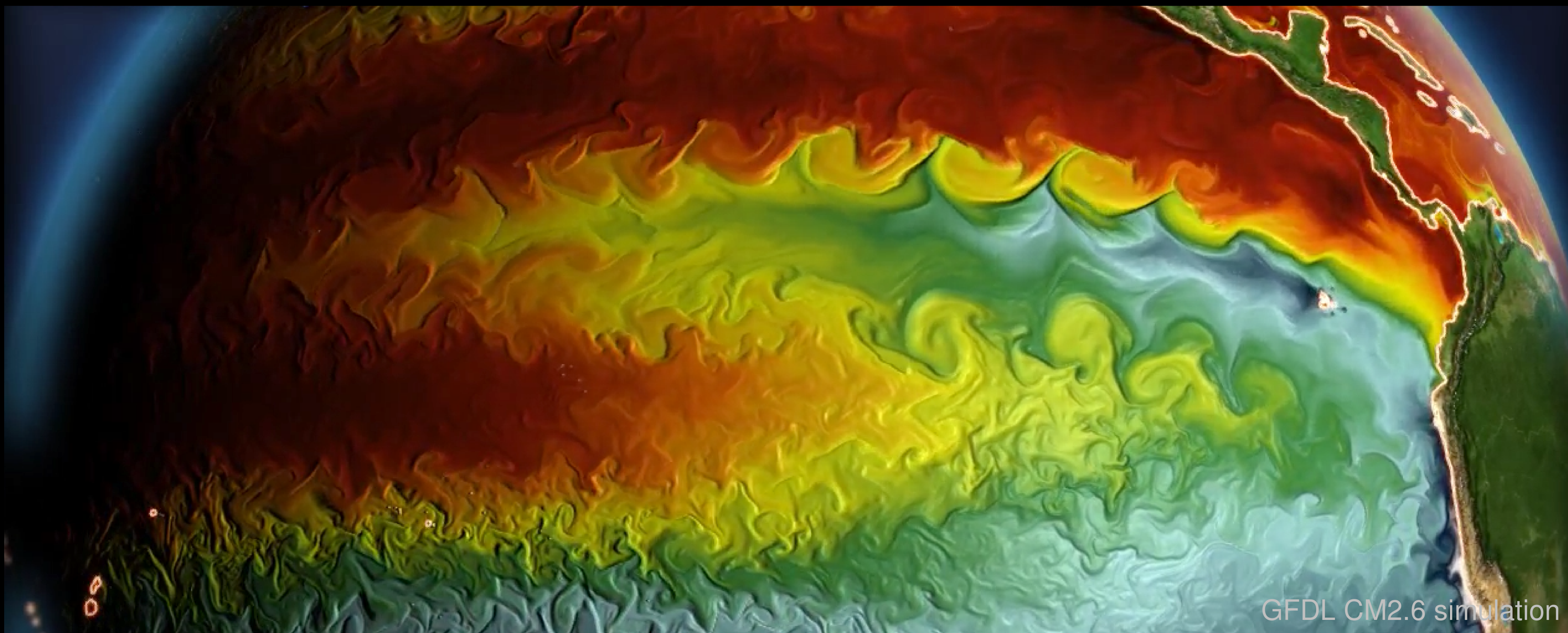
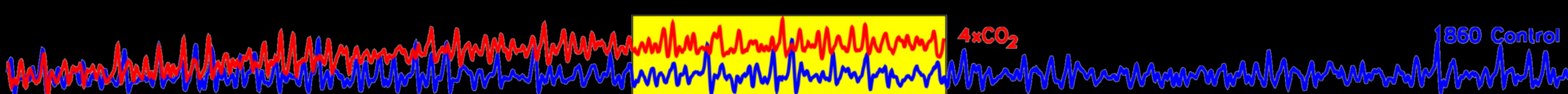
ENSO in Climate Models: Progress and Opportunities

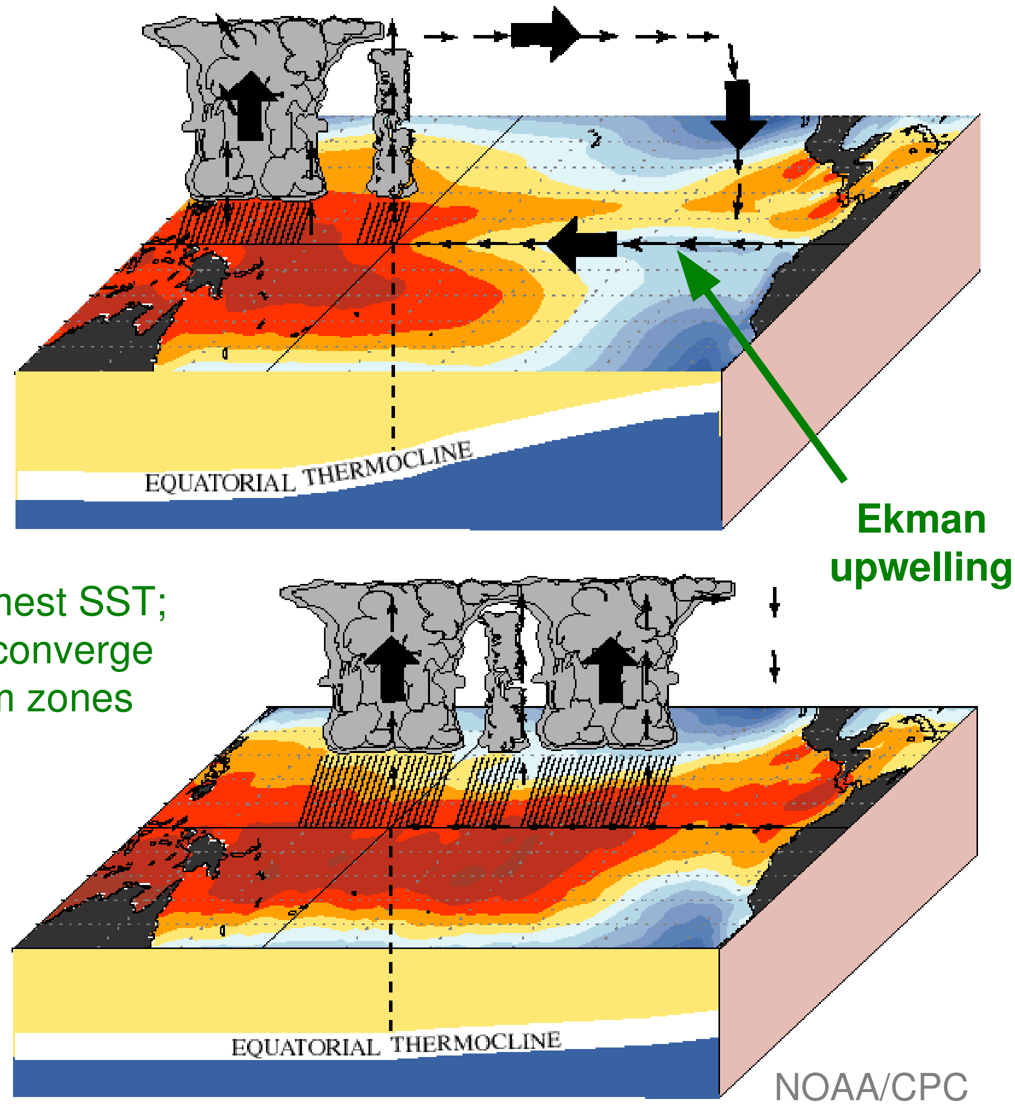




Andrew T. Wittenberg
NOAA/GFDL, Princeton, NJ, USA

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

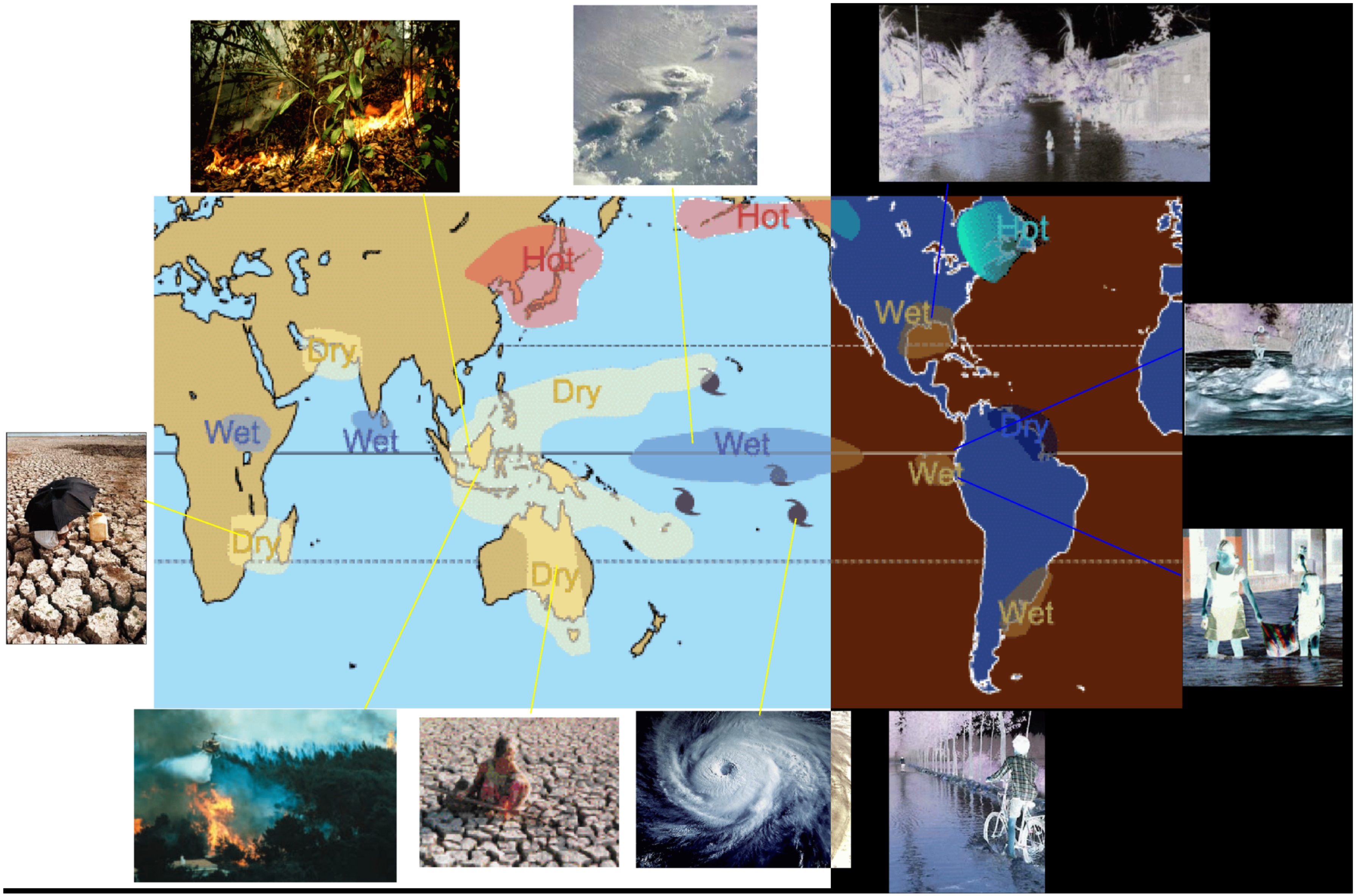
rain follows warmest SST;
surface winds converge
onto rainy/warm zones

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.

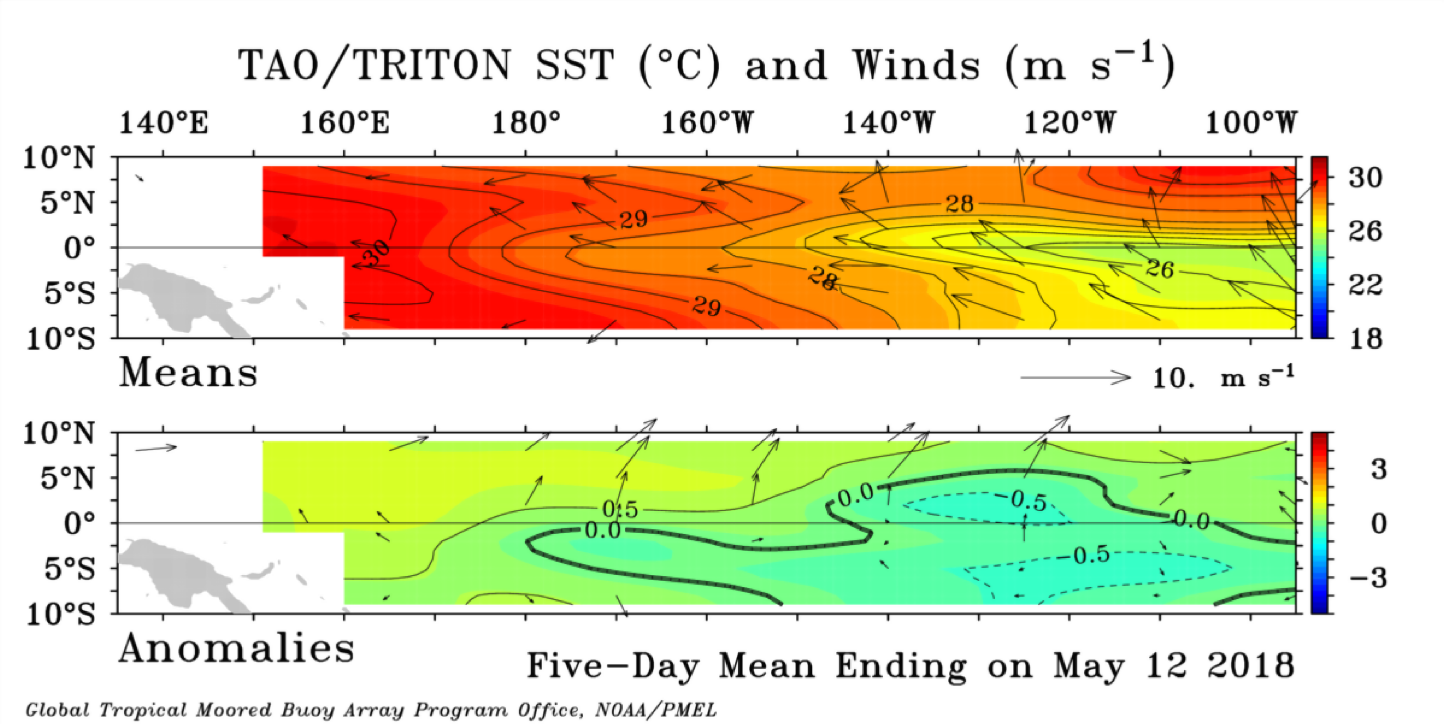
Global Impacts of ENSO



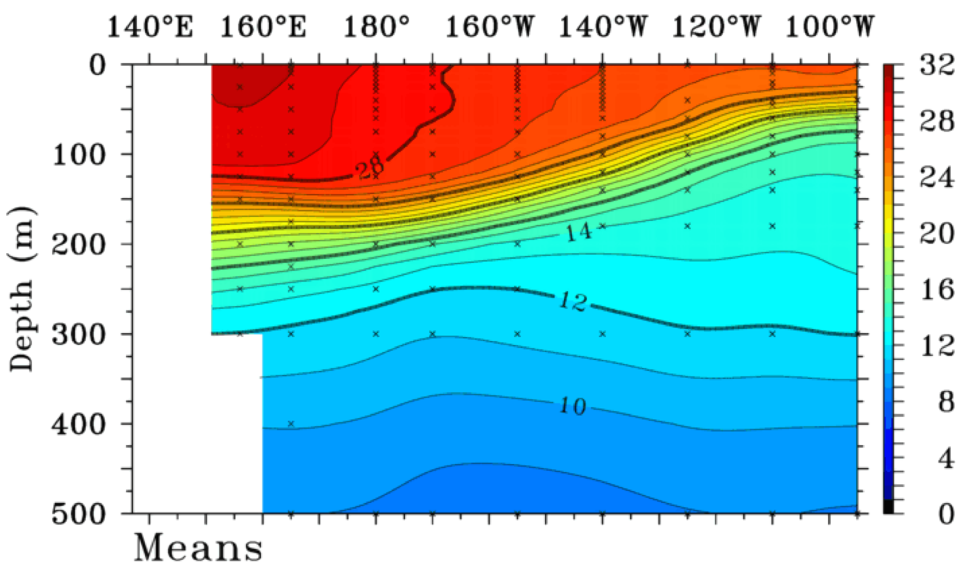
Rainfall shifts → affect global weather, terrestrial ecosystems, agriculture.
Weaker upwelling, altered currents → affect marine ecosystems & fisheries.

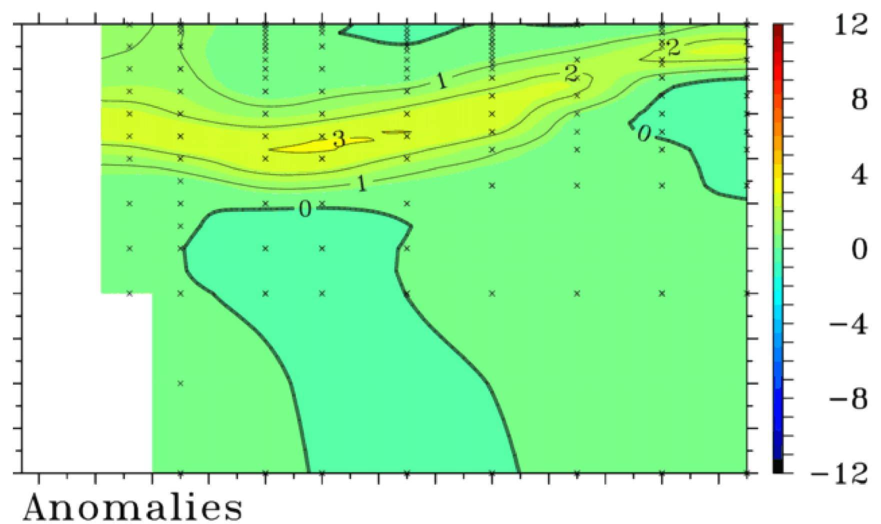
Present state of the tropical Pacific

http://www.pmel.noaa.gov/tao



temperature anomaly 2S:2N

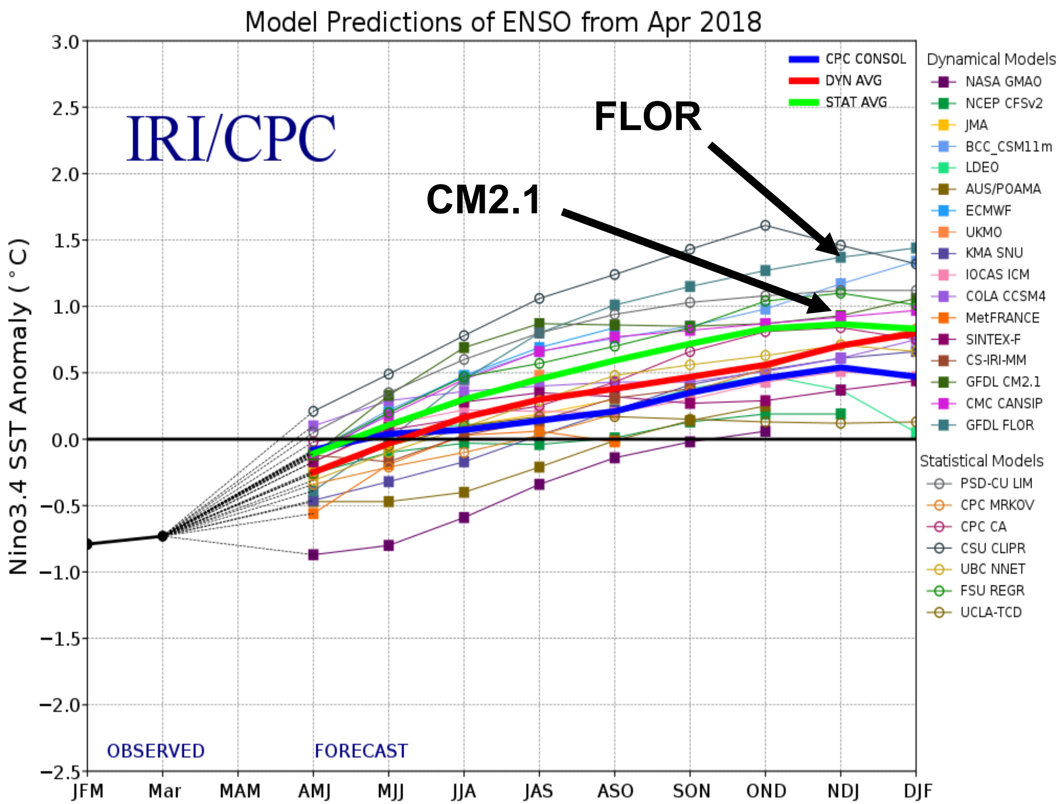


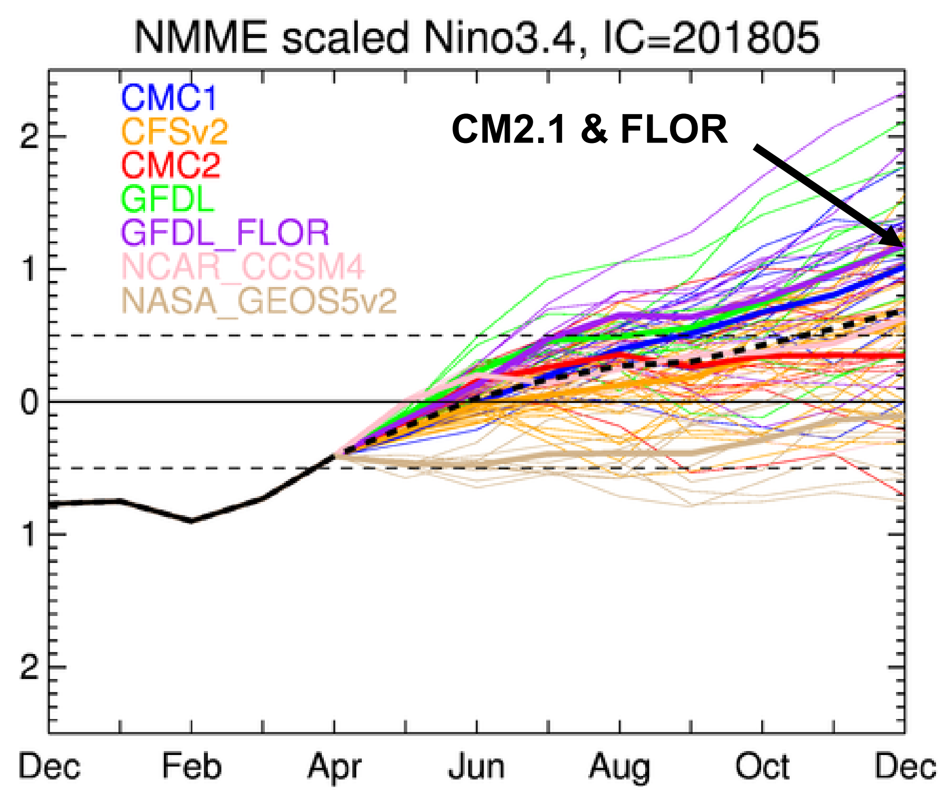


Latest ENSO Predictions

https://iri.columbia.edu/our-expertise/climate/forecasts/enso/current

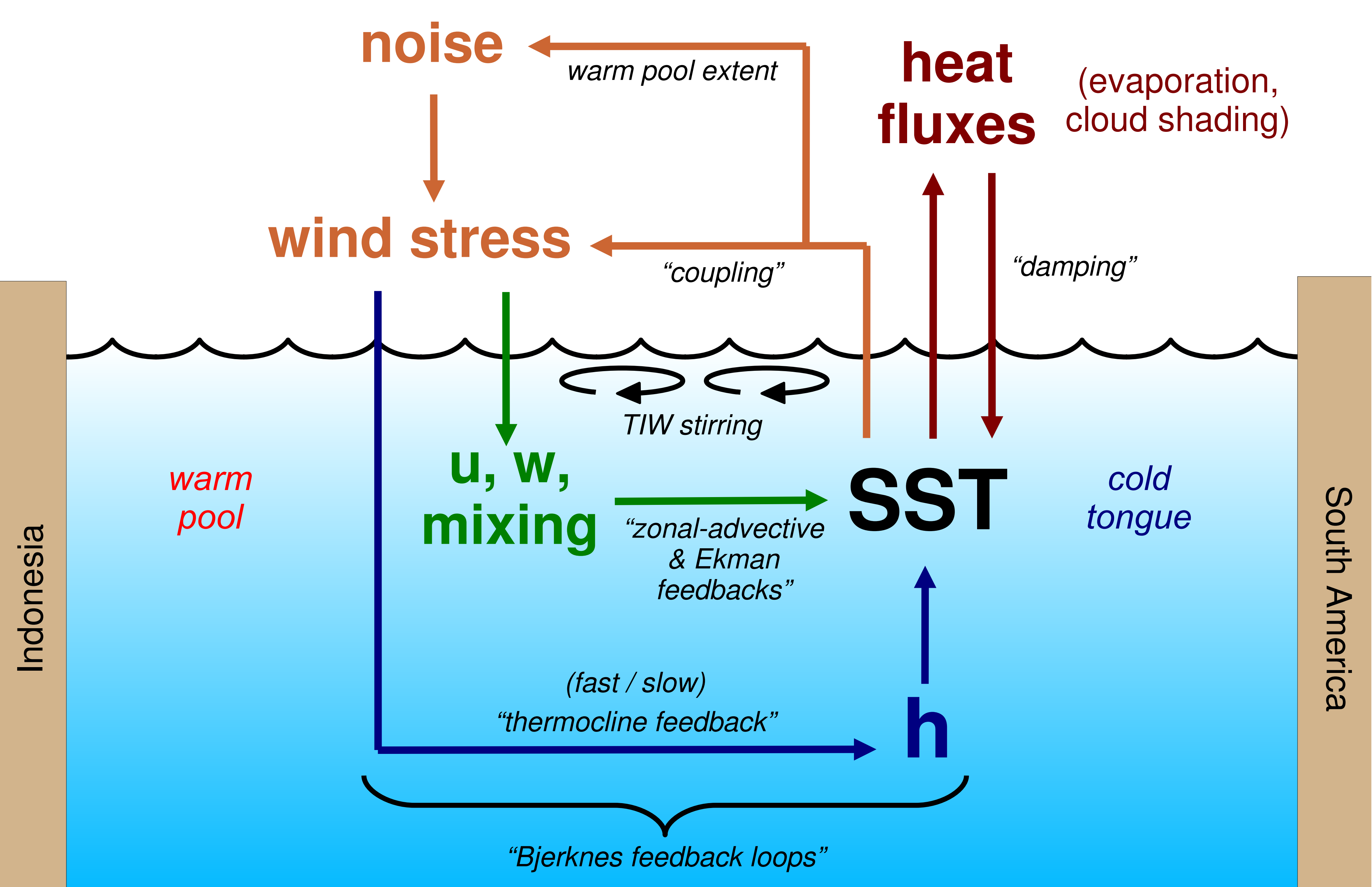
http://www.cpc.ncep.noaa.gov/products/NMME





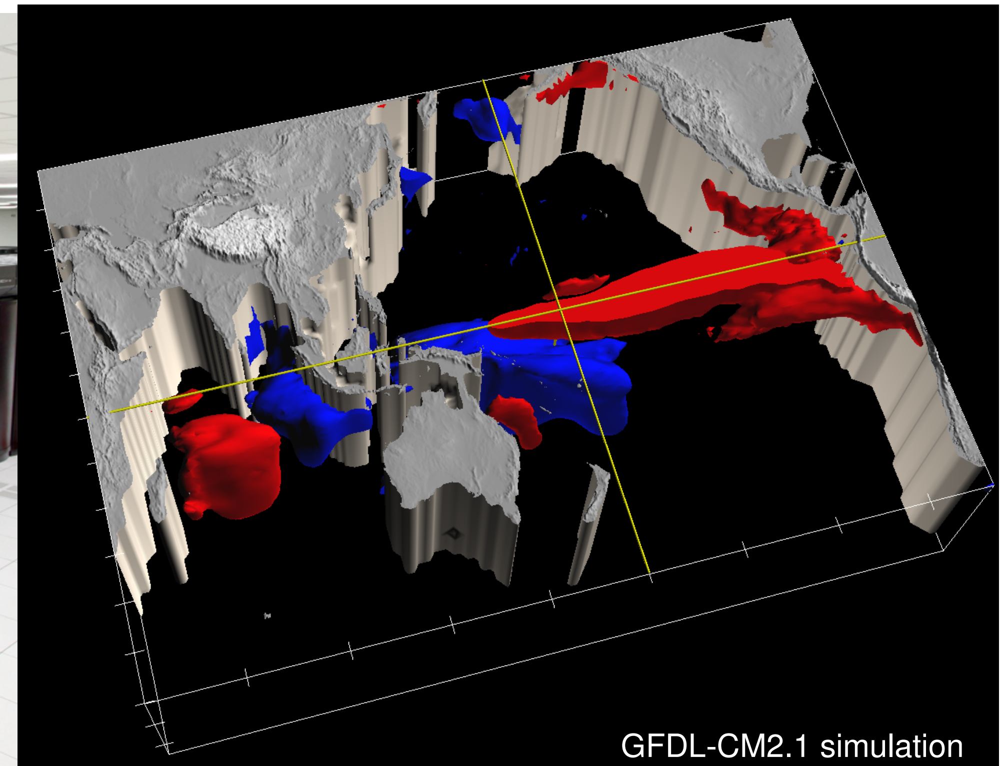
We might be headed for a weak El Niño.
(But in boreal spring, it's hard to know.)
Inter-model spread remains large → potential for improvement.

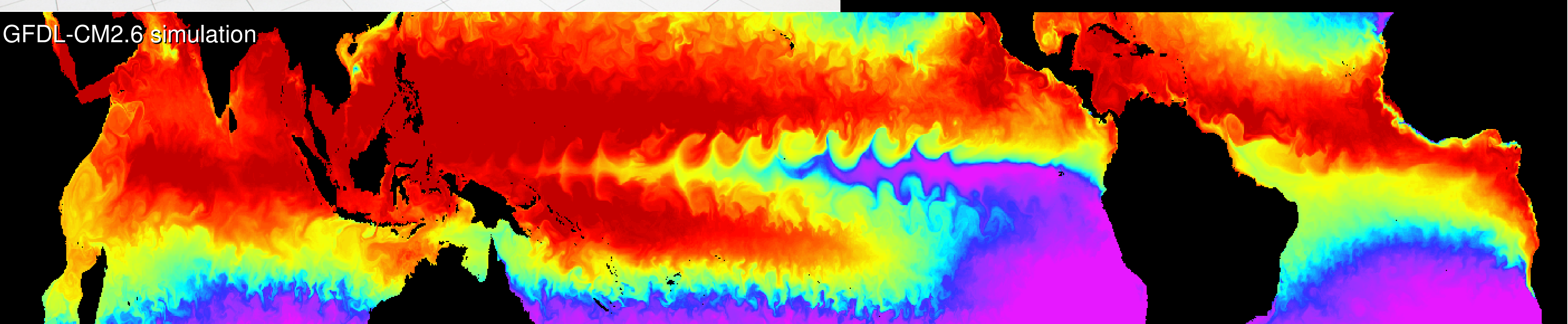
Key ENSO feedbacks



Coupled General Circulation Models (CGCMs) aim to integrate all of these processes.

Global ocean, atmosphere, land, ice, chemistry, biology, vegetation.
Ever-increasing resolution. But still *many* parameterized processes.

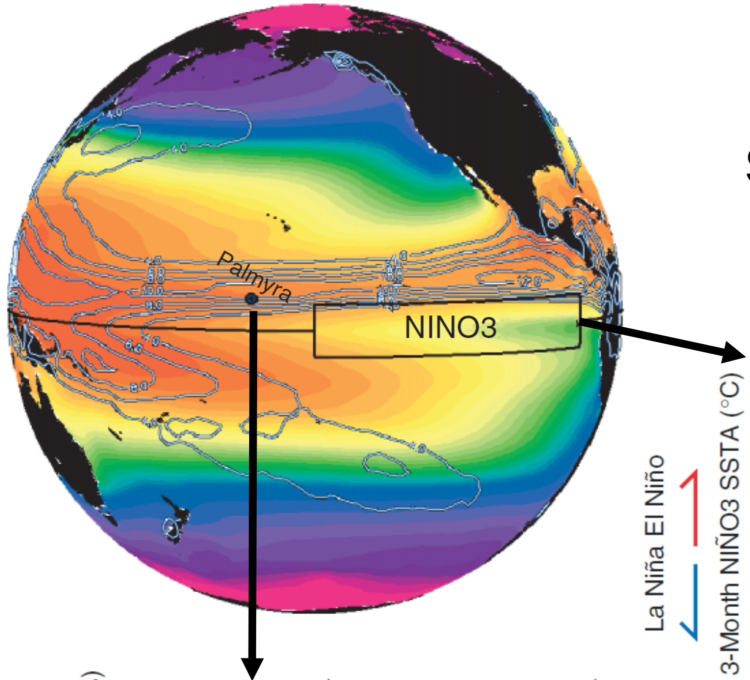




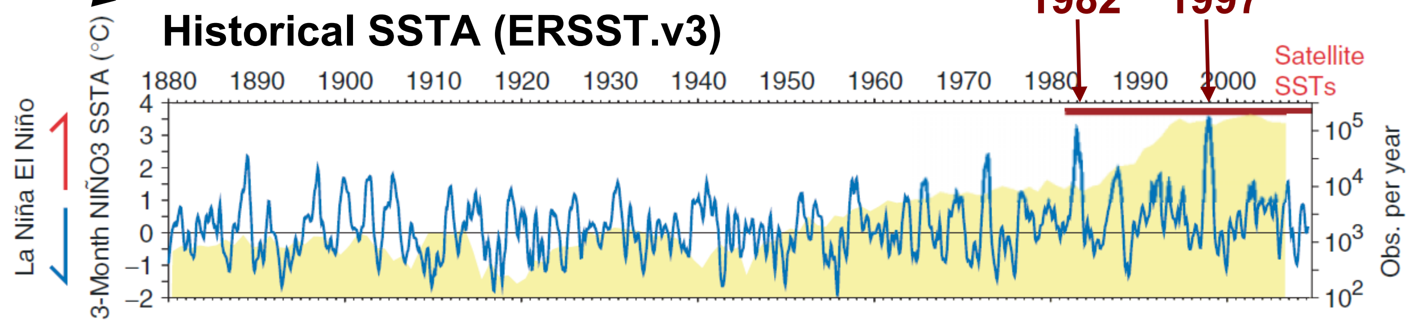
Intrinsic Modulation of ENSO

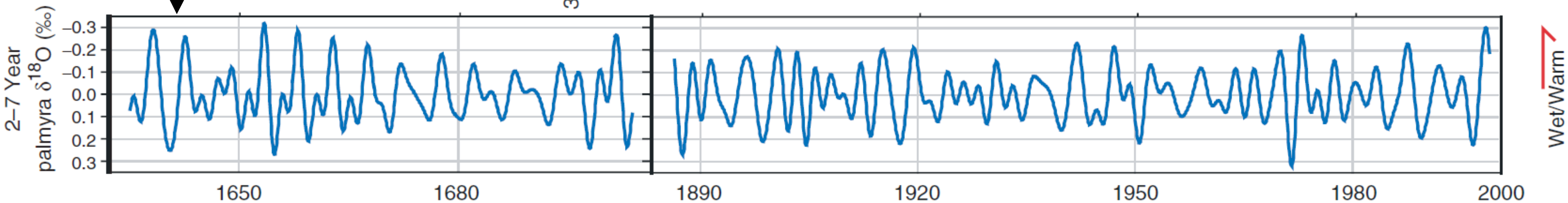
Both historical & paleo records suggest past modulation of ENSO

Vecchi & Wittenberg (WIREsCC 2010)

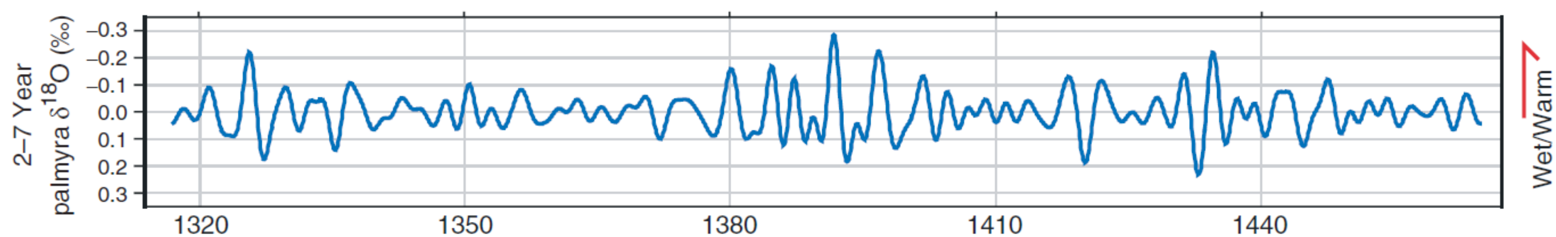


Historical SSTA (ERSST.v3)

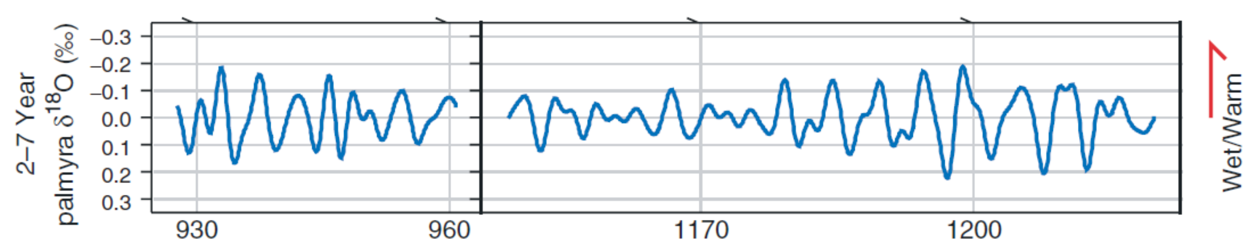




Palmyra corals (Cobb et al., Nature 2003)



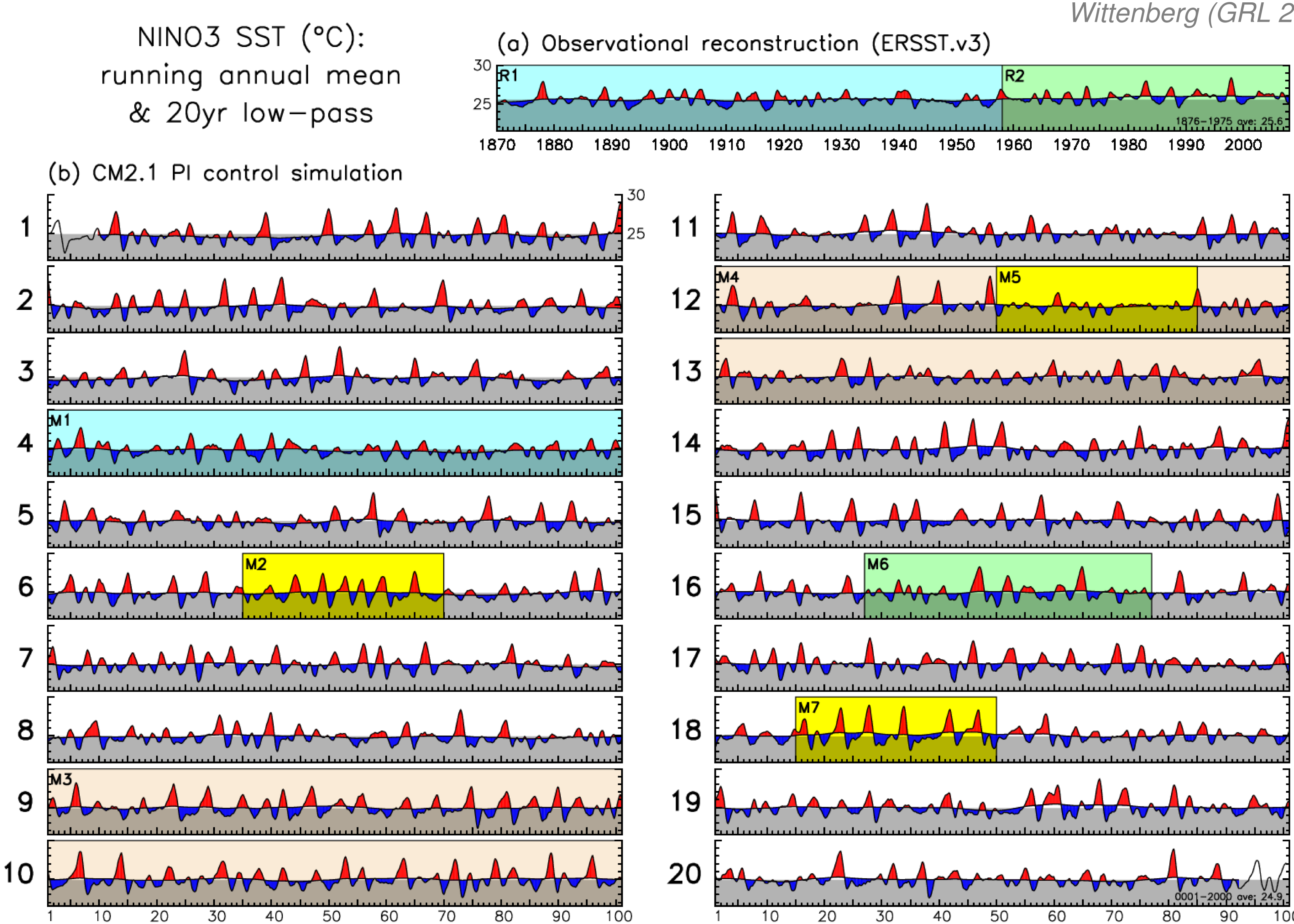
Multiproxy reconstructions:
e.g. Li et al. (NCC 2011);
Emile-Geay et al.
(J. Climate, 2013ab);
McGregor et al. (CP 2013)



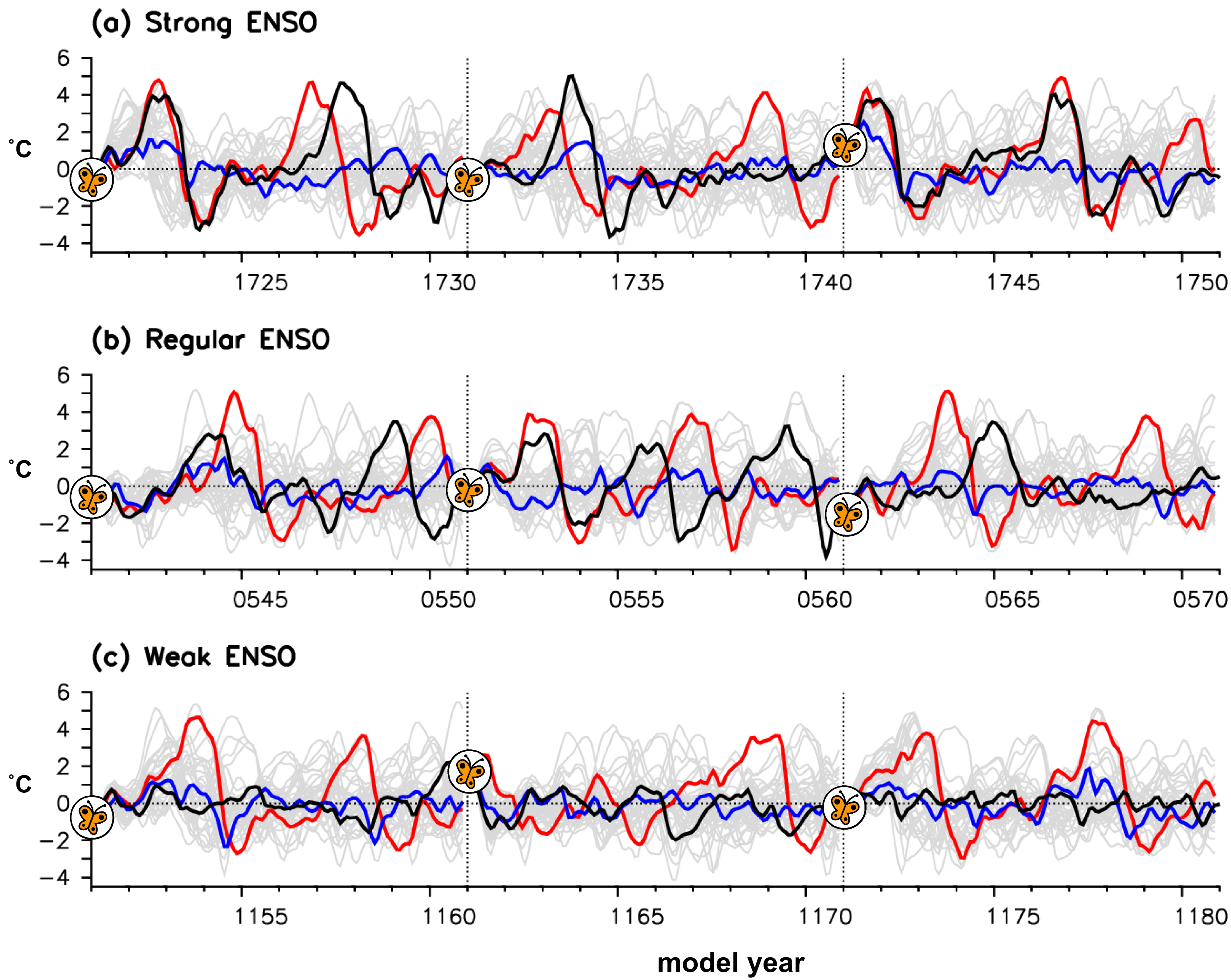
ENSO has existed for thousands, perhaps millions, of years.
Obscures detection of slower climate changes (decadal, global warming).

ENSO modulation in a 2000-year control simulation

Wittenberg (GRL 2009)



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,

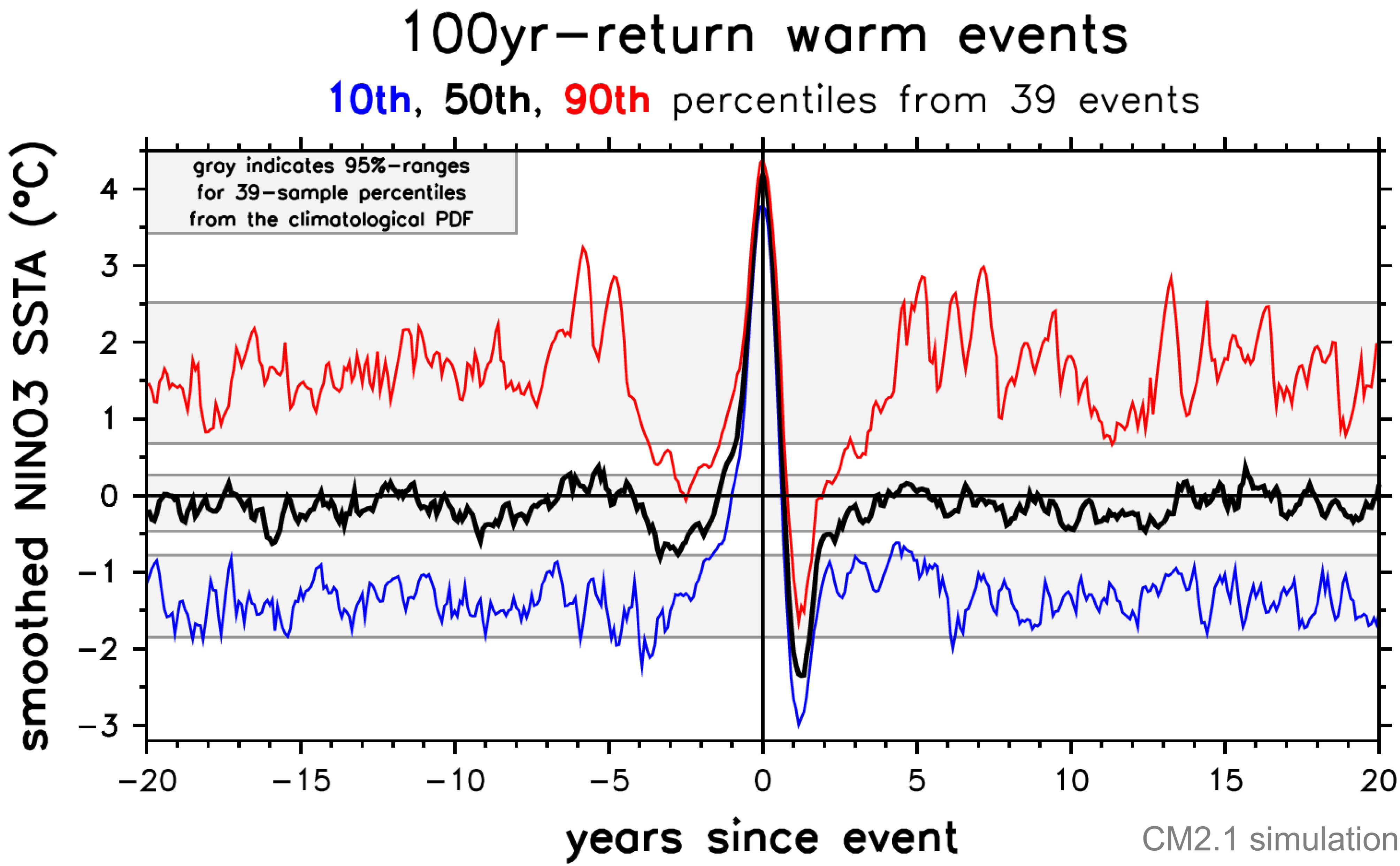
strongest,

all 40 members

Wittenberg et al. (J. Climate, 2014)

Best hope for long-term ENSO predictability?

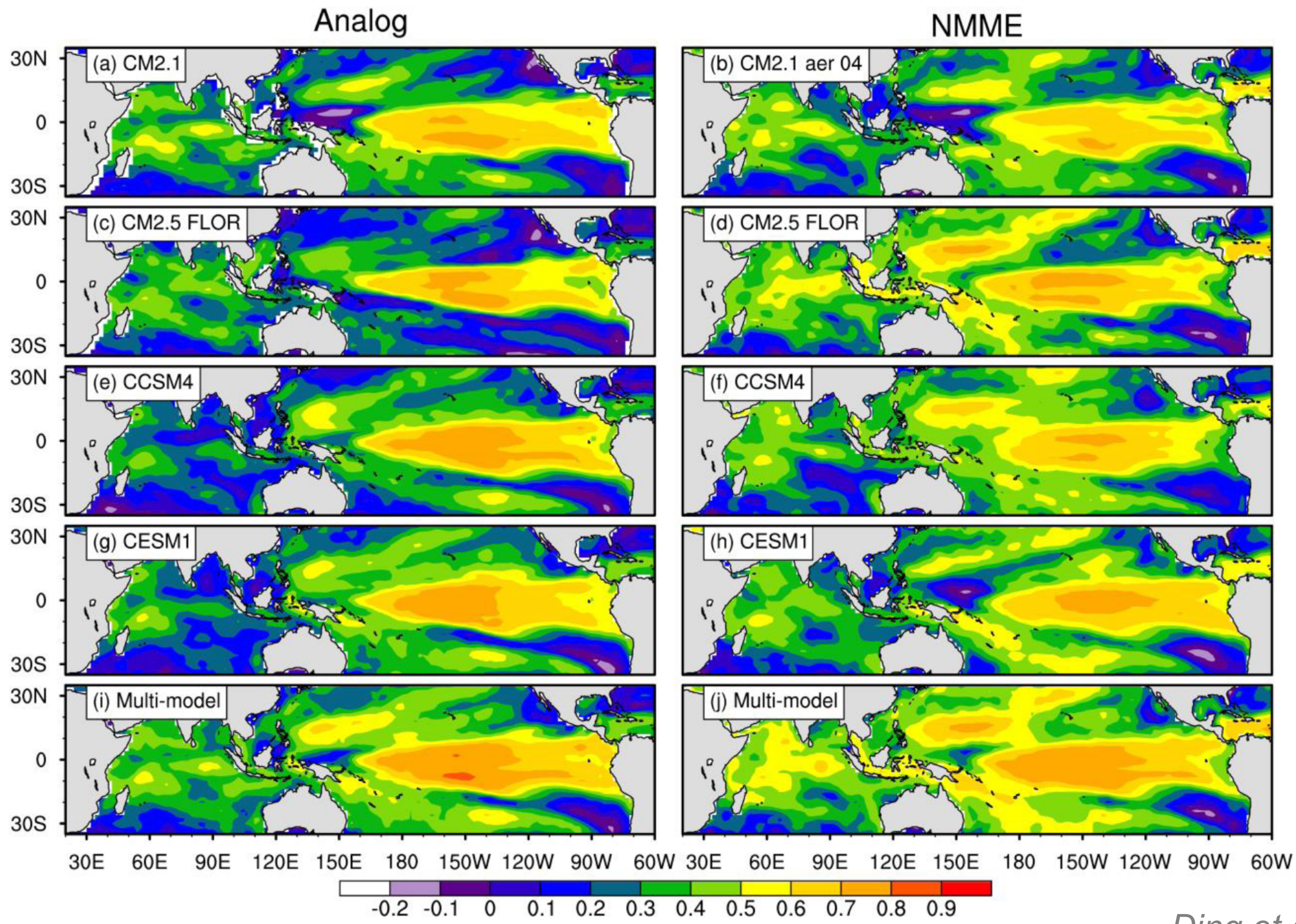
NINO3 memory might last 5yr, following strong warm events.



CM2.1 simulation

Model-Analog Forecasts

Use SST & SSH from long control runs as synthetic "libraries" of ENSO evolution.
SSTA correlation skill at 6mo lead, for 15-member analog ensembles.



Ding et al. (JC 2018)

In the equatorial Pacific, actually outperforms the NMME initialized forecasts!

Climate Change

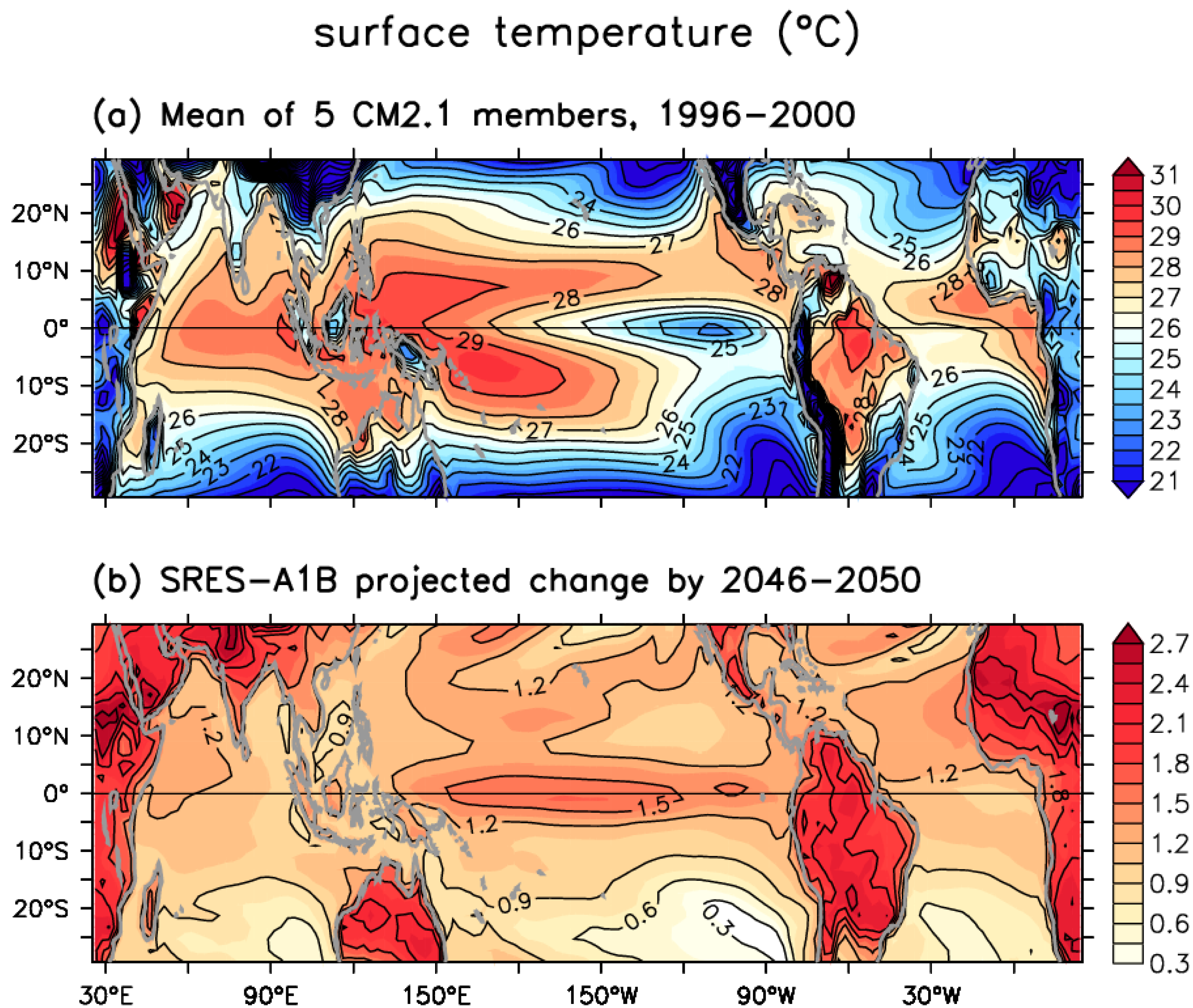
Projected surface temperature changes

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

Strongest warming over land & equatorial Pacific

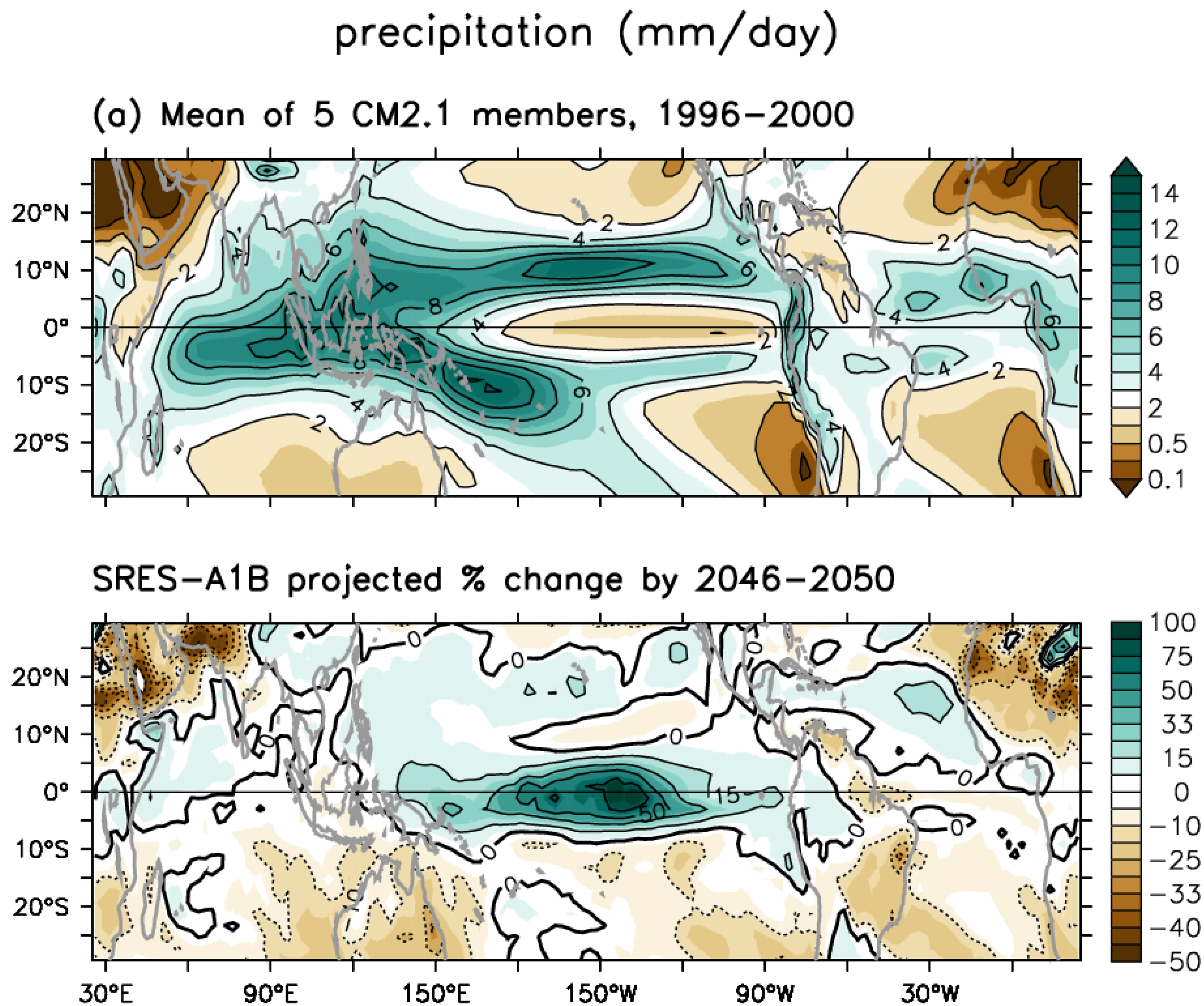
More warming in calm areas, and where winds weaken

Feedbacks from low clouds & ocean advection



Projected rainfall changes

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

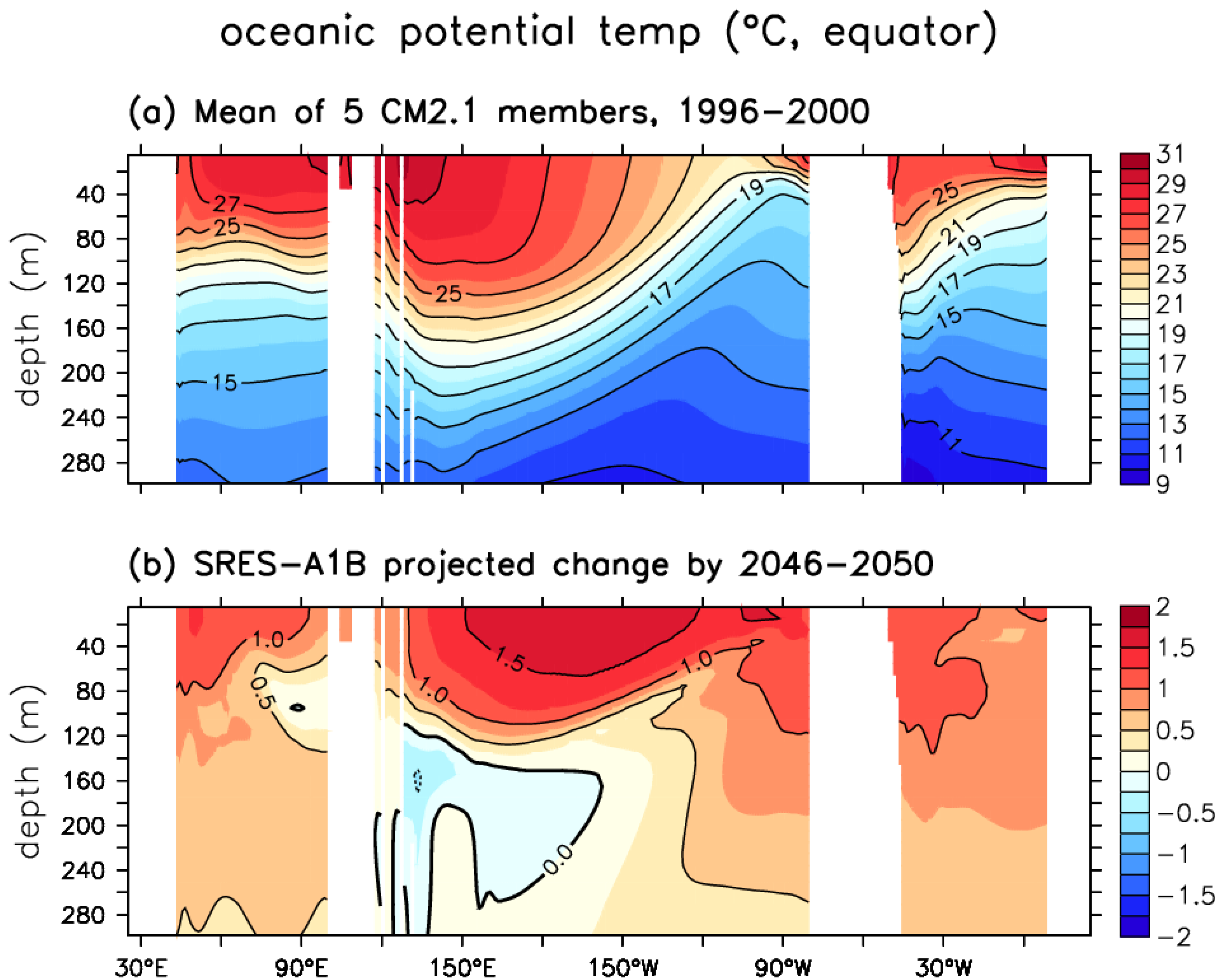


Broadly:
"the wet get wetter, the dry get drier".

Over tropical oceans:
"the warmer get wetter".

Projected upper-ocean temperature changes

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



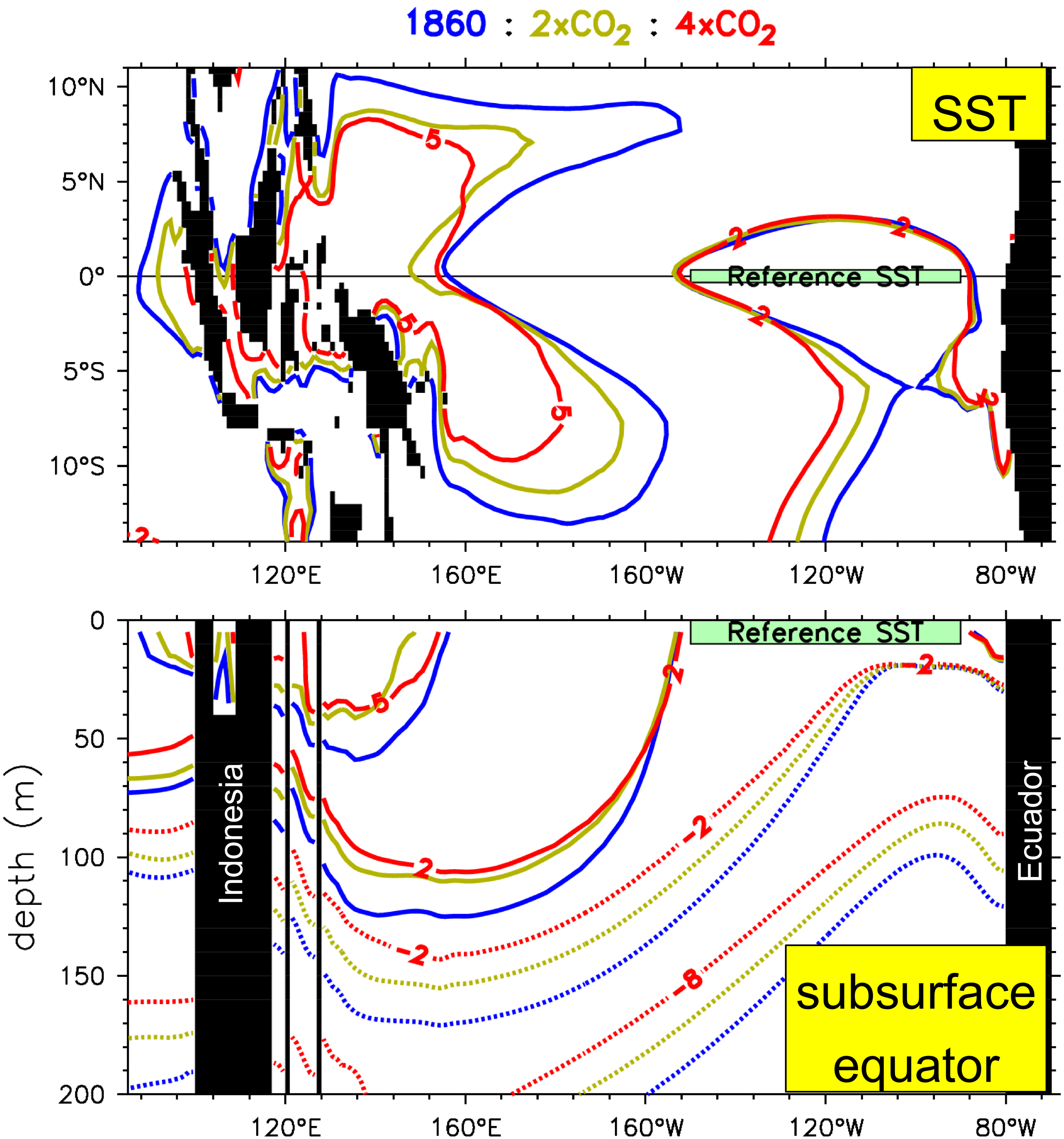
Tropical ocean more stratified

Stronger, shallower, and flatter equatorial thermocline

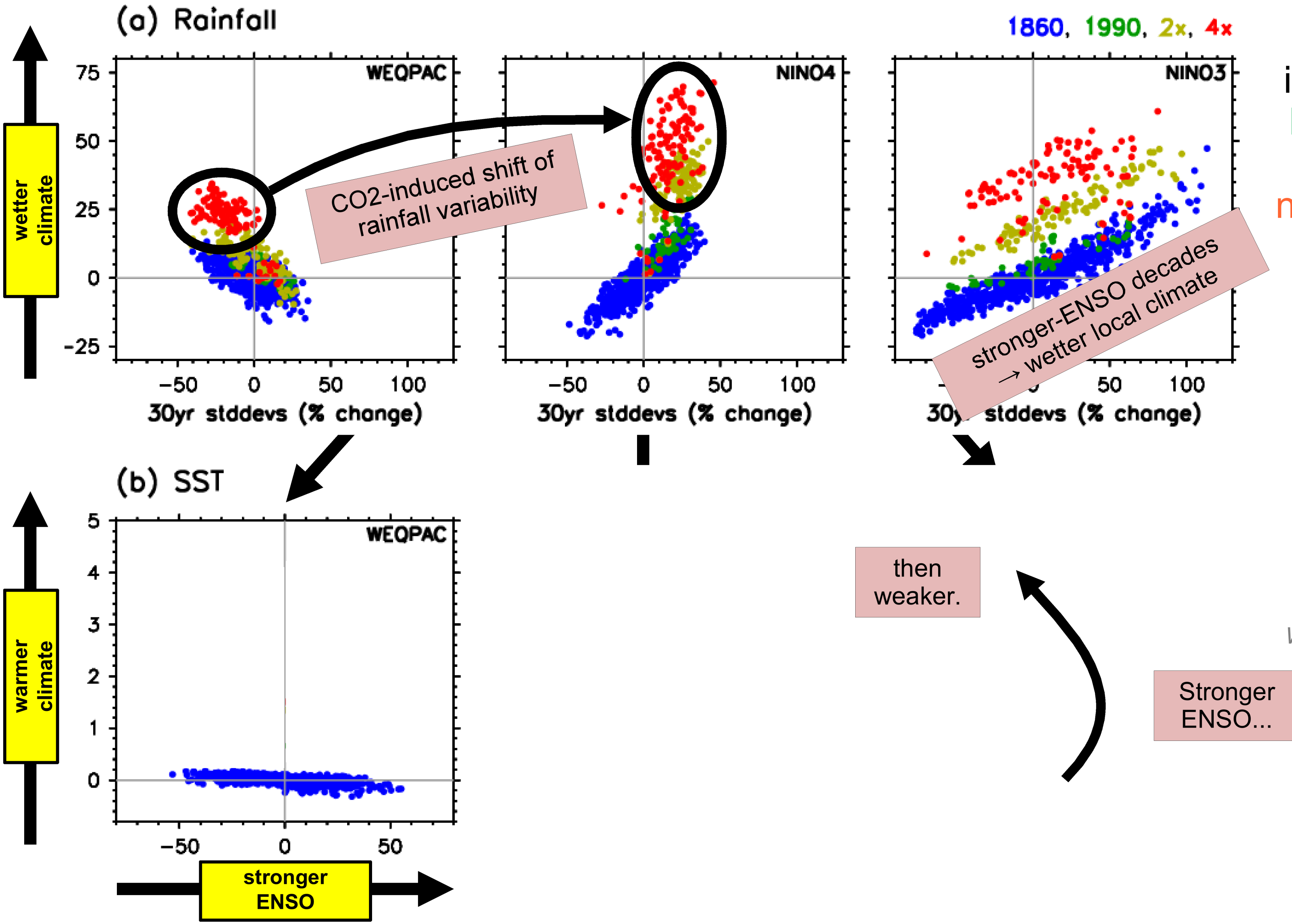
As CO_2 increases:

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



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)

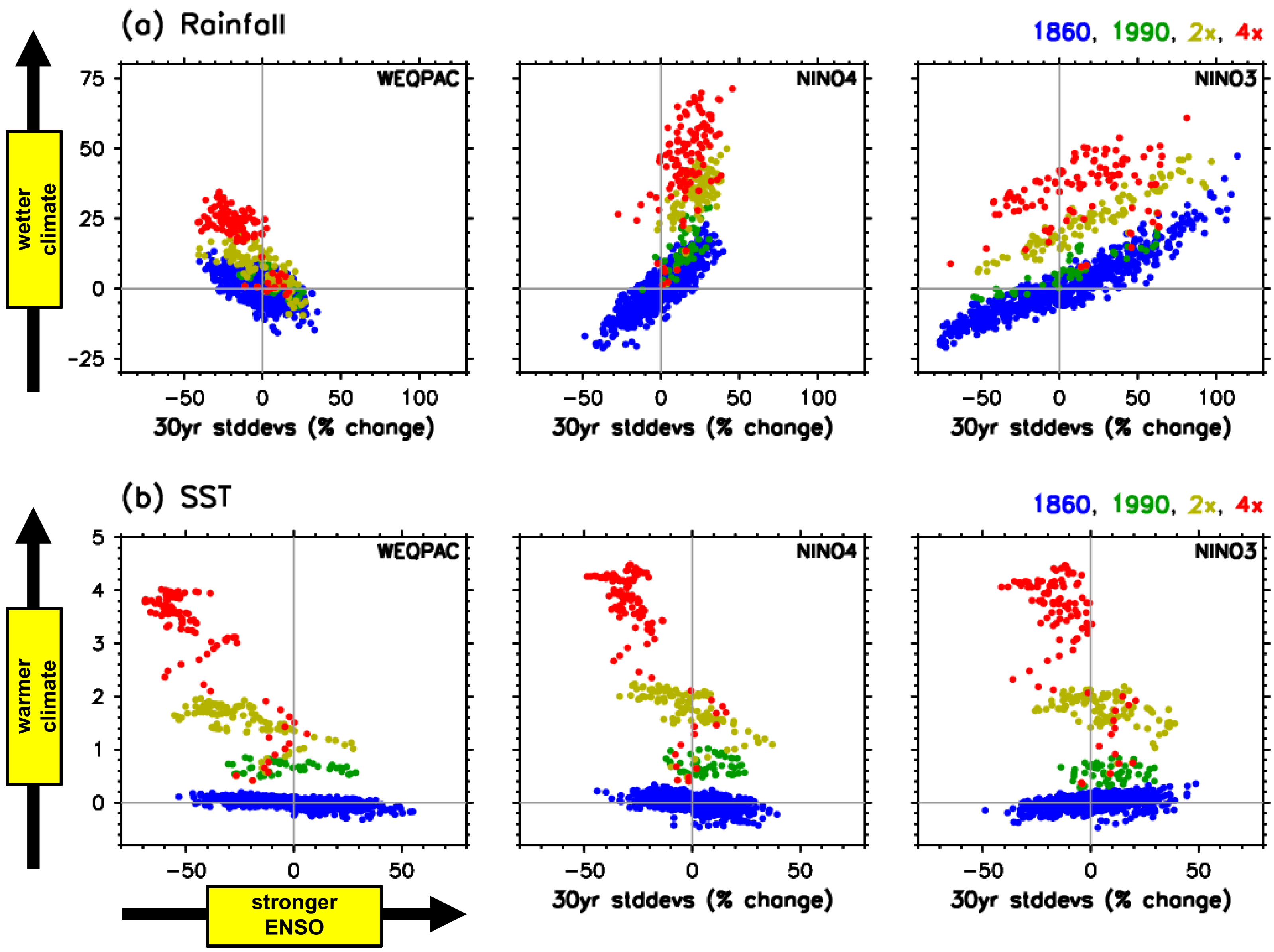
Cai et al. (2014)

Atwood et al. (2017)

Wittenberg (U.S. CLIVAR Variations, 2015)

CM2.1 simulation

ENSO response to increasing CO_2



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Power et al. (2013)

Cai et al. (2014)

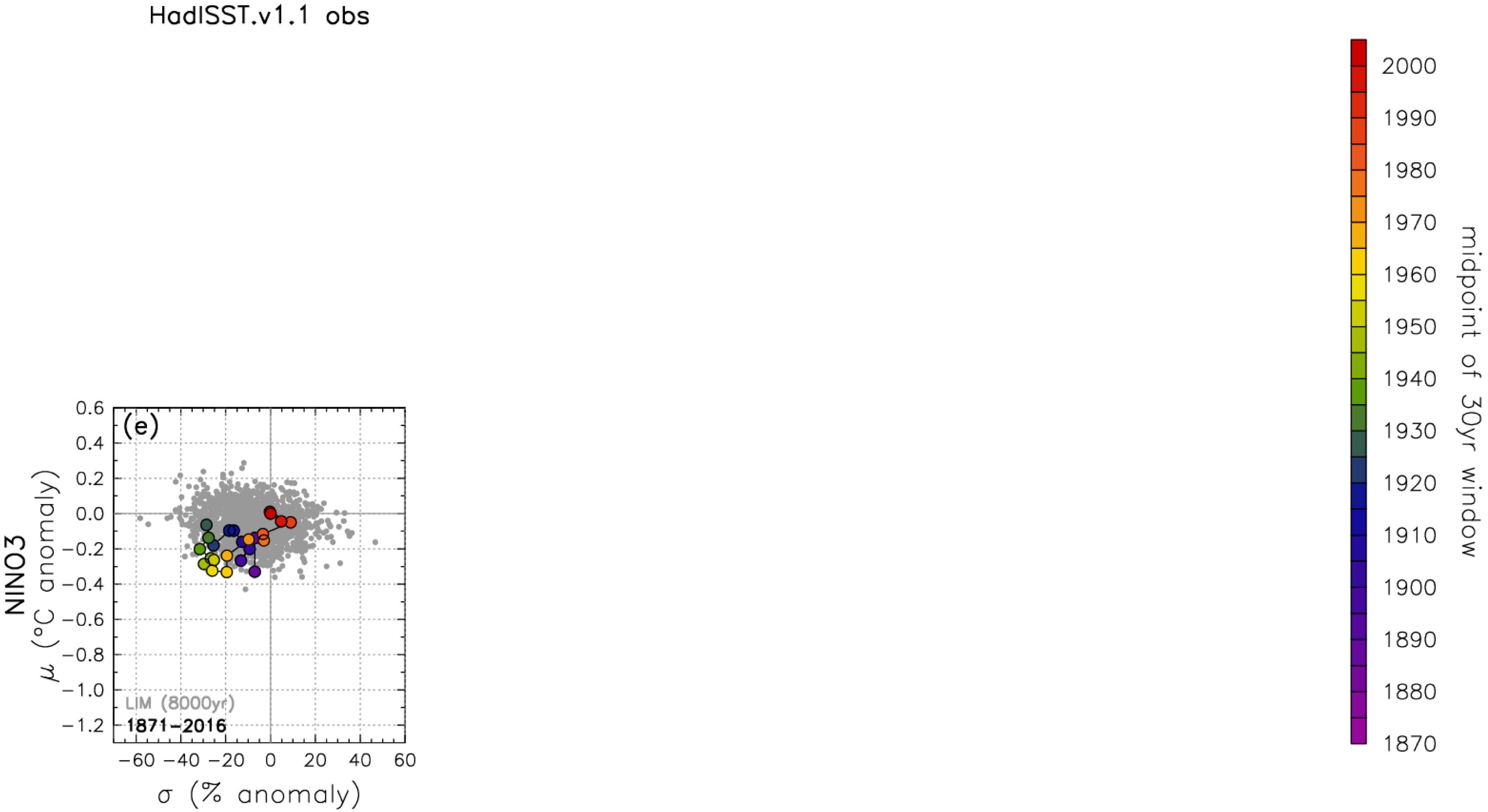
Atwood et al. (2017)

Wittenberg (U.S. CLIVAR Variations, 2015)

CM2.1 simulation

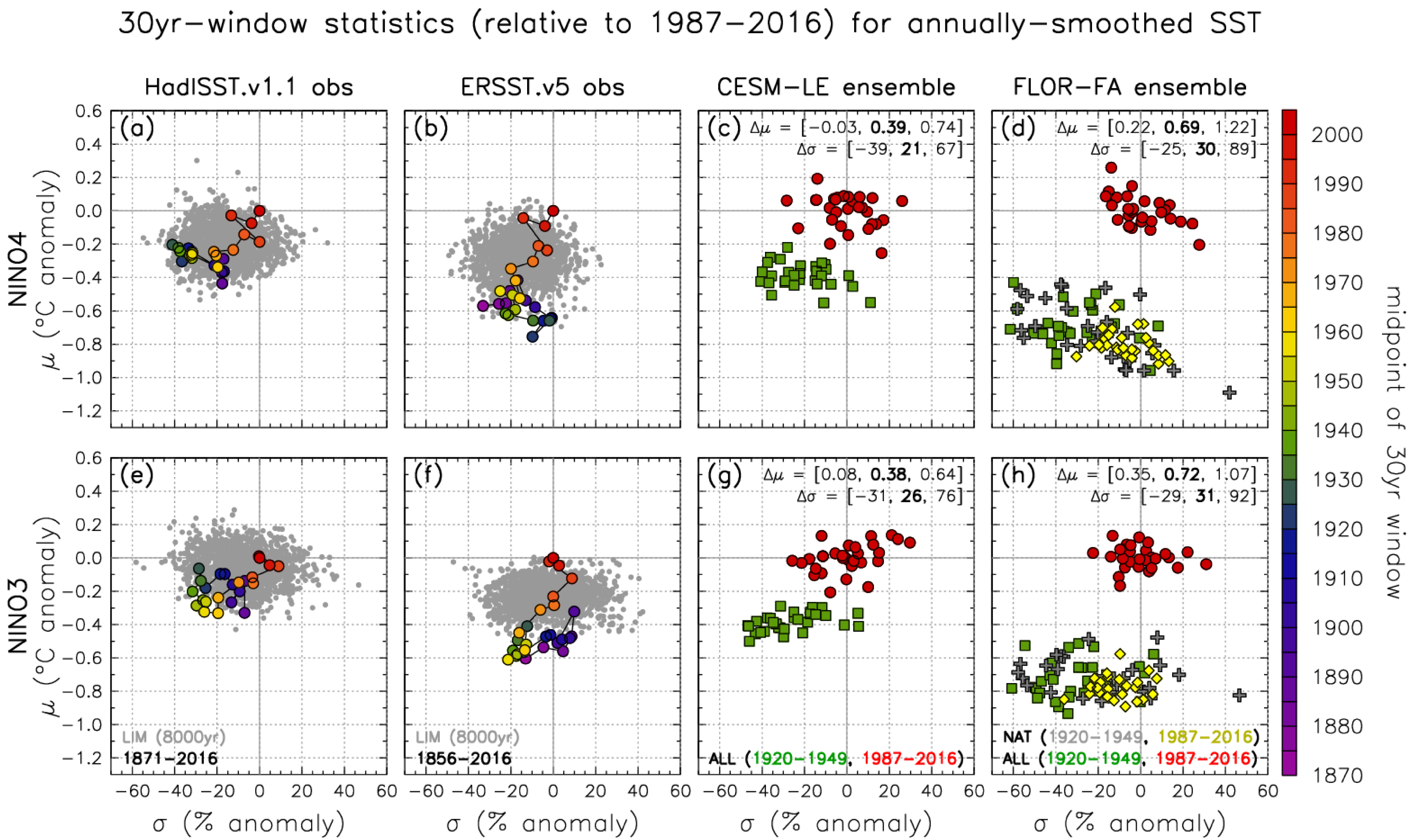
Observed & simulated mean/ENSO SST changes

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



Newman, Wittenberg, et al. (BAMS 2017)

Observed & simulated mean/ENSO SST changes

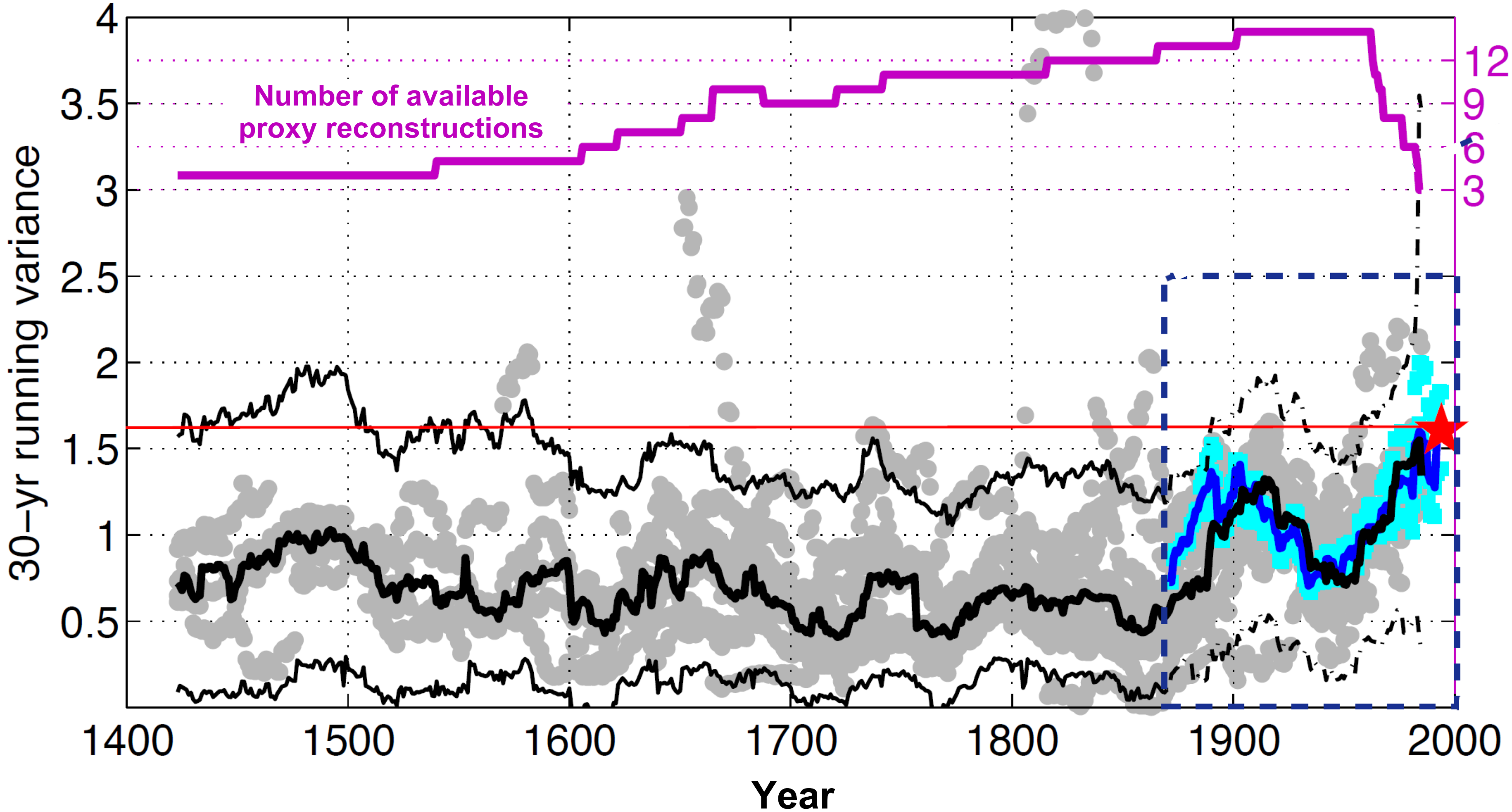


Mean change is marginally detectable. ENSO change, less so.

Newman, Wittenberg, et al. (BAMS 2017)

Reconstructing past variations in ENSO

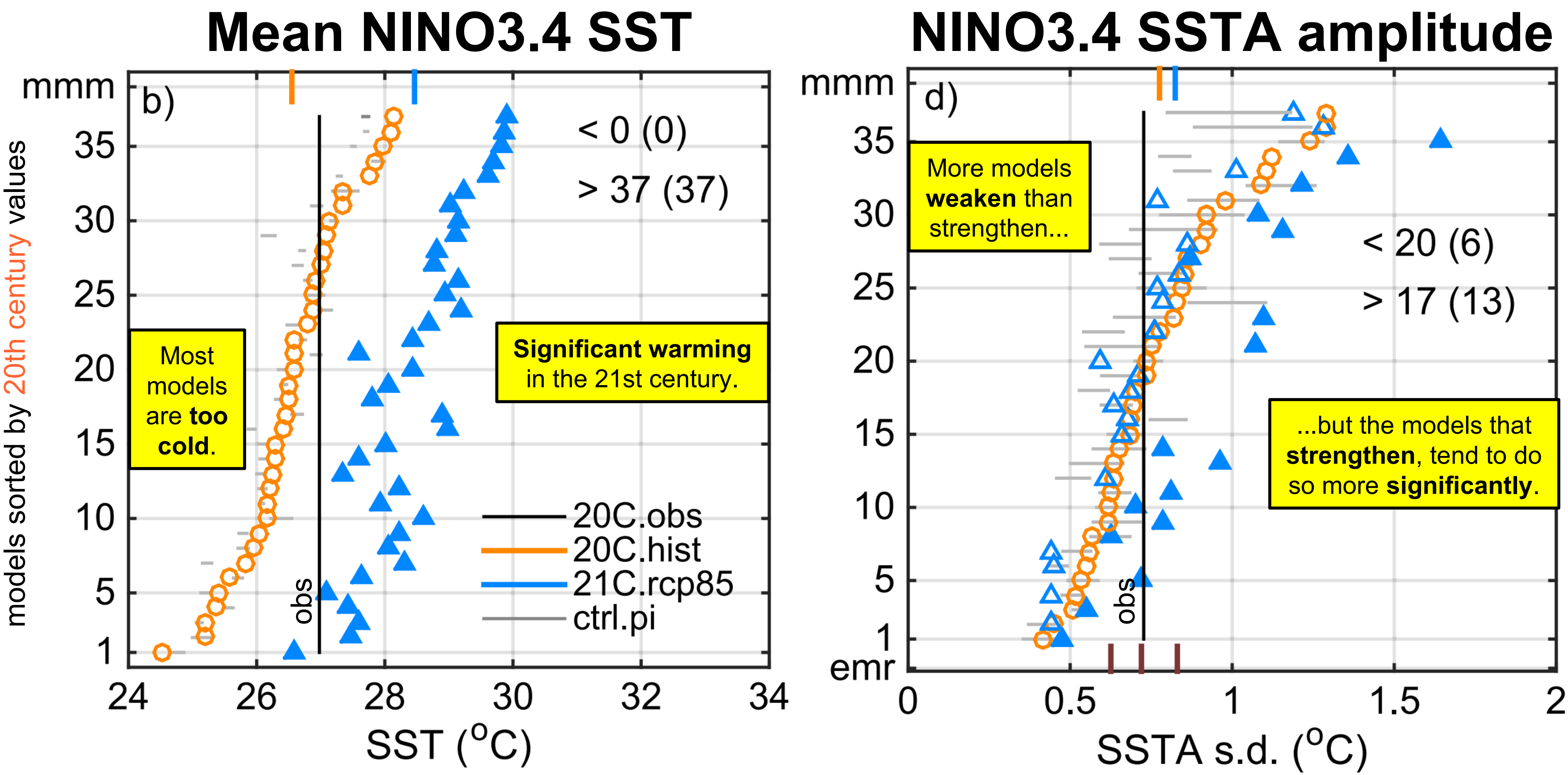
Proxy evidence suggests that ENSO activity has waxed & waned, with significant amplification in recent decades.



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)

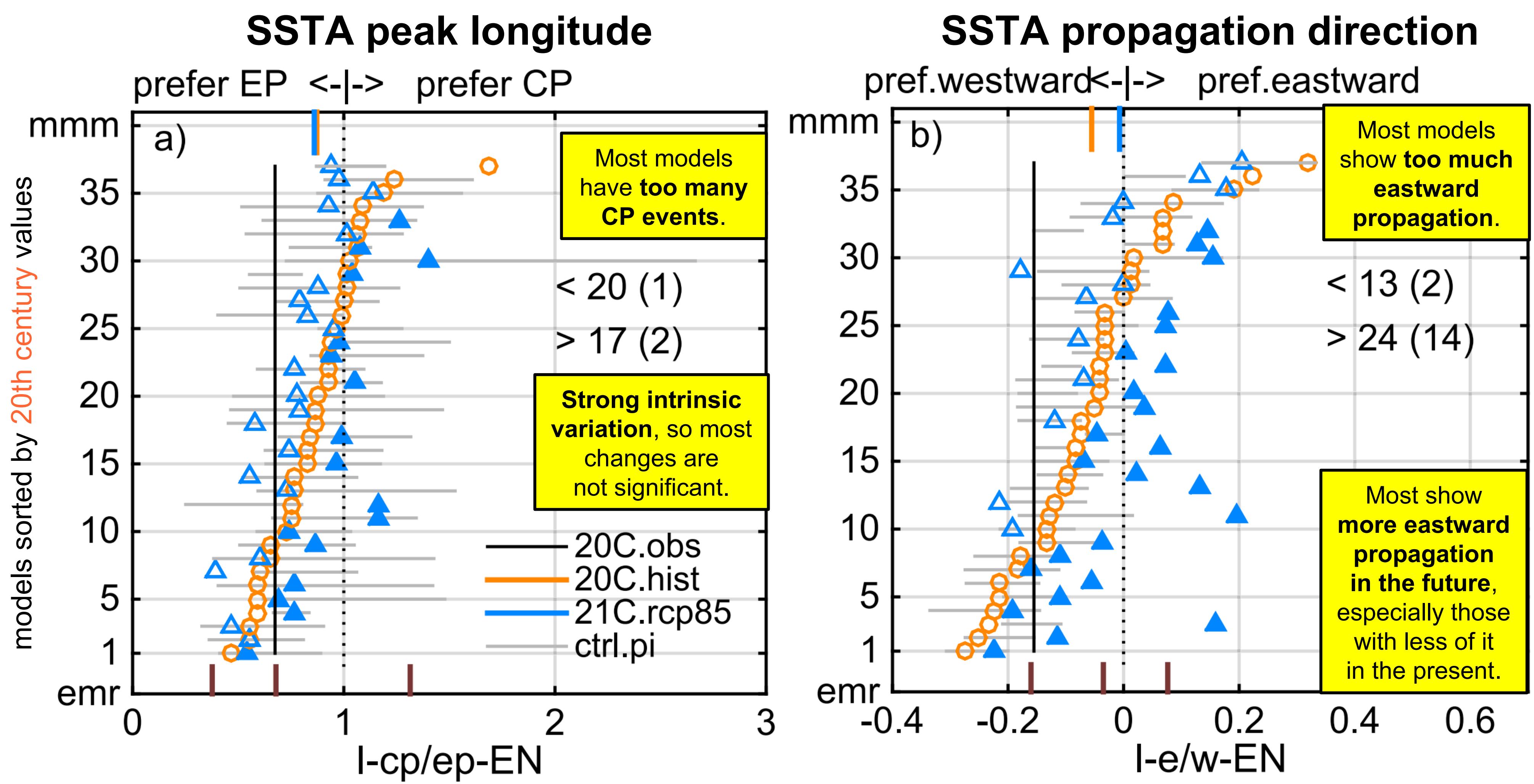
CMIP5 projections (PI, 1900-99, 2000-99)



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 projected 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

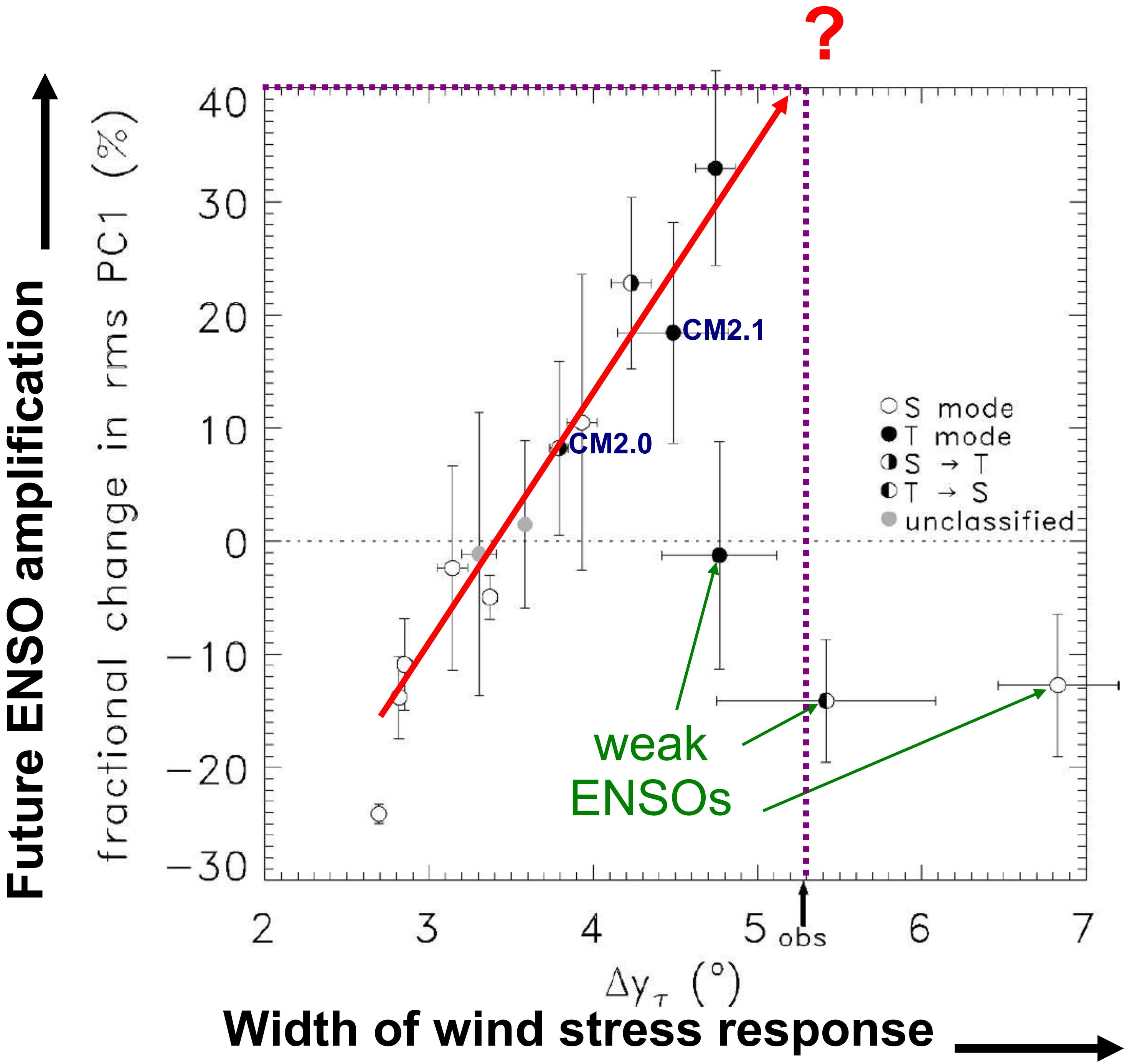
3. Ambiguous effects

- 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 $2xCO_2$

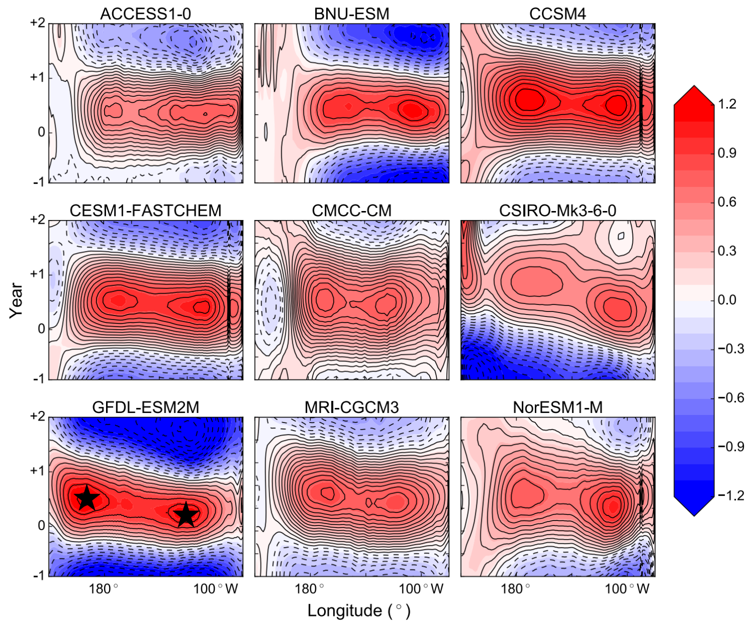
Merryfield (JC 2006)

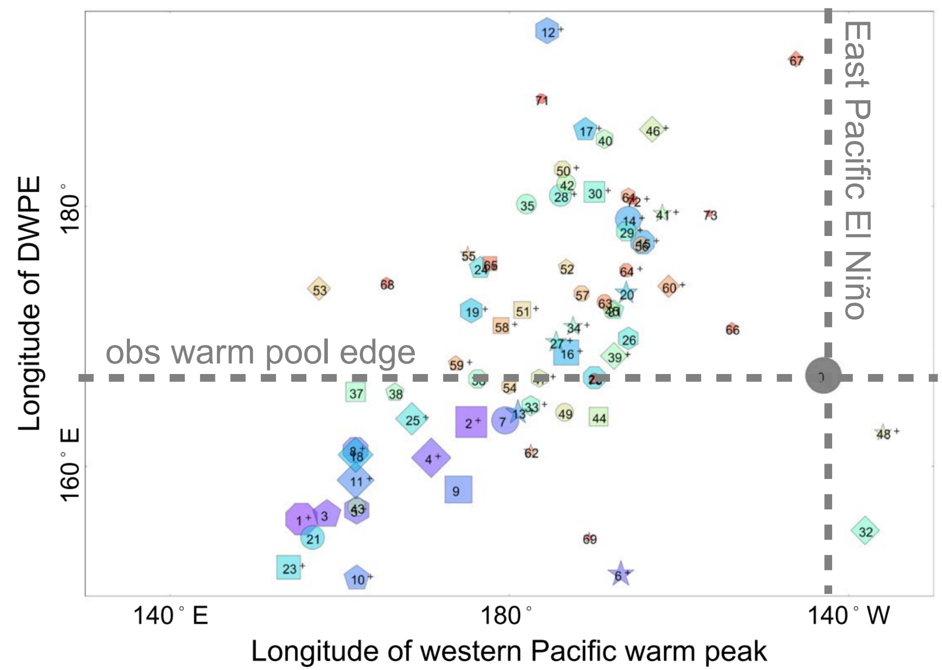
Vecchi & Wittenberg (WIREsCC 2010)

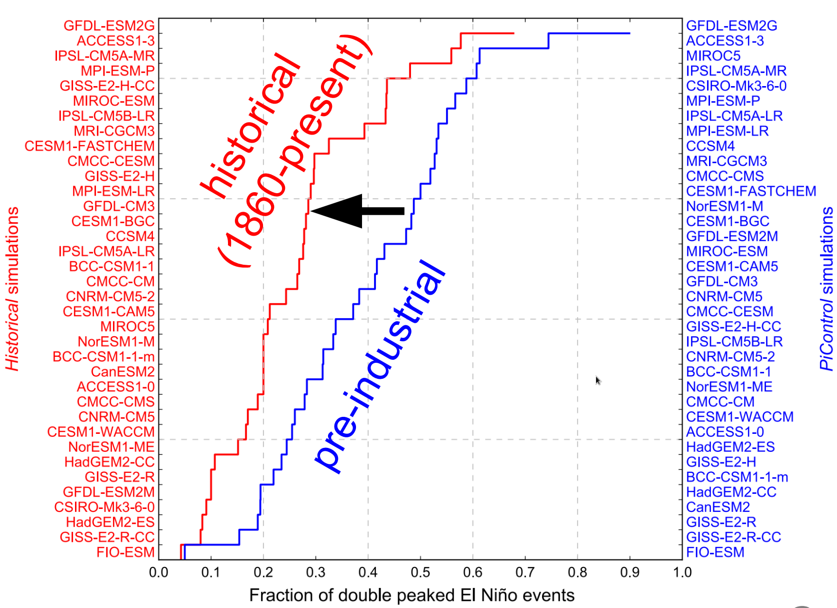
Opportunities for Improvement

The double-peaked El Niño

Composite El Niño in CMIP5 models
(equatorial SSTA)







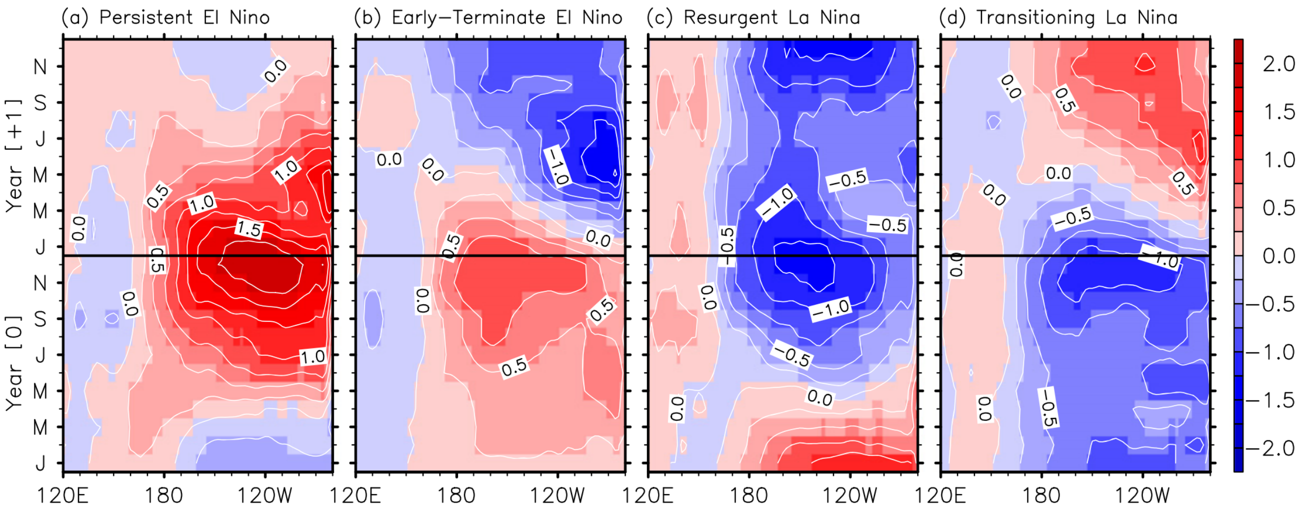
If warm pool is too far west, we get more **double-peaked El Niños** with western peaks that are **farther west**.

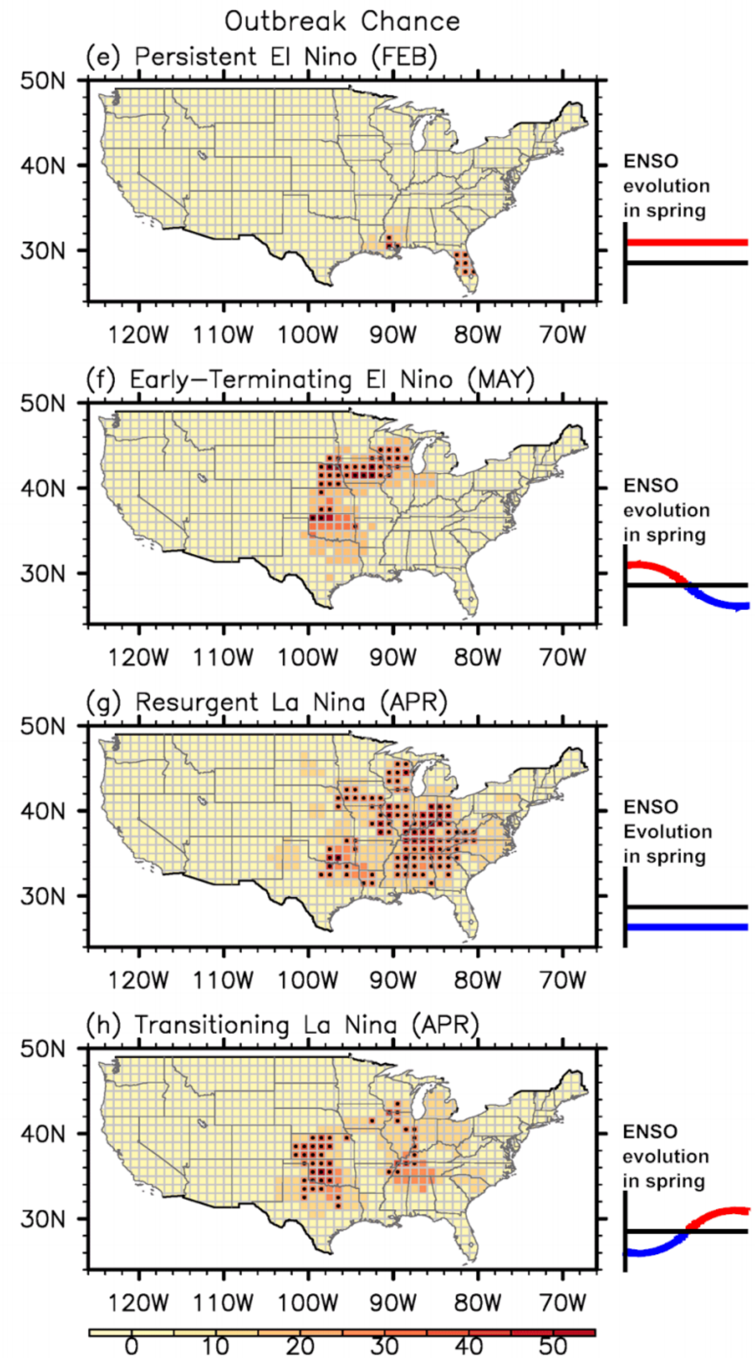
Present-day simulations show fewer double-peaked El Niños than pre-industrial.

Graham et al. (CD 2017)

Seasonal timing and ENSO impacts

Key archetypes of ENSO evolution



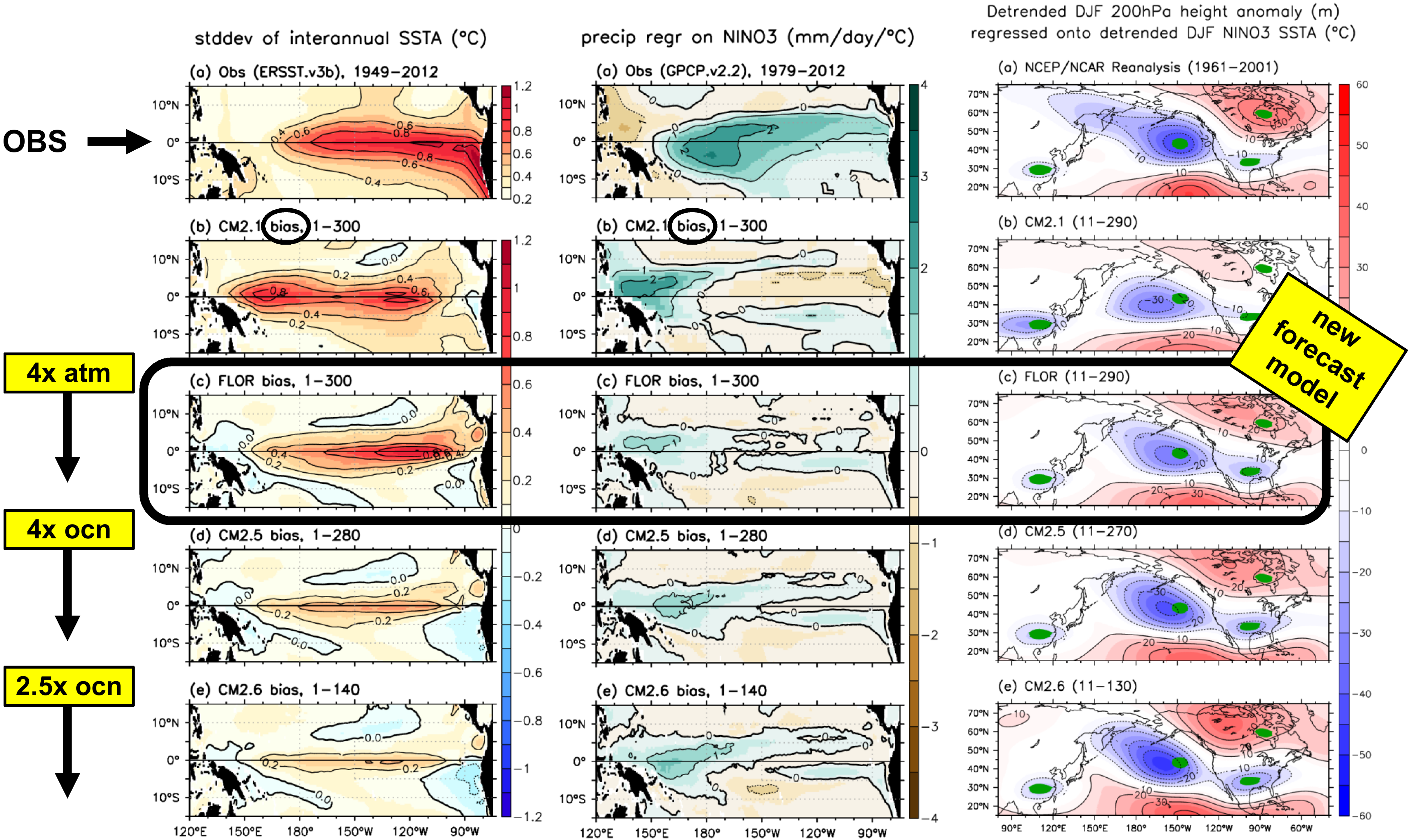


ENSO events show diverse temporal behavior in boreal spring – e.g. **persisting, terminating early, resurging, or transitioning**.

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

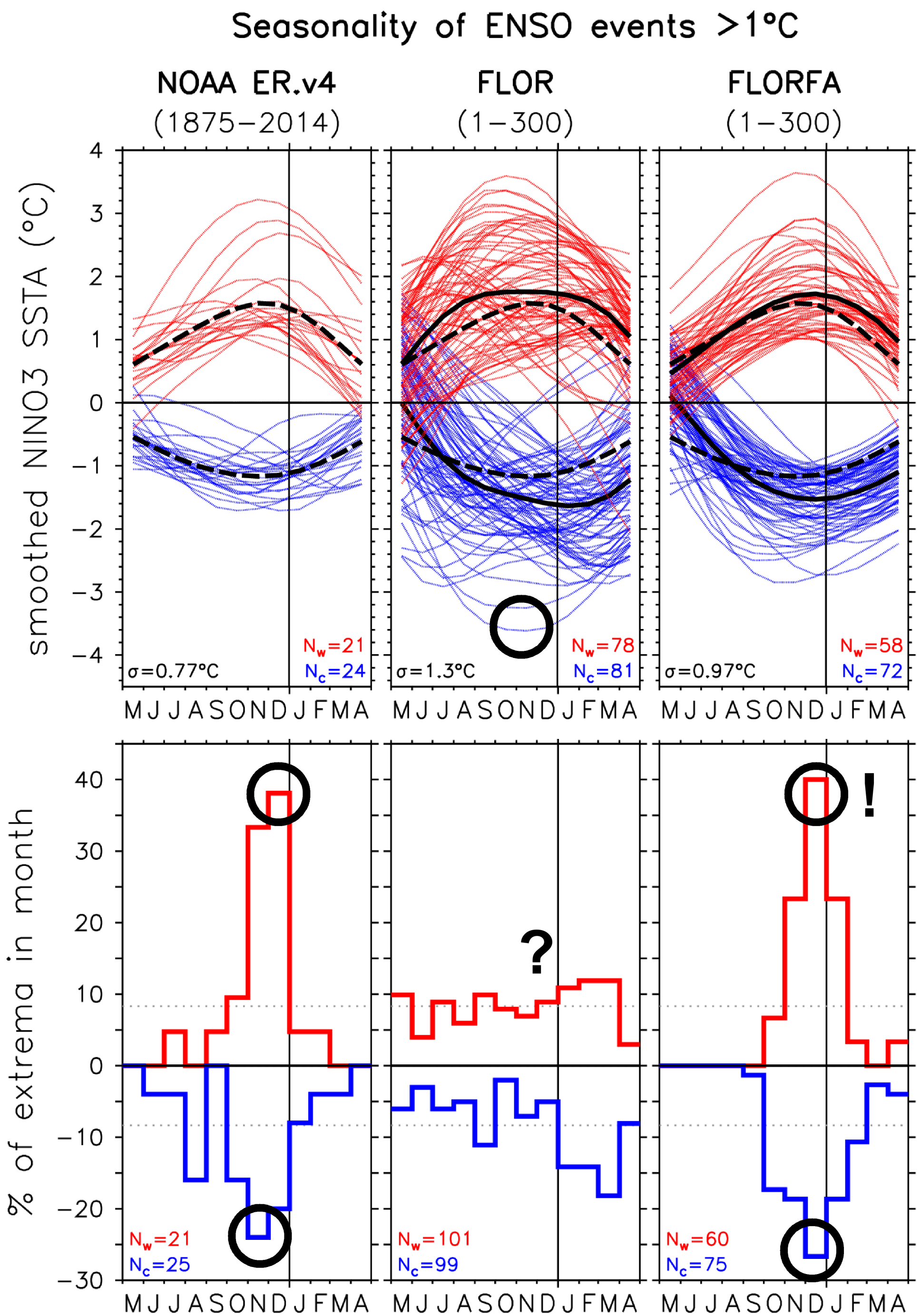
Lee et al. (GRL 2014; ERL 2016)

ENSO improvements with increasing resolution



Delworth et al. (2012); Vecchi et al. (JC 2014); Jia et al. (JC 2015); Wittenberg et al. (JAMES subm.)

Seasonal synchronization of ENSO



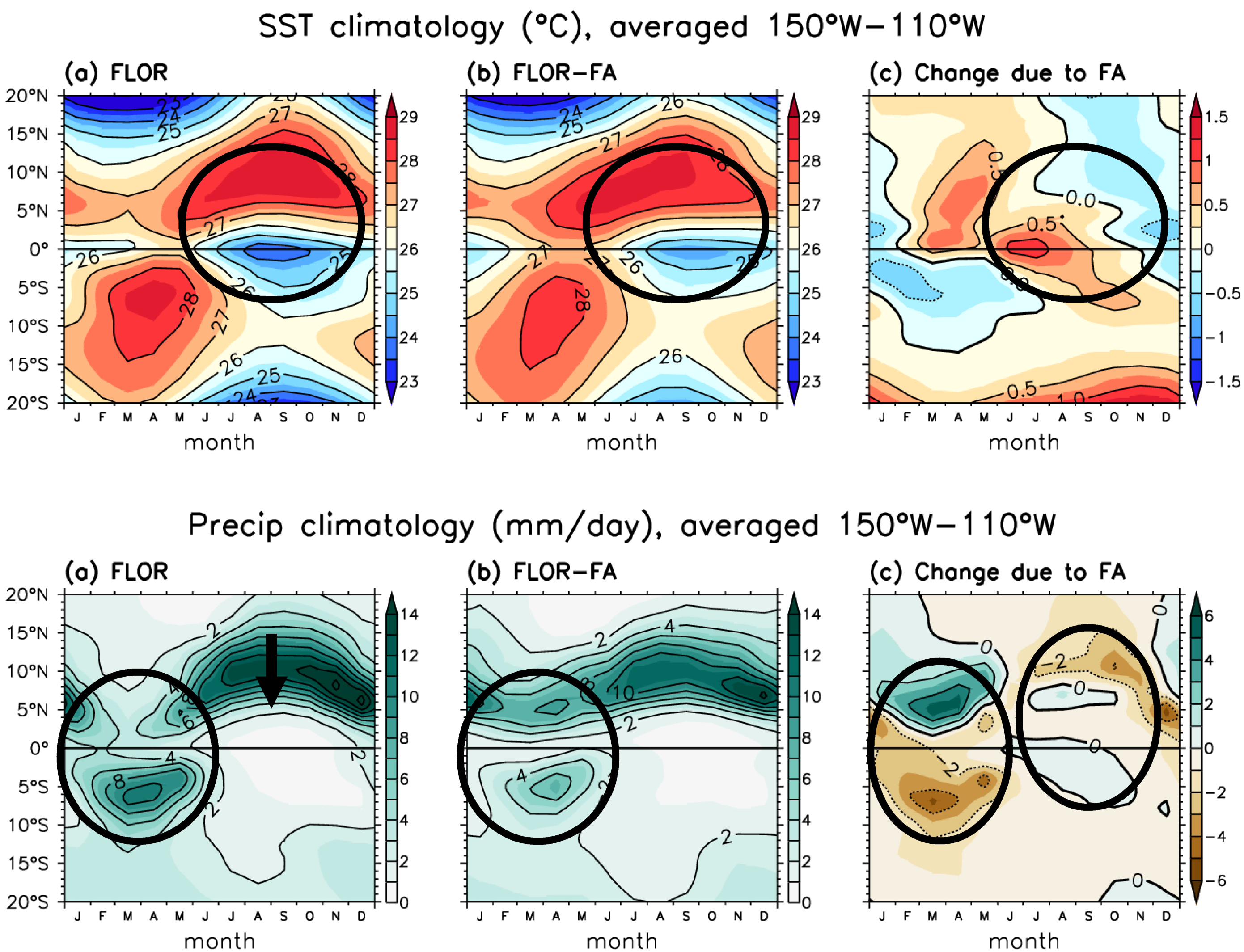
Observed events (especially strong ones) tend to peak during Oct-Dec.

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.

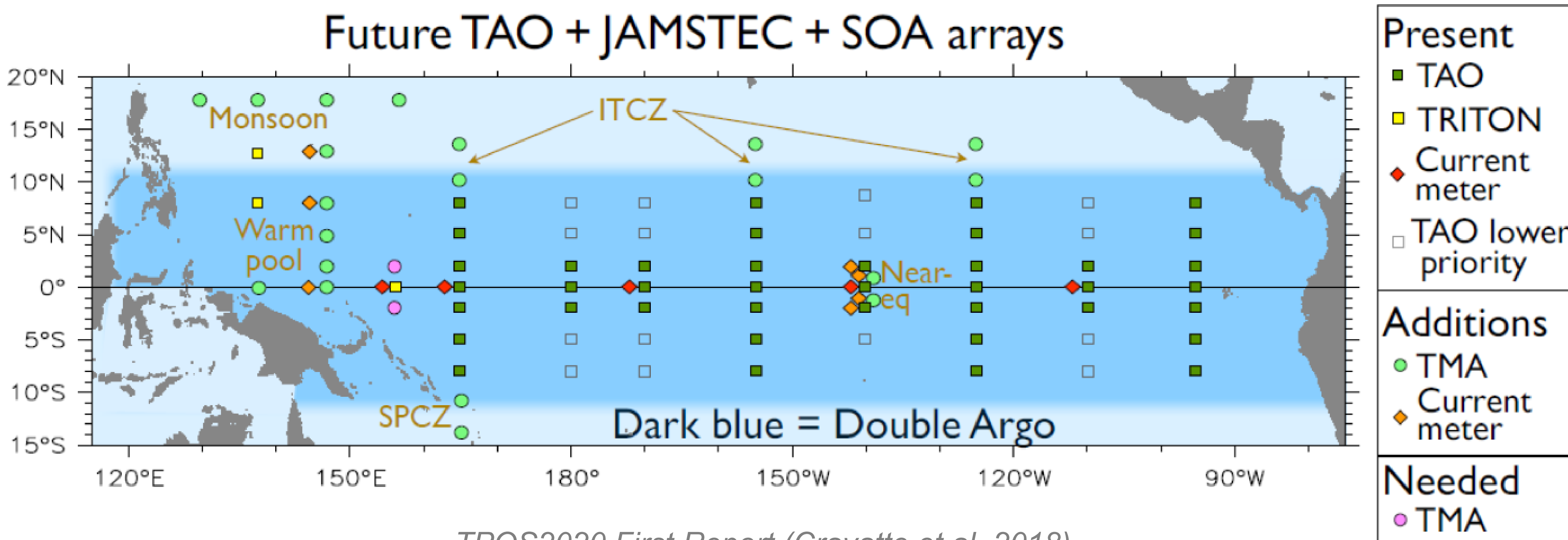
Flux adjustment weakens this dT/dy, aiding equatorial shifts of the ITCZ and extending ENSO through to Dec.

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.*

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.

Summary

1. ENSO: Earth's strongest interannual climate fluctuation

a. Remarkable progress in observing, modeling, understanding ENSO
b. Feedbacks, impacts are multiscale, nonlinear, seasonally-dependent

2. ENSO's past & future

a. Paleorecords suggest **ENSO recently strong** relative to prior 400yr
- But ENSO SSTA amplification not yet clearly detectable in instrumental records

b. Near term: Large multidecadal **intrinsic modulation** (unpredictable)
c. Forced response of ENSO & impacts: **nonlinear, regionally-dependent**
d. CMIP5 projections
- **Robust changes**: mean warming, more eastward SSTA propagation & rainfall sensitivity
- **Ambiguous changes**: ENSO amplitude & SSTA pattern
- Response depends on **competing changes in strong feedbacks**
- **Emergent constraints**: model diversity is useful!

3. Coupled GCM simulations of ENSO

a. **Biases** remain
- Equatorial cold tongue too strong, too far west
- Double-peaked El Niño; poor seasonal synchronization

b. But models are **improving**
- ENSO **patterns & teleconnections** improve with atmos/ocean grid refinement
- **Flux adustment** → better climatology → seasonal synchrony of ENSO → key for impacts

c. Need improved **observational constraints** for models → TPOS2020
d. As models improve: **model-analog** forecasts may be useful

Reserve Slides

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

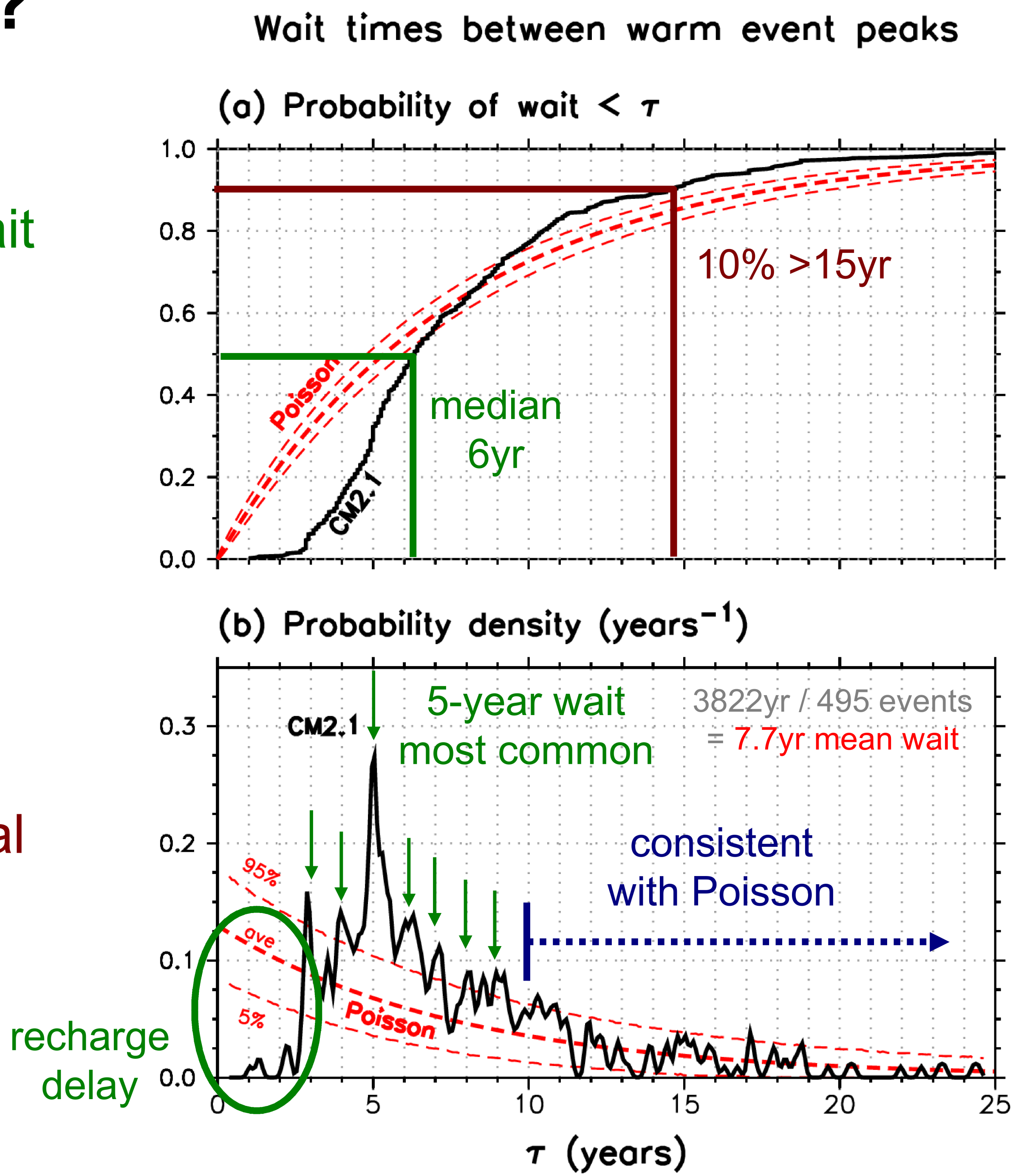
a. **Seasonal dT/dy** in east Pacific (ENSO seasonality)
b. **Coupled feedback** diagnostics (need obs constraints!)
c. **Subsurface flux adjustments** (3D-FA)

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)

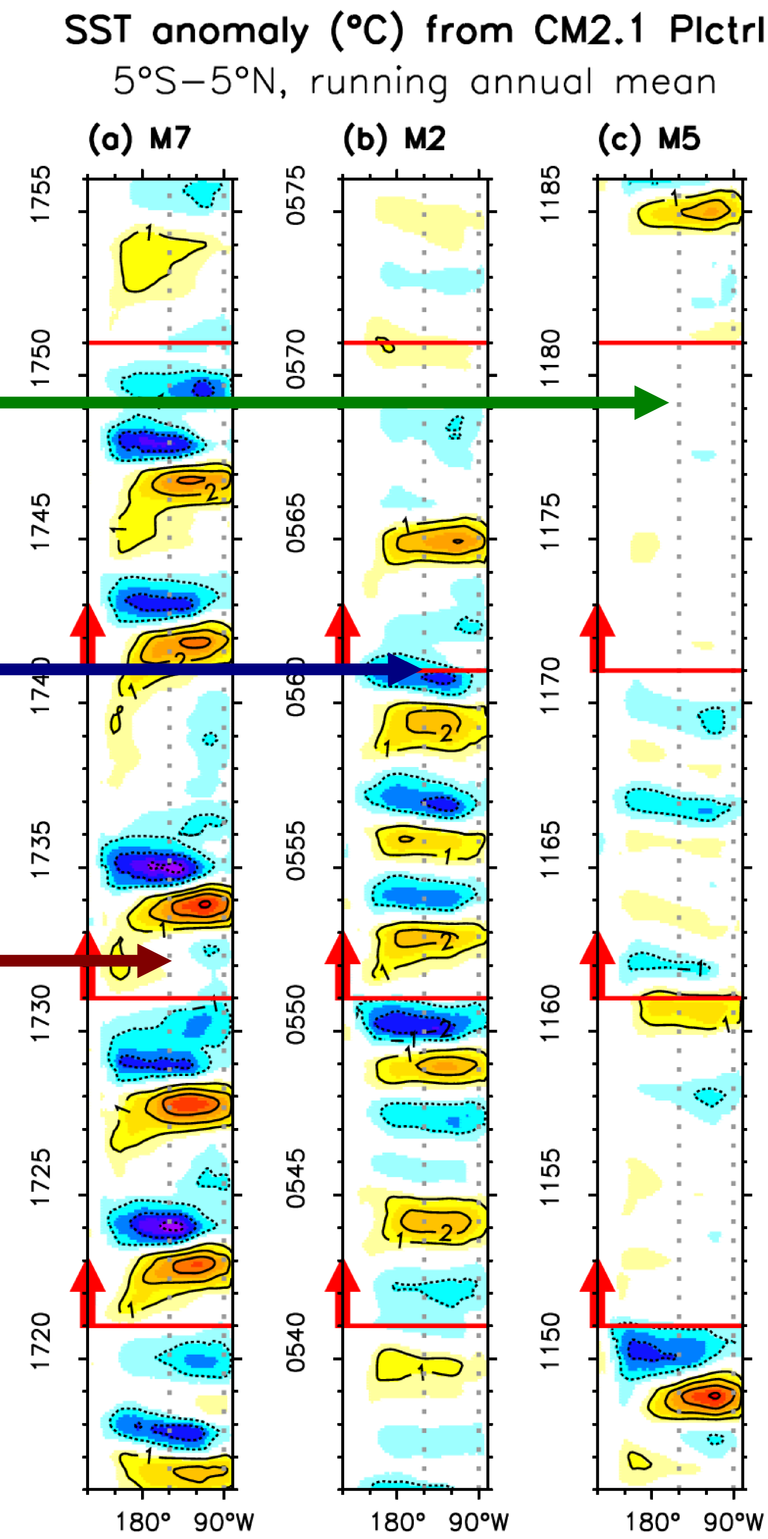
Epochs of unusual ENSO behavior

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

regular, westward propagating
(1960s & 70s)

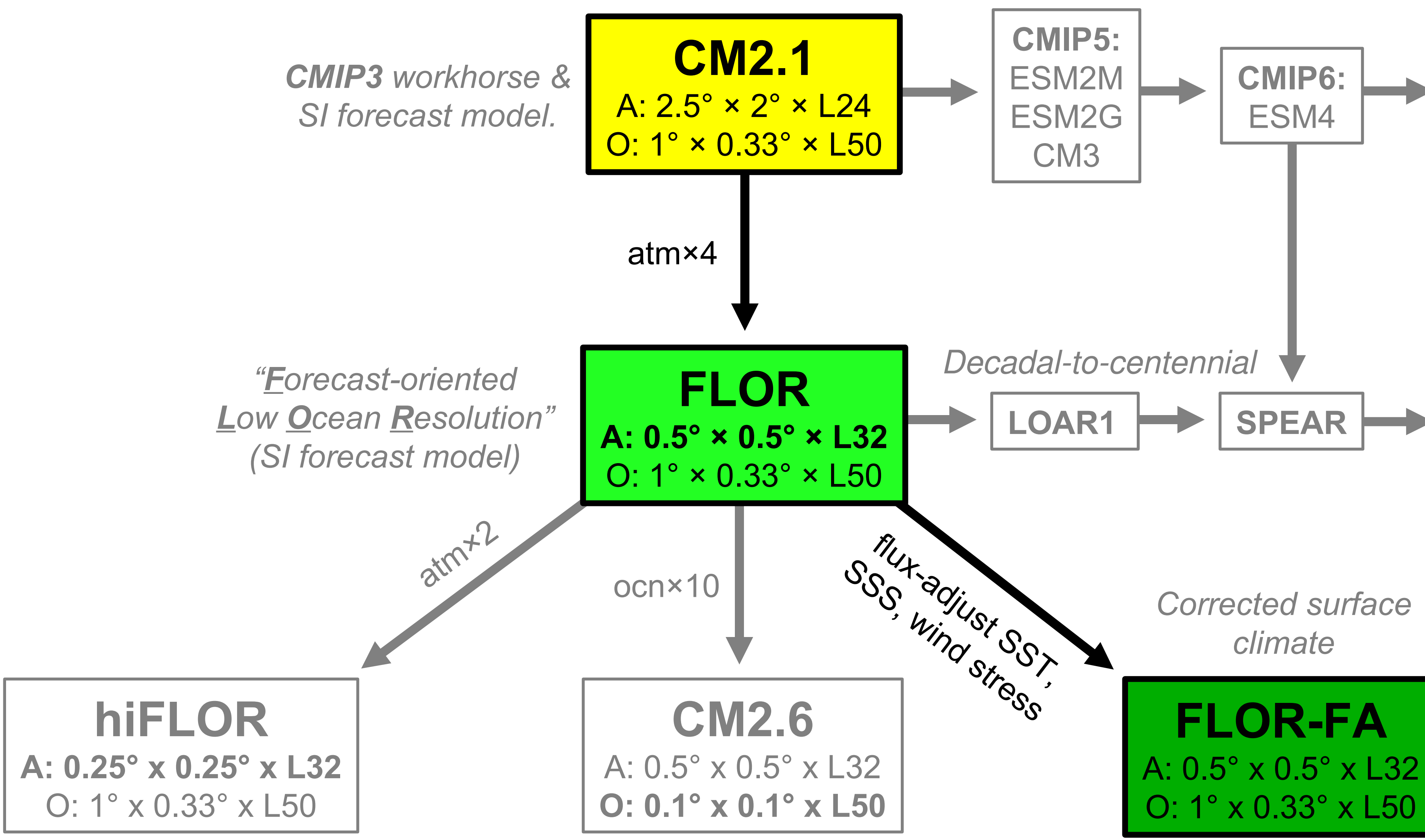
strong, skewed, long period, eastward propagating
(1980s & late 1990s)

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



Wittenberg et al. (J. Climate, 2014)

GFDL coupled GCM development



FLOR connects many of GFDL's newest climate models,

and is used extensively for seasonal-to-interannual research and forecasts.