Palaeogeography, Palaeoclimatology, Palaeoecology 315–316 (2012) 12–23

Contents lists available at SciVerse ScienceDirect

Palaeogeography, Palaeoclimatology, Palaeoecology

journal homepage: www.elsevier.com/locate/palaeo

Climate model predictions for the latest Cretaceous: An evaluation using climatically sensitive sediments as proxy indicators

Helen J. Craggs [a],*, Paul J. Valdes [b], Mike Widdowson [a]

[a] Department of Earth & Environmental Sciences, The Open University, Milton Keynes MK7 6AA, UK
[b] School of Geographical Sciences, University of Bristol, University Road, Bristol, BS8 1SS, UK

ARTICLE INFO

Article history:
Received 3 March 2011
Received in revised form 19 October 2011
Accepted 4 November 2011
Available online 12 November 2011

Keywords:
Climate modelling
Palaeoclimate
Proxy data
Late Cretaceous
Sediments

ABSTRACT

To date, many general circulation model (GCM) experiments have failed to reproduce the warm, high latitude temperatures suggested for the Cretaceous by geological proxy climate indicators, especially for the Northern Hemisphere and within continental interiors. The vast majority of these proxies are biologically based, and it is important to determine whether alternative sedimentologically based proxies indicate similar cold biases in models. Therefore, we have performed an evaluation of the very latest generation of climate model predictions for terrestrial sites using climatically sensitive sediments as palaeoclimate indicators. Evidence from the geological record, comprising coal/peat, evaporites, bauxite and laterite deposits, are portrayed on a series of palaeoclimate-data maps. These are then compared with the global distributions of potential deposits generated from model simulations of the Maastrichtian using versions of the Hadley Centre climate model. The Maastrichtian was chosen because of the greater range and sophistication of GCMs adapted for its climate simulation and sediment prediction than for other Cretaceous stages. This thus represents the first attempt at comparing such state-of-the-art models to lithological climate indicators and quantifying their relative performances.

For peat/coal, there is generally good correspondence between Maastrichtian model predictions for predicted potential deposits and the observed record. For evaporites, there is also very close agreement between predictions by the models and the geological record, minor differences between the individual model versions resulting from their differing levels of atmospheric CO_2 and the different palaeogeographical representations of intracontinental seaways in the Northern Hemisphere. For bauxites and laterites, the models predict less than half of the documented deposits, successfully portraying equatorial accumulations but omitting the majority of mid to high latitude deposits. The main discrepancy is therefore identified as the failure of all models to predict bauxite and laterite deposits corresponding with recorded accumulations within the mid to high latitudes of Europe and Asia. In many cases, the effects of CO_2 have minimal impact on the skill of model prediction. However, for evaporite distributions, the low CO_2 model is appreciably worse. In general, the best match across the geological data and models is achieved by the simulation with open Northern Hemisphere seaways.

Overall, these results confirm those inferred from biological proxies, showing that climate models have a serious cold bias in high latitudes and continental interiors during the Cretaceous and that the latest generation of climate models still produces results which are incompatible with the geological data. Levels of atmospheric CO_2 and uncertainties in palaeogeography cannot explain the discrepancy. The cold bias is common to many climate models, and suggests that a process or mechanism is poorly represented or omitted in the current generation of climate models, or that we are failing to recognise a major boundary condition change in the Cretaceous. If the former, this implies that we may be underestimating the extent of extreme future climate change at high latitudes and in continental interiors.

1. Introduction

The Cretaceous Period is widely recognised as a time of pronounced global warmth (Frakes, 1979; Frakes et al., 1992), with high levels of atmospheric carbon dioxide leading to a so-called ‘greenhouse’ climate (Barron and Washington, 1985; Barron et al., 1993). These conditions are considered to have produced a more equable climate system, with a reduced seasonal temperature cycle and absence of subfreezing polar temperatures, resulting in a reduced equator-to-pole temperature gradient (Barron, 1983; Sloan and Barron, 1990; Valdes et al., 1996).

Marine proxy evidence suggests sea-surface temperatures warmer than present-day (review in Savin, 1977). Examples include oxygen

---

* Corresponding author. Tel.: +44 1628 637899; fax: +44 1628 633357.
E-mail address: h.j.craggs@open.ac.uk (H.J. Craggs).

0031-0182/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.palaeo.2011.11.004

isotope data from well preserved planktonic foraminifer shells recovered from Late Cretaceous and Eocene outer continental shelf deposits of southern Tanzania (Pearson et al., 2001, 2007), where results indicated tropical sea surface temperatures ranging from 28 to 32 °C. The importance of using fossil material which had not been diagenetically altered was emphasised, together with the suggestion that such data should be used to constrain relative changes in palaeotemperature, rather than to predict absolute values (Pearson et al., 2002). Evidence from Mg/Ca ratios in calcitic shells may also be used to estimate the palaeotemperature of surface ocean waters (Elderfield and Ganssen, 2000; Nürnberg, 2000; Bice et al., 2006). An alternative quantitative technique for predicting palaeooceanographic temperatures is based on the composition of membrane lipids from marine planktonic microorganisms, using a palaeothermometer termed TEX_{86} (Jenkyns et al., 2004). Analysis of organic-rich black shales of early Maastrichtian age suggested average sea surface temperatures of approximately 15 °C for the Arctic Ocean although, at such high latitudes, results may be biased towards summer temperatures rather than the annual mean (Sluijs et al., 2006).

Evidence of warm, humid terrestrial environments during the Cretaceous is provided by the abundance of rich and diverse floras thriving at high palaeolatitudes (Hollick, 1930; Vakhrameev, 1991; Herman and Spicer, 2010; Spicer and Herman, 2010), whilst palaeoclimate parameters can be derived from plant fossils using the long-established relationship between leaf physiognomy and prevailing meteorological conditions (Bailey and Sinnott, 1915, 1916; Spicer, 1989; Spicer and Corfield, 1992). This correlation was used by Wolfe (1993) to develop a technique known as CLAMP (Climate Leaf Analysis Multivariate Program) enabling the prediction of quantitative climate parameters, and the methodology was subsequently adopted to analyse high latitude Late Cretaceous floras. Examples of mean annual temperature (MAT) ranged from 7 to 8 °C during the Turonian in Kamchatka, at palaeolatitude 72°N, to 12–13 °C during the Coniacian on the North Slope of Alaska, at palaeolatitude 75°N (Herman and Spicer, 1996, 1997, 2010), c.8 °C during the Coniacian in northeastern Russia, at palaeolatitude 78°N (Craggs, 2005) and 12–15 °C during the latest Cretaceous on South Island, New Zealand, at palaeolatitude 60°S (Kennedy et al., 2002). An alternative proxy is provided by analysis of fossil angiosperm wood anatomy (Francis and Poole, 2002; Poole et al., 2005), suggesting Late Cretaceous MATs ranging from c.7 to 14 °C on the Antarctic Peninsula. Fossil faunas may yield additional valuable palaeoclimatic evidence, as shown by Amiot et al. (2004), who used oxygen isotope analysis of continental vertebrate phosphatic remains to suggest a shallower latitudinal temperature gradient for the Late Cretaceous than occurs today.

The evidence provided by such proxies can be used to compare climate model predictions with the geological record at particular locations and for specified time periods (Barron and Washington, 1985; Upchurch et al., 1998; DeConto et al., 2000; Otto-Bliesner et al., 2002). In order to simulate these periods, we need to specify past levels of atmospheric CO_2, which can be inferred from a variety of different methods, including calcic palaeosols (Ghosh et al., 2001; Nordt et al., 2002, 2003) and from measurements of stomatal abundance in fossilised leaf cuticle (Beerling et al., 2002; Haworth et al., 2005; Quan et al., 2009). There is a relatively wide range of predictions, but results suggest Cretaceous atmospheric CO_2 levels ranging from approximately 1 to 5 × pre-industrial values. To date, many climate model predictions have failed to reproduce the warm high latitude temperatures suggested by the Cretaceous geological record, especially in the Northern Hemisphere and within continental interiors in winter (Sloan and Barron, 1990; Barron et al., 1993; Otto-Bliesner et al., 2002).

However, the vast majority of the terrestrial proxies described above are biological and it is important to verify that there are no significant systematic biases. An alternative terrestrial palaeoclimate indicator is available in the form of climatically sensitive sediments. These have the advantage of providing abundant widespread qualitative evidence of the global sedimentary record and this can be compared directly with model-predicted potential sedimentary deposits. In order to use this proxy in a more quantitative way, relationships between climate and particular sediments can be investigated (e.g. Lottes and Ziegler, 1994; Price et al., 1997).

Price et al. (1995) used these relationships to evaluate the climate models available at that time. However these models were generally atmospheric only and did not include a fully dynamic ocean. It was therefore decided to re-evaluate model predictions of climate regimes for terrestrial sites in terms of climatically sensitive sediments. The choice of Cretaceous stages, together with the climate model versions and lithologies used in this study, was dictated by the range of general circulation models (GCMs) adapted for Cretaceous climate simulations and by the potential sediment prediction schemes available within these simulations. Compromises were thus required, resulting in an initial focus on the late-Early to Late Cretaceous, covering the Aptian, Cenomanian and Maastrichtian stages (Craggs, 2007). A series of experiments highlighted the advantages of using the greater range and sophistication of GCM versions available for the Maastrichtian, spanning c.70.6 to 65.5 Ma (Gradstein et al., 2004), and the present study therefore concentrates on this particular stage. This represents the first attempt at comparing predictions generated by these state-of-the-art coupled atmosphere–ocean–vegetation models with lithological evidence from the geological record, as portrayed in palaeoclimate/geological data maps. It focuses on deposits of peat/coal, evaporites, bauxites and laterites, all of which have been shown to bear direct quantitative links to climate.

2. General circulation model, HadCM3L

The general circulation models (GCMs) used in this study are versions based on the HadCM3 GCM developed at the Hadley Centre for Climate Prediction and Research at the UK Meteorological Office. It consists of three linked components — an atmospheric model, an ocean model and a sea-ice model. HadCM3L is a version of HadCM3 which has been modified to incorporate a lower resolution ocean. Comprehensive descriptions of the models can be found in Gordon et al. (2000) and Hunter et al. (2008), but they are summarised below.

HadCM3 is a coupled atmosphere–ocean general circulation model (AOGCM) comprising the HadAM3 atmospheric model linked to a fully dynamic ocean model and a sea-ice model. The horizontal resolution of the atmosphere is 2.5° latitude × 3.75° longitude, equivalent to a grid spacing of 278 km north–south and 417 km east–west at the equator, reducing to 278 km × 295 km at 45° of latitude. It has 19 vertical layers and a 30-minute time step. A detailed description of HadAM3 can be found in Pope et al. (2000). Within the oceanic component, ocean bathymetry is prescribed, but sea-surface temperatures (SSTs) and oceanic heat transport are predicted by the model. In its standard version, the ocean has a horizontal resolution of 1.25° × 1.25°. However, for this current study, to meet the demands of spinning up the deep ocean in the Maastrichtian, a resolution of 2.5° × 3.75°, with 20 vertical layers, is used. This version of the model is called HadCM3L and it allows longer integrations. A full description of HadCM3 is given by Gordon et al. (2000), underlining its improvements over earlier versions.

2.1. Maastrichtian experiments

In order to reflect differing concentrations of atmospheric CO_2 and slight palaeogeographical modifications, four different versions of HadCM3L were used to perform simulations of the Maastrichtian climate (see Table 1). The Maastrichtian geography is based on reconstructions by P. Markwick (Markwick and Valdes, 2004) and