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

Eric Guilyardi & many colleagues

LOCEAN/IPSL, Paris
NCAS-Climate, University of Reading

Outline

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

Initialisation procedure

- Ensemble Kalman filter
- 3Dvar, 4Dvar
- nudging toward SST

Forecast

Lead time

Perturbation of initial state

Hindcasts = forecast of the past period

- Observation
- Nudged simulation

a, b and c Hindcasts

Historical data


SST in Niño 3 (°C)

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)

- **Decadal/longer time scale:**
  - 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

(a) Averaged SST Bias (5°S–15°S, 10°W–10°E)

(b) Averaged D20 Bias (5°N–10°N, 30°W–50°W)

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

• 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
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

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

Vannière et al. (2014)
Using additional simulations to demonstrate the source of error

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

Coupled simulation with wind correction

Toniazzo and Woolnough (2013)

Vannière et al. (2014)
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
The 5 steps

S1 Location / seasonality

S2 Time scale / chain of causality

S3 Local or remote

S4 Atmospheric / oceanic field responsible for the bias

S5 Direct effect / amplification by coupled feedbacks

Associated experiments

Historical or control experiment

Seasonal to decadal hindcasts

Regionally restored experiments

Ocean-only forced experiments

Vannière et al. (2014)

Fluxes

Ocean model
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

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

- 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

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

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

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
• 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-latitudes: 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

Hindcast: development in ~ 6 months
Ocean-only simulations:
- too strong SW heat flux
- too low latent heat flux
- no dynamical role of the wind

Hindcast: development in ~ 6 months
Ocean-only simulations:
- coupled bias
- EP warm bias modifies the wind seasonal cycle and initiate the upwelling
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)
- 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

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

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

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

Meridional wind is corrected with DFS4.3