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APPLICATION OF OCEAN MODELS FOR THE INTERPRETATION OF ATMOSPHERIC GENERAL CIRCULATION MODEL EXPERIMENTS ON THE CLIMATE OF THE LAST GLACIAL MAXIMUM

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Abstract. We examined the response of our ocean models of physical circulation and geochemical tracer distributions on atmospheric glacial forcing. The CLIMAP Project Members (1981) sea surface temperature (SST) was taken directly as a boundary condition The wind stress and freshwater flux were derived from the ice age response of an atmospheric general circulation model (AGCM). Near the surface, the ocean response in temperature and circulation reflects primarily the imposed glacial forcing fields. The simulated deep ocean response, especially in the North Pacific, is in conflict with the observational evidence. The glacial changes in the physical ocean circulation appear to be qualitatively as derived from sediment cores, but, probably, highly overestimated. The misfit between model and data is established clearly in the distribution of δ^{13}C, where a direct comparison with sediment core data is possible. The simulated AGCM freshwater flux, which is linked for example by the evaporation to the imposed SST field, is suspected to be the most probable reason for this conflict.

INTRODUCTION

Great efforts have been made during the last 15 years to reconstruct the surface climate of the last glacial maximum (LGM) from a very heterogeneous set of original data [CLIMAP Project Members, 1981]. As a result, we have now inter alia global maps of surface temperature for summer and winter and of ice coverage which can be taken to drive an AGCM. The glacial boundary conditions for the ocean general circulation model (OGCM), surface temperature, wind stress, and freshwater flux, are then available from the simulation of the atmospheric glacial response.

Although substantial progress has been made in modeling the atmospheric response to LGM boundary conditions [e.g., Kutzbach and Guetter, 1986; Broccoli and Manabe, 1987; Rind, 1987; Lautenschlager and Herterich, 1990], relatively little has been done on the glacial ocean circulation Aside from the somewhat inferential studies of Miller and Russell [1989] and Keffer et al. [1988], there has been no attempt to model the three-dimensional glacial response of the ocean and couple a global carbon model to a three-dimensional simulation of the ocean 18,000 years before present (18 ka).

In this study, we simulate the three-dimensional circulation of the ice age ocean and the effect on the ocean carbon cycle. Our approach is to force an OGCM with the results from an AGCM, which in turn has been forced with LGM boundary conditions from CLIMAP Project Members [1981]. The model generated output – upwelling, δ^{13}C, Δ^{14}C – are compared qualitativley to the deep–sea record Most of the comparisons involve data collected since original publication of the CLIMAP Project Members [1981] sea surface temperature (SST) field.

As will be seen in the results section, there are some significant differences between our model results and observations. Some readers may question the utility of reporting negative results. Although

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such objections might seem reasonable, we believe there are three justifications for our actions: (1) there are some areas where in fact there are agreements between models and observations; (2) it is useful to report the results as a benchmark for comparison of future runs with other models or different boundary conditions; (3) the most significant model-data discrepancy can be traced to a critical boundary condition, the CLIMAP Project Members [1981] Pacific SST field. Our results underline those of an earlier study [Rind and Peteet, 1985] as to the need for their reevaluation, but our results also extend the magnitude of the model-data discrepancies for 18 ka not only to tropical land areas but also to the oceanic thermohaline circulation and preservation of deep-sea sediments.

MODEL CHAIN

The Earth's climate is determined by the interaction of atmosphere, biosphere, ocean, and cryosphere. Simulations of future climate changes due to the increase of atmospheric carbon dioxide and other greenhouse gases are only reliable if the ability of the numerical models to simulate the present climate is shown as well as the ability of the models to simulate climatic states far away from the present one. Present-day available models are tuned to simulate present-day climate. Therefore it is a priori not clear that these models sucessfully simulate climatic states different from the present. Up to now, coupled ocean-atmosphere models suffer from the fact that the separately developed models do not balance each other with respect to the errors in the fluxes across the air–sea interface. Consequently, the climate of the coupled model exhibits a drift even in attempts to simulate the present climate. A systematic tuning of free parameters to remove such drifts would require so many experiments that even with today's computer facilities it is not feasible. It is convenient to introduce flux corrections [Sausen et al., 1988] in which mismatches of the fluxes of the present–day climate are added to the fluxes in the coupled system. By this technique the submodels can be coupled to a rather stationary model of the present climate which allows, at least, the investigation of the effect of small perturbations. For the simulation of a completely different climate state, however, with potentially increased impact of nonlinearities, the flux correction is conceptually not applicable. It is therefore still critical to look at the behavior of the subsystems.

AGCM Experiment

The AGCM used is the T21 model developed at the European Centre for Medium-Range Weather Forecasts (ECMWF) in Reading [Louis, 1984] and modified for climate simulations at the Meteorological Institute of Hamburg University [Dümenil and Schlese, 1987]. The T21 AGCM is based on the primitive equations including radiation, a hydrological cycle and a three–layer soil model, determining soil temperature and soil moisture. The model equations are solved in the spectral domain, truncated at wavenumber 21. This corresponds to a horizontal resolution of 5.6° in latitude and longitude. The ver-

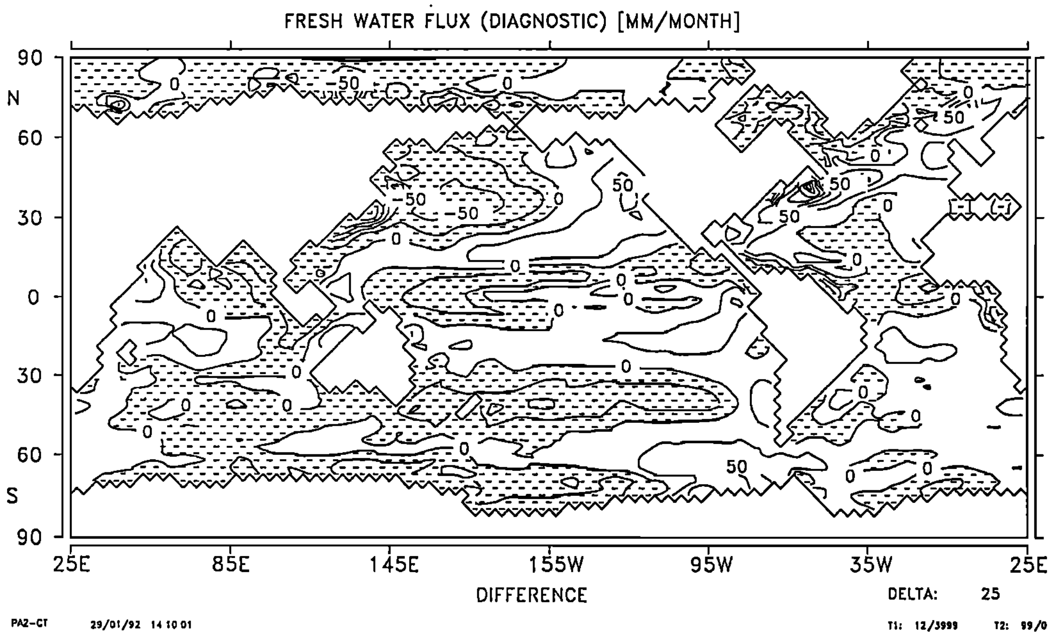

Fig. 1. Annual mean freshwater flux anomaly (LGM minus present-day) calculated from the T21 ice age experiment. Contour interval: 25 mm/month, negative anomalies are dashed.

tical coordinate is resolved by 16 levels in a hybrid coordinate system: the terrain-following sigma coordinate at low model levels is transformed to pressure coordinate at higher levels yielding surfaces of constant pressure in the stratosphere.

Two T21 experiments were performed over six annual cycles, a present-day control and the ice age response [Lautenschlager and Herterich, 1990]. For the LGM, the lower boundary conditions were obtained from CLIMAP Project Members [1981]. The last five model years were used to calculate the climate means and anomalies (ice age minus present). These 5-year mean anomalies were taken as driving forces for the ocean experiments, including computation of the annual mean freshwater flux anomaly (Figure 1) . The freshwater flux into the ocean is defined as precipitation minus evaporation plus river run-off.

OGCM Experiment

The OGCM used is the large-scale geostrophic global model developed at the Max-Planck-Institut für Meteorologie [Maier-Reimer and Hasselmann, 1987]. The model physics is based on the conservation of salt, heat, and momentum. Additionally, a thermodynamic sea ice model with simplified rheology is included. The prognostic equation for the vertical component of momentum is replaced by the hydrostatic approximation. The discretization in time is written in a rigorously implicit way (Euler backward differences). The resulting set of linear equations is solved iteratively for the baroclinic modes and by elimination for the barotropic mode The formulation almost completely suppresses gravity waves which would require a rather short time step in conventional circulation models with an explicit discretization in time. The model uses a time step of 30 days. The effective horizontal model resolution is 3.5°, and the vertical is resolved by 11 layers, six layers above 1000 m depth and five layers below. Details are given in the work by Maier-Reimer et al. [1991].

The OGCM was integrated with present-day boundary conditions until equilibrium was achieved.

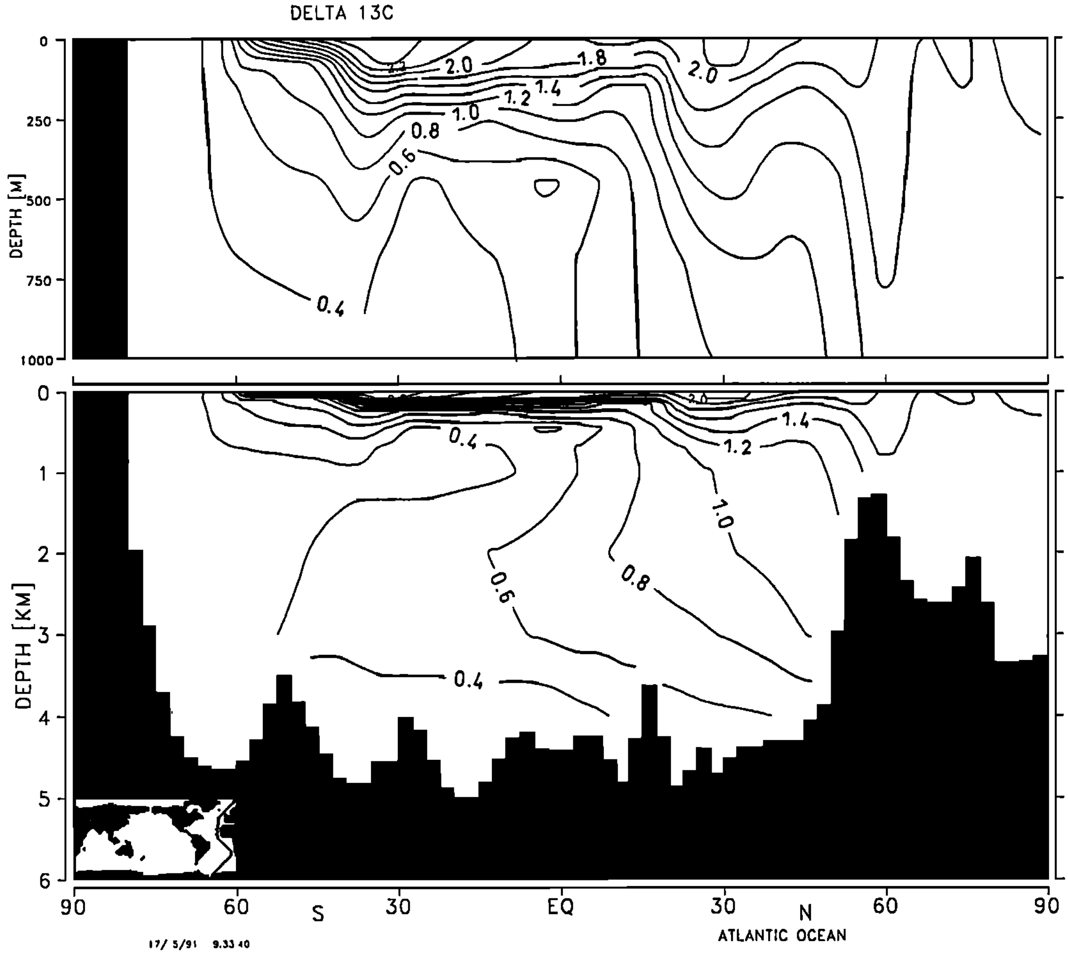

Fig. 2. Distribution of δ^{13}C in the eastern Atlantic. (a) OGCM response to present-day boundary conditions; (b) OGCM response to ice age boundary conditions. Contour interval: $0.2^0/_{00}$.

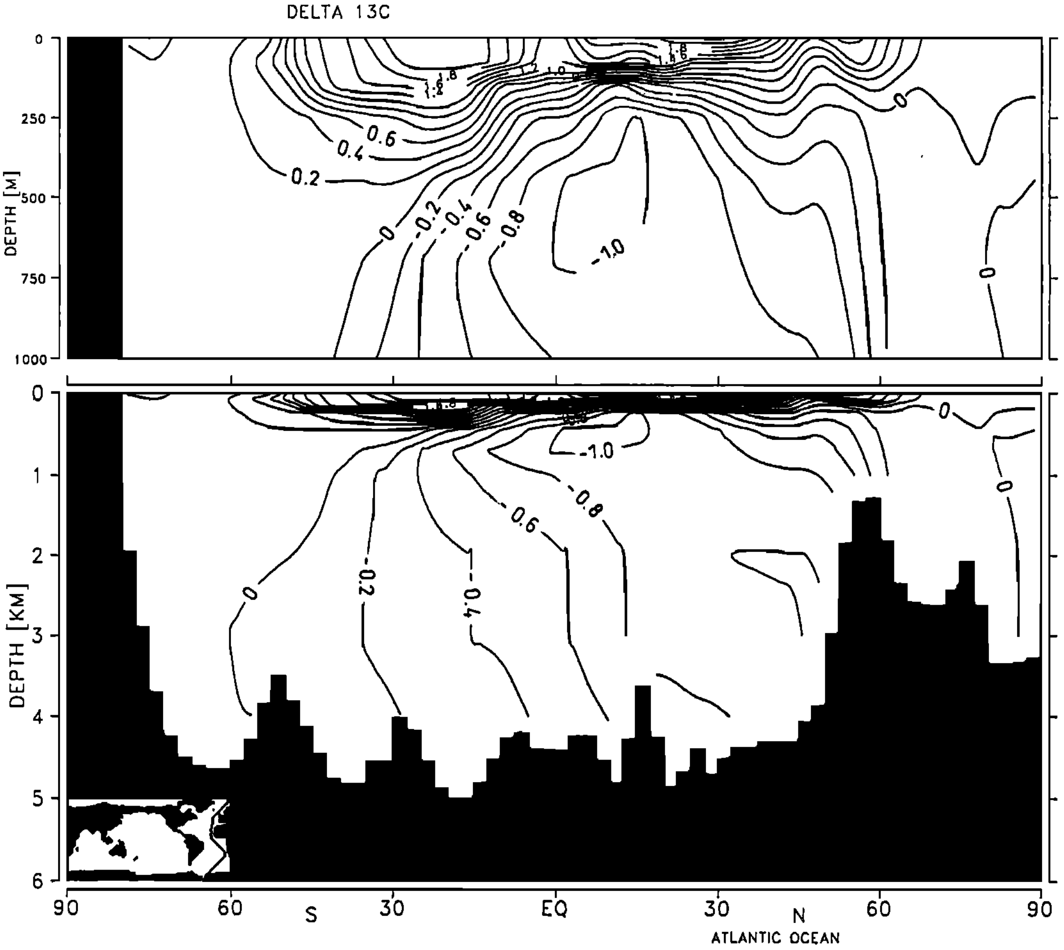

Fig.2 (continued)

Then, after 10,000 model years, the salinity boundary condition was changed into freshwater flux which had been diagnostically determined from the salinity boundary condition. Further model integration for 750 years did not show any changes in the present-day equilibrium ocean circulation. This ocean circulation was taken as present-day control experiment for comparison to the 18 ka experiments ("ice age runs"). Then the modern boundary conditions were changed to the ocean ice age forcing and the OGCM was integrated for 4000 years until a new equilibrium was achieved. For the SST the CLIMAP Project Members [1981] estimates are prescribed directly. The CLIMAP Project Members [1981] SST's were choosen as forcing in both models, the AGCM and the OGCM, for two reasons: (1) the two models were kept near the climate state inferred from the data; (2) it is impossible to integrate the T21-AGCM and the OGCM for some thousand years in the coupled mode. The AGCM anomalies of wind stress and freshwater flux were added to the present-day boundary fields to compile the ocean ice age forcing. All OGCM experiments as well as the AGCM runs were integrated including the annual cycle An overall surface salinity increase due to glacial sea level reduction does not affect the surface salinity gradients and was neglected in these experiments.

A major point of note in our study is that we force the ocean with freshwater fluxes, computed from the AGCM precipitation-minus-evaporation results, rather than attempt any paleo-estimates of salinity. For the ocean there are up to now only crude approximations of the contrast in surface salinity of the major oceans at the LGM as compared to the modern ocean. On the other hand, it is widely accepted that even small changes of salinity in the regions of deepwater formation affect crucially the deep circulation. For example, the pronounced difference between the modern Atlantic and Pacific is attributed exclusively to the very different freshwater budgets in the northern parts, characterized by the high precipitation in the northern Pacific [Warren, 1983], which is fed primarily by the evaporation excess in the Atlantic [Broecker et al., 1990]. The modern oceanic

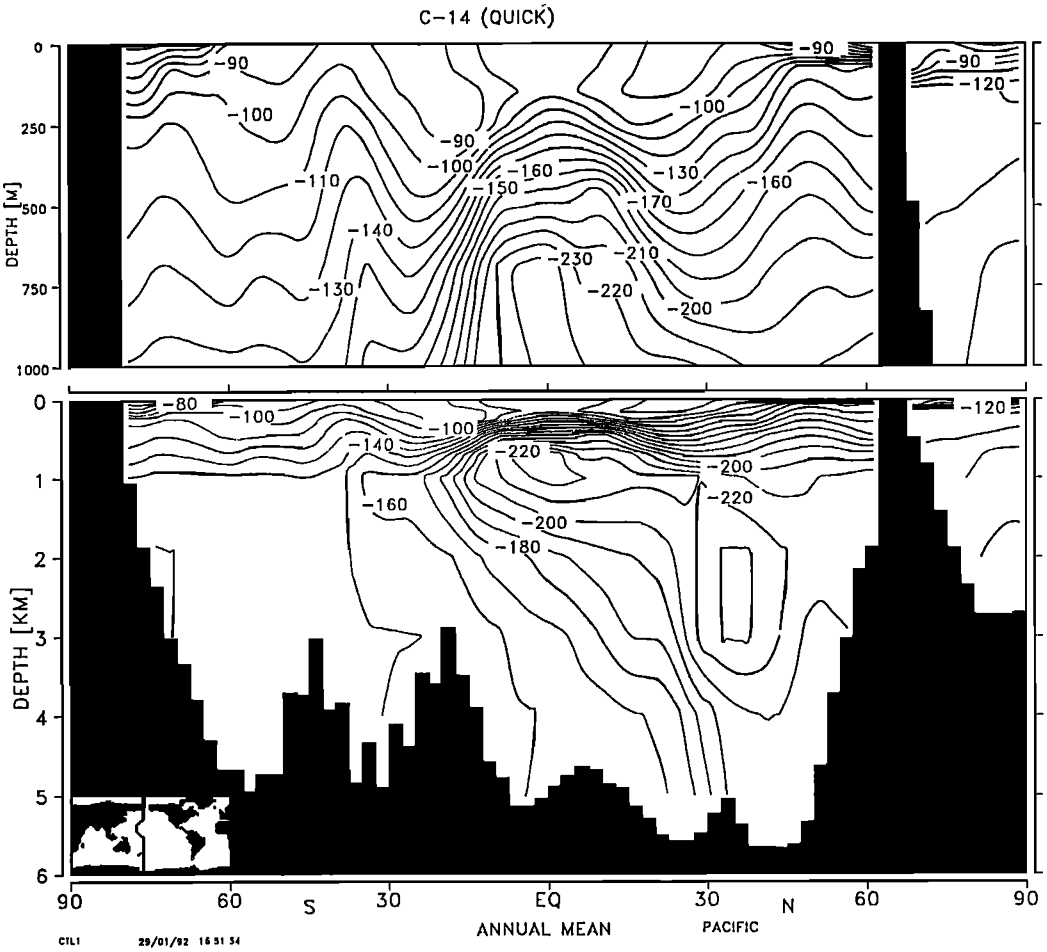

Fig. 3. Distribution of $\Delta^{14}C$ in the western Pacific. (a) OGCM response to present-day boundary conditions; (b) OGCM response to ice age boundary conditions. Contour interval: $10^0/_{00}$. Carbon 14 – age in years: $\Delta t \simeq -8033\ ln(1 + \Delta^{14}C/1000)$.

conveyor belt is driven primarily by the cooling of salty water in the northern Atlantic [Gordon, 1986]. Even for constant fluxes the Atlantic is believed to have the potential for at least two different modes of operation [Broecker et al., 1985]. This conjecture, which was anticipated from the analysis of an extremely simplified heat-salt oscillator [Stommmel, 1962], has been strongly supported by the results of numerical experiments with OGCM's [Bryan, 1986; Manabe and Stouffer, 1988].

Some attempts have been made to derive salinity changes from the oxygen isotope relation in foraminiferal communities [Duplessy et al., 1991]. Unfortunately, this technique fails in cold water where the lack of fractionation during brine formation and the disappearance of calcite producers in cold water disturbes the well established oxygen-salinity correlation of temperate waters. It is for that reason impossible to force an OGCM directly with reconstructed global surface salinity. Even though we cannot utilize this option, we can examine the effects of salinity changes on the thermohaline circulation with our $\delta^{13}C$ and $\Delta^{14}C$ proxies. These will be discussed in the next section.

The Carbon Cycle Model

The carbon cycle model computes the distribution of $\sum CO_2$ of ^{12}C, ^{13}C and ^{14}C as the result from nutrient limited new production in the given current field. Distinction is made between calcite production and the formation of soft tissue. Sinking particles of organic matter (POC) are remineralized provided there is enough oxygen. The calcite pool interacts with a bioturbated sediment layer. The variables of the model are alkalinity, phosphate as a limiting nutrient, oxygen, dissolved CO_2, POC, and calcite. In all carbon tracers the three isotopes are treated separately. In the atmosphere the CO_2 concentrations are supposed to be zonally mixed with a merid-

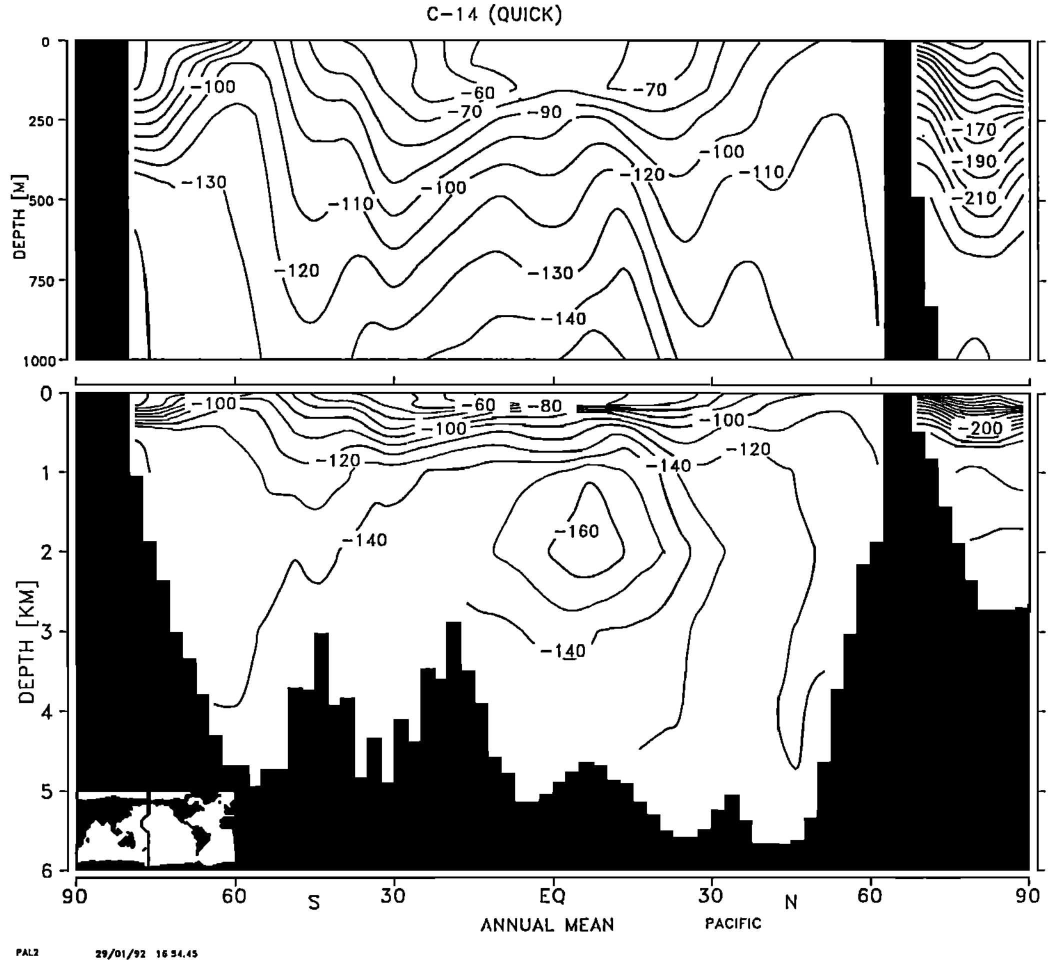

Fig.3 (continued)

ional diffusion of one hemisphere/year. In the gas exchange between ocean and atmosphere, the ^{13}C is fractionated according

$$F^{13} = (1.02389 - 9.483/(T + 273.16)) \cdot$$
$$\cdot F^{12} \sum {}^{13}CO_2 / \sum {}^{12}CO_2$$

where T is the local SST and F denotes the sea-to-air fluxes. For the implementation into soft tissue material we assume a constant fractionation of $-20^0/_{00}$. For radiocarbon we assume the square of these fractionation factors. Details of the model are given by Bacastow and Maier-Reimer [1990] and by Maier-Reimer and Bacastow [1990]. The inventories of the tracers were tuned carefully to produce a stationary preindustrial CO_2 concentration of 275 ppm for the control run.

The mixing ratio of the isotopes in dissolved carbon gives an information of organic carbon productivity and thus nutrient distribution and deep ocean circulation. The ratio δ^{13}C reflects the biological side – it is almost perfectly inverse to phosphate [Maier-Reimer and Bacastow, 1990]. Δ^{14}C after correction by the fractionation effects represents an integral measure of the time elapsed since the water mass last contacted the atmosphere. By comparing planktonic with benthic foraminifera that are found in the same sediment layer, the radiocarbon age difference between surface and bottom gives an information on the turnover time of the ocean, with an uncertainty of approximately 200 years [Lal and Suess, 1983].

The model simulates the modern distribution of δ^{13}C on a section in the eastern Atlantic (Figure 2a), comparing well with Kroopnick's [1985] evaluation of the GEOSECS δ^{13}C data. The model also simulates the present distribution of Δ^{14}C. The section of the western Pacific (Figure 3a), for instance, compares well with the GEOSECS data [Ostlund and Stuiver, 1980]. The deep Pacific has generally too high Δ^{14}C by approximately $20^0/_{00}$. We attribute this to a too strong mixing around Antarctica.

RESULTS

Comparison of simulated surface currents for the control run (Figure 4a) and for the ice age response experiment (Figure 4b) show that in the ice age experiment, the North Atlantic polar front migrated from its present position (65°N) to 45°N and the Gulf Stream crossed the Atlantic at 40°N. The Brazil current and the Atlantic equatorial current were intensified during LGM, and the surface currents in the North Pacific and in the Arctic Ocean were modified in agreement with glacial topography. The Bering Strait was closed because of a sea level reduction in the range of 100 – 150 m. In the ice age response, the strength of the Kuroshio increased and the strength of the East Australian current decreased compared to the present. The simulated glacial Indian Ocean currents showed a more zonal structure compared to the present. The Antarctic Circumpolar Current did not change noticeably north of the margins of permanent glacial sea ice coverage.

The glacial ocean response shows a slightly in-

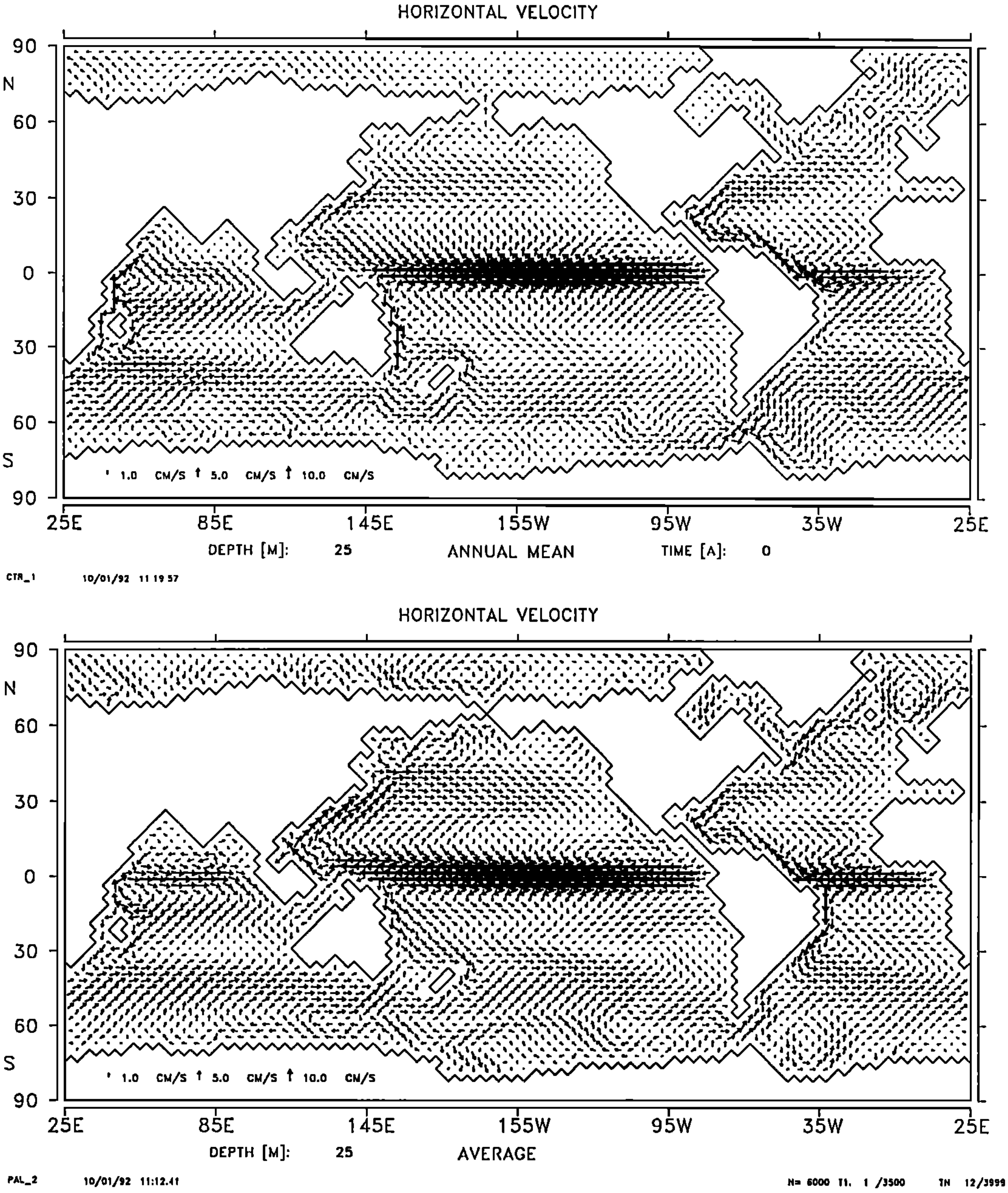

Fig. 4. Annual average of surface horizontal velocity. (a) OGCM response to present-day boundary conditions; (b) OGCM response to ice age boundary conditions.

creased upwelling in the equatorial East Atlantic and a decreased upwelling in the equatorial East Pacific. This reflects the glacial trade wind response in the AGCM: stronger trades in the East Atlantic and weaker trades in the East Pacific. Upwelling also decreased slightly in the Arabian Sea and in Bay of Bengal, regions where the the glacial summer monsoon circulation was reduced in the AGCM response.

As discussed earlier, salinity greatly affects the thermohaline circulation. The differences in surface salinities for the control run and for the ice age response (Figure 5) are directly related to the imposed freshwater anomalies. The larger glacial sea ice thickness around the north pole decreased the total amount of salinity in the uppermost model layer. The modern salinity contrast between North Atlantic and North Pacific, with higher salinities in the North Atlantic, was reversed in the glacial ocean response. The North Pacific surface water contained around $2^0/_{00}$ more salt than the North Atlantic water. The

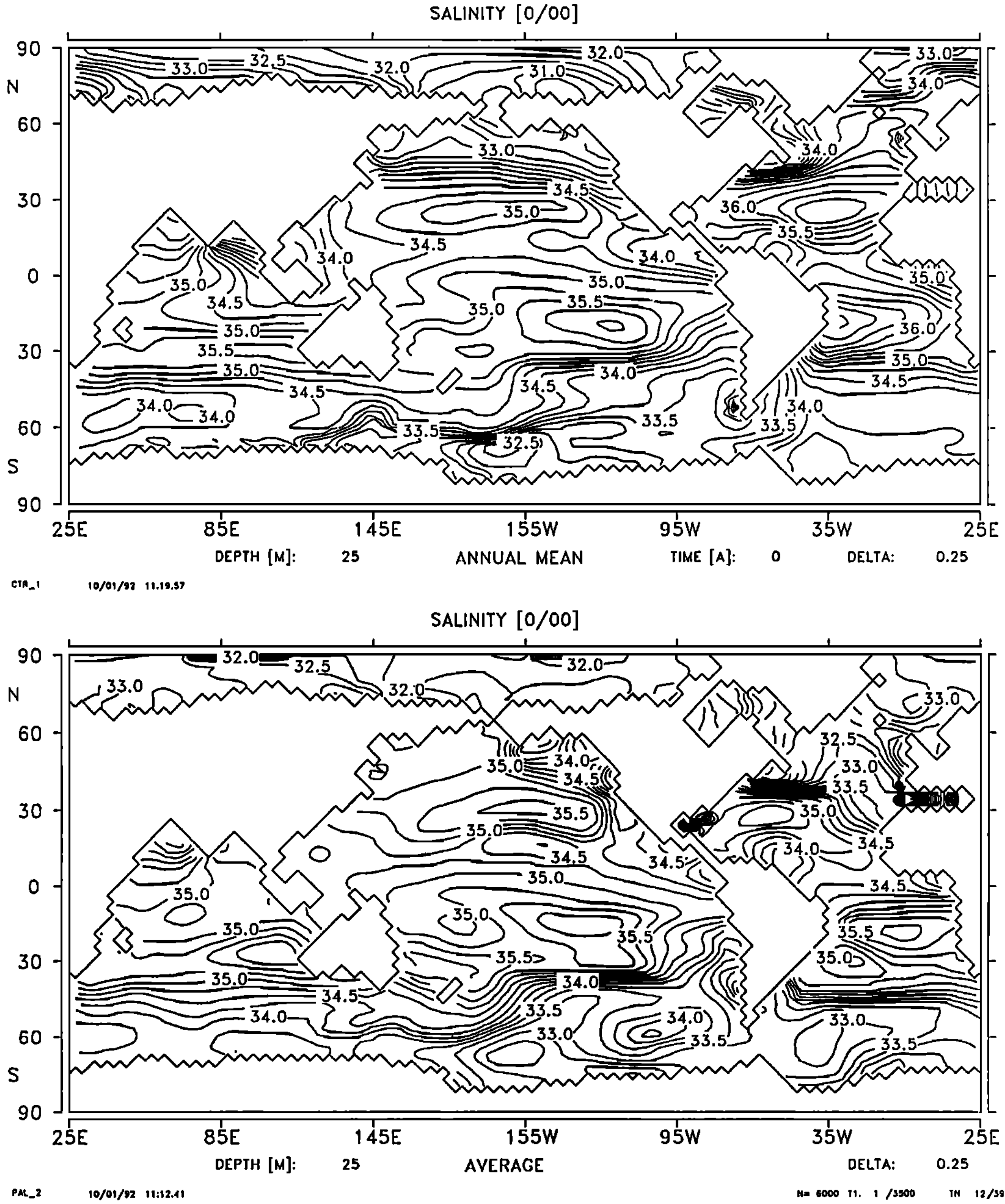

Fig. 5. Annual average of surface salinity. (a) OGCM response to present-day boundary conditions; (b) OGCM response to ice age boundary conditions not accounting for global $1^0/_{00}$ increase in salinity. Contour interval: 0.25 $^0/_{00}$.

modern salinity contrast between the equatorial Atlantic and the equatorial Pacific of $0.5^0/_{00}$ was reduced in the 18 ka simulation. The glacial surface salinity seemed to be slightly increased in the Weddell Sea and slightly decreased in the Ross Sea compared to the control run.

The zonally averaged meridional circulation for the Atlantic (Figure 6) and for the Pacific (Figure 7) shows that compared to the control experiment, the simulated glacial contributions to deepwater production of the Atlantic and of the Pacific were reversed. In the North Atlantic, deepwater production completely stopped in the ice age simulation and in the North Pacific thermohaline circulation started intensively. (This reversed pattern has a remarkable similarity to the first attempts to simulate the present climate with coupled OAGCM's [Bryan et al., 1975]). Compared to the present, the glacial bottom water was younger in the equatorial Pacific than at present (~ 300 years, C^{14}-age) and older in the equatorial Atlantic than at present (~ 300 years, C^{14}-age). The deep-sea temperature was reduced by 2°- 3°C in the Atlantic, by 1°- 2°C in the Pacific and by 2°C in the Indian Ocean.

DISCUSSION

Ocean model results can be compared with geological evidence obtained from deep-sea sediment cores. Comparing the simulations with these evidence, there is some (potential) agreement but also severe disagreement obtained.

Model-Data Agreements

The simulated temperature reduction of 1°- 3°C in the deep ocean fits into the suggested temperature decrease of 1°- 2°C [Chappell and Shackleton, 1986; Labeyrie et al., 1987].

The model agrees with the observations in the following areas. The North Atlantic polar front and Gulf Stream are displaced from their present posi-

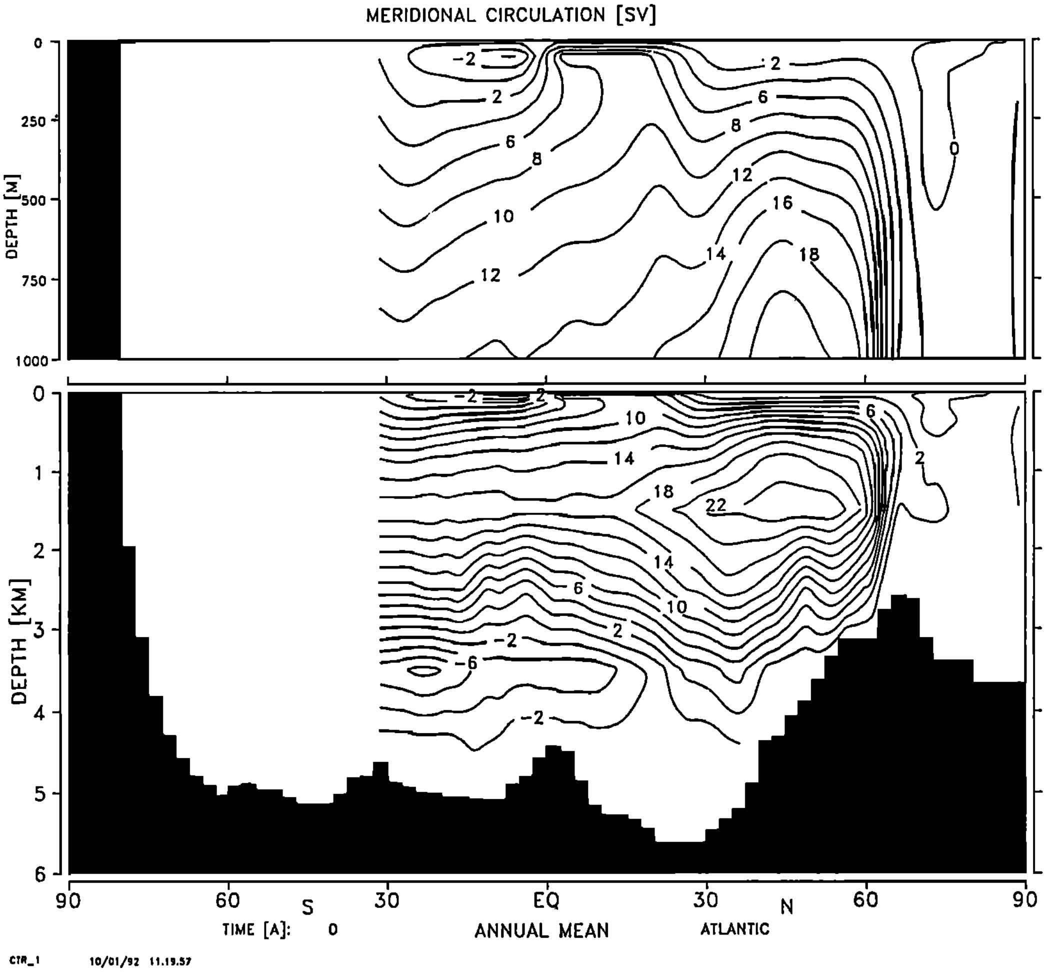

Fig. 6. Annual mean of averaged Atlantic meridional circulation. (a) OGCM response to present-day boundary conditions; (b) OGCM response to ice age boundary conditions. Contour interval: 2 Sv.

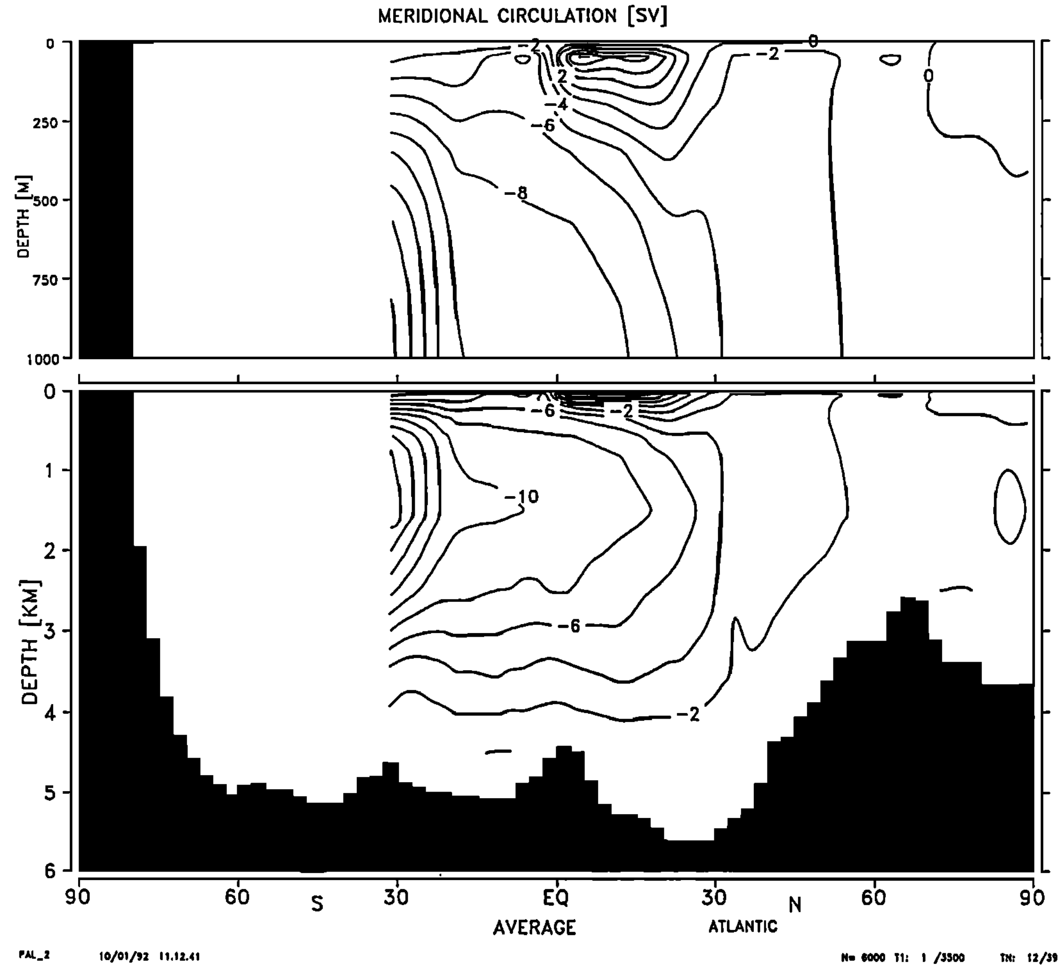

Fig.6 (continued)

tions to 45°N and 40°N, respectively [McIntyre et al., 1976]. Surface salinity in the subpolar North Atlantic may have been lower than present [McIntyre et al., 1976]. Upwelling increased in the equatorial Atlantic [Sarnthein et al., 1988].

The model indicates reduced glacial production of North Atlantic deep water, in agreement with Cd/Ca and $\delta^{13}C$ which indicates a reduction of 30 - 50% while the intermediate water was stronger ventilated [Boyle and Keigwin, 1987; Crowley, 1983; Duplessy et al., 1988]. The thermohaline circulation stopped in the Norwegian Sea but seemed to be active in the northeast Atlantic, possibly on the European continental shelf [Duplessy et al., 1980]. The deepwater circulation was dominated by the northward flow of Antarctic bottom water [Curry et al., 1988; Duplessy and Shackleton, 1985]. Apart from an overestimated reduction of thermohaline circulation and the correlated underestimated ventilation of intermediate water the OGCM response fits into the outlined conception of the glacial Atlantic. The model calculated only minor changes in the strength of the Anarctic outflow between the present and the LGM.

Data indicate a glacial reduction of the Indian summer monsoon and of the upwelling in the Arabian Sea. The LGM surface salinity gradients increased in both, the Arabian Sea and the Bay of Bengal [Duplessy, 1982]. Both models, the AGCM and the OGCM, are consistent with these data. The AGCM simulated the glacial reduction of the summer monsoon circulation and the OGCM computed consistently the glacial upwelling reduction and the surface salinity increase. Mesoscale ocean studies for this area agree with the presented OGCM results [Luther et al., 1990].

Apart from regional differences between model and data (like the missing increased equatorial upwelling at 18 ka in the Pacific) the glacial ocean response at the surface is comparable to the geological evidence.

Model-Data Disagreements

The major descrepancies between data and model appear in the glacial deep ocean response. Car-

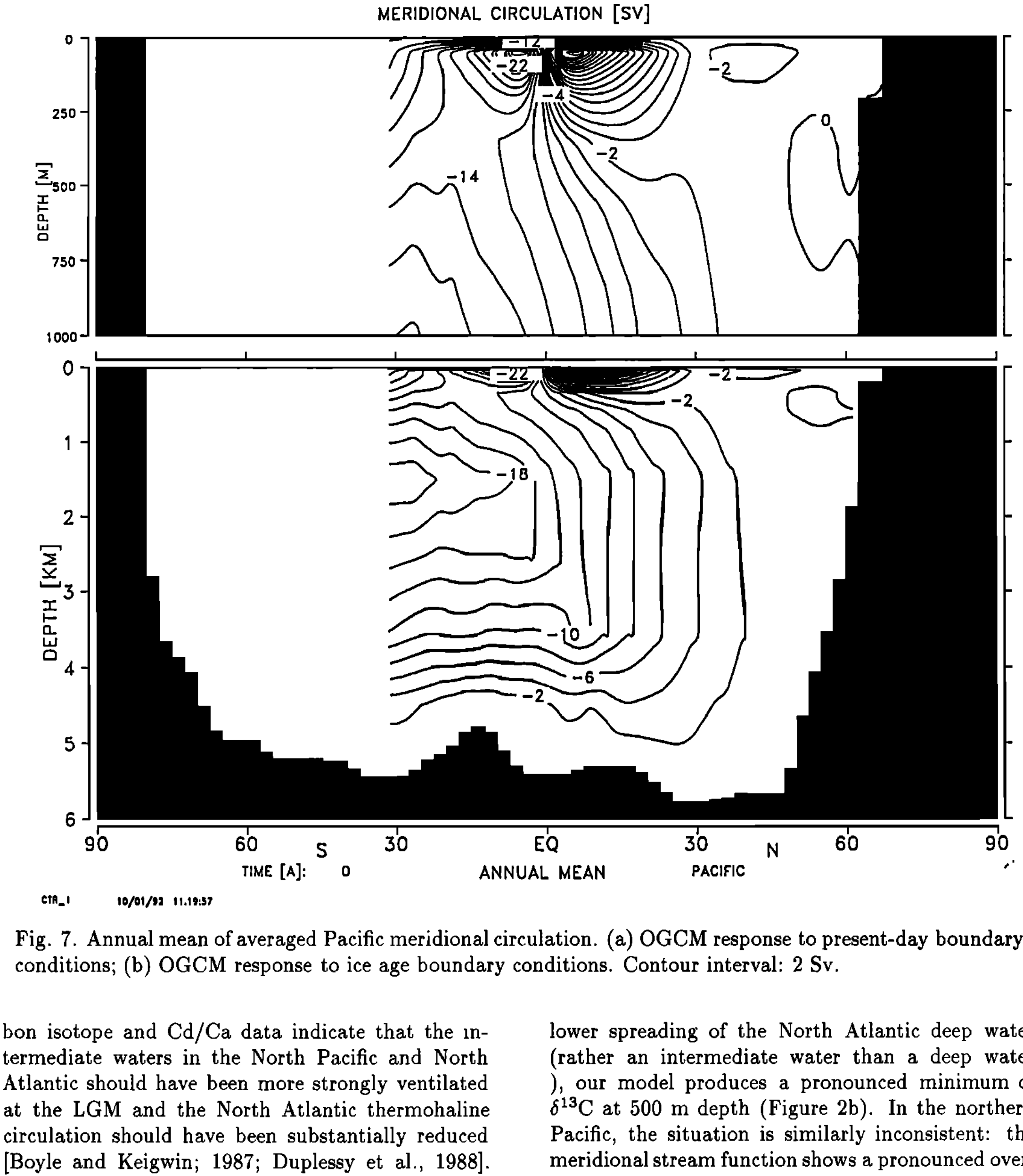

Fig. 7. Annual mean of averaged Pacific meridional circulation. (a) OGCM response to present-day boundary conditions; (b) OGCM response to ice age boundary conditions. Contour interval: 2 Sv.

bon isotope and Cd/Ca data indicate that the intermediate waters in the North Pacific and North Atlantic should have been more strongly ventilated at the LGM and the North Atlantic thermohaline circulation should have been substantially reduced [Boyle and Keigwin; 1987; Duplessy et al., 1988]. The glacial source of global deep water should have been from Antarctica with comparable strength as observed today [Oppo and Fairbanks, 1987; Duplessy et al., 1988]. This sketch yields a globally reduced deepwater overturn at 18 ka. The meridional stream function in the Atlantic of our glacial run (Figure 6b) seems to be roughly compatible with this outline while the meridional stream function in the Pacific (Figure 7b) shows incompatability.

A comparison of our carbon isotopes simulation based on the LGM response reveal discrepancies with data that are much more pronounced than the foregoing qualitative arguments. Whereas Duplessy et al. [1988] described a δ^{13}C distribution similar in structure as the modern one but with a much shallower spreading of the North Atlantic deep water (rather an intermediate water than a deep water), our model produces a pronounced minimum of δ^{13}C at 500 m depth (Figure 2b). In the northern Pacific, the situation is similarly inconsistent: the meridional stream function shows a pronounced overturning which would be compatible with the ideas of stronger production of intermediate water; the age difference between pelagic and benthic foraminifera [Broecker et al., 1988; Shackleton et al., 1988], however, is in clear contrast to our LGM response on radiocarbon distribution. The model, in fact, predicts (Figure 3) younger glacial deep water in the Pacific than at present. At this stage of model verification we have to state clearly that our model results are wrong.

Analysis of Model-Data Disagreements

The freshwater flux taken from the glacial AGCM response were identified as the most probable rea-

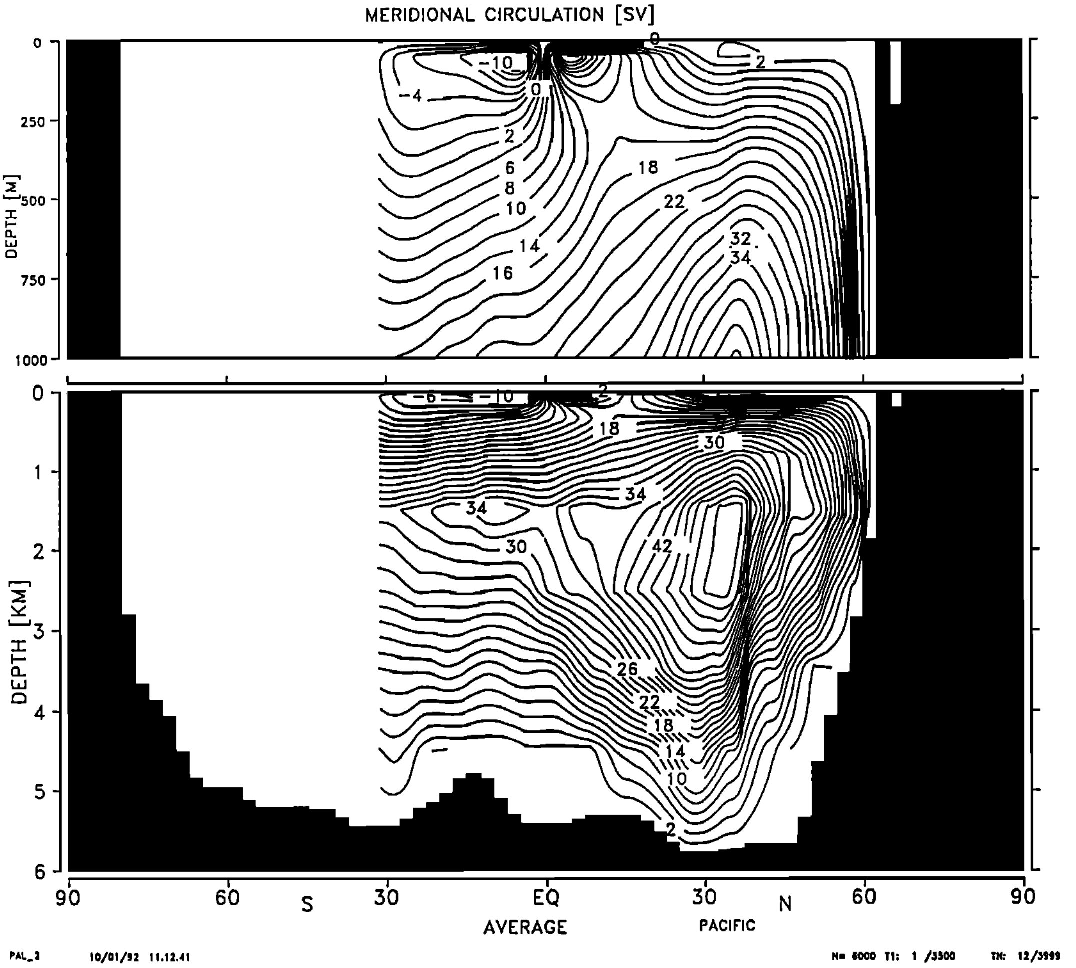

Fig.7 (continued)

son for the "dissimulation". It would be very useful to get more information about glacial ocean surface salinity, especially in the North Pacific, to verify the regional T21 LGM response in the freshwater flux. The glacial Aleutian pressure system was simulated 20° farther eastward than in the present-day control run. Therefore the simulated freshwater anomaly was positive in the eastern North Pacific and negative in the western part where the glacial deepwater production was simulated by the OGCM. The glacial location of the Aleutian pressure system could not be obtained from geological data in Alaska [Kutzbach and Wright, 1985]. However, the T21 pattern of freshwater flux anomaly are also simulated by other AGCM's using 18 ka CLIMAP boundary conditions [Joussaume, 1989; Miller and Russell, 1990].

The boundary forcing of the AGCM in the North Pacific should be connected with the prescription of the large marine ice extent. A recent reexamination of the primary geological data in that region provided indication that the CLIMAP reconstruction of ice coverage may have been overestimated (W. F. Ruddiman, personal communication, 1991). If so, we can expect that with a revised sea ice reconstruction our model results would exhibit a smaller departure from the modern ocean simulation than the LGM response discussed in this paper.

The CLIMAP SST field has also been challenged because of disagreements between AGCM results and observations over tropical land areas [Webster and Streeten, 1978; Rind and Peteet, 1985]. Although initial attempts at independently validating the CLIMAP SST's appear to have been supportive [Prell, 1985; Broecker, 1986], a more recent reexamination of the transfer functions in the Pacific does suggest that the SST field may need revision [Chen et al., 1991].

Thus the critical dependency of climate model results to the CLIMAP SST's is not just based on atmospheric models and tropical land areas, where in some cases the observations themselves are sparse. Our results indicate that, when ocean models are considered, model-data discrepancy may also extend to the validation of results with deep-sea sediments. Although more work is clearly required on OGCM studies of the ice age circulation, our results suggest that a satisfactory reconcilation with the sediment record may require reevaluation of CLIMAP SST reconstruction.

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