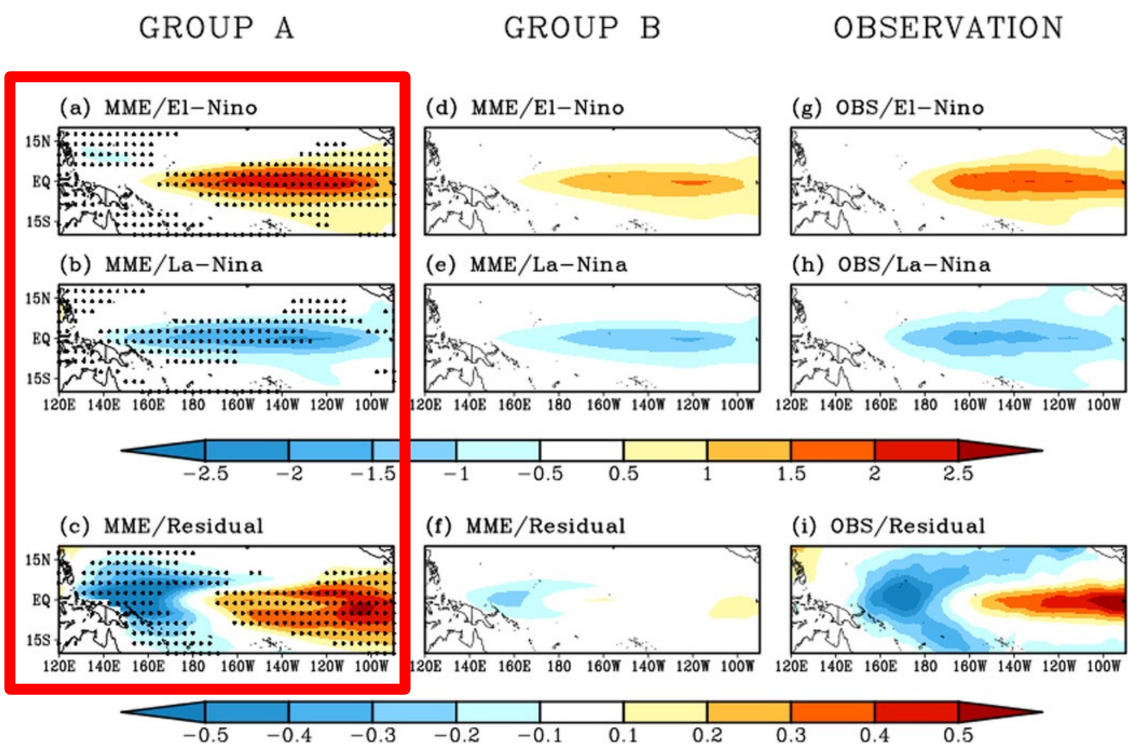
PDO & La Niña flavors:

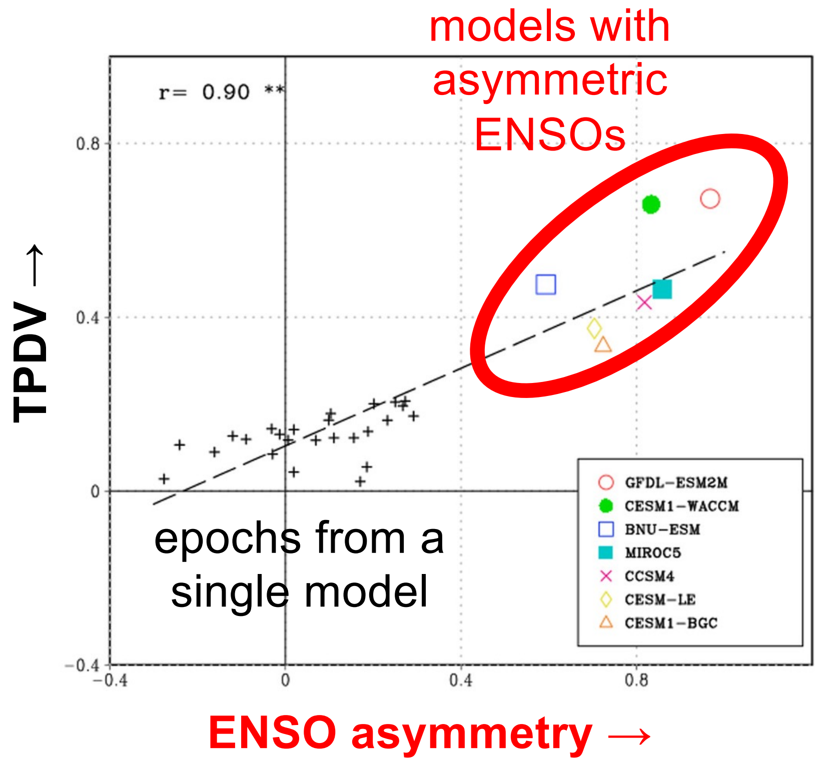
Too weakly related in CMIP5 models



Lin et al. (AAS 2018)

CMIP models: ENSO asymmetry linked to TPDV



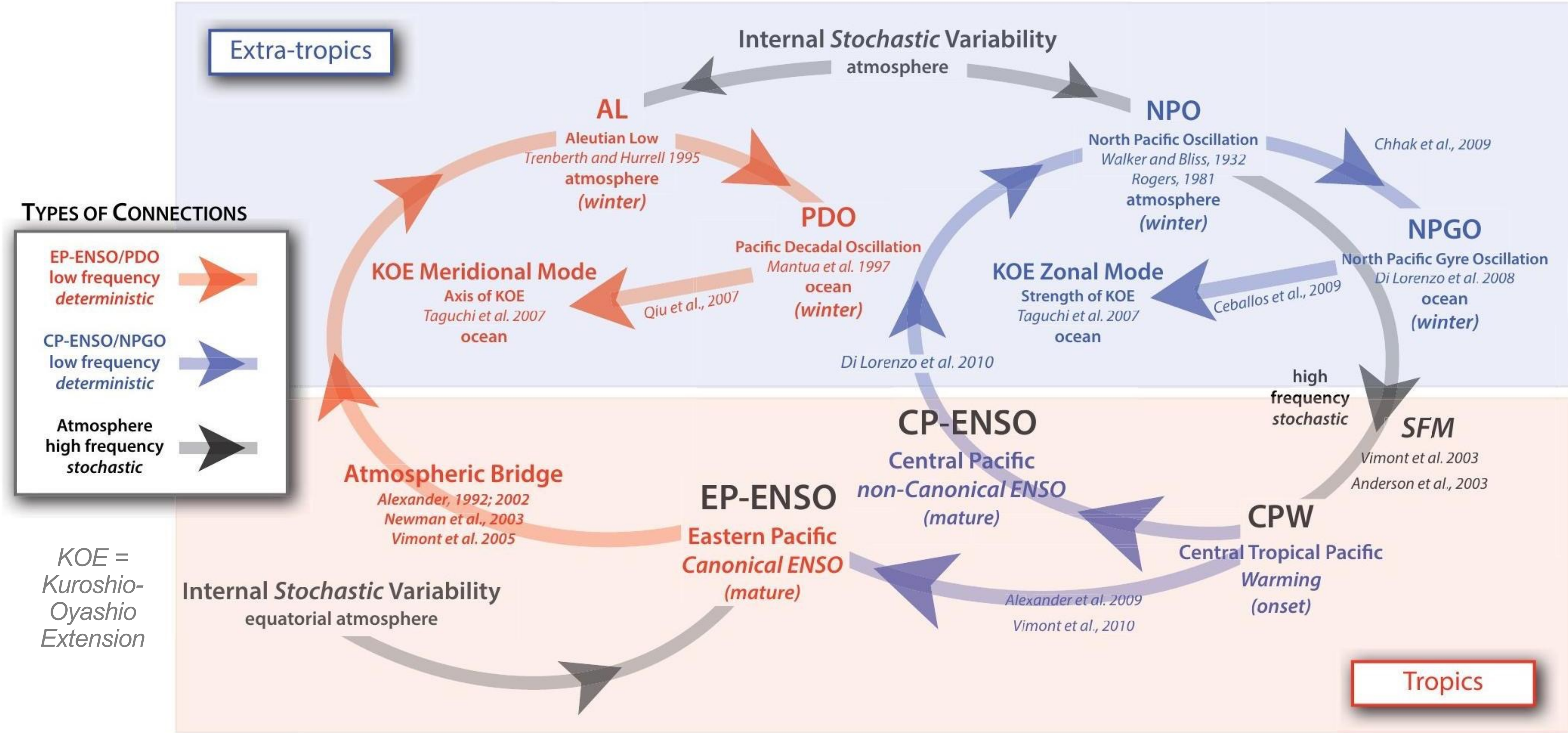


Models/epochs with **stronger/better ENSO amplitude, nonlinearity, asymmetry, zonal diversity**
→ stronger decadal residuals → **more TPDV**

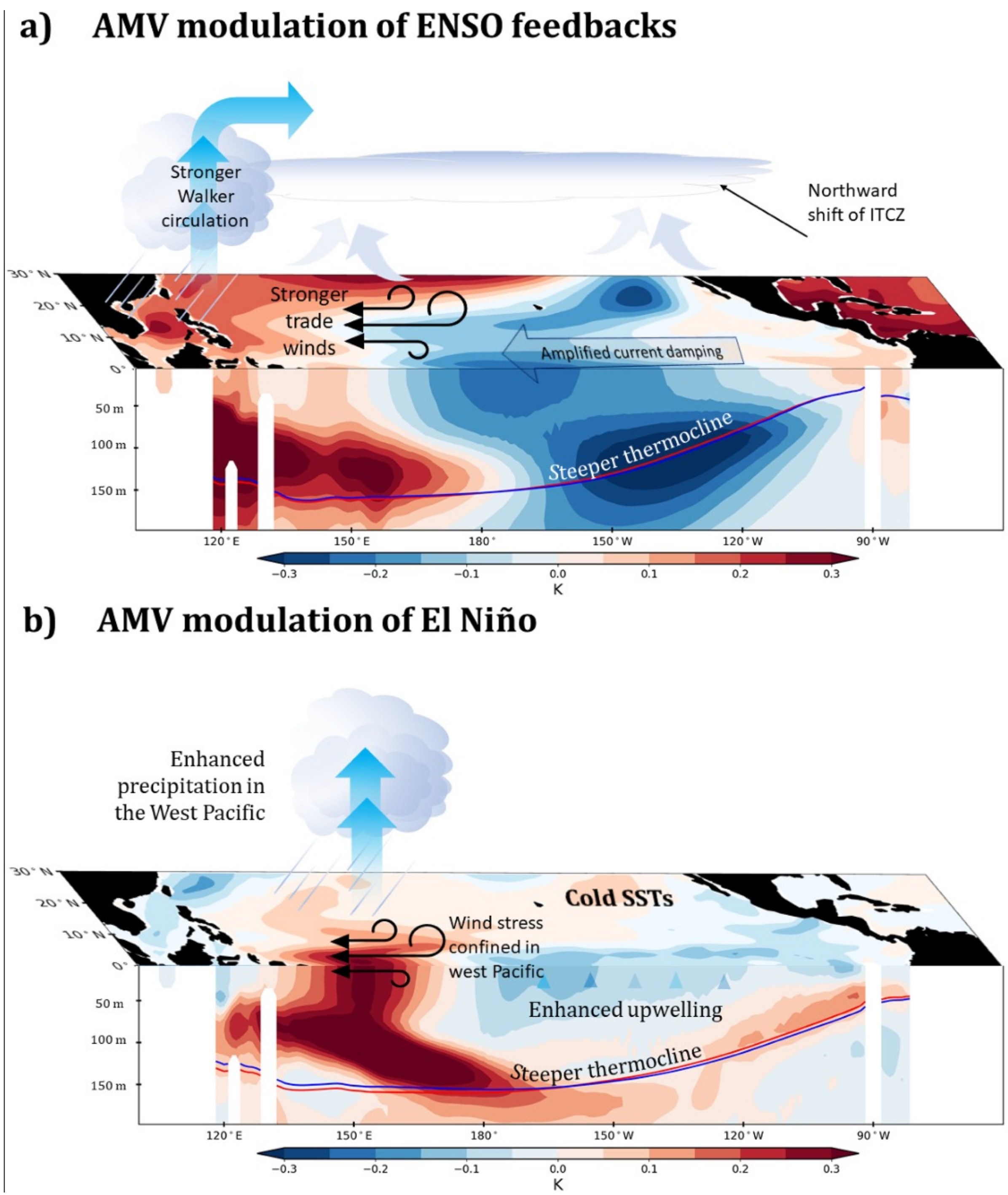
Kim & Kug (JC 2020): *https://doi.org/10.1175/JCLI-D-19-0123.1*

Pacific decadal interactions with ENSO

Di Lorenzo et al. (Oceanogr. 2013); also Meehl et al. (CD 2021)



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**?



AMV can affect ENSO

(CESM1 simulations)

Warm AMV

→ N-shift of Pacific ITCZ
→ stronger trades

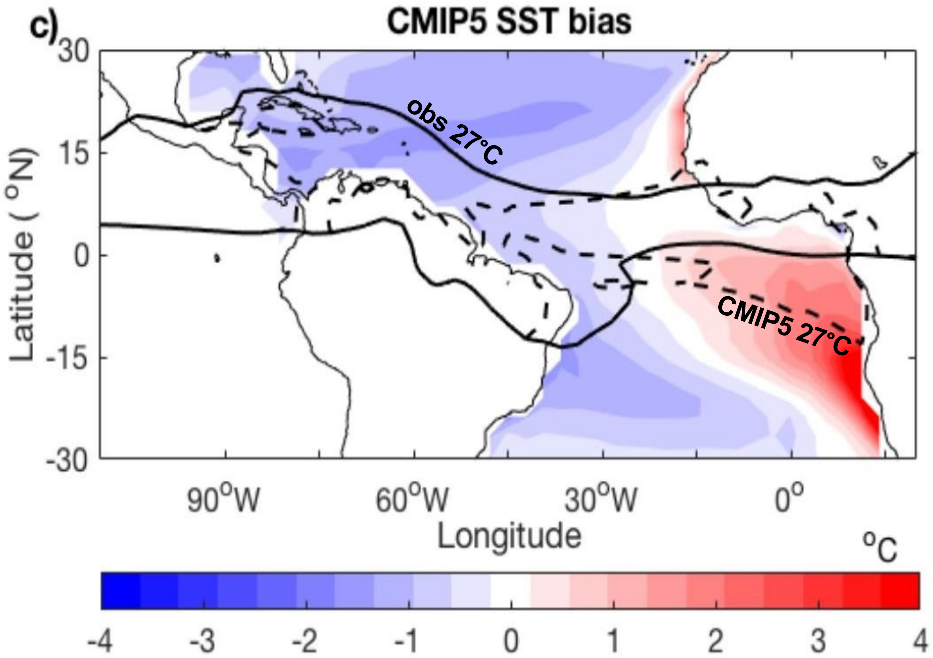
→ stronger *dh/dx* & *dT/dx*

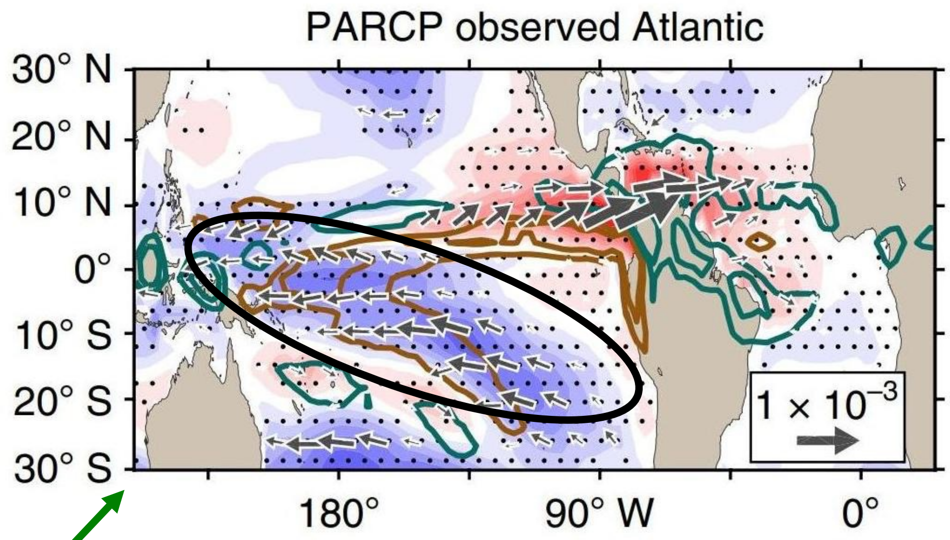
→ W-shift of τ_x response
→ weaker *h* feedback

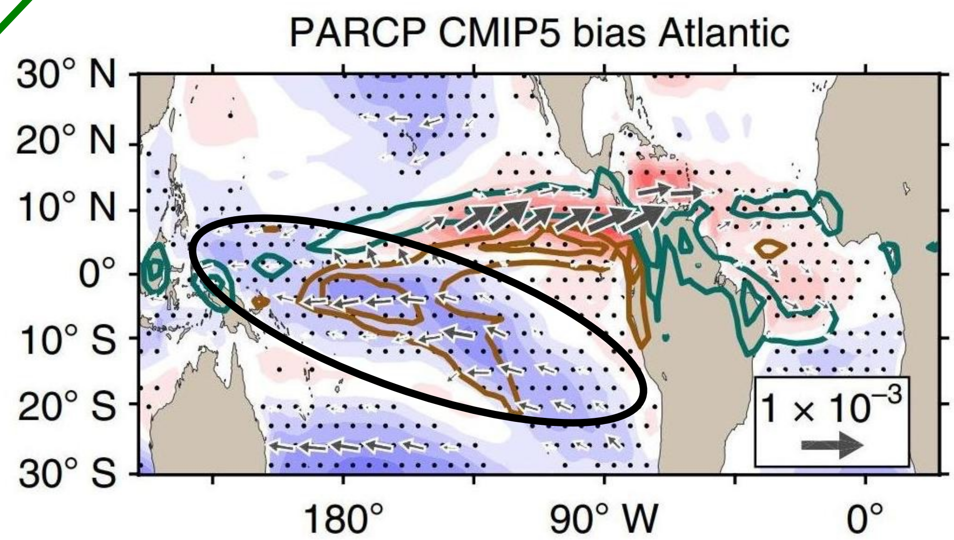
→ 10% weaker ENSO

Trascasa-Castro et al. (GRL 2021)
also Kang et al. (JC 2014)

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)

Summary 5: ENSO/decadal interactions

1. ENSO's *linear* dynamics changed in the late 1970s

- Shift to a **more El Nino-like mean state** → eastward shift of ENSO tau_x response
  → stronger thermocline feedback & recharge/discharge
  → **stronger ENSO, longer period, more eastward propagation** of SSTAs
- A different region of a *nonlinear* attractor? Or did the attractor itself change?
- Did the Pacific then shift *back* after 1998?
- Many CGCMs don't capture these shifts

2. Does internal TPDV feed back on ENSO?

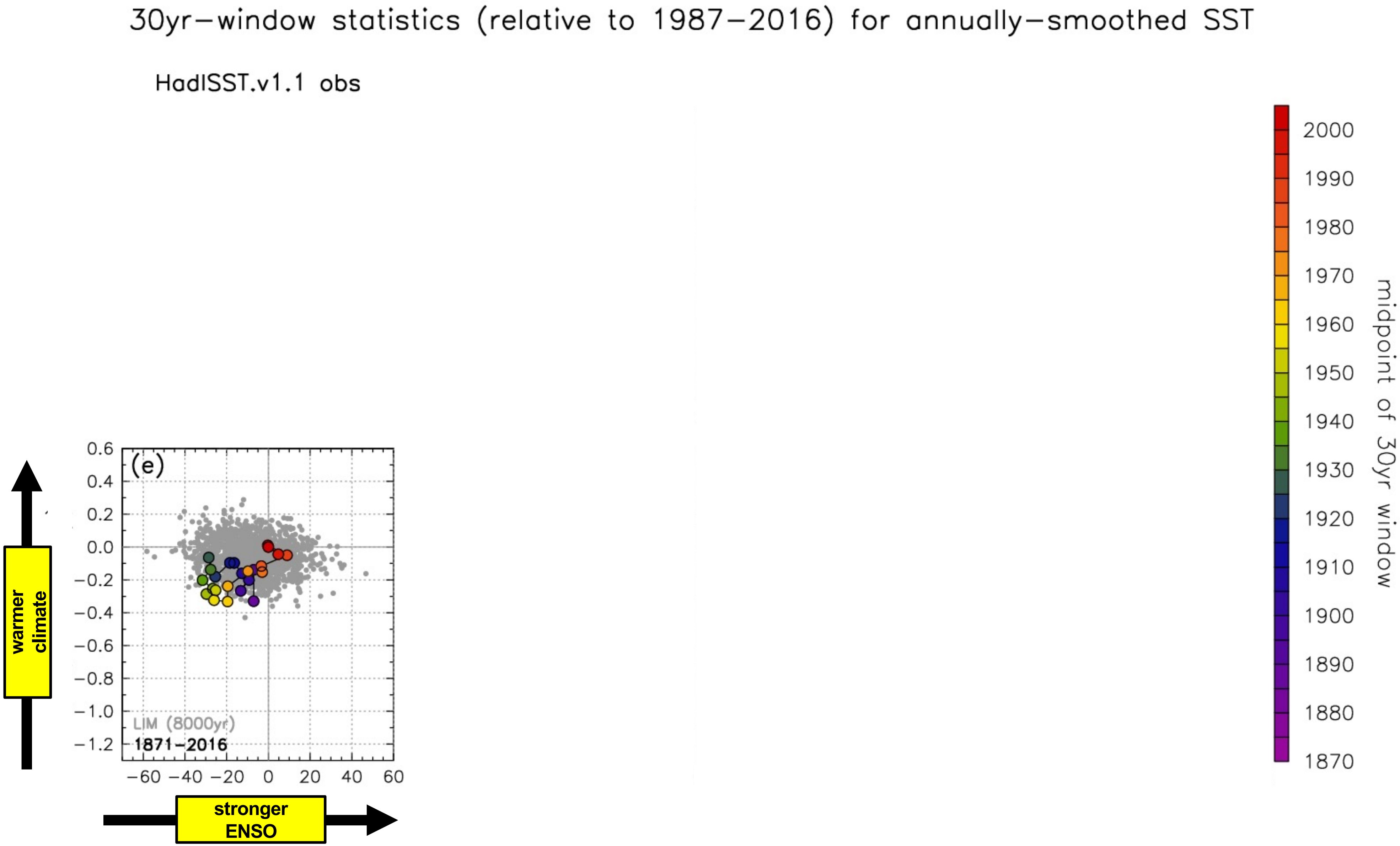
- CGCMs with **strong ENSO modulation**:
  ENSO rectification → mean trade winds → ocean y-overturning strength
  → y-width of ENSO SSTA & tau_x responses → thermocline feedback strength
  → ENSO amplitude?
- Models with better mean climate and/or **stronger/better ENSO** amplitude
  → stronger thermocline feedback
  → stronger & longer-period ENSO, better persistence + diversity + skewness
  → **stronger ENSO/TPDV link**, and stronger TPDV
- Are ENSO/decadal feedback loops closed & robust to noise?
- If so, do they lend **decadal predictability** to ENSO behavior, or to TPDV?

3. Interbasin modulation of ENSO

- Warm AMV → atmos bridge → Pacific ITCZ shifts north → stronger trades
  → tau_x response stuck in west Pacific → weaker thermocline feedback → weaker ENSO
- If add CMIP5 Atlantic SST bias → weakens Pacific response to Atlantic warming
- Warm Indian Ocean can also boost Pacific trade winds, weaken ENSO

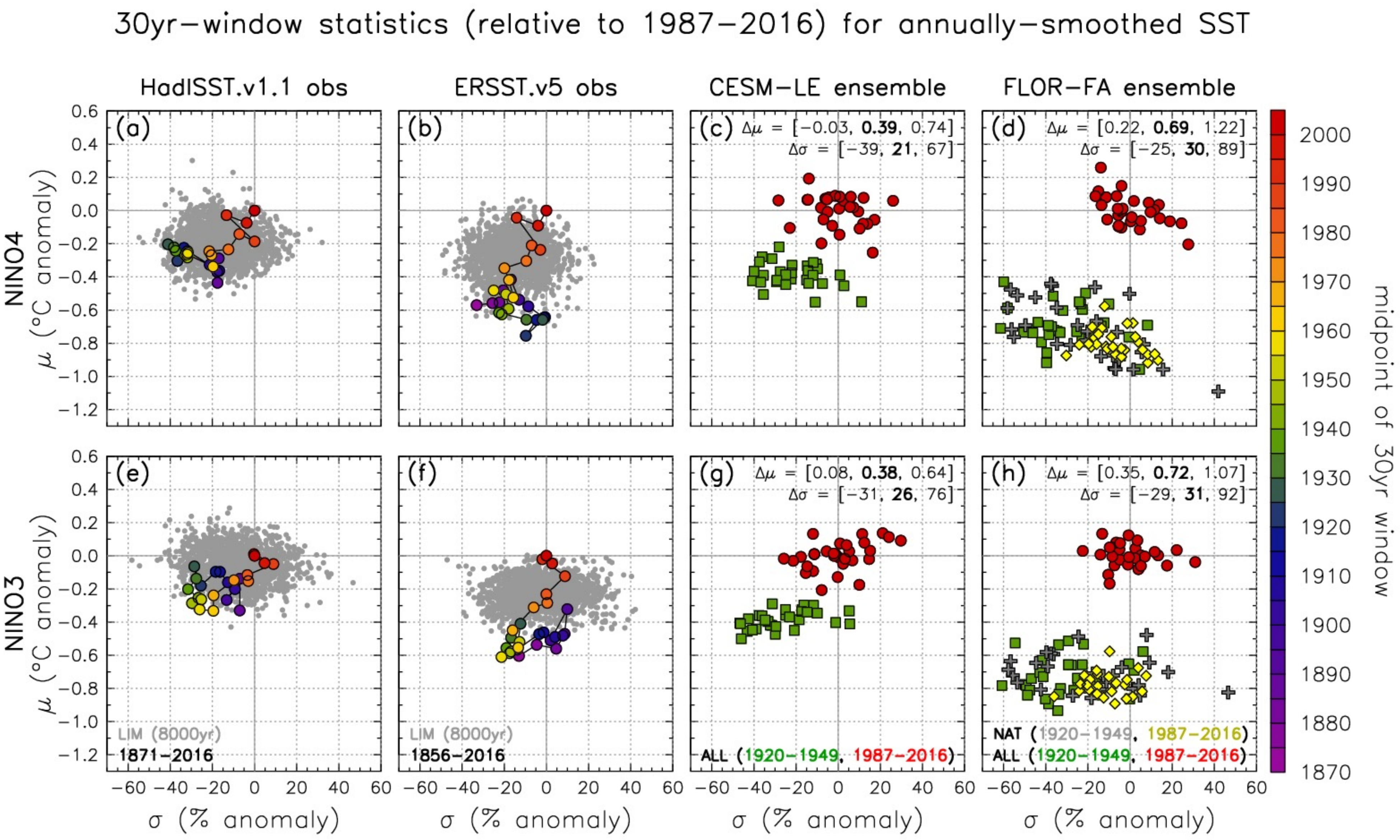
6. Past & future changes in ENSO

Observed & simulated mean/ENSO SST changes



Newman et al. (BAMS 2018): https://doi.org/10.1175/BAMS-D-17-0116.1

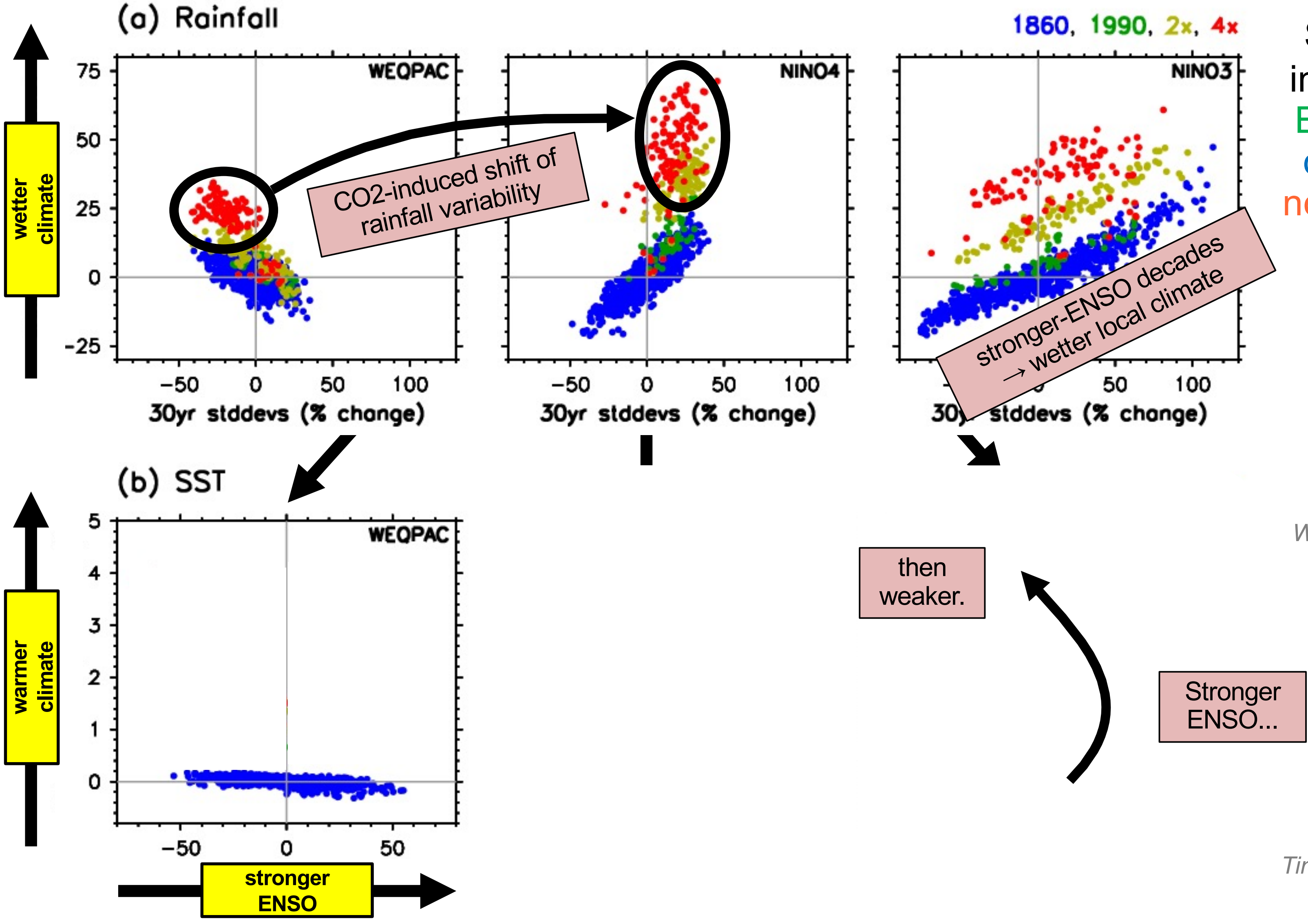
Observed & simulated mean/ENSO SST changes



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

Newman et al. (BAMS 2018): https://doi.org/10.1175/BAMS-D-17-0116.1

ENSO response to increasing CO_2



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

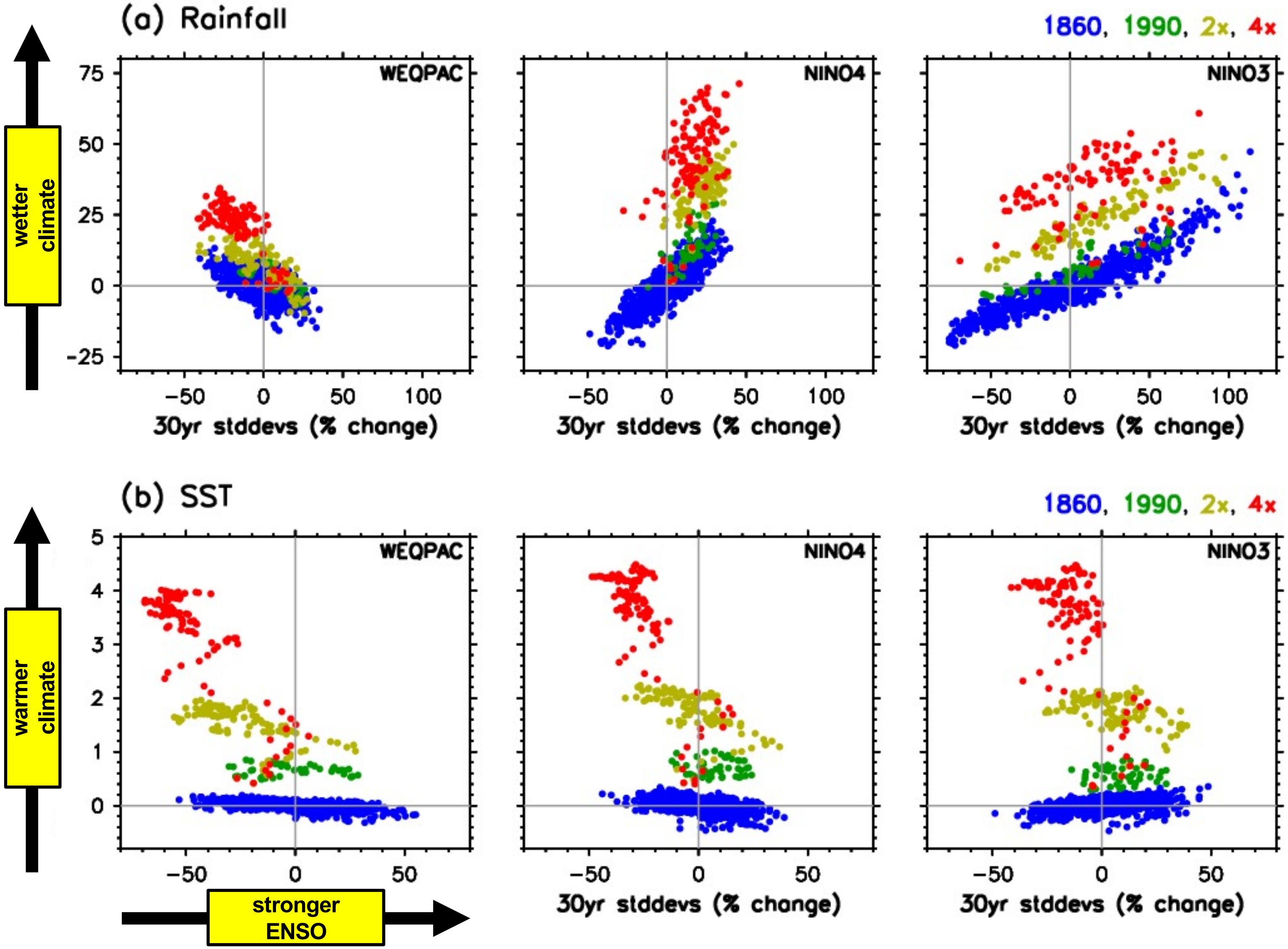
Vecchi & Wittenberg (2010)
Collins et al. (2010)
Xie et al. (2010)
DiNezio et al. (2012)
Watanabe & Wittenberg (2012)
Watanabe et al. (2012)
Ogata et al. (2013)
Power et al. (2013)

Knutson et al. (BAMS 2014)
Cai et al. (NCC 2014)
Delworth et al. (JC 2015)
Choi et al. (JC 2015)
Kam et al. (BAMS 2016)
Chen et al. (JC 2017)
Graham et al. (CD 2017)
Atwood et al. (CD 2017)
Timmermann et al. (Nature 2018)
Fedorov et al. (AGU 2020)
Stevenson et al. (2021)

Wittenberg (U.S. CLIVAR Variations, 2015)

CM2.1 simulation

ENSO response to increasing CO_2



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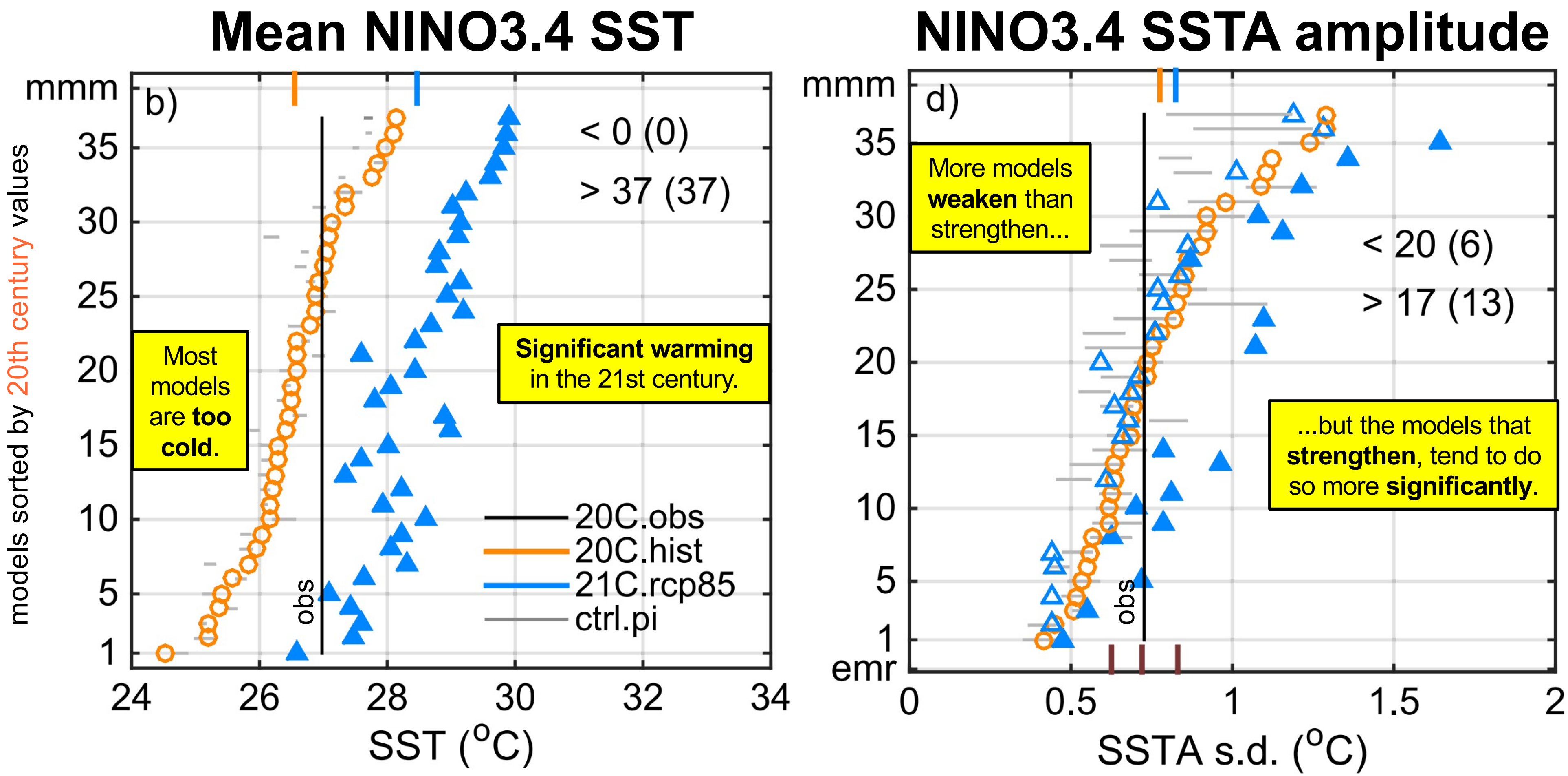
Timmermann et al. (Nature 2018)
Fedorov et al. (AGU 2020)
Stevenson et al. (2021)

Wittenberg (U.S. CLIVAR Variations, 2015)

CM2.1 simulation

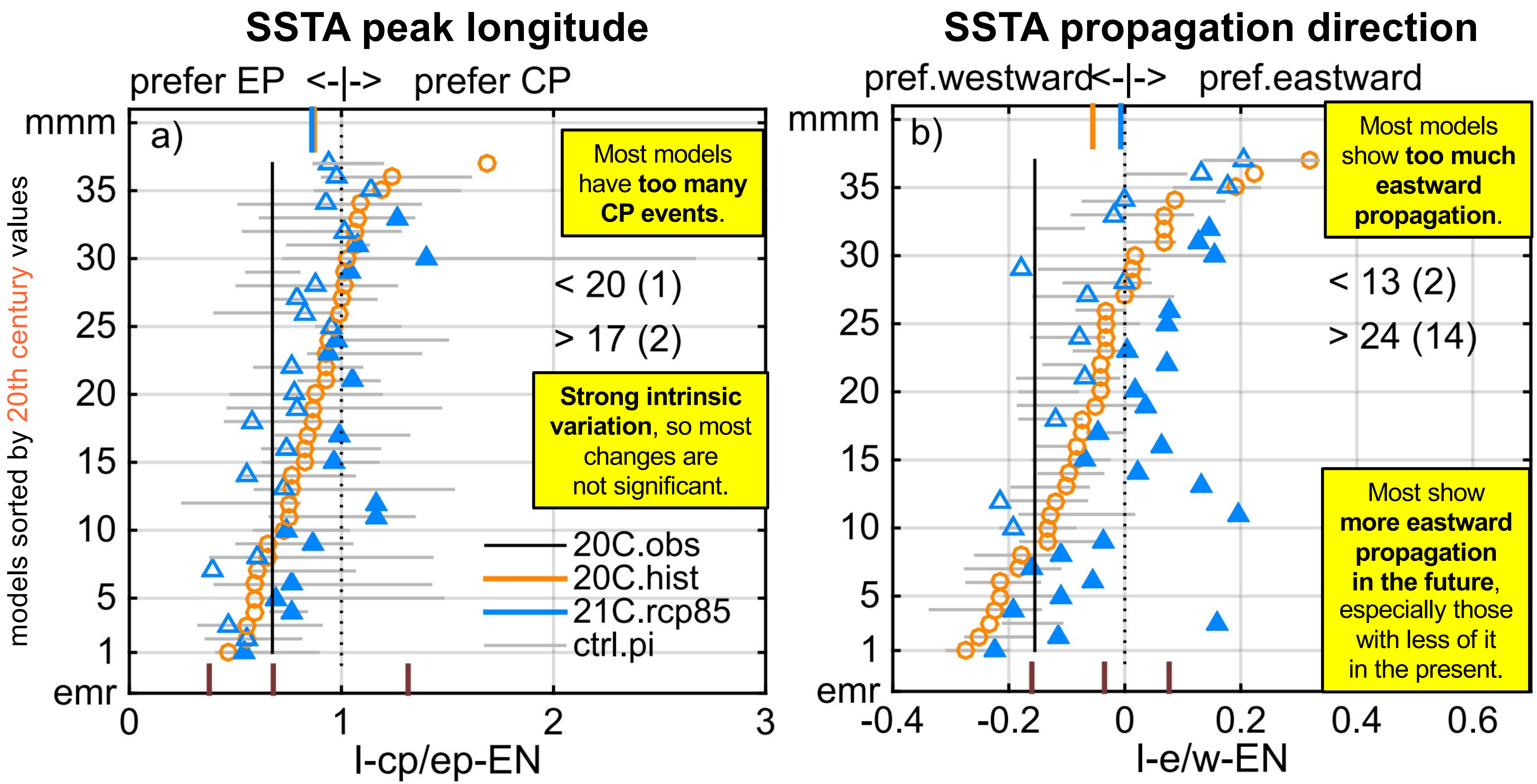
CMIP5 projections (PI, 1900-99, 2000-99)



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): https://doi.org/10.1175/JCLI-D-15-0901.1

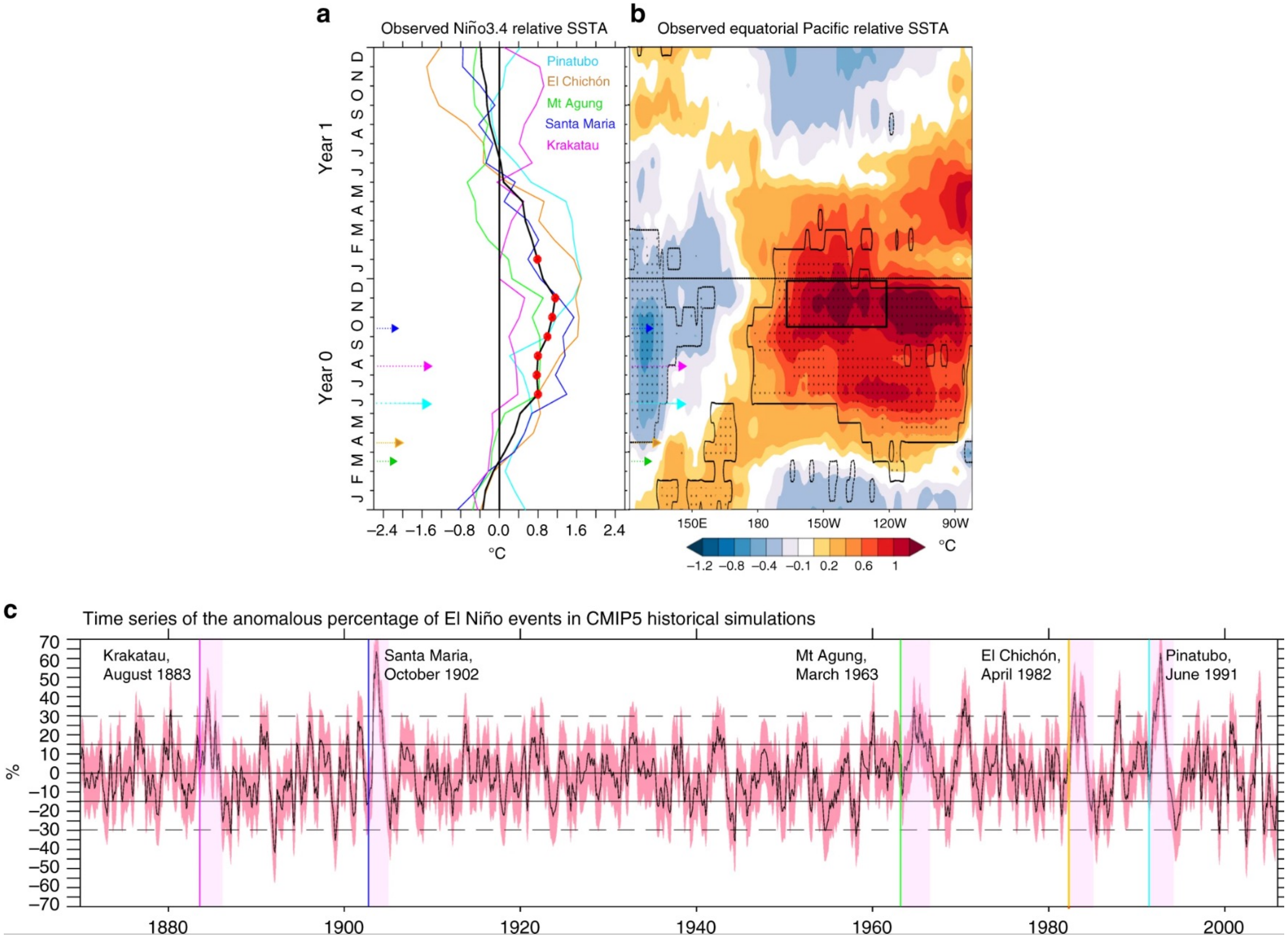
CMIP5 projections (PI, 1900-99, 2000-99)



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): https://doi.org/10.1175/JCLI-D-15-0901.1

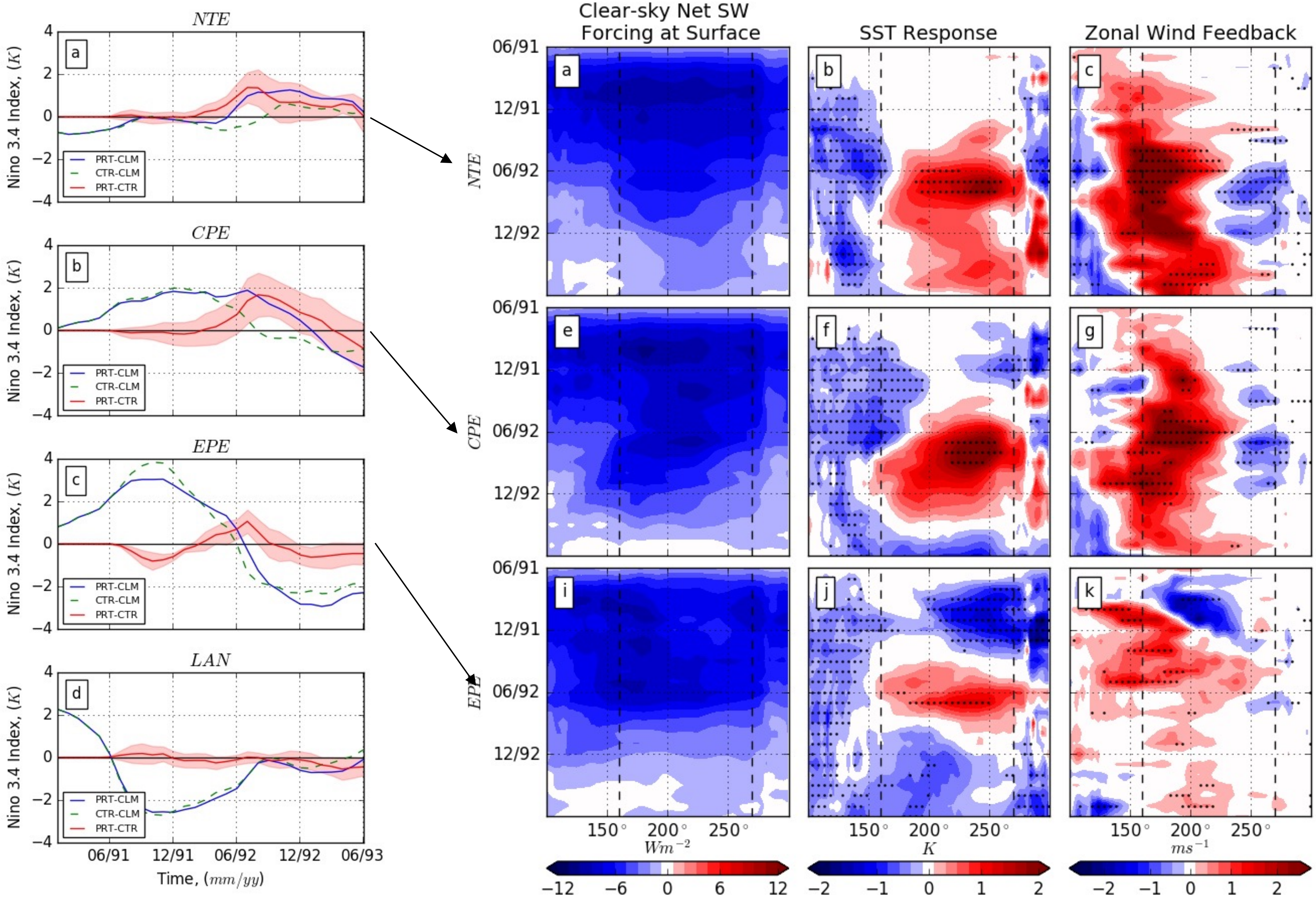
ENSO response to tropical explosive volcanic eruptions



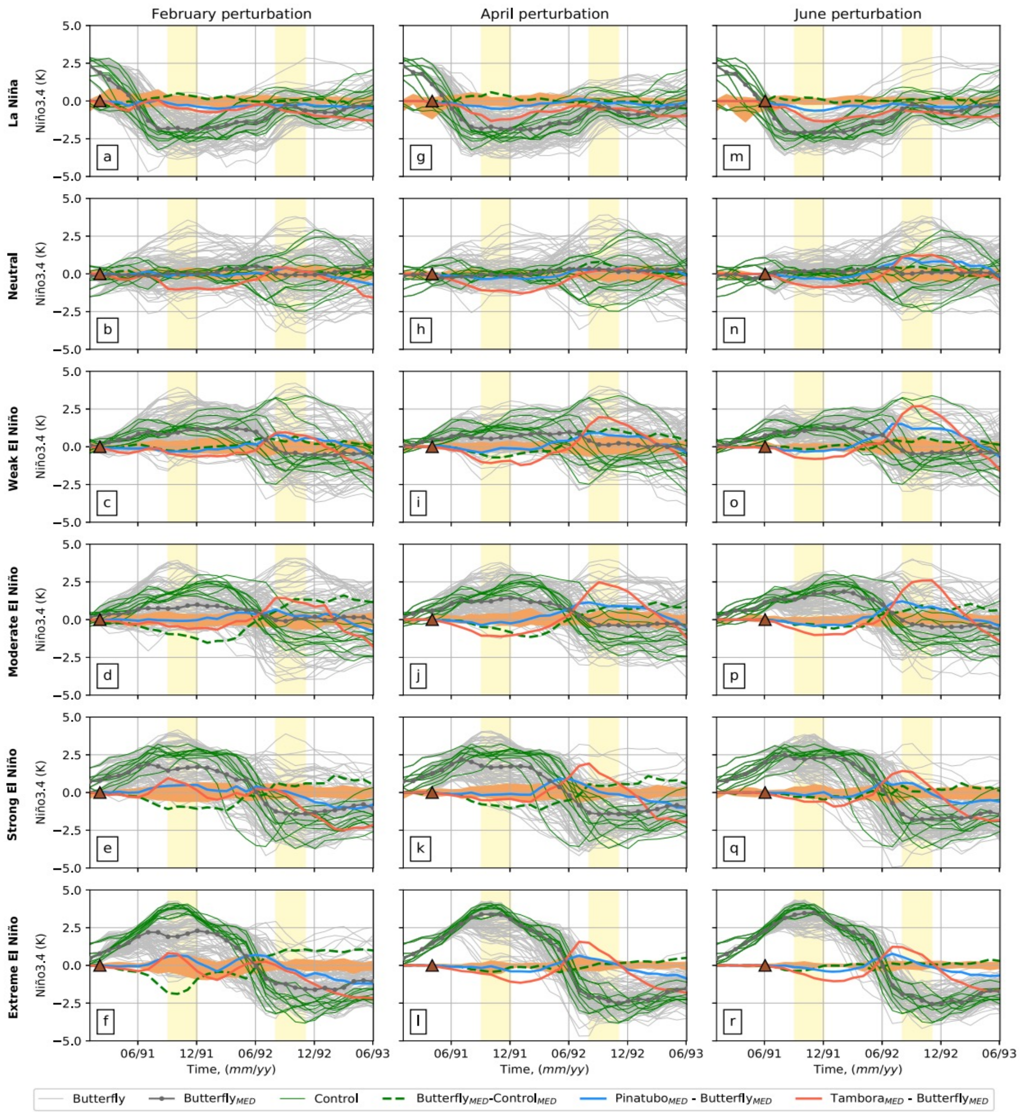
Khodri et al. (NCC 2017): *https://doi.org/10.1038/s41467-017-00755-6*

Response to Pinatubo eruption depends on ENSO phase

Predybaylo et al. (JGRA 2017): https://doi.org/10.1002/2016JD025796



ENSO response to tropical explosive volcanic eruptions



Predybaylo et al. (NCEE 2020): *https://doi.org/10.1038/s43247-020-0013-y*

Summary 6: Past & future changes in ENSO

1. Recent ENSO amplification in obs & many models

- Obs amplification not yet distinguishable from range expected from intrinsic modulation
- But *time-mean* warming in the equatorial Pacific is marginally detectable

2. Interplay of ENSO modulation, TPDV, and forced responses

- Intrinsic amplitude modulation might be large (+/- 50% in some models)
- ENSO response to climate change may be **nonlinear, time-dependent, regional**

3. Projected future changes in ENSO

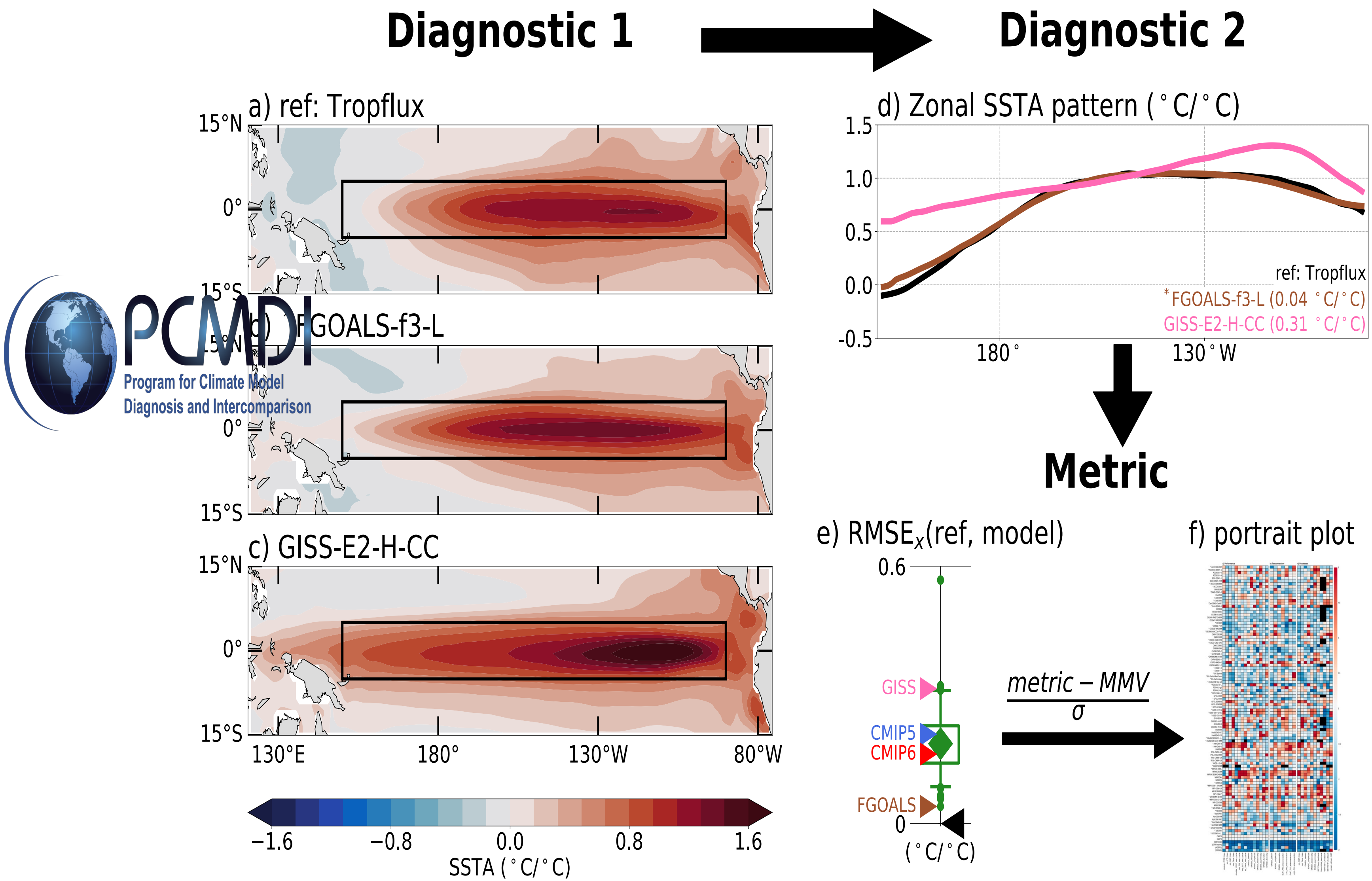
- Most robust: **stronger rain response**, **more eastward propagation** of equatorial SSTAs
- More models show significant SSTA **amplification** than significant weakening
- No clear consensus on how ratio of EP to CP events might change in the future

4. Volcanic eruptions can induce an El Niño-like response

- So random eruptions can affect ENSO's decadal behavior
- ENSO response depends on the season, ENSO phase, and location of the eruption

7. ENSO modulation:
Implications for evaluating models

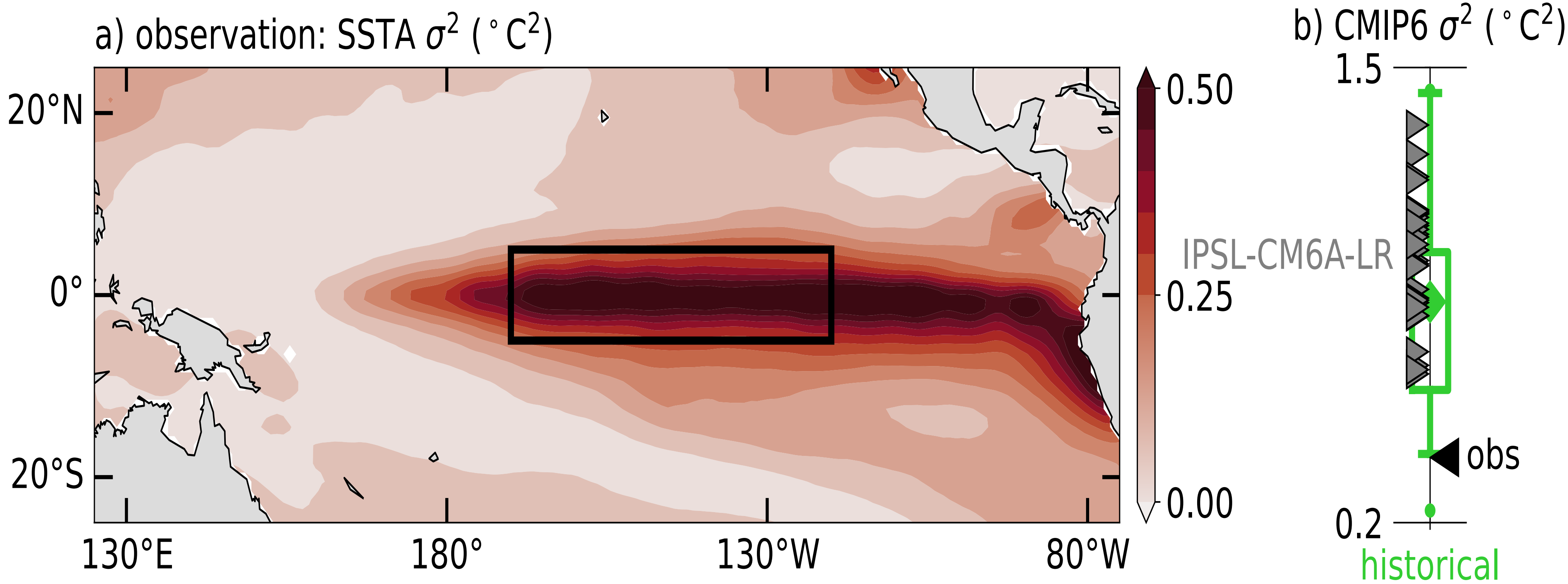
Metric = scalar comparing mod to a ref



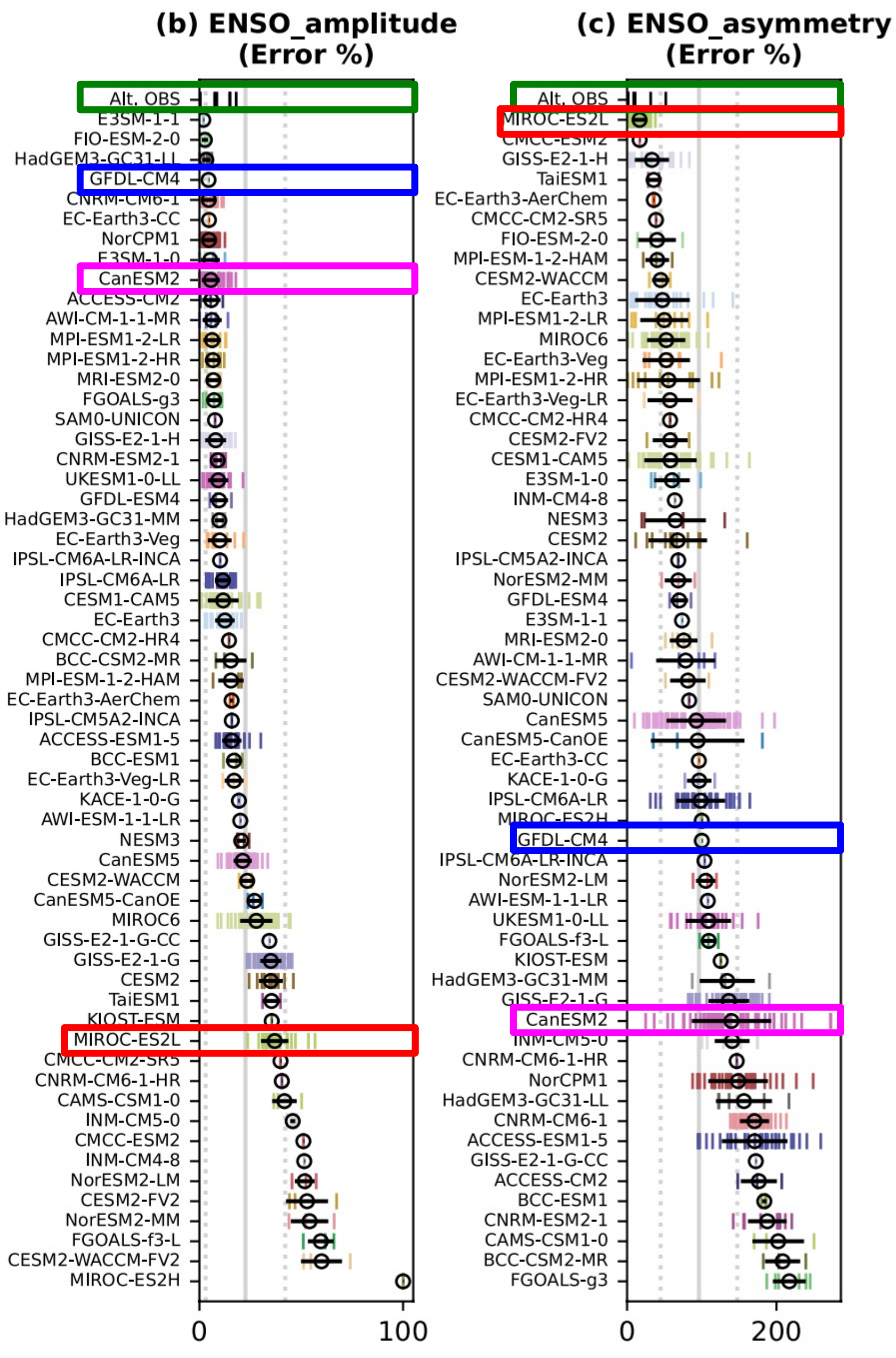
Planton et al. (BAMS 2021): https://doi.org/10.1175/BAMS-D-19-0337.1

https://cmec.llnl.gov/results/enso

ENSO amplitude = N3.4 SSTA variance



Planton et al. (BAMS 2021): *https://doi.org/10.1175/BAMS-D-19-0337.1*



CMIP6 (1850-2014) biases in ENSO amplitude & asymmetry

Many CGCMs now get a reasonable ENSO amplitude (stddev of NINO3.4 SSTA).

But they seem to struggle with ENSO nonlinearity & asymmetry (skewness of NINO3.4 SSTA).

Yet, note that **amplitude, and especially asymmetry, are *strongly modulated***, with large ensemble spread even on *centennial* scales.

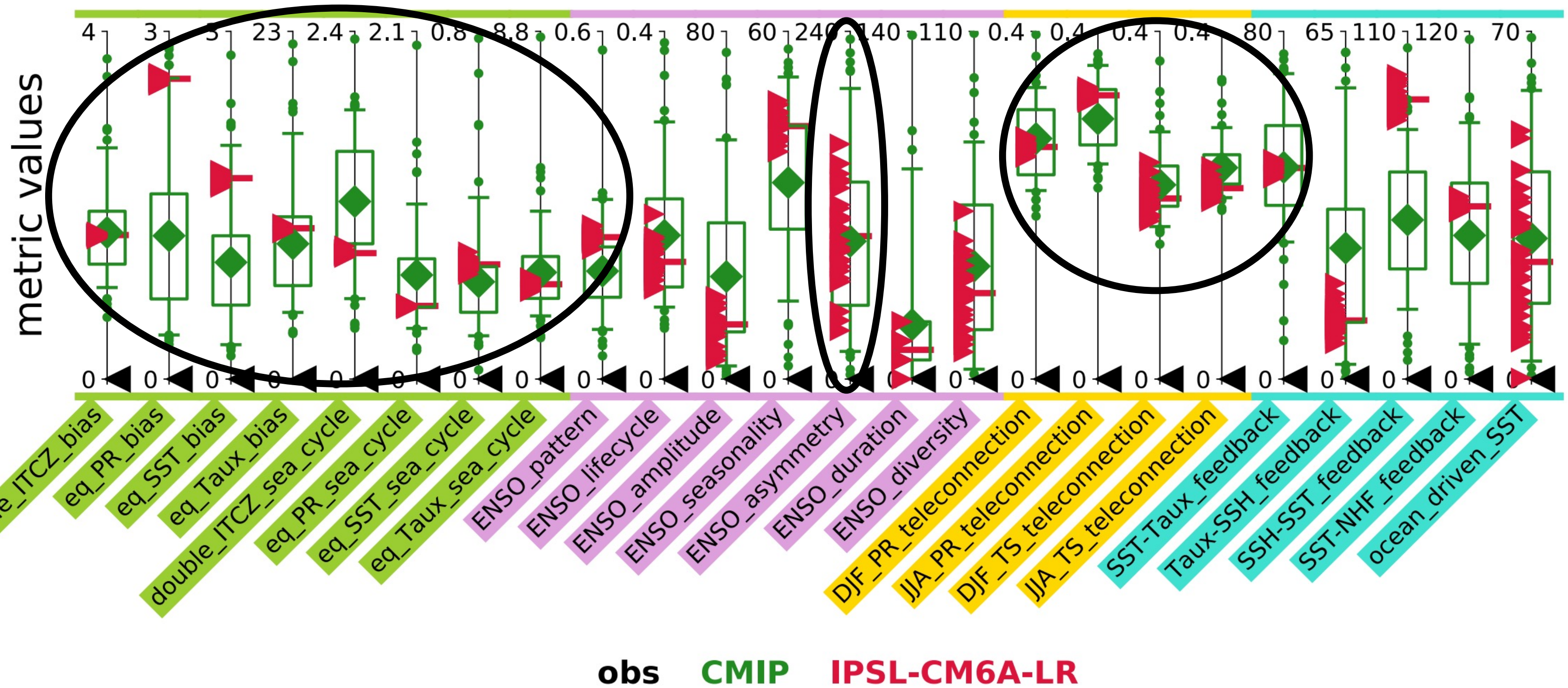
Lee et al. (GRL 2021)

https://doi.org/10.1029/2021GL095041

Implications for evaluating models

Some metrics (mean biases, teleconnections) are well constrained by available obs.

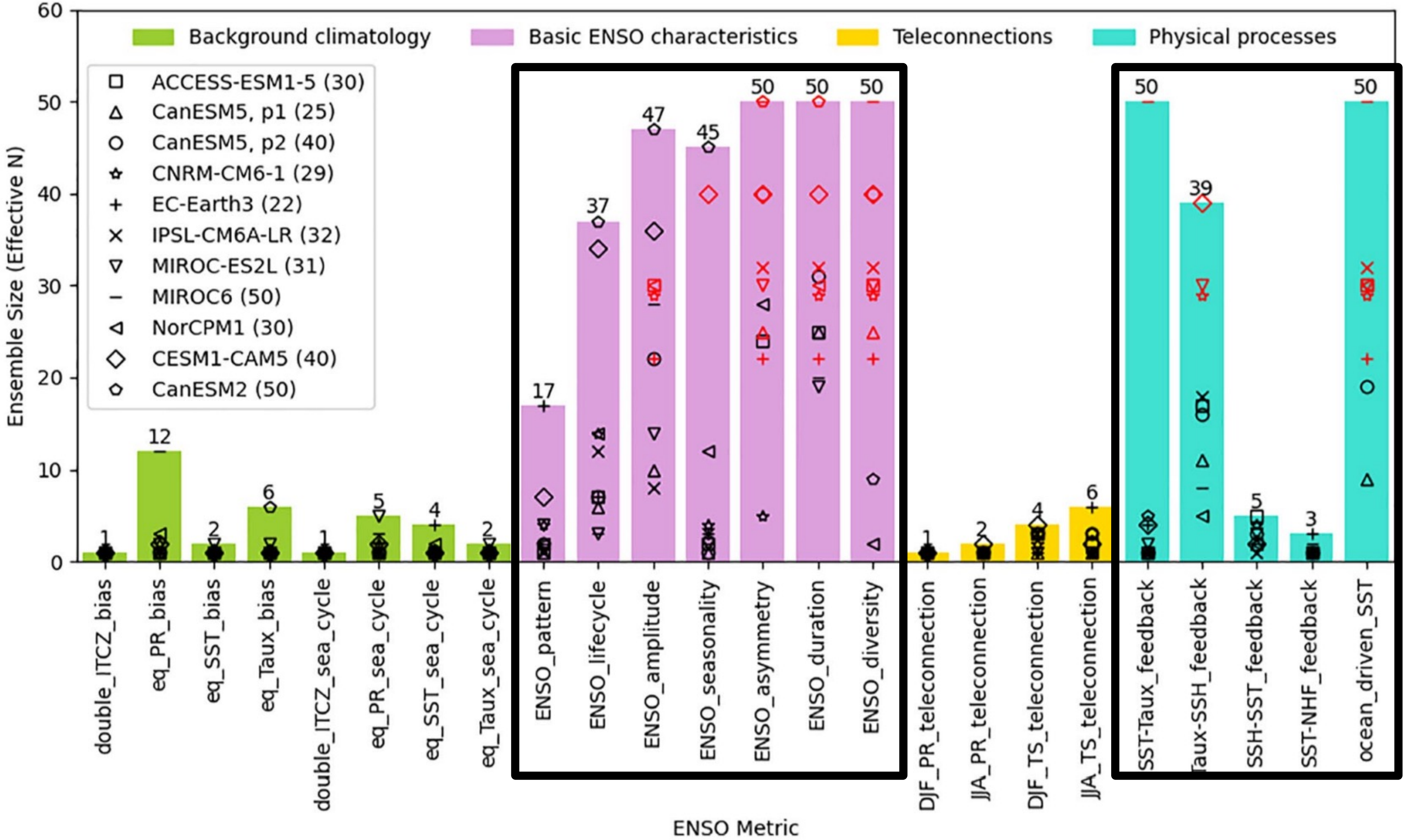
CLIVAR ENSO Metrics Package



For others (e.g. **ENSO asymmetry**), the ensemble spread from ENSO modulation is comparable to the CMIP inter-model spread, making it hard to evaluate models based on limited obs.

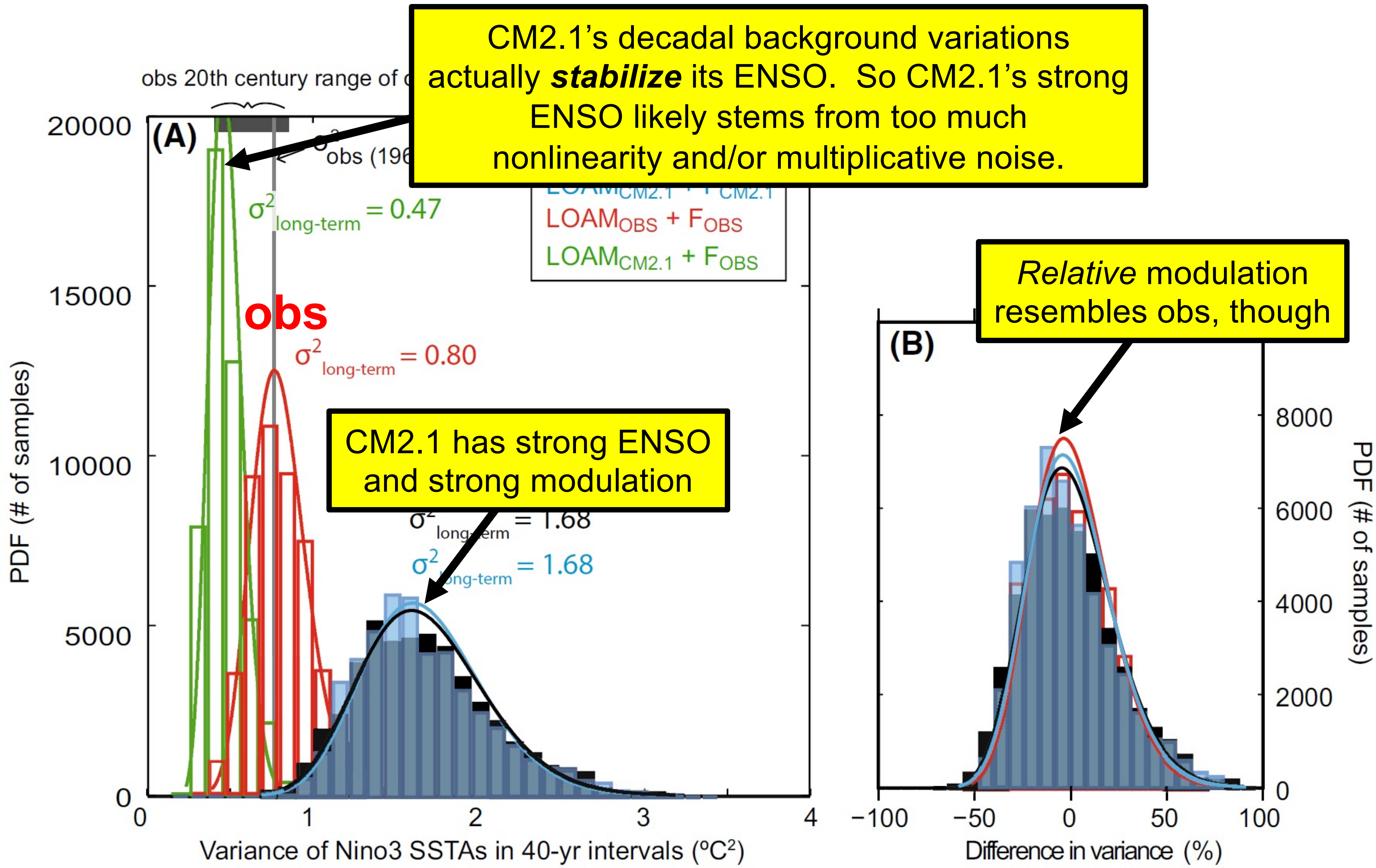
Planton et al. (BAMS 2021): https://doi.org/10.1175/BAMS-D-19-0337.1

Need a large model ensemble for some metrics



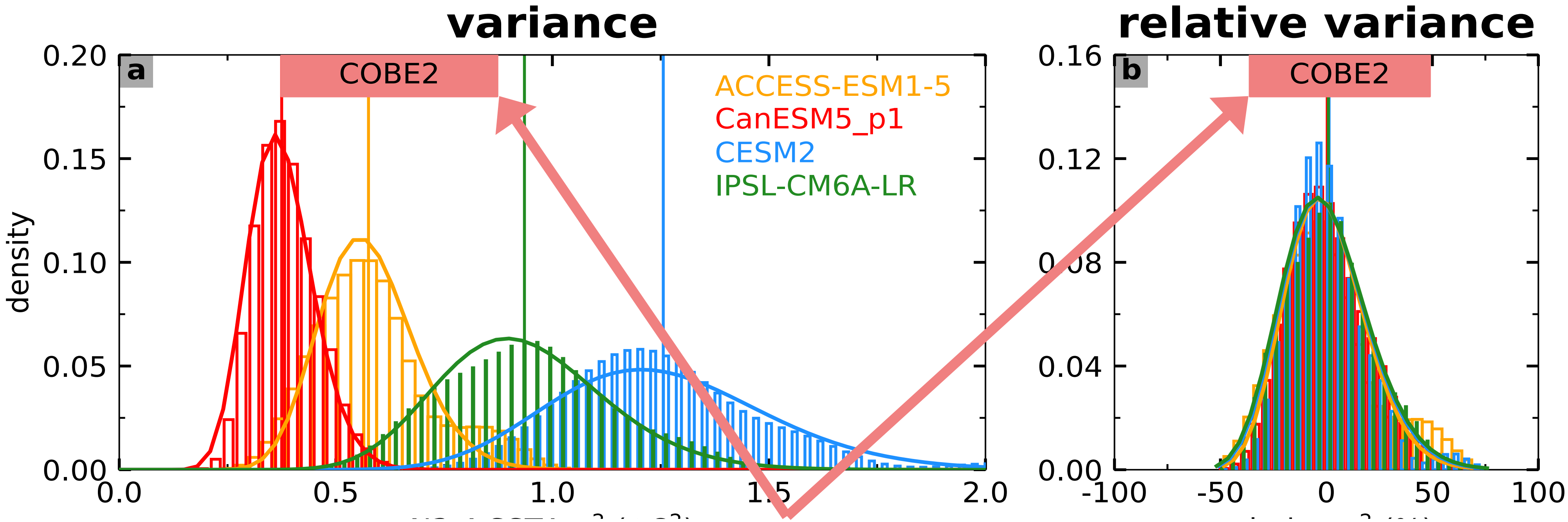
Lee et al. (GRL 2021): *https://doi.org/10.1029/2021GL095041*

ENSO modulation



Atwood et al. (CD 2017): https://doi.org/10.1007/s00382-016-3477-9

Figure 8: PDFs of ENSO amplitudes in piControl experiment



partially overlapping 30-year chunks (every 15 years) mixing internal variability, natural (e.g., volcanic eruptions,...) and anthropogenic forcings

Planton et al. (subm. to JC)

Amplitude modulation: "Variance of a variance"

Given a normal distribution with variance σ^2 the expected distribution of the sample variance of a random sample of size n is

$$s^2 = \frac{\sigma^2 \chi^2_{n^*-1}}{n^* - 1}$$

where $\chi^2_{n^*-1}$ is the Chi square distribution with n^*-1 degrees of freedom.

$$\mathrm{Var}\left(s^2\right) = \left(\frac{\sigma^2}{n^* - 1}\right)^2 \mathrm{Var}\left(\chi^2_{n^*-1}\right) = \left(\frac{\sigma^2}{n^* - 1}\right)^2 2(n^* - 1) = \frac{2\sigma^4}{(n^* - 1)}$$

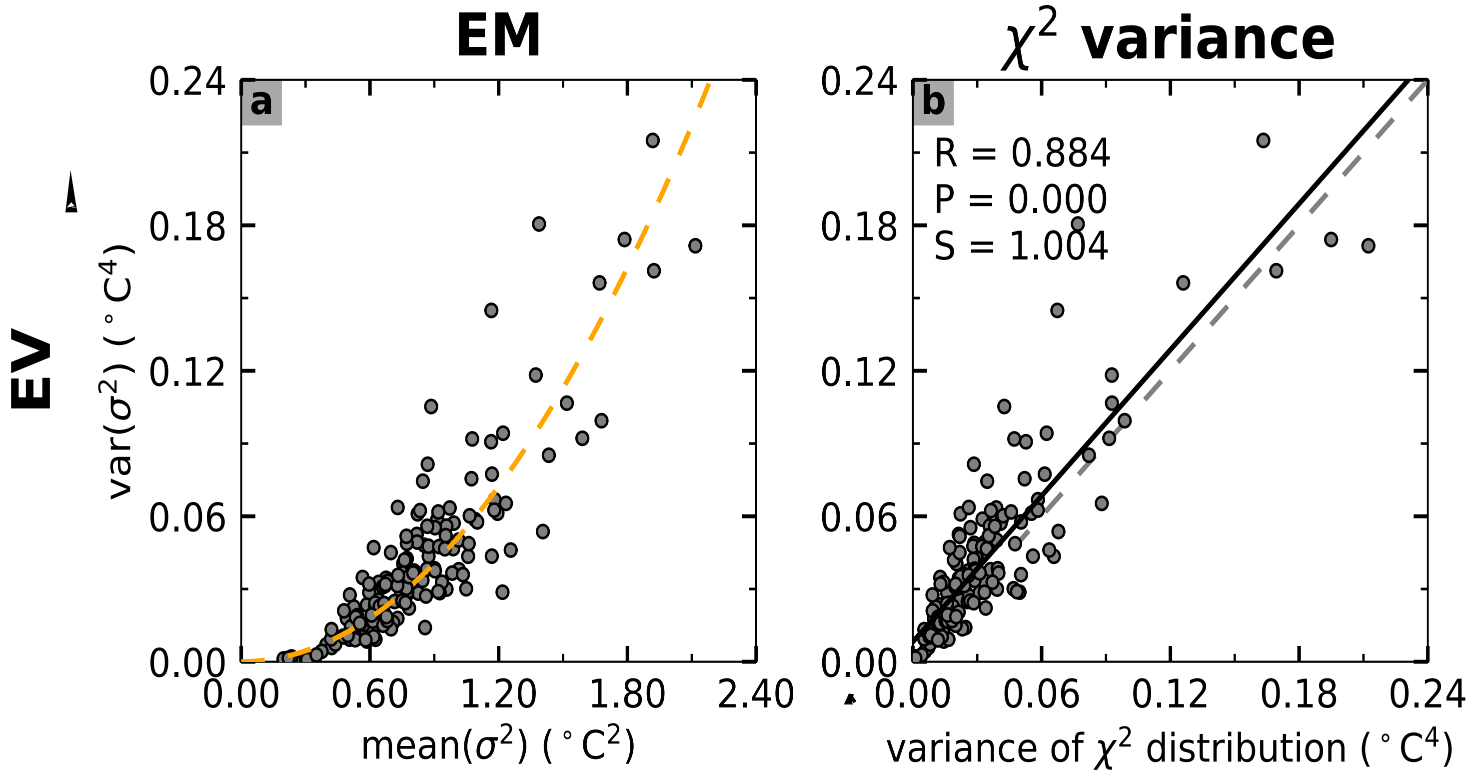
High variance or **small *n*** → **more *modulation*** of sample variance.

Strong ENSO, short record or longer time scale, small ensemble or rare events...

Atwood et al. (CD 2017): https://doi.org/10.1007/s00382-016-3477-9

CMIP6 modulation close to that expected of χ^2

ensemble variance = internal variability



expected variance if χ^2 distributed

$$IV \approx \frac{2}{n^* - 1} \times \overline{ENSO}^2$$

$$RES \approx \frac{4}{\Delta^2} \times IV$$

Planton et al. (subm. to JC)

Summary 7: Implications for evaluating models

1. Intrinsic modulation of ENSO metrics

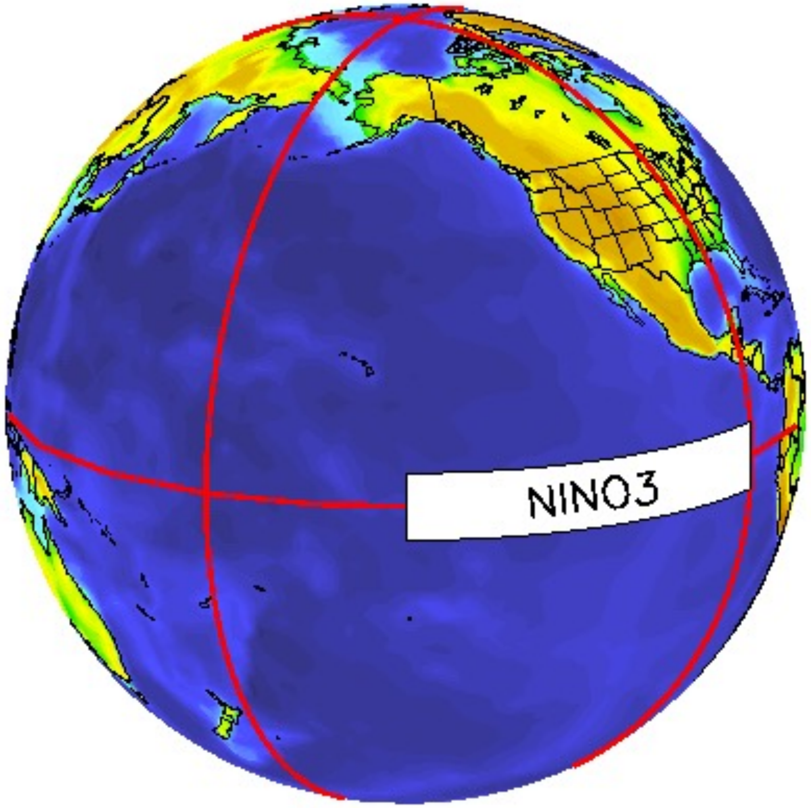
- **Mean biases, ENSO teleconnections are less modulated**; models better constrained by obs
- **ENSO amplitude, asymmetry, ocean feedbacks are strongly modulated**
  → Need much longer obs records, larger model ensembles to constrain these

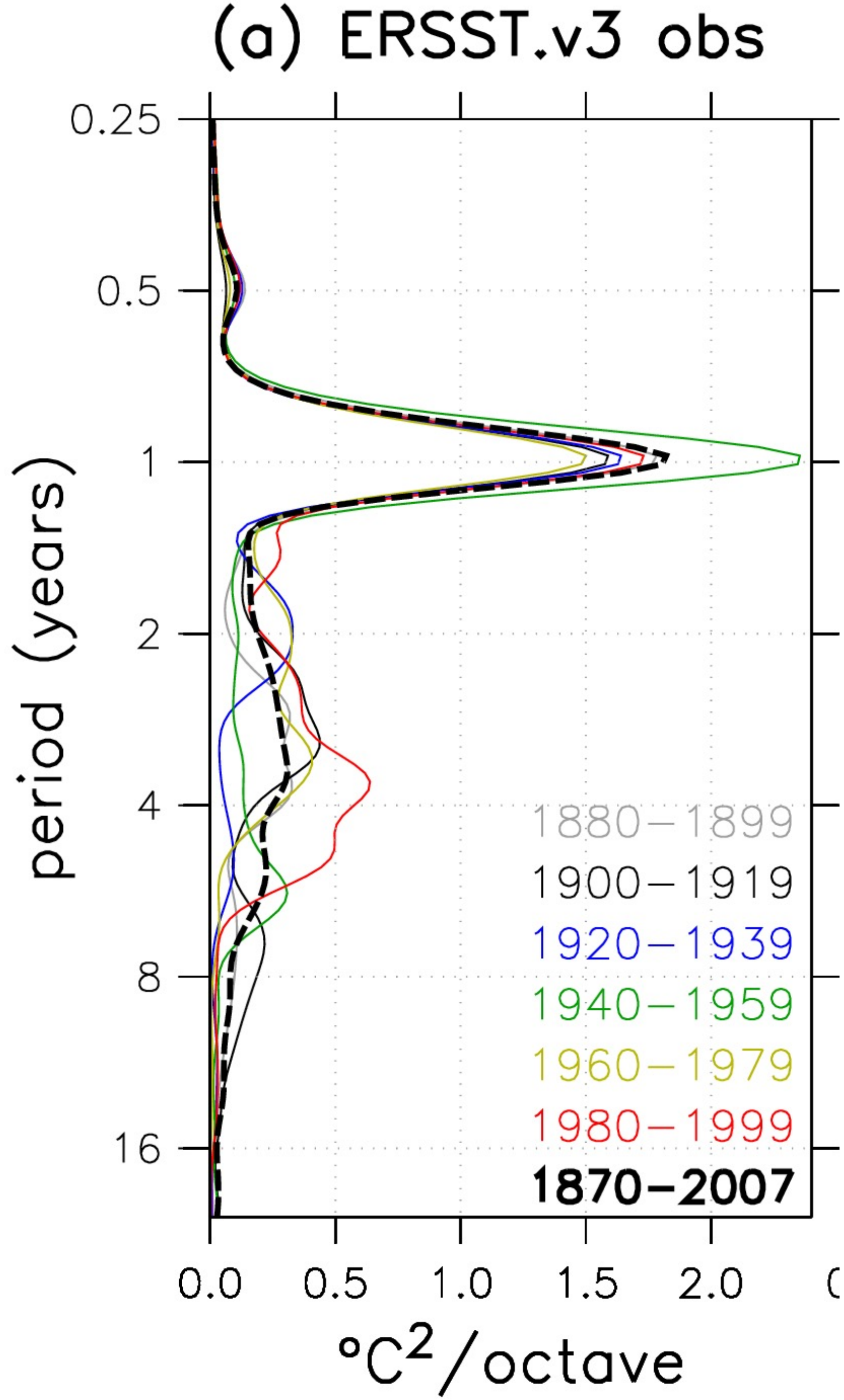
2. ENSO variances & spectra are roughly χ^2 distributed

- Strong ENSO variance → strong decadal modulation
- ***Relative* amplitude modulation** may be more comparable among models & obs
- High-variance regimes/models, and rare events (e.g. extremes)
  → require longer obs/model time series for robust comparison

8. Case study: Detecting changes in ENSO amplitude & spectrum

NINO3 SST spectrum

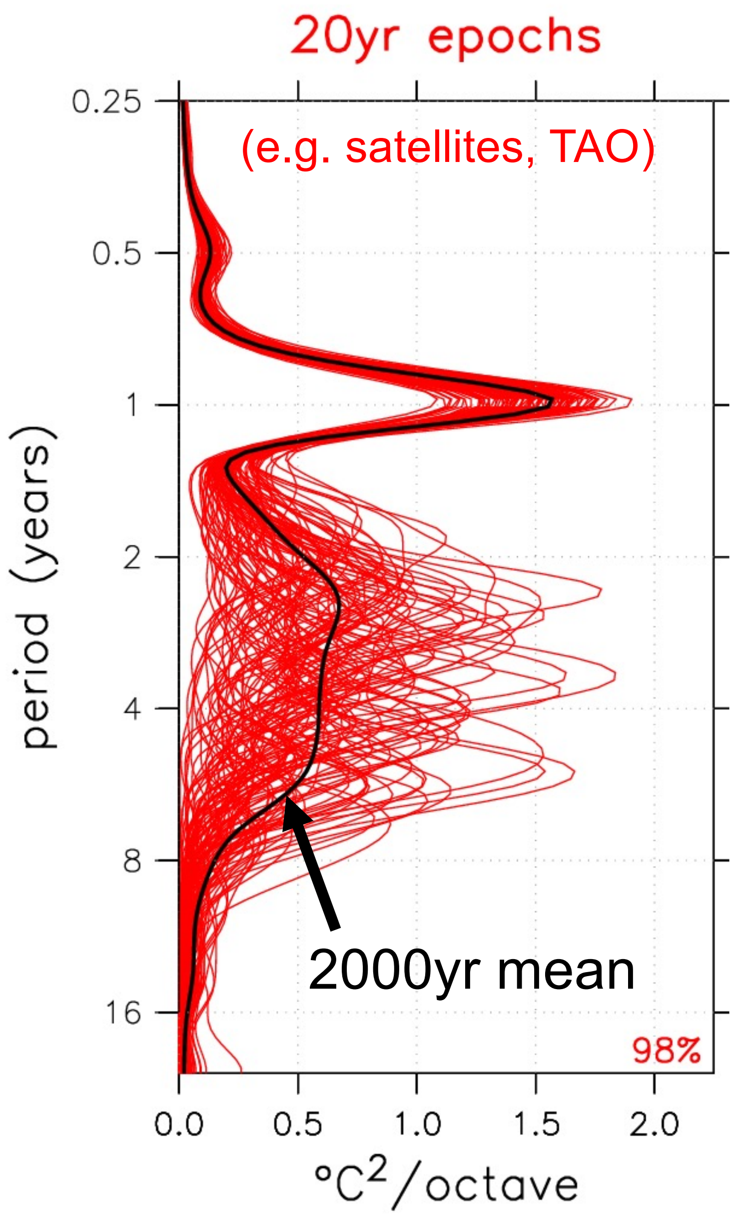




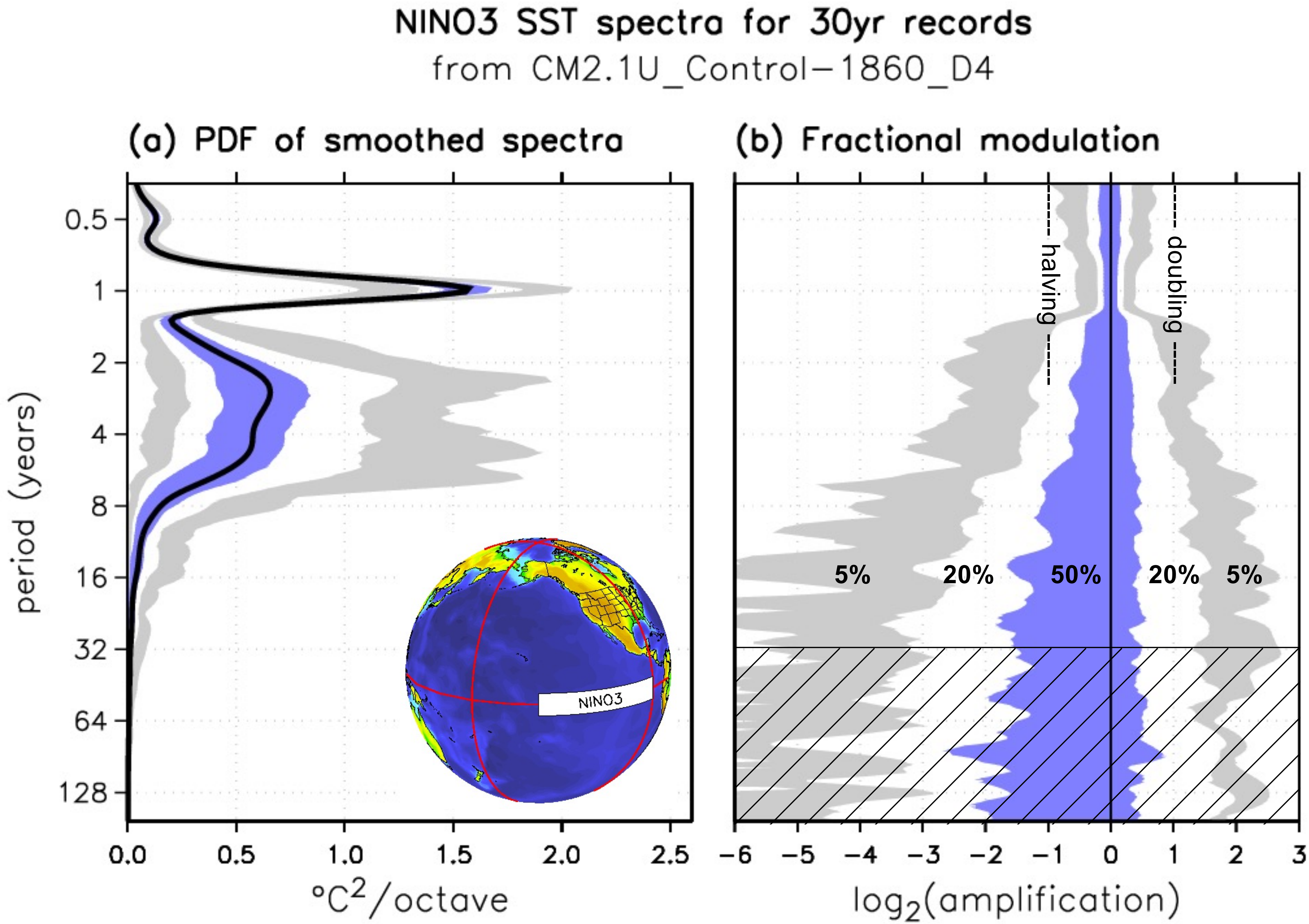
Wittenberg (GRL 2009)

https://doi.org/10.1029/2009GL038710

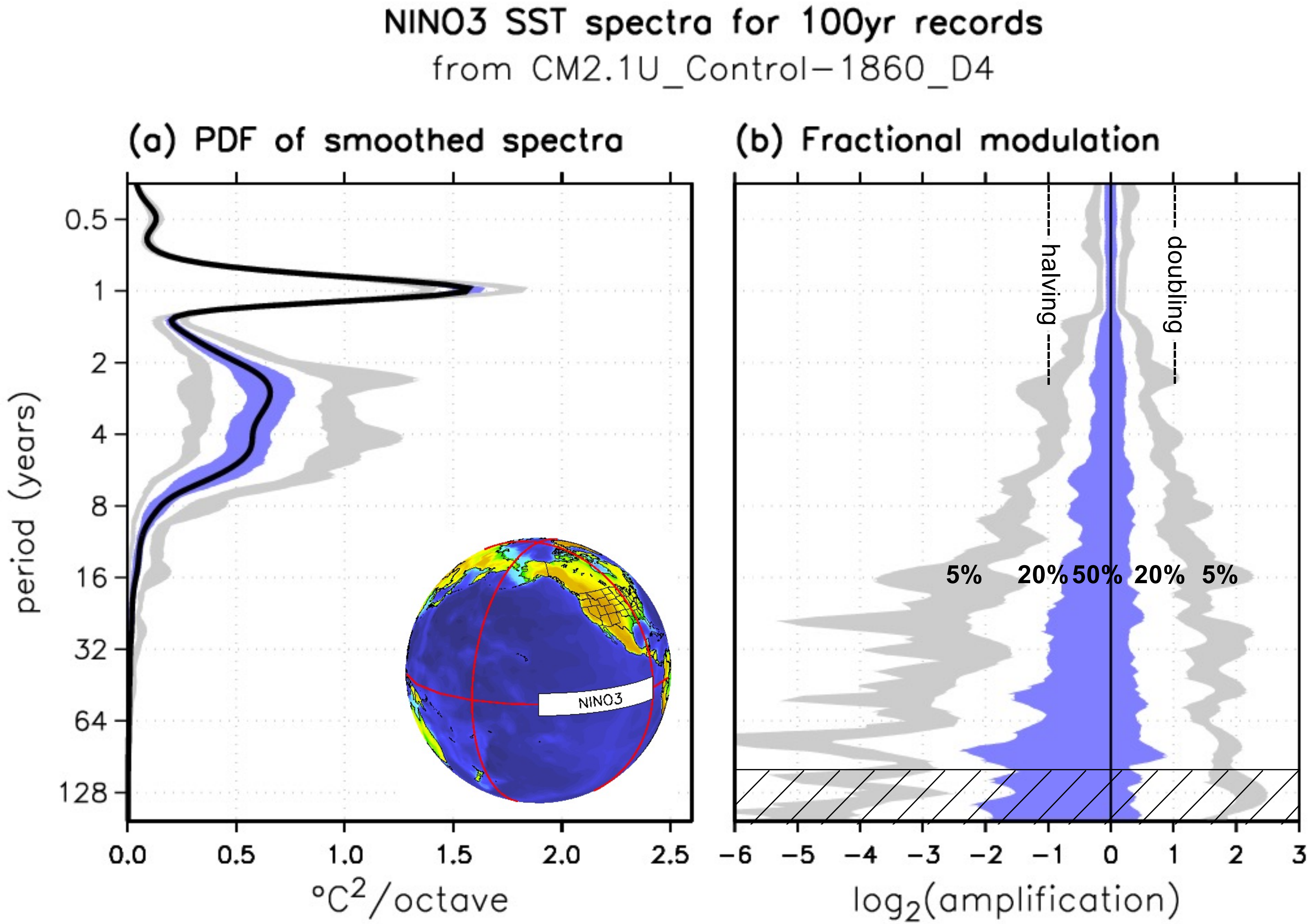
Modulation of NINO3 SST power spectrum



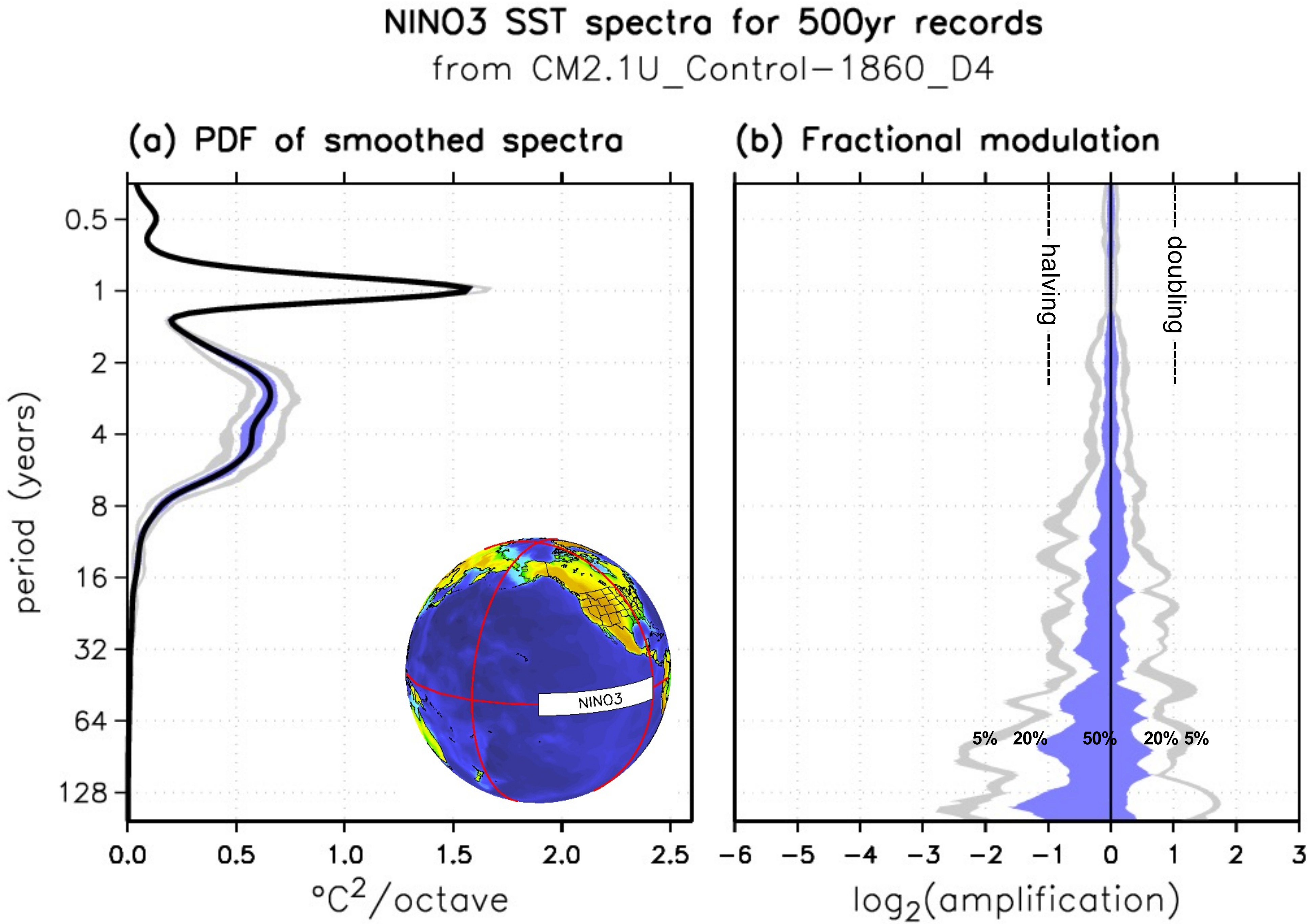
Wittenberg (GRL 2009): https://doi.org/10.1029/2009GL038710; also Stevenson et al. (JC 2010; GRL 2012)



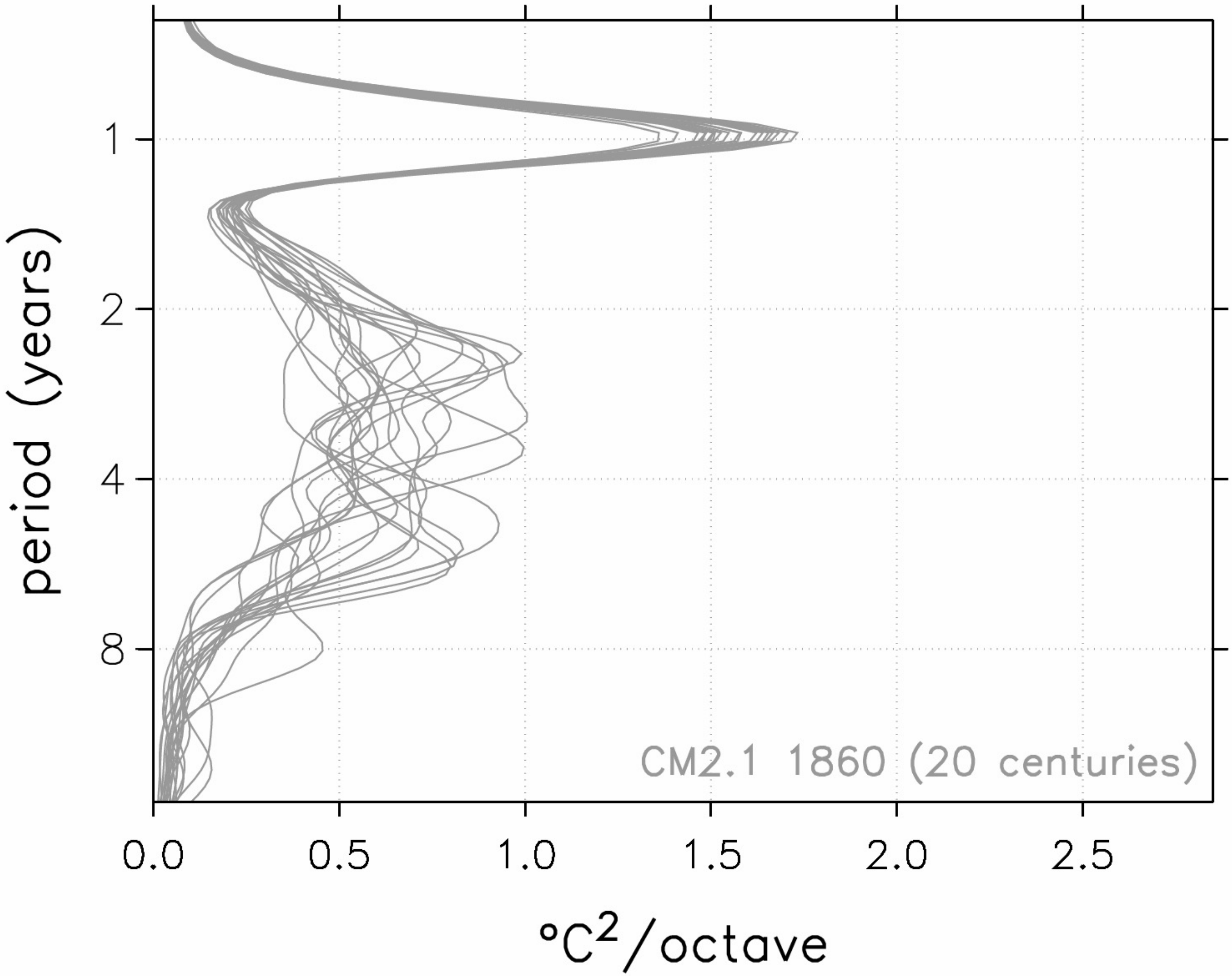
NINO3 SST spectra for 30yr records
from CM2.1U_Control-1860_D4
(a) PDF of smoothed spectra
(b) Fractional modulation
period (years)
0.5
1
2
4
8
16
32
64
128
0.0
0.5
1.0
1.5
2.0
2.5
°C²/octave
NINO3
halving
doubling
5%
20%
50%
20%
5%
−6
−5
−4
−3
−2
−1
0
1
2
3
log2(amplification)



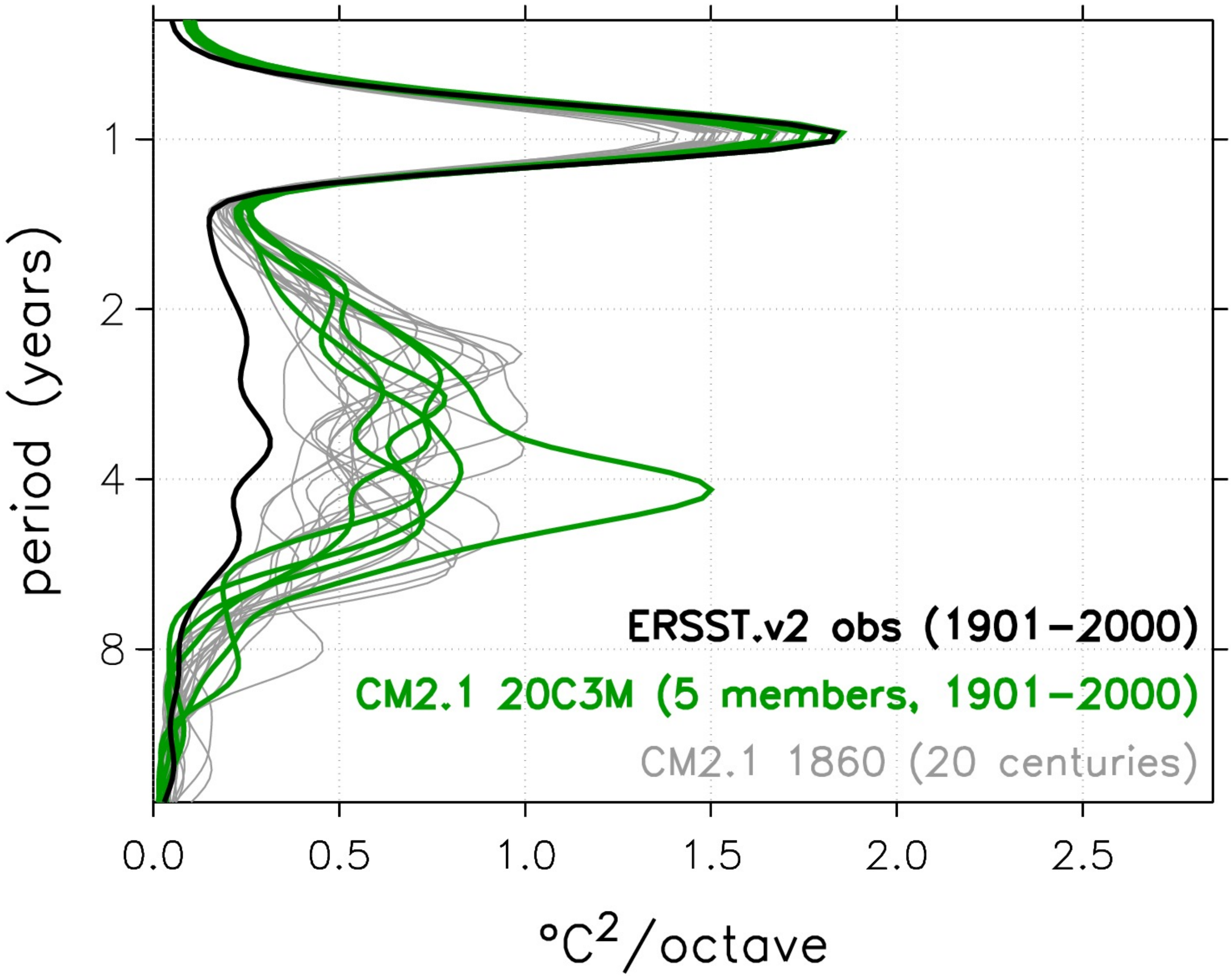
NINO3 SST spectra for 100yr records
from CM2.1U_Control-1860_D4
(a) PDF of smoothed spectra
(b) Fractional modulation
period (years)
0.5
1
2
4
8
16
32
64
128
0.0
0.5
1.0
1.5
2.0
2.5
°C²/octave
NINO3
halving
doubling
5%
20%
50%
20%
5%
−6
−5
−4
−3
−2
−1
0
1
2
3
log₂(amplification)


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)

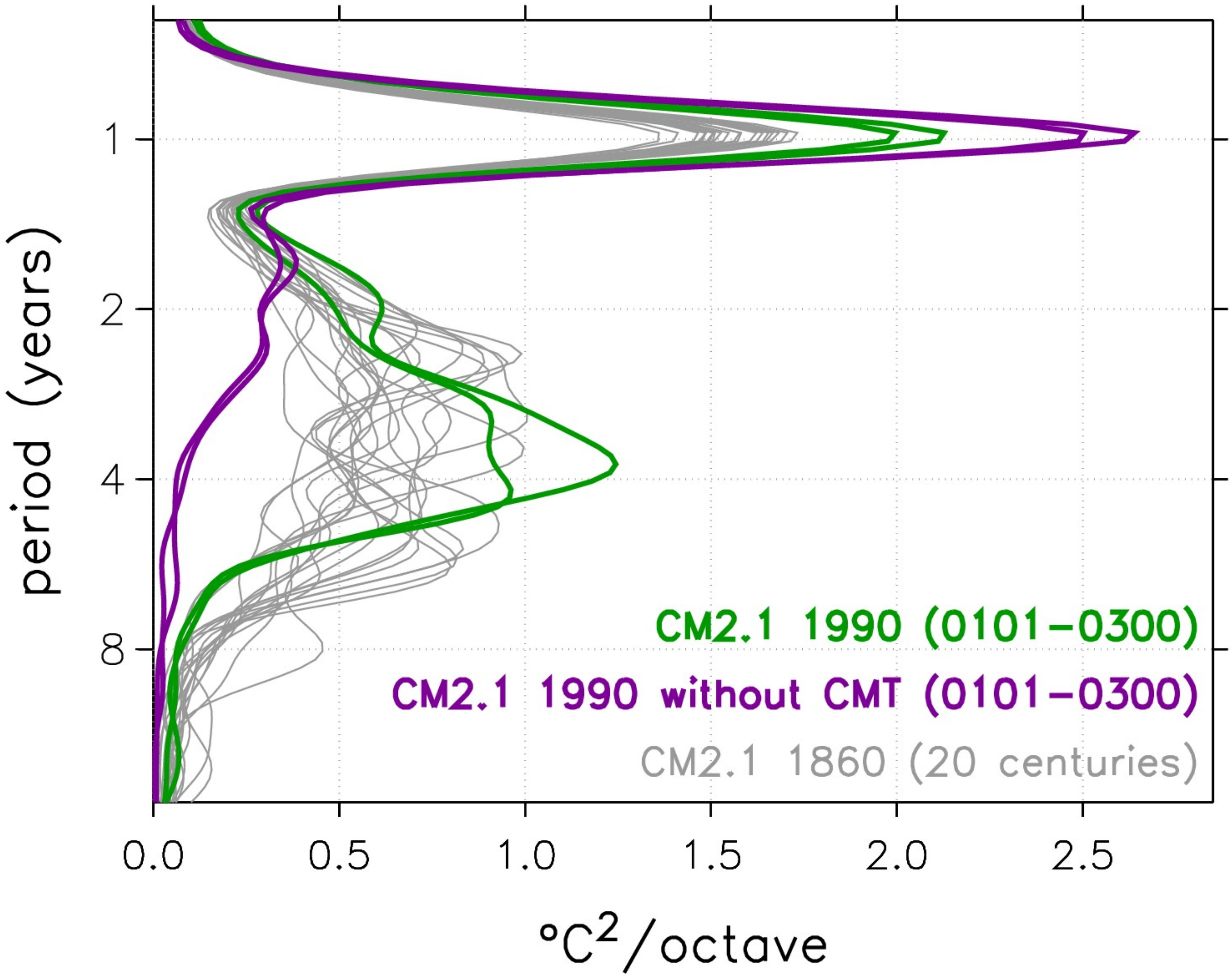
Given enough years, we *can* say...



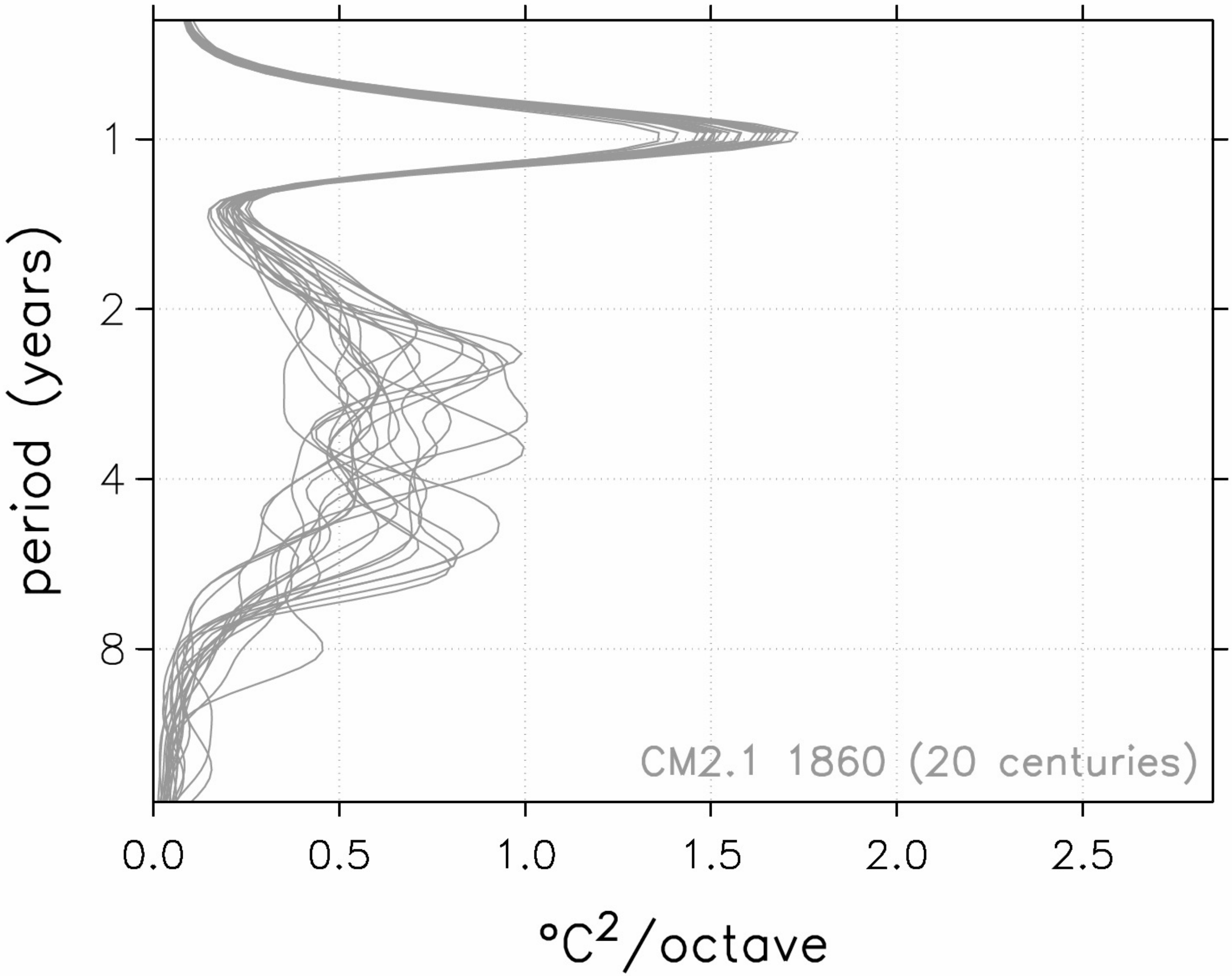
CM2.1 ENSO is too strong



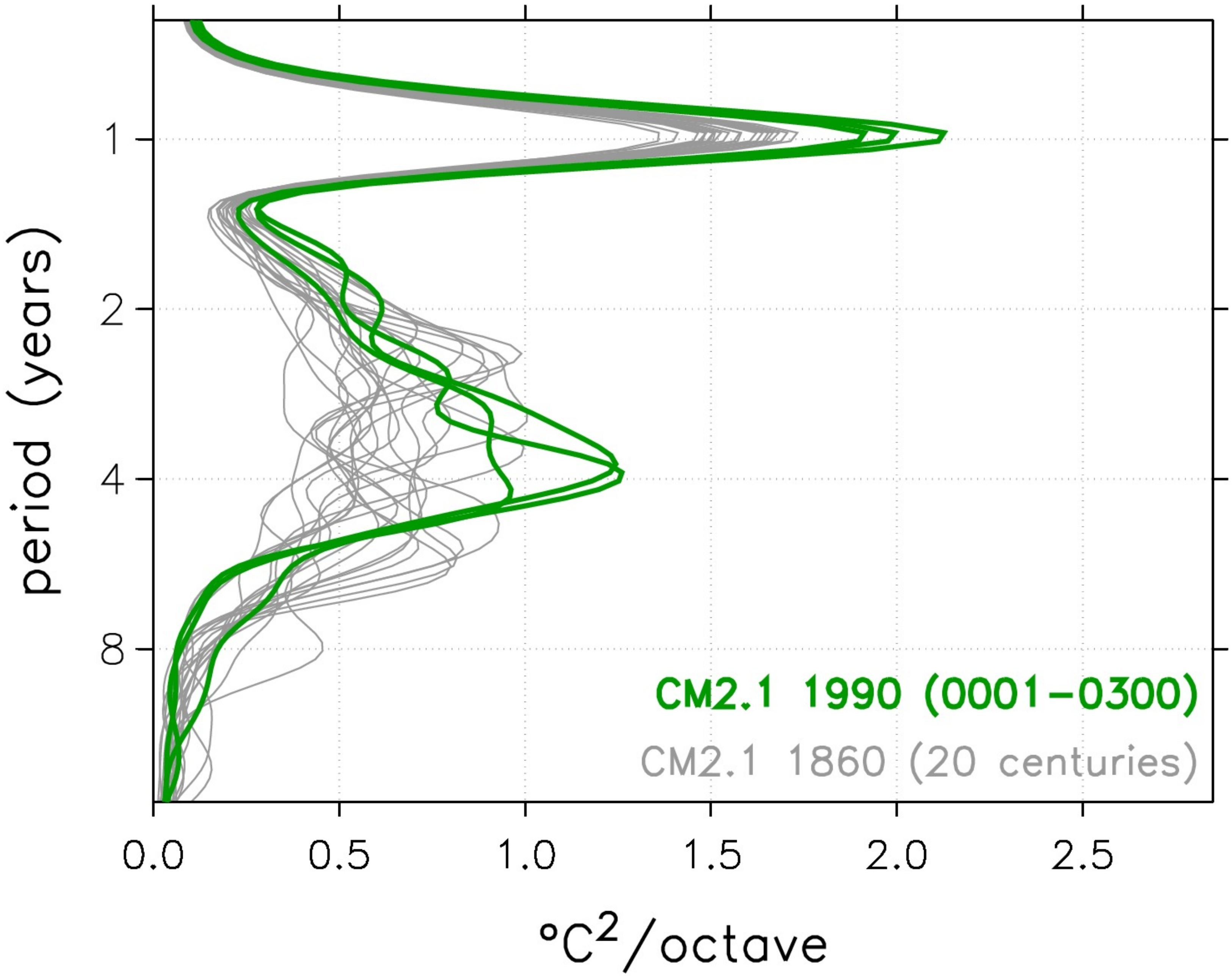
CM2.1 ENSO is very sensitive to some parameters



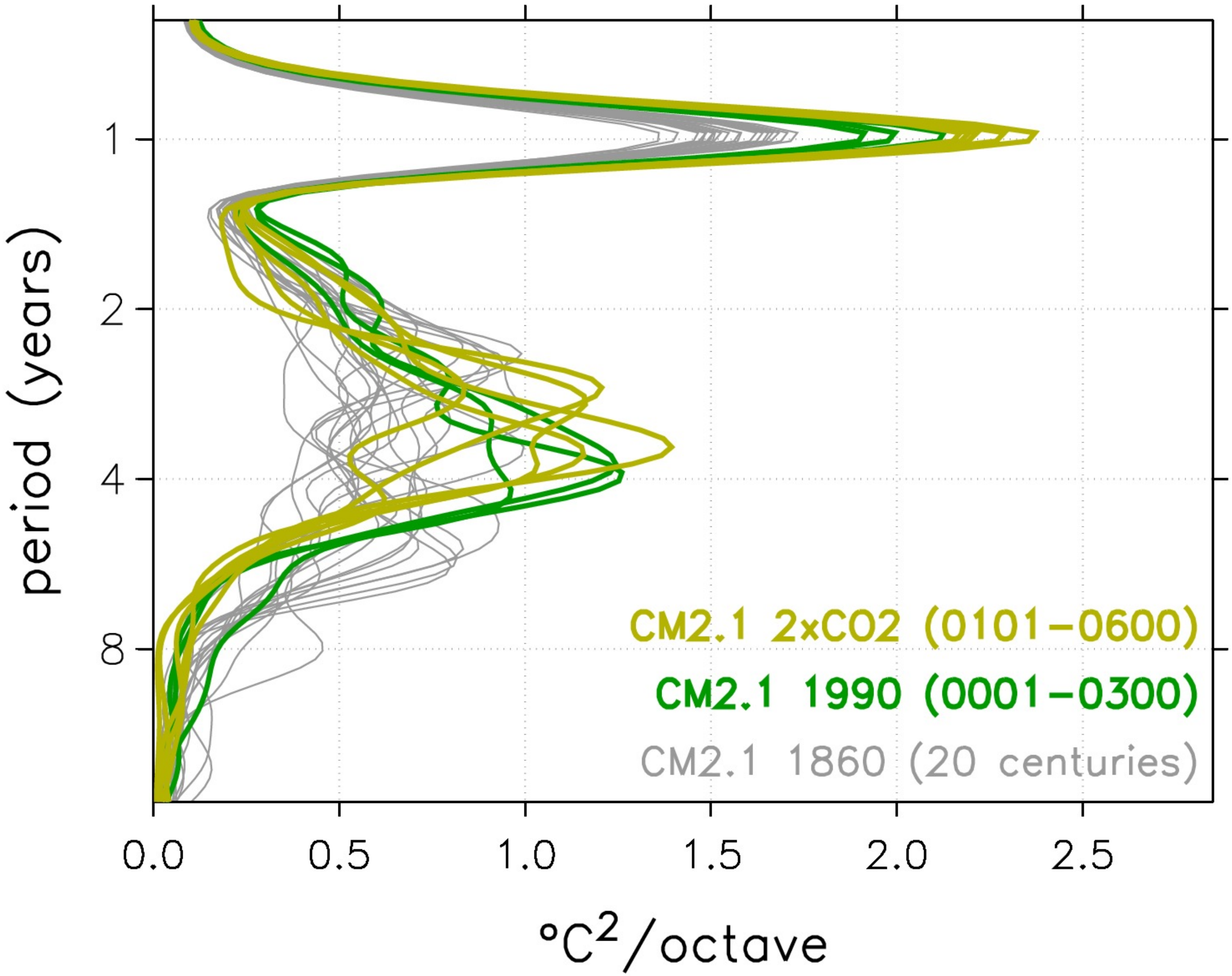
Pre-industrial range of 100yr spectra



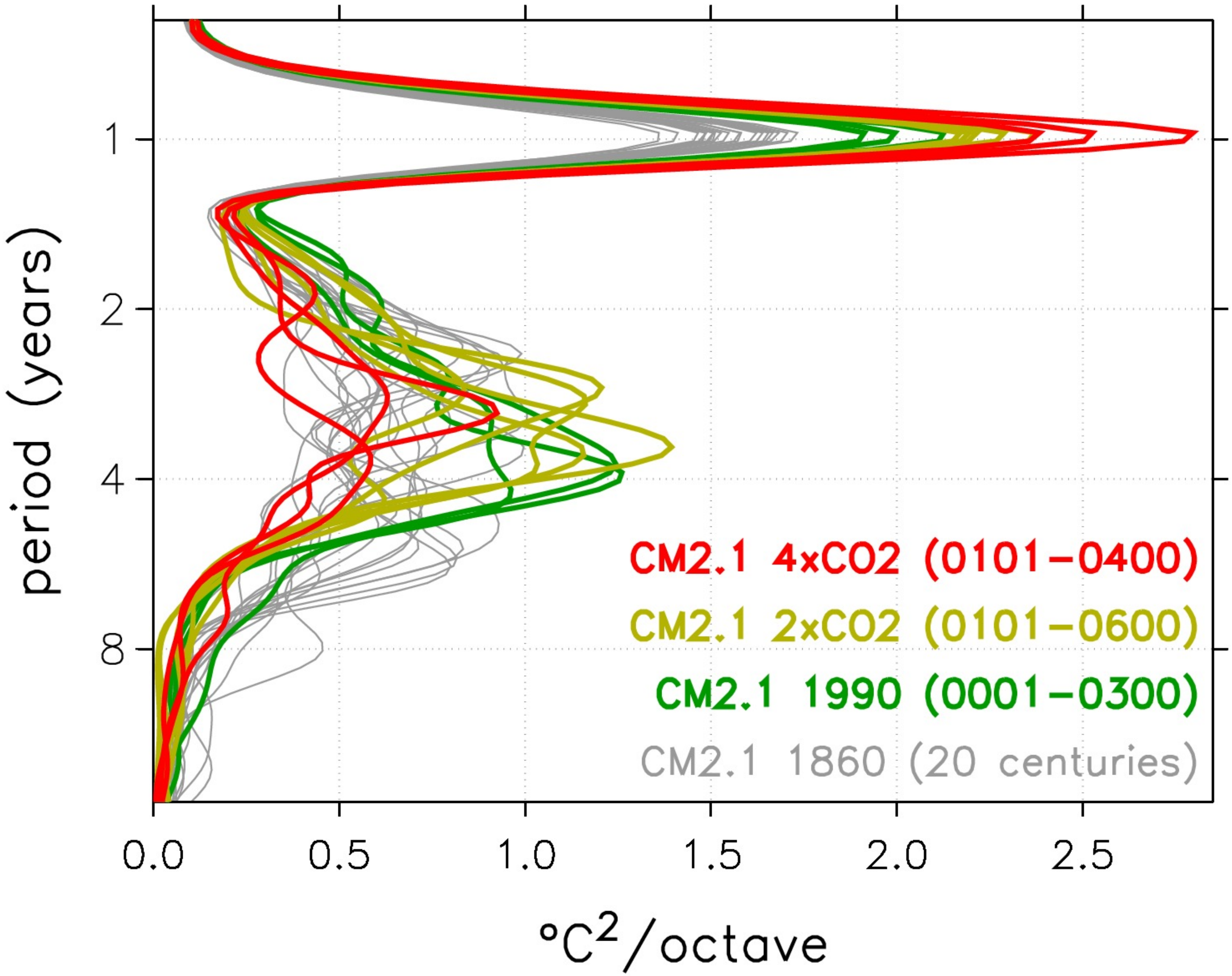
1990: ENSO strengthens, spectrum narrows



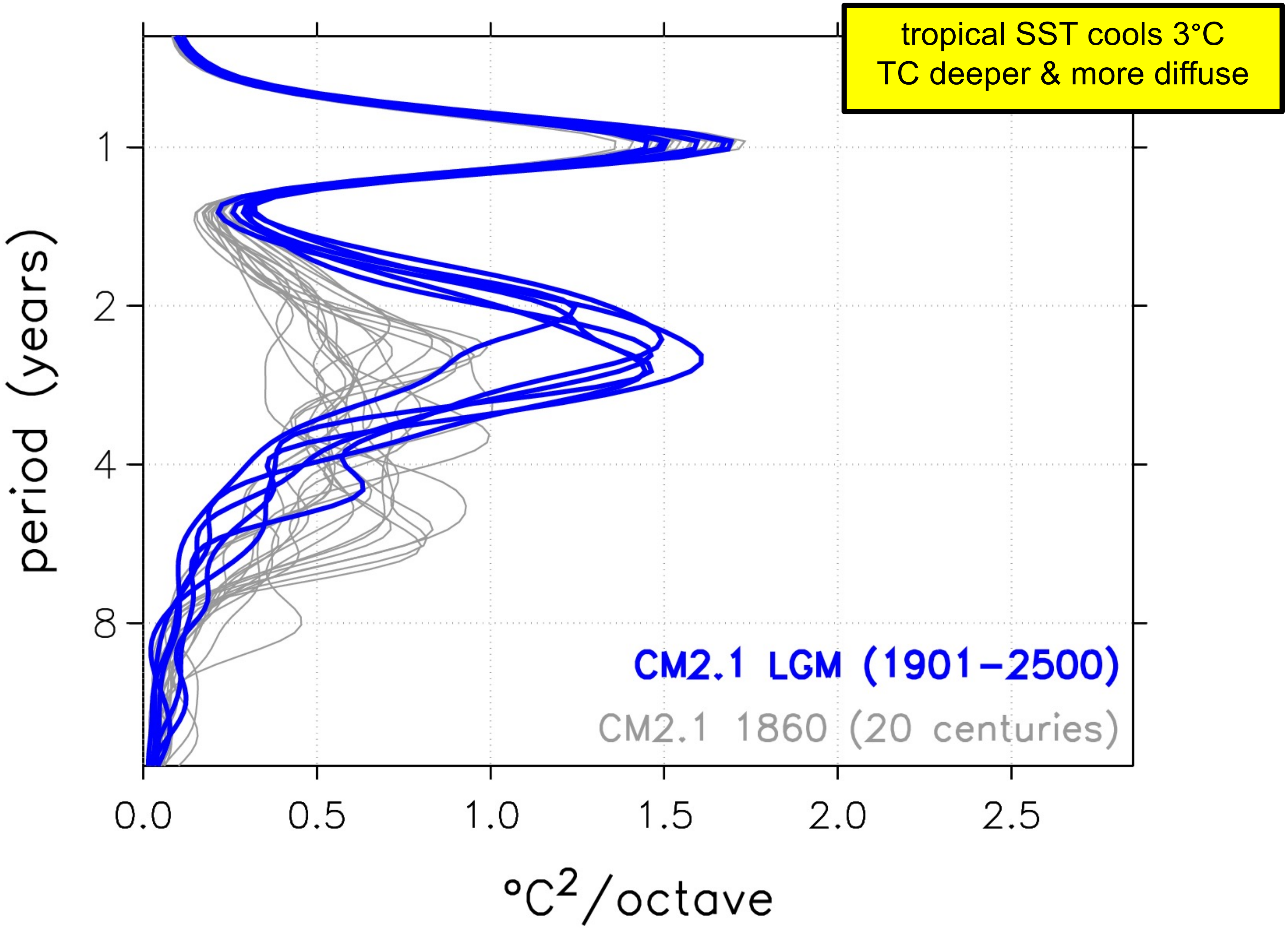
2xCO2: slightly shorter period than 1990



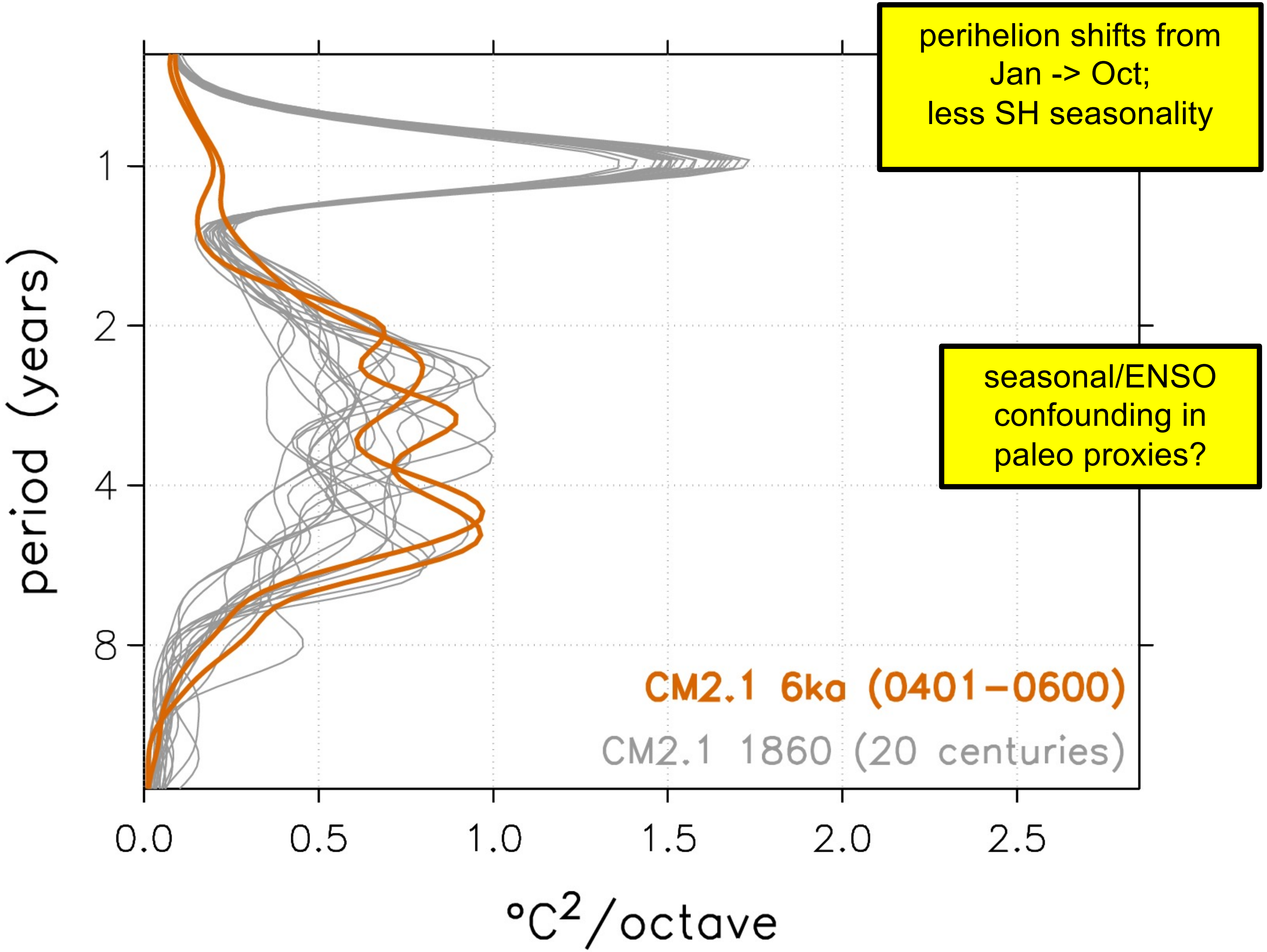
4xCO2: ENSO weaker than at 2xCO2



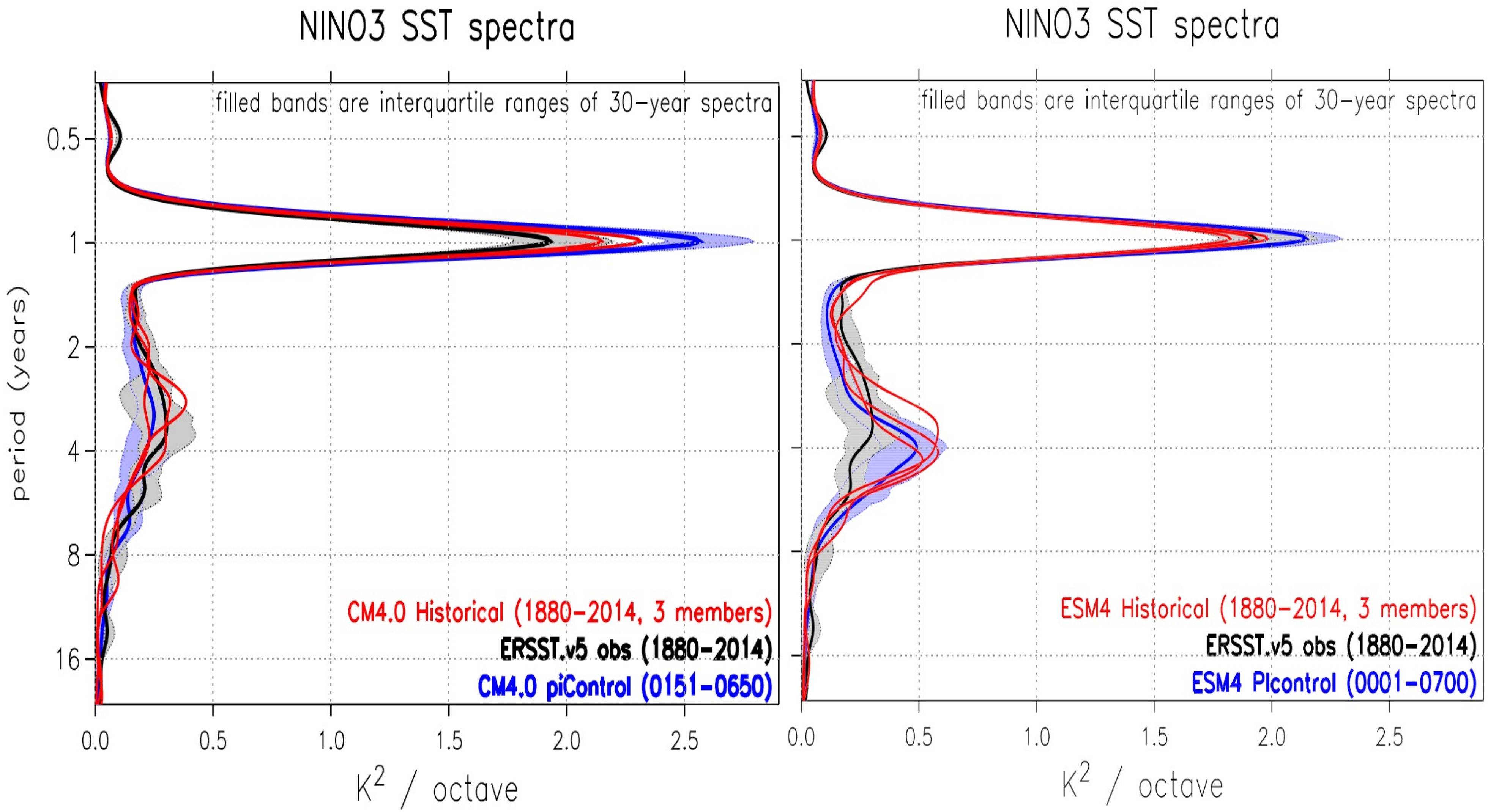
Last Glacial Maximum (20ka)



Mid-Holocene (6ka)



ENSO spectra in GFDL's CMIP6 models: CM4 and ESM4

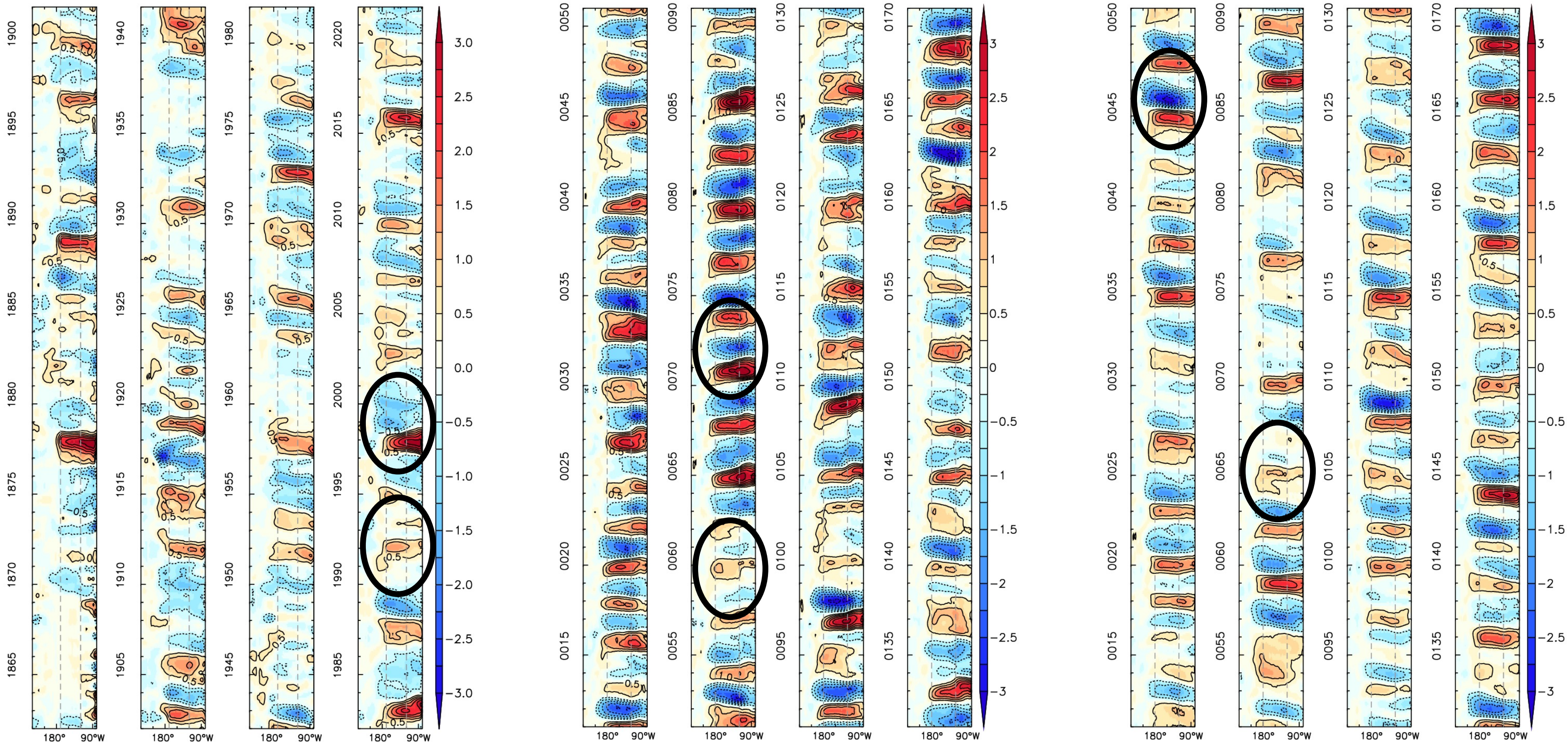


Held et al. (JAMES 2019)
https://doi.org/10.1029/2019MS002015

Dunne et al. (JAMES 2020)
https://doi.org/10.1029/2019MS001829

Equatorial Pacific SSTAs (°C, 160yr)

OBS (ERSST.v5) **FLOR** **FLOR-FA**



SSTA amplitude/pattern/propagation ***vary from decade to decade*** *in obs & simulations.*
FLOR SSTAs are too strong, frequent, and eastward-propagating, especially for cold events.
FA gives weaker ENSO SSTAs, with ***more westward propagation and positive skewness****.*

Wittenberg et al. (JAMES 2018): *https://doi.org/10.1029/2018MS001372*

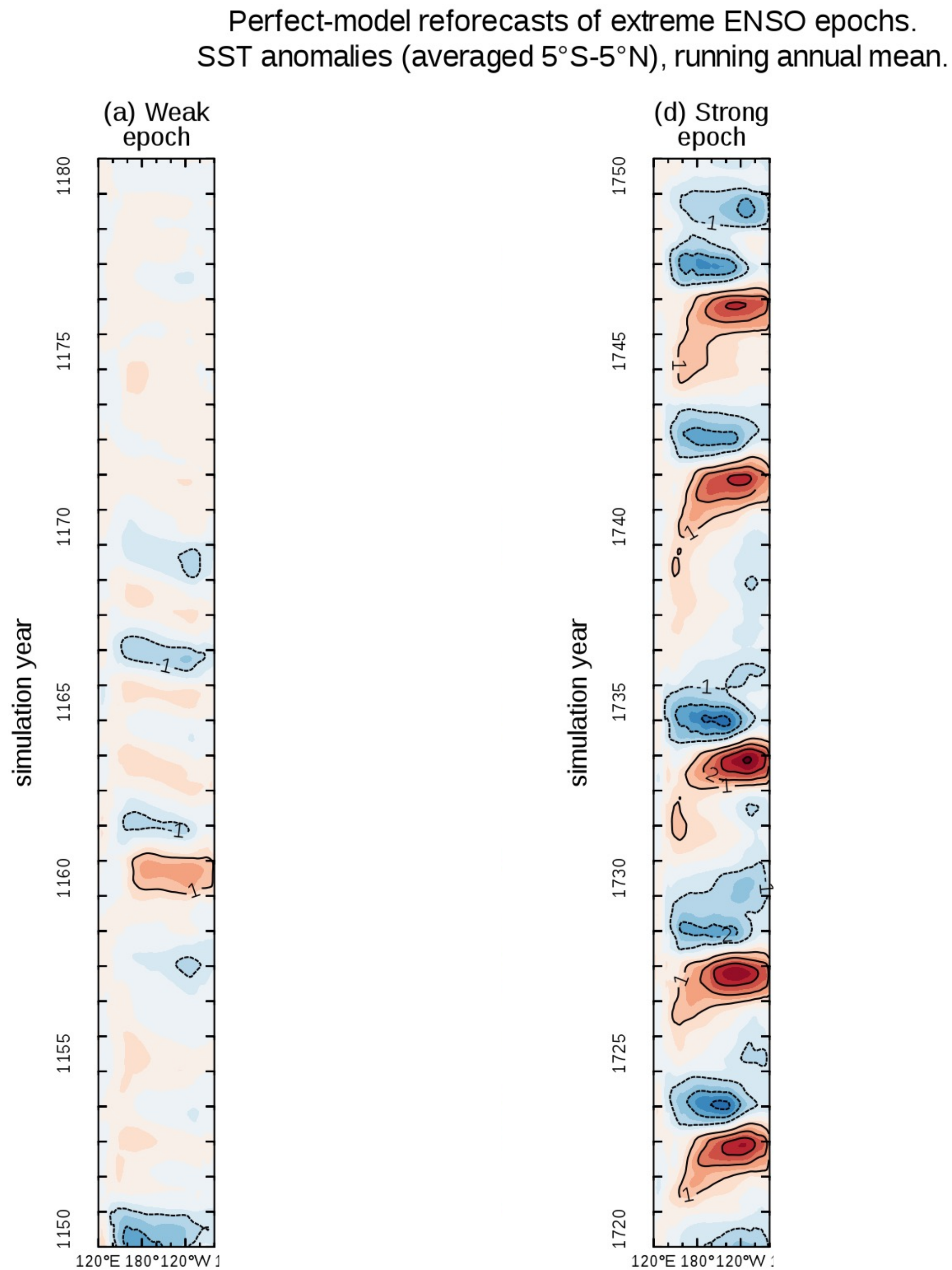
Summary 8: Detecting ENSO changes

1. We *can* detect certain forced changes, despite ENSO modulation
   - **Model biases, parameter sensitivities, past & future changes**
   - Despite strong **modulation** on decadal (& even centennial) scales
   - Detection can require **large ensembles** & centuries of simulation
   - We only have one historical record; but **paleo proxies** can help

2. Models have gradually improved
   - Long term: improve **resolution & physics**
   - Short term: add **bias corrections** (e.g. climatological flux adjustments, tendency corrections)
     → Can help improve ENSO behavior & teleconnections
     → Also help us understand *which* model biases affect ENSO

Reserve Slides

"Perfect" reforecasts of extreme ENSO epochs

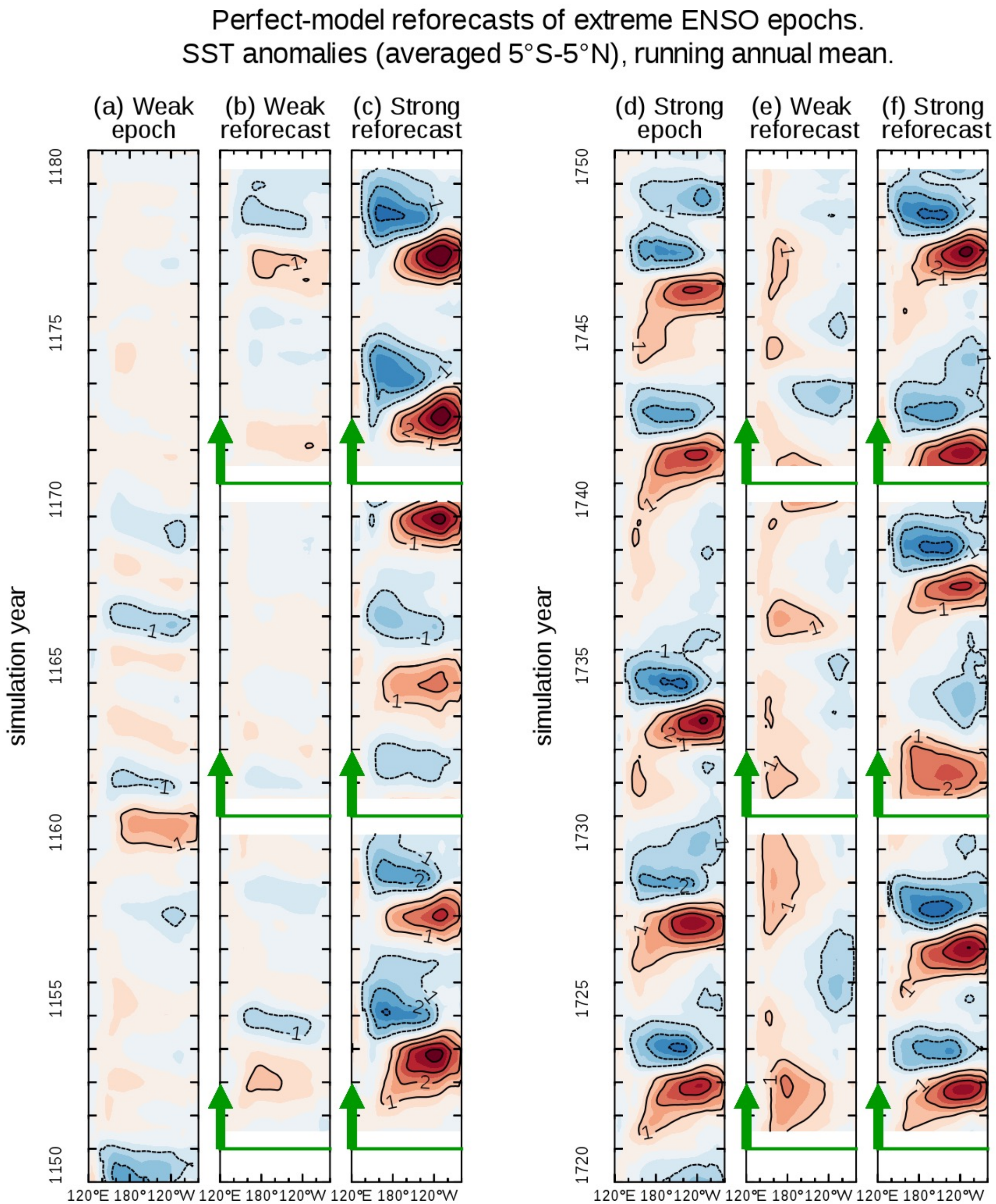


In the absence of external forcings, CM2.1's intrinsically-generated "extreme ENSO decades" can be *imitated*.

But the ENSO trajectories and statistics for these decades appear to be *unpredictable*.

Wittenberg et al. (JC 2014)
https://doi.org/10.1175/JCLI-D-13-00577.1
Fedorov et al. (AGU 2020)
https://doi.org/10.1002/9781119548164.ch8
Also: Feng & Tung (CD 2020)

“Perfect” reforecasts of extreme ENSO epochs



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Unresolved Questions

1. How unruly would ENSO be, if there were...

a. no decadal forcings at all?
b. only decadal forcings intrinsic to the ocean/atm system?
c. only intrinsic + natural forcings (volcanic, solar, orbital)?

2. How long an obs record do we need, to assess each of the above?

a. Must we actually observe numerous swings?
b. Or can we infer these swings from models & obs of the system dynamics?

3. To what extent has past modulation been natural/forced?

a. Historical & paleo records

4. How much of ENSO's modulation is predictable?

5. How/when will we detect anthro changes in ENSO behavior?

6. Given ENSO modulation, how to evaluate/compare ENSO models?

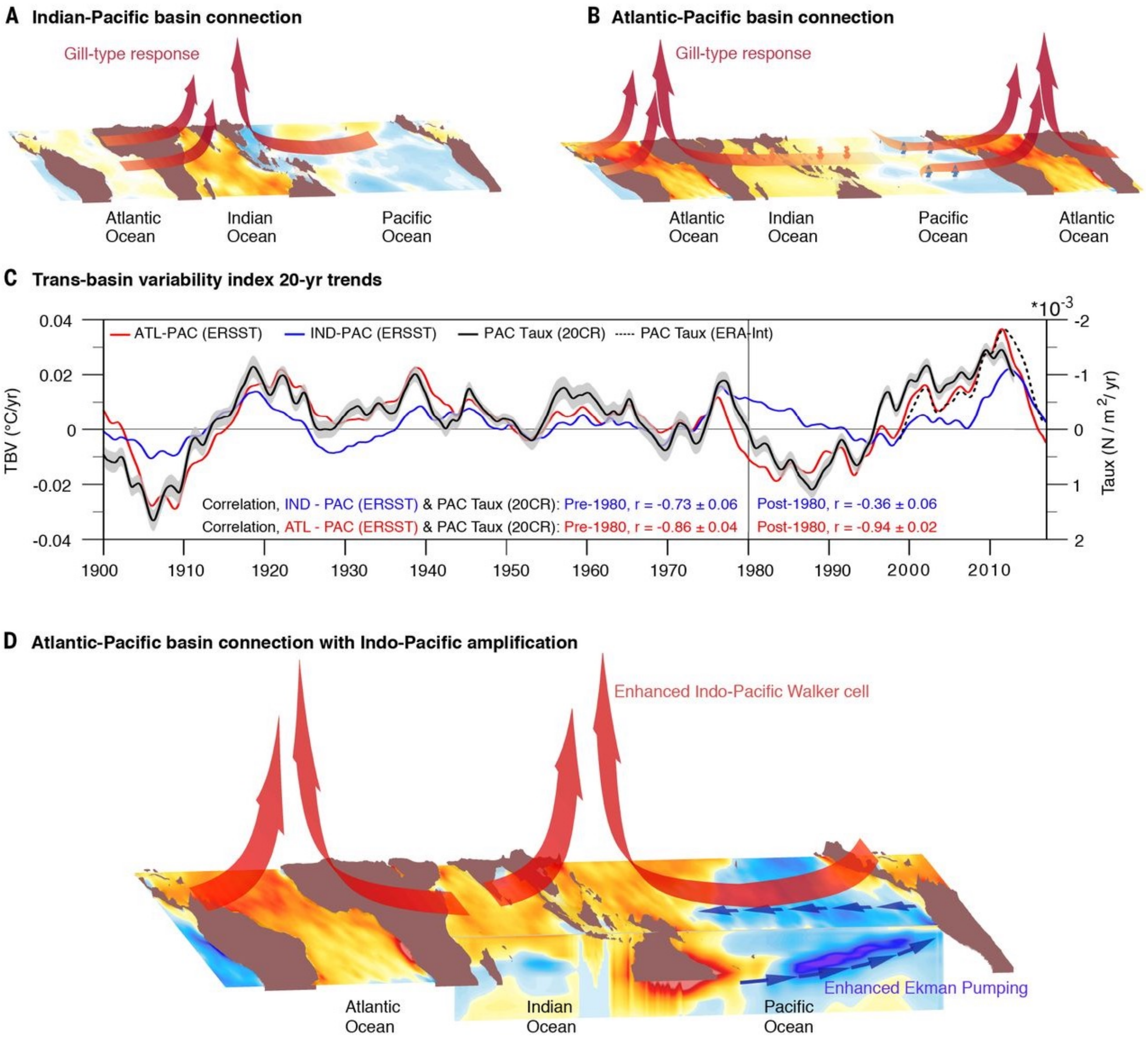
a. Recent obs may not fully represent what ENSO is capable of.

7. How do we best communicate future ENSO risks to stakeholders?

Ways Forward

1. **Longer/better obs & reconstructions**
    a. Data rescue & archaeology
    b. Frequently updated reanalyses, possibly including proxy data to help fill gaps
    c. Maintain/improve TPOS & global obs, especially toward improving CGCMs
2. **Better coordination among reanalysis providers**
    a. Eliminate unnecessary differences or known deficiencies (e.g. old bulk formulae)
    b. Provide more realistic error estimates
3. **Better models, more analysis**
    a. Attribute biases to specific processes → improve processes
    b. Coordinated analysis of ENSO modulation/change in CMIP (control/historical/future)
4. **Continued research on decadal drivers of ENSO modulation**
5. **Improve utility of conceptual & statistical frameworks**
    a. Test as predictors/discriminants of ENSO behavior in obs & models
6. **Develop communities of scientific liaisons, who can:**
    a. Communicate scientific developments & challenges to stakeholders
    b. Provide value-added products to stakeholders
    c. Consolidate diverse stakeholder needs & communicating them to scientists.
    d. Advocate for public/private support of research where it is most needed.

Interbasin interactions



Cai et al. (Science 2019)

https://doi.org/10.1126/science.aav4236