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SUMMARY

An atmospheric general circulation model (GCM) is used to simulate the climate of the Jurassic. It is found that the model gives first order agreement with geological data but that closer comparison is limited by uncertainties in the model and in the imposed boundary conditions. The model results suggest that the relative warmth of high latitudes is strongly influenced by changing sea ice and cloud cover. The implied oceanic heat transports are surprisingly small.

1. INTRODUCTION

There is increasing use of general circulation models in the study of Mesozoic climates. This method of palaeoclimate research has many different motivations. Geological data suggested that climate has significantly changed on all time scales, but from data alone it is almost impossible to separate clearly the various processes that have caused this change. By careful use of GCMS in conjunction with data, it is possible to increase our understanding of the controlling influences on climate change.

Further, simulating such distant climates and comparing the results to the geological data is potentially an important way of testing the GCMS in a climate régime very different to that of present day. The benefit of choosing these periods is that the changes in boundary conditions (such as continental position and elevation) are so substantial that they provide an extreme test for the models. Ideally the validation data should be widespread, well dated, and of high quality. It also needs to be assembled into a global dataset, a challenging task.

An additional motivation for modelling the Mesozoic is that GCMS can provide an estimate of the depositional environment for the whole globe. This can help guide the interpretation of the geological record, particularly in regions where previous data coverage is low. The improved interpretation may also feedback onto the model or data comparisons, although care must always be taken to recognize the possibility of circular arguments.

Such research clearly depends on the models being accurate to some reasonable degree. This accuracy is influenced by uncertainties in the boundary conditions for the model as well as errors within the model itself. The boundary conditions include continental position and elevation, atmospheric composition (especially CO_2, CH_4, O_2, O_3), solar forcing, orbital parameters, and sea surface temperature (SST). This latter quantity has to be a boundary condition, since the current generation of coupled ocean–atmosphere GCMS are still in development and have difficulty simulating present day conditions accurately (Mitchell, this volume). Mixed layer ocean models can also be used to simulate the sea surface temperature. However in these models the horizontal oceanic heat flux has to be specified instead of the sea surface temperature itself. However, even if the boundary conditions were known precisely, the models would still be unlikely to produce the correct climate. This is related to the fact that GCMS explicitly represent processes down to a certain scale and that there are important processes that act on smaller scales. These processes cannot be ignored, instead their effects are estimated (or parameterized) using the larger scale circulation. Parameterizations are the major source of errors for present day climate simulations.

The effects of uncertainties in the boundary condition can be estimated by running sensitivity experiments, using a range of reasonable boundary conditions. It is harder to estimate the errors due to parameterizations and other sources of model errors. A comparison of a present day model with present day data gives only a lower bound on the magnitude of this error because, to a certain extent, the model has been tuned for the present day. It may have the wrong sensitivity when the boundary conditions are changed.

One possibly important way of estimating model errors is to compare the results from different climate models. The Jurassic provides a good example of this type of work as there are now three published models for this period, using versions of the U.K. University Global Atmospheric Modelling Programme (UGAMP) (Valdes & Sellwood 1992), the National Center for Atmospheric Research (NCAR) (Moore *et al.* 1992; hereafter referred to as MHRJ), and the Goddard Institute for Space Studies (GISS) (Rind and Chandler 1991 & Chandler *et al.* 1992) models. The first two of these are for the Kimmeridgian stage (150 Ma BP) and provide the opportunity for detailed comparisons.

However, to understand the reasons for differences

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(and whether one simulation is more believable) can be difficult, particularly if the boundary conditions are not identical. It is therefore useful to examine the sensitivity of one model to changing the parameterizations. The UGAMP model is particularly well suited to this as an important part of the associated research programme is to develop and test a range of different parameterizations.

In this paper, we will show examples of each method for testing the reliability of climate model simulations of the Jurassic. Section 2 contains a brief description of the model used here and some results for the present day climate. Section 3 will show the results for the Kimmeridgian stage and compare it to the geological record. The following section will compare the results to those of MHRJ. Finally there will be a short summary and conclusion.

2. MODEL DESCRIPTION

The model used in similar to that in Valdes & Sellwood (1992). It is a version of the UGAMP model which is based on the ECMWF forecast model. It is a spectral model and all of the results shown here are using a truncation at total wavenumber 31. The nonlinear terms and the parameterized processes are computed on a grid of 96 longitudes and 48 latitudes. This is a higher resolution than that of the NCAR and GISS models.

Increasing horizontal resolution would, at first sight, appear to be advantageous. For instance, higher resolution will better simulate small scale atmospheric processes such as mid-latitude depressions. However, many climate modelling groups have found that increasing resolution gives no clear improvement (indeed in some cases there is a clear deterioration) in the models ability at simulating present day climate. This suggests that model performance is currently limited by inadequacies in parameterization schemes which have perhaps been tuned to lower resolution models. Increasing horizontal resolution may require extensive modifications to the sub-grid parameterizations.

The UGAMP model is somewhat different in that it is derived from a high resolution numerical weather forecast model (triangular truncation at total wavenumber 106). A set of resolution experiments for present day conditions (Valdes & Blackburn 1989; Boer *et al.* 1991) showed that, in terms of the mean climatology of the model, such high resolution is not justified. However, the model performed significantly better at T42 resolution (128 × 64 grid points) compared to T21 (64 × 32 grid points). Further unpublished work showed that T31 was also significantly better than T21. This transition was particularly noticeable in the mid-latitude storm track regions. The changed resolution better resolved the depression belts which transport a significant amount of moisture, momentum and heat towards the pole.

The current version of the model has a number of significant changes over that used in Valdes & Sellwood (1992) (hereafter referred to as VS). The most important of these is that a new convective scheme is being used. The original scheme was based on Kuo (1965, 1971) whereas the new scheme is a version of that by Betts (1986) and Betts & Miller (1986). This change makes a significant impact on many aspects of the general circulation of the model. The changes are mostly beneficial, particularly in the tropics.

Another major change to the model is the use of a different vertical advection scheme (total variance diminishing). This is beneficial to the treatment of moisture in the model. The other parameterizations are as in VS, including the radiation scheme of Morcrette (1990) and the three-layer soil model.

Before proceeding to the Jurassic simulations, it is important to show the skill of the model in predicting the present day climate. Here we will present only a few results from a 10 year integration with present day boundary conditions.

When run with prescribed sea surface temperature, it is possible for the model to radiate to space more or less energy than it receives. If the model and sea surface temperatures were perfect, the net imbalance should be near zero. In practice, we found an imbalance of 7.4 W m^{-2}. The net outgoing longwave radiation exceeds the net incoming solar radiation. The size of this imbalance, although quite large, is fairly typical of such models (e.g. Chandler *et al.* 1992).

The fact that the model is out of balance causes a problem in interpreting the energy balance for other periods. In general, we will assess the energy balance of the model relative to the present day. Thus we aim for the palaeoclimate model to have a 7.4 W m^{-2} imbalance.

In the context of the energy balance, it is simple to calculate the models implied northward heat transport by the atmosphere and by the ocean. The atmosphere–ocean system must transport energy from the equator (where it is input by the Sun) to higher latitudes (where it is emitted in the form of longwave radiation). Observational studies suggest that the atmosphere and ocean transport roughly equal amounts (Carissimo *et al.*, 1985). Figure 1 shows the northward heat flux deduced from observations and from the model. It can be seen that the maximum oceanic heat transport implied by the model is in reasonable agreement with that from observations. In the Northern Hemisphere it peaks too far north. In the Southern Hemisphere, the ocean transport is somewhat better. However in both hemispheres, the total transport is far too small. It seems likely that this is the result of the model having excessive albedo for tropical clouds. The result is that the atmosphere and ocean has to transport less than observations would suggest.

The simulated near surface temperatures (not shown) are broadly similar to observations. Figure 2 shows the difference between the models 1000 mb temperature and that based on a 10 year climatology of ECMWF initialized analyses. This is a very stringent test of the model. The magnitude of the errors are similar to other modelling groups (e.g. Gates *et al.* 1990). In most areas the errors are relatively small.

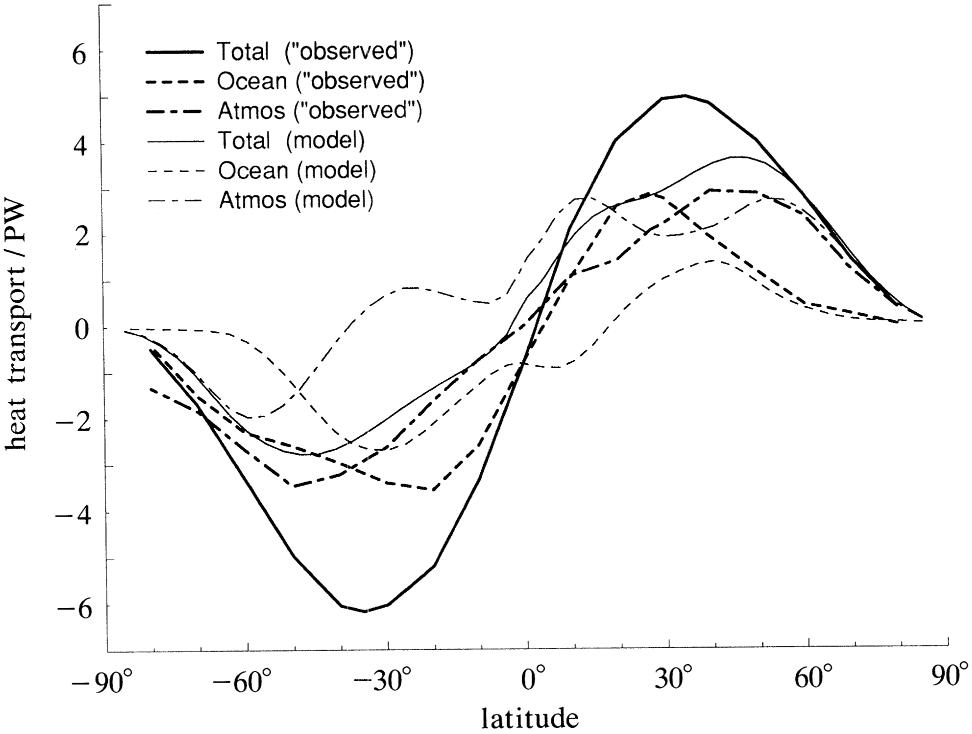

Figure 1. Northward heat transport as a function of latitude for the present day. The thick lines are the observed values, the thinner lines are from the model. The solid, dotted, and dashed lines shows the total, oceanic and atmospheric components respectively.

The exception to this is the Northern Hemisphere winter over snow covered land. The model is up to 18°C cooler than observations suggest. This appears to be related to the relatively crude treatment of snow in the model. In particular, the thermal properties of snow are not properly represented within the soil model. In addition, the albedo is set to a relatively high value of 0.8 and which does not decrease as the snow gets older.

Away from the surface, the model performs considerably better. For instance, at 500 mb (about 5 km) the typical temperature errors are less than 3°C. This is a good illustration of the fact that GCMS are at their weakest for near surface climate.

The modelled zonal mean precipitation for the two solstitial seasons is shown in figure 3. The zonal averages show a sharp peak in the tropics with secondary peaks in mid-latitudes. The results broadly match those from other models and from observations, though the JJA tropical rainfall is probably excessive (although the data coverage is notoriously unreliable in these regions).

The regional distribution of percipitation for the seasons (not shown) captures the movement of the intertropical convergence zone (ITCZ) and the rainfall maxima in the mid-latitude storm track regions. The DJF simulation is reasonable but the summer Indian monsoonal precipitation is displaced to the east. The model does not capture well the flow of moist, tropical air into northeast India. Instead the moist air flows into the Bay of Bengal.

The simulation of mean surface pressure and mid-latitude depressions, especially in the Southern Hemisphere, has been shown to be particularly sensitive to model resolution (Manabe *et al.* 1978; Hansen *et al.* 1983). Consistent with this, the current model successfully simulates the Antarctic circumpolar trough. The mid-latitude, oceanic storm tracks are approximately 30% weaker than observed which is typical of other high resolution models (Hall *et al.* 1993).

Finally in this section, it is worth noting that the global, annual average cloud cover given by the model is 58%. This is in reasonable agreement with Stowe *et al.* (1989) who found values in the range 49% to 56% and Beryland and Strokina (1980) who suggested 60% cloud cover. The regional distribution (not shown) indicates that the model is overestimating cloud cover in the Northern Hemisphere winter continental region and in the region of Antarctic throughout the year. However, it should be cautioned that satellite retrieved cloud cover over the ice covered Antarctic is potentially unreliable.

3. THE KIMMERIDGIAN SIMULATION

To simulate the late Jurassic some, but not all, of the boundary conditions on the model are modified. In all of the experiments described here, the solar constant and all orbital constants remain as for the present. Carbon dioxide concentrations are raised to 4 times present day values, a typical value for the Mesozoic (Berner 1987). The albedo of non-snow covered land is set to 0.16 and the roughness length to 1.0 m, values typical for shrubland. The model was integrated for 12 years and the last 8 years are used for diagnostics.

As in VS, the palaeogeographic reconstructions of A. Smith (personal communication 1991) and estimates of orography based on general plate tectonic

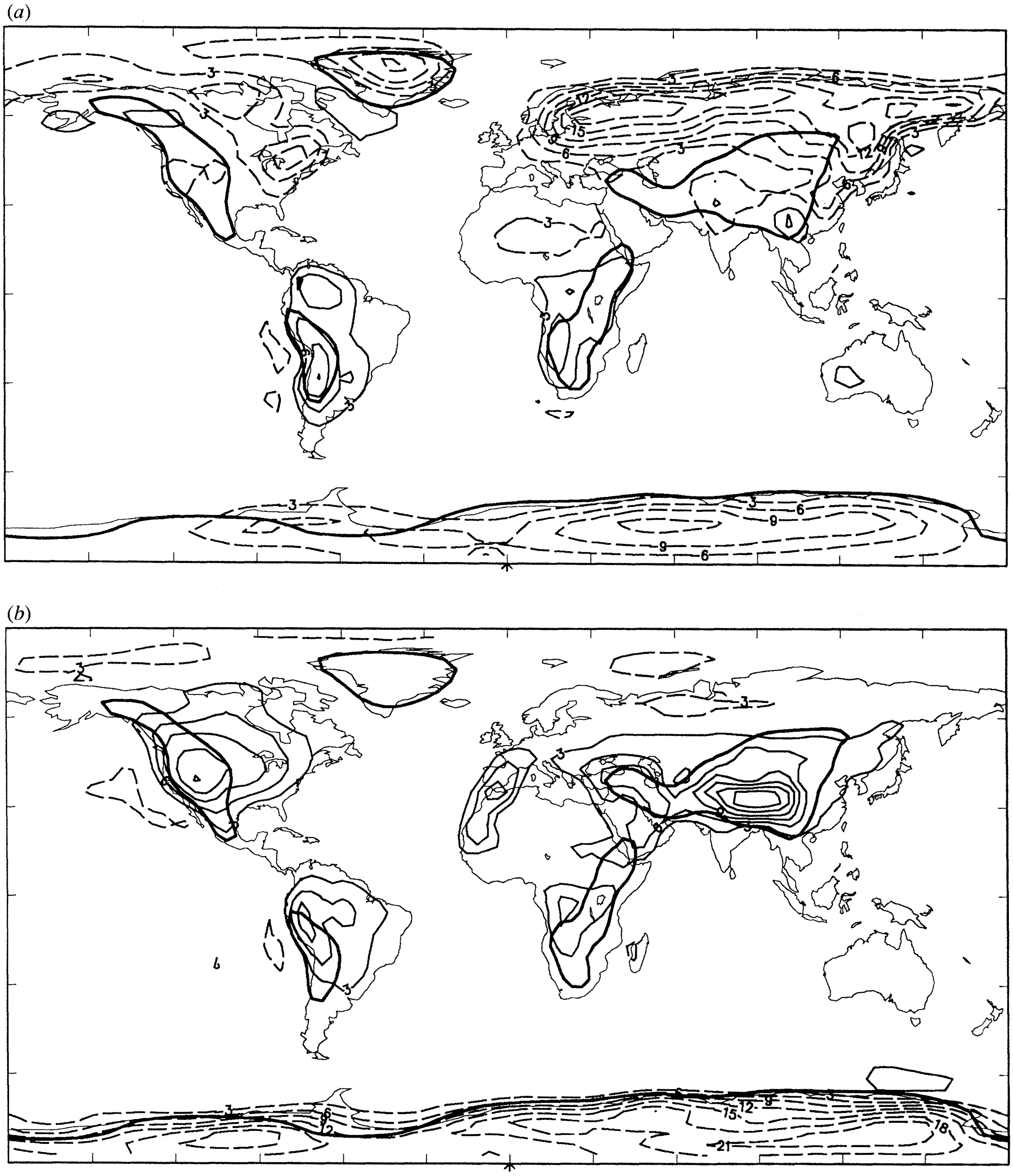

Figure 2. The difference between the model 1000 mb temperature (i.e. near surface air temperature) as simulated for (*a*) December–February (DJF) season, and (*b*) June–August (JJA) season. The counter interval is 2°C, and negative contours are dashed. The thick solid line shows the outline of the 1 km orography. Any data within these regions have been extrapolated a significant distance below the surface and are therefore unreliable. A longitude–latitude projection has been used.

considerations are used. The typical uncertainties in palaeographic reconstructions are generally considerably smaller than those for other boundary conditions, particularly given that the resolution of the model is only about 4°.

A further serious problem with simulating this period is how to model or impose the sea surface temperature (SST). In this paper, we specify the SST, using a simple, zonally symmetric profile ranging from 27°C in the tropics to 0°C at the poles. These estimates are very crudely based on oxygen isotope results (e.g. Stevens & Clayton 1971; G. Price, personal communication), although these estimates are very sparse and potentially unreliable.

The advantages of this approach are two fold. By constraining SST in this manner, it is possible to isolate more clearly the processes that are influencing the simulation. Further, by examining the energy balance of the model, it is possible to deduce if the model is consistent with the SST or whether increased concentrations of greenhouse gases are needed to bring the model to equilibrium.

This approach was followed by Chandler *et al.* (1992) who found that a model of the early Jurassic

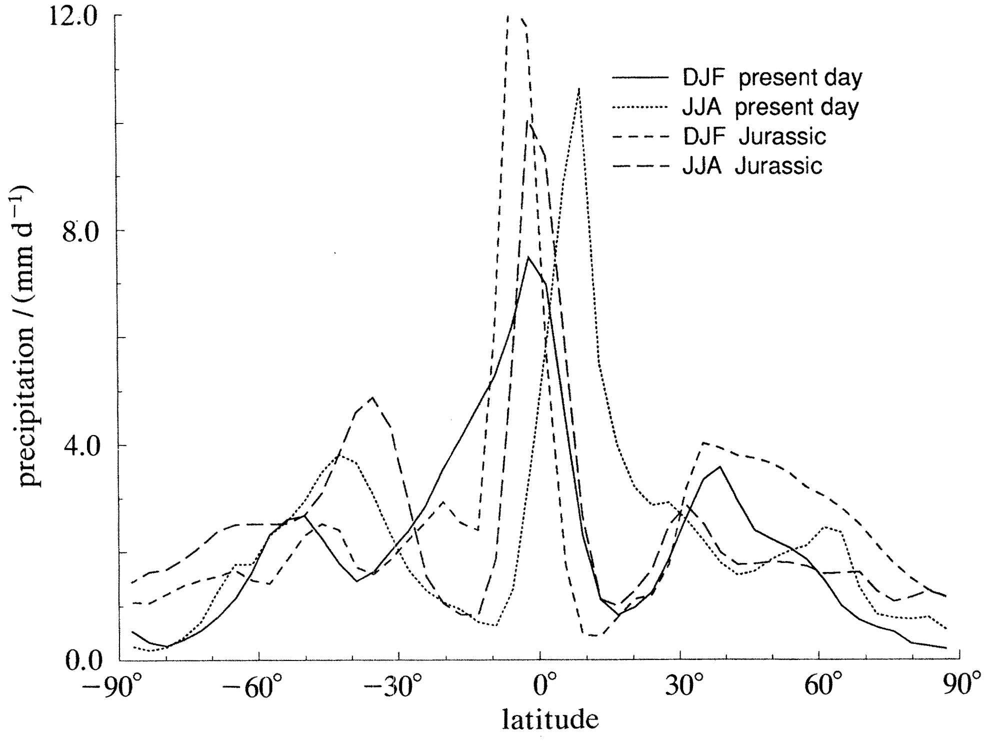

Figure 3. The zonal mean total precipitation in the model for DJF and JJA for present day and Jurassic (Kimmeridgian) conditions.

was in energy balance, without elevated greenhouse gas concentrations. This result makes the very important point that the warmth of the Early Jurassic could be sustained purely by a changed oceanic heat transport. However, the cause of such large changes in ocean circulation is at present unclear.

The simulated energy balance in this palaeoclimate run is better than that for the present day run, the energy imbalance being 6.3 W m^2. The balance would be the same as the present day run if the CO$_2$ concentration had only been increased by a factor of approximately 3, instead of 4. This result broadly agrees with that of Chandler *et al.* (1992) in that the major changes in Jurassic climate appear to be associated with changes in northward heat transport although Chandler *et al.* (1992) found that they needed no CO$_2$ increase.

The energy balance in this model is considerably

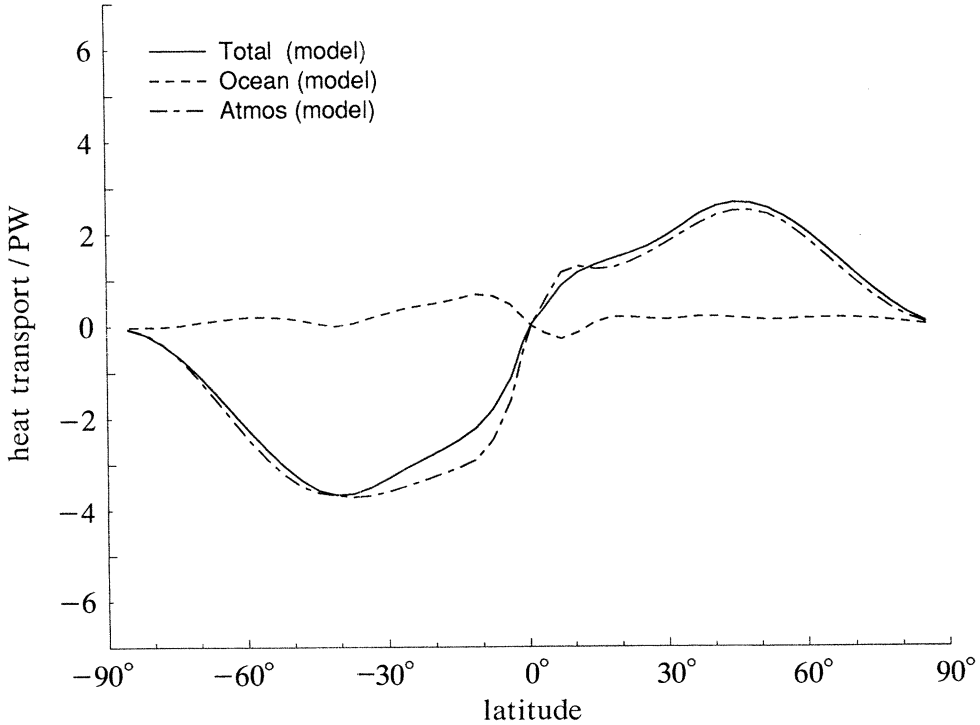

Figure 4. Simulated northward heat flux from the Kimmeridgian simulations. The conventions are as in figure 1.

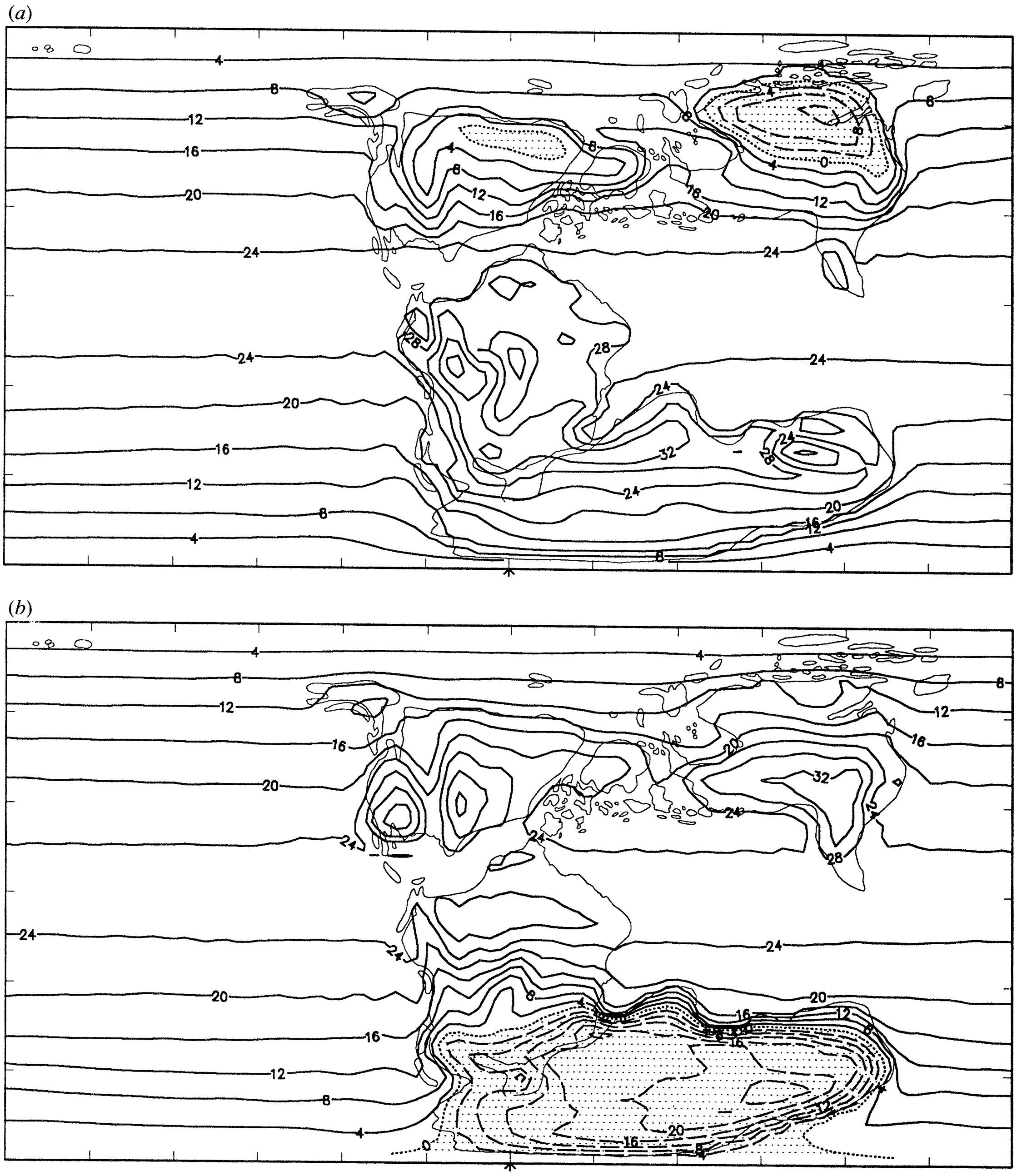

Figure 5. Surface air temperature (at 2 m height) for the Kimmeridgian simulation for (*a*) December–February, and (*b*) June–August. The contour interval is 4°C and negative temperatures are shaded.

better than that in the model using the original (Kuo) convection scheme (described in VS). The improvement is related to a dramatic change in the cloud cover. The Kimmeridgian simulation with Kuo convection had a global, annual average total cloud cover of 72% (an increase of 18% compared with the corresponding present day model). The Betts-Miller model shows an increase of only 1%. The biggest difference occurs in the middle layer cloud cover over the tropical oceans, which decrease from 48% in the original run to 24% here.

This change can be related to an improved treatment of the tropical boundary layer inversion. The Kuo scheme underestimated the inversion, allowing too much water vapour and thus high relative humidity in the layers above. Since the cloud prediction scheme is based on relative humidity, this results in extensive medium level cloud cover. The Betts-Miller scheme considerably improves the treatment of the inversion, and hence medium layer cloud cover decreases.

It is worth noting that the model for present day conditions also shows the same sensitivity to middle layer cloud but not in total cloud cover. Both schemes do equally well compared to observations. The total cloud cover does not change as much because the biggest changes in medium level cloud occur in the tropics, where convective and high cloud cover is extensive and effectively accounts for the total cloud cover. For the Kimmeridgian simulation, there is less

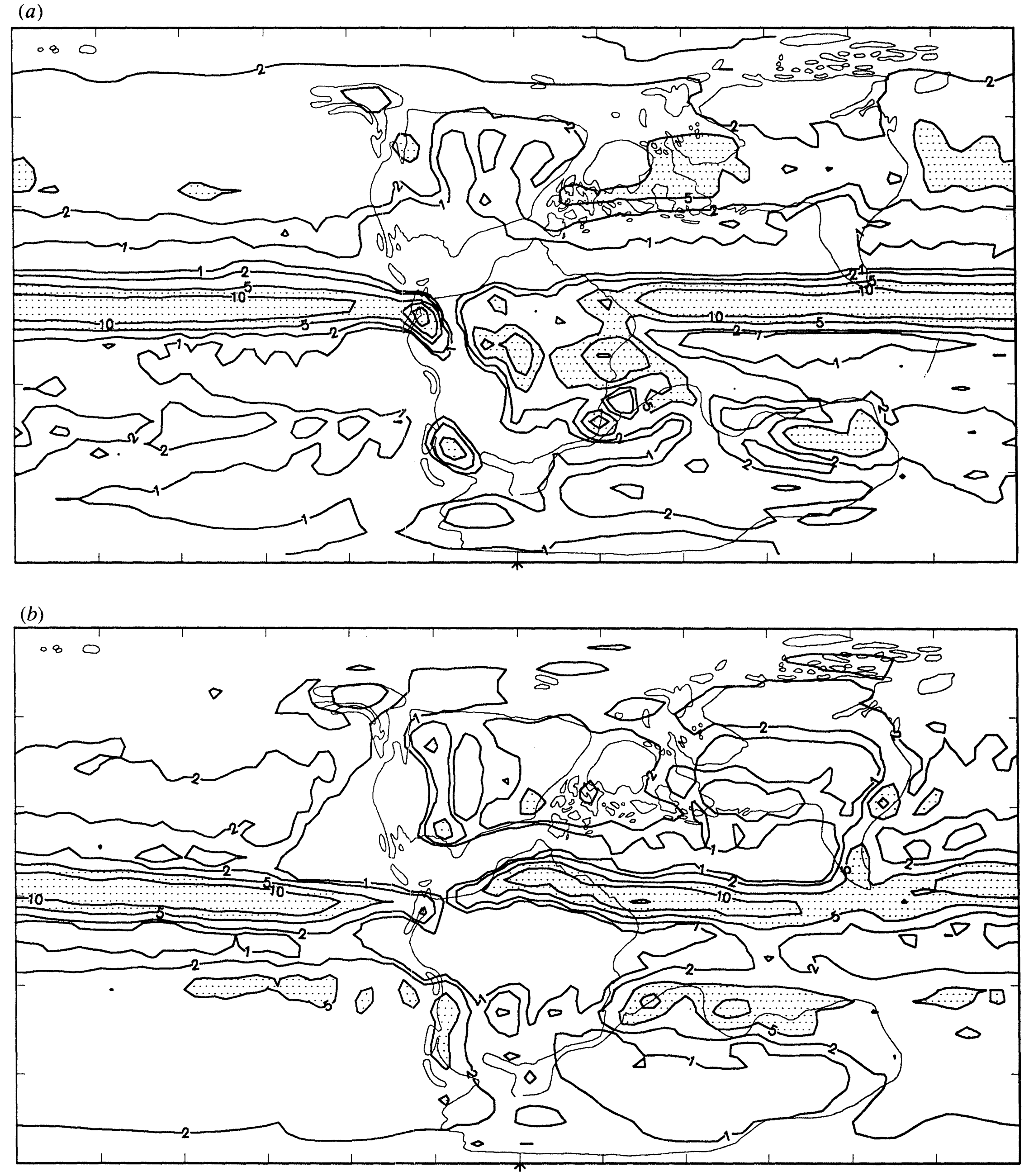

Figure 6. The simulated total precipitation from the Kimmeridgian simulation for (*a*) December–February, and (*b*) June–August. The units are in mm d^{-1} and the contours are at 1, 2, 5, 10 and 20 mm d^{-1}. Values in excess of 5 mm d^{-1} are shaded.

tropical high and convective clouds, and thus the total cloud cover is more affected by that at medium levels.

Very surprisingly, the implied ocean heat transport has substantially decreased from the present day in both hemispheres (figure 4). For much of the large Panthalassa (palaeo-Pacific) ocean, the total annual mean, surface vertical heat flux is small, with large values only near the coasts, and the zonal mean is much reduced compared to the present. Associated with this, the implied total atmospheric heat transport remains roughly constant. This is related to changes in the cloudiness and surface albedo (mainly related to snow and ice cover).

Despite the large difference in cloud cover, the new model's surface temperature (figure 5) is similar to that shown of the previous model. The global, annual average temperature is 20.1°C. The winter hemisphere temperatures drop below zero, especially in the Southern Hemisphere. This low temperature is the result of the large continental land mass, and is further enhanced by the orography. The Southern Hemisphere orography deflects the prevailing westerlies, allowing the air over the continent to cool further.

The Northern Hemisphere winter is not nearly as extreme. There is only a very small area of subfreezing temperatures over North America and Greenland, and a slightly larger, area of lower temperatures over Siberia. There is less extreme continentality in the Northern Hemisphere. In addition, unlike the Southern Hemisphere orography, the North Ameri-

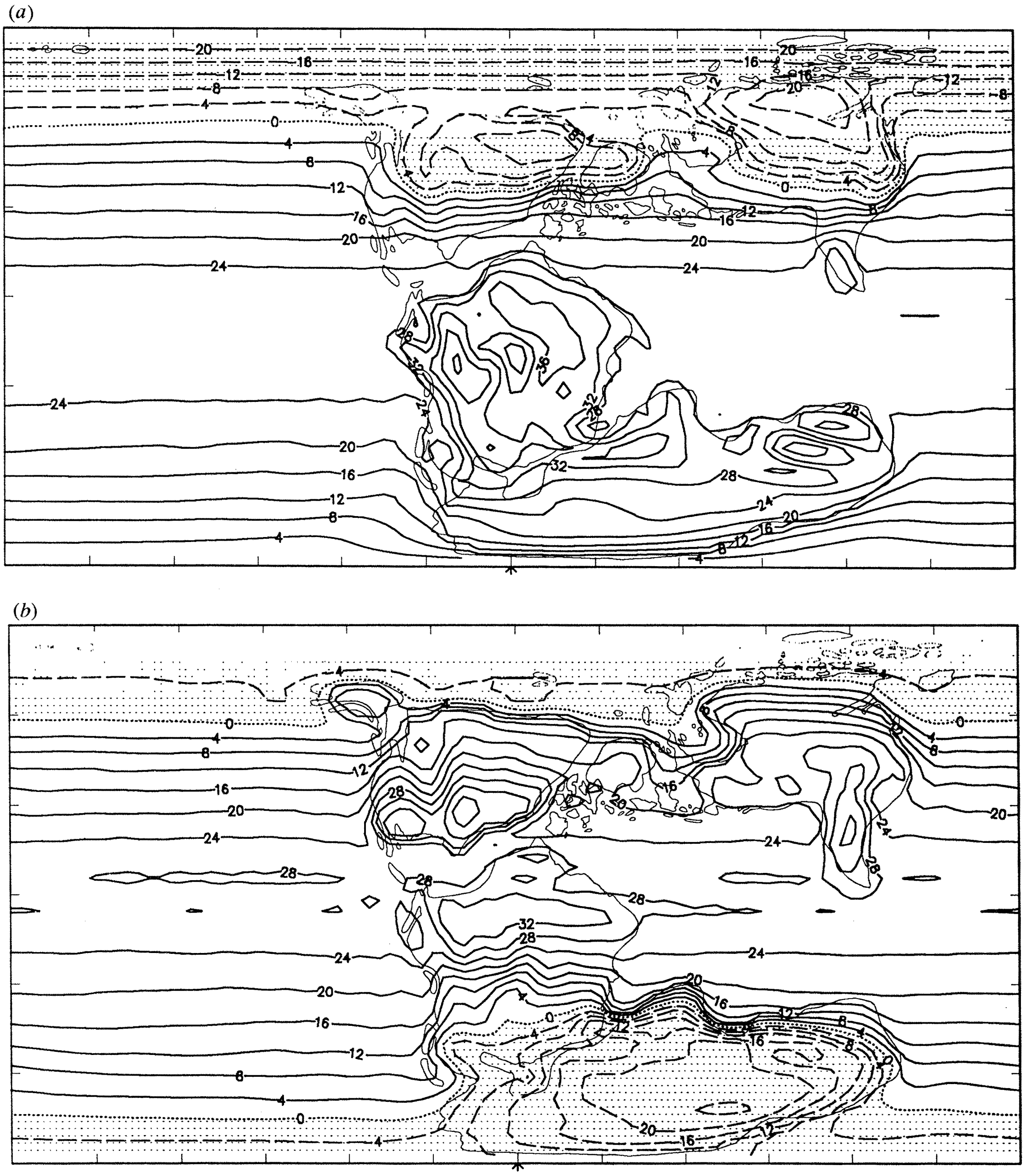

Figure 7. The surface air temperature (at 2 m height) for the Kimmeridgian simulation but using approximate zonal values of sea surface temperature based on the model of Moore *et al.* (1992). All conventions as in figure 5.

can orography acts to deflect warm, tropical air onto the Eastern American continent. The sub-freezing temperatures are considerably less extreme than found by MHRJ, or by Chandler *et al.* (1992) (for the early Jurassic).

The new model's total precipitation (figure 6) is significantly different to that of the model with Kuo convection. The global, annual mean precipitation is 2.9 mm d^{-1} compared with 2.6 mm d^{-1} for the previous model (and 2.7 mm d^{-1} for the new model run for the present day). The largest differences are in the tropics. The ITCZ is both narrower and stronger and more closely confined to the equator. The original model had significant precipitation over the seaway linking the Panthalassa (palaeo-Pacific) ocean and the Tethyan ocean. The new model reaches a maximum further south, with heavy monsoonal rainfall extending over much of Africa during the Southern Hemisphere summer.

The rainfall shows less significant differences in the Northern Hemisphere, though in general the amounts with the new model are greater. There is a small arid region on the southern edge of N. America and there is a clear rain shadow in the lee of the North American orography.

This rainfall pattern is in reasonable agreement with the geological record in the Northern Hemisphere, but the comparison is less favourable in the Southern Hemisphere. Evaporites occur over the southern coast of America and the northern coast of Africa, in agreement with the model. However, the interior of Africa and S. America has also been interpreted as arid, though the main data source is for the early Jurassic (Frakes 1979). In contrast, the model is predicting monsoonal rainfall. Thus it is possible that the new model is over-estimating the strength of the summer monsoon.

4. COMPARISON WITH THE NCAR MODEL

As noted in § 3, the current model is significantly warmer in winter than the NCAR simulation of MHRJ. In an attempt to understand better the differences between this model and MHRJ, we have rerun the present model but with sea surface temperatures similar to MHRJ. This was done in a relatively crude manner, using estimates of the zonal mean only.

The resulting mean surface temperatures is shown in figure 7. High latitude land temperatures have dropped by up to 10°C. The North American temperatures are now very similar to those in MHRJ but the Siberian temperatures are still somewhat higher. This could be caused by the fact that the ocean temperatures immediately adjacent to Siberia are still somewhat higher than those in MHRJ.

The energy balance of this simulation is very similar to before. The new simulation requires a 4 times present day CO_2 concentrations for balance, rather than the 3 times present day concentrations required by the "control" simulation described in § 3. This is consistent with MHRJ who used the higher concentration. Considering the crudeness of the comparison, the agreement is acceptable.

This result suggests that much of the difference between the two models is related to the treatment of the ocean. The model of MHRJ includes no explicit treatment of oceanic heat transport. It assumes that the atmosphere is transporting all of the heat from equator to pole. The model in Valdes & Sellwood (1992) and in this paper specified a sea surface temperature, with a consequent implicit oceanic heat transport.

5. SUMMARY AND CONCLUSIONS

In this paper, we have examined the ability of a GCM to simulate the climate of the Jurassic. The accuracy of the model simulation is constrained by our knowledge of the boundary conditions, and by the accuracy of the parameterisations in the model. For the former, the sea surface temperature and the surface elevation are particularly important. For the latter, changes in the parameterization of clouds and convection are known to make substantial modifications to the simulated climate.

The models predict a large seasonal range in the land surface temperatures but the current model predicts relatively limited regions of slightly subfreezing temperatures, particularly in the Northern hemisphere. This lack of severe freezing temperatures is certainly not inconsistent with the classical interpretation of equable Mesozoic climates.

The precipitation pattern is also broadly consistent with the geological record. However the large differences in the tropical rainfall pattern between the new model and that used in VS is a graphical illustration that the prediction of tropical precipitation is one of the most uncertain aspects of many climate models. It could be argued that since these predictions are volatile, it is premature to attempt to test them against the geologic record. However from a modelling viewpoint, any additional evidence to verify the predictions of tropical rainfall would be beneficial.

The model results appear to be quite different to those from other simulations. It seems that the major reason for this is the choice of ocean model. A mixed layer ocean model with no ocean heat transport, used in some studies, may exaggerate the equator to pole temperature gradient. This will result in the atmospheric and total northward transport being misrepresented. The most surprising result of the present study, is that the implied oceanic poleward heat flux is smaller than for the present day. This is completely opposite to the previous results of Rind & Chandler (1991). Given that the mean westerlies are weaker (because of the reduced temperature gradients), and that there are limited possibilities for strong western boundary currents in the ocean (since there is only one major ocean), the weakness of the implied ocean heat flux is not perhaps physically unrealistic. However, since the northward heat fluxes are poorly modelled for the present day climate, the result has to be treated with some caution.

Further work is needed to understand the differences between the models and their implied ocean and atmospheric heat transports. Such studies should be done with models using boundary conditions that are as similar as possible so that a clearer understanding of the model–model comparisons can be developed.

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