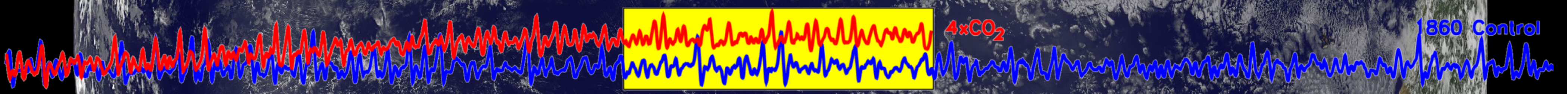
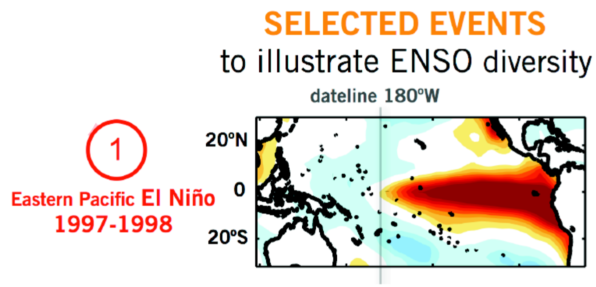
ENSO Dynamics, Diversity, and Change

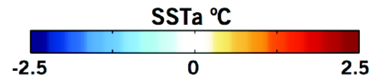


Andrew Wittenberg
NOAA/GFDL, USA

NOAA
GOES-11
5 Oct 2011
1800 UTC

ENSO diversity in observations

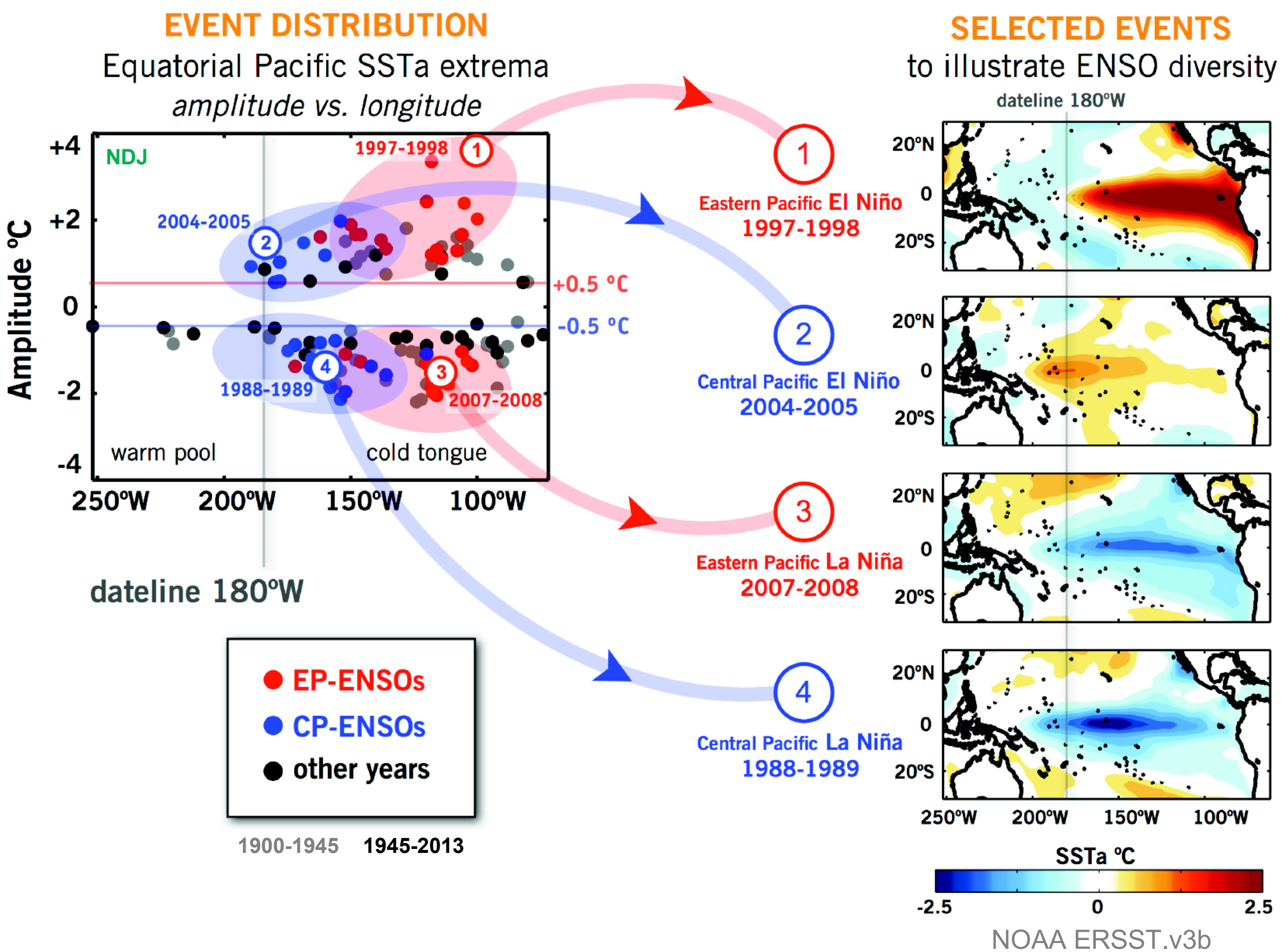




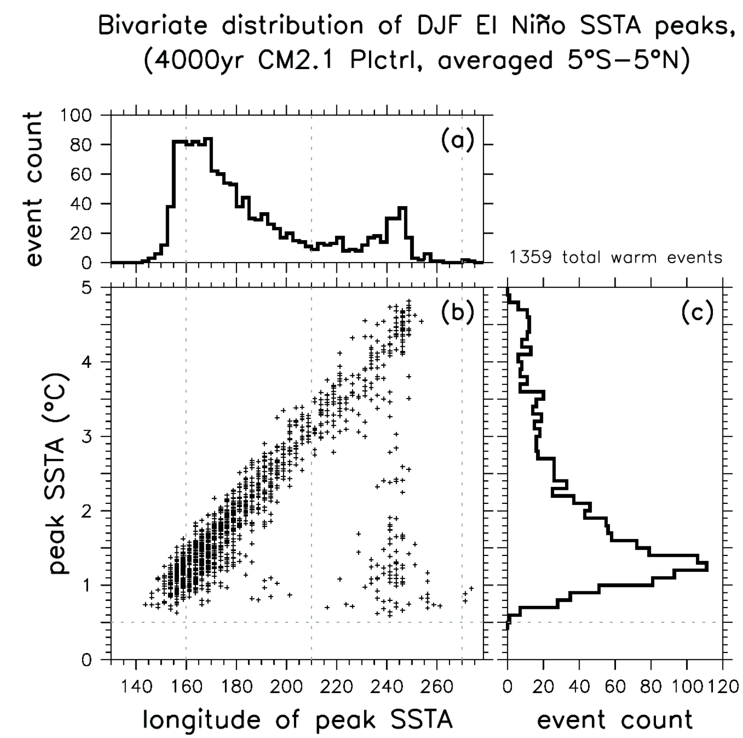
NOAA ERSST.v3b

U.S. CLIVAR Working Group on ENSO Diversity: *Capotondi et al. (BAMS 2015)*
Kug et al. (JC 2010); Graham et al. (CD 2017); Chen et al. (JC 2017); Atwood et al. (CD 2017)

ENSO diversity in observations & models

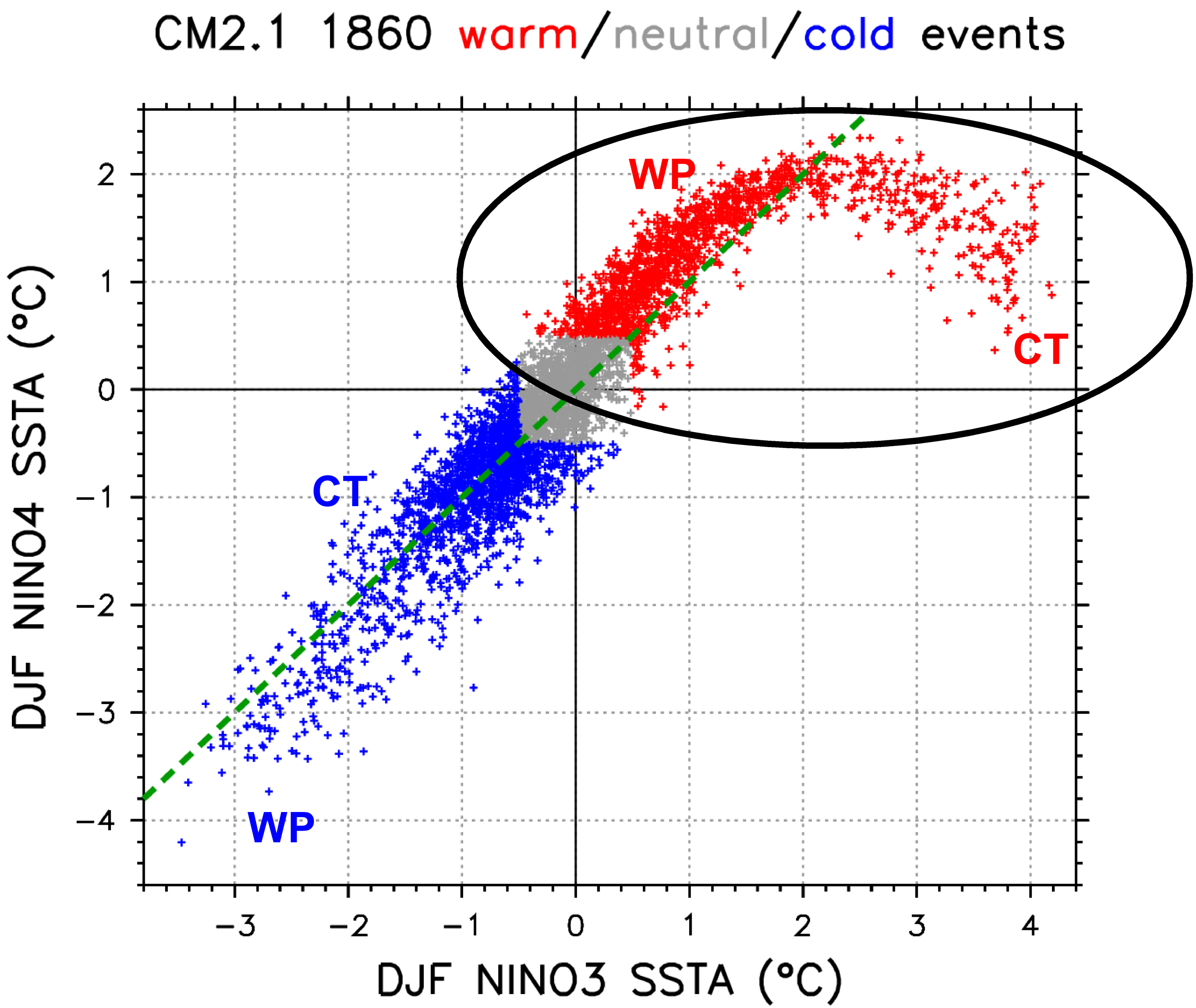


CM2.1 simulation



U.S. CLIVAR Working Group on ENSO Diversity: *Capotondi et al. (BAMS 2015)*
Kug et al. (JC 2010); Graham et al. (CD 2017); Chen et al. (JC 2017); Atwood et al. (CD 2017)

An ENSO continuum



Composite CM2.1 warm events (NDJ anomalies)

SST

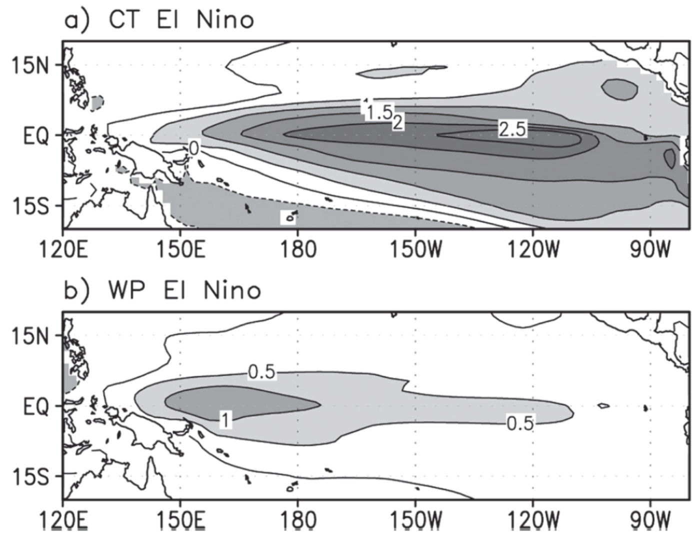


FIG. 3. SST anomaly (°C) composite of the (a) CT El Niño and (b) WP El Niño during ND(0)J(1).

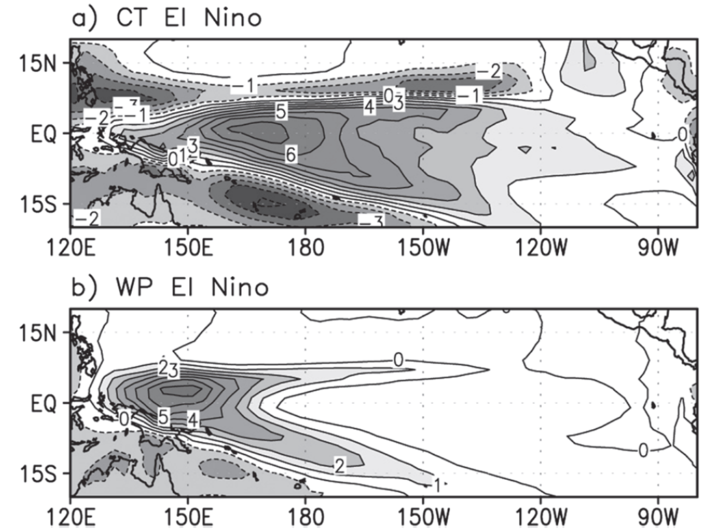


FIG. 4. As in Fig. 3, except for precipitation (mm day^{-1}).

precip

zonal wind (925mb)

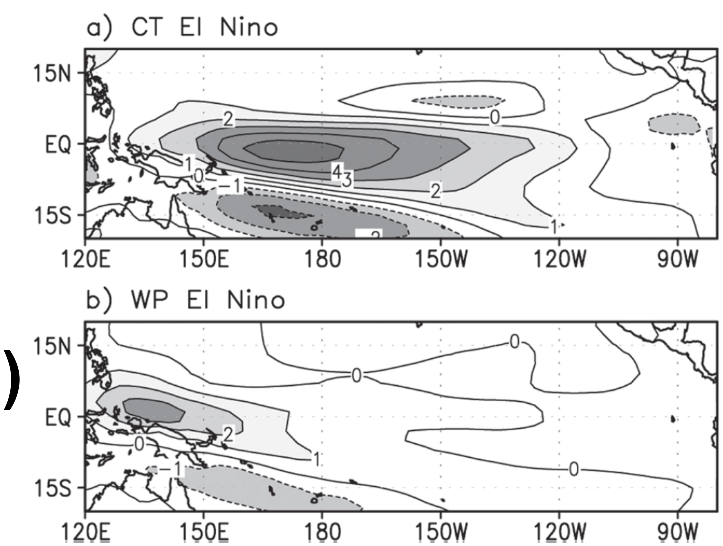


FIG. 5. As in Fig. 3, except for zonal wind at 925 hPa (m s^{-1}).

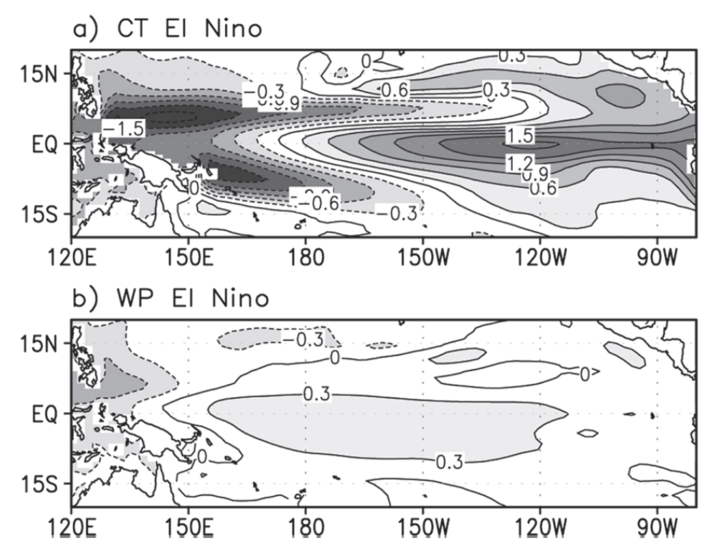


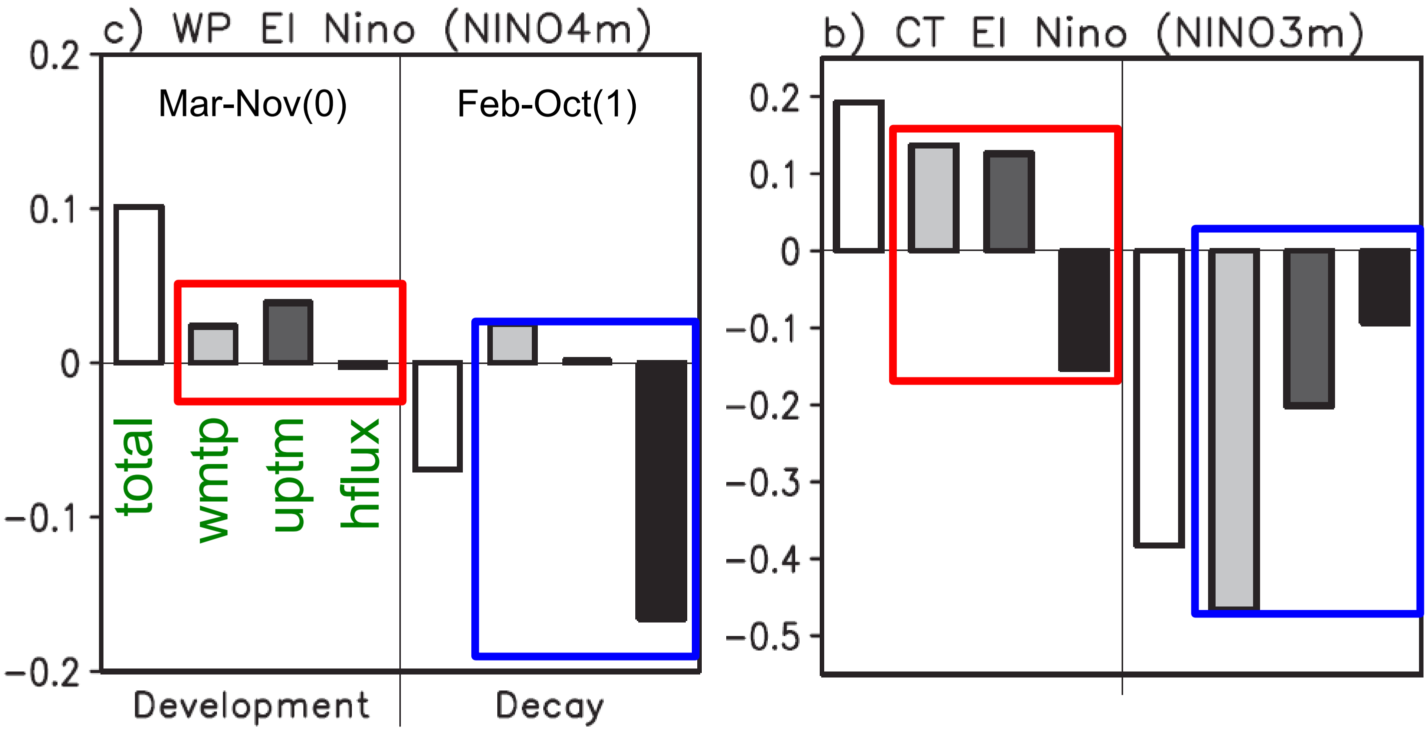
FIG. 6. As in Fig. 3, except for heat content (K).

heat content (top 300m)

Kug et al. (JC 2010)

Composite CM2.1 SSTA tendency terms

growth via zonal & vertical advection



evaporation & cloud shading

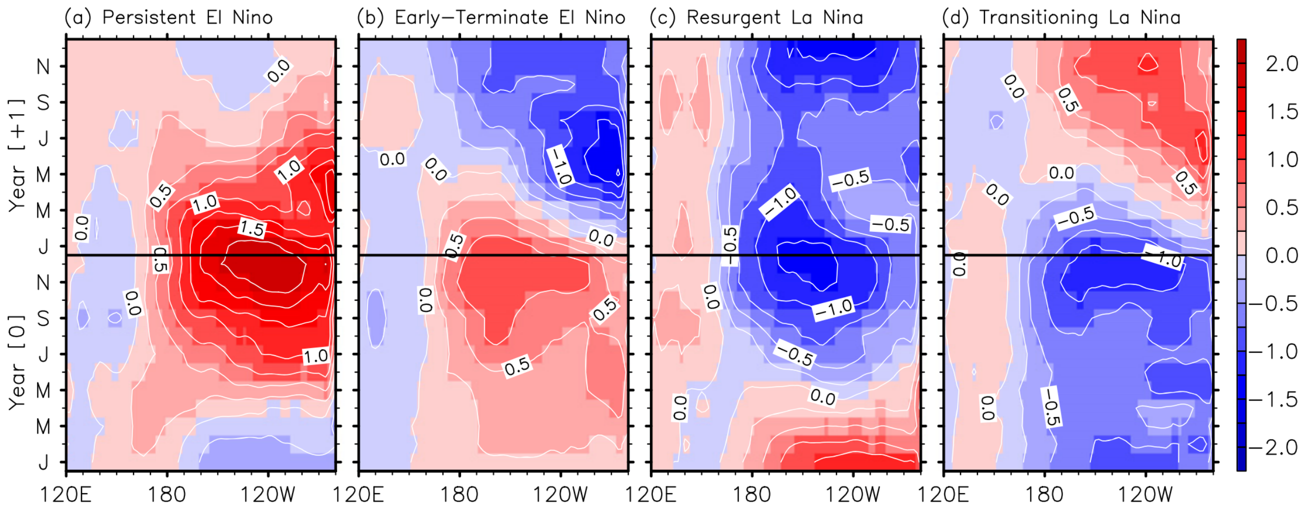
poleward HC discharge & thermocline re-tilt

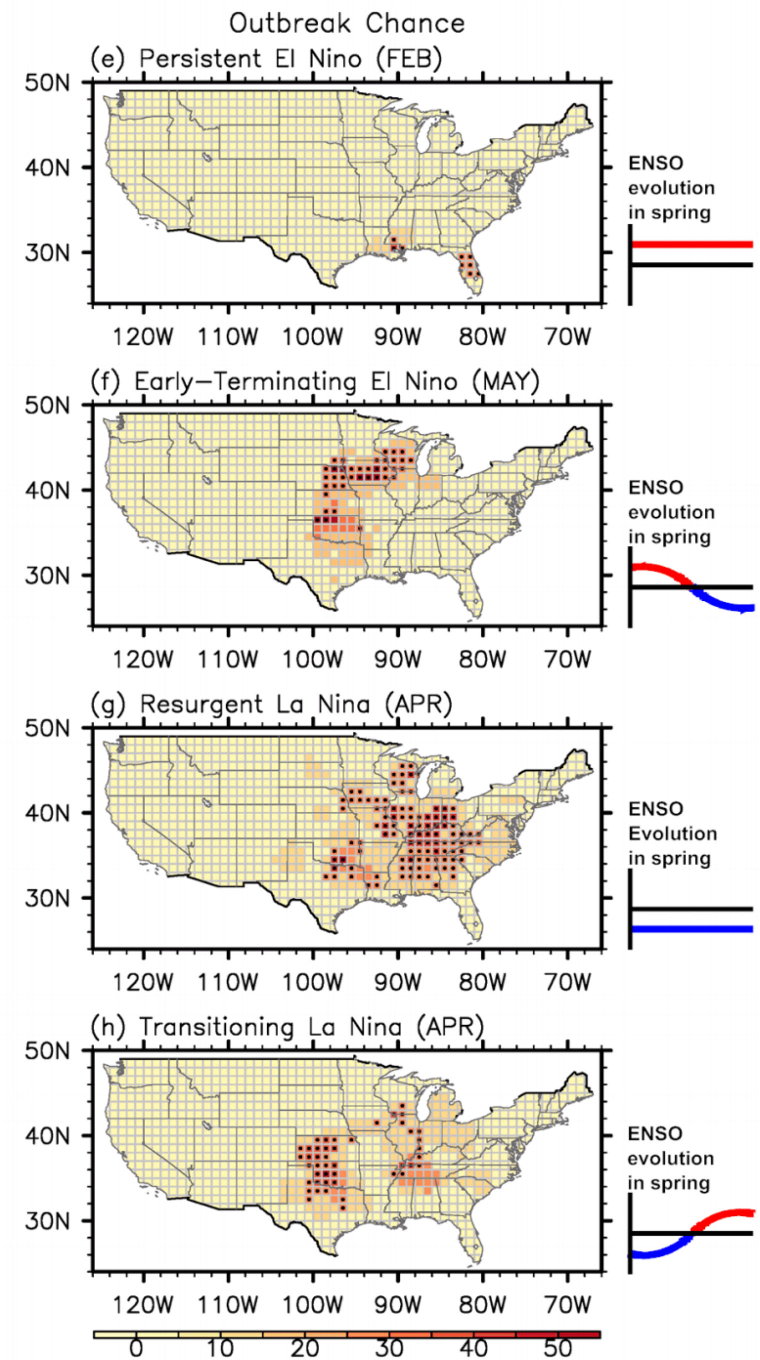
FIG. 11. SST tendency (open bar), SST tendency according to the thermocline feedback (light-gray bar), the zonal advective feedback (dark-gray bar), and net flux (black bar) for (a),(b) CT El Niño and (c),(d) WP El Niño (K month^{-1}). Each magnitude is calculated over 2°S–2°N, 170°–110°W [(b),(d) Niño-3m region] or 2°S–2°N, 140°E–170°W [(a),(c) Niño-4m region]. Period of development (decay) is defined from March (0) to November (0) [from February (1) to October (1)].

Kug et al. (JC 2010)

ENSO's impacts depend on its seasonal timing

Key archetypes of ENSO evolution





ENSO events show diverse temporal behavior in boreal spring – e.g. **persisting, terminating early, resurging, or transitioning**.

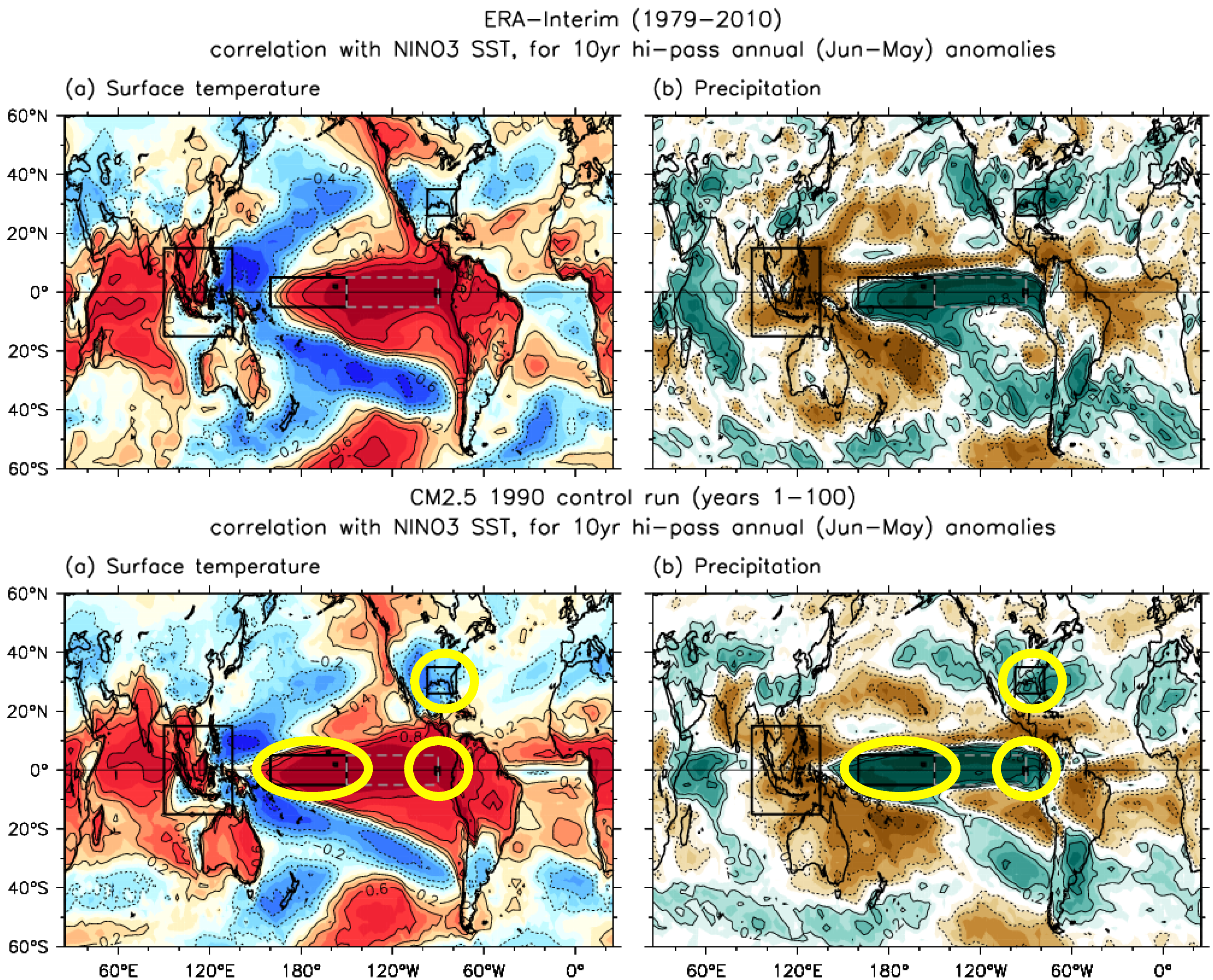
This significantly affects their impacts – e.g. **tornado outbreak frequency** over the United States.

Lee et al. (GRL 2014; ERL 2016)

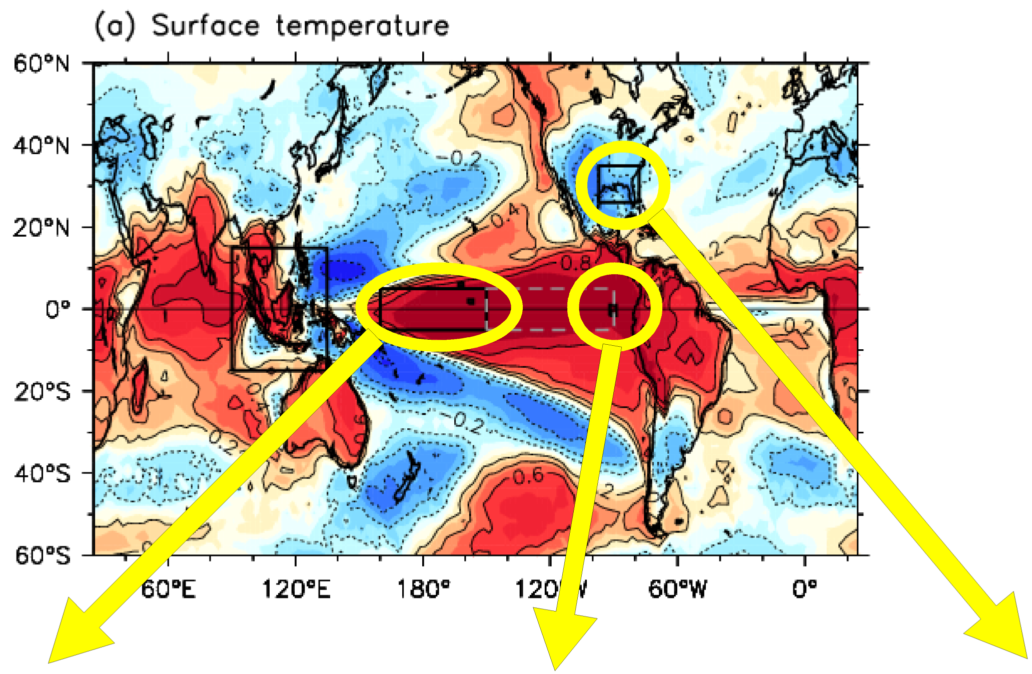
ENSO's impacts on regional climates

Obs

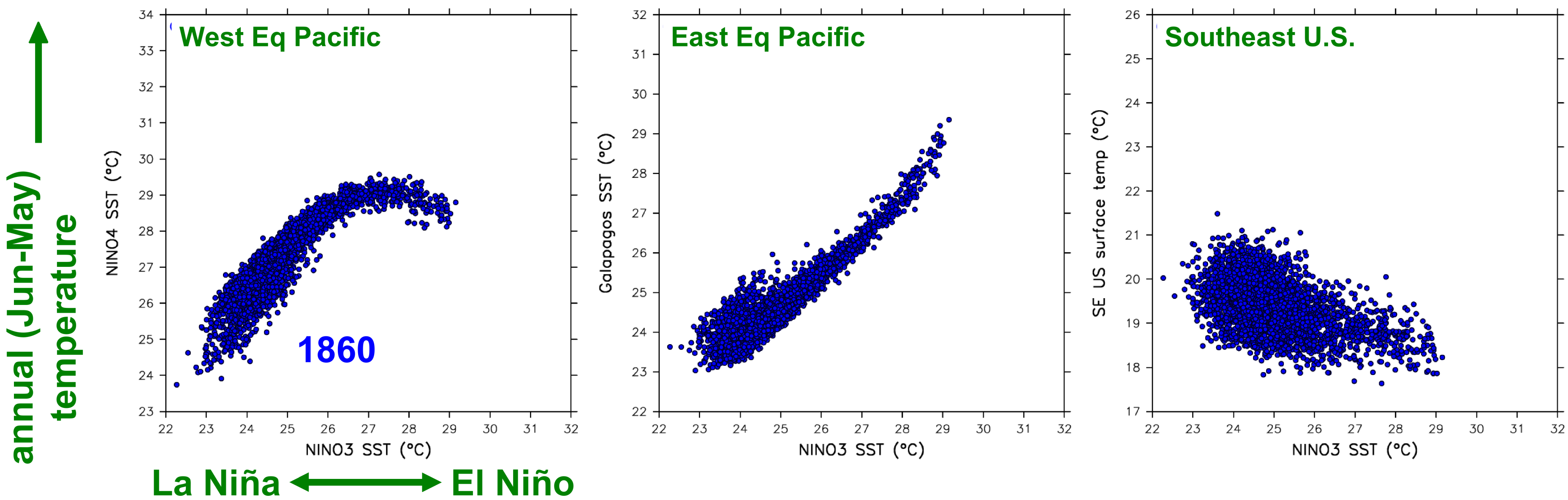
Model



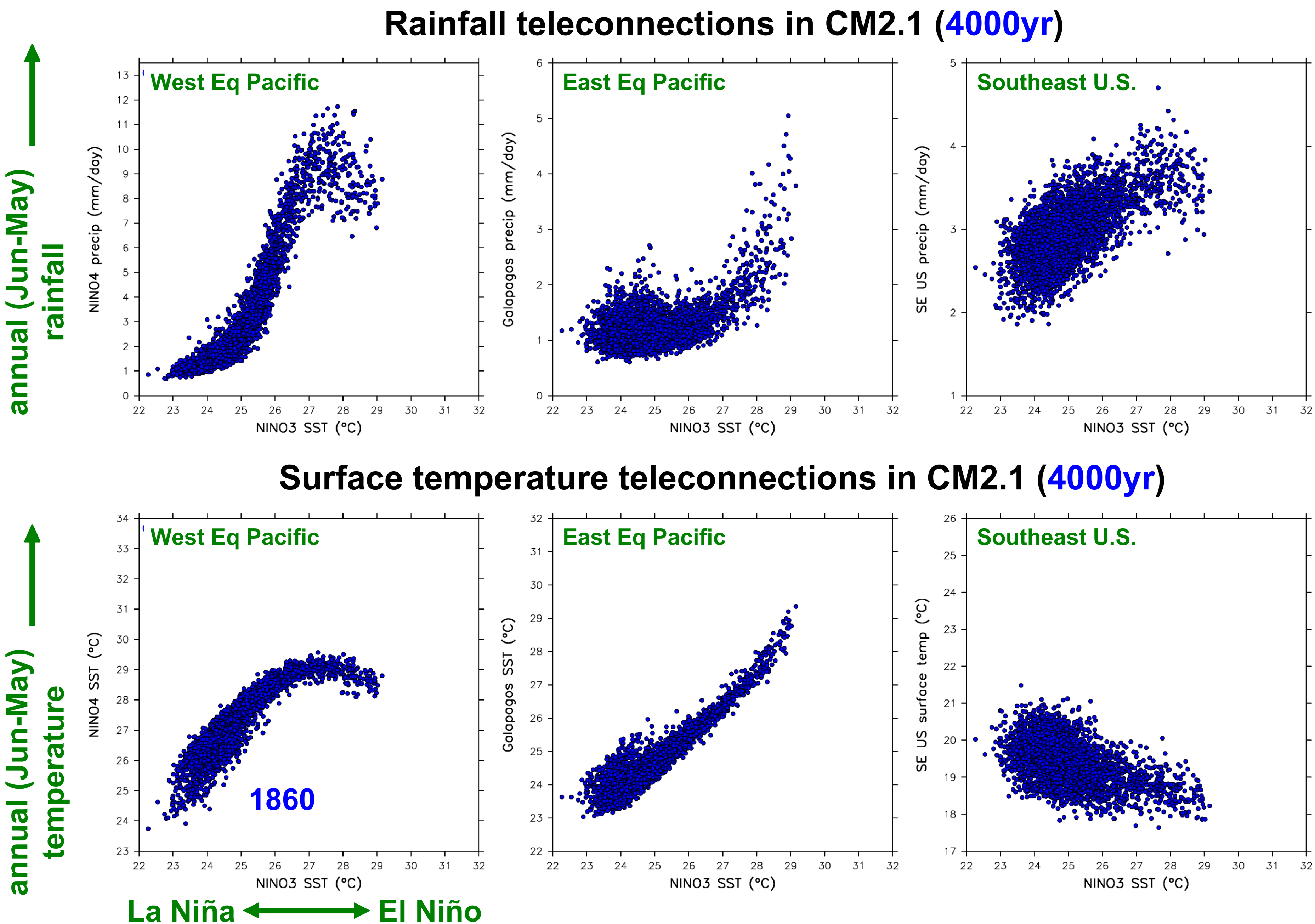
Extreme ENSO events have nonlinear impacts



Surface temperature teleconnections in CM2.1 (4000yr)

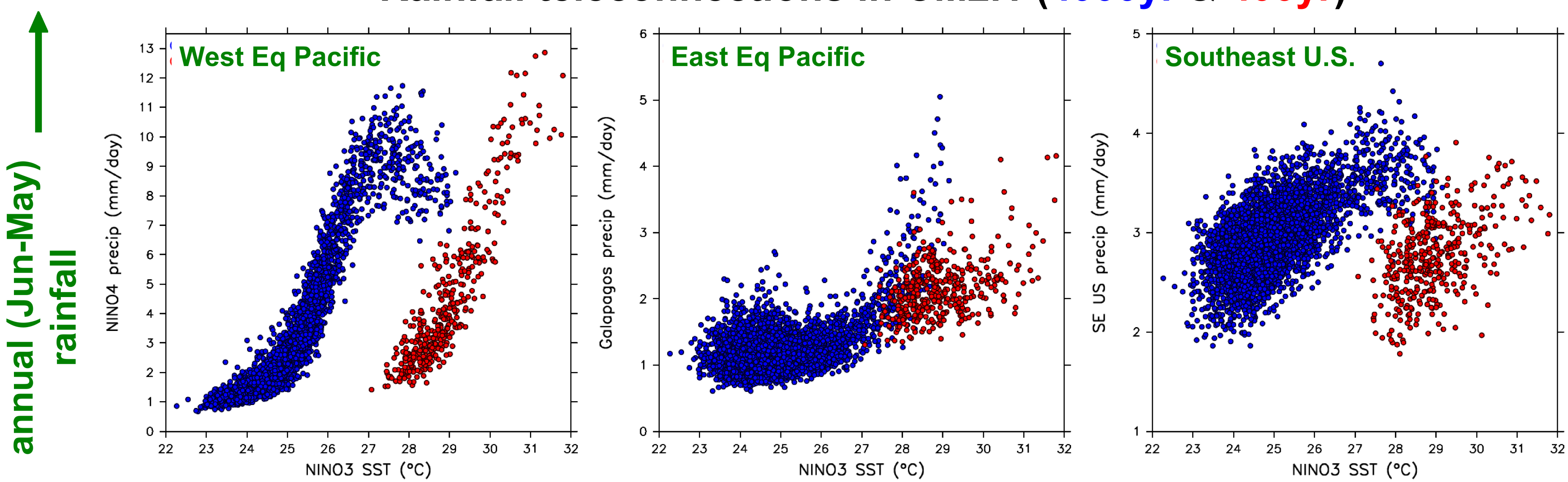


Extreme ENSO events have nonlinear impacts

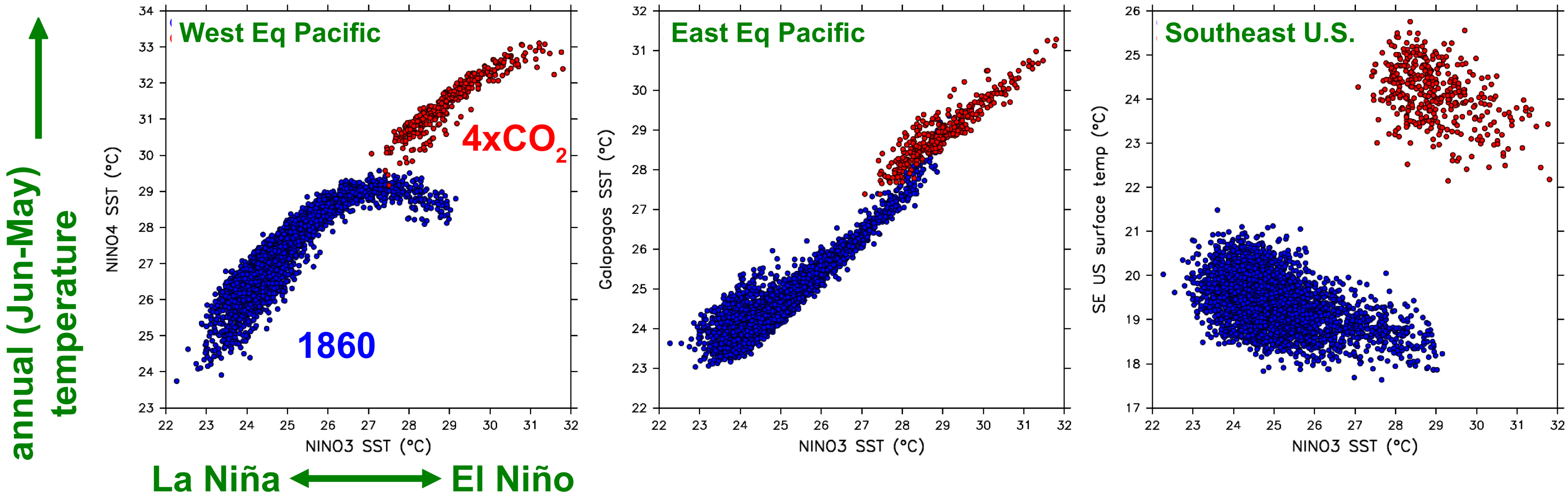


Increasing CO_2 alters ENSO impacts

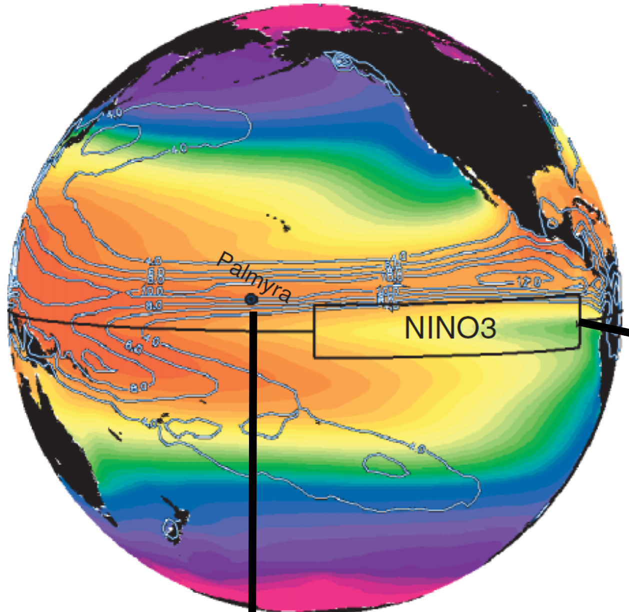
Rainfall teleconnections in CM2.1 (4000yr & 400yr)



Surface temperature teleconnections in CM2.1 (4000yr & 400yr)

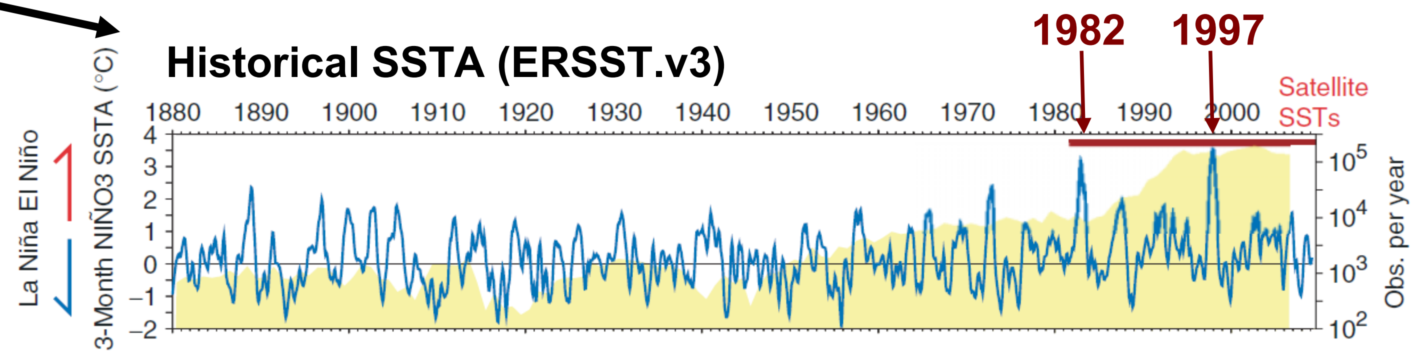


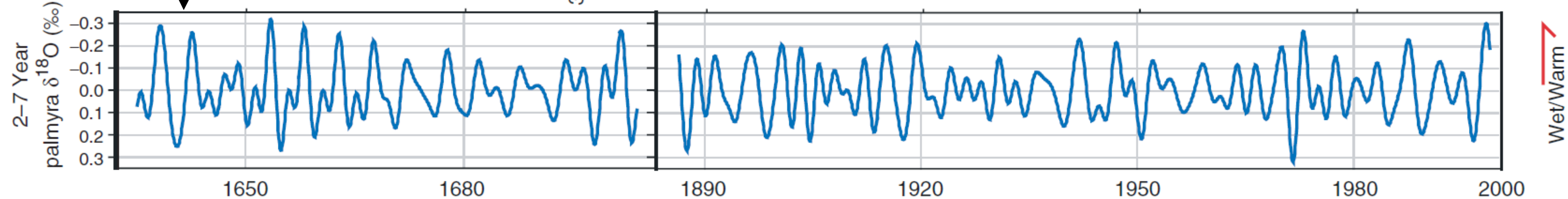
Both historical & paleo records suggest past modulation of ENSO



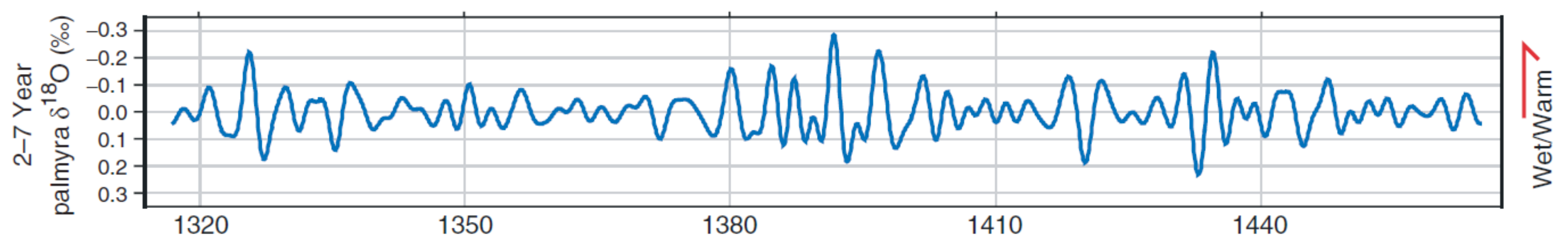
Vecchi & Wittenberg (WIREsCC 2010)

Historical SSTA (ERSST.v3)

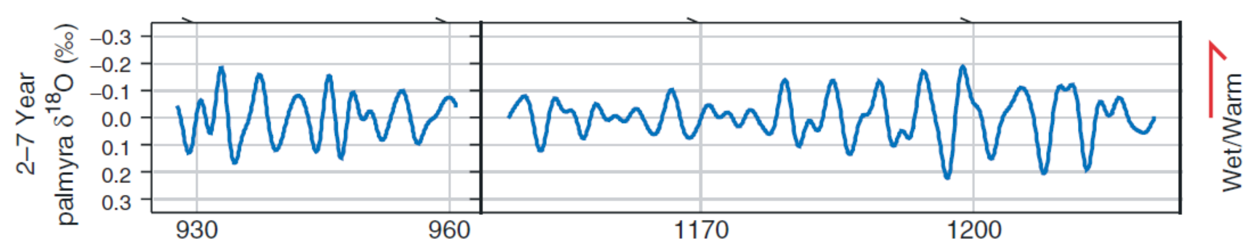




Palmyra corals (Cobb et al., Nature 2003)



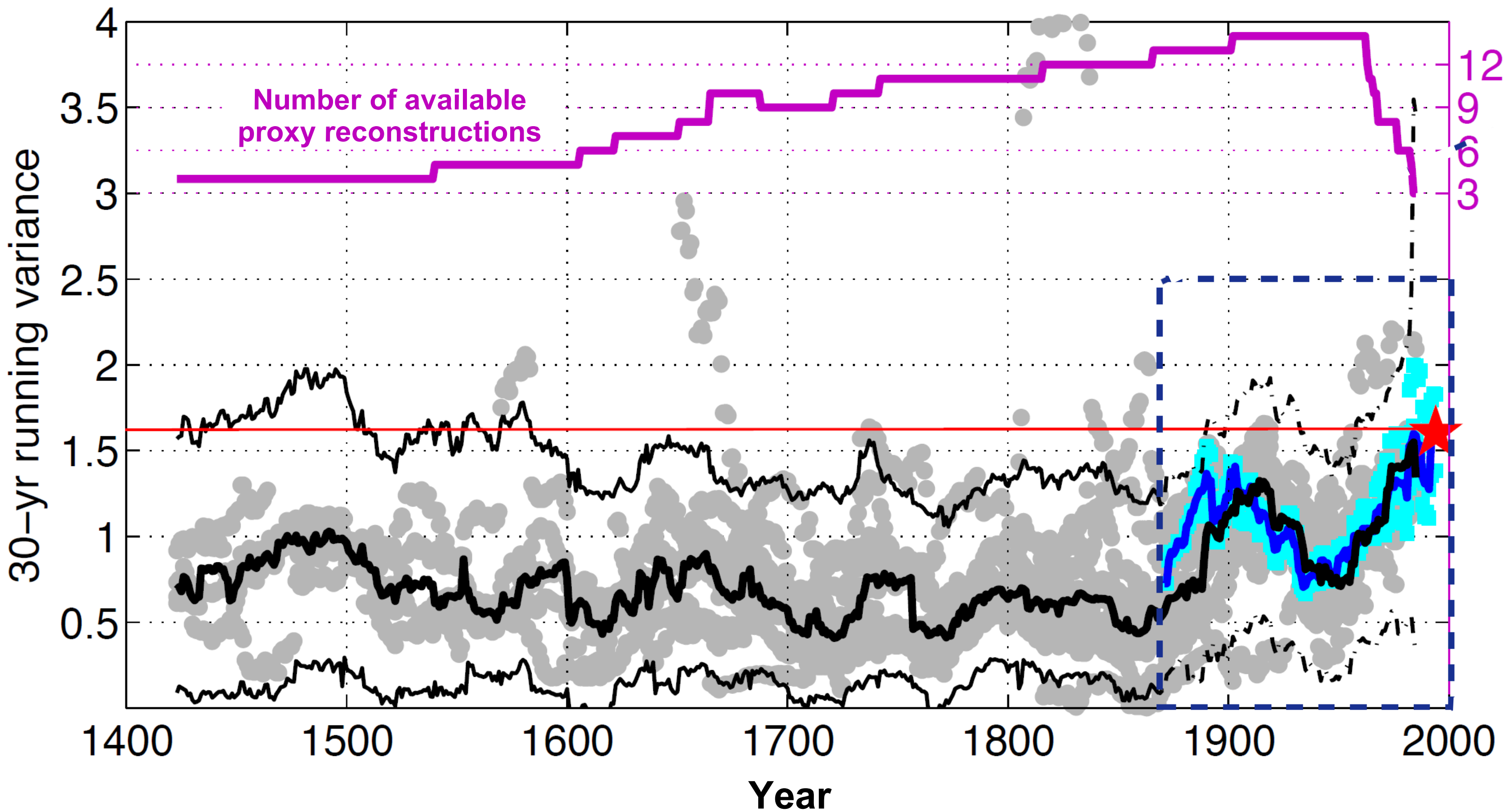
Multiproxy reconstructions:
e.g. Li et al. (NCC 2011);
Emile-Geay et al.
(J. Climate, 2013ab);
McGregor et al. (CP 2013)



ENSO has existed for thousands, perhaps millions, of years.
Obscures detection of slower climate changes (decadal, global warming).

Reconstructing past variations in ENSO

Proxy evidence suggests that ENSO activity has waxed & waned, with significant amplification in recent decades.

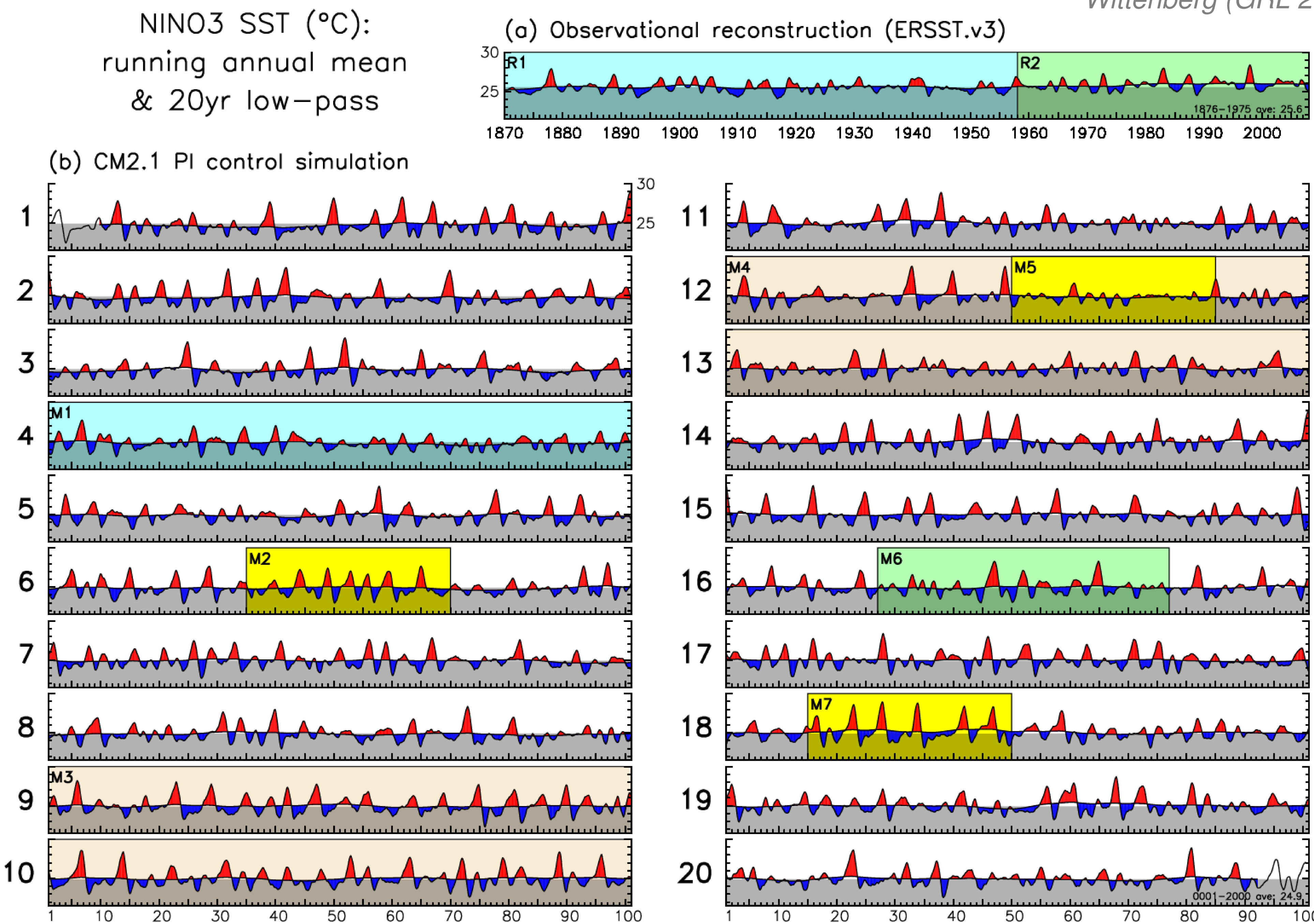


Multiproxy meta-reconstruction (from corals, tree rings, lake sediments & ice cores) of 30-year running variance of 10-yr lowpass July-June annual-mean NINO3.4 SSTs.

McGregor et al. (Clim. Past, 2013)

ENSO modulation in a 2000-year control simulation

Wittenberg (GRL 2009)

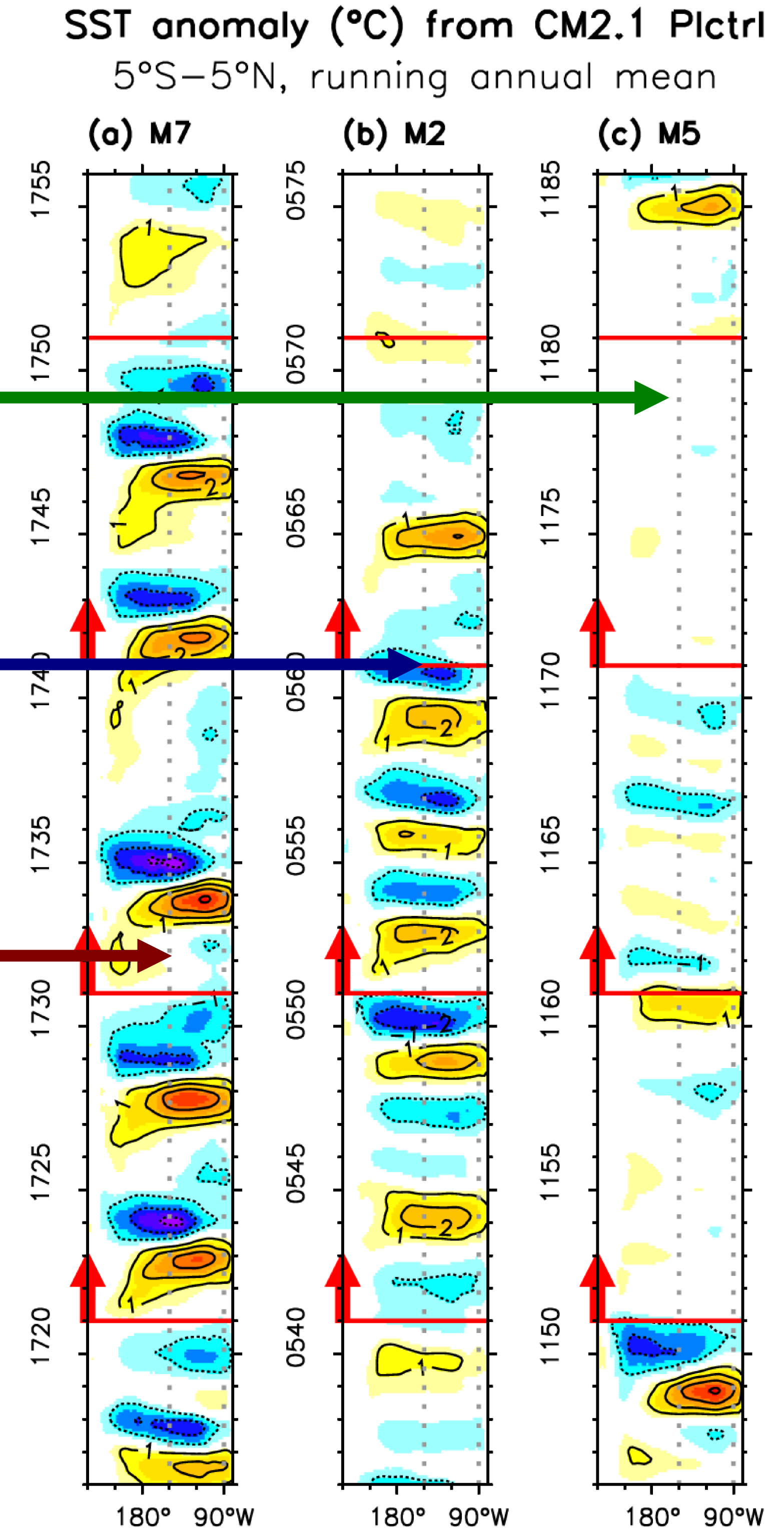


Epochs of unusual ENSO behavior

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

regular, westward propagating
(1960s & 70s)

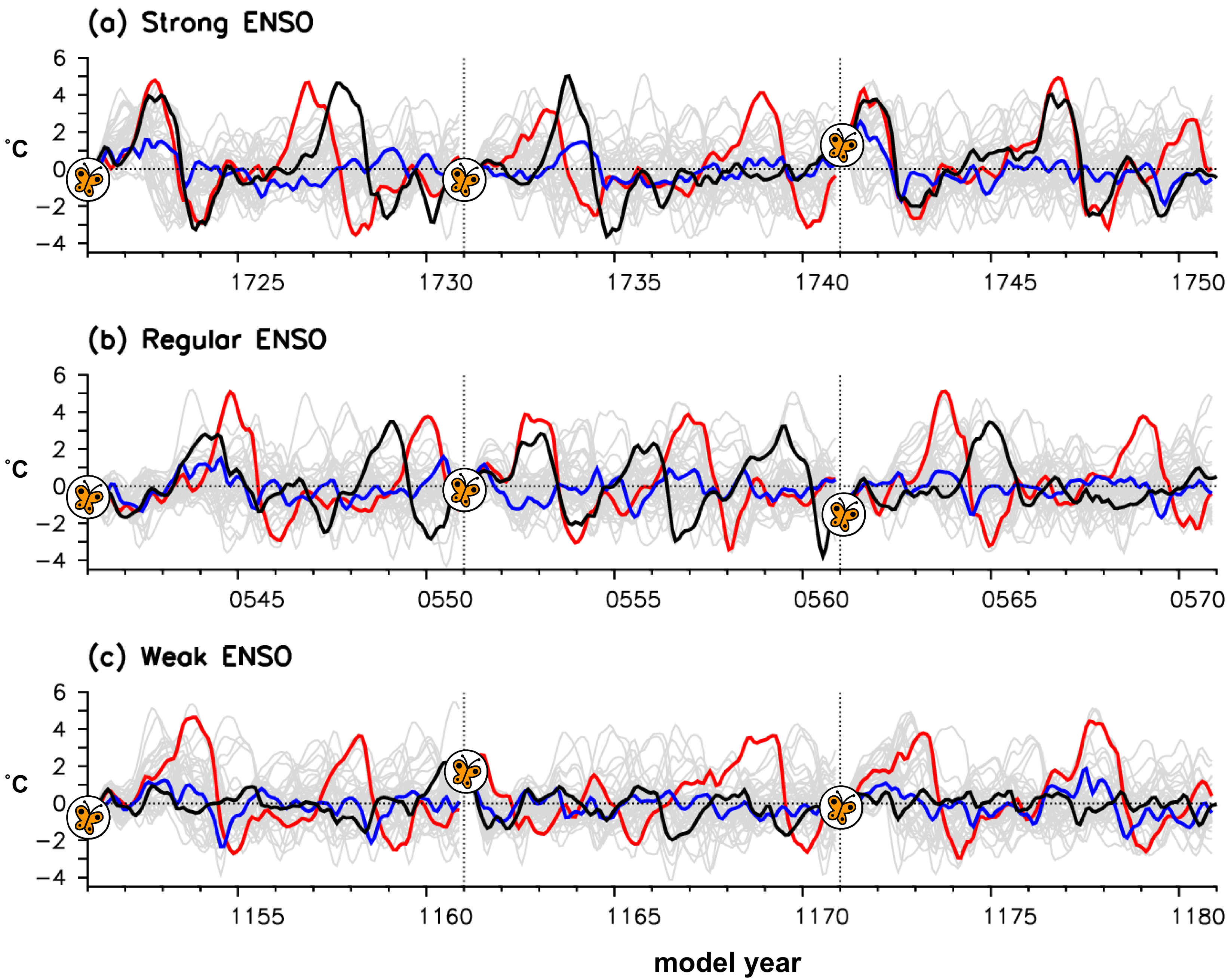
strong, skewed, long period,
eastward propagating
(1980s & late 1990s)



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

Wittenberg et al. (J. Climate, 2014)

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:

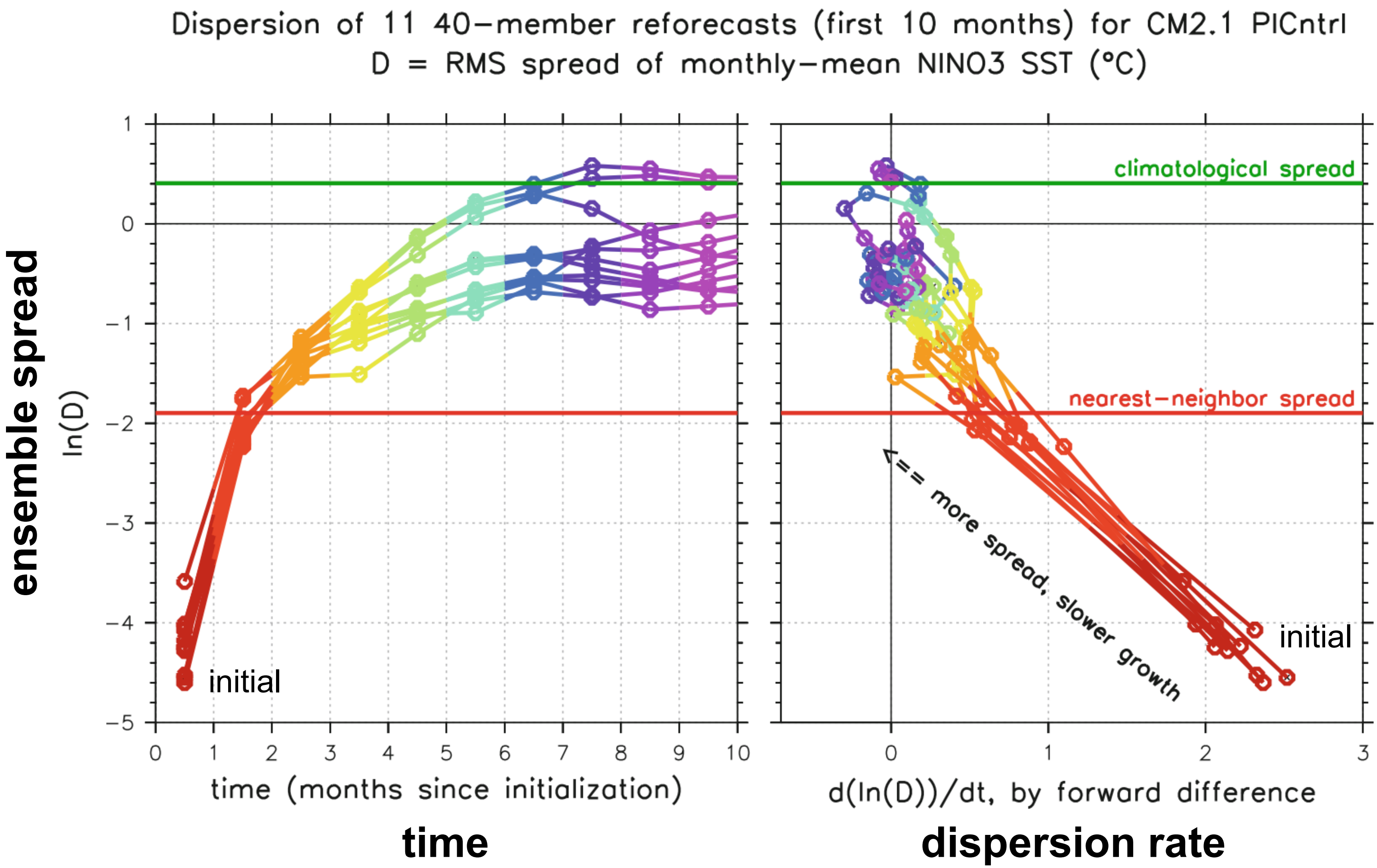
weakest,

strongest,

all 40 members

Wittenberg et al. (J. Climate, 2014)

Initial growth of tiny perturbations in CM2.1



Ensemble exceeds the 333yr-analog spread in **1-2 months**.
Climatological spread reached in as little as **7 months**.

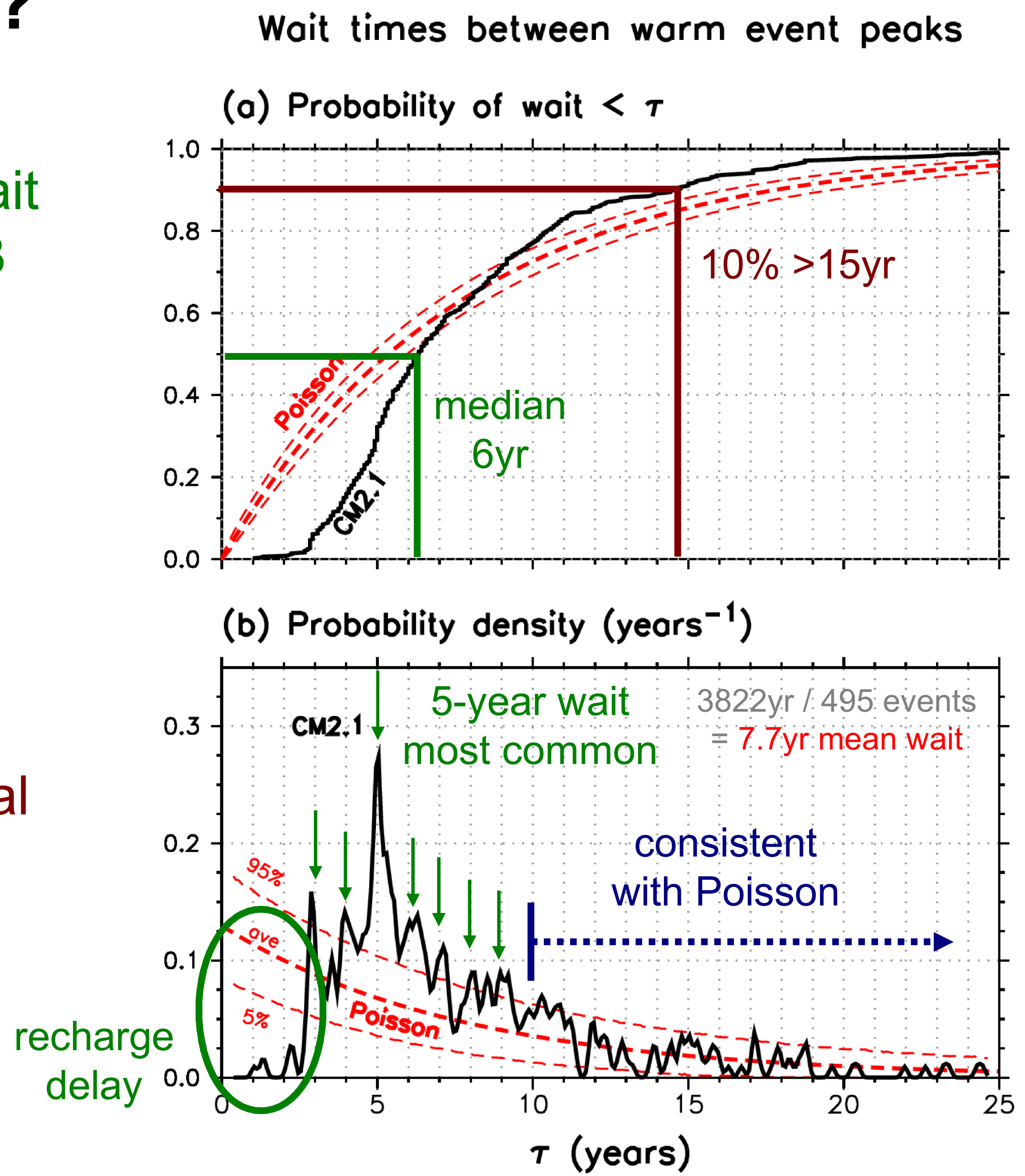
Karamperidou et al. (CD 2014)

Long-term memory?

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

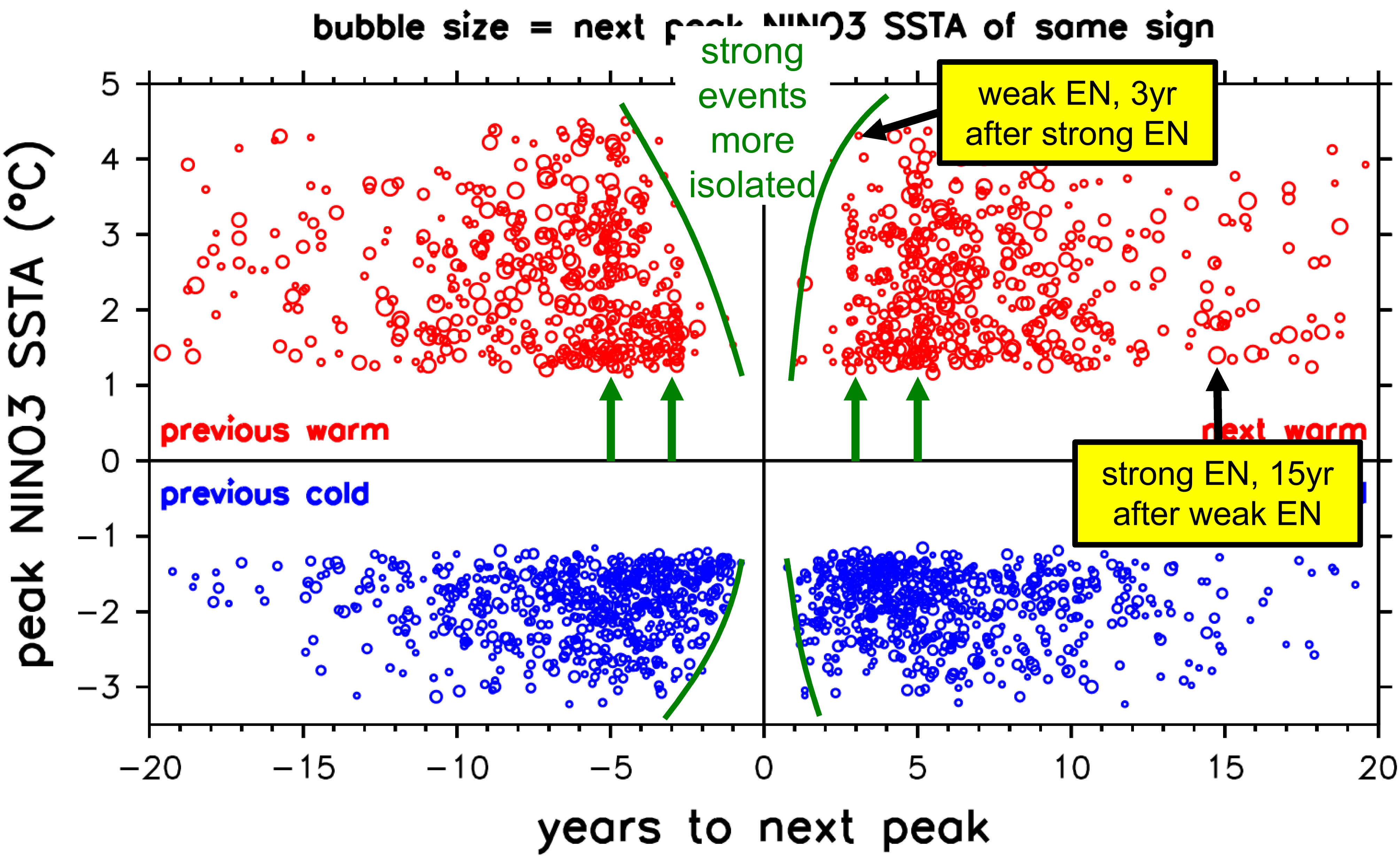
But beyond 10 years?

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



Wittenberg (GRL 2009)

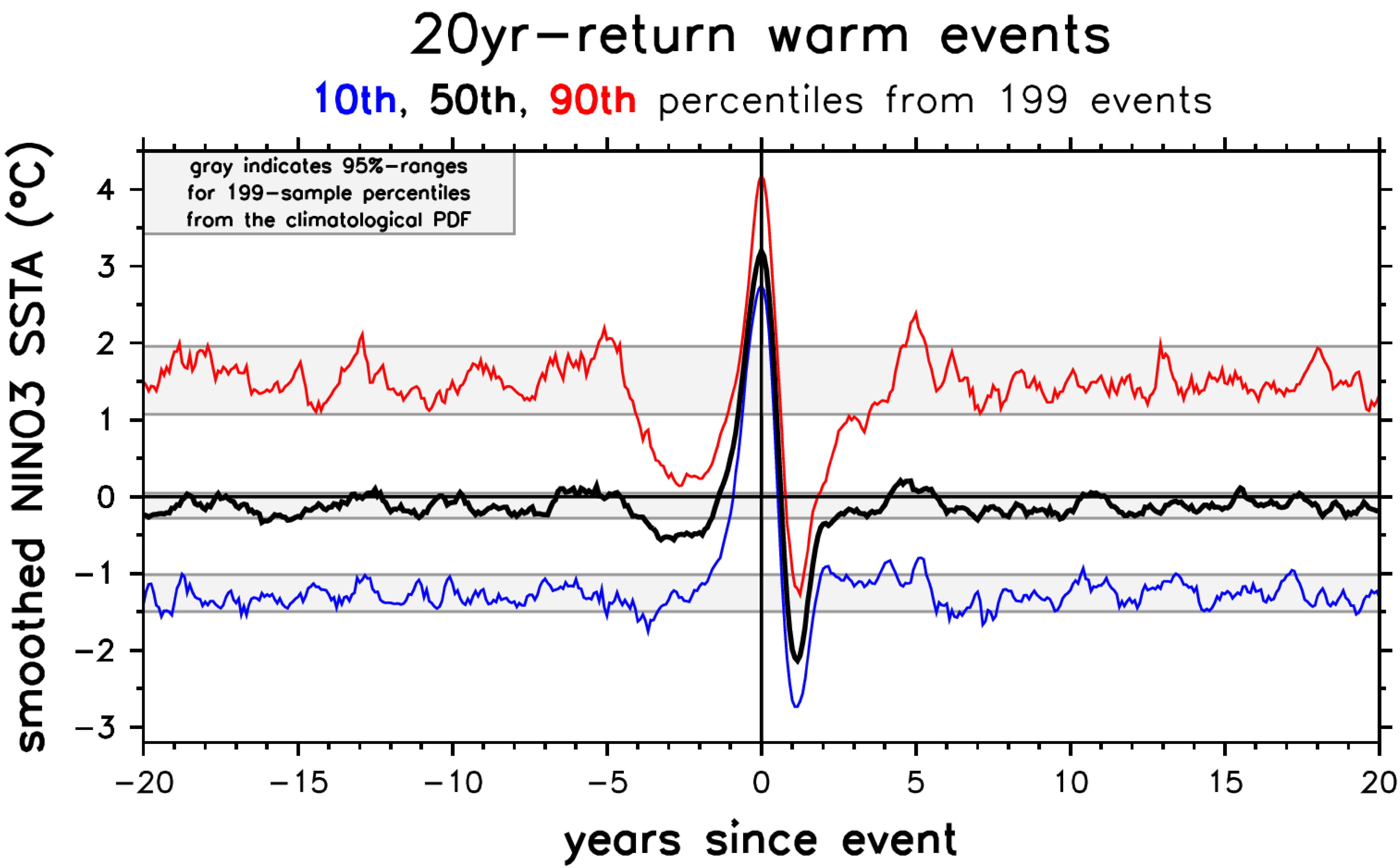
ENSO events and their nearest neighbors



CM2.1 simulation

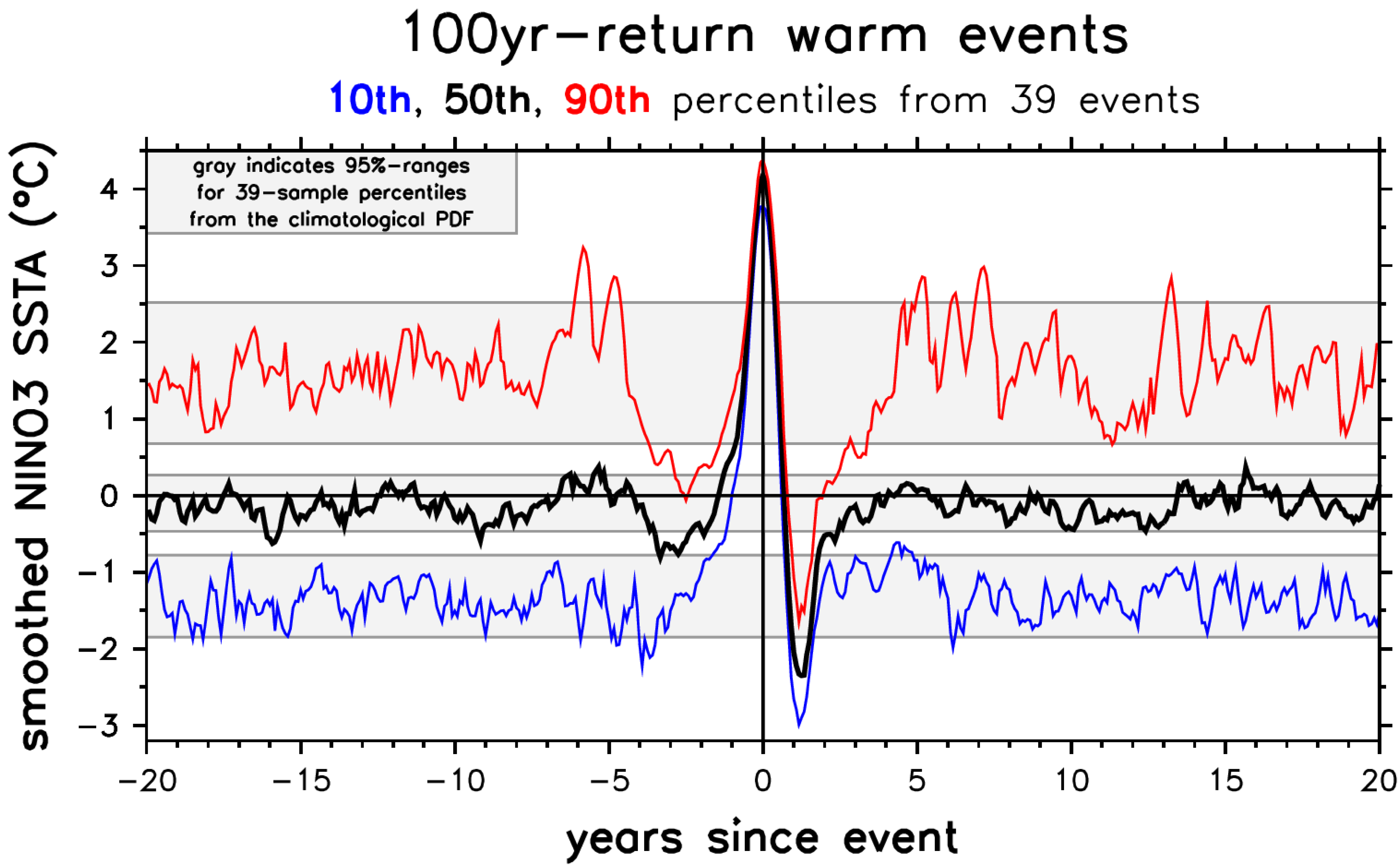
Best hope for long-term ENSO predictability?

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



Best hope for long-term ENSO predictability?

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



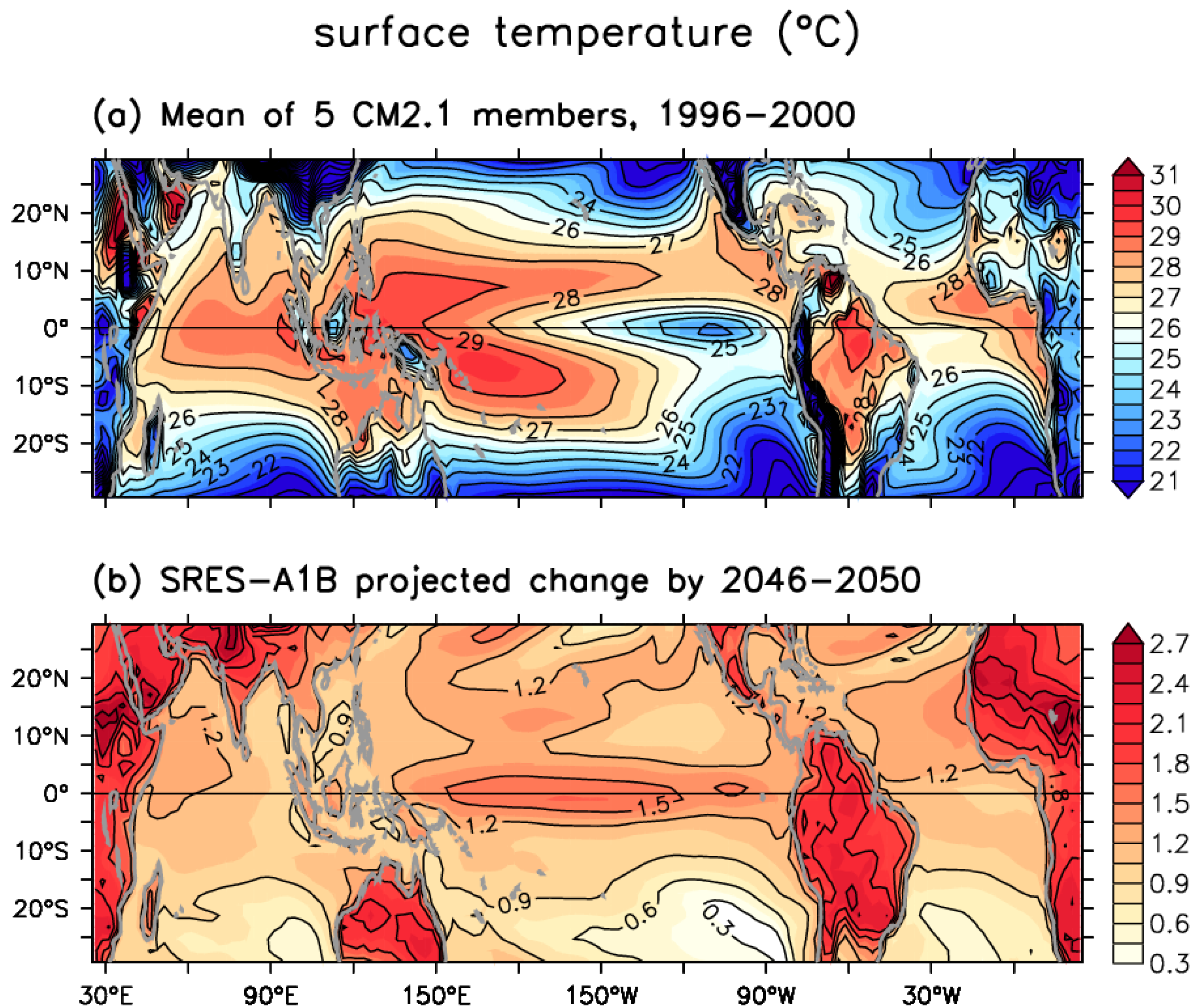
Projected surface temperature changes

Vecchi et al. (2008)
Vecchi & Wittenberg (2010)
Collins et al. (2010)
Xie et al. (2010)

Strongest warming over land & equatorial Pacific

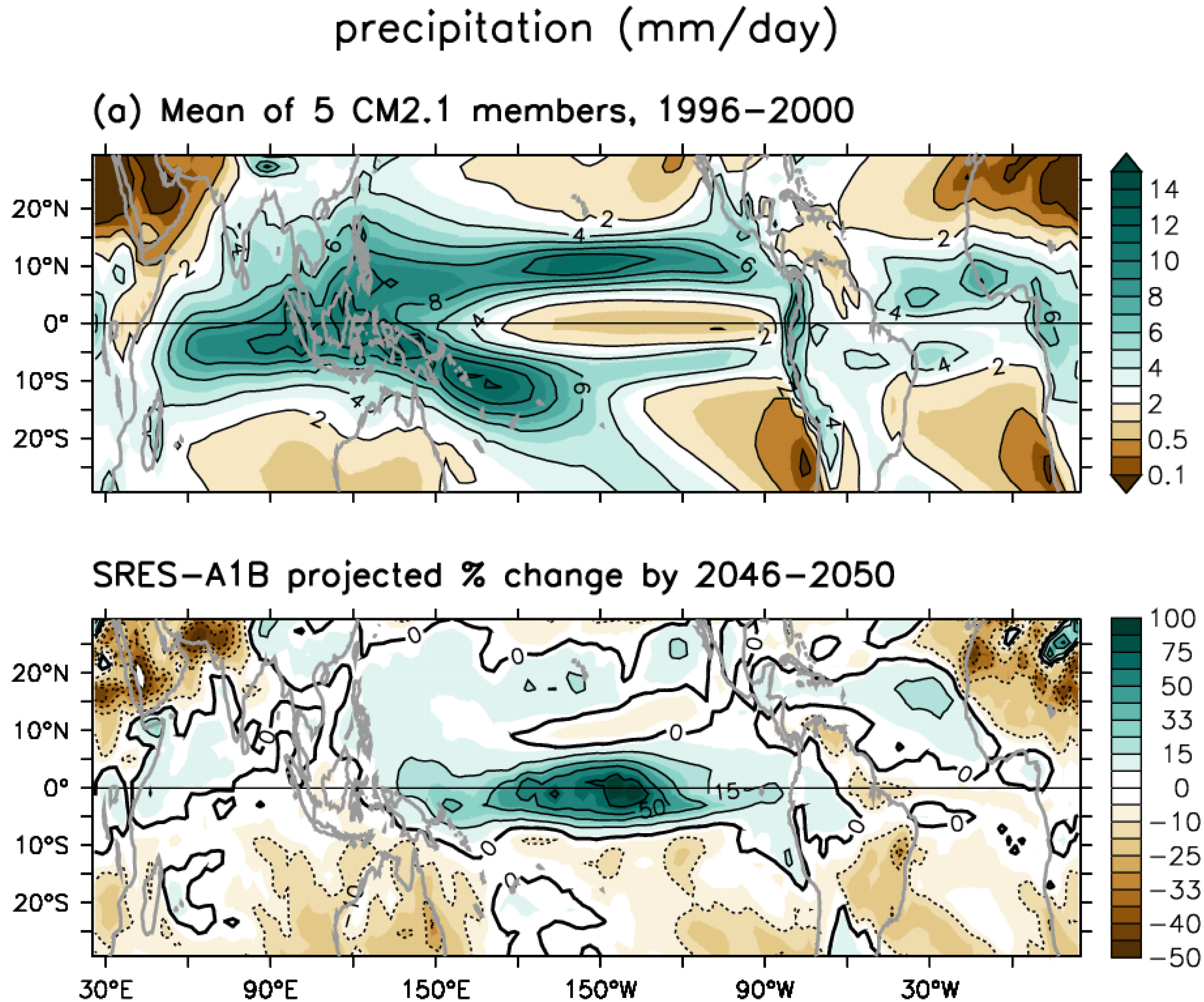
More warming in calm areas, and where winds weaken

Feedbacks from low clouds & ocean advection



Projected rainfall changes

Held & Soden (2006)
Vecchi & Wittenberg (2010)
DiNezio et al. (2010)
Xie et al. (2010)

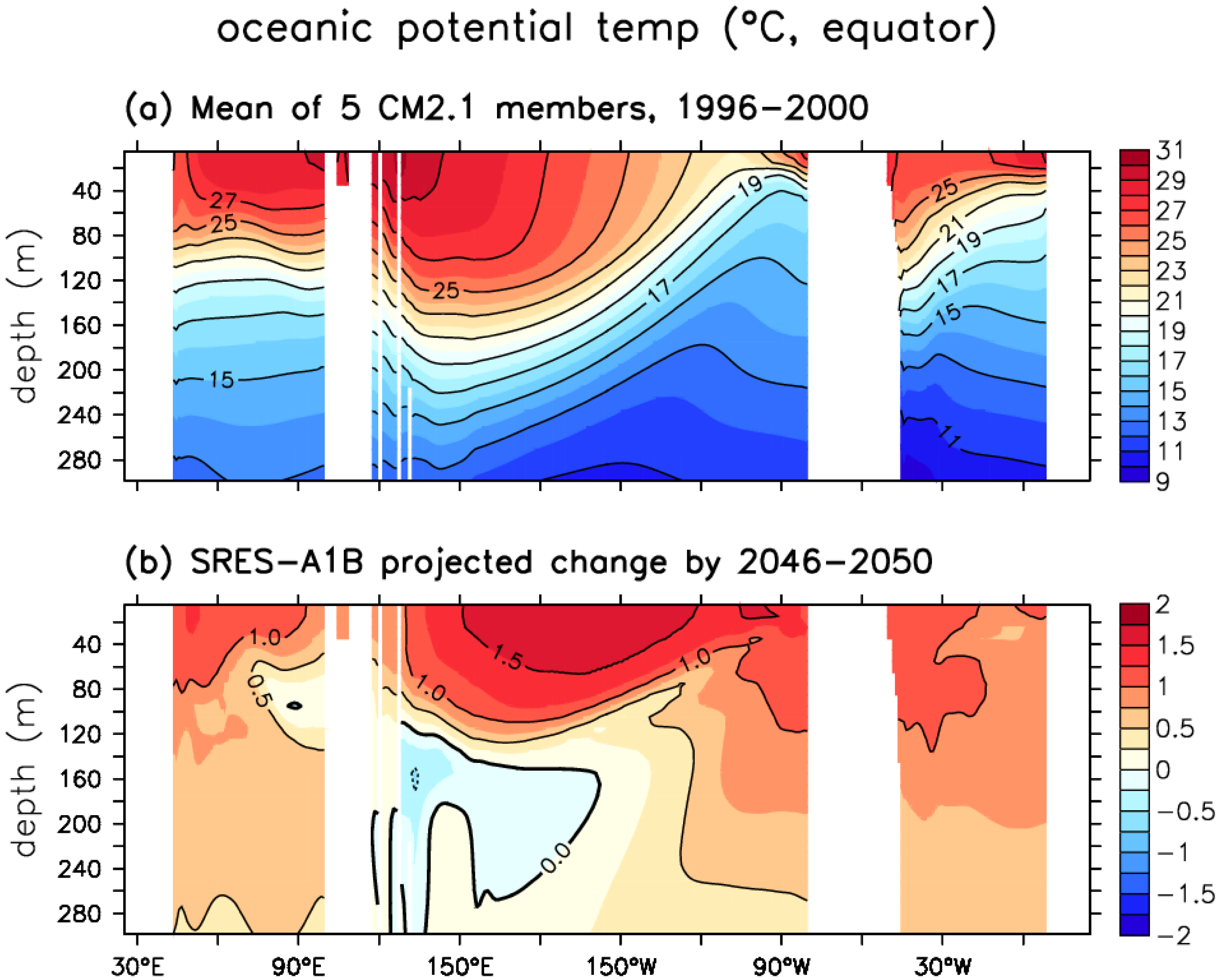


Broadly:
"the wet get wetter, the dry get drier".

Over tropical oceans:
"the warmer get wetter".

Projected upper-ocean temperature changes

DiNezio et al.
(JC 2009, EOS 2010)
Collins et al. (2010)



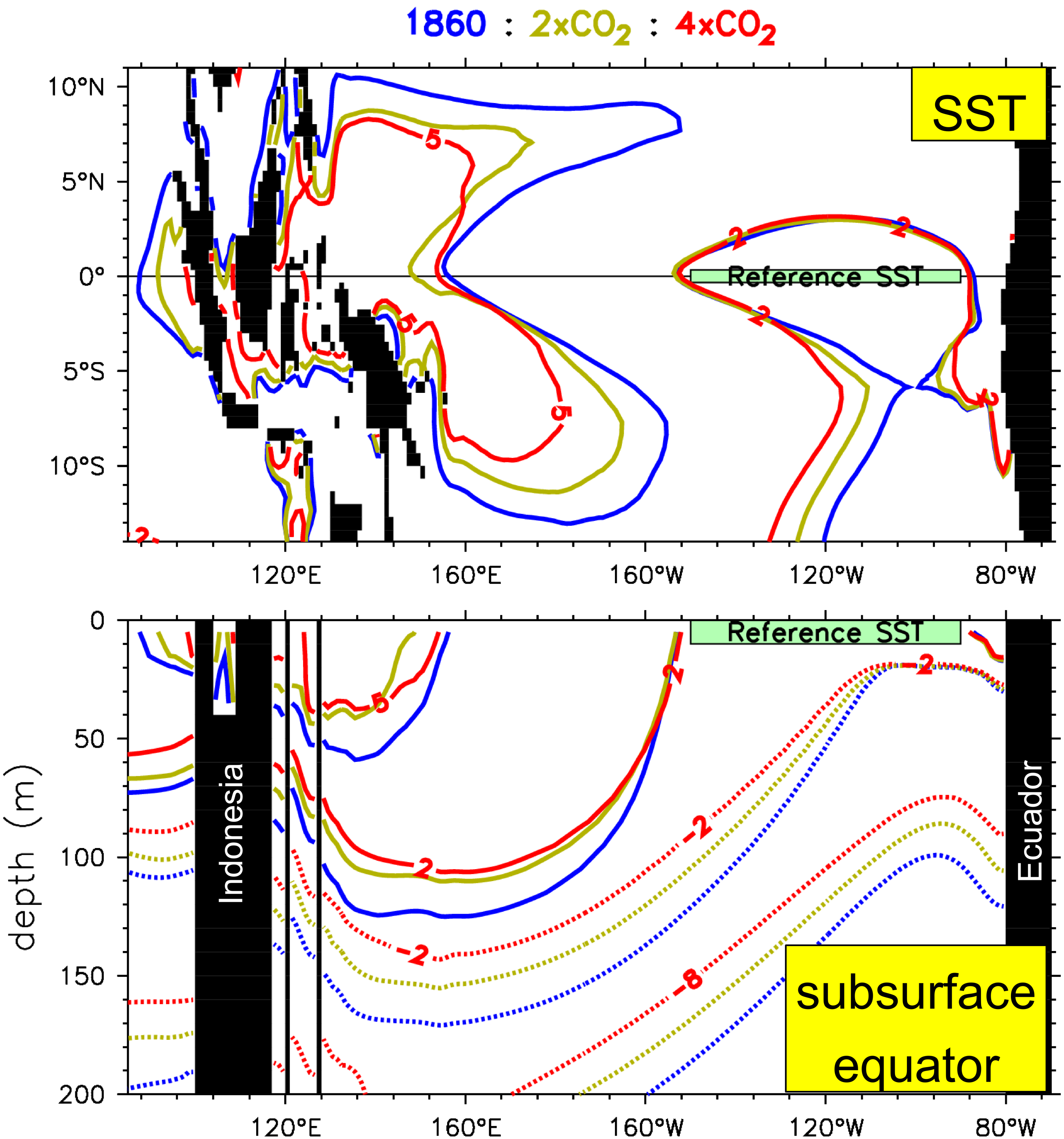
Tropical ocean more stratified

Stronger, shallower, and flatter equatorial thermocline

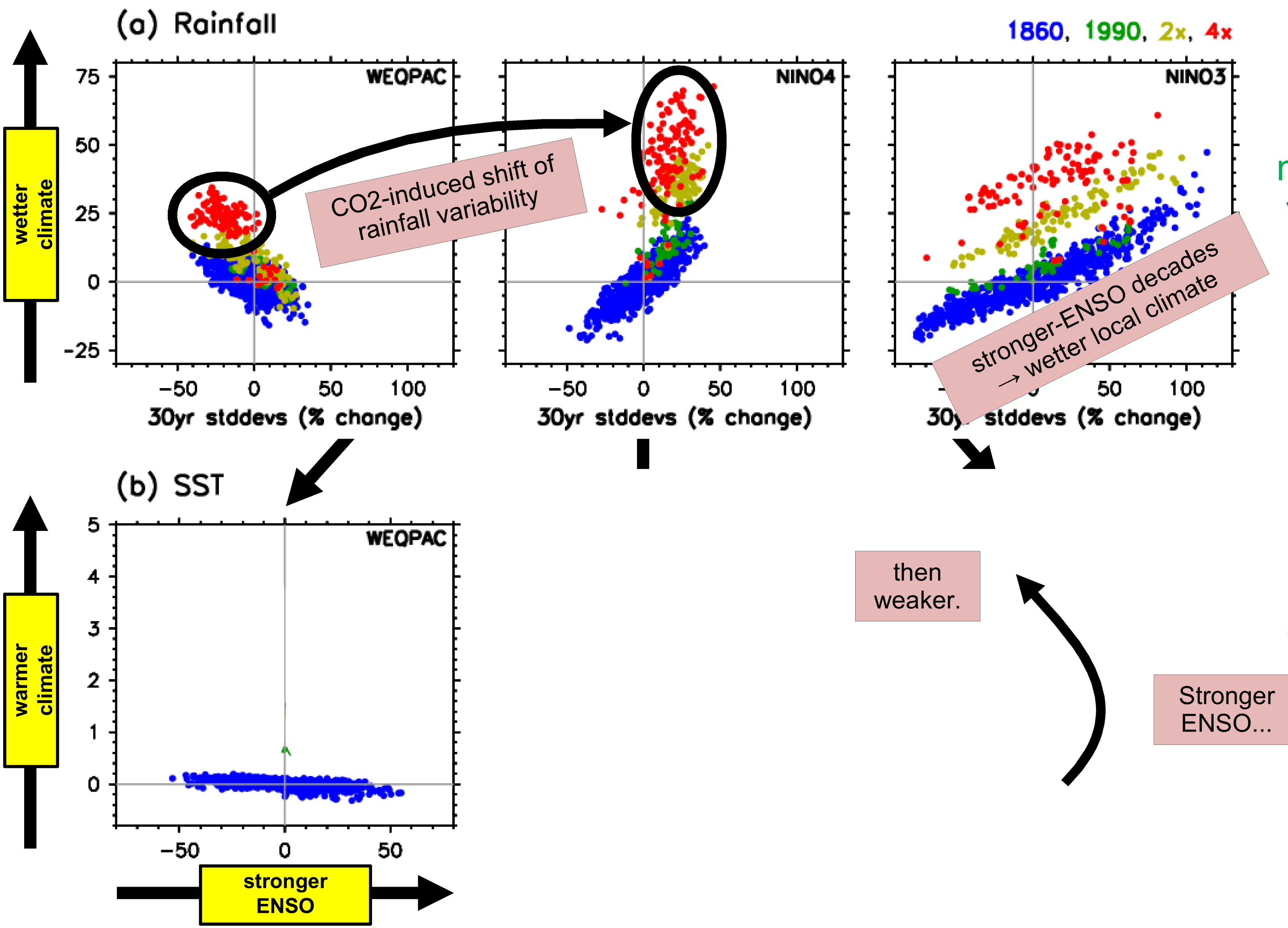
As CO_2 increases:

Relative to ECT SSTs, the warm pool contracts.

Relative to ECT SSTs, cold water moves closer to the surface.



ENSO response to increasing CO_2



CM2.1 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)

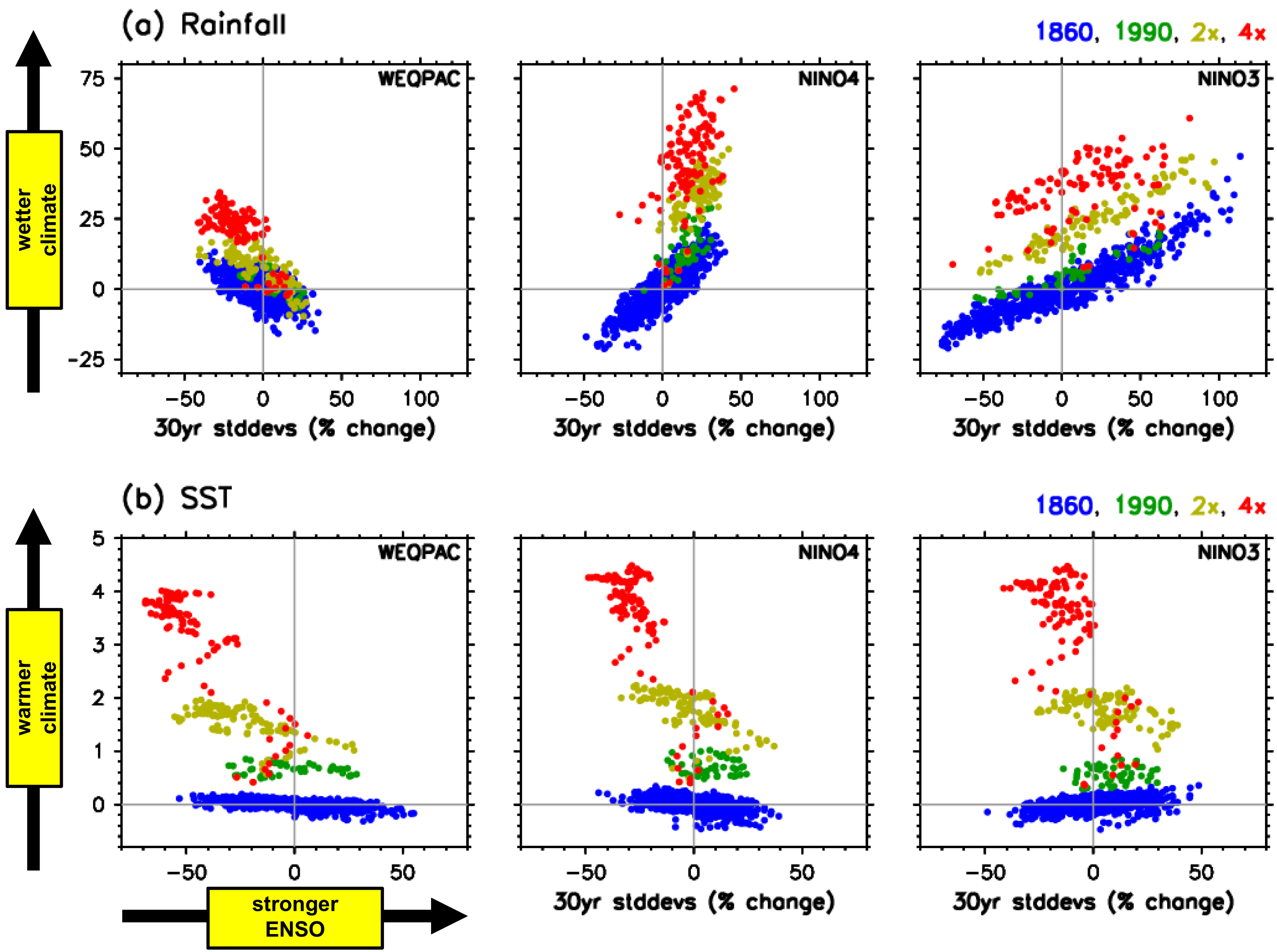
Watanabe et al. (2012)

Ogata et al. (2013)

Power et al. (2013)

Cai et al. (2014)

ENSO response to increasing CO_2



CM2.1 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)

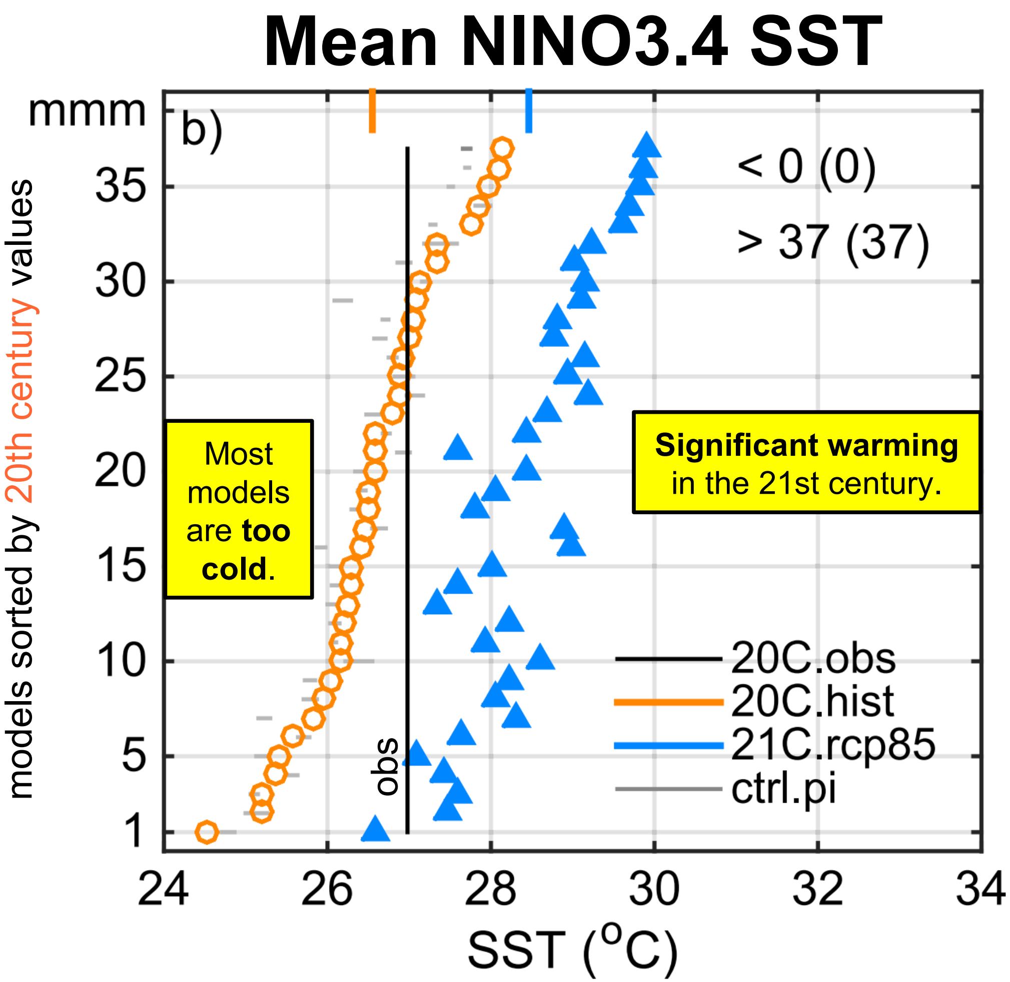
Watanabe et al. (2012)

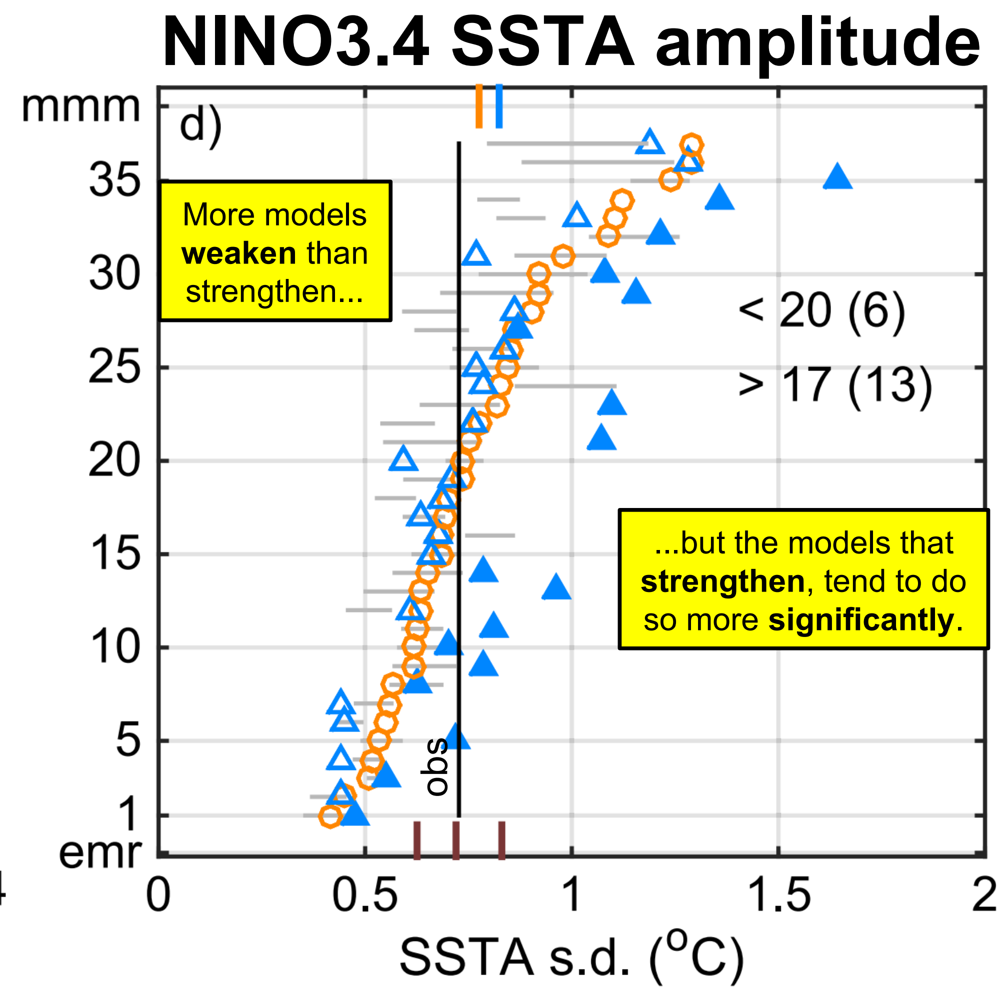
Ogata et al. (2013)

Power et al. (2013)

Cai et al. (2014)

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

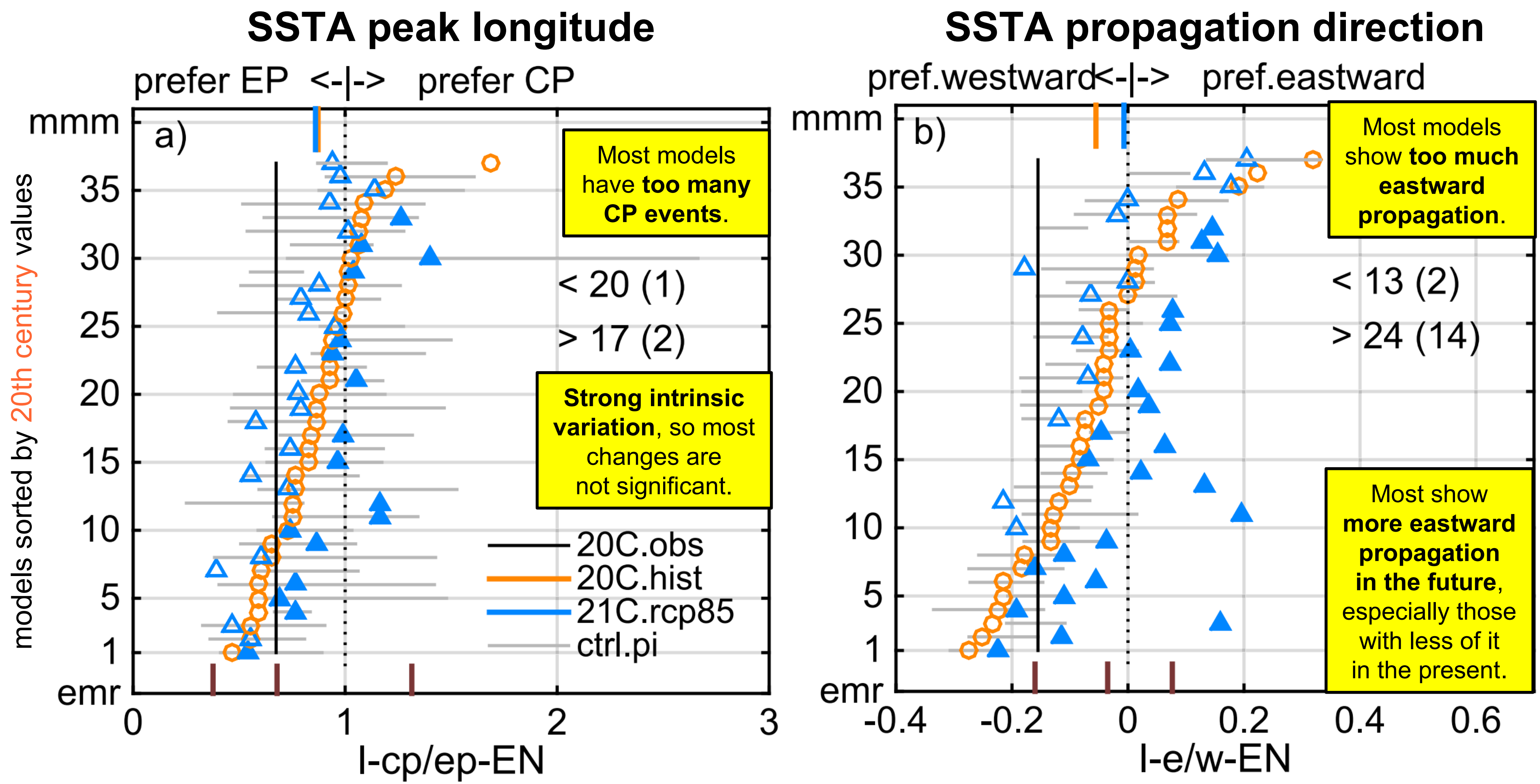




All the models show **significant mean warming** in the 21st century.
But **ENSO SSTAs** weaken in some models, strengthen in others.

Chen et al. (JC 2017)

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



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

Chen et al. (JC 2017)

Competing changes in ENSO feedbacks

1. Amplifiers

- stronger rainfall & wind stress responses to SSTAs
- intensified thermocline, shallower mixed layer
- weaker refresh of surface waters from below
- weaker SST barrier for equatorial shifts of convection

2. Dampers

- stronger evaporative & cloud-shading responses
- weaker upwelling -> surface less connected to thermocline
- smaller dynamic warm pool -> less room for warming

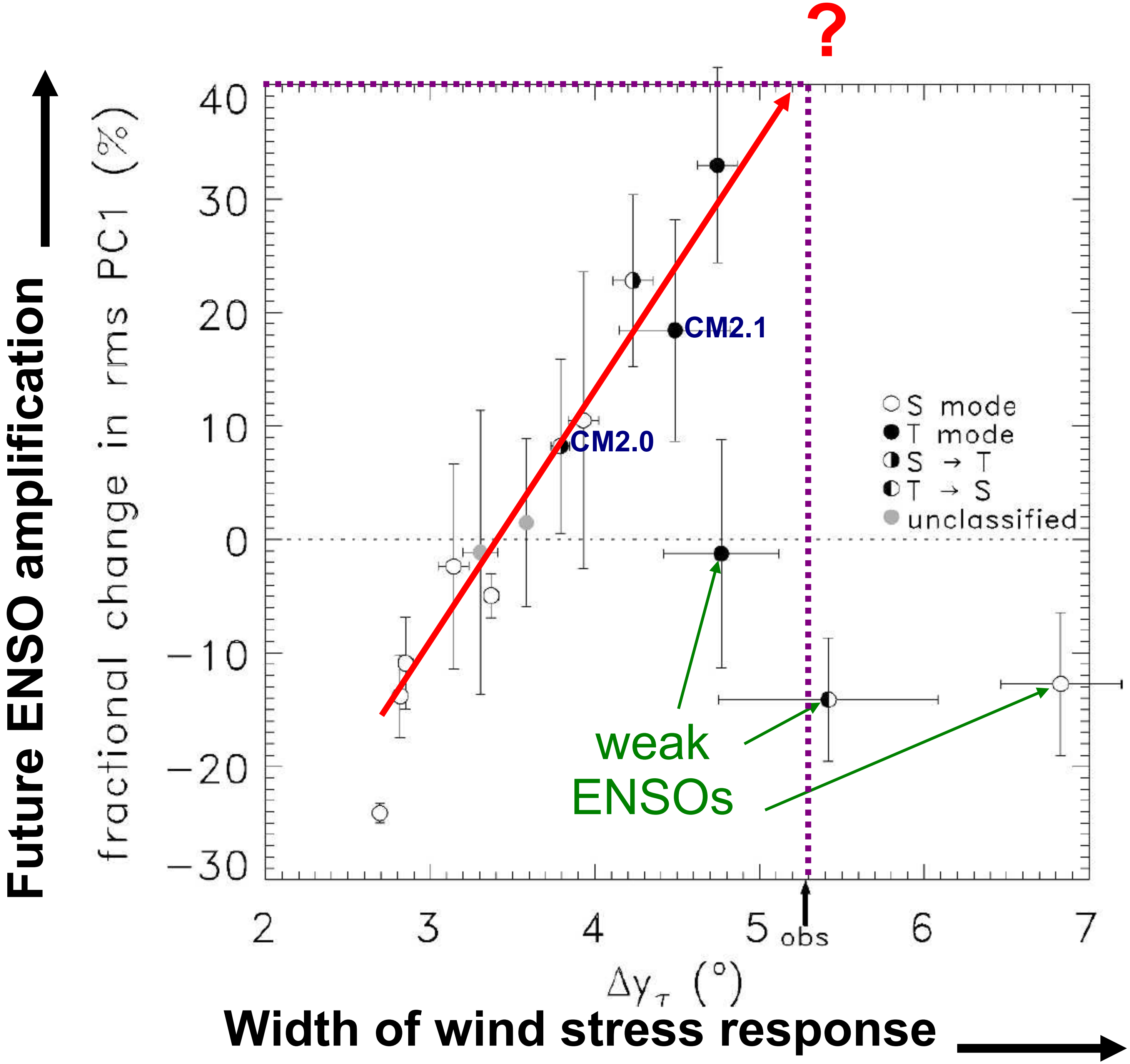
3. Ambiguous effects

- stronger intraseasonal wind variability?

Guilyardi et al. (BAMS 2009); Vecchi & Wittenberg (WIREs CC 2010)
Collins et al. (Nature Geosci. 2010); DiNezio et al. (JC 2009; EOS 2010; JC 2012); Cai et al. (2014)

Ongoing activities with CLIVAR Working Groups,
D. Battisti, A. Atwood, M. Cane, C. Karamperidou, F.-F. Jin, J. Brown, F. Graham

Can we extrapolate ENSO projections to reality?

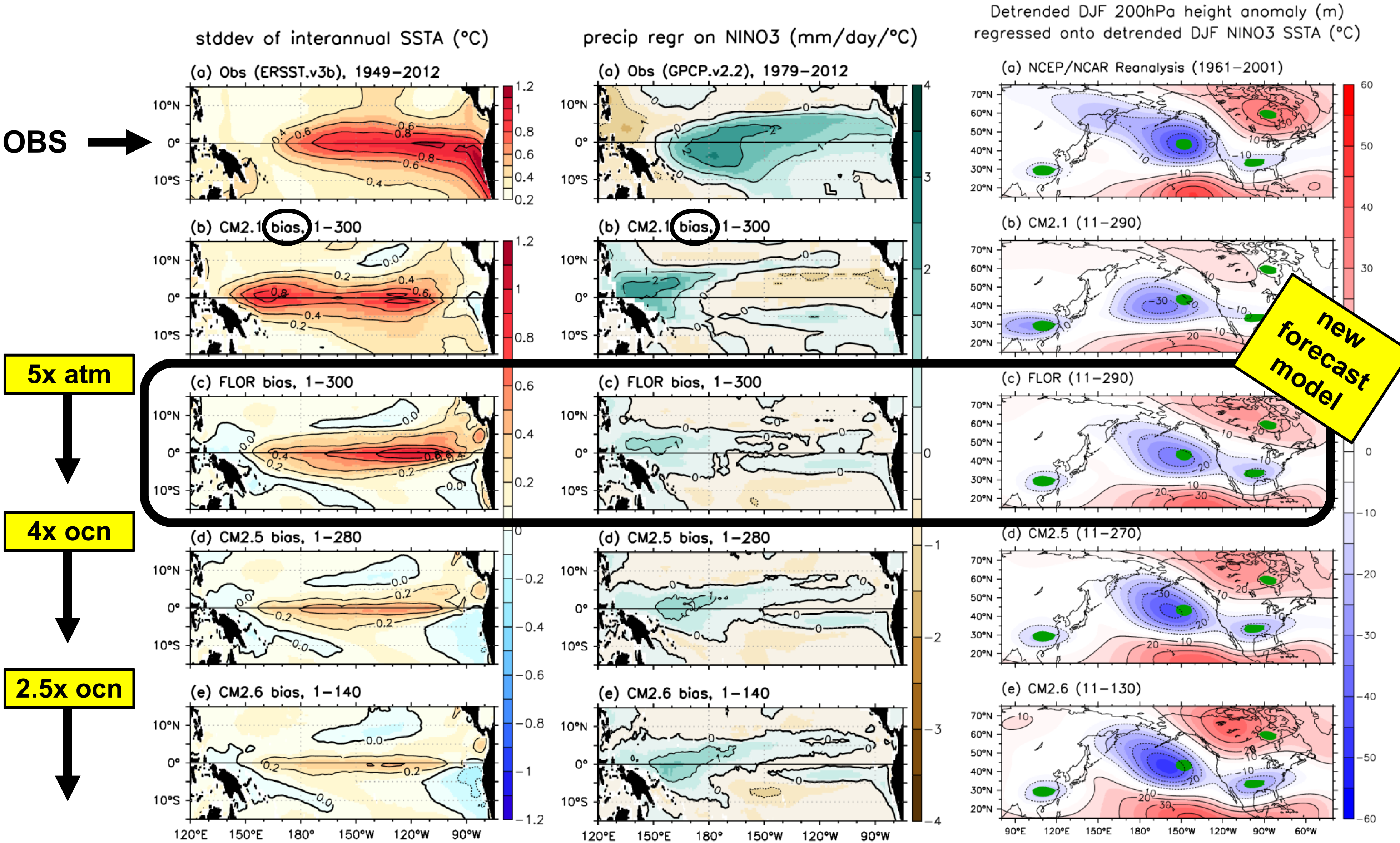


The "most realistic" pre-industrial ENSOs show amplification at $2xCO_2$

Merryfield (JC 2006)

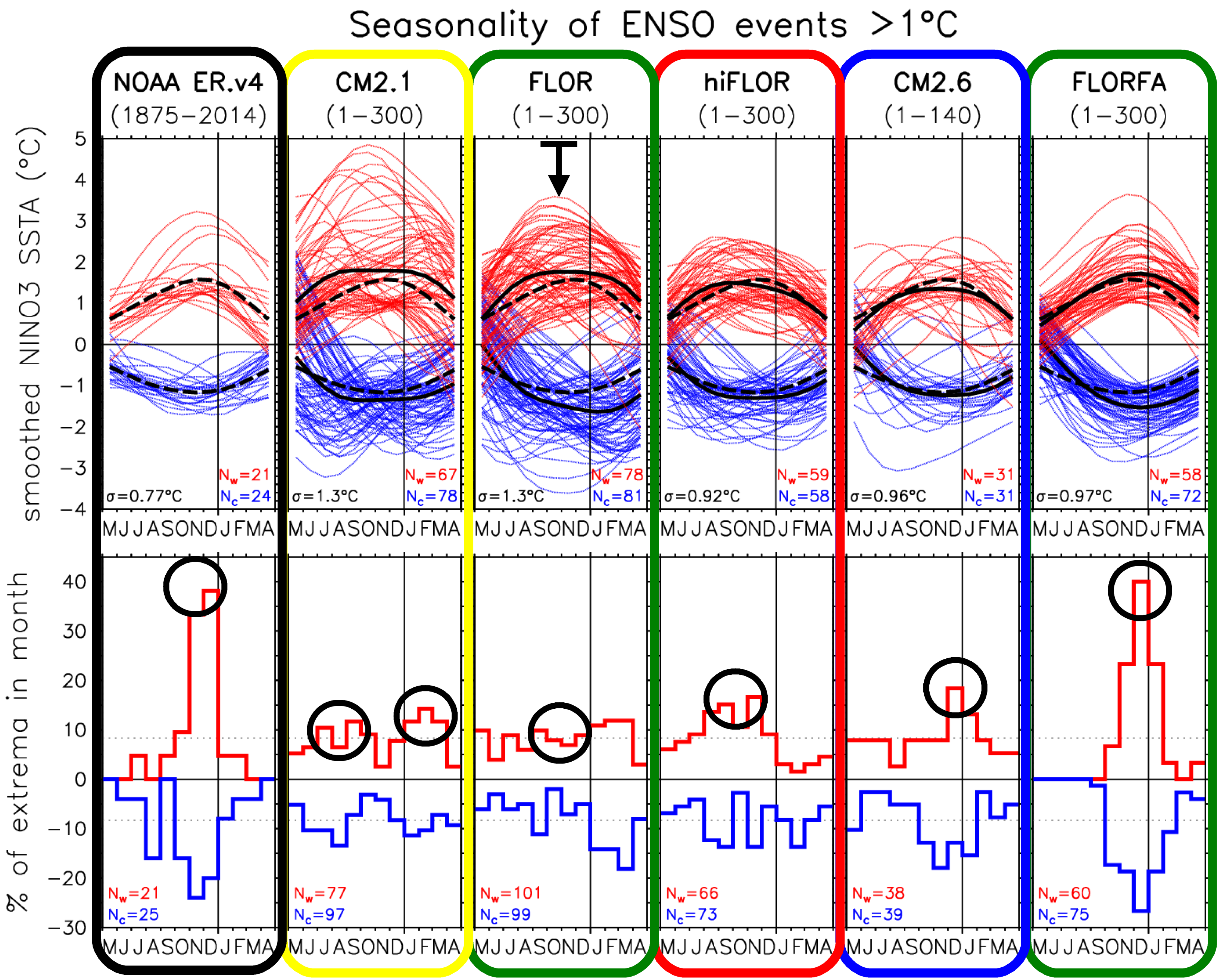
Vecchi & Wittenberg (WIREsCC 2010)

ENSO improvements with increasing resolution



Delworth et al. (2012); Vecchi et al. (JC 2014); Jia et al. (JC 2015); Wittenberg et al. (in prep)

Seasonality & diversity of ENSO events



Obs events peak in Nov/Dec.

CM2.1 was *semiannually* synchronized!

Atmos/ocean refinement *slightly* improves seasonality, but weakens skewness.

Flux adjustment nails the seasonality, due to improved SST/rain/wind climatologies.

Summary

1. ENSO diversity

a. **Continuum of flavors;** strong El Niños are different

b. **Nonlinear regional impacts:** stakeholder-dependent

- various paleo proxies record different aspects of ENSO

c. **Intrinsic modulation:** may be unpredictable

- may dominate the ENSO we experience in the next few decades
- Have we observed long enough? How long must we run models?

2. ENSO changes

a. **Stronger ENSO** in past 30yr than previous 400yr

b. **Changing patterns of variability**, especially for rainfall

c. **Unprecedented climates:** Change in mean state vs. variance

- West Pacific SST; central Pacific rainfall

d. **Future vulnerability** depends on region & stakeholder

e. Competing feedbacks + optima + model biases → **uncertainty in projections**

3. ENSO models & dynamics

a. **CGCMs are improving:** teleconnections, dynamics, predictions

- atmospheric & oceanic formulations both matter
- correcting the climatology improves ENSO's seasonal timing

b. **Renewed attention to conceptual frameworks & metrics**

- e.g. nonlinear delayed oscillator → captures key ENSO asymmetries

Next steps

1. Improve AGCM climatology & ENSO feedbacks

a. **Moisture budget:** reduce tropical evap/rainfall; improve rainfall gradients
b. **Surface fluxes:** bulk formulae, skin temperature, diurnal cycle
c. **Clouds** & cloud radiative feedbacks
d. **Off-equatorial wind stress curl** response to ENSO (precip pattern, CMT)

2. Improve OGCM climatology & ENSO feedbacks

a. **Shoal the equatorial thermocline** (mixing, solar penetration, diurnal cycle)
b. **Resolve TIWs** (critical during La Niña)
c. **Mixed layer heat budget** (need obs constraints → **TPOS-2020**)

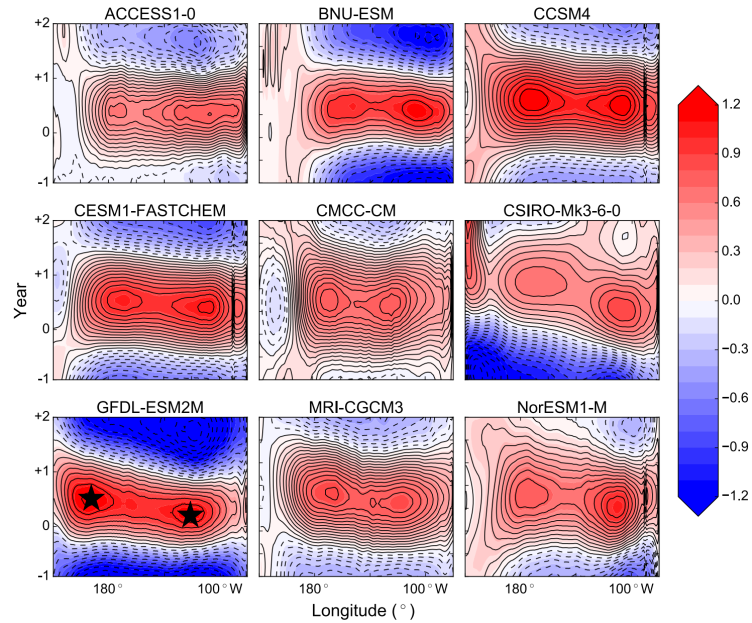
3. Improve coupled interactions

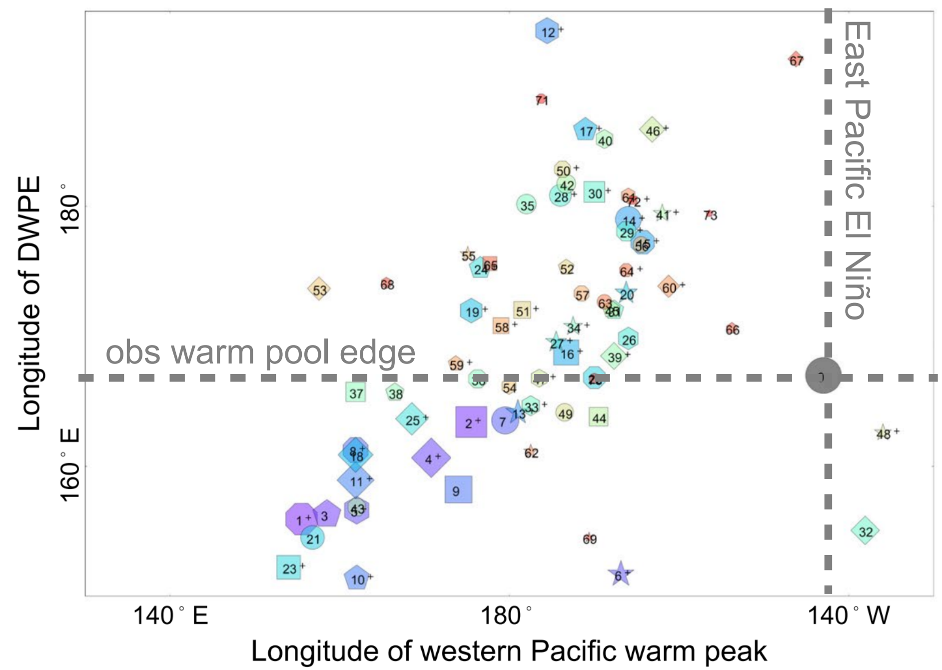
a. **Seasonal dT/dy** in east Pacific (ENSO seasonality)
b. **Coupled feedback** diagnostics (need obs constraints!)
c. **Subsurface flux adjustments** (3D-FA)

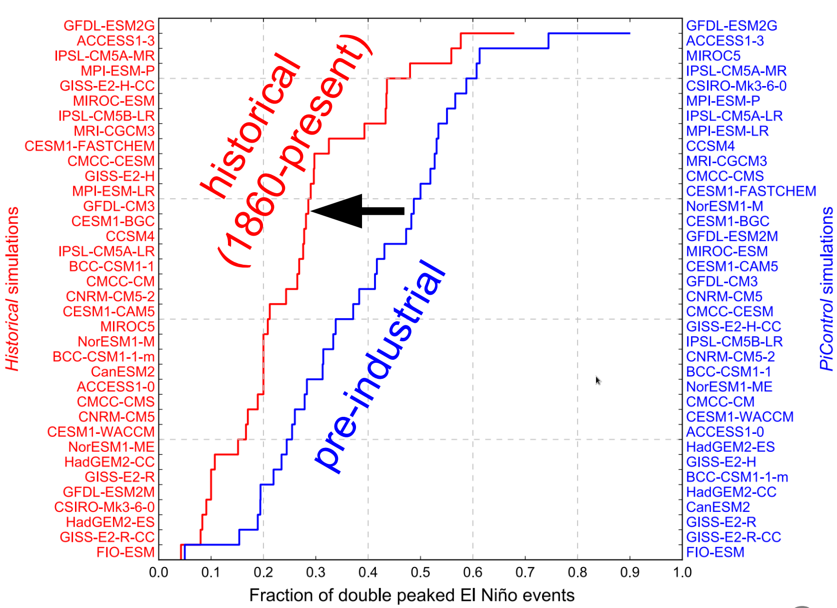
Reserve Slides

The double-peaked El Niño

Composite El Niño in CMIP5 models
(equatorial SSTA)





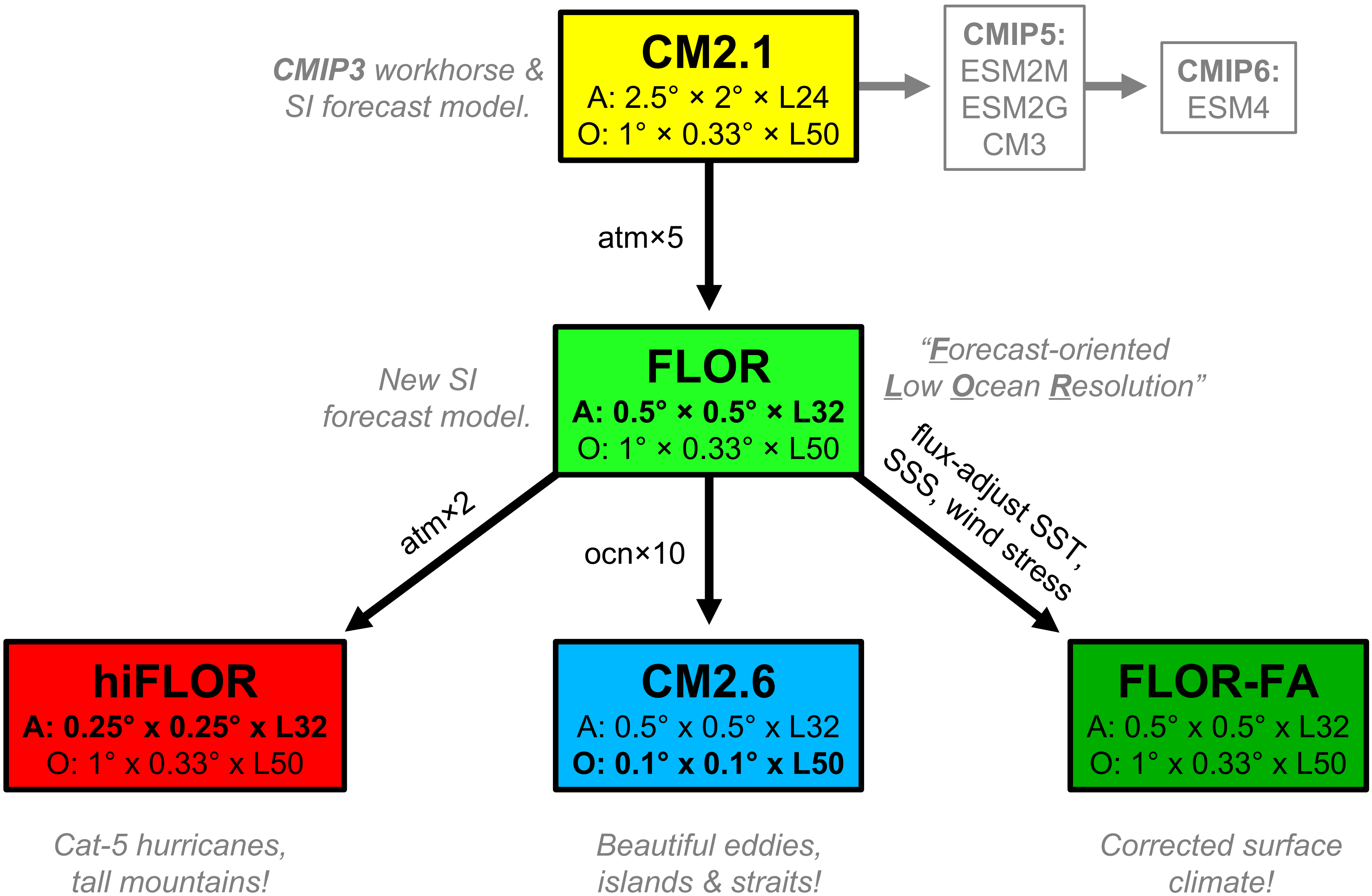


If warm pool is too far west, get more **double-peaked El Niños**, with western peaks that are **farther west**.

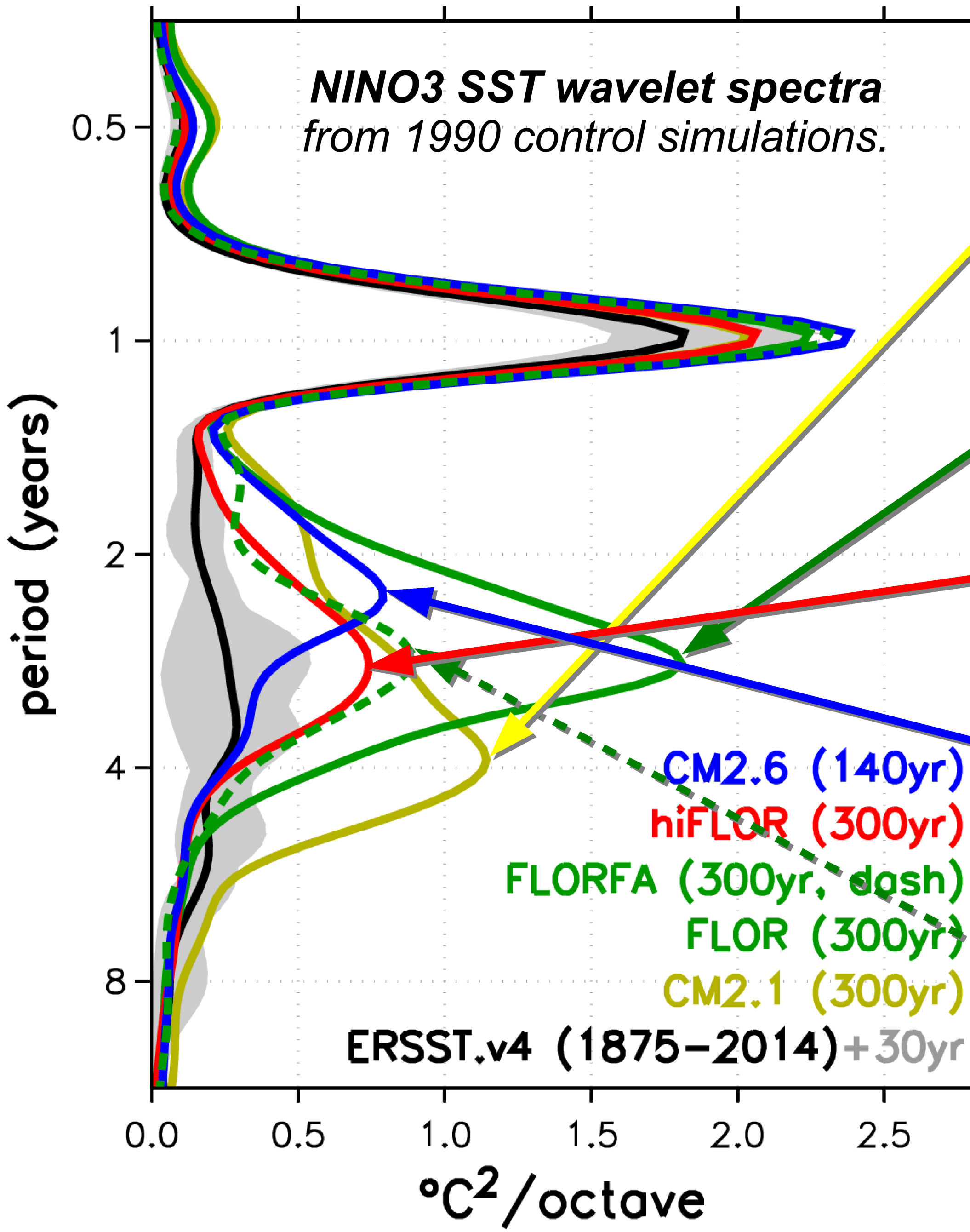
Present-day simulations show fewer double-peaked El Niños than pre-industrial.

Graham et al. (CD 2017)

GFDL's high-res model development path



ENSO amplitude & period



CM2.1 ENSO was too strong,
but time scale looked good.

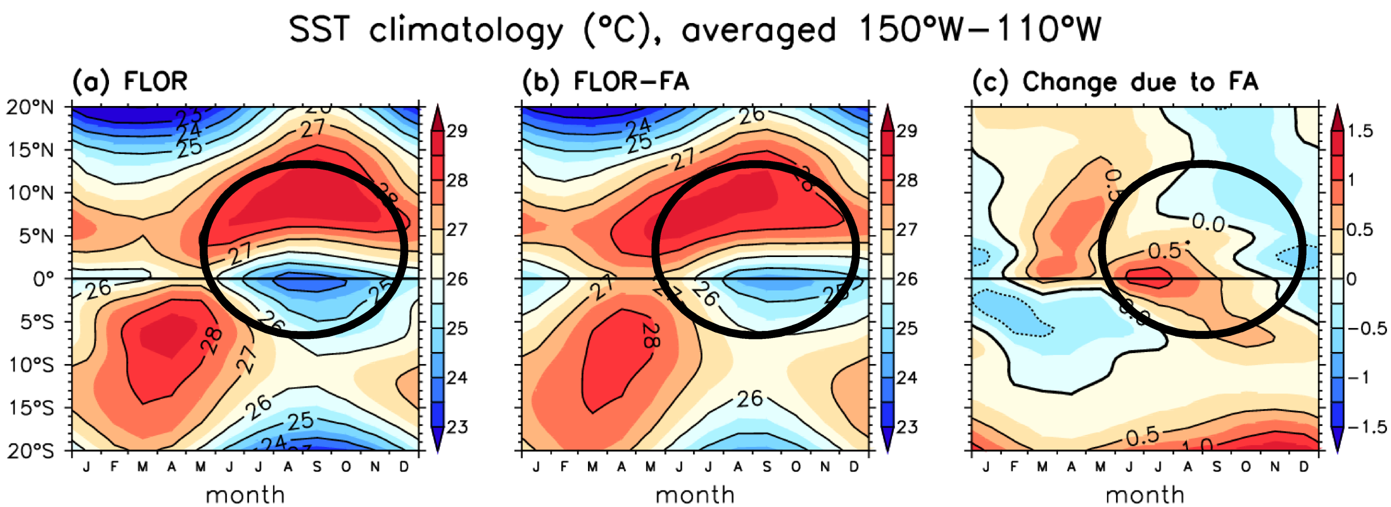
FLOR's atmos refinement
shortens period, narrows spectrum.

HiFLOR's atmos refinement
weakens ENSO.

CM2.6's oceanic refinement
weakens ENSO, shortens period.

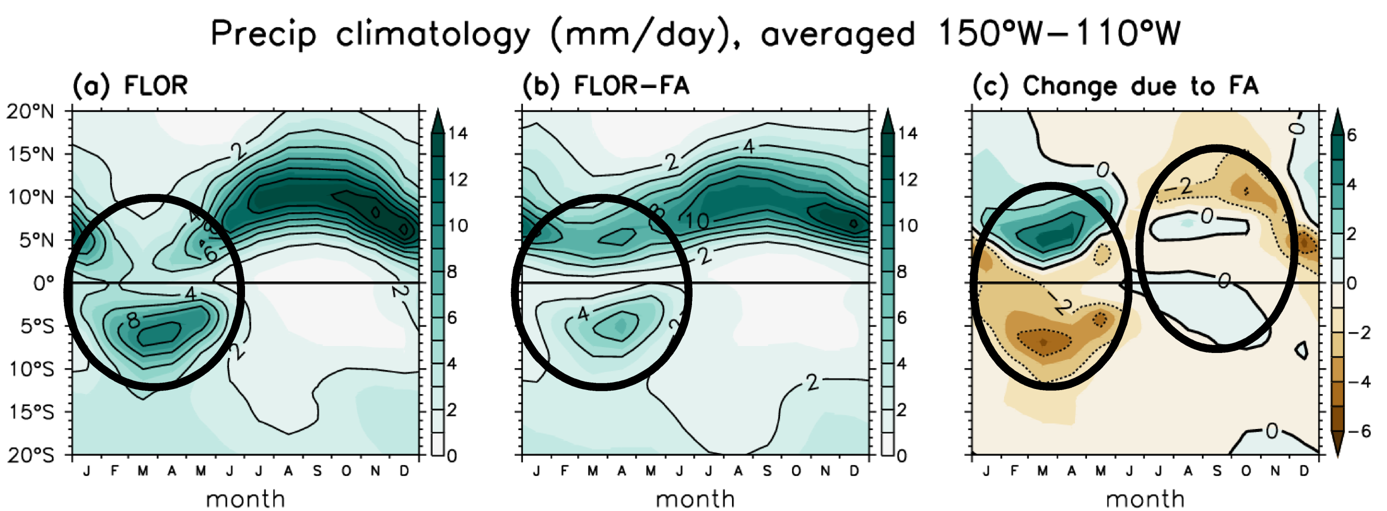
Surface flux adjustment
weakens ENSO.

East Pacific climatological SST & rainfall



FLOR overestimates dT/dy in the eastern equatorial Pacific during Jul-Nov.

FA weakens this dT/dy, facilitating equatorial shifts of ITCZ during ENSO growth season.

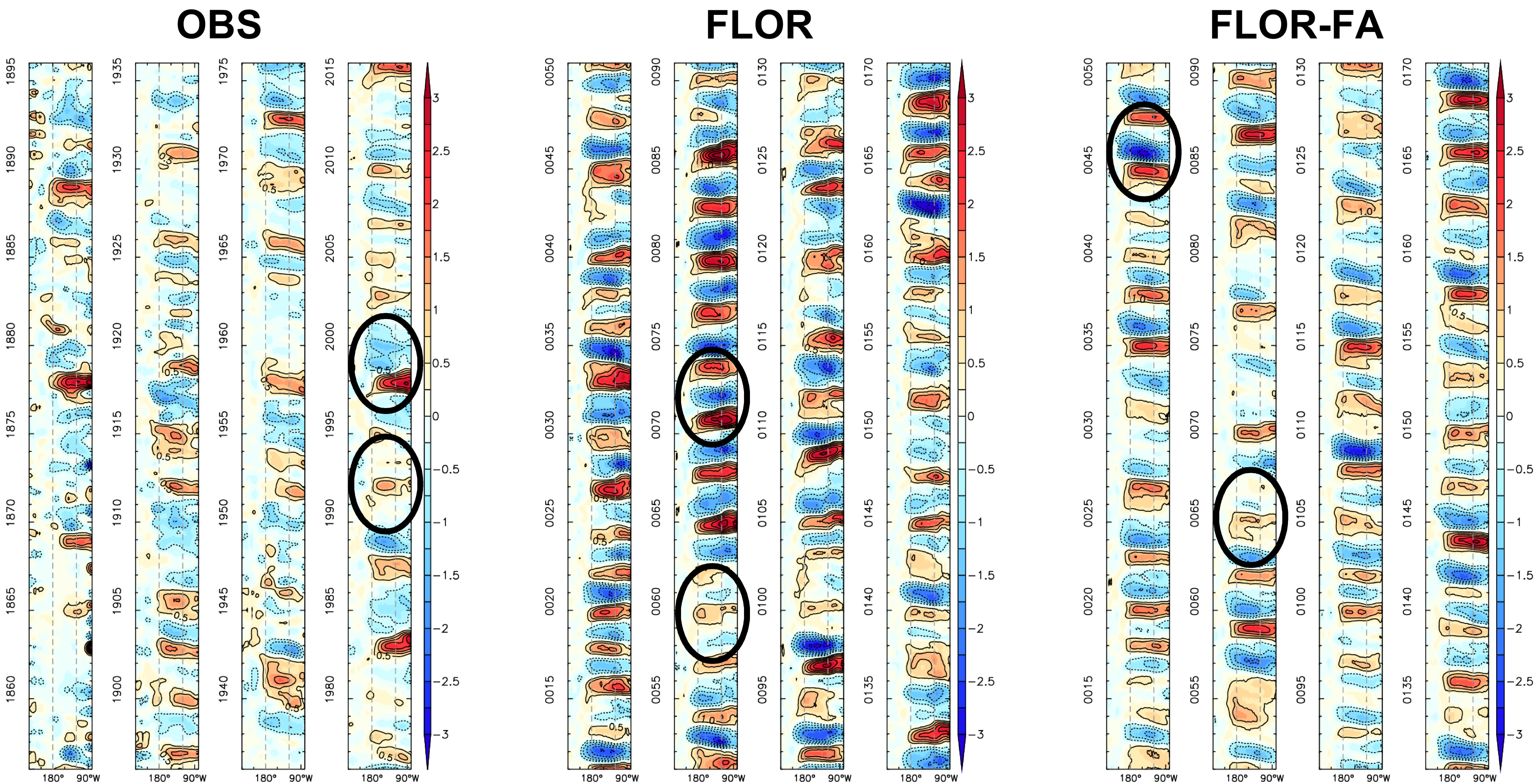


FA weakens the spurious Jan-May southern ITCZ.

During Jul-Nov, FA shifts the northern ITCZ slightly closer to the equator.

FA sensitizes the northeast Pacific ITCZ to equatorial SSTAs in Jul-Nov, seasonalizing the Bjerknes feedback and synchronizing ENSO to the end of the calendar year.

Equatorial Pacific SSTAs (°C, 160yr)



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

Summary: ENSO in a flux-adjusted CGCM

1. FLOR global coupled GCM

a. **High-res atmosphere** → climate & ENSO forecasts improved over CM2.1
b. But ENSO too strong & frequent, not seasonally synchronized

2. FLOR with flux adjustments (FLOR-FA)

a. **Corrects climatological SST/winds**, greatly improves mean rainfall
b. **Deepens climatological thermocline along equator**
- weaker off-equatorial trade winds → less Sverdrup divergence from equator
- reveals a latent OGCM bias → motivates attention to equatorial mixing & solar penetration

3. FA impacts on ENSO in FLOR

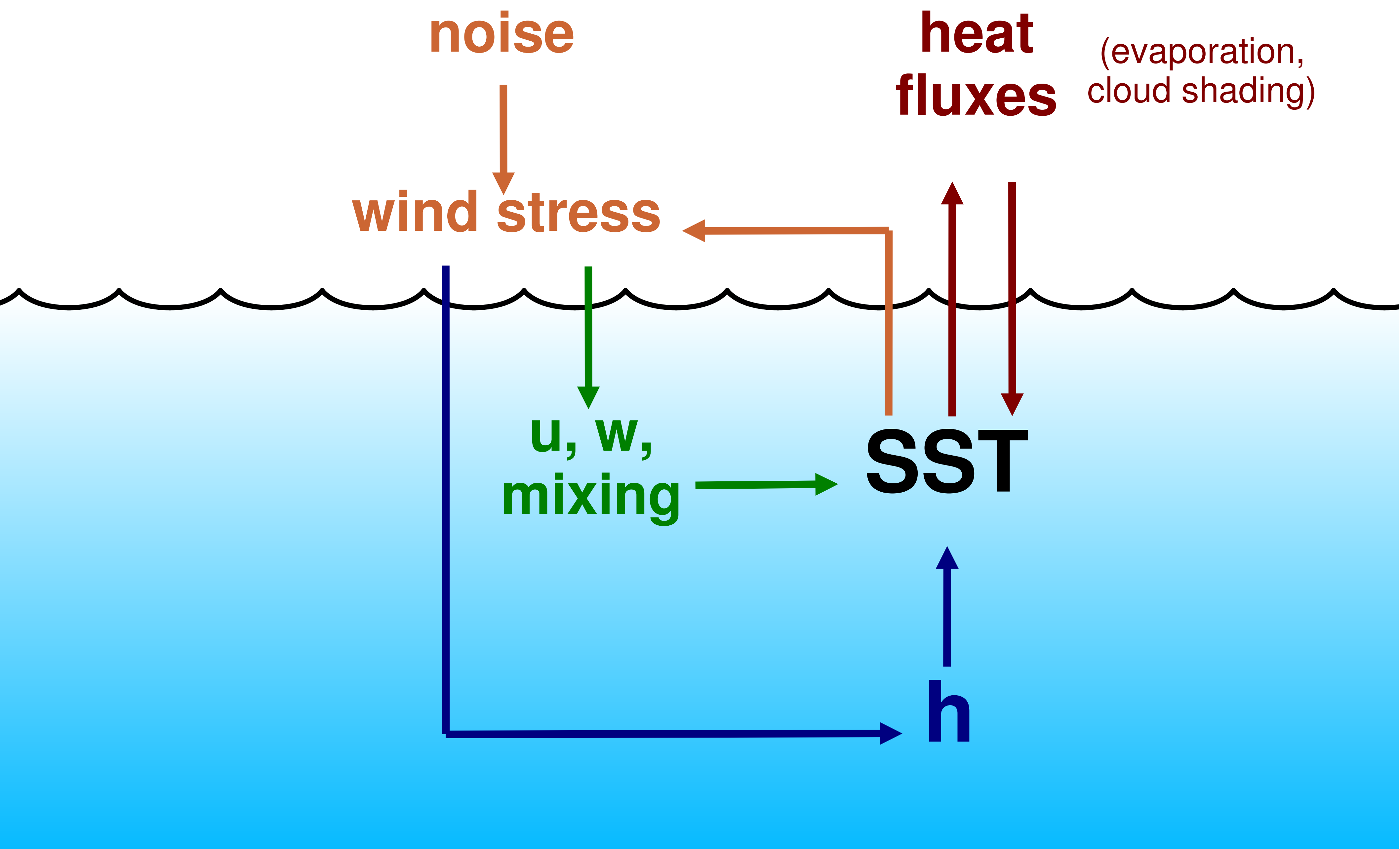
a. **ENSO weakens**
- *despite* weaker SSTA→flux damping and stronger SSTA→wind coupling
- trumped by deeper mean thermocline, weaker h'→Te' coupling
- weaker thermocline feedback → more westward propagation of SSTAs
- less interdecadal modulation of ENSO

b. **ENSO period doesn't change**
- off-equatorial anomalous cyclonic curl still too strong → excessive Sverdrup feedback

c. **Atmospheric responses/teleconnections shift westward**
- drier central equatorial Pacific + weaker ENSO → harder to shift convection eastward

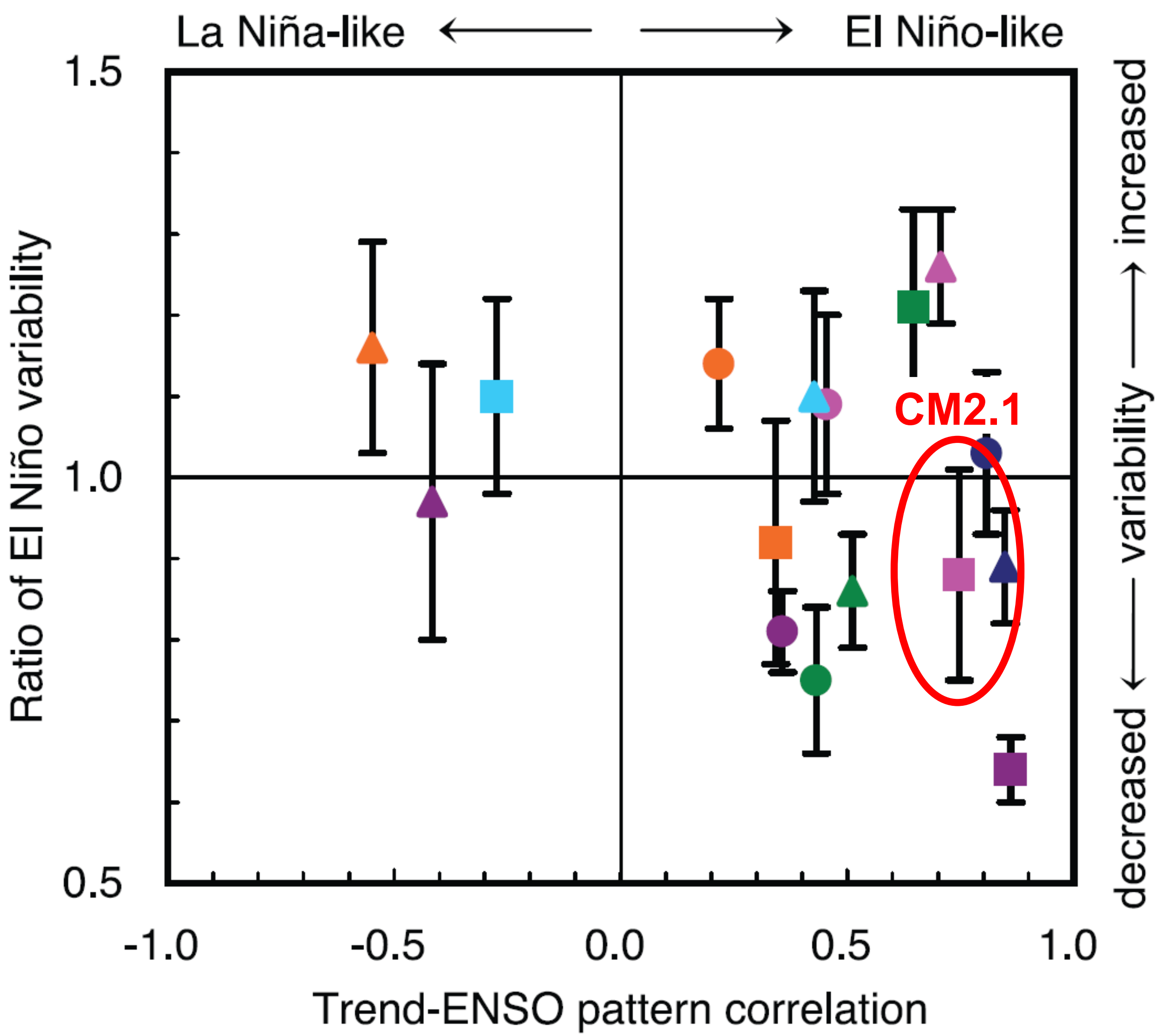
d. **ENSO synchronizes to end of calendar year**
- eastern equatorial Pacific dT/dy barrier weakens in Jul-Nov relative to Jan-May
- stronger Bjerknes feedback in Jul-Nov → ENSO peaks near Dec

Key ENSO feedbacks



Projected ENSO changes (CMIP3/AR4)

std(SLP.PC1 of SRES.A2 (2051-2100))
/ std(SLP.PC1 of 20C3M)
30S-30N, 30E-60W
van Oldenborgh et al. (OS 2005)



correl(SST trend of 1%/yr, SST.PC1 of PICTRL)
10S-10N, 120E-80W
Yamaguchi & Noda (JMSJ 2006)

Weak/ambiguous *near-term* anthropogenic impacts on ENSO

Intrinsic modulation

Reviews:

Meehl et al. (IPCC-AR4 2007)

Guilyardi et al. (BAMS 2009)

Vecchi & Wittenberg (WIREs CC 2010)

Collins et al. (Nature Geosci. 2010)

ENSO theory revisited

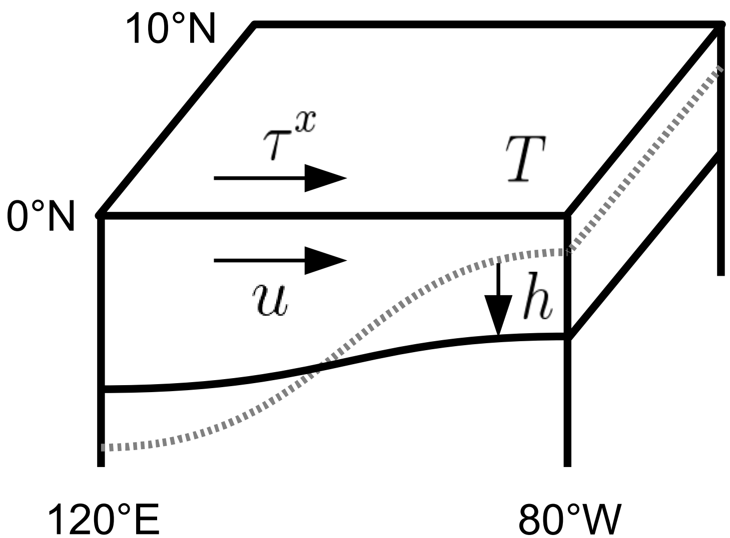
Existing conceptual models of ENSO have issues:

- Linear frameworks miss key asymmetries in obs (Choi et al. 2013)
- "BJ index" accumulates errors (Graham et al., CD 2014)
- "Unified Oscillator" at odds with obs & CGCMs (Graham et al., JC 2015)

Back to basics:

At ENSO time scales, a delayed oscillator with

$$\dot{T}(t) = \frac{T(t)}{6.25\text{mo}} - \frac{T(t-5\text{mo})}{5\text{mo}}$$



captures **94% of the variance** of obs NINO3 dT/dt. (Graham et al., JC 2015)

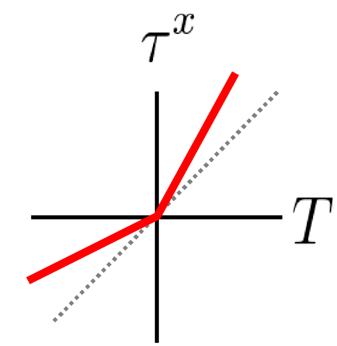
Good reference point... but what about ENSO nonlinearity?

Modified delayed oscillator

Choi et al. (J. Climate, 2013)

stronger wind response
during warm events

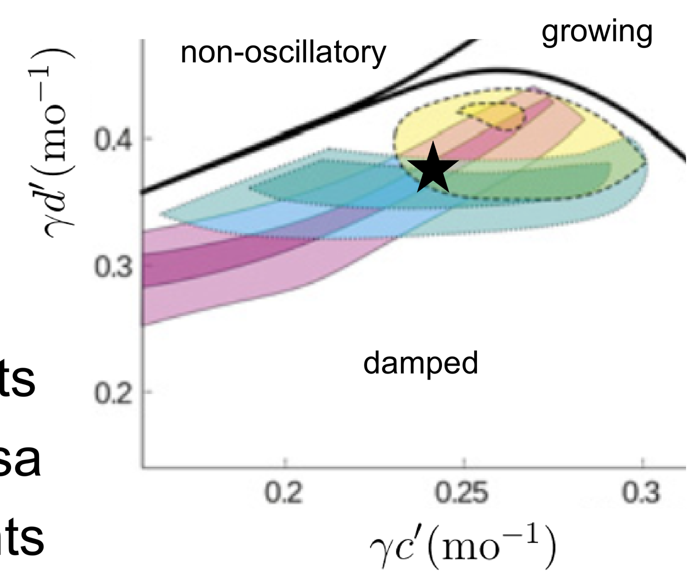
$$\tau^x = \gamma\left(T + r|T|\right) + \text{noise}$$



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

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

CM2.1 SSTA peaks vs. calendar month

abs(NINO3) > 1 stddev

warm events are stronger & rarer than cold events

strong warm events peak in SON

less synchronization of cold events & weak warm events