A Comparison of Climate Model Sensitivity with Data from the Last Glacial Maximum

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ABSTRACT

An attempt has been made to use paleoclimatic data from the last glacial maximum to evaluate the sensitivity of two versions of an atmosphere/mixed-layer ocean model. Each of these models has been used to study the CO_2-induced changes in climate. The models differ in their treatment of cloudiness, with one using a fixed cloud distribution and the other using a simple parameterization to predict clouds. The models also differ in the magnitude of their response to a doubling of atmospheric CO_2, with the variable cloud model being nearly twice as sensitive as the fixed cloud version. Given the distributions of continental ice sheets, surface albedo, and the reduced carbon dioxide concentration of the ice age, the climate of the last glacial maximum (LGM) is simulated by each model and compared with the corresponding simulation of the present climate. Both models generate differences in sea surface temperature and surface air temperature which compare favorably with estimates of the actual differences in temperature between the LGM and the present. However, it is difficult to determine which version of the model is more realistic in simulating the ice age climate for two reasons: 1) the differences between the two models are relatively small; and 2) there are substantial uncertainties in the paleoclimatic data. Nevertheless, the similarity between the LGM simulations and the available paleoclimatic data suggests that the estimates of CO_2-induced climate change obtained from these models may not be too far from reality.

1. Introduction

Mathematical models have been used extensively in order to evaluate the sensitivity of climate to various perturbations. These have included changes in topography, solar constant, atmospheric CO_2 concentration, and other factors which can alter climate. Particular attention has been given to the sensitivity to changes in atmospheric CO_2 content, so as to allow an estimate of the expected impact of increasing CO_2 on climate.

Unfortunately, there are large differences among the estimates of climate sensitivity which have been obtained by different models. For example, Manabe and Stouffer (1979, 1980) have shown that the global mean surface air temperature of their model increases by about 4°C in response to the *quadrupling* of atmospheric CO_2. Recently, Hansen *et al.* (1984) constructed a model that produces a 4°C warming in response to the *doubling* of atmospheric CO_2. Since Manabe and Wetherald (1980) found that the sensitivity of their climate model to higher CO_2 varies almost linearly with the logarithm of the CO_2 increase, the sensitivity of Hansen's model is approximately twice as large as that of Manabe and Stouffer's model.

Hansen *et al.* (1984) attribute this difference in sensitivity between the two models to a positive feedback from CO_2-induced changes in cloud cover which are taken into account in their model but not in the model of Manabe and Stouffer. Recently, Manabe and Wetherald (personal communication, 1984) found that a version of their model with interactive cloud cover produces a sensitivity of 4.0°C for doubled CO_2, while a version with fixed zonally uniform cloud cover produces a 2.3°C warming. Since the simulations of the present climate from the two versions of the model differ from each other, attributing this sensitivity difference entirely to the cloud feedback process may not be justified. Nevertheless, their results appear to support the hypothesis of positive cloud feedback. As Hansen *et al.* (1984) have noted, the parameterization of the interactive process involving cloud cover, radiative transfer, and atmospheric state is at a very primitive stage of development at present. Therefore, it is premature to conclude that the results from the model with interactive cloud cover are more reliable than those from the model with fixed cloud cover.

In view of the present state of the art of cloud parameterization, it is desirable to assess the sensitivity of these models in the light of other independent information. This study represents an attempt to do this by simulating the climate of the last glacial maximum (LGM) and comparing the results with estimates of the LGM climate as reconstructed by the CLIMAP Project (CLIMAP Project Members; 1976, 1981). Hansen *et al.* (1984) used a version of their atmospheric general circulation model (GCM), in which sea surface temperature (SST) was prescribed, to simulate the LGM climate and to evaluate the sensitivity of their model. They found an imbalance of radiation at the top of their model's atmosphere, indicating that it was at-tempting to cool further than the prescribed SST would allow. Hansen *et al.* interpreted this radiation imbalance as an indication that either their model is too sensitive due to overly large cloud feedback, or that the CLIMAP estimates of LGM SST used as a lower boundary condition are too warm.

In the models used for this study, SST is predicted rather than specified as a lower boundary condition. This enables a comparison to be made between the model results and the LGM SST as estimated by CLIMAP. Land-based paleoclimatic data are also available to be compared with the LGM climate simulated by the models. In so doing, the sensitivities of models with and without predicted cloudiness can be evaluated by examining their ability to reproduce the cold ice age climate.

2. Experimental design

The climate models used for this study are constructed by coupling a general circulation model of the global atmosphere with a simple model of the oceanic mixed layer. The atmospheric GCM uses the spectral method, in which the horizontal distributions of atmospheric variables are represented by a limited number of spherical harmonics. The horizontal resolution of the atmospheric GCM is determined by the degree of truncation of the spectral components. For this study, 15 components have been retained in both the zonal and meridional directions, adopting the so-called rhomboidal truncation. The oceanic mixed layer model is a static isothermal layer of water with uniform thickness. The process of sea ice formation is explicitly incorporated into the model, but the effect of heat transport by ocean currents is not included. Seasonally varying insolation is prescribed at the top of the atmosphere.

In the fixed cloud (FC) model, the distribution of cloud cover is prescribed with respect to latitude and height but does not vary with season. This eliminates the cloud feedback process from the model. The variable cloud (VC) model uses a simple parameterization for cloud cover in which cloudiness is predicted wherever the relative humidity reaches or exceeds 99%. The optical properties assigned to various types of cloud cover are listed in Table 1. Other aspects of the cloud prediction scheme are discussed in more detail in Wetherald and Manabe (1980).

The FC model is essentially the same as the one used by Manabe and Stouffer (1980) with the exception of the following: 1) the meridional distribution of total cloud cover is taken from Berlyand *et al.* (1980) and the vertical distribution from London (1957); 2) the albedo values assigned to snow and sea ice are slightly modified; and 3) the thickness of the oceanic mixed layer is given as 50 m to yield a realistic amplitude of the seasonal variation in sea surface temperature. The VC model incorporates the same albedo parameterization for snow and sea ice, and the same mixed layer depth as the FC model.

In order to obtain a quasi-equilibrium model climate, each model is time-integrated over a period of 15–20 years, using the present distributions of insolation, continental ice sheets, and the albedo of snow-free surfaces. After a stable climatic condition is reached, an additional 15 years of time integration is performed. In future references, these integrations will be identified as the standard simulations. Figure 1 illustrates the latitudinal distribution of zonally averaged annual mean surface air temperature from the standard simulations of both models. For reference, the observed values of zonal mean surface air temperature (Crutcher and Meserve, 1970; Taljaard *et al.*, 1969) are also plotted on the same figure. According to this figure, the surface air temperatures simulated by both models are quite close to the observed values throughout the Northern Hemisphere and much of the Southern Hemisphere. South of 45°S, the model simulations are somewhat too warm, particularly over the Antarctic Continent. In all but the polar regions, the VC model is slightly warmer than the FC model.

TABLE 1. Cloud optical properties used in the VC model.*

	Thin clouds			Thick clouds
	High	Middle	Low	
Approximate height (km)	10.5–∞	4.0–10.5	0–4.0	
Reflectivity				
Visible and UV (wavelength < 0.7 μm)	21	45	65	65
Near infrared (wavelength > 0.7 μm)	19	35	55	55
Absorptivity				
Visible and UV	0	0	0	0
Near infrared	4	30	30	30
Longwave emissivity	60	100	100	100

* Heights are in kilometers; other quantities are in percent. Thin cloud indicates a cloud that occupies only one finite-difference level, whereas thick cloud occupies more than one contiguous finite-difference level.

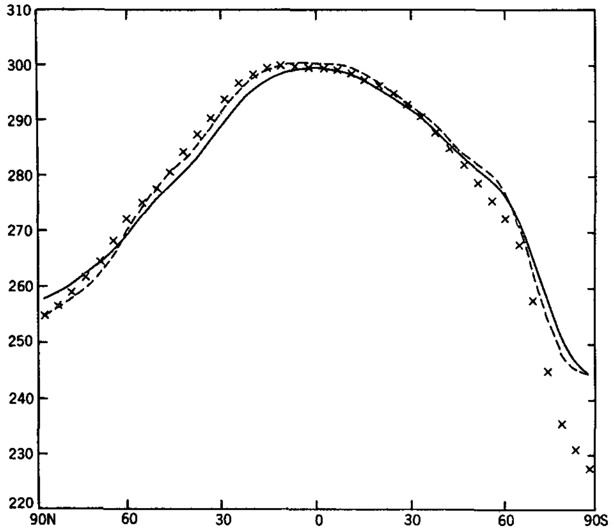

FIG. 1. Latitudinal distribution of zonally averaged annual mean surface air temperature from the FC model (solid line) and the VC model (dashed line). For reference, observed zonal mean surface temperatures from Cruther and Meserve (1970) and Taljaard *et al.* (1969) are also indicated by the crosses.

A comparison of model sea ice area with observed data (Table 2) indicates that both models provide a good estimate of the seasonal minimum ice extent in the Northern Hemisphere. Both models overestimate the extent of Northern Hemisphere sea ice in winter, a bias which may result from the absence of oceanic heat transport from both models. The impact of neglecting this process is greatest in winter, when the warm Kuroshio and Gulf Stream carry large amounts of heat into high latitudes. In the Southern Hemisphere, both models provide a good simulation of the seasonal maximum ice extent. The FC model compares favorably with the observed seasonal minimum sea ice extent in the Southern Hemisphere, while the VC model overestimates summer ice.

The relatively good agreement between simulated and observed SST and sea ice, which occurs despite the absence of oceanic heat transport, may be attributable to a specific parameterization used in both models. In the computation of shortwave radiation, it is assumed that cloud albedo is independent of solar zenith angle, which is contrary to theoretical considerations (e.g., Fritz, 1954). Neglecting the zenith angle dependence results in cloud albedos which are too large at low latitudes and too small at high latitudes. This causes net incoming solar radiation to be overestimated at high latitudes and underestimated at low latitudes. This compensates, at least in part, for the lack of oceanic heat transport.

As is done for the simulation of the present climate, extended numerical time integrations of the FC and VC models are performed to simulate the LGM climate. The models are run using the distribution of continental ice sheets from the LGM (approximately 18 000 years B.P.) and incorporating the differences in snow-free land albedo between the LGM and the present. Both the ice sheet distribution and the continental albedo differences are taken from the CLIMAP reconstructions of LGM surface conditions (CLIMAP Project Members, 1981). In addition, it is assumed that the CO_2 concentration in the model atmosphere is 200 ppm by volume based upon results from the recent chemical analysis of air bubbles trapped in the Antarctic and Greenland Ice Sheets (Neftel *et al.,* 1982). For the determination of incoming solar radiation at the top of the model atmosphere, the present values of orbital parameters of the earth are used because they differ little from the 18 000 yr B.P. values. A summary of the boundary conditions used in the LGM and present simulations is given in Table 3. As with the standard simulations, the models are run until a quasi-equilibrium climate is reached, with the subsequent eight years retained for analysis.

TABLE 2. Comparison of sea ice area simulated by the FC and VC models with observed data.*

	FC	VC	Observed
	Northern Hemisphere		
Maximum	22.8	20.5	14.1
Minimum	6.0	7.9	7.1
	Southern Hemisphere		
Maximum	13.1	14.3	15.0
Minimum	3.1	7.6	2.5

* The observed Northern Hemisphere sea ice area is taken from Walsh and Johnson (1979), while that for the Southern Hemisphere is from Zwally *et al.,* (1983). Units are 10^6 km^2.

3. Model sensitivity for LGM simulation

Globally-averaged differences in surface air temperature (i.e., the temperature at the model's lowest finite-difference level, located at approximately 70 m above the earth's surface) produced by the FC and VC models for LGM boundary conditions and for CO_2 doubling are listed in Table 4. The larger sensitivity of the VC model to the LGM boundary conditions is consistent

TABLE 3. Boundary conditions and other model input parameters for the present and LGM climate simulations.

	Standard	LGM
Land–sea distribution	Present	18,000 yr B.P.
Continental ice distribution	Present	18,000 yr B.P.
Atmospheric CO_2 concentration	300 ppm	200 ppm
Snow-free land albedo	Present	18,000 yr B.P.
Orbital parameters	Present	Present

TABLE 4. Globally-averaged differences in surface air temperature (°C) between LGM and the present as simulated by the FC and VC models. [Corresponding differences for doubled CO_2 ($2 \times CO_2$) are included for comparison.]

	FC	VC
LGM	−3.6	−4.7
$2 \times CO_2$	2.3	4.0

with the larger sensitivity of this model to increased CO_2, although the degree of amplification of the sensitivity is not as large. For a doubling of CO_2, the sensitivity of the VC model is greater than that of the FC model by 74%, while for the LGM boundary conditions the sensitivity is greater by only 31%.

[Not all of this difference in sensitivity between the two versions of the model can necessarily be attributed to cloud feedback. Spelman and Manabe (1984) have shown that the sensitivity of a model depends upon its distribution of surface temperature. Since the distributions of surface air temperature and sea ice simulated by the FC and VC models are slightly different (see Fig. 1 and Table 1) some portion of the difference in sensitivity between the models may be attributable to the differences in their simulations of the present climate. In order to properly evaluate the contribution of cloud feedback, it would be necessary to repeat the CO_2 doubling experiment without interactive cloudiness, using the cloud distribution taken from the VC simulation of the present climate. Preliminary results from such an experiment (R. T. Wetherald, personal communication, 1984) indicate that cloud feedback is responsible for about half the difference in sensitivity between the FC and VC models, while the remainder most likely results from differences in simulating the present climate.]

One reason for the less dramatic amplification of model sensitivity for the LGM simulation can be found by examining the changes in cloud cover and net incoming solar radiation at the top of the atmosphere produced by the VC model and shown in Fig. 2. For a doubling of CO_2, the model indicates reduced cloud cover from about 45°N to 30°S, with increased cloudiness poleward of these latitudes. An increase in net incoming solar radiation results from the reduction of cloudiness (and hence planetary albedo) in low latitudes. This change in the net incoming solar radiation due to the change of cloud cover in low latitudes of the model enhances the CO_2-induced warming and is partly responsible for the increased sensitivity of the VC model relative to the FC model. The increased cloudiness in high latitudes does not result in a decrease in net incoming solar radiation, since surface albedos in high latitudes are greatly reduced as a result of the decrease in snow cover and sea ice in the warmer high-CO_2 climate.

In the colder LGM simulation, one might expect cloud cover changes opposite those found in the doubled CO_2 experiment. This is only partly the case, as the corresponding region of increased low latitude cloudiness is confined primarily to between 10°N and 40°S, with a reduction in cloud cover elsewhere. Thus, the area over which a positive feedback can contribute to LGM cooling is smaller, and the amplification of model sensitivity by cloud feedback is also smaller. The large decrease in total cloudiness at high latitudes in the LGM simulation is relatively unimportant, since the increase of surface albedo due to the expanded area of continental ice, snow cover, and sea ice more than compensates for the reduction in cloud cover, produc-

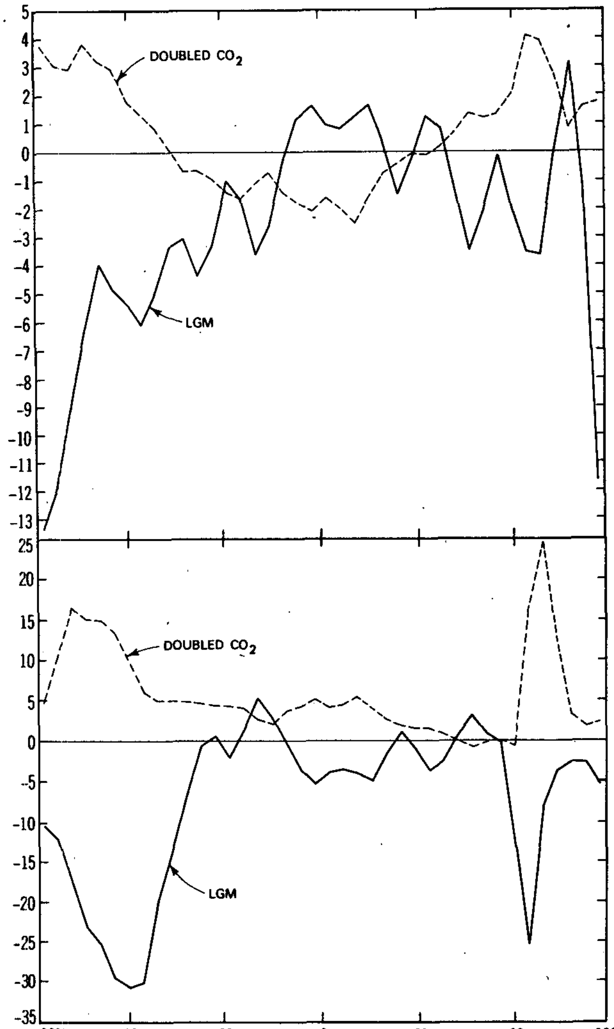

FIG. 2. Latitudinal distribution of zonally-averaged differences in annual mean total cloud cover and net incoming solar radiation between the LGM and present simulations (solid line). The corresponding differences between the doubled CO_2 and present simulations are also plotted for comparison (dashed line). Top: Total cloud cover (in percent). Bottom: Net incoming solar radiation at the top of the atmosphere (in W m^{-2}).

ing a decrease in net incoming solar radiation. While the precise mechanisms responsible for the different pattern of cloud cover change in the LGM simulation are not completely understood, the presence of the Northern Hemisphere ice sheets may contribute to decreased cloudiness over a wide area.

Table 5 contains area-averaged SST differences between the LGM and standard simulations for both the FC and VC models. The SST differences as estimated by CLIMAP from an analysis of microfossils in deep-sea sediments (CLIMAP Project Members, 1981) are included for comparison. The area averages were computed by using only those gridpoints which represent oceans in both the LGM and present cases. Averaged globally, the SST cooling indicated for both versions of the model is somewhat larger than the cooling estimated by CLIMAP, with the VC model producing the larger reduction in SST. Both the FC and VC models simulate larger SST reduction in the Northern than in the Southern Hemisphere, a finding consistent with the CLIMAP estimates.

To examine the SST changes in more detail, Fig. 3 illustrates the latitudinal distribution of the difference in annually averaged zonal mean SST between the LGM and the standard simulations for both the FC and VC models. For comparison, the corresponding SST differences as determined by CLIMAP are also plotted. From this figure, it is evident that the degree of correspondence between the model SST differences and the CLIMAP estimates is dependent on latitude. Poleward of 65°N, both models drastically underestimate the SST difference between the LGM and the present. This is a direct result of the excessive sea ice produced in the standard simulations of both models due to the absence of poleward heat transport by the oceans. From 45–55°N, the results of both models compare favorably with the CLIMAP estimates, although the FC model may be slightly more realistic. Near the equator the cooling simulated by the models is quite close to the CLIMAP estimates, while in the subtropics, both models overestimate the decrease in SST, with the FC model being somewhat closer to the CLIMAP SST reduction. The reason for this disagreement in the subtropics will be more clearly illustrated in a subsequent discussion of the geographical distribution of SST differences. It is the main reason that the CLIMAP estimates of the hemispheric mean differences in SST between the LGM and the present are

TABLE 5. Area-averaged differences in annual mean SST (°C) between the LGM and present as simulated by the FC and VC models and as estimated by CLIMAP.

	FC	VC	CLIMAP
Northern Hemisphere	−2.6	−2.8	−1.9
Southern Hemisphere	−1.5	−2.2	−1.3
Global	−2.0	−2.4	−1.6

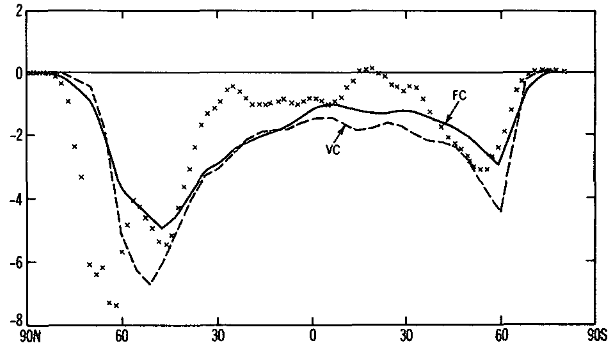

FIG. 3. Latitudinal distribution of zonally-averaged annual mean SST difference between the LGM and present simulations from the FC model (solid line) and the VC model (dashed line). The corresponding SST differences as estimated by CLIMAP, indicated by crosses, are included for comparison.

smaller than the corresponding differences simulated by either version of the model as Table 5 indicates. In the high latitudes of the Southern Hemisphere, the FC model produces a SST reduction closely resembling that found by CLIMAP, while the VC model overestimates the magnitude of the cooling in this region.

A more complete indication of the strengths and weaknesses of the LGM simulations produced by the FC and VC models can be obtained from the maps of the differences in annually averaged SST shown in Fig. 4. These can be compared with the annual mean SST differences estimated by CLIMAP, which were computed by averaging the February and August values. The larger sensitivity of the VC model is apparent from the increased area of SST reduction greater than 2°C when compared with the FC model. Both models are similar in the overall pattern of SST differences, comparing favorably with the CLIMAP data in the North Atlantic and the Southern Ocean. The region of maximum reduction in SST in the North Atlantic is well defined in both simulations, corresponding with the CLIMAP data in both location and magnitude. In the Southern Ocean, the belt of maximum cooling produced by both models is located somewhat poleward of the comparable feature in the CLIMAP SST differences. Both models simulate the relative coldness of the North Atlantic as compared with the North Pacific in accordance with the CLIMAP estimates. The most prominent discrepancies between the model simulations and the CLIMAP data occur in the subtropics and middle latitudes of the Pacific Ocean, where the CLIMAP reconstruction indicates large areas in which the LGM SSTs were about the same or slightly higher than today. These regions contribute prominently to the smallness of the reduction of zonal mean SST near 25°N and 20°S evident in the CLIMAP estimates. Both models fail to reproduce these features, simulating instead cooling at all latitudes. In addition, the regions of large temperature decrease in the vicinity of the Kuroshio and Gulf Stream are not reproduced by the

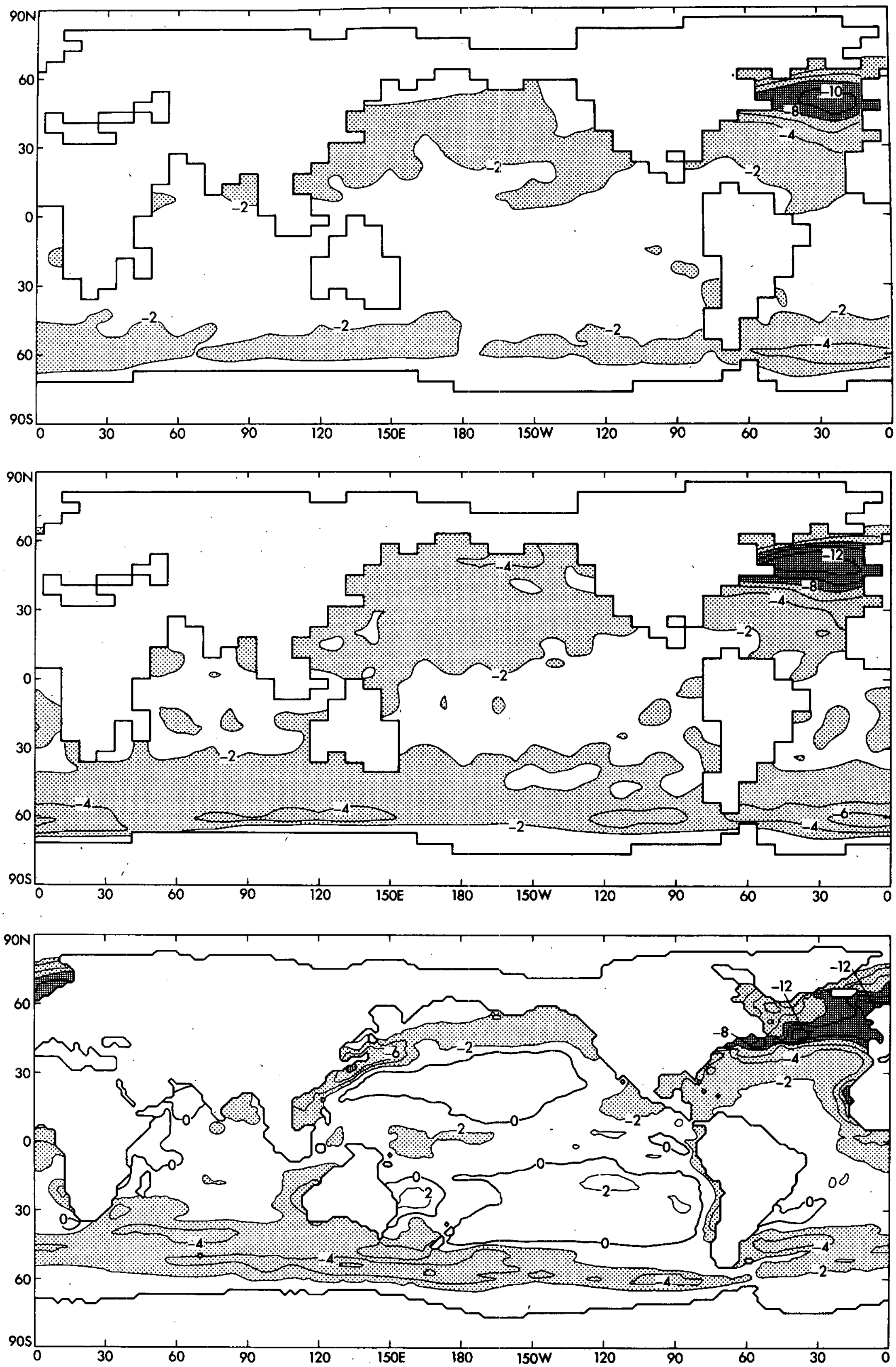

FIG. 4. Geographical distribution of sea surface temperature differences between the LGM and the present (in degrees K). Top: FC model. Center: VC model. Bottom: CLIMAP estimates.

models. It is tempting to speculate that these features are the result of mechanisms not incorporated in the models used for this study, such as changes in ocean circulation, but the current understanding of the LGM ocean circulation is insufficient to evaluate this possibility.

Figure 5 contains annually averaged zonal mean differences in surface air temperature between the LGM and standard simulations for both the FC and VC models. In computing the zonal means over land, only gridpoints representing ice-free land were used. Similarly, only gridpoints representing ocean in both simulations were used to compute the zonal means over the sea. In general, the pattern of temperature change according to latitude is very similar for the two models, with the VC model simulating somewhat larger cooling. This is consistent with the globally averaged differences in SST and surface air temperature presented earlier.

There are substantial latitudinal variations in the differences in surface air temperature between the LGM and standard simulations. In general, temperature differences are somewhat larger over land than over the sea, except poleward of approximately 45°N. Both models indicate large reductions in surface air temperature in the high latitudes of the Northern Hemisphere. The reductions are particularly large over the oceans, where thicker and more extensive sea ice cover in both LGM simulations results in very low air temperatures by insulating the atmosphere from the underlying ocean. This process is discussed in more detail by Manabe and Broccoli (1985). Elsewhere, the simulated difference in temperature between the LGM and present becomes much smaller in the tropics. In the tropics, the zonal mean cooling is quite uniform with latitude. The temperature differences increase with latitude in the midlatitude Southern Hemisphere toward a maximum in high latitudes. The increased sensitivity of both models in high latitudes is typical of the "polar amplification" found in many other climate sensitivity studies (e.g., Manabe and Stouffer, 1980) and mainly attributable to ice–snow–albedo feedback. The polar amplification in surface air temperature is much more pronounced than that of SST, which is prevented from falling below its freezing point of −2°C. In the Northern Hemisphere extratropics, additional cooling results from the local influence of the continental ice sheets.

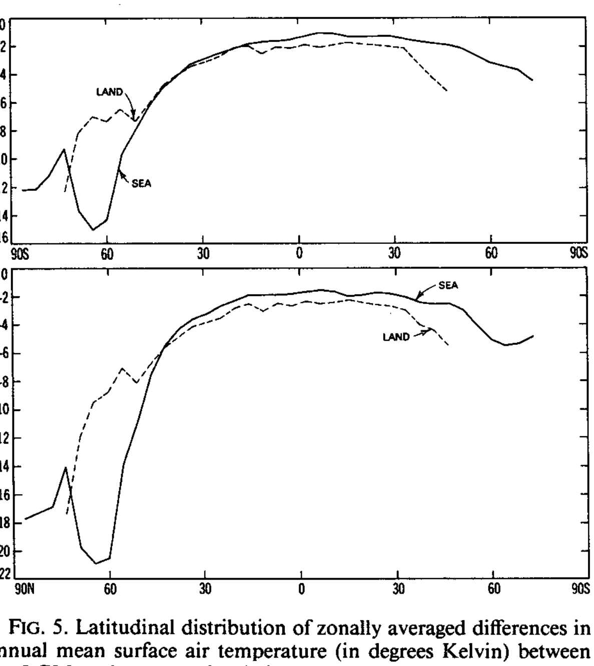

FIG. 5. Latitudinal distribution of zonally averaged differences in annual mean surface air temperature (in degrees Kelvin) between the LGM and present simulations. Top: FC model. Bottom: VC model.

The sensitivities of the models over the continents can be evaluated by comparing the surface air temperature differences between the LGM and standard simulations with the corresponding differences as compiled by Peterson *et al.* (1979) from a wide variety of geological data. Table 6 compares the temperature differences between the LGM and the present as simulated by the FC and VC models with estimates of the actual temperature differences obtained from Peterson *et al.*'s compilation. The temperature differences are averaged over three latitude belts: the Northern Hemisphere extratropics (30–65°N), the tropics (30°N–30°S), and the Southern Hemisphere extratropics (40–50°S). The choice of boundaries for the latitude belts is determined by the availability of the geological data. Only model gridpoints with nearby paleotemperatures are used in the compilation of this table, and the number of gridpoints used is indicated in the first column. In order to maximize the number of observations used in the comparison, all available paleotemperature data are used irrespective of the precision of the geological dating.

In the extratropics of the Northern Hemisphere, where the LGM paleotemperature data are most abundant, both models produce temperature differences which are comparable in magnitude to the geological data. The FC model is in very close agreement, while the VC model slightly overestimates the temperature differences. In the tropics and in the Southern Hemisphere extratropics, the difference in annual mean surface air temperature over land simulated by both models grossly underestimates the corresponding paleoclimatic temperature difference. The sensitivity of the VC model is slightly larger than the FC model, but it is still too small by a factor of 2. Using only the best-dated paleotemperatures from Peterson *et al.* (1979) for the comparison does not change the conclusions drawn from this analysis.

It is interesting that the low latitude SST differences simulated by both models are larger than the CLIMAP SST differences, whereas, over low latitude continents, the simulated differences in surface air temperature are smaller than the differences reconstructed from the geological data. This results from the apparent disparity

TABLE 6. Comparison of difference in annual mean surface air temperature (°C) between the LGM and present as simulated by the FC and VC models with land-based paleoclimatic data. The paleotemperature difference for each latitude belt represents an arithmetic average of all available values from Peterson *et al.* (1979). For computing the differences from both models, only model gridpoints with nearby paleotemperatures were used.

	Number of points	FC	VC	Paleoclimatic observations
Northern Hemisphere extratropics (30°–65°N)	23	−8.0	−9.6	−7.8
Tropics (30°S–30°N)	14	−2.1	−2.5	−5.6
Southern Hemisphere extratropics (40°–50°S)	5	−2.0	−2.7	−5.4

between the SST differences estimated by CLIMAP for the tropical oceans and the consensus of land-based temperature differences based on botanical and geological data, which has been examined in detail by Webster and Streten (1978) and by Rind and Peteet (1985). An interesting question is why the CLIMAP SST differences are small in the low latitude oceans. Both models employed in this study fail to reproduce this feature.

It is important to keep in mind that the models used in this study treat the ocean as a static mixed layer and do not include ocean dynamics. For this reason, changes in the wind-driven ocean circulation between the LGM and the present cannot be simulated by the models used in this study. One can speculate that a change in the wind stress over the tropical oceans might have an effect on low latitude SST, but no major changes in the strength of the trade winds are present in either LGM simulation. A more complete evaluation of the LGM ocean circulation must await the development of more realistic models of the global atmosphere–ocean system.

4. Conclusions

Despite the discrepancies identified in Section 3, the simulated temperature differences obtained from both models are generally comparable to the paleoclimatic estimates. In other words, both the FC and VC models have sensitivities roughly in agreement with the estimated change in temperature between the LGM and present climates. The differences between the models are, in most cases, small in magnitude. For example, based on the CLIMAP SST data, both models are comparable in performance in the high latitude Northern Hemisphere. In the Southern Hemisphere, the FC model is somewhat better in the tropics, subtropics, and high latitudes where both models overestimate the reduction of SST. When a comparison is made with continental paleotemperatures, the FC model is in slightly better agreement in the Northern Hemisphere extratropics. The VC model is closer to the continental paleotemperature data in the tropics and the Southern Hemisphere where both models underestimate the reduction in surface air temperature.

It is, however, difficult to decide which of the two models produces the more realistic sensitivity to LGM boundary conditions. In the Northern Hemisphere extratropics, where the land-based paleoclimatic data are most abundant, both models are in reasonably good agreement with continental paleotemperatures and CLIMAP SST. In the tropics, the large disparity between estimates of the LGM reduction in tropical SST and land-based evidence of reduced tropical surface air temperature is a primary obstacle which precludes a definitive evaluation of model sensitivity. The FC and VC models are quite similar in overall sensitivity, and the tropical LGM cooling produced by both is "bracketed" by the smaller cooling found in the CLIMAP SST data and the larger cooling indicated by the continental paleotemperatures. Thus, the apparent disparity between the two categories of paleoclimatic data in low latitudes is much larger than the difference between the two versions of the model.

Until this disparity in the estimates of LGM paleoclimate is resolved, it is difficult to use data from the LGM to evaluate differences in low latitude sensitivity between climate models. Nevertheless, the results from this study suggest that the sensitivity of both models used in this study may not be too far from reality, since both show a reasonable degree of success in simulating the less controversial LGM cooling of the extratropics. While the present study may not resolve the uncertainties that exist in assessing the sensitivity of climate to increased CO_2, it does suggest that estimates of CO_2-induced climate change obtained from these models may be regarded with some additional confidence.

The success of the models in simulating the LGM climate is particularly interesting in the light of an earlier study by Manabe and Broccoli (1985), in which a model very similar to the current FC model was used to examine the influence of the LGM continental ice sheets on climate. They found that while the inclusion of the ice sheets resulted in a Northern Hemisphere cooling which was slightly smaller but similar to that estimated for the LGM, little or no reduction in temperature occurred in the Southern Hemisphere. To explain the absence of a Southern Hemisphere response, Manabe and Broccoli suggested that a mechanism other than those included in their experiment was necessary to extend the Northern Hemisphere cooling to the Southern Hemisphere, such as the lowered LGM atmospheric CO_2 content or changes in ocean circulation. In the current study, the reduction of atmospheric CO_2 is included in the LGM simulations. Its success in producing a cooling of reasonable magnitude in both hemispheres appears to be consistent with the CO_2 hypothesis. Work is in progress to study in more detail the contribution of reduced CO_2 to the simulated LGM climate.

Finally, it should be emphasized that the models used for this study do not include the effect of horizontal heat transport by ocean currents. Despite this simplification, the latitudinal distributions of surface air temperature simulated by the models compare favorably with the observed distribution. As pointed out in Section 2, this agreement may be indicative of compensating effects brought on by inaccuracies in the formulation of the model and does not necessarily imply that the influence of oceanic heat transport on surface air temperature is small. Evidence from faunal, chemical, and isotopic studies of deep sea sediments suggests that the production of deep water in the North Atlantic Ocean was greatly reduced during the LGM (e.g., Boyle and Keigwin, 1982). Therefore, the poleward heat transport due to thermohaline overturning may have been reduced in the North Atlantic during the LGM. Such a reduction cannot occur in the present models, since it does not incorporate poleward heat transport by ocean currents. The absence of oceanic heat transport is one of the reasons that the models fail to simulate the large SST difference in the North Atlantic poleward of 60°N. In order to incorporate the effect of the ocean circulation in the simulation of the LGM climate, a coupled ocean-atmosphere model with realistic geography should be used in future studies of ice age climates.

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