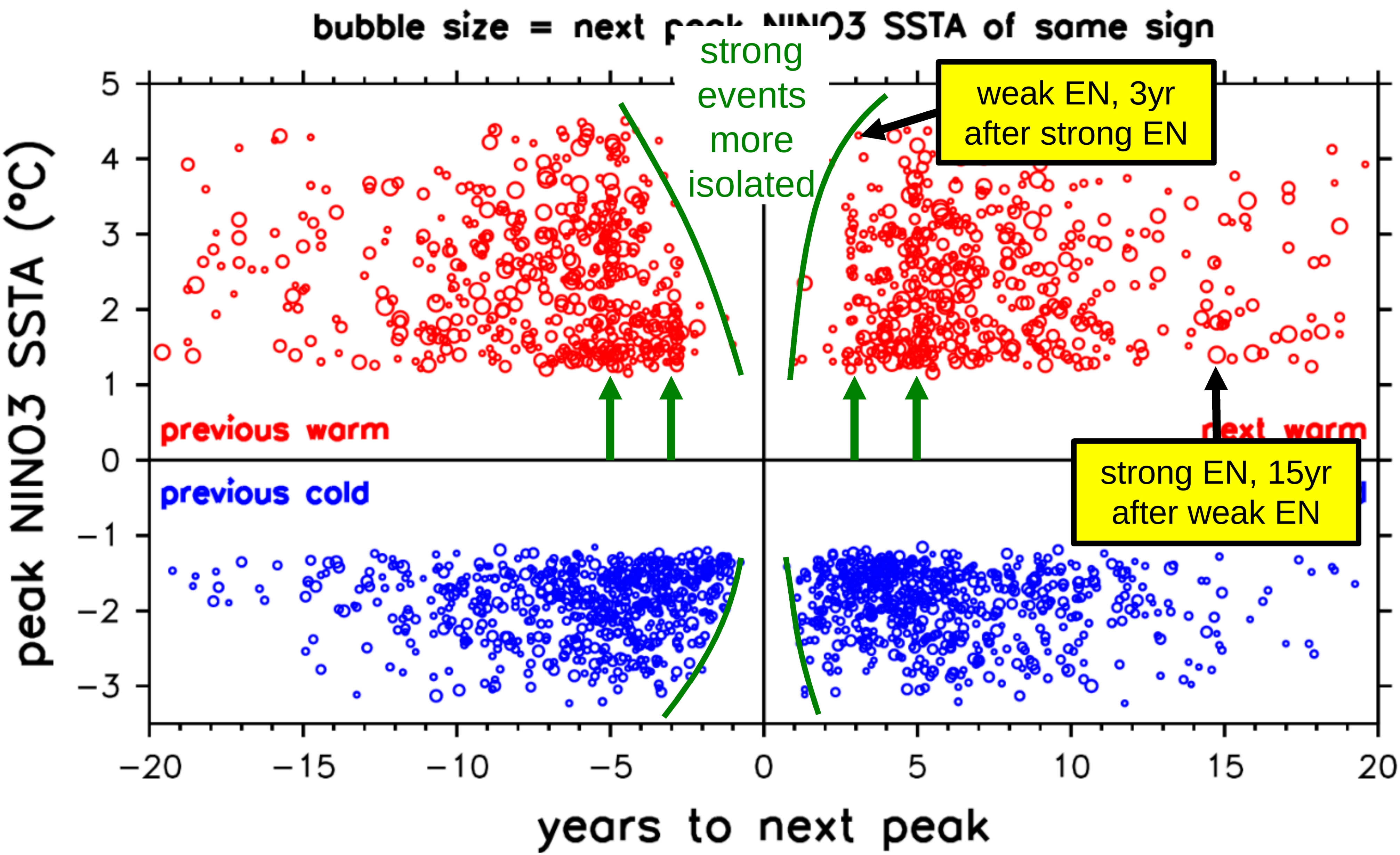
Reserve Slides

ENSO events and their nearest neighbors



CM2.1 simulation

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Climate Change

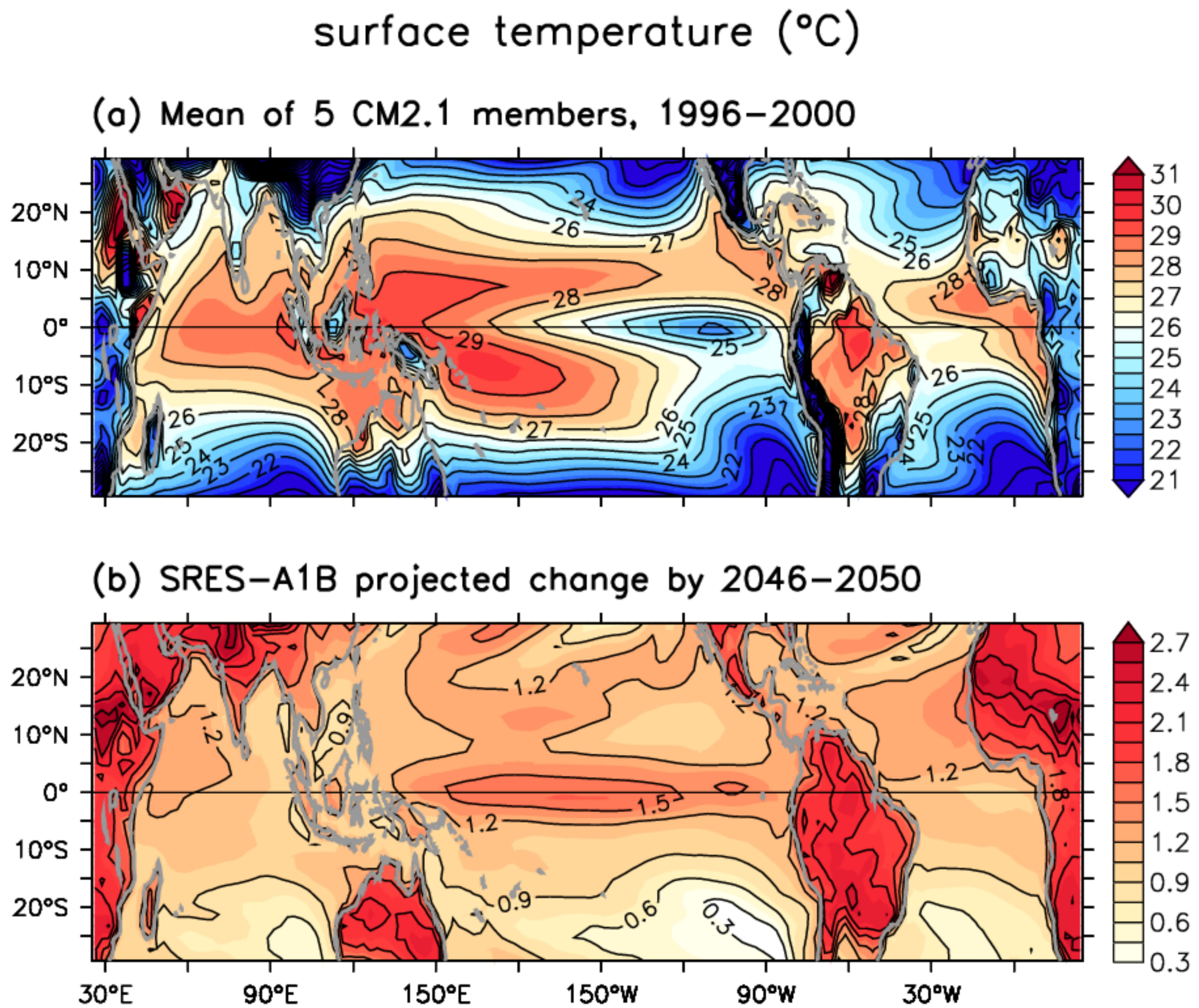
Projected surface temperature changes

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



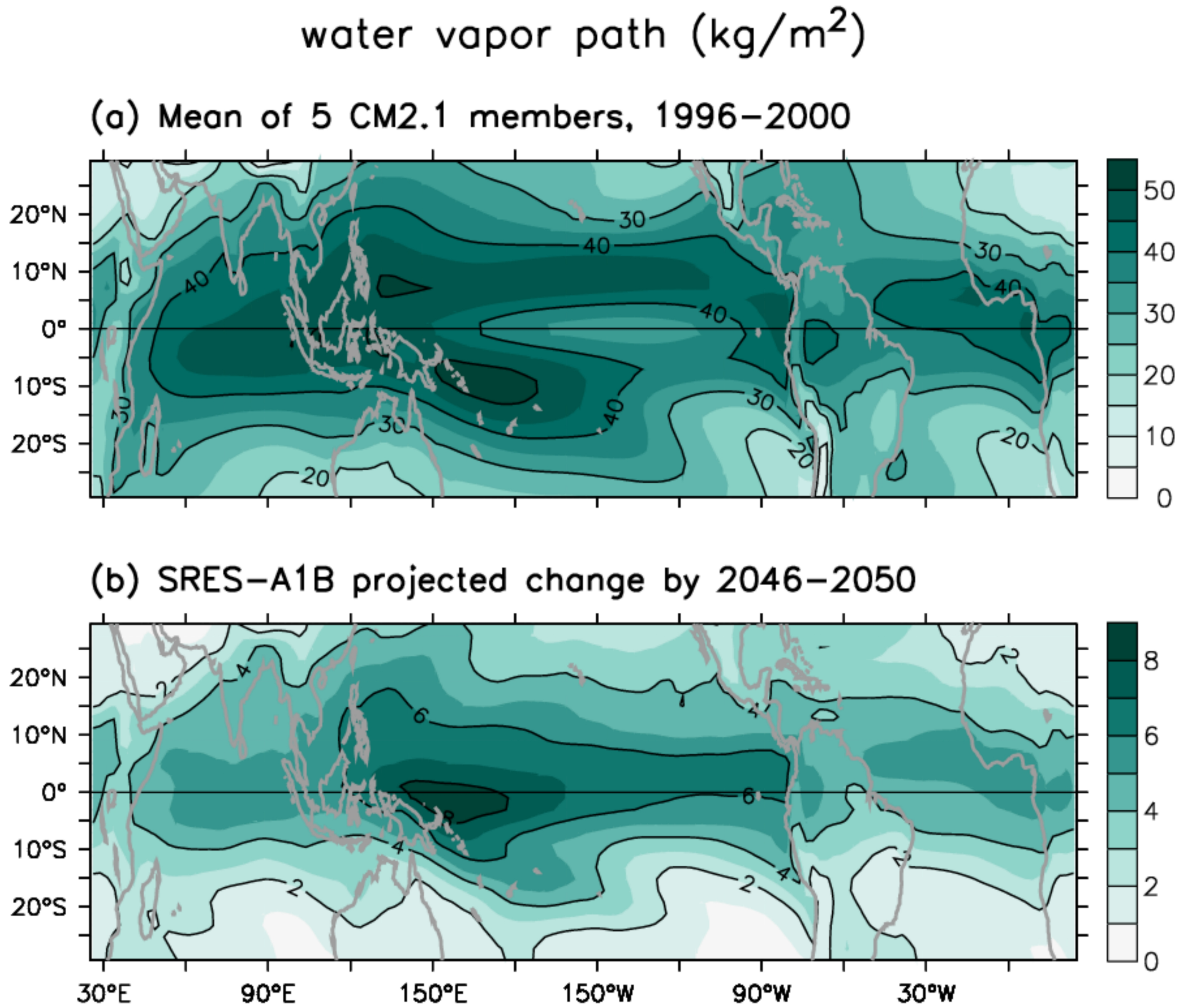
Projected change in atmospheric water vapor

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

Tropics today:
~40 kg of water vapor

Warmer sea surface
→ wetter air.

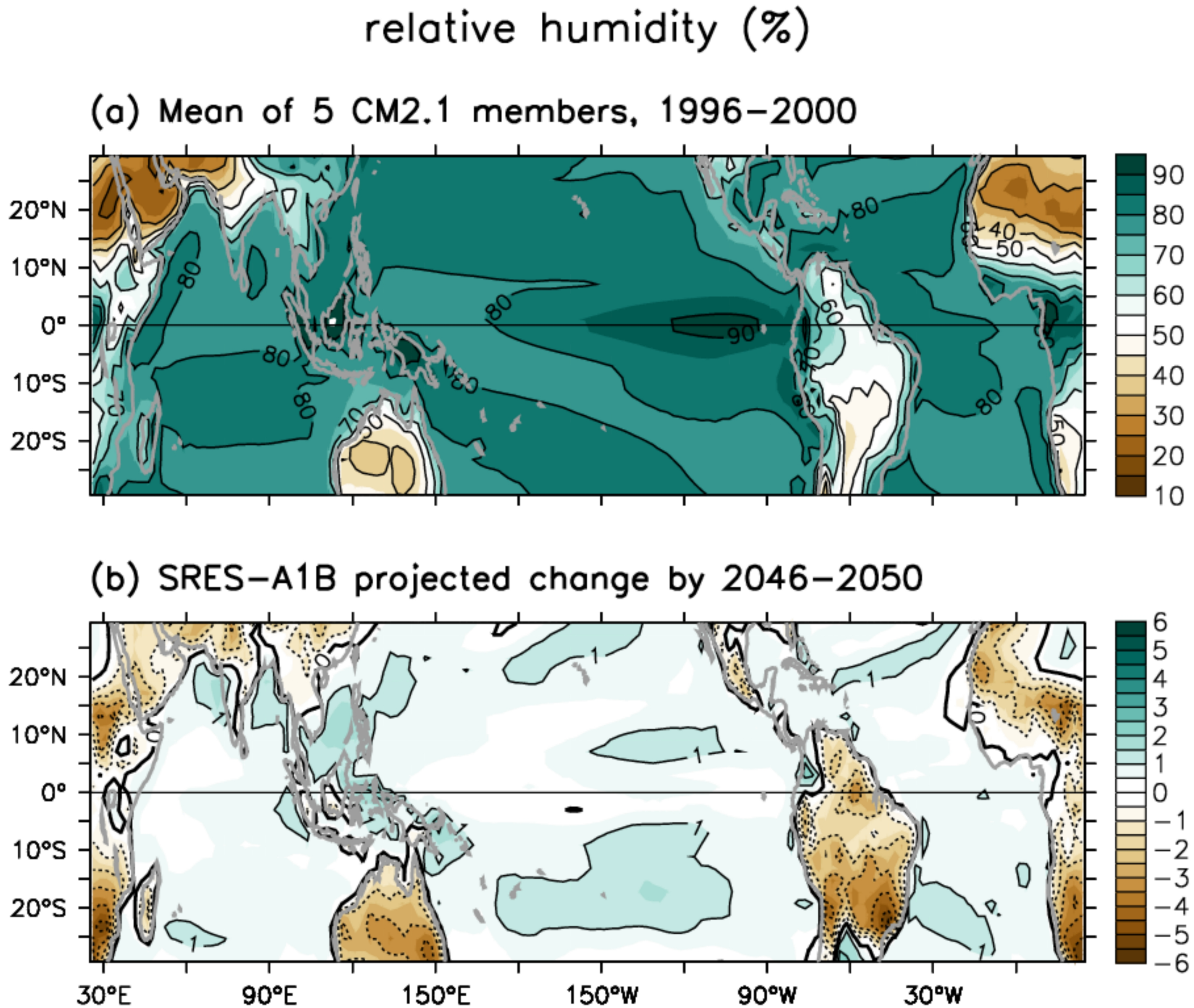
2050: +4 kg



Projected relative humidity changes

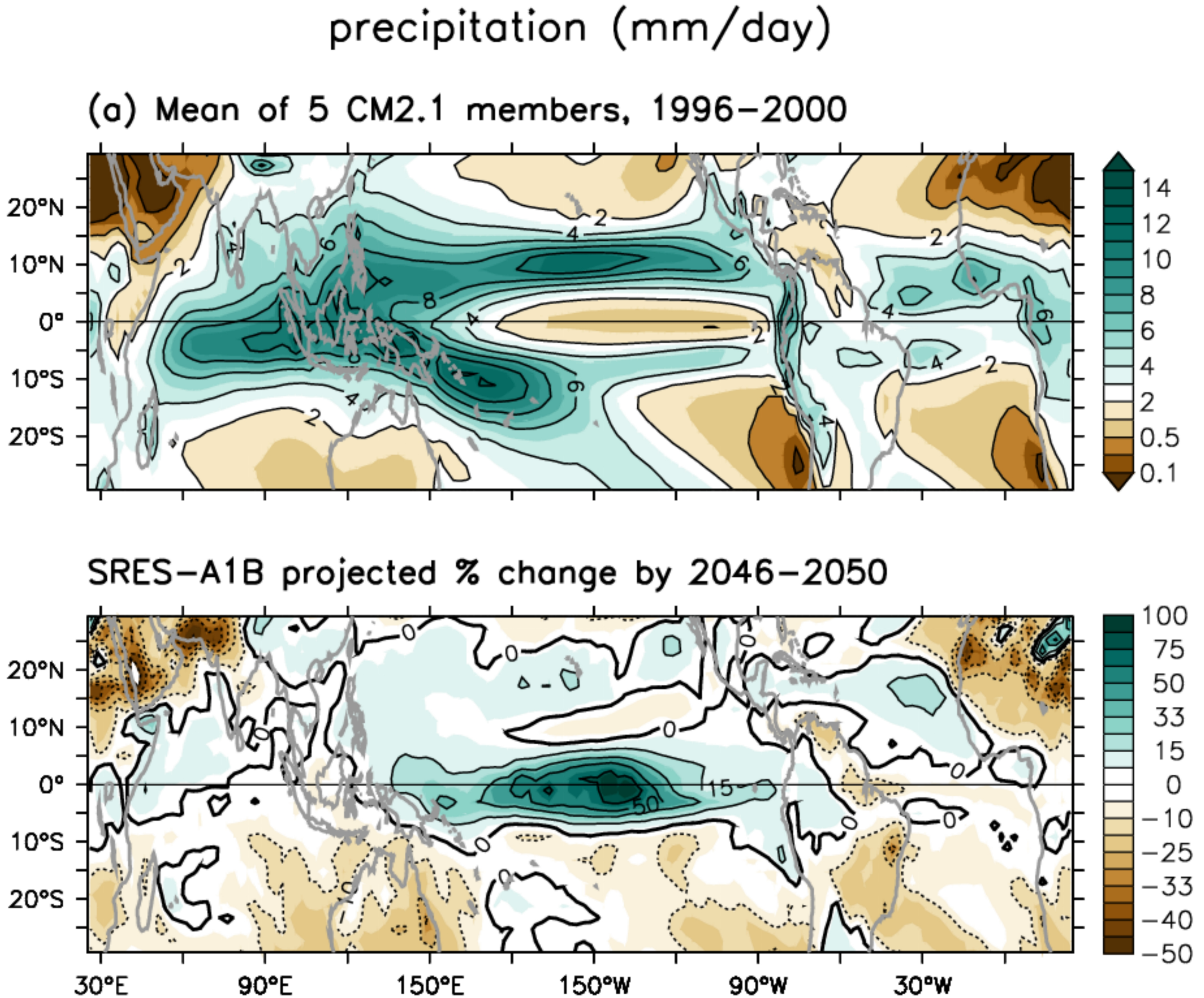
Vecchi & Wittenberg (2010)
Collins et al. (2010)
Xie et al. (2010)

As convective overturning weakens, relative humidity increases by up to 1.5% over the tropical Pacific.



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".

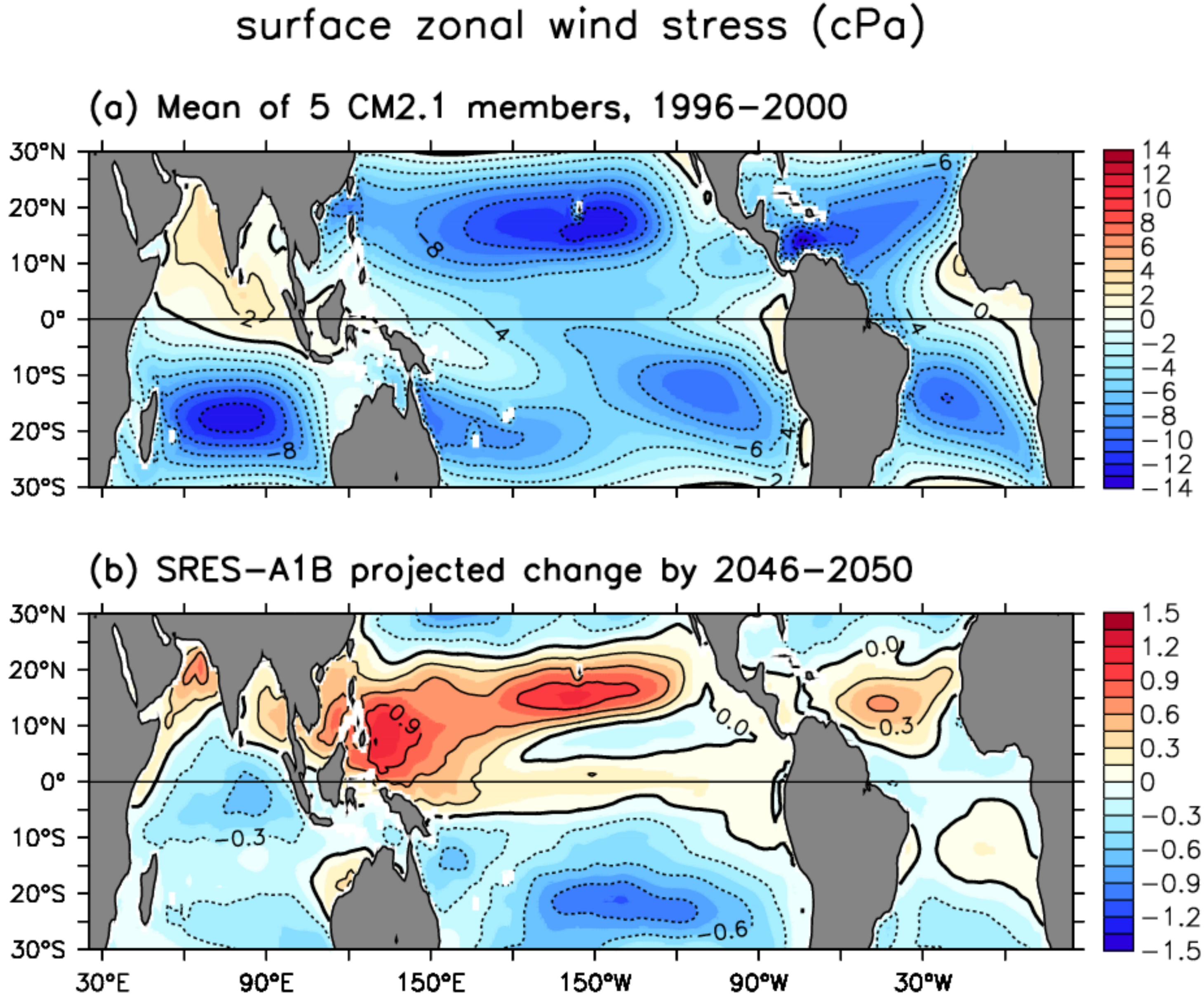
Projected surface zonal wind stress changes

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

Weaker *equatorial* Pacific trade winds.

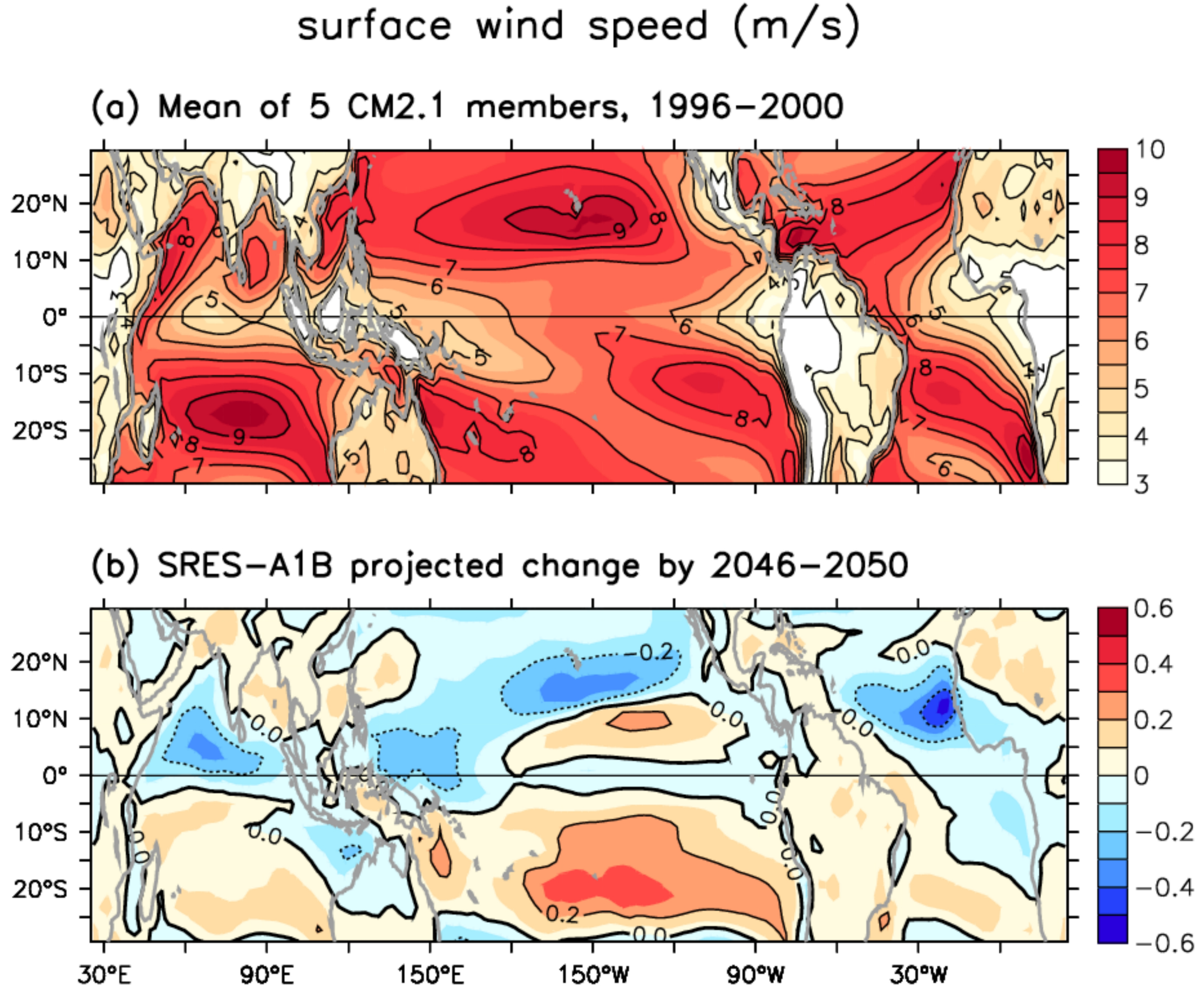
More symmetric climatology.

Pacific trades (and cyclonic curl) strengthen in north, weaken in south.

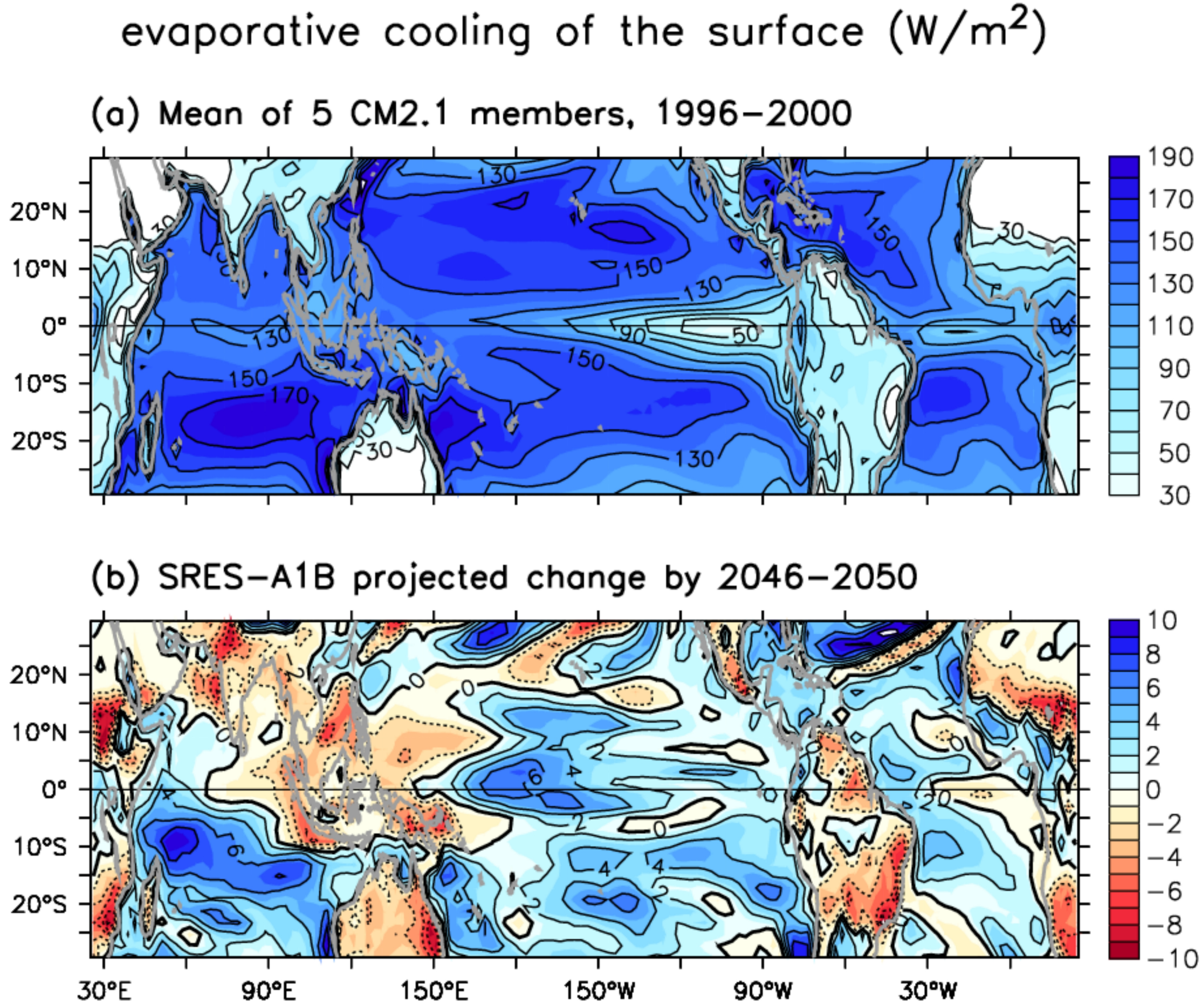


Projected surface wind speed changes

Wind speed change dominated by the zonal component.



Projected evaporation changes



Changes have lots of x & y structure.

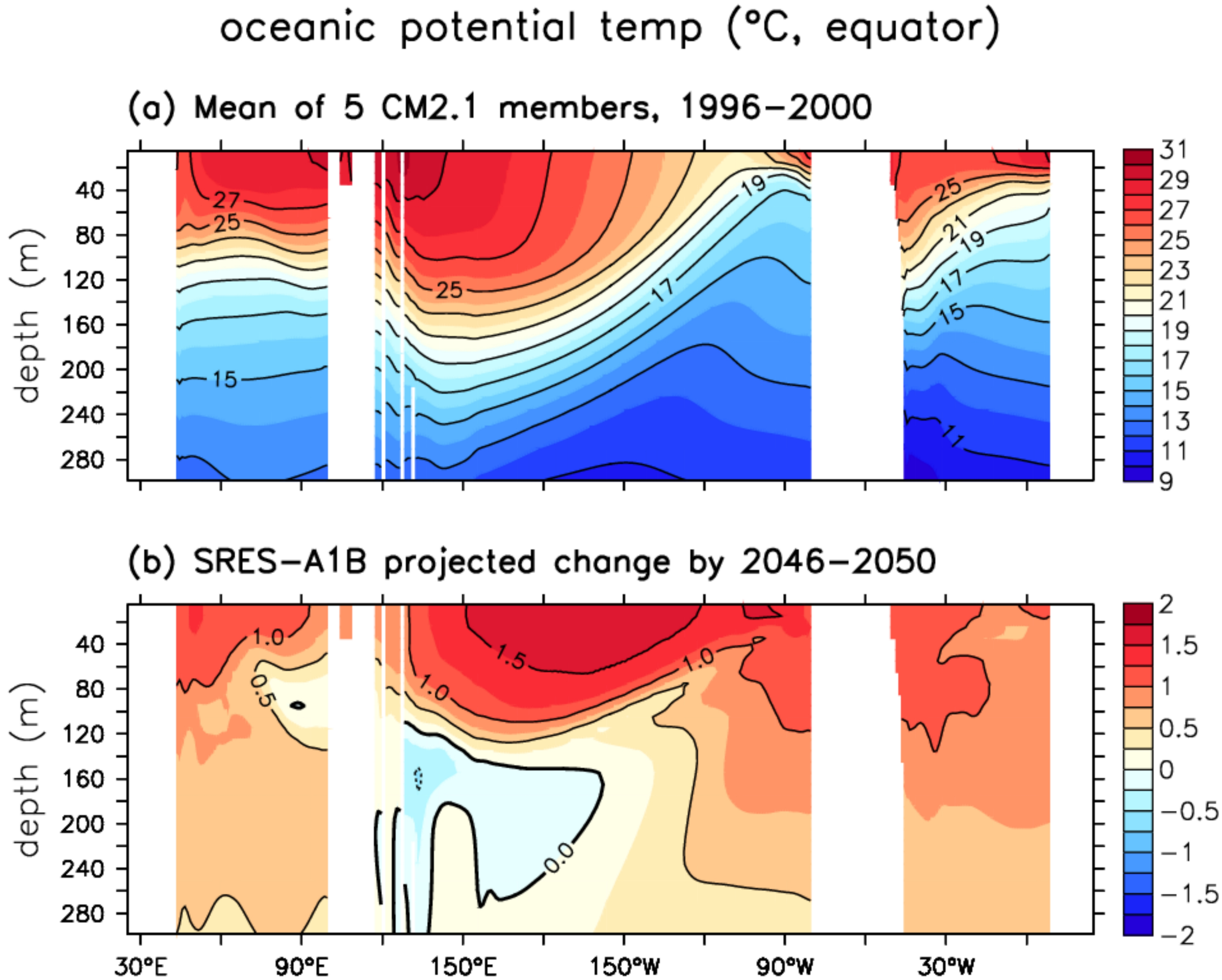
Would a thinner mooring array resolve these evaporation changes?

Projected upper-ocean temperature changes

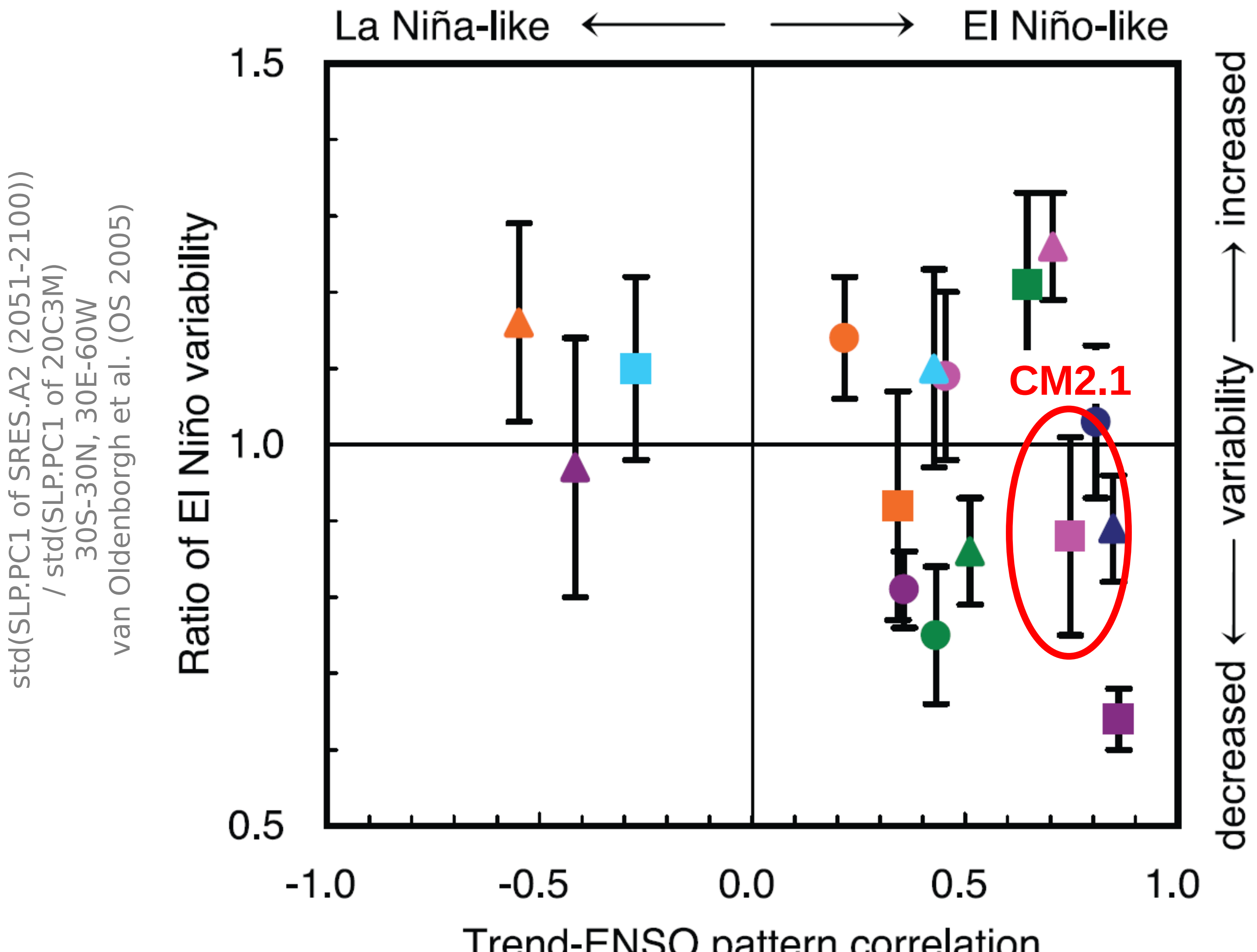
DiNezio et al.
(JC 2009, EOS 2010)
Collins et al. (2010)

Tropical ocean more stratified

Stronger, shallower, and flatter equatorial thermocline



Projected ENSO changes (CMIP3/AR4)



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)

Composite CM2.1 warm events (NDJ anomalies)

SST

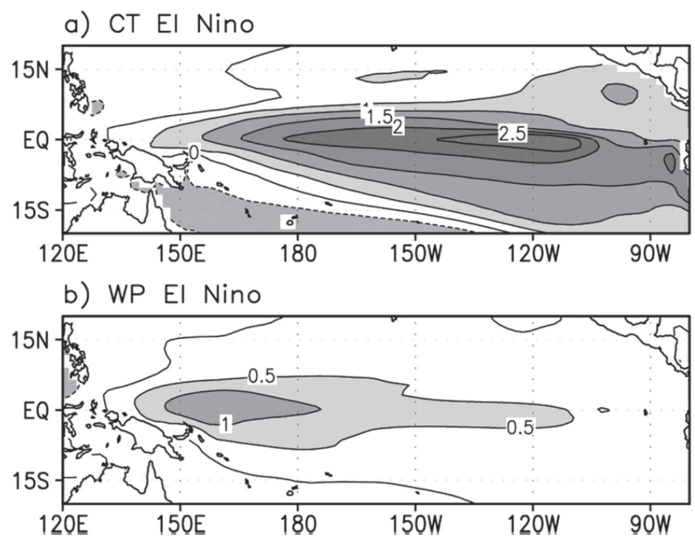


FIG. 3. SST anomaly (°C) composite of the (a) CT El Niño and (b) WP El Niño during ND(0)J(1).

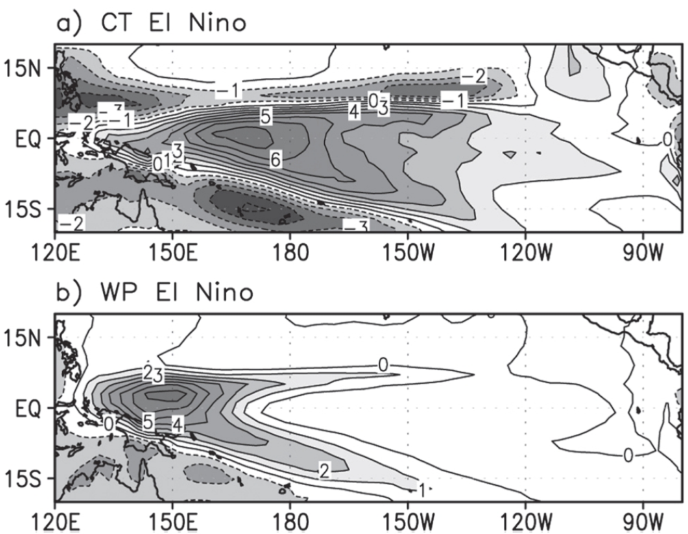


FIG. 4. As in Fig. 3, except for precipitation (mm day^{-1}).

precip

zonal wind (925mb)

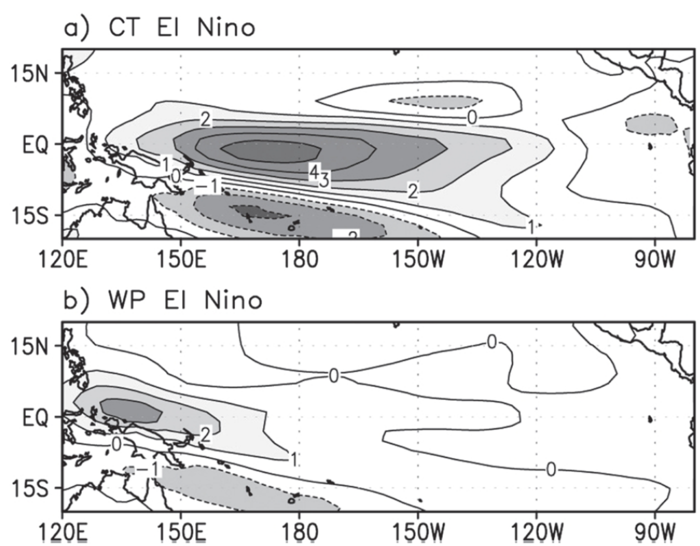


FIG. 5. As in Fig. 3, except for zonal wind at 925 hPa (m s^{-1}).

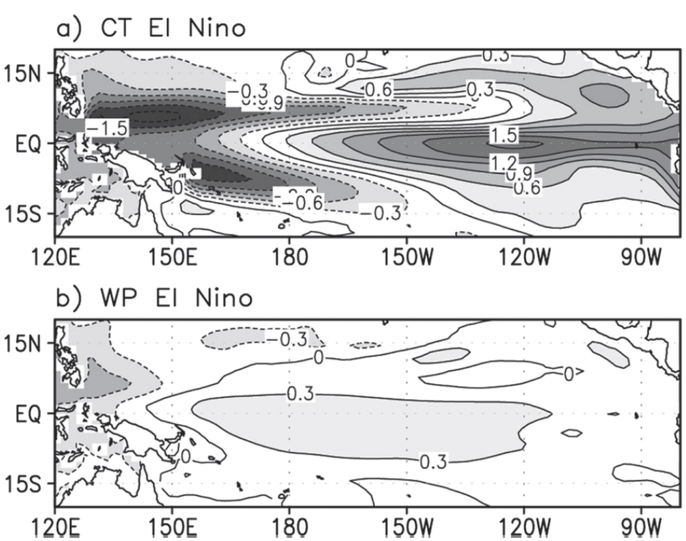


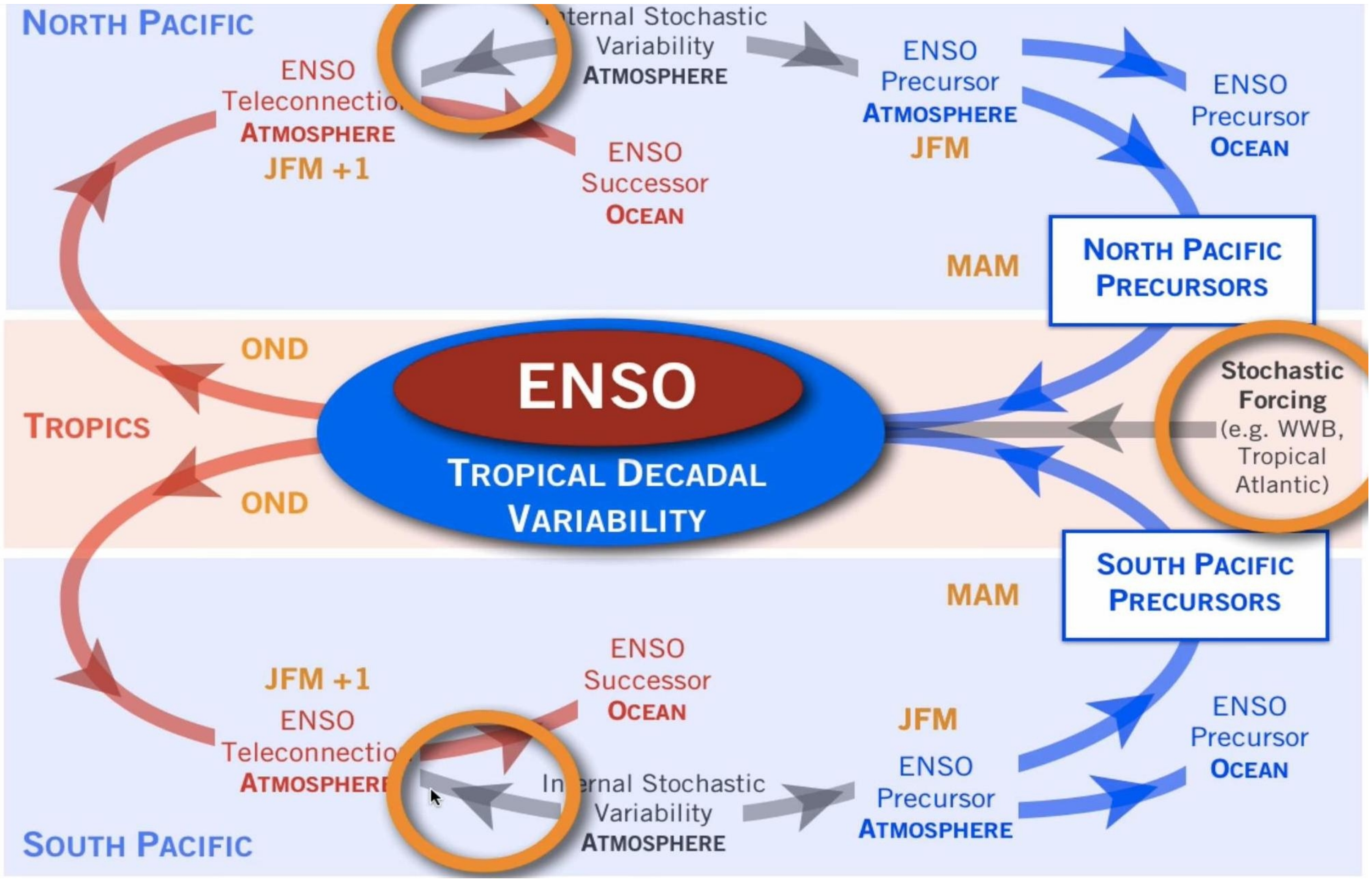
FIG. 6. As in Fig. 3, except for heat content (K).

heat content (top 300m)

Kug et al. (JC 2010)

Pacific decadal interactions with ENSO

Zhao & Di Lorenzo (NG subm.)



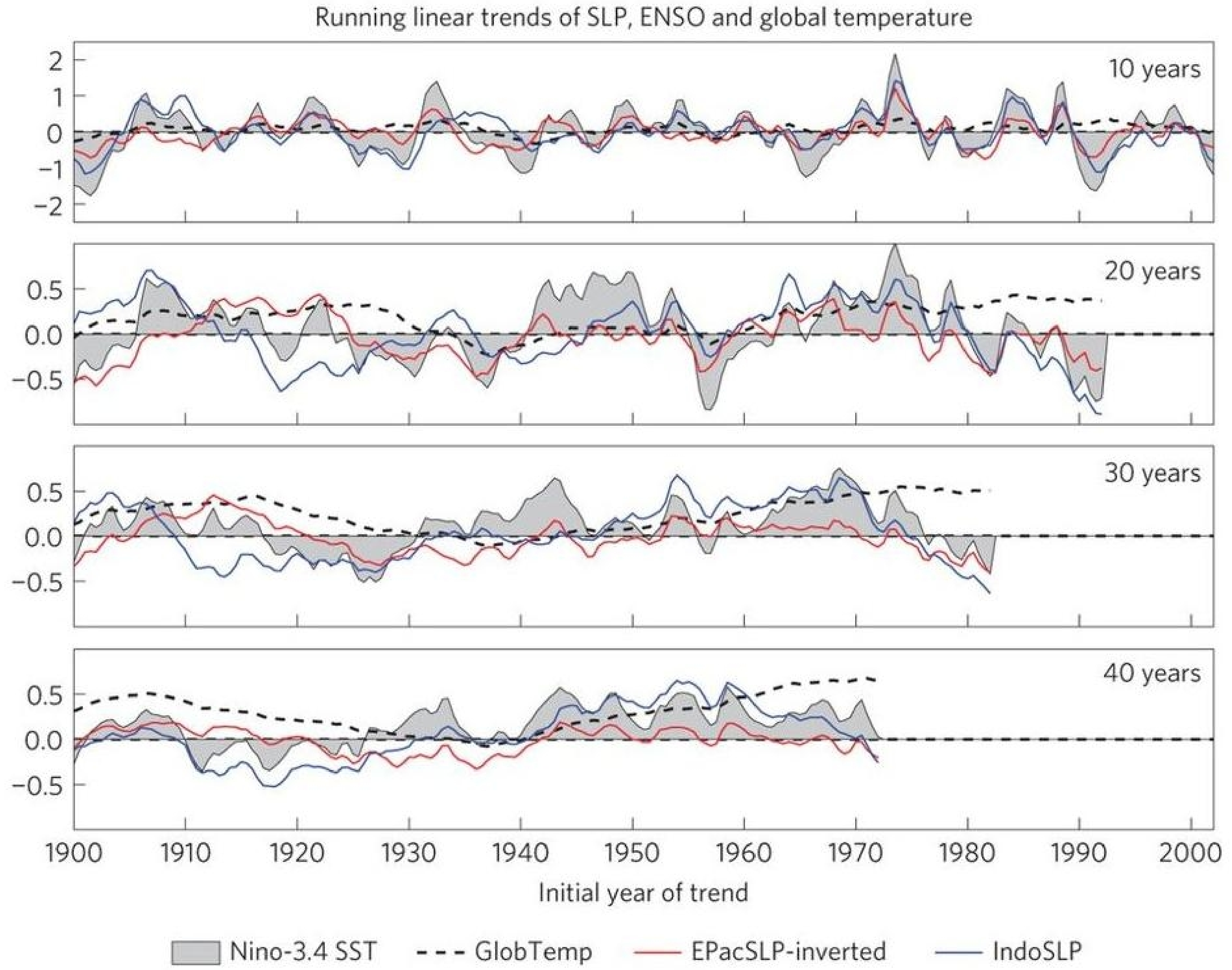
Decadal modes interact with ENSO.
Mediated by surface heat & momentum fluxes,
both on- and off-equator.

EqPac SST & SLP trends: Mean of 9 reanalyses

EqPac -dP/dx tracks NINO3.4 SST, even at multidecadal scales.

Past signals beyond 20-year periods appear to have been weak.

What about the future?



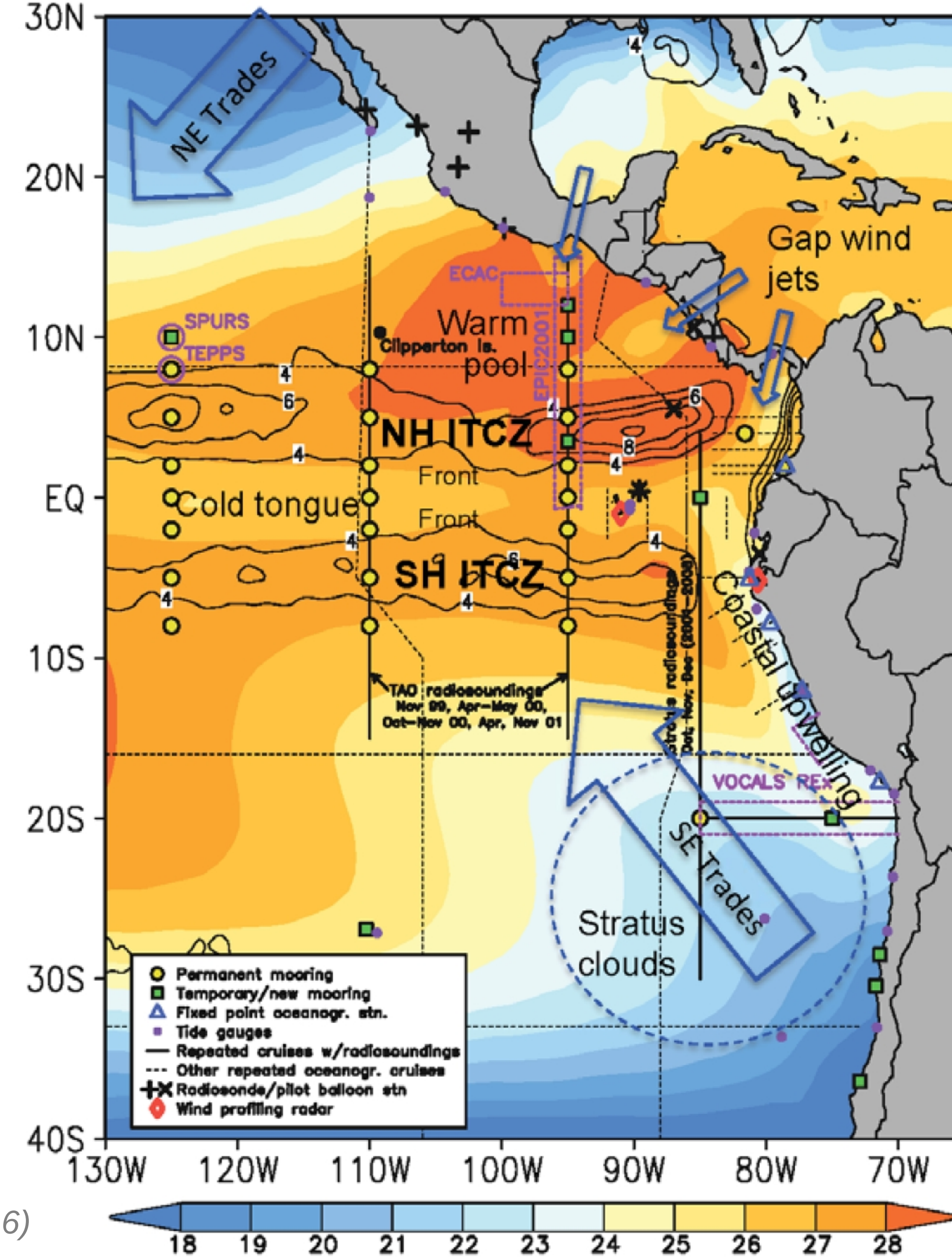
Trends are shown for Niño-3.4 SST (grey shading) and global temperature (black dashed). SLP trends are based on the average of all available data sets (excluding ICOADS) and expressed as the change (hPa) over the window length. Niño-3.4 SST and global average temperature are the change (°C) over the window length.

L'Heureux et al. (NCC 2013)

East Pacific Climate System

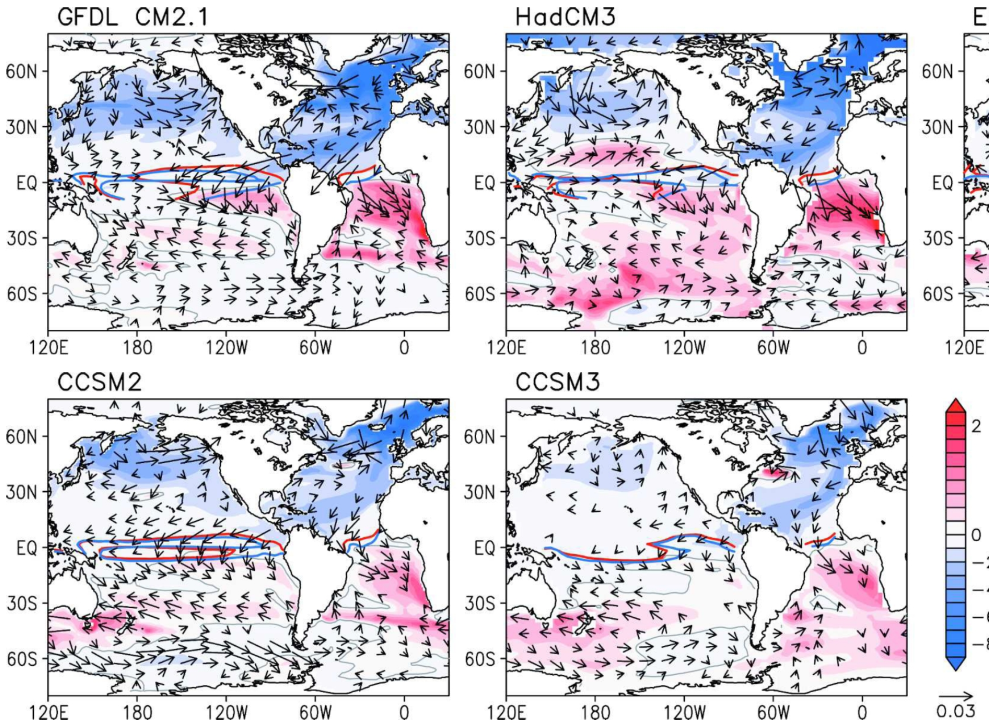
So how will background SST gradients change in the future?

Weaker dT/dy & dT/dx?

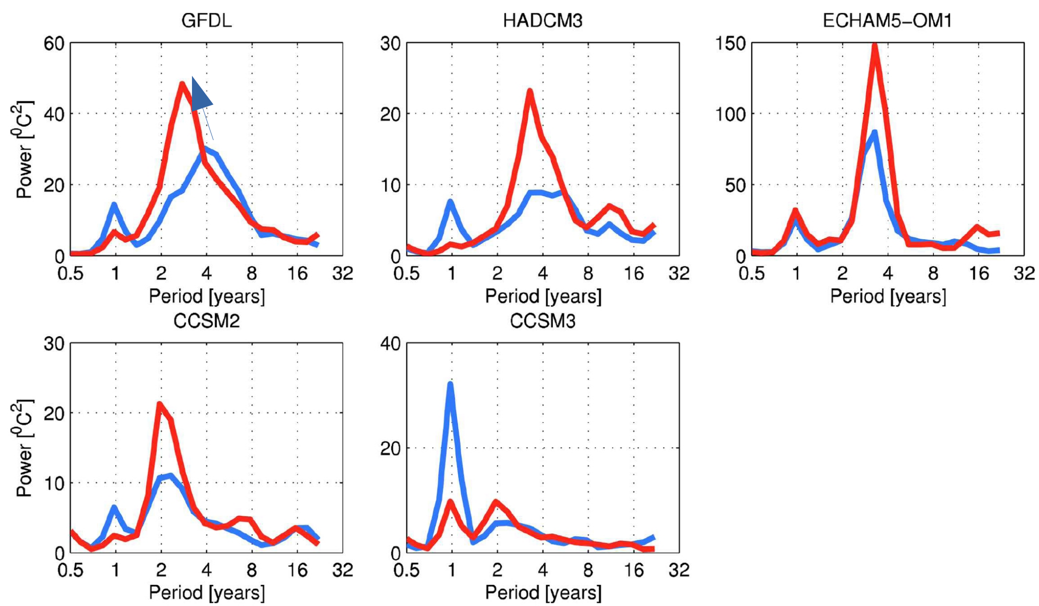


Cravatte et al. (2016)

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)

Composite CM2.1 SSTA tendency terms

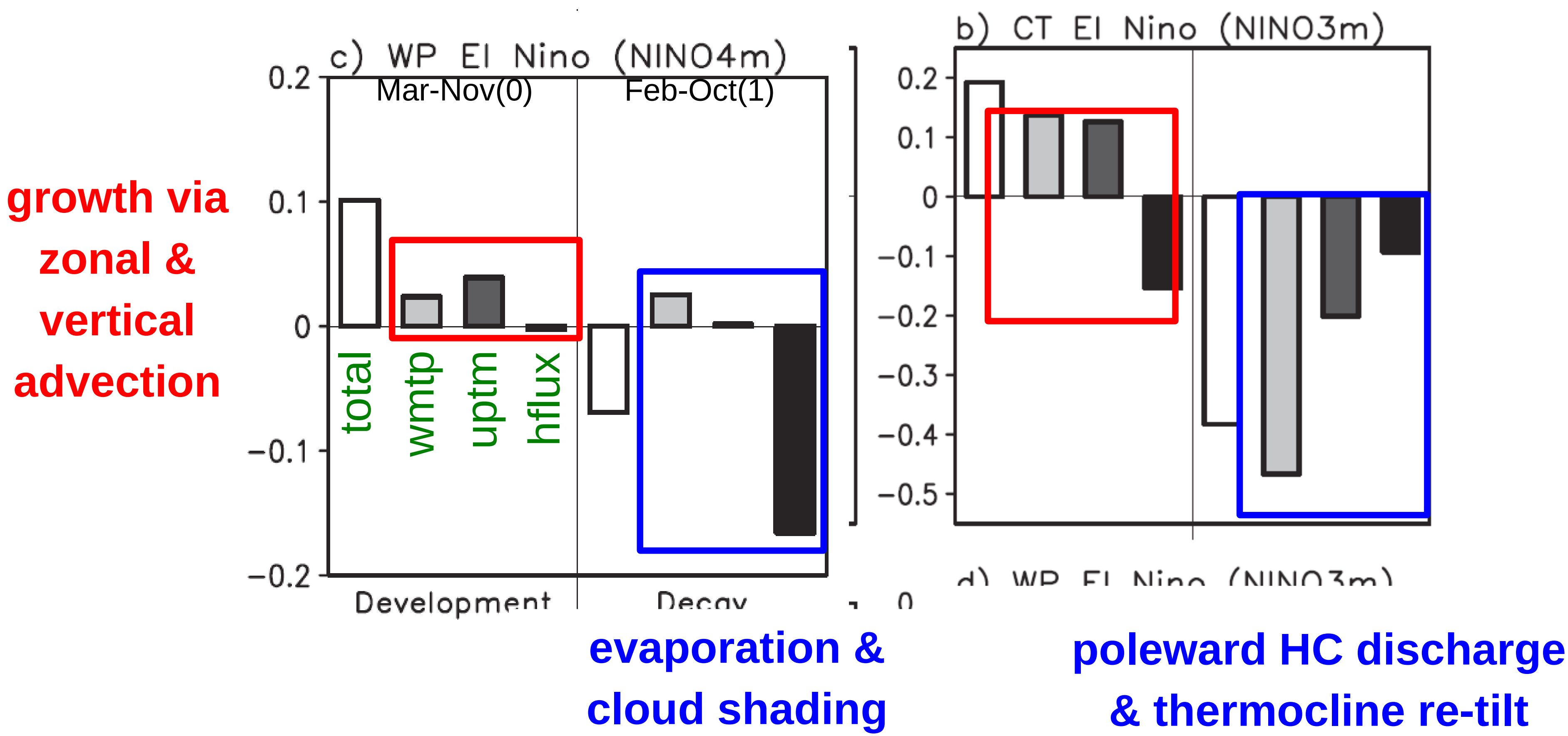
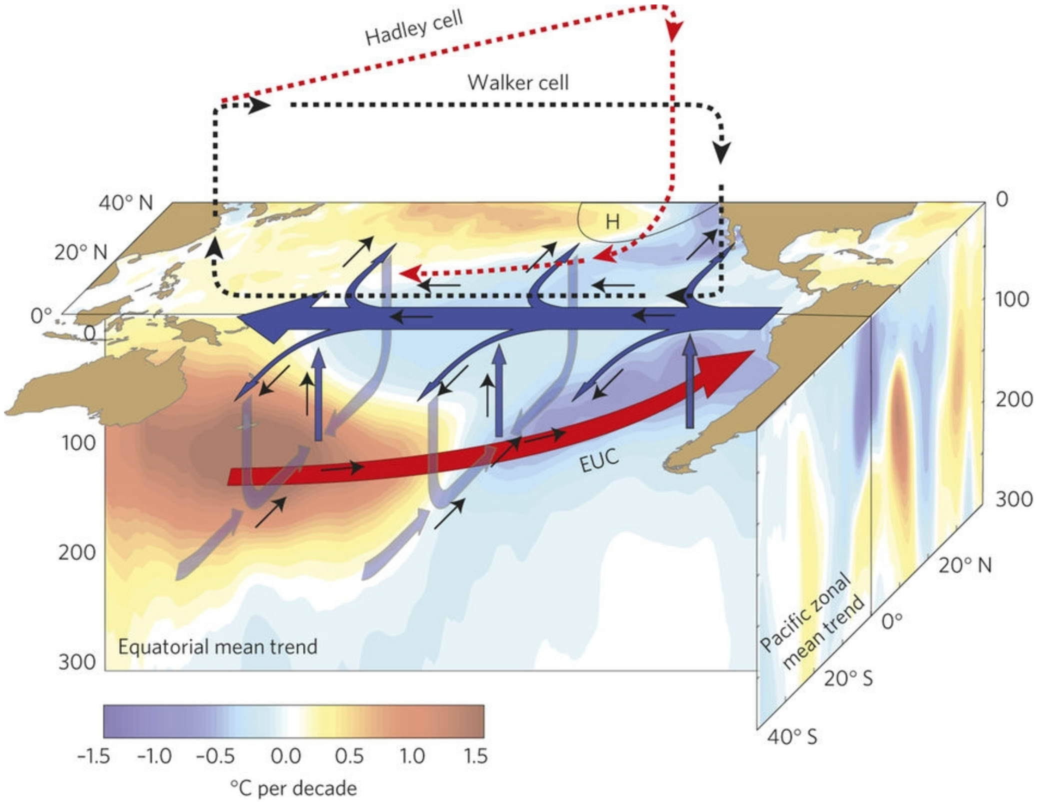


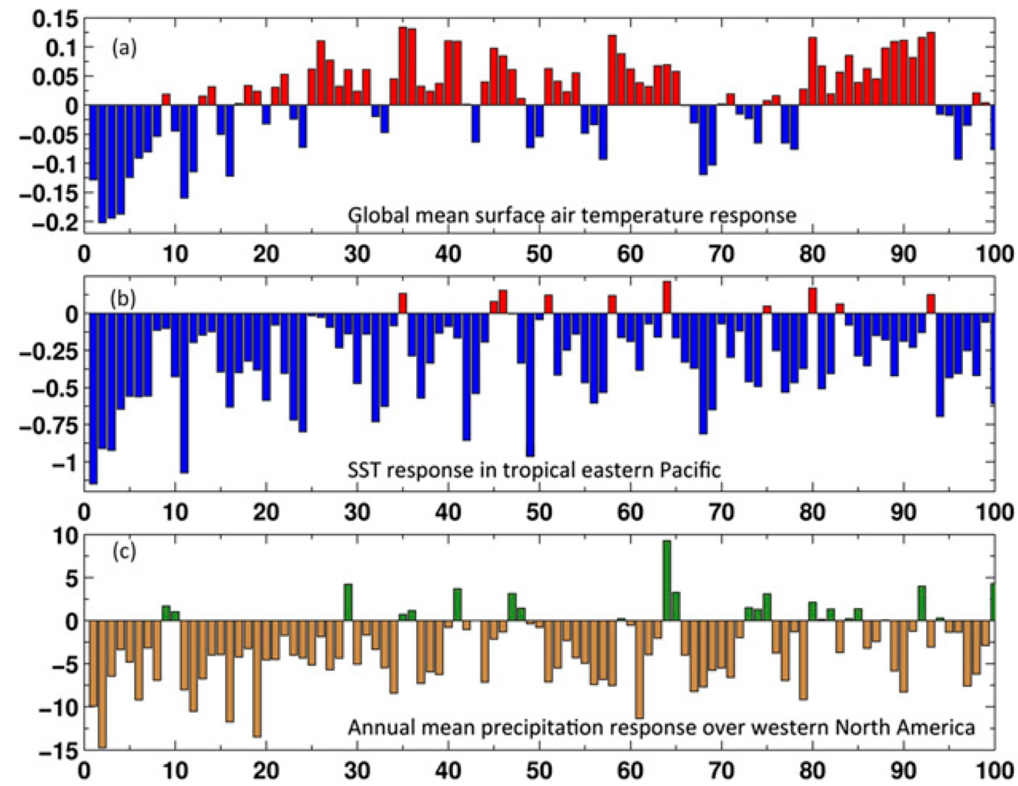
FIG. 11. SST tendency (open bar), SST tendency according to the thermocline feedback (light-gray bar), the zonal advective feedback (dark-gray bar), and net flux (black bar) for (a),(b) CT El Niño and (c),(d) WP El Niño (K month^{-1}). Each magnitude is calculated over 2°S–2°N, 170°–110°W [(b),(d) Niño-3m 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)

Pacific trends affect global climate



England et al. (2014)



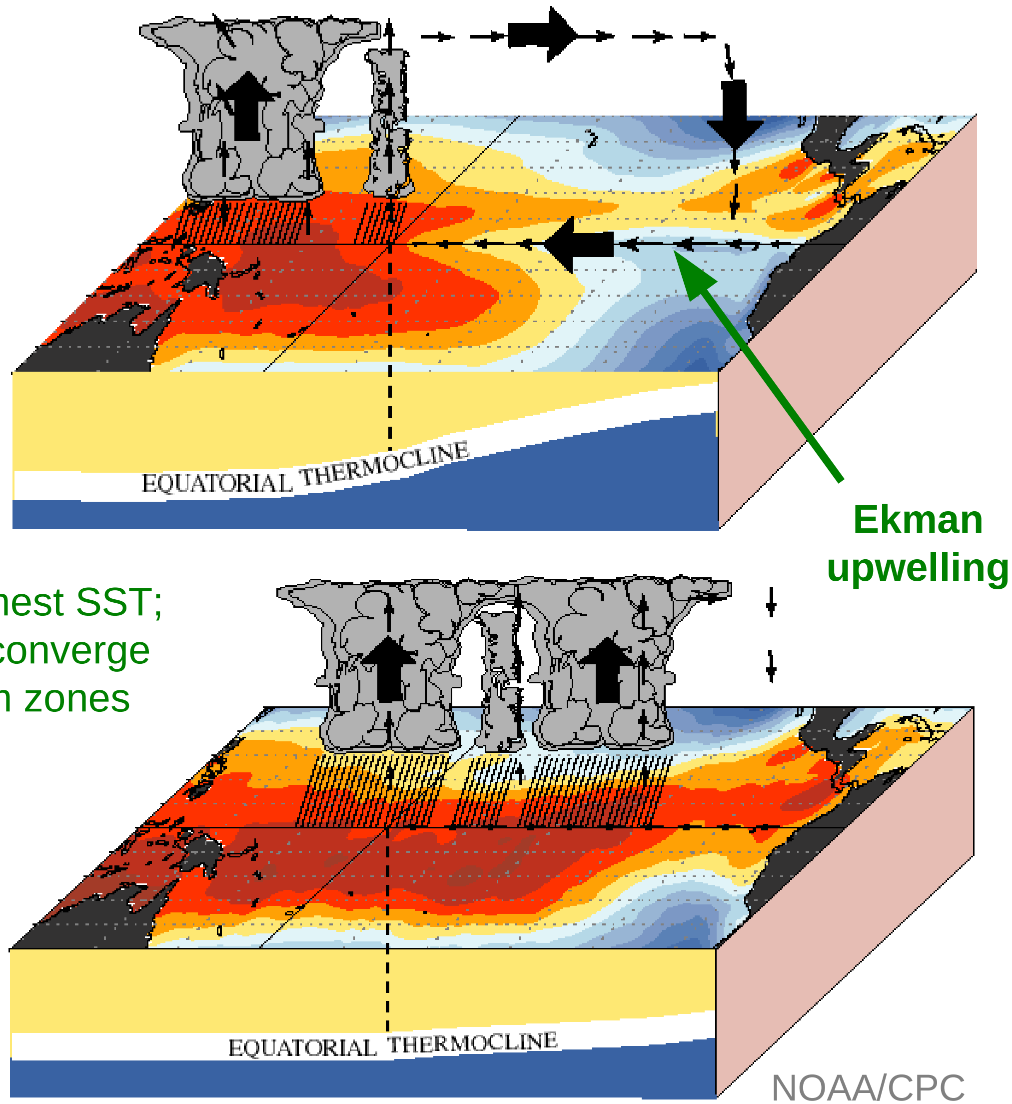
Delworth et al. (2015)

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)

Earth's dominant interannual climate fluctuation: The El Niño / Southern Oscillation (ENSO)

Normal



Asymmetric:
cold tongue, warm pool;
ITCZ north of equator;
easterly trade winds;
sea level slopes **up** to west,
thermocline **down** to west

rain follows warmest SST;
surface winds converge
onto rainy/warm zones

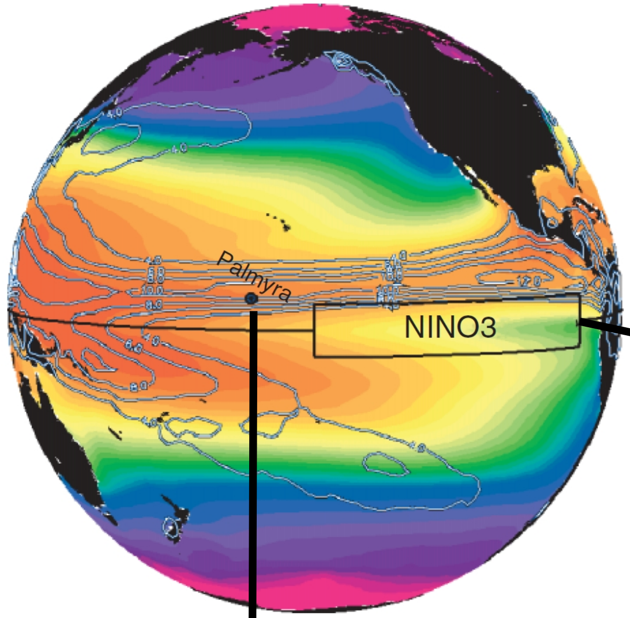
El Niño

Events occur at
irregular intervals (2-8yr);
peak around Nov-Dec;
last about a year;
often followed by La Niña

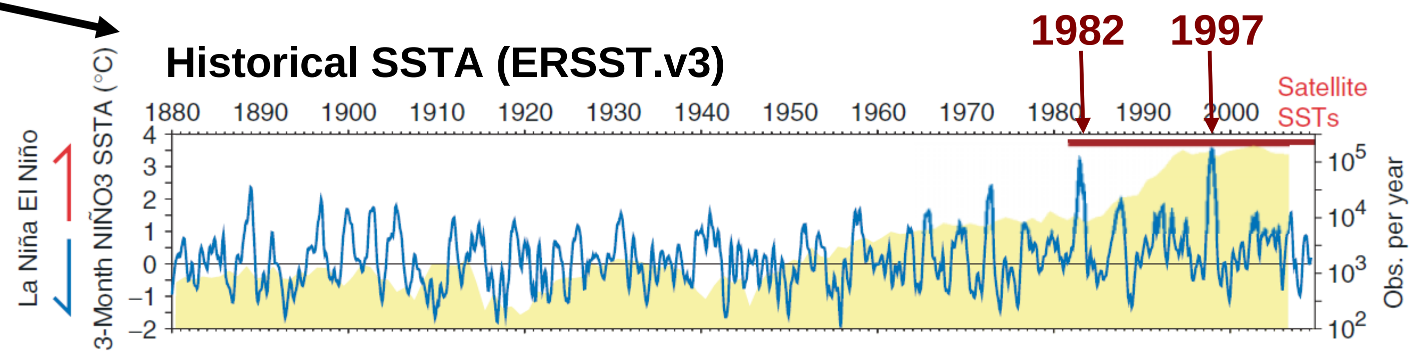
Fundamentally coupled phenomenon,
involving troposphere + top 300m of the tropical Pacific ocean.

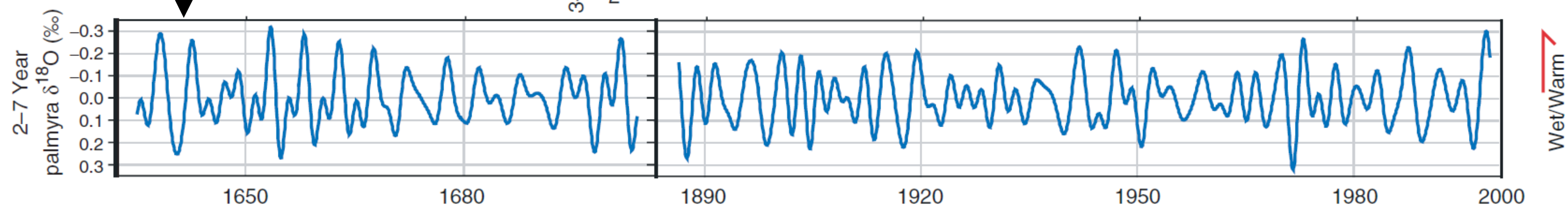
Intrinsic Modulation of ENSO

Both historical & paleo records suggest past modulation of ENSO

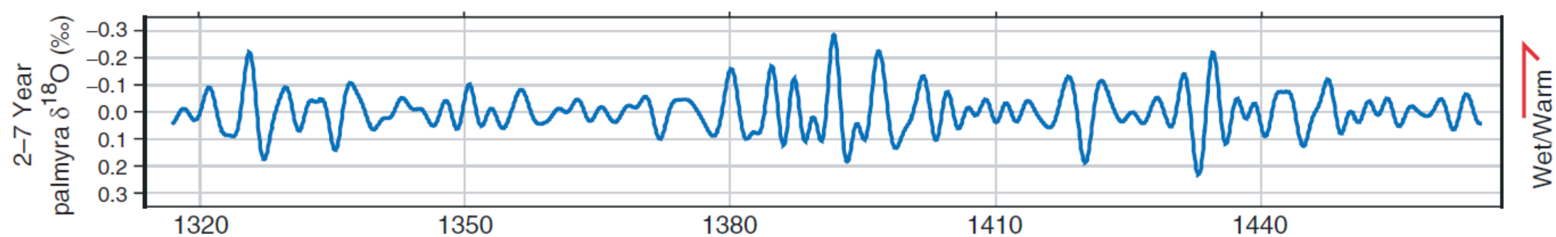


Vecchi & Wittenberg (WIREsCC 2010)

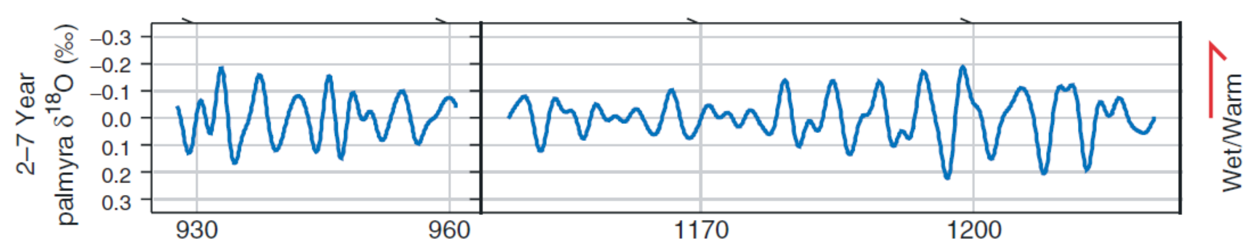




Palmyra corals (Cobb et al., Nature 2003)



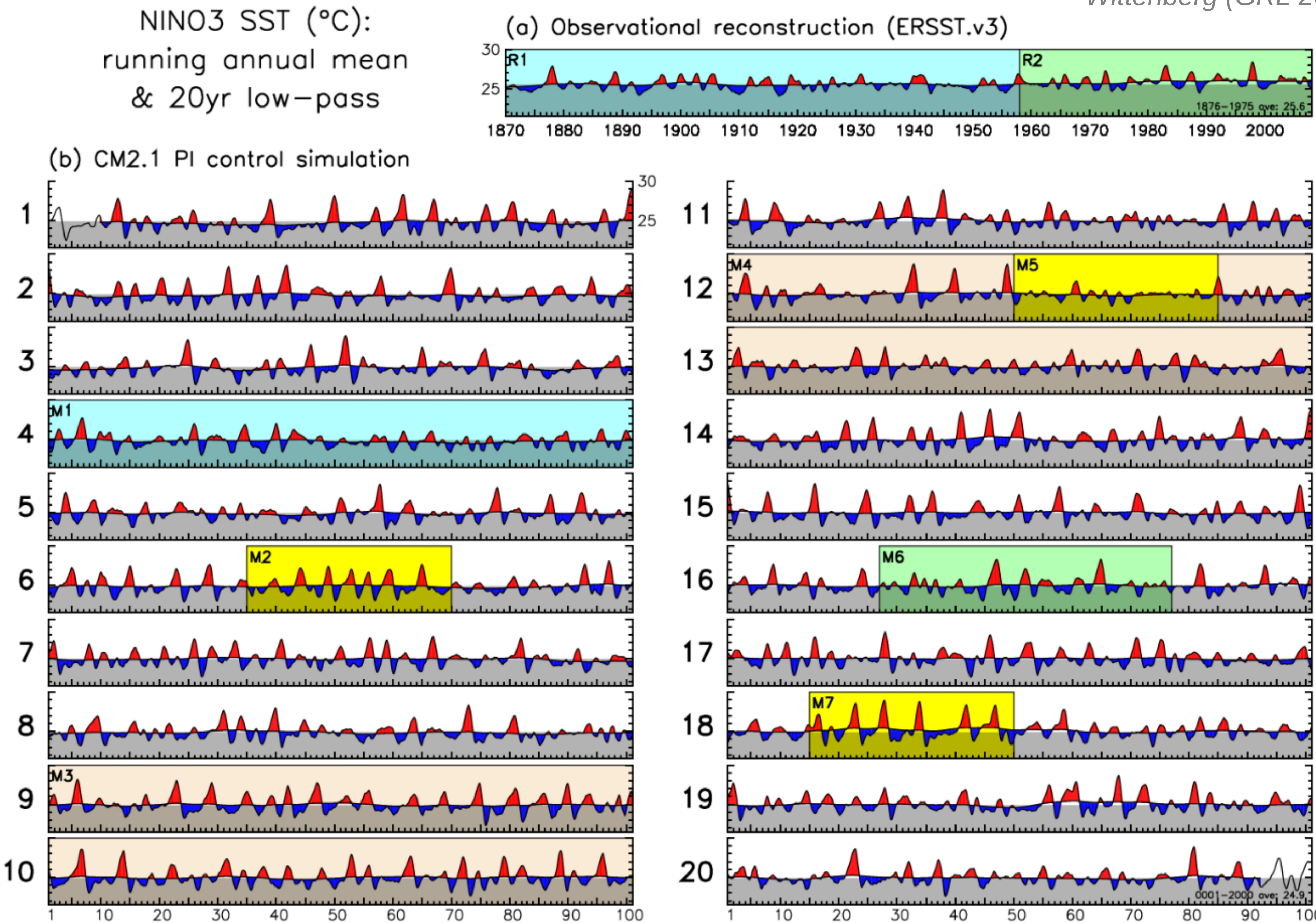
Multiproxy reconstructions:
e.g. Li et al. (NCC 2011);
Emile-Geay et al.
(J. Climate, 2013ab);
McGregor et al. (CP 2013)



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

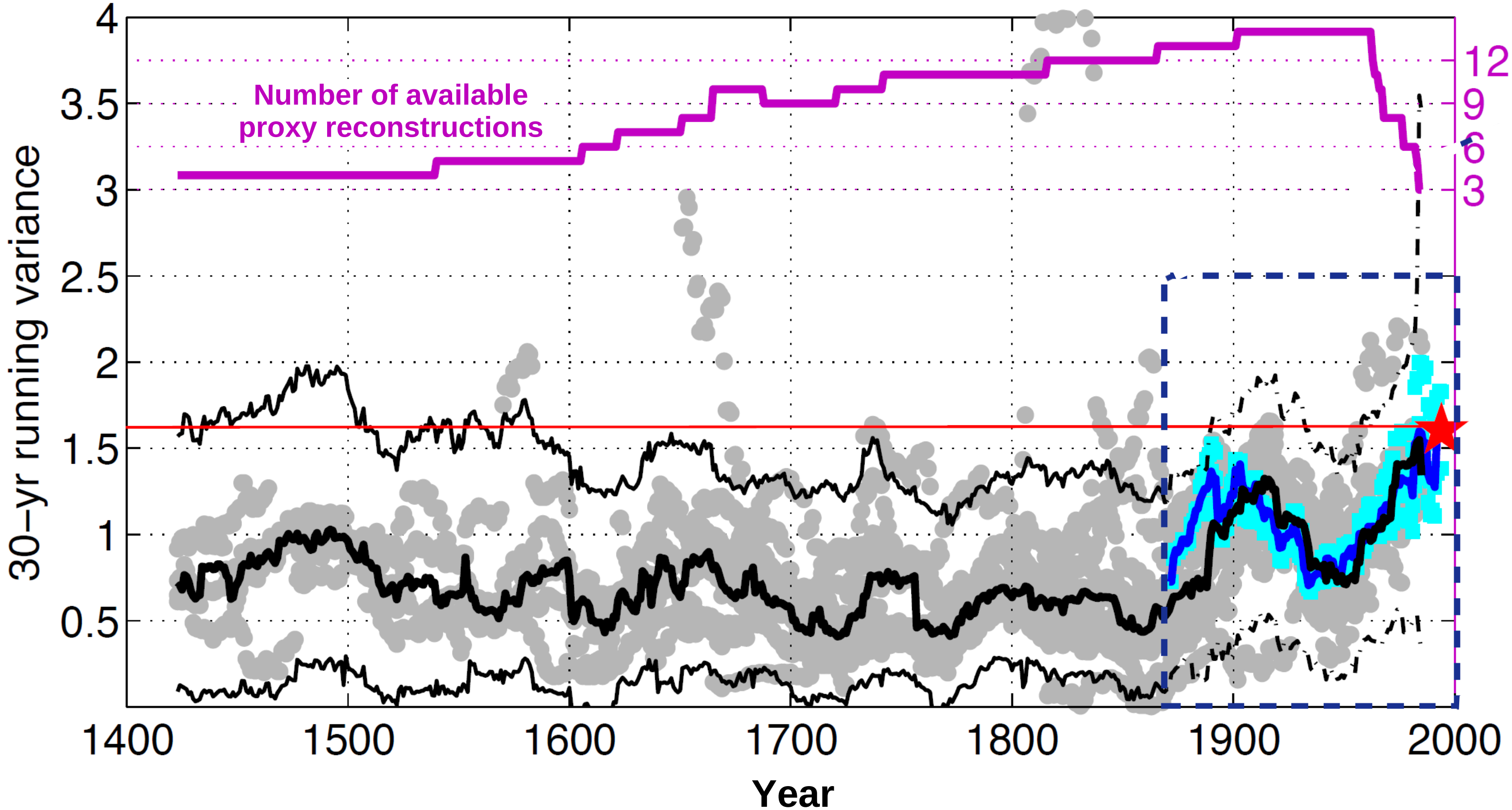
ENSO modulation in a 2000-year control simulation

Wittenberg (GRL 2009)



Reconstructing past variations in ENSO

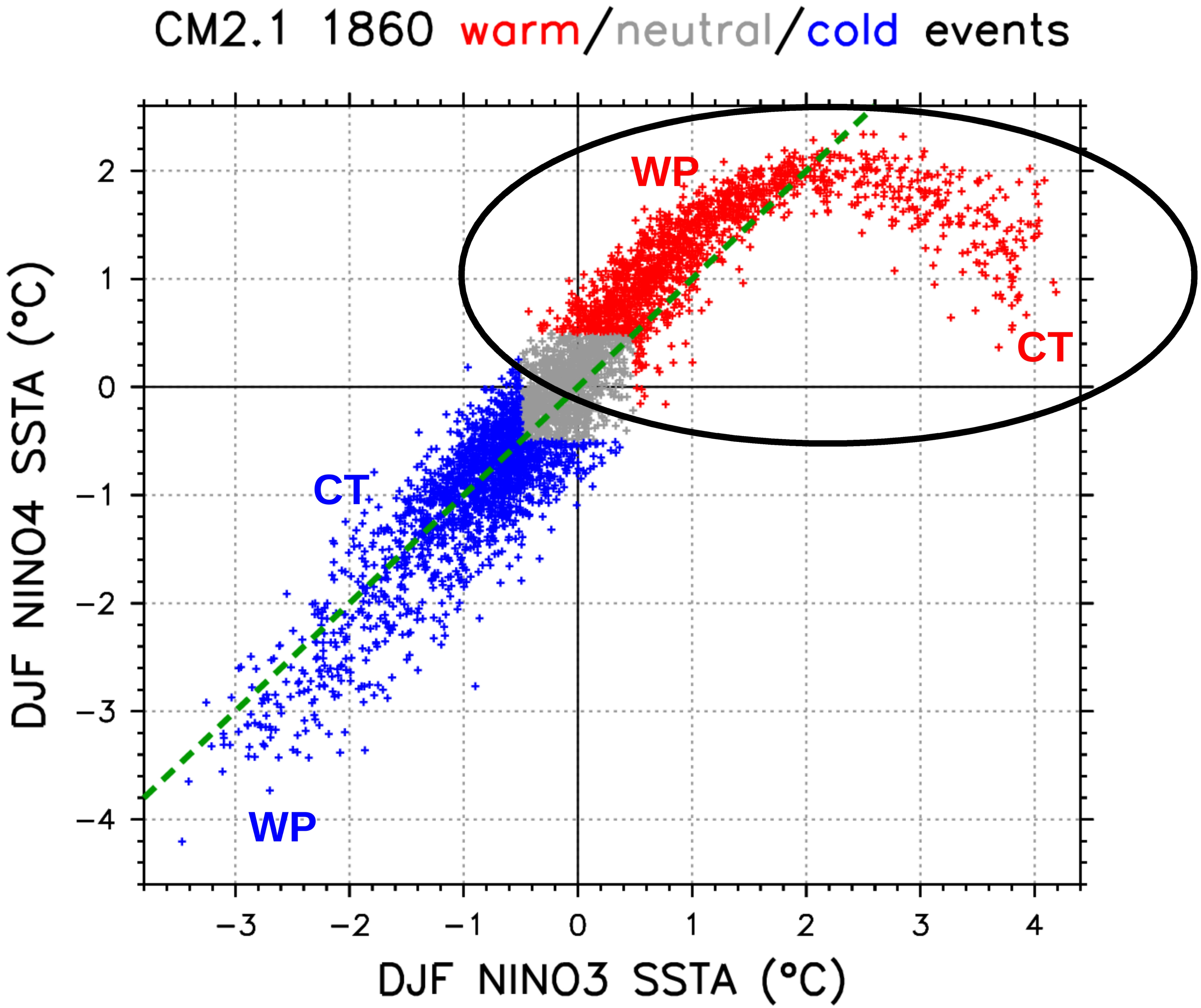
Proxy evidence suggests that ENSO activity has waxed & waned, with significant amplification in recent decades.



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.

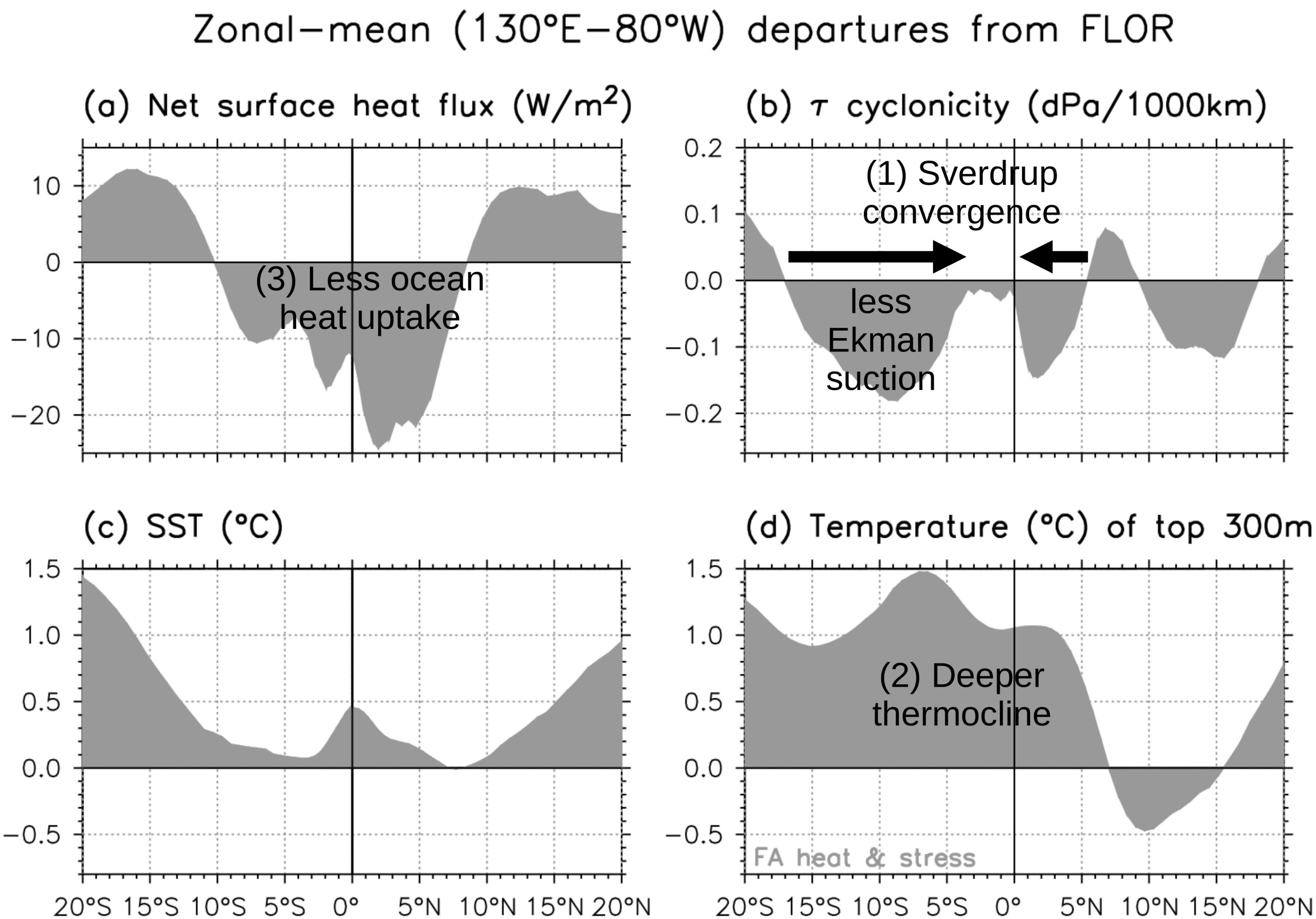
McGregor et al. (Clim. Past, 2013)

An ENSO continuum



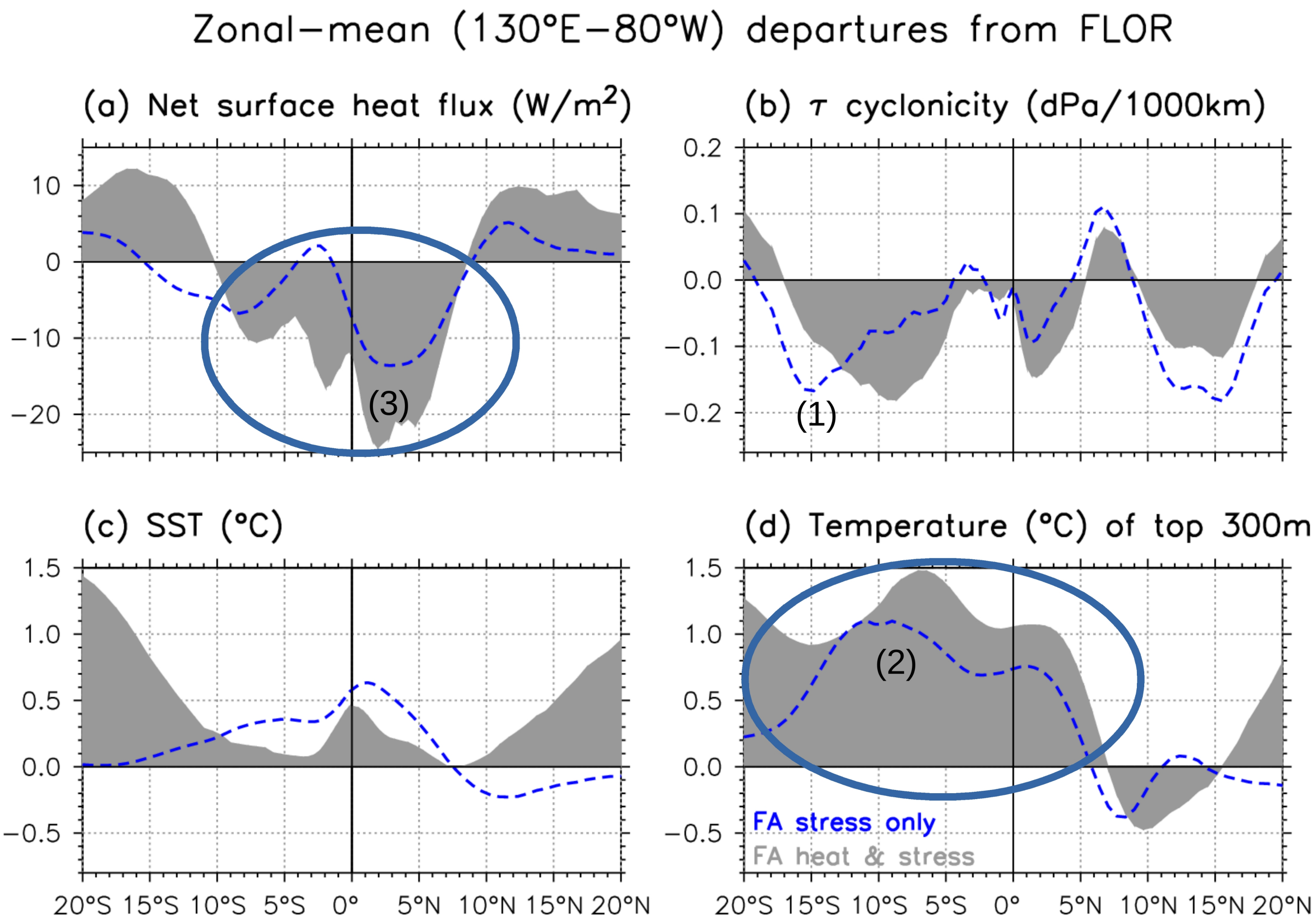
Opportunities for Improvement

Impact of flux adjustments (Pacific zonal mean)



The **FA** weakens the wind stress cyclonicity, **deepening the thermocline** and weakening ocean heat uptake near the equator.

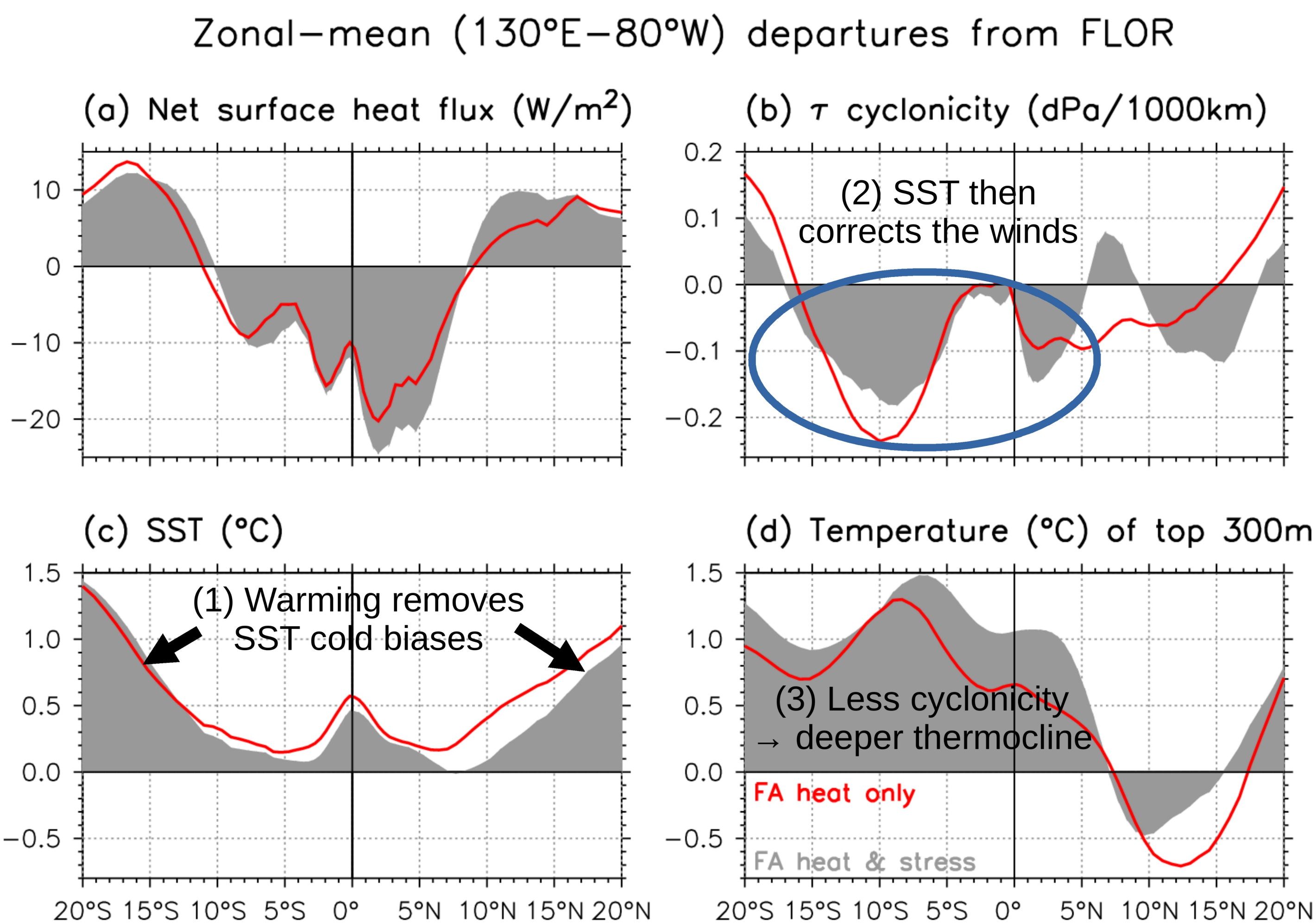
Impact of flux adjustments (Pacific zonal mean)



The **FA** weakens the wind stress cyclonicity, **deepening the thermocline** and weakening ocean heat uptake near the equator.

Stress-only FA has a similar effect on the thermocline & heat uptake. So the **off-equatorial wind stress curl** is crucial!

Impact of flux adjustments (Pacific zonal mean)



The **FA** weakens the wind stress cyclonicity, **deepening the thermocline** and weakening ocean heat uptake near the equator.

Stress-only FA has a similar effect on the thermocline & heat uptake. So the **off-equatorial wind stress curl** is crucial.

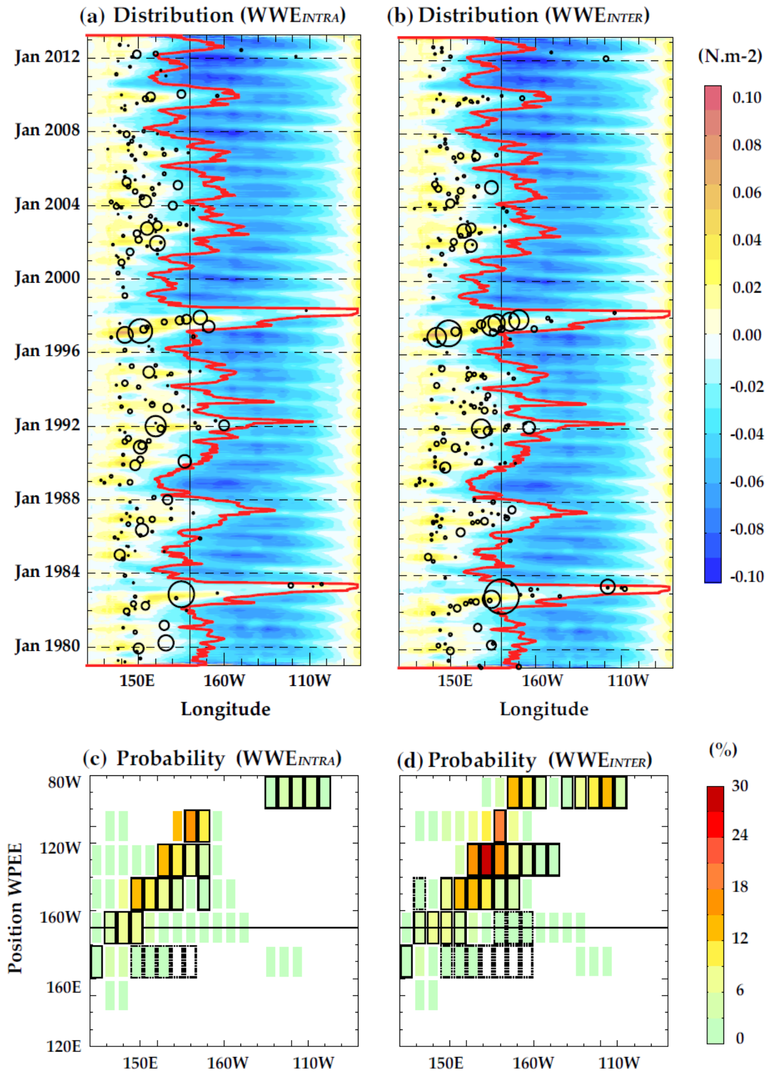
Heat-only FA does this too. But indirectly: corrected SST → corrects winds. So **off-equatorial surface heat flux** is crucial as well.

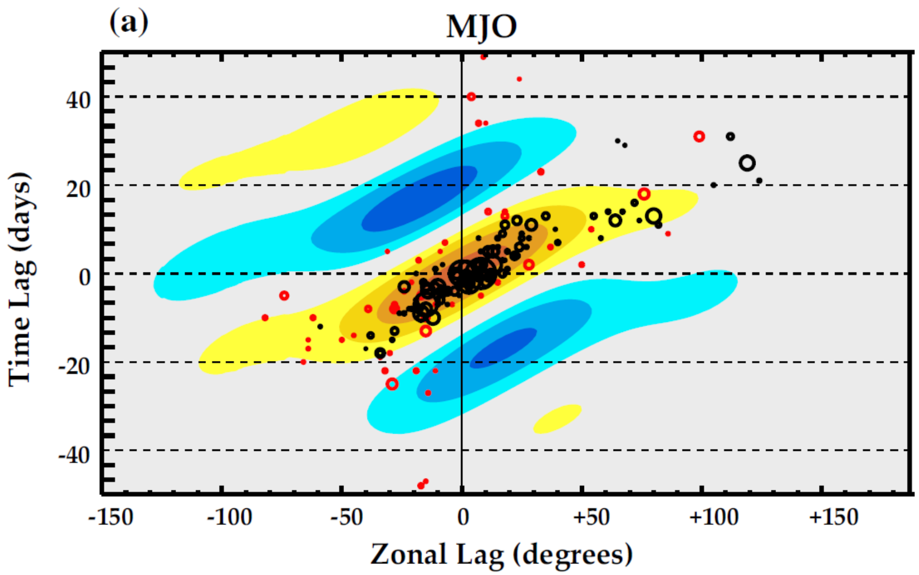
Off-equatorial heat flux & wind stress affect equatorial thermocline & heat uptake.

We need reliable observations of time-mean off-equatorial fluxes!

Intraseasonal Interactions

WWE modulation & rectification





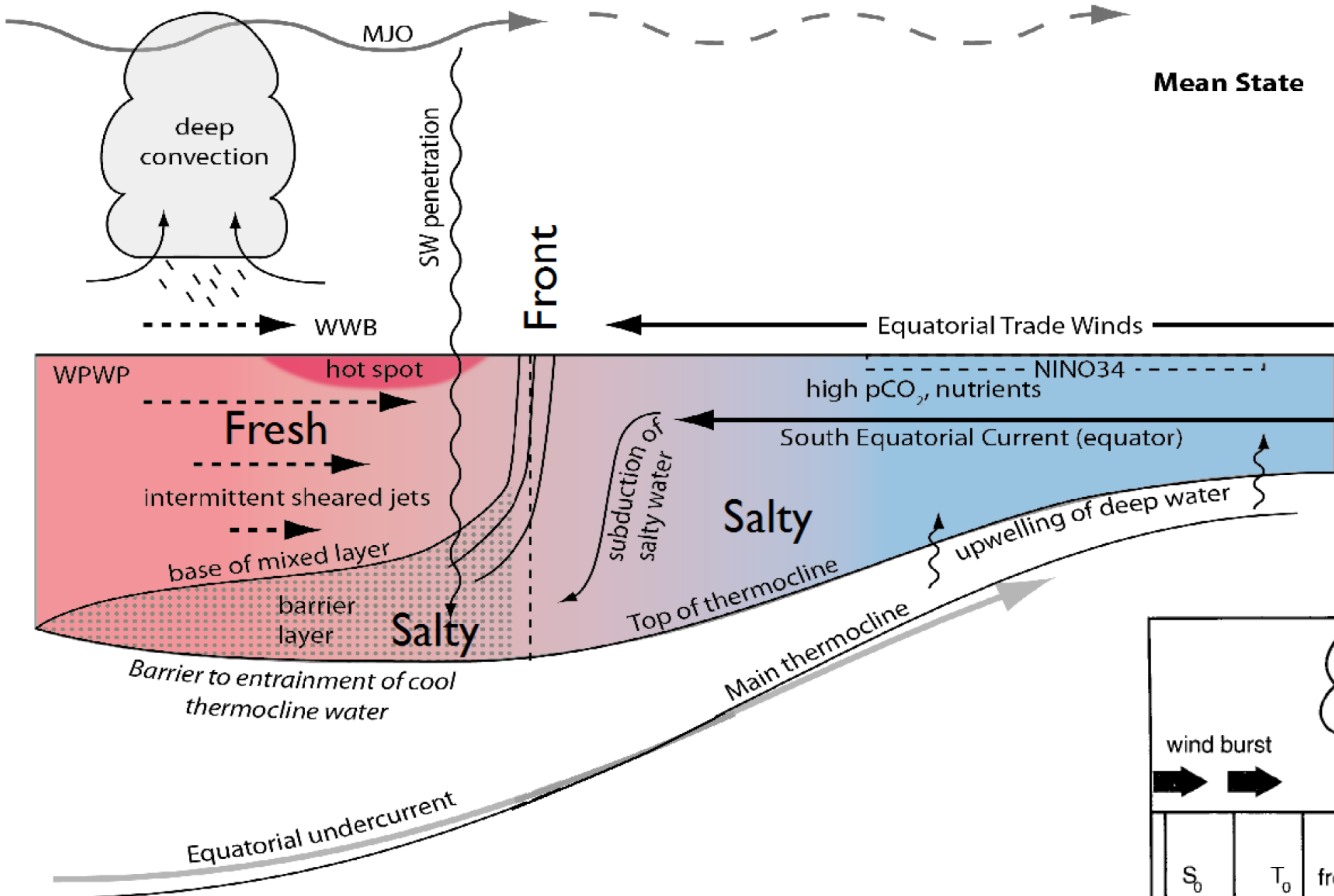
Puy et al. (2016)

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

"multiplicative noise"

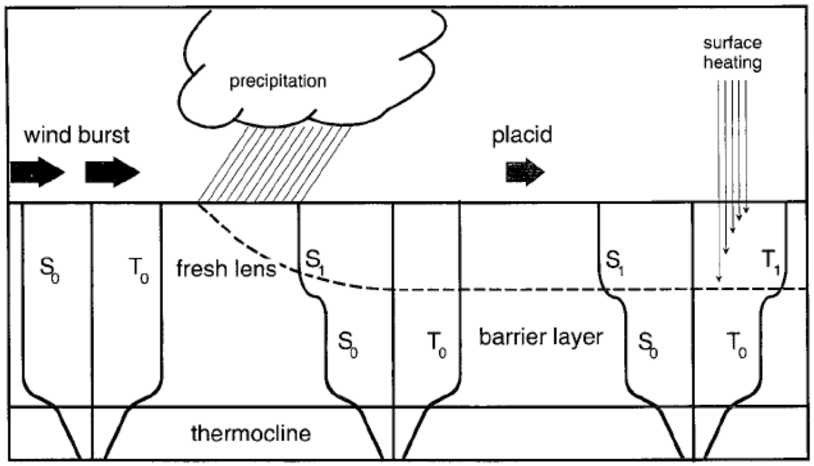
WWEs spread east with the warm pool; modulated by MJO.
Contribute to EN/LN **asymmetry** & seasonality.
Make strong ENs hard to predict, especially through boreal spring.

Salinity barrier layers



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

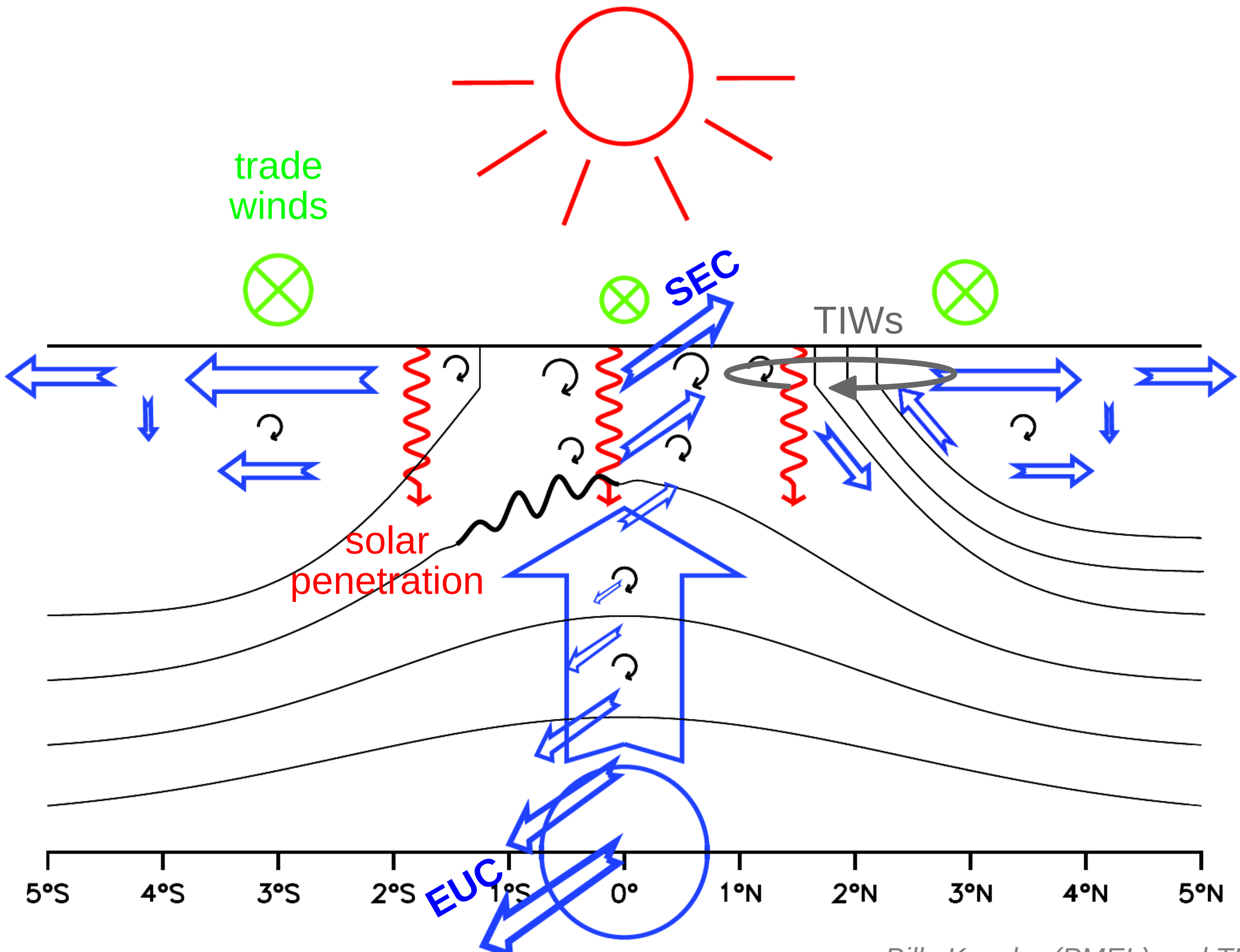
Anderson et al. (1996)



TPOS/Brown et al. (2015)

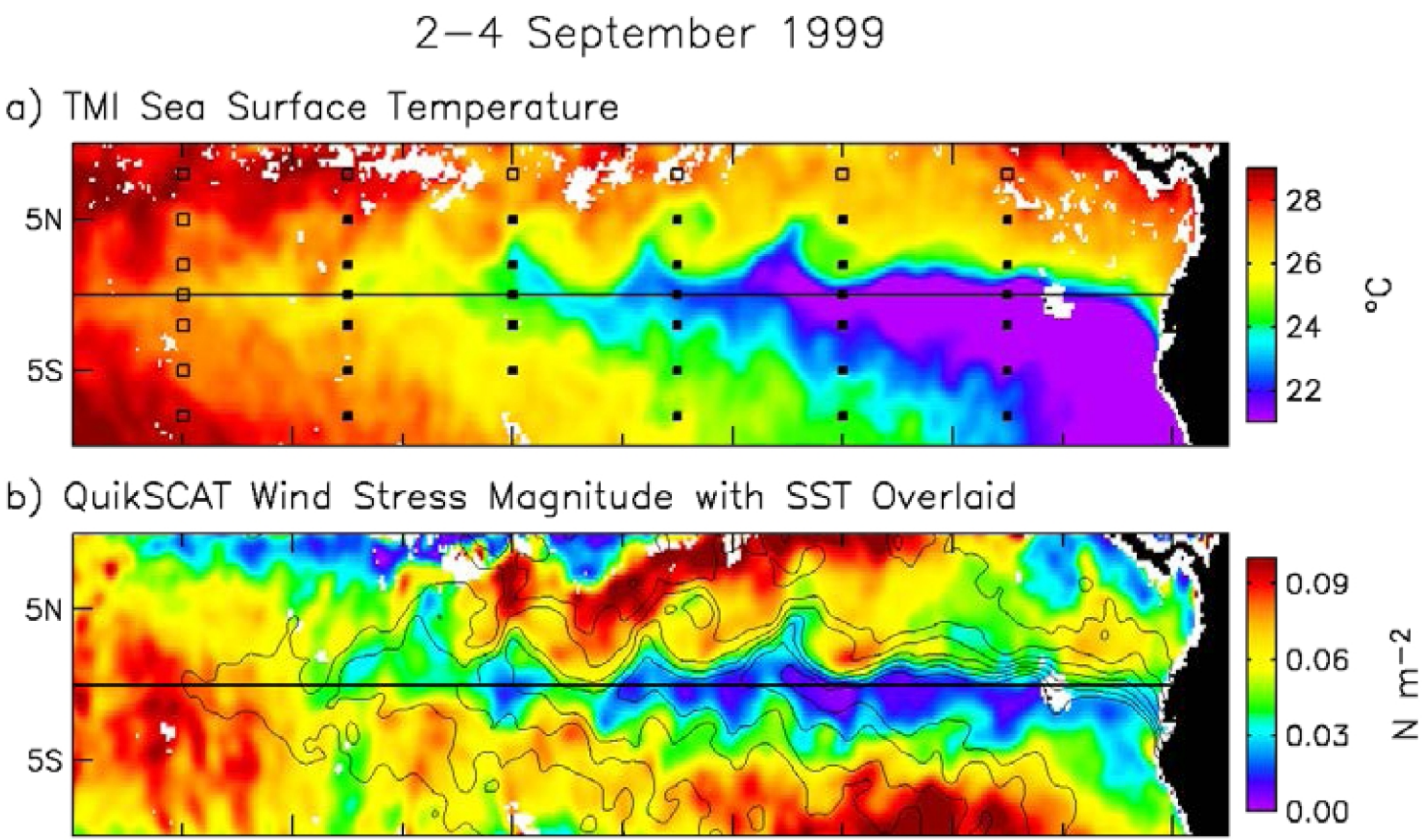
Heavy rain shoals the mixed layer, boosts coupling/noise at EN onset.
Contributes to EN/LN asymmetry.

Meridional structure of the equatorial Pacific



Billy Kessler (PMEL) and TPOS2020

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)

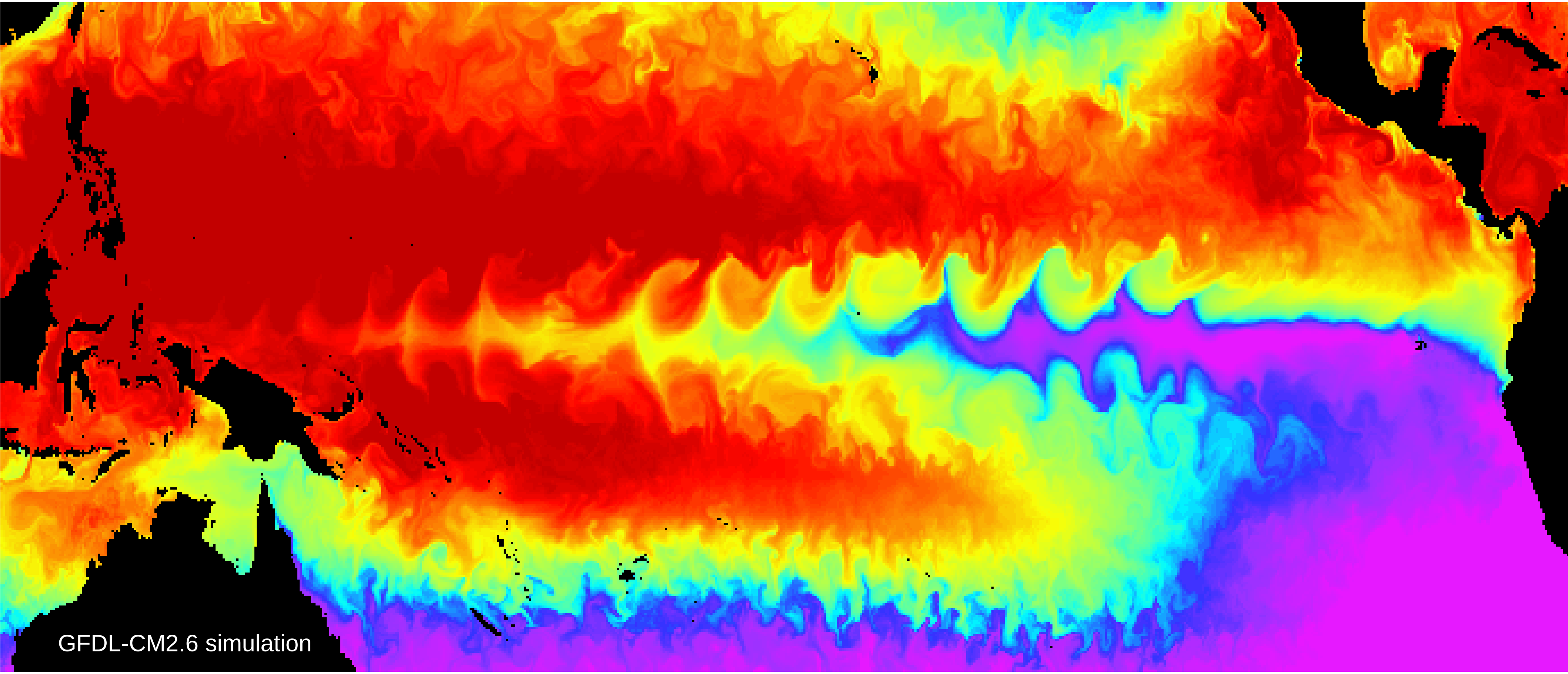
Ray et al. (2019)

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.

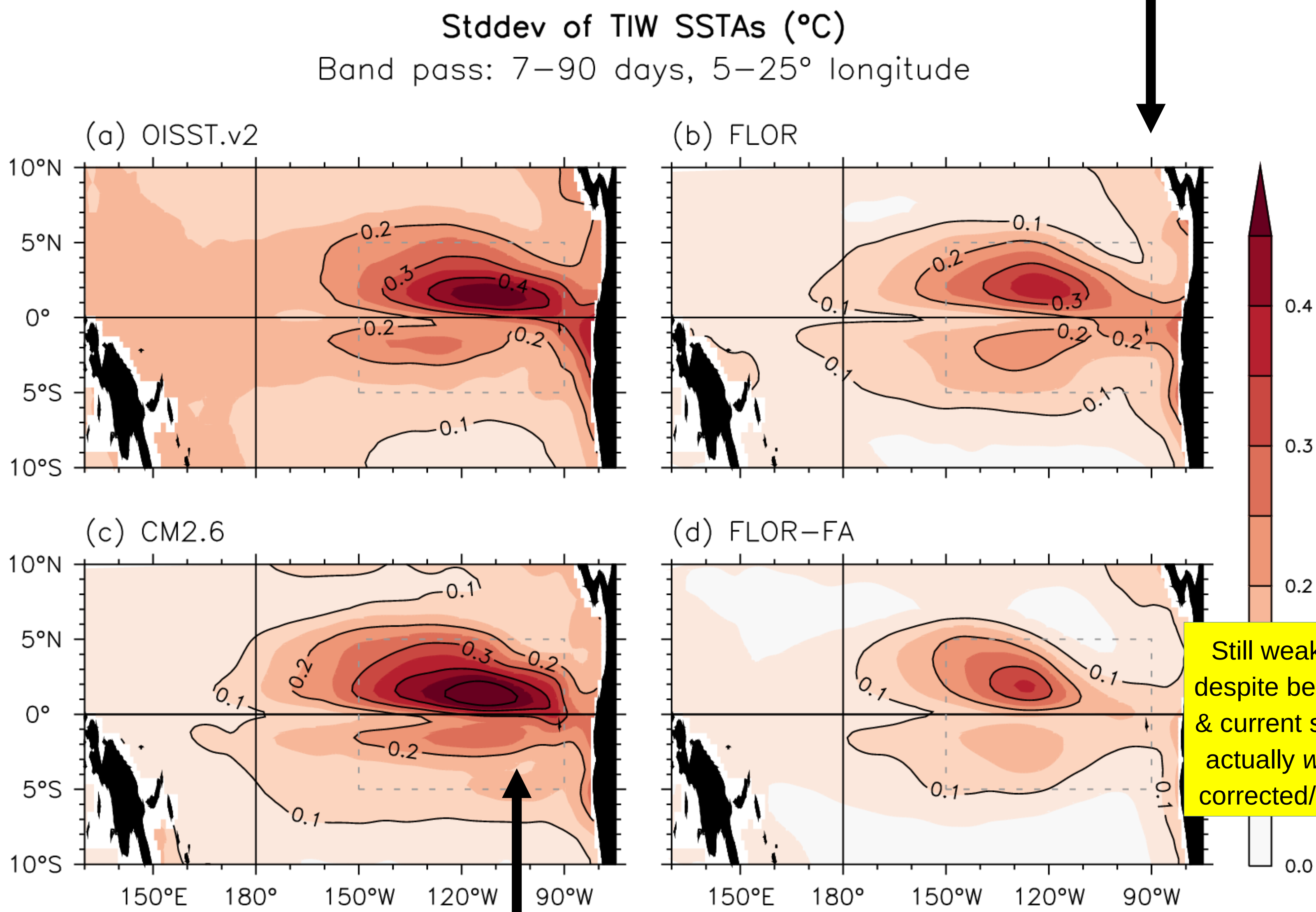
Tropical Instability Waves (TIWs)

TIWs stir off-equatorial surface heat equatorward,
induce vertical mixing & cooling at depth

--> enhance thermal stratification near the equator.



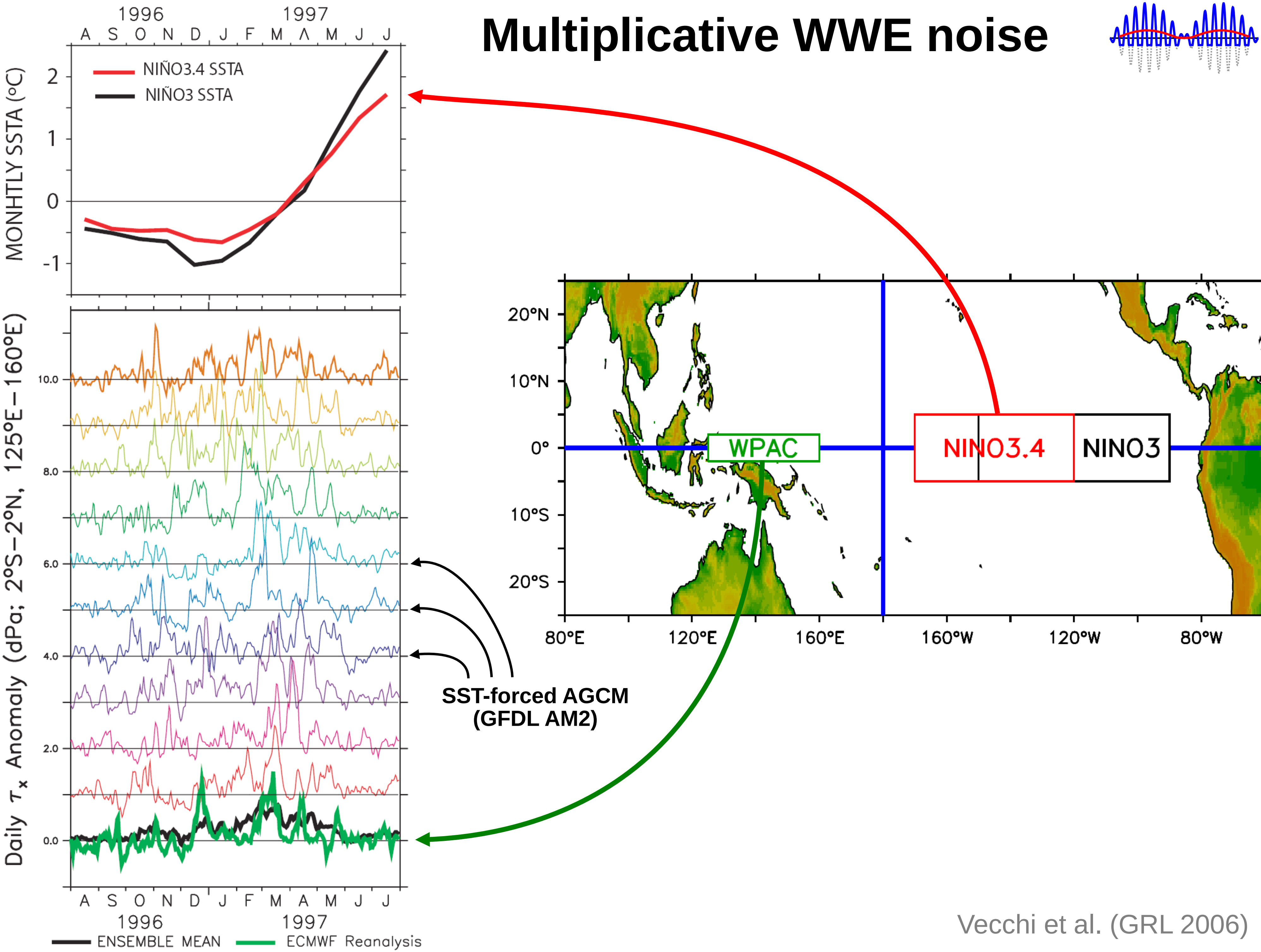
With a **1x0.33° ocean**, **TIWs are too weak** in FLOR & FLOR-FA
→ **weak restratification** at equator.



Still weak in FLOR-FA, despite better wind stress & current shears. (SSTAs actually *weaken*, due to corrected/weaker dT/dy.)

CM2.6 (**0.1° ocean**) has much stronger TIWs (and stronger equatorial dT/dz).
Need observational constraints for TIW-driven mixing & heat budget.

Multiplicative WWE noise

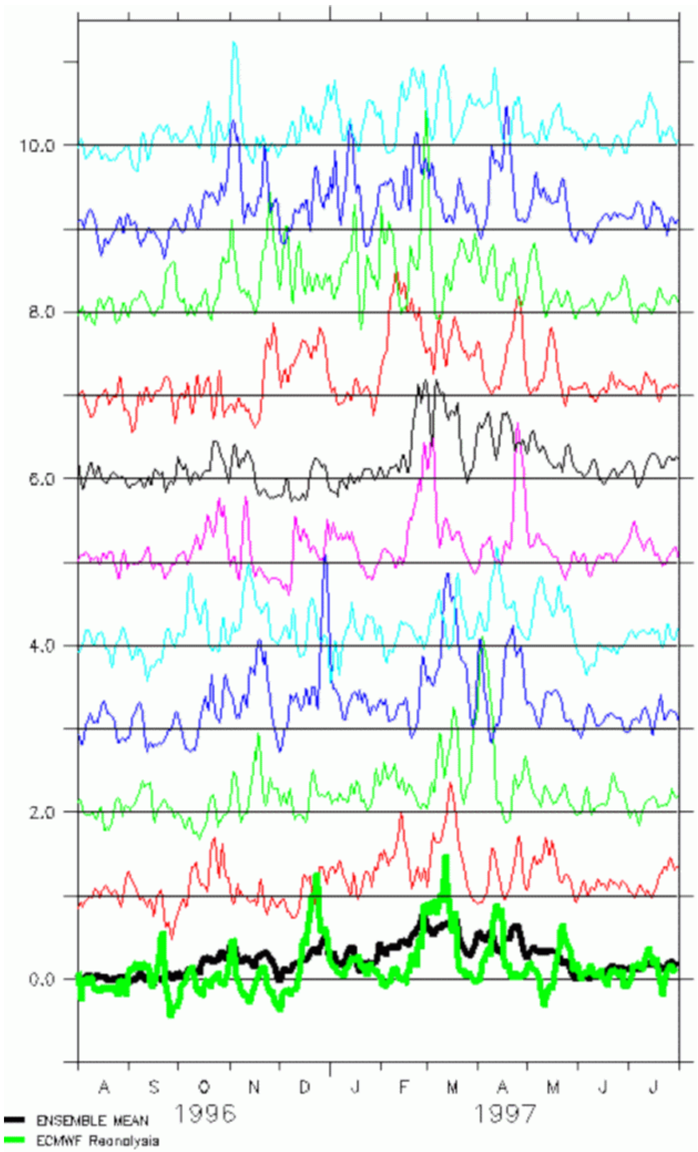


Vecchi et al. (GRL 2006)

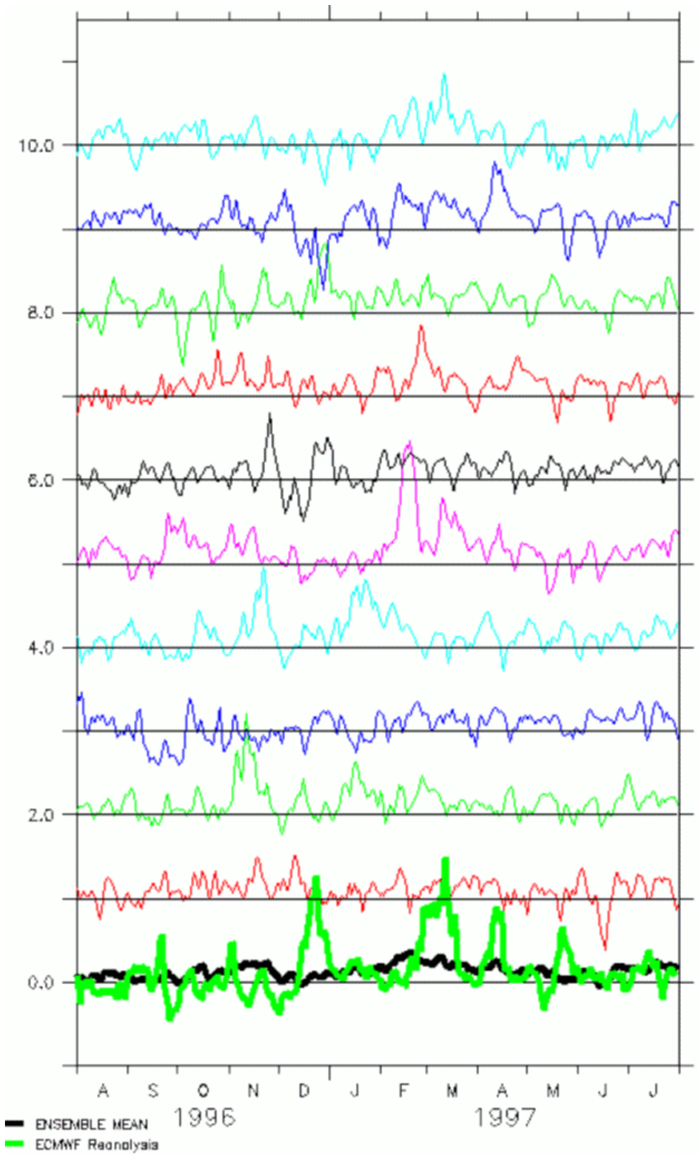
Stochastic forcing: A role for the Indian Ocean

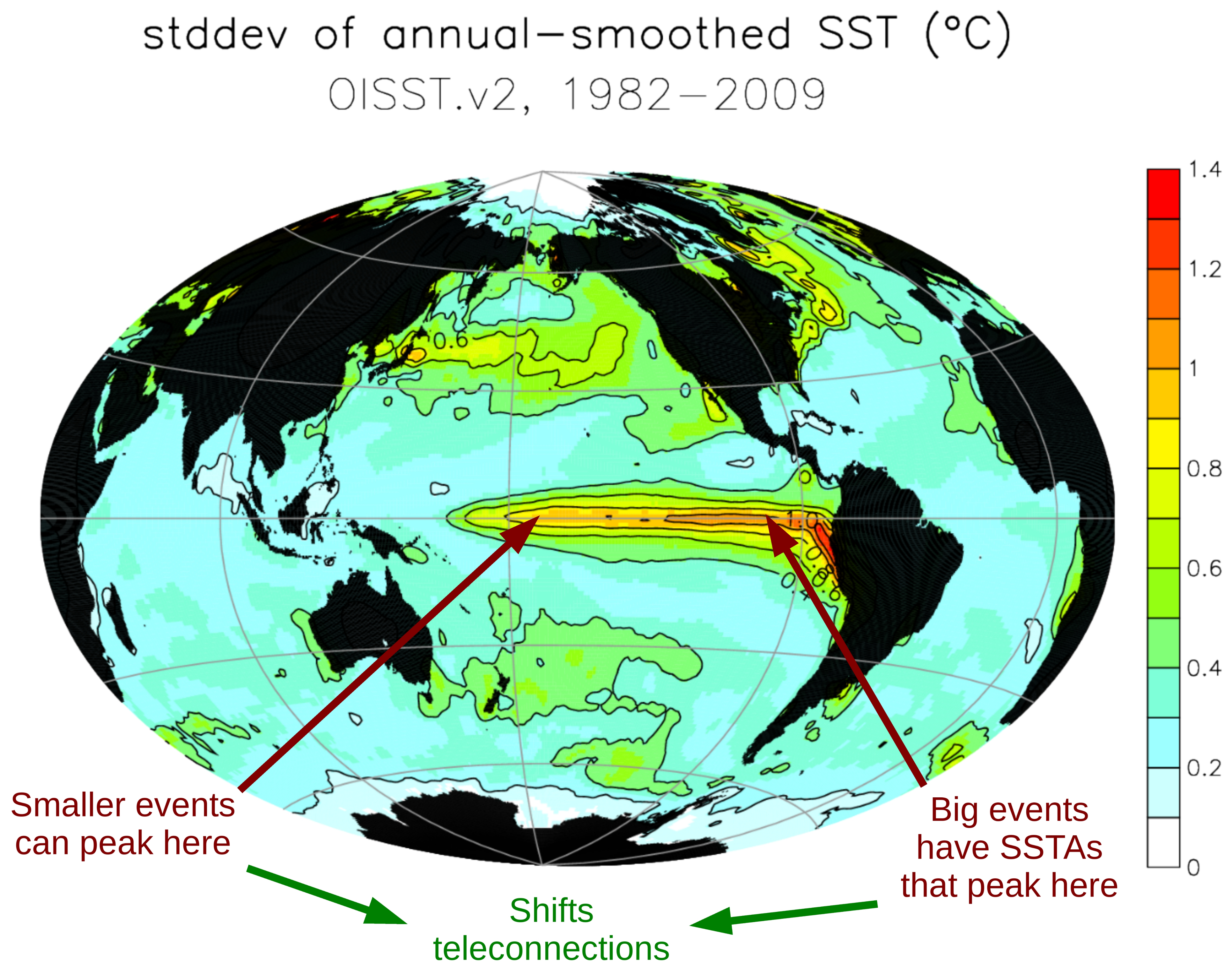
Daily west-Pacific zonal stress from 10 AM2 runs

Observed SST forcing



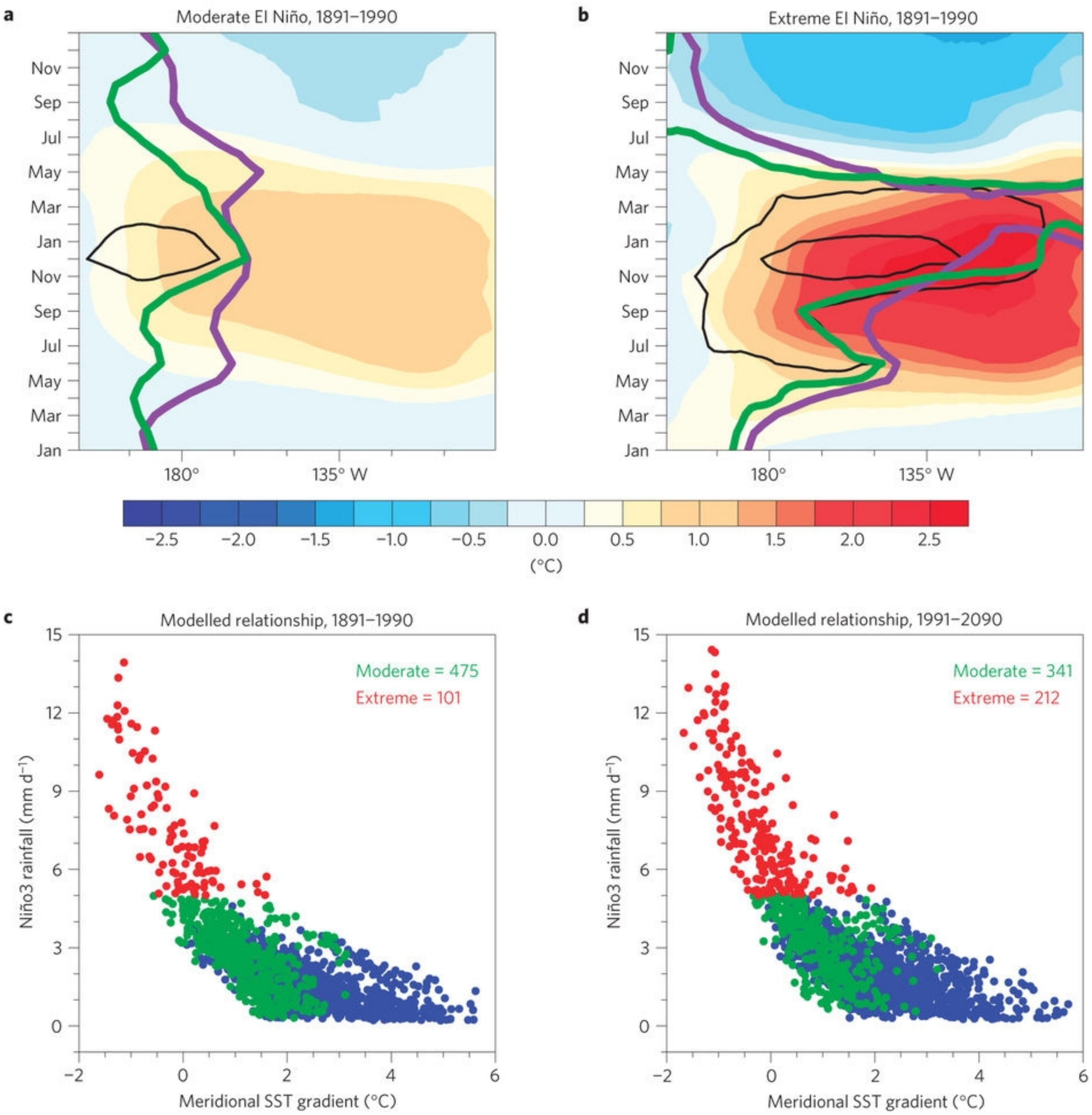
Warm East Indian



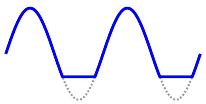

stddev of annual-smoothed SST (°C)
OISST.v2, 1982–2009
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.6
1.0
Smaller events can peak here
Big events have SSTAs that peak here
Shifts teleconnections

Climate Change

Background SST affects ENSO rain response



Cai et al. (2014)



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

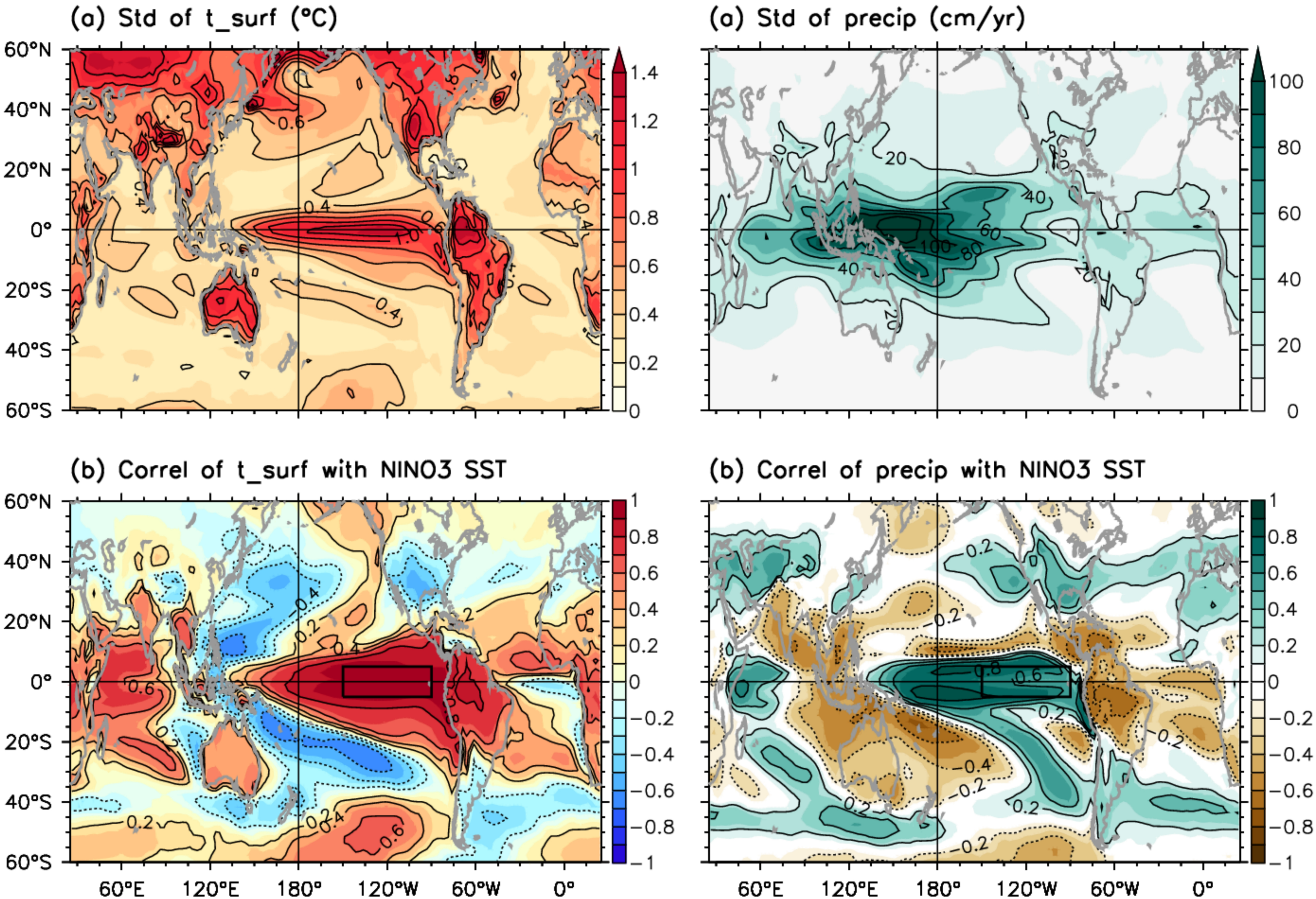
So how will background SST gradients change in the future?

Weaker dT/dy & dT/dx?

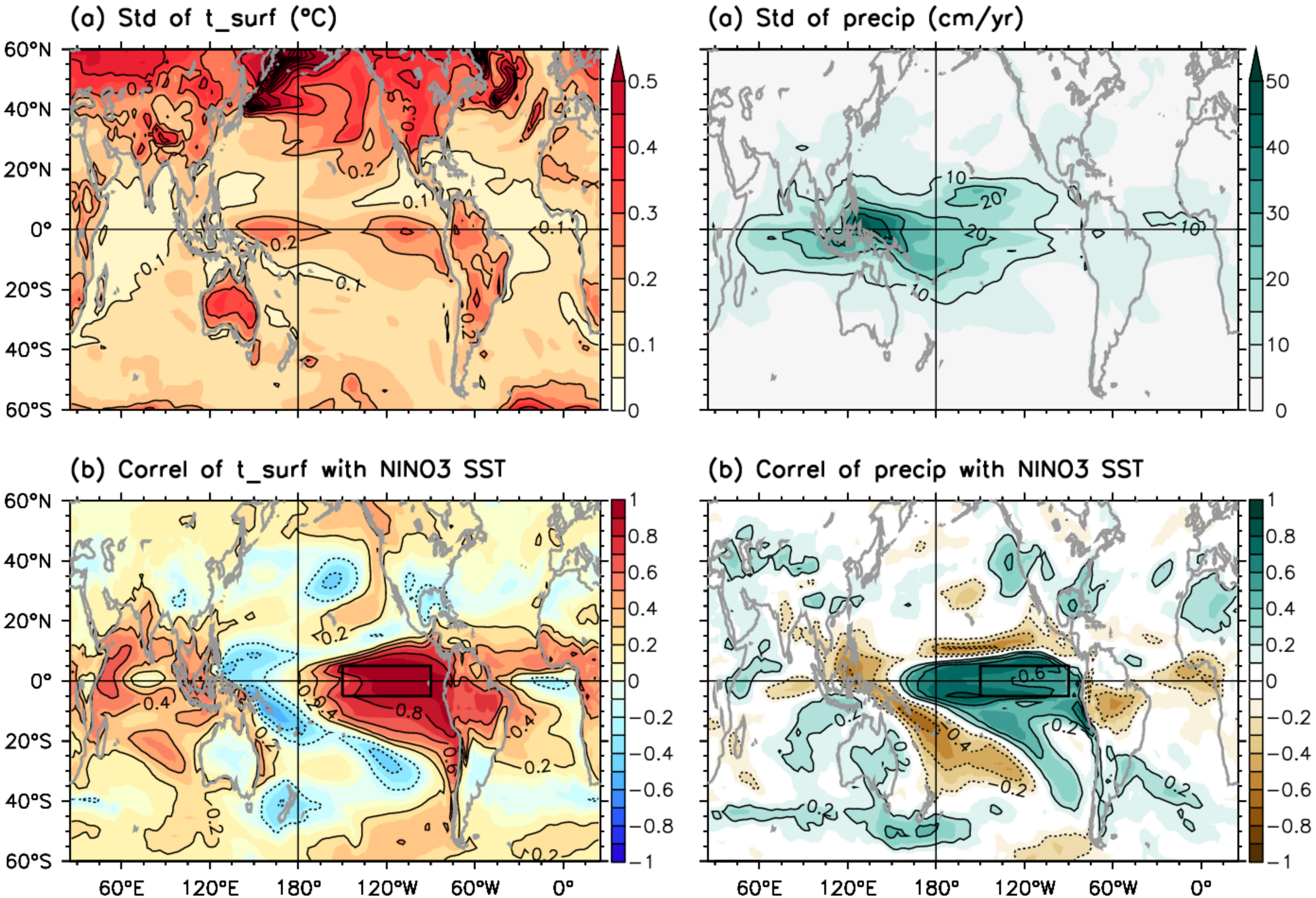
Relatively warmer Indian & Atlantic Oceans?

Luo et al. (2012)
Wieners et al. (2017)

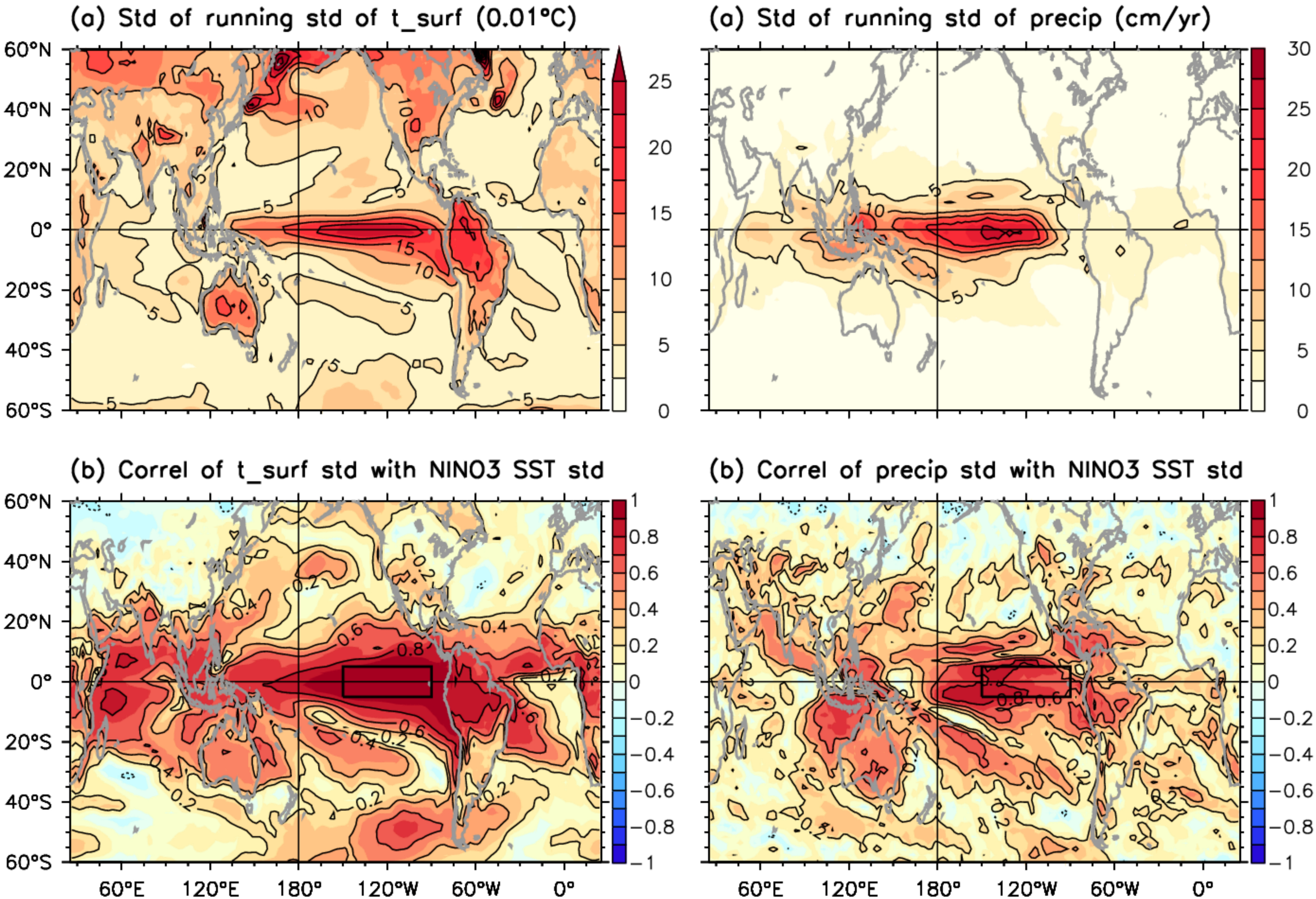
Interannual variability patterns in CM2.1



Intrinsic multidecadal variability in CM2.1



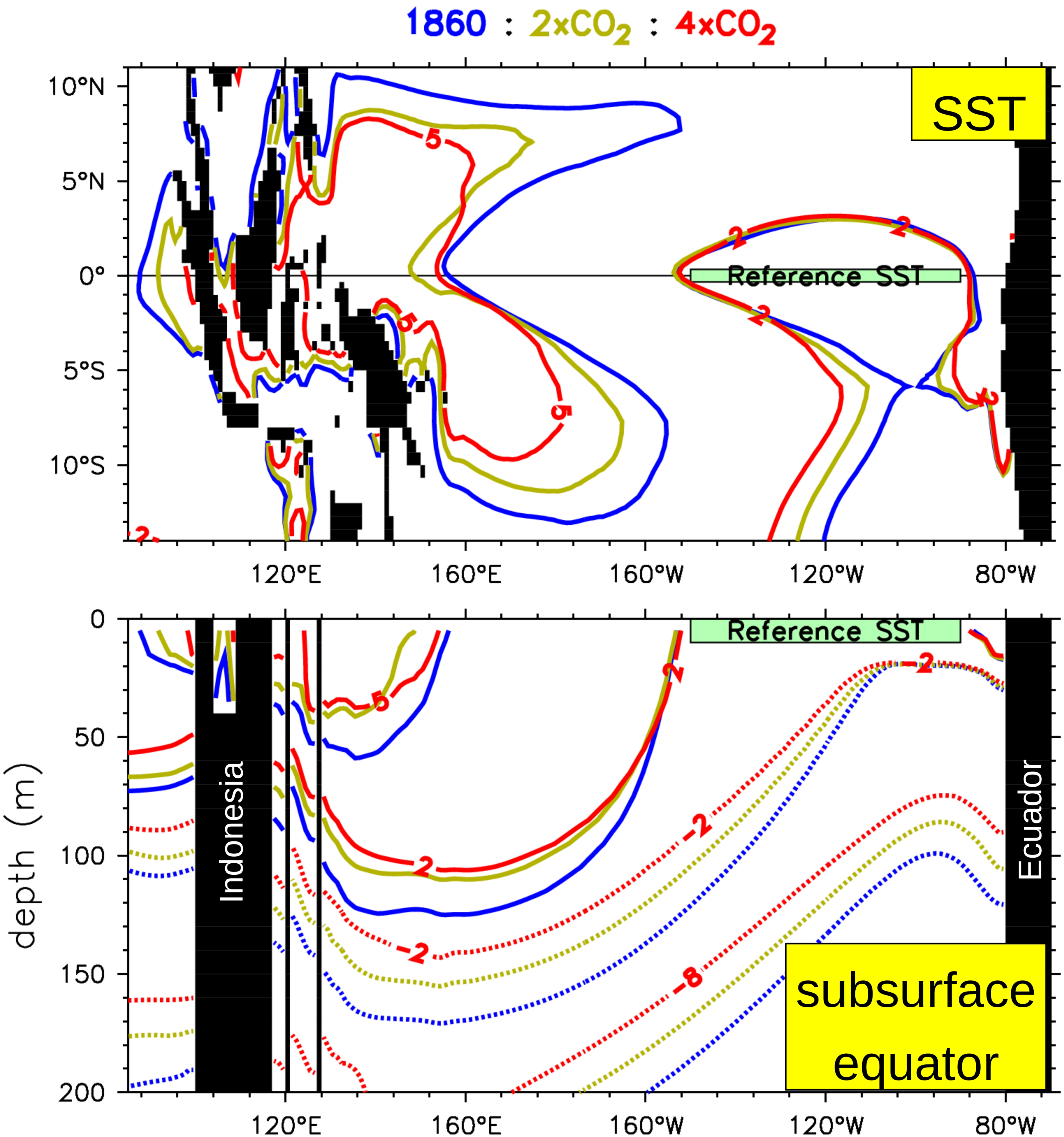
Decadal modulation of interannual variability



As CO_2 increases:

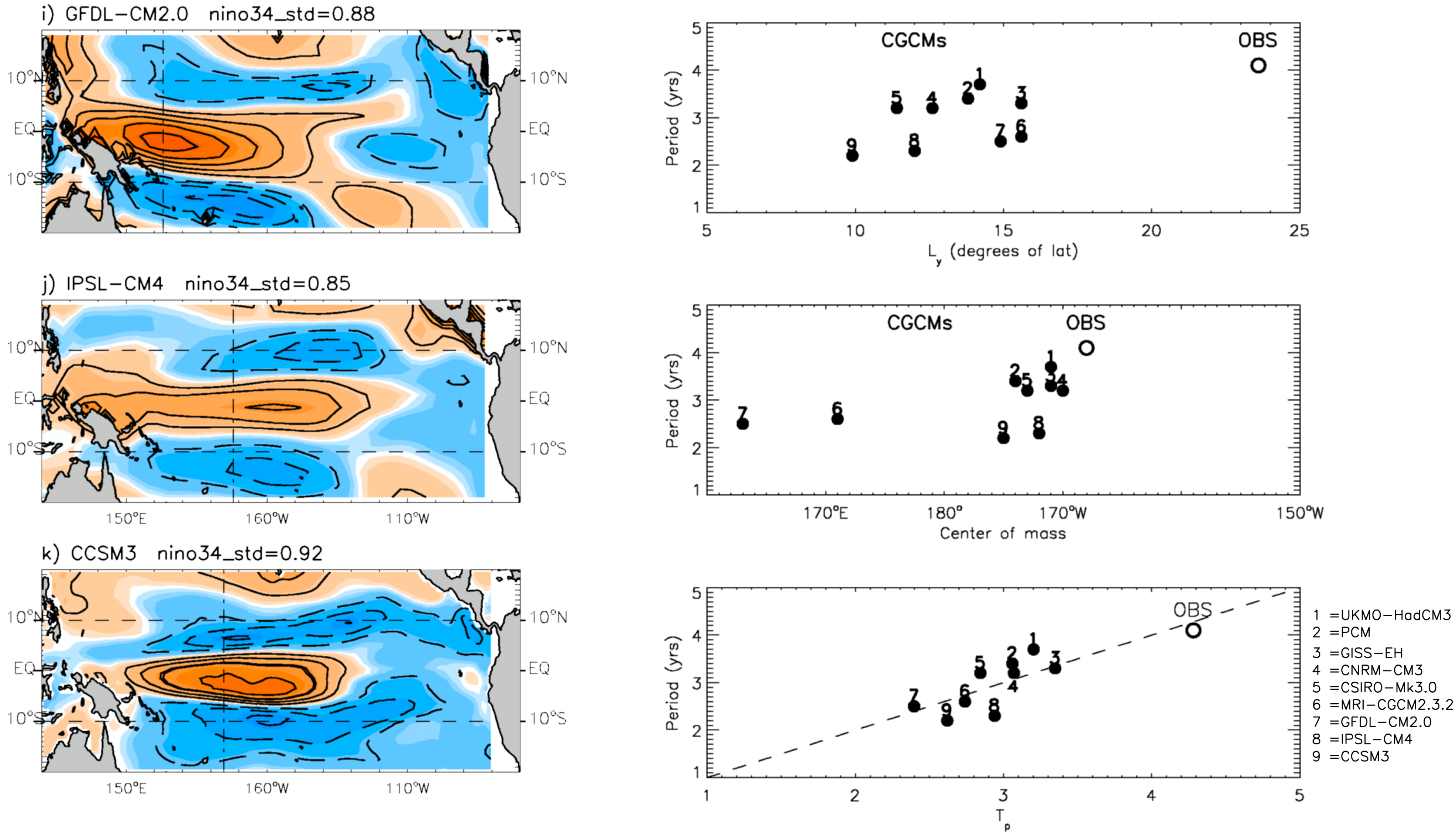
Relative to ECT SSTs, the warm pool contracts.

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



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

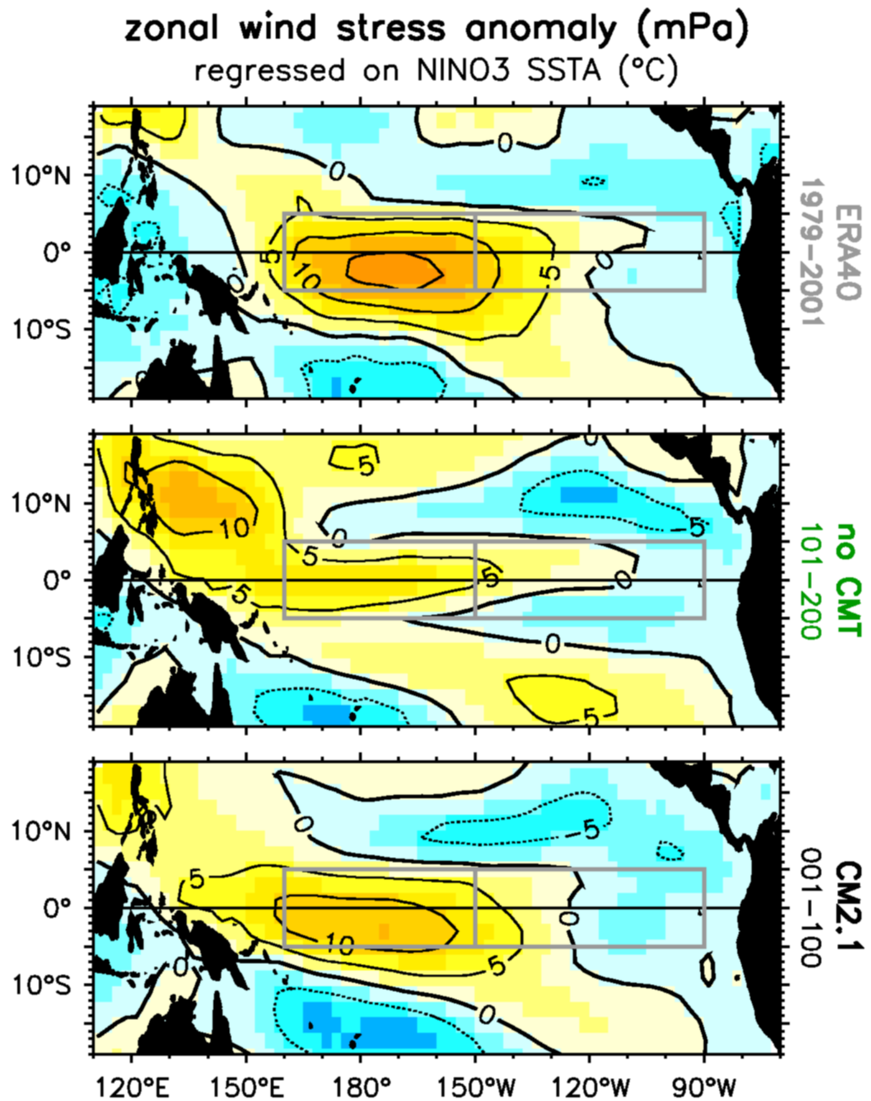
Capotondi et al. (*Ocean Modelling*, 2006)

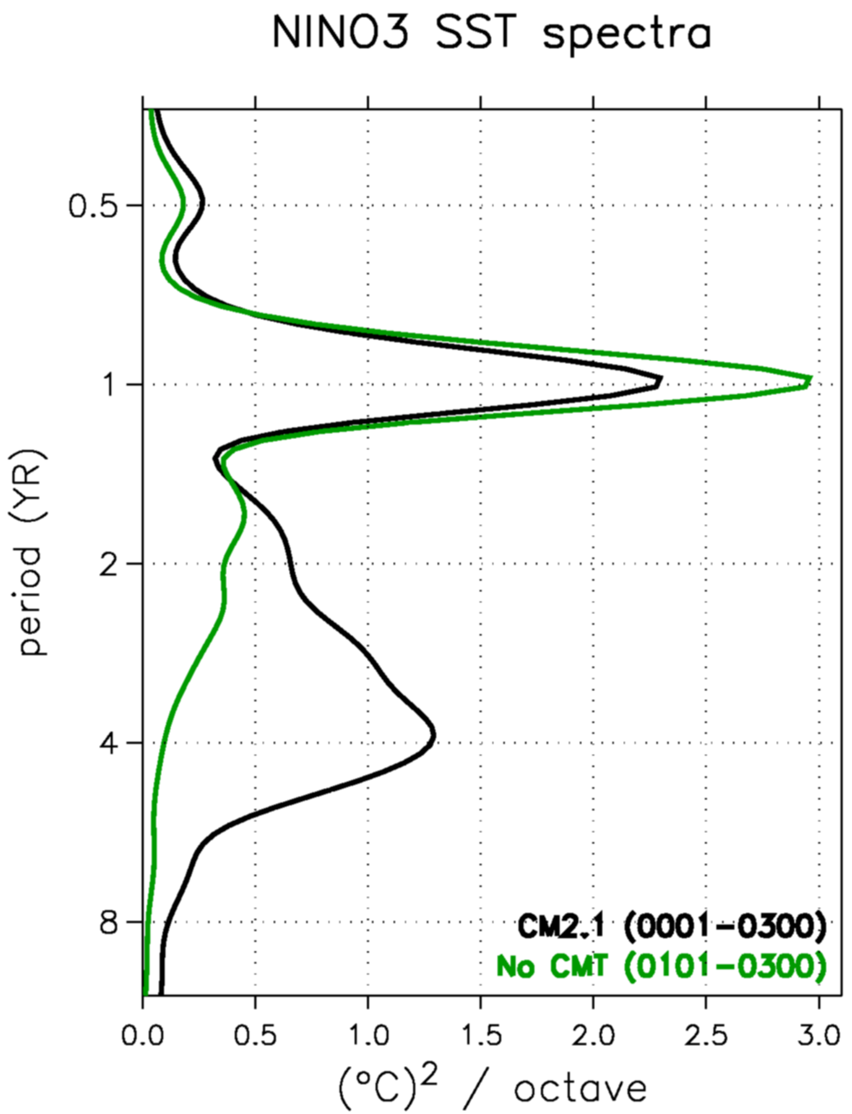


$T_p = 3.05 + (L_y - 14°)/9.6° + (C - 184°)/30°$

$corr(T, T_p) = 0.82 +/- 0.15$

Convective Momentum Transport (CMT)

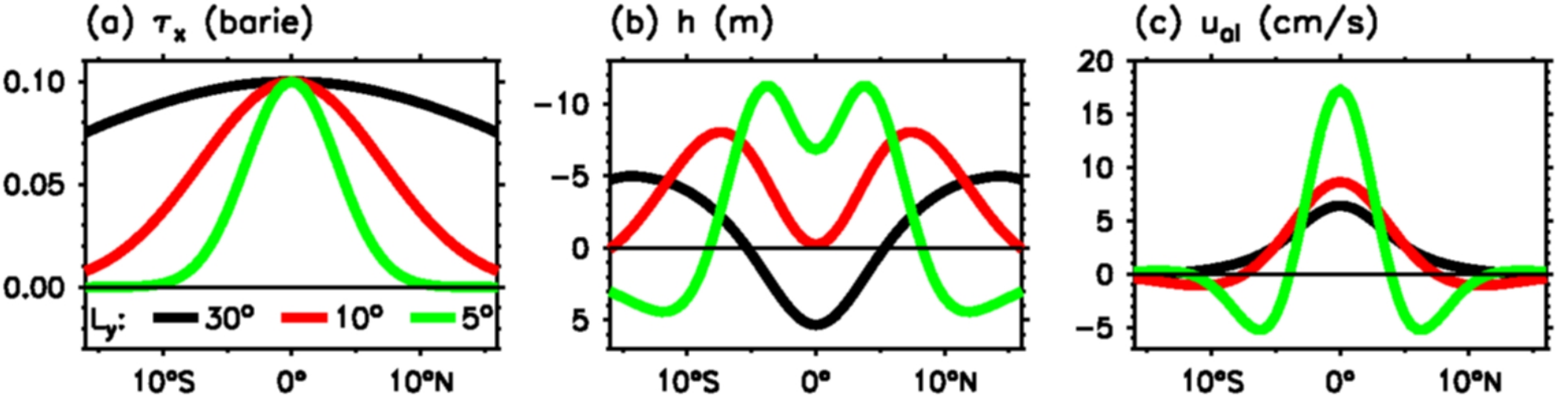




Broader westerly anomalies → longer ENSO period

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

Equatorial adjustment to off-equatorial stress



Wittenberg (2002)

ENSO onset: “CMIP3-average” anomaly regressions

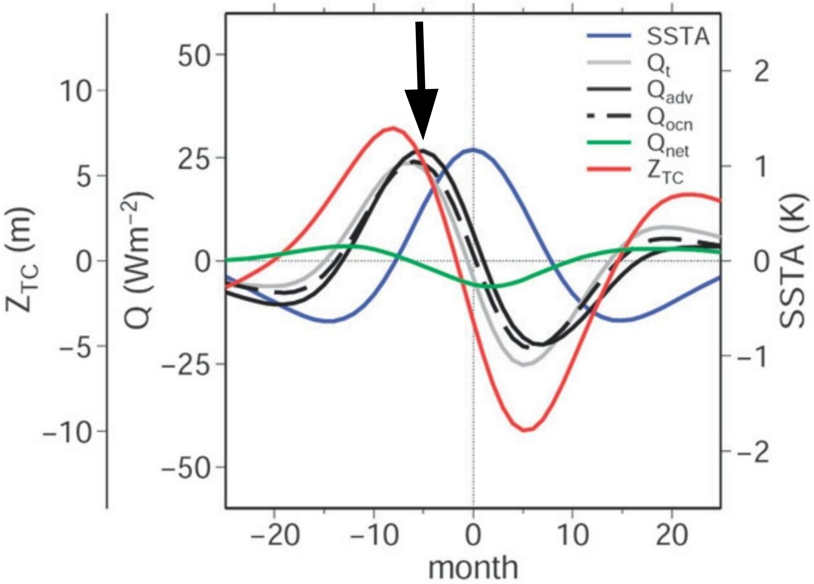


FIG. 1. Multimodel composite heat budget during the development, transition, and decay of warm ENSO events. Month zero is when SST anomalies peak. Black solid and dashed lines are the ocean dynamical heating computed using resolved currents (Q'_{adv}) and as a residual of the heat budget (Q'_{ocn}), respectively. The green line is the net atmospheric heat flux (Q'_{net}). Positive values of heating terms indicate a warming tendency. The red line is the depth of the thermocline (Z_{TC}). All variables are seasonal anomalies averaged over the models Niño-3.4m region (2.5°S–2.5°N, 180°–110°W).

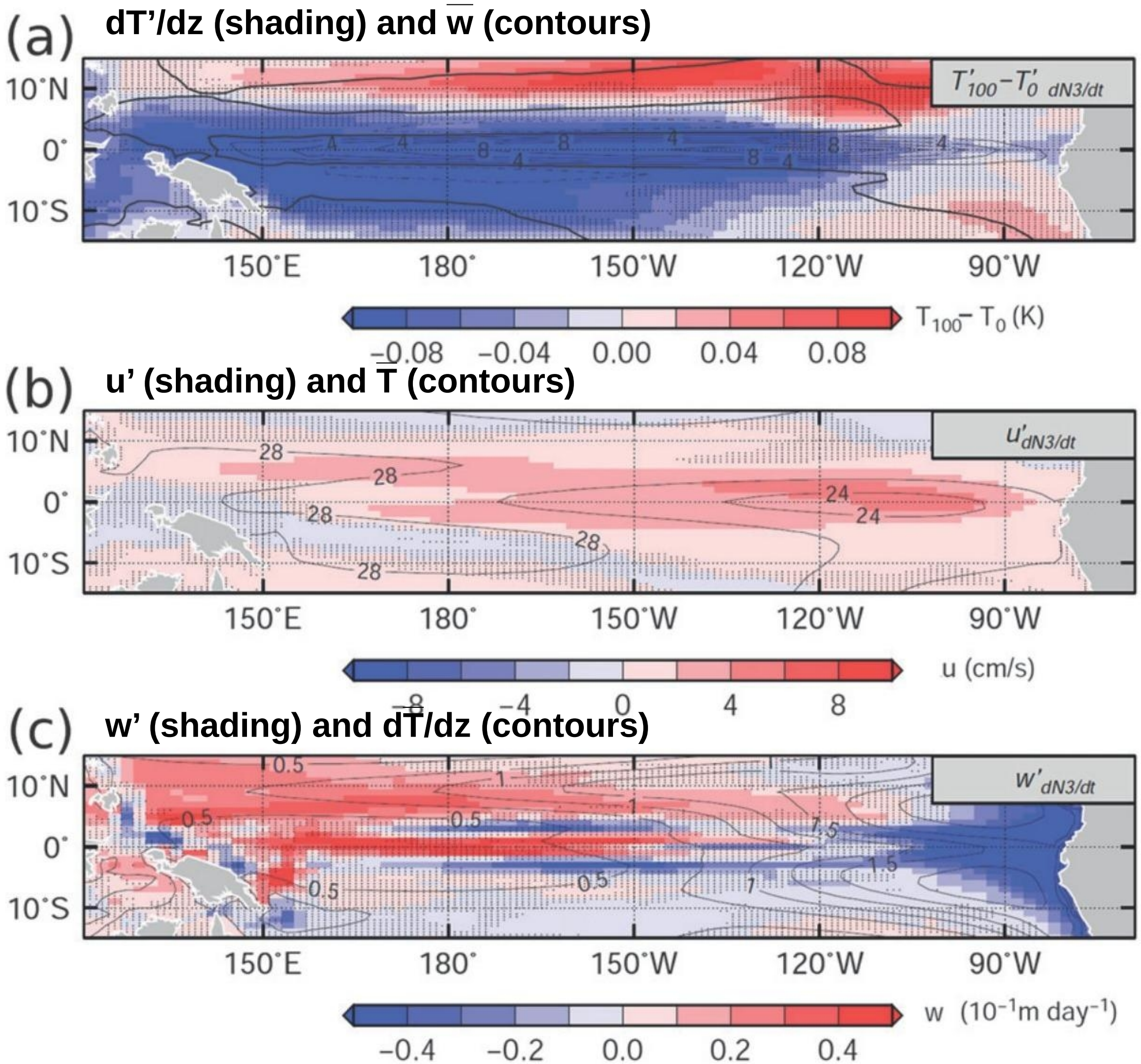


FIG. 3. Multimodel mean regression of (a) vertical stratification, (b) zonal velocity, and (c) upwelling anomalies on the normalized ∂N3/∂t index. These variables are averaged over the upper 100-m surface layer before computing the regressions. Contours show the multimodel ensemble-mean annual-mean climatology of (a) upwelling averaged over the surface layer, (b) sea surface temperature, and (c) vertical stratification averaged over the surface layer. The contour interval is 2×10^{-5} m s^{-1}, 2°C, and 0.25 K m^{-1}.

But there’s still large inter-model spread in the ocean heat budget.

Need obs constraints for equatorial $\overline{w}$ and w’!

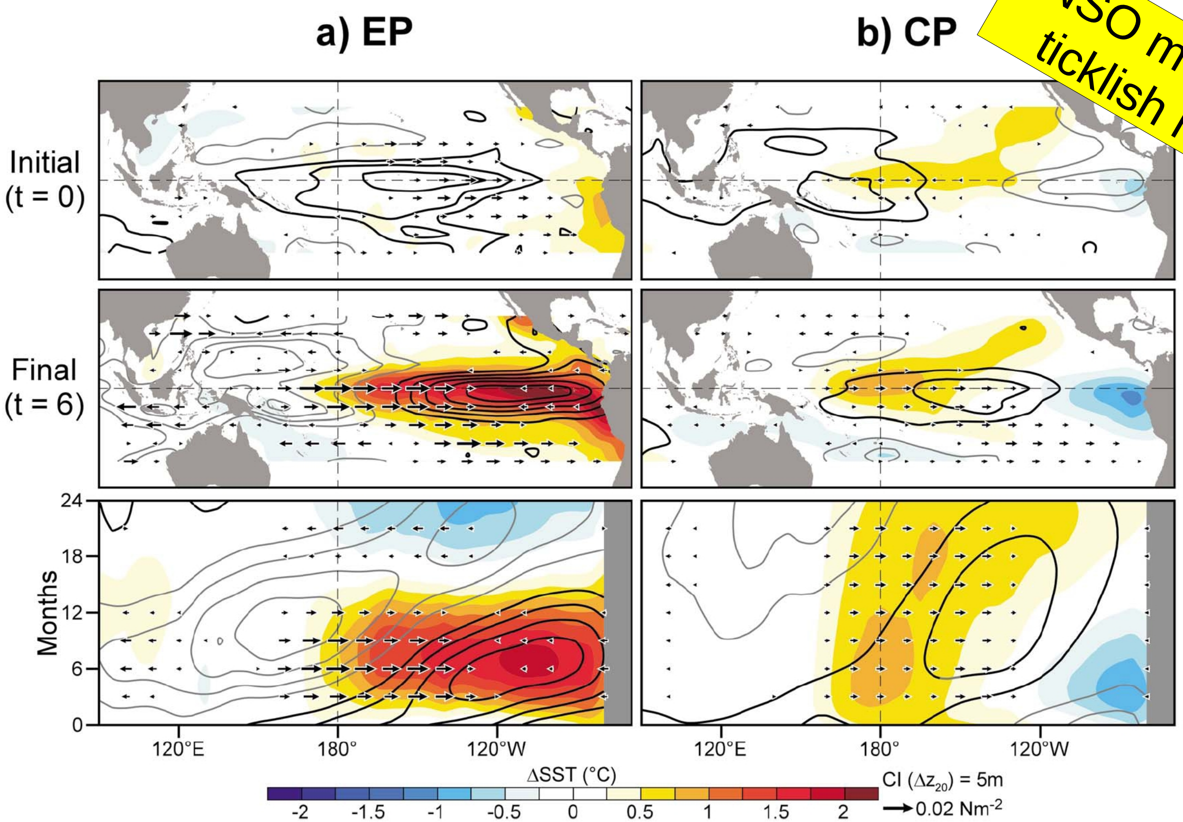
DiNezio et al. (JC 2012)

Transient growth in non-normal systems

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

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

ENSO modes are ticklish here.

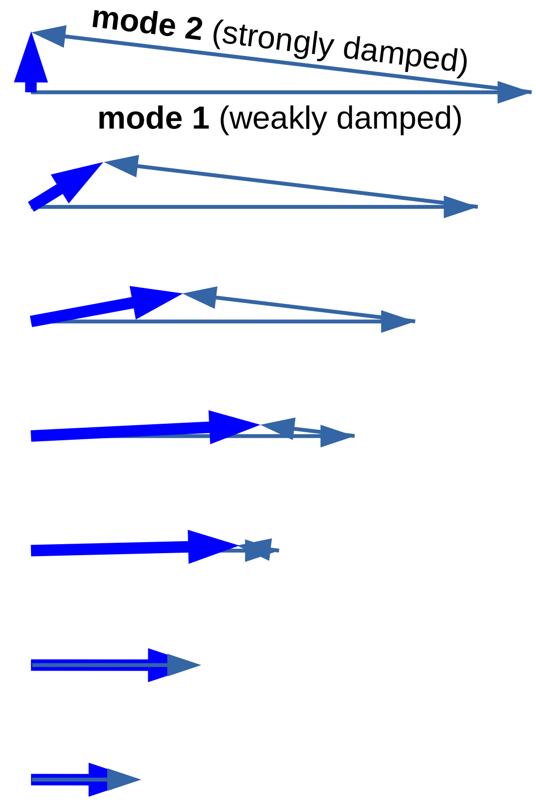


Newman et al. (2011)

Strong initial cancellation.

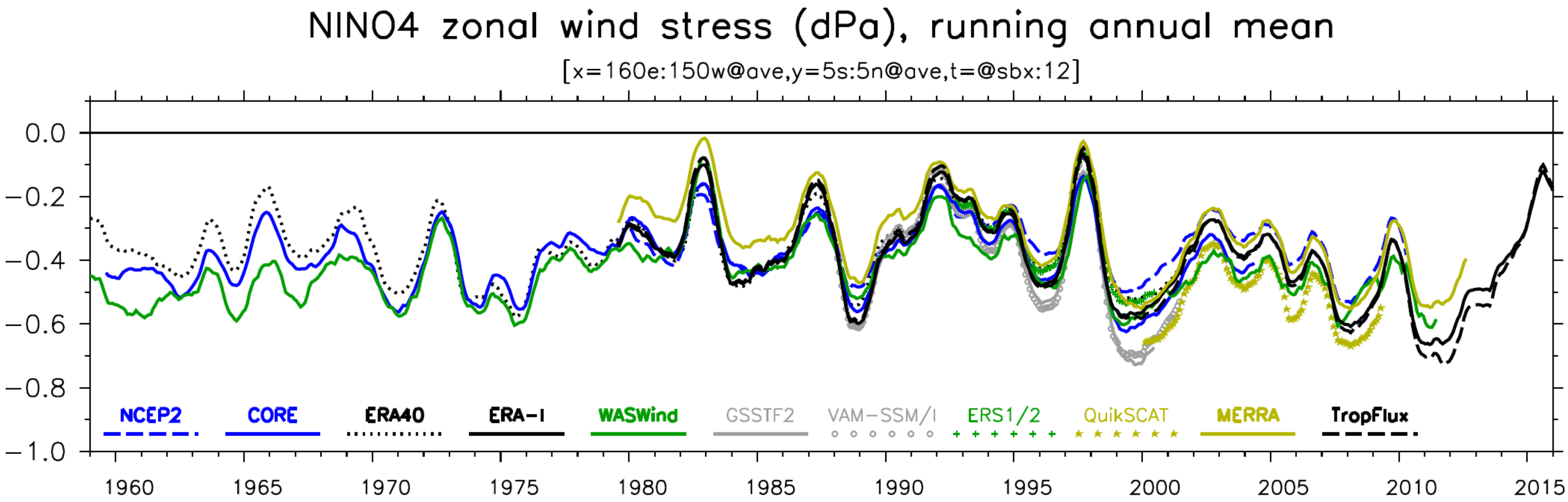
Much less cancellation.

Only one mode remains.



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

Diverse wind stress estimates



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

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

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

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

Shortwave feedbacks differ strongly among reanalyses

Need better obs constraints for models.

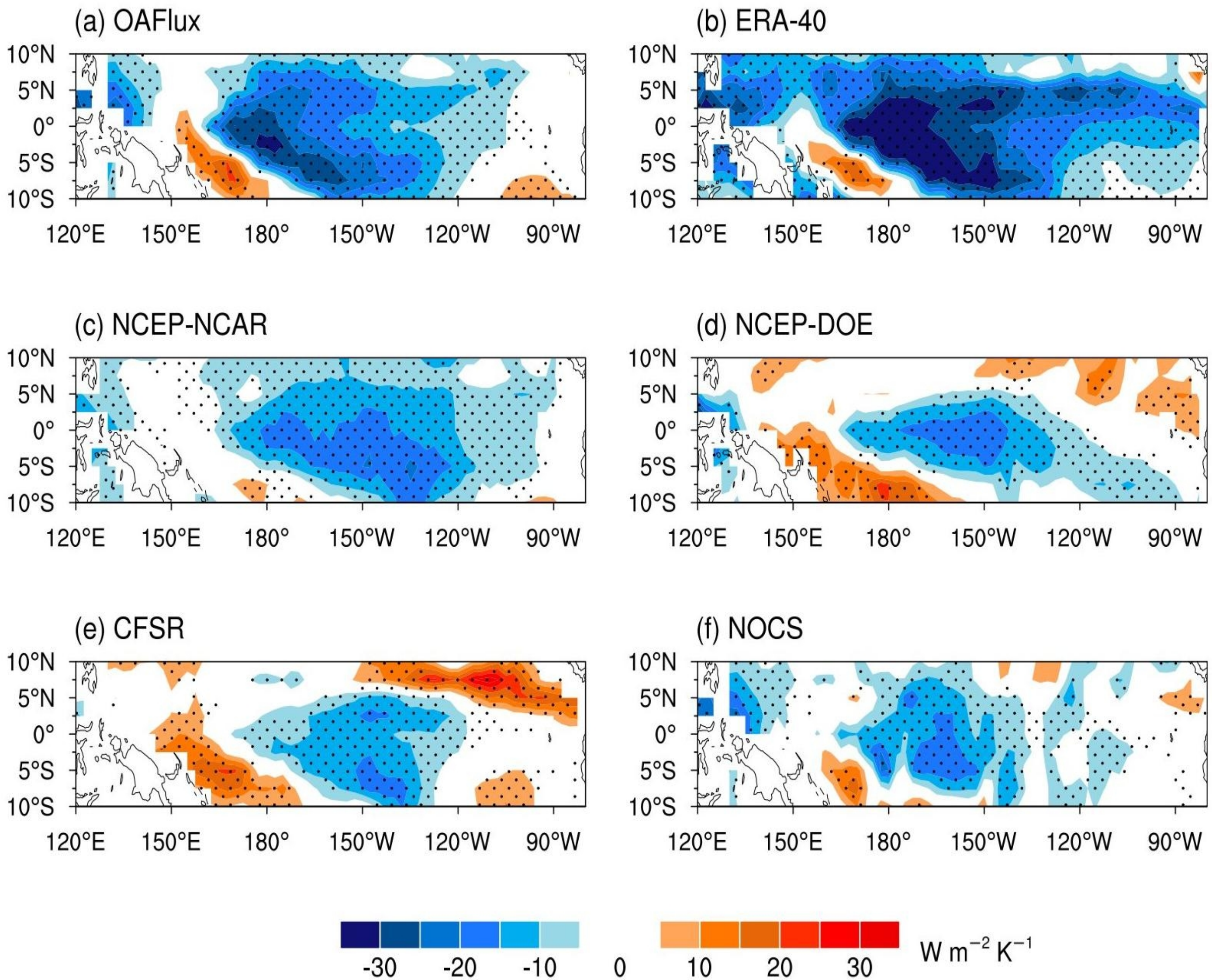
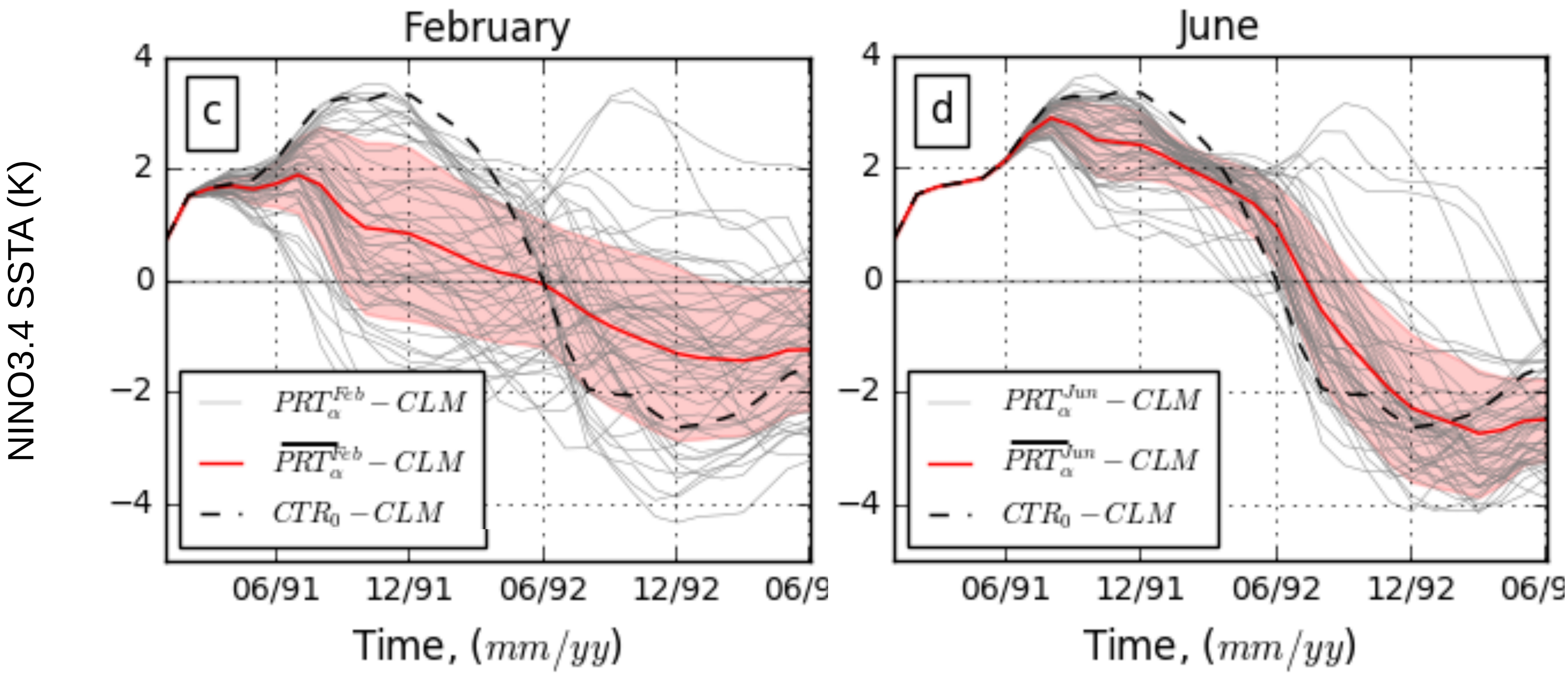


FIG. 9. The CSFI derived from several reanalysis datasets. Stippling indicates that regressions are significant at the 95% confidence level, based on the Student's *t* test.

Ying & Huang (JC 2016a)

Response to Pinatubo eruption depends on seasonal timing

(Predybaylo et al., JGRA 2017)

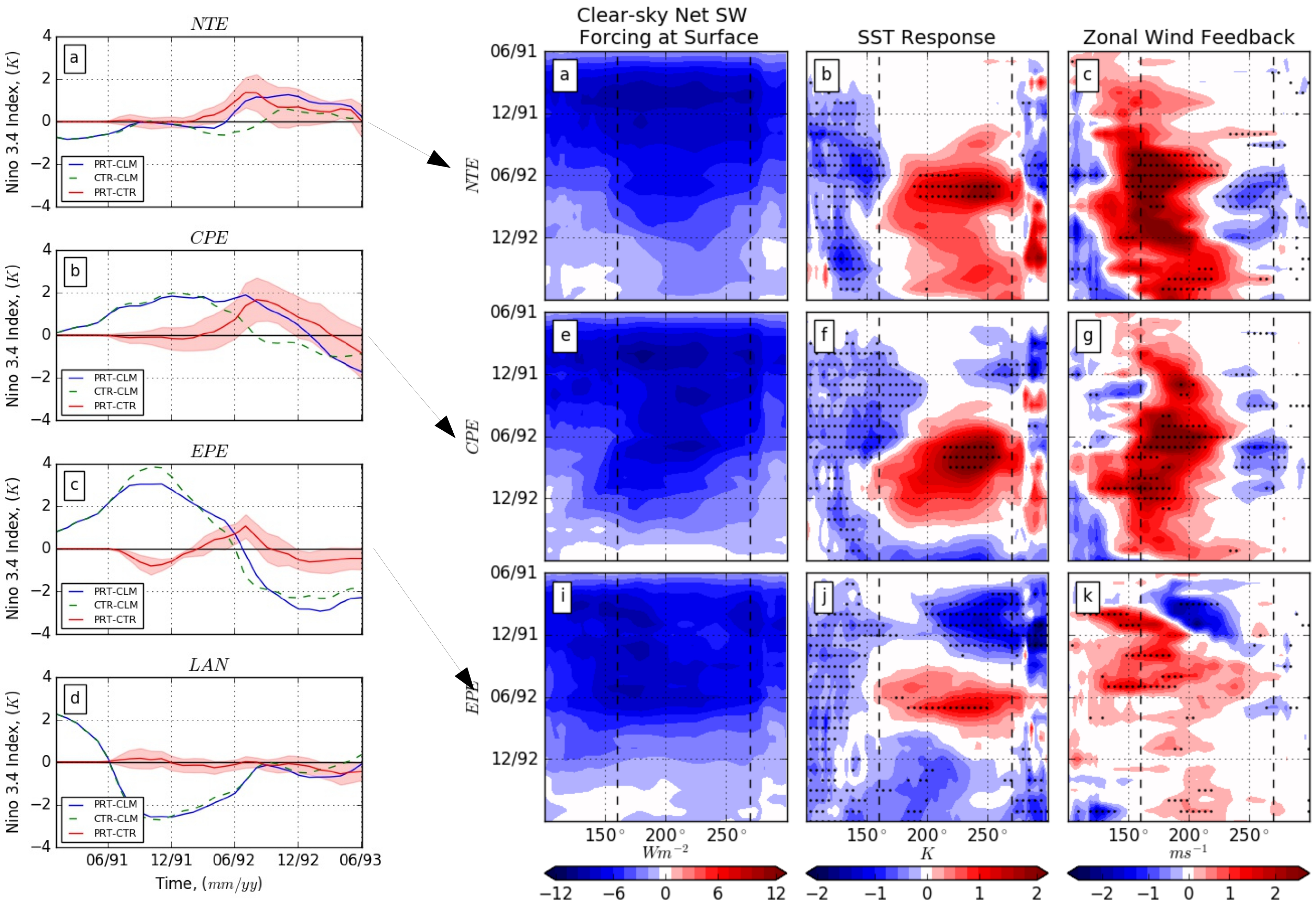


Signal-to-noise ratio is stronger for a June eruption than a February eruption.

A winter Tambora might affect ENSO less than a summer Pinatubo.
(Real Pinatubo was June 1991; Tambora was April 1815.)

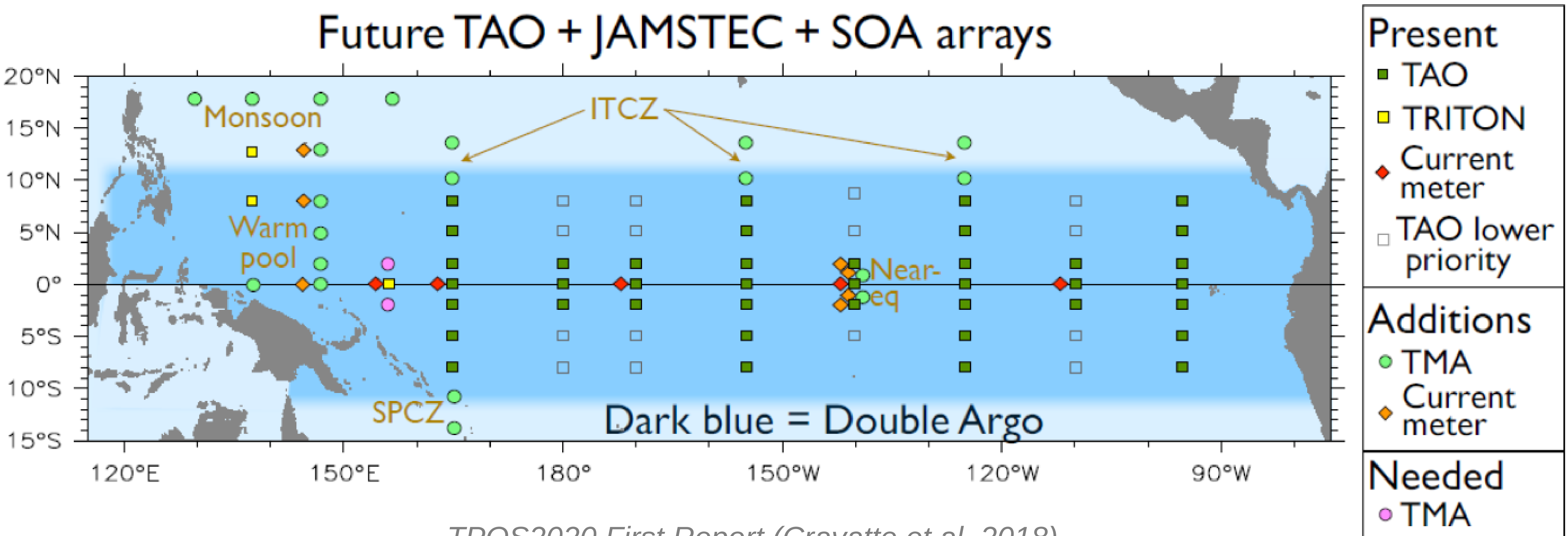
Response to Pinatubo eruption depends on ENSO phase

(Predybaylo et al., JGRA 2017)



TPOS2020: Proposed redesign of the Tropical Pacific Observing System

Moorings, robotic floats, satellites, ships, gliders, ...



TPOS2020 First Report (Cravatte et al. 2018)
http://tpos2020.org

Goals: Enhance monitoring, improve forecasts, advance understanding & models.