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SENSITIVITY OF LATE-GLACIAL AND HOLOCENE CLIMATES TO THE COMBINED EFFECTS OF ORBITAL PARAMETER CHANGES AND LOWER BOUNDARY CONDITION CHANGES: "SNAPSHOT" SIMULATIONS WITH A GENERAL CIRCULATION MODEL

FOR 18, 9, AND 6 ka BP

by

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ABSTRACT

Sensitivity experiments can be used to illustrate the response of the general circulation to prescribed changes in lower boundary conditions (such as ocean temperature) or external forcing conditions (such as solar radiation). The climatic record from the late-glacial and the Holocene provides examples for both types of prescribed change experiments. A number of general circulation model experiments have been carried out. These are reviewed.

At 18 ka BP, orbital parameter values were very much like those of today, but the lower boundary conditions (ocean temperature, ice-sheet extent, etc.) were very different. The change in ocean temperature, and ice-sheet extent and thickness, were prescribed from the results of the Climate: Long-range Investigation Mapping and Prediction (CLIMAP) project.

At 9 ka BP, orbital parameter values were very different from present, leading to increased radiation in July and decreased radiation in January (compared to present). The North American ice sheet still covered a significant area, so that lower boundary conditions also differed from the present ones. The combined and individual effects of these prescribed changes on the general circulation are reviewed, particularly in the context of changes of the monsoon circulation.

At 6 ka BP, the solar radiation distribution differed from that of today in much the same fashion as at 9 ka BP, although the magnitude of the change was reduced. Lower boundary conditions were probably very similar to those of today.

A series of experimental results from 18, 9, and 6 ka BP are presented as "snapshot" estimates of the paleoclimate of those times. The results are based upon simulations with the community climate model of the National Center for Atmospheric Research.

1. INTRODUCTION

The Cooperative Holocene Mapping Project (COHMAP) aims at producing global maps of paleoclimatic conditions for 3, 6, 9, 12, and 15 ka BP (Webb 1984). These maps, along with the Climate: Long-range Investigation Mapping and Prediction (CLIMAP) reconstruction of climatic conditions for 18 ka BP (CLIMAP Project Members 1981), will provide "snapshots" of past climates at intervals of 3 ka covering a period of major climatic change: full glacial, deglaciation, full interglacial, present. Diagnostic studies of the changes in the large-scale climatic patterns should advance our knowledge of the dynamics of climate.

To complement the sequence of global paleoclimatic maps, COHMAP is preparing a sequence of general circulation model experiments for the same times: 3, 6, 9, 12, 15, and 18 ka BP. Whereas zonal-average climate models are well suited for a wide range of paleoclimate sensitivity experiments involving orbital parameter changes, lower boundary condition changes, and internal feedback parameterizations (for example, Suarez and Held 1976, 1979, Schneider and Thompson 1979, Birchfield and others 1982), the general circulation model provides the unique opportunity for detailed regional- and continental-scale intercomparisons of model simulations with the observed paleoclimate.

The paleoclimate simulations described here are for 6, 9, and 18 ka BP and involve studies of the response of a general circulation model to both lower boundary condition changes (sea-surface temperature, glacial ice, etc.) and changes of the seasonal cycle of solar radiation. This summary is in the form of a brief progress report because many aspects of the computational work planned by COHMAP remain incomplete. The experiments for 3, 12, and 15 ka BP must be finished, and further experimentation is planned for all of the designated times using improved versions of the general circulation model. Moreover, detailed intercomparison of the model results and the paleoclimatic observations remains to be accomplished.

2. REVIEW OF PREVIOUS WORK

Gates (1980, 1982) has reviewed paleoclimate modeling studies and summarized the problems and approaches. In order to simulate the past climate

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with a general circulation model, it is necessary to specify certain external conditions, such as the magnitude and seasonal distribution of solar radiation, and certain lower boundary conditions, such as the location and size of ice sheets. Ice sheets are, of course, an integral part of the climate system and would not be specified as a boundary condition in a completely general climate model. However, the time required for the growth and decay of ice sheets is long compared to the time-scale of processes normally included in atmospheric general circulation models, and it is therefore convenient for some purposes to prescribe the ice sheet or other lower boundary conditions and study a restricted (less general) climate system.

The sequence of paleoclimate experiments planned by COHMAP involves specification of both external and lower boundary conditions and combinations thereof. The sensitivity of a low resolution general circulation model to changes of Earth's orbital parameters has been studied by Kutzbach (1981) and Kutzbach and Otto-Bliesner (1982). The seasonal cycle of solar radiation at 9 ka BP was strikingly different from the present because the perihelion was in July (it is now in January) and the axial tilt of the Earth was greater then. There was an amplified seasonal cycle of solar radiation in the northern hemisphere compared to the present (more radiation in July, less in January) and the general circulation model simulated stronger summer and winter monsoon circulations over Africa and southern Asia. In one version of the 9 ka BP experiment, the location and size of the remnant North American ice sheet was specified in order to isolate both the combined and separate model response to 9 ka BP radiation and ice-sheet conditions (Kutzbach and Otto-Bliesner 1982).

The general circulation model experiments with 9 ka BP boundary conditions have been repeated with a different general circulation model, the National Center for Atmospheric Research Community Climate Model (NCAR CCM) with similar results (Kutzbach and Guetter in press). The NCAR CCM has higher spatial resolution and more detailed physical parameterizations compared to the low resolution model used in the earlier experiments, and therefore the results can be compared more readily with paleoclimatic evidence.

At around 18 ka BP, the external solar radiation conditions were similar to those at present (in July and January), but there were major changes, compared to present, in sea-surface temperature patterns, sea-ice extent, land albedo, and, of course, ice-sheet location and size. A number of experiments with general circulation models have used the lower boundary conditions specified by CLIMAP (1976) in order to simulate the atmospheric circulation for the time of glacial maximum (Gates 1976[a], [b], Manabe and Hahn 1977).

3. DESCRIPTION OF MODEL AND EXPERIMENTS

3(a). Model

A description of the NCAR CCM and its simulation of the modern January and July climate is provided by Pitcher and others 1983. The model incorporates atmospheric dynamics based upon the equations of fluid motion; it includes radiative and convective processes, condensation, and evaporation. A surface heat budget is computed over land. Orographic influences of mountains (and ice sheets) are included. Sea-surface temperatures, sea-ice limit, and snow cover are prescribed. The model has nine vertical levels and a spectral representation, to wave number 15, of the horizontal fields of wind, temperature and moisture. The spectral representation is converted to a grid of 4.4° latitude by 7.5° longitude.

The version of the NCAR CCM used here was configured for so-called perpetual July and January experiments (Pitcher and others 1983); the model was run for 120 simulated days but with solar radiation held constant for January 16 or July 16 values. The experiments were started with all model variables set at values for day 400 of an NCAR CCM control simulation, but with the solar radiation and/or lower boundary conditions changed from modern to 18, 9, or 6 ka BP values. The first 30 days of each 120-day simulation were treated as an adjustment period and ignored. The final 90 days of each simulation were then averaged and compared to the control (modern) simulation.

Further details on the experimental procedure and the statistical testing of the results are found in Kutzbach and Otto-Bliesner (1982) and Kutzbach and Guetter (in press).

3(b). Experiments

The changes of solar radiation and lower boundary conditions for 18, 9, and 6 ka BP are summarized in Table I. The reasons for prescribing the lower boundary conditions for 6 and 9 ka BP at modern values are detailed in Kutzbach and Otto-Bliesner (1982). The one exception was the North American ice sheet, which, at 9 ka BP, still covered 30 grid points in the model, i.e. an area of 5.4 x 10^6 km . The simulated climate of 9 ka BP is mainly a response to the changed orbital parameters; the North American ice sheet has a major effect on the simulated climate only in the vicinity of the ice sheet itself (Kutzbach and Otto-Bliesner 1982, Kutzbach and Guetter in press). At 18 ka BP, the solar radiation values for January and July are within 1% of modern values at all latitudes, but there are major changes in lower boundary conditions. For example, the North American ice sheet covers 77 model grid points (14.4 x 10^6 km^2) and the European ice sheet covers 56 model grid points (7.9 x 10^6 km^2). The 18 ka BP conditions for sea-ice extent, sea-surface temperature, and land albedo are found in CLIMAP (1981). The lower boundary conditions from CLIMAP (1981) differ somewhat from CLIMAP (1976) estimates.

TABLE I. ORBITAL PARAMETER VALUES AND LOWER BOUNDARY CONDITIONS FOR GENERAL CIRCULATION EXPERIMENTS FOR PRESENT CONDITIONS (0) AND FOR 6, 9 AND 18 ka BP.

Time ka BP	Eccentricity	Tilt (°)	Longitude of perihelion (°)	Lower boundary conditions
0	0.016724	23.44	102.04	control values (Pitcher and others 1983)
6	0.018682	24.11	260.89	Same as present (0)
9	0.019264	24.24	311.22	Same as present (0) but with North American ice sheet
18	0.019454	23.44	163.73	CLIMAP (1981)

4. RESULTS

A detailed description of the results of the 6, 9, and 18 ka BP simulations is in preparation. This preliminary report summarizes certain area-average results for the land surface and for the region of the monsoon climates of the northern hemisphere, and certain global-average statistics (land plus ocean) (Table II).

For July, the increased solar radiation at 6 and 9 ka BP (compared to present) is associated with higher northern hemisphere land temperature (higher by 1.5 and 1.8 K, respectively) and increased monsoon rains (greater by 1.1 and 1.4 mm d^{-1}, or about 20%). In contrast, the changed lower boundary conditions at 18 ka BP are associated with lower northern hemisphere land temperature (lower by 5.7 K) and decreased rains (about 10% less for the global average, the northern

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TABLE II. AREA-AVERAGE VALUES OF INCOMING SOLAR RADIATION (S), SIMULATED SURFACE TEMPERATURE (T), AND PRECIPITATION(P)

	Variable	Space average	0 ka	6 ka	(Δ)	9 ka	(Δ)	18 ka	(Δ)
(a) July									
S	(W m^{-2})	NH	451	476	(25)	488	(37)	454	(4)
T	(°C)	NH,L	20.7	22.2	(1.5)	22.5	(1.8)	15	(-5.7)
		G,L&O	15.8	16.2	(0.4)	16.2	(0.4)	12	(-3.8)
		Monsoon	27.6	28.3	(0.7)	28.8	(0.5)	25.6	(-2.0)
P	(mm d^{-1})	NH,L	4.1	4.6	(0.5)	4.9	(0.8)	3.7	(-0.4)
		G,L&O	3.9	3.9	(0)	3.9	(0)	3.6	(-0.3)
		Monsoon	6.4	7.5	(1.1)	7.8	(1.4)	5.7	(-0.7)
(b) January									
S	(W m^{-2})	NH	227	213	(-14)	208	(-19)	225	(-2)
T	(°C)	NH,L	-10.8	-12.2	(-1.4)	-12.3	(-1.5)	-18.2	(-7.4)
		G,L&O	11.0	10.5	(-0.5)	10.4	(-0.6)	7.0	(-4.0)
		Monsoon	15.7	13.8	(-1.9)	14.3	(-1.4)	11.2	(-4.5)
P	(mm d^{-1})	NH,L	1.6	1.6	(0)	1.6	(0)	1.4	(-0.2)
		G,L&O	3.6	3.6	(0)	3.6	(0)	3.5	(-0.1)
		Monsoon	1.1	1.2	(0.1)	1.1	(0)	1.0	(-0.2)

Space averages are for northern hemisphere (NH), northern hemisphere land (NH,L), global average of land and ocean (G, L & O), and that portion of the tropical land surface bounded by 8.9°N and 22.2°N (Monsoon). Values are for the modern control (0 ka), 6 ka BP (6 ka), 9 ka BP (9 ka), and 18 ka BP (18 ka). The difference of paleoclimate-minus-control (Δ) is shown in parentheses. Part (a) is for July, part (b) is for January.

hemisphere land average, and the monsoon-region average).

For January, the decreased solar radiation at 6 and 9 ka BP (compared to present) is associated with lower temperatures. Precipitation changes are small. With boundary conditions for 18 ka BP, the northern hemisphere land temperature is lowered by 7.4 K and precipitation is decreased.

Viewed as a sequence of climatic "snapshots", these area-averaged results indicate that, compared to present, the climate of 18 ka BP was colder and drier than now in both July and January; seasonality (the July to January range) was not greatly different than now. By 9 ka BP, and continuing to 6 ka BP, the climate had warmed dramatically compared to conditions at 18 ka BP. Moreover, the amplified seasonal cycle of solar radiation in the northern hemisphere produced an increased range of the seasonal temperature extremes (warmer northern hemisphere summers and colder northern hemisphere winters) and increased summer monsoon rains. During the period since 6 ka BP, the seasonal extremes of northern hemisphere land temperature have been reduced and monsoon rainfall has decreased.

With this overview of the broad-scale features of the simulated climate of the past 18 ka, a more detailed analysis of regional climatic sequences (for North America, for polar regions, etc.) will be prepared and compared with the paleoclimatic record.

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