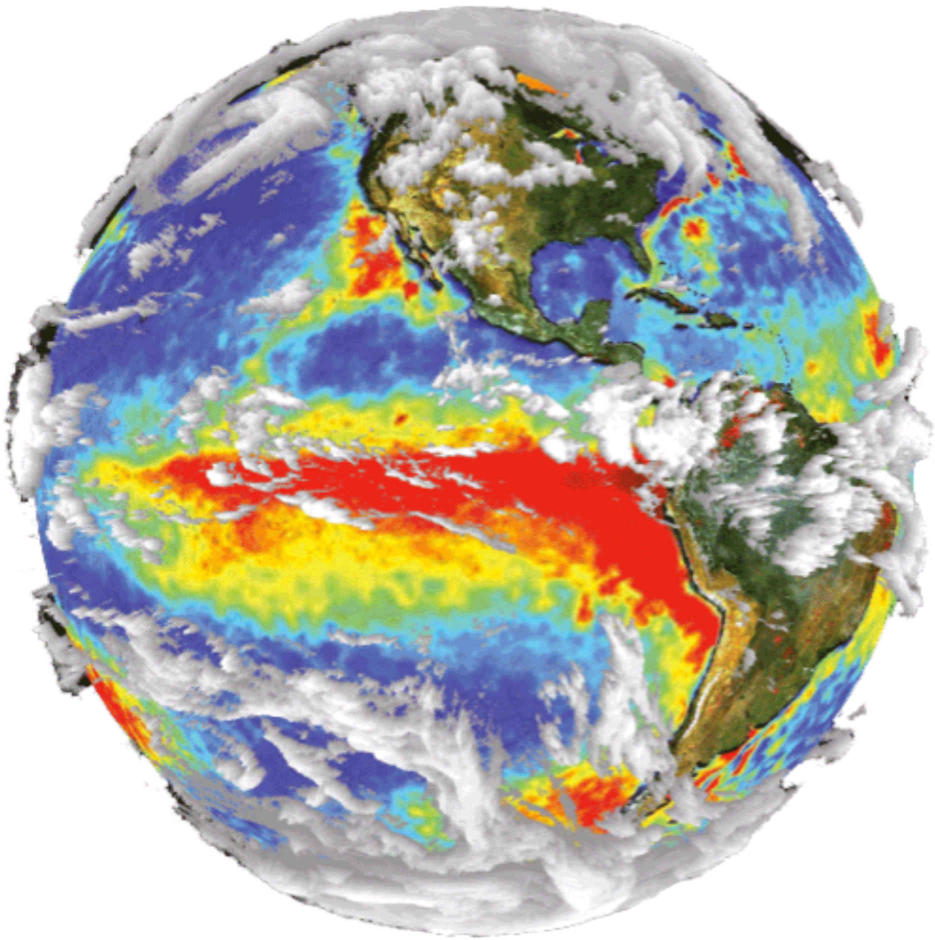
Understanding ENSO in CGCMs: from statistics to process-based metrics



H. Bellenger, E. Guilyardi, M. Lengaigne, J. Leloup, J. Vialard

IPSL/LOCEAN, Paris

CLIVAR PP, Lijiang, China
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LOCEAN · cnrs · Institut Pierre Simon Laplace · University of Reading · National Centre for Atmospheric Science

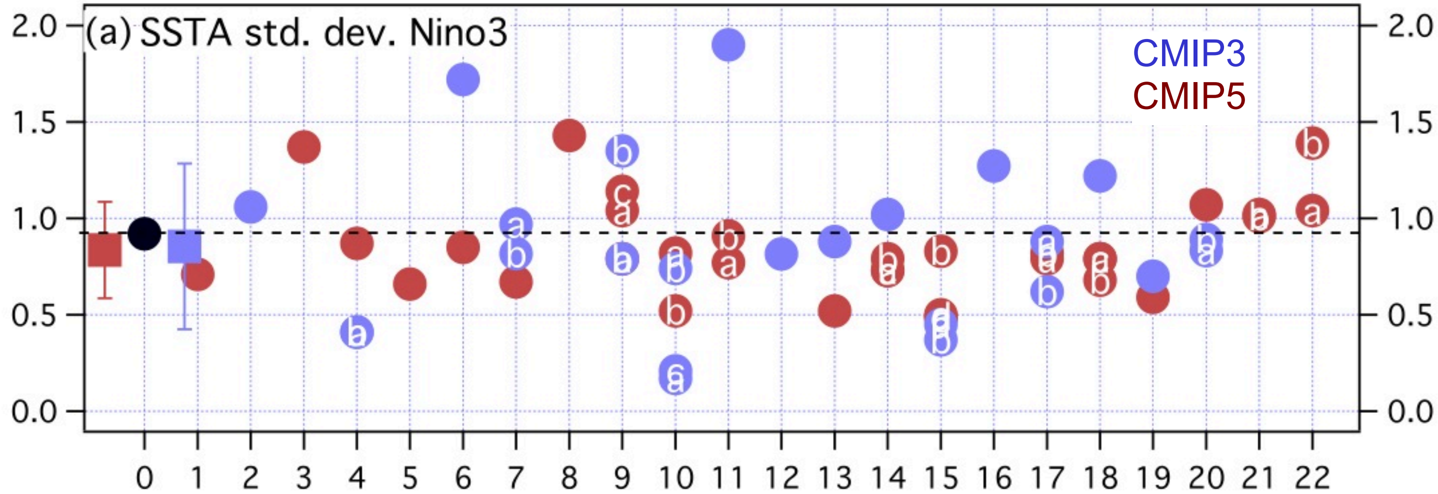
Outline

1. Diagnosing ENSO in coupled GCMs
    - Metrics, CMIP5 vs. CMIP3
2. Role of atmosphere processes
3. ENSO in a changing climate
4. Outlook

El Niño in coupled GCMs - amplitude

Standard deviation SSTA (C) in Niño3

ENSO Amplitude



Observations

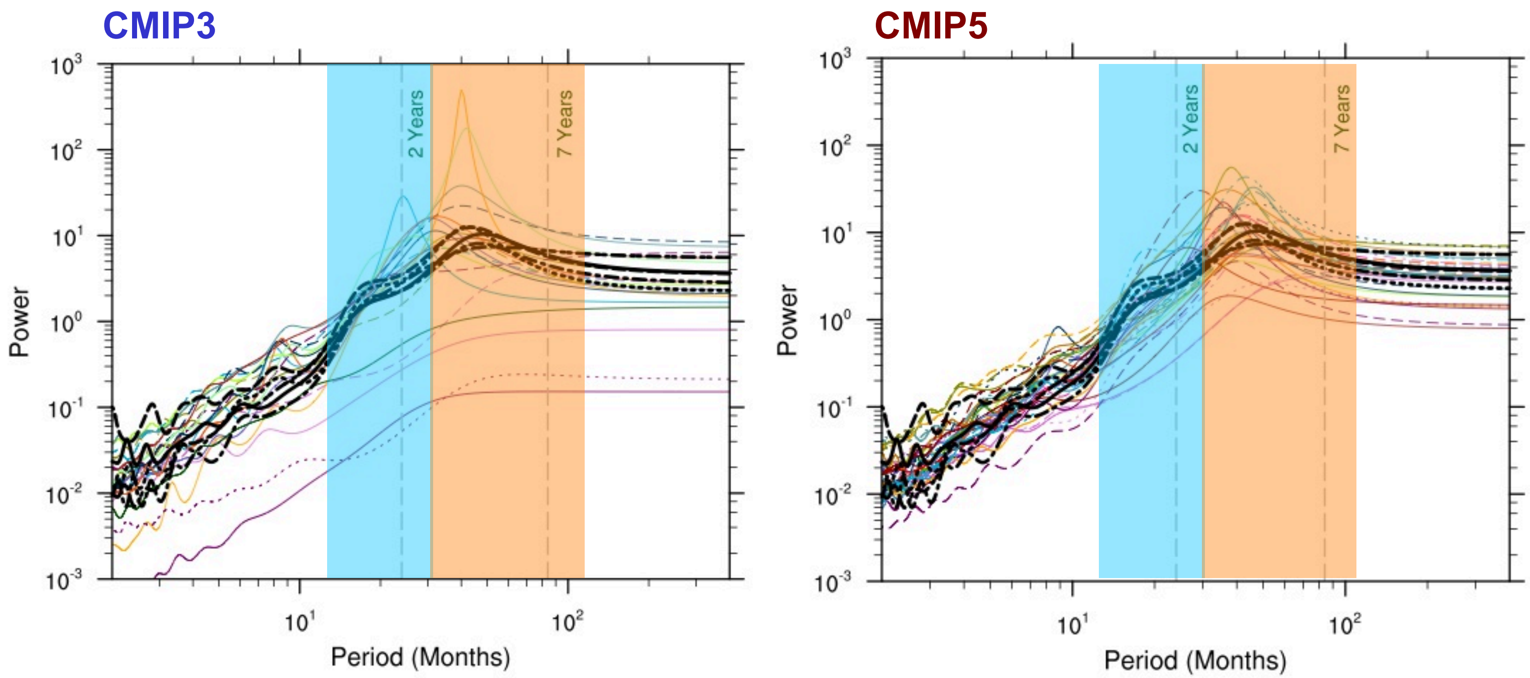
Modelling centers

- ENSO amplitude in CMIP3: very large diversity of simulated amplitude
- Range reduced in CMIP5 (improved mean state ? tuned in modelling development process ?)

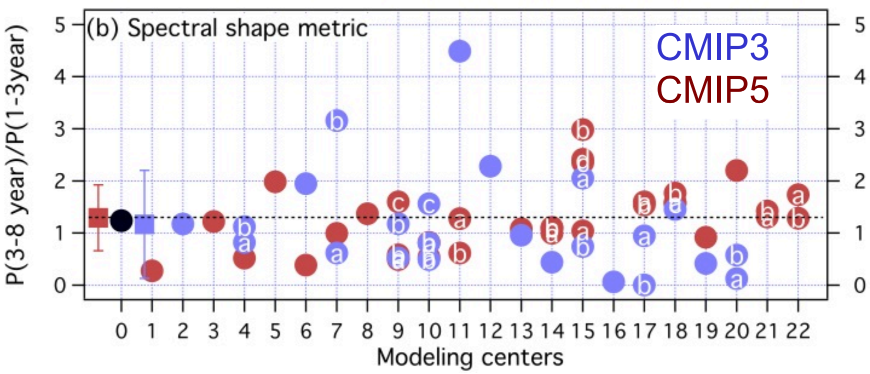
Bellenger et al. 2013

El Niño in coupled GCMs - frequency

Niño3 SSTA spectra



Courtesy K. AchutaRao



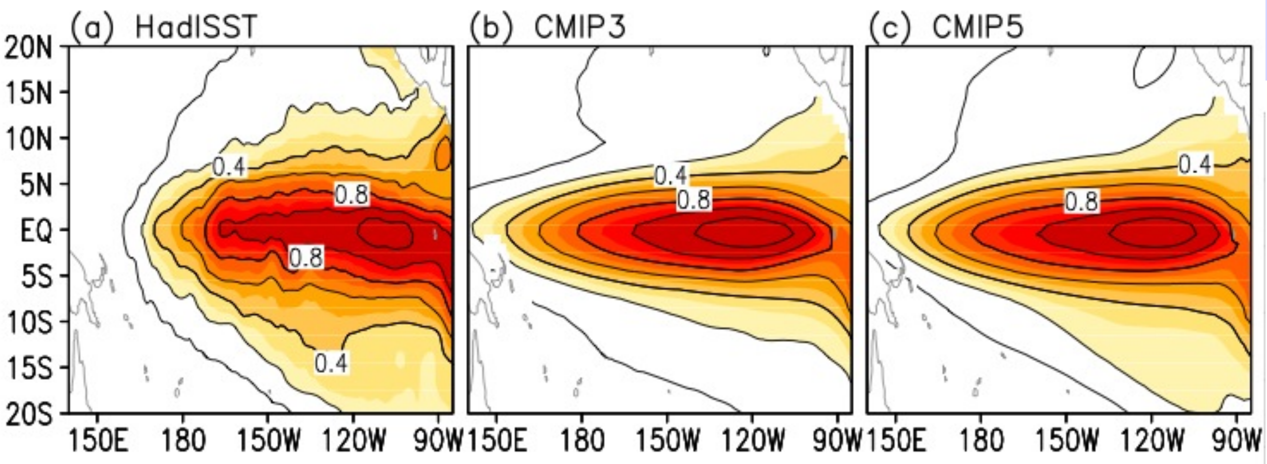
- Improved spectra in CMIP5
- No more models with no ENSO
- Shift towards lower frequency as in obs

Bellenger et al. 2013

El Niño in coupled GCMs - structure and timing

- Westward zonal extension
- Too small meridional extension
- With impacts on periodicity
  (Capotondi et al. 2007)
- Little change in CMIP5

SST standard deviation



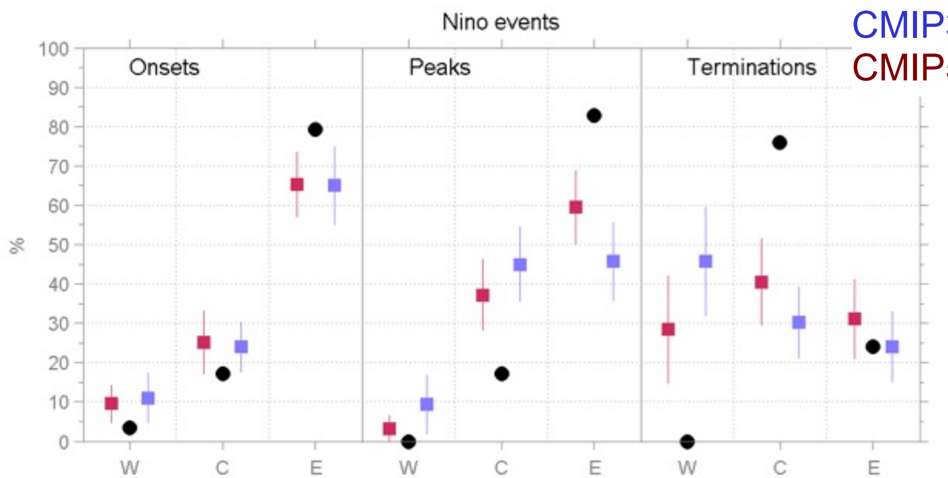
Zhang and Jin 2012, Zhang et al. 2013

Time sequence of El Niño:

- Onset correctly located
- Peak located too centrally
- Termination too much in West (rather than in East Pacific)
- Marginal improvement in CMIP5

Neural network analysis following Leloup et al. (2008)

CMIP3
CMIP5



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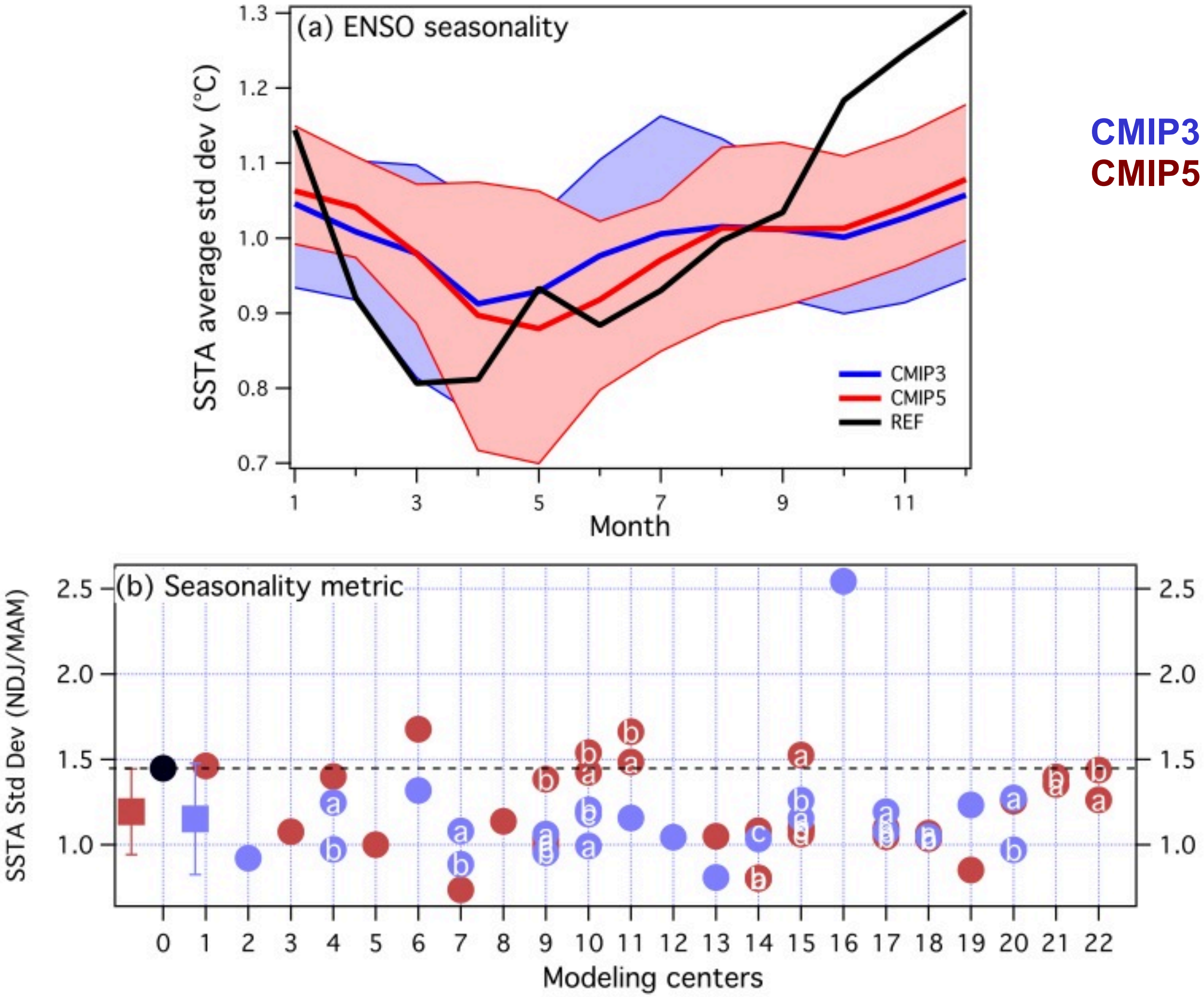
El Niño in coupled GCMs - seasonality



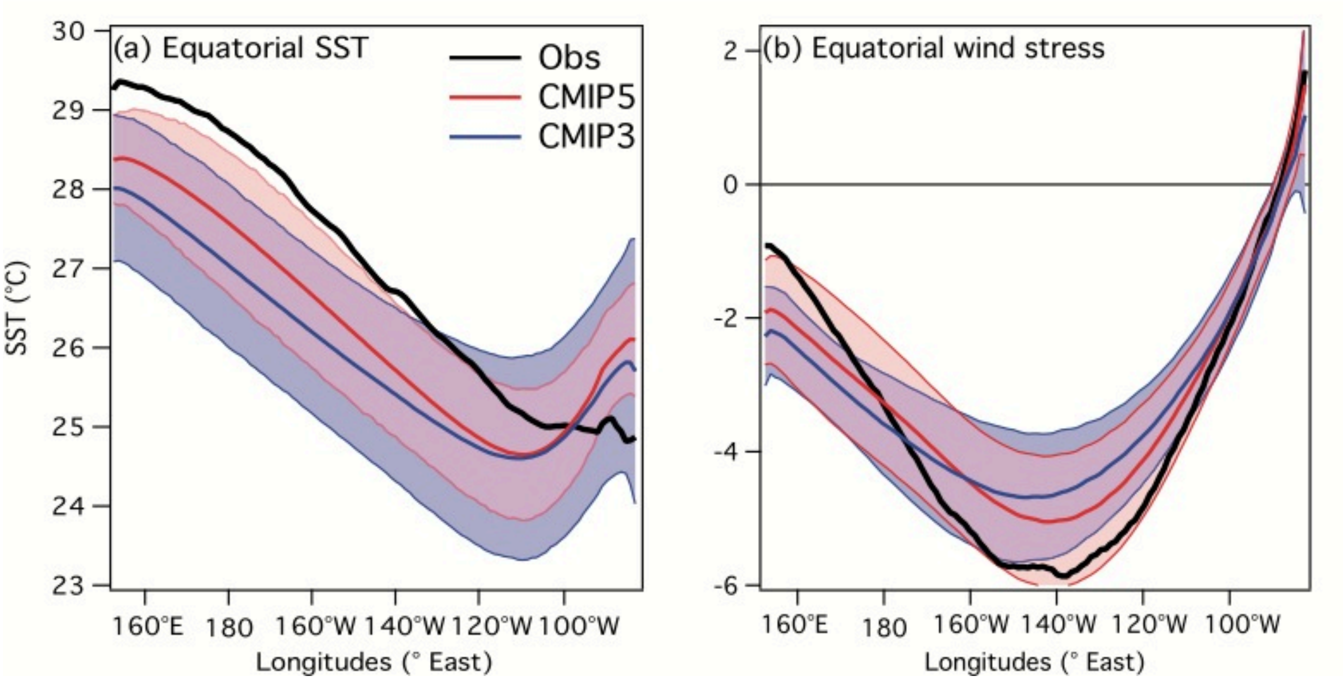
CMIP3
CMIP5

- Few models have the spring relaxation and the winter variability maximum
- Slight improvement in CMIP5

Bellenger et al. 2013

Mean equatorial SST and zonal wind structure in CMIP models

SST



Zonal wind stress

- Cold tongue extends too far west, opens the warm pool
- Zonal wind too strong in west Pacific (caveat ERA40)
- CMIP5 shows improvement in west in SST

Bellenger et al. 2013

2. Role of atmosphere during ENSO

1 - Classical theory:

Dynamical positive Bjerknes feedback: m

Negative heat flux feedback: a (SHF, LHF)

e.g.: the BJ coupled-stability index for ENSO I_{BJ}

Mean advection and upwelling (damping)

$$\frac{\partial \langle T \rangle}{\partial t} = 2I_{BJ}\langle T \rangle + F[h],$$

$$2I_{BJ} = -\left(\frac{\langle \bar{u} \rangle}{L_x} + \frac{\langle -2y\bar{v} \rangle}{L_y^2} + \frac{\langle H(\bar{w})\bar{w} \rangle}{H_m} \right) - \alpha$$

α : atmosphere heat flux feedback (local linear)

Zonal advection feedback

Ekman pumping feedback

$$+ \mu_a \beta_u \left\langle -\frac{\partial \bar{T}}{\partial x} \right\rangle + \mu_a \beta_w \left\langle \frac{\partial \bar{T}}{\partial z} H(\bar{w}) \right\rangle$$

Thermocline feedback

$$+ \mu_a^* \beta_h \left\langle \frac{H(\bar{w})\bar{w}}{H_m} a \right\rangle,$$

μ_a: Bjerknes feedback or linear "coupling strength"

$$\beta_u = \beta_{um} + \beta_{us}, \quad F = -\left\langle \frac{\partial \bar{T}}{\partial x} \right\rangle \beta_{uh} + \left\langle \frac{H(\bar{w})\bar{w}}{H_m} a \right\rangle.$$

2 - Dominant role of AGCM in coupled AOGCMs

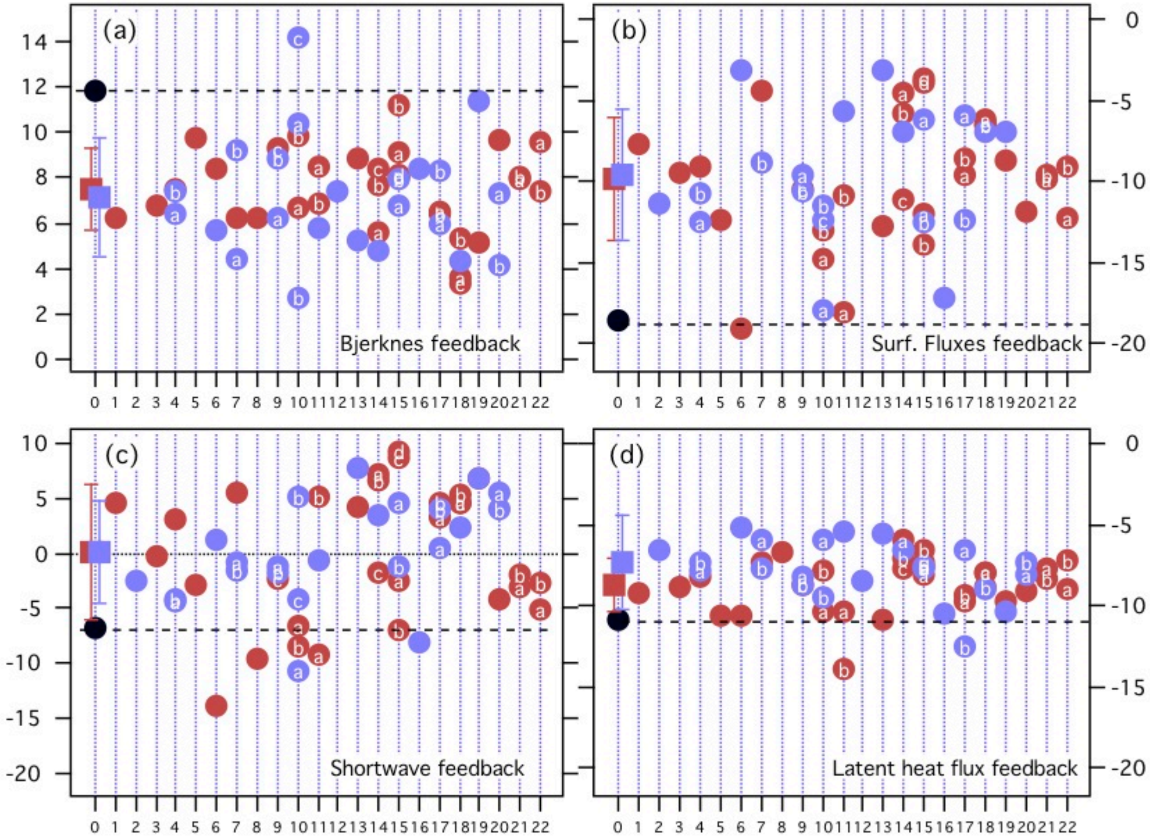
OGCM only modifies the amplitude

(Schneider 2002, Guilyardi et al. 2004, 2009, Kim et al. 2008, Neale et al. 2008, Sun et al. 2008, 2010)

Atmosphere feedbacks in CMIP3/CMIP5

Bjerknes m

a Total Heat Flux



SW Heat Flux a_{SW}

a_{LH} Latent Heat Flux

Models underestimate both m and a (error compensation)

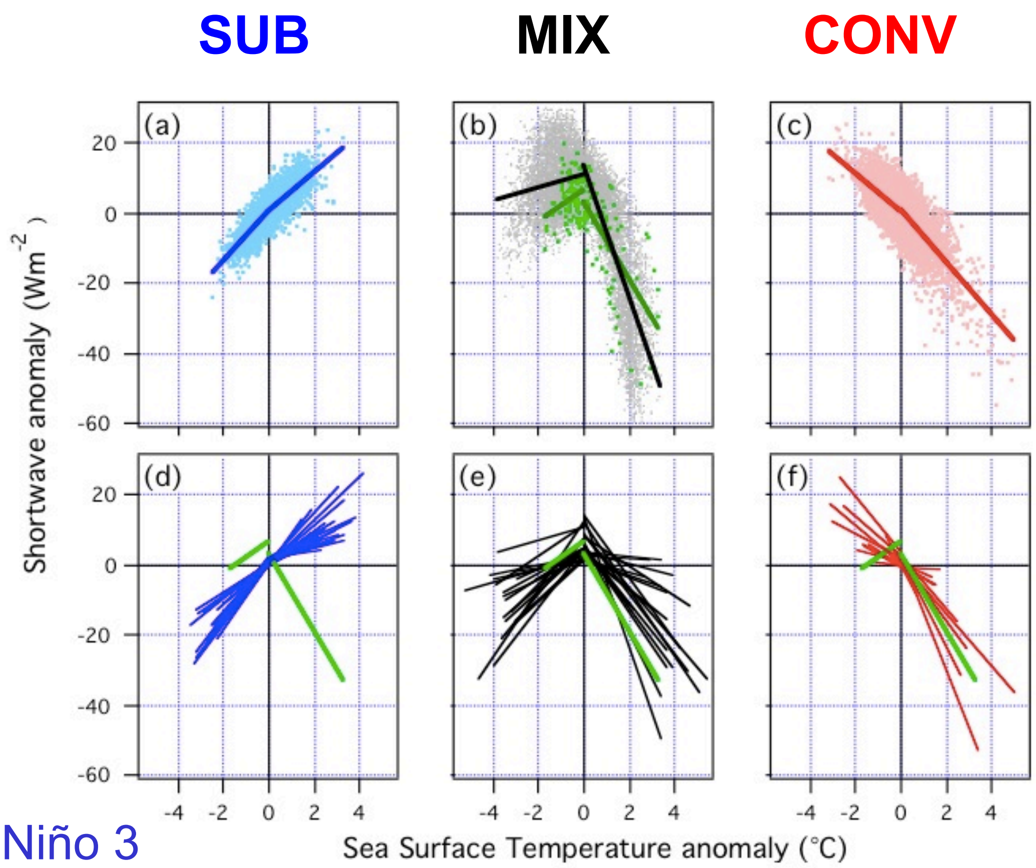
Shortwave feedback a_{SW} main source of errors and diversity (sign change !)

No clear evolution from CMIP3 to CMIP5

Bellenger et al. 2013,
based on Lloyd et al. (2009, 2010, 2012)

Non-linearities in α_{SW} in East Pacific

- Theory assumes linear a whereas strong a_{SW} non-linearities in observations
- SSTA<0 Subsidence regime $a_{SW} > 0$ SSTA> 0: Convective regime $a_{SW} < 0$
- Models differ considerably in their simulation of this non-linearity



Niño 3

Observations (MIX)

Subsident models

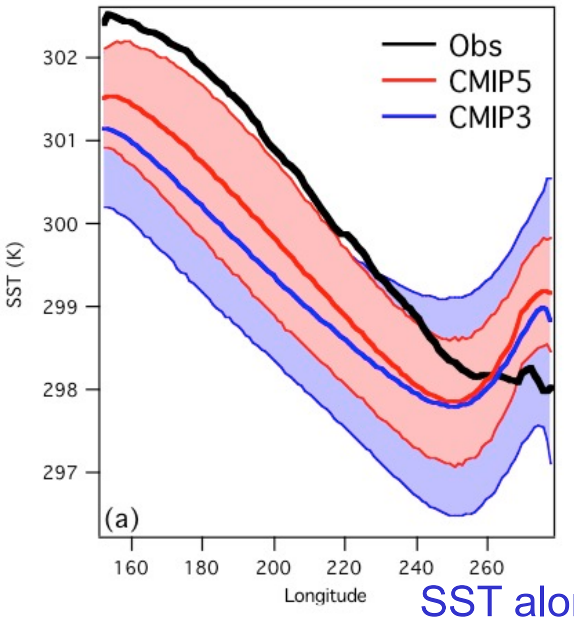
Convective models

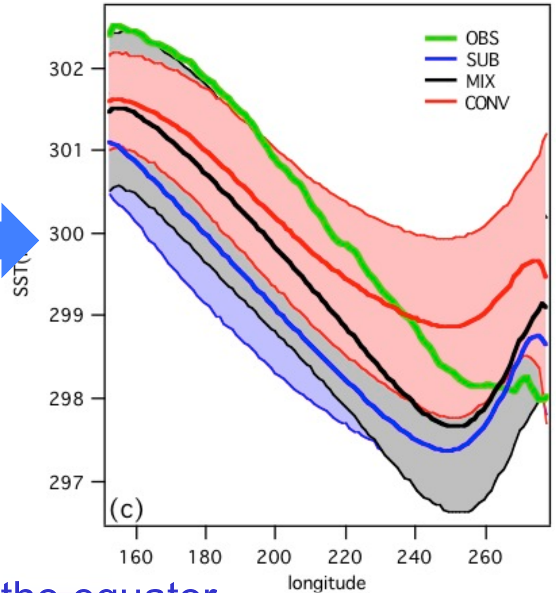
CMIP3 and CMIP5 models: 1/3rd in each category

Bellenger et al. 2013,

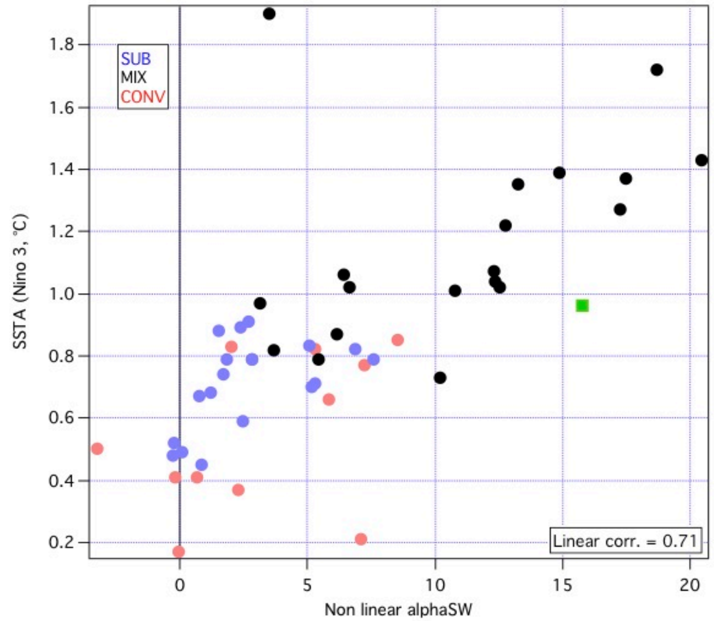
Non-linearities in α_{SW} in East Pacific

Classify CMIP3+5 models according to a_{SW} non-linearities





SST along the equator



MIX and CONV closer to obs in West Pac

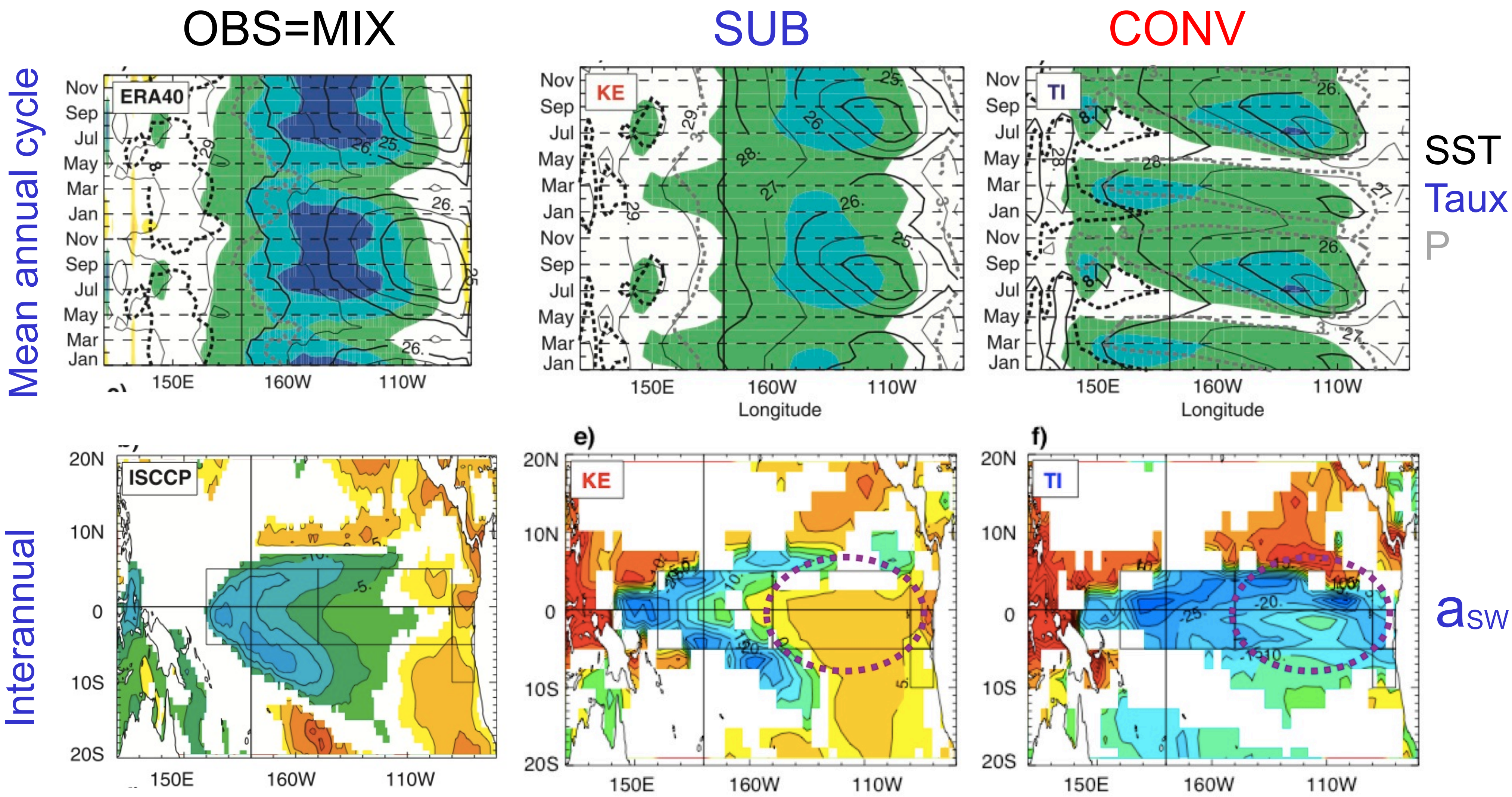
Bellenger et al. 2013

Only MIX models 1) have right W-E slope and 2) can have large ENSO amplitude

Second key message:

Better heat flux feedbacks, and ENSO, also come with better mean state

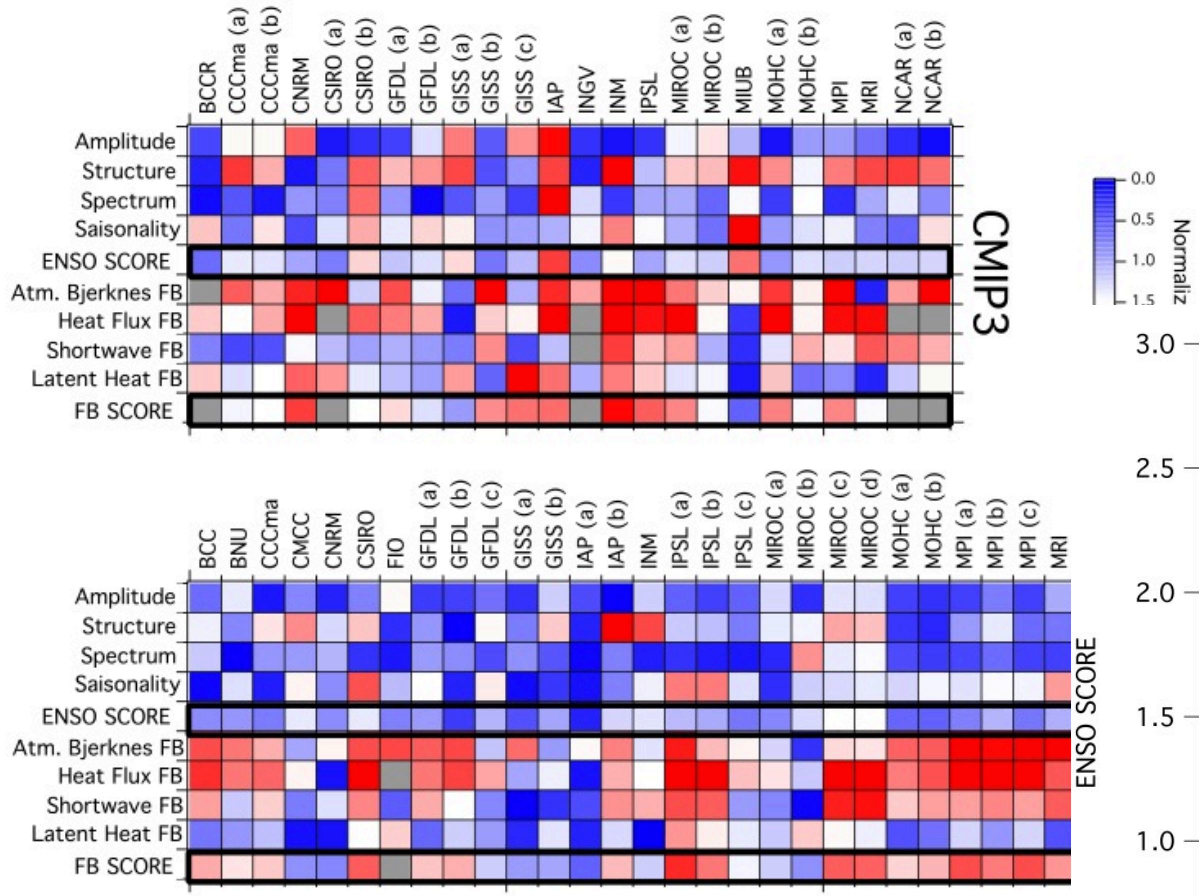
Mean state and inter-annual errors: same causes

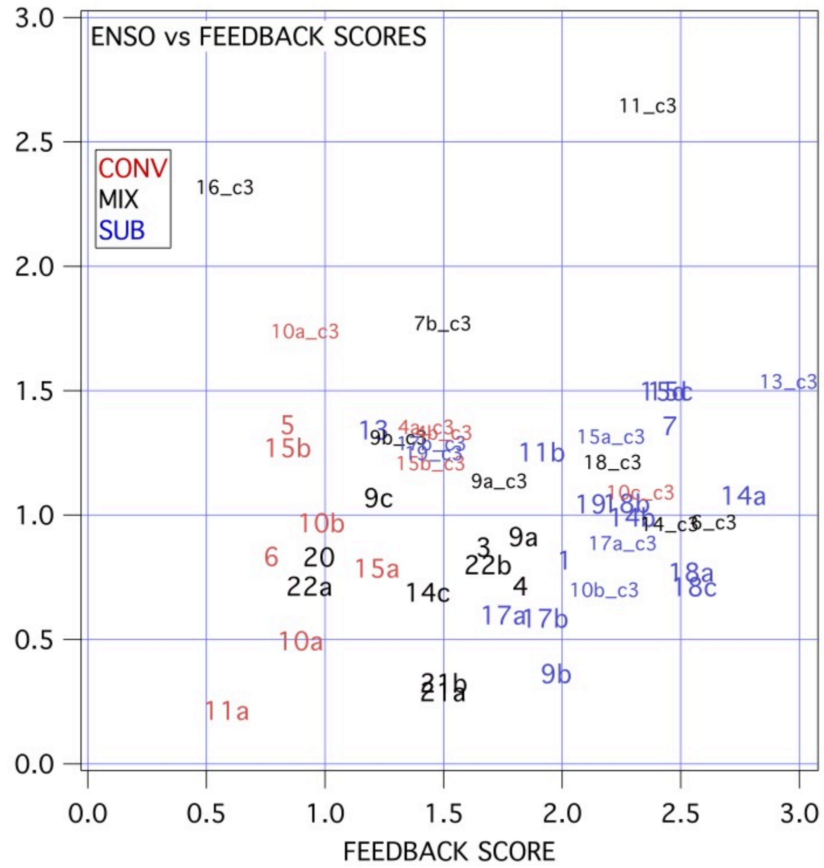


Convection triggered… never or… too often

Simple metrics vs. process-based

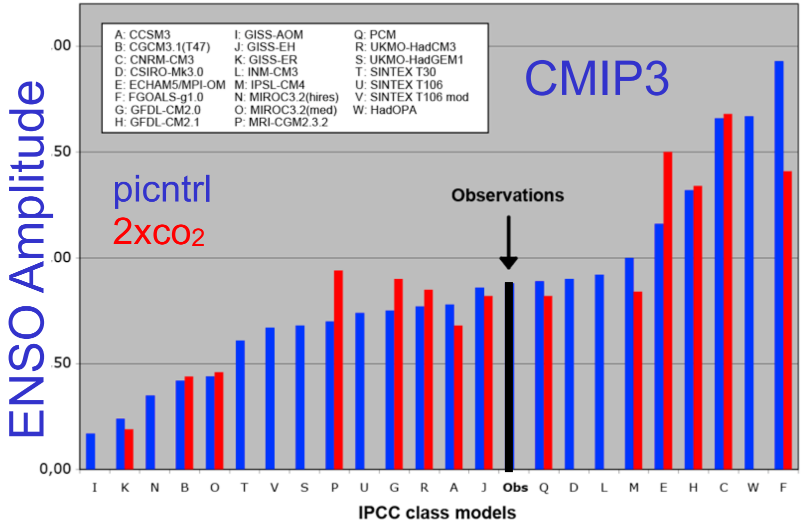
Bellenger et al. 2013

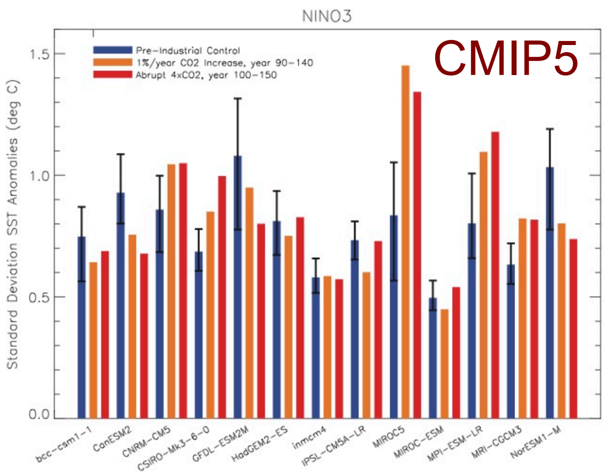




No clear relation between ENSO stats and atmosphere feedbacks (ocean feedbacks)

3. El Niño in a changing climate

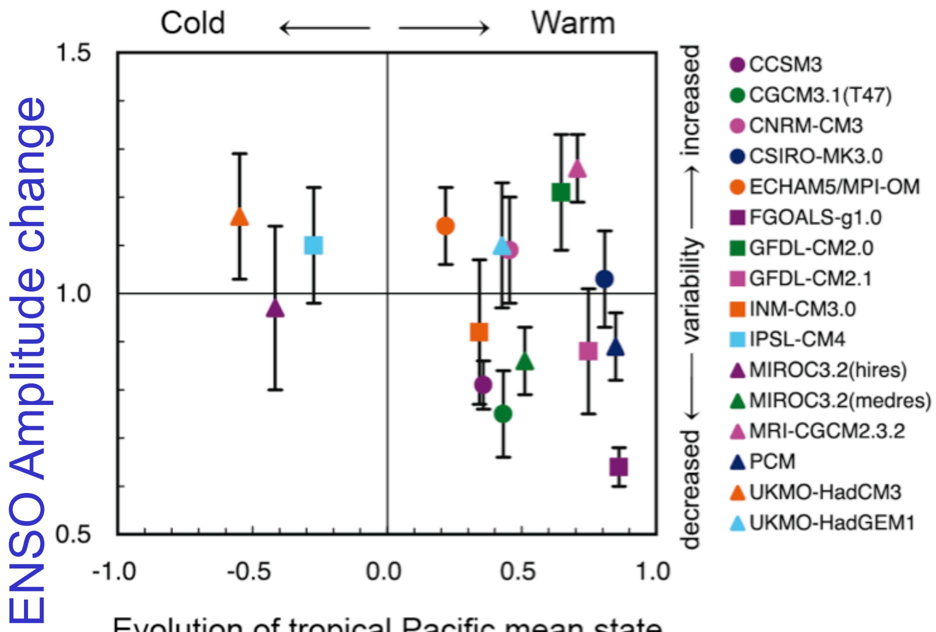




IPCC (2007), Guilyardi et al. (2009a), Collins et al. (2010)

Model biases dominate over scenario

Evolution of mean state
has little impact



CMIP3 SRES A2 vs. pdcntrl

But are 50-year statistics long enough ?

Summary: El Niño in coupled GCMs

Clear improvement since ~15 years

- More models get Mean and Annual cycle and ENSO statistics right !

but:

- Amplitude: improved in CMIP5. Process-based analysis: likely via error compensation
- Frequency: progress towards low frequency/wider spectra but still errors
- SPL: few models have the spring relaxation and the winter variability maximum
- Structure and timing: westward extension and narrowing around equator, issues with time sequence (onset, termination)

CMIP5 shows no major change

- Multi-model improvement comes from less poor-performing models
- Improved mean state in West Pacific
- Less amplitude diversity but still large process-based errors
- CMIP3 + CMIP5 can be used as one ensemble

Summary: role of atmosphere

- The atmosphere controls ENSO properties in CGCMs
  - Latent heat flux feedback well captured
  - Bjerknes feedback too weak but unrelated to ENSO amplitude
  - Danger of error compensations: process-based evaluation required

- Shortwave heat flux feedback a_{SW} is the key
  - The convective and subsidence regimes have to be captured
  - As well as their spatial (west vs. east) and temporal structures
  - Main errors comes from SW heat flux feedback (role of clouds, convection and large scale circulation). Specific role of non-linearities
  - Evidence that improving the mean and annual cycle will also lead to process-based ENSO improvement

- Why this dominant role of the atmosphere ?
  - Limitations from AGCMs systematic errors (dynamics, clouds)
  - But also new physically-based evidence of this dominant role
  - Time to revisit ENSO theory

In conclusion

- Three key messages:
  - Get right ENSO statistics for the right reasons (correct processes)
  - Better feedbacks, and ENSO, also come with better mean state
  - To understand if ENSO has changed, statistics will only help us in 200+ years. In the mean time we have to rely on physical understanding
- Still some way to go to use CGCMs to explore ENSO mechanisms
- New approaches:
  - Process-based evaluation of ENSO in GCMs development phase
  - Bridging ENSO theory and GCMs (BJ index, LOAM,…)
  - Use of initialised simulations to understands model errors (Vannière et al. 2012, 2013)
- Active community
  - 5 dedicated workshops and sessions in the last year
  - Proposal for a CLIVAR coordinated effort on a Focused & Integrated Research Opportunity

ENSO in a Changing Climate

Proposal for a **CLIVAR coordinated effort** on a Focused & Integrated Research Opportunity
Eric Guilyardi, Mat Collins, Wenju Cai, Tony Lee, Mike McPhaden, Andrew Wittenberg, *et al.*

- Despite 30 years of progress, ENSO continues to surprise us and challenge our assumptions. It remains a major unsolved climate puzzle with enormous societal impacts.

- Operational need: there has been a lack of recent progress in prediction (e.g. an apparent reduction of forecast skill since the 2000s).

Ongoing community activities & readiness

- Strong momentum by the community to study ENSO diversity, its mechanisms, teleconnection, and impacts (large volume of literature on these topics in the past 4-5 years; an active US CLIVAR Working Group on these topics).
- An increasingly large number of studies of ENSO using CMIP5 models and how ENSO may change in a warming world (proposed ENSO Task Team effort).

Areas primed for progress in the next 5-10 years of CLIVAR

- Improve the understanding of different physical processes that influence ENSO characteristics (frequency, amplitude, diversity,…).
- Synthesize existing ENSO evaluation methods in GCMs including bridges to theory and use of initialised simulations.
- Propose ENSO evaluation protocols and develop a strategy for coordinated ENSO analysis/metrics of CMIP models; develop and maintain an interactive website (including contribution to CMIP6).
- Sustain observing systems for ENSO research and prediction; and identify new observations needed to better constrain ENSO processes, both for the current climate and for past climates.
- Improve the understanding of how ENSO might change in the future.
- Enhance international collaboration between observationists and modelers for studies of ENSO
- Enhance applications of ENSO analysis and forecast products for targeted user communities.
- Build research capacity by contributing to the development of the next generation of talents dealing with ENSO science and prediction.