



Modelling equable climates of the Late Cretaceous: Can new boundary conditions resolve data–model discrepancies?

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ABSTRACT

Late Cretaceous (Maastrichtian) climate and vegetation is modelled using the HadCM3L fully-coupled atmosphere–ocean model and the TRIFFID dynamic vegetation model. We investigate data–model inconsistencies in the high-latitudes and continental interiors by exploring the sensitivity of modelled terrestrial climate to vegetation treatment, changing atmospheric $p\text{CO}_2$ levels and the representation of Arctic seaway connections. We expand on previous work by using millennial-scale GCM runs with dynamic vegetation to allow for improved representations of ocean heat transport and terrestrial boundary conditions.

Incorporating realistic vegetation drives high-latitude warming particularly during summer through reductions in surface albedo and induced atmosphere–ocean feedbacks. Resulting regional warming can exceed 10 °C. As $p\text{CO}_2$ rises some regions cool as deciduous to evergreen change increases albedo. Incorporating enhanced Arctic connectivity, reconfigured ocean heat transport drives widespread terrestrial warming of ~3 °C and >5 °C regionally. Applying sensitivities in combination significant palaeobotanical data–model inconsistencies in the northern high-latitudes and continental interiors remain. Further work is required to resolve climate and vegetation model deficiencies and improve the interpretation and geographic distribution of quantitative climate-sensitive geological proxies.

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1. Introduction

Through the interpretation of widespread geological climate proxies, the Cretaceous has been characterised as a period of elevated global temperatures (Frakes, 1979; Barron, 1983; Hallam, 1985). The term *climate equability* has been used to describe reduced seasonal extremes and shallow equator-to-pole temperature gradients common to Cretaceous climate reconstructions. These characteristics have been the focus of numerous modelling studies that have attempted to reconcile numerical climate models with available geological evidence, the goal to identify sources of warmth in the polar regions and climate equability in continental interiors. Early studies invoked elevated $p\text{CO}_2$ to warm the poles (Barron and Washington, 1985), yet the atmospheric levels required were generally unsupported and resulted in low-latitudes that were too hot (the cool tropics paradox). Enhanced ocean heat transport was shown to redistribute some of this heat to the high-latitudes (Barron et al., 1995). Later studies investigated means of achieving this enhanced transport such as the divergence of warm equatorial waters driven by Tethys circum-global currents (Hotinski and Toggweiler, 2003) and tropical cyclones driven by warmer SSTs (Emanuel, 2001). The role of geography had been investigated by Barron et al. (1995)

and later Donnadieu et al. (2006) who found geography played a strong climatic role particularly in the high-latitudes, mainly through changes in planetary albedo and the presence of poleward-bound seaways. The opening and closure of Eocene Arctic seaways were investigated by Shellito et al. (2009) and Roberts et al. (2009). With opened Bering Strait and Turgai seaways, Shellito et al. (2009) found Arctic warming whereas Roberts et al. (2009) found warming when the Turgai and Norway–Greenland seaway were closed. Others considered the effect of modelled lakes (Sloan, 1994) and vegetation (Otto-Bliesner and Upchurch, 1997; DeConto et al., 1999; Otto-Bliesner et al., 2002). Realistic high-latitude vegetation led to warming due to albedo changes and land–ocean feedbacks, whilst large inland lakes acted to buffer regional winter extremes of continental interiors.

Problems persist in the modelling of the high-latitudes and continental interiors and so questions remain unanswered. (1) What mechanisms deliver and trap heat in the high-latitudes? (2) What drives reduced seasonality in continental interiors? (3) Can high-latitude warming be realised without unrealistic warming of the low-latitudes? This study attempts to address these questions.

Whilst the Cretaceous is not analogous given significant geographical differences with the modern, it nevertheless provides a suitable test-bed to evaluate the performance of climate models under warmer climates. This is particularly important as IPCC Representative Concentration Pathways (RCP 4.5–8.5) suggest potential 2200–2300 $p\text{CO}_2$

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levels similar to the Cretaceous (Solomon et al., 2007; Hay, 2010). Despite changed geography and extinct biota, simulating these distant past climates could identify potentially unrepresented climate dynamics and feedbacks that may become important in the near-future.

We use an IPCC/AR4-generation climate model, used extensively in palaeoclimate modelling, to investigate whether improvements in the specification of boundary conditions alone can reconcile these proxy-model differences. We advance on previous modelling studies (Valdes et al., 1996; DeConto et al., 1999, 2000; Spicer et al., 2008) by (1) using long millennial-scale GCM integrations to better capture modes of thermohaline circulation, (2) investigating model representations of potentially important Arctic seaways, and (3) using a dynamic vegetation model under varying $p\text{CO}_2$ levels to provide a range of realistic land surfaces. Evaluation of predicted terrestrial climates is conducted against quantitative geological proxies and reconstructions of vegetation and animal distributions.

The model representation of the evidence-supported warm and equable high-latitudes and continental interiors has been a long-standing problem in palaeoclimate modelling. Our objectives are to investigate how improvements in the specification of GCM model boundary conditions can address the following objectives:

1. Reconcile proxy-model comparisons of the Late Cretaceous high-latitudes where modelled climates are cold-biased, particularly during winter months.
2. Reconcile proxy-model comparisons within continental interiors in which modelled climates are too extreme i.e. cold winters and hot summers typical of modern.
3. Can 1 and 2 be addressed without unrealistic warming of low-latitudes i.e. the cool-tropics paradox.

We focus on the Maastrichtian stage as there is a significant database of widespread climatically-sensitive geological evidence for model evaluation and that the model boundary conditions (i.e. geography, atmospheric $p\text{CO}_2$) are relatively well constrained compared to earlier time periods.

2. Methods

2.1. The climate model: The HadCM3L GCM

2.1.1. Model description

An in-depth description of the climate model used in this study can be found within Gordon et al. (2000); Cox et al. (2001). The GCM consists of atmosphere, ocean and sea-ice models which are dynamically and thermodynamically coupled (Gordon et al., 2000). The horizontal resolution is 2.5° in latitude by 3.75° in longitude, equivalent to 278×417 km at the equator and 278×295 km at 45° latitude. There are 19 vertical levels in the atmosphere and 20 in the ocean and model coupling occurs once a simulated day. The terrestrial surface includes a water catchment and river routing scheme to return fresh water (in terms of salinity changes) to the ocean. The ocean model is identical to that in HadCM3 (Gordon et al., 2000) except for modifications that account for reduced spatial resolution (Gent and McWilliams, 1990). No subgrid-scale ocean flow is prescribed as is the case in this model for the modern Mediterranean and Indonesia throughflow. The coupled model has been used within the IPCC 4th assessment (Solomon et al., 2007) and the PMIP2 study (the second Palaeoclimate Modelling Intercomparison Project Gladstone et al., 2005). HadCM3 has been used successfully in a number of other Quaternary (Singarayer and Valdes, 2010) and pre-Quaternary modelling studies including the Pliocene (Haywood and Valdes, 2004; Lunt et al., 2008), Oligocene (Lunt et al., 2007) and early Eocene (Tindall et al., 2010). The model is well suited for long millennial-scale integrations as it is fast on modern hardware and attains a satisfactory state of equilibrium with minimal drift in key model diagnostics.

2.1.2. Model performance

Compared against modern climatologies, the model has a number of climate biases that may influence this study. Other than temperature biases arising from model topographical bias (often coinciding with sparse observational data) terrestrial temperatures are generally within $\pm 3^\circ\text{C}$ of observational datasets (i.e. Legates and Willmott (1990) and New et al. (1999)). Regional biases have been diagnosed. In the northern high-latitudes, high-pressure and resulting cold biases reflect weaknesses of North Atlantic westerlies and subsequent warm air advection (Pope et al., 2000; Martin et al., 2006). A dry bias in tropical precipitation is seen in the Amazonian region, North Africa, India and maritime East Asia. Regarding the ocean, the low resolution ocean model HadCM3L shares many biases with the documented high-resolution model HadCM3. Many of these biases are exasperated given the coarser grid. The model exhibits a warm bias in the southern ocean (Gordon et al., 2000) a consequence of weak overturning. Regional cold biases in the North Atlantic and North Pacific are a consequence of inadequate representation of heat fluxes and steep temperature gradients associated with major currents (Gordon et al., 2000). Other regional anomalies arise due to imperfect representations of surface heat fluxes, vertically integrated cloud cover, vertical mixing and low-level winds. Sea ice extent can extend too far equatorward particularly during winter due to inadequate heat advection from low-latitudes, aforementioned wind biases and parameterisations associated with Ekman and eddy transport.

These biases will manifest themselves directly in absolute predictions (i.e. point-wise proxy-model comparisons) whereas within difference plots (i.e. Maas2 vs Maas4) their contribution is uncertain and cannot be determined unequivocally as responses are potentially non-linear.

HadCM3 has a climate sensitivity (the response to a doubling of $p\text{CO}_2$) of 3.3°C which is near-average (range 2.1 – 4.4°C) of AR4-generation climate models (Solomon et al., 2007). We therefore expect a $p\text{CO}_2$ response similar to existing Cretaceous modelling studies.

2.2. The TRIFFID dynamic vegetation model

2.2.1. Model description

We use the TRIFFID vegetation model (Top-down Representation of Interactive Foliage and Flora Including dynamics, Cox (2001), Cox et al. (2001)) coupled to the HadCM3 climate model. TRIFFID calculates the distribution and characteristics of five plant types (broad and needle leaf trees, C_3 and C_4 grasses, and shrubs) using a Lotka-Volterra competition model and a carbon balance model in which vegetation change is driven by photosynthetic and respirations carbon fluxes calculated by the MOSES 2.1 land surface scheme (Met Office Surface Exchange System, Cox et al. (2001)). TRIFFID therefore represents the direct effects of $p\text{CO}_2$ on the vegetation and subsequent biogeophysical feedback-effects on climate. Evidence from molecular clock techniques (Christin et al., 2008; Vicentini et al., 2008) support Oligocene origins for C_4 grasses. The origins of C_3 grasses remain uncertain although grass phytoliths within dinosaur coprolites (Prasad et al., 2005) and rice paddies (Prasad et al., 2011) support diverse ancestral grasses during the latest Cretaceous. We therefore assume that during the Maastrichtian ancestral analogues were present with similar biogeophysical land-surface parameters such as albedo and surface roughness (e.g. herbaceous angiosperm), an approach similar to others (e.g. DeConto et al. (2000), Donnadieu et al. (2009)). This assumption is adequate as the MOSES–HadCM3 coupling is carried out without land–atmosphere carbon fluxes so that changes in terrestrial carbon do not alter atmospheric $p\text{CO}_2$ concentrations. The different carbon fixation routes adopted by C_3 and C_4 grasses therefore play no role. Within an asynchronous coupling with HadCM3, TRIFFID is run to equilibrium every 5 years of simulated climate, an iterative process suitable for steady-state runs which ensures a mutual climate-vegetation equilibrium is attained within centennial-scale runs.

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