Proxies and processors: Integrating palaeoclimate archives with climate system models

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Overview

• Data-model integration

• Example 1: El Niño over the past 8,000 years

• Example 2: Climate of the past 2,000 years

• Example 3: Regime classification

• Conclusions
Data-model integration
Palmyra Island: El Niño over the past millennium

Cobb et al. (2003), Nature
But what about the future?

Guilyardi et al. (2009), BAMS
Integrating the data and the models

- Data-model integration is a two-way process
- The data constrains the model simulations
- The models provide the dynamical interpretation of the data
Example 1:
El Niño over the past 8,000 years
What is El Niño?

- El Niño–Southern Oscillation (ENSO) is the dominant mode of internal variability within the coupled atmosphere-ocean system.
- Irregular period of $\sim 2–7$ years.
- Average state of the system involves strong easterly trade winds pushing warm water to the east.
- In an El Niño event, these winds slacken and the warm water flows eastwards.
- Increased rainfall in the eastern Pacific, reduced rainfall in the west.
El Niño has changed over the Holocene ...

- ENSO variability has increased over the past 8,000 years
- El Niño events have increased in frequency and magnitude
- Evidence of a peak in ENSO variability at 2–1 ka BP
- Strong variability on centennial and millennial timescales
- These changes provide an opportunity to learn more about ENSO dynamics

Moy et al. (2002), Nature
Data: the coral record
El Niño centres of action

Normal years

El Niño years

CMAP Estimated Precipitation (mm/day)

IGOSS SST anomaly (°C)
Severe El Niño events at $\sim 2$ ka?

McGregor and Gagan (2004), GRL
Extending the record: Microatolls from Kiritimati

*Porites* head coral

*Porites* microatoll

Growth

Top of coral

Growth

10 cm
Modern coral $\delta^{18}O$ from Kiritimati calibrated against satellite sea surface temperature

McGregor et al. (in prep.), Geochimica et Cosmochimica Acta
The Holocene $\delta^{18}$O record from Kiritimati

Woodroffe et al. (2003), *GRL*
Standard deviation of Kiritimati $\delta^{18}$O: a measure of El Niño variability
Model: CSIRO Mk3L

• Low-resolution coupled general circulation model:
  – Atmosphere: $5.6^\circ \times 3.2^\circ$, 18 vertical levels
  – Ocean: $2.8^\circ \times 1.6^\circ$, 21 vertical levels
  – Sea ice: Dynamic-thermodynamic
  – Land surface: Static vegetation

• Three transient simulations of the past 8,000 years

• Orbital forcing only

Pre-industrial control simulation: PC1 of monthly SST anomalies
Simulated changes in El Niño variability

Amplitude of SST variability in Nino 3.4 region (ENSO band)

Phipps and McGregor (in prep.), GRL
El Niño variability: data-model comparison

Amplitude of SST variability in Nino 3.4 region (ENSO band)

Phipps and McGregor (in prep.), GRL
NH summers were warmer at 8 ka ...
... which enhanced the Asian summer monsoon ...

June–July–August mean sea level pressure, 8 ka minus 0 ka BP (hPa)

... and made it harder for El Niño events to develop

El Niño variability: data-model comparison

Amplitude of SST variability in Nino 3.4 region (ENSO band)

Phipps and McGregor (in prep.), GRL
Challenge: Low-frequency variability

Amplitude of SST variability in Nino 3.4 region (ENSO band)

Phipps and McGregor (in prep.), GRL
Example 2:
Climate of the past 2,000 years
Last 2,000 years: Boundary conditions well known

MacFarling Meure et al. (2006), GRL
Last 2,000 years: Abundance of proxy data

Mann et al. (2008), *PNAS*
NH surface air temperature

Mann et al. (2008), *PNAS*
Radiative forcing: GHGs
Radiative forcing: GHGs+solar

![Radiative forcing graph](image-url)
Radiative forcing: GHGs + solar + volcanic

The chart shows a timeline from 0 to 2000 calendar years, with radiative forcing measured in Wm$^{-2}$. The graph includes four lines representing greenhouse gases, solar irradiance, and volcanic aerosols. The data indicates significant fluctuations over time, particularly around the year 1600 with a large negative forcing event.
Transient simulations of the past 2,000 years

• CSIRO Mk3L climate system model v1.2

• Forcings:
  – Changes in the Earth’s orbital geometry
  – Changes in atmospheric CO₂, CH₄ and N₂O concentrations (MacFarling Meure et al., 2006)
  – Changes in solar irradiance (Steinhilber et al., 2009)
  – Volcanic aerosols (Gao et al., 2008)

• 3×3 transient simulations of the past 2,000 years:
  – Orbital + greenhouse gases
  – Orbital + greenhouse gases + solar
  – Orbital + greenhouse gases + solar + volcanic
NH surface air temperature: GHGs
NH surface air temperature: GHGs+solar
NH surface air temperature: all forcings
SH surface air temperature: all forcings

Temperature relative to 1961–1990 mean (°C)

Calendar year

SH surface air temperature
Rainfall in SW Australia: all forcings
Rainfall in the Mallee: all forcings
El Niño: all forcings

Amplitude of SST variability in Nino 3.4 region (ENSO band)
Example 3:

Regime classification
Kidson weather types

Ackerley et al. (in prep.), Clim. Past
DJF MSLP anomalies (6ka minus 0ka, hPa)

Ackerley et al. (in prep.), Clim. Past
Mean SAT anomaly (6ka minus 0ka, °C)

Ackerley et al. (in prep.), Clim. Past
Conclusions

- The integration of palaeoclimate archives with climate models can provide new insights into the nature of the climate system.

- Proxy data can be used to constrain and evaluate the models, while the models provide a dynamical framework within which to understand past changes.

- However, data-model integration presents challenges e.g. metrics, baselines, low-frequency variability.

- Regime classification is a promising tool for data-model integration, and should be applied to the Australian region.