Understanding El Niño in coupled GCM
new perspectives

Eric Guilyardi
IPSL/LOCEAN, Paris & Walker Institute, Univ. Reading

Outline:

- Representation of El Niño in coupled GCMs
- Attributing shortcomings to model errors
    - link with background state
    - physical mechanisms
- Strategies forward

3rd WGNE Workshop on Systematic Errors in Climate and NWP Models
San Francisco, February 12-16, 2007

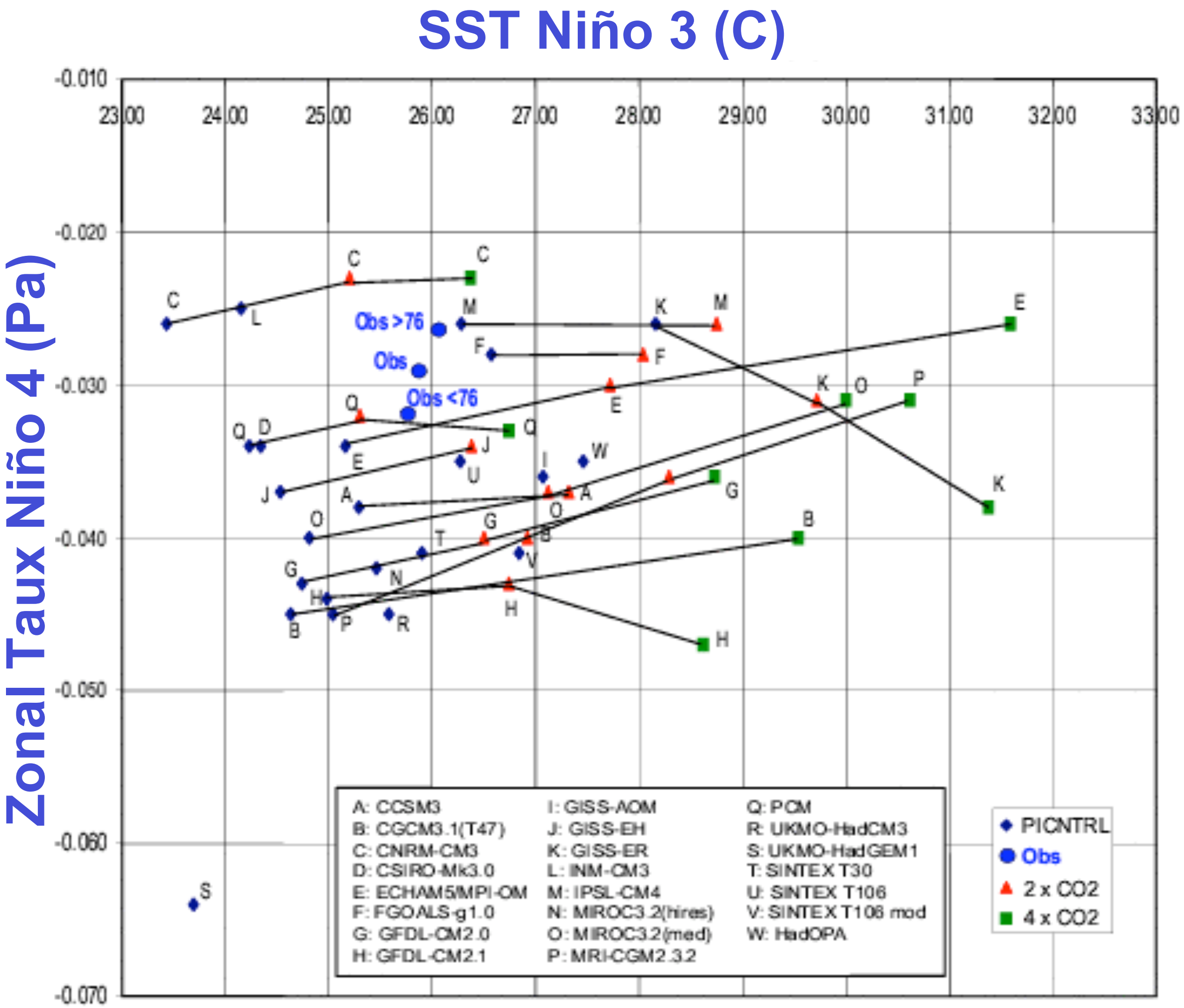
El Niño in coupled GCMs

Which metric ?

- Amplitude
- Frequency
- Seasonal phase lock
- ENSO modes and types
- others (posters and talks)

Analysis on control climate of IPCC AR4 models (CMIP
(some older MIPs and scenario discussion)

El Niño in coupled GCMs – mean state

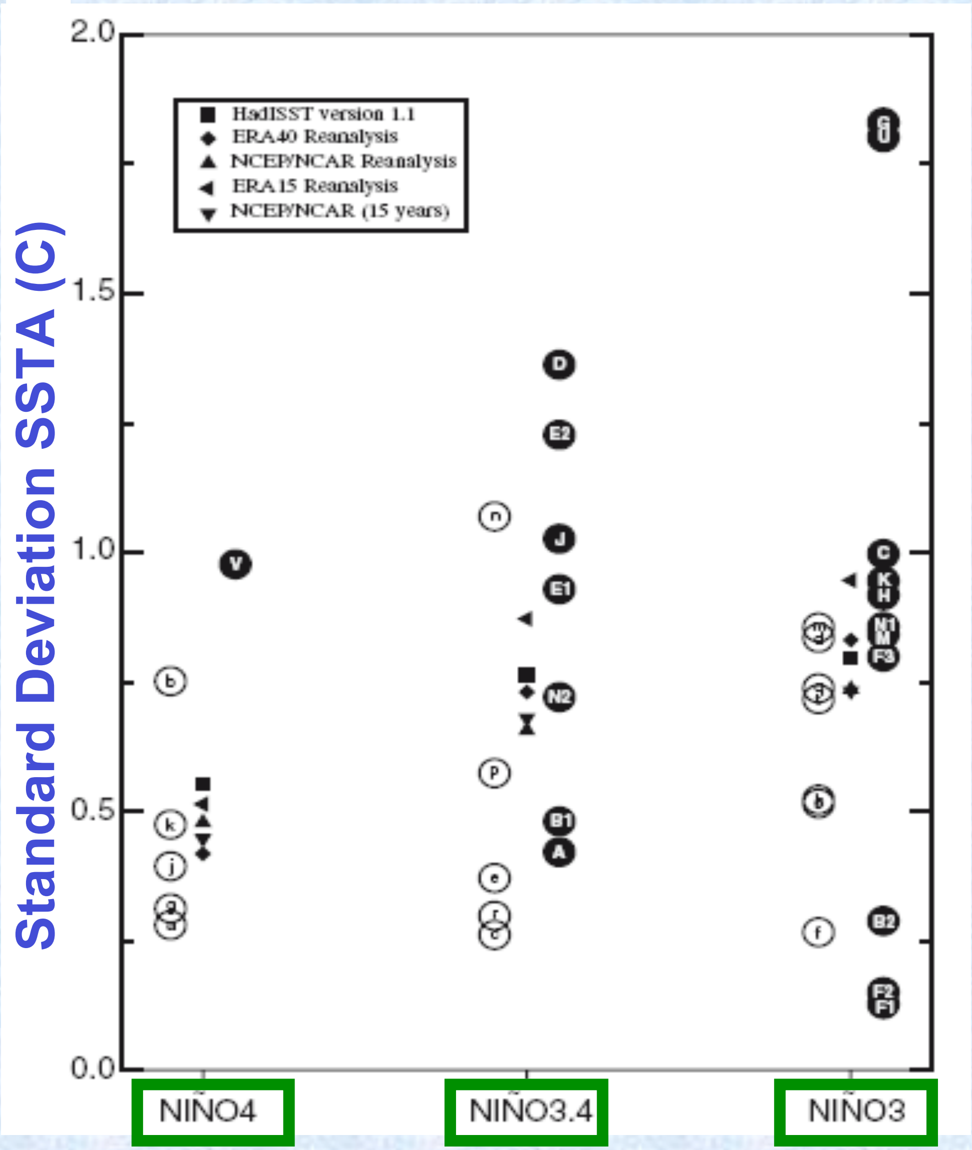


Guilyardi (2006)

Trade winds too stro

Spring relaxation oft
missing

El Niño in coupled GCMs - amplitude



Classic metric:
SST standard deviation

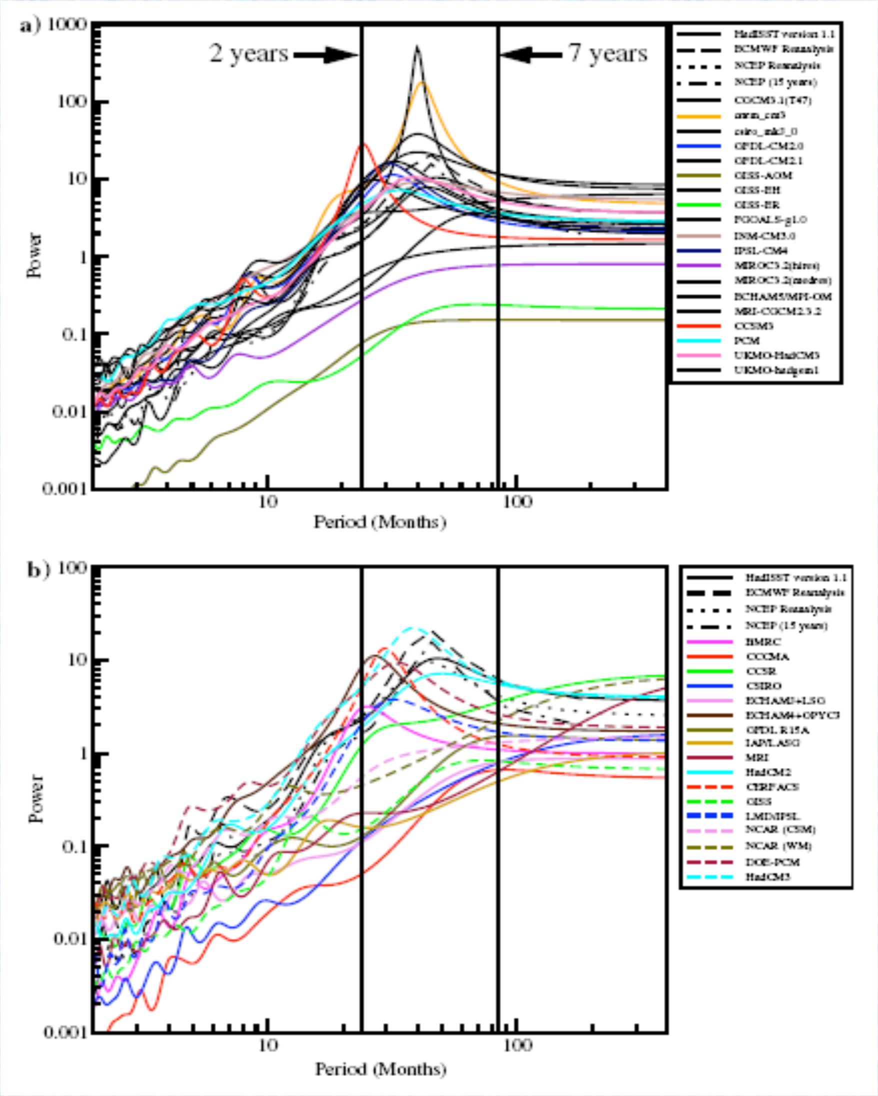
IPCC TAR (○) too weak

IPCC AR4 (●) large diversit

Observed range in Niño3

AchutaRao & Sperber (2006) → **Poster**

El Niño in coupled GCMs - frequency



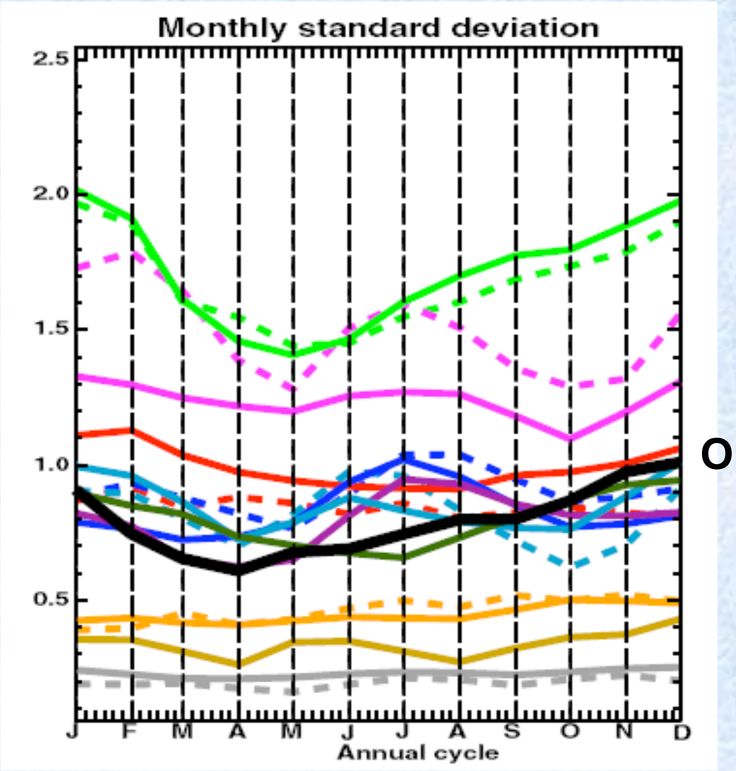
Classic metric:
maximum power of Niño3
SSTA spectra

IPCC AR4: improved towards
low freq. but still large diversit

IPCC TAR: to high frequency

AchutaRao & Sperber (2006)

El Niño in coupled GCMs – seasonal phase loc

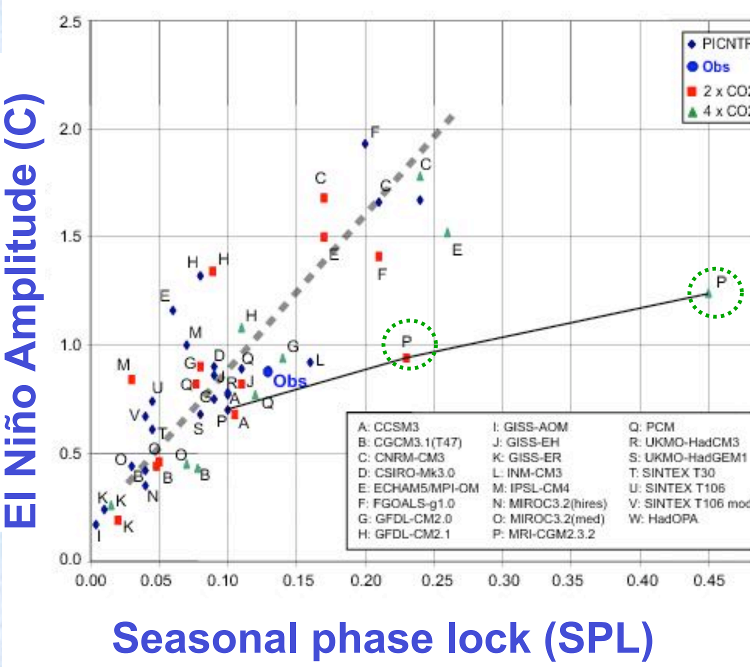


Observations

Subset of IPCC AR4 models

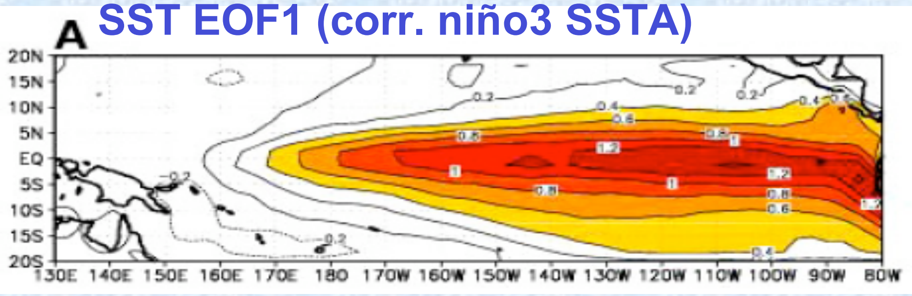
Classic metric:
Monthly Niño3 SSTA std. dev.

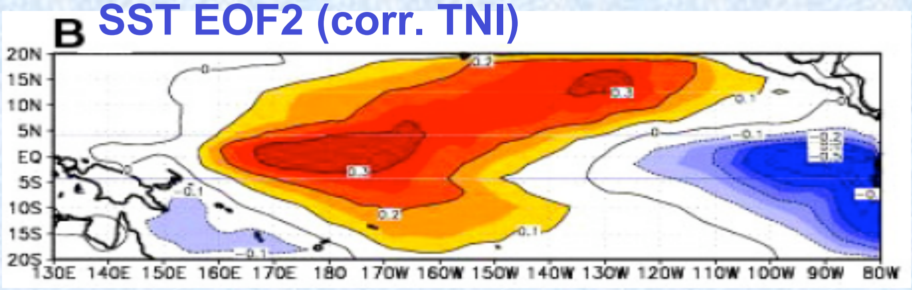
Very few models have the spring relaxation and the winter maximum



Guilyardi (2

El Niño in coupled GCMs – T vs. S modes

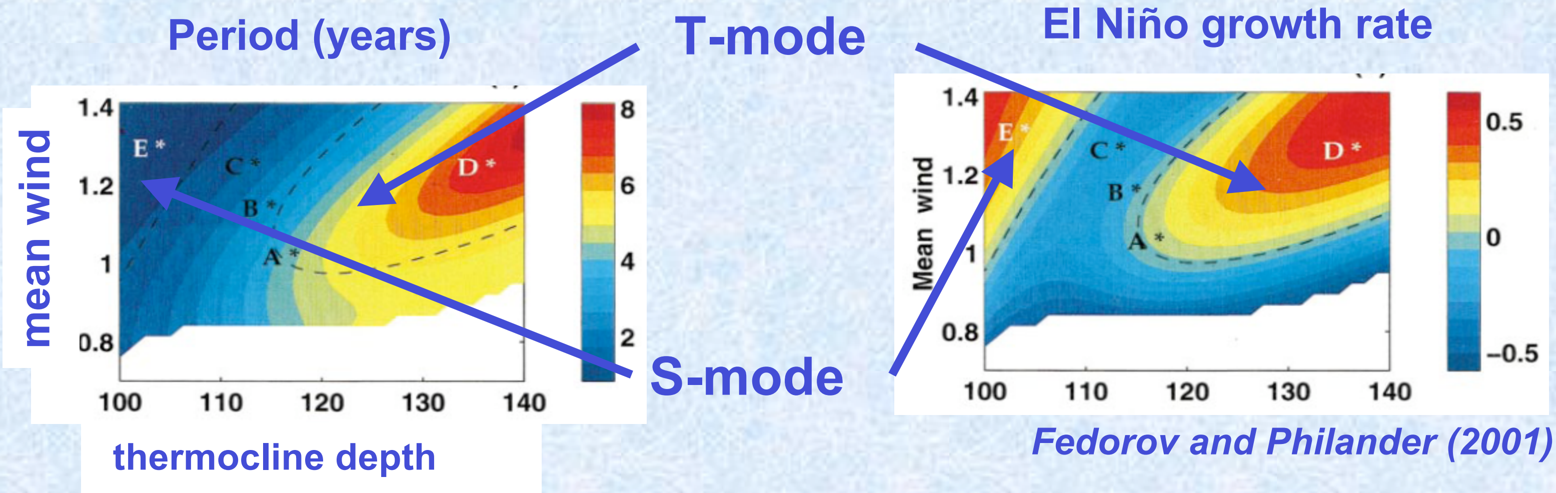

SST EOF1 (corr. niño3 SSTA)


SST EOF2 (corr. TNI)

TNI: Trans-niño index

Kumar al. (2006)

- T-mode (thermocline, “slow”): subsu west Pacific, amplitude ++, SSTA: W – period ~5 years (> 1976)
- S-mode (SST, “rapid”): surface, central/east Pacific, weaker amplitude, W, 2-3 years (< 1976)
- Other modes (“mobile”)
- Observations: “hybrid” mode

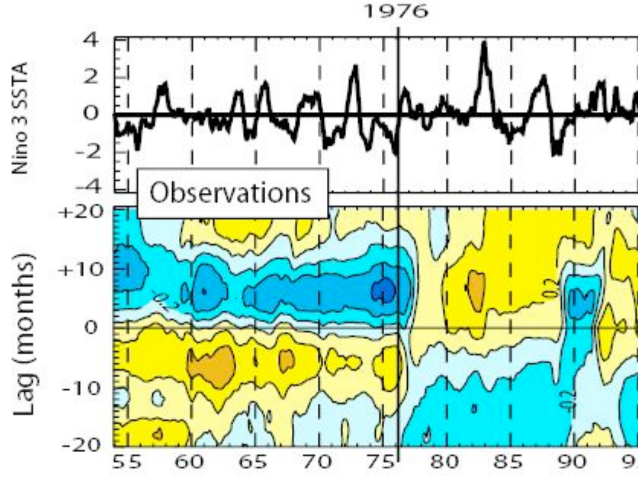

Period (years)

El Niño growth rate

Fedorov and Philander (2001)

El Niño in coupled GCMs – T vs. S modes

Defined by lag-correlation of TNI with Niño3 SSTA *(Trenberth & Stepaniak 2001)*



S-mode T-mode

S/T- mode analysis in IPCC AR4 *(Guilyardi 2006)*

- Most models have an S-mode (related to too strong trade winds?)
- Few models exhibit hybrid El Niño modes, like observed

- [these exhibit significant El Niño change to larger amplitude (+10/40 %) in warmer (2xCO$_2$ and 4xCO$_2$) climate]

El Niño in coupled GCMs – teleconnections

Tropical teleconnections with ENSO not well represented:

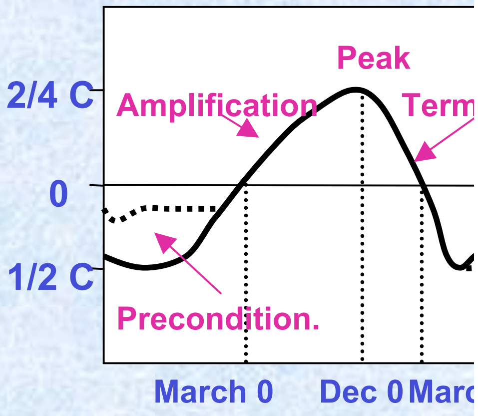
- **ENSO <u>much too dominant over local modes</u> (WAM,** *Joly al. 2007***)**
- **Links with monsoon/IODM** *(Gualdi al. 2003, Fisher al. 2005, Terray and Dominia*
- **Links with tropical Atlantic**
- **Issue: which is influencing which ?**

- **More presentations and posters on this (J. Meehl, A. Turner,...)**

El Niño in coupled GCMs – conclusions/issues

- <u>Amplitude</u>: models diversity much larger than (recent) observed diversity
- <u>Frequency</u>: progress towards low frequency/wider spectra but still errors
- <u>SPL</u>: very few models have the spring relaxation and the winter variability maximum but amplitude of El Niño is related to SPL.
- <u>Modes</u>: very few model exhibits the diversity of observed ENSO mod most are locked into a S-mode (coherent with too strong trade winds)

- **Evaluation** = f(metrics): El Niño much more complex than indices and correlation of indices (proposals by Pacific panel & others)
- but most IPCC AR4 ENSO studies converge on conclusions
- standard set of <u>basic</u> diagnostics required



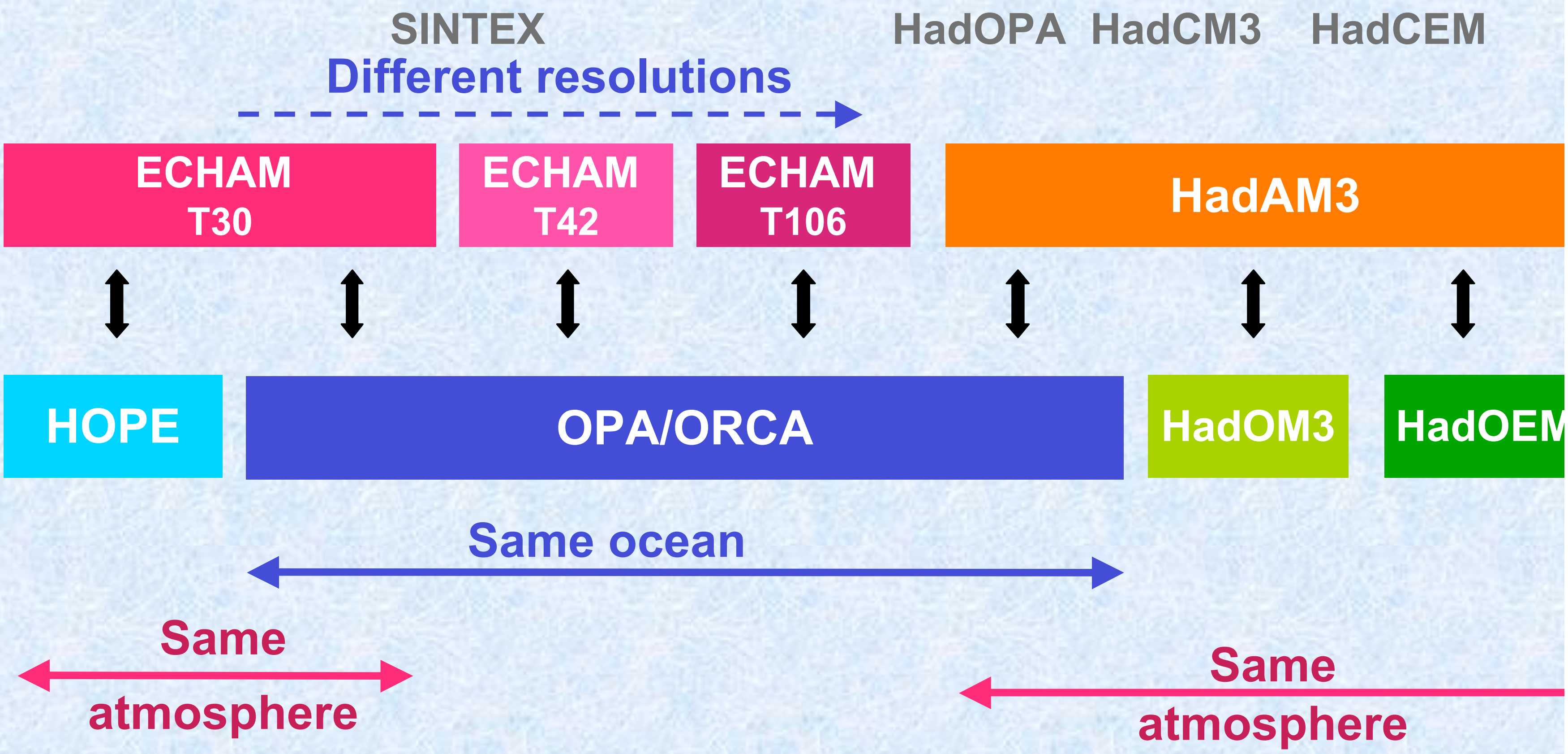
SST anomaly in Ni

Origin of modelled El Niño errors

- Respective role of ocean and atmosphere models
- Role of mean state and annual cycle
- Use of simpler ENSO frameworks
- Physical mechanisms

Respective roles of ocean and atmosphere

The modular approach:



SINTEX

Different resolutions

HadOPA HadCM3 HadCEM

ECHAM T30

ECHAM T42

ECHAM T106

HadAM3

HOPE

OPA/ORCA

HadOM3

HadOEM

Same ocean

Same atmosphere

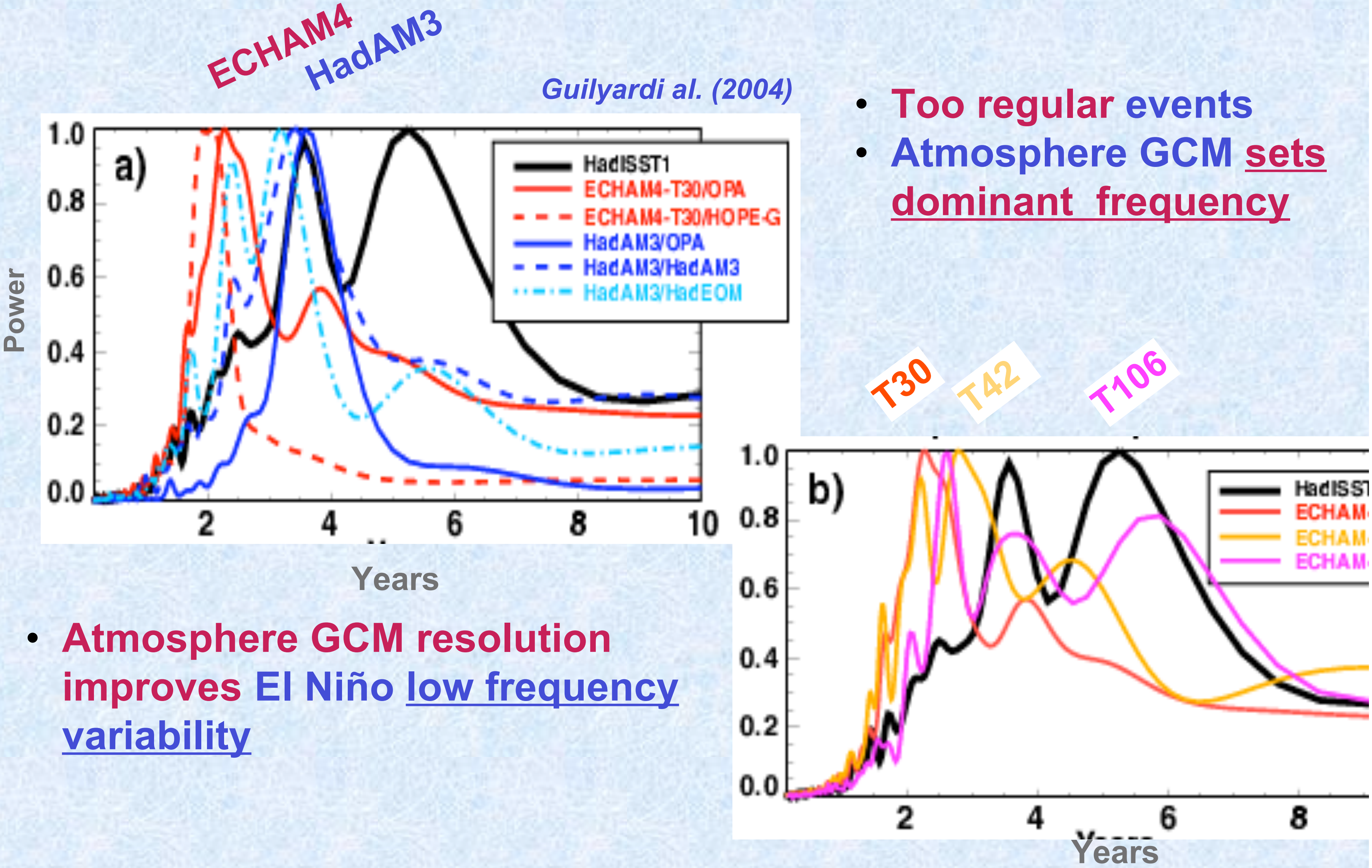
Same atmosphere

Intercomparison → identify mechanisms/biases origin

Guilyardi al. (2004)

Respective roles of ocean and atmosphere

El Niño frequency :



Guilyardi al. (2004)

- **Too regular events**
- **Atmosphere GCM <u>sets dominant frequency</u>**

- **Atmosphere GCM resolution improves El Niño <u>low frequency variability</u>**

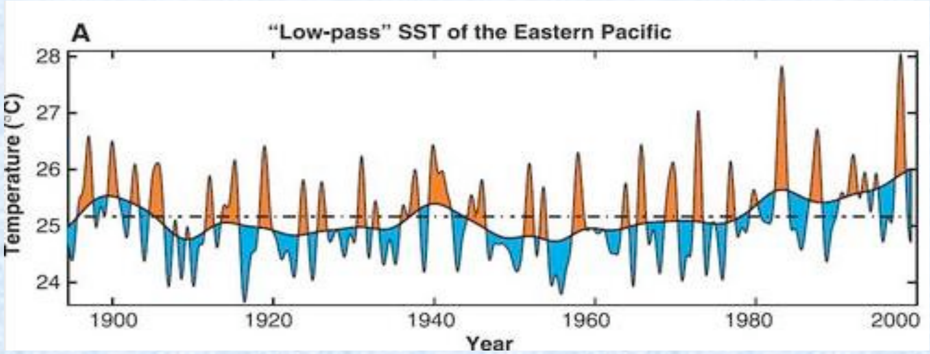
Role of mean state errors in El Niño errors

Numerous studies addressed this issue (several posters):

- **Trade winds strength** (inverse relation with ENSO amplitude)
- **Equatorial thermocline position** (favouring one mode rather than ano
- **ITCZ position and "double ITCZ" bias** (favouring "summer" El Niñ

No clear general relation in IPCC AR4 models

- "Non-linearity" required for mean state to have an impact (i.e for sca interactions)
- Guidance from simpler framework analysis
- El Niño errors can also lead to mean state errors *(An & Jin 2004, Sun & Zh*



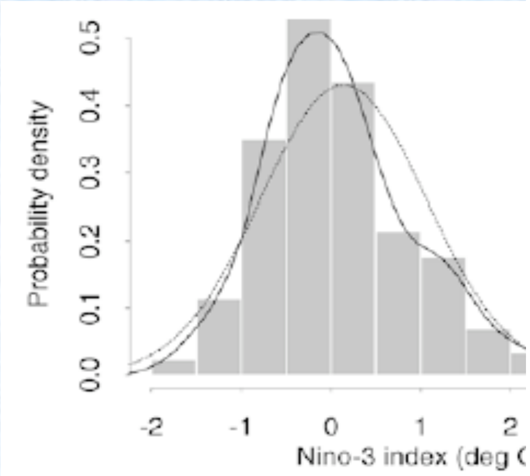
El Niño changing or mean state evolving ?

Fedorov & Philander (2000)

Role of mean state errors in El Niño errors

Linear vs. non-linear ENSO regime *(Hannachi al. 2001, Flugël al. 2004, An Jin 2004, Yeh & Kirtman 2007)*

- **"null hypothesis“: amplitude = f("noise"+ damping via coupled feedbacks) = linear system**
- **in the non-linear regime, amplitude = f(mean state+damping)**

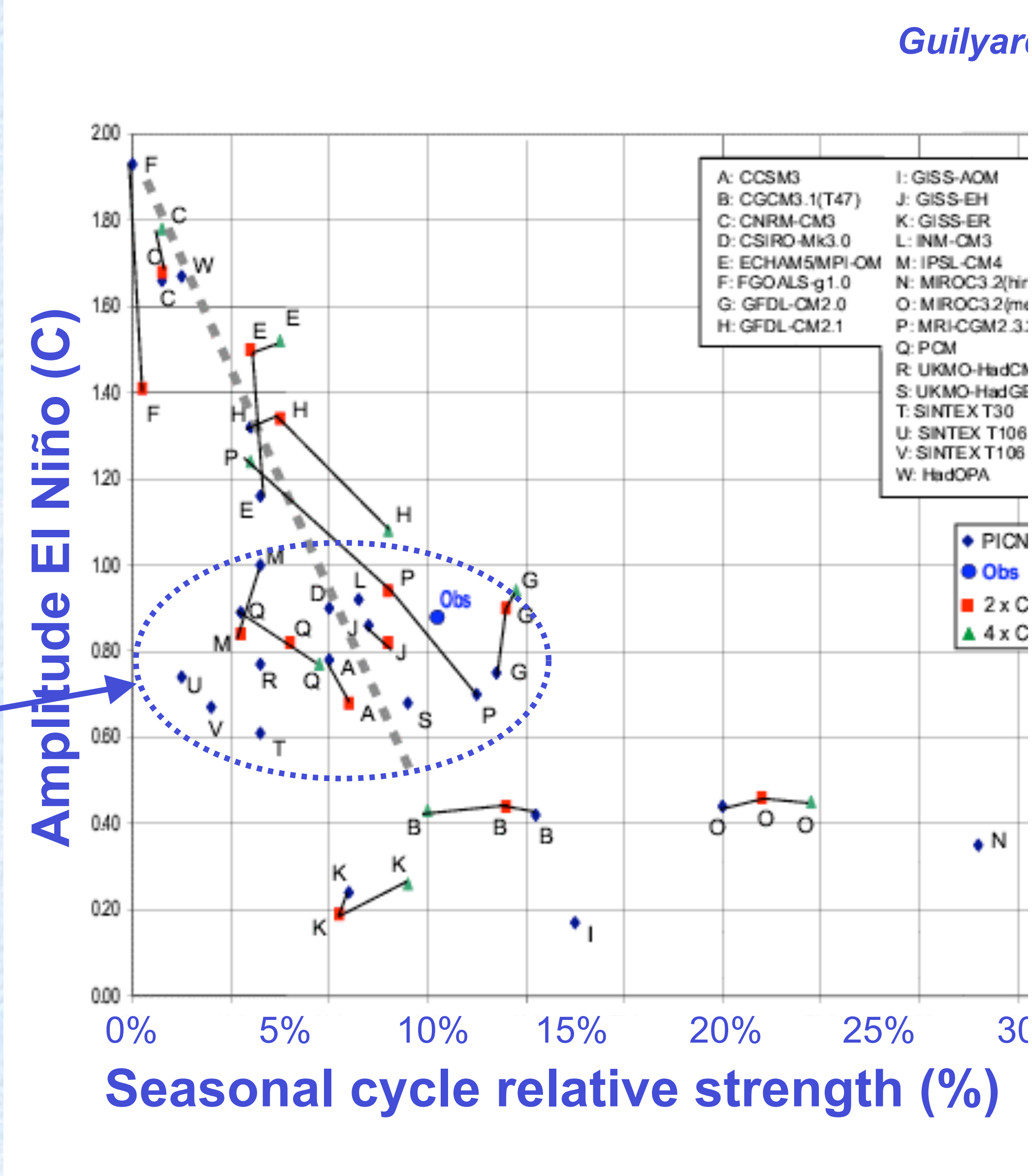


- **Evidence that observed ENSO is in the non-linear ("non-normal") regime** *(Hannachi al. 2001, An & Jin 2004, Monahan & Dai 2004)*
- **Non-linear physics always acts to warm the SST, hence the warm/cold asymmetry** *(An & Jin 2004)*

<u>Most GCMs are in the linear regime</u> (skewness~0, *van Oldenborgh al. 2005, Hannachi al. 2001 for CMIP2***)**

Role of annual cycle errors in El Niño errors

- **El Niño amplitude : <u>inverse relation</u> with seasonal cycle relative amplitude**
- **Agrees with theory and observations**
- **Large SC: more difficult to “disrupt” it into an El Niño**
- **Less clear for models near observations**



Guilyar

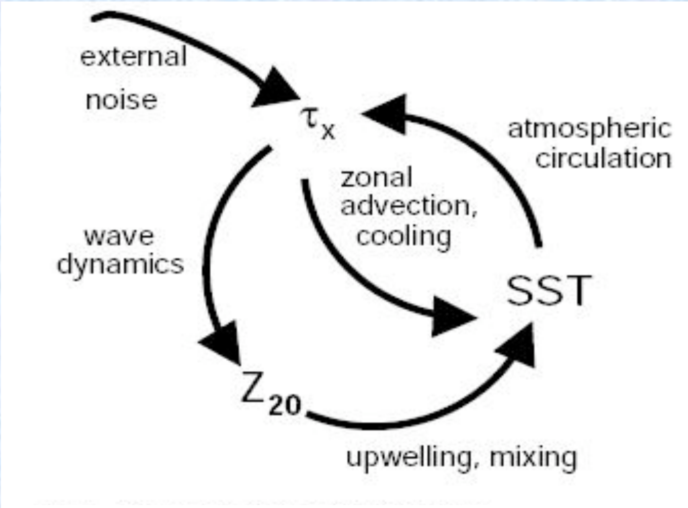
Analysing GCMs via simpler frameworks

- Prescribe mean state from GCM to intermediate complexity model (I the tropical Pacific
- Compare ENSO characteristics from both models (GCM and ICM)
- If they fit, explain GCM biases via ICM mechanisms
- Example in CNRM-CM3:
  - Quasi-biennial GCM behaviour due to too shallow thermocline in western-central Pacific *(Dewitte al. 2007)*

ENSO theories:

- Self-sustained oscillator (linear framework)...
- ...or stable mode (or weakly damped) triggered by stochastic atmospheric forcing (non-linear framework) ?
- relative role of West Pacific vs. East Pac. oscillator varies in mode (poster by Jin-Yi Yu)

Physical mechanisms



van Oldenborgh al. 2005

Non linear processes:

- **NL dynamical heating ($\nabla_x T$ + U in phase,** *An & Jin 2004***)**
- **"Multiplicative noise" - MJO** *(Lengaigne al. 2004)*

Atmosphere response to SSTA

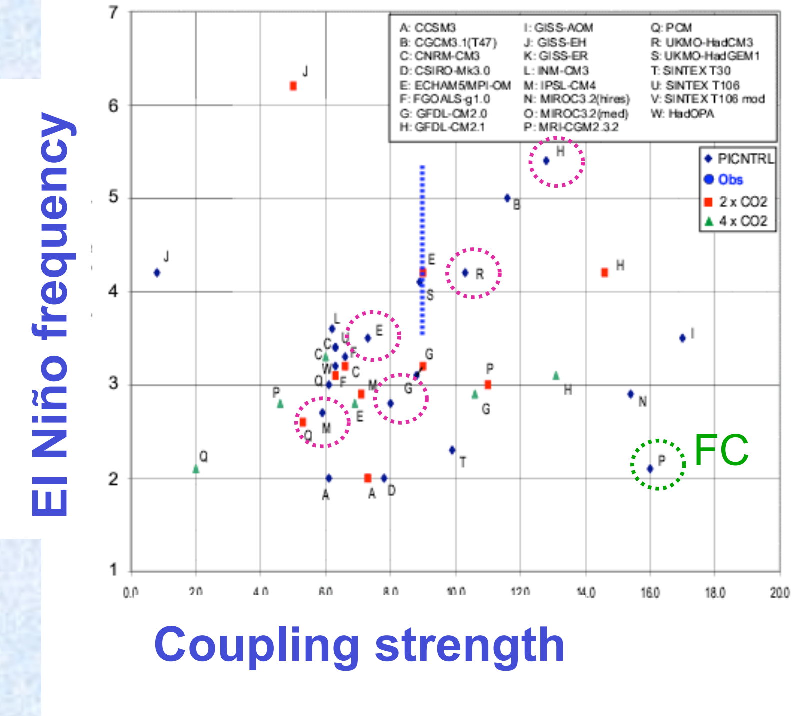
- **Bjerknes wind stress feedback** *(va Oldenborgh al. 2005, Guilyardi 2006)*
- **Meridional response of wind stres** *Wang 2000, Capotondi al. 2006, Merryfield 2*
- **Radiative and cloud feedbacks** *(Su 2006, Bony al. 2006)*

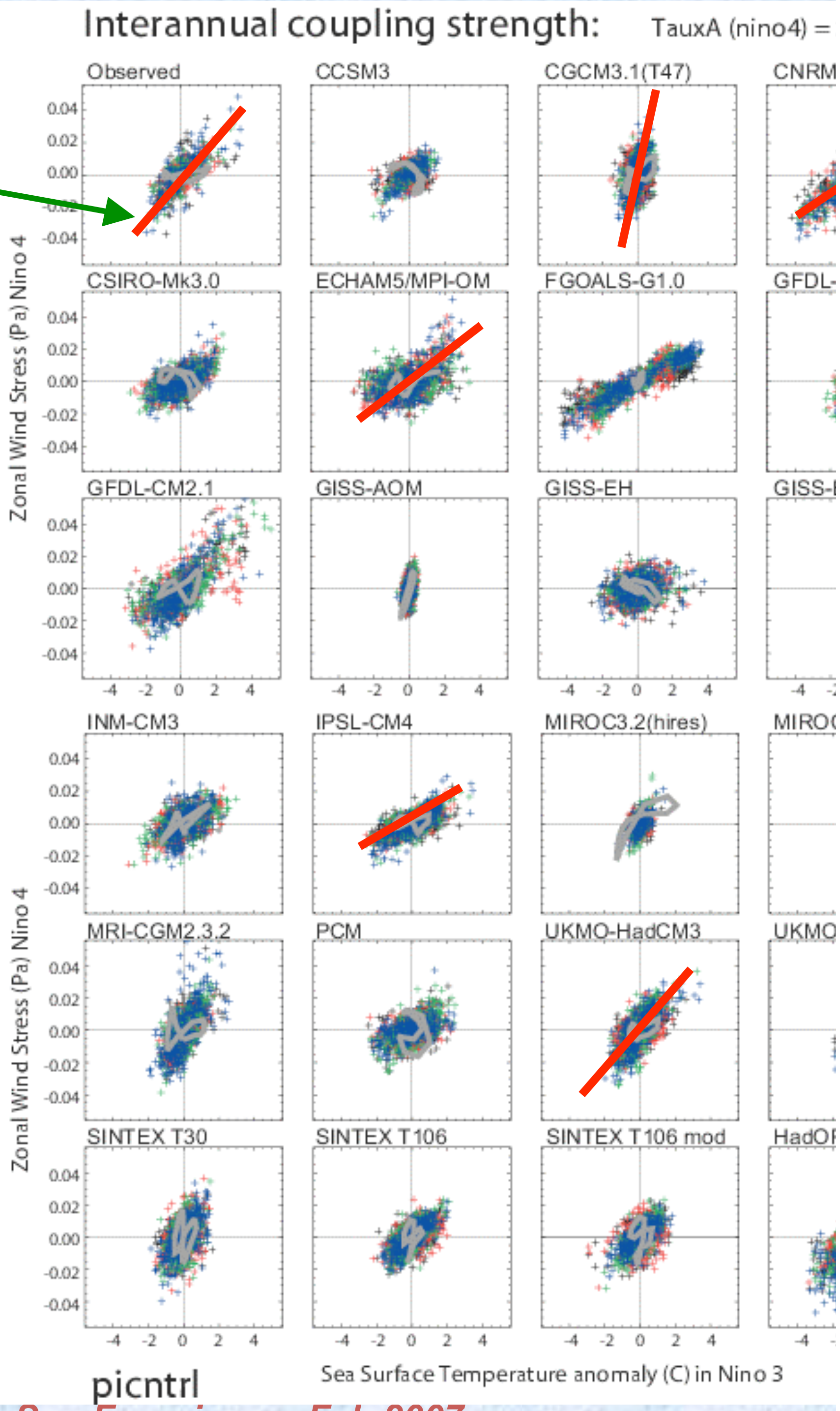
Ocean response to τ anomalies

- **Upwelling, mixing, ("thermocline feedback", "cold tongue dynamics")** *(M 2001, Burgers & van Oldenborgh 2003)*
- **Zonal advection** *(Picaut al. 1997)*
- **Wave dynamics (Kelvin and Rossby**
- **Energy Dissipation** *(Fedorov 2006)*

Bjerknes feedback and coupling strength α

- Theories link increased α to:
  - larger amplitude
  - lower frequency
- No clear link with amplitude
- Link with frequency ?



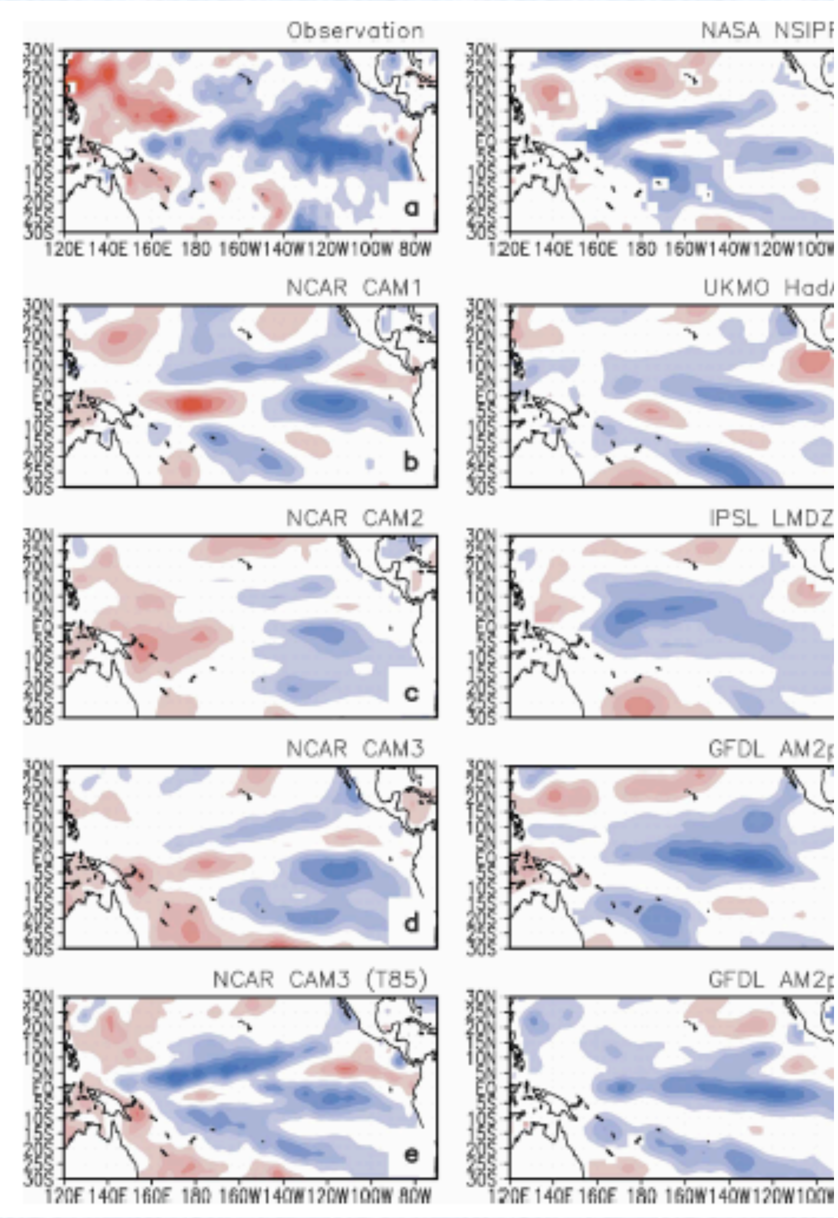


(Guilyardi 2006)

Radiative feedbacks

Analysis of 9 AMIP forced AGCM (IPCC AR4) *(Sun al. 2006)*

- Too weak negative net feedback from atmosphere leads to unrealistically high sensitivity to small flux errors
- Main contributors: cloud albedo and atmosphere transport feedbacks
- Linked to a too strong water vapour feedback (underestimation of equatorial precipitation response)



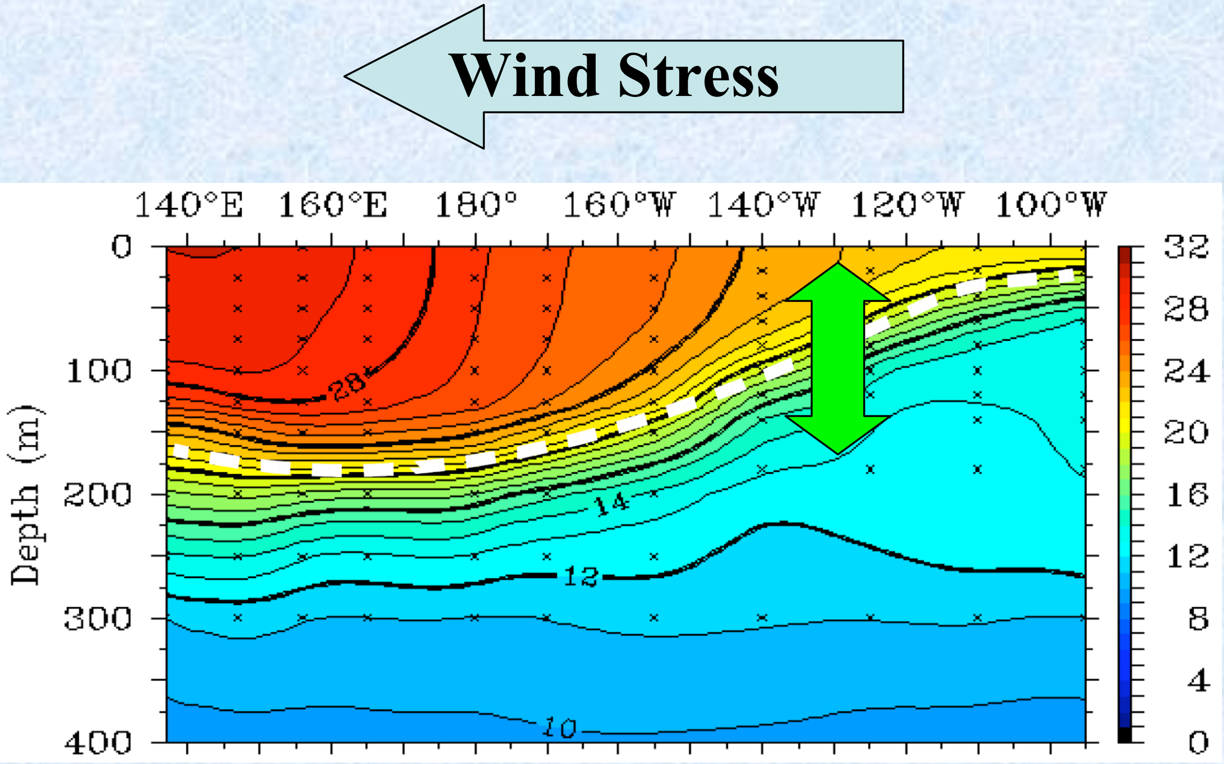
→ Poster

Response of net surface heating to ENSO warr

Ocean dissipation: "Energetics of El Niño"

Potential and Kinetic Energy

Brown & Fedorov (2006) →



$$\boxed{dE/dt = W + \text{Dissipation}}$$

Winds act on the sur of the ocean, moving thermocline up and ("wind work" W)

The "Potential energ is stored in the slop the thermocline:

El Niño = min E

La Niña = max E

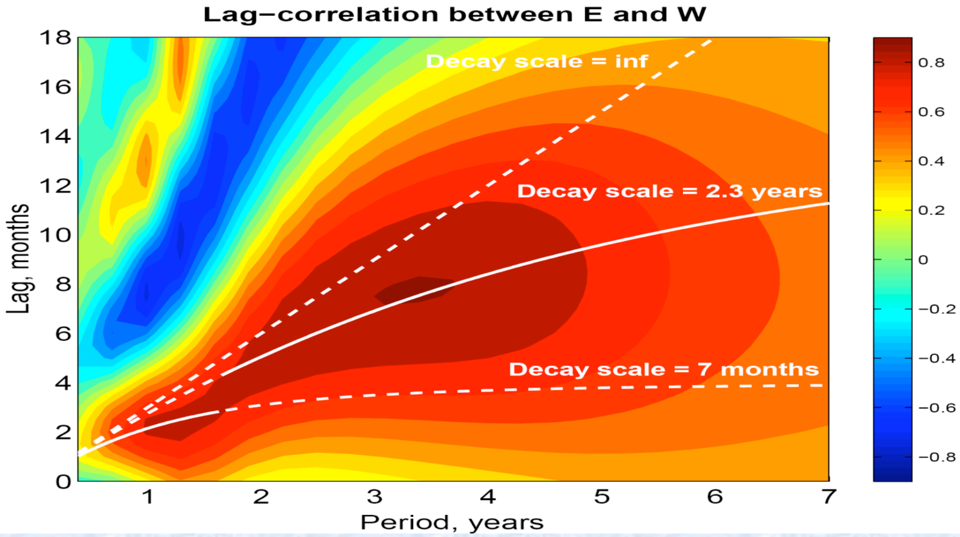
The "decay scale" is lag between E and W

Based on Goddard and Philander (2000)

Ocean dissipation "decay scale"

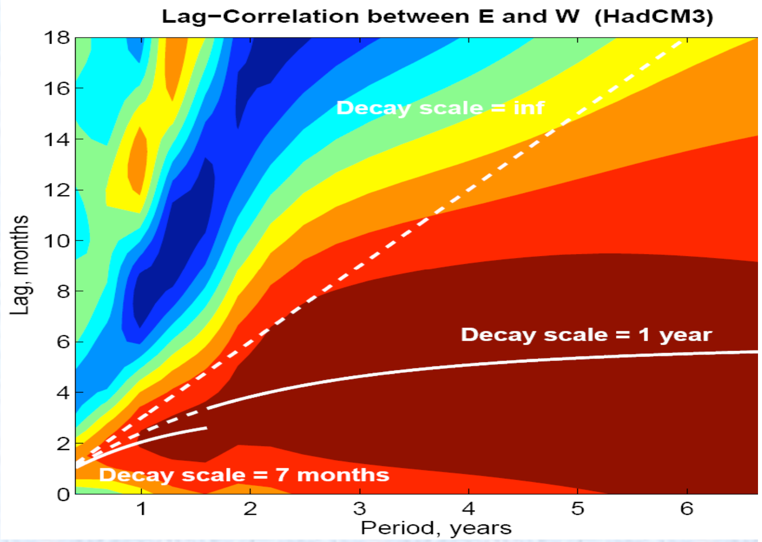
Brown & Fedor

OGCM forced by reanalysis winds (50y)

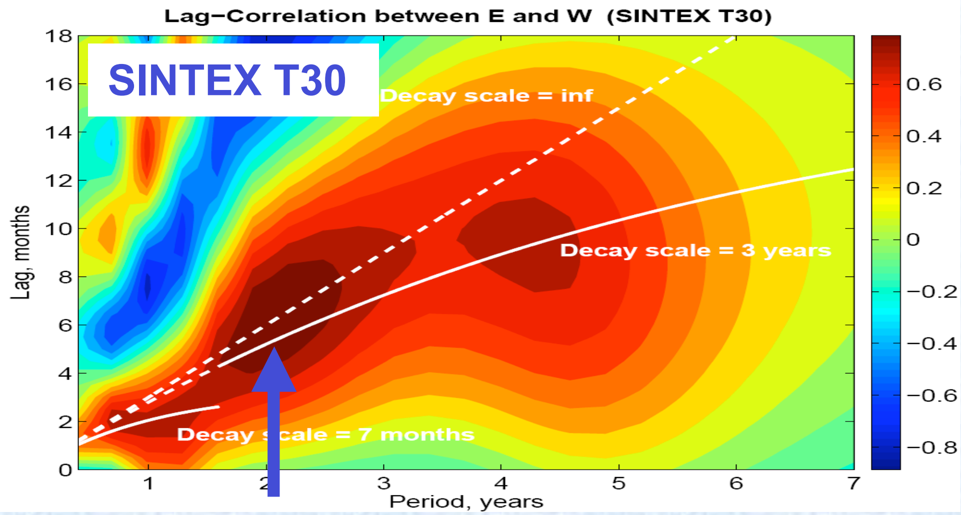


decay scale = 2.3 y

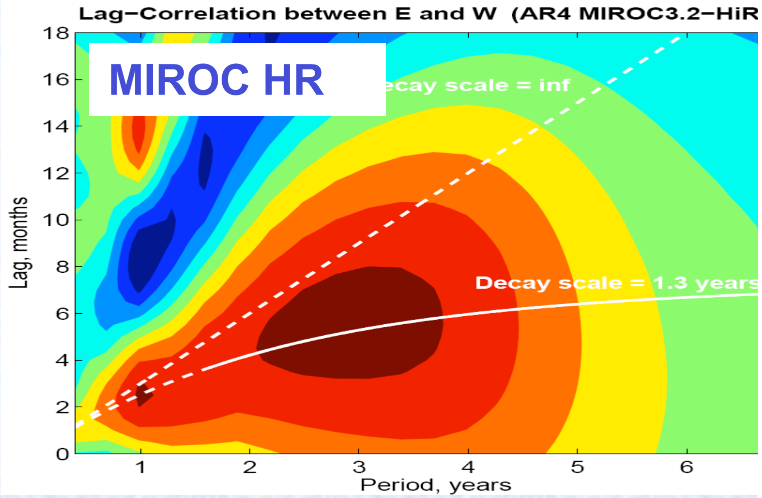
HadCM3



decay scale = 1 y (very dissipative)



2 year peak



Weak ENSO amplitude

Specific models analysis

Ocean/atmosphere error compensation:

- HadAM3/HadOM3 amplitude El Niño = 1.0 C
- HadAM3/OPA amplitude El Niño = 1.8 C !!!
- (but ECHAM4/OPA = 0.6)
- Previous analysis has shown that HadAM3 over-reactivity to is balanced by HadOM3 much too strong dissipation

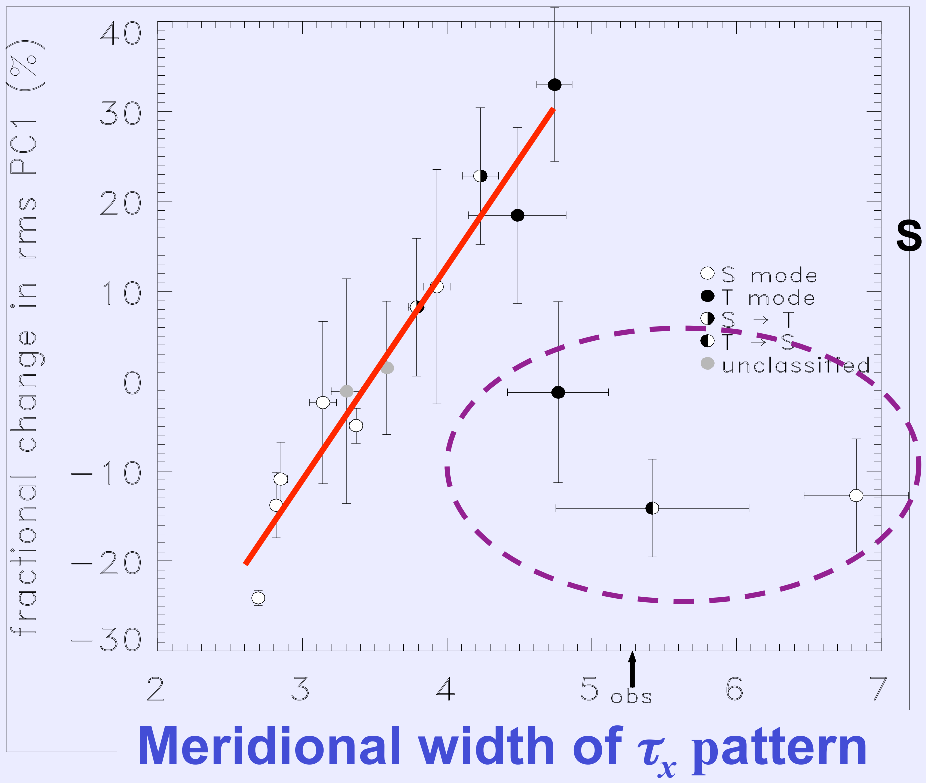
- **GFDL**: poster by Andrew Wittenberg et al.
  - suite of automated diagnostics + HCM
- **CCSM3**: talk+posters by Ed Schneider, Guang Zhang et al.
  - work on physical parameterisations, addressing tropical biases
- **HadCM3**: posters by Mat Collins, Thomas Tonazzio et al.
  - perturbed physics ensemble (QUMP)

Response to climate change

- **Model errors/differences much larger than scenario differences**
- **Dependence of ENSO on mean state = f(non linearity)** *(Yeh & Kirtman 200*

- **Function of meridional response of wind stress** *(Capotondi al. 2006, Merryfi 2006)*

ENSO amplitude change (pre-ind. to 2xCO2)



S → T mode ev
(Guilyardi 2006

These model
unrealistically
ENSO amplitu

Merryfield (2006)

Conclusions

El Niño errors in coupled GCMs:

- too large diversity of amplitude (dominate over response to CO_2 i
- too frequent, single-peaked, SST-type El Niño events
- linear regime
- CMIP3 (IPCC AR4) models show clear improvement over CMP2 m

Analysis suggest:

- atmosphere GCM has a dominant role (strongest biases ?)
- ocean GCM modulates amplitude (but via strong bias)
- mean and annual cycle of wind stress too strong (S- mode)
- no clear relation between mean state and ENSO amplitude (linea regime)
- amplitude easier than frequency to relate to model errors

Number of new and promising approaches (thanks to IPCC AR4 and
community is ready to go further and integrate them

Model development to improve ENSO

Strategy:

- **Tune each component in forced mode**
- **Couple and hope for the best !**
- **Tuning of ENSO itself highly risky (metric ? + error compensati**
- **Evaluate ENSO with standard set of diagnostics and in multi-m** **help identify weak links** (i.e. “ENSOMIPs”)
- **Identify biases and likely origin**
- **Improvement of key mechanisms then follows**
- **Issue of flux-corrections** (in non-linear regime)

Atmosphere GCM resolution required **(minimum ~1deg)**

- **to "see" ocean GCM structures (upwelling, TIW, WBC,...)**
- **to alleviate convection on/off behaviour**

Atmosphere dynamical/radiative feedbacks

- **still not fully understood (but key)**

Strategies forward

Organised metrics towards “standard ENSO assessment’

- Basic diagnostics: wide agreement, led by PCMDI → AR5
- Then "theory-dependent" analysis by sub-groups
- Simpler models framework promising

Dedicated multi-model sensitivity studies to assess robustness of mechanisms (EU DYNAMITE)

Evaluation requires additionnal observations (further off-equator, ARGO, quality surface fluxes,...)

- *ENSO breakout session Wednesday pm*
- *Ad-hoc ENSO group meeting Friday pm*

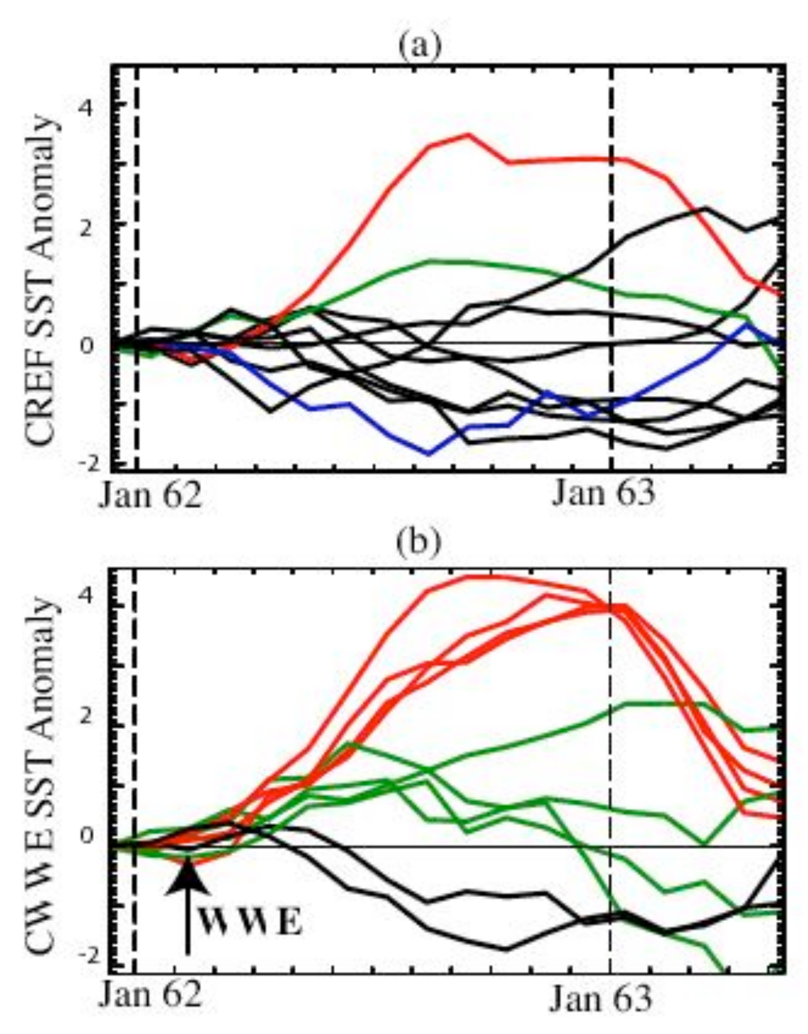
Proposal for ENSO basic/essential metrics

From joint NCAS/IPSL/Hadley Centre effort

- **maps + sections mean state and annual cycle variables** (SST, τ, U,
- **annual cycle** (nino4 τ_x vs. nino3 SSTA) **longitude/time at equator an 10S/10N lat/time diagrams in W/C/E Pacific** (SST, τ, precip,...)
- **standard deviation & skewness maps of SST and τ_x**
- **SSTA nino3 & SO time serie stats + mean value + annual cycle (SP**
- **coupling strength diagnostic**
- **normalised spectra, autocorrelations of nino3 SSTA**
- **validation data: TAO profiles +... and same physics forced runs (C set-up)**
- **other analysis fonction of biases from these “essentials”**

Impact of WWB on El Niño triggering in a CG

Nino 3 SSTA 10 members



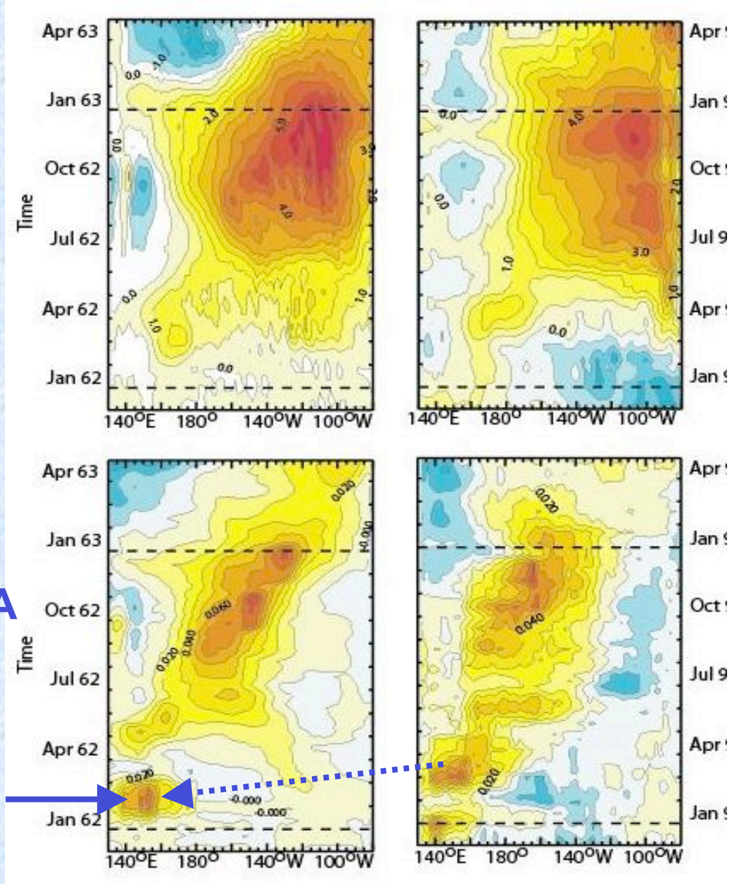
HadOPA Ensemble with WWE

Obs. El Niño 1997/98

SSTA

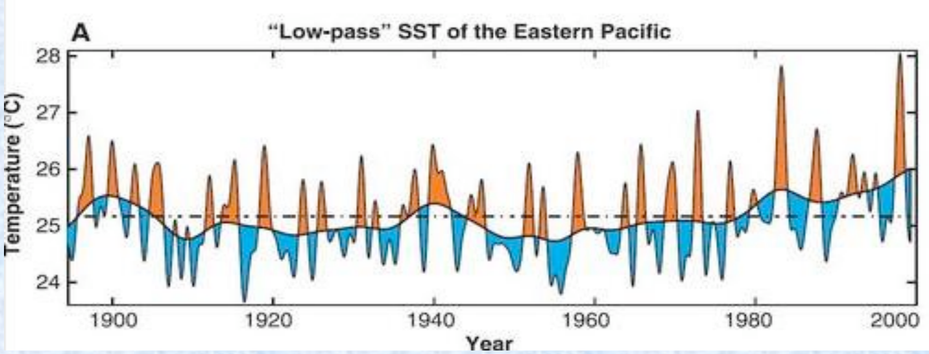
TauxA

WWE



Lengaigne al. (2004)

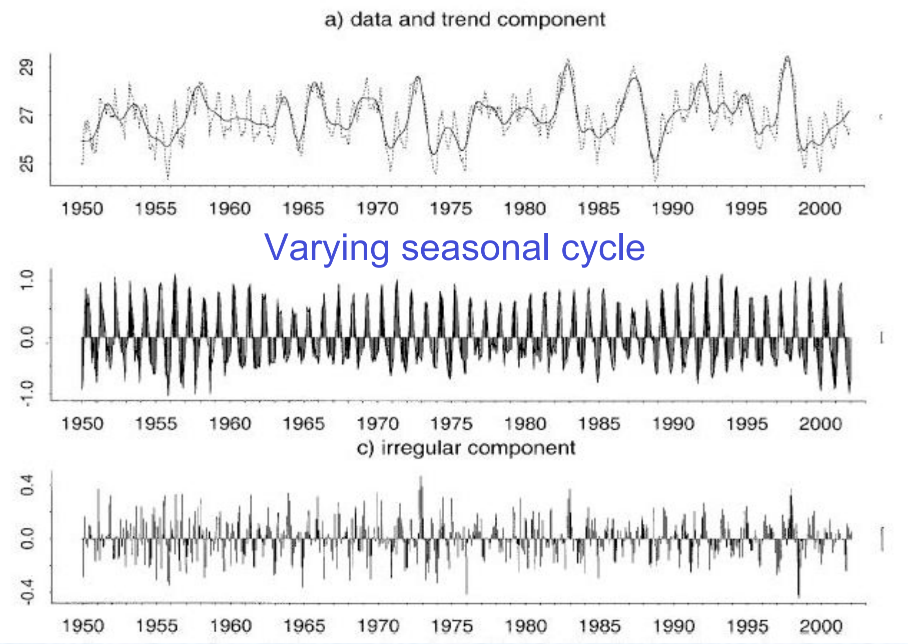
El Niño = variations around a mean state an a seasonal cycle



Fedorov & Philander, Science (2000)

El Niño changing or mean state evolving ?

Varying seasonal cycle:

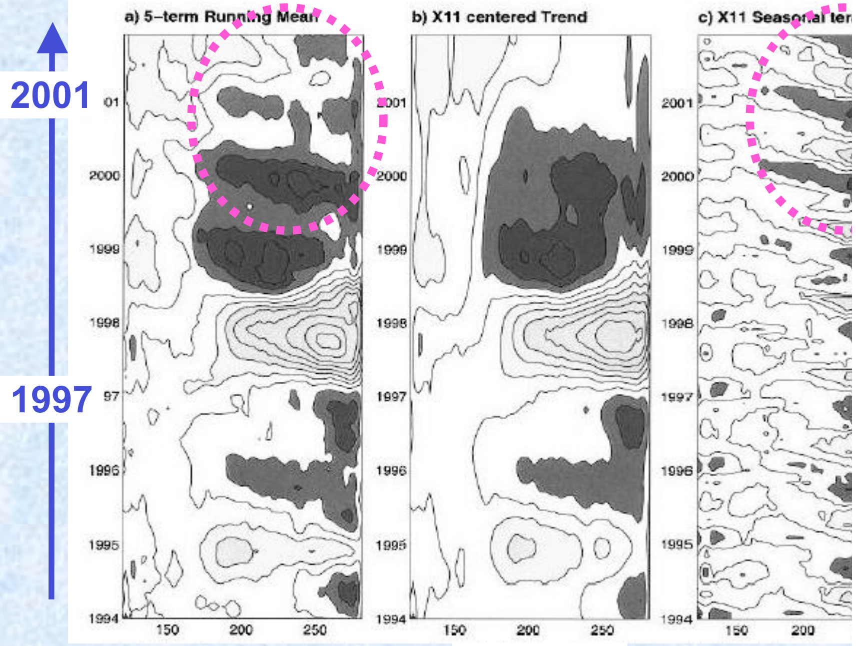


Varying seasonal cycle

Constant seasonal cycle

Varying seasonal cycle

Season

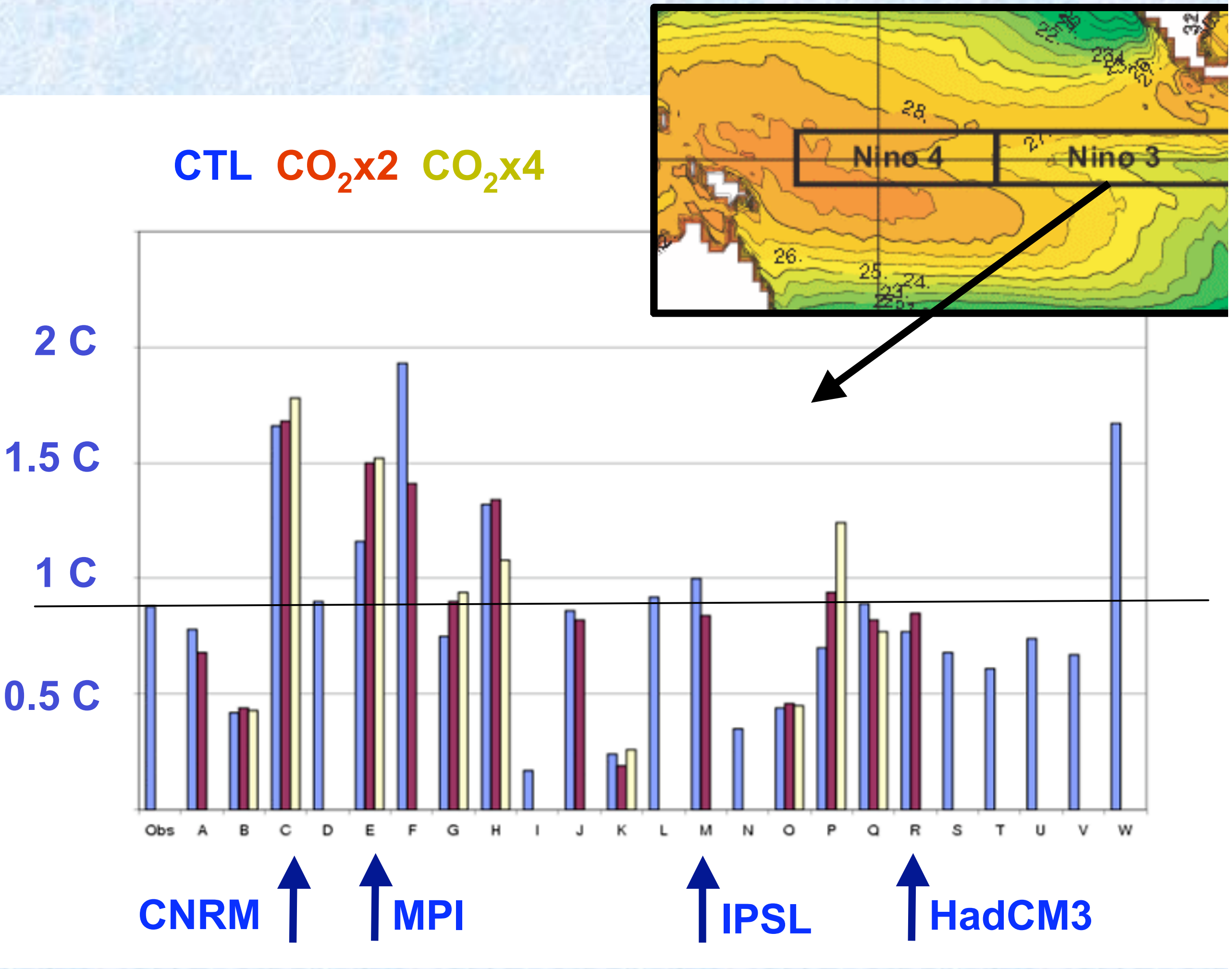


Pezzulli et al, J Clim (2005)

Longitude

Amplitude

- **Diversity !**
- Average of scenario:
  <u>no tendency</u>



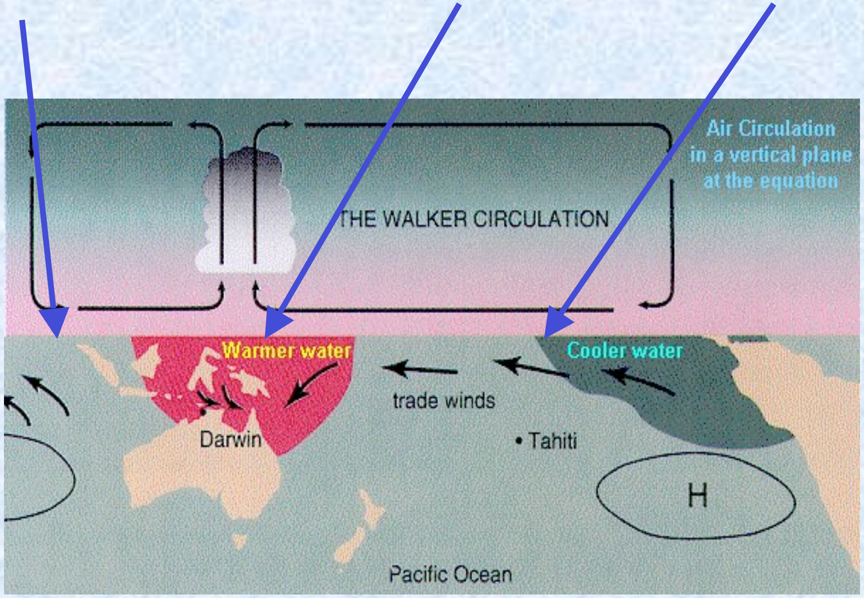
➡ **Can we refine the diagnostic metrics ?**

Indian ocean links

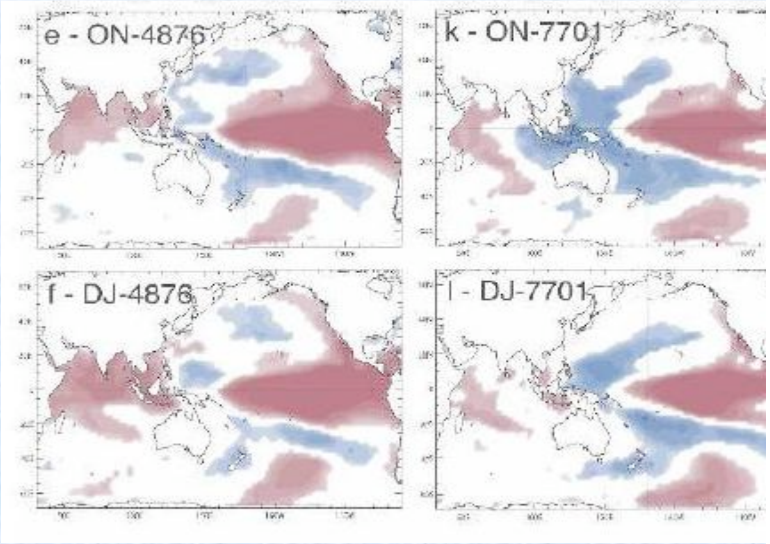
- **MJO generated from the Indian ocean**
- **<u>"Tripolar" variability:</u>**

Indian ocean / indonesian warm pool / Pacific ocean

Indian dipole (IOD) **Convection** **El Niño**



1976 "Climatic shift":

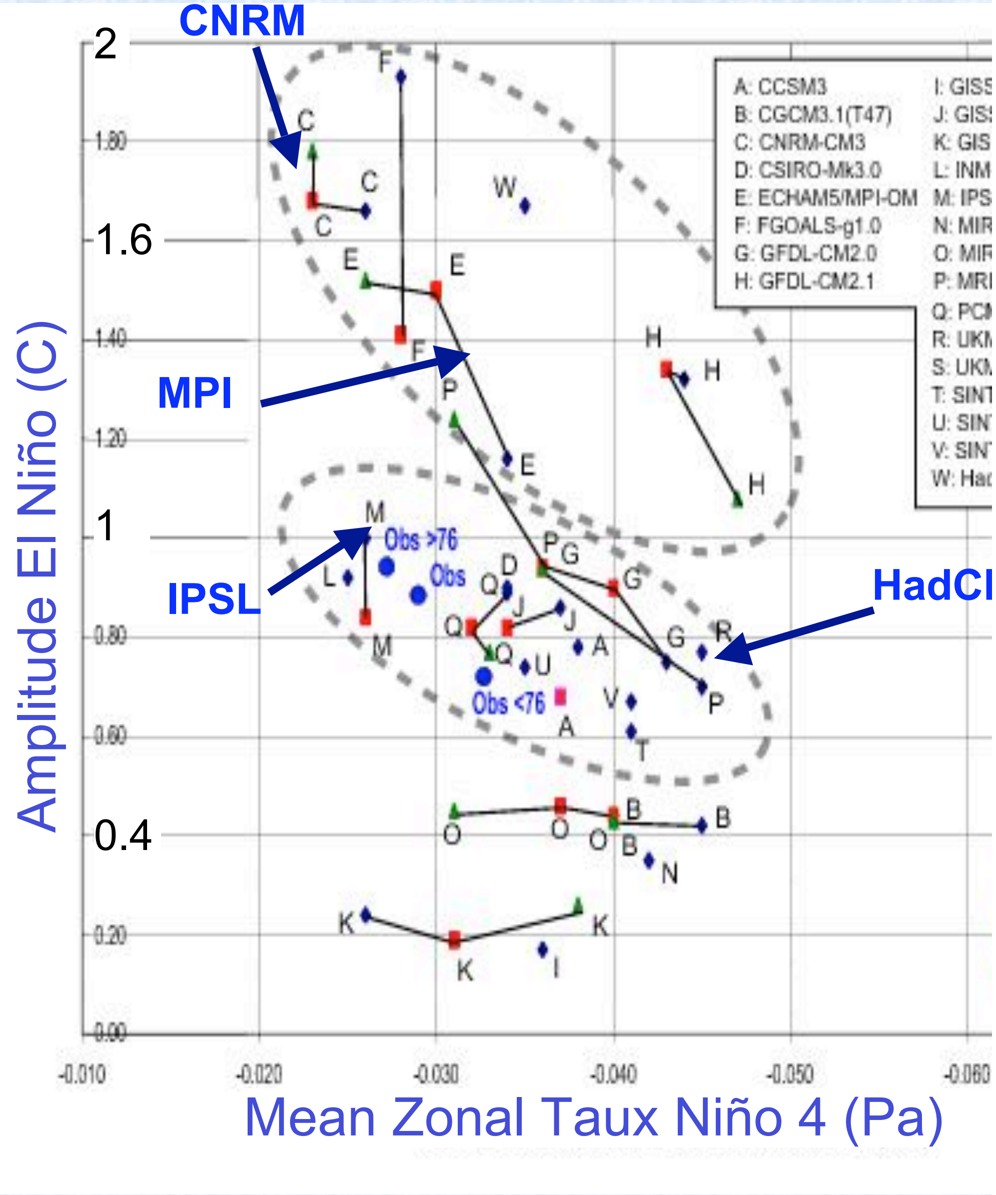


Terray & Dominiak, J Clim (2005

Mean state and El Niño amplitude

- 2 groups
- **El Niño amplitude : <u>inverse relationship</u> with trade winds intensity**
- Agrees with observation and theory (1976 shift)

- Relation holds in scenarios



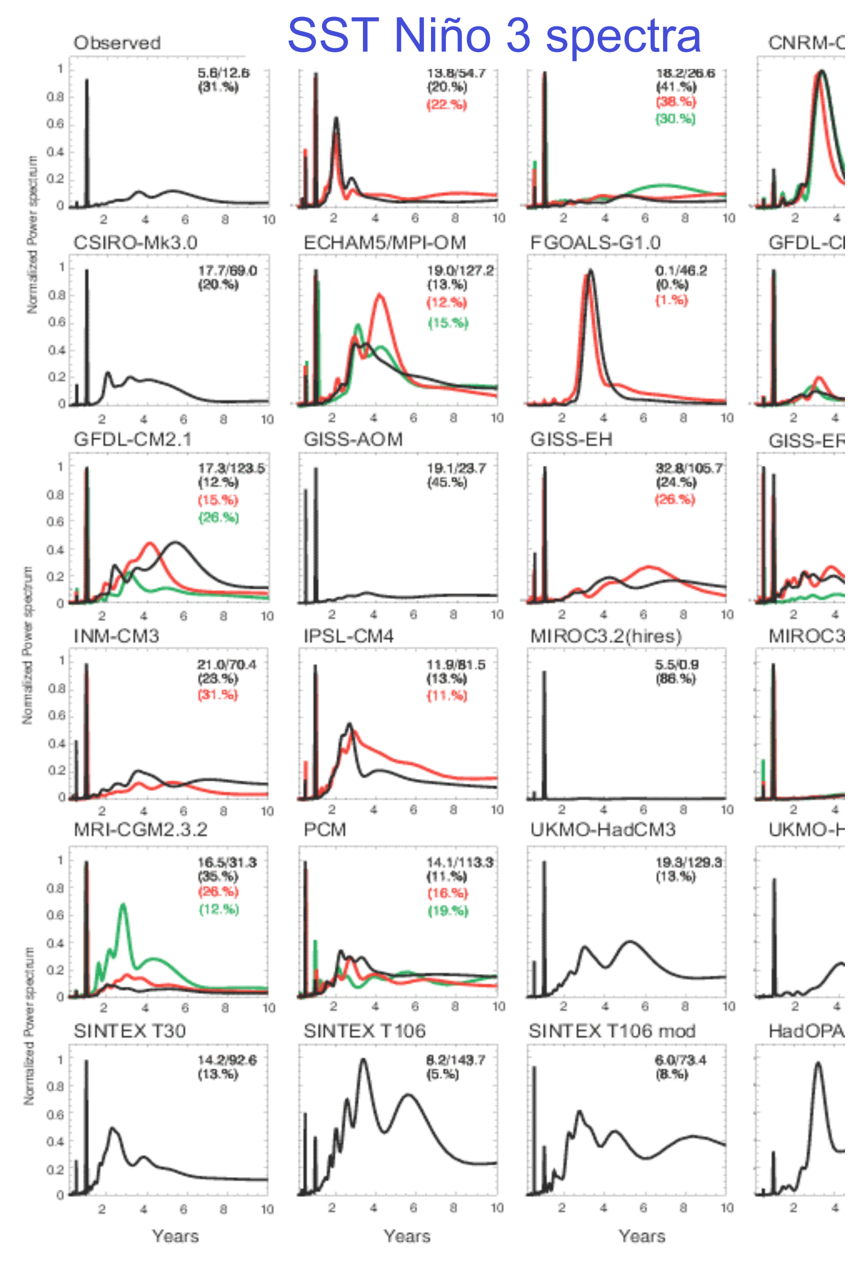
El Niño in IPC

Seasonal cycle relative strength

$$\text{Definition} = \frac{\varepsilon[\text{spectral} \le 1 \text{ year}]}{\varepsilon[\text{spectral total}]}$$

- **Observations = 9 %**
- **Models: from 0% à 55% !**

- Scenario: little change but:
  - GFDL-CM2.1, PCM (+)
  - MRI-CGM2.3.2 (-)



El Niño modes

[Refined metrics]

- **S-mode**: weak ampl., E → W, surface, 2-3 years (< 1976)
- **T-mode**: ampl. ++, W → E, subsurface, ~5 years (>1976)

- Define by lag-correlation of TNI* with Niño3 SSTA

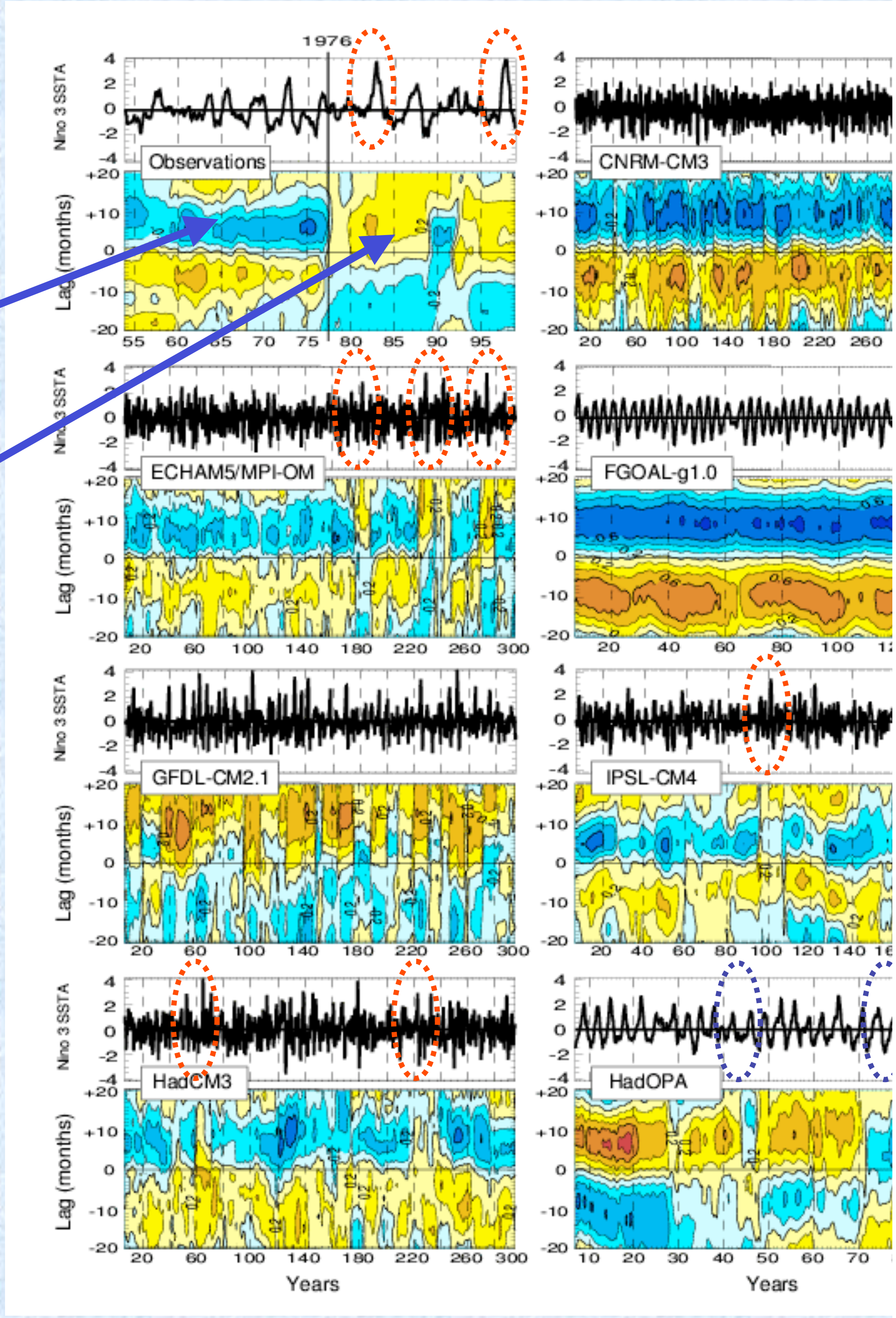
- Classification can be applied to GCMs !

CNRM: strong S-mode

IPSL: weak S-mode (~ hybrid)

MPI, HadCM3: hybrid mode

**Trans-Niño Index = measures East/West SST gradient*



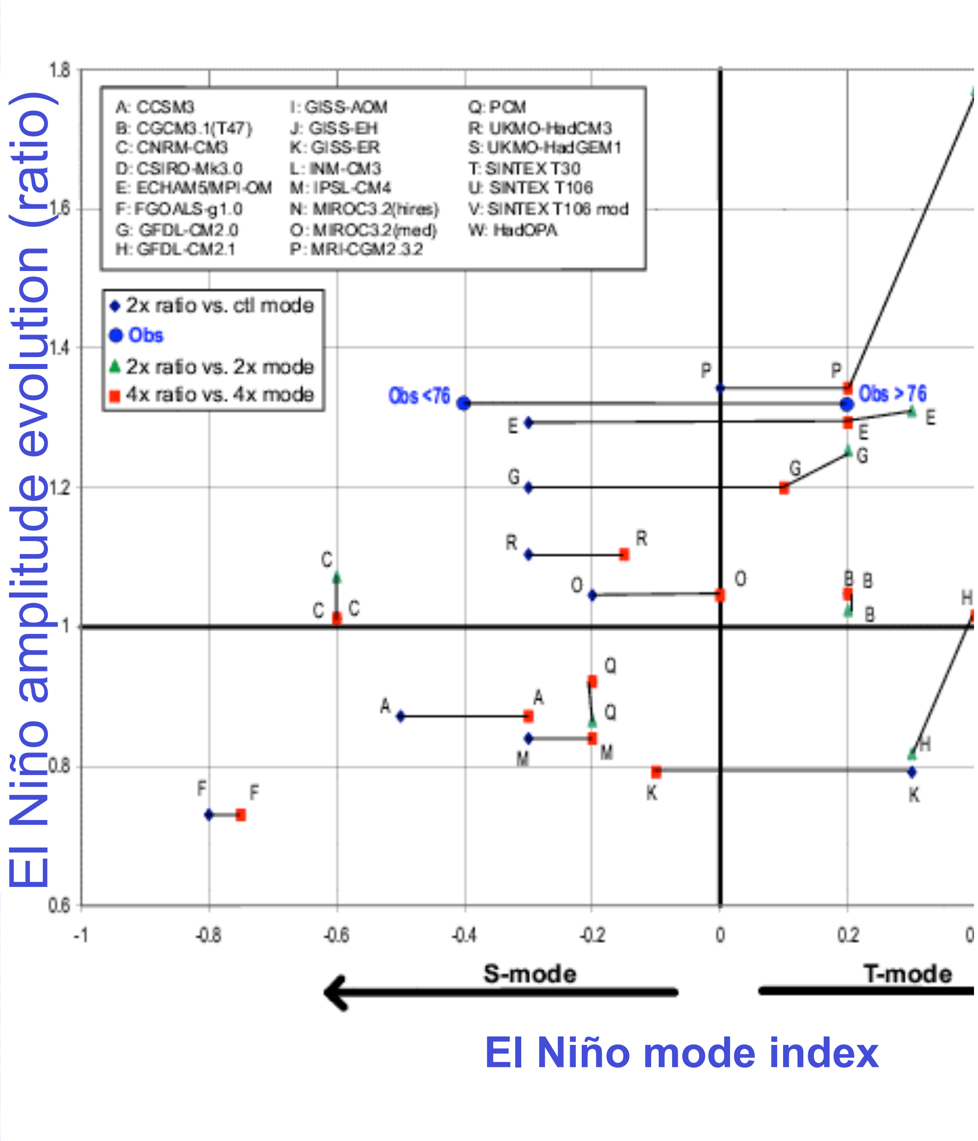
Modes and El Niño Amplitude evolution

- **Large amplitude changes are associated with a mode changes towards a T-mode**

- **Like observed**
  (pre/post 1976)

- **Likelyhood of increased El Niño amplitude in the futur ?**

- (caveat: 2xCO_2 and 4xCO_2)

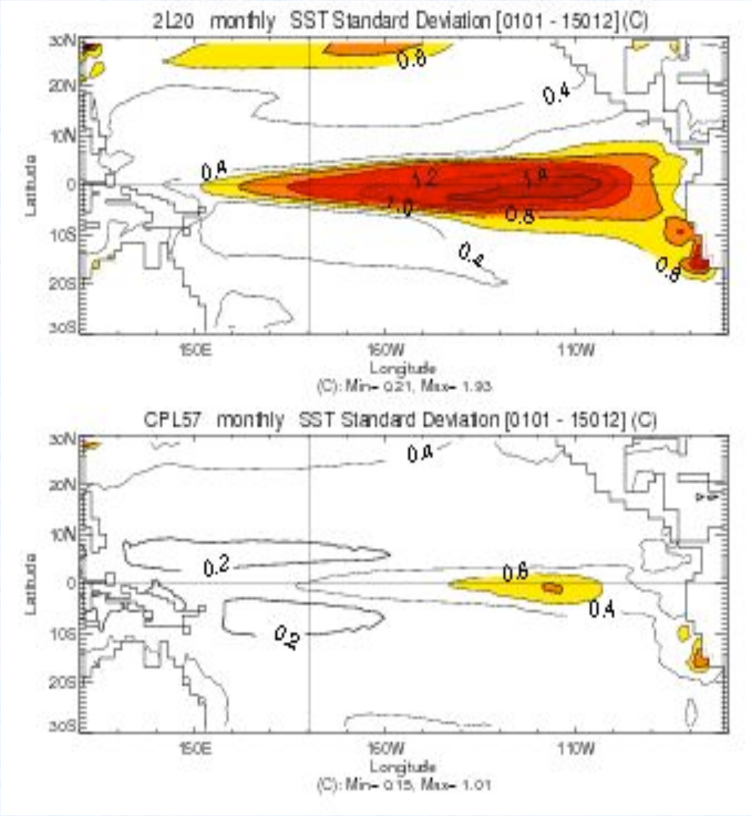


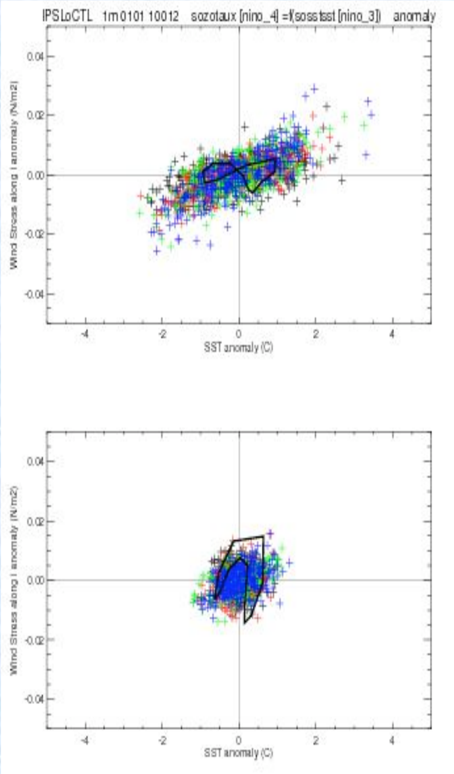
Atmosphere physics and ocean-atmosphere coupling

Example: change of atmosphere convection scheme in IPSL-CM4

IPSL/K-Emmanuel
(1.0 C) - in IPCC

IPSL/Tiedke
(0.36) – old scheme

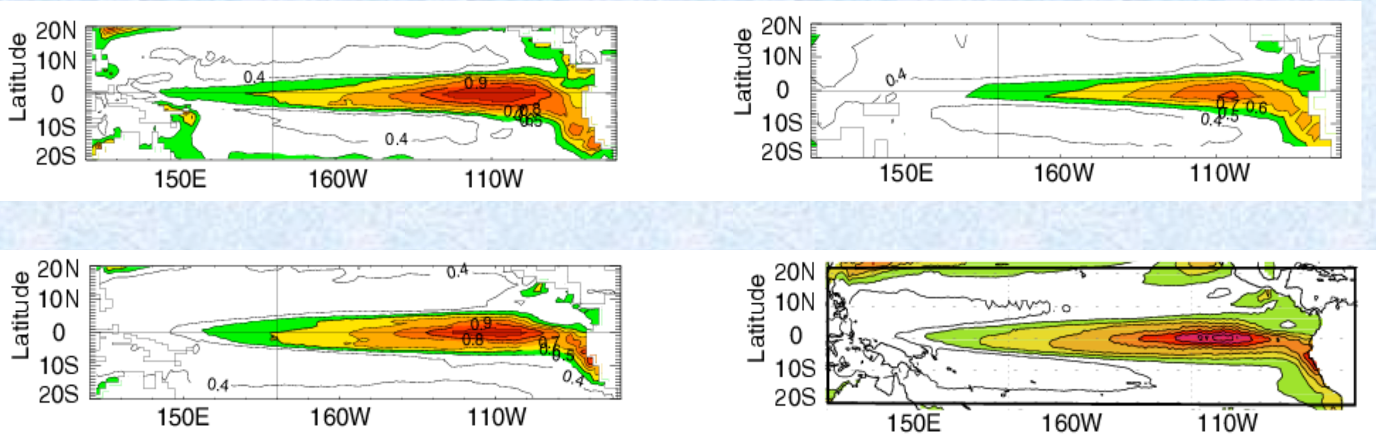




“Geometric” coupling and ocean-atmospher interpolation

SSTA std dev

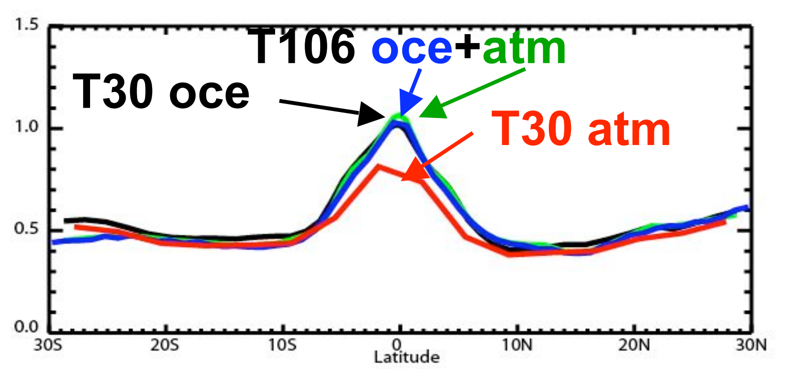
OPA ocean grid (0.5°) **Atmosphere grid**

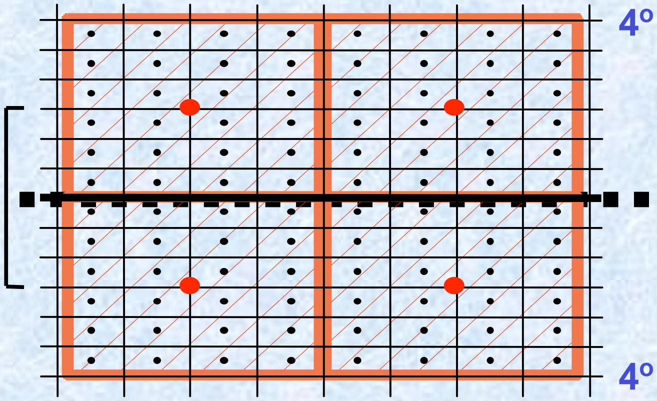


T30 (3.8°)

T106 (1°)

Zonal mean SST std dev

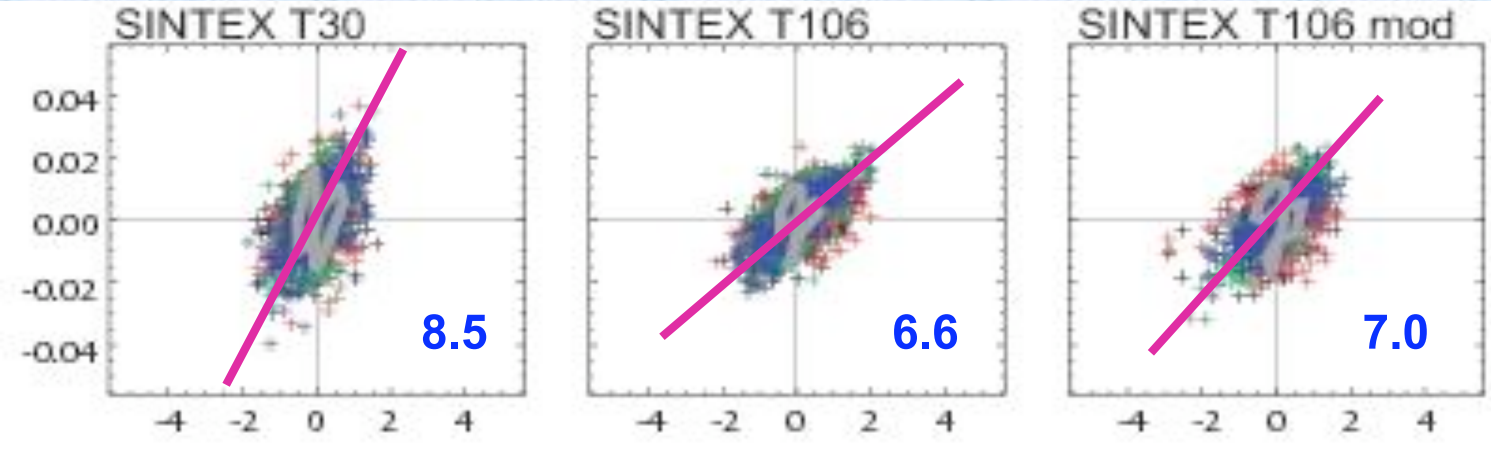




Equatorial Wave guide

Test: modify the interpolation

- SINTEX T106 mod = T106 with interpolation via T30



Coupling strength

El Niño amplitude	0.61	0.74	0.67

➡ Interpolation important but other atmosphere processes
well

Next step: modularity within a component

Why does HadAM3/OPA produces such large El Niño events ?

1) ocean physics
2) atmosphere physics (HadAM3 too reactive to SST or δ_x(SST) ?)

HadAM3 + HadOM3 = 1.0 °C

HadAM3 + OPA = 1.8 °C

HadAM3 + OPA+HadOM 3 Vert. Physics = 1.4 °C

HadAM3+ CAPE + OPA = 1.7 °C

HadAM3 + HadEOM = 1.2 °C