Using initialized simulations to diagnose the growth of systematic biases in the coupled system

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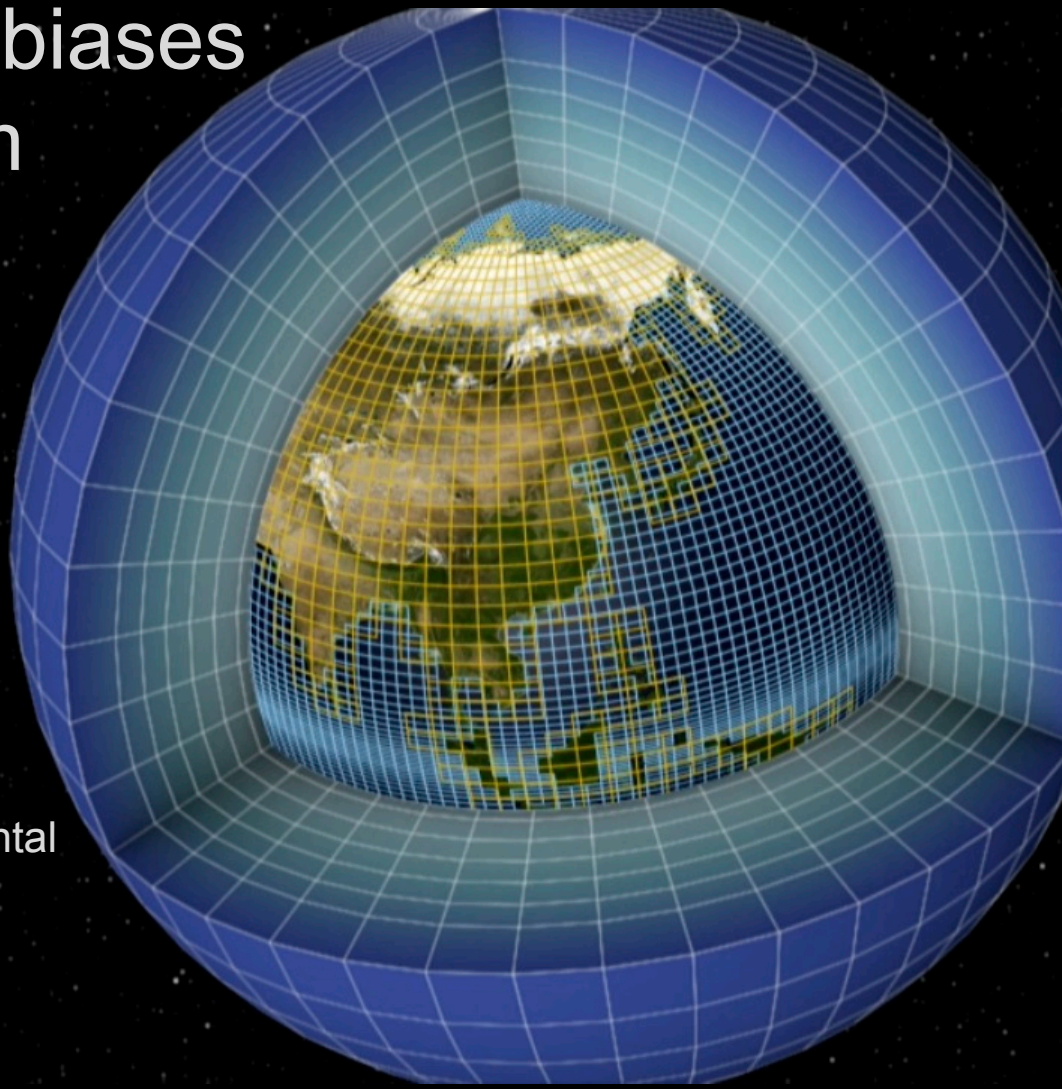

Outline

- Attributing SST errors to specific components and parameterisations
- Can we devise a systematic experimental approach to guide targeted model development ?
- Discussion points

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Institut Pierre Simon Laplace

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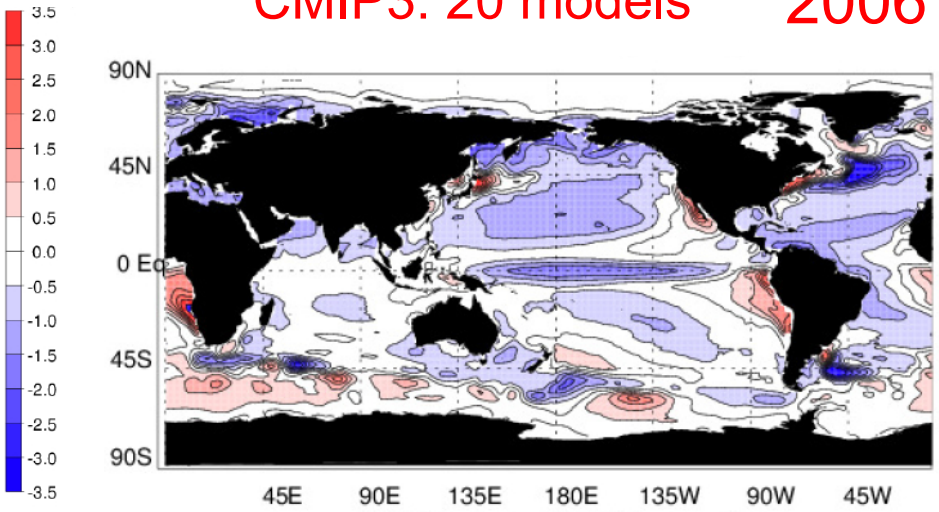
NATURAL ENVIRONMENT RESEARCH COUNCIL

GCMs suffer from systematic and pervasive biases

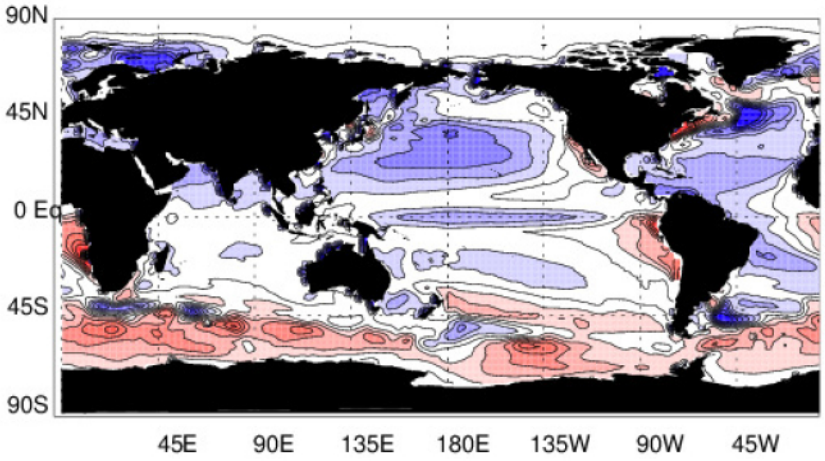
Quiz !

SST errors

CMIP3: 20 models 2006



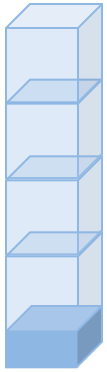
CMIP5: 21 models 2013

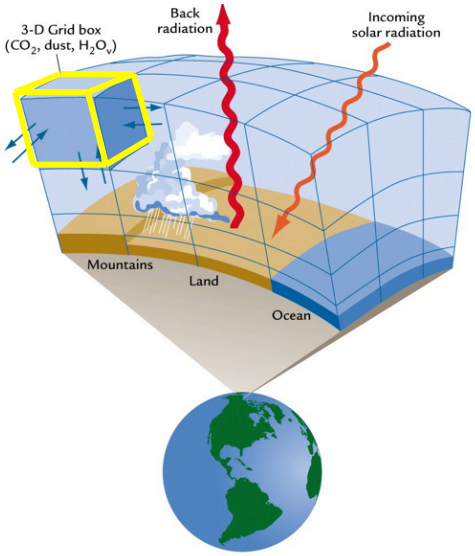


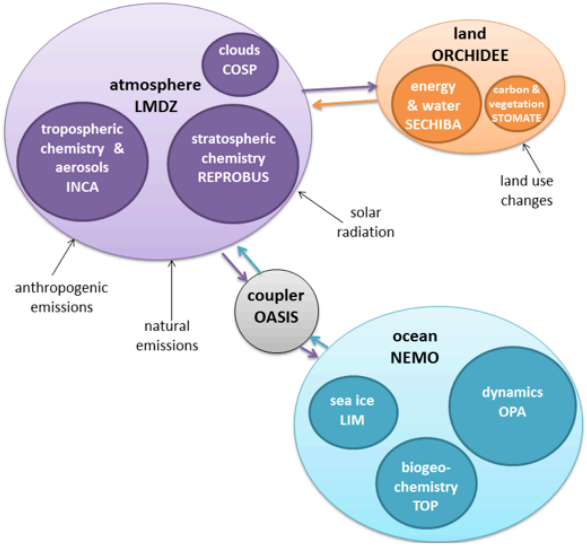
- Severe impacts on climate understanding and prediction
- WCRP & CLIVAR defined as a priority the understanding of climate models biases
- **Lack of progress: try out new strategies**

“Classical” CGCMs development path

Parameterization | **Component** | **Coupled model**







Model development process

Step 1
Parameterization constrained against field campaigns observation

Step 2
Tuning of component, adjustment of large scale balance

Step 3
Tuning of coupled model to balance global energy budget and exchanged fluxes

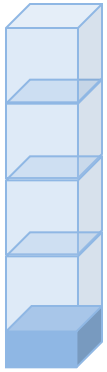
EVALUATION → **EVALUATION** → **EVALUATION**

- Each step generates biases
- Source in coupled model is difficult to identify because of **bias compensation**, **feedback amplification** and **non-linearities**
- This development strategy does not allow to predict the coupled model SST biases

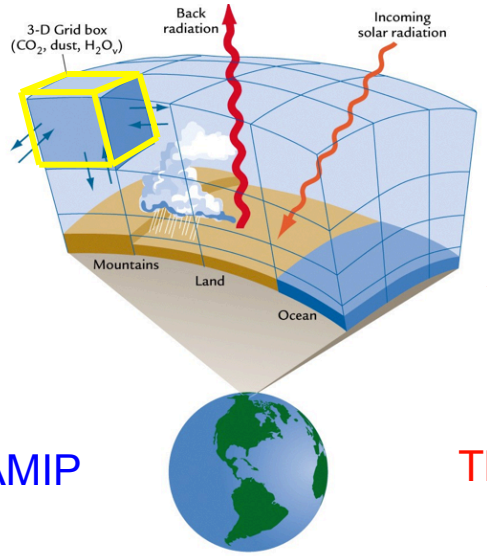
Working backwards

Parameterization | **Component** | **Coupled model**

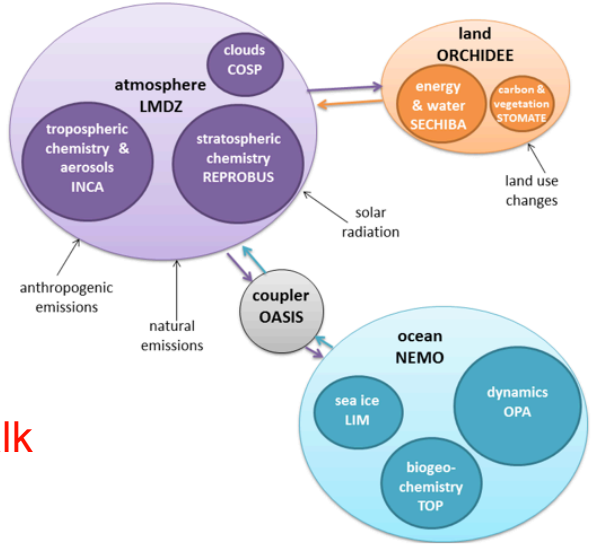
Model development process



e.g. T-AMIP



This talk



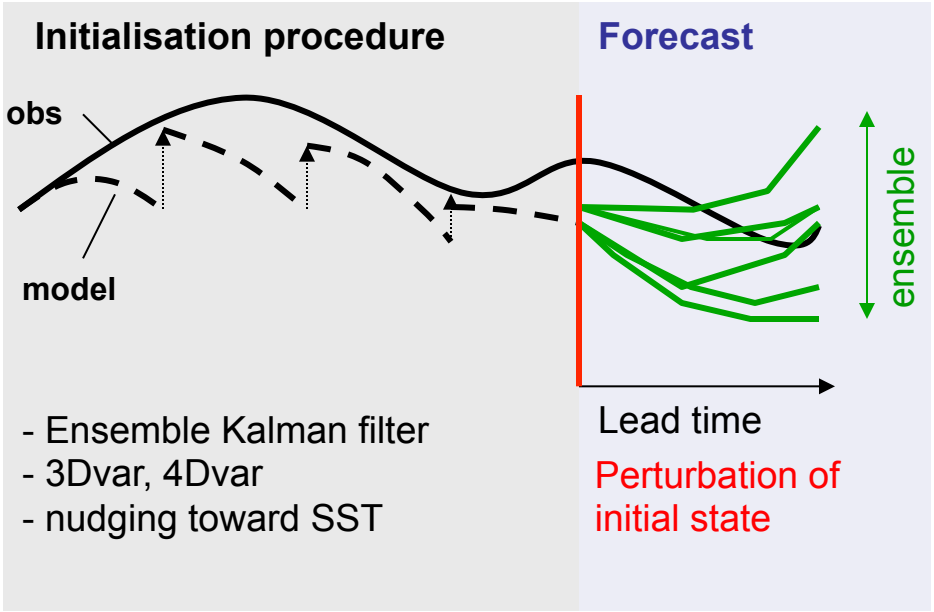
"Fast" physics errors

Atmosphere and ocean component errors

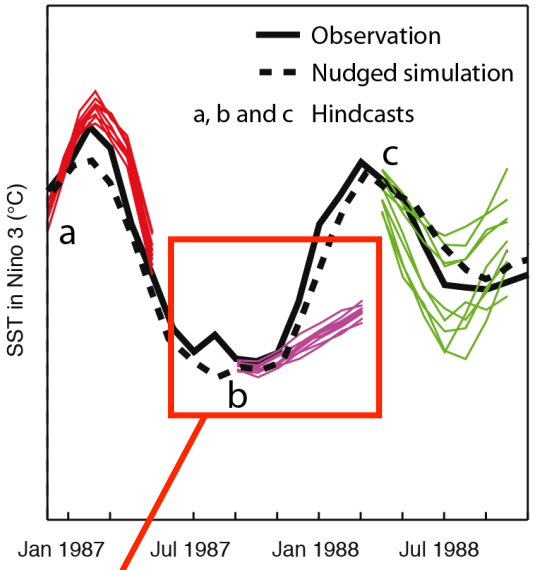
Long term coupled errors

↪ Use "reverse engineering" to attribute a **particular** bias of the coupled model to a component and back to a **specific** parameterisation

Using initialised simulations to understand model errors



Hindcasts = forecast of the past period



Adjustment time scale depends on physical processes involved

Hindcasts:

- ↪ Help distinguish time scale and location of error growth
- ↪ Help propose hypothesis for error source

Using coupled hindcast to understand model biases

Previous work on the development of SST errors and attribution to specific component biases:

- Seasonal/decadal time scale:
  - Tropical Atlantic: B. Huang et al. (2007)
  - Tropical Pacific : B. Vannière et al. (2013, 2014), J. Shonk et al. (2016)
- Decadal/longer time scale:
  - Tropical Atlantic: T. Toniazzo & S. Woolnough (2013)
  - North Atlantic & AMOC : B. Huang et al. (2015)

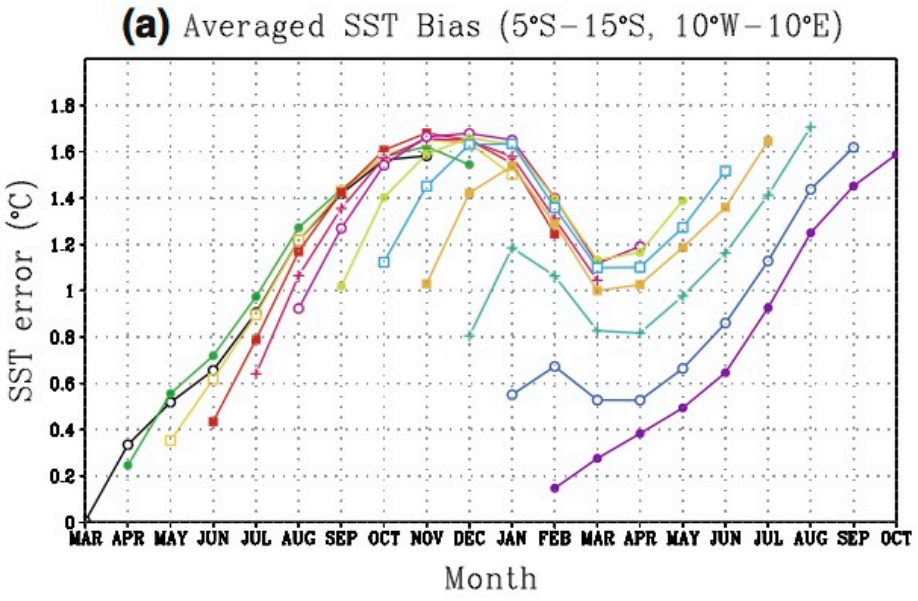
2 examples

Using coupled hindcast to understand model biases: example 1

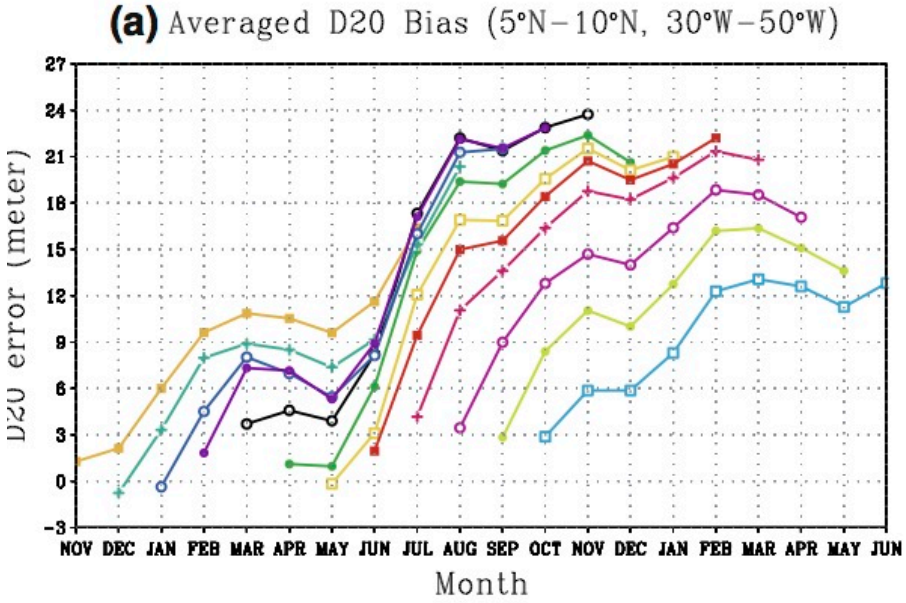
Development of SST and D20 errors in the tropical Atlantic

Huang et al. (2007)

NCEP hindcasts 9 months Lead time



SST error attributed to heat flux error

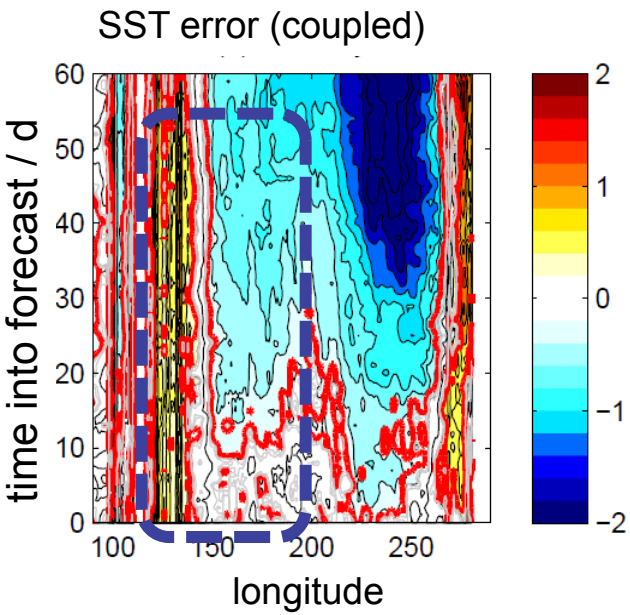


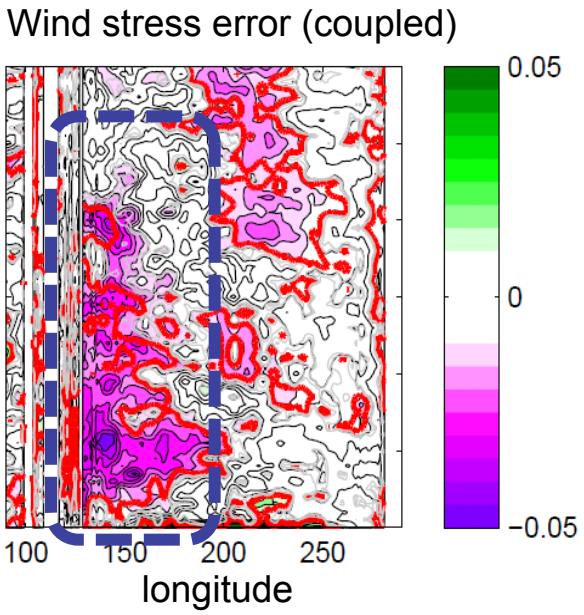
D20 error attributed to wind stress curl error

✓ Causality is *inferred* as no additional simulations are carried out

Using coupled hindcast to understand model biases: example 2

Development of SST errors in the equatorial Pacific in ECMWF system 4





- Cooling bias in west Pacific due to too strong trade winds
- Error appears in first 10 -20 days
- Exact same behaviour in uncoupled mode
- Model developers can focus analysis on uncoupled

Shonk et al. (2016) in prep

Using coupled hindcast to understand model biases

Previous work on the development of SST errors and attribution to specific model biases

- Seasonal time scale:
  - Tropical Atlantic: Huang et al. 2007
  - Tropical Pacific : Vannière et al. 2013, 2014, Shonk et al. 2016
- Decadal time scale:
  - Tropical Atlantic: Toniazzo & Woolnough 2013
  - North Atlantic AMOC, role of fresh water flux : Huang et al. 2015

Mechanisms that initiate SST drift usually associated to atmosphere

- Heat fluxes, wind stress (zonal, meridional, curl), fresh water flux

Two types of studies:

- *Infer* causality via diagnostics and physical understanding
- Actually *show* causality via additional simulations

Identifying the origin of SST mean state biases in the tropical Pacific in IPSLCM5A-LR

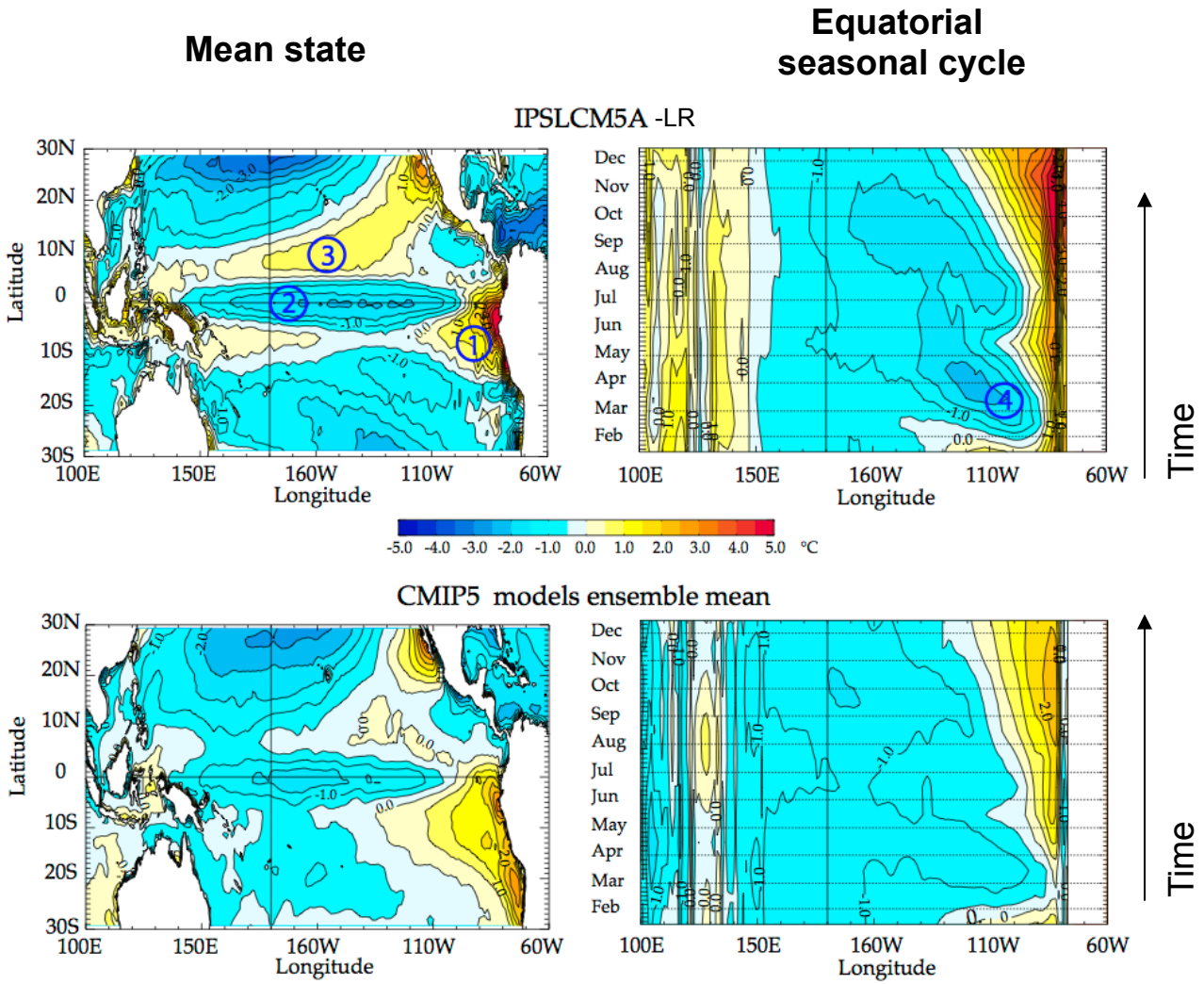
Mean state biases:

① Warm bias in the east Pacific

② Cold tongue bias

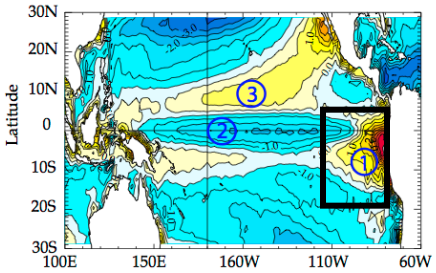
③ Warm bias on both side of the equator

④ Spurious spring upwelling bias

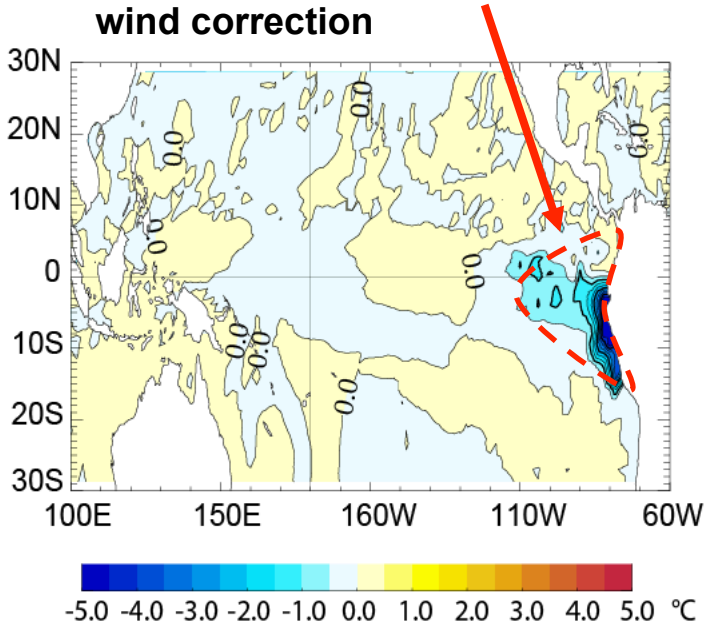


Vannière et al. (2014)

Using additional simulations to demonstrate the source of error

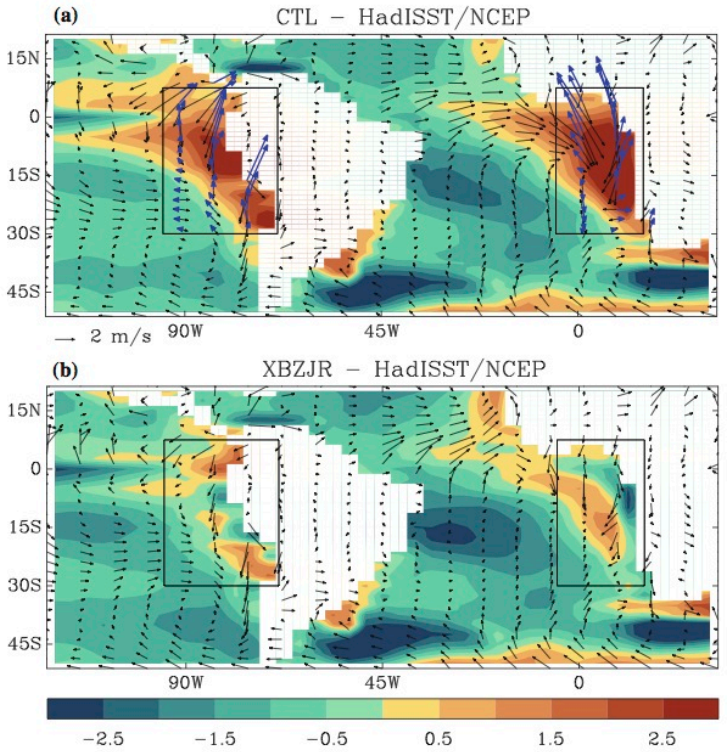


Oceanic simulation forced with fixed flux : impact of meridional wind correction



Vannière et al. (2014)

Coupled simulation with wind correction



Toniazzo and Woolnough (2013)

Can we devise a systematic experimental approach ?

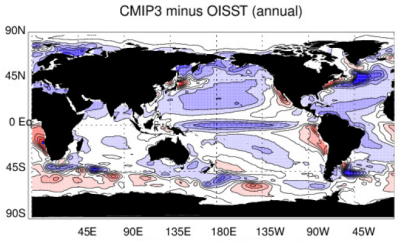
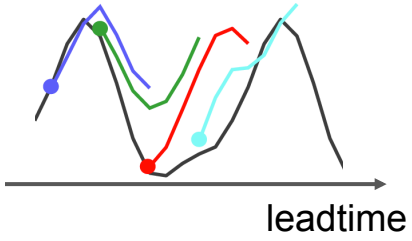
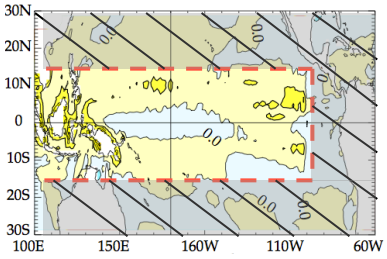
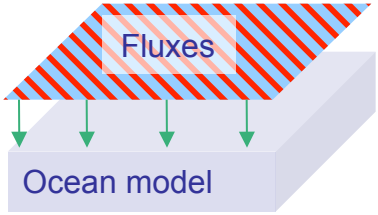
Vannière et al (2014) proposed a systematic approach to investigate the root cause of a SST bias in a climate model

5 steps for ‘solving the case’:

1. Identify the location and seasonality of the SST bias
2. Examine the time scales over which errors develop in different variables and link them together to build a chain of causality
3. Find whether the origin of the bias is local or remote
4. Determine if an atmospheric field or an oceanic field is at fault
5. Investigate whether the error is caused by the direct effect of that field, or by coupled feedbacks

Associated experiments in support of approach

Vannière et al. (2014)

The 5 steps	Associated experiments	
S1 **Location / seasonality**	**Historical or control experiment**	
S2 **Time scale / chain of causality**	**Seasonal to decadal hindcasts**	
S3 **Local or remote**	**Regionally restored experiments**	
S4 **Atmospheric / oceanic field responsible for the bias** S5 **Direct effect / amplification by coupled feedbacks**	**Ocean-only forced experiments**	

Identifying the origin of SST mean state biases in the tropical Pacific in IPSLCM5A-LR

Approach is applied to **cold tongue bias** in IPSL-CM5A-LR (S1)

① Warm bias in the east Pacific

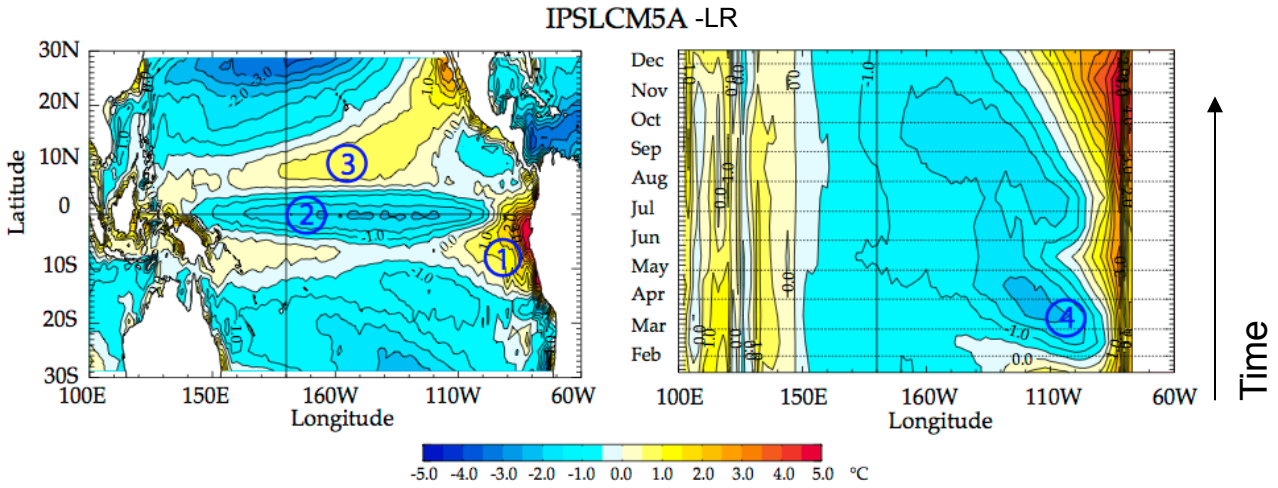
② **Cold tongue bias**

③ Warm bias on both side of the equator

④ Spurious spring upwelling bias

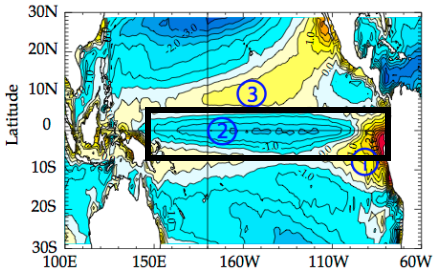
Mean state

Equatorial seasonal cycle

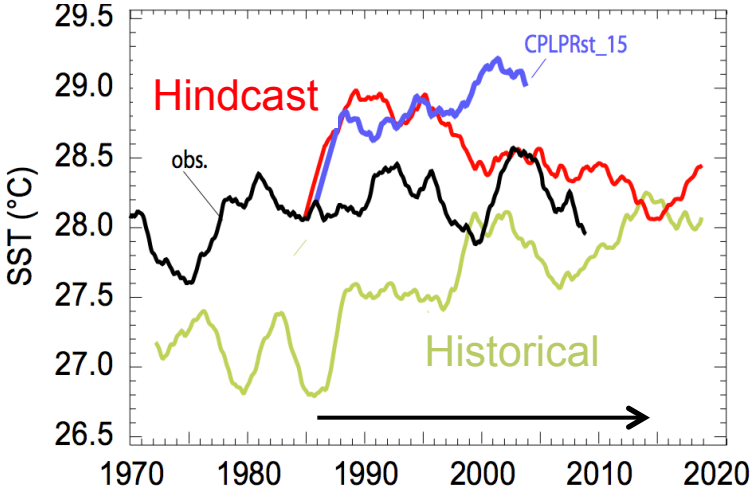


Vannière et al. (2014)

Cold tongue bias origin



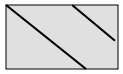
> S2 : Time scale → Cold tongue bias



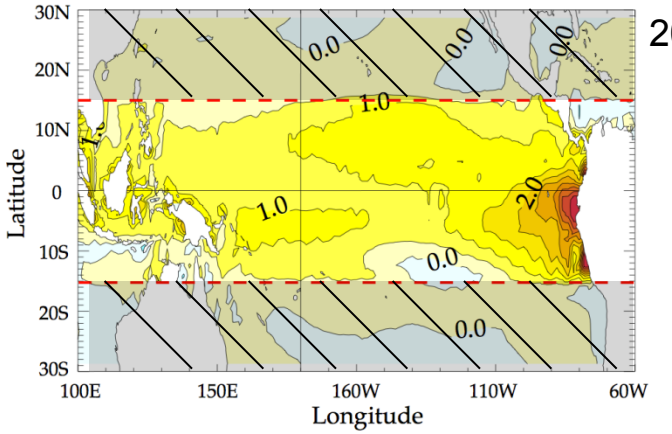
- ✓ It takes 30 years for the cold tongue bias to appear at the equator
- ✓ Hypothesis : ocean slow dynamics

> S3 : Geographical origin → Cold tongue bias

CPLPrst_15: Initialised simulation restored toward observed SST in midlatitudes



SST nudging

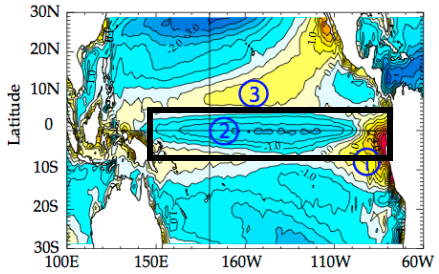


20-yr leadtime

- ✓ SST corrected in mid-latitudes
  ⊗ no development of the cold tongue bias

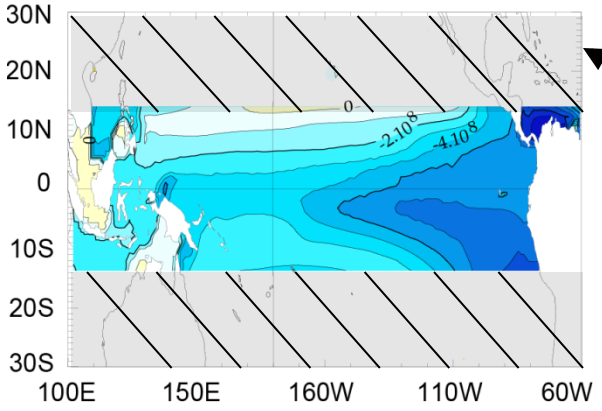
Vannière et al. (2014)

Cold tongue bias origin



> S4 : Ocean only simulation → reproduce cold tongue bias

Ocean only simulation (bulk) 300m heat content



Nudging toward the hindcast mid-latitudes cold bias

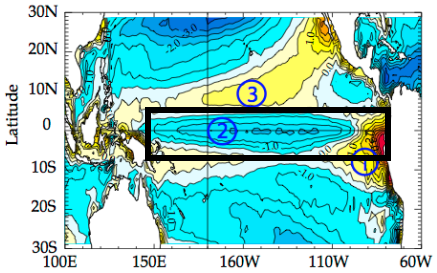
30 years leadtime

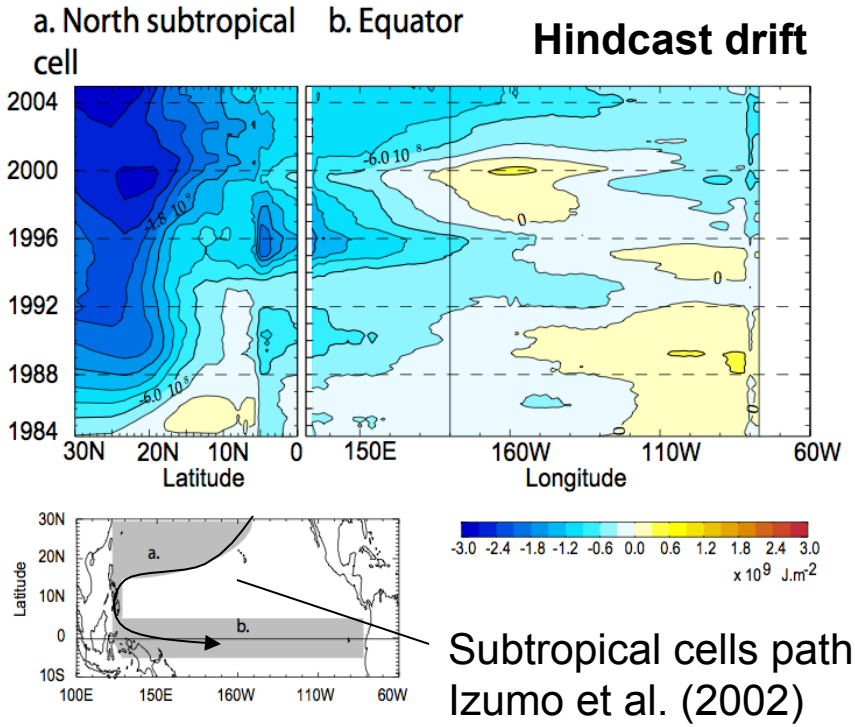
Experiment	Equatorial cooling trends of the 300m HTC ($J.m^{-2}.mth^{-1}$)
Hindcast	-1.35 10^6
Ocean only with SST restoring	-1.73 10^6
Ocean only without SST restoring	0.1 10^6

- ✓ When the midlatitudes cold SST bias is prescribed in an ocean-only experiment, the cold tongue bias develops at the equator
- ✓ The cooling trend is similar to that simulated by the control hindcast

Vannière et al. (2014)

Cold tongue bias origin





Subtropical cells path according to Izumo et al. (2002)

A possible cause of the midlatitude cold bias propagation is the advection by subtropical cells

Differs from other sources of the cold tongue bias (Vannière et al. 2013)

- Bjerknes feedback (Met Office)
- Atmospheric component wind errors (INGV)
- or otherwise proposed in many studies

Vannière et al. (2014)

Summary and discussion points (1/2)

- New approaches needed to address SST systematic errors
- Strategy to relate **coupled errors** to the **errors in one component** independently of the coupling:
  - 5 step 'case solving' approach
  - Requires range of dedicated simulations, including initialized
  - Proof of concept from several studies (tropical Pacific and Atl.)
  - Further benefits/costs to explore:
    - Apply during model development phase
      - cheap (300 years)
      - but need to develop a 'tool box', i.e. several types of simulations (one time investment)
    - Precise types of simulations will depend on 'case' i.e. SST bias – no 'standard' set
  - Can't be directly applied to SST interannual variability biases (ex: ENSO) but can be applied to ENSO mechanisms and feedbacks (not shown)

Summary and discussion points (2/2)

- But, AMIP/T-AMIP is the starting point in the tropics
  - Most SST errors initially due to fast atmosphere biases
- Decadal bias investigation : start with simplified forcing (better signal/noise ratio)
- Prospects for high-resolution to ameliorate climate biases
  - No systematic impact of HR, although dynamics better
  - Works together with physical parameterisations
  - Coherence of air-sea interactions and horiz./vert. resolution
- Atmosphere and ocean biases that lead to SST, SSS bias
  - Fluxes, usually an atmosphere cause
  - Near the equator: wind stress, wind stress and wind stress
    - Data assimilation won't help
  - Mid-latitutes: subduction in the ocean, fresh water fluxes

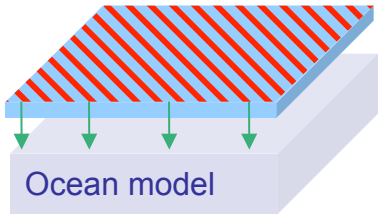
Ocean-only forced experiments

Bulk formulation

Computed interactively with low level atmospheric fields

Coupled model
Ex: 10M wind

Observation
Ex: (t2m, q2m, SW, LW..)
DFS4.3, Brodeau et al. 2010



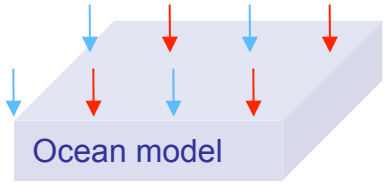
- damping of SST errors
- dynamical and thermodynamical effects of wind

Fixed flux formulation

Air-sea fluxes prescribed

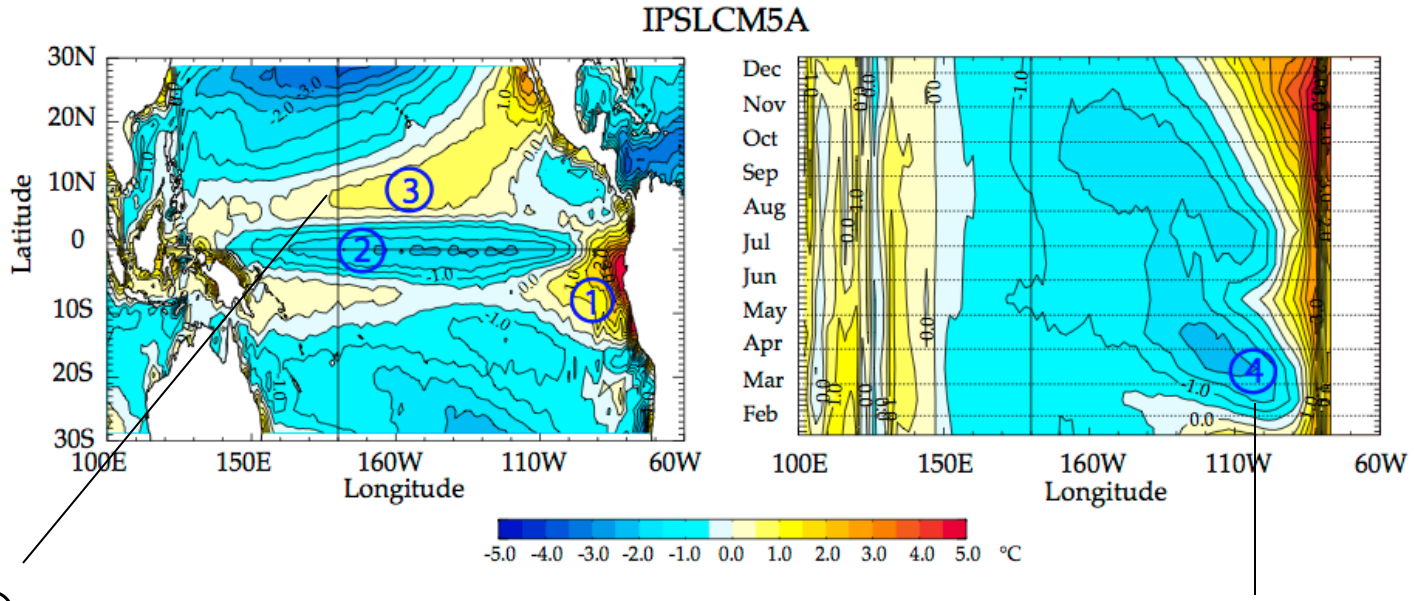
Coupled model
Ex: Wind stress

Observation
Ex: (solar HF, non-solar HF…)



- development of SST errors
- dynamical effect only of wind

Origin of the other SST biases



③

Hindcast : development in ~ 6 months

Ocean-only simulations :

- too strong SW heat flux
- too low latent heat flux
- no dynamical role of the wind

④

Hindcast : development in ~ 6 months

Ocean-only simulations :

- coupled bias
- EP warm bias modifies the wind seasonal cycle and initiate the upwelling

CGCMs mean state biases in the tropical Pacific

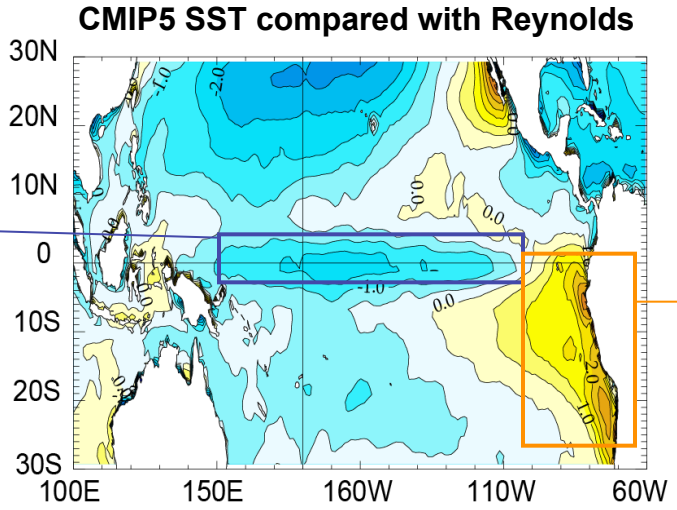
Cold tongue bias :

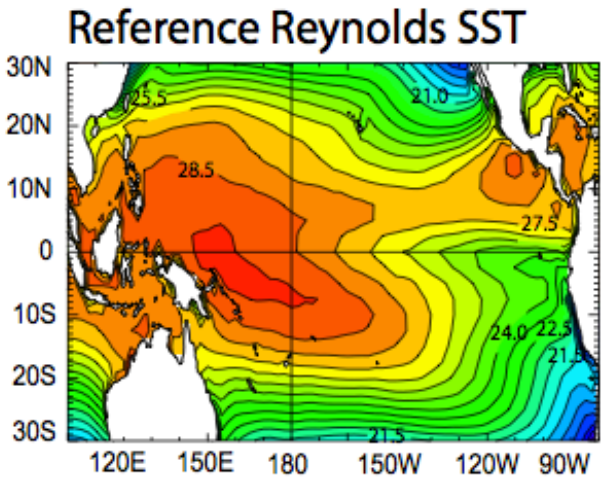
- too strong easterlies at the equator

- amplification by coupled feedbacks such as Berknes feedback (Dijkstra and Neelin 1995, Lin 2007)

- too diffuse thermocline (Davey et al. 2002)

…





East Pacific warm bias :

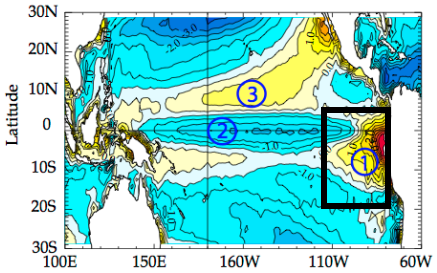
- meridional and coastal wind (deSzoeke et Xie 2008, Large et Danabasoglu 2006)

- low level clouds (Mechoso et al. 1995, Ma et al. 1996, Wang et al. 2004)

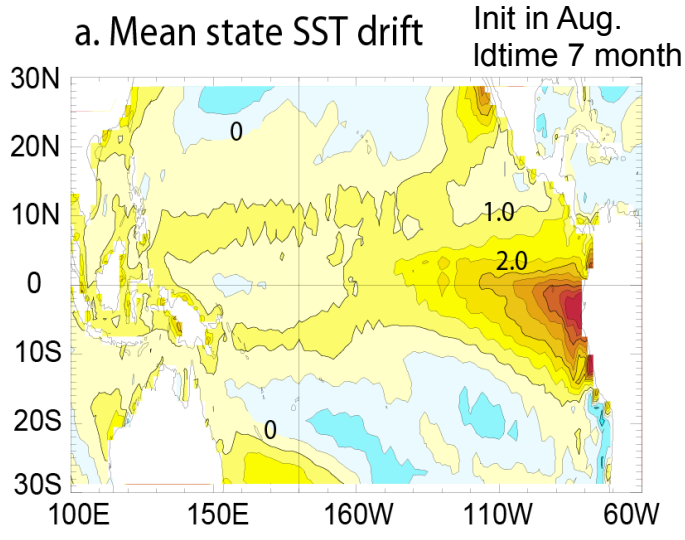
- eddies (Colas et al. 2012)

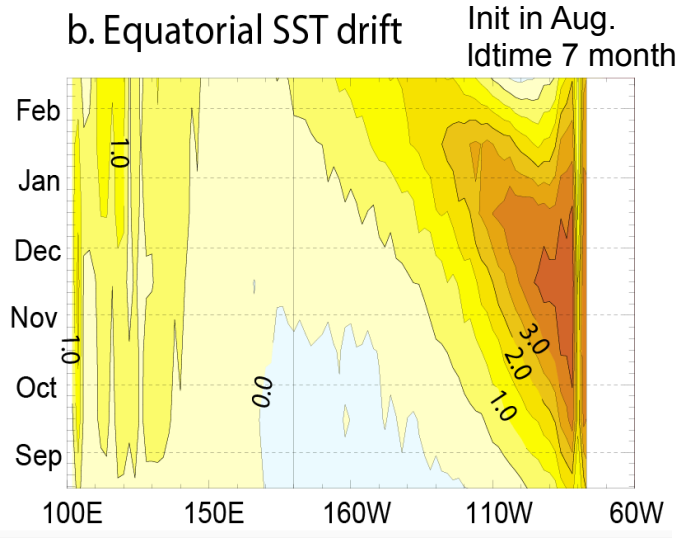
- possible interaction with the double ITCZ bias

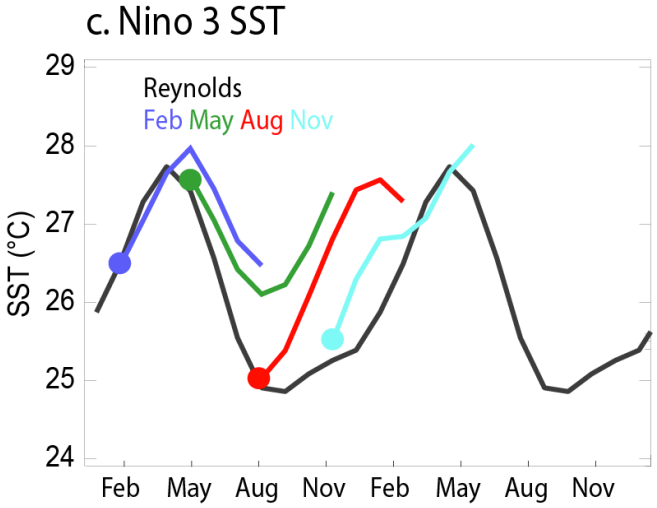
Origin of the East Pacific warm bias



> S2 : Time scale and propagation → EP warm bias



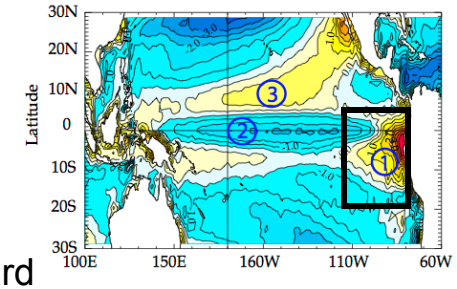




✓ Development of the warm bias at the Peruvian coast and propagation toward the west

✓ Development of the warm bias whatever the start date is and maximum development of the bias during the upwelling period.

Origin of the East Pacific warm bias

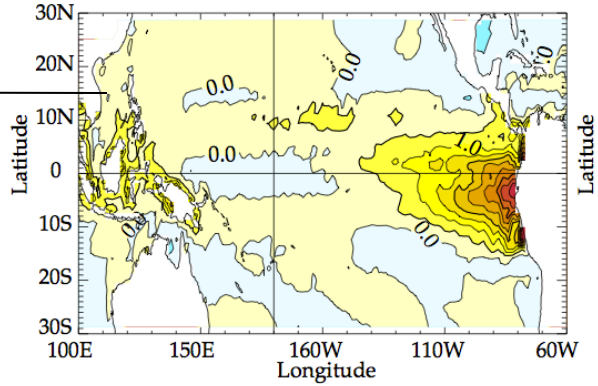


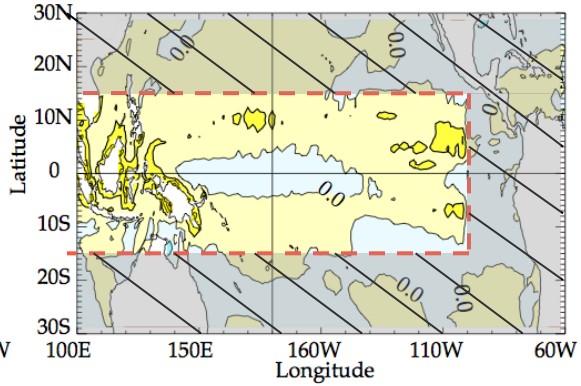
> S3 : Geographical origin → EP warm bias

Hindcast + wind from the simulation nudged toward SST

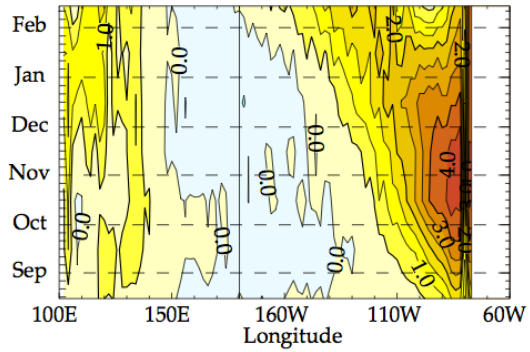
Hindcast + nudging toward SST

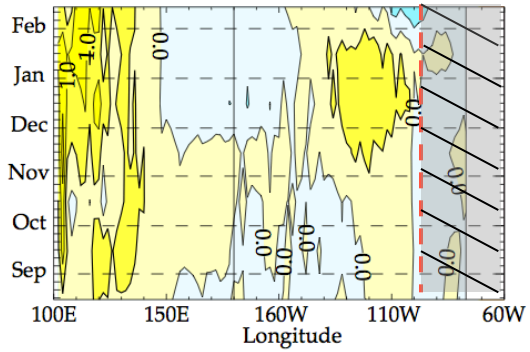
No SST bias feedback on the surface wind





SST nudging



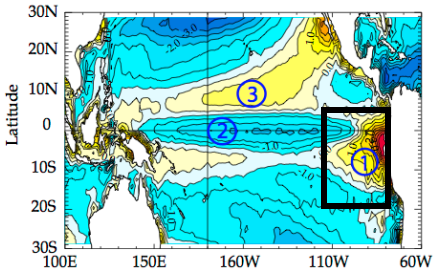


The amplification of the warm bias doesn't require a dynamical coupling

Advection is a key process for the westward propagation of the bias

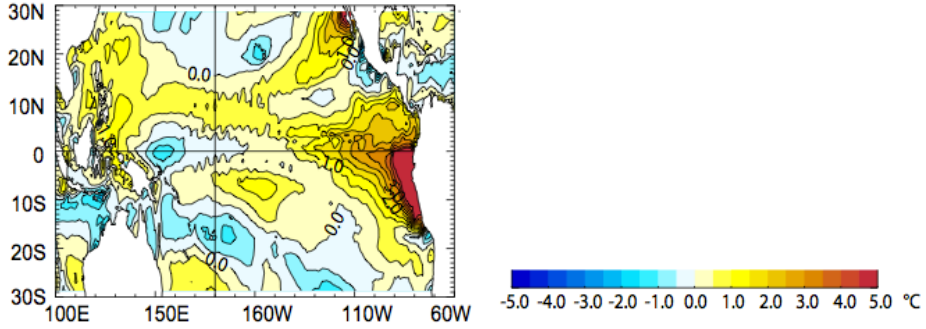
✓ The warm bias is generated at the Peruvian coast and is advected by oceanic currents toward the west.

Origin of the East Pacific warm bias

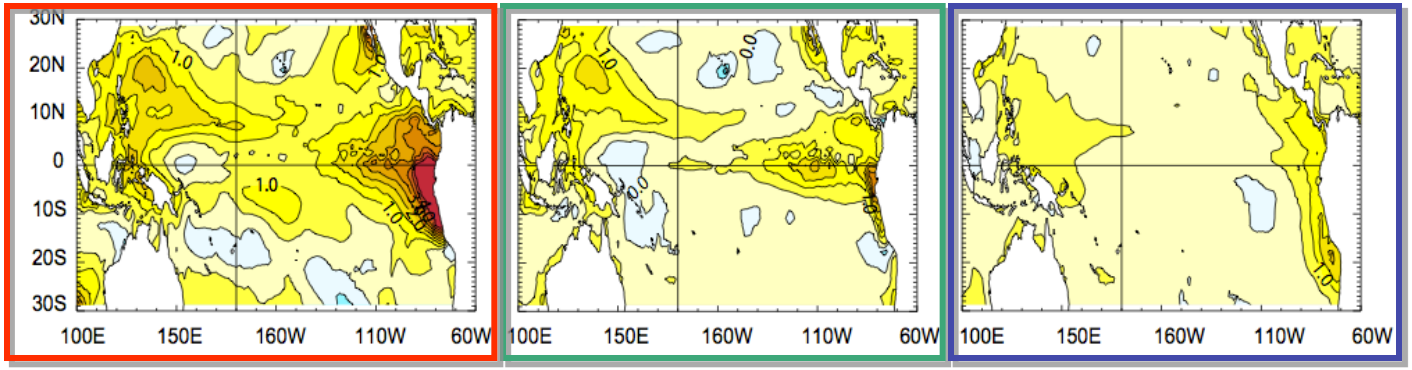


> S4 : Field responsible for the bias → EP warm bias

SST errors in hindcasts
3 month ldtime



Ocean-only simulations (bulk)



All field from the hindcast

10m wind impact

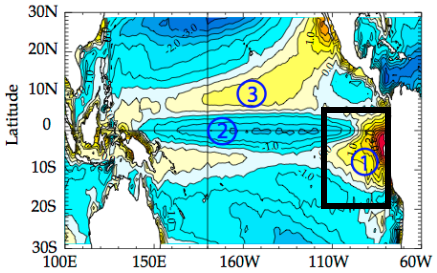
SW impact

✓ Ocean-only simulation forced by hindcasts fields ⇒ decomposition of the different contributions to SST biases

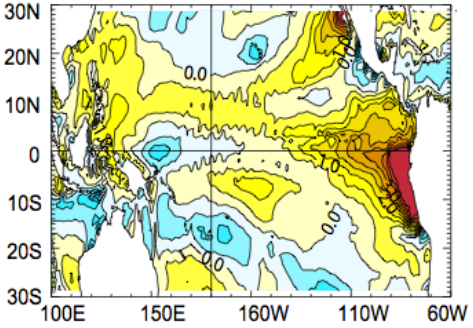
✓ 10m wind represent the main contribution to the warm bias

Origin of the East Pacific warm bias

> S5 : Degree of coupling → EP warm bias

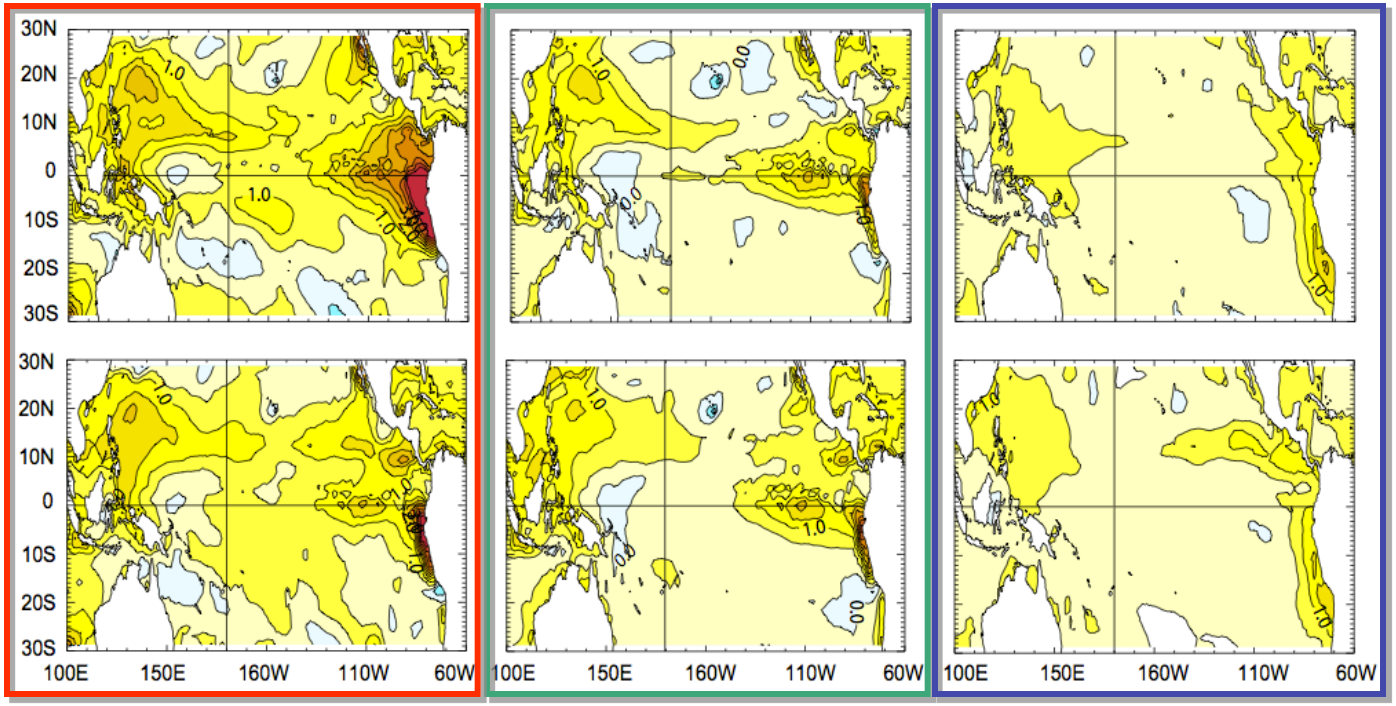


SST errors in hindcasts after a 3 month lead time



Hindcast forcing

AMIP forcing



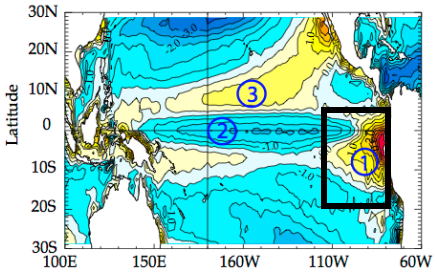
All field coming from the model

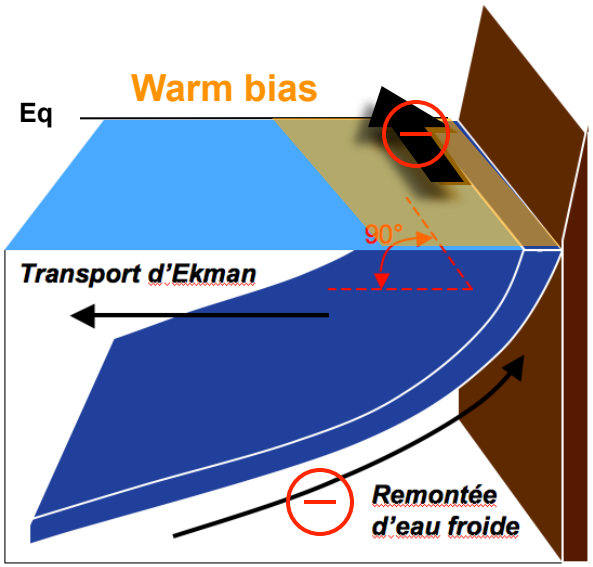
10m wind impact

SW impact

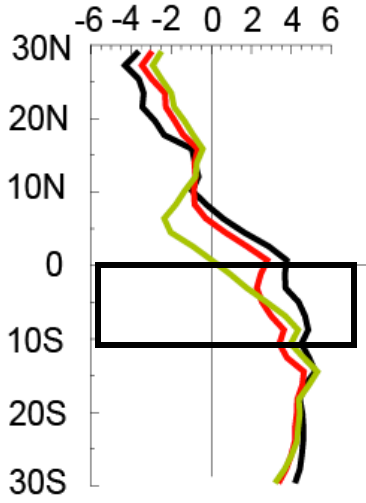
✓ EP warm bias is due to a direct effect of the atmosphere component error and the coupling has little impact.

Origin of the East Pacific warm bias



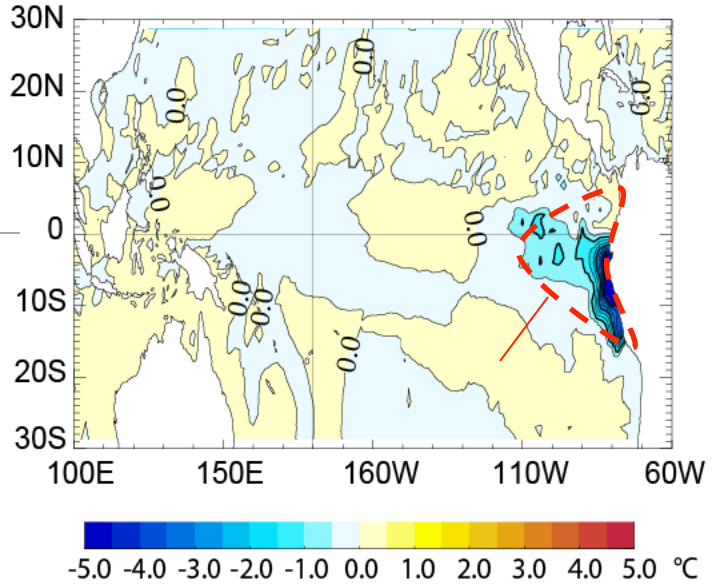


Meridional wind along the Peruvian coast



Observation
AMIP
Historical

Oceanic simulation forced with fixed flux : impact of meridional wind correction



✓ East Pacific warm bias = meridional wind component at the Peruvian coast

Meridional wind is corrected with DFS4.3