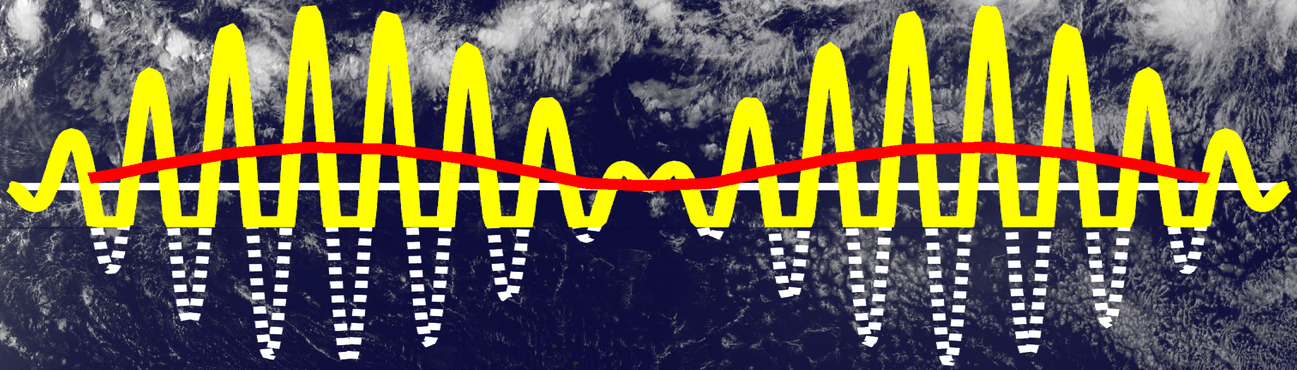
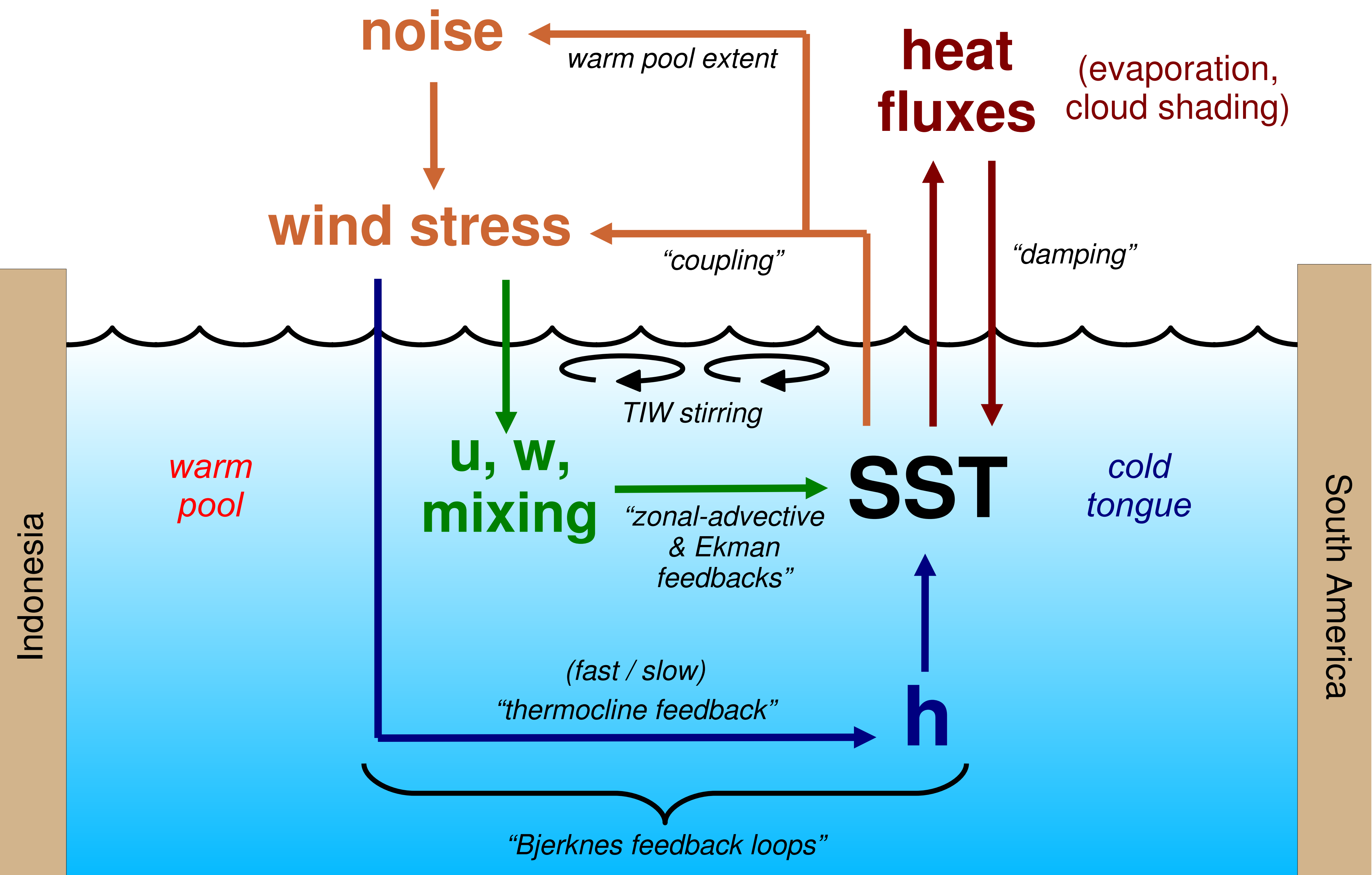
Time scale interactions of ENSO



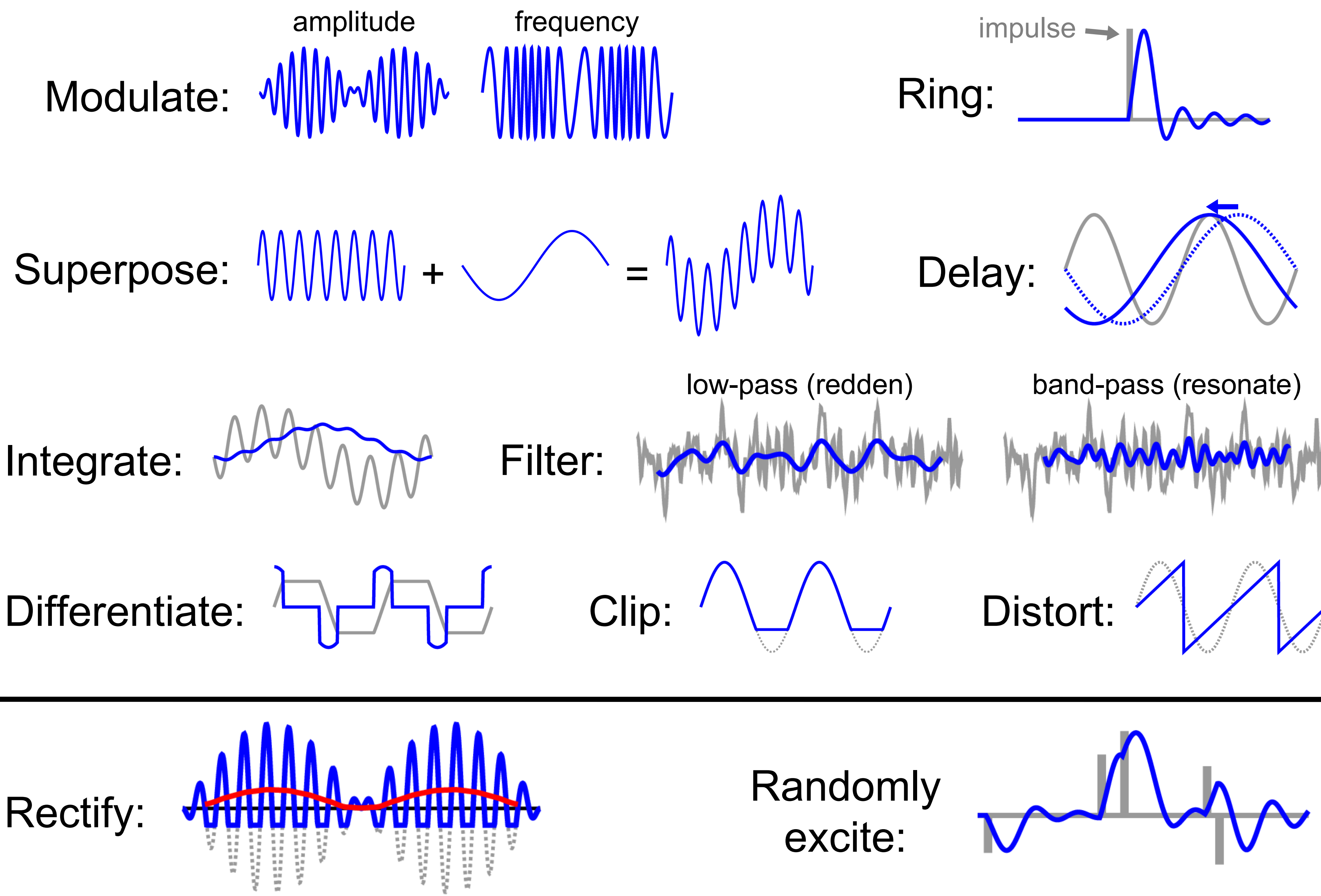
Andrew Wittenberg
NOAA/GFDL, USA

NOAA
GOES-11
5 Oct 2011
1800 UTC

Key ENSO feedbacks

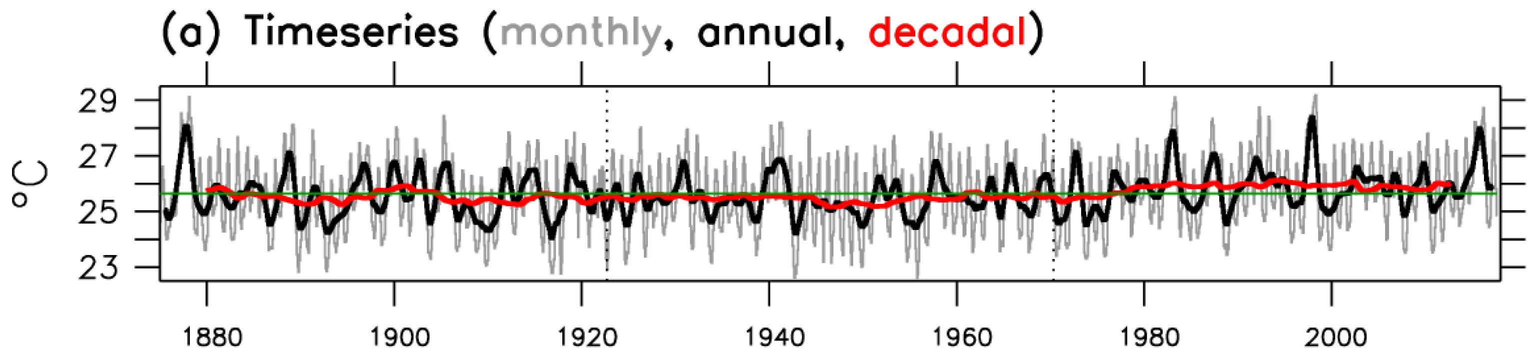


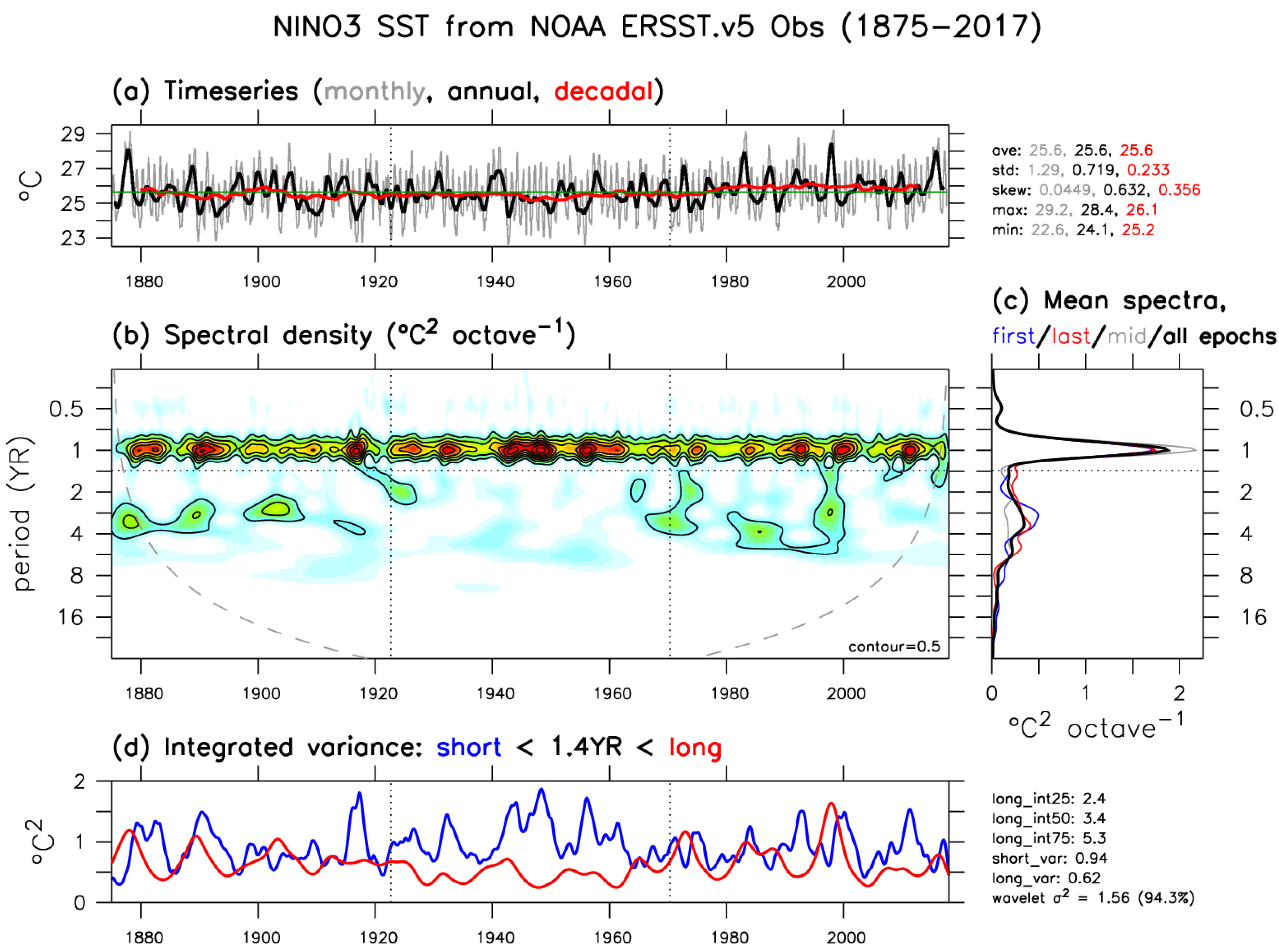
How can time scales interact?



ENSO time scales

NINO3 SST from NOAA ERSST.v5 Obs (1875–2017)




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 (°C² octave⁻¹)
period (YR)
contour=0.5
(c) Mean spectra,
first/last/mid/all epochs
°C² octave⁻¹
(d) Integrated variance: short < 1.4YR < long
°C²
long_int25: 2.4
long_int50: 3.4
long_int75: 5.3
short_var: 0.94
long_var: 0.62
wavelet σ² = 1.56 (94.3%)

ENSO theory revisited

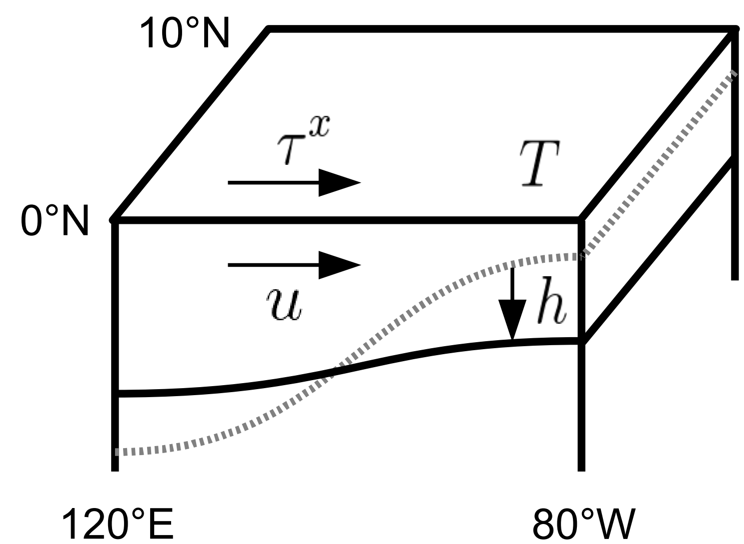
Existing conceptual models of ENSO have issues:

- 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

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

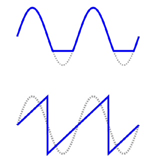


captures **94% of the variance** of obs NINO3 dT/dt. (Graham et al., JC 2015)

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

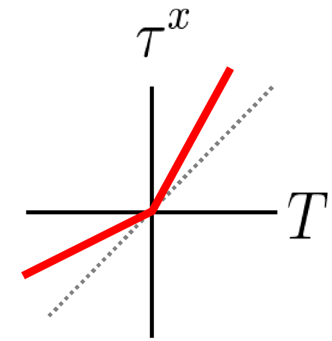
Modified delayed oscillator

Choi et al. (J. Climate, 2013)



stronger wind response
during warm events

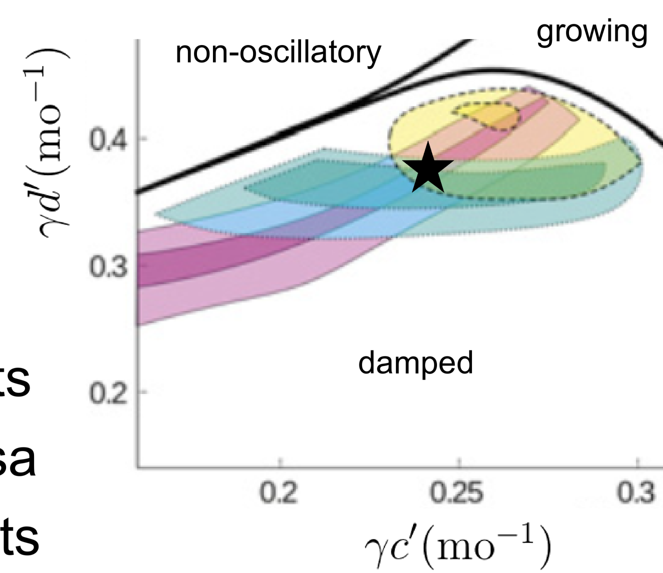
$$\tau^x = \gamma\,(T + r|T|) + \text{noise}$$



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

local damping — local growth — delayed remote feedback

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



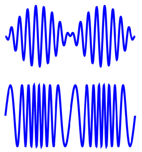
Reproduces observed asymmetries in

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

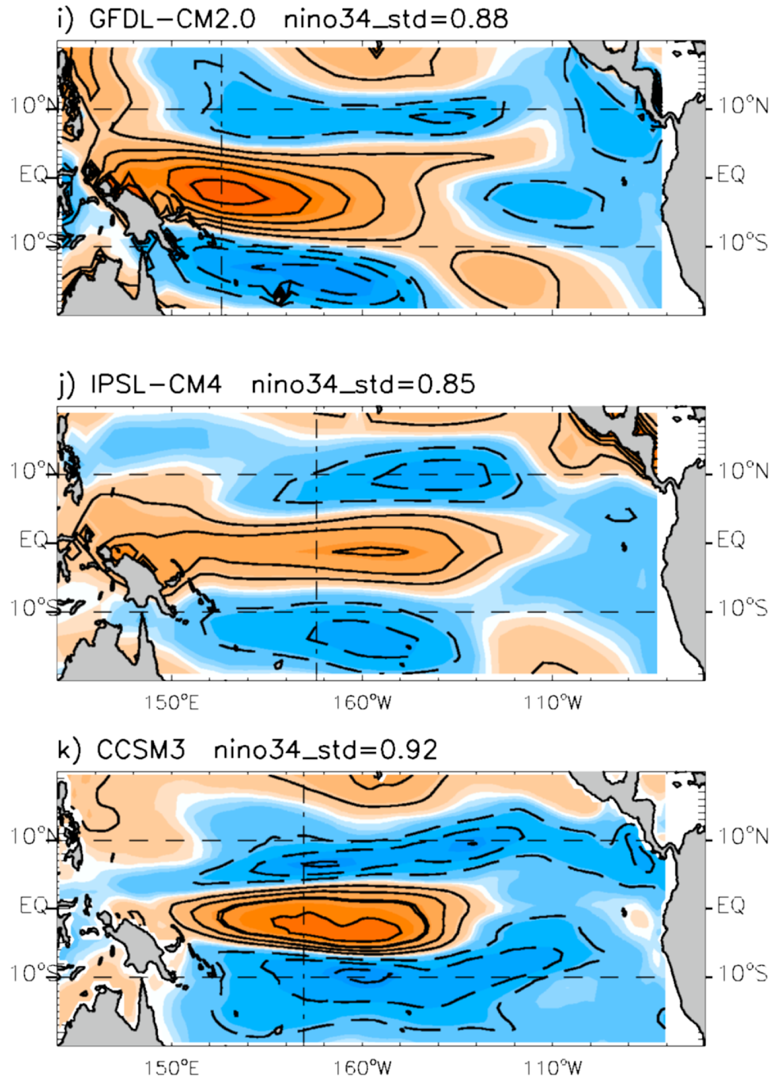
Stronger coupling during El Niño → stronger growth, faster transition & overshoot

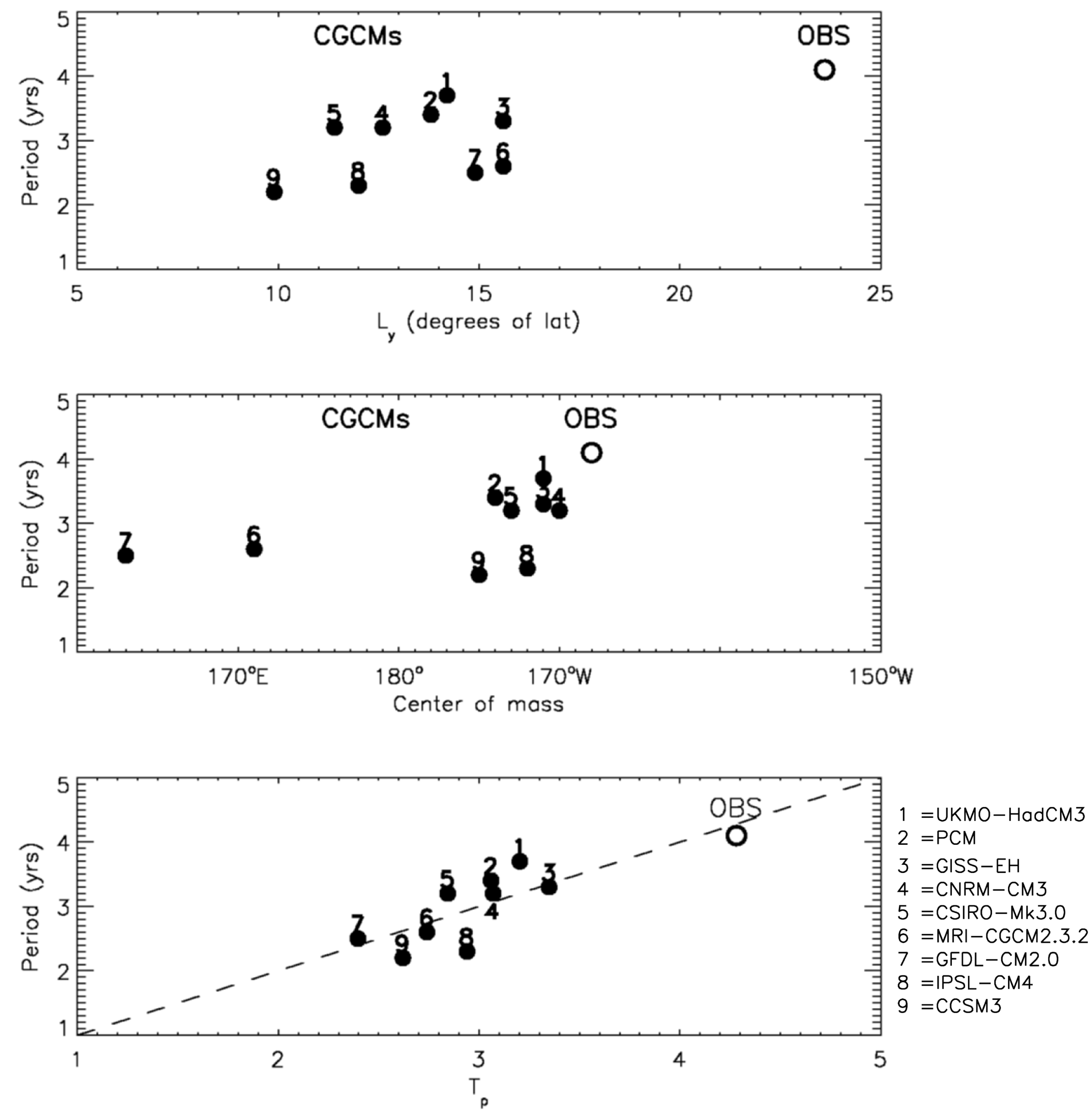
Weaker coupling during La Niña → milder, slower, susceptible to noise

ENSO period vs. y-width/longitude of zonal stress anomalies



Capotondi et al. (*Ocean Modelling*, 2006)

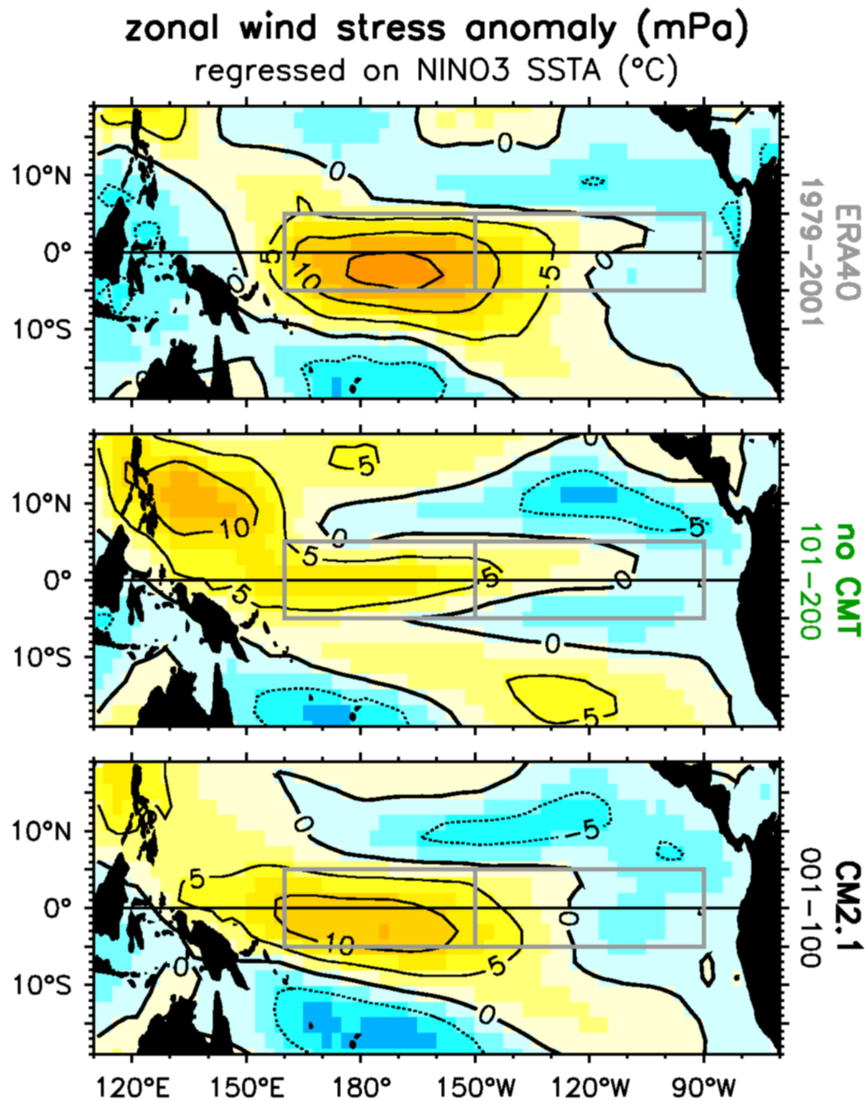


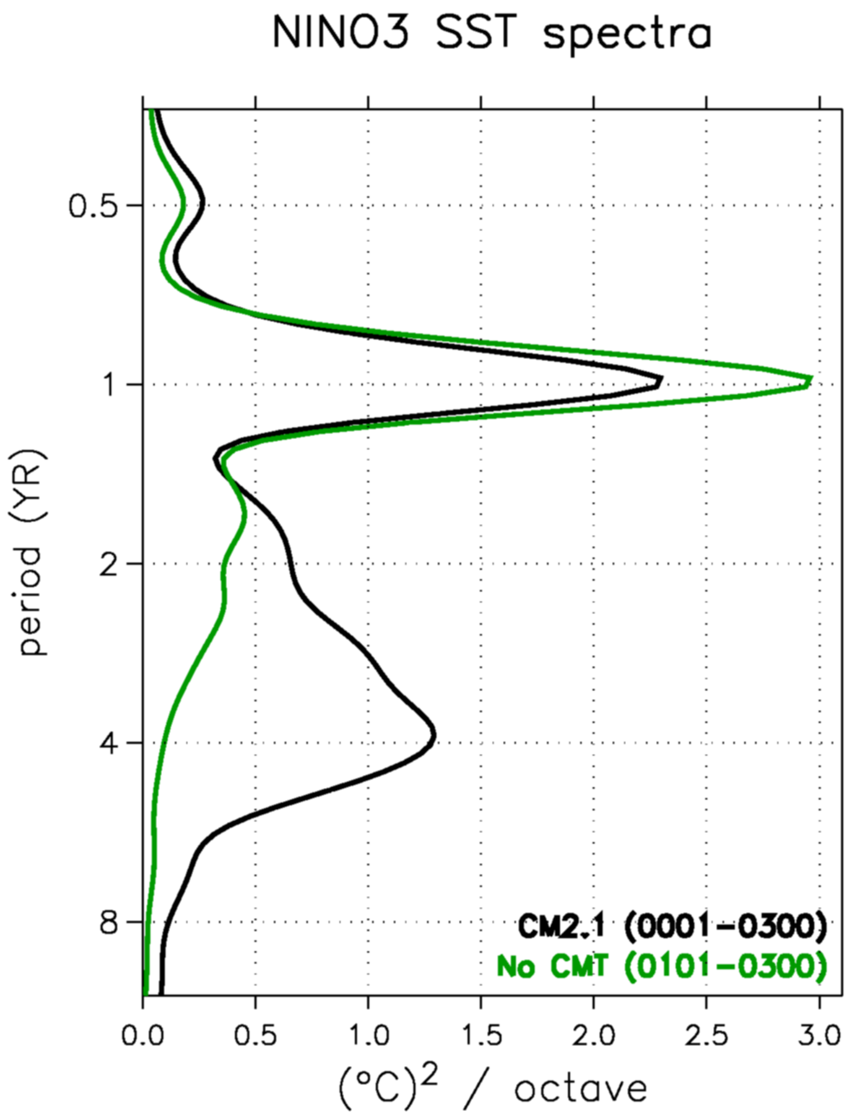


$T_p = 3.05 + (L_y\text{-}14°)/9.6° + (C\text{-}184°)/30°$

$\text{corr}(T, T_p) = 0.82 \pm 0.15$

Convective Momentum Transport (CMT)



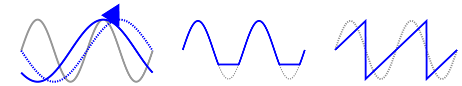


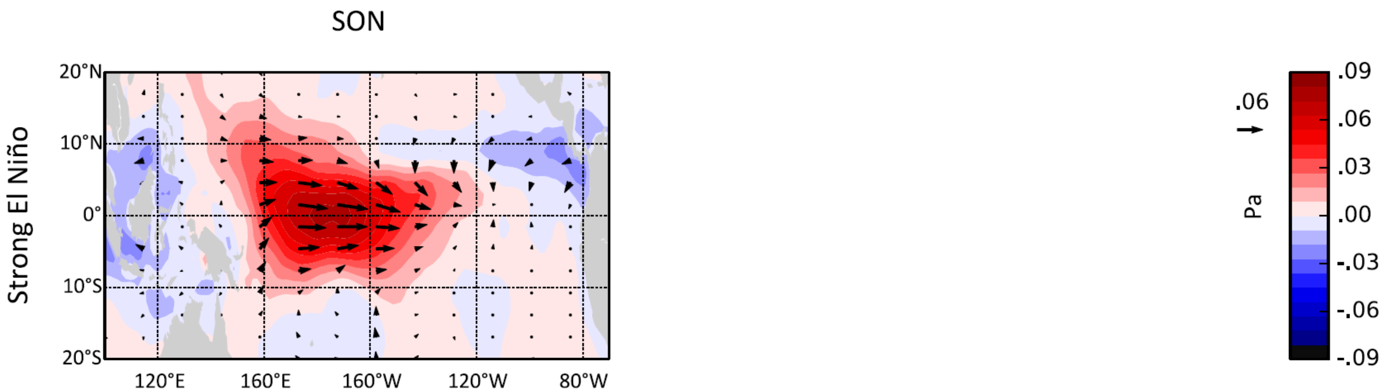
Broader westerly anomalies → longer ENSO period

Wittenberg et al. (2006); Kim et al. (2008); Neale et al. (2008)

Seasonal Interactions

Seasonal southward wind shift





Harrison & Vecchi (1999)

Vecchi & Harrison (2003, 2006)

Lengaigne et al. (2006)

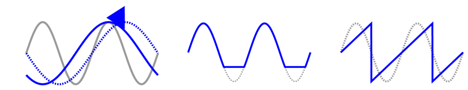
McGregor et al. (2012, 2013)

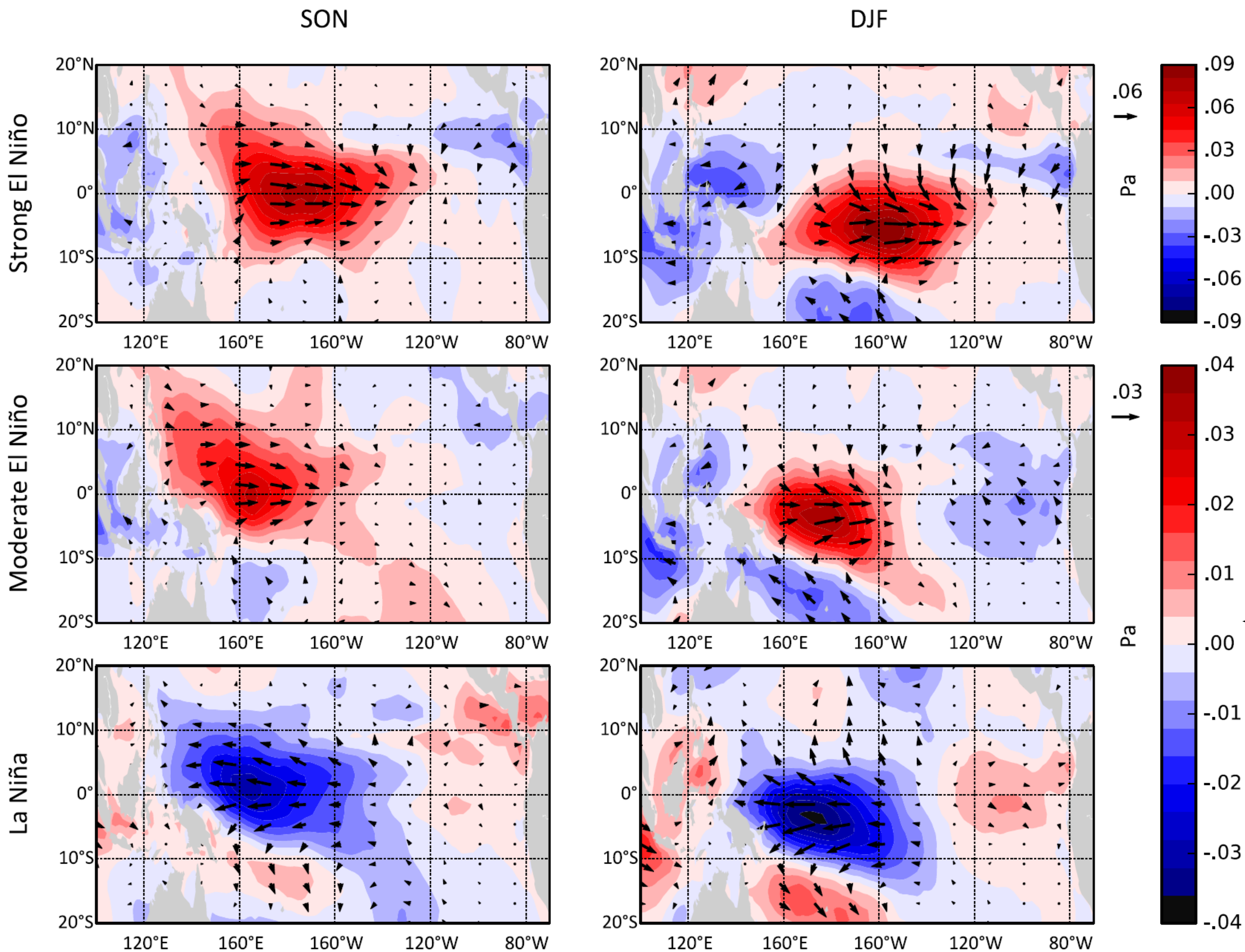
← ***Abellán & McGregor (2016)***

Abellán et al. (2017)

Helps **terminate** El Niño (especially strong ones), **synchronize** ENSO to the annual cycle, and **shorten EN relative to LN**. Underestimated by most CGCMs.

Seasonal southward wind shift





Harrison & Vecchi (1999)

Vecchi & Harrison (2003, 2006)

Lengaigne et al. (2006)

McGregor et al. (2012, 2013)

Abellán & McGregor (2016)

Abellán et al. (2017)

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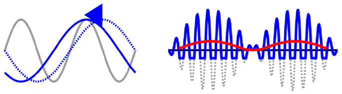


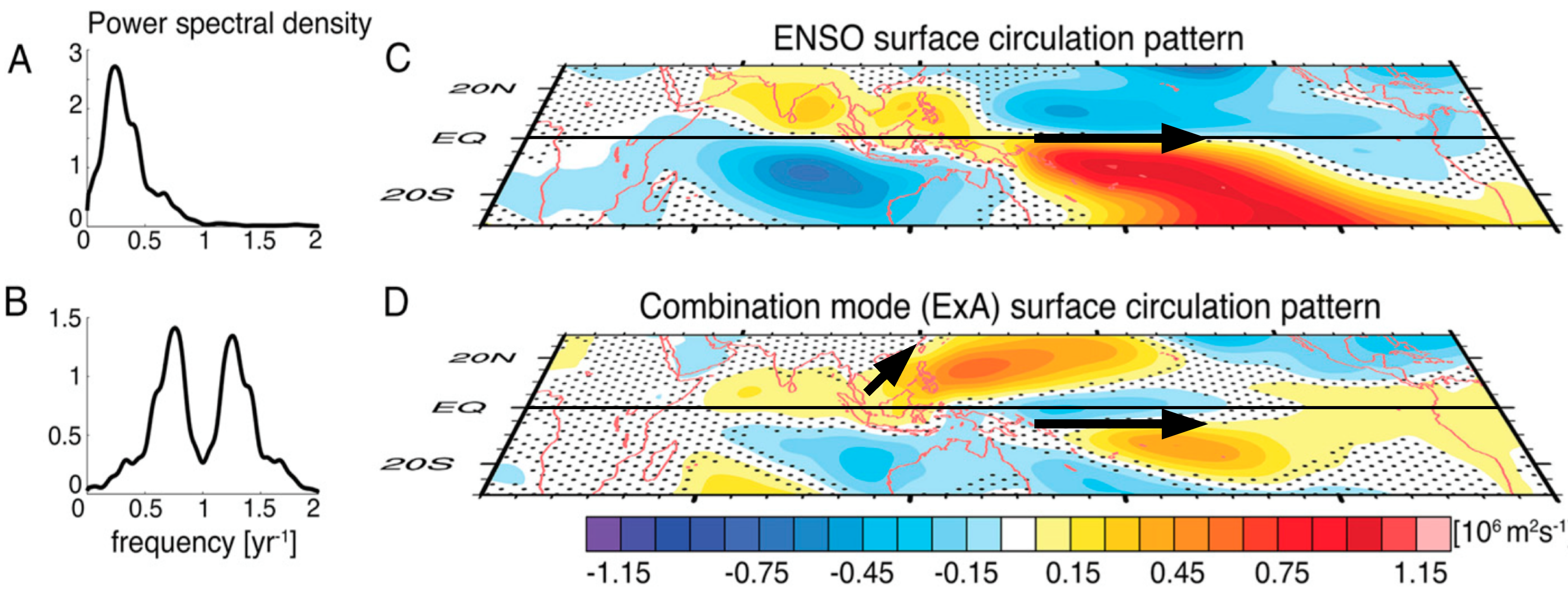
Combination modes (C-modes)

Stuecker et al.
(PNAS 2015)

trig identity!

$$2 * \cos(\omega_A * t) * \cos(\omega_E * t) = \cos((\omega_A+\omega_E) * t) + \cos((\omega_A-\omega_E) * t)$$

seasonality (1 yr)	ENSO (2-4 yr)	high-freq C-mode (6-9 mo)	low-freq C-mode (15-18 mo)



C-modes **modulate the East Asian monsoon**,
accelerate El Niño termination (shift wind anomaly southward)

Strong El Niño SSTAs terminate later/eastward

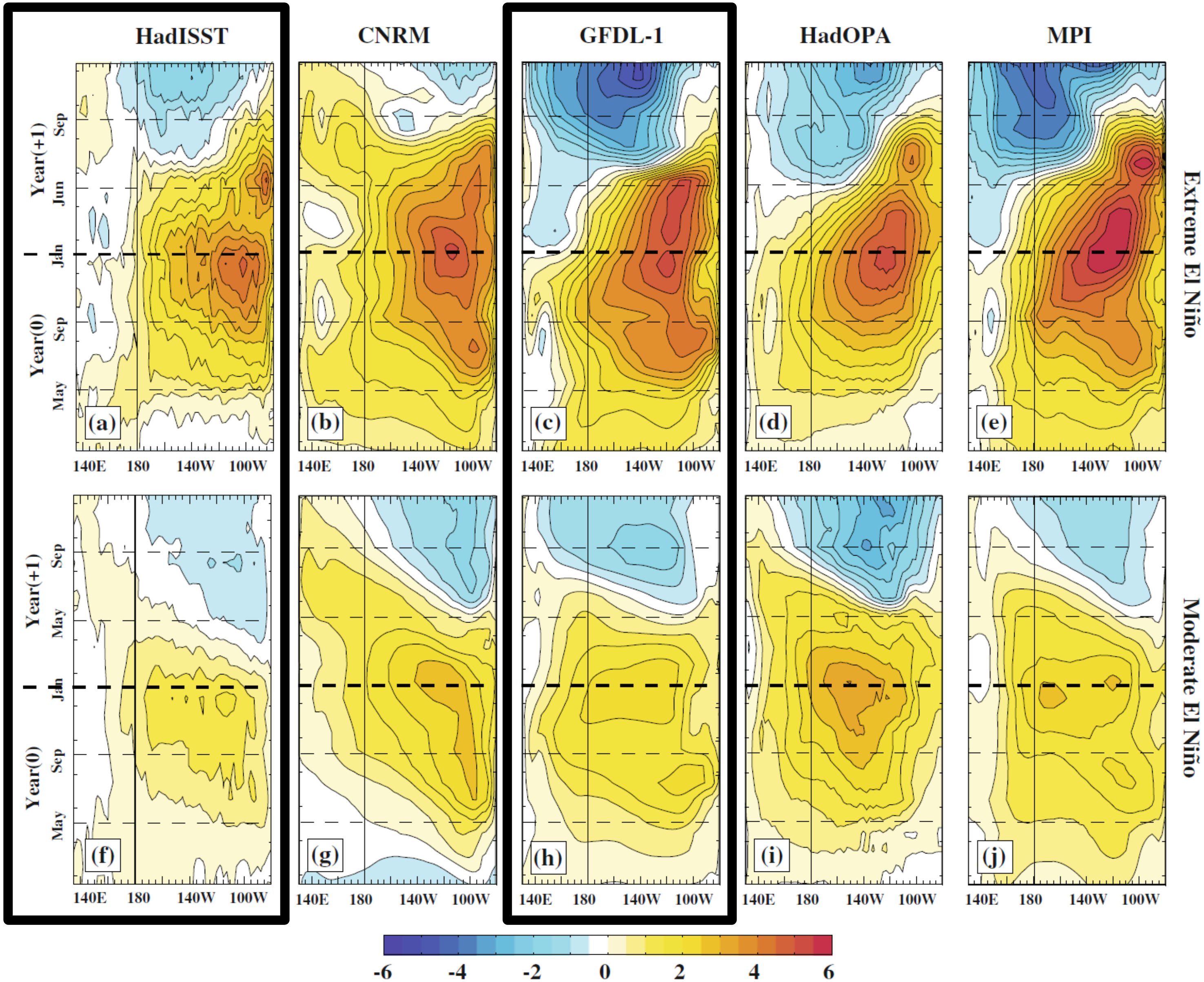
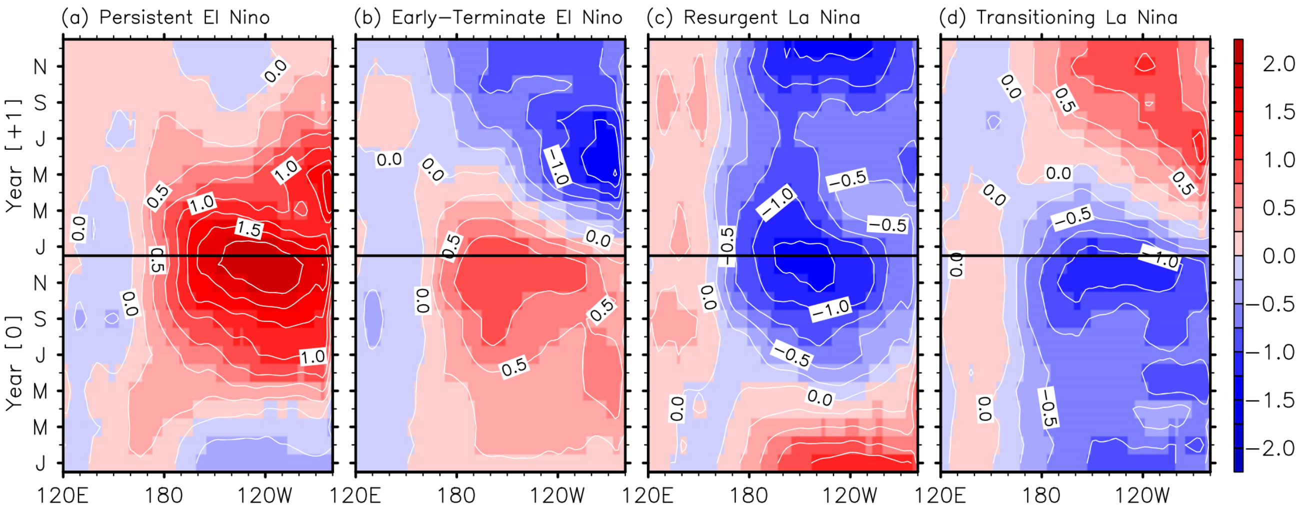


Fig. 3 Time–longitude evolution of the equatorial Pacific SSTA for (**a**–**e**) extreme and (**f**–**j**) moderate El Niño composites for HadISST dataset and four climate models (CNRM, MPI, GFDL-1 and HADOPA)

Lengaigne & Vecchi (CD 2010)

Seasonal timing and ENSO impacts

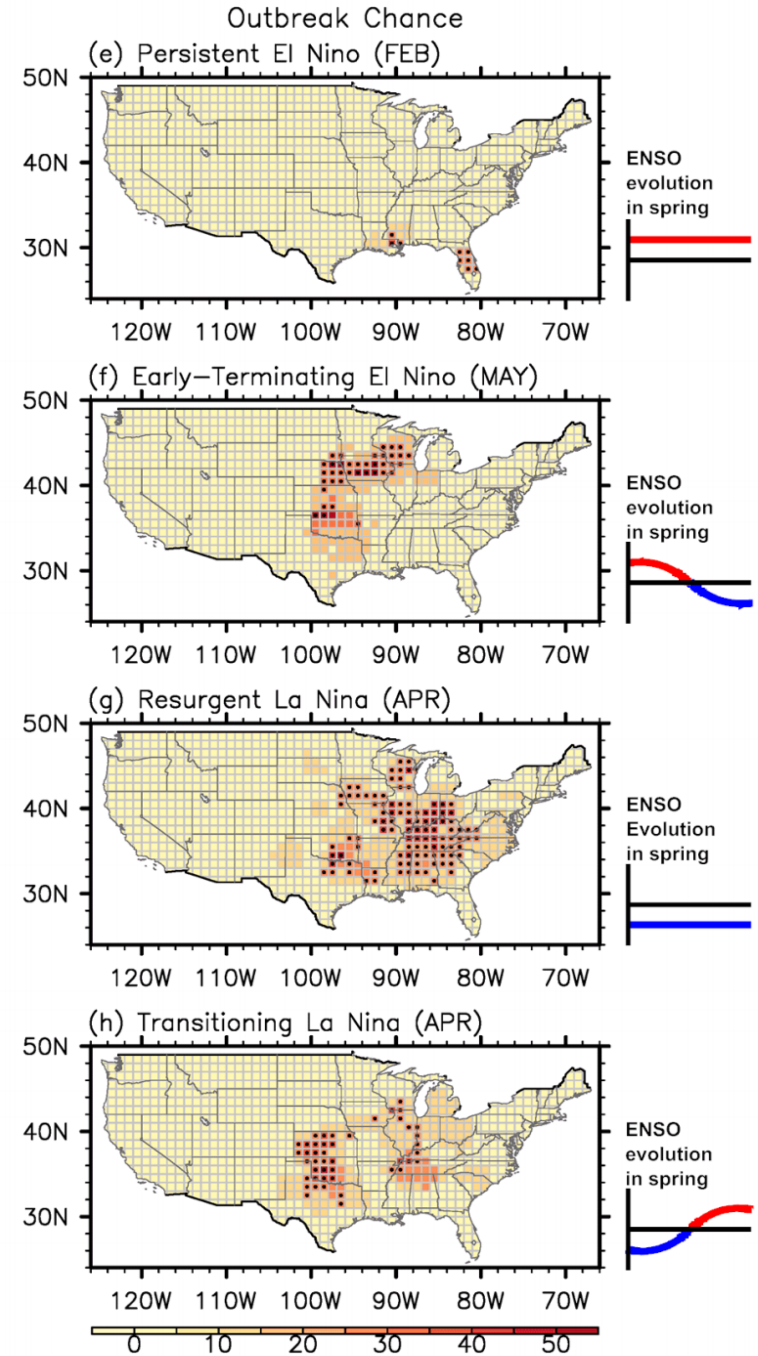
Key archetypes of ENSO evolution



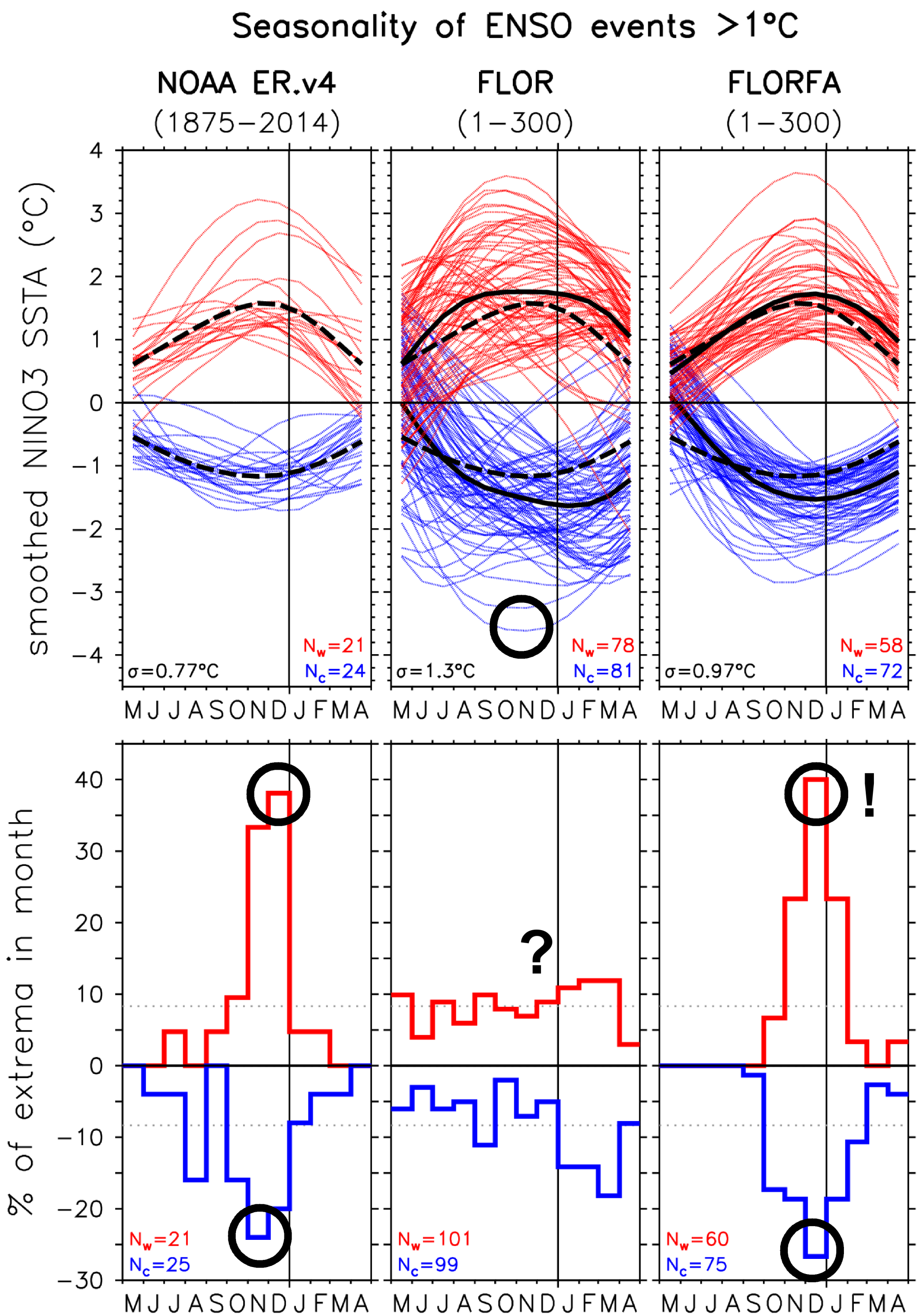
ENSO events show diverse temporal behavior in boreal spring – e.g. **persisting, terminating early, resurging, or transitioning**.

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

Lee et al. (GRL 2014; ERL 2016)



Seasonal synchronization of ENSO



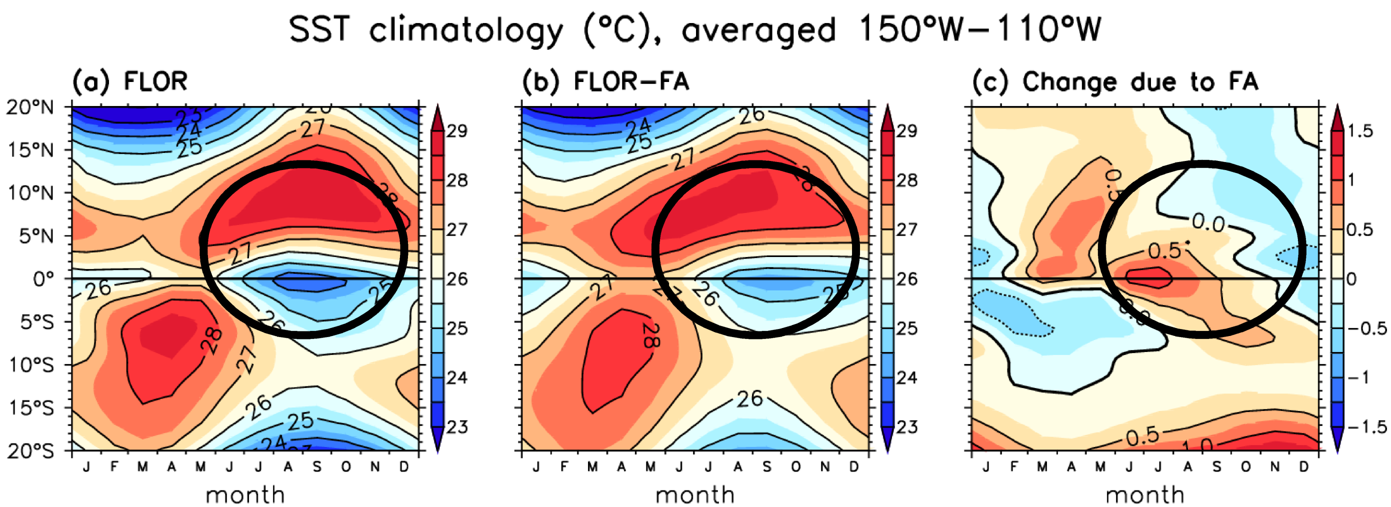
Observed events (especially strong ones) tend to peak during Oct-Dec.

GFDL-FLOR CGCM's events show little seasonal synchrony, except for the strongest events.

And its cold events are far too strong.

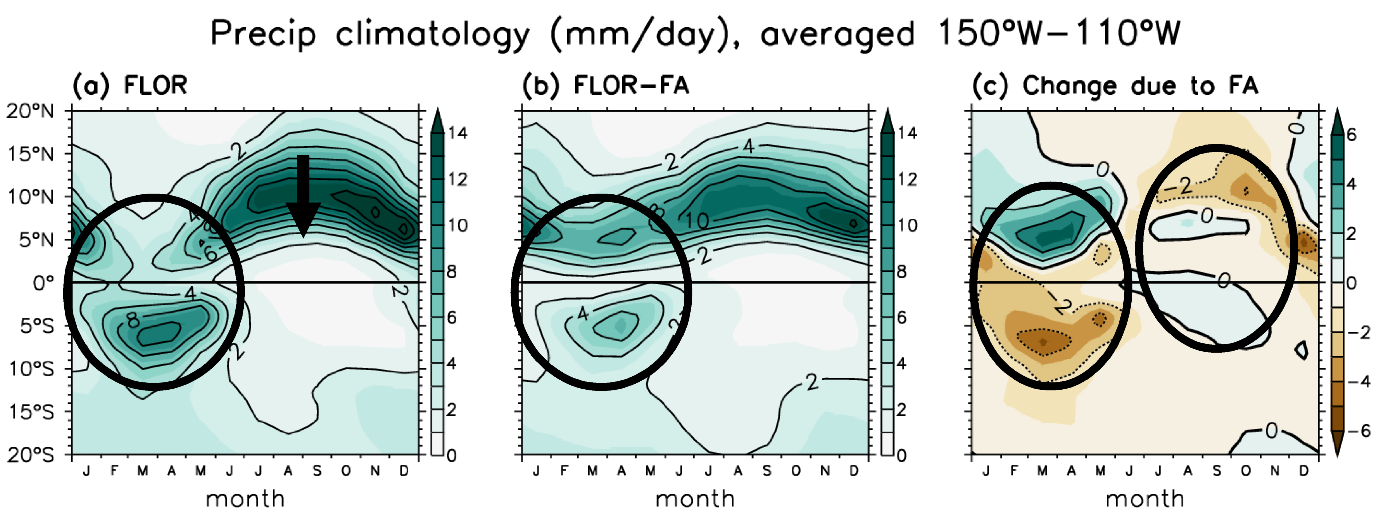
Flux-adjusting SST & wind stress **synchronizes ENSO events** to the end of the calendar year**,** and **greatly improves the positive skewness** of NINO3 SSTAs.

Seasonal cycle of east Pacific SST & rainfall



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

Flux adjustment weakens this dT/dy, aiding equatorial shifts of the ITCZ and extending ENSO through to Dec.



FA weakens equatorial deep convection during Dec-Jun, but shifts the ITCZ equatorward during Jul-Nov.

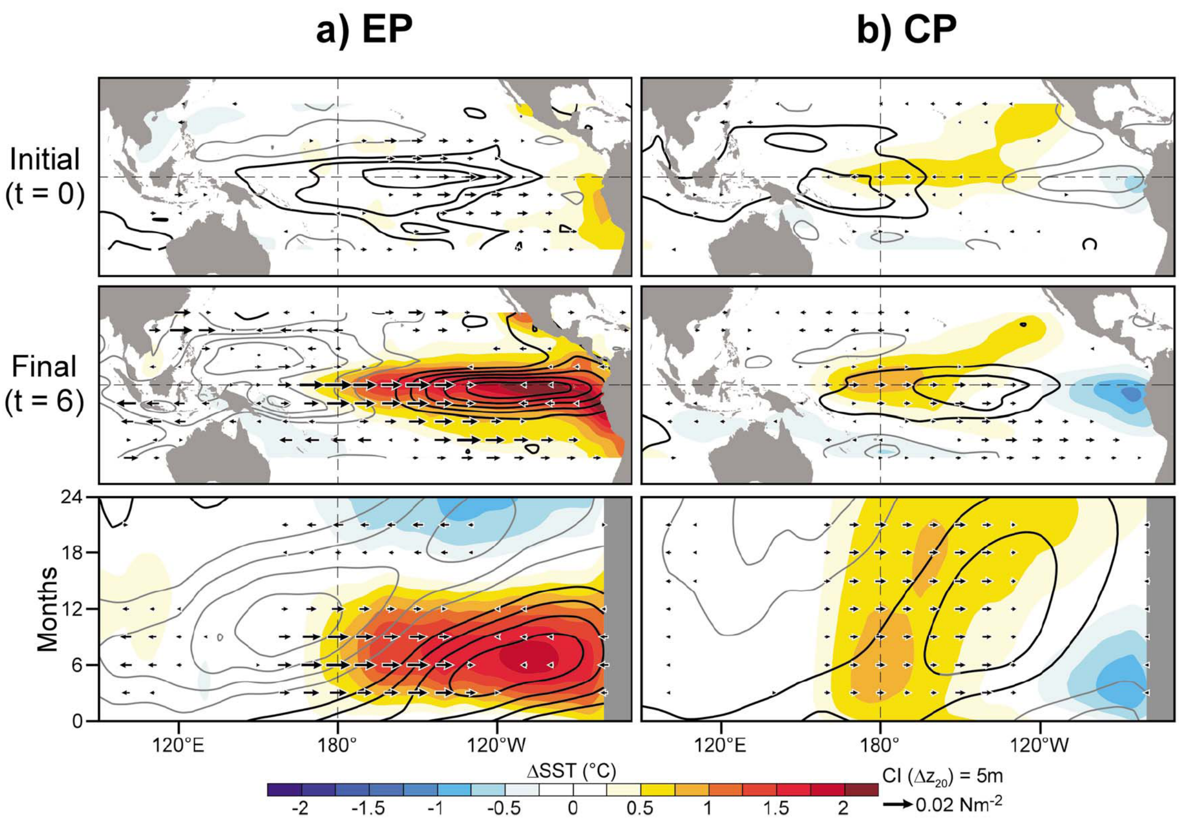
***FA sensitizes the northeast Pacific ITCZ to equatorial SSTAs in Jul-Nov**, seasonalizing the Bjerknes feedback and **synchronizing ENSO** to the end of the calendar year.*

Intraseasonal Interactions

Transient growth in non-normal systems

d**x**/dt = **Lx** + noise

where **L** is *stable*, but *not self-adjoint*
→ eigenmodes not orthogonal

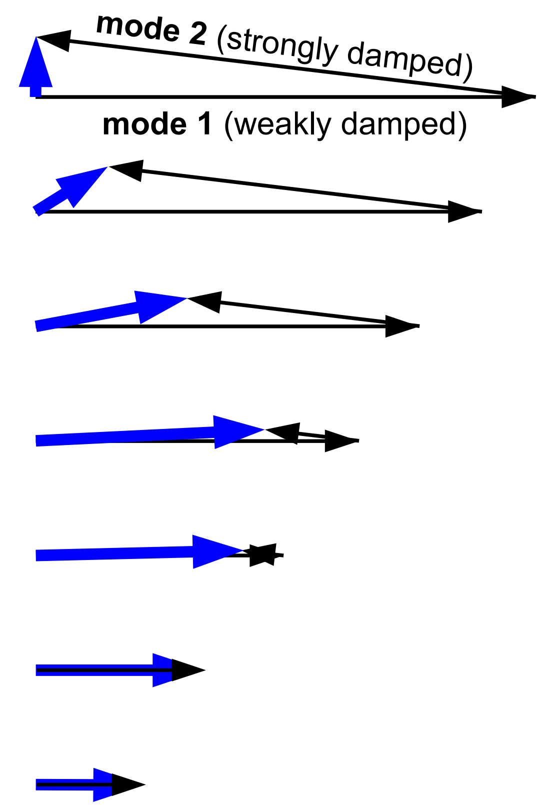


Newman et al. (2011)

Strong initial cancellation.

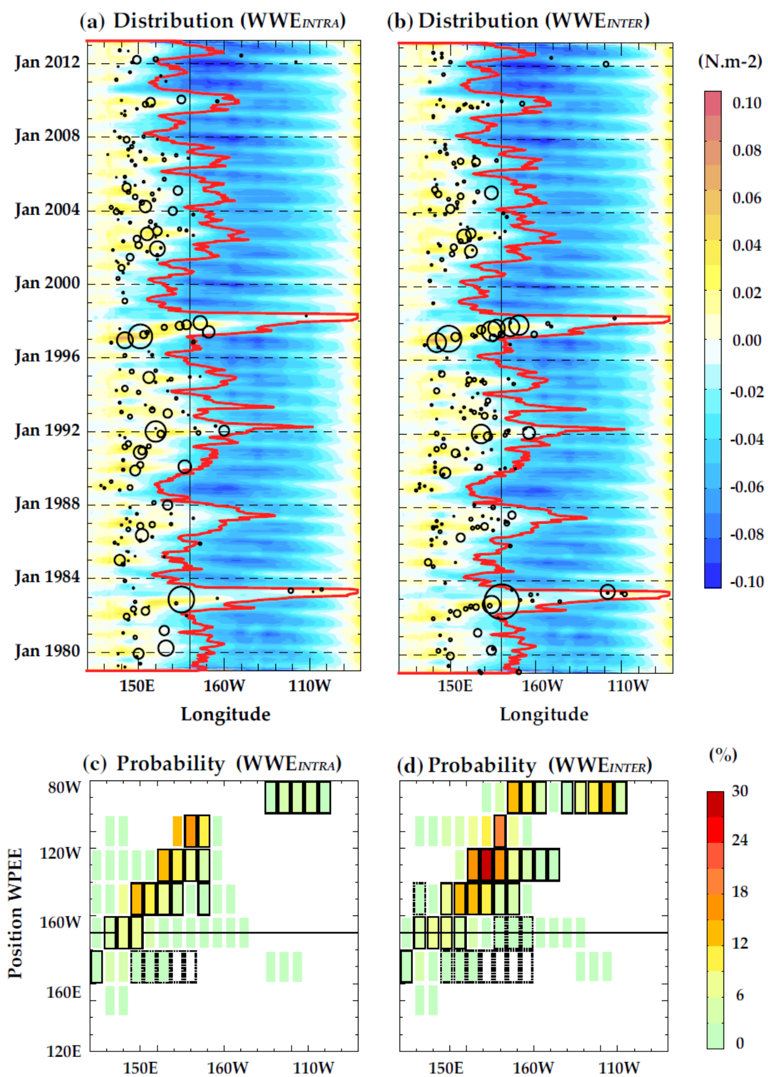
Much less cancellation.

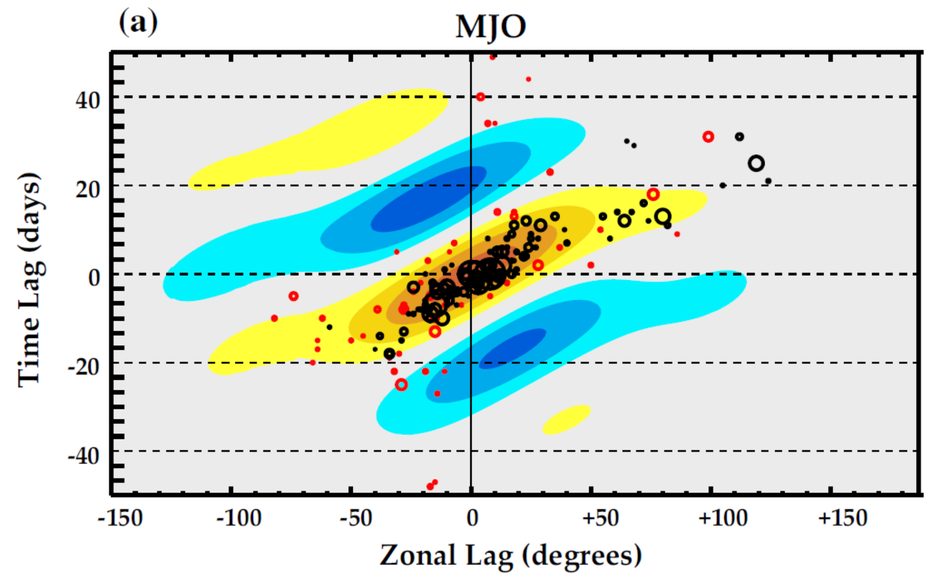
Only one mode remains.



Introduces **new time scales** which are continually excited by stochastic forcing.

WWE modulation & rectification





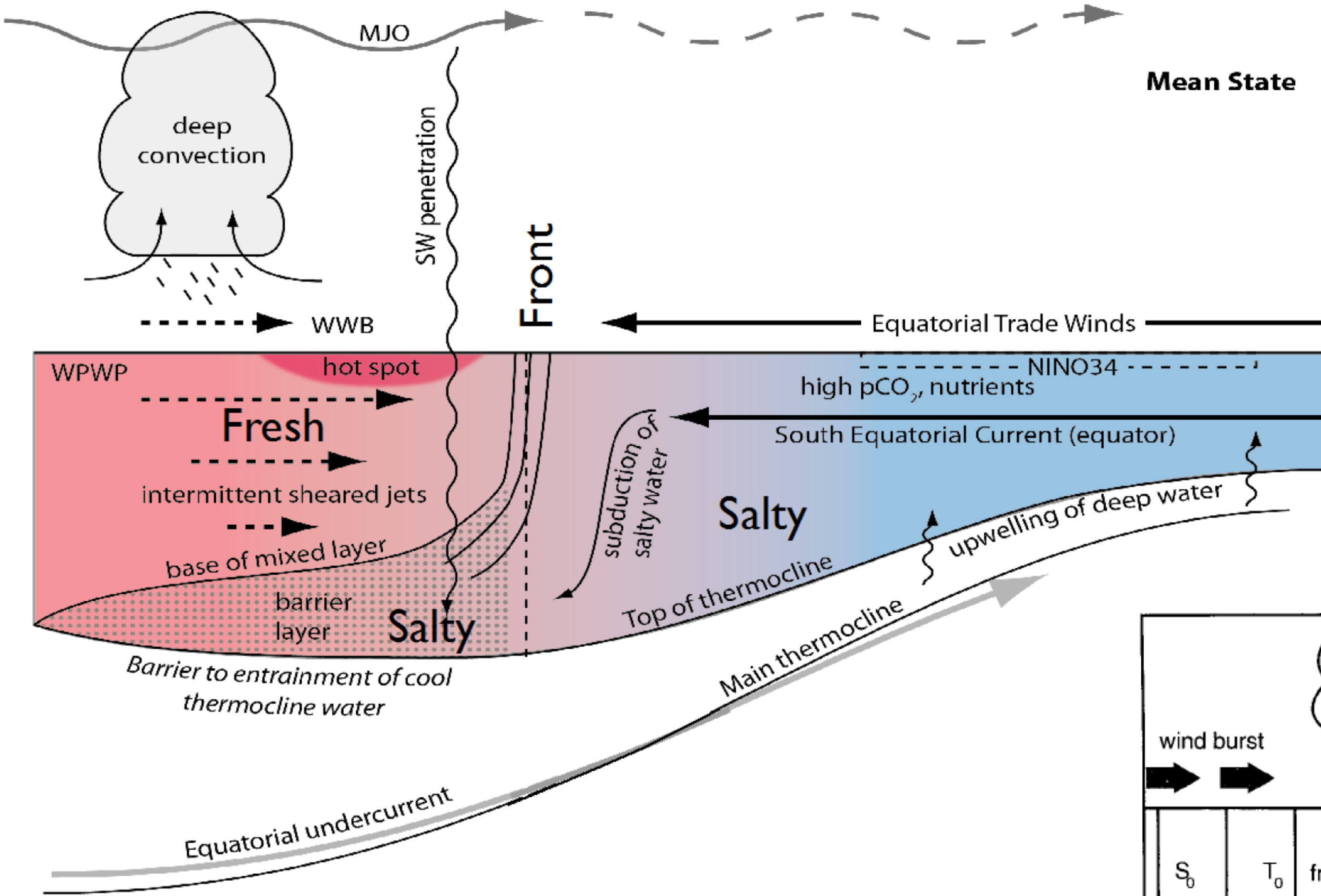
Puy et al. (2016)

Gebbie et al. (2007); Thual et al. (2016); Levine et al. (2016); Levine & Jin (2017); Hayashi & Watanabe (2017)

"multiplicative noise"

WWEs spread east with the warm pool; modulated by MJO.
Contribute to EN/LN **asymmetry** & seasonality.
Make strong ENs hard to predict, especially through boreal spring.

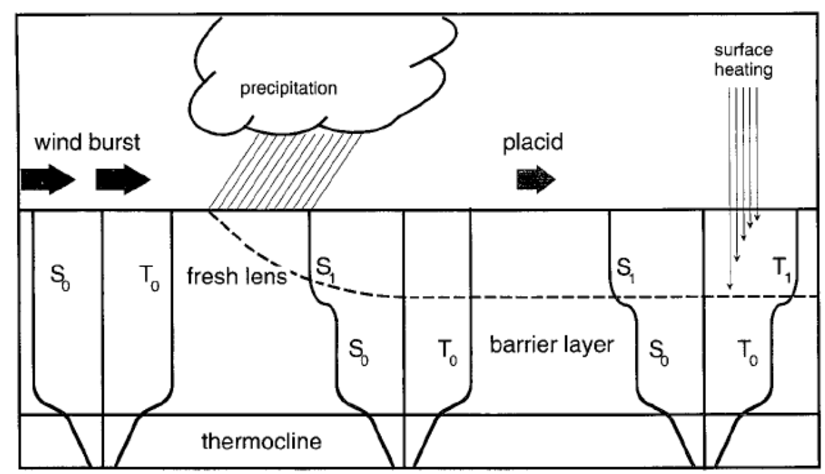
Salinity barrier layers



Maes et al. 2005;
Maes & Belamari (2011)
Zhu et al. (2014)

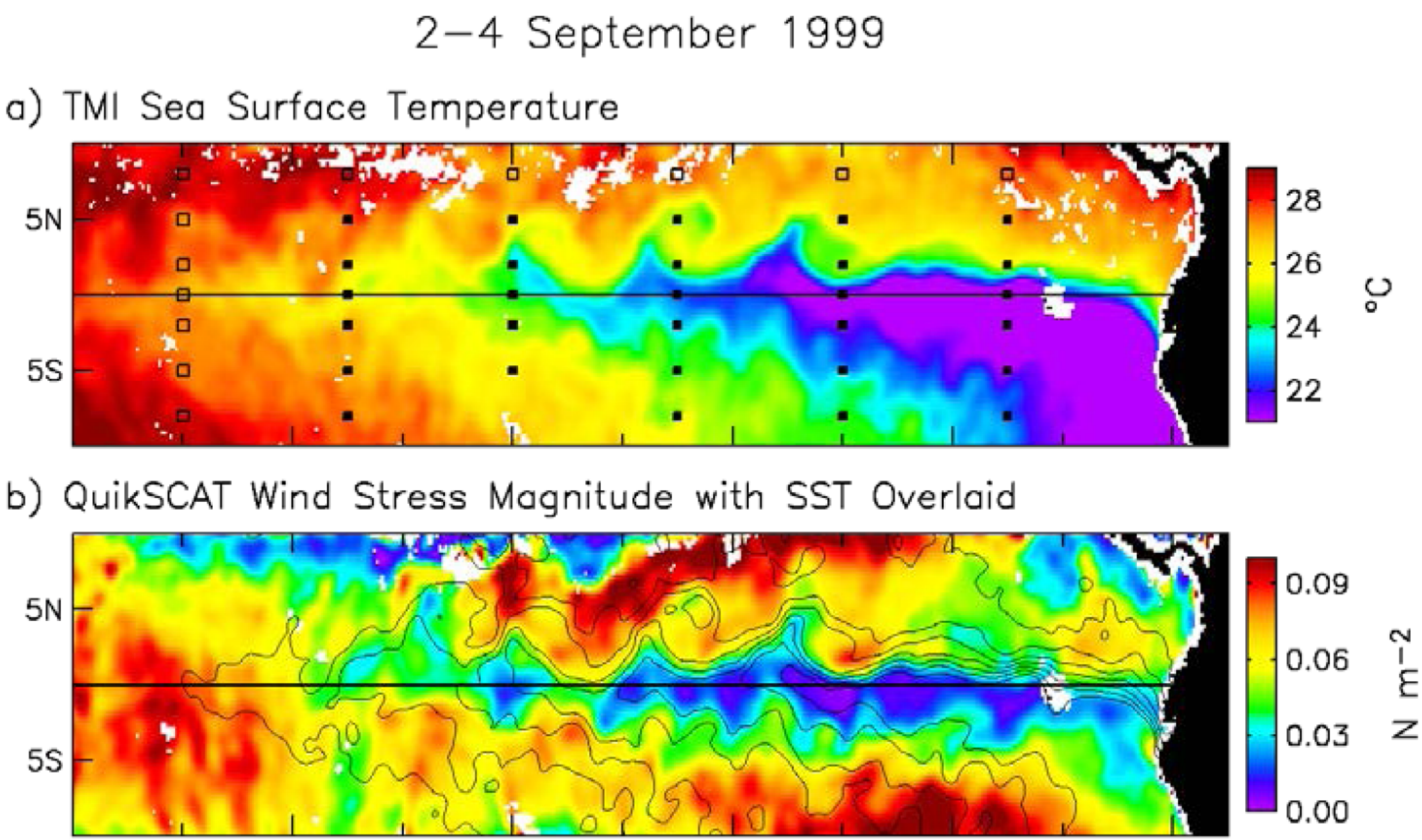
TPOS/Brown et al. (2015)

Anderson et al. (1996)



Heavy rain shoals the mixed layer, boosts coupling/noise at EN onset.
Contributes to EN/LN asymmetry.

Tropical Instability Waves (TIWs)



Chelton et al. (2001)

Jochum et al. (2004, 2007)

Menkes et al. (2006)

Imada & Kimoto (2012)

Graham (2014)

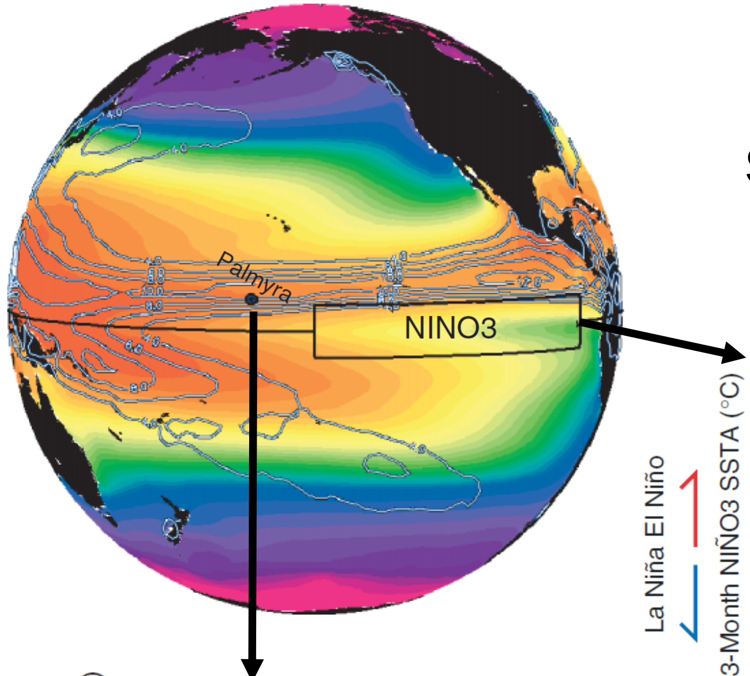
Holmes & Thomas (2015)

Zhang (2016)

TIWs draw heat from atmosphere, stir heat equatorward (esp. during LN)
→ boost EN/LN **asymmetry**. Induce **wind stress noise**.
TIW heat transport & entrainment **stratify** the equator → affect ENSO.

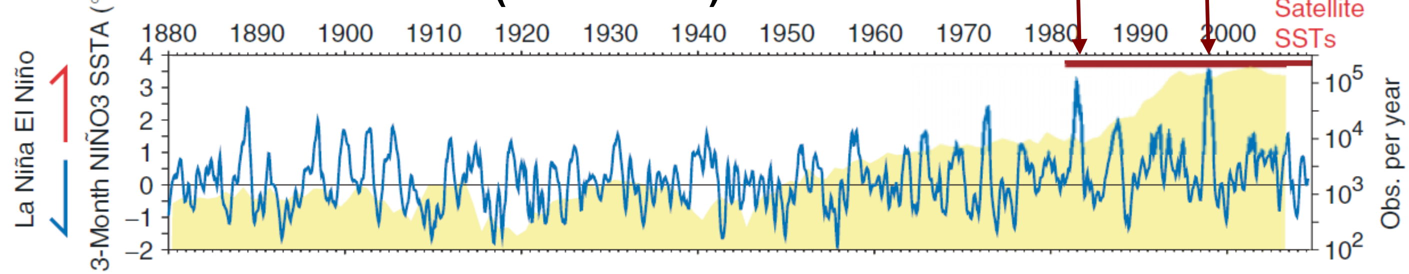
Intrinsic Modulation of ENSO

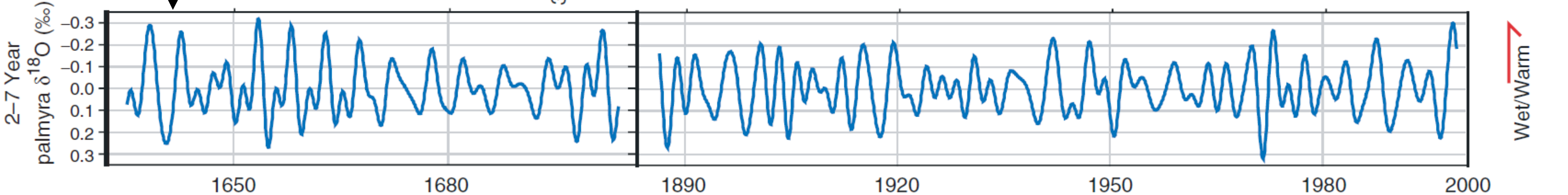
Both historical & paleo records suggest past modulation of ENSO



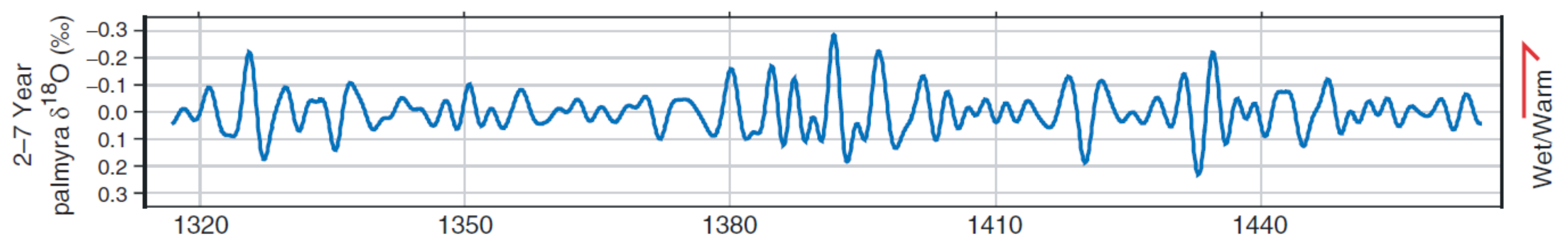
Vecchi & Wittenberg (WIREsCC 2010)

Historical SSTA (ERSST.v3)

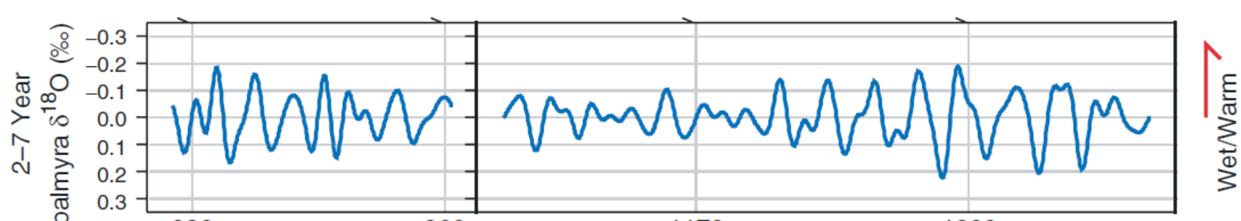




Palmyra corals (Cobb et al., Nature 2003)

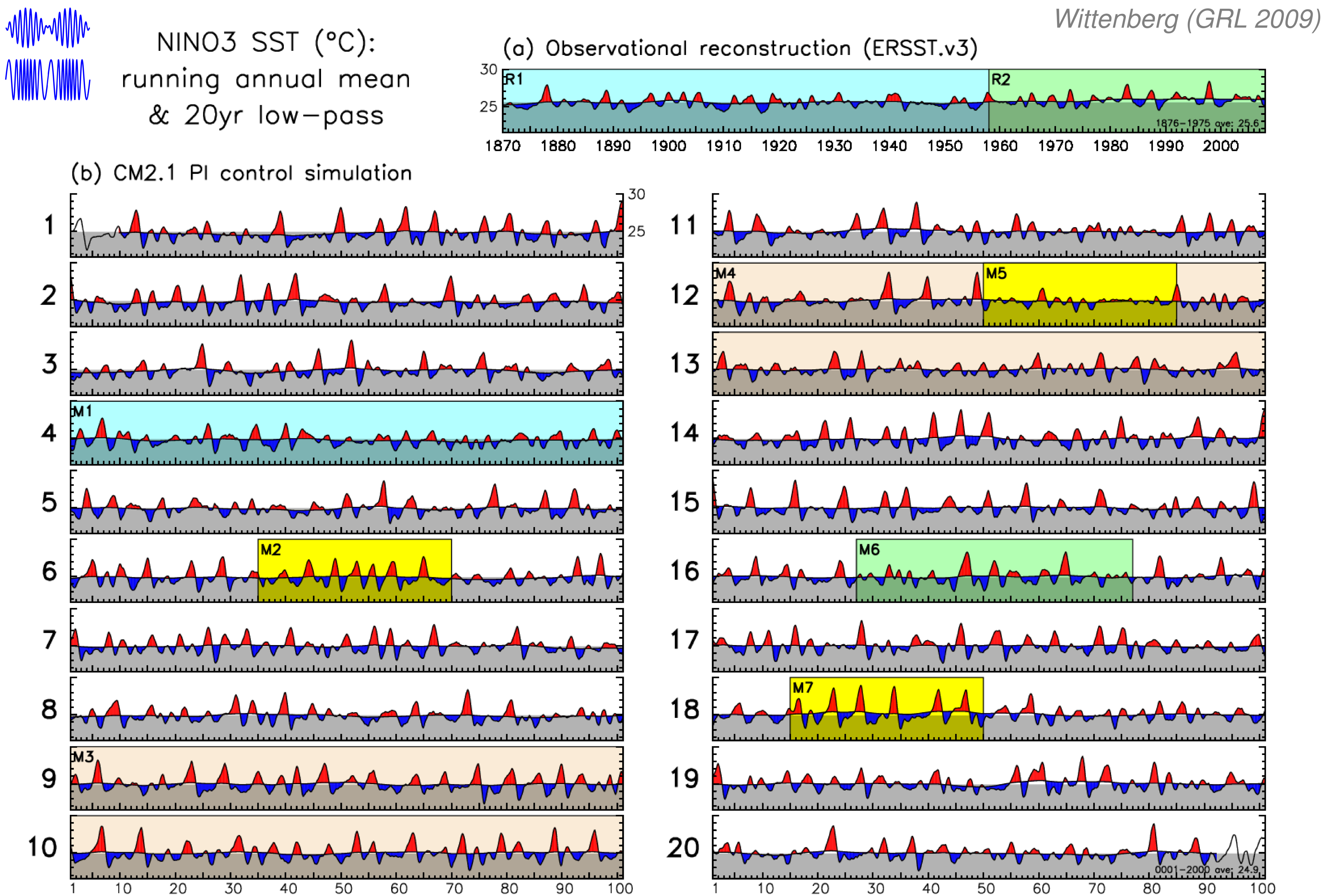


Multiproxy paleo reconstructions:
see Kim Cobb's talk

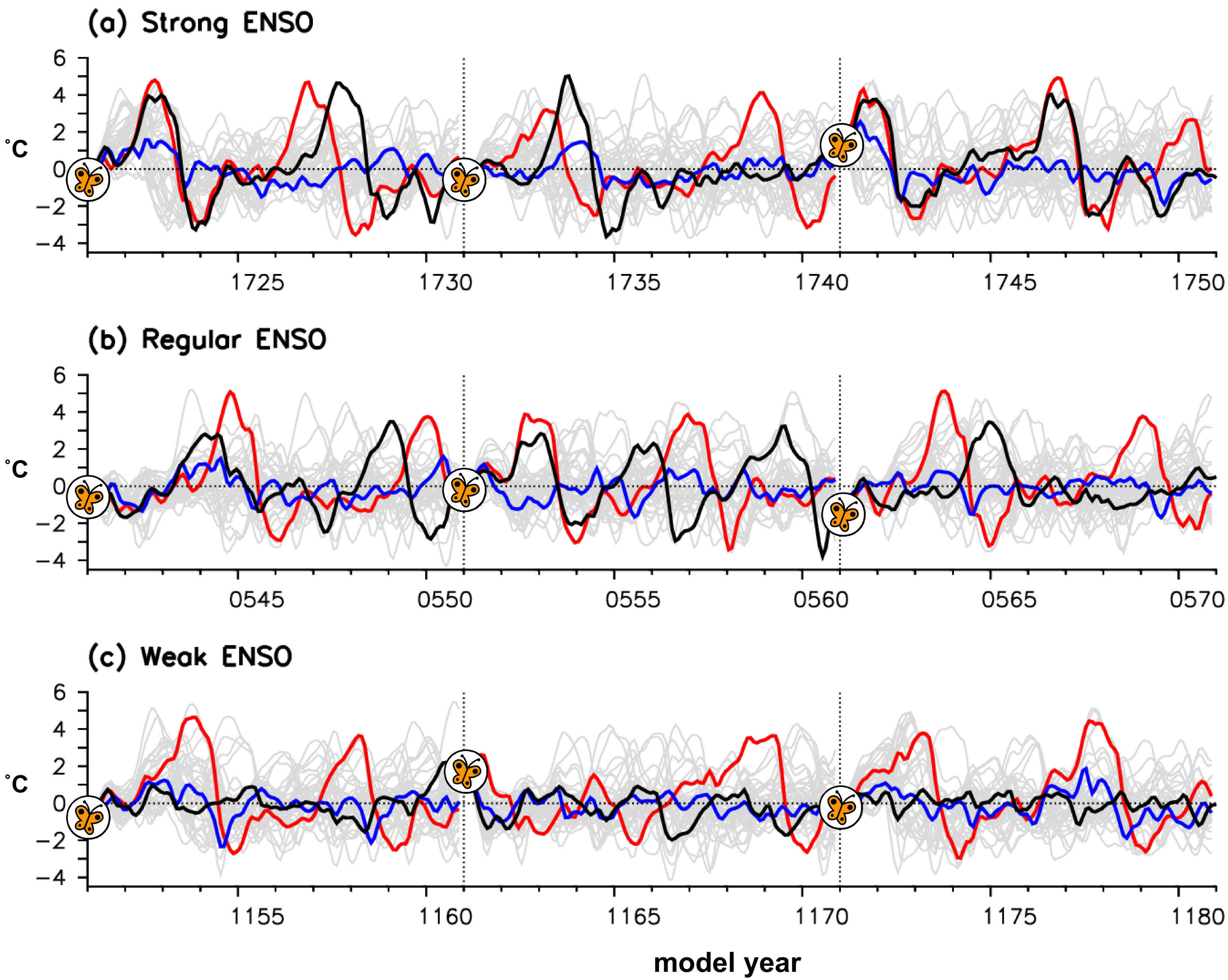


ENSO has waxed & waned for millennia. How does it **interact** with other time scales? What causes its **spectrum**, **skewness**, **irregularity**, and **diversity**? Is it **changing**?

ENSO modulation in a 2000-year control simulation



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:

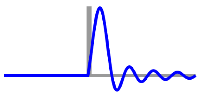
weakest,

strongest,

all 40 members

Wittenberg et al. (J. Climate, 2014)

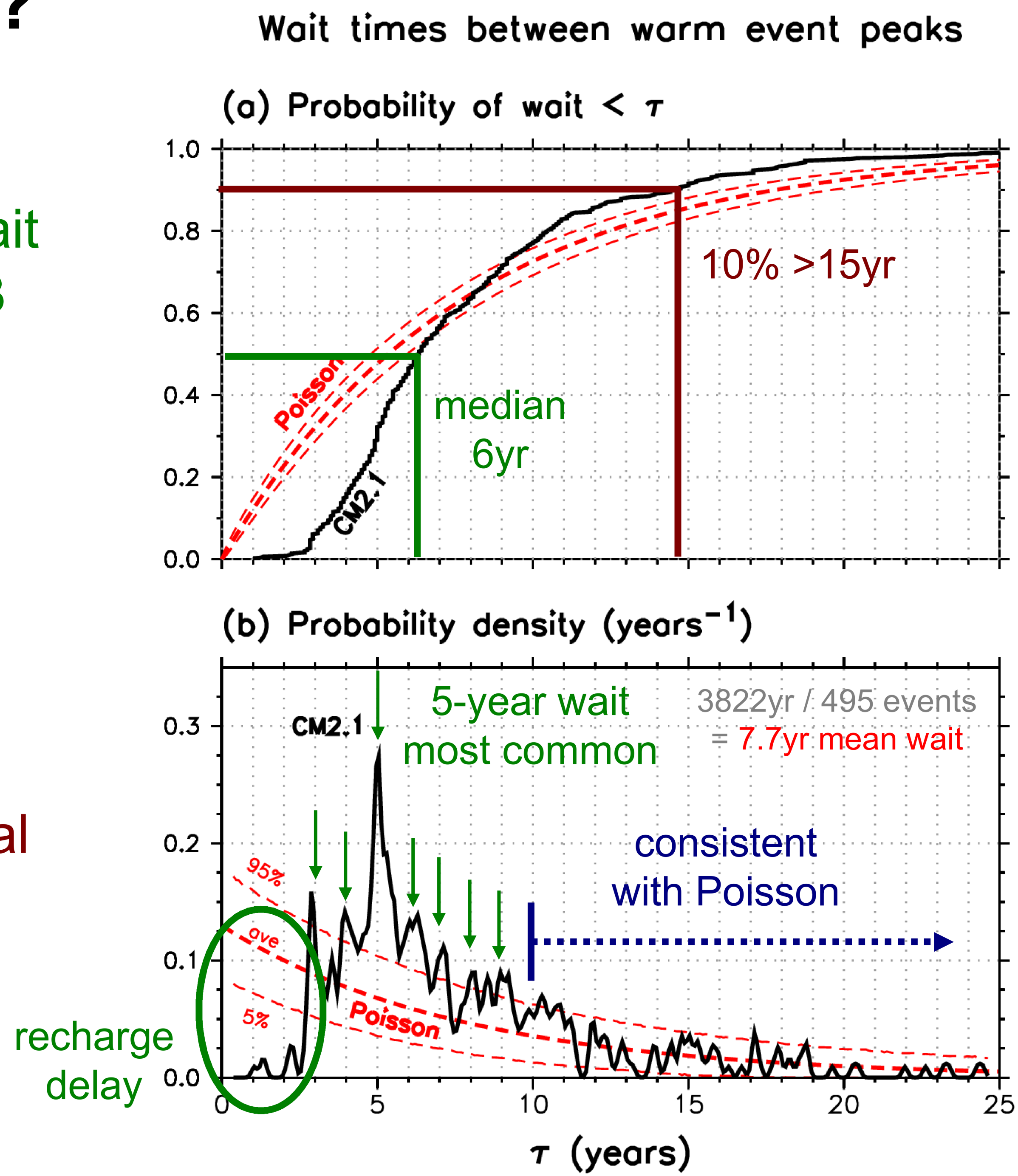
Long-term memory?



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

But beyond 10 years?

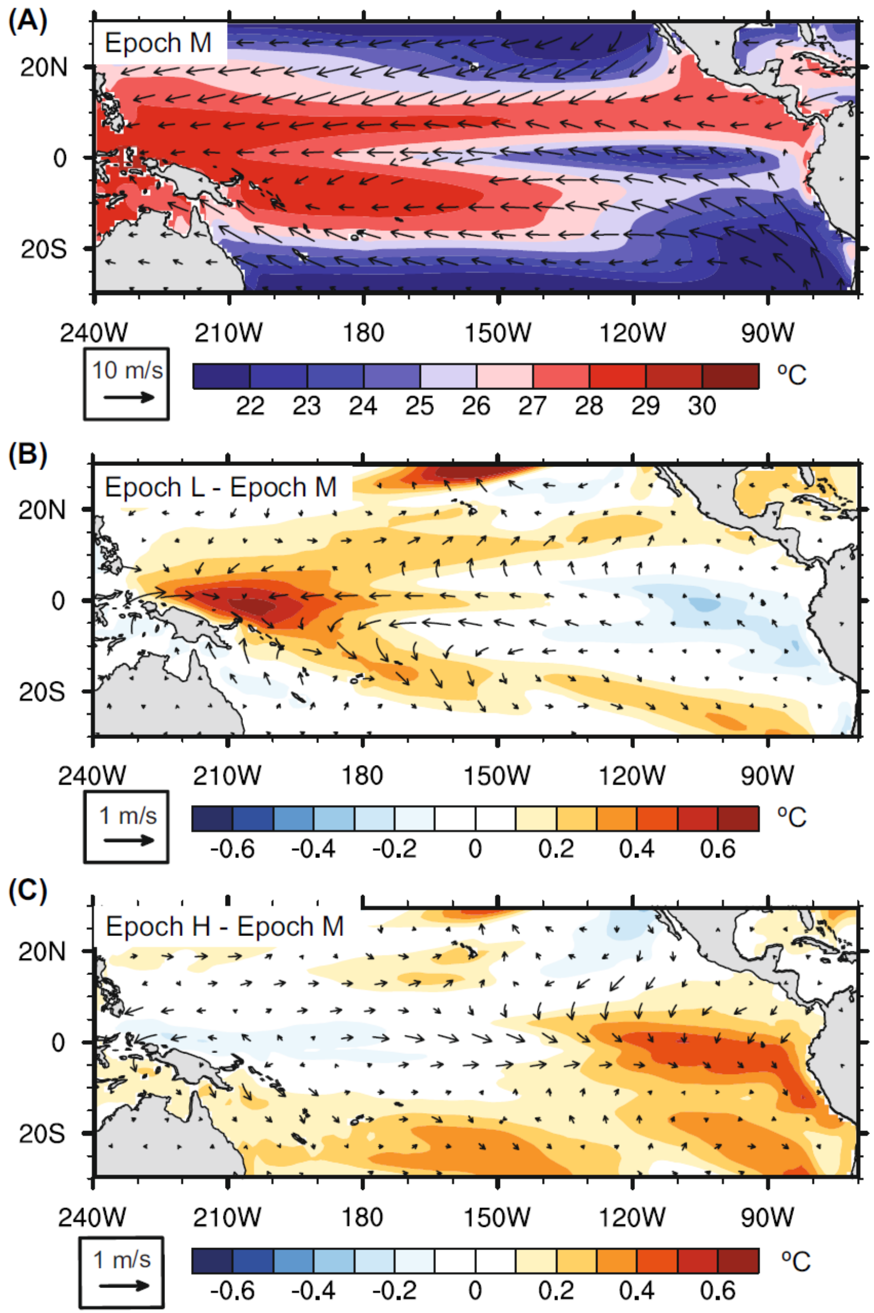
Even a *purely* memoryless ENSO would give occasional waits of 20 years or more, as seen in CM2.1.



Wittenberg (GRL 2009)

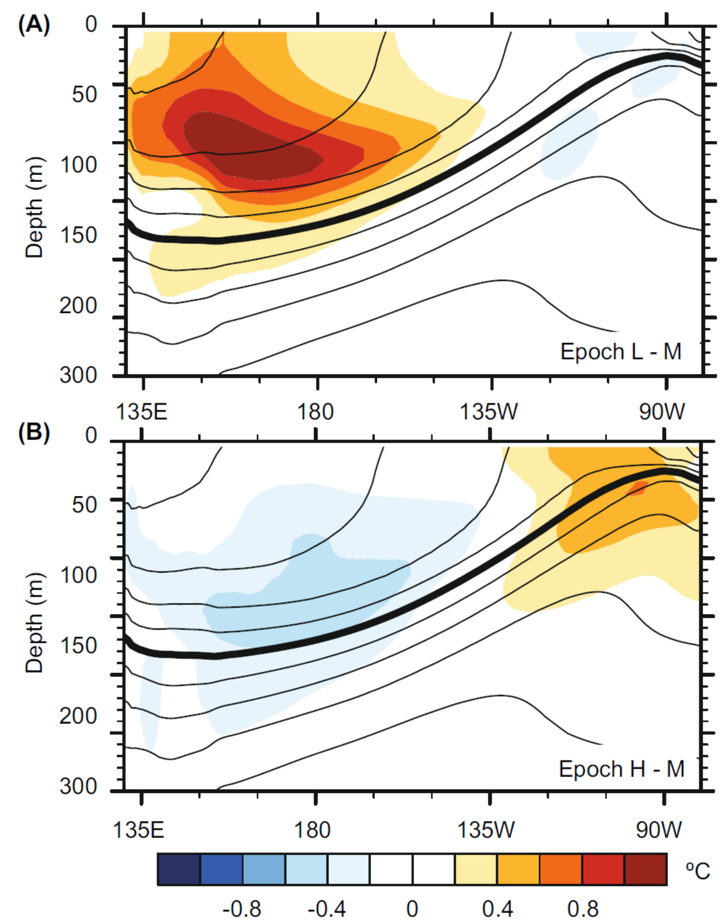
Decadal Interactions

ENSO rectification

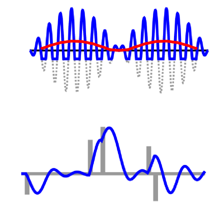


Atwood et al. (Climate Dyn., 2017)

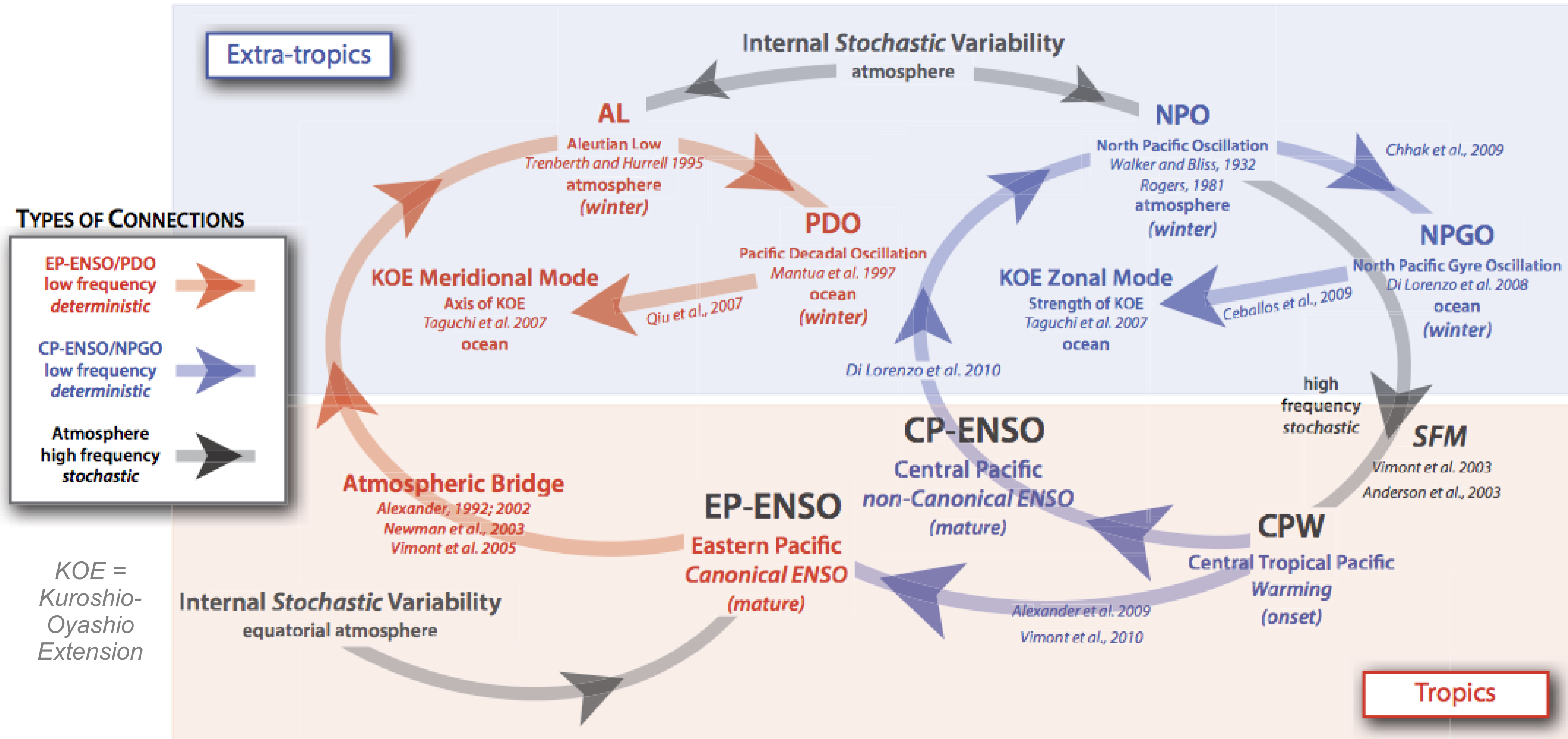
also Ogata et al. (2013),
Schopf & Burgman (2006),
Burgman et al. (2008),



Pacific decadal interactions with ENSO

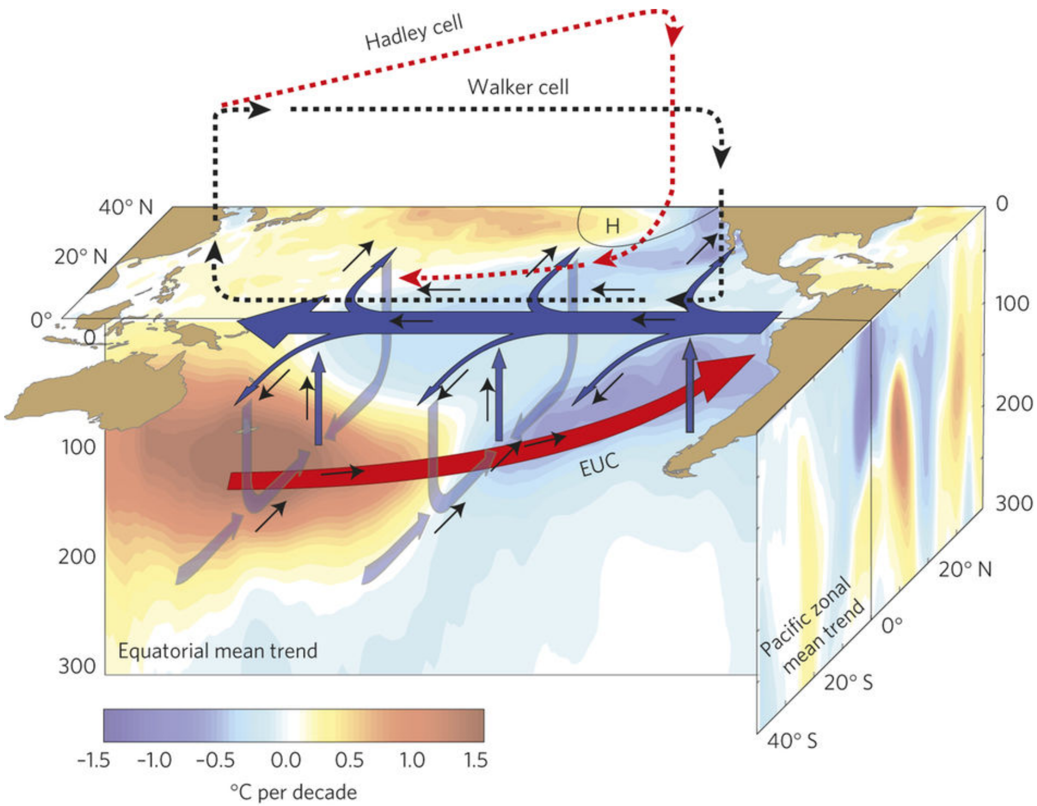


Schematic by Emanuele Di Lorenzo

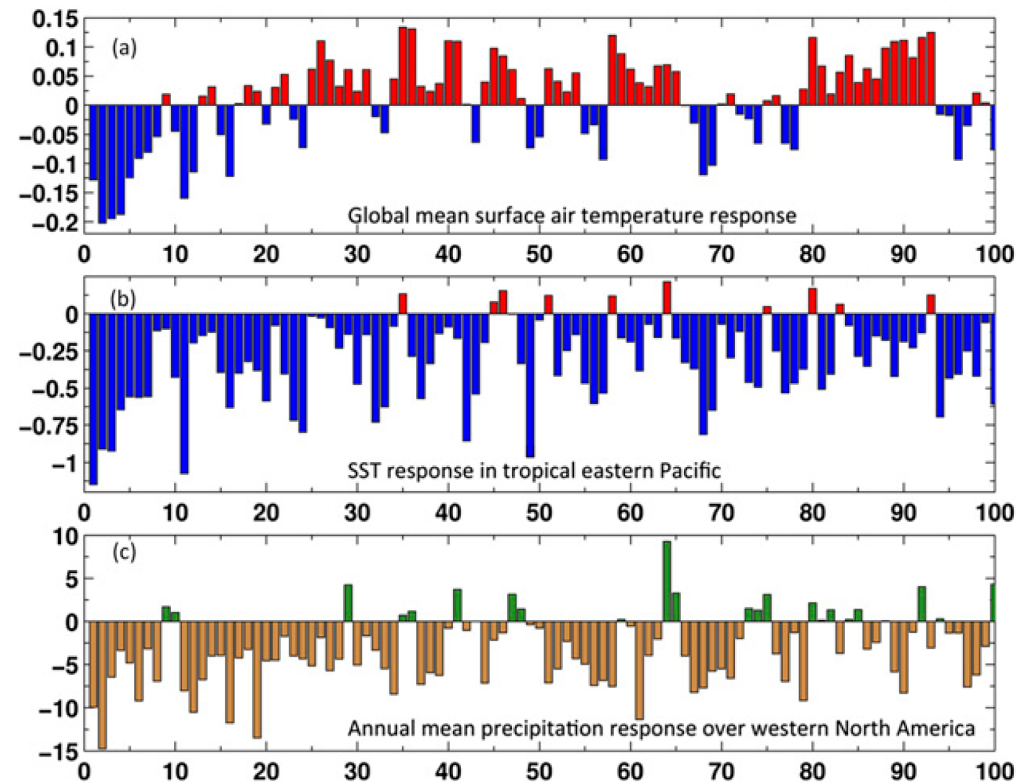


PDO & NPGO may interact with ENSO flavors.
Are these open or closed loops?
To what extent do these links imply predictability?

Pacific trends affect global climate



England et al. (2014)

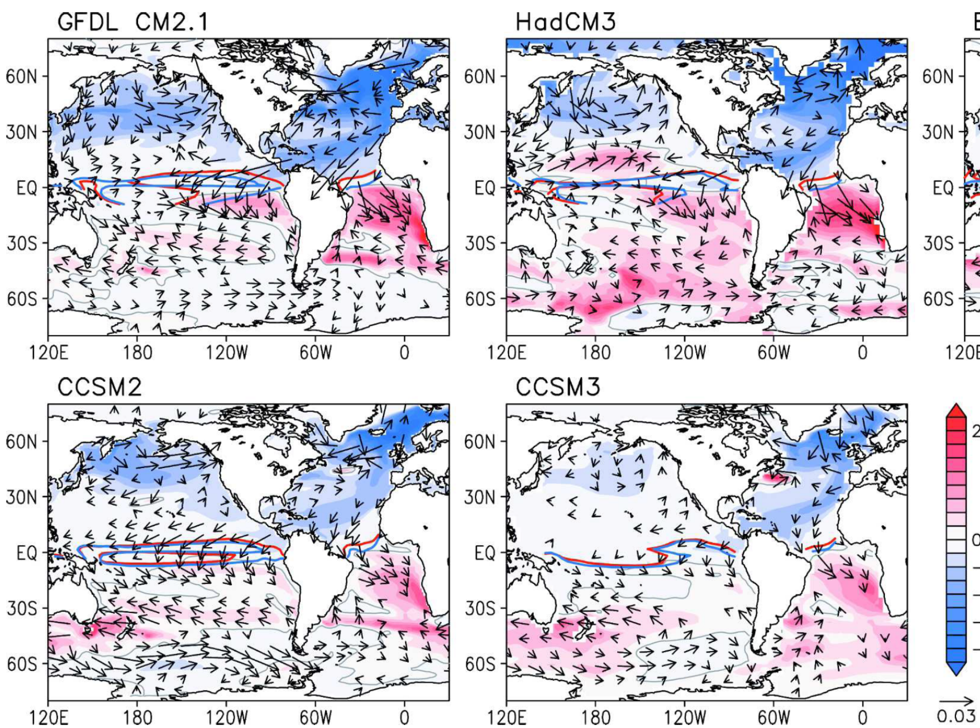


Delworth et al. (2015)

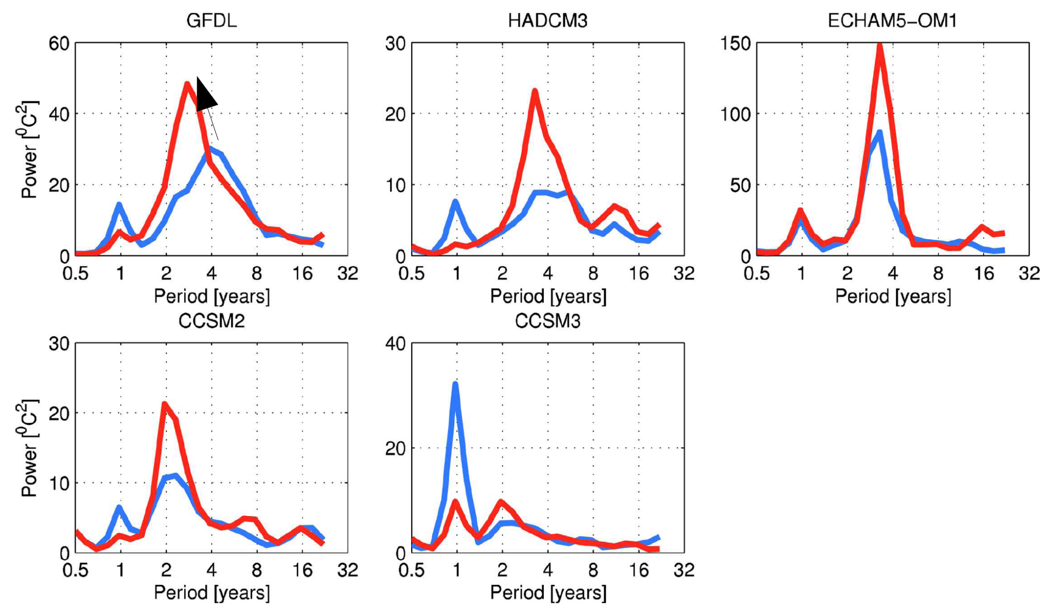
Stronger trade winds can drive transient global cooling (hiatus), greater ocean heat uptake, drought over the western U.S.

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

AMOC can affect annual cycle & ENSO



Timmermann et al. (2007)

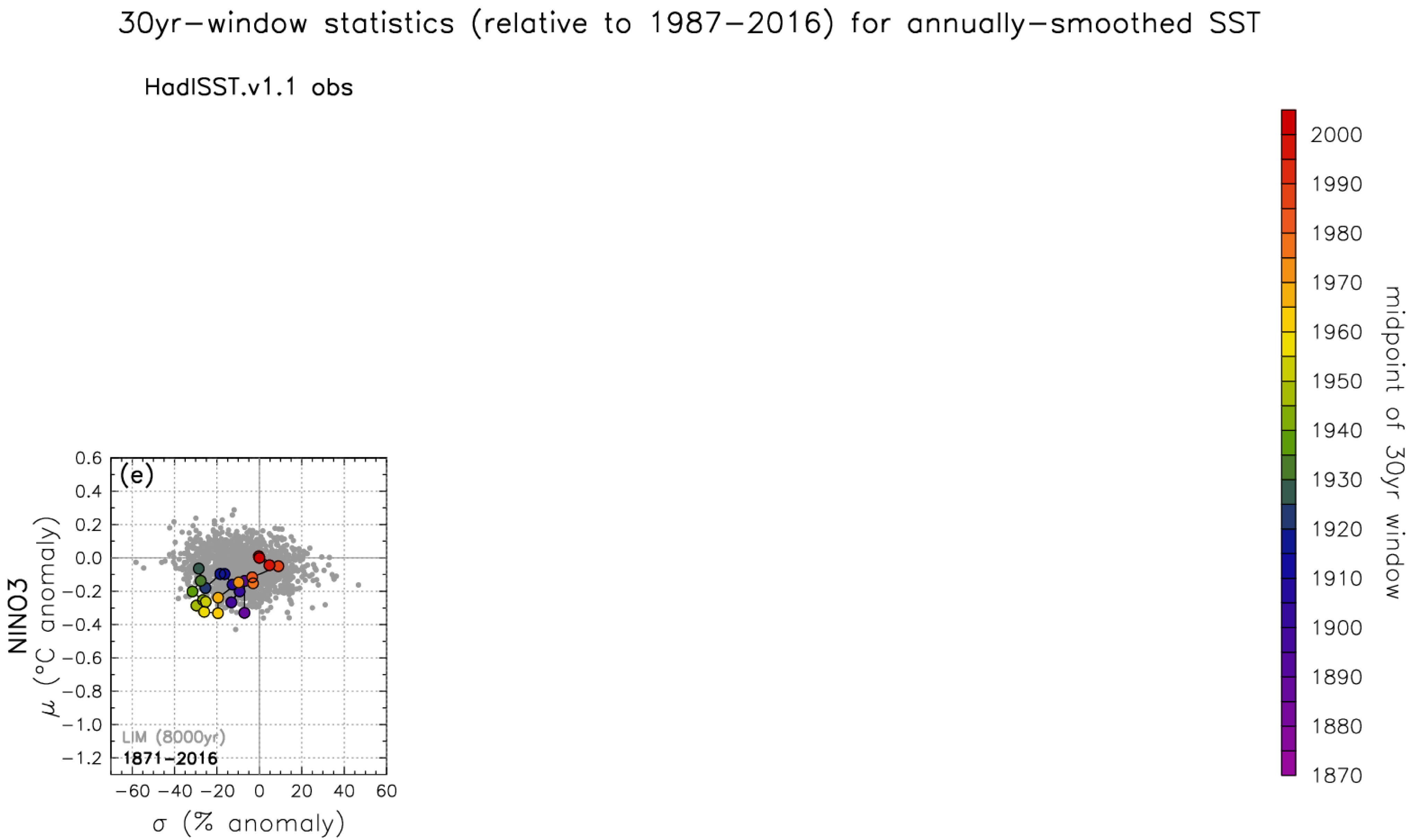


Weaker AMOC → cooler N. Atlantic → southward shift of ITCZ
→ less y-asymmetry → weaker annual cycle, stronger ENSO(?)
CGCM biases → diverse wind / thermocline / ENSO changes.

Dong & Sutton (2007); Svendsen et al. (2014); Liu et al. (2014); Yu et al. (2015); Williamson et al. (2017)

Climate Change

Observed & simulated mean/ENSO SST changes



Newman, Wittenberg, et al. (BAMS 2017)

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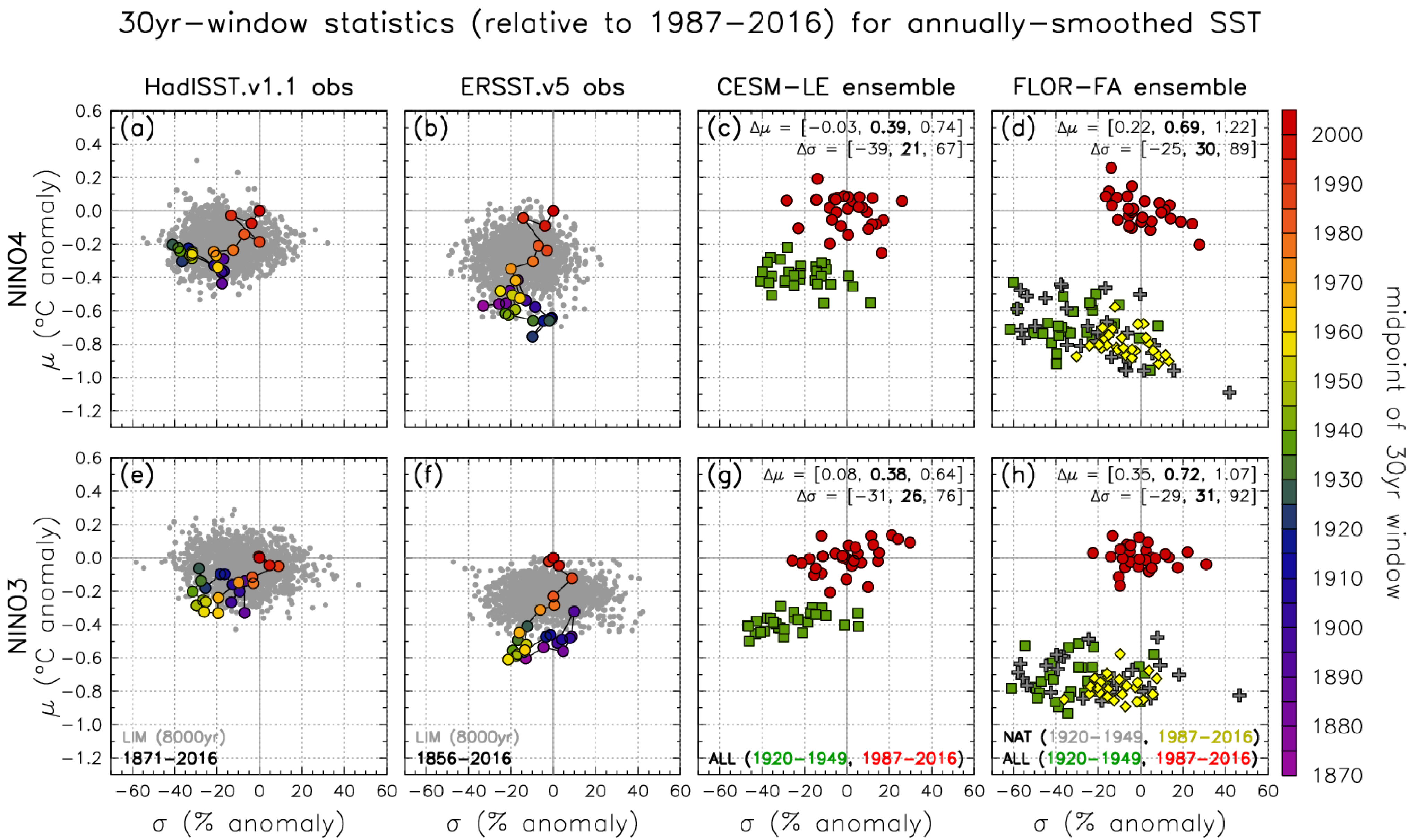
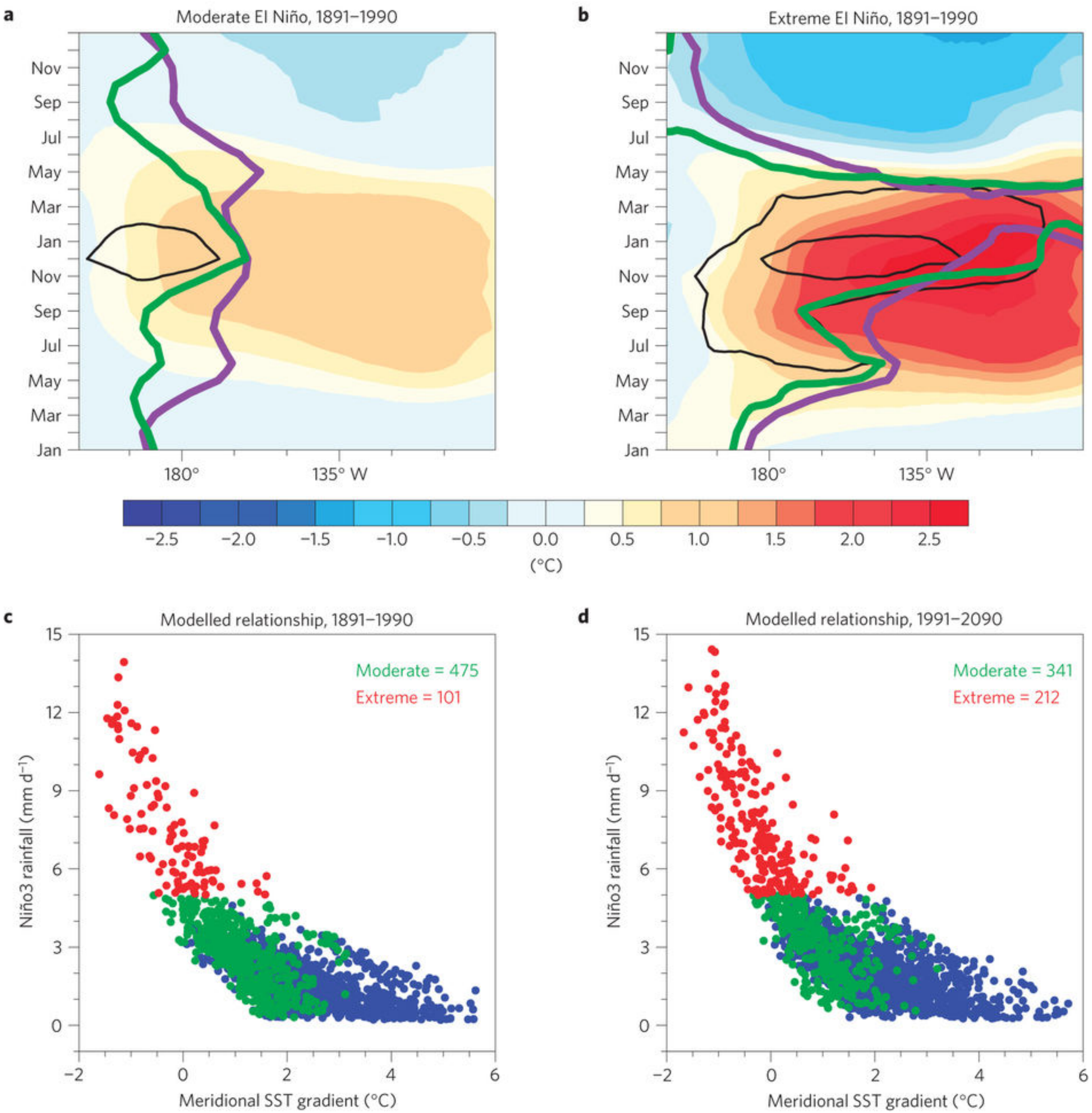


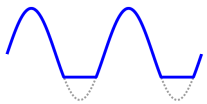
Mean change is marginally detectable. ENSO change, less so.

Newman, Wittenberg, et al. (BAMS 2017)

Background SST affects ENSO rain response



Cai et al. (2014)



Power et al. (2013)
Cai et al. (2012, 2014, 2015ab)

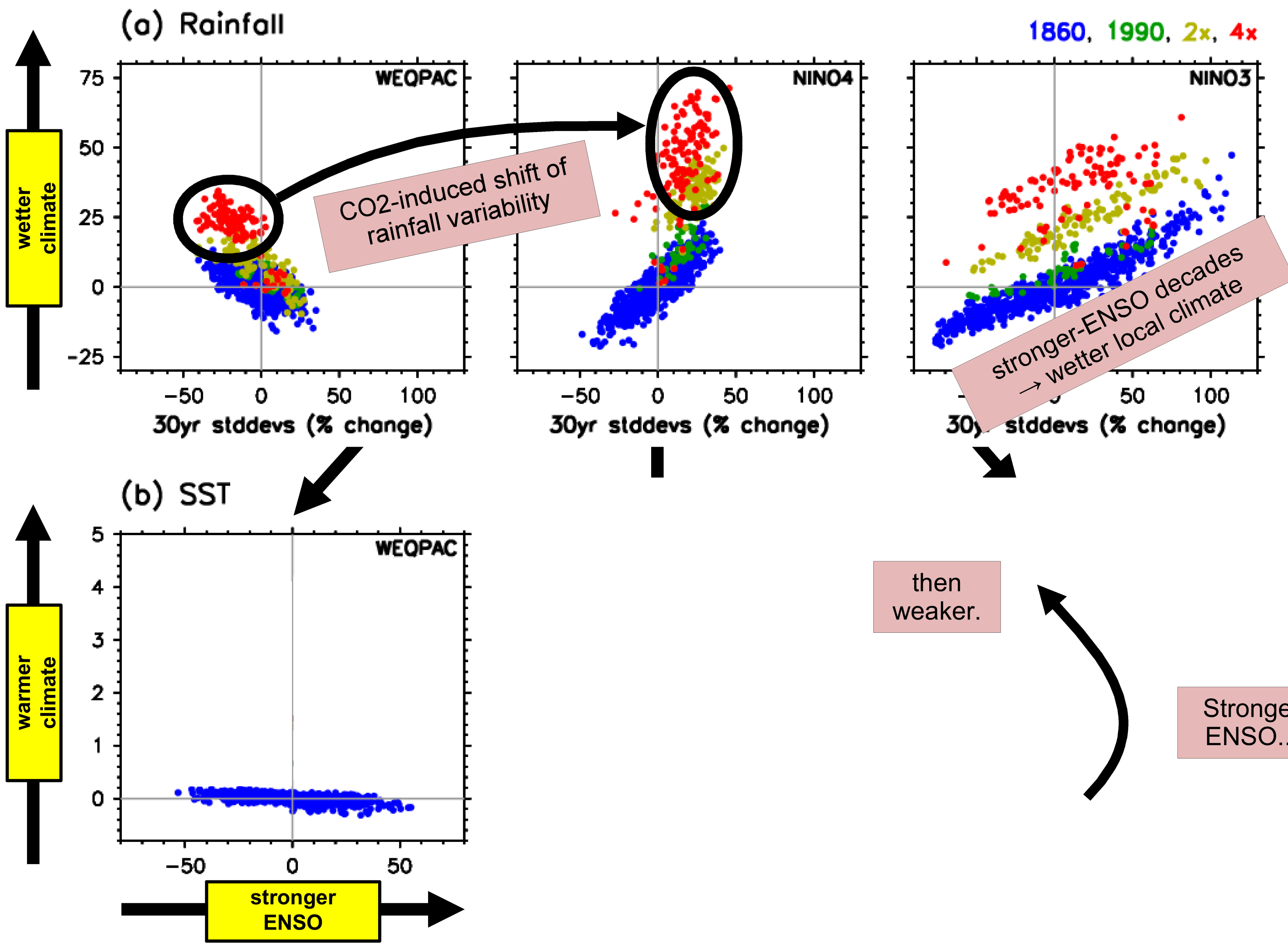
So how will background SST gradients change in the future?

Weaker dT/dy & dT/dx?

Relatively warmer Indian & Atlantic Oceans?

Luo et al. (2012)
Wieners et al. (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)

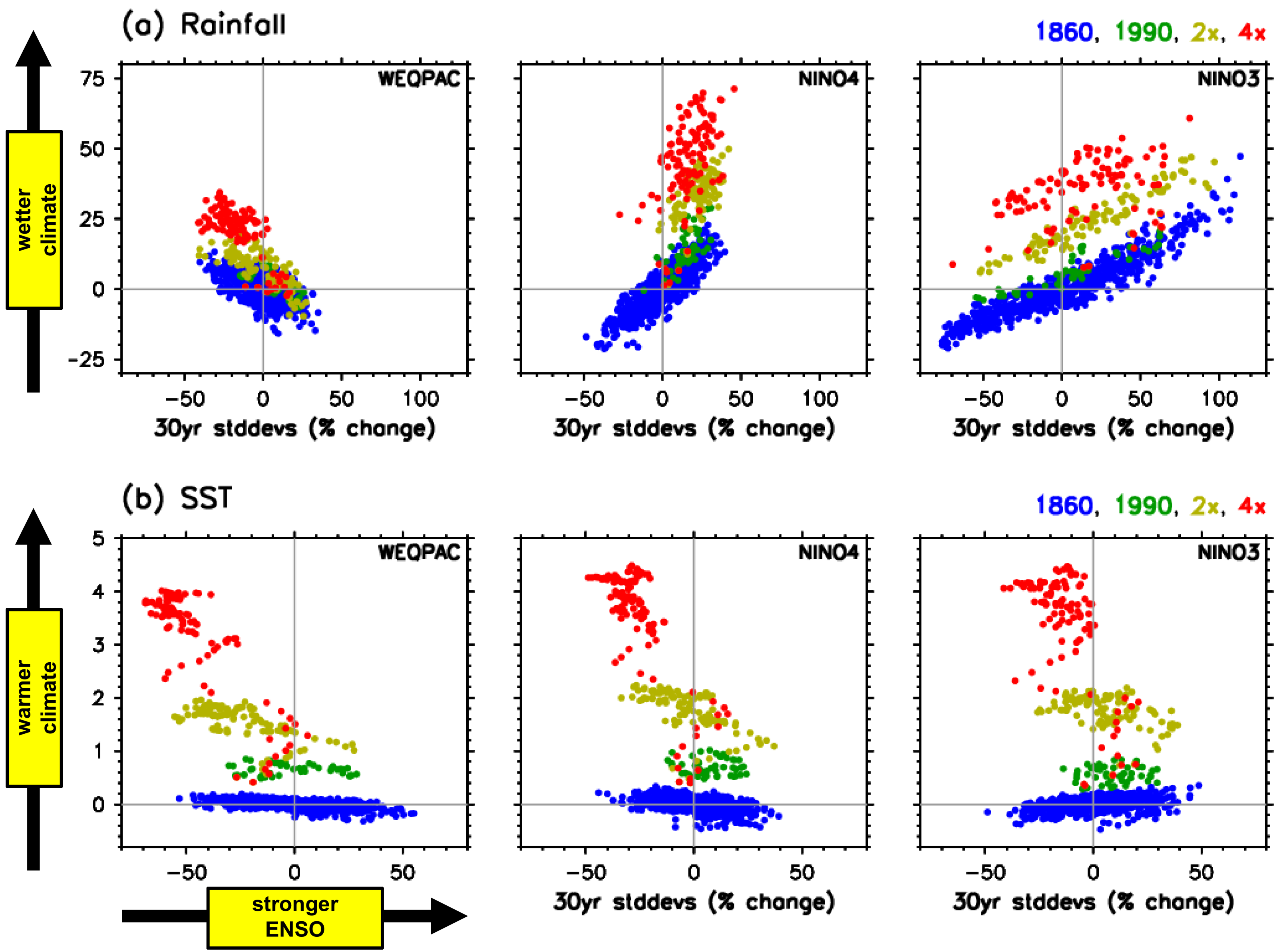
Cai et al. (2014)

Atwood et al. (2017)

Wittenberg (U.S. CLIVAR Variations, 2015)

CM2.1 simulation

ENSO response to increasing CO_2



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CM2.1 simulation

Summary (1 of 2)

ENSO involves rich interactions across a vast range of time scales.

1. Seasonal-to-interannual scales

a. Spikes + frequency modulation → **broad spectrum**
b. Non-normal dynamics → **transient growth**, new time scales
c. Structure & nonlinearity of **wind stress response** is key
  - Period, amplitude; asymmetries of amplitude, duration, transition probability

2. Annual interactions

a. **Seasonal migrations of convection → synchronization & asymmetry**
  - Onset (WWEs)
  - Termination (southward shift)
b. **Combination modes** (6-9 & 15-18 months)
c. **Extreme El Niños** terminate later → affects seasonal teleconnections

3. Intraseasonal interactions

a. **WWEs a crucial multiplicative noise forcing** for ENSO
  - Intensity & frequency increase as warm pool extends eastward
  - Make strong El Niños hard to predict (especially across boreal spring)
b. Transient **salinity stratification** could affect ENSO coupling in west Pacific
c. **TIWs** affect ENSO
  - stratify equatorial water column
  - selectively damp La Niña SSTAs → asymmetry
  - may contribute to wind stress noise near equator

Summary (2 of 2)

4. Decadal interactions

a. **Interdecadal modulation**
- Need not imply long-term memory, or secular changes
- Intrinsic component may obscure ENSO statistics beyond a few years

b. **Rectification**
- Modulation + asymmetry → rectifies into longer time scales
- Quiet-ENSO epochs have stronger zonal constrasts of SST & thermocline depth
- Sustaining such a state can boost global ocean heat uptake, contribute to decadal drought

c. **Extratropical & inter-basin interaction**
- PDO & NPGO in the Pacific
- AMOC in the Atlantic
- Interactions are uncertain, and vary among models.

5. Anthropogenic changes

a. Detectable changes in the background state
- **Warming Indian Ocean & West Pacific**

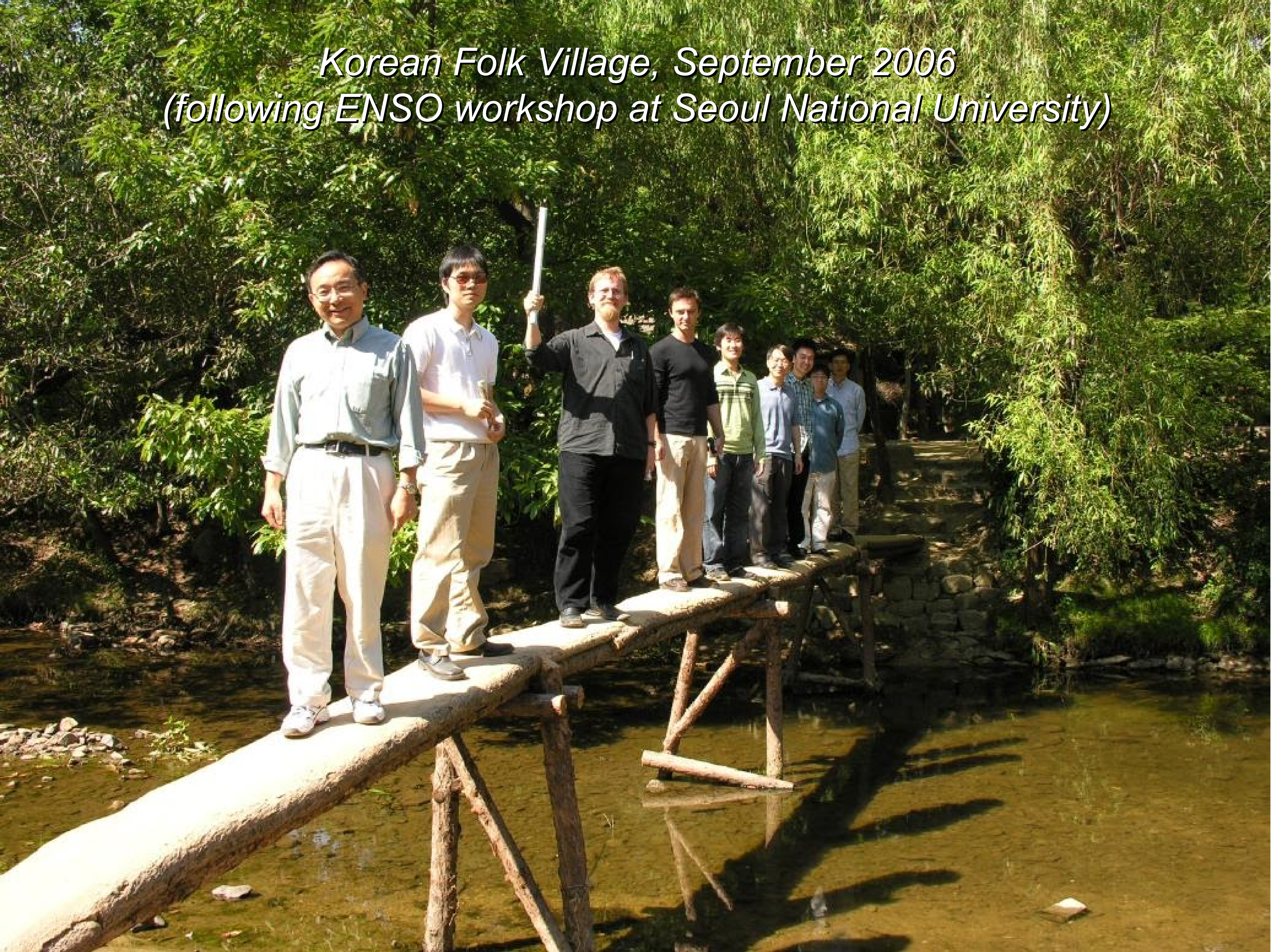
b. ENSO effects not yet clearly detectable in obs

c. Model projections suggest **stronger rain fluctuations** in the future
- Especially in the central equatorial Pacific

d. **Large uncertainties** about the future of ENSO
- Depends on how background dT/dx & dT/dy change

Understanding & models are improving, but still much work to do...

Reserve Slides


Korean Folk Village, September 2006
(following ENSO workshop at Seoul National University)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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)