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**SENSITIVITY OF CLIMATE MODELS: COMPARISON OF SIMULATED
AND OBSERVED PATTERNS FOR PAST CLIMATES**

Progress Report

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PROGRESS REPORT

SENSITIVITY OF CLIMATE MODELS: COMPARISON OF SIMULATED AND OBSERVED PATTERNS FOR PAST CLIMATES

SECTION I. INTRODUCTION

Predicting the potential climatic effects of increased concentrations of atmospheric carbon dioxide requires the continuing development of climate models. Confidence in the predictions will be much enhanced once the models are thoroughly tested in terms of their ability to simulate climates that differ significantly from today's climate. As one index of the magnitude of past climate change, the global mean temperature increase during the past 18,000 years is similar to that predicted for carbon dioxide doubling. Simulating the climatic changes of the past 18,000 years, as well as the warmer-than-present climate of 6000 years ago and the climate of the last interglacial, around 126,000 years ago, provides an excellent opportunity to test the models that are being used in global climate change research (Webb and Wigley, 1985).

During the past several years, we have used paleoclimatic data to test the accuracy of the NCAR CCM0 (National Center for Atmospheric Research, Community Climate Model, Version 0), after changing its boundary conditions to those appropriate for past climates (Kutzbach and Guetter, 1986; Webb et al., 1987; Prell and Kutzbach, 1987; COHMAP, 1988). We have assembled near-global paleoclimatic data sets of pollen, lake level, and marine plankton data (COHMAP, 1988) and calibrated many of the data in terms of climatic variables (Webb et al., 1992a). We have also developed methods that permit direct quantitative comparisons between the data and model results (Webb et al., 1987; 1992a). Our comparisons have shown both some of the strengths and weaknesses of the model.

The research so far has shown the feasibility of our methods for comparing paleoclimatic data and model results. Our research has also shown that comparing the model results with the data is an evolutionary process, because the models, the data, and the methods for comparison are continually being improved. During 1991, we have continued our studies and this Progress Report documents the results to date. During this year, we have completed new modeling experiments, compiled new data sets, made new comparisons between data and model results, and participated in workshops on paleoclimatic modeling.

Section II. RESEARCH ACCOMPLISHMENTS DURING 1991

A key research accomplishment for 1991 has been the completion of a joint-edited book (Wright et al., 1992) documenting the data and modeling results of COHMAP's

reconstruction of the climates and vegetation of the past 18,000 years, which includes chapters by Kutzbach et al. (1992), Kutzbach and Webb (1992a, b), and Webb et al. (1992a, b). The book includes chapters describing data from all areas of the globe and describes the comparison between data and model results for each region. Other activities have included the use of raw pollen-derived climatic estimates to check the CCM0 and CCM1 simulations for 6 ka, attendance at the NATO Workshop on Paleoclimatic Modeling in June and helping to set plans for PMIP (Paleoclimate Modeling Intercomparison Project), and participation in the Workshop at Lamont in November to update the boundary conditions used in GCM paleoclimatic experiments. We have made a set of simulations examining the sensitivity of CCM1 to ice sheet height and area, determining sensitivity coefficients that allow us to quantify the model response. We have used several of the CCM0 COHMAP simulations to derive sensitivity coefficients relating the model response to orbital insolation changes (Oglesby et al., in prep.). We also published articles including a summary chapter by Kutzbach and Webb (1991) on paleoclimatology in *Quaternary Landscapes* (Shane and Cushing, 1991); a chapter on the spectrum of climatic variability (Webb, 1991); a chapter on long-term environmental change (McDowell et al. 1990); and a Ph.D. thesis (Smith, 1991), which contains data and interpretations from ostracodes supportive of the pollen-derived climate estimates used to check the model results.

SECTION III. MODEL EXPERIMENTS

Processing of Model Output

The major switch of NCAR to a new operating system required that we devote considerable time to modifying our programs for processing model history tapes. This work is now complete. In addition, have substantially modified our processing procedures to incorporate full seasonal cycle diagnostics. Formerly, we analyzed "pertetual" January and July results. Now, we have developed efficient procedures for obtaining monthly-average, seasonal-average, and annual-average results with appropriate statistical significance testing for each averaging interval.

Model/model comparisons

Our comparison of model simulations for 6 ka with two different GCM's, the NCA CCM1 and the UKMO, continues.

The NATO Workshop of May 1991 adopted a strategy for model/model comparisons for simulations of 18 ka and 6 ka. Kutzbach is a member of the international advisory board for model/model comparisons.

Model Sensitivity Studies

A critical component in understanding late Quaternary paleoclimates is the occurrence of large continental ice sheets. We have designed a series of CCM1 simulations investigating model sensitivity to ice sheet area and height. We varied ice sheet size from 0.5 to 1.7 times that at the last glacial maximum and varied the height of these ice sheets from sea level to almost 3000 meters. Ben Felzer, a graduate student at Brown, has made all necessary model simulations, and we are currently completing the analysis and interpretation of the results.

A key characteristic of Milankovitch orbital insolation changes is their seasonal variations, while CO₂ changes are more or less seasonally invariant (allowing for a small seasonal cycle due to the biosphere which at any rate is not usually accounted for in climate models). Thus, a question of interest becomes the model sensitivity to changes in the solar constant, which causes changes in insolation that are invariant with respect to season. R. Oglesby taught a graduate seminar at Brown on Climate Modeling (Fall 1991). As a class project, we made a series of simulations with plus/minus 1%, 2%, 5%, and 10% changes in the solar constant.

In addition, work is underway in collaboration with S. Clemens and D. Murray of Brown University to compare the Asian monsoon as simulated by various versions and configurations of CCM. Preliminary results suggest that the simulation of the monsoon is better when fixed sea-surface temperatures and a fixed surface hydrology is used than when these quantities are computed, despite the latter being a more realistic, physically consistent way of modeling climate. We have focused in particular on the role of soil moisture feedbacks as the reason for the degradation in model performance. Clemens and Oglesby are involved in a study aimed at investigating the sensitivity of the Asian monsoon to southern Indian Ocean sea-surface temperatures. This study required making several simulations with anomalies in sea-surface temperature added to select regions of the southern Indian Ocean. We found that when sea-surface temperatures were computed, the transport of water vapor from these region to the Asian monsoon region increased as sea-surface temperatures cooled, consistent with observations, while the opposite was true when sea-surface temperatures were held fixed during the model integration. This points to the need to compute sea-surface temperatures to properly capture the physics of the monsoon. We are currently preparing a paper for publication reporting on the results of this study. R. Oglesby has also been actively engaged in a project with D. Martinson of Lamont-Doherty Geological Observatory aimed at coupling his sophisticated sea ice and oceanic mixed-layer model to CCM; subsequently this model combination will be used for sea ice and sea-surface temperature sensitivity studies. The required computer code coupling is

nearly complete, and we expect to have final testing and then production runs in the near future.

Generic precession/tilt experiments

Kutzbach and Gallimore are completing two manuscripts describing the results of simulations with idealized changes of axial tilt and time of perihelion in order to isolate the unique climatic responses to these two kinds of insolation forcing (Gallimore and Kutzbach, 1991; Kutzbach and Gallimore, 1991). The model used for the experiments is the UW LRM with interactive mixed-layer ocean. Vavrus (UW grad student) has modified this model to incorporate sea-ice lead parameterization and ice-drift parameterizations. He will then repeat the above-mentioned experiments to estimate more accurately the high-latitude response of climate to insolation changes.

SECTION IV. OCEAN DATA AND COMPARISONS WITH MODEL RESULTS

During Year I, we have made progress toward ocean data-model comparison in the following three areas:

1) Developing a more comprehensive marine data set to compare to atmospheric and ocean simulations,

To upgrade the data set for modern Pacific Ocean sediments (the major weakness of the current data set), we have planned a sampling trip to Scripps Institution of Oceanography in mid October to obtain an extensive set of coretop (modern) samples for our global data base. We will also be meeting with Laurent Labeyrie (Gif) to arrange acquisition of French samples from the Southern Ocean and the Northwest Pacific. These data will make a significant addition to our existing global data for modern sediments.

In concert with obtaining these data, we have continued to evaluate our quantitative estimation techniques and the calibration data upon which they are based. One study "Estimating sea-surface temperatures from tropical Pacific planktonic foraminifers: comparison of Imbrie-Kipp method and modern analog technique" by Min-Te Chen, J. Imbrie and W. Prell is in second draft and nearly ready for publication. This study suggests that the preservation state of the sediments may lead to systematic SST biases in both the estimation method. We are making additional experiments to examine the validity of this suggestion and of the test data used in the study.

We have also evaluated different strategies for paleotemperature estimation. Overlapping data sets for multiple fossil groups (especially in the eastern equatorial Pacific) are now sufficient to test three strategies for paleotemperature estimation. Pisias's work in the eastern equatorial Pacific

shows that paleotemperature equations based on ocean wide data basis versus more regionally restricted data sets predict somewhat different paleotemperatures in a suite of geologic records spanning the past 150,000 years. To determine the reliability of different paleotemperature predictions we are using a test data set from the equatorial Pacific that includes data from foraminifera and radiolarian microfossil groups. A set of paleotemperature estimates, which use the strategy of an ocean-wide equation is essentially complete.

2) Identification of new samples to improve the last glacial maximum (LGM, 18 ka) sea surface temperature (SST) boundary conditions

Since the reconstruction of the LGM sea surface temperature by CLIMAP (1981), many new samples from the 18 ka interval have identified and can be used to provide better spatial constraints for the SST patterns. In addition, the stratigraphic and chronologic methods for identification of LGM interval have been greatly improved.

To identify new LGM samples, we conducted a computer search to find references that contained new stratigraphic data for the late Quaternary or Holocene and identify cores that should contain a documented LGM (18ka) level. We identified 485 references, which we reviewed to determine the type and utility of the stratigraphic data and if an LGM level had an identified. We found 372 cores that have documented LGM levels or appear to contain the LGM level. Most of the potential new LGM samples are in the Atlantic (209), but the Pacific (101) and Indian (53) oceans also have significant new data as do the marginal seas (Mediterranean, 5; and Arctic, 5). Most of the cores have multiple stratigraphic records that commonly include $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ data and carbonate dissolution indices. In other efforts to improve the LGM boundary conditions, Pisias (OSU) has been recounting the LGM radiolarian samples which provide coverage in many areas of the Pacific where carbonate fossils are not preserved.

In recognition of our efforts in this area, we have been invited to participate in a workshop on Late Quaternary Paleoclimate Boundary Conditions to be held at Lamont-Doherty Geological Observatory in November. This workshop is being sponsored by NASA/GISS and LDGO to coordinate efforts to improve the boundary conditions for the Paleoclimate Modeling Intercomparison Project (PMIP) (see Section VII, Workshops).

3) Developing a two-dimensional (water depth versus latitude) transect of $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ for the Indian Ocean.

One result of the LGM ocean experiments is the hypothesis that glacial thermohaline circulation was drastically different

compared to present. Because modern thermohaline circulation and water mass distribution are reflected in the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ of planktonic and benthic foraminifera, these indices can be used to reconstruct two-dimensional transects (depth versus latitude) for the last glacial maximum to examine the pattern of water masses and infer circulation. We have made considerable progress in constructing two-dimensional transects of the eastern and western Indian Ocean for the LGM. Over 60 LGM samples have been identified and the benthic foraminiferal isotopic data analysed or compiled from the literature. Our findings are in draft form in "Intermediate and Deep Water Circulation in the Indian Ocean during the Last Glacial Maximum" by Jiajie Chen and Warren L. Prell. Our results confirm the existence of a deep thermocline near 2000 m but suggest that it is limited to the northern Indian Ocean along with the highly negative $\delta^{13}\text{C}$ (nutrient rich) deep waters. We also find considerable heterogeneity in the deep waters between the northeastern and northwestern basins of the Indian Ocean suggesting a complex ventilation during the LGM. These results are being finalized and will be submitted for publication within this year.

SECTION V. TERRESTRIAL DATA AND COMPARISONS WITH MODEL RESULTS

Completion of the book (Wright et al., 1992) on *Global Climates Since the Last Glacial Maximum* makes available chapters describing the model results from CCM0 for each 3000 year interval from 18 ka to present and chapters describing the paleoclimatic data for most regions of the globe including South America, North America, Europe, the Soviet Union, the Middle East, China, Australia, New Zealand, and Africa. Each chapter contains information about the data and discusses how well the data match the model results. Both qualitative and quantitative comparisons are made. A synthesis chapter (Webb et al. 1992b) summarizes the results from all regions.

The synthesis chapter describes how the regional chapters demonstrate that the NCAR CCM simulates the general geographic patterns and patterns of changes for selected climatic variables. In Alaska, the model and data both show increasingly cold dry conditions from eastern to western Beringia at 18 ka. By 12 ka, the simulated July mean temperature and annual precipitation are near their modern values in good agreement with the pollen data. The period of maximum summer warmth was at 9 ka for both the data and model results, and the subsequent trends in temperature and moisture are similar in both the data and model.

In northwestern Canada, summer temperatures were higher than today at 9 ka both in the model results and in the data, which show the arctic tree line north of its present position. At 6 ka, black spruce was more abundant indicating the development of cooler and moister conditions than those at 9 ka. Such

conditions are also simulated by the model. Since then the southern border of the boreal forest has moved south as summers have cooled.

In the western US, temperatures and moisture patterns at 18 ka and 9 ka agree well with the simulated patterns of atmospheric circulation there. The split in the winter jet stream and the consequent displacement of the southern branch and its associated storm tracks far to the south led to moister than present conditions in the Great Basin at 18 ka, but easterlies in the Northwest made conditions drier than today there. At 9 ka, the subtropical high was expanded and moisture levels decreased.

In eastern North America, the data and model results agree that temperatures a) were lower than today at 18 ka, b) increased after that date, c) increased most rapidly between 12 and 9 ka, and d) reached a maximum in the central region at 6 ka. The data and model results also agree that the modern gradients for July and January temperatures were established at 9 ka and that conditions were drier than present at 9 ka in the northeastern United States (Webb et al., 1992a).

In Europe, the patterns of simulated and inferred January temperatures are in qualitative agreement at 9 and 6 ka. The patterns of July temperatures show less agreement, but the simulated and inferred temperatures at 6 ka were higher than present in the continental interior. The simulations correctly indicate drier than present conditions over most of Europe at 9 ka.

The regional studies also reveal several differences between the data and the NCAR CCM results. In Alaska, the model simulated January temperatures higher than present at 18 ka in strong contradiction to the geological evidence for winters colder than today. In the western United States, the pattern and timing of temperature increases differed from those simulated by the model at 12 and 9 ka. The simulation showed an earlier temperature increase than apparently the data recorded. In eastern North America, the model correctly simulated colder-than-present conditions from 18 to 12 ka in the south but not nearly so cold as those inferred from the pollen data. In the Midwest, the model correctly simulated dry conditions from 9 ka onwards but incorrectly simulated maximum dryness at 9 ka instead of 6 ka as indicated by the pollen and lake-level data.

In Europe, the simulated July temperatures at 9 ka were higher than present across the whole continent, with the highest anomalies in the south. In contrast, the temperatures inferred from pollen data were lower than present in all regions but the north. At 6 ka the data and model results agree that temperatures were generally higher than today, although the simulated values were not so high as those inferred in the north and the simulated values were higher rather than lower than present in the south. Inferred and simulated moisture patterns

also differ because the simulated values indicate conditions drier than present in central Europe at 6 ka and drier than present in southern Europe at 9 and 6 ka. These conditions contrast with the interpretations of wetter than present conditions inferred from data.

Overall the data show more agreement with the model results than disagreement, but improvements to the model, boundary conditions, and data are needed and in progress (see Section III).

Other new results this year include a detailed quantitative comparison of the model-simulated and pollen derived climate estimates for eastern North America for 6000 yr B.P. The model-results being compared were for CCM0 for perpetual January and July and with fixed SST's and soil hydrology vs. CCM1 with seasonal cycle calculations and interactive slab ocean and soil hydrology (see Section III). The comparison with the data showed CCM1 produced drier conditions in central North America than CCM0 for 6 ka and therefore produced moisture conditions there that better resemble the data than was the case for CCM0. The analysis of the results are currently under study.

SECTION VI. EQUILIBRIUM SENSITIVITY COEFFICIENTS

During 1991, considerable progress has been made on the model studies involving the computation of equilibrium sensitivity coefficients, which quantify the model response to changes in a boundary condition or external forcing. A paper reporting on the paleoclimatic implications of the CO₂ sensitivity study of Oglesby and Saltzman (1990, 1992) has been prepared and submitted for publication to the *Journal of Climate* (Equilibrium Climate Statistics of a GCM as a Function of Atmospheric CO₂: II Implications for Paleoclimates by R. J. Oglesby and B. Saltzman). Important results include: (i) the 200 ppm model world is more susceptible to glaciation than the (present-day control) 330 ppm world; (ii) even at high CO₂ (such as three times present day levels) mid-continental interiors in winter are well below freezing, in apparent contradiction with geologic evidence from warmer earth periods; and (iii) snow and sea ice extent show a strongly logarithmic response as a function of CO₂.

Computation and analysis of equilibrium sensitivity coefficients relating the model response of important climatic variables to orbital insolation changes, performed by Hong Shao for her master's degree research, has been completed and a manuscript is in the final stages of preparation for submission to a refereed journal. (A Systematic Study of GCM Sensitivity to Changes in Solar Radiation by R. J. Oglesby, H. Shao, T. Webb III, W. L. Prell, and J. Kutzbach). This study used the CCM0 COHMAP simulations at 0 Ka, 3 Ka, 6 Ka, 115 Ka, and 126 Ka and

expands the previous work of Prell and Kutzbach (1987). The model sensitivity to these insolation changes is large and dominantly linear for many climatic variables. In July, the sensitivity of surface temperature, surface pressure, and precipitation to insolation changes over the North Africa and South Asia monsoon region is large, with, for example, an average increase of 7.5% in precipitation per 1% increase in solar radiation. In contrast, the sensitivity for surface temperature and surface pressure is small and there is almost no sensitivity for precipitation over the relatively smaller continent of North America. In January, regions showing the greatest sensitivity are in the (summer) southern hemisphere.

These two studies and the papers that have resulted from them lay a foundation for comparing the past and future effects of CO₂ changes with the paleoclimatic effects of Milankovitch orbital insolation changes. We (Prell and Kutzbach) are also calculating the sensitivity of monsoonal climate variables to changes in orography (mountains and plateaus) for comparison to other climate forcings, such as changes in Milankovitch insolation and CO₂.

A third critical component (besides CO₂ and orbital insolation changes) in understanding late Quaternary paleoclimates is the presence of large continental ice sheets. As described in the Model Experiments section a series of experiments examining CCM1 sensitivity to ice sheet area and height has been made. Analysis and interpretation of these simulations is considerably more difficult than for insolation or CO₂ changes because of the local nature of ice sheets, and the changing topography. Preliminary results suggest large responses over and adjacent to the ice sheets, but relatively little response elsewhere. Unlike for insolation or CO₂, the sensitivity of such quantities as surface pressure and temperature cannot be uniformly categorized as linear or linear, instead the nature of the response must be determined on a region-by-region basis.

Finally, computation of sensitivity coefficients for the solar constant study is currently underway. Preliminary results suggest a response seasonally similar to that of orbital insolation changes, being fairly large and linear for surface temperature over continental interiors.

SECTION VII. WORKSHOPS

We were key participants in two international workshops concerned with paleoclimatic modeling. The first was a NATO Workshop on Paleoclimatic Modeling in Paris. T. Webb and R. Oglesby attended and made presentations and J. Kutzbach was chosen to serve on the Steering committee for future research. The major result of the meeting was to set up PMIP (Paleoclimatic Modeling Intercomparison Project) with a mixture of scientists

concerned data and modeling on the Steering Committee. Plans were made to use several global climate models to simulate 6 and 18 ka and then to compare the results both with the data and with other model results.

The second workshop was in November at Lamont and is a follow-up to the Paris meeting. T. Webb, W. Prell, and R. Oglesby attended and helped plan a research effort to update both the sea-surface and terrestrial boundary conditions used for modeling 18 ka. These new boundary conditions will be used in the models for PMIP.

R. Oglesby also convened a session at the spring 1991 AGU meeting on "Atmospheric CO₂ Variability Throughout Geologic Time". He gave a talk on the paleoclimatic implications of GCM sensitivities to CO₂ changes.

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