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Modelling 500,000,000 years of climate change with a GCM – the role of CO_2, paleogeography, insolation, and ice extent during the Phanerozoic

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During the Phanerozoic (the last ~0.5 billion years), the Earth has experienced massive changes in climate, spanning the extensive glaciations of the Permo-Carboniferous (~300 million years ago), to the mid-Cretaceous super-greenhouse (~100 million years ago). Recently, several studies have used geological data to reconstruct global mean temperatures through this period, as a way of characterising the zeroth-order response of the Earth system to its primary forcings. However, there has been little modelling work that has focussed on these long timescales, due to uncertainties in the associated boundary conditions (e,g., CO_2 and paleogeography) and to the computational expense of carrying simulations spanning these long timescales. Recently, paleogeographic (Scotese and Wright, 2018) and CO_2 reconstructions (Foster et al, 2017) have emerged, and model and computational developments mean that we can now run large ensembles of relatively complex model simulations. In particular, here we present an ensemble of 109 simulations through the Phanerozoic, with a tuned version of HadCM3L that performs comparably with CMIP5 models for the modern, and is also able to produce meridional temperature gradients in warm climates such as the Eocene in good agreement with proxy data. We show that the model produces global mean temperatures in good agreement with proxy records. We partition the response to changes in the different boundary conditions (CO_2, paleogeography, ice extent, and insolation), and, through energy balance analysis, to surface albedo versus cloud versus water vapour changes. We also illustrate the ocean and atmospheric circulation changes, with a focus on the role of the changing geography (e.g. the role of a coherent circumglobal ocean in the early Phanerozoic).