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Geological evaluation of multiple general circulation model simulations of Late Jurassic palaeoclimate

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Abstract

General circulation models (GCMs) are currently used to predict future global change. However, the robustness of GCMs should be evaluated by their ability to simulate past climate regimes. Their success in 'retrodiction' can then be assessed by reference to the geological record. Geological evidence provides a database that can be used in the estimation of sea surface temperatures, orography and other proxy data useful in palaeoclimatic studies. These data can then be used to refine the prescribed boundary conditions for running GCMs themselves. Results from a series of modelling experiments, run with Late Jurassic (Kimmeridgian) boundary conditions, and using the UK University Global Atmospheric Modelling Programme (UGAMP) GCM and the UK Meteorological Office GCM are presented. Simulations from these two quite independently generated models, although subtly different, confirm a generally warmer Jurassic Earth with arid zones over the Tethys and SW USA, parts of Gondwana dominated by 'monsoonal' systems and convective rainfall generally higher over the oceans than at present. Circum-polar wetlands are also indicated. These results generally conform well to the distributions of known facies in these regions. Modelled cloudiness is also higher in the Jurassic, and although unconfirmed geologically, such conditions would have contributed to greenhouse conditions at high latitudes and could have influenced both terrestrial biomes and marine ecosystems. Using one of the GCMs (UGAMP) we have also investigated the role of orbital parameters for high latitude climate. At times of 'minimum seasonal forcing' (comparable with an orbital geometry affecting the Earth at 115 ka BP) parts of Antarctica could have sustained a modest ice sheet over areas exceeding 1 km elevation, but such modelled sheets would have been ephemeral features and very dynamic in character. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

On account of growing interest in the mechanisms of climate change, controls of eustasy and the potential use of Milankovitch cyclicity in high resolution stratigraphy, it is important to understand the ways in which orbital forcing might effect changes in climatic patterns on the earth. General circulation models (GCMs) have been extensively used to study past climate change. The aim of such work is to help understand the causes of climate change, and to test models that are themselves used to predict future climate

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change (whether anthropogenically or naturally driven).

The Late Jurassic is a particularly interesting time interval to study because 'greenhouse' conditions are generally agreed to have existed on an Earth assumed to have been essentially free of polar ice caps [reviewed in Hallam (1985, 1993) and Crowley and North (1991)], although the possibility of Late Jurassic ice is discussed by Frakes et al. (1992). There is a rich and diverse geological and palaeontological database, particularly for continental areas, although the record is not so good in oceanic regions. Still, sufficient data exist to allow model predictions to be evaluated. Thus the robustness of the models themselves may be evaluated by applying them to ancient times from which palaeoclimate data are diverse, both in type and distribution. The uncertainties in the models may be more fully appreciated when inter-model comparisons are made using an identical input for each [e.g. land–sea mask, orography, sea-surface temperature (SST) profile, etc.].

Over the past few years we have employed a version of the GCM of the UK Universities Global Atmospheric Modelling Programme (UGAMP) to model climate patterns for selected times in the past (e.g. Kimmeridgian, Cenomanian, Early Eocene; Valdes and Sellwood, 1992; Price et al., 1995; Valdes et al., 1996; Sellwood and Valdes, 1996). More recently we have begun to use the independently developed UK Meteorological Office (UKMO) GCM. This latter model is widely used for present and future climate change experiments and is an important part of the scientific and political decision-making process. The differences in output between these two different models throw light on the robustness of the models themselves, and upon the workings of climate regimes very different from those we experience today. GCMs of the Late Jurassic have also been run by Ross et al. (1992) and Moore et al. (1992a,b), and simpler conceptual-type models have been used by Parrish (1982) and Scotese and Summerhayes (1986). Valdes et al (1995) also considered the role of orbital variations. They found that, in the UGAMP model, changes in orbital forcing could initiate a small ice cap in the southern hemisphere. However, the result is very sensitive to the simulation of temperature in the 'control' Kimmeridgian simulation (i.e. using orbital parameters for present day). Thus, to gain greater confidence in this result we need to provide further confirmation of the model-predicted temperatures.

This paper is organised as follows. Section 2 describes the two GCMs used in the study and Section 3 evaluates the 'control' Kimmeridgian climates of the two models. Section 4 then considers the implications of the results for modelling orbital variations. The paper ends with a more general discussion and conclusions.

2. Model descriptions

The UGAMP and UKMO models are radically different, sharing no common components. They are both high-resolution models and have a similar range of parameterisations, but no two schemes are identical. The details of the UGAMP have been described in Valdes (1993) and Valdes and Sellwood (1992). It is spectral and operates on a horizontal grid of $3.75^\circ \times 3.75^\circ$ (96 longitudes and 48 latitudes; i.e. about 500 km^2). The UKMO model is a grid point model operating with 96 longitudes and 72 latitudes. It includes the same processes as in the UGAMP model, but the details of each parameterisation scheme are different. The biggest differences occur in the treatment of the land surface. The UGAMP model includes vegetation only through variations in albedo and surface roughness. The UKMO model also includes a detailed treatment of evapotranspiration. This makes it difficult to match the two schemes completely, but in both Kimmeridgian simulations we use parameters appropriate to shrub land everywhere. For more details of the UKMO model see Hewitt and Mitchell (1996) and references cited therein.

Both models have been adapted to Kimmeridgian boundary conditions by changing the coastlines [Fig. 1; from Smith et al. (1994)], mountains (mean height; Fig. 1), land surface type, sea surface temperature (SSTs), and carbon dioxide concentration. To ensure that the two models used identical conditions we directly converted the UGAMP resolution orography into the UKMO

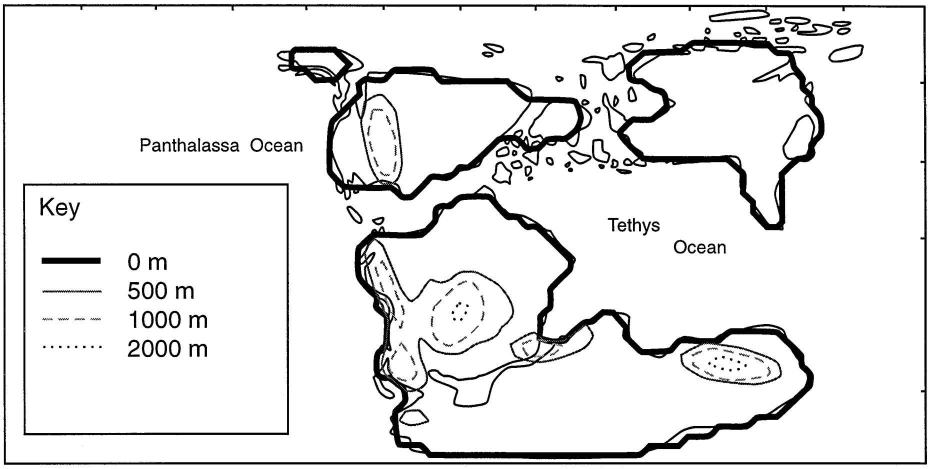

Fig. 1. The Kimmeridgian land-sea mask and orography as used in all model simulations. India, Antarctica and Australia form one large land mass, joined to Africa and South America by a small land bridge. Australia (centred near 60°S, 120°W) has a small area of high relief.

resolution orography. Thus the two models used identical orography. We prescribed a zonally uniform SST of $27^{\circ} \times \cos(\text{latitude})$ and it did not change with the seasons, as justified in Valdes (1993) and Valdes and Sellwood (1992). The temperatures were consistent with the energy balance of the models, provided that carbon dioxide concentrations were three to four times present-day values. Such figures are consistent with those calculated by Berner (1992). By fixing these temperatures, we have implied a change of poleward transport of oceanic heat flux. It was found that the annual mean oceanic heat transport was significantly weaker than that of the present day. SSTs were also parameterised identically in both models. Both models employ very different land surface regimes, but land surface was set at shrub-type vegetation everywhere in both models. All other parameters were kept at their present-day values.

In order to examine the UGAMP model's response to Milankovitch variations we used a similar approach to that used for many future climate change scenarios (Gates et al., 1990), namely a mixed layer ocean (Valdes et al., 1995) in which the ocean is modelled as a single thermodynamic slab 50 m thick, with a prescribed oceanic heat flux that is the annual mean value derived from the simulation in Valdes (1993). It has both longitudinal and latitudinal structure, but no seasonal variations. This approach is similar to that used by Barron et al. (1993) and Oglesby and Park (1989) for modelling Cretaceous orbital variations, except that they used an oceanic heat transport that was a simple multiple of the present-day value. However, as we currently have no way of determining palaeo-ocean heat flux, either approach represents a gross simplification of the true climate system. The important aspect to note is that SSTs can now vary seasonally, as well as when orbital changes are applied.

3. Simulations

With the UKMO model we performed a single experiment of total length 7 years, averaging the last 6 years. With the UGAMP model we performed an identical experiment. The experiment was actually longer, but we only sampled the same period as for the UKMO. These form our Kimmeridgian 'base' simulations. In addition, we also compared these simulations with those described in Valdes et al. (1995). These simulations used a slab ocean model with prescribed ocean heat flux deduced to reproduce as closely as possible the SSTs used here. The first simulation used the same orbital parameters as in the base simulations. The resulting climate was almost identical and we do not need to consider it further. The other two experiments used orbital parameters at two extremes of orbital variations. In this paper we will only concentrate on the orbital change equivalent to that which occurred 115 kyr BP (obliquity: 22.41°; eccentricity: 0.04142; longitude of perihelion: 291.02°). This corresponds to less solar insolation in summer and hence cooler conditions in both hemispheres.

3.1. *Results for the 'control' simulations*

The basic patterns for all parameters were similar in both models, but there are some subtle but significant differences between them. We highlight these below and in Table 1.

In the 'base' simulation using UGAMP the average global temperature is 20°C compared with 14.1°C today. A warmer Earth should be a more humid earth and this is reflected in a slightly increased cloud cover (58% for the Kimmeridgian as opposed to 55% at present) and a higher total rainfall (2.6 mm day^{-1} by comparison with 2.3 mm day^{-1} today). A significant difference between the Kimmeridgian and the present is, for the Kimmeridgian, the focusing of rainfall over the oceans, the relative dryness of continents and the increased moisture in circum-polar areas, regions that today have generally low precipitation. In both models cloud cover is particularly high over polar areas (Sellwood and Valdes, 1997), but more so in the UGAMP than in the UKMO model.

A comparison between the annual mean surface air temperature output for both models is given in Fig. 2a and b. The UGAMP mean surface temperatures show the Tethys to have been an essentially warm water system (with only very small seasonal variations). Continental temperatures only fall to just below zero over Siberia, the lowest values occurring over simulated cordilleran uplands. Arctic coastal areas are modelled to be essentially ice-free. In the southern hemisphere the generally low-lying (Antarctic–India–Australian) parts of the disintegrating Gondwana continental mass experience warm to hot summer temperatures but with winter lows of −24°C over localised rift-related uplands resulting in an annual mean below zero. The UKMO model shows similar patterns (Fig. 2b). The differences in continental temperature predictions between the two models are best expressed in terms of a temperature difference map (Fig. 2c), in this case the difference in annual mean surface air temperature. The UKMO model is colder. The biggest differences occur in the summer season (not shown). These differences are mostly due to the differences in convective schemes employed by the models and in the way that they treat the evaporation of soil moisture. In the UGAMP scheme the soil dries out quickly and so the soil warms up quickly. In the UKMO model the soils dry out more slowly, so soils warm more slowly. Wetter continental interiors allow more evaporative cooling and this results in the UKMO model being 6°C, or more, cooler than the UGAMP model (see Fig. 2c).

The annual mean surface temperature output from both models shows a substantial part of disintegrating Gondwana as being sub-zero. If such sub-zero mean annual temperatures are

Table 1
UGAMP and UKMO GCM parameter comparison[a]

	UGAMP		UKMO	
	'base'	'control'	'base'	'control'
Global surface air temp. (°C)	19.5	13.6	18.0	13.5
Cloud cover (%)	58	56.6	56	57
Global precip. (mm/d)	2.8	2.5	33.5	3.1

[a] N.B. 'control' simulations were run with present-day orbital parameters, namely obliquity: 23.44°; eccentricity: 0.0167; longitude for perihelion relative to vernal equinox: 282.04°.

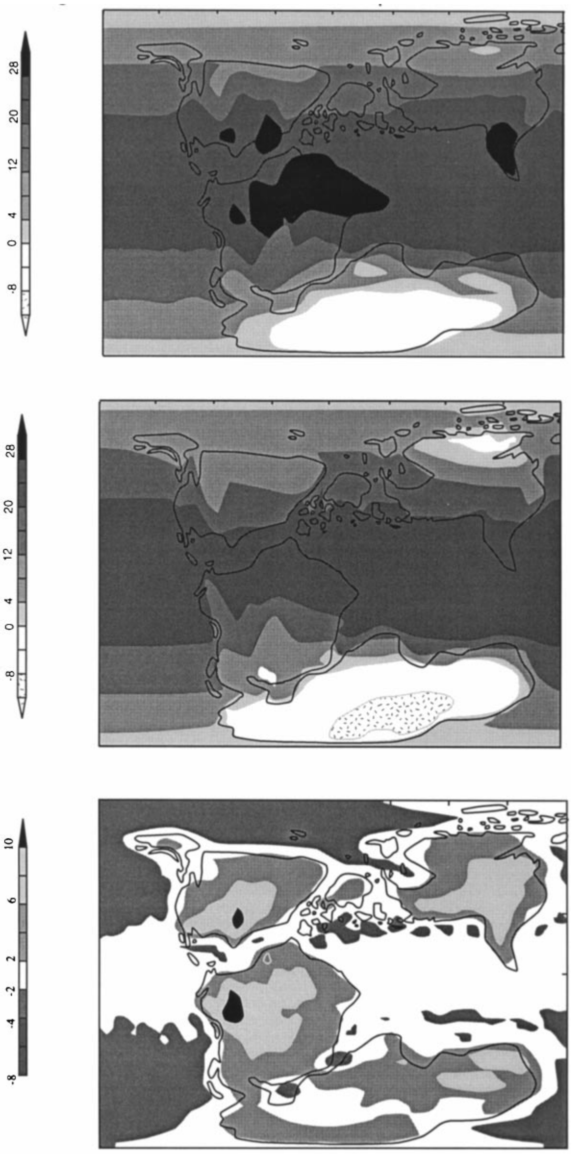

Fig. 2. Kimmeridgian annual mean surface air temperature (°C): (a) UGAMP model; (b) UKMO model; (c) difference in values as UGAMP minus UKMO.

sustained today for more than two successive years the area experiencing them is defined as having permafrost. The UKMO model also indicates a small region with sub-zero mean annual temperatures in NE Siberia, whereas the UGAMP model predicts no sub-zero values in the northern hemisphere. Permafrost features are readily recognisable in Quaternary and Recent deposits but have yet to be described from Mesozoic successions. However, modelling suggests the most likely areas where such features might be found if depositional conditions were appropriate to preserve them.

Annual total precipitation for both models is given in Fig. 3a and b. In the UGAMP model the total precipitation for DJF and JJA [not illustrated here but can be seen in figs. 4–6 of Valdes (1993)] follows the maximum in the SSTs and subtly shifts with the inter-tropical convergence zone (ITCZ). Large areas with heavy rainfall occur over the oceans and large tracts of continental interiors (e.g. North America and Asia) have low rainfall and correspond with known desert facies (e.g. Bluff Sandstone and Recapture aeolian Members of the Morrison Fm. with their associated sabkha deposits; Blakey et al., 1988). There is a band of heavy precipitation over the Equatorial Tethyan Ocean in JJA that only impinges on land in a small belt over Northern Africa and the Eurasian peninsula. This predicted area of precipitation over Africa is in reasonably good agreement with geological observations of bauxite, coal and evaporite distributions (Fig. 4a and b, Price et al., 1997). Monsoon systems typify SE Asia in the JJA period, whereas Eastern Arabia, Central Africa and Brazil have a monsoon in DJF. The percentage differences in total precipitation between the two models are very significantly dissimilar, with the UGAMP model predicting mid-latitude arid zones (e.g. the Gulf of Mexico) much better than the UKMO model (which predicts very heavy winter rainfall in an area known to have evaporites; Fig. 4).

The formation of evaporites and other hydrologically sensitive deposits is probably more clearly shown by examining, for the UGAMP model, the surface soil moisture for DJF (Fig. 5a) and JJA (Fig. 5b), and in the UKMO model in Fig. 6a and b. This is a more straightforward diagnostic than the ‘precipitation minus evaporation’ field since, in the latter, evaporation should be a measure of the potential evaporation, not the actual value. Soil moisture takes this into account. Regions that are seasonally dry are regions where, potentially, either laterites or evaporites may form (Sellwood and Price, 1993). Such regions occur over many of the areas bordering the tropical Tethys Sea

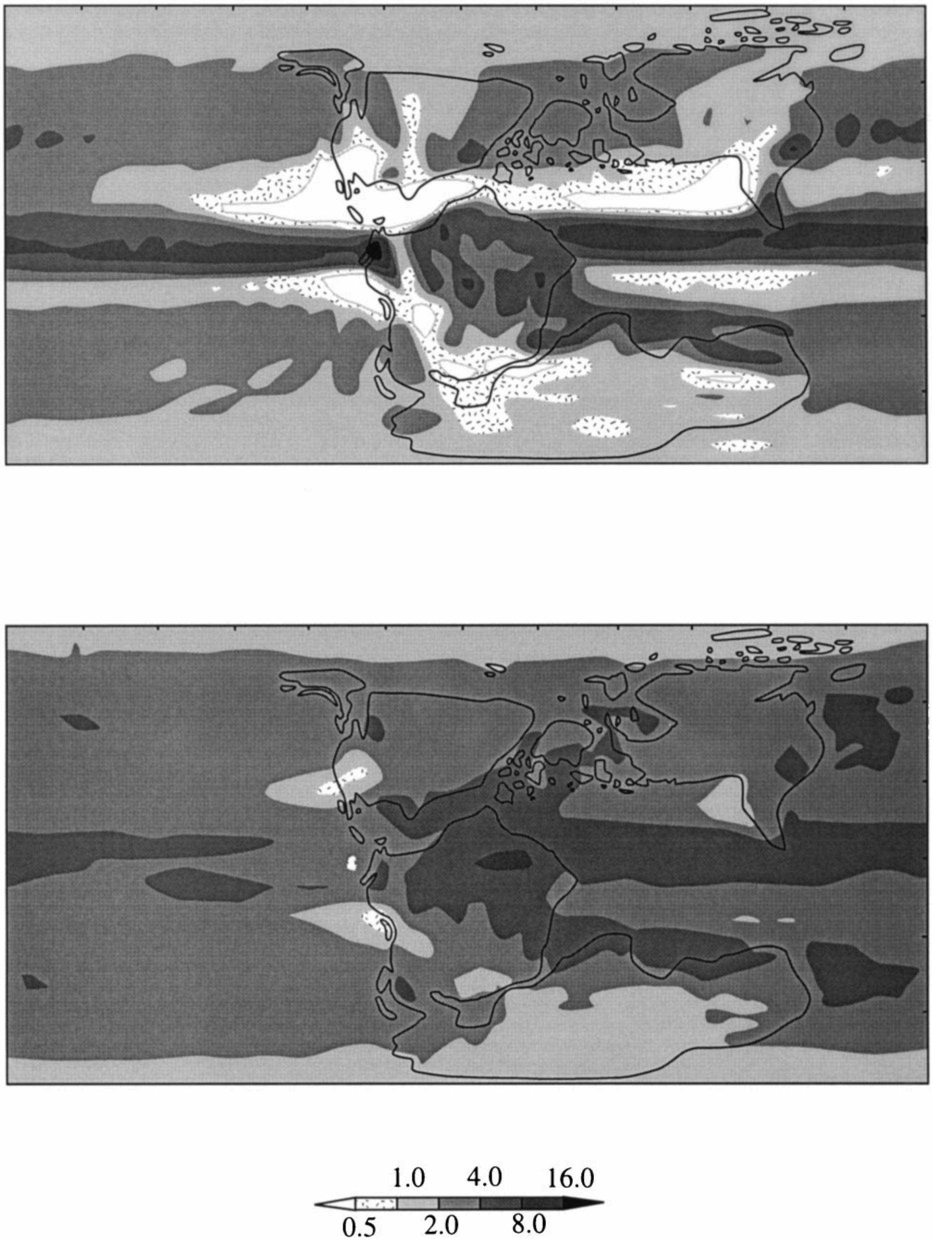

Fig. 3. Annual mean precipitation (millimetres per day): (a) UGAMP model; (b) UKMO model.

(Fig. 4). Again, the patterns are similar between the models but the figures clearly show that the UKMO model is generally wetter. In general, there is poorer agreement with data for the UKMO model.

4. A Jurassic ice cap?

At high latitudes in the southern hemisphere the large and mostly low-lying pieces of the Gondwana landmass experience large seasonal

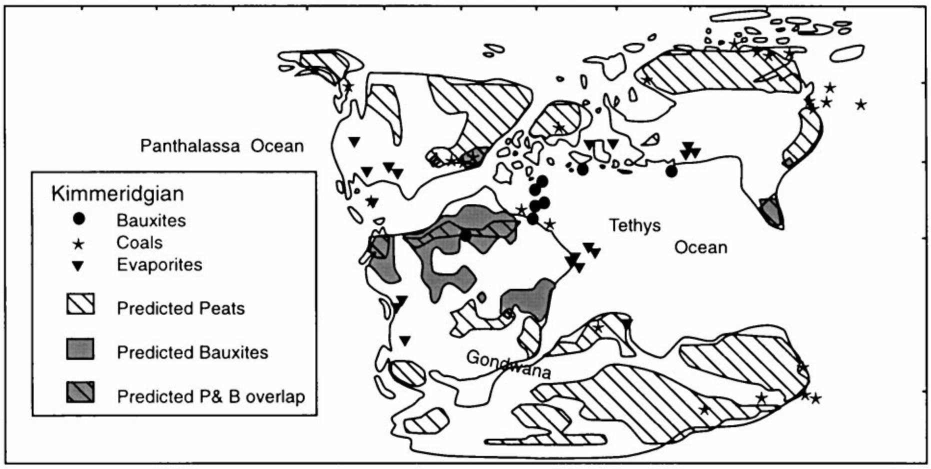

Fig. 4. Areas predicted by the UGAMP model as having the potential to accumulate peats and bauxites. Actual occurrences of Kimmeridgian bauxites, coals and evaporites are shown for comparison with the model predictions.

variations in temperature. Both models predict winter temperatures dropping to as low as −20°C, resulting in heavy snow over much of the continent (see Figs. 7 and 8). Both models predict much warmer temperatures in summer (greater than +20°C). This warmth is enough to melt all of the snow, but the snow-free time can be quite short (3 months for the UGAMP model and 2 months for the UKMO model). In the northern hemisphere, both models show a similar behaviour but the snow-free period is much longer. These results show that the 'control' climates of both models are similar, with respect to high latitude temperature and snow. This is an important result. In Valdes et al. (1995) we examined the sensitivity of the UGAMP model to changes in orbital forcing. For the case of an orbit with reduced summer insolation (orbital parameters equivalent to 115 kyr ago, which effectively had a reduced seasonal forcing, termed 'minimum seasonal forcing') the model predicted cooler summers and less melting of winter snow. In the northern hemisphere this did not change the intrinsic characteristics of the climate. However, in the southern hemisphere the cooler summers resulted in the potential for some regions to experience snow lasting throughout the year. Fig. 9 (for DJF, the southern hemisphere summer) shows that the seasonal mean has an extensive region of snow cover. Further examination shows that the snow does disappear for a very short period in February. This would imply that the UGAMP model is very close to the threshold for the development of an ice sheet. This threshold is entirely governed by the summer temperature. If this rises too high, then the snow will melt. The model intercomparison shows that the UGAMP predictions are robust and that the real Jurassic climate is likely to be close to this threshold. The result is further confirmed by the recent work of Valdes and Glover (1999), who showed that the UGAMP model, when used for Quaternary palaeoclimates, correctly simulates the initiation of the last glacial cycle because it has a good 'control' climate and a realistic climate sensitivity.

We also tested the extent to which the UGAMP model could sustain an ice sheet on the low-lying southern continents. This involved 'seeding' the 'control' simulation with an initial condition that included 5 m of snow cover upon all land poleward of 45° latitude. The ice melted rapidly in both hemispheres. Within three simulated years the 'seeding' ice sheets had contracted to much smaller areas and there was no region in which an ice sheet grew thicker. So, any ice sheet produced at high altitudes in a cold Milankovitch phase would

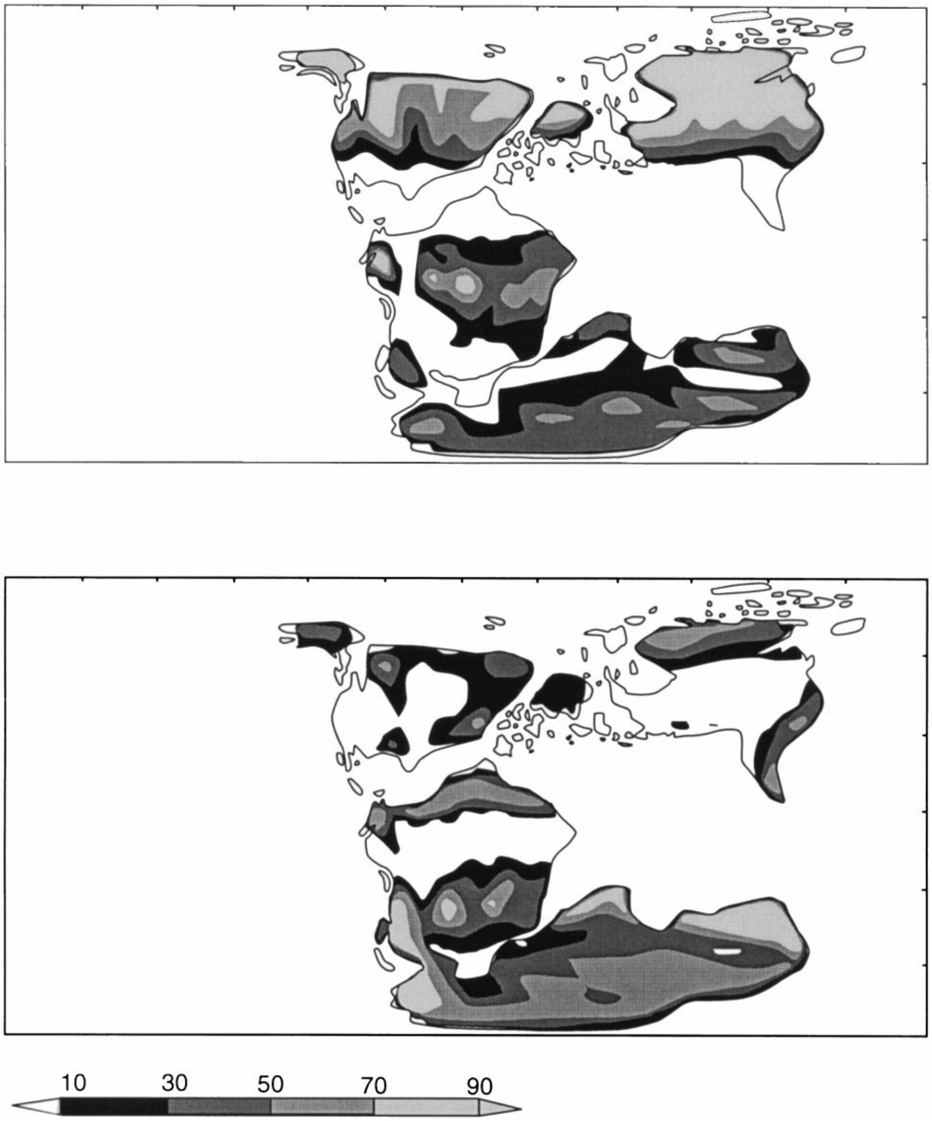

Fig. 5. UGAMP output showing surface soil moisture. Saturation scale is 0% saturation through to 100% saturation using contour intervals of 10%: (a) DJF; (b) JJA.

have quickly melted when the orbital parameters returned to those comparable with present-day values. But the possibility still exists, over high latitude southern uplands, for ice to both accumulate, and disappear, on a Milankovitch time-scale, and in volumes sufficient to produce metre-scale changes in sea-level. The land area covered by snow in the 'minimum seasonal forcing' run was approximately $6–9 \times 10^6$ km^2. If such an ice sheet did wax and wane, then it could have easily resulted in metre-scale variations of sea level.

Although these results appear to be robust, there is one major caveat. Both models are sensitive to the precise choice of SST and ocean heat flux. Moore et al. (1992a,b) used a very different prescription of ocean heat transport, and this resulted in much colder seasonal temperatures. The papers did not describe the resulting prediction

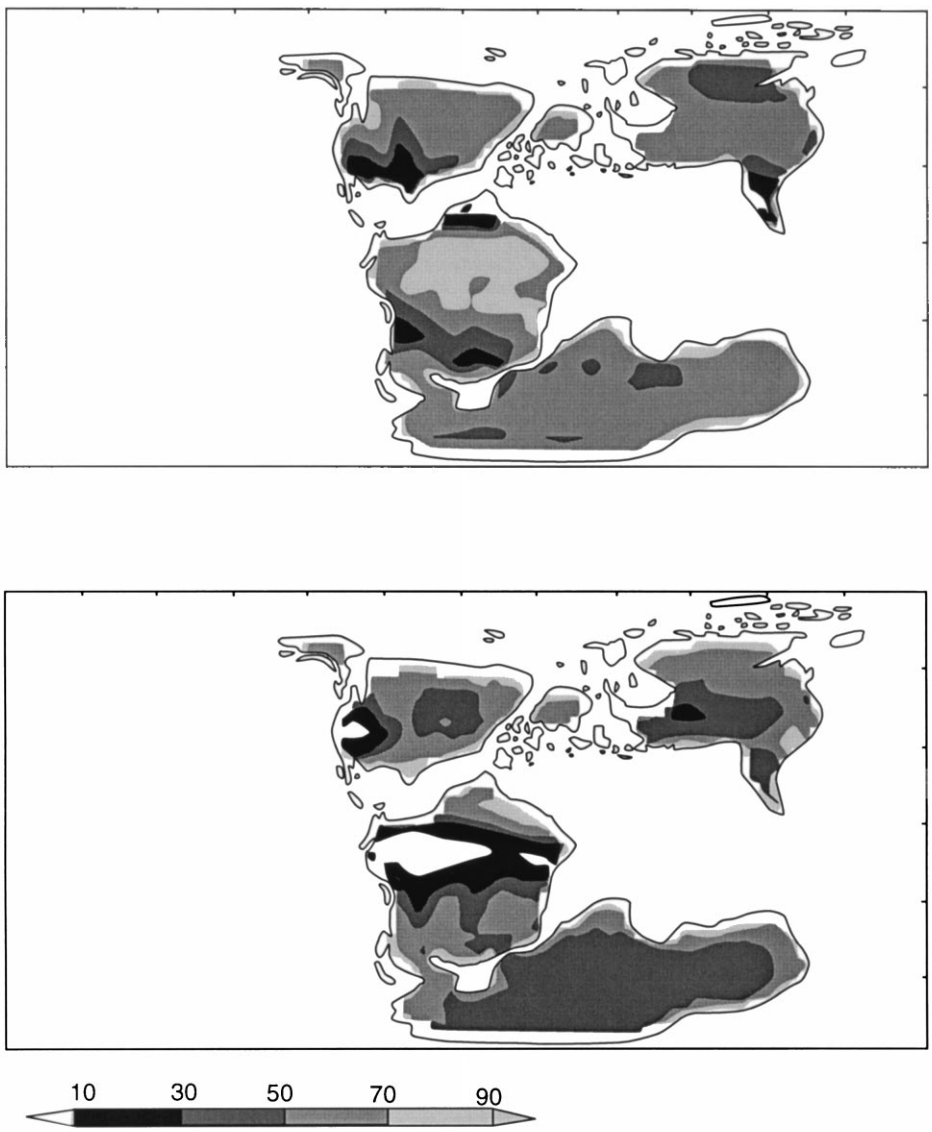

Fig. 6. UKMO output showing surface soil moisture. Saturation scale is 0% saturation through to 100% saturation using contour intervals of 10%: (a) DJF; (b) JJA.

of snow cover, though the colder temperatures would suggest that it was close or even past the threshold for perennial snow.

5. Discussion

The distribution of climatically sensitive facies (climate proxies) such as coals, evaporites, bauxites, laterites and diagnostic palaeosols suggests that the UGAMP model is doing reasonably well in simulating the Kimmeridgian climate (Valdes et al., 1995; Price et al., 1997). In addition, the distributions of high and low pressure systems and their associated circulation patterns, which might produce upwelling, conform reasonably well with the distributions of known organic-rich marine sediments (Price et al., 1995). This is clearly seen

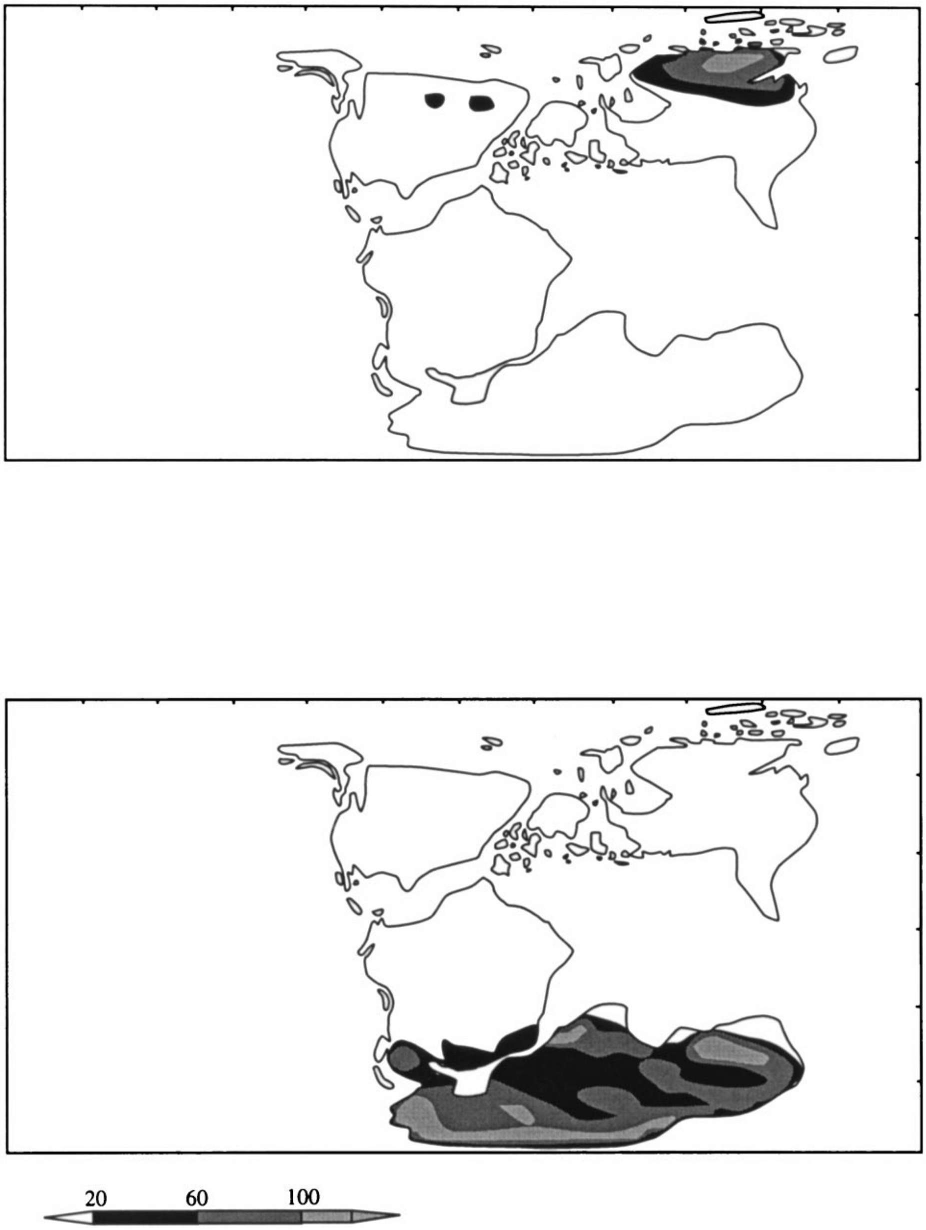

Fig. 7. UGAMP output of snow depth (contour in centimetres of water equivalent): (a) 'control' DJF snow thickness; (b) 'control' JJA snow thickness.

in the large differences between the UKMO and UGAMP 'base'. The UKMO model appears to be doing less well in certain respects, for example in the prediction of mid-latitude humid and arid zones, indicating, for example, a humid Gulf of Mexico, which was a region of known Late Jurassic evaporite deposition.

However, a major problem with all models is that of continental interior temperatures that appear to be too low in winter, by comparison

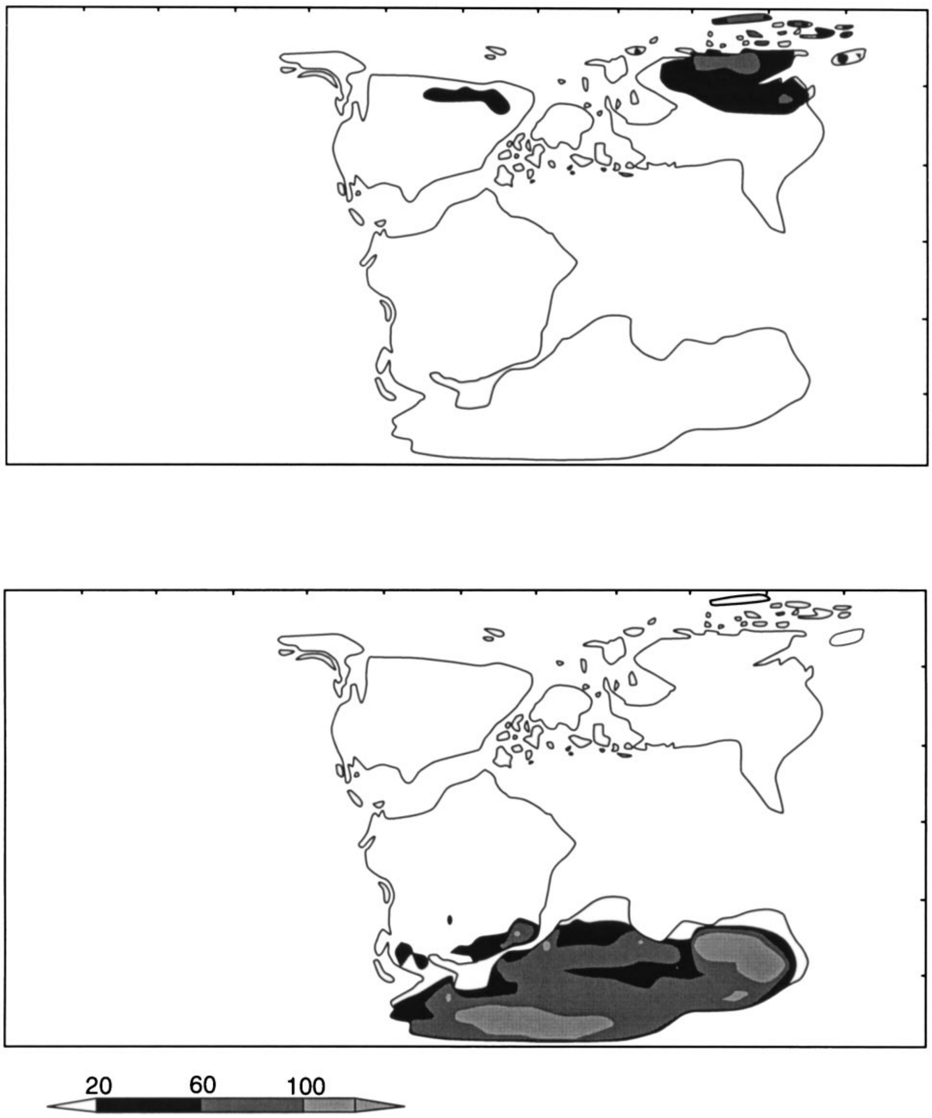

Fig. 8. UKMO output of snow depth (contour in centimetres of water equivalent): (a) 'control' DJF snow thickness; (b) 'control' JJA snow thickness.

with the palaeontological data suggesting frost-free floras and rich reptilian biotas. This is a problem being addressed by several modelling groups, both for the Mesozoic and Cenozoic. One possibility is that the GCMs are not handling well the moisture balance of the planet when it is in a 'greenhouse' mode. Another is that the palaeontological data require some re-evaluation, but only future work will solve this problem. Dinosaur distributions have been used to provide arguments against the low temperatures modelled for high latitude continental areas in the Mesozoic. New evidence (Ji et al., 1998; Swisher et al., 1999; Xu et al., 1999) from NE China (Liaoning Province) shows that some dinosaurs living in this particular region, and at a time close to the Jurassic–

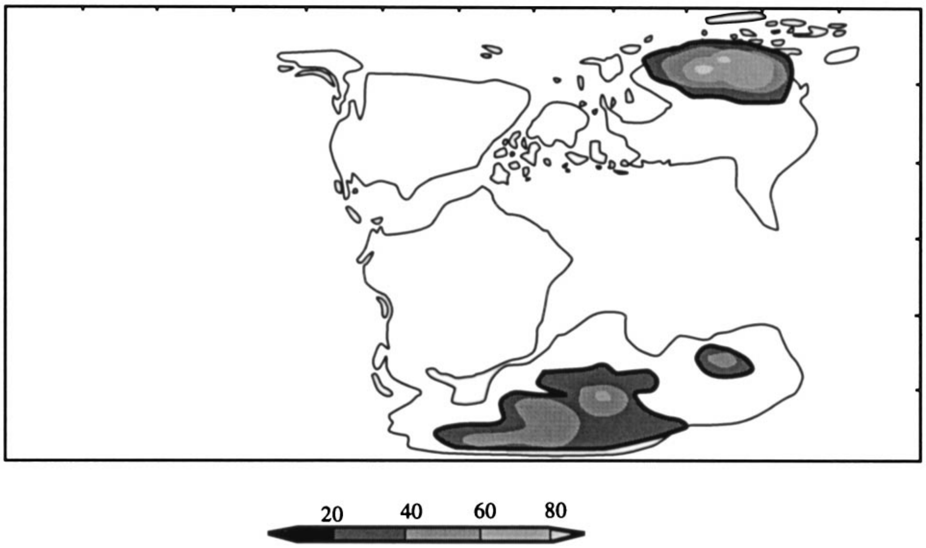

Fig. 9. UGAMP output of snow depth (contour in centimetres of water equivalent) at 'minimum seasonal forcing' output for DJF (southern hemisphere summer) showing snow retention over Gondwana.

Cretaceous boundary, were feathered, probably for insulation, and thus throws doubt on some of the arguments concerning limited heat tolerances of some dinosaurs. This was a region that, in both the UGAMP and UKMO models, experienced average temperatures close to zero during the winter. But such temperatures should not have bothered feathered, and possibly migratory, dinosaurs with nearly bird-like metabolism.

Model simulations do provide useful predictions ('postdictions'). They suggest that the Jurassic tropics could have experienced significant Milankovitch variations, the variations being mainly seen in the hydrological cycle. In mid-latitudes, large changes in soil moisture would also be expected to be associated with changes in rainfall from mid-latitude depressions, which would have become more active during times of maximum seasonal forcing. These model predictions are, perhaps, reflected in the general absence of evaporites within Tethyan peri-tidal successions, a general predominance of kaolinitic clay suites in Atlantic–Tethyan sediments (Chamley, 1989), and the localised development of bauxites (Fig. 4). It is also interesting to speculate on the extent to which clouds, and cloud cover, affected greenhouse conditions on the planet and whether dense cloud systems, particularly those in polar regions, influenced ecosystems (Sellwood and Valdes, 1997; Sloan et al., 1992).

The most significant unknowns that affect the model output, and provide model errors, are: palaeogeography, palaeo-orography, SSTs and ocean heat flux. In addition, major changes in CO_2 composition would impact on model simulations. These are areas requiring more research so that the models might be more closely constrained.

GCM studies provide an investigation of short time slices. However, they have the ability to predict regional climate change (i.e. from wetter to drier, warmer to cooler, more and less stormy, etc.). Some of the climate signals are strong (i.e. from humid to arid) and should be well recorded in geological proxies; others may be subtle, requiring special sites such as anoxic basins for their preservation. Research initiatives such as the UK Natural Environment Research Council's Rapid Global Geological Events (RGGE) programme, which involves an integrative study of the Kimmeridge Clay in Southern England, will allow such subtle signals as clay mineralogical and geochemical variations to be investigated on the millimetre- to decimetre-scale required for the recognition of Milankovitch signals.

6. Conclusions

GCM simulations for the Late Jurassic are in reasonably good agreement with facies usually considered to be climate proxies.

The UGAMP model provides a better prediction of humid and arid zones in low-to mid-latitudes than does the UKMO model.

The Earth is modelled as being generally warmer during the Late Jurassic than at present.

The Earth was generally more humid, but the higher humidity is expressed in the models by more cloud cover in polar regions and greater rainfall over oceanic areas.

The southern continents (Antarctica–India–Australia), comprising disintegrating Gondwana, were generally free of an ice cap but may have had extensive areas of permafrost.

These same continents may have developed a dynamic ice cap during times of 'minimum seasonal forcing', corresponding with times when orbital parameters were comparable with those 115 ka BP.

The output from the UKMO model, although predicting an Earth warmer than today, gives predicted temperatures significantly lower than those from the UGAMP model, reflecting different model behaviour.

Low continental interior temperatures, as seen in both models, may indicate that the GCMs are not handling well the moisture balance of the planet when it is in a 'greenhouse' mode, or that the palaeontological data suggesting warm temperatures require some re-evaluation.

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References

Barron, E.J., Fawcett, P.J., Pollard, D., Thompson, S., 1993. Model simulations of Cretaceous climates: the role of geography and carbon dioxide. Philos. Trans. Biol. Sci. R. Soc. London 341, 307–316.

Berner, R.A., 1992. Palaeo-CO_2 and climate. Nature 358, 114

Blakey, R.C., Peterson, F., Kocurek, G., 1988. Synthesis of late Paleozoic and Mesozoic eolian deposits of the western interior of the United States. Sediment. Geol. 56, 3–125.

Chamley, H., 1989. Clay sedimentology. Springer, Berlin.

Crowley, T.J., North, G.R., 1991. Paleoclimatology. Clarendon Press, Oxford.

Frakes, L.A., Francis, J.E., Syktus, J.I., 1992. Climate Modes of the Phanerozoic. Cambridge University Press, Cambridge. 274 pp

Gates, W.L., Rowntree, P.R., Zeng, Q.-C., 1990. Validation of climate models. In: Houghton, J.T., Jenkins, G.J., Ephraums, J.J. (Eds.), Climate change: the IPCC scientific assessment. Cambridge University Press, pp. 93–130.

Hallam, A., 1985. A review of Mesozoic climates. J. Geol. Soc. London 142, 433–445.

Hallam, A., 1993. Jurassic climates as inferred from the sedimentary and fossil record. Philos. Trans. Biol. Sci. R. Soc. London 341, 287–296.

Hewitt, C.D., Mitchell, J.F.B., 1996. GCM simulations of the climate of 6 kyr BP: mean changes and interdecadal variability. J. Climate 9, 3505–3529.

Ji, Q., Currie, P.J., Norell, M.A., Ji, S.-A., 1998. Two feathered dinosaurs from northeastern China. Nature 393, 753–761.

Moore, G.T., Hayashida, D.N., Ross, C., Jacobson, S.R., 1992a. Paleoclimate of the Kimmeridgian/Tithonian (Late Jurassic) world: I. Results using a general circulation model. Palaeogeogr. Palaeoclimatol. Palaeoecol. 93, 113–150.

Moore, G.T., Cirbus Sloan, L., Hayashida, D.N., Umrigar, N., 1992b. Paleoclimate of the Kimmeridgian/Tithonian (Late Jurassic) world: II. Sensitivity tests comparing three different paleotopographic settings. Palaeogeogr. Palaeoclimatol. Palaeoecol. 95, 229–252.

Oglesby, R.J., Park, J., 1989. The effect of precessional insolation changes on Cretaceous climate and cyclic sedimentation. J. Geophys. Res. 94, 14793–14816.

Parrish, J.T., 1982. Upwelling and petroleum source beds, with reference to the Paleozoic. Am. Assoc. Petrol. Geol. Bull. 66, 750–774.

Price, G.D., Sellwood, B.W., Valdes, P.J., 1995. Sedimentological evaluation of general circulation model simulations for the greenhouse Earth: Cretaceous and Jurassic case studies. Sediment. Geol. 100, 159–180.

Price, G.D., Valdes, P.J., Sellwood, B.W., 1997. Quantitative

palaeoclimate GCM validation: Late Jurassic and mid-Cretaceous case studies. J. Geol. Soc. London 154, 769–772.
Ross, C.A., Moore, G.T., Hayashida, D.N., 1992. Late Jurassic paleoclimate simulation — paleoecological implications for ammonoid provinciality. Palaios 7, 487–507.
Scotese, C.R., Summerhayes, C.P., 1986. Computer model of paleoclimate predicts coastal upwelling in the Mesozoic and Cenozoic. Geobyte 1, 28–42.
Sellwood, B.W., Price, G.D., 1993. Sedimentary facies as indicators of Mesozoic palaeoclimate. Philos. Trans. Biol. Sci. R. Soc. London 341, 225–233.
Sellwood, B.W., Valdes, P.J., 1996. Climate simulations for the greenhouse Earth. Sci. Spectra 5, 58–63.
Sellwood, B.W., Valdes, P.J., 1997. Geological evaluation of climate general circulation models and model implications for Mesozoic cloud cover. Terra Nova 9, 75–78.
Sloan, L.C., Walker, G.C., Moore, T.C., Rea, D.K., Zachos, J.C., 1992. Possible methane-induced polar warming in the early Eocene. Nature 357, 320–322.
Smith, A.G., Smith, D., Funnell, B.M., 1994. Atlas of Mesozoic and Cenozoic Coastlines. Cambridge University Press, Cambridge. 99 pp
Swisher III, C.C., Wang, Y.-q., Wang, X.-l., Xu, X., Wang, Y., 1999. Cretaceous age for the feathered dinosaurs of Liaoning, China. Nature 400, 58–61.
Valdes, P.J., 1993. Atmospheric general circulation models of the Jurassic. Philos. Trans. Biol. Sci. R. Soc. London 341, 317–326.
Valdes, P.J., Glover, R.W., 1999. Modelling the climate response to orbital forcing. Philos. Trans. R. Soc. London Ser. A: 357, 1873–1890.
Valdes, P.J., Sellwood, B.W., 1992. A palaeoclimate model for the Kimmeridgian. Palaeogeogr. Palaeoclimatol. Palaeoecol. 95, 47–72.
Valdes, P.J., Sellwood, B.W., Price, G.D., 1995. Modelling Late Jurassic Milankovitch climate variations. In: House, M.R., Gale, A.S. (Eds.), Orbital Forcing Timescales and Cyclostratigraphy, Geological Society Special Publication vol. 85, 115–132.
Valdes, P.J., Sellwood, B.W., Price, G.D., 1996. Evaluating concepts of Cretaceous equability. Palaeoclimates 2, 139–158.
Xu, X., Tang, Z.-l., Wang, X.-l., 1999. A therizinosauroid dinosaur with integumentary structures from China. Nature 399, 350–354.