# Insights into the paleoclimate of the PETM from an ensemble of EMIC simulations

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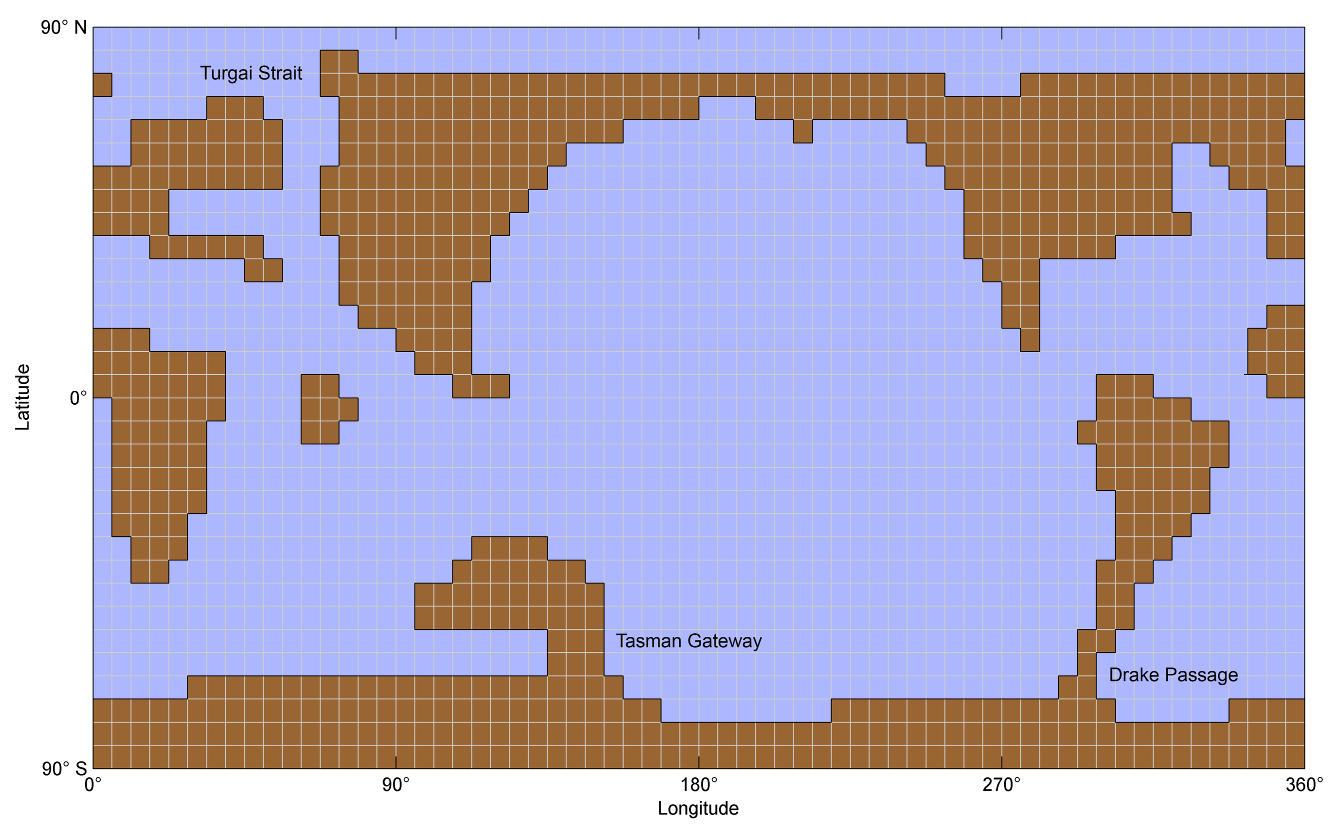
## 1. Modelling the Eocene

In the early Eocene, several episodes of global warming were associated with pulses of $CO_2$ into the atmosphere, with periods of rapid warming and variation in carbon cycle processes. In particular, during the Palaeocene-Eocene Thermal Maximum (PETM) of 55.8 Ma, $CO_2$ levels varied considerably, peaking at up to several times modern values, and with emission rates of similar magnitude to the present day burning of fossil fuels (Kennett and Stott, 1991). Studying the PETM may therefore provide valuable insights into future global warming, and acidification and de-oxygenation of the oceans.

General Circulation Models (GCMs) can provide climate simulations with high resolution in space and time, but require very powerful computers and long periods of time for each run. In simpler models, known as Earth system Models of Intermediate Complexity (EMICs), some of the complex dynamics of the atmosphere and oceans have been parameterized, allowing EMICs to run much faster than GCMs (Weber, 2010). The speed of EMICs permits an "ensemble" of model simulations to be run, in which forcing parameters are varied within limits encompassing our understanding of the climate conditions, allowing statistical analysis of results to be carried out.




## 2. PLASIM-GENIE and GENIE-1

PLASIM-GENIE is an EMIC which includes 3D spectral atmospheric dynamics, but does not include the ocean biochemistry modelling of GENIE-1 (Ridgwell et al., 2007). We have applied PLASIM-GENIE with an Eocene paleogeography at a resolution of 64 x 32 x 32 (lon x lat x ocean depth), T21 atmosphere with 10 vertical levels, and equally spaced latitude cells to provide increased resolution at high latitudes. Major continental configurations and ocean connections are incorporated, with the shallow Turgai Strait linking the Arctic to the Tethys (Akhmetiev et al., 2012), but with neither the Tasman Gateway (Exon et al., 2004) nor the Drake Passage (Barker and Burrell, 1977) yet open.

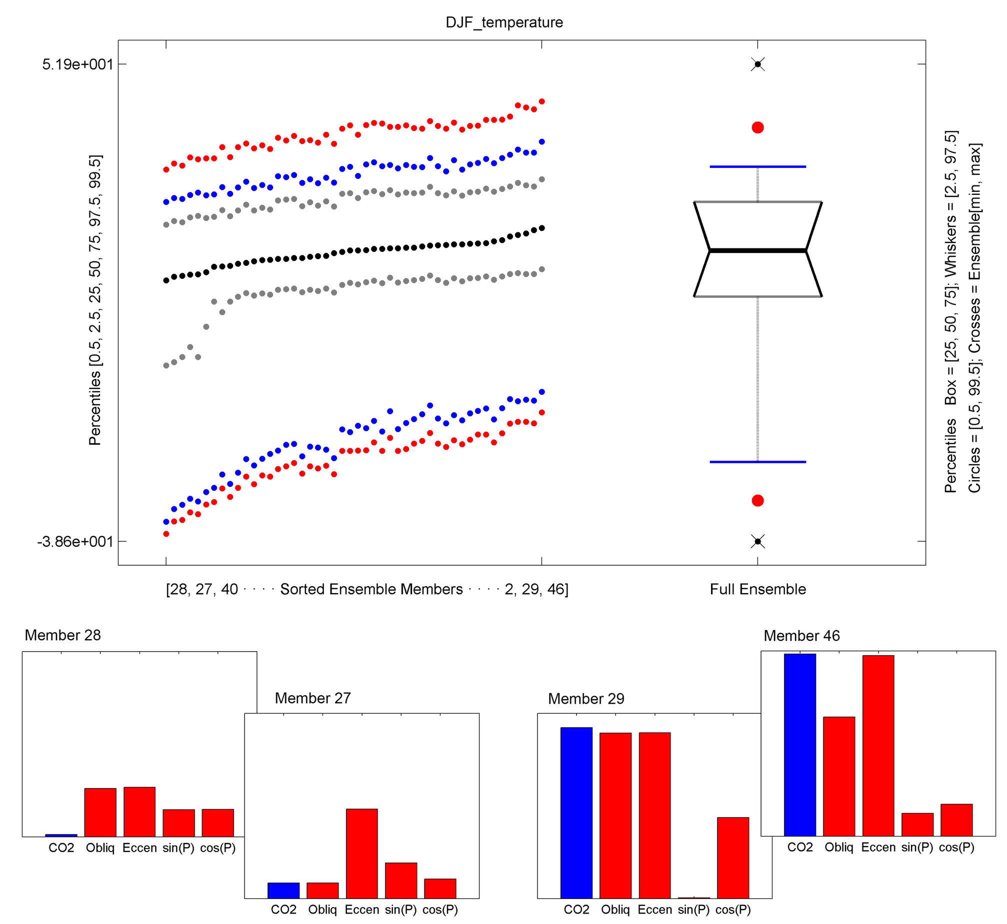
We configured a 50-member ensemble of PLASIM-GENIE model configurations with a Latin hypercube of four forcing parameters, comprising $CO_2$, and the orbital parameters obliquity, eccentricity and precession, to be run to a quasi-equilibrium state in 1000 years. Output fields are saved as 100 year averages over each grid cell.

| Parameter | Min | Max |
|---|---|---|
| $CO_2$ (ppm) | 280 | 1150 |
| Obliquity (°) | 22 | 24.5 |
| Eccentricity (-) | 0 | 0.06 |
| Precession (°) | 0 | 360 |

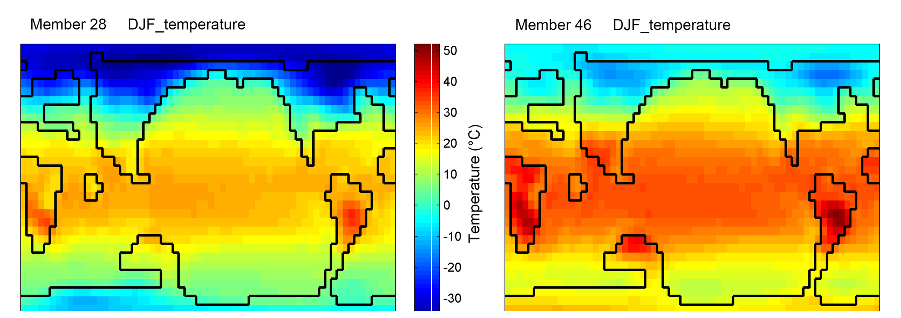
Two of the model runs failed due to hardware problems. The results of the remaining 48 ensemble members allow the relative importance of the $CO_2$ and orbital forcing parameters on the Eocene climate to be investigated, and also provide boundary conditions for subsequent modelling with GENIE-1, which will include nutrient inputs ($PO_4$) as a varying forcing parameter (Monteiro et al., 2012).

## 3. Model Results

Output for each ensemble member comprises a large set of 2D and 3D field values. We illustrate our approach to investigation of the relationships between forcing parameters and output fields, with a presentation of the results for a single 2D field, DJF_temperature, the 100 year average of the mean surface air temperature for December, January and February, i.e. northern winter, for each grid cell.

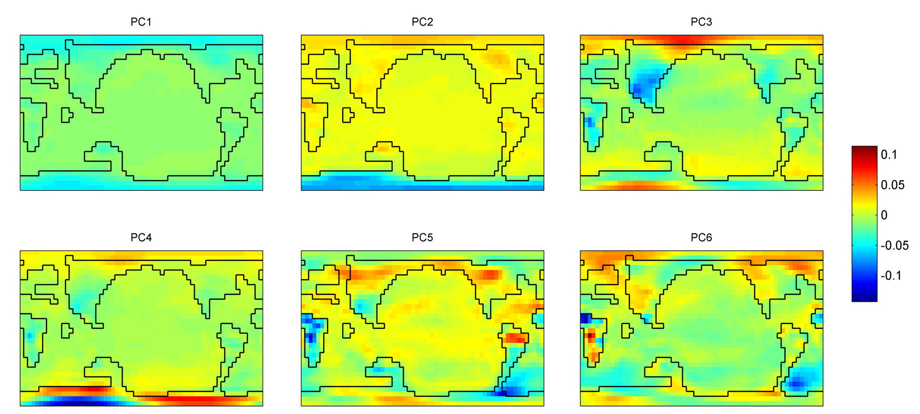



Percentiles of DJF_temperature values for each ensemble member, plotted in ascending median order, together with the normalised forcing factor values for the ensemble members with the lowest and highest values of DJF_temperature, suggest a strong correlation between $CO_2$ and DJF_temperature.



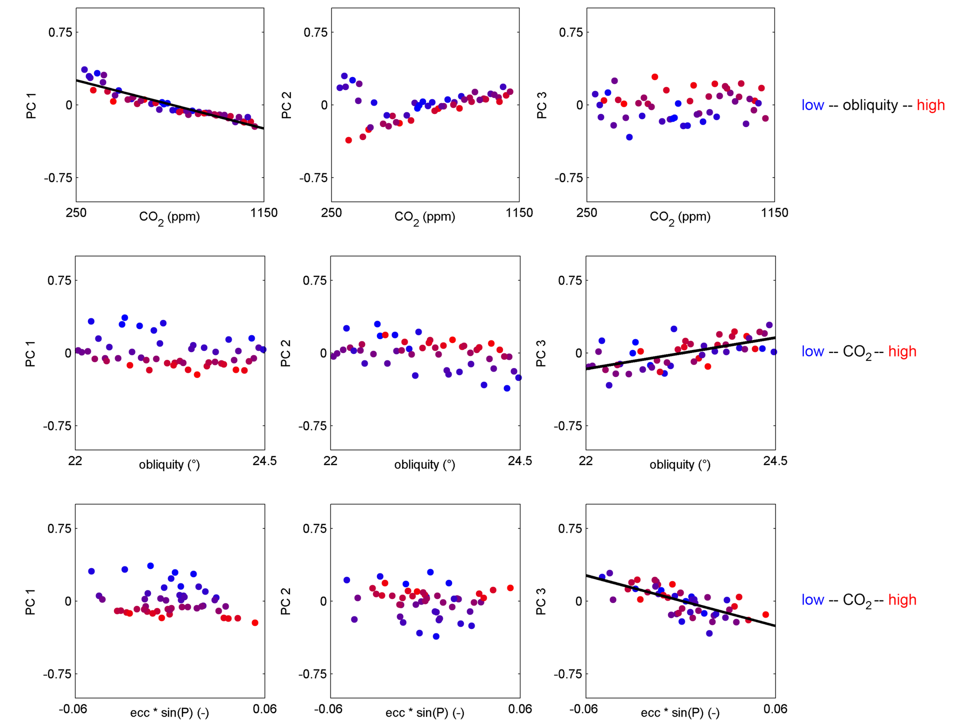

## 4. Singular Value Decomposition

We apply singular value decomposition (SVD) to the output of the full ensemble, to reduce the dimensionality of the results to sets of principal components and their corresponding scores, for comparison with the variation in the forcing parameters (Holden and Edwards, 2010). The first six principal components of DJF_temperature variation driven by $CO_2$ and orbital parameters are illustrated.



The first principal component of DJF_temperature, PC1, explains 92% of the variance in DJF_temperature across the ensemble of simulations, and its effect is almost uniformly distributed across the Earth, with small equator-pole gradients. The second principal component explains 6% of the variance, with a marked contrast between north and south high latitudes. The third principal component explains less than 1% of the variance, but shows some equator-pole differences, with a marked low area over southern Asia.

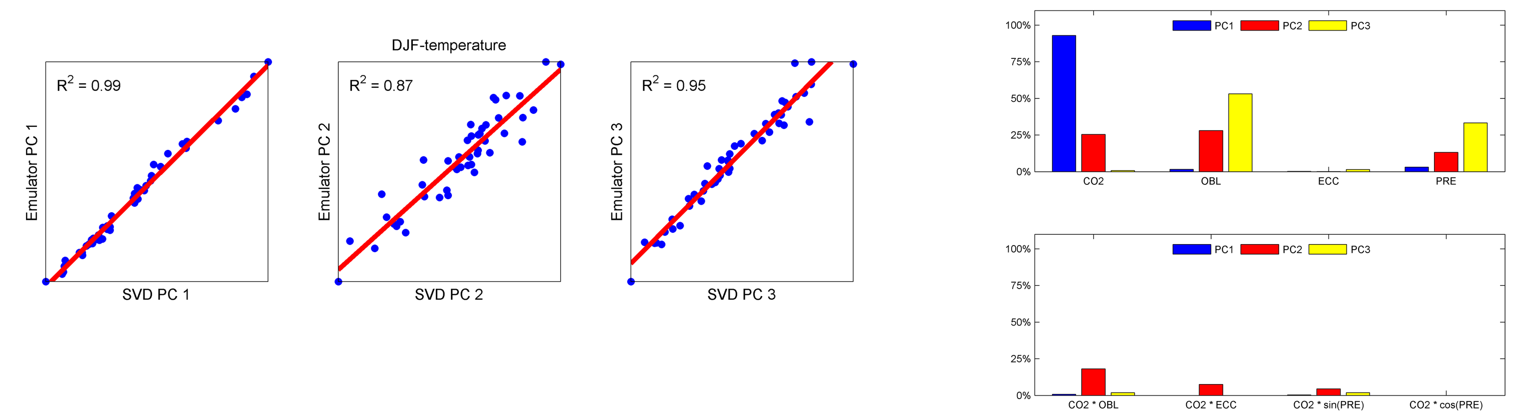
We illustrate the relationships between each of $CO_2$, obliquity, and eccentricity x sin(precession), and the first three principal component scores for DJF_temperature. Values for each ensemble member are colour coded from blue to red in increasing order of obliquity, $CO_2$, and $CO_2$ respectively. Regression lines are shown where correlation coefficients exceed ±0.5.



There is clearly a strong correlation between $CO_2$ and the first principal component score. The second principal component score shows clear correlation with $CO_2$ at moderate to high values of $CO_2$, but divides into two branches at low values of $CO_2$, with high and low values of obliquity. High obliquity enhances seasonality, and combines with low $CO_2$ to cool the Arctic, and warm the Antarctic during the northern winter. The third principal component, with a small effect on the equator-pole temperature gradient, is influenced by all three orbital parameters.

## 5. Model Emulator

We apply a linear modelling method (Holden et al., 2015), to regress the SVD reduced dimension model outputs onto the forcing parameters, and infer from the derived relationships the main effects indices, providing a measure of the variation in each model output field associated with each forcing parameter.



We show the principal component scores computed for DJF_temperature by SVD, plotted against the scores estimated by applying the emulator model, and the main effect indices for the first three score emulators of DJF_temperature.

The first principal component of DJF_temperature has a score which is dominated by $CO_2$, with very small contributions from precession and obliquity. The score of the second principal component of DJF_temperature has a more complex relationship to the forcing parameters, with similar contributions from obliquity, $CO_2$ and precession, and eccentricity only contributing in combination with $CO_2$.

## 6. Conclusions

Our modelling of the climate during the PETM, using an ensemble of simulations covering variation in $CO_2$ and orbital forcing parameters, has shown that although $CO_2$ dominates the resulting climatic variation, the orbital parameters can exert subtle but significant influence, and we suggest that orbital factors should not be ignored in modelling studies of past climates.

Further modelling with PLASIM-GENIE, with its atmospheric dynamics, will investigate polar stratospheric clouds as possible factors in the equable climate paradox, and GENIE-1 will be deployed to study ocean de-oxygenation.

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