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Projecting the response of climate to orbital variations in the Pliocene using an emulator

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Introduction

The mid-Pliocene occurred between 3.264 and 3.025 Ma, and was characterized by several periods of relatively warm climatic conditions (see Fig. 1 for example). It has been researched extensively, in part due to the availability of proxy data, allowing for data/climate model comparisons, but also because it is thought that it can give insights into the characteristics of future climate, due to the fact that periods of the mid-Pliocene were characterised by CO_2 levels similar to present. However, it is now being realised that the orbital forcing during the mid-Pliocene is also important for properly understanding its relevance to future climate. Computational resource limitations associated with running General Circulation Model (GCM) experiments often restrict the number of simulations that can realistically be carried out, inhibiting the study of the long-term evolution of climate on orbital timescales (>10s kyr).

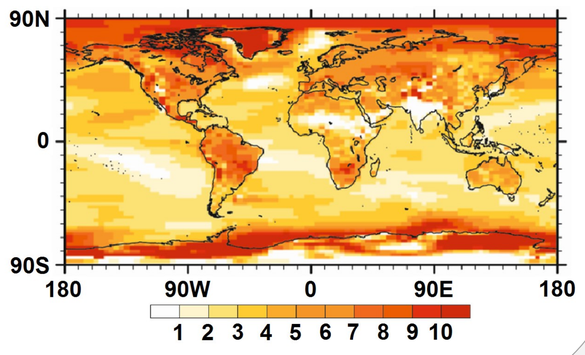

Fig. 1. Mean annual Pliocene surface air temperature anomaly (°C) for interglacial Marine Isotope Stage K1 (3.06 Ma) compared to a pre-industrial control, predicted using HadCM3. From Prescott et al. (2014)[1].

Objectives

- Develop an emulator that can project the climate resulting from any combination of atmospheric CO_2 and orbital conditions.
- Use it to project the evolution of climate over the period 3.04 to 3.08 Ma (1 kyr intervals), which includes the Marine Isotope Stage (MIS) K1 interglacial period (3.06 Ma).
- Compare the model results to proxy data for the same period.

Emulator

Experimental Design

- Used the HadCM3 general circulation model[2], coupled with the MOSES2.1 land surface scheme and the TRIFFID vegetation scheme[3].
- Ensemble of 40 snapshot simulations (Fig. 2).
  - Varying atmospheric CO_2 and orbital parameters (eccentricity, obliquity, longitude of perihelion).
  - Constant modern-day ice sheets.
- Simulations run for 500 years, with climatological means calculated from the final 50 years.

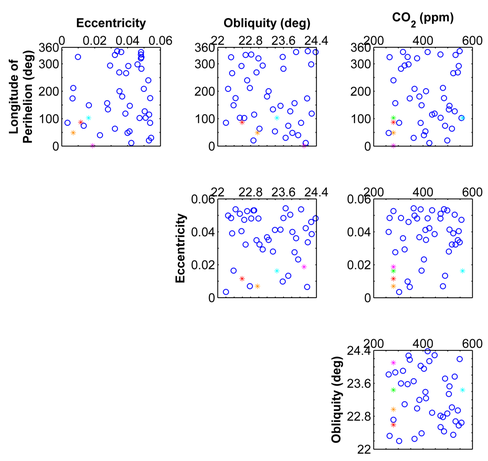

Fig. 2. Distribution of 40 simulations over 4-D parameter space, sampling orbital parameters and atmospheric CO_2.

Emulator

Description

- **An emulator is a fast statistical model calibrated on the output from the simulator (HadCM3).**
- **Derived from a small number of model runs filling the entire 4-D input space (CO_2, eccentricity, obliquity, longitude of perihelion).**
- **Role is to predict the simulator outputs from untried experiments without having to actually run them.**
- Follows a Gaussian process framework[4].
- The output of the simulator ($f(x)$) is fully specified by a combination of:
  - A mean function, which gives the prior expectation of $f(x)$ for any input of x.
  - A covariance function, which gives the prior covariance between $f(x)$ and $f(x')$ for any inputs of x and x'.
- Data used to build the emulator:
  - Parameter values of 40 member ensemble (x).
  - Output data from HadCM3 for ensemble (mean annual 1.5 m SAT).

Evaluation

- To validate the emulator, it was used to reproduce mean annual 1.5 m SAT for 2 out-of-sample time periods, one with pre-industrial orbital and CO_2 conditions, the other for conditions at -6 kyr.
- The emulator is able to reproduce the global mean temperature index to within ±3% of the modelled values (Table 1).
- SAT anomalies for individual grid-boxes are less than ±3°C (Fig. 3).

Experiment	Global mean temperature index (°C)		
	Modelled	Emulated	Anomaly
Pre-industrial	4.06	4.12	+0.06
-6 kyr	4.27	4.38	+0.11

Table 1. Global mean temperature index (°C) for pre-industrial and -6 kyr experiments.

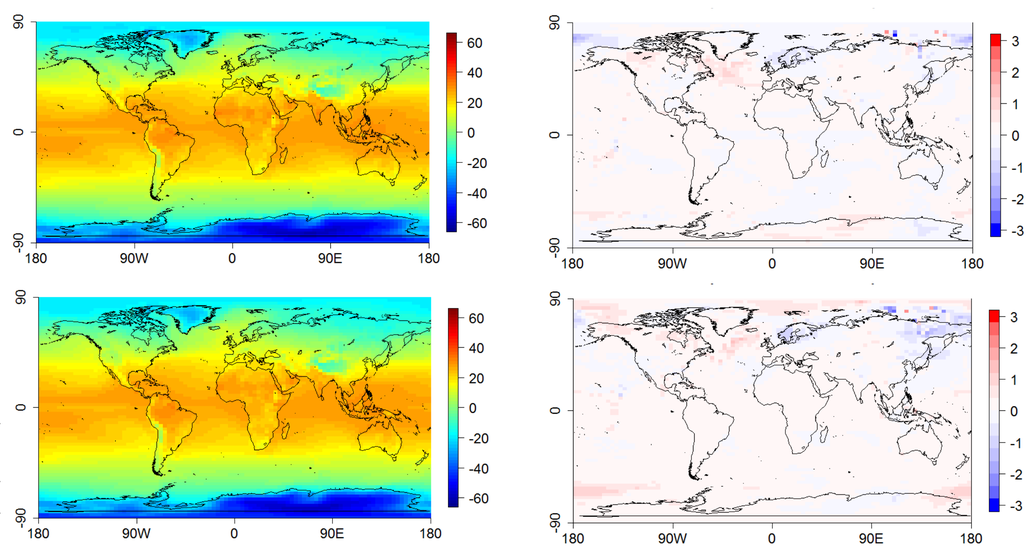

Fig. 3. Mean annual 1.5 m SAT (°C) for pre-industrial (top panel) and -6 kyr (bottom panel) orbital and atmospheric CO_2 conditions. Left panel: SAT predicted using HadCM3 model. Right panel: SAT anomaly predicted using the emulator (emulated SAT minus modelled SAT).

Application to the Pliocene

- The emulator was used to simulate climate at 1 kyr intervals over the period 3.08 to 3.04 Ma for Ocean Drilling Program (ODP) sites 999 and 1313.
- The major features of surface warming at 3.06 Ma predicted using the emulator (Fig. 4) are similar to those modelled using HadCM3 by Prescott et al. (2014)[1].
- A model-data comparison was also performed, comparing the evolution of emulated SAT to sea surface temperature (SST) estimated from paleo proxy data (Mg/Ca and alkenone) for the same period (Fig. 5).
- The differences in the temperature estimates may be due to uncertainties associated with either the modelling process or with the proxy data reconstructions, which are subject to errors of up to several degrees.

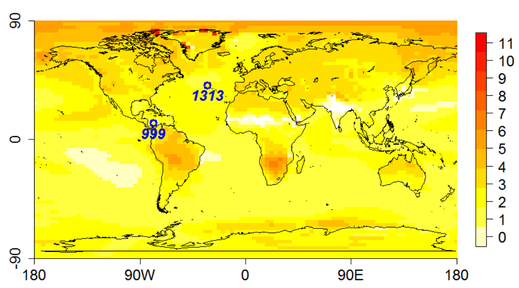

Fig. 4. Mean annual Pliocene SAT anomaly (°C) for interglacial Marine Isotope Stage K1 (3.06 Ma) compared to a pre-industrial control, predicted using the emulator. Also shown are the locations of ODP sites 999 (12.74°N, 78.74°W) and 1313 (41.00°N, 32.57°W).

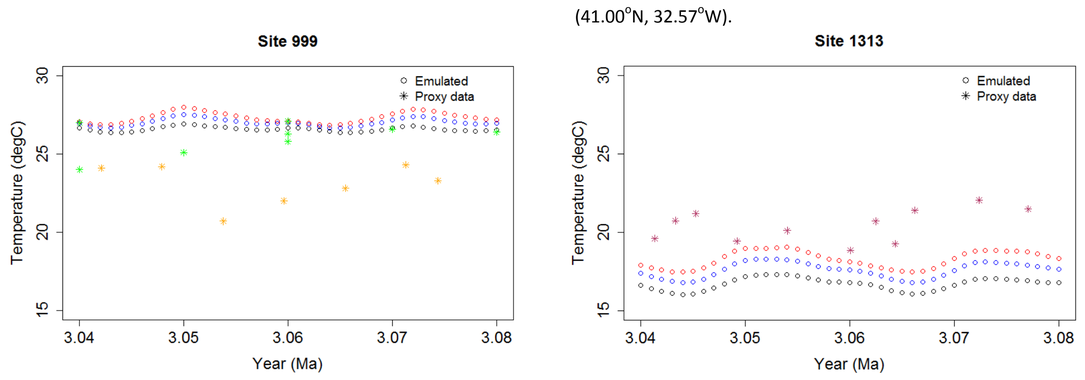

Fig. 5. Mean annual SAT (°C) at 2 ODP sites, predicted using the emulator (o) and proxy data (*). Emulated SAT is for constant atmospheric CO_2 values of 280 (black), 250 (blue) and 400 ppm (red). Left panel: Site 999. SST proxy data is Mg/Ca data of O'Brien et al. (2014)[5] (green), and Groeneveld (2005)[6] (orange). Right panel: Site 1313. SST proxy data is alkenone data of Dowsett and Herbert (unpublished)[7] (maroon).

Conclusions + Future Work

- The emulator is a statistical model calibrated on the output from HadCM3.
- May provide a powerful tool for rapidly predicting the long-term evolution of climate, an otherwise impossible task using conventional climate simulation.
- Possible applications to both past and future climate.
- Future work could include optimising the emulator further, emulating other periods in the Pliocene, and/or performing a more detailed model-data comparison.

References

[1] Prescott et al. (2014) EARTH PLANET SC LETT
[2] Gordon et al. (2000) CLIM DYNAM
[3] Cox et al. (2000) NATURE
[4] Oakley + O'Hagan (2004) BIOMETRIKA
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[6] Groeneveld (2005) PhD Thesis
[7] Dowsett + Herbert (unpublished)

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