Investigating the role of orbital forcing on East Asian monsoons using a statistical emulator

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1. Introduction

Classic paleoclimate records that span several hundreds of thousands of years (kyr), such as the Chinese speleothem records, provide us with an exciting test of our understanding of the Earth system. In particular, they allow us to explore the relative importance of orbital vs. CO_2 vs ice sheet forcings, and the mechanisms by which the Earth system translates these forcings into a proxy response. However, this represents a considerable challenge to traditional modelling methods, because our most comprehensive and complex models are too inefficient to represent these timescales.

A possible solution is an emulator, which is a statistical model calibrated on the output from a more complex model (here, a general circulation model). It can act as a useful tool for rapidly simulating the long-term evolution of climate, both past and future[1], due to its relatively low computational cost.

Here, an emulator is developed that can project the climate resulting from any combination of atmospheric CO_2 concentrations, orbital conditions and global ice volumes (within the sample limits). It is used to explore the sensitivity of the East Asian (EA) monsoon to these climate forcings during the middle to late Pleistocene (-300 to 0 kyr after present (AP)). The emulated climate reconstructions are compared to $\delta^{18}O$ data from speleothem records from China (see Fig. 1 for location).

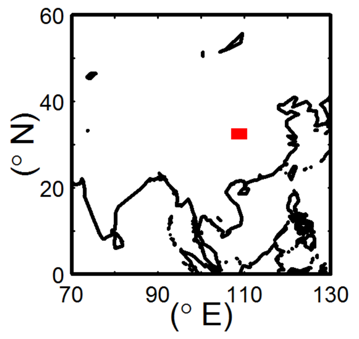


Fig. 1. Map of South-East Asia.

2. Emulator

- Calibrated on a relatively small number of simulations run using the HadCM3 GCM[2], which sample the 5-D input space:
  - Two ensembles of 60 snapshot simulations (Fig. 2) with varying atmospheric CO_2 and orbital configurations.
    - One ensemble had constant pre-industrial ice sheets, the other had reduced (PRISM4 Pliocene[3]) ice sheets.
  - One ensemble of 62 snapshots covering the last 120 kyr, with varying CO_2, orbit and ice sheet extent[4].
- Role is to predict the GCM outputs from untried experiments without having to actually run them.
- The output of the simulator ($f(\boldsymbol{x})$) is modelled by a Gaussian process, whose prior is fully specified by a combination of:
  - A mean function, which gives the expectation of $f(\boldsymbol{x})$ for any input of $\boldsymbol{x}$.
  - A covariance function, which gives the covariance between $f(\boldsymbol{x})$ and $f(\boldsymbol{x'})$ for any inputs of $\boldsymbol{x}$ and $\boldsymbol{x'}$.

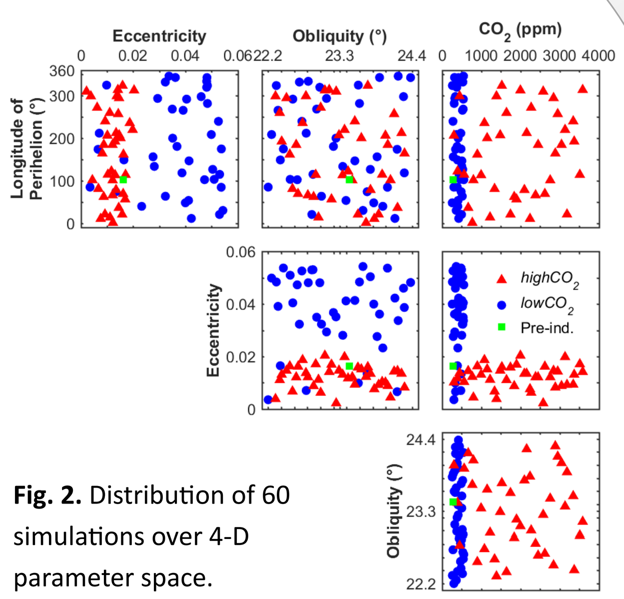


Fig. 2. Distribution of 60 simulations over 4-D parameter space.

Evaluation

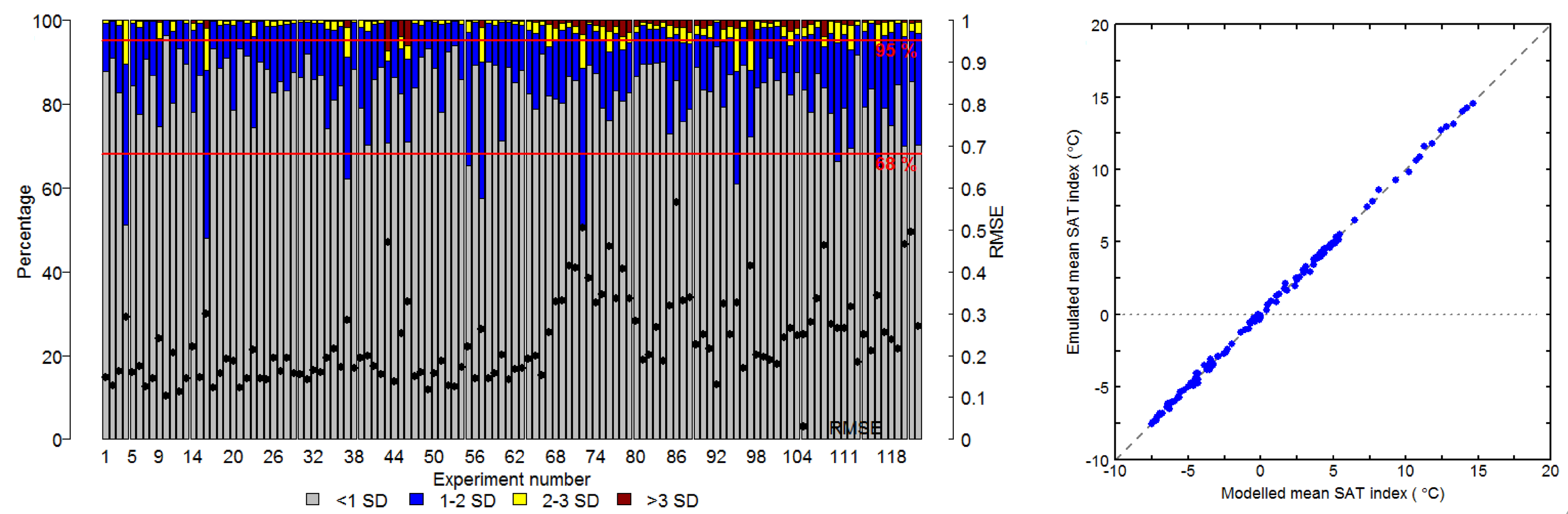


Fig. 3. Evaluation of the performance of the glacial emulator using leave-one-out cross-validation (reproducing surface air temperature). In the left panel, bars give the % of grid boxes in each left-out experiment predicted within different standard deviation (SD) bands.

For further information about the theoretical basis of this emulator please see: Lord *et al.* (2017) *Climate of the Past*. DOI: 10.5194/cp-13-1539-2017.

3. Results

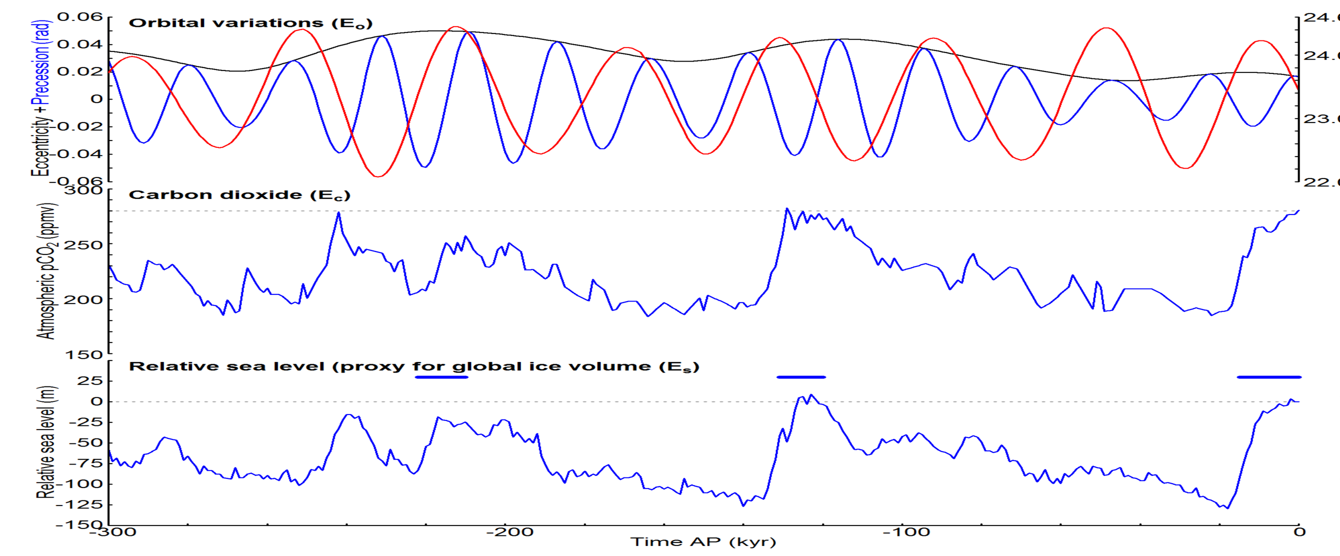


Fig. 4. Climate forcings applied to the emulator.

- An ensemble of experiments (denoted **E**) was performed by forcing the emulator with variable orbit[5] (**o**), atmospheric CO_2[6] (**c**) and relative sea level[7] (**s**) applicable for the last 300 kyr (Fig. 4).
- To assess the sensitivity of these variables, different combinations of these forcings were applied, e.g. orbital forcing only ($\mathbf{E_o}$).
- When not applied, forcings were kept constant at their pre-industrial values.
- Precipitation and surface air temperature changes at a location in central China (Fig. 1) were emulated (Fig. 5), and compared to $\delta^{18}O$ data from speleothem records (Fig. 6).

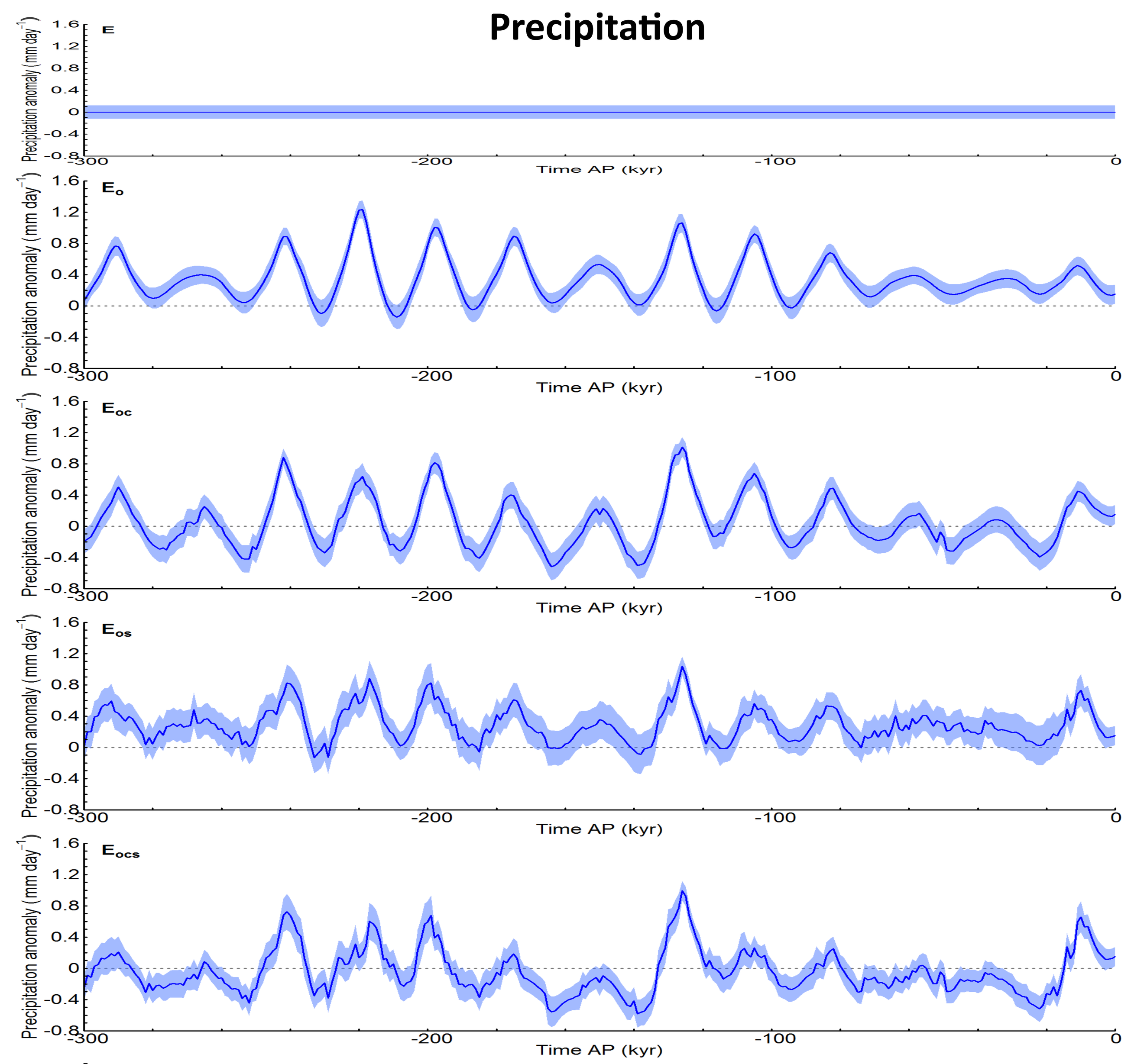
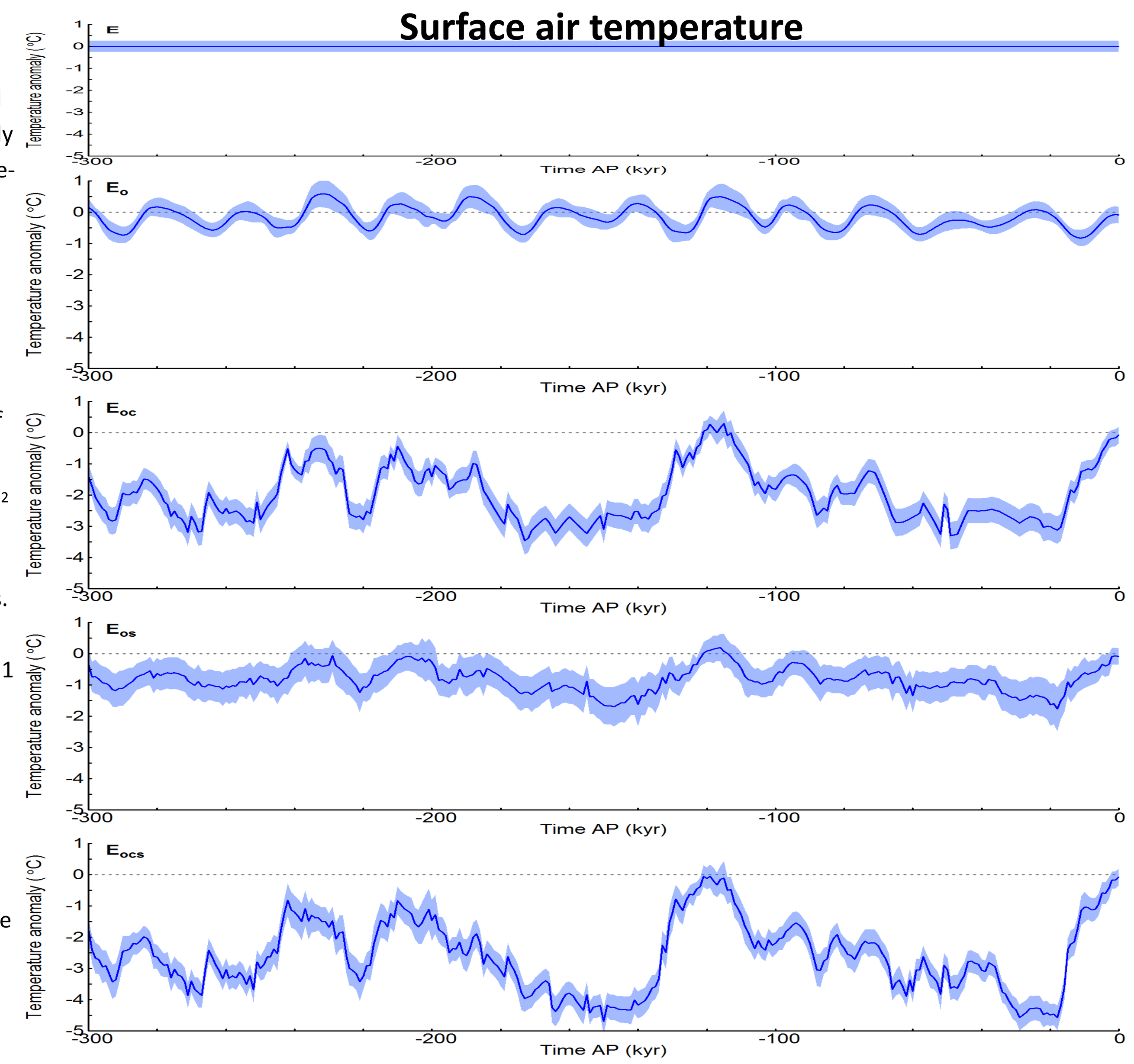


Fig. 5. Emulated climate (anomaly compared to pre-industrial) over the last 300 kyr at the central China site, in response to different combinations of orbital (**o**), atmospheric CO_2 (**c**) and relative sea level (**s**) forcings. Climate is modelled every 1 kyr. Error bands represent the emulated grid box posterior variance (1 SD). Experiment $\mathbf{E_{ocs}}$ includes all three forcings.



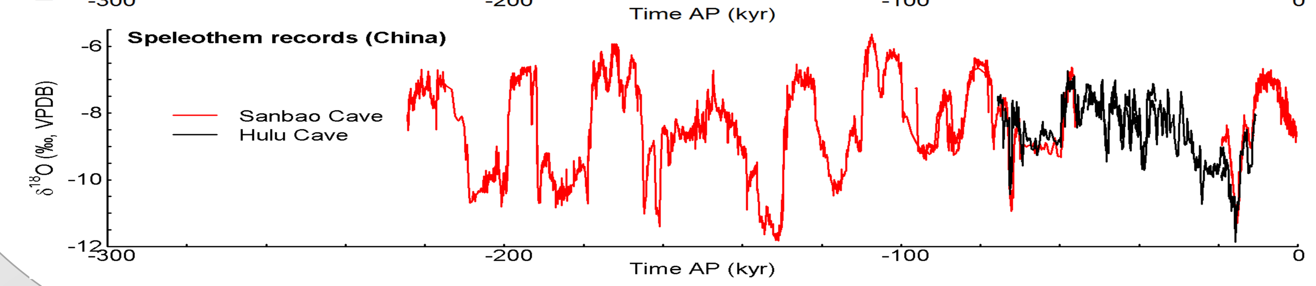


Fig. 6. $\delta^{18}O$ records from the Sanbao[8] and Hulu[9] caves in China covering the last 224 kyr. For comparison, the Hulu record is plotted 1.6‰ more negative to account for the higher Hulu values[8].

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References

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4. Conclusions

- The modelled precipitation has a much better agreement than modelled temperature with speleothem $\delta^{18}O$.
- The emulated precipitation with all forcings is able to reproduce the $\delta^{18}O$ record well, capturing the timing and duration of the maxima and minima in $\delta^{18}O$.
- However, the relative intensity of the maxima and minima are not always reproduced, for example the maxima in $\delta^{18}O$ around -160 to -180 kyr AP is relatively weak in our model simulation.
- CO_2 has relatively little effect on the modelled precipitation, ice sheets and sea level provide some sub-orbital variability, but the majority of the modelled response is due to the orbital forcing.
- This volume of sensitivity studies could only be carried out using an emulator, given the long timescales being considered, making it a powerful tool.