GCM-Data Intercomparison: The Good News and The Bad

Stanley L. Grotch

ABSTRACT: General circulation models *(GCMs)* are probably the most sophisticated theoretical tools we have to simulate possible climatic effects of increasing CO_2 and other greenhouse gases. Because of tremendous social and 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 (e.g., global, hemispheric, zonal), substantial differences are more apparent as the scale is reduced to areas 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.

Introduction

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 is discussed. In these intercomparisons, the spatial scale over which 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 are highlighted.

Simplified Model Descriptions and CO_2 Doubling Experiments

General circulation model 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

In: J.L. Betancourt and V.L. Tharp, editors. 1991. *Proceedings of the Seventh Annual Pacific Climate (PACLIM) Workshop, April 1990*. California Department of Water Resources. Interagency Ecological Studies Program Technical Report 26.

(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:

- 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 "$1 \times CO_2$ run").

- 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 "$2 \times CO_2$ 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 Xs are the monthly, seasonally, or annually averaged gridpoint values of a particular variable (*e.g.*, surface air temperature, precipitation) for the last 3 to 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 modeling 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 1991), 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, and four assume diurnally averaged solar radiation (*i.e.*, a sunset at a constant zenith angle appropriate to the time of year). For 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 is to illustrate the range of results currently available and to highlight certain issues of which the non-modeler may be unaware.

The Problem of Spatial Scale

Because GCM climate simulations are very expensive, requiring substantial amounts of time on large supercomputers, there is an obvious practical incentive to reduce these costs by using as coarse a spatial grid as 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 about 3,000 grid points (Figure 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°×5° grid is magnified, focusing on an area of the scale of the continental United States (as in Figure 2) or further, covering only the western states (as in Figure 3), it becomes apparent that difficulties are likely to arise using so few gridpoints for regional scale predictions. Most modelers would agree that it would be unwise to use any single (or few) gridpoints as surrogates for small scale regional climates.

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; Schutz-Gates 1971, 1972) and for precipitation (Jaeger 1976; 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, this good large-scale agreement provides no assurance that agreement on smaller scales will be as accurate.

Figure 1
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.

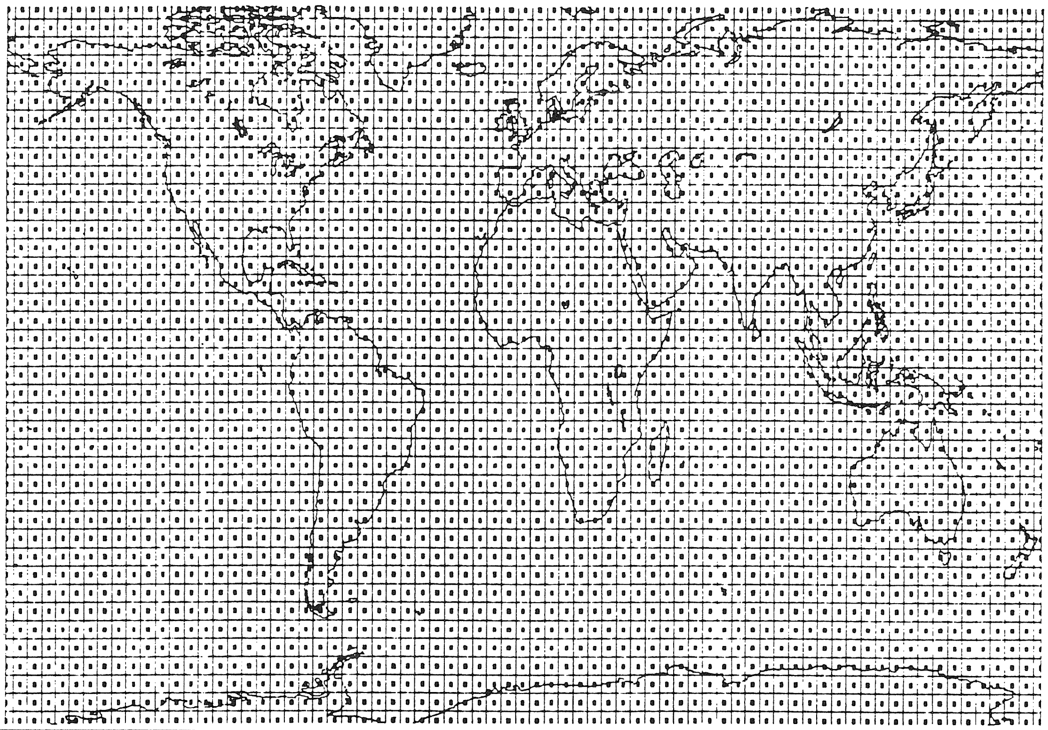


Figure 2
OUTLINES OF A 4° LATITUDE BY 5° LONGITUDE GRID
OVER THE CONTINENTAL UNITED STATES

For this area there are less than 50 points over the land areas.
The central darkened rectangle is a 1°×1° area at the center of the 4°×5° grid box.

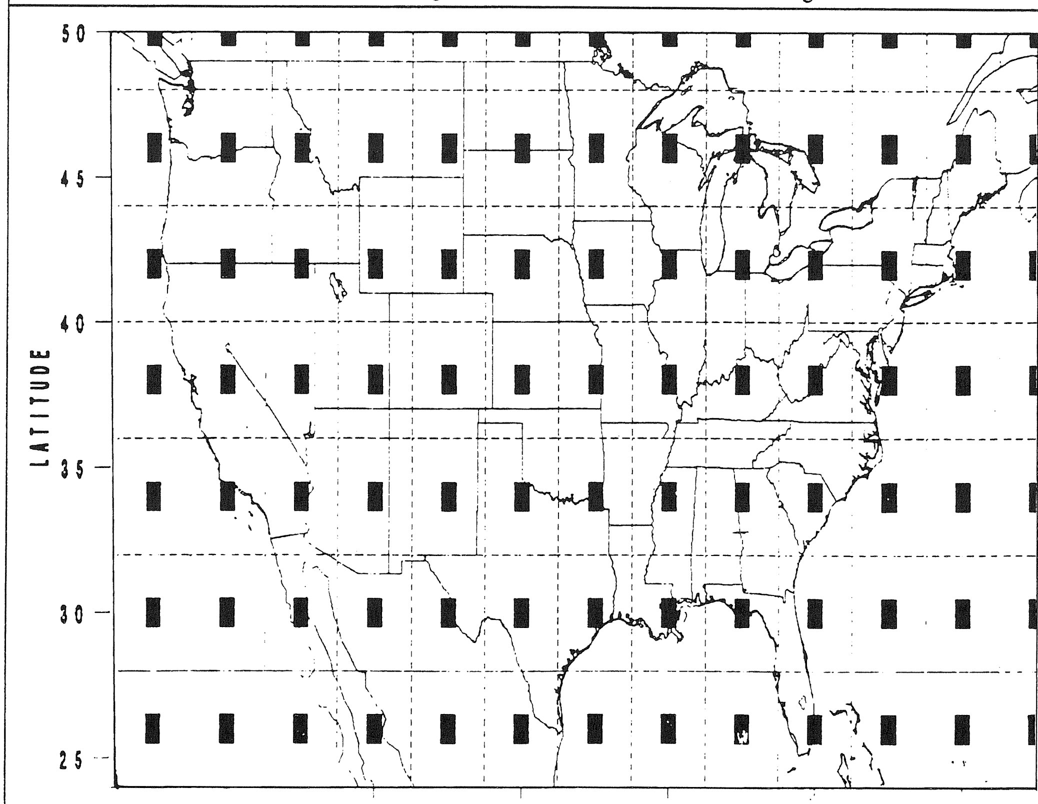


Figure 3
OUTLINES OF A 4° LATITUDE BY 5° LONGITUDE GRID
OVER THE WESTERN UNITED STATES

For the three western states, the grid is too coarse for any detailed predictions on these scales.
The central darkened rectangle is a 1°×1° area at the center of the 4° × 5° grid box.

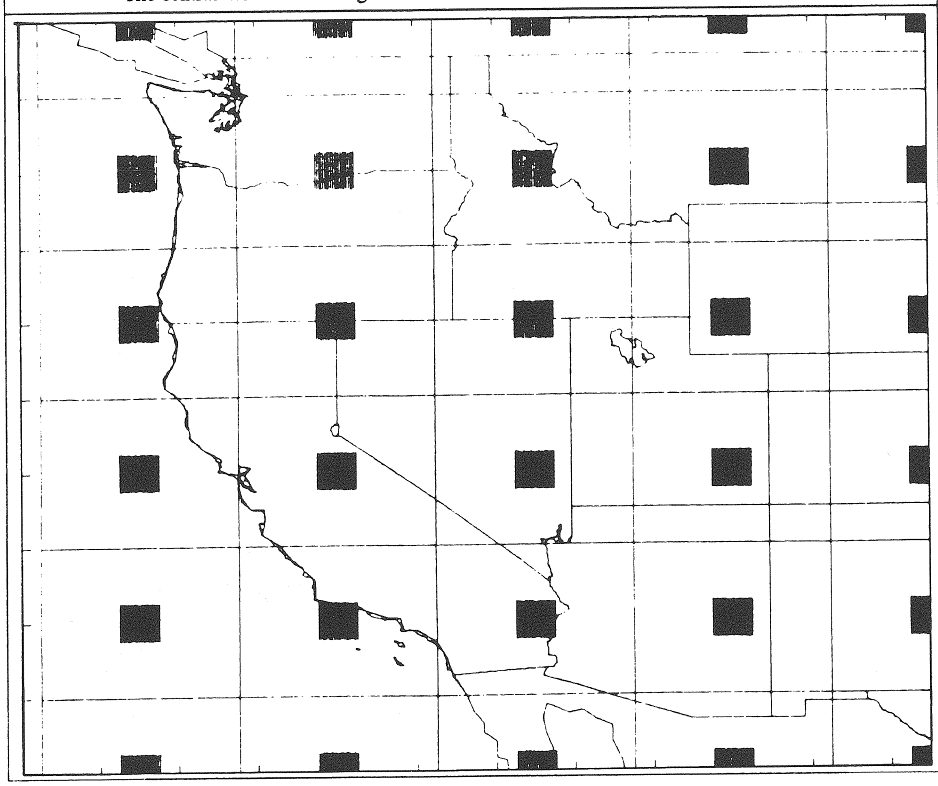


Table 1
GLOBALLY AVERAGED DJF/JJA
SEASONAL TEMPERATURES
(°C)

Model	Dec/Jan/Feb	Jun/Jul/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

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). Figure 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 similar, there are 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 Figure 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 substantial differences in these simulations of the present climate. Analogous results are seen for the simulated precipitation fields generated by these GCMs. Figure 6 displays the zonal distributions for seasonally averaged control DJF precipitation (mm/day). These distributions are similar in general shape, but at many latitudes large (>100%) discrepancies result. Figure 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, large percentage discrepancies arise throughout much of the United States, making such predictions quantitatively suspect on these smaller scales.

Figure 4
LATITUDINAL DISTRIBUTIONS OF ZONALLY AVERAGED DJF AND JJA SURFACE AIR TEMPERATURE SIMULATED BY 7 GCMs COMPARED WITH THE OORT AND SCHUTZ-GATES OBSERVATIONAL DATA SETS

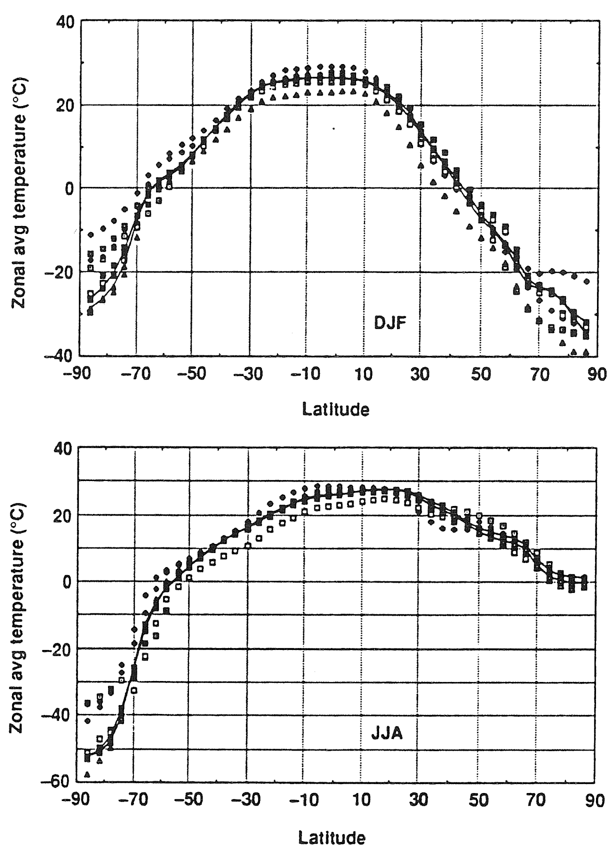
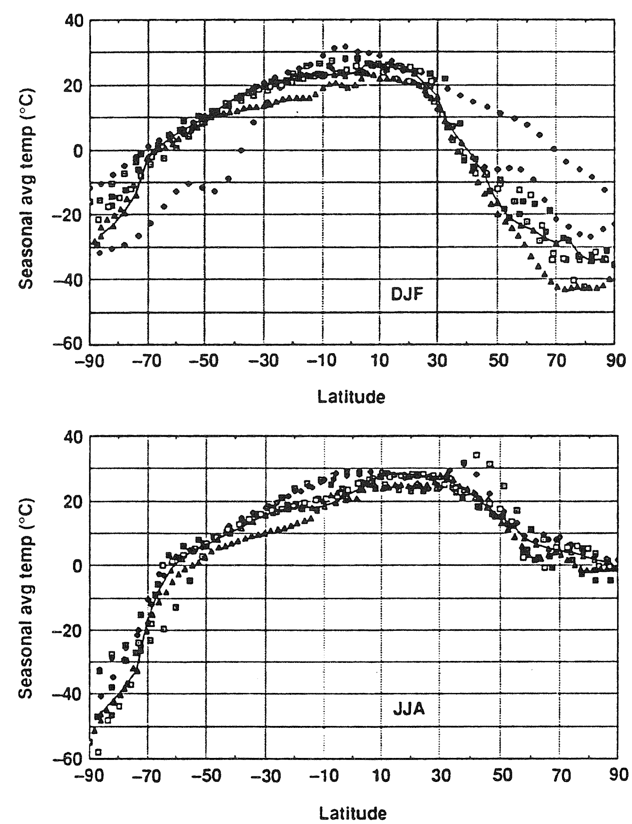


Figure 5
LATITUDINAL DISTRIBUTIONS OF DJF AND JJA SURFACE AIR TEMPERATURE PREDICTED BY 7 GCMs CONTRASTED WITH OORT'S HISTORICAL DATA ALONG THE MERIDIAN 80°W LONGITUDE

Oort's data are represented by the solid line.



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.

It is obvious, but often overlooked, that there are an infinite number of distributions that 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, 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 agree perfectly, 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, then reassign them spatially in an arbitrary manner. When

Figure 6
ZONALLY AVERAGED DJF PRECIPITATION FOR THE CURRENT CLIMATE
AS SIMULATED BY 7 GCMs

Although the general behavior of these curves is similar, there are large percentage differences at many latitudes.

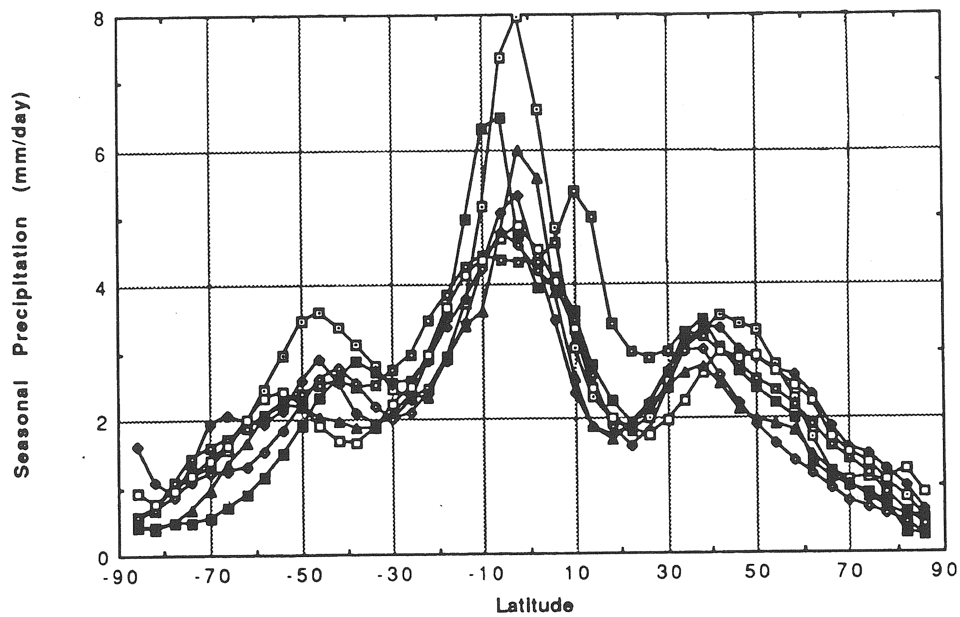
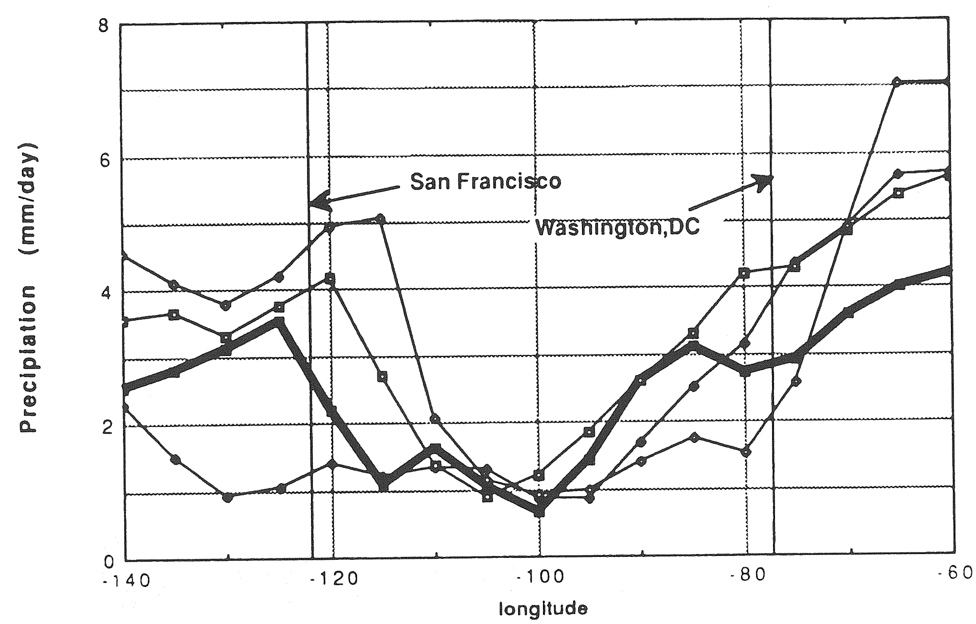


Figure 7
LONGITUDINAL DISTRIBUTION OF SIMULATED DJF PRECIPITATION ($1 \times CO_2$) AT A LATITUDE OF 38°N ACROSS THE UNITED STATES

Data from three of the higher resolution models are contrasted with Jaeger's historical data (solid heavy line).



compared with the original distribution, the permuted one will produce identical averages and standard deviations; in fact, all percentiles will be identical, yet spatially the two could be entirely different. Two other examples — one hypothetical, one real — illustrate some of the pitfalls that await the unwary if simple averages are relied upon as primary measures of agreement rather than more detailed spatial distributions.

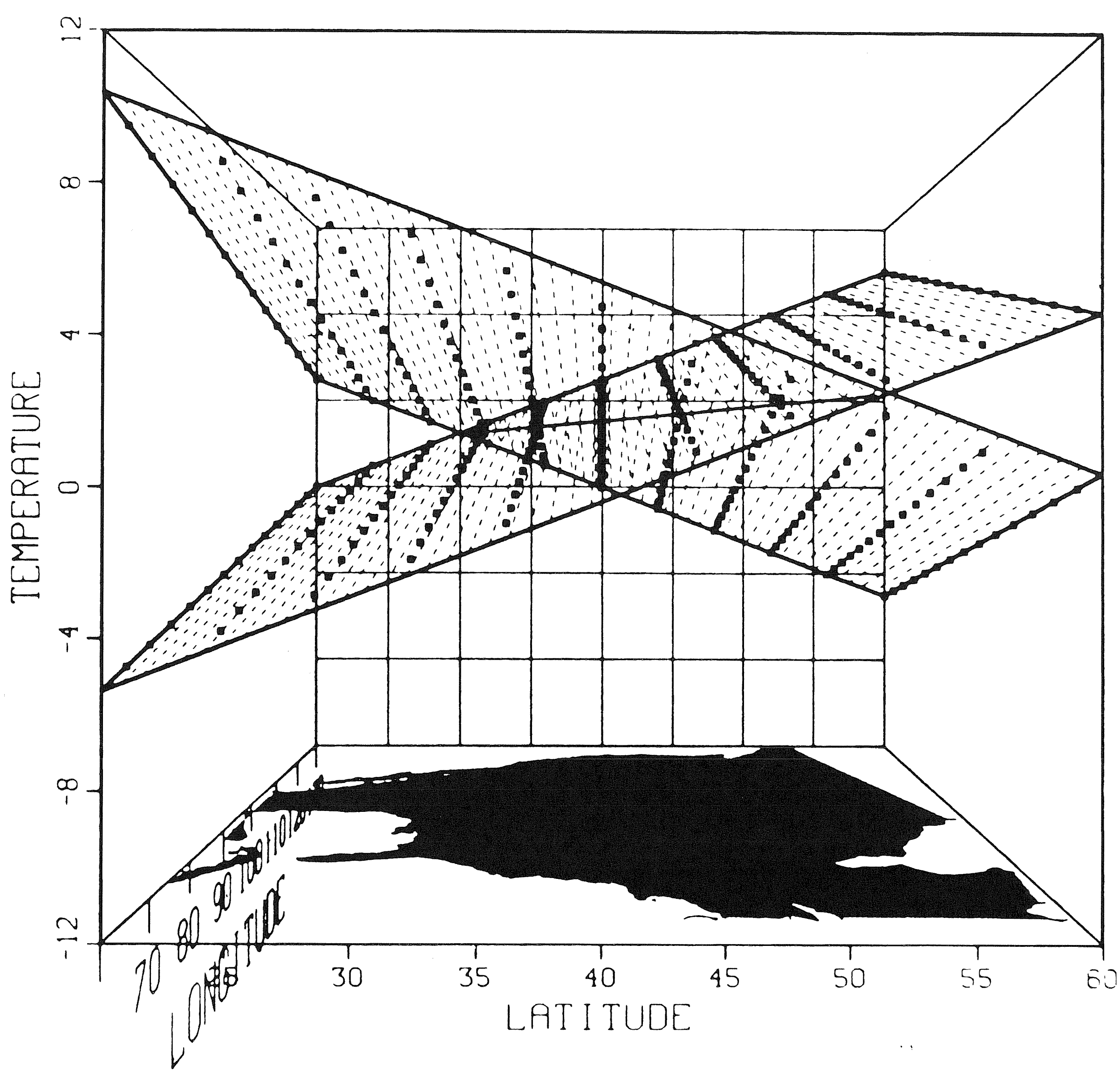
Consider first this *hypothetical* example. For a region centered over North America, two GCMs predict identical average surface temperature increases due to a doubling of CO_2: 2.50°C. Given this perfect agreement, how spatially similar are the predicted changes within this area? Where are the largest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

Figure 8

SUPERPOSED SPATIAL DISTRIBUTIONS OF CHANGE IN TEMPERATURE OVER NORTH AMERICA DUE TO A DOUBLING OF CO_2, AS HYPOTHETICALLY PREDICTED BY TWO MODELS

View looking west from off the Atlantic coast.



little. The two distributions could, of course, be spatially identical but, on the other hand, they could still be quite different, as shown in Figure 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 totally different.

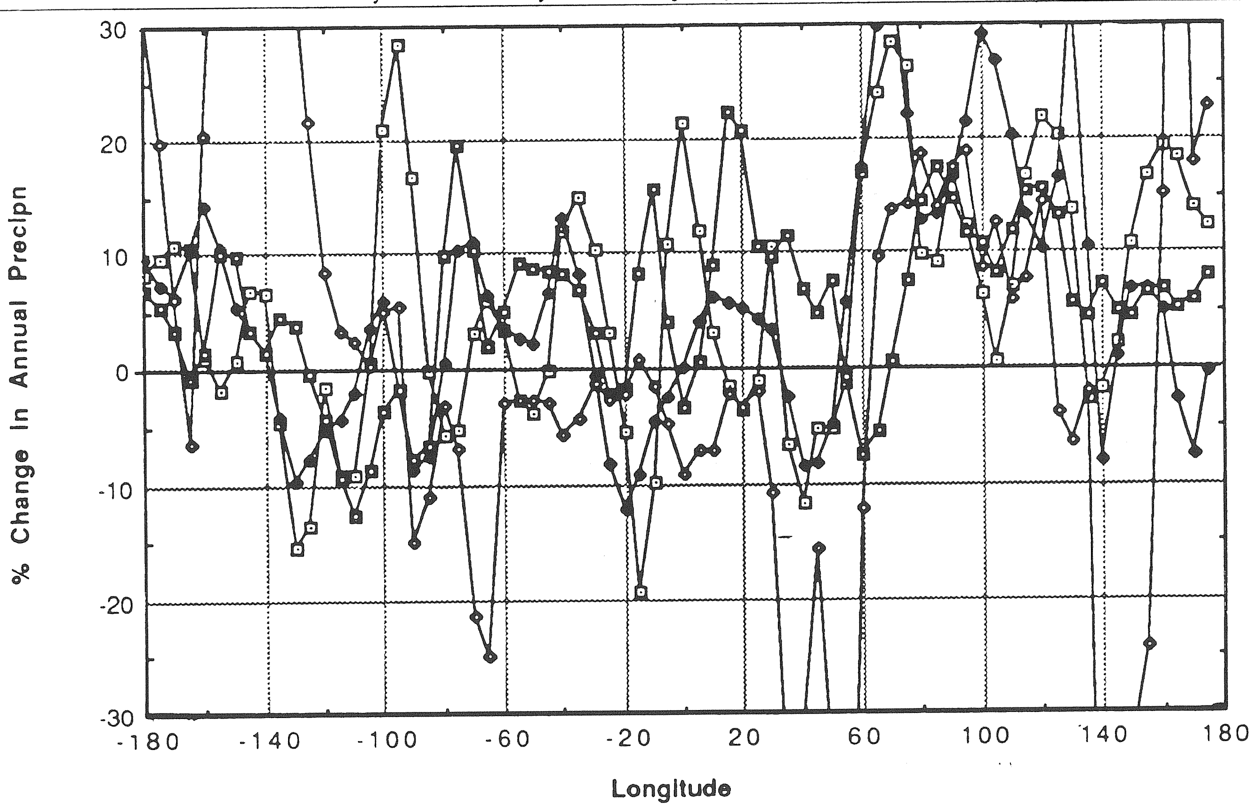
A more appropriate quantitative measure of model agreement is a direct point-by-point comparison (only feasible when the data are on, or have been interpolated to the same grid). For the data in this example, temperature differences as large as the combined range of the two initial distributions occur. Although the two models predict identical averages over North America, there are temperature differences between the predictions that 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 *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 latitude 34°N are shown in Figure 9. Although all four 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.

Figure 9

LONGITUDINAL DISTRIBUTIONS OF THE PREDICTED CHANGE IN ANNUAL PRECIPITATION AFTER A DOUBLING OF CO2, 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.



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 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.

Acknowledgments

The author is grateful to the six modeling groups (led by George Boer, James Hansen, Syukuro Manabe, John Mitchell, Michael Schlesinger, and Warren Washington) for making the model results available and for their comments on an earlier report elaborating on these results.

The suggestions of my colleagues (Curt Covey, Hugh Ellsaesser, Steve Ghan, Mike MacCracken, Jerry Potter, and Karl Taylor) are especially acknowledged.

This work was performed under the auspices of the Department of Energy Atmospheric and Climate Research Division by the Lawrence Livermore National Laboratory under contract W-7405-ENG-48.

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. U.S. Dept. of Energy. DOE/NBB-0084.

Grotch, S.L., and M. MacCracken. 1991. "The Use of General Circulation Models to Predict Regional Climate Change". *J. of Climate* 4:386-303.

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

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 Wetter dienstes,* 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. 1989. Personal communication.

_______. 1987. "Large Scale Changes of Soil Wetness Induced by an Increase in Atmospheric Carbon Dioxide". *J. Atmos. Sciences*, 44:1211-1235.

_______. 1986. "Reduction in Summer Soil Wetness Induced by an Increase in Atmospheric Carbon Dioxide". *Science*, 232:626-628.

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*. National Oceanic and Atmospheric Admin. 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" in *Projecting the Climatic Effects of Increasing Carbon Dioxide*. Ed. M.C. MacCracken and F.M. Luther. U.S. Dept. of Energy. DOE/ER-0235. Washington, DC. pp. 2-147.

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*. Rand Corporation. R-1029-ARPA. Santa Monica, CA.

_______. 1971. *Global Climatic Data for Surface, 800 mb, 400 mb, January*. Rand Corporation. R-915-ARPA. Santa Monica, CA.

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

Wilson, C.A., and J.F.W.B. Mitchell. 1987. "A Doubled CO_2 Climate Sensitivity Experiment with a Global Climate Model Including a Simple Ocean". *J. of Geophys. Research*, 92:13315-13343.