Model Simulations of Cretaceous Climates: The Role of Geography and Carbon Dioxide [and Discussion]

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Model simulations of Cretaceous climates: the role of geography and carbon dioxide

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SUMMARY

A general circulation model (GENESIS) with seasonally varying solar insolation and a mixed layer ocean is applied to assess the role of continental geometry and increased levels of carbon dioxide to explain the warmth of the Cretaceous period. Model experiments suggest that the role of geography is negligible, in contrast to early model studies with mean annual solar insolation and a simple energy balance ocean. Higher atmospheric carbon dioxide (4 times present) resulted in a 5.5°C globally averaged surface temperature increase, close to the lower limit required to explain the geologic record. Mid-Cretaceous carbon dioxide concentrations of 4–6 times the present day concentrations are a reasonable explanation of Cretaceous warmth if the GENESIS model provides an accurate estimate of climate sensitivity to geography and carbon dioxide.

1. INTRODUCTION

The climate of the Cretaceous, with globally averaged surface temperatures 6–14°C higher than at present, represents one of the warm climate extremes of the Phanerozoic (Barron 1983). Since the formulation of plate tectonic theory, changing geography has become one of the most frequently cited explanations of Cretaceous warmth (e.g. Beaty 1978; Donn & Shaw 1977). Increased levels of atmospheric carbon dioxide were also offered as a plausible explanation (e.g. Budyko & Ronov 1979; Fischer 1982). More recently, the carbon dioxide hypothesis received credible quantitative support from the geochemical model of Berner *et al.* (1983) and Berner (1991). Berner (1991) calculates Cretaceous CO_2 levels of 2–6 times the present day values. Freeman & Hayes (1992) have also determined Cretaceous CO_2 levels from fractionation of carbon isotopes from phytoplankton and have calculated values of 4 times the present day values. Cerling (1991) used evidence from palaeosols to determine Mesozoic CO_2 values of 4–9 times present day concentrations.

Early general circulation model (GCM) studies (Barron & Washington 1984) suggest that Cretaceous geography would result in substantial warming relative to the present day but that this warming would be insufficient to explain Cretaceous temperatures. From climate model studies, Barron & Washington (1985) suggest that an increase in atmospheric CO_2 of approximately 4 times the present day would provide a plausible explanation of Cretaceous warmth. The values of Cretaceous atmospheric CO_2 from geochemical models and observations are within the range of estimates derived from the early climate model results (2–10 times) of Barron & Washington (1985). However, to date, the GCM studies of the relative roles of geography and CO_2 in the Cretaceous have relied on mean annual simulations with simple energy balance oceans with no heat capacity. Mean annual models probably do not give a realistic estimate of climate sensitivity and certainly are inadequate for comparing model predicted temperatures with geologic observations. Wetherald & Manabe (1981) and Washington & Meehl (1983, 1984) describe differences in model sensitivity for mean annual and seasonal cycle GCMs. The experiments described here are based on a full seasonal cycle GCM to address: (i) whether geography is a sufficient mechanism to explain Cretaceous climate or whether higher CO_2 is required; and (ii) what level of CO_2 might be needed to explain the warmth of the Cretaceous.

2. MODEL DESCRIPTION

The model experiments employ GENESIS (version 1.02), developed by Pollard & Thompson (1992*a*,*b*), which is an extensively modified version of the NCAR community climate model CCM1. The atmospheric model is coupled to a 50 m slab mixed layer ocean in which the ocean heat transport is included following Covey & Thompson (1989). The major differences from CCM1 (Williamson *et al.* 1987) include: (i) new solar radiation scheme (Thompson *et al.* 1987); (ii) a diurnal cycle; (iii) water vapor advection based on a semi-Lagrangian method following Williamson &

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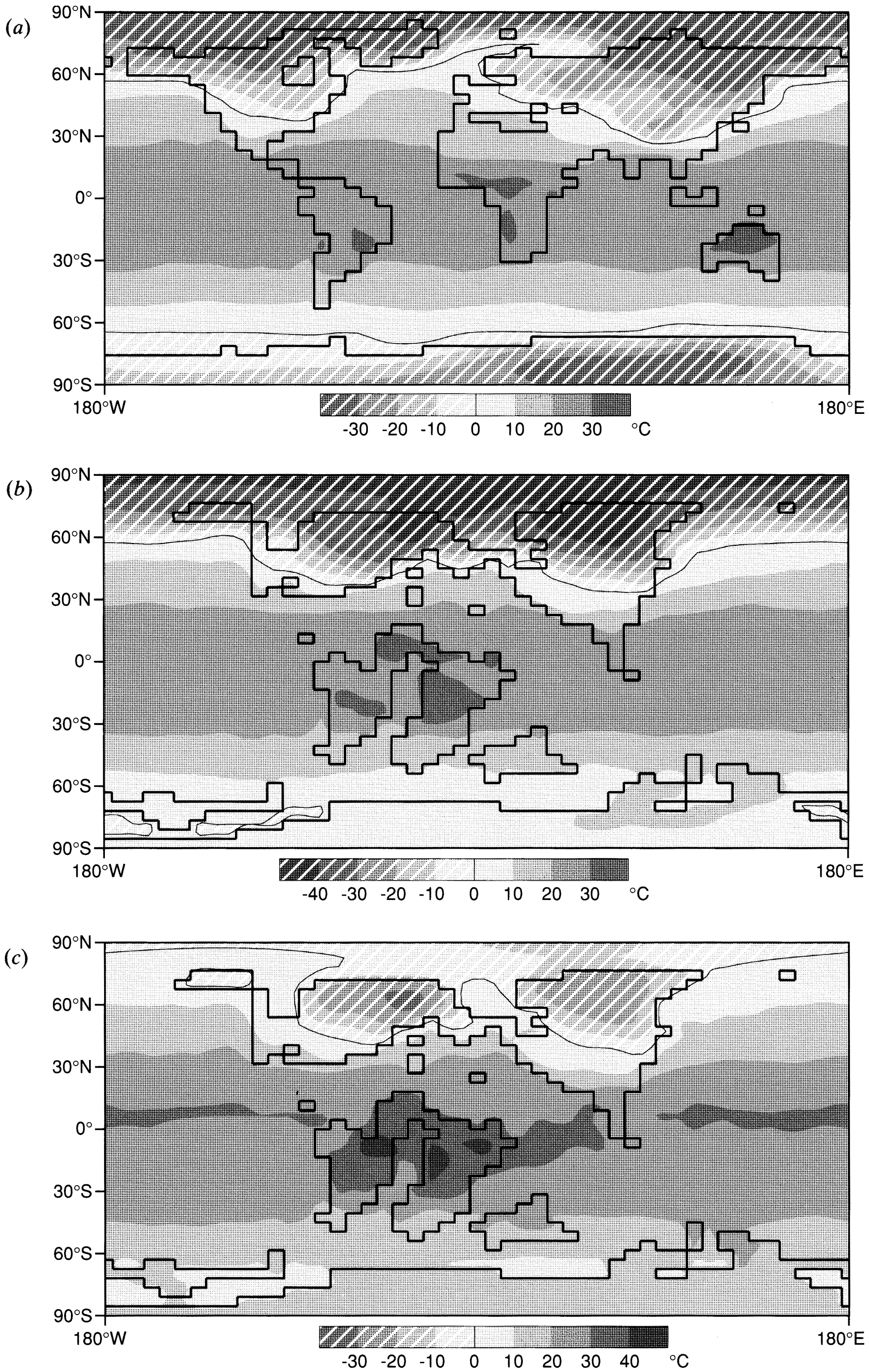

Figure 1. Model predicted surface temperatures (°C, 5° contour interval): (*a*) December, January, February average, Present day; (*b*) December, January, February average, Cretaceous; (*c*) December, January, February average, Cretaceous with 4 times CO_2; (*d*) June, July, August average, Present day; (*e*) June, July, August average, Cretaceous; (*f*) June, July, August average, Cretaceous with 4 times CO_2.

Rasch (1989), Rasch & Williamson (1990) and Williamson (1990); (iv) a new cloud parameterization similar to Slingo & Slingo (1991) and new constraints on stratus clouds when the specific humidity is very low; (v) an explicit sub-grid plume model (simplified for instance from Kreitzberg & Perkey 1976; Anthes 1977, sec. 4, etc) for atmospheric convection; (vi) a 2° × 2° surface resolution with an atmospheric GCM

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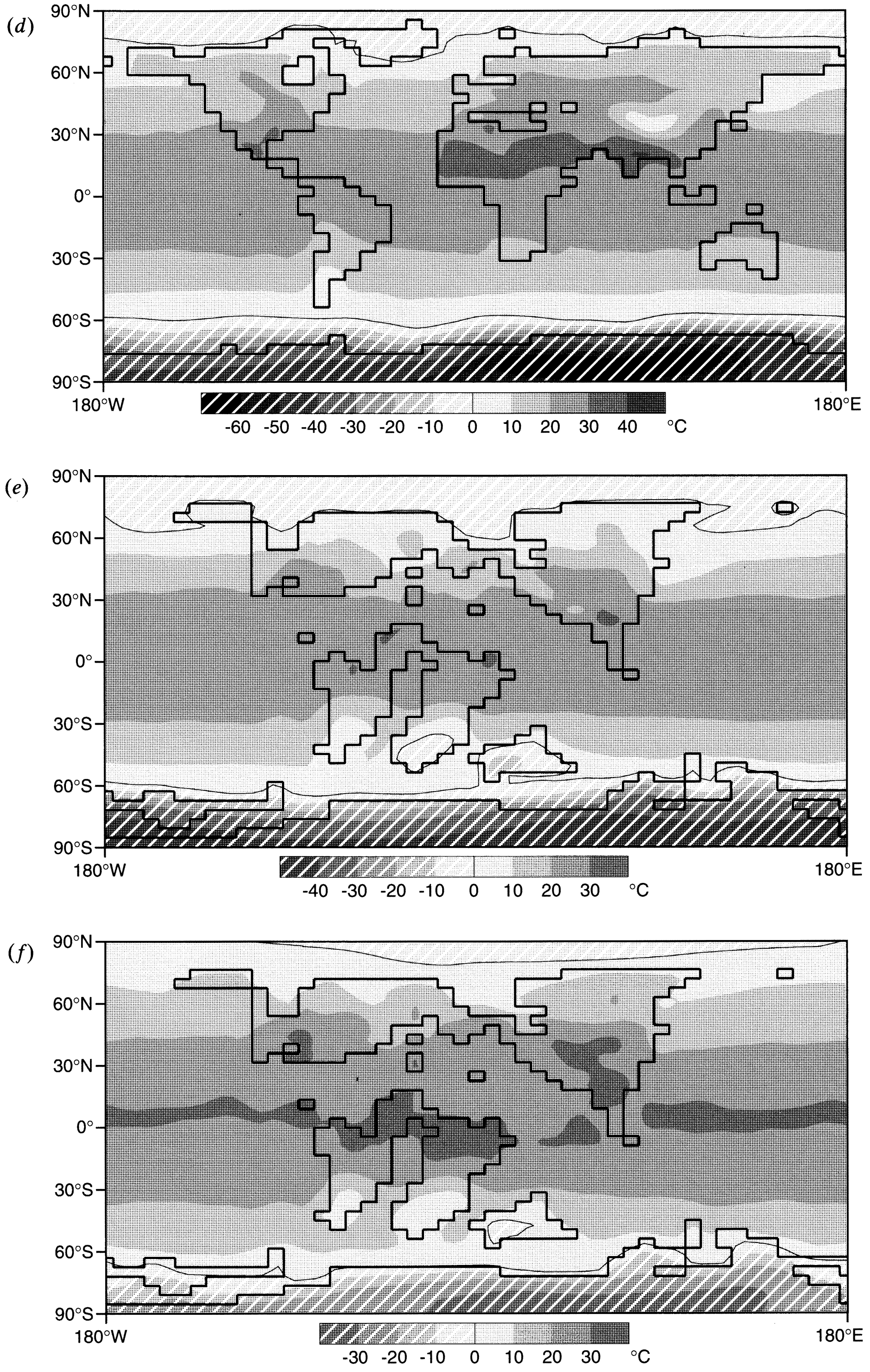

Figure 1 (*contd*)

horizontal resolution of R15 (4.5° latitude × 7.5° longitude); (vii) a land-surface transfer model (LSX) to account for the physical effects of vegetation; (viii) a six-layer soil model; (ix) an improved snow model used for snowcover on soil, ice and sea-ice, and including fractional coverage when the snow thickness is less than 15 cm; and (x) a six-layer sea-ice thermodynamic model following Semtner (1976) and Harvey (1988).

The Cretaceous experiments are based on the continental geography and topography utilized in previous experiments by Barron & Washington (1984, 1985). The solar constant and the Earth's orbit are maintained at present day values. The 'control' value

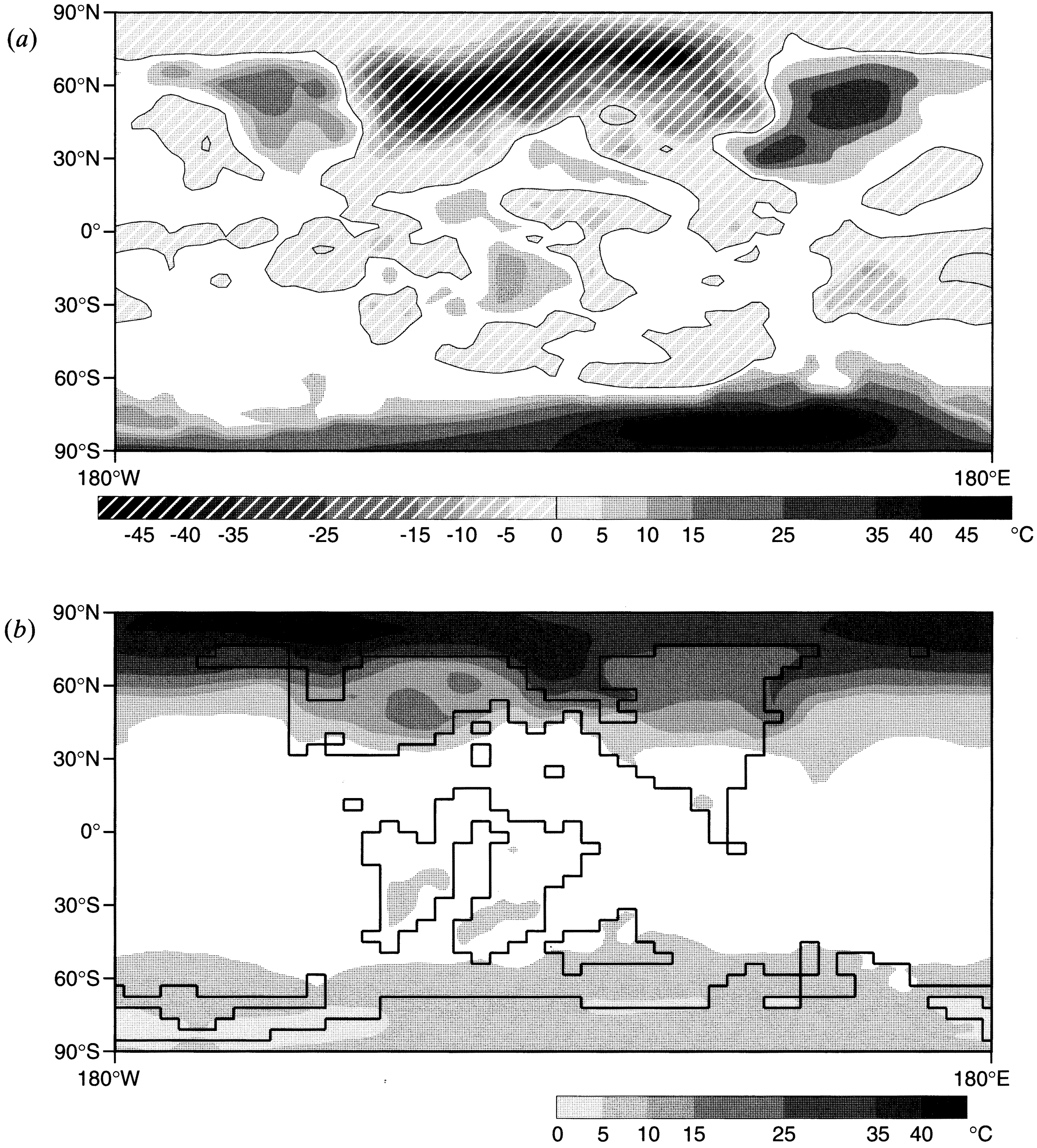

Figure 2. Differences between model experiments (°C, 5° contour interval): (*a*) Cretaceous minus Present day; December, January, February averages; (*b*) Cretaceous 4 times CO_2 minus Cretaceous; December, January, February averages; (*c*) Cretaceous minus present day; June, July, August averages; (*d*) Cretaceous 4 times CO_2 minus Cretaceous; June, July, August averages.

of specified oceanic heat transport (prescribed as temporally and longitudinally constant oceanic heat convergence) for GENESIS was developed based on a best fit with modern observations, which is approximately 15% of the transport calculated by Carissimo *et al.* (1985). For the Cretaceous experiment the heat convergence averaged at each latitude is unchanged from the control, however, because of the change in geography, the heat transport is spread over a different number of gridpoints. This implies reduced poleward heat transport in the Atlantic, and increased poleward heat transport in the Pacific. Atmospheric CO_2 is specified at modern values and then the experiment is repeated with 4 times present day CO_2 concentrations (1360 p.p.m.) following Barron & Washington (1985). In the absence of comprehensive soil and vegetation data a single vegetation type (mixed trees and groundcover) and a single soil type (medium texture and colour) are specified in each experiment. The objective is to determine the model sensitivity to changes only for a different palaeogeography with and without higher atmospheric CO_2.

Each of these seasonal cycle experiments were executed for a period of 15 years, appropriate to

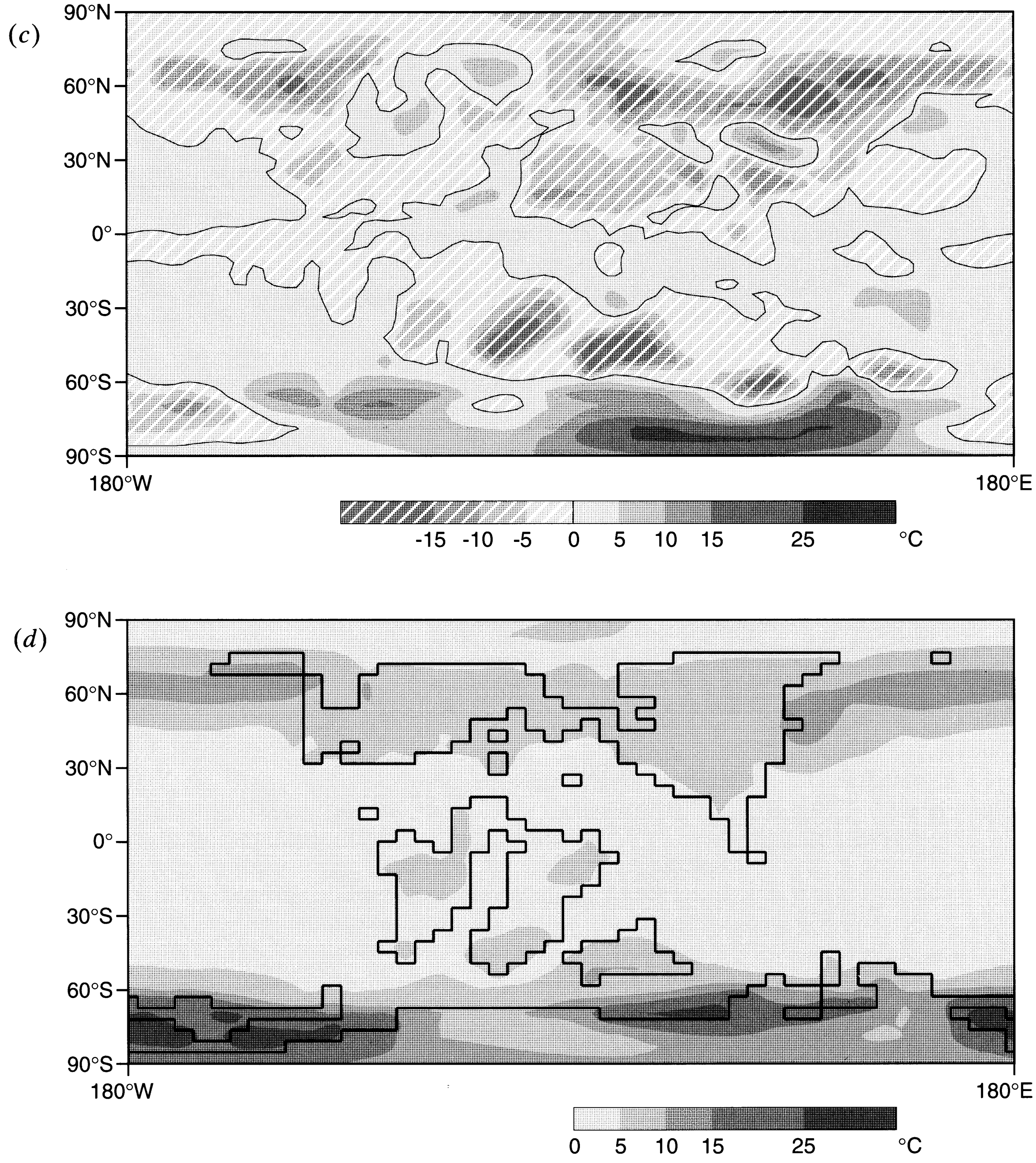

Figure 2 (*contd*)

examine model equilibrium, and averages based on the last three years of simulation are utilized for experiment comparisons. The period of three years for an averaging time is designed to reduce model natural variability in comparison of different model experiments. However, a three year averaging time may not be sufficient for sea ice and continental interiors in winter which have year to year variations of up to 5–7°C (Cao *et al.* 1992).

3. MODEL RESULTS

The model results do not indicate substantial global sensitivity to a change from present day geography to mid-Cretaceous geography, while the increase in atmospheric carbon dioxide concentration resulted in a large global warming.

(*a*) *Surface temperatures*

The change from present day geography to mid-Cretaceous geography resulted in a global cooling of 0.2°C. This result is very different from mean annual models which predicted a 4.8°C temperature increase (Barron & Washington 1984). A similar experiment to the one described here was repeated using a mixed layer version of the mean annual model of Barron & Washington (1984) to confirm that the much reduced sensitivity was not a product of use of the GENESIS model. Only the results of the GENESIS model will be described below. With the exception of Antarctica, systematic latitudinal cooling is not evident. Central Antarctic temperatures are as much as 47°C higher in summer and as much as 27°C higher in winter because permanent ice has not been specified on Antarctica in the Cretaceous. The lack of ice results in substantially lower continental elevations.

In large part, the surface temperature changes are dominated by the movement of land and ocean areas (figures 1 and 2). In subtropical and tropical latitudes, the response of continental regions becoming oceanic and ocean regions becoming continental is very similar. For example, the present day position of Australia was oceanic in the Cretaceous and the model predicted a summer temperature which is 12.7°C lower in the Cretaceous. The South Atlantic was very small in the Cretaceous, and this more continental region has a predicted summer warming of 12.3°C. Consequently, the temperature difference between the two simulations in the tropics and subtropics reflects largely the changes in the position of the continents. In the zonal average, tropical temperatures show little difference between the present and Cretaceous simulations (figure 3).

At middle to high latitudes the change in geography also dominates the response of the model. However, the land and sea responses are very different. Present day continental regions which are oceanic in the Cretaceous are substantially warmer in winter (25–35°C) and are cooler in summer (20°C). Present day oceanic regions which are continental in the Cretaceous are substantially cooler in winter (as much as 45°C) and are somewhat warmer in summer (9°C). Some of the differences in response reflect the fact that during the Cretaceous, North America, Greenland, Europe and Asia were joined as one larger land mass and the widespread epieric seas poleward of the landmass are ice covered in the simulation, yielding a very continental climate.

In both summer and winter the Northern Hemisphere is, on average, cooler above 40°N in the Cretaceous simulation than in the present day control experiment. The model response to increased carbon dioxide concentration is substantially different. The globally averaged surface temperature increases by 5.5°C, close to the lower limit suggested by Barron (1983) as required to explain geologic observations. In winter the Arctic is nearly above freezing with the central region having predicted temperatures of −5 to −10°C. In the Pacific Ocean, the 0°C isotherm is displaced poleward in winter from 60°N to above 80°N. The maximum warming is associated with oceanic regions just poleward of the Western Interior of North America and Europe (41°C). Winter warming, associated with sea ice removal, is in general larger than summer warming. Coastal regions of Antarctica warmed by more than 30°C in winter in the high CO_2 case. Mid-latitude continental regions warmed by 5–25°C in winter. The interiors of the Northern Hemisphere continents above 30–35°N still experience winter sub-freezing temperatures. India and South Africa have sub-freezing winters in the case with present day CO_2 and above freezing winters in the case with four times carbon dioxide.

In summer, the Arctic remains at temperatures near freezing, but is largely ice free in the high CO_2 case. Ocean surface temperatures in the mid-latitudes of the Northern Hemisphere increase by as much as 12°C in the high CO_2 case and continental regions are 5–10°C warmer at 60°N. The margin of Antarctica is warmer in summer by approximately 9°C.

The tropical temperature changes are small but significant. The higher CO_2 case resulted in ocean temperature increases in the tropics of 1.5–2.0°C. Continental temperature increases in the tropics exceed 5°C for the higher CO_2 case. Zonal plots (figure 3) demonstrate that significant warming occurs at every latitude.

(*b*) *Snow cover and sea ice*

The area of snow cover closely follows the predicted zero degree isotherm in the temperature plots of figure 1. From the present day to the Cretaceous, the changes in snow cover reflect the changes in land-sea distribution as described earlier and also the decrease in elevation of the Cretaceous continents (Tibetan Plateau and Antarctica). For increased CO_2 in the Cretaceous, snow cover decreases everywhere except in the interior of the continents of North America and the interior of Antarctica. The increases in snow cover in these regions are small, however. Without higher specified CO_2, the Cretaceous is predicted to have permanent snow in Northwest Alaska, at the North Pole and in the interior of Antarctica (trace amounts in summer). For the higher CO_2 case, permanent snow exists only in the interior of Antarctica and the summer snow cover is only in trace amounts.

In the present day simulation, sea ice exists poleward of 70°N and 60°S. In the Cretaceous simulation sea ice still exists poleward of 70°N, but extends to 65°N in the areas of the Pacific which are continental in the present day. Cretaceous sea ice is simulated in the embayments and seaways that surround Antarctica. For the higher CO_2 case, only a small area of the central Arctic has sea ice cover even in winter. The inland seaways of Antarctica have predicted sea ice cover during both summer and winter, but the regions around Antarctica are largely ice-free.

(*c*) *Zonal winds and storm tracks*

The zonally averaged vertical profiles of the wind for each of the Cretaceous simulations indicate that the Northern Hemisphere jet stream winds are very similar to the present day. Even with global warming, the model is maintaining the vertically integrated temperature structure in the atmosphere. There are some differences from the present day simulation which indicate geographic influences, specifically during summer. The two Cretaceous simulations have similar core jet stream wind speeds, but the value is substantially different than in the present day simulation (20% weaker in the Cretaceous Southern Hemisphere summer and 40% stronger in the Cretaceous Northern Hemisphere summer). In winter, the jet is apparently dominated by the gradient of insolation, while in summer land–sea thermal contrasts must play

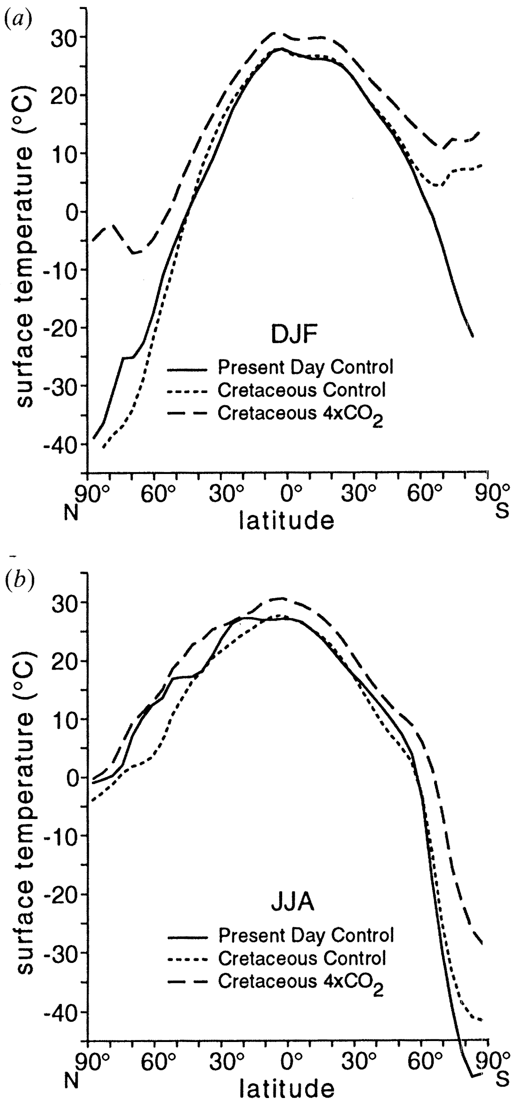

Figure 3. Zonally averaged surface temperatures (°C) with respect to latitude for each model experiment. (*a*) December, January, February averages; (*b*) June, July, August averages.

a significant role and hence there are significant differences between the simulations for present and Cretaceous geography. The fact that increased atmospheric carbon dioxide did not result in substantial change in the vertically integrated meridional temperature gradient or the speed of the jet stream is an important result for the interpretation of model predicted Cretaceous warming.

In the Northern Hemisphere winter Cretaceous simulations, the storm track crosses the northern portion of the Cretaceous Western Interior Seaway, strengthens in the coastal region of the northern bight of Tethys south of Greenland and off the eastern coast of Asia. The position of the storm track is similar for both Cretaceous simulations, with the exception that the 4 times CO_2 case has a more zonal storm track. The centers of storm track activity described above are somewhat weaker in the high CO_2 simulation. In the Southern Hemisphere winter Cretaceous simulations, the storm track is located on the Pacific margin of Antarctica and is strengthened to the east of India. Again, the position is similar for both Cretaceous simulations, however the centers of storm activity are somewhat weaker for the high CO_2 simulation.

(*d*) *Clouds*

Cloud cover changes contribute to the simulated temperature response to geography and carbon dioxide. The regions of increased oceanic area in the Cretaceous (e.g. Tethys) are characterized by greater lower cloud amounts. The removal of the Antarctica ice cap decreases low cloud amount and increases middle level clouds. Higher carbon dioxide concentrations brings higher low level cloud amounts at almost every latitude in the zonal average. Lower cloud amounts are found above this region in middle and low latitudes. The largest increases in cloud are in polar regions, particularly in the winter hemispheres.

4. DISCUSSION

Unlike previous model experiments (e.g. Barron & Washington 1984), the GENESIS simulations suggest that geography plays little role in explaining Cretaceous warmth. The Barron & Washington (1984) simulation, using a mean annual GCM for Cretaceous continental geometry and no specified permanent ice, resulted in a 4.8°C increase in globally averaged surface temperature compared with the present day. The temperature increase in the Northern Hemisphere was the result of decreased continental area at higher latitudes and the warming in the Southern Hemisphere was the result of decreased continental ice cover and lower topographic elevation of Antarctica. In the GENESIS simulations the Northern Hemisphere was actually characterized by slight cooling. In the zonal average, Antarctica warmed by more than 5°C in winter and 30°C in summer compared to the present day control run. Regional temperature increases for Antarctica were much greater.

The differences between the mean annual simulation and the seasonal cycle simulation become critical in determination of the role of geography in Cretaceous warmth. One possibility is that this result is model dependent. The mean annual experiment was completed with an early version of the NCAR community climate model (CCM) while GENESIS has substantial improvements added to the basic formulation of the CCM. However, an additional experiment (not reported here) using a seasonal cycle version of the CCM in other respects identical to the Barron & Washington (1984) experiment produced a very similar result to the seasonal cycle simulation reported here. Evidently, the difference must be associated with the addition of a mixed layer to the model and the fact that the solar insolation is varying seasonally.

A mean annual simulation incorporates substantial solar insolation at the poles in a perpetual mode, and the energy balance ocean lacks any thermal inertia. The analysis of the GENESIS model results suggests that the seasonal cycle model results in a more continental climate in the Cretaceous. North America, Greenland and Europe are joined as one land mass. In terms of area, the land fraction poleward of 40°N is less than the present. However, in the seasonal experiment, the seaways poleward of the Cretaceous land mass are covered in sea ice during winter. The result is a very continental winter climate, similar to a larger supercontinent. The Cretaceous oceanic regions which are continental today because of the opening of the North Atlantic are characterized by warmer surface temperatures. However, the joining of the Cretaceous continents produces a greater cooling over the land and sea ice areas. The net result for the winter zonal average is a slight cooling poleward of 45°N in the Cretaceous simulation in comparison with the present day model experiment. In the Northern Hemisphere summer, the climate is less continental. Sea ice melts and the increased oceanic area, which modulates temperatures through evaporative cooling, results in lower zonally averaged Cretaceous summer temperatures over much of the hemisphere in comparison with the present day experiment.

Given this interpretation, the use of models which are based on annual insolation and which lack thermal inertia are suspect in providing estimates of climate sensitivity to changes in high latitude land–sea distribution. The mean annual simulation also apparently biases the warming due to the removal of the Antarctic ice cap, although both mean annual and seasonal cycle versions resulted in substantial warming at high southern latitudes.

A second major issue is the amount of carbon dioxide required to maintain Cretaceous warmth if the change in geography is a negligible forcing factor for changes in global temperature. The mean annual experiment of Barron and Washington (1985) for a 4 times increase in carbon dioxide resulted in a 3.6°C increase in globally averaged surface temperature compared to the Cretaceous experiment with present day carbon dioxide concentrations. The seasonal cycle experiment described here resulted in a much greater sensitivity to the quadrupling of carbon dioxide concentration (5.5°C). The maximum temperature increases occur in the Northern Hemisphere winter at higher latitudes and during both winter and summer at high southern latitudes. The warming occurs at all longitudes at high latitudes indicating a substantial role by ice-albedo feedback in the enhancement of the carbon dioxide warming and a winter warming enhancement through the removal of sea ice. These effects should be much greater in the experiments described here than in the mean annual experiment which already had a substantial reduction in snow and ice cover in the Cretaceous base experiment.

The warming in the Cretaceous experiment with enhanced carbon dioxide is at the very lower limit of interpretations of Cretaceous temperatures (e.g. Barron 1983). The assessment of carbon dioxide levels from geochemical analyses (Berner 1991; Cerling 1991; Freeman & Hayes 1992) which range from 2–9 times present day values appear to be entirely appropriate from a climate model perspective. Based on GENESIS experiments, 4 times CO_2 appears to be a lower limit, and if globally averaged surface temperatures were as much as 12°C higher than at present, then the upper limit from the geochemical analyses would be more appropriate. Carbon dioxide concentrations of 4–6 times present concentrations are a reasonable explanation of Cretaceous warmth.

However, general circulation model sensitivities to a doubling of carbon dioxide range from 1.5 to more than 4.5°C (Intergovernmental Panel on Climate Change 1990). These differences reflect the importance of different parameterizations (e.g. clouds, land surface–atmosphere interaction) in model development. GENESIS sensitivity (2.3°C increase in globally averaged surface temperature for a doubling of carbon dioxide) is in the lower range of sensitivity for similar GCM experiments. If the climate system has a greater sensitivity, closer to the upper limit of the IPCC assessment, then the amount of carbon dioxide required to explain the warmth of the Cretaceous could be closer to a range of 3–5 times modern concentrations.

An additional point of significance for the carbon dioxide experiments is that tropical temperatures increase substantially, 1.5–2.0°C over the oceans and more than 5°C over the land areas. The increases predicted for the tropics are at the upper limit of tropical surface ocean temperatures interpreted from oxygen isotopic values from planktonic foraminifera (for a review, see Barron 1983). Higher levels of carbon dioxide may produce tropical temperatures which exceed temperature tolerances for some organisms or which exceed the values obtained from oxygen isotopic measurements.

The increase in tropical temperatures due to higher concentrations of carbon dioxide is closely tied to the fact that GENESIS appears to maintain the total poleward heat transport in the model. The decrease in sensible heat transport by the model associated with large polar warming and a decreased equator-to-pole surface temperature gradient is compensated for by increased latent heat transport. The increase in tropical temperatures results in increased latent heating of the tropical atmosphere through the Clausius–Clapeyron relationship. The vertically integrated temperature gradient in the atmosphere is maintained because polar warming is accompanied by a smaller, but significant increase in tropical temperatures which results in latent heating of the tropical atmosphere. The tendency to maintain the total poleward heat transport is not an unusual feature of mixed layer GCMS (Barron 1987). However, recent studies which incorporate significant changes in oceanic heat transport suggest that a change in the role of the ocean could influence the total poleward heat transport and the characteristics of the tropical surface temperatures (Covey & Thompson 1989; Rind & Chandler 1991; Barron *et al.* 1993). The role of the ocean has not been addressed by the model experiments described here, and consequently the predictions for the tropical regions must remain tentative.

5. CONCLUSIONS

The seasonal cycle simulations with GENESIS suggest that Cretaceous continental geometry played a negligible role in explaining the global warmth of the Cretaceous.

The difference between previously published mean annual simulations which suggested that Cretaceous geometry played a significant role in Cretaceous warmth, and the experiments described here is a product of seasonally varying insolation and the role of thermal inertia, in conjunction with the specific configuration of the Northern Hemisphere continents.

The experiment for a quadrupling of atmospheric carbon dioxide for the Cretaceous experiment resulted in a 5.5°C globally averaged surface temperature increase, close to the lower limit required to explain Cretaceous warmth. Carbon dioxide concentrations of 4–6 times present values are a likely explanation of the Cretaceous warmth.

The major uncertainties in the above estimate reflect uncertainties in model parameterizations for clouds and land–atmosphere interaction and the lack of an explict ocean in the GCM calculations.

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Discussion

A. Berger (*Université Catholique de Louvain, Belgium*). What is the sensitivity of the simulated climate to the change in orbital parameters and insolation?

E. J. Barron. Although numerous Cretaceous model experiments for changes in orbital parameters have been completed, none of these experiments have yet been based on a full seasonal cycle experiment. In each case, perpetual (fixed) July or January insolation was specified. Further, the GENESIS model has not been utilized as yet for Cretaceous orbital experiments. For these reasons, a comment on the model sensitivity is not appropriate at this time.

P. Valdes (*Department of Meteorology, University of Reading, U.K.*). Given that the solar constant may have been less by about 1–2%, what CO_2 values does this suggest for your model simulations?

E. J. Barron. The best estimates for the mid-Cretaceous solar constant is about 0.9% less than the present day according to Gough (1977). This would imply that the estimate of 4 to 6 times the present day carbon dioxide required to achieve Cretaceous warmth estimated in this paper would be an underestimate since the solar constant was lower.

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