THE NUMERICAL SIMULATION OF THE ICE AGE CLIMATE

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ABSTRACT

Using the IAP two–level general circulation model, the ice age July climate was simulated through the surface conditions of 18 000 years before present assembled by the CLIMAP Project. Comparing with the present July simulation results, the ice age atmosphere is found to have a substantially lower temperature, precipitation, and cloudiness, higher sea–level pressure, especially in the high latitude land region of the Northern Hemisphere and Antarctica. When the CO_2 content is set as the modern value the climatic response is very small, which shows that the problems of CO_2 sensitivity should be studied by means of coupled models. It is also pointed out that there are some common characteristics between CO_2–induced climatic changes and the ice age surface condition–induced climatic changes, which may give us some insight into how climate responds to external forcings.

Key words: numerical simulation, ice age climate, CO_2 content

I. INTRODUCTION

The last ice age reached its maximum about 18 000 years ago. As an example of dramatic climate change, it is revealed by the evidence from ocean and lake sediments, and from records of soil structure and vegetation cover (Flint, 1971; West, 1968). It is known that the ice age climate was both colder and slightly drier than the present climate. It is great convenient for the modelers to have the ice age surface conditions reconstructed by the CLIMAP Project in 1976 and 1981 (CLIMAP Project Members, 1976; 1981) through collecting and studying the large amount of paleoclimatic sample materials (M76 and M81 in brief).

The first man who simulated the ice age climate using GCMs was Williams et al. (Williams, 1974; Williams and Barry, 1975). Of course the boundary conditions he used are not those given by the CLIMAP Project. In 1976, Gates did the simulation using the materials assembled by the CLIMAP Project in 1976 with the two–level general circulation model of Oregon State University (OSU) (Gates, 1975; 1976). They both obtained reasonable results. But it is necessary to point out that M81 is different from M76. For example, the global average sea surface temperature of M81 is 0.7 K higher than that of M76. Besides, the M81 contains more information than M76. Hence many other researchers used different models to simulate the ice age climate by using M81 after Gates. They are Manabe and Hahn (1977), Hansen et al. (1984), Manabe and Broccoli (1985), Broccoli and Manabe (1987) and Kutzbach and Guetter (1986). In 1987, Prell and Kutzbach made an experiment to study the monsoon variability of the past 150 000 years by means of a GCM which shows a good relation between orbital forcing changes and monsoon variability. In 1986, Kutzbach and Guetter studied the effects of changing orbital parameters and the earth's surface conditions on climate through a set of numerical experiments. In 1987, Manabe and Broccoli carefully studied the impacts of continental ice sheet, atmospheric CO_2

content and land albedo on the climate of the last glacial maximum. All these studies greatly deepened our understanding of the ice age climate. But there are differences between different model results, not only in the amplitude of meteorological variables, but also in the geological distribution of these meteorological variables. So it is valuable to conduct further study using different models.

The model used here is IAP GCM. After finishing the control run and the ice age run, the authors made another experiment which took the CO_2 content 330 ppm (modern value) and the LGM surface conditions to evaluate the effects of CO_2.

II. BRIEF DESCRIPTION OF THE IAP GCM

The IAP two–level global grid point model with its "dynamic frame" designed on the basis of research work by Zeng and his cooperators (Zeng, 1979; Zeng et al., 1985; Zeng et al., 1986) is used. The so–called "standard atmosphere" is introduced to the model and the perturbation to the " standard atmosphere" is used as predicted variables. The careful design of the differential system maintains the conservation of the available energy. So the "dynamic frame" is substantially different from that of other models. The parameterization schemes are mostly the same as those of OSU GCM. Basic tests prove the high computing accuracy of the model. Other experiments show that the model has quite good ability in simulating the mean climate patterns, the East Asian monsoon, the seasonal abrupt changes of the East Asian atmospheric circulation, and even the low–frequency variations and teleconnection phenomena.

III. THE ICE AGE BOUNDARY CONDITIONS AND THE EXPERIMENT DESIGN

We got the LGM earth's surface conditions from M81. The mean July sea surface temperature of the ice age is 1.7 K higher than it is now. The differences between the ice age and present SST are much higher in high latitude ocean than low latitude ocean. It should be pointed out that the mean temperature of the modern ocean used here is only 1.3 K higher than that of the ice age ocean. The area of the land ice and sea ice is much larger in the ice age. The elevation of orography above sea level in the ice age is higher due to the lower level of sea surface and the larger land ice cover at that time. The albedo of the ice age earth surface is greater than it is.

All the three runs started from May 31 of the third year in the seasonal simulation of the model. The lower boundary conditions are fixed for modern July in experiment 1 and ice age July in experiment 2. The orbital parameters use the modern value in all experiments due to the little difference between present and ice age. CO_2 content is prescribed as 330 ppm in experiment 1 and 3 200 ppm in experiment 2. Each experiment is run for 75 days. We use the mean values of the last 30 days for comparison.

IV. RESULTS

1. *The Ice Age July*

First we discuss the surface air temperature shown in Fig. 1. The temperature at most regions is much lower than it is. The differences can reach −20 K to −30 K (ice age minus present) in the western part of Eurasia, North America and the Antarctica, but are relatively smaller in low latitude regions and ocean area. We also note that the surface temperatures are higher in the North Pacific and South Pacific than those at present. This is because that the prescribed ice

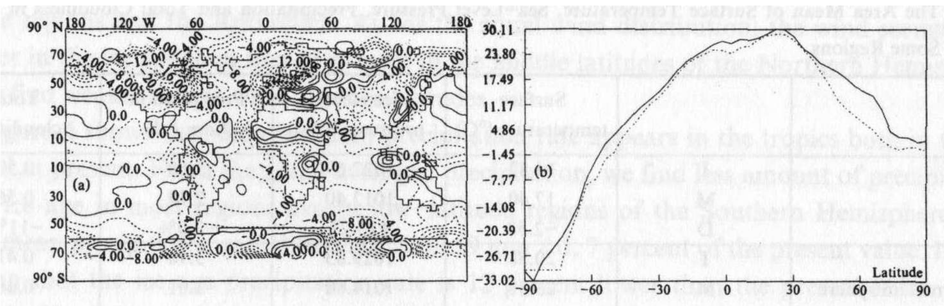

Fig. 1. The simulated July surface temperature (°C). (a) The global distribution of the difference between ice age and present; (b) the latitudinal distribution of zonal mean: —— present; ······ ice age.

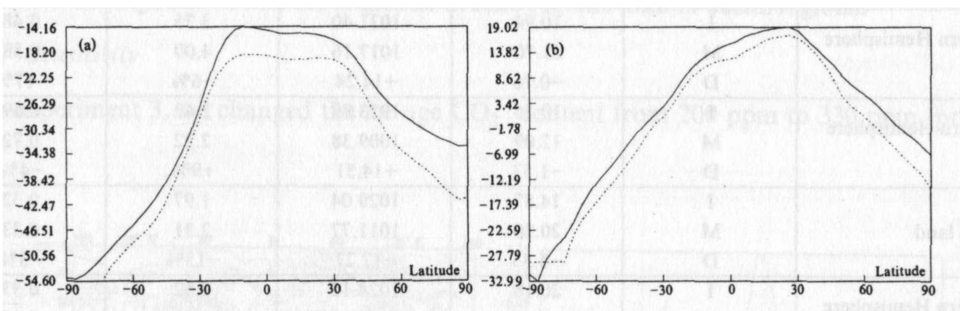

Fig. 2. The latitudinal distributions of zonal mean temperature (°C) for 400 hPa (a) and 800 hPa (b).

age SST is higher than the modern SST in this area. The most striking characteristics of zonal distribution of surface air temperature is that the temperature differences are the greatest at high latitudes of the Northern Hemisphere and the Antarctica. From Table 1 we can see that the mean global July surface air temperature difference between ice age and the present is −2.58 K, with −2.79 K in the Northern Hemisphere and −2.38 K in the Southern Hemisphere. Also we find that the land regions have greater temperature difference than the ocean regions have (−5.32 K and 1.21 K respectively).

We can also have a look at the situation in the free atmosphere shown in Fig. 2. At 400 hPa, the zonal averaged temperature difference is quite large at all latitudes of the Northern Hemisphere and the South Polar region. While at 800 hPa, the zonal averaged temperature difference is nearly the same at all altitudes, only a little bigger at high latitudes and the Antarctica.

Sea–level pressure distributions are shown at Fig. 3. At most regions, sea–level pressure is greater in ice age than it is now, especially in the Northern Hemisphere high latitudes and South Polar regions, with greater pressure differences in land regions than in ocean regions (17.27 hPa and 14.40 hPa respectively). It can be seen that the pattern of sea–level pressure distribution of the ice age is almost the same as that of present, for example, the high pressure system in the Pacific Ocean and in the northern Atlantic Ocean and the low pressure system in the Qinghai–Xizang Plateau. But it seems that the zonality of the ice age is stronger and the meridionality is weaker than these at present.

Table 1. The Area Mean of Surface Temperature, Sea–Level Pressure, Precipitation and Total Cloudiness in July for Some Regions

		Surface temperature (°C)	Sea–level pressure (hPa)	Precipitation (mm / d)	Total cloudiness
Global	I	14.82	1027.69	2.60	0.50
	M	17.40	1012.40	2.79	0.56
	D	−2.58	+15.29	−7.0%	−11%
Northern Hemisphere	I	20.58	1029.83	3.16	0.41
	M	23.37	1014.80	3.61	0.48
	D	−2.79	+15.03	−12%	−6%
Southern Hemisphere	I	9.05	1025.51	2.05	0.60
	M	11.43	1010.03	1.97	0.64
	D	−2.38	+15.48	+4%	−6%
Global ocean	I	14.79	1026.95	2.96	0.61
	M	16.00	1012.55	2.95	0.66
	D	−1.21	+14.40	+0.00%	−8%
Northern Hemisphere ocean	I	10.94	1031.40	3.75	0.48
	M	21.70	1017.16	4.00	0.58
	D	−0.76	+14.24	−6%	−17%
Southern Hemisphere ocean	I	10.56	1023.89	2.42	0.69
	M	12.09	1009.38	2.22	0.72
	D	−1.53	+14.51	+9%	−4%
Global land	I	14.87	1029.04	1.97	0.32
	M	20.20	1011.77	2.31	0.33
	D	−5.33	+17.27	−15%	−3%
Northern Hemisphere land	I	20.18	1028.12	2.52	0.33
	M	25.90	1011.28	3.02	0.34
	D	−5.72	+16.84	−17%	−3%
Southern Hemisphere land	I	4.33	1030.86	0.87	0.31
	M	8.88	1012.74	0.92	0.32
	D	−4.55	+18.12	−5%	−3%

* I: ice age; M: modern; D = I−M

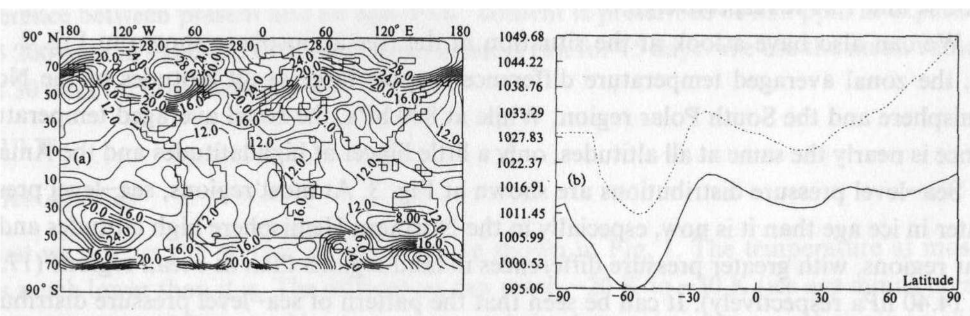

Fig. 3. As in Fig. 1, but for the sea–level pressure (hPa).

We can also find the similarity in the distribution patterns between ice age and present 500 hPa geopotential height. The greatest difference also appears in the Northern Hemisphere high latitude regions and the Antarctica. As for the zonal wind distribution, the wind seems to be stronger in the ice age than that at present in the middle latitudes of the Northern Hemisphere. But we find weaker ice age wind at other latitudes.

Figure 4 shows that the maximum precipitation rate appears in the tropics both in the ice age and at present. From the zonal averaged precipitation, we find less amount of precipitation in the ice age in most regions except low–latitude regions of the Southern Hemisphere. The global mean precipitation rate difference is −0.19 mm / d, 7 percent of the present value. It is interesting that the ice age precipitation rate is 12 percent lower than the present value in the Northern Hemisphere, but is a little higher than that at present value in the Southern Hemisphere. The total cloudiness is also smaller in ice age, especially in the Northern Hemisphere tropics. The ice age global mean cloud amount is 11 percent less than the present value, with 6 percent decrease in the Northern Hemisphere.

The water content is lower in the ice age than at present. The greatest difference is in the tropics. The mixing ratio difference is greater in land regions than in ocean regions.

2. *CO_2 Sensitivity*

In experiment 3, we changed the ice age CO_2 content from 200 ppm to 330 ppm (present

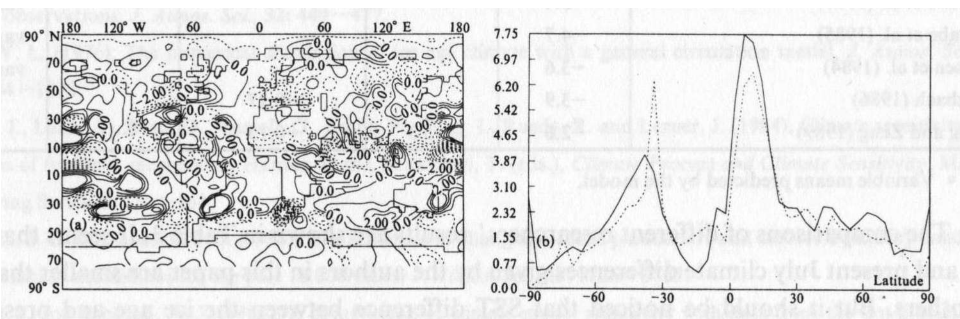

Fig. 4. As in Fig. 1, but for precipitation (mm / d).

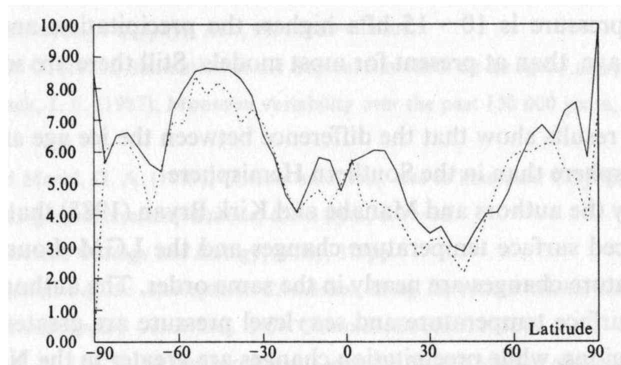

Fig. 5. As in Fig. 1, but for the total cloud amount.

value). We can make a comparison. Table 2 shows that the difference is quite small, for example, the differences are just 0.1 K for surface temperature and 1 percent for precipitation rate. But these results do not mean that the impact of lower CO_2 content on the formation of the ice age climate is negligible. They just tell us that we must use coupled ocean–atmosphere models to study CO_2 sensitivities.

Table 2. The Area Mean Change after CO_2 Content Increases from 200 to 330 ppm

	$\triangle T_s$ (°C)	$\triangle P_{sl}$ (hPa)	$\triangle P_r$ (%)	$\triangle C_l$ (%)
Global	0.08	−0.01	−1.	0.0
Northern Hemisphere	0.07	0.11	+0.3	2
Southern Hemisphere	0.09	−0.12	−3.4	2
Global ocean	0.06	−0.66	3	2
Global land	0.11	0.05	5	0.0

V. COMPARISONS WITH OTHER RESULTS AND DISCUSSIONS

The results here qualitatively agree with major paleoclimatic evidences and other modelers' results. The ice age July climate is colder and drier, and has less precipitation. But there still are some differences.

Table 3. The Climate Differences (The Ice Age—the Present July) Simulated by Different Models

	$\triangle T_s$ (°C)	$\triangle P_{sl}$ (hPa)	$\triangle P_r$ (mm / d)	$\triangle C_l$ (%)	$\triangle$SST (°C)
Gates (1975)	−4.9	+12.7	−0.61	−2.5	−2.3
Manabe et al. (1977)	−5.4				variable*
Manabe et al. (1985)	−4.7				variable*
Hansen et al. (1984)	−3.6				variable*
Kutzbach (1986)	−3.9		−0.27		−1.7
Wang and Zeng (1989)	−2.6	+15.3	−0.19	−11	−1.3

* Variable means predicted by the model.

The comparisons of different researchers' results are shown in Table 3. It seems that the ice age and present July climate differences given by the authors in this paper are smaller than those by others. But it should be noticed that SST difference between the ice age and present prescribed here is 0.4 K smaller than the CLIMAP estimates. So we may conclude from several studies on the ice age climate modelling that July surface temperature difference is 3—5 K lower, the sea–level pressure is 10—15 hPa higher, the precipitation and cloudiness are 10 percent less in the ice age, than at present for most models. Still there are some interesting findings:

(1) The authors' results show that the difference between the ice age and present is greater in the Northern Hemisphere than in the Southern Hemisphere.

(2) It is noticed by the authors and Manabe and Kirk Bryan (1985) that the numerical value of double–CO_2–induced surface temperature changes and the LGM–boundary–condition–induced surface temperature changes are nearly in the same order. The authors also want to point out that changes of surface temperature and sea–level pressure are greater in high latitude regions than in other regions, while precipitation changes are greater in the Northern Hemisphere tropics than in other regions (Washington and Meehl, 1989).

(3) It seems that model–simulated CO_2–induced climatic cooling in the ice age was only 0.1 K (Hansen's result was 0.2 K). We understand that it is necessary to use coupled models if we want to study the climatic effects of CO_2.

VI. CONCLUDING REMARKS

The IAP GCM successfully modeled the July climate of the last glacial maximum. The results agree with those of others' and with main paleoclimatic evidences. The LGM conditions caused greater changes in the Northern Hemisphere than in the Southern Hemisphere, in land regions than in ocean regions. The authors noticed that there were some similarities between CO_2–induced climatic changes and the LGM surface condition–induced climatic changes. It seems that the climatic system to some extent responds in a similar way to some different external forcings.

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