3. ENSO in the Mid Holocene

Paleo data indicates interannual variability in the tropical Pacific was reduced by ~80% from the modern.

Tudhope et al. 2001
### 3. ENSO in the Mid Holocene

What do climate models say about the early/mid Holocene?

<table>
<thead>
<tr>
<th>Model</th>
<th>Reduction in nino3 variance at 6ka</th>
<th>comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCSM(1999)</td>
<td>none</td>
<td>weak ENSO in present</td>
</tr>
<tr>
<td>FOAM(02)</td>
<td>20%</td>
<td></td>
</tr>
<tr>
<td>CCSM 1.4(02)</td>
<td>20%</td>
<td></td>
</tr>
<tr>
<td>HadCM3(06)</td>
<td>10%</td>
<td></td>
</tr>
<tr>
<td>CAM+RGO</td>
<td>38%</td>
<td>simple ocean with no change in its mean state</td>
</tr>
</tbody>
</table>

Many hypotheses for the reduced variance have been postulated, though few have been tested.
Sea Surface Temperature in CCSM1.4

SST in the mid Holocene is ~1 °C cooler than the modern tropics
More Mean State Changes in CCSM1.4

Changes in each mean field are typical 10% of the climatology

Roberts 2007; Battisti et al 2008
How can we *know* why ENSO changed?

The ENSO mode is the first eigen (Floquet) mode of LIM & LOAM; the first eigenvalue is period and growth rate.*

\*Build linear inverse model (LIM) of the climate model output

Climate Model
How can we *know* why ENSO changed?

- **Climate Model**: Build linear inverse model (LIM) of the climate model output

- **LOAM**: Insert present day mean state from climate model into LOAM
  - The ENSO mode is the first eigen (Floquet) mode of LIM & LOAM; the first eigenvalue is period and growth rate*

- **Force LOAM Stochastically*:** Examine ENSO variance, etc
How can we know why ENSO changed?

Build linear inverse model (LIM) of the climate model output

The ENSO mode is the first eigen (Floquet) mode of LIM & LOAM; the first eigenvalue is period and growth rate*

Insert present day mean state from climate model into LOAM

Force LOAM Stochastically*

Insert mid-Holocene mean state from climate model into LOAM

Examine ENSO variance, etc
How can we *know* why ENSO changed?

**Climate Model**

Build linear inverse model (LIM) of the climate model output

**LOAM**

The ENSO mode is the first eigen (Floquet) mode of LIM & LOAM; the first eigenvalue is period and growth rate*

Insert present day mean state from climate model into LOAM

Force LOAM Stochastically*

Insert mid-Holocene mean state from climate model into LOAM

Examine ENSO variance, etc

Insert partial mean state changes to identify impacts on ENSO
The ENSO Mode in CCSM

The ENSO Mode in the CCSM is obtained by fitting a linear inverse model to the simulated SST anomalies, and taking the leading eigenmode of the dynamical operator (see, eg, Penland and Sardeshmukh 1995)

<table>
<thead>
<tr>
<th></th>
<th>var(nino3) / var(nino3 pres)</th>
<th>period (years)</th>
<th>decay (year⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCSM(pres)</td>
<td>1.00</td>
<td>3.27</td>
<td>0.55</td>
</tr>
<tr>
<td>CCSM(8.5ka)</td>
<td>0.81</td>
<td>3.78</td>
<td>0.56</td>
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</table>
Does LOAM capture the mid Holocene ENSO changes in CCSM?

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<td>1.00</td>
<td>2.15</td>
<td>0.70</td>
</tr>
<tr>
<td>LOAM(8.5ka)</td>
<td>\textbf{0.79}</td>
<td>\textbf{2.92}</td>
<td>\textbf{0.74}</td>
</tr>
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</table>

LOAM captures the increase in the period of the ENSO, and (not shown) the structural changes seen in the early Holocene CCSM simulation.
Is the ocean important?

Yes. Changes in the ocean mean states along *enhance* the variance of ENSO (stronger currents, SST gradients, upwelling)

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<td><strong>0.74</strong></td>
</tr>
<tr>
<td>LOAM(pres) + ocn</td>
<td>1.35</td>
<td><strong>2.87</strong></td>
<td>0.81</td>
</tr>
</tbody>
</table>
The ENSO Mode

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<td>0.79</td>
<td>2.92</td>
<td>0.74</td>
</tr>
<tr>
<td>LOAM(pres) + atm</td>
<td>0.51</td>
<td>2.27</td>
<td>0.63</td>
</tr>
<tr>
<td>LOAM(pres) + $T_{atm}$</td>
<td>0.49</td>
<td>2.30</td>
<td>0.62</td>
</tr>
<tr>
<td>LOAM(pres) + $u_{atm}$</td>
<td>1.12</td>
<td>2.11</td>
<td>0.71</td>
</tr>
</tbody>
</table>

Yes. Colder mean state SST renders the atmosphere less responsive to SST anomalies (reduced Bjerknes feedback).
ENSO in the mid Holocene (in the CCSM): a summary

• LOAM with CCSM1.4 mean states captures the CCSM1.4 ENSO characteristics

• ENSO is reduced in mid Holocene mainly because the ENSO mode is more stable:
  – Lower climatological SST renders the atmosphere less responsive to SST anomalies (reduced Bjerkness feedback)
  – Ocean mean state changes lengthen the period of the mode and shift its peak to the east Pacific

• No change in the amplitude of stochastic forcing is necessary to explain the reduction in ENSO variance

Roberts 2007; Battisti et al 2008
<table>
<thead>
<tr>
<th>Model</th>
<th>Reduction</th>
<th>Hypothesis</th>
<th>Actual Reason</th>
</tr>
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<tbody>
<tr>
<td>FOAM</td>
<td>20%</td>
<td>Increase stability of ENSO mode due to weakened thermocline</td>
<td>Unknown; poor ENSO physics in control</td>
</tr>
<tr>
<td>(Liu et al 2000)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CAM+RGO</td>
<td>38%</td>
<td>Increase stability of ENSO mode due to weakened thermocline</td>
<td>Reduction in the amplitude of stochastic forcing</td>
</tr>
<tr>
<td>(Chiang et al 2008)</td>
<td></td>
<td></td>
<td>(Chiang et al 2008)</td>
</tr>
<tr>
<td>Zebiak/Cane</td>
<td>Smaller instability in the ENSO mode due to enhanced Trades and</td>
<td>Decreased instability in the ENSO mode due to</td>
<td></td>
</tr>
<tr>
<td>(Clement et al 2000)</td>
<td></td>
<td>changed seasonality</td>
<td>enhanced Trades and &amp; changed seasonality</td>
</tr>
<tr>
<td>CCSM1.4</td>
<td>20%</td>
<td>Ditto</td>
<td>Increase stability of ENSO mode due stabilized</td>
</tr>
<tr>
<td>(Otto-Bliesner et al 2003)</td>
<td></td>
<td></td>
<td>atmosphere (Battisti et al 2008)</td>
</tr>
<tr>
<td>HADCM3</td>
<td>12%</td>
<td>Ditto</td>
<td>Increase stability of ENSO</td>
</tr>
<tr>
<td>(Brown et al 2006)</td>
<td></td>
<td></td>
<td>mode due to weaker thermocline (Battisti et al 2008)</td>
</tr>
</tbody>
</table>
ENSO in the Last Glacial Maximum (in the CCSM): a summary

• Observations suggest the variance in ENSO was enhance by ~25% or more compared to that in the present day (Tudhope et al 2001)
• In the CCSM, ENSO variance increases by 14%
• LOAM with mean states from the LGM CCSM reproduces the changes in the stability and temporal and spatial structure of ENSO seen in the CCSM
• ENSO variance is enhanced in the LGM compared because the ENSO mode is less stable:
  – Lower climatological SST renders the atmosphere less responsive to SST anomalies (reduced Bjerkness feedback), but …
  – The ENSO mode is much less stable because of changes in the mean state of the ocean (sharper and shallower thermocline)
  – (There is no change in the amplitude of stochastic forcing)
4. ENSO in the future: the impact of Global Warming

First EOF of tropical Pacific SST (all AR4 IPCC models)
Models w/ realistic ENSO space/time variability

Why? The leading candidate is unrealistic mean states in the tropical Pacific:

- ENSO is extremely sensitive to subtle changes in the structure of the climatology (Zebiak 1987 ... Neelin et al 1988 ... Fedorov and Philander 2001 ...)

- inadequate representation of the processes acting in the ENSO mode (e.g., ocean mixing; atmospheric convection; horizontal resolution)

Little progress after two decades of working on the models.

Only one model used in the last IPCC assessment simulated ENSO variability that did not violate the robust observational constraints.

Collins et al. 2005
4. ENSO in the future: the impact of Global Warming

A pathway forward: living with biases in the tropical Pacific climatology

Approximate the future mean state
Augment the observed (1970-2008) mean state with the mean state changes (2100 - current)

Calculate the change in the stochastic forcing of ENSO (SFM)

Insert into LOAM project the ENSO (and other) mode under the future mean state

Force LOAM Stochastically*

Estimate the impact of ENSO in 2100 perform a TOGA integration of the atmospheric portion of the AR4 model

Work in progress, Vimont and Battisti
5. Summary

- ENSO is the leading pattern of interannual climate variability:
  - due to coupling between atmosphere & ocean in the tropical Pacific;
  - atmosphere and ocean teleconnections broadcast climate anomalies on a global scale;

- The theory of ENSO is well established:
  - ENSO is the leading eigenmode of coupled atmos/ocean system in the tropical Pacific; features Bjerknes Feedbacks and basin-scale dynamical adjustment of the ocean

- The ENSO mode is consistent with the ‘robust observations’:
  - Spatial structure of composite anomalies in SST, precipitation, winds, etc.; processes responsible for evolving the SST anomalies; a concentration of variance at 3-7 years; peaking at the end of the calendar; etc.
  - Theory is also consistent with weak (no) ENSO-like variability in the Atlantic (Indian) Ocean basins.
5. Summary

• ENSO theory/mode suggests ENSO is predicable up to two years in advance
  – provided the foundation for designing the observing system that is now in place to initialize the forecast models.

• The amplitude, spatial and temporal structure of ENSO is highly dependant on:
  – The mean state of the tropical Pacific
  – The structure and amplitude of the noise forcing

• The Linear Atmosphere/Ocean model is an effective tool for evaluating the physics of ENSO
  – In the modern day climate
  – In kitchen sink climate models
5. Summary

• The amplitude of ENSO was greatly reduced in the mid Holocene. Why?
  – Several climate models reduce ENSO, and analysis using LOAM shows that they do so for different reasons

• We don’t yet know how ENSO (or its teleconnected impacts) will change in the future due to greenhouse warming
  – only one IPCC-class model has a realistic ENSO due to biases in the climatological mean state

• Combining the future mean states projected by the AR4 models with the linearized atmosphere/ocean model (LOAM) is a plausible way forward