Understanding ENSO in climate models: from statistics to process-based metrics

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Seasonal Prediction Webinar - Oct. 2014
Outline:

- ENSO statistics – from CMIP3 to CMIP5
- Mean state in the Tropical Pacific
- ENSO in a warming climate
- Process-based ENSO evaluation, focus on atmosphere

This talk:
- Mean state and ENSO statistics in CMIP are improving and new robust information about ENSO in the future
- But process-based performance still an issue
El Niño in coupled GCMs - amplitude

<table>
<thead>
<tr>
<th>Modelling centers</th>
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<tbody>
<tr>
<td>• ENSO amplitude in CMIP3: very large diversity of simulated amplitude</td>
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<tr>
<td>• Range reduced in CMIP5 (improved mean state ? tuned in modelling development process ?)</td>
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Bellenger et al. (2013)
El Niño in coupled GCMs - frequency

Niño3 SSTA spectra

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

Courtesy K. AchutaRao

Bellenger et al. 2013
Mean equatorial SST and zonal wind structure in CMIP models

- Cold tongue extends too far west, opens the warm pool
- Zonal wind too strong in west Pacific
- CMIP5 shows improvement in west (30% reduction in cold tongue error)

Bellenger et al. (2013), Lee et al. (2013)
El Niño in coupled GCMs - seasonality

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

Bellenger et al. 2013
ENSO in a warming climate

Still no model agreement on mean amplitude change in future (IPCC AR5)
Extreme El Niños have the largest impact and distinctive SST gradients signature


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Still no model agreement on mean amplitude change in future (IPCC AR5)
Extreme El Niños have the largest impact and have distinctive SST gradients signature

**Observations (1979-2010)**

- Extreme El Niño, 1979-2010
- Moderate El Niño, 1979-2010

**CMIP3 + CMIP5 models**

- Extreme El Niño, 1891-1990
- Moderate El Niño, 1891-1990

**SST Anomaly**

- Doubling of occurrence of extremes (RCP8.5)

- 20th C = 17%
- 21st C = 38%

*Cai et al. Nature CC (2014)*

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ENSO extremes increase in a warming climate

Projected surface warming over the eastern equatorial Pacific occurs faster than the surrounding ocean waters

Reduced meridional gradient of SST

More occurrences of atmospheric convection in the eastern equatorial region

Increased occurrence of extreme El Niño


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21st C = 38 % !!!
Process-based evaluation: key role of atmosphere during ENSO

Dominant role of AGCM in coupled AOGCMs


The Southern Oscillation is an atmosphere-only mode


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

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

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

Mean advection and upwelling (damping)

Negative heat flux feedback: $\alpha$ (SHF, LHF)

Dynamical positive Bjerknes feedback: $\mu$

Zonal advection feedback

Ekman pumping feedback

Thermocline feedback

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

Linear stability analysis of recharged oscillator SST equation (Jin et al. 2006, Kim et al. 2010)
Atmosphere feedbacks in CMIP3/CMIP5

Models underestimate both $\mu$ and $\alpha$ (error compensation)

- Shortwave feedback $\alpha_{SW}$ main source of errors and diversity (sign change !)
- Errors in cloud response to dynamics and (low) cloud properties
- No clear evolution from CMIP3 to CMIP5

Bellenger et al. CD (2013), based on Lloyd et al. (2011, 2012)
Source of $\alpha_{SW}$ errors

$\alpha_{SW}$ map (ISCCP)

Convective regime $\alpha_{SW} < 0$
Subsidence regime $\alpha_{SW} > 0$

Both co-exist in Niño3

$\frac{\partial SW}{\partial SST} = \frac{\partial \omega_{500}}{\partial SST} \times \frac{\partial TCC}{\partial \omega_{500}} \times \frac{\partial SW}{\partial TCC} \approx \alpha_{SW}$

- $\alpha_{SW}$ error have their origin in the AGCM: cloud response to dynamics and (low) cloud properties
- When coupled, the dynamics also plays a role (SST drift)

Lloyd et al. (2011, 2012)
Non-linearities in $\alpha_{SW}$ in East Pacific

- Strong $\alpha_{SW}$ non-linearities in observations
- SSTA<0 Cold tongue **subsidence** regime $\alpha_{SW} > 0$
- SSTA>0 Warm pool **convective** regime $\alpha_{SW} < 0$

**Observations (MIX)**

MIX
Non-linearities in $\alpha_{SW}$ in East Pacific

Classify CMIP3+5 models according to $\alpha_{SW}$ non-linearity

SST along the equator

MIX and CONV closer to obs in West Pac
MIX has correct east-west slope
Only MIX models can have large ENSO amplitude (and extreme El Niños)
Better heat flux feedbacks, and ENSO, also come with better mean state

Bellenger et al. 2013

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Performance vs. process-based metrics

First indication of quality of models
No clear relation between ENSO stats and atmosphere feedbacks (need ocean feedbacks)

Bellenger et al. 2013

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ENSO in CMIP5: summary

• Marginal improvement of ENSO statistics in CMIP5 vs. CMIP3
  • better mean state, less poor performing models, groups check ENSO stats

• Using rainfall = F(merid SST grad), scenario shows doubling of number of extreme El Niños in 21st century (RCP8.5)

• Poor modelling of ENSO feedbacks suggest that “improvements” in ENSO often result from error compensation
  • Little change from CMIP3 to CMIP5

• Large 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