

**SLTR97-0001
Department 6850 Letter Report**

May 23, 1997

FUTURE CLIMATE MODELING SCENARIOS

**F. J. Schelling
Sandia National Laboratories
Albuquerque, NM**

**S. L. Thompson
National Center for Atmospheric Research
Boulder, Colorado**

**Prepared for:
U.S. Department of Energy
Yucca Mountain Site Characterization Office
P.O. Box 30307
North Las Vegas, NV 89036**

**Prepared by:
TRW Environmental Safety Systems
Sandia National Laboratories
1180 Town Center Drive
Las Vegas, NV 89134**

Acknowledgments: The essential contributions of David Pollard and Christine Shields in conducting the analyses described in this report, and the assistance of Charles D'Ambra in providing quality assurance and software configuration management support, are gratefully acknowledged.

TABLE OF CONTENTS

<u>Section</u>		<u>Page</u>
	Executive Summary.....	1
1	Introduction.....	3
2	Computer Models	4
2.1	Global Climate Model Selection	4
2.2	GENESIS Global Climate Model Description	4
2.3	Regional Climate Model Selection.....	6
2.4	RegCM2 Regional Climate Model Description	6
3	Software Qualification Process	7
3.1	Global Climate Model Code Validation.....	7
3.2	Regional Climate Model Code Validation	8
3.3	Nested GENESIS/RegCM2 Climate Model Code Validation	9
3.4	Other Considerations and Limitations.....	9
3.5	Climate Model Validation	10
4	Climate State Selection and Description	12
5	Sources of Model Input	14
6	Model Output and Conclusions	18
6.1	Current Climate Simulation.....	18
6.2	Paleoclimate Simulation.....	20
6.3	Initial Greenhouse Climate Simulation	22
6.4	Extreme Greenhouse Climate Simulation	23
7	Summary.....	25
8	References.....	26

Executive Summary

This report (future climate modeling scenarios) summarizes the future modeling activity conducted from late 1994 through mid-1997 for the Yucca Mountain Site Characterization Project (YMP), and includes a description of the computer codes used, the software qualification process followed, a description of the climate states modeled by this activity, the reasoning behind their selection, and an identification of the sources of model input and conclusions drawn from the evaluation of model output.

Climate simulations were performed for four climate states at the National Center for Atmospheric Research (NCAR) using a regional climate model code (RegCM2) driven by the GENESIS general circulation model code. Before performing the climate simulations, the codes were qualified under the software quality assurance requirements of the YMP and placed under configuration management controls. The four climate states modeled included the present-day climate, a full-glacial climate state such as the one that existed 21,000 years ago, the present climate in the presence of a doubled carbon dioxide content, and the present climate under extreme "greenhouse" conditions of a six-fold increase in carbon dioxide.

For the full glacial climate simulation, temperatures in the region of Nevada were observed to be 1-3°C colder than at present in winter and 2-6°C colder in summer. Increased winter precipitation in southern Nevada and increased year-round soil moisture (an annual increase of about 20 mm for the Yucca Mountain area, Nevada) was also observed for this climate state. For the doubled carbon dioxide climate state, a uniform temperature increase across the western U.S. was observed for all seasons. For the Yucca Mountain area, this increase was 2-3°C. A significant increase in winter precipitation, and a less significant decrease in summer precipitation was observed under these conditions for southern Nevada. In comparison to the doubled CO₂ simulation, the more extreme conditions of the 6 x CO₂ simulation produced a much drier Yucca Mountain climate (in terms of soil moisture, runoff, and infiltration), less winter precipitation, and much higher temperatures. These results indicate that a trend toward a wetter climate seen in comparing the present-day climate to the doubled CO₂ climate did not continue when extended to the six-fold CO₂ climate.

The results of this limited modeling effort demonstrated that the models do a credible job of representing regional climate under varying climatic conditions, and yielded results for potential future conditions that

appear reasonable and not unduly surprising. Perhaps the most useful observation that can be abstracted from these results for use in assessing the future performance of the potential repository at Yucca Mountain, is that conditions observed for climate states other than the present (with the possible exception of temperature changes observed for the extreme greenhouse state) are similar to the range of conditions reflected in the paleoclimate record. It may thus be possible to develop conceptual models for representing the performance effects of future climate based on the record of past climate change.

The following table summarizes the acceptance criteria and report location in which these criteria are addressed for YMP Milestone: SP26BMD *"Future Climate Modeling Scenarios."*

Criteria	Report Section
Description of the computer codes used	Section 2 Computer Models
Software qualification process followed	Section 3 Software Qualification Process
Description of the climate states modeled	Section 4 Climate State Selection and Description
Reasoning behind their selection	Section 4 Climate State Selection and Description
Identification of the sources of model input	Section 5 Sources of Model Input
Conclusions drawn from the evaluation of model output	Section 6 Model Output and Conclusions
Statement acknowledging that any stratigraphy used in the report is consistent with the Reference Information Base	Section 1 Introduction
Q and Non-Q information	Section 1 Introduction
Record Accession and ATDT numbers	Section 8 References

Section 1 INTRODUCTION

This report summarizes the numerical modeling of potential future climate states that was performed during the period from late 1994 through mid-1997 for the U.S. Department of Energy Office of Civilian Radioactive Waste Management's (OCRWM) Yucca Mountain Site Characterization Project (YMP) under Site Characterization Plan (SCP) Study 8.3.1.5.1.6, "Future Climate Modeling." During that time, a Study Plan (Schelling and Zak, 1994) was prepared, approved, and issued; numerical climate modeling codes were selected and qualified under the requirements of the OCRWM quality assurance program, and several potential future climate states were selected and analyzed using the modeling codes. This work was performed at the National Center of Atmospheric Research (NCAR) under contract to Sandia National Laboratories (SNL).

This work was conducted under WBS 1.2.3.6.2.1.6 subject to the quality assurance controls specified in SNL Work Agreement WA-106, "Future Climate Modeling." No stratigraphy is used in this report. All information in this report is considered indeterminate or non-Q, due to its having been acquired external to the YMP quality assurance program. Record Accession numbers for cited sources are shown in the references section. None of the information in this report is considered either "acquired" or "developed" data representing site characterization data collected for the YMP; therefore, no Automated Technical Data Tracking numbers were requested for this information.

The computer models selected for this work are described in Section 2.0, and the software qualification process used for the modeling codes is described in Section 3.0. The modeled climate states discussed include a simulation of the present-day climate, a paleoclimate state representing the last glacial maximum of about 21,000 years ago (21 Ka BP), a representative greenhouse climate state having double the carbon dioxide concentration of today's atmosphere, and an extreme (six times carbon dioxide concentration) greenhouse climate state. A discussion of these climate states is provided in Section 4.0. Sources of input used to develop the modeling simulations are described in Section 5.0. The results of each of these simulations and the conclusions drawn from the analysis of the model output have been reported earlier and are summarized in Section 6.0. Finally, Section 7.0 summarizes the results of the numerical climate modeling work as it relates to other work in the climate program being conducted for the project and to the basic site characterization objective of determining the suitability of the Yucca Mountain site as a potential repository for high-level radioactive nuclear waste.

Section 2 COMPUTER MODELS

2.1 GLOBAL CLIMATE MODEL SELECTION

More than 30 general circulation models (GCMs) are in use around the world (Gates, 1992). Although there are many similarities among them, in their present versions the models differ significantly in both how they treat specific climate processes and in the results they produce for specified global initial and boundary conditions (Boer et al., 1992). In principle, GCM selection is a significant task; however, in practice, the choice is restricted. Some of the models reflect older technology, and either do not include the best available parameterizations of climate processes, are computationally inefficient, or do not run on the most cost-effective computers. Other models are designed for specific uses (e.g., long simulated-time runs that make it necessary to eliminate diurnal variations), and most do not accommodate nesting with regional-scale climate models.

For the purposes of this study, it was important to select a model that: (1) was available (including personnel and computing resources needed to run it); (2) was fully GCM-based, with the capability for incorporation of predicted sea surface temperatures (SSTs), sea ice, and up-to-date land surface processes; (3) was well-established and documented in the open literature; and (4) had a background of use for paleoclimate studies (as an indicator of robustness for large variations in boundary conditions). Taking these considerations into account, a version of the NCAR Community Climate Model (CCM) was selected for this work. The CCM version selected was the Global Environmental and Ecological Simulation of Interactive Systems (GENESIS) model (Pollard and Thompson, 1993).

2.2 GENESIS GLOBAL CLIMATE MODEL DESCRIPTION

The GENESIS global climate model consists of an atmospheric general circulation model (AGCM) coupled to surface models of soil, snow, sea ice, and slab ocean, and includes a Land-Surface-Transfer Model (LSX) that computes near surface fluxes in the presence of vegetation. GENESIS originated from the NCAR Community Climate Model Version 1 (CCM1, described in Williamson et al., 1987), although most modules have been extensively modified or replaced since work began in 1989. An exception is the spectral dynamics, whose core remains essentially unchanged. The model dynamics use the spectral transform method in the horizontal for mass, heat, and momentum. A sigma-coordinate

system is used with 18 vertical levels. A diurnal cycle is included, with solar radiation calculations performed every 1.5 hours. The solar radiation scheme of Thompson et al. (1987) is used, which performs delta-Eddington calculations for all layers. The single-effective-cloud approximation of Thompson et al. is avoided and multi-layer randomly overlapped clouds are included in the solar calculations. Also, the solar effect of background tropospheric aerosols can be included. The infrared radiative effects of other trace gases (CH₄, N₂O, CFCs) are treated explicitly instead of being lumped with CO₂; this work was done by Prof. Wei-Chyung Wang's group at SUNY/Albany.

Water vapor is advected in grid space by semi-Lagrangian transport, essentially as described in Williamson and Rasch (1989), Rasch and Williamson (1990), and Williamson (1990). Convection in the atmosphere is treated using an explicit sub-grid plume model along the lines of Anthes (1977, section 4) for instance, and the same model is also used to simulate planetary boundary layer mixing. The cloud scheme predicts explicit cloud water amounts (Sundqvist, 1978; Tiedtke, 1994). Gravity wave drag is included in the atmospheric dynamics, and a dynamic Courant spectral truncation in the upper stratosphere is used for numerical stability. Passive tracers can be advected using the same semi-Lagrangian scheme as for water vapor. A hybrid (sigma-pressure) vertical coordinate is used for the semi-Lagrangian transport to reduce spurious diffusion in the stratosphere. The prescribed AGCM topography over the Himalaya has been augmented by envelope orography, whereby large-scale elevations are increased slightly to account for the tendency of synoptic weather systems to flow over the mountain tops and not descend into the valleys (Wallace et al., 1983).

The nominal AGCM resolutions are a spectral horizontal grid of T31 (3.75 degrees latitude and longitude) and 18 vertical levels. In GENESIS, the AGCM and surface grids are independent of each other. Because natural surface fields (vegetation, soil variations, etc.) tend to have scales of variability smaller than the horizontal scale of synoptic weather systems, it is desirable in global climate models for the surface-model grid to be somewhat finer than the AGCM grid. Fields are transferred between the AGCM and the surface by bilinear interpolation (AGCM to surface) or straightforward area-averaging (surface to AGCM) at each time step. The nominal surface grid resolution used by the vegetation, snow, sea-ice, and ocean models is 2 degrees by 2 degrees. The nominal time step for both the AGCM and surface models is 30 minutes, though shorter time steps may also be utilized.

2.3 REGIONAL CLIMATE MODEL SELECTION

As with GCMs, there are a fair number of regional climate models available in principle, but not in practice. In particular, only a few have been modified to accommodate nesting with GCMs and to treat surface processes in detail. For the last several years, NCAR investigators have been working with regional climate models based upon the NCAR-Pennsylvania State University limited area model MM4 (Anthes et al., 1987). There is considerable positive experience with this model in a nested environment. For that reason, the current version of that model, RegCM2 (Giorgi et al., 1993a and 1993b), was selected for the nested modeling. A detailed description of RegCM2 is given in the references cited, along with commentary on how it differs from its predecessors.

2.4 RegCM2 REGIONAL CLIMATE MODEL DESCRIPTION

The RegCM2 model uses a one-way nesting technique where the output from either a global observational data set or from a GCM provides the driving initial and time-dependent lateral boundary conditions. This modeling technique allows for the regional climate effects of sub-GCM grid scale forcings, due to features such as mountain ranges, coastlines, and large lakes, to be represented in a physically-based way (Giorgi and Mearns, 1991; Giorgi et al., 1993a, b; Giorgi et al., 1994). The main motivation for the development of RegCM2 stems from the observation that the representation of sub-GCM grid scale forcings is critical to accurately simulate the regional distribution of climatic variables, such as precipitation and surface air temperature over various regions of the United States. The RegCM2 code has been used for a series of applications including experiments ranging from a few days in length (Dickinson et al., 1989) to multi-year simulations over the U.S. and Europe (Giorgi et al., 1993a, 1993b; 1994).

Section 3 SOFTWARE QUALIFICATION PROCESS

The YMP software qualification process involves placing the acquired software under configuration management controls, conducting validation tests to establish that the codes perform as expected, and generating documentation to support the intended use of the codes. Although the climate modeling codes being developed at NCAR are continually evolving and improving, for the purposes of this study, recent versions of the two codes, GENESIS and RegCM2, were placed under configuration control and, except for a few minor corrections, used without modification for the work described here. This section concludes with a description of the model validation activity performed to determine the extent to which the numerical modeling results reflect realistic behavior.

3.1 GLOBAL CLIMATE MODEL CODE VALIDATION

A validation analysis was performed for the stand-alone GENESIS GCM code to determine how well the global model simulated the present climate, given present global boundary conditions. For the present climate, validation is typically done by evaluating global indices of agreement between observed and predicted climates. This evaluation, for example, includes comparisons of monthly mean values of standard climate fields between observational data compilations and model results. Typical of the parameters evaluated in this manner are surface air temperatures and humidities, precipitation and cloud amounts, wind direction and velocity at various heights, surface snow amounts, and possibly, soil moisture and runoff. Comparisons can also be made of near surface diurnal cycles and variability. These evaluations include both objective methods, such as comparison of root mean square differences between parameter values, and more subjective methods such as an evaluation of distribution maps.

A report of the validation analysis for the stand-alone GENESIS code was submitted as "Validation Report for GENESIS Global Climate Model," (Pollard et al., 1995). Code validation, the process of establishing that the configuration-managed version of the code performs as expected, was performed by conducting a control run of the code under present-day climatic conditions. The control case was run for a simulated 24 hour period, which was considered adequate for determining code performance. Following the simulation, mean temperature, total cloud cover fraction, and precipitation rate were evaluated and root mean square differences (RMS) over the applicable domains compared between the control run and output from a control run supplied with the acquired software. Results from the

numerical comparison yielded RMS differences of 0.080°C, 0.021, and 0.729 mm/day, respectively, for the three parameters, which satisfied the validation criteria established in the Life Cycle Plan for the code.

3.2 REGIONAL CLIMATE MODEL CODE VALIDATION

A similar process was followed in validating the regional climate model code for this work, and is described in an earlier report (D'Ambra et al., 1994). Initial and boundary conditions for the RegCM2 code were determined for present-day observed meteorology (wind components, temperature, and water vapor as a function of altitude and surface pressure) from gridded weather analyses available from the European Center for Medium Range Weather Forecasting (ECMWF) (Trenberth and Olson, 1988). A reasonably long term simulation was then performed using this input to validate the RegCM2 code. The basic assumption is that, because the driving meteorological fields are taken from observed datasets and are thus realistic, model errors are mainly due to deficiencies in the internal model physics. The quality of the validation, conducted in much the same manner as that described for the GCM validation, is evaluated using standard statistical techniques and other more objective techniques developed for this purpose.

Again, a 24-hour simulation was performed and the RMS differences in temperature over the entire domain and in precipitation at surface grid points at 12 and 24 hours were evaluated. The domain used in the control run consisted of 78x121 (latitude by longitude) grid points and 17 vertical levels. Spacing between surface grid points was 50 kilometers. The 24-hour simulation was initialized using ECMWF data for April 1, 1981, at 0 GMT (Greenwich Mean Time). All of the major physics packages incorporated into the model, including the boundary layer scheme, the precipitation parameterizations, the radiation package, the land surface package, and the lake model package, were exercised during the validation run. After correcting a few initial problems that developed on installing the code on a previously unused hardware platform, results indicated RMS temperature differences of less than 0.04°C at 12 and 24 hours, but unacceptably large precipitation differences (8% at 12 hours and 4% at 24 hours). Upon examining the situation and correcting a subroutine used for data input, acceptable precipitation differences of 0.06% at 12 hours and 0.87% at 24 hours were obtained.

3.3 NESTED GENESIS-RegCM2 MODEL CODE VALIDATION

Finally, the performance of the nested codes was examined to establish how well GENESIS reproduces the boundary conditions used to drive the regional RegCM2 modeling code. If GENESIS performed well when evaluated against global indices of success, but did poorly in predicting the boundary conditions used to drive the RegCM2 model, the usefulness of the regional model results would be questionable. For this validation analysis, gridded weather analyses from the ECMWF were again used for the comparison (Trenberth and Olson, 1988). As noted above, this data set was also used to generate boundary conditions for the validation of the stand-alone version of the RegCM2. Demonstrating that the GCM adequately reproduces these conditions is an important step in the GCM validation process.

3.4 OTHER CONSIDERATIONS AND LIMITATIONS

There are additional concerns underlying any dependence upon climate model results. The equations used in climate modeling are nonlinear and coupled. Such equations frequently exhibit regions of multiple solutions and chaotic behavior over a portion of the range of the input parameters. If such were the case here, there would be no guarantee that the output from a specific modeling exercise would be generally meaningful, in that slightly different initial or boundary conditions might produce substantially different results. Due to limited resources and schedule for this work, this question was not specifically addressed, but the reasonableness of the output was examined for all climate states investigated.

The sheer complexity of climate systems and the numerical models that simulate them makes it difficult to analyze their tendency toward chaotic behavior. The two aspects of chaotic behavior of concern to the modeling program described here are sensitivity of solutions to initial conditions and long-term internally generated variability of solutions. The climatological solutions of atmospheric GCMs are not known to be sensitive to the initial state of the model except in certain extreme cases, e.g., an initially ice-covered world will remain so and not return to present conditions. Thus, sensitivity to initial conditions does not appear to present a potential problem for atmospheric GCMs. The same holds true for regional climate models because, in practice, they are simply limited domain versions of atmospheric GCMs. Some oceanic GCMs, however, do show the potential for two or more steady-state solutions for a common input forcing. This behavior arises from the dynamics of the model's thermohaline circulation and is not necessarily unrealistic. In fact, this behavior may be reflected in the actual observed climatic instability (Broecker and Denton, 1990). However, the models used in this study are not fully coupled;

rather, the effects on the atmosphere of the most common oceanic GCM anomalous behavior are simulated by prescribing altered sea surface temperatures.

Long-term internally generated variability of climate model solutions is a potential problem because it is impractical to run a nested system for hundreds of simulated years or even decades. By long term, here we mean variability on the interannual to interdecadal time scale. Regional models are not likely to produce long-term variability on their own, but are much more likely to merely respond to long-term variability in the GCM-derived boundary conditions that drive them. Long-term global climate variability that would be sensed by a regional model would likely come from interannual changes in sea surface temperatures (e.g., El Nino events), slowly evolving sea ice or snow cover changes, or perhaps changes in terrestrial soil moisture. The latter two effects are already included in GENESIS and most other global climate models. Accurately modeling interannual and interdecadal variability of sea surface temperatures is an experimental area of research that would require at least an oceanic GCM.

In a nested model, climate simulation errors can originate either from the large-scale fields provided by the driving GCM (e.g., location and intensity of the jet stream and storm tracks) or from the internal physics of the regional model. The former source of error is handled by the element of GCM model validation that focuses on present climate reproduction of the regional climate model boundary conditions. A goal of the regional climate model validation is to identify, quantify, and, if possible, correct model biases and uncertainties due to physics formulations and model configuration (e.g., domain size and model resolution).

3.5 CLIMATE MODEL VALIDATION

Having demonstrated that the codes acquired for use by the YMP executed as expected, a more significant activity was the model validation effort, which is used to determine the extent to which model predictions reflect natural behavior and to develop confidence in the ability of the model to represent such behavior. The extent to which the models can be validated against observational data depends on the comprehensiveness and quality of the available data. These comparisons were performed for the purpose of demonstrating that model simulations predict conditions similar to that expressed by the natural climate system. One does not expect to establish in advance quantitative acceptance limits for determining a satisfactory level of agreement between model results and observational data; rather, the

validation results guide the determination of the extent to which reliable interpretations and conclusions can be drawn from simulation results.

Reports describing model validation results for the stand-alone RegCM2 code were submitted as "Report on RegCM2 Current Climate Model Validation Analysis, (Thompson et al., 1994) and "Revised RegCM2 Current Climate Model Validation Analysis," (Thompson et al., 1995a).

Validation of the combined GCM/RegCM system was performed to establish the ability of the combined codes to reproduce climate conditions over the region of interest for the two validation states of the present-day climate and the selected past climate state. These model validation analyses were reported in "Nested GENESIS-RegCM2 Current Climate Model Validation Analysis," (Thompson et al., 1995a), and "Nested GENESIS-RegCM2 Paleoclimate Model Validation Analysis," (Thompson et al., 1995b). For validation, the GCM present-day climate simulation was first performed and evaluated against available observations. The GCM model output then was used to drive the nested RegCM2 and the resulting high-resolution climatology compared with available high resolution regional observational datasets, e.g., ECMWF data sets (Trenberth and Olson, 1988). This comparison, along with the previous separate RegCM2 and GCM validation tests, gives quantitative information both on the ability of the coupled model system to simulate the climate of the region and on the relative contribution of the driving GCM and the nested RegCM2 model components to total model system biases.

After validating model performance for present-day climate conditions over the region of interest, a second validation simulation was done to test the coupled model system's ability to reproduce climate conditions different from the present. This validation simulation was done by comparing modeled paleoclimate conditions with periods for which high quality data are available on both model boundary conditions (SSTs, ice sheet, sea ice, and vegetation cover) and the southwestern regional climate. The climate state selected for this simulation was the last glacial maximum 18,000 BP (Before Present) to 21,000 BP (Benson et al., 1990; CLIMAP, 1981). The procedure for the paleoclimate validation analysis was similar to that described for the present climate. A GCM paleoclimate simulation was first performed, and the meteorological output from this simulation used to drive the nested regional model over the region of interest. The resulting model climatology was then compared with available paleoclimate evidence. The principal difference is that the uncertainties are much larger for the paleoclimate validation than for the present climate validation.

Section 4 CLIMATE STATE SELECTION AND DESCRIPTION

The present climate and full glacial validation runs are useful not only for validation purposes, but also as potential future climate simulations. The original plan (Schelling and Zak, 1994) anticipated simulating the following seven climate states:

- a. Present Climate
- b. Intermediate Glacial.
- c. Full Glacial
- d. Super-Glacial
- e. Super-Interglacial
- f. Reduced North Atlantic Deep Water
- g. Extreme Greenhouse/Constrained Storm Track

Climate states b through e were selected to evaluate the effects on the regional climate of southern Nevada under different polar ice sheet conditions, including: the most recent glacial maximum (case c) which existed between 10,000 and 40,000 years ago and reached a maximum glacial extent about 21,000 years ago; an intermediate climate state (case b) between the glacial maximum and the present-interglacial climate state; a more extreme super-glacial climate state (case d) than the last glacial maximum, such as that which occurred 150,000 years ago; and a climate state (case e) in which ice sheet coverage is significantly less than under today's climate. Two additional states (cases f and g) were defined, which were considered potential extreme states likely to produce increased precipitation in the southern Nevada region. In one of these (case f), sea-surface temperatures (SSTs) would be constrained in response to global warming, i.e., cold SSTs in the North Atlantic and warmer SSTs elsewhere; in the other (case g), boundary conditions would be artificially defined to maximize sea-surface temperatures and to constrain atmospheric circulation to deliver frequent low-pressure storm systems to the southwestern United States.

Because of schedule and resource constraints, it was possible only to simulate a total of four climate states, including:

- a. Present Climate
- b. Full-Glacial
- c. Initial Greenhouse (2 x CO₂)

d. Extreme Greenhouse (6 x CO₂)

The first two of these were included in the original plan; the final two were included to investigate the effects of global warming induced by an increase in atmospheric carbon dioxide. Investigation of the range of glacial states (cases b, d, and e in the original plan list) was not performed.

Reports for each of these analyses were prepared and submitted as: a) "Nested GENESIS-RegCM2 Current Climate Model Validation Analysis," (Thompson et al., 1995a); b) "Nested GENESIS-RegCM2 Paleoclimate Model Validation Analysis," (Thompson et al., 1995b); c) "NCAR Climate Modeling System Future Climate Analysis: 2 x Carbon Dioxide Greenhouse Forcing," (Thompson et al., 1996); and d) "NCAR Climate Modeling System Future Climate Analysis: 6 x Carbon Dioxide Greenhouse Forcing (Milestone SP2610M4)," (Thompson et al., 1997).

These future climate simulations were performed in a manner similar to that used in the validation tests. The GCM climate simulations for the identified potential future global climate states were performed first, using the selected global initial and boundary conditions. The meteorological outputs from these simulations then were used to drive the nested RegCM for each case over the region of interest. The difference is that, for potential future climates, there are no available climatological data against which to compare the results. However, one can compare the results against paleoclimate data for roughly similar global climate states to ascertain whether the results are reasonable.

Section 5 SOURCES OF MODEL INPUT

The simulation of a climate state with GENESIS is dependent upon the specification of initial and boundary conditions for the selected state. Four key datasets must be specified to provide global climate boundary conditions for simulating past, present, and potential future climates corresponding to the selected global climate states. They are: (1) seasonal insolation at the top of the atmosphere; (2) atmospheric greenhouse gas composition and concentration; (3) ice volume and placement; and (4) sea surface temperature distribution.

The latitudinal and seasonal distribution of energy from the sun over the surface of the earth drives atmospheric circulation. Past changes in the insolation field due to gravitational perturbation of the earth's orbital parameters by the other planets has significantly modulated climates during the last 2 million years (Hays et al., 1976). The past and future insolation regimes can be calculated with a high degree of confidence for the next 200,000 yr. The insolation model is available as an acquired code (Berger, 1978).

The burning of fossil fuels and the release of radiatively important trace species are expected to result in a significant increase in the greenhouse effect by the middle of the next century (National Research Council, 1982; Dickinson and Cicerone, 1986; IPCC, 1990 and 1992). The resulting temperature and regional climate changes are anticipated to be significant (e.g., Manabe and Wetherald, 1986; Schlesinger and Mitchell, 1987; Ramanathan 1988; Crowley, 1989 and 1990) and may result in a climate realization unique in the earth's history. Because the half-life for removal of the CO₂ from the atmosphere is a few thousand years (Sundquist, 1985), an enhanced greenhouse effect will likely influence future climate at least over the next few thousand years. However, because of other human global impacts, eventual removal of the CO₂ from fossil fuel combustion may not return the climate system to its condition before the age of fossil energy.

There have been continuous variations in the CO₂ content of the atmosphere throughout the history of the earth, but the anticipated levels of CO₂ for the near future have not been equaled in tens of millions of years and certainly never during the Pleistocene (Crowley and North, 1991). Although the mechanisms responsible for such fluctuations are not well understood, the record of atmospheric CO₂ fluctuations is available from ice cores (Barnola et al., 1987; Neftel et al., 1988) and can be explicitly

specified for simulations of climate at least since the last interglacial. For simulations of climates of the more distant past for which direct CO₂ measurements do not exist, reasonable estimates can be made based on the similarity of CO₂ and ice volume fluctuations over the last 130,000 years (Crowley and North, 1991).

The amount and spatial distribution of ice strongly affects the atmospheric circulation and is a necessary boundary condition for past and potential future climate simulations. These distributions are reasonably well known for the last 18,000 years and are available as an acquired dataset from the NOAA National Geophysical Data Center (CLIMAP, 1981; Kutzbach and Guetter, 1986; Peltier, 1993). For simulations of global climate states prior to the last glacial maximum, the global ice volume is reasonably well known (Imbrie et al., 1984), but the spatial distribution of the ice less so. Nevertheless, reasonable estimates for ice volume and the area covered can be developed, as they can for potential future climate state simulations.

Sea surface temperature distributions play a key role in forcing the atmospheric circulation and in determining total global precipitation. Reasonable estimates of these distributions are available for the period since the last glacial maximum (CLIMAP, 1981; COHMAP, 1988). A more limited set of temperature estimates is available for more distant times (Imbrie et al., 1989). Conjectures supported by some modeling results suggest that substantial oceanic circulation changes may accompany global climate changes. In principle, one could use fully interactive coupled ocean-atmosphere GCMs (in which the ocean is represented in as much detail as the atmosphere and in which coupling is bi-directional) to ascertain these circulation changes and their effect on sea surface temperature distributions, but, in practice, these coupled models are in such an early stage of development that the results cannot presently be accepted with confidence. Fortunately, it is possible to include the effects of plausible ocean circulation changes in the numerical models by altering the distributions used as boundary conditions for each selected global state.

Shown below are the sources of information used as input to the modeling codes and those observational data sets used for comparison with model output.

Current Climate Model Validation Simulation Input Data Sets

The GENISES model used the U.S. Navy Fleet Numerical Oceanographic Center global 10-minute elevation data set (Cuming and Hawkins, 1981; Kineman, 1985) for the Atmospheric General Circulation Model (AGCM) topography, AGCM gravity wave drag surface roughness, and for the surface grid topography. The zonally symmetric data set of Bath et al. (1987), which varies with latitude, pressure level, and month, was used for setting AGCM ozone amounts. Soil textures in each soil layer were taken from the global soil data set of Webb et al. (1993). Monthly sea surface temperature and sea-ice field prescriptions were taken from the global 2x2 degree data set of Shea et al. (1990), which is based primarily on ship data collected between 1950 and 1979.

The regional climate model, RegCM2, uses the half degree NCAR/PSU Landuse-Terrain data set (Guo and Chen, 1993) for topography, but uses the EROS Data Center half degree landuse data set (EROS, 1993) for landuse, because it provides more detailed land type information.

For performing the model validation comparisons of model output with observation, several sources of observational information were used. For surface air temperature, the data of Crutcher and Meserve (1970) and Taljaard et al. (1969) were used for oceans and Antarctica; and that of Leemans and Cramer (1990) for other land masses. Sea level pressures and precipitation observations from Shea (1986) were used for comparisons made for these parameters. Regional climatology and 500-mb heights used the information available from the ECMWF (Trenberth, 1992), and regional precipitation was taken from Legates and Willmott (1990).

Input used in setting up the paleoclimate simulation used the 1x1 degree ICE-4G reconstruction of Peltier (1994) for topography and ice sheet distribution, and the 2x2 degree CLIMAP reconstruction for 21 Ka BP (CLIMAP, 1976) adjusted for seasonal sea surface temperature variability for the land-ocean map. Orbital parameters were calculated for 21 Ka BP. And finally, for the atmospheric gas concentrations, based on measurements of gases in Antarctic ice cores (Lorius et al., 1990), the values for ozone and N₂O set to present-day levels; chlorofluorocarbons set to zero; CO₂ reduced to 235 ppm, methane reduced from 1.653 to 0.7 ppm.

For the simulations with enhanced carbon dioxide concentrations (the "greenhouse" climate states), the only change to the input used for the current climate simulation was to vary the CO₂ concentration, for

which values of 700 ppm (volumetric) and 2100 ppm were used for the “initial” (2 x CO₂) and “extreme” (6 x CO₂) simulations, respectively. For the current climate simulation, a value of 350 ppm was used.

Section 6 MODEL OUTPUT AND CONCLUSIONS

6.1 CURRENT CLIMATE SIMULATION

For the model simulation of the present-day climate, the global model resolution was a horizontal computational grid of approximately 3.75 x 3.75 degrees with 18 vertical levels. The surface model was run on a 2 x 2 degree grid. The regional model domain size and perimeter locations were chosen to be centered over the western United States area of interest. Boundary locations were designed to maximize the distance between the perimeter and the interior regions of interest, which was intended to provide sufficient distance for mesoscale circulations to develop from synoptic scale disturbances that propagate into the regional grid. A horizontal resolution of 50 km was chosen as the highest resolution that is computationally economical and practical for the climate analysis; a typical vertical resolution for current climate model analysis was used. Two independent 14-month periods were simulated with the regional model, using output from the GENESIS model to update boundary condition data for the regional model. The first two months of each simulation were discarded as model "spin up," and the remaining 12 month periods were combined to form a 2-year model climatology. These results were presented in a report "Nested GENESIS-RegCM2 Current Climate Model Validation Analysis," (Thompson, et al., 1995), which includes a number of figures showing more details of the results than are presented here.

GENESIS Results:

The validity of the global climate model to adequately simulate climatic conditions was established by comparing model output against observational data for four key parameters: surface air temperature, precipitation, 500 mb height, and sea level pressure. The following observations and conclusions were drawn from this analysis.

Surface Air Temperature: The basic seasonal pattern of air temperature changes was reasonably well simulated by GENESIS. It was observed, however, that the model had a tendency to be too cold over much of the United States with errors of 4-6° C over large areas, except in July when a positive error region of 4-6° C was observed over central North America. No obvious consistent temperature bias was evident over the U.S. Southwest.

Precipitation: The global model captured the large seasonal change in broad precipitation, clearly showing the winter-dominated precipitation regime of the U.S. west coast. However, the model tends to bring the winter west coast rainfall too far inland as a consequence of inadequate topographic resolution.

500 mb Height: GENESIS displays a consistent “cold” bias in that the 500 mb heights are too low by 5-10 meters or more over most of North America in all months. The essential stationary wave patterns are reasonably well simulated, however. GENESIS tends to de-emphasize the ridge along the west coast, but overemphasizes the trough over Hudson Bay.

Sea Level Pressure: Sea level pressure is a derived field that attempts to compensate for surface pressure variations due to topography. It is important since it correlates with meteorological conditions near the surface, and in particular, gives information about near-surface wind speed and direction. GENESIS captures the annual variation and spatial patterns in sea level pressure quite well, matching observations typically within 4 mb and with maximum errors in the range of 8-10 mb. The model does tend to somewhat over-predict the “thermal low” over the western U.S. in mid-summer.

Nested GENESIS/RegCM2 Results

The validity of the nested climate model was also established by evaluating the behavior of these same four parameters. In this analysis, comparisons were made against both observational data and the output of the stand-alone regional code driven by observational data.

Surface Air Temperature: In general, the nested model shows a pronounced cold bias over land in all seasons except summer. Driving the regional model with the global model tended to amplify the tendency of the regional model to produce colder than observed winter temperatures. The temperature errors in all seasons appear to be due to using the global climate model data as input, rather than being intrinsic errors of the regional model. The nested model yielded temperatures about 7°C too cold over southern Nevada in winter, but gave values close to observed in the summer.

Precipitation: Precipitation is important from a hydrologic perspective, and is subject to high interannual variability, both in the model and in the observational data, particularly in arid regions. This variability may explain differences between the model results and observed climatology. Such differences arising from statistical sampling errors can be amplified by the short time periods used in this analysis (two years for the nested simulation). The model results indicated for precipitation, as it did for temperature, that driving the regional model with the global model tends to exacerbate inherent problems in the regional model. Excessive precipitation extends into the continental interior over the Pacific Northwest in all but the summer season. There is little precipitation bias over Nevada in the summer season.

500 mb Height: Results for this parameter also showed an increased bias for the nested model over the regional model alone. 500 mb heights are consistently too low, particularly in winter; with negative errors averaging about 80 meters in winter and about 20 meters in summer. The general pattern and seasonal changes of the implied 500 mb winds, however, agree reasonably well with observations.

Sea Level Pressure: Unlike the other three parameters, the sea level pressure predictions matched observations fairly well. The model correctly simulates the seasonal transition over the western U.S. from a dominant winter high pressure regime to the “thermal” low over the southwest in the summer. The winter and summer magnitudes also compared favorably. The high in winter is somewhat too far south and the summer low is centered too far east.

6.2 PALEOCLIMATE SIMULATION

A simulation of the climate of 21 Ka BP, or 18 Ka BP radiocarbon age scale, was performed as a test of the model’s ability to deal with large surface condition changes, primarily sea surface temperatures and ice sheet configuration, and to develop confidence in the model’s ability to represent climate states different from the present. This simulation had two main objectives: (1) to show that RegCM2 remains numerically stable when forced with large, but realistic, changes in surface and perimeter boundary forcings; and (2) to compare the simulated climate with observation based interpretations of the paleoclimate to the extent that the short duration of the simulation allows.

RegCM2 was run for a North American domain over a period of four simulated months with surface and domain perimeter boundary forcing conditions appropriate for a time 21Ka BP. This is approximately the time of the last glacial maximum, or the maximum extent of ice during the most recent Ice Age. Model output was time-averaged over the months of September through November for comparison with the current climate model simulation.

The simulation results were provided earlier in the report, "Nested GENESIS-RegCM2 Paleoclimate Model Validation Analysis," (Thompson, et al., 1995), which contains a number of figures providing more detailed results.

GENESIS Results:

Surface Air Temperatures: The presence of the large ice sheet and lower sea surface temperatures force a strong cooling over most of North America in all seasons. The cooling exceeds 20°C over eastern Canada where the ice sheet reaches its greatest height. Over the U.S. southwest, the cooling ranges from 2-10°C in winter and summer.

Precipitation: Precipitation changes in the global simulation are somewhat more variable in space and time. The results indicated that precipitation decreases occur over much of the western U.S. in January with, however, a slight increase shown over the southwest. In summer, precipitation is shown to increase over all of the western U.S.

200 mb Heights: This field was selected for examining the average position of the jet stream. Of particular interest are the observations for January, which shows a stronger ridge over the Pacific northwest and a stronger trough over eastern Canada and extending down to the south-central U.S. in the paleoclimate simulation. This pattern is typical of other global climate models that have been run with ice age boundary conditions, indicating the formation of an enhanced "split jet" where the North American ice sheet acts to strengthen the subtropical jet while forcing the polar jet northward over Alaska and down over eastern Canada. The evidence for such a split jet was somewhat weaker in the nested simulation than in other reported simulations, due to the lower topography of the more recent Peltier ice sheet reconstructions used in the nested simulation.

Nested GENESIS/RegCM2 Results:

Surface air temperatures: In the nested model simulation, temperatures were found to be lower over virtually the entire domain in both winter and summer seasons. In the Nevada region, temperatures were observed to be 1-3 °C colder in winter and 2-6 °C colder in summer.

Precipitation: Winter precipitation over the Nevada/Utah region showed a decrease in the northern part of the region (presumably associated with the extreme cold), but an increase in the southern part of the region. The results for summer did not show any clear pattern of change. The results for spring, however, showed a tendency for increased precipitation under the conditions of this climate state. Also examined in this simulation was a measure of “effective” moisture, the net difference between precipitation and evapotranspiration. Again, the results for winter showed increased dryness in northern Nevada, but increased wetness to the south. The summer, however, appeared consistently dryer over most of Nevada. Consistent increases in soil moisture over the U.S. southwest was also observed in both winter and summer seasons, with an annual mean increase of about 20 mm in the Yucca Mountain area.

In comparison with available paleoclimate evidence, qualitative agreement was determined with respect to the consensus that the U.S. southwest was wetter 21 Ka BP than at present, and for areas of maximum temperature decrease in the northwestern and north-central states. However, the nested model did not appear to produce substantially milder changes in the deep southwest in comparison to the Great Basin. Paleoclimatic interpretations imply that the Great Basin was about 6 °C colder at that time, while the simulation showed a range of 2-10 °C colder, with somewhat larger cooling in summer than in winter.

6.3 INITIAL GREENHOUSE CLIMATE SIMULATION

A simulation of four years of the climatology for a climate state with a doubled carbon dioxide concentration was performed with the nested GENESIS/RegCM2 model to represent a potential future climate state in which greenhouse gas concentrations increase from anthropogenic forcing. The general conclusions drawn from this analysis were that the climate around the Yucca Mountain site under these conditions was found to warm by 2-3 °C year round, with increased precipitation in winter and reduced

precipitation in summer. This simulation was reported in "NCAR Climate Modeling System Future Climate Analysis: 2x Carbon Dioxide Greenhouse Forcing," (Thompson et al., 1996), which includes a number of figures showing more details of the results than are presented here.

Surface air temperatures: Results indicated a rather uniform temperature increase over the western U.S. in all seasons; for the Yucca Mountain area, the increase was 2-3 °C.

Precipitation: Precipitation was observed to increase dramatically in the winter season over all of California and extended inland to southern Nevada. In the summer season, however, precipitation tended to decrease over Southern Nevada. As was true in the other simulations performed for this study, substantial interannual variability in precipitation was observed over the four-year simulation period; the probability of error in the four-year time averaged results resulting from statistical sampling error should be kept in mind when drawing conclusions from these simulations.

6.4 EXTREME GREENHOUSE CLIMATE SIMULATION

A four-year simulation in which the CO₂ concentration is increased six-fold over the present-day concentration was performed as representative of an extreme potential future state having increased greenhouse gas concentrations due to anthropogenic forcing. In comparison to the earlier doubled CO₂ simulation, the more extreme conditions produced a much drier Yucca Mountain climate (in terms of soil moisture, runoff, and infiltration), less winter precipitation, and much higher temperatures, which indicates that a trend toward a wetter climate seen in comparing the present-day climate to the doubled CO₂ climate did not continue when extended to the six-fold CO₂ climate. These results were reported earlier in "NCAR Climate Modeling System Future Climate Analysis: 6 x Carbon Dioxide Greenhouse Forcing (Milestone SP2610M4)," (Thompson, et al., 1997), which includes a number of figures showing more details of the results than are presented here.

Surface air temperatures: In comparing the results of the simulation of the extreme greenhouse climate against the present-day climate, much warmer conditions are found throughout the western U.S. in all seasons. In southern Nevada, temperatures were higher by roughly 8° C in all seasons.

Precipitation: Not unexpectedly, precipitation showed considerably interannual variability, in winter in the vicinity of Yucca Mountain, varying between 1 and 4 mm/day over the four years of the simulation. As found in the earlier initial greenhouse climate simulation, winter precipitation in southern Nevada was found to increase, while summer precipitation decreased. The wintertime region of high precipitation also shifted far to the north, thus limiting the amount of precipitation in southern Nevada; indeed, the shift is so pronounced that most of the southwest receives less precipitation in the 6 x CO₂ case than was observed for the 2 x CO₂ case. This observation shows that the general pattern of increased precipitation found in the 2 x CO₂ case is not only a non-linear function of the CO₂ concentration, but non-monotonic as well, i.e., these simulations do not indicate that increased greenhouse gas concentrations would produce continued increases in rainfall in southern Nevada. However, it is noted that the simulations do not properly account for possible increases in the frequency of El Nino events, which could override these conclusions.

Section 7 SUMMARY

This report summarizes the numerical climate modeling activity performed over the last three years for the YMP. A significant portion of this effort was related to validating performance of the modeling codes used in this work in satisfying quality assurance requirements applicable to software and model development. A total of four climate states were simulated during the course of this study, including the present-day climate, a climate state representative of the full glacial conditions in existence about 21,000 years ago, and two "greenhouse" climate states, one representative of climatic conditions under an atmosphere containing a doubled carbon dioxide concentration, and an extreme state representative of conditions under an atmosphere having a six-fold increase in carbon dioxide concentration.

The results of this limited modeling effort demonstrated that the models do a credible job of representing regional climate under varying climatic conditions and yielded results for potential future conditions that appear reasonable and not unduly surprising. Results from the four climate states that were modeled as part of this effort do not permit future climatic trends to be identified and quantified. Perhaps the most useful observation that can be abstracted from these results for use in assessing the future performance of the potential repository at Yucca Mountain is that conditions observed for climate states other than the present are similar to the range of conditions reflected in the paleoclimate record, although temperature changes observed for the extreme greenhouse state may somewhat exceed those in the paleoclimate record. The paleoclimate synthesis report prepared by Forester et al. (1996) summarizes the work done for the YMP to reconstruct the paleoclimatic record for the Yucca Mountain region. Using this paleoclimate synthesis coupled with inferences from the climate modeling summarized herein, it may be possible to extrapolate present-day climatic conditions into the future for representing potential repository system performance under future climate conditions based on the record of past climate change.

Section 8 REFERENCES

- Anthes, R.A., "A cumulus parameterization scheme utilizing a one-dimensional cloud model," *Mon. Weather Rev.*, v. 105, pp. 270-286, (1977).
- Anthes, R. A., E. Y. Hsie and Y. H. Kuo, 1987. "Description of the Penn State/NCAR Mesoscale Model Version 4 (MM4)," NCAR Technical Note NCAR/TN-282 + STR, National Center for Atmospheric Research, Boulder, CO, 66 pp, (1987).
- Bath, L.M., M.A. Dias, D.L. Williamson, G.S. Williamson and R.J. Wolske, "User's Guide to NCAR CCM1," NCAR Technical Note NCAR/TN-286+IA, Boulder, CO, 173pp., (1987).
- Berger, A., "Long-Term Variations of Daily Insolation and Quaternary Climate Changes," *Journal of the Atmospheric Sciences*, v.35, pp.2362-2367, (1987).
- Benson, L. V., D. R. Currey, R. I. Dorn, K. R. Lajoie, C. G. Oviatt, S. W. Robinson, G. I. Smith, and S. Stine, "Chronology of Expansion and Contraction of Four Great Basin Lake Systems During the Past 35,000 Years," *Paleogeology, Paleoclimate, and Paleoecology*, 78:241-286. (1990).
- Boer, G. J., K. Arpe, M. Blackburn, M. Deque, W. L. Gates, T. L. Hart, H. le Treut, E. Roeckner, D. A. Schein, I. Simmonds, R. N. B. Smith, T. Tokioka, R. T. Wetherald, and D. Williamson, "Some Results From an Intercomparison of the Climates Simulated by 14 Atmospheric General Circulation Models," *Journal of Geophysical Research*, 97:12,771-12,786, (1992).
- Broecker, W. S., and G. H. Denton, "What Drives Glacial Cycles?," *Scientific American*, January, pp. 49-56, (1990).
- Climate: Long-range Investigation Mapping and Prediction (CLIMAP) Project Members, "The surface of the ice-age earth," *Science*, v.191, pp.1131-1137, (1976).
- Climate: Long-range Investigation Mapping and Prediction (CLIMAP) Project Members, "Seasonal Reconstruction Of The Earth's Surface At The Last Glacial Maximum," *Geological Society of America Map and Chart Series MC-36*, Boulder, CO, (1981).
- Cooperative Holocene Mapping Project (COHMAP) Members, "Climatic Changes of the Last 18,000 Years: Observations and Model Simulations," *Science*, 241:1043-1052, (1988).
- Crowley, T. J., "Paleoclimate Perspectives On A Greenhouse Warming," in *Climate and Geo-Sciences*, editors A. Berger, S. H. Schneider, and J. C. Duplessy, Dordrecht, the Netherlands:Kluwer, pp. 179-207, (1989).
- Crowley, T. J., "Are There Any Satisfactory Geological Analogs For A Future Greenhouse Warming?" *Journal of Climate* 3:1282-1292, (1990).
- Crowley, T. J. and G. R. North, *Paleoclimatology*, Oxford University Press. New York, NY, (1991).
- Crutcher, H.L., and J.M. Meserve, "Selected Level Heights, Temperatures, and Dew Points for the Northern Hemisphere," NAVAIR Publ. 50-1C-52, Washington, DC, (1970).

- Cuming and Hawkins, "TERDAT: The FNOC System for Terrain Data Extraction and Processing," Technical Report M11 Project M254 (2nd ed). Prepared for Fleet Numerical Oceanography Center, Monterey, CA. Published by Meteorology International Incorporated (1981).
- D'Ambra, C.A., C.S. Brodeur, and S.L. Thompson, "REGCM2 Validation Report," (SNL YMP WA-106 File) (1994).
- Dickinson, R. E., and R. J. Cicerone, "Future Global Warming From Atmospheric Trace Gases," *Nature* 319:109-115, (1986).
- Dickinson, R.E., R.M. Errico, F. Giorgi, and G.T. Bates, "A regional climate model for the western U.S.," *Climatic Change*, v.15, pp.383-422, (1989).
- EROS Data Center, Sious Falls-ESIC, "Conterminus United States Land Cover Characteristics Data on CD-ROM," U. S. Department of the Interior, U.S. Geological Survey, (1993).
- Forester, R., et al., "Synthesis of Quaternary Response of the Yucca Mountain Unsaturated and Saturated Zone to Climate Change," Yucca Mountain Project Milestone Report 3GCA102M, (1996). [RMS#: MOL.19970211.0026]
- Guo, Y. and S. Chen, "Terrain and Land Use for the Fifth-Generation Penn State/NCAR Mesoscale Modeling System (MM5): Program Terrain," NCAR Technical Note NCAR/TN-397+IA, Boulder, CO, (1993).
- Gates, W. L., "AMIP: The Atmospheric Model Intercomparison Project," *Bulletin of the American Meteorological Society*, 73:1962-1970, (1992).
- Giorgi, F. and L.O. Mearns, "Approaches to the simulation of regional climate change: A review," *Rev. Geophys.*, v.29, pp.191-216, (1991).
- Giorgi, F., M.R. Marinucci, and G.T. Bates, "Development of a second generation regional climate model (RegCM2). Part I: Boundary layer and radiative transfer processes," *Mon. Weather Rev.*, v.121, pp.2794-2813, (1993a).
- Giorgi, F., M.R. Marinucci, G.T. Bates and G. DeCanio, "Development of the second generation regional climate model (RegCM2). Part II: Convective processes and assimilation of lateral boundary conditions," *Mon. Weather Rev.*, v.121, pp.2814-2832, (1993b).
- Giorgi, F. C.S. Brodeur, and G.T. Bates, "Regional climate change scenarios over the United States produced with a nested regional climate model," *J. Climate*, v.7, pp.375-399, (1994).
- Hays, J. D., J. Imbrie, and N. J. Shackleton, "Variations In The Earth's Orbit: Pacemaker Of The Ice Ages," *Science*, 194:1121-1132, (1976).
- Imbrie, J., A. McIntyre, and A. Mix, "Oceanic Response To Orbital Forcing In The Late Quaternary: Observational and Experimental Strategies," in *Climate and Geo-Sciences*, editors A. Berger, S. H. Schneider, and J. C. Duplessy, Dordrecht, the Netherlands:Kluwer, pp. 121-164, (1989).

- Intergovernmental Panel on Climate Change (IPCC), *Climate Change: The IPCC Scientific Assessment*, J. T. Houghton, G. J. Jenkins, and J. J. Ephraums, editors, Cambridge, United Kingdom:Cambridge University Press, 358 pp, (1990).
- Intergovernmental Panel on Climate Change (IPCC), *Climate Change, 1992. The Supplementary Report to the IPCC Scientific Assessment*, J. T. Houghton, B. A. Cullandaer, and S. K. Varney, editors, Cambridge, United Kingdom:Cambridge University Press, (1992).
- Kineman, J. (ed.), "FNOC/NCAR Global Elevation, Terrain, and Surface Characteristics," Digital Dataset, 28 MB, NOAA National Geophysical Data Center, Boulder, CO, (1985).
- Kutzbach, J.E. and Guetter, P.J., "The influence of changing orbital parameters and surface boundary conditions on climate simulations for the past 18,000 years," *J. Atmos. Sci.*, v.43, p.1747, (1986).
- Leemans, R. and W.P. Cramer, "The IIASA database for mean monthly values of temperature, precipitation, and cloudiness of a global terrestrial grid," WP-41, International Institute of Applied System Analyses, Laxenburg Working Paper, IIASA, Laxwnburg, Austria, 60 pp., (1990).
- Legates, D.R., and C.J. Willmott, "Mean seasonal and spatial variability in gauge-corrected global precipitation," *Int. J. Climatol.*, v.10, pp.111-127, (1990)
- Lorius, C., J. Jouzel, D. Raynaud, J. Hansen and H. Le Treut, "The ice-core record: climate sensitivity and future greenhouse warming," *Nature*, v.347, pp.139-145, (1990).
- Manabe, S., and R. T. Wetherald, 1986. "Reduction In Summer Soil Wetness Induced By An Increase In Atmospheric Carbon Dioxide," *Science*, 232:626-628, (1986).
- National Research Council, 1982. "Carbon Dioxide and Climate: A Second Assessment," National Academy of Sciences, Washington, DC, 72 pp., (1982).
- Peltier, W. R., 1993. "Global Ice Cover and Topographic Heights at 1K Year Intervals for the Last 21 K Years," dataset archived at the National Atmospheric and Oceanic Administration (NOAA) National Geophysical Data Center, Boulder, CO, (1993).
- Peltier, W.R., "Ice age paleotopography," *Science*, v.265, pp.195-201, (1994).
- Pollard, D., and S. L. Thompson, 1993. "A Summary Description of the GENESIS Global Climate Model Version 1.02," NCAR Interdisciplinary Climate Systems Section Internal Documentation Report, National Center for Atmospheric Research, Boulder, CO, (1993).
- Pollard, D., C.A. D'Ambra, and S.L. Thompson, "Validation Report for GENESIS Global Climate Model," (SNL YMP WA-106 File) (1995).
- Rasch, P.J., and D.L. Williamson, "Computational aspects of moisture transport in global models of the atmosphere," *Quart. J. Roy. Meteor. Soc.*, v.104, pp. 677-690, (1990).
- Ramanathan, V., "The Greenhouse Theory Of Climate Change: A Test By An Inadvertent Global Experiment," *Science* 240:293-299, (1988).

- Schelling, F.J. and B.D. Zak, "Study Plan for Site Characterization Plan Study 8.3.1.5.1.6, 'Characterization of Future Regional Climate and Environments,'" (1994). [RMS#: NNA.19940609.0004]
- Schlesinger, M. E., and J. F. B. Mitchell, "Climate Model Simulations Of The Equilibrium Climatic Response To Increased Carbon Dioxide," *Reviews of Geophysics*, 25:760-798, (1987).
- Shea, D. J., "Climatological Atlas: 1950-1979. Surface-Air Temperature, Precipitation, Sea-Level Pressure, and Sea-Surface Temperature." NCAR Technical Note NCAR/TN-269+STR, 33pp plus 158 figs., (1986).
- Shea, D.J., K.E. Trenberth and R.W. Reynolds, "A Global Monthly Seas Surface Temperature Climatology," NCAR Technical Note NCAR/TN-345+STR, Boulder, CO, 167 pp., (1990).
- Sundqvist, H., "A parameterization scheme for non-convective condensation including prediction of water vapor content." *Quart. J. Roy. Meteorol. Soc.*, v.104, pp.677-690, (1978).
- Sundquist, E. T., "Geological Perspectives On Carbon Dioxide And The Carbon Cycle," in *The Carbon Cycle and Atmospheric CO₂: Natural Variations Archean to Present*, editors E. T. Sundquist and W. S. Broecker, American Geophysical Union, Washington, DC, pp. 5-60, (1985).
- Taljaard, JJ., Van Loon, H., H.L., and R.L. Jenne, "Climate of the Upper Air: Southern Hemisphere, Vol.1. Temperatures, Dew Points and Heights at Selected Pressure Levels," NAVAIR Publ. 50-1C-55, Washington, DC, (1969).
- Tiedtke, M., "Representation of clouds in large-scale models," *Mon. Weather Rev.*, v.121, pp.3040-3061, (1994).
- Thompson, S.L., V. Ramaswamy, and C. Covey, "Atmospheric effects of nuclear war aerosols in general circulation model simulations: influence of smoke optical properties," *J. Geophys. Res.*, v.92, 10942-10960, (1987).
- Thompson, S.L., C.A. Shields, and C.A. D'Ambra, "Report on RegCM2 Current Climate Model Validation Analysis," (1994). [RMS#: MOL.19950208.0053]
- Thompson, S.L., C.A. Shields, and C.A. D'Ambra., "Revised RegCM2 Current Climate Model Validation Analysis," (SNL YMP WA-106 File) (1995).
- Thompson, S.L., C.A. Shields, D. Pollard, and C.A. D'Ambra, "Nested GENESIS-RegCM2 Current Climate Model Validation Analysis," (SNL YMP WA-106 File) (1995a).
- Thompson, S.L., C.A. Shields, D. Pollard, and C.A. D'Ambra, "Nested GENESIS-RegCM2 Paleoclimate Model Validation Analysis," (SNL YMP WA-106 File) (1995b).
- Thompson, S.L., C.A. Shields, and D. Pollard, "NCAR Climate Modeling System Future Climate Analysis: 2 x Carbon Dioxide Greenhouse Forcing," (1996). [RMS#: MOL.19970206.0178]
- Thompson, S.L., C.A. Shields, and D. Pollard, 1997"NCAR Climate Modeling System Future Climate Analysis: 6 x Carbon Dioxide Greenhouse Forcing (Milestone SP2610M4)," (SNL YMP WA-106 File) (1997).

- Trenberth, K. E., and J. G. Olson, ECMWF Global Analyses 1979-1986: Circulation Statistics and Data Evaluation, NCAR Technical Note, NCAR/TN-300+STR, National Center for Atmospheric Research, Boulder, CO, 94 pp., (1988).
- Trenberth, K.E., "Global Analyses from ECMWF and Atlas of 1000 to 10 mb Circulation Statistics," NCAR Technical Note NCAR/TN-373+STR, Boulder, CO, (1992).
- Wallace, J.M., S. Tibaldi, and A.J. Simmons, "Reduction of systematic forecast errors in the ECMWF model through the introduction of envelope orography," *Quart. J. Roy. Meteor. Soc.*, v.109, pp683-717, (1983).
- Webb, R.S., C. E. Rosenzweig and E.R. Levine, "Specifying land surface characteristics in general circulation models: soil profile data set and derived water-holding capacities," *Glob. Biogeochem. Cycles*, v.7, pp. 97-108, (1993)
- Williamson, D.L., J.T. Kiehl, V. Ramanathan, R.E. Dickinson, and J.J. Hack. "Description of NCAR Community Climate Model (CCM1)." NCAR Technical Note NCAR/TN-285+STR, Boulder, CO, (1987).
- Williamson, D.L., and P.J. Rasch, "Two-dimensional semi-Lagrangian transport with shape-preserving interpolation," *Mon. Weather Rev.*, v. 117, pp. 102-129, (1989).
- Williamson, D.L., "Semi-Lagrangian moisture transport in the NMC spectral model." *Tellus*, v. 42A, pp. 413-428, (1990).