GCM-Data Intercomparison:
The Good News and the Bad

Stanley L. Grotch

Program for Climate Model Diagnosis and Intercomparison
Atmospheric and Geophysical Sciences Division
Lawrence Livermore National Laboratory

Presented at the 7th Annual
Pacific Climate Workshop
Pacific Grove, California
April 1990

September 12, 1990

MASTER

Abstract

General circulation models (GCMs) are probably the most sophisticated theoretical tools which we presently have to simulate possible climatic effects of increasing CO_2 and other greenhouse gases. Because of tremendous social/political pressures now being raised on the issue of greenhouse warming, these models are being called upon to make predictions of possible climate change on a broad range of spatial scales. Of particular importance for regional assessments are predictions at subcontinental spatial scales. As will be illustrated here using a variety of examples, although the models do simulate 'reality' very well on the 'grand' scale (eg., global, hemispheric, zonal), substantial differences are more apparent as the scale is reduced to areas which are particularly relevant to regional planners. It is particularly important that workers more clearly recognize the potential dangers in relying too heavily on simple summary statistics such as averages estimated over large regional scales. Many shortcomings are apparent in the model simulations of the present climate, indicating that further model improvements are needed to achieve reliable regional and seasonal projections of the future climatic conditions.

1. Introduction and Outline

General circulation models (GCMs) are being actively used to assess possible climate change due to increasing greenhouse gas concentrations. Because such simulations provide detailed climatic predictions at a wide range of scales, they are of particular interest to those making regional assessments of climatic change. It is especially important that workers using the results of such simulations be aware of some of the limitations of these results. In this study some of the positive results from these model simulations will be shown (the 'good news') and some of the deficiencies (the 'bad news') will also be highlighted.

Following an introductory section describing the nature of GCM climate simulations the issue of the spatial scales of such simulations is examined. A

comparison of the results of seven GCM simulations of the current climate and the predictions of these models for the changes due to a doubling of CO_2 will be discussed. In these intercomparisons, the spatial scale over which the results are compared varies from global to zonal (longitudinally averaged at a given latitude) to individual slices through the data along specified latitudes or longitudes. Finally, the dangers and pitfalls of relying on simple averages will be highlighted.

2. Simplified Model Descriptions and CO_2 Doubling Experiments

General circulation model (GCM) is the term given to numerical models that simulate the global climate by calculating the hour-by-hour evolution of the atmosphere in all three spatial dimensions based on the conservation laws for atmospheric mass, momentum, thermal energy, and water vapor. GCMs also typically include representations of surface hydrology, sea ice, cloudiness, convection, atmospheric radiation and other pertinent processes (Washington and Parkinson, 1986). Although coupled atmospheric-ocean studies have been performed for some time (Manabe and Bryan, 1969), research studies are only now coupling atmospheric and more realistic ocean GCMs (e.g., Manabe and Stouffer, 1986), which give full treatment to ocean momentum, salinity, and thermal energy, thereby allowing study of the time rate of climatic change under different greenhouse forcings.

In CO_2 doubling experiments two separate integrations are performed: (1) a so called 'control climate' in which conditions are assumed to simulate the present climate with atmospheric concentrations of CO_2 set at approximately current levels throughout the integration (termed the 'control' or '1 x CO_2 run'), and (2) a second calculation in which the atmospheric CO_2 concentration is instantly doubled, and the model is run until an equilibrium state is reached (termed the 'perturbed' or '2 x CO_2 run'). The desired perturbation of any climatic variable X, (ΔX), due to a doubling of CO_2 is estimated at all gridpoints as: $\Delta X = X(2 \times CO_2) - X(1 \times CO_2)$. Typically, the X's are the monthly, seasonally, or annually averaged gridpoint values of a particular variable (eg., surface air temperature, precipitation) for the last 3-10 years of each simulation.

Such simulations are termed "equilibrium" runs in distinction to "transient" integrations in which the CO_2 concentration is generally increased monotonically with time in the perturbed run. Because many more equilibrium experiments have been performed than transient runs, the intercomparisons here will analyze only equilibrium model results. This study focuses on seven equilibrium simulations that are referred to using mnemonics for the modelling groups: CCC (Boer, 1989), CCM (Washington and Meehl, 1984), GFDL (Manabe and Wetherald, 1987), GFDL-R30 (Manabe and Wetherald, 1989), GISS (Hansen et al, 1984), OSU (Schlesinger and Zhao, 1989), UKMO (Wilson and Mitchell, 1987). Further details on intercomparisons of four of these simulations may also be found in a Department of Energy report (Grotch, 1988), in a forthcoming paper (Grotch and MacCracken, 1990), and in the forthcoming UN/WMO report (IPCC, 1990).

The models considered here were chosen because it was possible to obtain gridpoint data for comparable perturbation simulations. These models have "realistic" geography and topography , treat the seasonal cycle, and interactively represent sea ice, ground hydrology, and cloud amount and distribution. Each modeling group has made what are thought to be valid, but different, approximations and adjustments in their attempts to include the most appropriate mechanisms for CO_2 studies (e.g., see Schlesinger and Mitchell, 1987). Three of the models (CCC, GISS. UKMO) include the full diurnal cycle of solar radiation while four assume diurnally averaged solar radiation (i.e., a sun set at a constant zenith angle appropriate to the time of year). For the purposes of this intercomparison, however, these models are each designed to be particularly suitable for CO_2 studies and are sufficiently similar in their major characteristics for their results to be compared.

This intercomparison study is not intended to be a "beauty contest" between models, resulting in the choice of any "best" model. Such an analysis would require a much more complete comparison on many scales (both spatial and temporal), a task particularly troublesome because there are no well-established case studies against which to adequately validate the models. Therefore, in many of the graphical intercomparisons, the specific model yielding a given result is not identified. Rather, the intent here is to illustrate the range of results

currently available and to highlight certain issues of which the non-modeller may be unaware .

3. The Problem of Spatial Scale

Because GCM climate simulations are very expensive, requiring very substantial amounts of computer time on large supercomputers, there is an obvious practical incentive to reduce these costs by using as coarse a spatial grid as is possible. Because of numerical stability considerations, computer time increases approximately with the inverse cube of the horizontal resolution. Until recently, the highest resolution simulations used grid spacings of about 4° in latitude by 5° in longitude (several hundred kilometers), resulting in a global grid of approximately 3000 grid points (Fig. 1). This resolution would appear adequate to capture the larger spatial features of climate.

However, because of concerns regarding greenhouse warming, there is considerable pressure to examine model predictions at much smaller spatial scales. When the 4° x 5 ° grid is magnified, focusing on an area of the scale of the continental United States as in Fig. 2, or further as in Figure 3, covering only the western states, it becomes apparent that difficulties are likely to arise using so few gridpoints for regional scale predictions. Most modellers would agree that it would be unwise to use any single (or few) gridpoints as surrogates for small scale regional climates.

4. Intercomparison of GCM Simulations and Historical Climate Data

In this section seven GCM predictions of surface air temperature and precipitation for the control (or model reconstructions of current) climate are compared with two historical data sets for temperature: Oort (1983) and Schutz-Gates (1971,1972) and for precipitation: Jaeger (1976) and Schutz-Gates (1971,1972) over different spatial scales. Table 1 presents both the December/January/February (DJF) and June/July/August (JJA) seasonally averaged and area-weighted global average temperatures. The agreement of the

global averages between model simulations and the two observational data sets is generally good and the seasonal cycle appears well simulated. For both seasons, the median of the seven simulations is within 1° C of Oort's value. If the calculated surface temperatures at individual gridpoint are cross correlated with the historical data, near-perfect correlations are obtained: 0.96-0.98. This is the "good news". However, as will be seen, this good large-scale agreement provides no assurance that agreement on smaller scales will necessarily be as accurate.

Because latitudinal variation is often the major dominant feature of many meteorological fields, it is natural to examine model/data predictions on this basis. The most common method for intercomparison is to examine the zonally averaged values of a given variable. The zonal average is the arithmetic average of all longitudinal gridpoints at a given latitude (or latitude band). Fig. 4 shows the zonally averaged DJF and JJA estimates for surface air temperature from the seven GCM simulations and compares them with the historical compilations of Oort and of Schutz and Gates. Although the general shapes of these distributions are very similar, there exist large differences at specific latitudes, even in these zonally averaged values. This provides a rationale for presenting model predicted climate change as departures from the control run rather than as departures from the present climate.

For regional assessments, however, even finer resolution is needed, and in Fig. 5 the latitudinal distribution of DJF and JJA surface air temperature along a specific meridian (80° W longitude) is shown. This cut, passing through the eastern United States, displays very substantial differences in these simulations of the present climate. Analagous results are seen for the simulated precipitation fields generated by these GCMs . Fig. 6 displays the zonal distributions for seasonally averaged control DJF precipitation (mm/day). These distributions are seen to be very similar in general shape, but at many latitudes very large (>100%) discrepancies result. Fig. 7 shows a cut through the DJF precipitation across the United States at a latitude of 38° N in which the three highest resolution model simulations are contrasted with Jaeger's observational data. Again, although the shapes are generally similar, very large percentage discrepancies arise throughout much of the United States, making such predictions quantitatively suspect on these smaller scales.

5. Dangers of Relying on Averages

Because the average is the single "best" number characterizing a distribution, both the climate community and particularly the general public have become beguiled by its constant application: e.g., "the global average temperature is expected to rise by near 3 ± 1.5°C due to a doubling of CO_2" (National Research Council, 1982). While the average is clearly important, its indiscriminate use can be quite misleading, as the following two examples will show.

It is obvious, but often overlooked, that there are an *infinite number* of distributions which will yield the same average. For two distributions to be truly spatially identical it is *necessary* that their averages agree, but it is by no means *sufficient*. Thus, as we will see, the agreement of two distributions, on average, is no guarantee whatever that the distributions are spatially the same, or in fact, necessarily even close. In fact, even if *all* of the higher moments of two distributions were to perfectly agree, they still could be *quite different*, spatially.

As a trivial illustration of this fact take all the gridpoint values predicted by a given model and mix them thoroughly and then reassign them spatially in an arbitrary manner. When compared with the original distribution the permuted one will produce identical averages, standard deviations, in fact, all percentiles will be identical, yet spatially the two could be entirely different. Two other examples, one hypothetical, one real, will illustrate some of the pitfalls which await the unwary if simple averages are relied upon as primary measures of agreement rather than more detailed spatial distributions.

Consider first the following *hypothetical* example. For a region centered over North America, two GCMs predict identical average surface temperature increases due to a doubling of CO_2: 2.50 °C. Given this perfect agreement , how spatially similar are the predicted changes within this area? Where are the largest and the smallest predicted changes located? What is the average absolute

or rms difference between the two predicted ΔT values over the region? For regional assessments, what are the ΔT values predicted, for example, over the mid-Atlantic states?

Other statistical characteristics of the two distributions should also be compared. In this example assume that not only the averages of the two distributions are identical, but so are their standard deviations and, in fact, *all* of their higher moments. What can we now infer about the spatial distributions of these predicted values? Unfortunately, still very little. The two distributions could, of course, be spatially identical, but on the other hand, they could still be quite different, as is shown in Fig. 8 in which the two spatial distributions describing these predicted values are seen in three-dimensions to both be planes. Although the two planes result in identical average ΔT values over the region, their spatial orientations are seen to be totally different.

A more appropriate quantitative measure of model agreement is a direct point by point comparison (only feasible when the data are on, or have been interpolated to the same grid). For the data in this example, temperature differences as large as the combined range of the two initial distributions occur. Although the two models predict identical averages over North America, there are temperature differences between the predictions which are 15°C. As is the case here, even when *all* statistical moments of two distributions *agree identically*, they can still be *quite different* spatially. In fact, if we were to permute all of the values at each latitude, the two predicted zonal distributions would also be identical.

As a second, *real* example consider the zonally averaged predictions of these seven GCMs for the percentage change in annual precipitation after a doubling of CO_2. Four of these models, at a latitude of 34°N predict virtually identical zonally averaged percentage changes: 5.5, 5.5, 5.7, 5.7 %. The actual spatial distributions longitudinally of these predicted changes along the latitude 34°N are shown in Figure 9. Although all four of these models predict virtually the same zonally averaged annual percentage changes in precipitation, the patterns are, in most cases, virtually uncorrelated spatially along this latitude. Once again, the fact that they are equal on average means little in describing more regional behavior.

Conclusions

Due to practical concerns regarding the potential climatic effects of greenhouse gases, there are great pressures to apply the results of GCM simulations to regional assessments. Although such simulations generally agree on the larger scale averages, on smaller regional scales and for seasonal periods, there remain differences among the projected changes in temperature and precipitation for these models that are of the same order as the perturbation. The large regional discrepancies found in simulating present climate reduce our assurance in the ability of GCMs to quantitatively predict regional climate change due to increasing greenhouse gases.

One cause of the different estimates of regional and seasonal sensitivity to a doubled CO_2 concentration is almost certainly related to the limitations in the quality of model simulations of the present climate. Improvement of sensitivity estimates will therefore require both a sustained effort to improve the climate models and investigations to determine the theoretical limits of the various time and space scales of climate predictability.

Because of the non-uniqueness of averages in describing distributions, workers should be more circumspect in relying on agreement of averages as indicators of smaller scale agreement.

Acknowledgements

Table 1

Globally Averaged DJF/JJA Seasonal Temperatures (°C)

Model	Dec/Jan/Feb	June/July/Aug
CCM	11.5	16.5
GFDL	12.8	17.2
GISS	12.7	15.8
OSU	14.2	17.3
UKMO	11.4	15.9
CCC	11.6	15.6
GFDL(R30)	8.1	12.8

Historical data

Oort	12.4	15.9
Schutz-Gates	12.2	16.1

REFERENCES

Boer, G., 1989, Canadian Climate Center, Toronto, Canada, personal communication.

Grotch, S.L., 1988, "Regional Intercomparisons of General Circulation Model Predictions and Historical Climate Data", TR041, DOE/NBB-0084,. Available from NTIS,Springfield, VA.

Grotch, S.L. and M. MacCracken, 1990, "The Use of General Circulation Models to Predict Regional Climate Change", accepted for publication in *J. of Climate.*

Hansen, J., A. Lacis, D. Rind, G. Russell, P. Stone, I. Fung, R. Ruedy, and J. Lerner, 1984, Climate Sensitivity: Analysis of Feedback Mechanisms, 130-163. In J.E. Hansen and T. Takahashi (eds.), *Climate Processes and Climate Sensitivity,* (Maurice Ewing Series, No. 5), American Geophysical Union, Washington, DC, 368 pp.

Intergovernmental Panel on Climate Change (IPCC), 1990, *Scientific Assessment of Climate Change,* World Meteorological Organization and the United Nations Environmental Program.

Jaeger, L., 1976, Monatskarten des Niederschlags fur die ganze Erde, *Berichte des Deutschen Wetterdienstes,* **139,** 1-38.

Manabe, S. and R. J. Stouffer, 1986, Two Stable Equilibria of a Coupled Ocean-Atmosphere Model, *J. of Climate,* **1,** 841-866.

Manabe, S., and R. T. Wetherald,1986, Reduction in Summer Soil Wetness Induced by an Increase in Atmospheric Carbon Dioxide, *Science,* 232, 626-628.

Manabe, S., and R. T. Wetherald, 1987, Large Scale Changes of Soil Wetness Induced by an Increase in Atmospheric Carbon Dioxide,"*J. Atmos. Sciences,* **44,** 1211-1235.

Manabe, S., and R. T. Wetherald, 1989, personal communication.

National Research Council, 1982, *Carbon Dioxide and Climate: A Second Assessment,,* Report of the Carbon Dioxide/Climate Review Panel , National Research Council, National Academy Press, Washington DC.

Oort, A.H., 1983, *Global Atmospheric Circulation Statistics, 1958-1973,* NOAA Professional Paper 14, U.S. Govt. Printing Office, Washington, DC.

Schlesinger, M.E., and J. B. Mitchell, 1985, Model Projections of the Equilibrium Climatic Response to Increased Carbon Dioxide, 82-147. In M.C. MacCracken and F.M. Luther (eds.) *Projecting the Climatic Effects of Increasing Carbon Dioxide,* (DOE/ER-0235), U.S. Department of Energy, Washington, DC, December 1985. Available from NTIS, Springfield, VA.

Schlesinger, M.E. and Z. C. Zhao, 1989, Seasonal Climatic Changes Induced by Doubled CO_2 as Simulated by the OSU Atmospheric GCM/Mixed-layer Ocean Model, *J. of Climate,* 2, 459-495.

Schutz, C., and W. L. Gates, 1972, *Global Climatic Data for Surface, 800 mb, 400 mb, July,* Report R-1029-ARPA. Rand Corporation, Santa Monica, California. Available from NTIS (AD-760283), Springfield, VA.

Schutz, C., and W. L. Gates, 1971, *Global Climatic Data for Surface, 800 mb, 400 mb, January,* Report R-915-ARPA. Rand Corporation, Santa Monica, California. Available from NTIS (AD-760283), Springfield, VA .

Washington, W.M., and G. A. Meehl, 1984, Seasonal Cycle Experiment on the Climate Sensitivity Due to a Doubling of CO_2 with an Atmospheric General Circulation Model Coupled to a Simple Mixed-Layer Ocean Model. *J. of Geophys. Research, 89,* 9475-9503.

Washington, W. M. and C. L. Parkinson, 1986, *An Introduction to Three-Dimensional Climate Modeling,* University Science Books, Mill Valley, CA, 422 pp.

Wilson, C.A., and Mitchell, J. F. W. B., 1987, A Doubled CO_2 Climate Sensitivity Experiment with a Global Climate Model Including a Simple Ocean, *J. of Geophys. Research, 92,* 13315-13343.
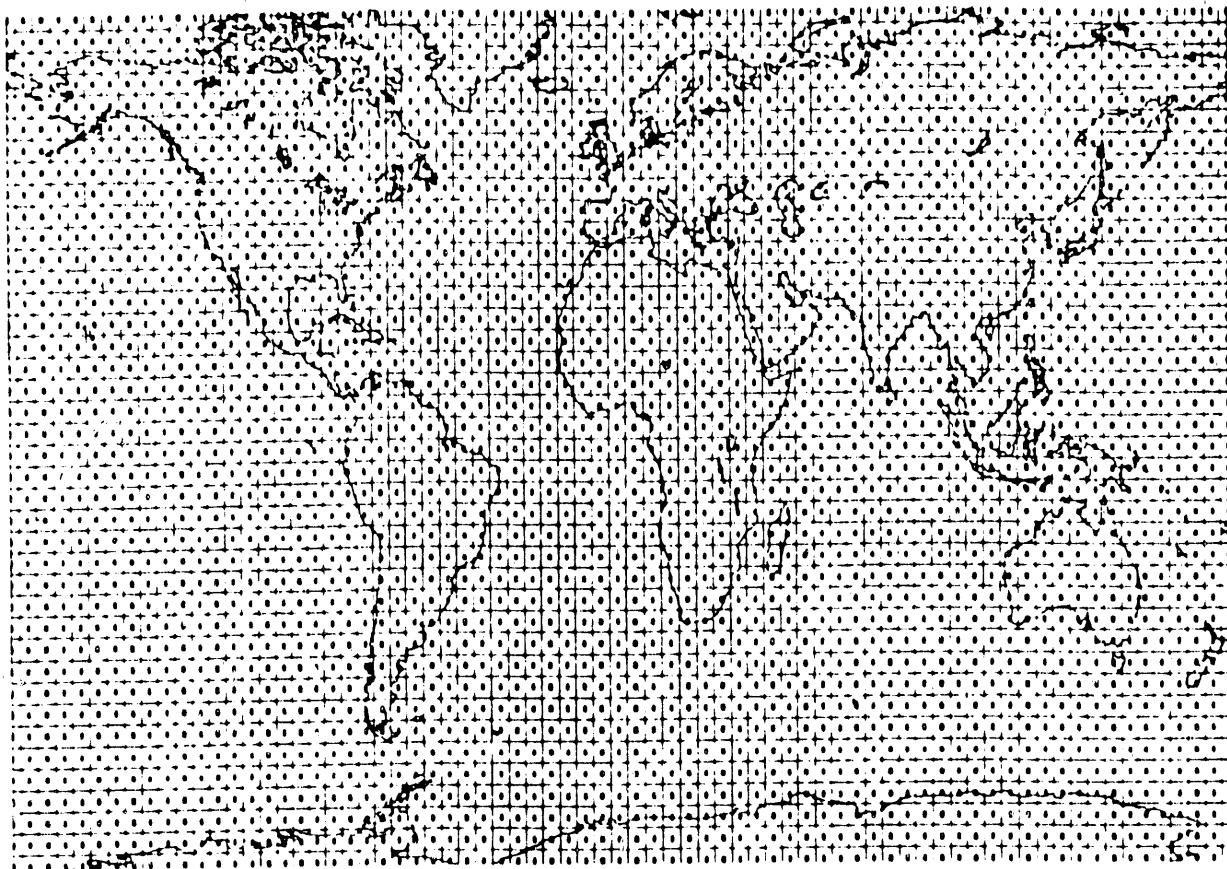
Figure 1.   The outlines of 4° latitude by 5° longitude grid over the globe. This grid of more than 3000 points appears adequate in capturing the larger scale climatic features on the global scale.
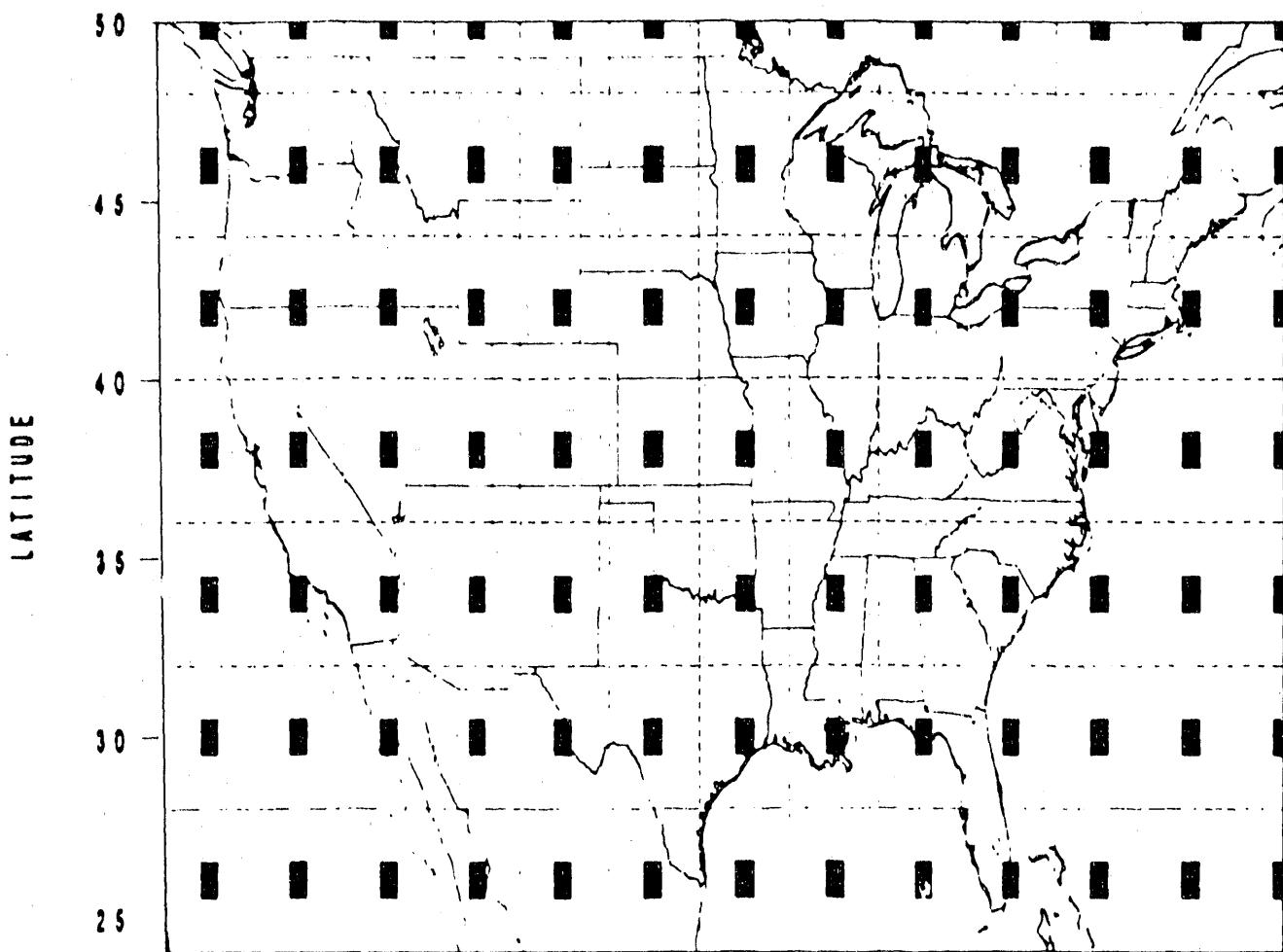
Figure 2.   The outlines of a 4° latitude by 5° longitude grid over the continental United States. For this area there are less than 50 points over the land areas. The central darkened rectangle is a 1° x 1° area at the center of the 4°x5° grid box.
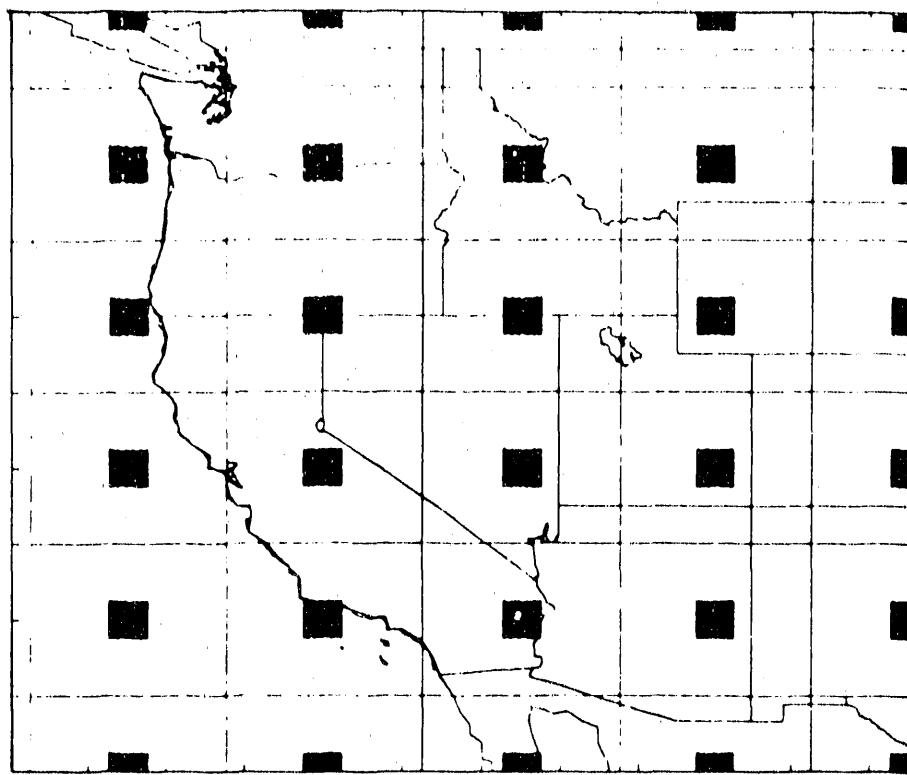
Figure 3.   The outlines of a 4° latitude by 5° longitude grid over the western United States. For the three western states, the grid is too coarse for any detailed predictions on these scales. The central darkened rectangle is a 1° x 1° area at the center of the 4°x5° grid box.
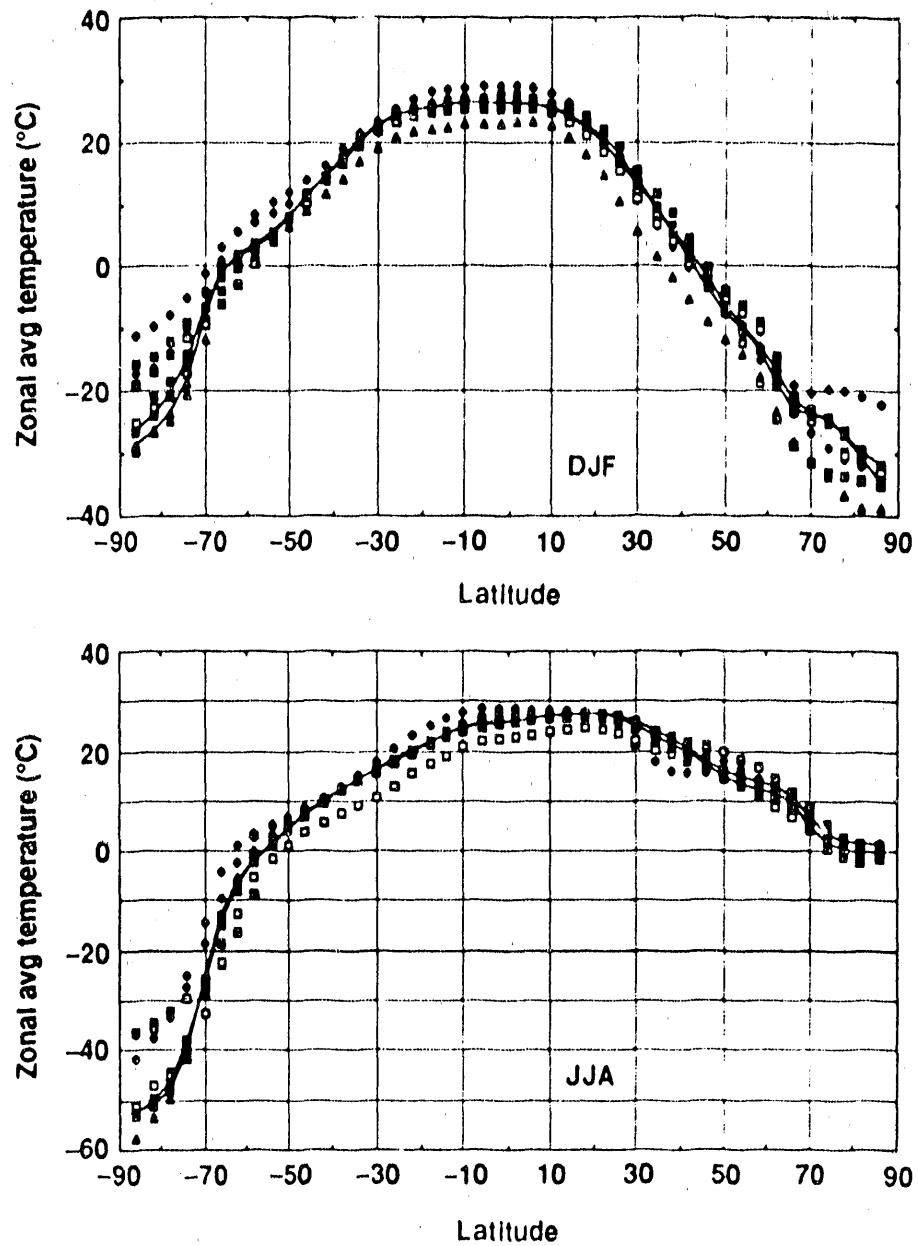
Figure 4.   The latitudinal distributions of zonally averaged Dec/Jan/Feb and June/July/August surface air temperature simulated by 7 GCMs are compared with the two observational data sets of Oort and Schutz-Gates.
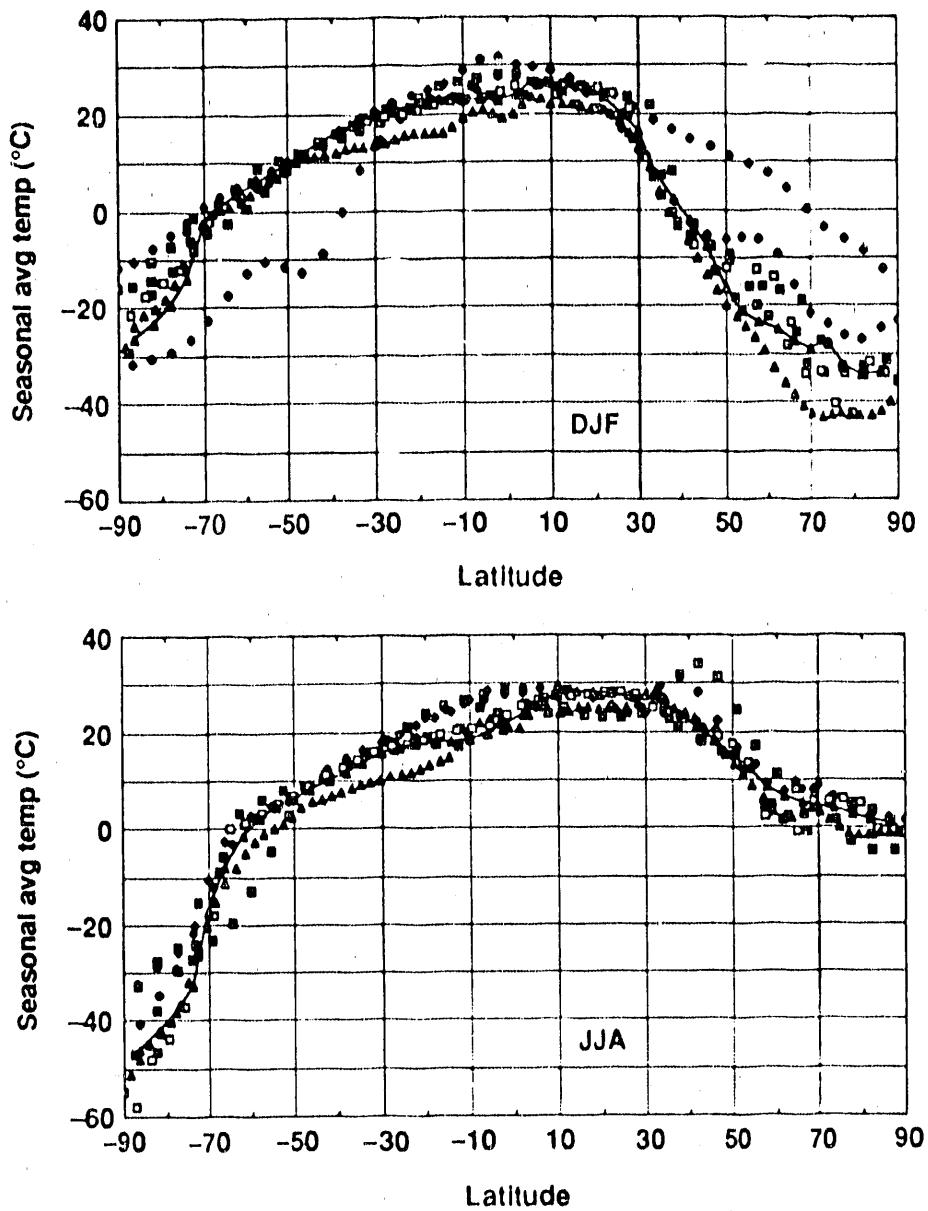
Figure 5. The latitudinal distributions of DJF and JJA surface air temperature predicted by seven GCMs are contrasted with Oort's historical data (solid line) along the meridian 80° W longitude.
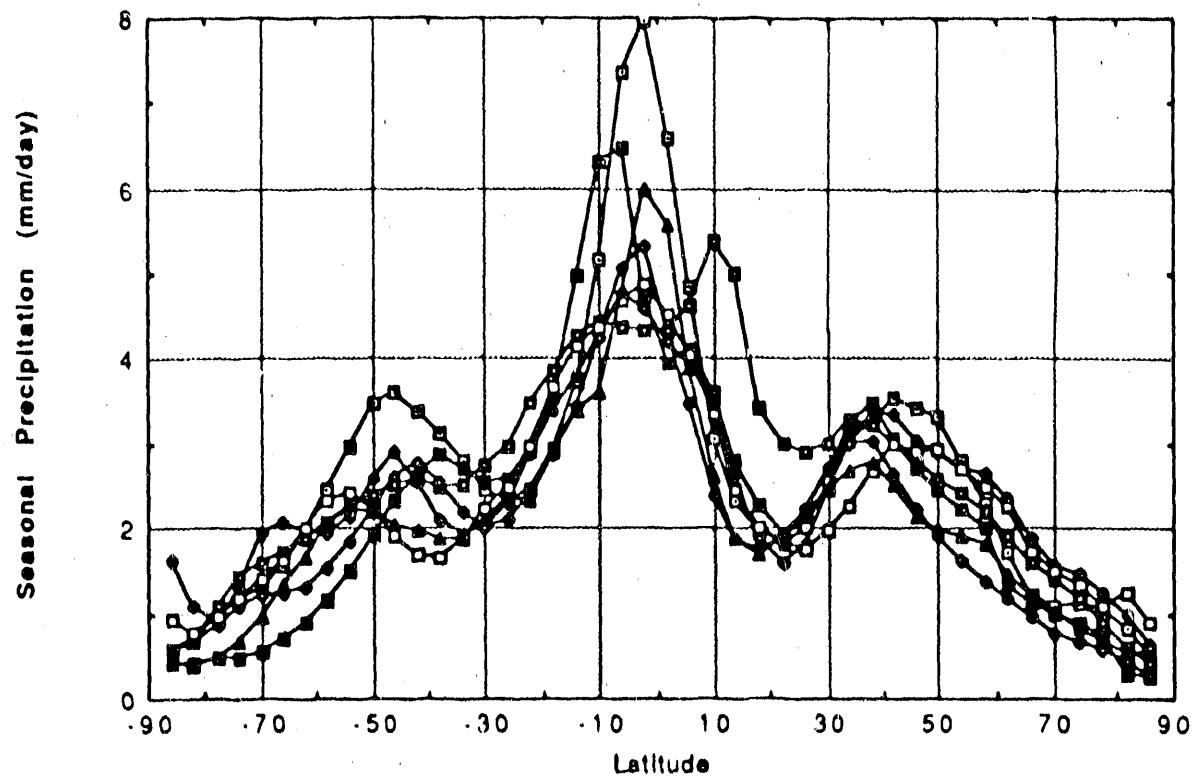
Figure 6. Zonally averaged DJF precipitation for the current climate as simulated by seven GCMs. Although the general behavior of these curves is similar, large percentage differences exist at many latitudes.
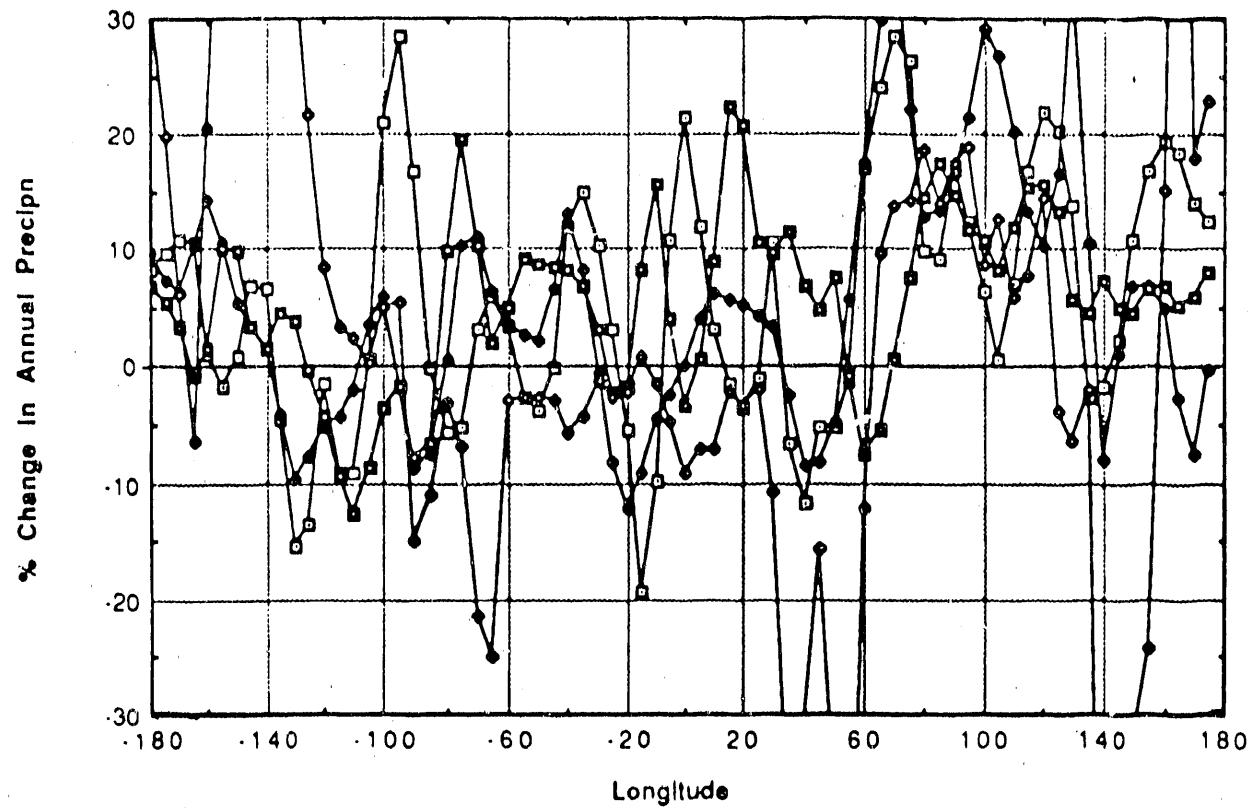
Figure 7. The longitudinal distribution of simulated DJF precipitation (1 x CO2) at a latitude of 38°N across the United States. Data from three of the higher resolution models are contrasted with Jaeger's historical data (solid heavy line).
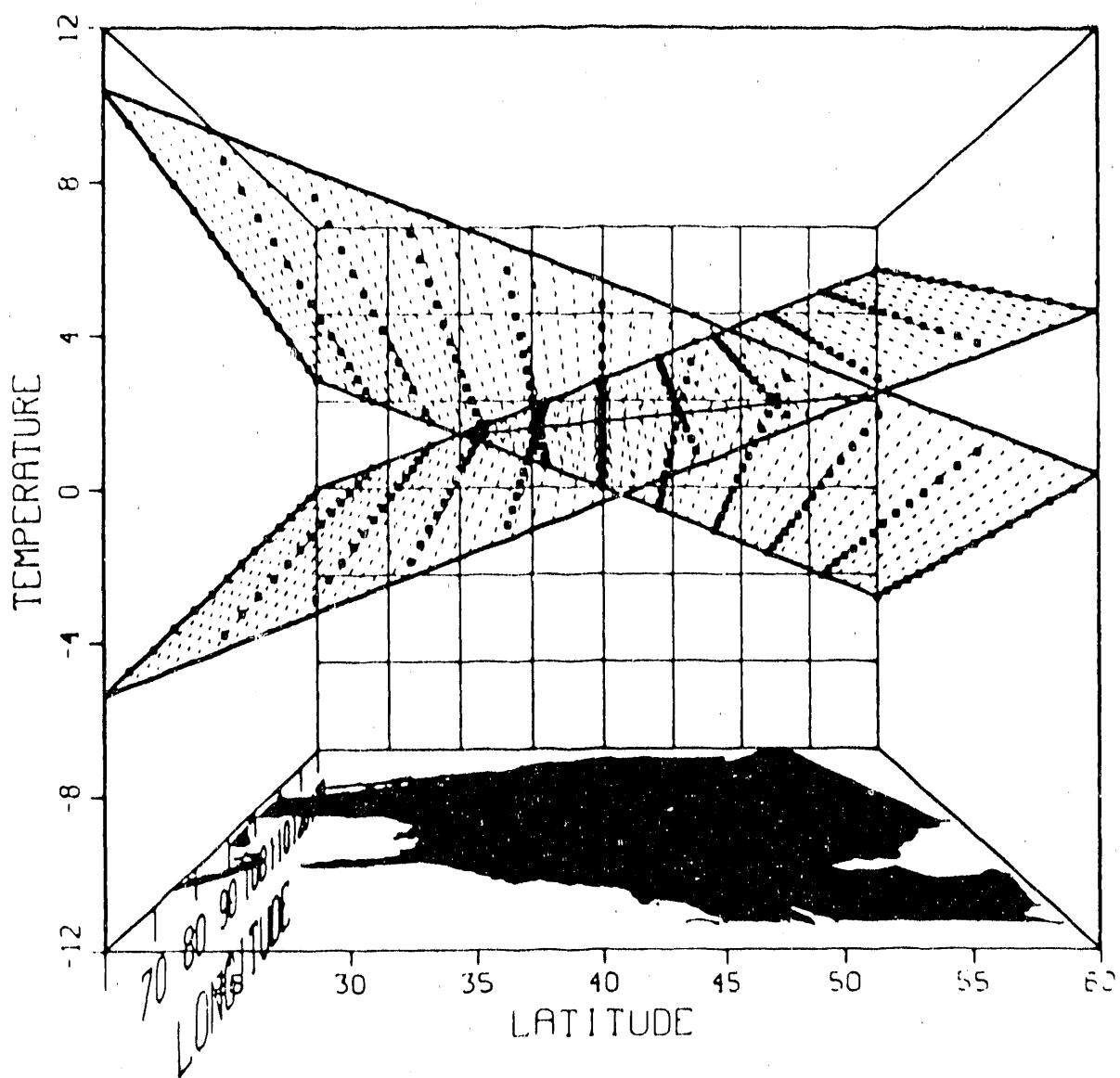
Figure 8. Superposed spatial distributions of hypothetically predicted change in temperature over North America due to a doubling of CO_2 by two models. Although the models predict precisely the same *average* change for the region, spatially they are *very different* on smaller regional scales. View looking west from off the Atlantic coast.
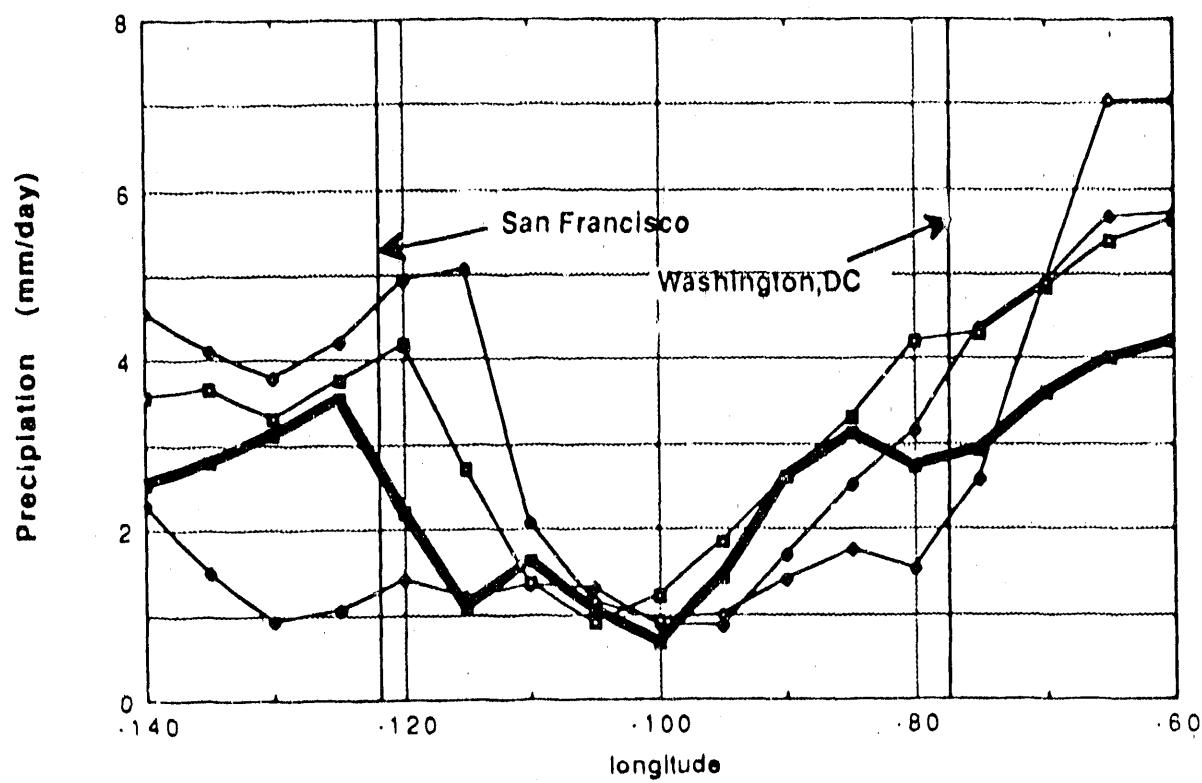
Figure 9. Longitudinal distributions of the predicted change in annual precipitation after a doubling of CO_2 as given by 4 GCMs along the latitude 34°N. These same four models predict virtually identical zonally averaged annual percentage changes in precipitation, yet most are virtually uncorrelated spatially at this latitude.

END

DATE FILMED

01/28/91