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Modelling the primary control of paleogeography on Cretaceous climate

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Abstract

The low thermal gradients and clement winters characterizing climates of the Cretaceous period reveal that the climate system has modes of behaviour quite different from the present. Recent proxy data analyses suggest that some aspects of climate change within the Cretaceous appear to be decoupled from CO_2 evolution at the geological time scale. Here, we investigate the impact of paleogeography on the global climate with the climate model FOAM, using a Early, Mid and Late Cretaceous continental configuration. We find that changes in geography from the Early to Mid-to-Late Cretaceous cause a large decrease of the seasonal cycle. First order identified processes are the decreased continentality of the mid-to-high latitudes from the Mid Cretaceous and the increase of the latent heat transport into the winter hemisphere which induce a wetter and a cloudier atmosphere capable of diminishing the winter cooling of the continents. Owing to the modifications of the seasonal cycle in response to the tectonic forcing, the equator-to-pole thermal gradient is reduced from the Early to Mid-to-Late Cretaceous. We nevertheless still do not succeed in simulating warm enough polar temperatures and a definitive theory still waits for an integrated approach explicitly accounting for each factor influencing the thermal gradient (ocean dynamics, stratospheric clouds, and vegetation). Our study also suggests a mechanism that can weaken the correlation between CO_2 and climate changes during the Cretaceous as evolving geography from the Early to Late Cretaceous, through the response of the water cycle and the changes in the thermal gradient, results in a 3.8 °C global warming at a constant atmospheric CO_2 level. This demonstrates that the paleogeography may affect the relation between pCO_2 and the climate history and consequently has to be accounted for when linking the atmospheric CO_2 evolution and the climate record at geological time scales.

Keywords: Cretaceous; paleoclimate; general circulation models; paleogeography; CO_2; water cycle; clouds feedbacks

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1. Introduction

During the Mesozoic era, and especially the Cretaceous, global temperatures are thought to have been considerably warmer than the present. The global warmth of the Cretaceous has generally been attributed to elevated levels of atmospheric CO_2 [1,2]. In recent years, several studies using records of $\delta^{18}O$ in foraminiferal calcite or in apatite tooth enamels have proposed a more nuanced description of the climate changes during the Cretaceous [3–5], highlighting a progressive warming from the Aptian to the Cenomanian–Turonian as well as icehouse interludes during the lower Cretaceous at the million-year scale. The warming trend observed from the Early to the Mid Cretaceous coupled to a reduction in atmospheric pCO_2 as recorded by different proxies during the same period [6] has been used by Veizer et al. [7] to question the role of CO_2 in regulating climates over Phanerozoic time scales. Going one step forward, a celestial mechanism has even been proposed to explain the relative uncorrelated atmospheric CO_2 level record to the climate record during this particular time period [8]. However, Royer et al. [6] have shown that the use of a pH corrected proxy record of climate yields a much better match between CO_2 variations and major climate shifts, undermining the arguments for cosmic ray fluxes as a significant driver of climate.

Another debate which surrounds the Cretaceous period concerns the concept of equability. Typically, the term “equable” means a reduced annual cycle of temperature and the absence of sub-freezing winters [9–11]. Besides equability, another typical feature of Cretaceous climates is a weak pole to equator temperature gradient, as compared to the modern climate. It should be noted, however, that the concept of equability does not strictly apply to the Early Cretaceous [12–14].

Several modelling studies have been devoted to the Cretaceous climate since the early 1980s and have demonstrated the importance of the oceanic circulation, the geographical distribution and the vegetation in explaining climate modes quite different from the present [15–20]. Among these studies, Barron’s pioneering work was designed to understand the factors controlling the generally warm Cretaceous climate. Barron identified a combination of three major variables, geography, CO_2 content (four times present-day CO_2) and oceanic heat flux to achieve the distribution of Mid-Cretaceous temperatures with the two latter being the most important [15]. Indeed, in 1993, Barron and colleagues published model experiments using the GENESIS model which suggested a negligible role of geography during the mid-Cretaceous [21] in contrast to early model studies with mean annual solar insolation and a simple energy balance ocean which predicted almost a 5 °C warming owing to the Cretaceous geography [16]. Rather than extending Barron’s work and comparing the impact of present-day geography with a mean Cretaceous geography, we would like to undertake a systematic study of the climatic changes induced by three different contrasted continental configurations occurring during the Aptian, the Cenomanian and the Maastrichtian stages. To our knowledge, only Poulsen and colleagues have undertaken such comparable studies but their papers were mainly focused on the response of the global oceanic circulation to tectonic changes occurring from Aptian to Albian [19,20,22]. In this study, paleoclimate simulations have been run for the Aptian, the Cenomanian and the Maastrichtian stages. Our aim is to determine the extent to which the major plate reorganization and sea level changes during the Cretaceous can have a large effect that might oppose CO_2 forcing and contribute to the equability. This sensitivity study demonstrates that first-order features of the Cretaceous climate records can be generated by atmospheric feedbacks occurring in response to changes of the tectonic forcing.

2. Model and experiments

The model experiments were completed using the fast ocean-atmosphere model (FOAM). The atmospheric component of FOAM is a parallelized version of NCAR’s Community Climate Model 2 (CCM2) with the upgraded radiative and hydrologic physics incorporated in CCM3 v. 3.6. The atmosphere runs at R15 spectral resolution ($4.5° \times 7.5°$) with 18 levels. FOAM successfully simulates many aspects of the present-day climate and compares well with other contemporary medium-resolution climate models [23]; it has also been used previously to investigate Cretaceous and Neoproterozoic climates [20,24,25]. For this study, the atmospheric model is linked to a 50-meter mixed-layer ocean, which calculates the oceanic heat transport as linear diffusion down the local ocean-temperature gradient, with the coefficient being tuned to yield realistic present-day climate. The diffusive heat transport is applied within cutoff seas just as in the rest of the ocean. Diffusive ocean heat transport is applied strictly, without imposing any constraint that total ocean heat divergence per unit latitude remains constant between simulations; such constraints can lead to spurious results. An energyconserving thermodynamic sea-ice model is used following Semtner [26]. It has to be recalled that a coupled ocean-atmospheric general circulation model (CGCM) may attain different equilibrium states and, therefore, provide different results. Certainly, it would be desirable to do these simulations with a dynamic ocean. However, a dynamic ocean increases the equilibration time from about 50 yr to about 2000 yr, which makes it practically impossible to cover the ranges of cases we wish to cover. Future work will certainly investigate the role of ocean dynamics; a well-documented set of slab ocean simulations provides a basis for comparison that will be invaluable in diagnosing the impact of ocean dynamics. In order to provide a sensitivity test to the slab ocean, two supplementary sets of runs have been performed, one with a diffusivity coefficient multiplied by three and another one with a zero diffusivity coefficient.

Three Cretaceous continental configurations accounting roughly for the location of the mountain ranges and their respective estimated elevations at that time, as well as the paleoshorelines have been used for this study (Fig. 1). As we have no direct information about past relief, we have compared the geodynamic context at that time with present-day analogue in order to attribute an elevation. The only resulting significant mountain reliefs (above 1000 m) are located (1) in southern Laurasia because of the gradual consolidation of many Asian land blocks; and (2) along the western coast of North America due to the Sevier orogeny and to the Colorado Laramide orogeny. This yields global average continental elevations approximately 100–200 m less than the present-day average of 744 m (Table 1). The paleopositions of large continents have been calculated using both oceanic kinematic parameters and the more recent apparent polar wander paths (to fix the paleolatitude grid) [27]. In all other respects, the boundary conditions were identical. Indeed, this study has been designed to isolate the sensitivity of the climate to changes in geography. As a result, the atmospheric CO_2 concentration was kept constant for the three experiments and set to 1120 ppm (four times the pre-industrial value), a high value typical of the Cretaceous [6]. The solar constant was decreased by 1% using the stellar evolution predicted by [28]. Earth orbital parameters were set to present-day values. In the absence of detailed data sets of Cretaceous biomes, surface types were set to average model surface characteristics (i.e., deciduous forest). Each simulation was run for 50 yr (in order to reach the steady-state) and the final 10 yr were averaged together to produce the conditions shown here. In addition, the significance of our result has been determined using Student's *t*-tests. All our results are significant at 99% level or above.

3. Results

With the prescribed atmospheric CO_2 level of 1120 ppm, the Cretaceous experiments have a global mean surface temperature considerably above the present-day one (which is 14.5 °C with the FOAM slab version): 18.8 °C, 20.8 °C and 22.6 °C for the Aptian, Cenomanian and Maastrichtian runs, respectively. The warming induced by the modification of the paleogeography is striking as there is a 3.8 °C (2 °C) warming between the Aptian and the Maastrichtian (Cenomanian) experiments despite the fact that the greenhouse gas concentration is the same for all three experiments. The warming over land and over ocean is around 5.35 °C and 2.8 °C between the Aptian and the Maastrichtian experiments which demonstrates that both land and ocean climates are affected by changes in paleogeography. The weak changes in mean global elevations between the three continental configurations ensure that the changes in mean global temperature are not due to this major variable (Table 1). Between the three runs, the larger changes in planetary albedo when compared to the surface albedo indicate that modifications occurring in the atmosphere may play a significant role in the warming simulated between the Early and the Late Cretaceous (Table 1). Changes in specific humidity probably also play a major role through the water vapour feedback that we will look into details below (Table 1). Although there is a modest net imbalance in the surface and top of atmosphere energy fluxes, the near-constancy of this imbalance across the runs eliminates concern that the imbalance has affected our conclusions (Table 1). In addition, it should be noted that the top of atmosphere imbalance does not imply a long-term climate drift in our runs. It rather comes from small deviation energy conservation in the surface flux parameterizations of the model. Using the database of the paleoclimate modelling intercomparison project (http://boulimix/pmip/database/models/index.html), we have calculated the TOA energy balances for present-day runs of the LMD5, the GISS, the CCM3, the GENESIS 2, the ECHAM 3 and the UGAMP climate models. Respectively, the values are 2.8, 3.05, − 1.1, 2.3, 3.9 and 6.2 W m^{-2}. Hence, values obtained in our FOAM experiments are in the range of most of climate models.

Looking at the distribution of the surface temperatures, the high latitudes are most affected by changes in paleogeography (Fig. 1). From the Aptian to the

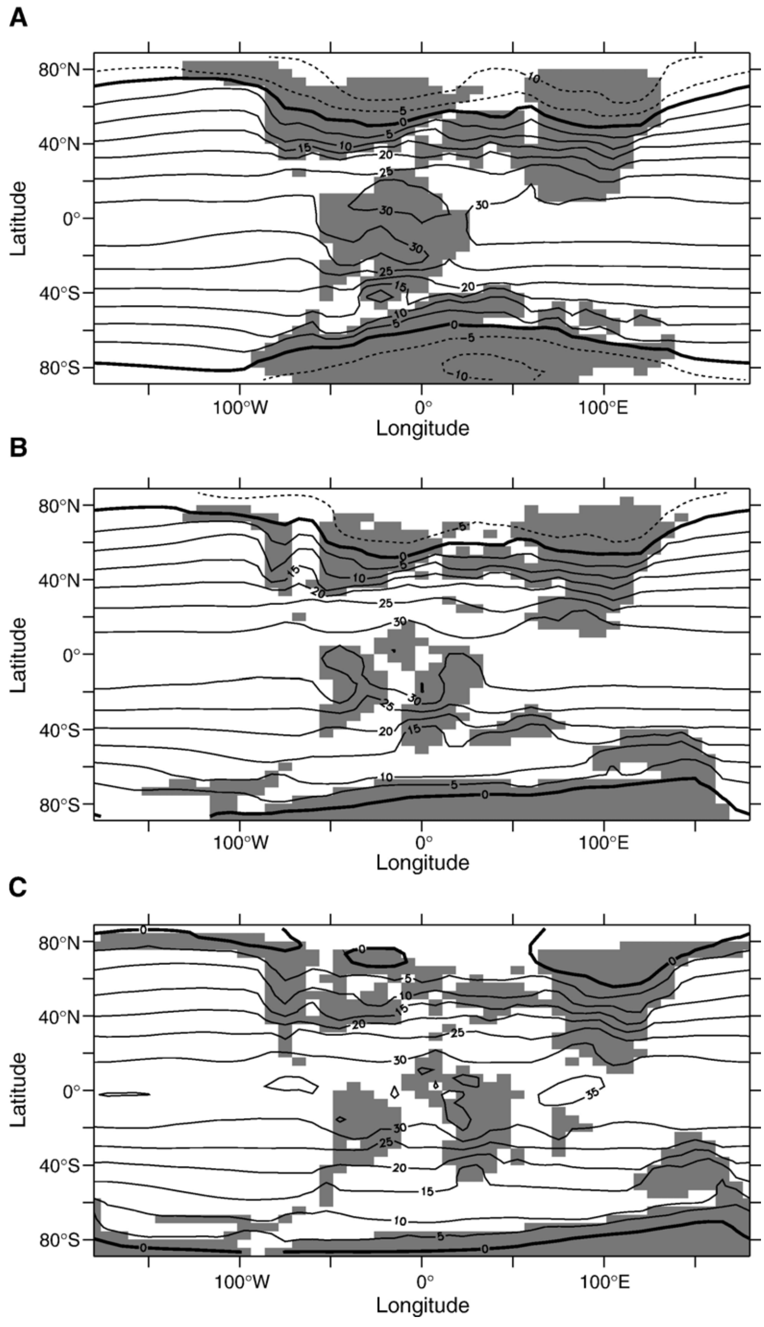

Fig. 1. Mean annual surface temperature (°C) as simulated for (A) the Aptian run, (B) the Cenomanian run and (C) the Maastrichtian run. Gray shading indicates Cretaceous continents. The Aptian one corresponds to a low sea level and to a period where the South Atlantic Ocean is open but not the Central Atlantic one. The Gondwana is divided into three plates including, Australia–Antarctica–India to the south, South America and Africa. The Cenomanian one occurs during the highest sea level (up to 150 m) which results in a large number of epicontinental seas flooding Europe, a large part of the Russian platform, North America and the northern margin of Africa. The Cenomanian is also characterized by the opening of the Central Atlantic Ocean. The last geography represents the Maastrichtian period which is characterized by a marine regression (when compared to the Cenomanian), by the achievement of the rifting between Australia, India and Antarctica and by an enlarged Atlantic ocean.

Cenomanian, the demise of Antarctica–Australia–India results in a retreat of the annual mean 0 °C isotherm (Fig. 1A–B). The appearance of the Western Interior Seaway displaces the isotherm by about 20° of latitudes. From the Cenomanian to the Maastrichtian (Fig. 1B–C), sea-ice at high latitudes completely vanishes. As a

Table 1
Climatic global mean values

	Surface albedo (%)	Planetary albedo (%)	Mean elevation (meters)	Specific humidity at 500 mbar (g/kg)	Surface energy balance (W m^{-2})	TOA energy balance (W m^{-2})
Aptian	18.5	33.7	665	1.75	3.1	3.3
Cenomanian	18.2	33.0	515	2.05	3.0	2.95
Maastrichtian	17.85	32.4	525	2.4	2.4	2.3

The surface energy balance is the difference between the net downward shortwave flux minus the sum of the net upward longwave flux, the latent heat flux and the sensible heat flux. The Top of Atmosphere (i.e., TOA) energy balance is the difference between the net downward shortwave flux and the net outgoing longwave flux.

result, the northern mid-to-high latitude continents have a temperate climate. We remind the reader that it is not our purpose to present a definitive theory of Cretaceous climate, which is in accord with the full range of proxy data. Among other things, the lack of a dynamic ocean in our simulations would make such a goal over-ambitious. We have set ourselves the more modest goal of estimating the magnitude of paleogeography effects, all other things being kept equal.

We now consider the mechanisms whereby paleogeography influences the simulated climate. Because land has less thermal inertia than ocean, paleogeography exerts a profound effect on the strength of the seasonal cycle [22,29], which can be rectified into annual mean changes via nonlinearities in the climate system. The change in paleogeography also provokes a number of changes in the Earth's radiation balance, which we shall proceed to diagnose (Table 2). To make the significance of the radiative changes easier to understand, in the following discussion we have translated changes in radiative fluxes approximately into surface temperature changes using a sensitivity coefficient of 2 (W/m2)/°C, which incorporates clear-sky water vapour feedback at a strength typical of most IPCC models (see, e.g., [30] or [31]). It does not incorporate cloud or ice/snow albedo feedback, which in our discussion will be treated as explicit radiative forcings.

Because land has a higher albedo than ocean, putting more land in the Tropics where it is exposed to intense sunlight would tend to reduce solar absorption and yield a cooling of the climate, and conversely when land is moved to higher latitudes. This effect turns out to account for very little of the warming effect we see: we calculate that the changes in surface specification lead to an increase of 0.3 °C (0.05 °C) from the Aptian to the Cenomanian (Maastrichtian) (Table 2). A more important influence is the change in clear-sky albedo. This is associated with increased atmospheric near-infrared solar absorption, arising from increased water vapour content in the warmer simulations. Globally averaged, this effect produces a warming of 1.05 °C (1.45 °C) between the Aptian and the Cenomanian (Maastrichtian) (Table 2). Cloud radiative feedbacks are also significant. They lead to a warming of 0.4 °C (1.25 °C) between the Aptian and the Cenomanian (Maastrichtian). Specifically, a decrease of the cooling effect of the clouds, which is the result of the low altitude clouds which reflect sunlight, is simulated (Table 2). The warming effect of the high altitude clouds (which decrease the outgoing longwave radiation) increases between the Aptian and the Cenomanian (Maastrichtian). Hence, both types of clouds act to enhance the global radiative effect (Table 2).

Although our simulations do not have a dynamic ocean, sea ice margins can be very sensitive to small

Table 2
Global mean values of the radiative forcing terms

	Clear sky net downward SW flux at the surface	Clear sky net downward SW flux at the TOA	LW cloud radiative forcing	SW cloud radiative forcing	Cloud radiative forcing
Aptian	224.1	287.4	32.7	−51.6	−18.9
Cenomanian	224.7 (0.6)	289.5 (2.1)	33.7 (1)	−51.8 (−0.2)	−18.1 (0.8)
Maastrichtian	224.2 (0.1)	290.3 (2.9)	34.3 (1.6)	−50.7 (0.9)	−16.4 (2.5)

The longwave (i.e., LW) cloud radiative forcing is calculated at the TOA and is equal to the OLR clear sky minus the OLR (OLR for outgoing longwave radiation). The shortwave (i.e., SW) cloud radiative forcing is calculated at the TOA and is equal to the net downward SW flux minus the clear sky net downward SW flux. The cloud radiative forcing is the sum of both previously described terms. Note that negative values represent "the cooling term". Note that numbers in parentheses are the calculated difference between each run for the radiative forcing term of interest. They then allow us to calculate an induced temperature change (see in the text).

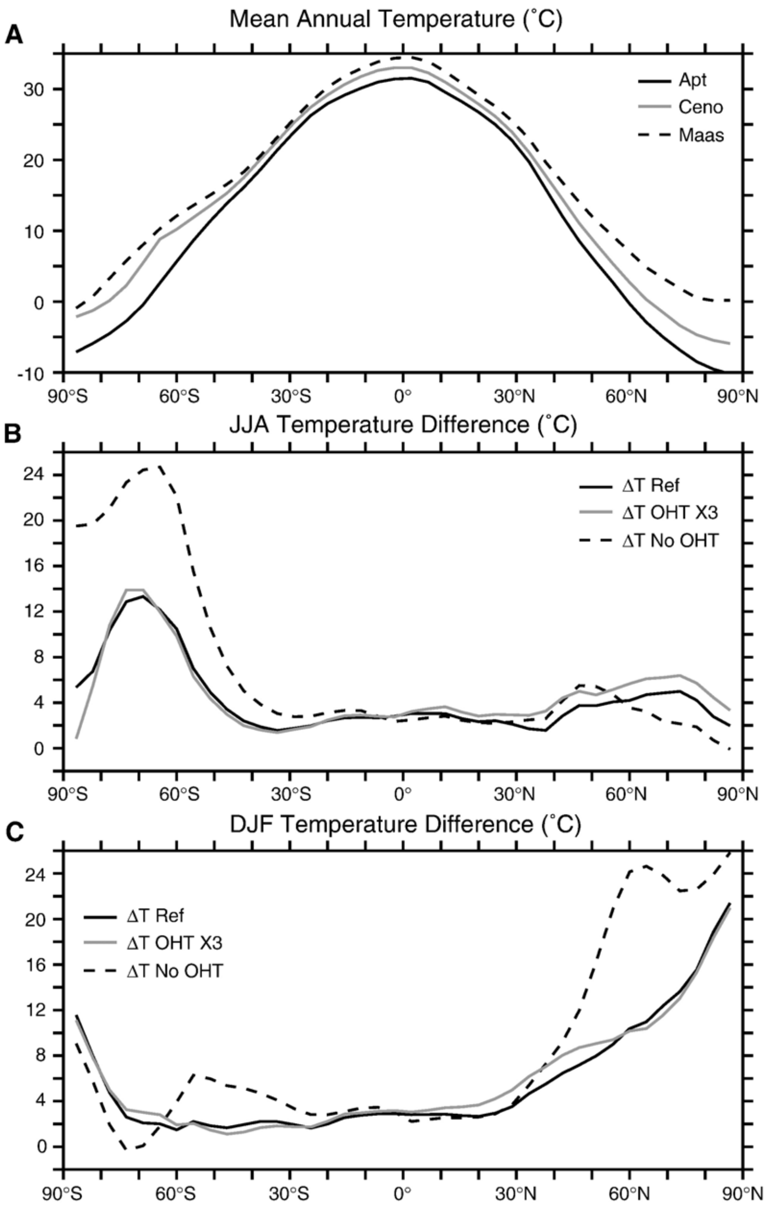

Fig. 2. Zonal surface temperature (°C). (A) Mean annual, (B) mean December–January–February difference and (C) mean June–July–August difference. For panels B and C, black lines are the temperature difference for the reference runs (see in the text) whereas gray lines are for the runs with a diffusivity coefficient multiplied by three. One can note the relatively constant difference in zonal temperature for different values of the diffusion. Dashed black lines are for the runs in which we arbitrary set the ocean heat transport to zero.

meridional heat fluxes in the ocean, so it is important to examine heat fluxes yielded by the mixed layer ocean model. The fluxes are similar in all three cases. They peak in the Northern and Southern subtropics, with maximum values near 1 PW. The flux across 60N is about 0.25 PW, while that across 60S is about 0.5 PW. These are modest fluxes, somewhat smaller than those found in the modern ocean. The main object of this remark is to point out that the relatively equable climates in our simulations do not require unrealistically large ocean heat fluxes for their maintenance. The heat fluxes in themselves would not be enough to cause much polar warming, but they do play a significant role in polar climate in the simulation because their effect is amplified by their influence on sea ice, making it easier for elevated CO_2 to maintain ice-free summers and nearly ice-free winters.

In general, the paleogeography induces a number of changes in the seasonality and in the atmosphere's hydrological cycle, which then account for much of the warming in the Maastrichtian case. We will now take a closer look at these changes. For brevity, we focus on the Aptian and the Maastrichtian simulations as the differences observed between the Aptian and the Cenomanian simulations arise from the same causes. Parallel to the warming trend, the meridional temperature gradient of the Maastrichtian becomes shallower than the Aptian one (Fig. 2A). The comparison of the seasonal temperature gradients demonstrates that the flattening of the gradient is more the result of the winter high latitude warming occurring during the Maastrichtian rather than a tropical cooling or an induced summer warming mechanism (Fig. 2B–C). In each hemisphere, the mean zonal temperature increases by 6 °C (or more) for the latitudes greater than 50° during the winter. This warmth has its origin in the geographical changes occurring during the Maastrichtian at mid-to-high latitudes, i.e., more ocean and seaways, which prevent drastic winter cooling given their high thermal heat capacity. Fig. 3 demonstrates the decrease of the seasonal contrast over the mid-to-high latitude continents between the Aptian and Maastrichtian runs. Given the simple slab ocean model used for this study and in particular the parameterization of the oceanic heat transport with a straightforward diffusion law, one can have some doubt concerning the accuracy of our results. With a diffusivity coefficient multiplied by 3 (by 0), the Cretaceous experiments have a global mean air temperature of 18.55 °C (14.1 °C), 20.8 °C (17.9 °C) and 22.7 °C (19.8 °C) for the Aptian, Cenomanian and Maastrichtian runs, respectively. Hence, the warming from the Aptian to the Maastrichtian appears relatively independent of the value of the oceanic heat transport used in our runs. In addition, the preferentially winter mid-to-high latitude warming simulated in our reference runs still holds when setting the ocean heat transport to zero everywhere or when multiplying the diffusivity by three (Fig 2B–C). This clearly confirms the primary role played by the land-ocean distribution and allows us to rule out large biases due to the slab ocean modelling.

Other positive feedbacks act to induce a warmer world in our simulations. Fig. 4 shows that the simulated Maastrichtian atmosphere has higher water vapour

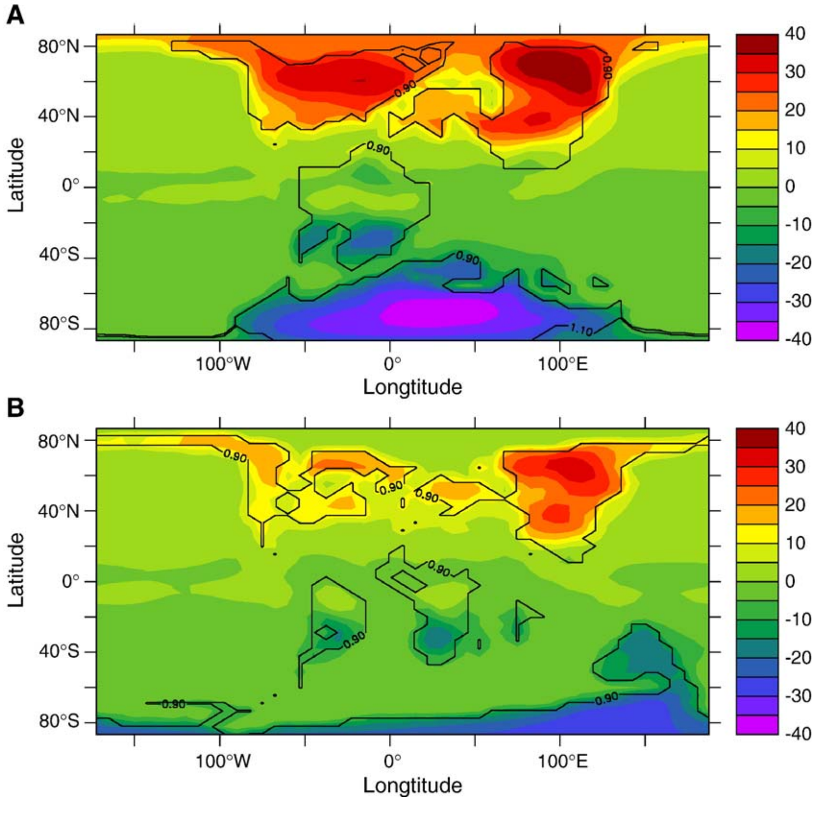

Fig. 3. Surface temperature difference between the summer and the winter northern hemisphere (°C) as simulated for (A) the Aptian run and (C) the Maastrichtian run.

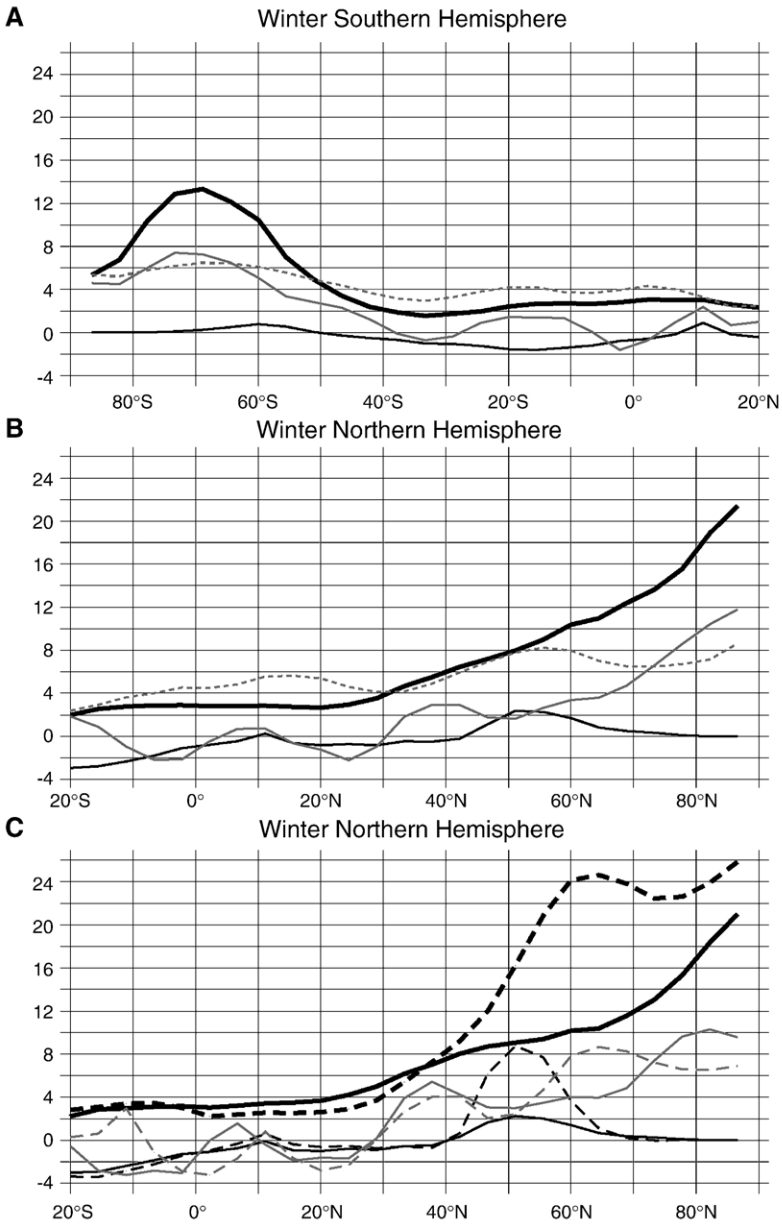

Fig. 4. Zonally averaged diagnostics difference between the Maastrichtian and the Aptian runs for (A) JJA and (B) DFJ. The thick black lines show the simulated difference in surface temperature. The black lines show the temperature effect resulting from the changes in surface albedo. The gray lines show the temperature effect resulting from the changes in cloud radiative forcing. The dotted gray lines show the difference in specific humidity at the 500 mbar level in percentage but divided by 10 to match the temperature scale (i.e., a difference of 2 represents a 20% increase of water vapour atmospheric content). (C) Same as panel B but either for the runs with a three times increases of the diffusivity coefficient tuning the oceanic heat transport (full line) or for the runs with no oceanic heat transport (dashed lines).

content, particularly in high latitude winter. An examination of the relative humidity (not shown) indicates that most of this effect is associated with the increase in high latitude temperature with relative humidity held approximately fixed, rather than with more subtle circulation-induced increases in relative humidity. The increase in humidity also increases the supply of moisture available for making clouds. Fig. 4 clearly reveals the importance of the cloud effect on winter surface temperature. We have calculated that the cloud induced temperature changes can reach more than 6 °C in some places. The cloud feedback is thus an important contributor to the warmer winter simulated in our Maastrichtian run. The role played by the snow albedo feedback is significant, but less impressive than the cloud feedback. There is a warming of 2–3 °C occurring over 50–60° of latitudes where the retreat of winter snow takes place during the Maastrichtian. The feedbacks we highlight here are still active in our sensitivity runs (Fig. 4C). Nevertheless, in the runs with no ocean heat transport, the snow albedo feedback becomes a major contributor and may explain the larger temperature difference simulated during the mid-to-high winter latitude between the Aptian and the Maastrichtian (Fig. 4C). We have calculated a 1.8 °C cooling owing to changes in surface albedo between the Maastrichtian and the Aptian in contrast with the minor cooling of 0.05 °C calculated for the reference runs (Table 2).

Large-scale meridional latent heat transport is among the important factors that control the mid-to-high latitude supply of water which is available for making clouds. Looking at the mid-latitude maximum latent heat transport, an increase of 0.3–0.5 PW is produced by

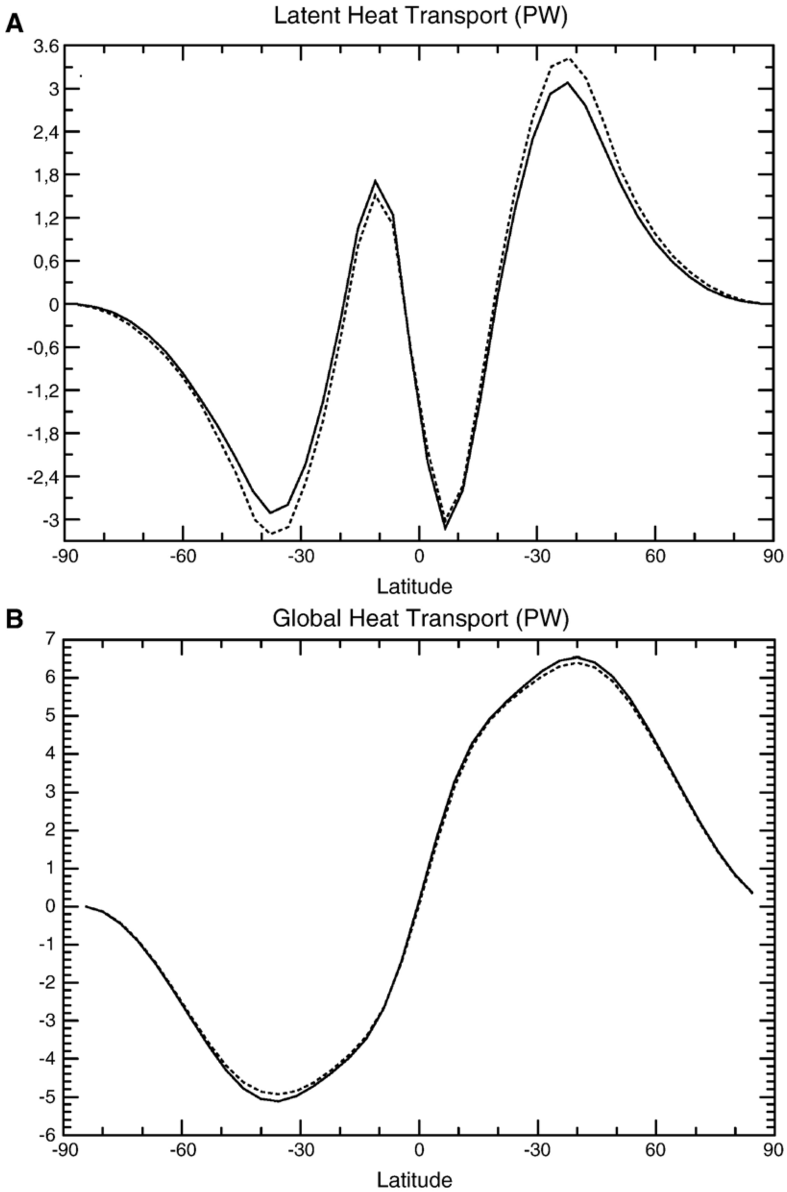

Fig. 5. (A) Mean annual latent heat transport (PW) for the Aptian run (solid line) and for the Maastrichtian run (dashed line). (B) Same as panel A but for the global meridional heat transport (ocean+atmosphere).

the Maastrichtian paleogeography when compared to the Aptian one (Fig. 5A). The latent heat transport is mainly affected by the typical meridional velocity, the saturation specific humidity and the temperature representative of the subtropical moisture source regions [32]. Though the low Maastrichtian gradient favours a decrease of the meridional velocity, the warmer tropical temperatures and the greater moisture content of subtropical and mid-latitude air compensate the former effect and generate a substantial increase of the latent heat fluxes. The latitude of the storm-track axis can also influence the latent heat transports [33]; however, it remains located over the 38–42 latitude band in both runs. The opening of the Central Atlantic Ocean may also induce a modest increase in the latent heat flux, which in turn, could produce a more efficient moisture source for the storm-tracks. It is important to note that we do not explain the flattening of the equator-pole thermal gradient during the Maastrichtian by an increase of the meridional global heat transport as it has been suggested and tested several times in the past. Indeed, in our runs, the global heat transport primarily responds to the zonal mean thermal gradient and thus appears weaker during the Maastrichtian than during the Aptian (Fig. 5B).

Any result that depends in part on cloud feedbacks cannot be considered definitive, since the nature of cloud feedbacks varies considerably with the details of the parameterization. The significance of our result lies in the fact that at least one physically defensible parameterization scheme yields cloud effects that make it somewhat easier to explain the Cretaceous climates discussed here (see [34] for a discussion of the cloud parameterization used in our simulations). In other words, the absolute magnitude of warming predicted by the model may not be exact, but the general mechanism – the changes in the general atmospheric circulation owing to continental drift, and direction of consequent temperature response – may be common to a broad class of models which increase winter cloudiness in response to increased moisture supply, and in which cloud greenhouse effect dominates in the weakly illuminated winter season.

4. Discussions

To our knowledge, this is the first time that three different Cretaceous paleogeographies with realistic shorelines and water inland bodies are tested within the same GCM. Our simulations indicate that the tectonic forcing has the potential to influence climate in a way that is consistent with observations. The effect of continentality had already been proposed and quantified by [29] but in the regional context of the Western Interior Seaway. We show here, in a more general context, that water cycle feedbacks associated with paleogeographic changes help to understand the Cretaceous climate. The dislocation of the Gondwana and the sea level changes act together to induce warmer winter as seen between the Aptian and both Cenomanian and Maastrichtian runs. The larger transport of water in the winter hemisphere is at the origin of a positive cloud feedback which preferentially affects the winter season. While the amplitude of the warming is strong (between 5 and 20 °C), absolute values of winter modelled-temperature for the Cenomanian and Maastrichtian runs are still well below 0 °C in the continental interiors where they reach − 15 °C. Other factors which have not been accounted for here can produce a greater warming at high latitudes. A more realistic vegetation cover, the effect of polar stratospheric clouds or the inclusion of an explicitly resolved ocean dynamics could help resolve the mismatches between model results and data [18,35,36]. Only a model study integrating all factors could help in resolving the low thermal gradient paradox. Indeed, the key question remains unanswered: what mechanism maintains warm poles without warming the tropics? In summary, we conclude that the tectonic forcing may have set the stage for the equability of the Mid to Late Cretaceous but it is not the only factor.

Though not completely novel, the other interesting implication of our study concerns the relative role of the paleogeography and of the atmospheric CO_2 content on the annual temperature of the global climate. As discussed by [7], discrepancies between pCO_2 and climate proxies suggest that during the Cretaceous, pCO_2 was not the primary control on climate change. Rather than questioning the primary role of the atmospheric CO_2, our modelling results allow us to put forward that the atmospheric CO_2 is not the whole story and that, owing to the overwhelming effect and interplay between the paleogeography, the water cycle and the seasonal response, the climate system may undergo subtle climatic changes (as the 4 °C global warming simulated here between the Aptian and the Maastrichtian runs). The identified atmospheric feedbacks including changes in planetary albedo, in water vapour distribution and in meridional latent heat transport are all poorly represented in zonal energy balance model as the one used in [7] whereas they appear to be of primary importance when focusing on ancient greenhouse climates. Our study implies that the use of a global relationship between pCO_2 and temperature independent of the geography in long time scale carbon cycle model [37,38] may induce significant errors. Future modelling works are planned to simulate interactively the climate and the atmospheric content CO_2 (as in [39]) in order to provide an explicit picture of the links between geography, CO_2 and climate occurring during the Cretaceous.

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References

[1] E.J. Barron, W.M. Washington (Eds.), Warm Cretaceous Climates: High Atmospheric CO_2 as a Plausible Mechanism, AGU, Washington, DC, 1985.
[2] R.A. Berner, Atmospheric carbon dioxide levels over Phanerozoic time, Science 249 (1990) 1382–1386.
[3] L.J. Clarke, H.C. Jenkyns, New oxygen isotope evidence for long-term Cretaceous climatic change in the Southern Hemisphere, Geology 27 (1999) 699–702.
[4] B.T. Hubert, D.A. Hodell, C.P. Hamilton, Middle–Late Cretaceous climate of the southern high latitudes: stable isotopic evidence for minimal equator-to-pole thermal gradients, Geol. Soc. Amer. Bull. 107 (1995) 1164–1191.
[5] E. Pucéat, C. Lécuyer, S.M.F. Sheppard, G. Dromart, S. Reboulet, P. Grandjean, Thermal evolution of Cretaceous Tethyan marine waters inferred from oxygen isotope composition of fish tooth enamels, Paleoceanography 18 (2003), doi:10.1029/2002PA000823.
[6] D.L. Royer, R.A. Berner, I.P. Montanez, N.J. Tabor, D.J. Beerling, CO_2 as a primary driver of Phanerozoic climate, GSA Today 14 (2004) 4–10.
[7] J. Veizer, Y. Goddéris, L.M. François, Evidence for decoupling of atmospheric CO_2 and global climate during the Phanerozoic eon, Nature 408 (2000) 698–701.
[8] N.J. Shaviv, J. Veizer, Celestial driver of Phanerozoic climate? GSA Today 13 (2003) 4–10.
[9] R. Amiot, C. Lécuyer, E. Buffetaut, F. Fluteau, S. Legendre, F. Martineau, Latitudinal temperature gradient during the Cretaceous Upper Campanian–Middle Maastrichtian: $\delta^{18}O$ record of continental vertebrates, Earth Planet. Sci. Lett. 226 (2004) 255–272.
[10] A.B. Herman, R.A. Spicer, Palaeobotanical evidence for a warm Cretaceous Arctic Ocean, Nature 380 (1996) 330–333.
[11] R.A. Spicer, R.M. Corfield, A review of terrestrial and marine climates in the Cretaceous with implications for modelling the greenhouse Earth, Geol. Mag. 129 (1992) 169–180.
[12] L.A. Frakes, J.E. Francis, A guide to Phanerozoic cold polar climates from high-latitude ice-rafting in the Cretaceous, Nature 333 (1988) 547–549.
[13] G.D. Price, The evidence and implications of polar ice during the Mesozoic, Earth-Sci. Rev. 48 (1999) 183–210.
[14] T. Steuber, M. Rauch, J.P. Masse, J. Graaf, M. Malkoc, Low-latitude seasonality of Cretaceous temperatures in warm and cold episodes, Nature 437 (2005) 1341–1344.
[15] E.J. Barron, P.J. Fawcett, W.H. Peterson, D. Pollard, S.L. Thompson, A simulation of mid-Cretaceous climate, Paleoceanography 10 (1995) 953–962.
[16] E.J. Barron, S.L. Thompson, W.W. Hay, Continental distribution as a forcing factor for global-scale temperature, Nature 310 (1984) 574–575.
[17] B.L. Otto-Bliesner, E.C. Brady, C. Shields, Late Cretaceous ocean: coupled simulations with the national center for atmospheric research climate system model, J. Geophys. Res. 107 (2002) (Art. No. 4019).
[18] B.L. Otto-Bliesner, G.R. Upchurch Jr., Vegetation-induced warming of high latitude regions during the Late Cretaceous period, Nature 385 (1997) 804–807.
[19] C.J. Poulsen, E.J. Barron, M.A. Arthur, W.H. Peterson, Response of the mid-Cretaceous global oceanic circulation to tectonic and CO_2 forcings, Paleoceanography 16 (2001) 576–592.
[20] C.J. Poulsen, A.S. Gendaszek, R.L. Jacob, Did the rifting of the Atlantic Ocean cause the Cretaceous thermal maximum? Geology 31 (2003) 115–118.
[21] E.J. Barron, P.J. Fawcett, D. Pollard, S. Thompson, Model simulations of Cretaceous Climates—the role of geography and carbon-dioxide, Philos. Trans. R. Soc. Lond., B Biol. Sci. 341 (1993) 307–315.
[22] C.J. Poulsen, E.J. Barron, C.C. Johnson, P.J. Fawcett, Links between major climatic factors and regional oceanic circulation in the mid-Cretaceous, in: E.B.T. Barrera, C.C. Johnson (Eds.), Evolution of the Cretaceous Ocean–Climate System, Special Paper-Geological Society of America, vol. 332, Geological Society of America, Boulder, 1999.
[23] R.L. Jacob, Low Frequency Variability in a Simulated Atmosphere Ocean System, Ph. D. Thesis, University of Wisconsin-Madison, Wisconsin, 1997.
[24] R.T. Pierrehumbert, High levels of atmospheric carbon dioxide necessary for the termination of global glaciation, Nature 429 (2004) 646–649.
[25] C.J. Poulsen, R.T. Pierrehumbert, R.L. Jacob, Impact of ocean dynamics on the simulation of the Neoproterozoic "snowball Earth", Geophys. Res. Lett. 28 (2001) 1575–1578.
[26] A.J. Semtner, A model for the thermodynamic growth of sea-ice in numerical investigations of climate, J. Phys. Oceanogr. 6 (1976) 379–389.
[27] J. Besse, V. Courtillot, Apparent and true polar wander and the geometry of the geomagnetic field over the last 200 Myr, J. Geophys. Res. 107 (2002) (No 2300).
[28] D.O. Gough, Solar interior structure and luminosity variations, Sol. Phys. 74 (1981) 21–34.
[29] P.J. Valdes, B.W. Sellwood, G.D. Price, Evaluating concepts of Cretaceous equability, Palaeoclimates 2 (1996) 139–158.
[30] R.A. Colman, B.J. McAvaney, A study of general circulation model climate feedbacks determined from perturbed sea surface

temperature experiments, J. Geophys. Res. 102 (1997) 19383–319402.
[31] I.M. Held, B.J. Soden, Water vapor feedback and global warming, Annu. Rev. Energy Environ. 25 (2000) 441–475.
[32] R.T. Pierrehumbert, The hydrologic cycle in deep-time climate problems, Nature 419 (2002) 191–198.
[33] R. Caballero, P. Langen, The dynamic range of poleward energy transport in an atmospheric general circulation model, Geophys. Res. Lett. 32 (2005), doi:10.1029/2004GL021581.
[34] R.T. Pierrehumbert, Climate dynamics of a hard snowball Earth, J. Geophys. Res. 110 (2005).
[35] R.G. Najjar, G.T. Nong, D. Seidov, W.H. Peterson, Modeling geographic impacts on early Eocene ocean temperature, Geophys. Res. Lett. 29 (2002).
[36] L.C. Sloan, D. Pollard, Polar stratospheric clouds: a high latitude warming mechanism in an ancient greenhouse world, Geophys. Res. Lett. 25 (1998) 3517–3520.
[37] R.A. Berner, Z. Kothaval, GEOCARB III: a revised model of atmospheric CO2 over Phanerozoic Time, Am. J. Sci. 301 (2001) 182–204.
[38] K. Wallmann, Controls on the Cretaceous and Cenozoic evolution of seawater composition, atmospheric CO_2 and climate, Geochim. Cosmochim. Acta 65 (2001) 3005–3025.
[39] Y. Donnadieu, Y. Goddéris, G. Ramstein, A. Nedelec, J.G. Meert, A ‘snowball Earth’ climate triggered by continental break-up through changes in runoff, Nature 428 (2004) 303–306.