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REGIONAL FORECASTING WITH
GLOBAL ATMOSPHERIC MODELS

FINAL REPORT

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May 1994

Prepared by Applied Research Corporation
for Pacific Northwest Laboratory
under Contract DE-AC06-76RLO 1830
with the U.S. Department of Energy

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FOREWORD

This report was prepared by the Applied Research Corporation (ARC) at College Station, Texas under subcontract to Pacific Northwest Laboratory (PNL) as part of a global climate studies task. The task supports site characterization work required for a high-level nuclear waste repository and is part of the Performance Assessment Scientific Support (PASS) Program at PNL, which is under the direction of the Yucca Mtn. Project Office (YMPO), Las Vegas, Nevada. The work is under the overall direction of the Office of Civilian Radioactive Waste Management (OCRWM), U.S. Department of Energy Headquarters, Washington, D.C.

The scope of the report is to present the results of the fifth and sixth years' work on the atmospheric modeling part of the global climate studies task. The development of boundary conditions are discussed, as are model validation experiments and preliminary projections of future climate change, and finally development of a precipitation data base for the Yucca Mtn. vicinity. The introduction summarizes the main points of each of the substudies, with detailed information left for the appendices.

SUMMARY

This is the final report for Pacific Northwest Laboratory contract #017113-A-B1 and 188484-A-B1 to the Applied Research Corporation (ARC). The purpose of the project was to conduct model simulations for past and future climate change with respect to the proposed Yucca Mtn. repository. Not all the original proposed work on this contract has been completed because of project termination, budget cutbacks, and funding hiatuses. Nevertheless we can report on three main topics: (1) boundary conditions for paleo-hindcast studies. These conditions are necessary for conduction of three-four model simulations. The boundary condition have been prepared for future runs; (2) validation of climate models. This topic has two subcategories: (a) comparing the atmospheric general circulation model (GCM) with observations and other GCMs; and (b) development of a better precipitation data base for the Yucca Mtn. region for comparisons with models. These tasks have been completed; (3) preliminary assessments of future climate change. Energy balance model (EBM) simulations suggest that the greenhouse effect will likely dominate climate change at Yucca Mtn. for the next 10,000 years. The EBM study should improve rational choice of GCM CO₂ scenarios for future climate change.

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1.0 INTRODUCTION

Applied Research Corporation (ARC) is pleased to submit its final report covering years five and six on "Regional Forecasting With Global Climate Models," Pacific Northwest Laboratory (PNL) Contract Nos. 017113-A-B1 and 188484-A-B1. Reports for the two years are combined because of a hiatus and cutback in funding. Even though the entire global modeling project has not reached its scientific completion, this is nevertheless a final report because of funding decisions made by the U.S. Dept. of Energy Yucca Mtn. Project Office.

Our report covers seven main topics: (1) preparation of boundary conditions for the last glacial maximum; (2) description of the control run and sensitivity experiments of the atmospheric general circulation model (GCM) to be used in subsequent climate modeling work to be completed under another contract; (3) a description of precipitation characteristics in the Yucca Mtn. environs; (4) A description of additional ice sheet reconstructions to be used as boundary conditions for future climate modeling work; (5) model projections of temperature change over the next 10,000 years; (6) a description of Quality Assurance (QA) related activities; and (7) a brief discussion of factors responsible for delays in implementing the provisional climate modeling plan for Yucca Mtn. Our Summary will discuss these topics in the same order, and a full description of the first six subjects is given in the Appendices, also in the same order.

2.0 BOUNDARY CONDITIONS FOR THE LAST GLACIAL MAXIMUM

A new set of boundary conditions has been prepared for last glacial maximum conditions (21,000 BP, years before present). A full description of the revised boundary conditions is given in Appendix A. Briefly, we have incorporated a new ice sheet developed by the Univ. of Maine. This ice sheet has a smaller overall volume consistent with new estimates of global sea level changes. Secondly, we have developed a vegetation data base based on a well-dated pollen data set, to be used as input to the new GENESIS (see Appendix B) general circulation model (GCM). A soil color map has been modified to meet the requirements of the GCM. We have also modified the sea ice field around Antarctica and adjusted the sea-surface temperature (SST) fields to make them more consistent with comparisons against the control run. The boundary conditions are now ready for simulations for the last glacial maximum.

3.0 DESCRIPTION OF GENESIS CLIMATE MODEL EXPERIMENTS

In further preparation for analysis of climate model results, we compared a control run of the GENESIS model (version 1.02.A) against a selected set of observations and also other GCMs. These results are reported in full in Appendix B. The purpose of this study was to determine the level of fidelity in which GENESIS agrees with observations and also with other GCMs. The motivation for the latter part of the study is that it will not be possible to conduct simulations for Yucca Mtn. with all the climate models available. Yet it is critical to know just how the climate model being used compares with others. We accordingly compared GENESIS to those a major intercomparison conducted with nineteen other GCMs.

We found that overall the GENESIS control run agrees well with observations in terms of temperature fields. However, the precipitation in this version of GENESIS was greater than observed and also greater than most other GCMs. We conclude by noting that a relatively wet model is not necessarily a drawback to Yucca Mtn. studies, because one can assume that any precipitation changes reported with the model might be maximum changes for a model to produce. However, coding changes in the model result in less precipitation than those reported herein (S. Thompson and D. Pollard, personal communication, 1993). Thus the relevance of these results and implications to future Yucca Mtn. studies depends on choice of GENESIS version for future experiments.

4.0 PRECIPITATION VARIATIONS AT YUCCA MTN.

In order to better interpret model precipitation products from control and perturbation runs, we need a more accurate knowledge of precipitation variations in the vicinity of Yucca Mtn. We therefore undertook an analysis of precipitation variations in the three nearest stations surrounding the mountain, compared them to precipitation fluctuations elsewhere, and found that El Nino is primarily responsible for wet years in southwest Nevada. This information is contained in Appendix C.

The maximum precipitation increases during the 20th century around Yucca Mtn. are 100-200% above normal. These increases also apply to the Little Ice Age and last glacial maximum. These values may represent a threshold level for precipitation increases at Yucca Mtn.

Circulation patterns associated with El Ninos therefore represent the optimal pattern responsible for importing moisture to the Yucca Mtn. site. Any assessment of future climate changes at Yucca Mtn. due to, for example, greenhouse warming should consider potential changes due to higher-frequency ENSO-type fluctuations in addition to any changes in the basic state.

5.0 PRE-GLACIAL MAXIMUM ICE SHEETS

Part of the goal of the Yucca Mtn. climate plan is to test models in the hindcast mode to see how they respond to known changes in boundary conditions. These "hindcast" simulations can be tested against geologic data. Since the Wisconsin glacial maximum comprises less than 1% of Pleistocene time, it is necessary to consider other boundary conditions that may have affected Yucca Mtn. in the past. These boundary conditions could also affect Yucca Mtn. in the future (Imbrie and Imbrie, 1980; Newton et al., 1990).

We considered three scenarios -- a superglacial and two glaciations of an intermediate-size. The superglacial scenario was dictated in the original contract in order to test the system response to extreme changes in boundary conditions. There is also some support from the geologic record for a glaciation slightly larger than the Wisconsin glaciation (Crowley and North, 1991, pp. 115-116).

The intermediate-level glacial scenarios were chosen based on the hypothesis that circulation changes in the southwest U.S. are not linearly related to ice volume. As ice volume and area and orbital insolation change, so too will the steering of low pressure systems into the region. For example, there is geologic data indicating that the maximum of glaciation and wetness of the western U.S. occurred during the early phases of the last glacial cycle (Richmond, 1972; Phillips et al., 1990). We hypothesize that the combination of small ice sheets and modified orbital forcing could be responsible for such a pattern.

Accordingly, we interacted with the Univ. of Maine group previously on contract with PNL (Hughes and Fastook, 1990) to produce reconstructions for (1) an ice sheet that was areally more extensive than the last glacial maximum but exceeding it in volume

by only ~10%; and (2) two intermediate glacials that would produce sea level drops of 15 m and 50 m. The results are reported in Appendix D and have been configured for input into general circulation models.

One of the more interesting results of the ice sheet simulations is that for the small ice sheet (15 m sea level drop), glaciation is primarily in the Canadian Arctic and western Cordillera of Canada. These results may provide some explanation for the differences in extent of glaciation in this region between early glacial and late glacial. The large response in the western U.S. presumably reflects the fact that orbital configurations favorable to minimum summer insolation receipt triggers the largest glacial response in upland regions that already have cooler summers. The west-east asymmetry in ice extent, combined with altered insolation forcing, makes this simulation a prime target for future modeling studies.

6.0 MODELING THE EFFECT OF GREENHOUSE WARMING FOR THE NEXT 10,000 YEARS

Although greenhouse emissions are expected to peak within the next few centuries, geochemical models suggest atmospheric CO₂ levels may remain above present for more than 10,000 years (Sundquist, 1991). The long time scale reflects the long time constants for buffering of the anthropogenic peak by the ocean carbonate system. To address the potential longterm warming from the greenhouse signal, we conducted some simulations of global average temperature changes for the next 10,000 years. The results are discussed in Appendix E.

The most important conclusions from the study are that greenhouse warming will peak from about 2200-2400 AD, that temperatures could exceed levels of the ice-free Cretaceous (100 million years ago) by 50%, and that the greenhouse effect could dominate Milankovitch (orbital insolation) forcing for the next 10,000 years.

7.0 QUALITY ASSURANCE WORK

Since the last annual report, there have been eleven codes and eight application documentation packages processed under the ARC QA Program. Managed data bases comprise archives from external sources and archives of results generated for reportable results under this program. All data and all software under configuration control are archived on magnetic media transferable to PNL upon request.

The results of the acquired NCAR GENESIS Global Climate Model reported here and in Appendix B were generated by model software that has not been verified. The conditions leading to this event and further considerations are discussed in Appendix F. However, the model results reported here, along with the supporting procedural documentation, may be accepted as valid testing support for follow-on qualification of the model by others.

An overview of the implementation of this QA Program is presented in Appendix F.

8.0 DELAYS IN PROGRAM PROGRESS

Although this is a final report we have been unable to produce all the deliverables originally called for in the PNL-ARC contract. This development reflects two factors: (1) transfer of the contract, before completion, to another contractor; (2) extensive budget cuts and frequent funding hiatuses during the last three years of the ARC contract. As the project now stands the setup work has been done for the hindcast experiments originally proposed in the climate plan (Crowley et al., 1990, Appendix A). Substantial progress has been made on model validation, and the groundwork has been laid for rational choice of future CO₂ experiments. Future workers will hopefully be able to capitalize on these efforts to bring the project to a timely completion.

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APPENDIX A

BOUNDARY CONDITIONS FOR THE GENESIS
SIMULATION FOR THE LAST GLACIAL MAXIMUM

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APPENDIX A

BOUNDARY CONDITIONS FOR THE GENESIS

SIMULATION FOR THE LAST GLACIAL MAXIMUM

A.1 INTRODUCTION

In the last ten years a number of modeling groups have conducted general circulation model (GCM) simulations for the last glacial maximum, using boundary conditions developed by CLIMAP (e.g., Hansen et al., 1984; Kutzbach and Guetter, 1986; Lautenschlager and Herterich, 1990; Joussaume, 1993). However, since the CLIMAP reconstruction was completed in 1981, several important changes in the original boundary conditions have been identified. For example, Burckle and Cooke (1983) suggested that the sea ice margin in parts of the Southern Ocean was as much as 5° of latitude south of the position mapped by CLIMAP. Fairbank's (1989) reconstruction of a 120-m sea level drop for the glacial maximum resulted in lower estimates of ice volume than originally developed by CLIMAP. The sea level results were in accord with glaciological work indicating that the ice sheets probably did not have time to reach an equilibrium profile during their "short" stay at glacial maximum magnitudes (Andrews et al., 1983).

Another feature different from the original reconstructions involves new U-Th absolute dating measurements (Bard et al., 1990) indicating that the timing of the last glacial maximum was 3,000 years older than originally mapped by CLIMAP (i.e., 21,000 BP). Sensitivity experiments indicate that this difference affects model-generated temperature fields (Hyde and Peltier, 1993). This realization requires modification of the orbital insolation values used for the simulation.

In addition to the above changes, the effect of ice-age vegetation changes on the atmospheric circulation has not been adequately addressed. One feature of the GENESIS GCM is that it has such a land package (Pollard and Thompson, 1993). This option requires specification of vegetation and soil characteristics not heretofore used in glacial maximum simulations.

Finally, there is some flexibility in specification of sea surface temperature (SST) fields for the glacial maximum. Although most investigators have used the absolute SST estimates from CLIMAP, those values were based on a control SST field different from that normally used by most investigators. In order to make comparisons of differences between the glacial maximum and present more consistent, a different method of approach is to subtract the CLIMAP anomaly fields from the SST fields used for the GENESIS control run (Yip and Crowley, 1993).

In this report we summarize all the changes that have been made to the glacial maximum boundary conditions in preparation for new glacial maximum GCM runs. We use a new ice sheet developed by Hughes and Fastook (1990), the modified sea ice fields from Burckle and Cooke (1983), a vegetation reconstruction based on well-dated sites, and a modified SST field differenced from the standard Alexander and Mobley (1976) SST data sets.

A.2 LAND ICE

Our new ice sheet reconstruction is based on the work of J. Fastook and T. Hughes of the University of Maine (UM), who developed a new ice sheet model under a project funded by PNL (Hughes and Fastook, 1990). This is a time-domain model that allows for the nonequilibrium elements of ice sheet growth. The one primary boundary condition established for the model is that global ice volume should approximately equal to an equivalent 120 m sea level drop; this is the target value from the sea level study of Fairbanks (1989).

Figure A.1 illustrates the new ice sheet reconstruction from the UM group. The differences between this reconstruction and CLIMAPs is most evident in the difference map, shown in Fig. A.2. As postulated by others, the nonequilibrium element of the new ice sheet, and the new, smaller, global ice volume constraint, produced a maximum elevation for the Laurentide Ice Sheet almost 1000 m lower than the previous reconstruction. Another difference is that there is a Siberian ice sheet. This accords with some glaciological data from Arctic islands off Siberia (M. Grosswald, personal communication), but must still be considered in the category of not completely confirmed.

The global sea level drop produced by the new U.M. ice sheet field is 114.5 m. This calculation includes changes in the profile of the Antarctic ice sheets due to sea level drops. The total sea level fall calculated from the new U.M. field compares favorably with the data of Fairbanks (1989).

A.3 SEA ICE AND SEA SURFACE TEMPERATURES

Figure A.3 illustrates the new February and August sea ice and SST fields. As stated in the introduction, the SST fields were developed by taking the CLIMAP SST anomalies and subtracting them from the Alexander and Mobley (1976) data sets. For comparison, we also illustrate (Fig. A.4) the difference between the Alexander and Mobley SST fields and those used by CLIMAP, which were based on the reconstructions by the U.S. Naval Oceanographic Office (1967).

Figure A.3 also illustrates the sea ice fields for the new run. In accordance with the work of Burckle and Cooke (1983), and subsequent partial verification of their work by Crowley and Parkinson (1988), the sea ice field in the Pacific sector is shifted southward approximately 5° of latitude. The gap left by this shift required stipulation of new SSTs. This was done in the following manner: All temperatures along a longitudinal grid line

from the new sea ice line grid point to the SST at an equatorward reference latitude were replaced with values of a linear interpolation from the equatorward gridpoint temperature to a value of -2°C inserted at the gridpoint of the new sea ice line. The equatorward reference latitude was chosen to approximate the location of the southern oceanic polar front; in the western hemisphere we chose 50°S , in the eastern hemisphere it was 48°S .

A.4 ORBITAL INSOLATION FORCING

As given by Berger (1978), the orbital insolation values for 21,000 BP are eccentricity (0.018994), obliquity (22.949°), and longitude of perihelion (114.42°). These are the values that are also being used by PMIP (Paleoclimate Modeling and Intercomparison Project).

A.5 TRACE GAS CHANGES

There were significant decreases in CO_2 , N_2O , and CH_4 during the last ice age (Leuenberger and Siegenthaler, 1992). Measurements from ice cores give the following concentrations at 21,000 BP (Raynaud et al., 1993; Leuenberger and Siegenthaler, 1992): CO_2 (200 ppm), CH_4 (350 ppb), and N_2O (190 ppb). According to the PMIP Newsletter No. 2 (Joussaume et al., 1993), the total change in trace gas forcing (ice age vs. present) is -3.4 W/m^2 .

A.6 VEGETATION

There were large changes in vegetation during the last glacial maximum (e.g., Adams et al., 1990) that are important to consider in any model that allows for vegetation/atmosphere interactions. Since the Adams et al. (1990) study did not illustrate data locations, we decided to construct a new map based on a well-dated pollen data set developed by Webb et al. (1993). This work is based on the extensive studies undertaken by the COHMAP group (1988). Five additional sites were added to the Webb

et. al. (1993) study based on new studies. These sites are listed in Table A.1. Note that in some cases we did not include all the samples listed by Webb et. al., because there was either uncertainty about actual vegetation classification or several sites were close together and would not be resolvable on the grid system we used. We also compared our results with regional-scale reconstructions of van der Kaars (1991) and Clapperton (1993).

As discussed in Pollard and Thompson (1993), the vegetation index for the GENESIS GCM is based on the work of Dorman and Sellers (1989) and has twelve categories. The separate categories and their ecological designation are listed in Table A.2.

The new vegetation data base for our reconstruction has 216 sites and is illustrated in Plate A.1. The vegetation reconstruction for the last glacial maximum is illustrated in Plate A.2. For comparison we also include the vegetation reconstruction of Dorman and Sellers (1989) for the present climate.

Overall, there is a fair amount of agreement between the vegetation reconstructions of our study and those of Adams et al. The primary difference is that Adams et al. have slightly more tropical rainforest and desert, whereas our reconstruction converts some of these areas to savanna, resulting in larger savanna values for us than for Adams et al. Given the spottiness of data coverage in low latitudes (Plate A.1), we consider these differences to be within the realm of uncertainty of the data.

A.7 SOIL COLOR

A soil color map for the last glacial maximum was developed from the CLIMAP reconstructions of present and last glacial maximum soil types. Each grid point in the standard GENESIS soil color map was lightened or darkened according to the change at

that grid point in the CLIMAP glacial maximum minus present difference.

The GENESIS soil color code uses 8 classifications from light to dark, while the CLIMAP codification employs 15 classes from bright white to dark. It was unreasonable to attempt to correlate equivalent albedos between the two schemes, since the range of values and basic assumptions (eg. spectral dependence, moisture content, solar zenith angle, and direct vs. diffuse beam) were markedly different. Since CLIMAP produced maps of both the present and last glacial maximum soil types, a method was implemented whereby the percentage increase/decrease at each grid point in CLIMAP classification code, between present and last glacial maximum, was used to adjust the GENESIS map of present soil color code in the same percentage of its classification range. This method assumes a linear relationship between class and albedo. This is the case in the GENESIS color scheme, and the CLIMAP scheme is sufficiently linear for these purposes. The new soil color map is illustrated in Plate A.3.

Plate A.4 shows the derived GENESIS soil color differences, glacial maximum minus present. The units of difference are those of the GENESIS soil color classification, and are displayed only for the ice-free land points in common between the two periods. When these differences are added to the present GENESIS soil color field, the result (not shown) is a diverse field with an unreasonable amount of complexity which implies more information content than the CLIMAP data can justify.

The global (area-weighted) average of the changes in soil color of Plate A.4 is -0.35. In other words land albedo was slightly higher during the glacial maximum. However, since this value is less than a 1.0 unit change in soil color for the GENESIS classification scheme, we deem it reasonable to conduct an initial glacial maximum simulation with no change in soil color from the present. It may also be justifiable to conduct further

sensitivity experiments with soil color lightened in some regions (eastern North America and China, Europe, and South America), for the higher albedo in these regions might alter local temperature and moisture fields.

A.8 SOIL TEXTURE

The final field needed for generation of boundary conditions for the last glacial maximum involves soil texture. The GENESIS soil texture scheme is derived from the BATS (Biosphere Atmosphere Transfer Scheme) biosphere model (Dickinson et al., 1986). We found it very difficult to develop an objective scheme for generating a glacial maximum soil texture scheme. The reason is that the present soil texture scheme has at best an imperfect correlation with climate. For example, Plate A.4 illustrates the soil texture classification in GENESIS for North America. Note that some of the soil categories extend west-east across the continent, cutting across a very large climatic gradient in moisture. Similarly, the same soil texture can be found in Canada and in southeast U.S.

Although we cannot offer a definitive explanation for the factors responsible for soil texture distribution, we suggest that it must at least in part be controlled by underlying bedrock and topography -- factors which would not change on a glacial-interglacial time scale. We therefore chose to use the present soil texture field for the glacial maximum boundary conditions.

A.9 REFERENCES

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Paleovegetation Data Distribution

Plate A.1. Locations of Sites used to Reconstruct 21,000 BP Vegetation Field. Data are from Webb et al. (1993) and Table A.1. See text for further discussion.

Vegetation (Present)

Vegetation (Glacial Maximum)

Plate A.2. Vegetation Reconstruction for (a) the Present; and (b) Last Glacial Maximum.

LSX Soil Texture - North America

Plate A.3. Soil Texture Classifications for the Present used in the GENESIS Climate Model (from Wilson and Henderson-Sellers, 1985).

Soil Color (Glacial Maximum Minus Present)

Plate A.4. Differences in Soil Color (Ice Age vs. Present).
Negative values indicate higher albedo for ice-age soils.

LAST GLACIAL MAXIMUM ICE ON GENESIS LSX 2X2 GRID

Fig. A.1. Revised Ice Sheet Reconstruction for the Last Glacial Maximum. Contour interval is 500 m.

Fig. A.2. Difference in Revised Ice Sheet Reconstruction and Original CLIMAP (1981) Reconstruction. Contour interval is 500 m.

Fig. A.3. Revised SST and Sea Ice Fields for the Last Glacial Maximum for (a) February and (b) August (see text for discussion). Contour interval is 2°C .

Fig. A.4. Difference Between Present SST Fields of U.S. Naval Oceanographic Office (1967) and Alexander and Mobley (1976) for (a) February and (b) August. Contour interval is 1°C.

TABLE A.1. Sites for Last Glacial Maximum Pollen Boundary
 Conditions These are the Compilation of Webb et al.
 (1993). W1, (etc.) refers to Webb et al. site;
 W1 ref. refers to Webb et al. page number.

SAMPLE	SITE	SITE #	LAT (-S) (N)	LONG (-°W) (°E)	CODE	REF.
1	Kuwasenkoko Swamp, Zaire	W1	-2	29	7	W1
2	South Africa	W3	-29	26	7	W1
3	South Africa	W8	-28	25	7	W2
4	Zambia	W10	-11	32	6	W3
5	ne Angola	W11	-7	21	6	W3
6	Kalambo Falls, Zambia	W12	-8	31	6	W3
7	Cameroon	W13	6	11	6	W4
8	Lake Chad, Africa	W14	13	14	11	W4
9	Niger	W15	18	12	11	W4
10	Niger	W16	19	13	11	W4
11	Mali	W17	16	4	11	W5
12	Senegal	W18	16	-16	11	W5
13	A.-B. Massif, Niger	W20	20	-9	11	W5
14	Muchoya Swamp, Uganda	W22	-1	30	7	W6
15	K. Swamp, Kenya	W24	1	35	7	W6
16	Ethiopia	W27	11	42	9	W7
17	Sudan	W31	13	34	8	W8
18	s Tunisia	W35	34	10	6	W9
19	Algeria	W36	23	5	8	W9
20	Algeria	W38	29	2	6	W9
21	Uganda	W40	-1	30	7	W10
22	Nile R., Upper Egypt	W42	25	33	11	W10
23	Namibia	W43	-25	15	7	W11
24	Niger Delta	W46	5	6	7	W12
25	Ghana	W48	7	-1	7	W12
26	Cameroon	W49	5	10	6	W13
27	Sahel Zone	W50	10	8	7	W13
28	Sudan	W51	19	26	11	W13
29	Sudan	W52	17	28	11	W14
30	Sudan	W53	17	27	11	W14
31	n Lake Tanganyika	W54	-4	29	6	W14
32	Trop. Africa	W55	10	10	6	W15
33	Lake Tanganyika	W56	-6	30	6	W15
34	Nile Basin	W57	15	30	11	W15
35	Ethiopia	W58	8	39	9	W15
36	Uganda	W59	-1	30	7	W16
37	Uganda	W60	-1	30	9	W16
38	Morocco	W61	33	-5	7	W16
39	Chad	W62	21	18	11	W17
40	Congo	W64	-1	16	6	W17

SAMPLE	SITE	SITE #	LAT	LONG	CODE	REF.
			(-S) (N)	(-°W) (°E)		
41	South Africa	W65	-24	29	7	W18
42	Lake Victoria	W66	-1	33	7	W18
43	Zambia	W67	-9	30	6	W18
44	Burundi	W71	-3	30	7	W20
45	Burundi	W72	-4	30	7	W20
46	w Alaska	W76	66	-163	10	W21
47	Alaska	W77	67	-158	10	W22
48	St. Lawrence I., Alaska	W78	63	-170	10	W22
49	ne Beringia Russia	W81	70	-180	10	W22
50	Yukon Ter., Canada	W83	68	-138	10	W23
51	Siberia	W85	68	162	10	W23
52	Ped Pond, Alaska	W86	67	-142	10	W23
53	Ranger Lake, Alaska	W87	67	-154	10	W24
54	Squirrel Lake, Alaska	W89	67	-161	10	W24
55	c. Beringia	W90	67	180	10	W24
56	Joe Lake, Alaska	W92	67	-157	10	W25
57	Tiinkdhul Lake, Alaska	W93	67	-143	10	W25
58	Sithyl. Lake, Alaska	W95	66	-151	10	W25
59	cen. w Beringia, Russia	W96	66	170	10	W25
60	Yukon Riv., Alaska	W97	65	-144	10	W26
61	Imuruk Lake, Alaska	W98	65	-163	10	W26
62	Isabella Lake, Alaska	W101	65	-148	10	W26
63	Tanana Valley, Alaska	W102	64	-147	10	W27
64	Bering Sea	W103	64	-175	10	W27
65	Tanana Valley, Alaska	W105	63	-144	10	W27
66	St. Michael Is., Alaska	W106	63	-162	10	W27
67	w Beringia	W109	62	149	10	W28
68	Tungak Lake, Alaska	W111	62	-163	10	W28
69	Beringia	W115	60	-179	10	W29
70	s Coastal Beringia	W117	59	-171	11	W29
71	Nushagak, Alaska	W118	59	-157	11	W29
72	Bristol Bay, Alaska	W119	59	-158	10	W30
73	se England	W126	52	0	10	W32
74	Netherlands	W129	52	5	10	W33
75	Campine Pl., Belgium	W131	51	3	7	W33
76	Pyrenees, France	W132	43	0	7	W33
77	ne France	W133	48	6	7	W33
78	Grotte Gazel, France	W135	43	2	7	W34
79	Sch. Hols., Germany	W139	54	9	10	W35
80	Stillfried and der March	W143	48	16	10	W36
81	D.V., Czechoslovakia	W144	49	17	10	W36
82	Zamora, Spain	W147	41	-6	8	W36
83	Cueva del Toll, Spain	W148	42	2	7	W37
84	n Italy	W149	45	12	7	W37
85	Po River Valley, Italy	W150	45	10	7	W37
86	c Italy	W154	42	12	7	W38
87	Slovenia	W156	46	15	8	W38

SAMPLE	SITE	SITE #	LAT	LONG	CODE	REF.
			(-S) (N)	(-°W) (°E)		
88	L.Barje, Slovenia	W157	46	14	8	W39
89	nw Greece	W158	40	21	7	W39
90	n Greece	W159	41	25	7	W39
91	s Lithuania	W162	54	24	4	W40
92	Belorus	W163	55	30	4	W40
93	Puchka River, Russia	W165	59	40	10	W40
94	Colney Heath, England	W167	51	1	10	W41
95	Padul, s Spain	W169	37	-4	8	W41
96	Ariege, France	W170	43	1	7	W41
97	c France	W172	45	4	4	W42
98	Lyonnais, France	W176	46	5	8	W43
99	Monticchio, Italy	W177	41	16	8	W44
100	J-H Tan, Taiwan	W182	24	121	3	W46
101	Lake Biwa, Japan	W183	35	136	3	W46
102	Hielongjiang, PRC	W184	47	133	4	W46
103	ne China	W185	46	131	4	W46
104	Huanghe River, PRC	W188	41	110	9	W47
105	n China	W192	42	110	9	W47
106	n China	W192	46	110	10	W47
107	Fenzhuang, Beijing, China	W193	40	116	9	W48
108	Hebei, PRC	W196	39	116	6	W48
109	Ningxia, PRC	W198	38	106	9	W49
110	Qinghai, PRC	W199	38	96	11	W49
111	c China	W200	37	111	9	W49
112	Huanghai Sea, PRC	W201	37	123	7	W49
113	Qinghai-Tibet, PRC	W205	36	87	11	W50
114	Potou, Luochan, PRC	W207	36	109	7	W50
115	Quinling Shan, PRC	W208	36	103	9	W50
116	n Xingjiang, PRC	W213	35	111	9	W51
117	Lantian, Shaanxi, PRC	W215	34	109	8	W52
118	Yangtze River Delta	W217	31	120	3	W52
119	Sanjiang Plain, PRC	W219	26	109	3	W52
120	Xi Hu, Yunnan, PRC	W220	26	100	3	W53
121	Nonggong Lake, PRC	W224	22	100	6	W53
122	Sankhu, Kathmandu, Nepal	W226	27	85	7	W54
123	Chad. River, Russia	W229	59	100	4	W55
124	Biya River, Russia	W232	52	85	4	W56
125	e Siberia, Russia	W233	55	135	10	W56
126	w Siberia, Russia	W234	55	95	4	W56
127	Mass.	W242	41	-71	10	W58
128	New York	W245	41	-74	10	W58
129	near Trenton, NJ	W246	40	-75	10	W59
130	Coastal Pl., NJ	W248	40	-74	4	W59
131	Chester Co., se Penn.	W249	40	-76	10	W59
132	Snow Hill, MD	W254	38	-75	4	W60
133	Buckle Bog, MD	W256	40	-79	4	W61
134	Clarks Cave, Bath Co. VA	W257	38	-80	4	W61

SAMPLE	SITE	SITE #	LAT (-S) (N)	LONG (-°W) (°E)	CODE	REF.
135	Hack Pond, Shen., VA	W258	38	-79	4	W61
136	Boring B3, Ches. Bay, VA	W259	37	-76	4	W91
137	Rockyhock Bay, NC	W261	36	-77	4	W62
138	Singletary Lake, NC	W262	34	-78	4	W62
139	Anderson Pond, TN	W264	36	-85	4	W62
140	Quicksand Pond, GA	W265	34	-85	3	W63
141	Pigeon Marsh, GA	W267	35	-85	3	W63
142	Lake Annie, FL	W270	27	-81	3	W64
143	Goshen Springs, Ala.	W271	32	-86	2	W64
144	Memphis, TN	W272	35	-90	3	W64
145	Buried Wood, Ohio	W273	41	-84	4	W64
146	Sidney, Ohio	W274	40	-84	4	W65
147	Monton Loess, Ill.	W277	41	-90	9	W65
148	Pittsburg Basin, Ill.	W280	39	-89	4	W66
149	Loess Profiles, Iowa	W282	42	-93	9	W66
150	Muscotah Marsh, Kansas	W284	40	-96	4	W67
151	Arrington Marsh, Kansas	W285	39	-96	4	W67
152	Boney Spring, Missouri	W287	38	-93	4	W67
153	Big Bend, TX	W290	29	-103	3	W68
154	Rich Lake, TX	W296	33	-102	4	W69
155	Estancia Playa, New Mexico	W299	35	-106	4	W70
156	San Aug. Pl., New Mexico	W302	34	-108	8	W71
157	Ajo Mtn., AZ	W305	32	-113	9	W72
158	Laguna Salada, AZ	W307	34	-110	4	W72
159	Potato Lake, AZ	W308	34	-111	4	W72
160	Rampart Cave, N. AZ	W310	36	-114	4	W73
161	Mohave D., NV	W314	36	-115	4	W74
162	Nevada	W318	40	-119	4	W75
163	se Calif.	W319	34	-115	4	W75
164	s Calif.	W324	35	-117	4	W76
165	Santa Cruz Island, Calif.	W326	34	-120	4	W77
166	Rancho La Brea, Calif.	W328	35	-118	4	W77
167	Point Sal Ridge, Calif.	W329	35	-121	4	W77
168	Karamik B., sw Turkey	W400	38	31	7	W90
169	Sogot Golu, sw Turkey	W401	37	30	7	W90
170	Ghab Val., nw Syria	W402	36	36	6	W90
171	Lake Hula, Israel	W406	33	36	6	W91
172	Lake Z., w Iran	W407	36	46	7	W92
173	Hindu Kush, Afghan.	W409	33	68	9	W92
174	Konya II, Turkey	W412	37	33	7	W93
175	Sagarejo, Georgian Rep.	W413	42	45	6	W93
176	n Mexico	W420	27	-104	8	W95
177	Lake Morira, Guyana	W423	4	-59	6	W95
178	Ogle Borehole	W424	7	-58	6	W95
179	Alliance, Surinam	W425	6	-55	6	W96
180	Caribbean S. Am., Surinam	W426	2	-55	6	W96
181	Katira Creek, Brazil	W430	-9	-63	7	W97

SAMPLE	SITE	SITE #	LAT (-S) (N)	LONG (-°W) (°E)	CODE	REF.
182	Gulf of Calif., Mexico	W433	27	-112	8	W97
183	Lake Patzcuaro, Mexico	W434	20	-102	4	W97
184	El Valle, Panama	W437	9	-80	7	W98
185	Laguna Ciega, Colombia	W438	6	-72	7	W98
186	El Abra, Colombia	W439	5	-74	7	W99
187	Alsacia, Colombia	W444	4	-74	7	W100
188	Serra dos, Brazil	W448	-6	-50	7	W100
189	Peruvian Highland	W449	-11	-76	8	W101
190	Salitre, Brazil	W450	-19	-47	6	W101
191	Gruta, Argentina	W453	-35	-68	7	W102
192	Laguna, Chile	W454	-34	-71	2	W102
193	Chilean Lake District	W457	-40	-72	6	W102
194	Peurto Varas	W459	-41	-73	6	W103
195	Taiq., Isla de Chiloe	W465	-42	-73	6	W104
196	Chile, Argentina	W467	-43	-72	6	W105
197	Chile, Argentina	W469	-50	-73	10	W105
198	San Luis, Argentina	W471	-33	-67	7	W106
199	Lake Hawea, New Zealand	W476	-45	169	10	W107
200	Greta Cuttin, New Zealand	W481	-43	171	10	W108
201	Grey Valley, New Zealand	W482	-42	171	10	W108
202	w Tasmania, Australia	W489	-42	145	7	W110
203	Midland Tasmania, Australia	W491	-42	147	7	W110
204	New South Wales, Australia	W496	-35	149	7	W111
205	Lancefld Swamp, Australia	W502	-36	145	7	W113
206	Wyrrie Swamp, Australia	W512	-37	141	6	W115
207	Lake Leake, s Australia	W513	-38	141	7	W115
208	near Eucla, w Australia	W515	-32	129	7	W116
209	Timor Sea, Australia	W517	-11	127	7	W116
210	Queensland, ne Australia	W518	-17	146	8	W116
211	nw Tasmania	W526	-41	145	7	W118
212	c. Texas		31	-99	6	A
213	e.c. Texas		31	-97	3	A
214	L. Barombi, Cameroon		4	9	6	B
215	Serra d. Carajas, Brazil		-6	-50	7	B
216	Salitre, Brazil		-19	-46	6	B

A Toomey et al., 1993
B Servant et al., 1993

TABLE A.2. Vegetation Classification of Dorman and Sellers (1989) used as Input for Their Simple Biosphere (SiB) Model and also the GENESIS GCM Land-surface Package (Pollard and Thompson, 1993). Table modified from Dorman and Sellers (1989, Table 1).

SiB Biome	Classification	Area (10 ⁶ km ²)
1	Broadleaf-evergreen trees (<u>Piptodenia</u> , <u>suavolens</u> , <u>Bocoa viridiflora</u>)	16.06
2	Broadleaf-deciduous trees (<u>Quercus alba</u> L.)	4.99
3	Broadleaf and needleleaf trees (<u>Quercus alba</u> L., <u>Pinus strobus</u> L.)	5.60
4	Needleleaf-evergreen trees (<u>Picea sitchensis</u> , <u>Picea abies</u>)	14.73
5	Needleleaf-deciduous trees (<u>Larix decidua</u>)	6.16
6	Broadleaf trees with groundcover (<u>Acacia</u> Senegal, <u>Andropogon</u> Gayanus)	17.96
7	Groundcover (<u>Agropyron dasystachyum</u>)	4.43
8	Broadleaf shrubs with groundcover (<u>Larrea tridentata</u> , <u>Agropyron dasystachyum</u>)	10.70
9	Broadleaf shrubs with bare soil (<u>Larrea divaricata</u> , <u>Eucalyptus socialis</u>)	11.97
A	Dwarf trees and shrubs with groundcover (tundra) (<u>Calluna vulgaris</u> , <u>Hypnum cupressiforme</u> , <u>Carex rigida</u>)	7.08
B	No vegetation: bare soil	15.73
C	Broadleaf-deciduous trees with winter wheat (<u>Quercus alba</u> L., <u>Triticum durum</u>)	18.45
D	Perennial land ice	19.68

APPENDIX B

SELECTED CIRCULATION STATISTICS AND SENSITIVITY
EXPERIMENTS FOR THE GENESIS GCM (VERSION 1.02.A)

by

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and

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APPENDIX B

SELECTED CIRCULATION STATISTICS AND SENSITIVITY

EXPERIMENTS FOR THE GENESIS GCM (Version 1.02.A)

B.1 INTRODUCTION

A new climate model, termed GENESIS, has recently been developed at the National Center for Atmospheric Research (Bonan et al., 1992; Pollard and Thompson, 1993; Thompson and Pollard, 1993). This model is being used for paleoclimate experiments and simulations for future climate change. Although the model developers have undertaken their own comparisons of their mixed-layer ocean runs with observations, herein we conduct a separate analysis comparing prescribed sea-surface temperatures (SSTs) with climatology. We also compare GENESIS results with an intercomparison of 19 other GCMs (Cess et al., 1990; Randall et al., 1992) as well as examine the effect of one coding change in the model. The purpose of this report is to describe some of the findings of these simulations.

B.2 MODEL

The GENESIS GCM (versions 1.02 and 1.02.A) originated from the NCAR Community Climate Model Version 1 (CCM1, described in Williamson et al., 1987). It has undergone extensive recoding for ease of use and to include new model physics. It has the same number of vertical levels (12) and horizontal resolution (4.5° by 7.5°) as the CCM1. The horizontal and vertical variables are discretized using spectral transformation and finite-difference methods, respectively, except for the water vapor transport scheme (see below). However, the methods for handling most of the

important physical processes in the model have been changed. Several features of the model include:

- A diurnal cycle, with solar-radiation calculations performed every 1.5 hours. Infrared-radiation calculations are performed by the AGCM every time step of 0.5 hour. Computations of absorptivities and emissivities of H_2O , CO_2 and O_3 gases are done once every 24 hours.

- A cloud parameterization similar to Slingo and Slingo (1991) has been adopted with three possible types of clouds: stratus, anvil cirrus and convection. A new constraint on stratus clouds has been added when the specific humidity is very low in order to achieve realistically low amounts in the polar regions in winter.

- A semi-Lagrangian method for transport of water vapor has been added (Williamson and Rasch, 1989; Rasch and Williamson, 1990; Williamson, 1990). The method uses cubic interpolation in all directions and "operator splitting" between horizontal and vertical advections. This was added to avoid the unphysical holes and ripples produced by spectral fields with sharp spatial gradients such as moisture.

- A surface package called the land-surface-transfer model (LSX) has been included. This replaces the surface temperature calculation routines of the CCM1 and includes the computation of exchange of momentum, thermal energy, and water mass between the atmosphere and land surface taking into account the effects of vegetation. LSX is adapted heavily from the earlier BATS (Dickinson et al., 1986) and SiB (Sellers et al., 1986) schemes. The surface package also includes multilayer models of soil, snow, and sea ice. A related modification is that the GCM grid is now independent of the surface grid. This allows different grid sizes for the GCM and LSX models. The fields are transferred between grids by either bilinear interpolation or area-averaging.

B.3 MODEL SIMULATIONS

Because there are sometimes significant differences between SST fields obtained from mixed-layer ocean models and observed SST fields, we used observed SSTs to isolate model differences from atmospheric observations due solely to the atmospheric portion of the model. This approach significantly shortens atmospheric model run time as does changing the LSX resolution to $4.5^\circ \times 7.5^\circ$ to match the AGCM resolution. The model has been run for 39 months for the control run, with only the last 2 years being used for all seasonal mean field calculations except for the precipitation field where the last 3 years are used. Longer 5-year runs with prescribed SSTs (e.g., Fig. B.1) indicate that most model fields have settled into equilibrium after approximately the first 1-2 years of startup (Crowley et al., 1993).

Two different sets of nearly identical runs were made for the control case. This step was necessitated because there was a coding error in the specification of the orbital insolation package. This error altered the insolation receipt by season from that which actually occurs. Because some earlier runs had been made with the original, uncorrected insolation package (Crowley et al., 1993), we wanted to test the sensitivity of those results to the change in the orbital insolation package. The experiment designations are NEW CONTROL (version 1.02.A) for the correct orbital routine and OLD CONTROL (version 1.02) for the original, erroneous orbital routine.

For both the control runs and GCM intercomparison studies, prescribed SSTs and sea ice were taken from the Alexander and Mobley (1976) data set. For the intercomparison studies (Cess et al., 1990; Randall, et al., 1992; Boer, et al., 1991; 1992) only a prescribed July SST field has been specified, with sea ice fixed and SSTs increased or decreased by 2°C globally. Since the time scale of the atmospheric response to a forcing is 30-60 days, a 180 day simulation is sufficient to reach a new steady state.

Only the last 80 days of the simulation have been used for intercomparison. All simulations used the envelope topography designation in the model.

According to Cess et al. (1990) there was a practical reason for doing the $\pm 2^\circ\text{C}$ experiments. A standard climate change simulation with a mixed-layer ocean requires large amounts of computer time to reach a new equilibrium. An attractive alternative that eliminates the above difficulty is to specify a $\pm 2^\circ\text{C}$ sea surface temperature (SST) perturbation in a perpetual July simulation for the purpose of intercomparing model climate sensitivity. This procedure can be thought of as an inverse climate change simulation. Rather than introducing a direct radiative forcing (G) into the models, the climate change is instead prescribed. The models in turn produce their respective forcing in accordance with $G = \Delta F - \Delta Q$, where F and Q respectively denote the global-mean emitted infrared and net downward solar fluxes at the top of atmosphere (TOA). The change in surface climate, expressed as the change in global-mean surface temperature ΔT_s , can be related to the radiative forcing G , as defined earlier, by $\Delta T_s = \lambda_g G$, where λ_g is the climate sensitivity parameter $\lambda_g = (\Delta F/\Delta T_s - \Delta Q/\Delta T_s)^{-1}$.

B.4 RESULTS

B.4.1 Comparison with Observations

Temperature

For the standard control run (NEW CONTROL), a comparison of zonally-averaged temperatures (Fig. B.2) with observations (Crutcher and Meserve, 1970; Taljaard et al., 1969) indicates fairly good agreement, although there is a slight accentuation in the model's annual cycle over land as compared to observations. A map portrayal of this comparison (Fig. B.3) shows a fairly uniform bias over North America and Eurasia, although exceptions of the

opposite sign occur over Greenland, the Tibetan Plateau, and Africa.

Large temperature differences (up to 16°C) between the model output and observations are seen in the area corresponding to the sea ice field around Antarctica. The reasons for these differences are not entirely clear. We conjectured that these differences might be partially explained by the fact that the observed temperatures are specified as being 2 meters above the surface while the illustrated model field is a surface temperature field, which for sea ice could be significantly different than for the overlying free atmosphere. However, this possibility is not supported by a comparison of the surface and 2 meter temperature fields of the model (Fig. B.4). Significant differences were seen in this latter comparison over areas of permanent ice cover, reflecting the capability of ice to become much colder than the air 2 meters above it.

Because the model is too warm over part of the Antarctic Ice Sheet but too cold over the adjacent sea ice (Fig. B.3), it is possible that a more efficient downslope transfer of cold air from the Antarctic interior to the sea ice margin occurs in the model than in the real world. This process may reflect an inability of the model to capture the full strength of the shallow inversion layer over the Antarctic Ice Sheet. This inability may in turn reflect two limitations of the model: a vertical resolution inadequate to simulate the shallow inversion layer and smoothed topography which enhances downslope flow (rather than allowing the cold air to pond on a broad plateau).

Latitude-height plots of zonally averaged air temperature for the prescribed SST run for DJF and JJA are shown in Fig. B.5. In the Thompson and Pollard (Fig. 6e; 6f, 1993) study, the control run is colder than observations at the tropopause poleward of 30° - 60°S and poleward of 60°N in both January and July. Conversely, the control run is warmer than observations below the tropopause

along 40°-90°S (cf. Thompson and Pollard, Fig. 6e; 6f, 1993) in the same months. The atmospheric temperature and zonal winds in our control run are comparable with those of Thompson and Pollard.

A comparison of the NEW CONTROL vs. the OLD CONTROL (Fig. B.6) indicates only minor differences in temperatures due to the correction in the orbital calculation code. However, because the original coding error involved the eccentricity parameter, larger errors developed when simulations were done with an extreme orbital configuration (results not shown).

Precipitation

Although the model reproduces zonal profiles qualitatively similar to those occurring in the real world, it is generally wetter than observations. In July the model is as much as 65% wetter than the Jaeger (1976) data set and 62% wetter than the more recent Legates and Wilmott (1990) data set between 70°N and 70°S (Fig. B.7a). In January, for which the Schutz and Gates (1971) data set was also available for comparison, the model was 95% wetter than the Schutz and Gates data, 67% wetter than the Jaeger data, and 21% wetter than the Legates and Wilmott data in the same latitude range. Further clarification of these differences will require investigation of inherently difficult issues involving both the physical parameterizations of rainfall in the model and assessment of precipitation data sets.

The geographic distribution of precipitation produced by GENESIS is compared to the observations of Jaeger (1976) in Figures B.8 and B.9. The model precipitation field in January (Figure B.8) evidences the observed well-developed bands over South America, Africa and Indonesia which move north over central America and Africa in July (Fig. B.9). In addition, the model results show a pocket of precipitation, very intense in July, off the west coast of central America which has a weak observational counterpart only in July. Peak precipitation patterns in Asia

show a persistent high over Indonesia with a seasonal high over China in July. The precipitation increase over India-Tibet in July that reflects the monsoon circulation is rather small and is in fact one of the very few areas of significant size where the model isn't wetter than the observations. This discrepancy may reflect in part an apparent anchoring of the Intertropical Convergence Zone (ITCZ) over Indonesia in the model as opposed to its observed northward movement (see below). The reasons for these model responses are unclear.

The question arises as to the causes for a systematic bias in GENESIS precipitation fields with respect to observations. Although we cannot provide a definitive explanation for this phenomenon, there are several pieces of information we can use that yield clues to an eventual explanation. This information can be split into two general categories, the first pertaining to zonally persistent differences and the second to differences of a more regional nature. The first category is best exemplified by the comparison of zonal mean precipitation patterns in Figure B.7. Although the absolute differences between model and observed precipitation vary significantly with latitude, the percentage errors are fairly constant between about 70°N and 70°S. D. Pollard (personal communication) attributes this difference to an average excess in surface solar flux of 30 Wm^{-1} which, if converted to latent heat, would correspond to about 1 mm/day of surface evaporation. This is just about equal to the global precipitation error evidenced by GENESIS. Pollard hypothesized that tropospheric aerosols, thus far turned off in the model, may be able to absorb at least some of this excess 30 Wm^{-1} before it reaches the surface, thereby modifying heating convection, and precipitation patterns. Preliminary experiments with interactive aerosols appear to significantly decrease global precipitation in GENESIS (D. Pollard, personal communication).

To explore errors of the second nature, we first examined the model precipitation fields for January and July (Figures B.10 and B.11) for individual years in order to determine whether regions of high precipitation consistently occur in the same places. Results indicate that they do. Next we compared the model precipitation fields from our control run to the precipitation produced by Thompson and Pollard (Fig. 20, 1993) with calculated SSTs. The motivation for this comparison is that prescribed and calculated SSTs sometimes differ significantly, especially in regions where there is cool water (eastern boundary currents, upwelling zones, etc.). If our precipitation fields agree with those of Thompson and Pollard, then the indication would be that the regions of high precipitation are not primarily influenced by SST.

A comparison of our precipitation fields to those produced by Thompson and Pollard indicates that both simulations have high precipitation centered over 10°N, 90°W (west of central America) and a split Asian monsoon -- moderately high precipitation over east Asia, low over India, and high again over Indonesia. The similar response in both models, with different SST fields, suggests that land-sea distribution may play an important role in anchoring zones of high precipitation, with the absolute levels of modeled precipitation peaks varying seasonally with solar insolation forcing and SST.

The apparent anchoring of precipitation peaks by the land-sea distribution, and their primary restriction to low latitudes, leads us to conjecture that some type of land-sea convergence effects, perhaps due to frictional differences, may be focusing precipitation in some regions. The high absolute values of the rainfall fields further suggest that precipitation events do not shut down in the model as they do in the real world. This may represent either some type of convective instability or the absence of a key negative feedback in the model. Because the

extreme wet features are primarily restricted to low latitudes, where absolute moisture levels are highest, we conjecture that an instability, if it exists, only occurs after latent heat release from condensing moisture reaches some critical value.

At this stage the above ideas must be considered speculation and they are offered in the hope that they may be useful to other investigators examining the problem. As hearsay evidence indicates that the same type of precipitation levels occur in the CCM2, it would be interesting to compare CCM2 results with GENESIS precipitation fields.

Comparisons for Southwest Nevada

Because this study was undertaken to develop a baseline description of the model for the purpose of simulating climate variations for the Yucca Mountain nuclear waste disposal site, we discuss specific precipitation fields for Nevada and the Yucca Mountain environments. We undertook two comparisons - (1) a somewhat large-area comparison for the region 35° - 40° N, 115° - 120° W, in which model statistics were compared to the smoothed climatological data sets of Jaeger (1976); and (2) a more nearly point-specific comparison, in which the model output for Yucca Mountain (37.5° N, 116.5° W) was compared to precipitation variations for a triangle of three stations surrounding Yucca Mountain -- Beatty, Desert National Wildlife Reserve, and Las Vegas.

The comparison (Table B.1) indicates that the model precipitation is greater than observations for the larger-area comparison and much greater than the more localized observational triangle around Yucca Mountain. These results are not unexpected, for it is well known that when a low-resolution climate model such as GENESIS smooths topography, the Western Cordillera of the U.S. is transformed into a single ridge east (i.e., downwind) of Yucca Mountain. Higher-resolution gridded models (Dickinson et al.,

1989; Giorgi et al., 1992) correctly place Yucca Mountain in the lee of the Sierran orographic barrier, resulting in much less precipitation than we simulated. Since the Yucca Mountain projections will involve GENESIS coupled to the high-resolution model, a more appropriate comparison with observations must await that coupling. The numbers included herein are therefore mainly for reference.

Zonal wind

The general structure and pattern of the zonal wind (Fig. B.12) agrees reasonably well with observations (Fig. 7.15, Peixoto and Oort, 1992). Simulated maximum westerly jets in both hemispheres are at the same altitude and latitude, but they are slightly stronger than those observed (43 m/s vs. 39 m/s in DJF; 47 m/s vs. 35 m/s in JJA). This same response occurs in the Thompson and Pollard simulation (Fig. 9, 1993). The observed easterlies region between 25°S and 40°N in the whole air column is captured in this experiment in JJA but is absent in DJF.

B.5 Comparison with other GCMs

B.5.1 Temperature

The surface temperature differences (ΔT_s) between the +2°C and -2°C experiments are shown in Table B.2. Because the SST difference is fixed in the $\pm 2^\circ\text{C}$ simulation, the ΔT_s of 3.96°C in GENESIS and of 4.02°C in the other 19 GCMs is to be expected. A rather interesting feature appears in a contour plot of temperature difference vs. height (Fig. B.13), where the $\sim 4^\circ\text{C}$ average surface temperature difference increases with height to almost 7°C in the upper troposphere along the equator. We attribute these changes to amplification of latent heat release due to increased precipitation in the upper troposphere as will be discussed below. This result has potential implications for ice-age model-data comparison of climate change in the tropics (Rind

and Peteet, 1985), where larger temperature differences (ice age vs. present) are inferred for upper levels than at the surface (cf. Crowley and North, 1991, p. 75).

B.5.2 PRECIPITATION

Precipitation is a basic climate variable and the only one in this report directly related to the moisture budget. When the SST is increased from -2°C to $+2^{\circ}\text{C}$, the global average precipitation increases 0.52 mm/day. This compares to a range of 0.42 ± 0.10 mm/day (Randall et al., 1992, Table 6) in 19 other GCMs. Moreover, as shown in Fig. B.14, zonal-average precipitation in GENESIS is wetter than in most other GCMs. Because the results of the intercomparison run were not available for distribution, we were unable to rigorously compare model statistics. However, we undertook a semi-quantitative comparison by determining the midpoint between the extremes of the 19 GCM study (Fig. B.14) and comparing that midpoint with GENESIS. The results indicate that GENESIS is 50% wetter than the midpoint of the other GCMs (4.31 mm/day vs. 2.87 mm/day). Again, the reason for the differences are not well understood and require more analysis.

Fig.B.15 illustrates the zonal average precipitation for the $\pm 2^{\circ}\text{C}$ GENESIS runs, indicating that warmer SSTs produce a larger increase in equatorial rainfall than at mid-latitudes (about 1.7 vs. 0.9 mm/day). This amplification may explain the upper troposphere temperature/height anomalies at the equator discussed above.

B.5.3 SENSITIVITY ANALYSIS

A plot of the global climate sensitivity (λ_g) vs. cloud feedback ($\Delta\text{CRF}/G$) where ΔCRF is the change in cloud radiative forcing induced by a change in climate and G the global mean direct radiative forcing) for the 19 GCM experiments is shown in Fig. B.16. Note that even though the cloud parameterization has

been altered, GENESIS is located fairly close to CCM1 in this plot. GENESIS also agrees reasonably well with the GCMs in intercomparison of surface temperature ($\Delta T_s/\Delta N$) versus cloud radiative forcing at the top of the atmosphere [$\Delta(RCF_{top}/\Delta N)$] and of solar cloud radiative forcing at the surface [$\Delta(SWCF_{sfc})$] versus at the top of the atmosphere [$\Delta(SWCF_{top})$] (Fig. B.17) where N is net surface energy flux. Table B.3 shows that most of the downward flux fields in GENESIS are on the high end by more than one standard deviation, and vice versa for outgoing fluxes. However, the net surface energy flux (N) is still in the same range as other GCMs. This is indicative of no overall surface temperature warming. The top of the atmosphere energy budget fields in Table B.4 also show good agreement between GENESIS and other GCMs.

The global climate sensitivity parameter (λ_g) for GENESIS is 0.63, which compares to 0.65 ± 0.26 in other GCMs (Cess et al., 1990). For comparison we note that the sensitivity of GENESIS to a CO₂ doubling is 2.1°C (Thompson and Pollard, 1993). Another interesting result seen in Table B.2 is that $\lambda_g/\lambda_{gc} > 1$, where λ_{gc} is the clear-sky global climate sensitivity. This denotes a positive cloud feedback (i.e., $\Delta CRF/G$ is positive). In the perpetual July simulation, water vapor feedback is the primary clear-sky feedback because, as mentioned earlier, sea ice feedback is suppressed and snow is not present in most places in the northern hemisphere summer.

B.6 SUMMARY AND CONCLUSIONS

In summary, GENESIS agrees fairly well with observations for land surface temperature, although the annual cycle is slightly too large. The present version GENESIS is considerably wetter than observations and wetter than most other GCMs. This result implies that some caution is needed in interpreting some of the precipitation results. Many of the flux fields are more or less

in line with other GCMs (Tables B.3 and B.4). The global climate sensitivity parameter (λ_g) for GENESIS in the latter two experiments is 0.63, which compares favorably to 0.65 ± 0.26 in other GCMs.

Because this study was undertaken as a test of a model that will be used for examining precipitation variations at the proposed Yucca Mountain nuclear waste disposal site, the application of GENESIS precipitation products to this problem may not necessarily be a disadvantage. The reason for this is that one of the prime concerns of the site involves possibility of increased groundwater recharge in the future. A number of model runs will be made to test various scenarios for future climate change. If these simulations indicate that recharge may not be a problem even with a "wet GCM", then we can conclude that other, drier, GCMs would yield projections of a less extreme nature. However, if a revised version of GENESIS is used that has less global precipitation, the above argument would have to be revised.

B.7 REFERENCE

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a

b

FIGURE B.1. Demonstration that Relatively Short Runs With GENESIS Yield Stable Statistics. Figure illustrates a 5-year run for an idealized supercontinent centered on the South Pole. Note that (a) South Pole temperature and (b) snow cover areas are quite consistent from year-to-year (Results from Crowley et al., 1993).

a

b

FIGURE B.2. Zonal Mean Surface Temperature over Land for Control Run and Observations (from Crutcher and Meserve, 1970) for (a) DJF and (b) JJA.

a

b

FIGURE B.3. 2 Meters Above Surface Temperature Difference Between Control Run and Observations (from Crutcher and Meserve, 1970) for (a) DJF and (b) JJA.

FIGURE B.4. Differences Between Temperature at 2 m and Surface for (a) DJF and (b) JJA.

MEAN AIR TEMPERATURE - DJF OF CTRL RUN (2YR MEAN)

MEAN AIR TEMPERATURE - JJA OF CTRL RUN (2YR MEAN)

FIGURE B.5. Zonal Mean Atmospheric Temperature in Control Run for (a) DJF and (b) JJA.

FIGURE B.6. Surface Temperature Differences between New Control Run and Old Control Run for (a) DJF and (b) JJA.

ZONAL MEAN PRECIPITATION - OBS. VS. MODEL

ZONAL MEAN PRECIPITATION - OBS. VS. MODEL

FIGURE B.7. The Model Precipitation in the Control Run VS. Observations of Jaeger (1976) and Legates and Willmott (1990) for (a) July and (b) January, in Which the Schutz and Gates (1971) Data File is also available.

FIGURE B.8. January Precipitation in (a) Control Run, (b) Observations (Jaeger, 1976), and (c) Observations Minus Control Run.

FIGURE B.9. July Precipitation in (a) Control Run, (b) Observations (Jaeger, 1976), and (c) Observations Minus Control Run.

FIGURE B.10. Model Precipitation for January of (a) Year 2, (b) Year 3, and (c) Year 4. Contour interval is 10 mm/day.

FIGURE B.11. Model Precipitation for July of (a) Year 1, (b) Year 2, and (c) Year 3. Contour Interval is 10 mm/day.

MEAN ZONAL WIND COMP. - DJF OF CTRL RUN (2YR MEAN)

MEAN ZONAL WIND COMP. - JJA OF CTRL RUN (2YR MEAN)

FIGURE B.12. Zonal Mean Zonal Wind Component for Control run in (a) DJF and (b) JJA.

AIR TEMP. DIFFERENCE - PJULY (+2C MINUS -2C)

FIGURE B.13. Zonal Mean differences in Air Temperature Between +2°C and -2°C Perpetual July Simulations.

FIGURE B.14. The Zonally Averaged Precipitation of the -2°C Simulation from Randall et al. (1992, Fig. 10; Thin Red Lines) and the same Field from GENESIS (Thick Blue Line with Open Circles).

FIGURE B.15. Zonally Averaged Precipitation for +2°C and -2°C Perpetual July Simulations.

FIGURE B.16. Global Sensitivity Parameter λ_g (km^2W^{-1}) vs. Cloud Feedback Parameter ($\Delta\text{CRF}/G$) Where ΔCRF is the Change in Cloud Radiative Forcing Induced by a Change in Climate and G the Global Mean Direction Radiative Forcing) for the 19 GCMs (Open Circles) and GENESIS (Solid Dot). GENESIS values are $\lambda_g=0.6336$, $\Delta\text{CRF}/G = 0.5650$. Background plot from Cess et al., 1990, Fig. 2. (CCM1 point indicated by circle with cross).

Surface Temperature vs. Cloud Radiative Forcing at Top of Atmosphere

Solar Cloud Radiative Forcing Surface vs. Top of Atmosphere

FIGURE B.17. (a) Surface temperature $[\Delta(T_s)/\Delta(N)]$ vs. cloud radiative forcing at top of atmosphere $[\Delta(RCF_{top}/\Delta(N)]$, and (b) solar cloud radiative forcing at the surface $[\Delta(SWCF_{sfc})]$ vs. at the top of the atmosphere $[\Delta(SWCF_{top})]$ for 19 GCMs and GENESIS (solid dot). Background plot is from Randall et al, 1992, Fig. 3 and Fig. 5.

TABLE B.1. Comparison of Model-Generated Precipitation for Larger Area Observations (From Jaeger, 1976) and a Compilation of Data for Beatty, Desert NWR, and Las Vegas by McGuirk et al. (1993).

	Source	DJF	JJA	Annual
Area Comparison	Model	3.64	2.42	2.51
	Observed ¹	1.33	0.89	1.23
"Point" Comparison	Model Yucca Mtn. (37.5° N, 116.5° W)	3.90	1.97	2.31
	Observed S. W. Nevada ² (avg. 3 stations)	0.43	0.27	0.32

1: from Jaeger (1976)

2: from McGuirk et al (1993)

TABLE B.2. Comparison of Summarized +2°C Minus -2°C Results Between 19 GCMs and GENESIS.

General	19 GCMs	GENESIS
Climate Sensitivity Parameter (λ_g)	0.65 ± 0.26	0.63
Clear-Sky Climate Sensitivity Parameter (λ_{gc})	0.47 ± 0.05	0.41
Cloud Feedback Parameter	See Fig. 16	0.565
Emitted Infrared v. Surface Temperature	2.46 ± 0.41	2.52
Clear-Sky Emitted Infrared v. Surface Temp.	2.34 ± 0.2	2.52
Net Downward Solar Flux v. Surface Temp.	0.72 ± 0.69	0.94
Clear-Sky Downward Flux v. Surface Temp.	0.20 ± 0.18	0.05
Total Cloud Amount (%)	$-2.1 \pm 1.3\%$	-0.55%
Surface Fields		
Net Energy Flux (W/m^2)	-7.61 ± 2.55	-8.68
Net Downward Solar Flux (W/m^2)	0.39 ± 2.55	2.40
Net Upward Longwave Flux (W/m^2)	3.27 ± 1.98	2.79
Net Downward Radiative Flux (W/m^2)	3.42 ± 5.19	5.19
Latent Heat Flux (W/m^2)	-12.15 ± 3.17	-15.38
Upward Sensible Heat Flux (W/m^2)	1.77 ± 0.96	1.55
Net Downward Clear-Sky Solar Flux (W/m^2)	-2.98 ± 0.36	(-1.91)
Net Upward Clear-Sky Longwave Flux (W/m^2)	7.29 ± 2.56	8.73
Net Downward Clear-Sky Radiative Flux (W/m^2)	4.35 ± 2.51	6.82
Solar Cloud Radiative Forcing (W/m^2)	2.58 ± 2.33	4.31
Longwave Cloud Radiative Forcing (W/m^2)	-3.8 ± 1.28	(-5.94)
Cloud Radiative Forcing (W/m^2)	-1.19 ± 1.98	-1.63
Precipitation (mm/day)	$.42 \pm 0.1$	(.53)
Temperature (°C)	$4.02 \pm .17$	3.96
Top-of-Atmosphere Fields		
Net Downward Solar Flux (W/m^2)	3.20 ± 2.07	3.78
Net Upward Longwave Flux (W/m^2)	-10.14 ± 1.37	-9.99
Net Downward Radiative Flux (W/m^2)	-6.85 ± 2.07	-3.8
Net Downward Clear-Sky Solar Flux (W/m^2)	0.66 ± 0.4	(0.18)
Net Upward Clear-Sky Longwave Flux (W/m^2)	-9.39 ± 0.81	-9.92
Net Downward Clear-Sky Radiative Flux (W/m^2)	-8.67 ± 0.76	(-9.74)
Solar Cloud Radiative Forcing (W/m^2)	2.59 ± 1.91	3.60
Longwave Cloud Radiative Forcing (W/m^2)	-0.64 ± 1.42	-0.07
Cloud Radiative Forcing (W/m^2)	1.81 ± 1.99	3.53
Planetary Albedo (%)	N/A	-1.93%

TABLE B.3. Comparisons of Summarized Surface Energy Budget Fields
Between Average of 19 GCMs and GENESIS.

Surface Fields	19 GCMs	GENESIS
Net Energy Flux (W/m^2)	-4.64 ± 7.56	-5.4
Net Downward Solar Flux (W/m^2)	162.10 ± 10.34	(193.5)
Net Upward Longwave Flux (W/m^2)	65.74 ± 5.43	(49.7)
Net Downward Radiative Flux (W/m^2)	96.35 ± 13.11	(143.8)
Latent Heat Flux (W/m^2)	-80.95 ± 12.86	(121.8)
Upward Sensible Heat Flux (W/m^2)	20.22 ± 7.54	27.4
Net Downward Clear-Sky Solar Flux (W/m^2)	219.06 ± 11.04	(232.4)
Net Upward Clear-Sky Longwave Flux (W/m^2)	95.83 ± 10.44	90.1
Net Downward Clear-Sky Radiative Flux (W/m^2)	121.66 ± 14.17	(142.3)
Solar Cloud Radiative Forcing (W/m^2)	-60.61 ± 8.74	(-38.9)
Longwave Cloud Radiative Forcing (W/m^2)	30.96 ± 3.07	(40.4)
Cloud Radiative Forcing (W/m^2)	-29.68 ± 9.26	(1.5)
Precipitation (mm/day)	2.79 ± 0.43	(4.2)
Temperature ($^{\circ}\text{C}$)	N/A	14.8

TABLE B.4. Comparisons of Summarized Top of Atmosphere Fields
Between Average of 19 GCMs and GENESIS.

Top-of-Atmosphere Fields	19 GCMs	GENESIS
Total Cloud Amount (%)	53 $\pm$ 8%	59.8%
Net Downward Solar Flux (W/m ²)	234 $\pm$ 14	240.4
Net Upward Longwave Flux (W/m ²)	238 $\pm$ 9	244.4
Net Downward Radiative Flux (W/m ²)	N/A	-3.8
Net Downward Clear-Sky Solar Flux (W/m ²)	284 $\pm$ 10	286.8
Net Upward Clear-Sky Longwave Flux (W/m ²)	267 $\pm$ 8	275.6
Cloud Radiative Forcing (W/m ²)	-21 $\pm$ 9	-15.5
Planetary Albedo (%)	N/A	29.2%

APPENDIX C

PRECIPITATION VARIATIONS IN SOUTHERN NEVADA

by

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APPENDIX C

PRECIPITATION VARIATIONS IN SOUTHERN NEVADA

C.1 INTRODUCTION

Yucca Mtn. Nevada is a potential site for the high-level nuclear waste repository. One reason for considering this site is the extreme aridity at present that results in a very deep water table. Because nuclear waste remains an environmental hazard for tens of thousands of years, it is necessary to inquire into the history of precipitation variations at Yucca Mtn. and environs to determine how much precipitation may have differed from the present.

Previous studies indicate that southern Nevada had high lake levels in the Pleistocene (Smith and Street-Perrott, 1983; e.g., Benson and Thompson, 1987). Precipitation may have been roughly a factor of two greater than present (Spaulding et al., 1984; Benson and Thompson, 1987). Other studies (Enzel et al., 1989, 1992; Stine, 1990) indicate that on centennial time scales nearby southern California and the Mojave Desert record increased precipitation about 400 and 3600 years ago. These were generally cold times in the Holocene (Crowley and North, 1991). On interannual time scales increased Pacific Coast precipitation has been linked to large-scale circulation changes associated with El Niño/Southern Oscillation (ENSO) and Sudden Stratospheric Warmings (SSW) (Blasing and Fritts, 1975; Schonher and Nicholson, 1989; McGuirk and Douglas, 1988).

The purpose of this paper is to determine how precipitation in Southern Nevada correlates with changes in southern California and whether these changes are also related to large-scale

circulation changes. A second purpose is to determine the magnitude of precipitation changes associated with wet events in southern Nevada so that we have a more quantitative constraint on the range of natural variability.

A critical assumption that we make is that the climate of Yucca Mtn. is assumed to be represented adequately by stations surrounding it within limited distances. These proxies for Yucca Mtn. will be adequate only if their precipitation signatures are all the same. In mountainous terrain, small distances can lead to large changes in microclimate. However, it is assumed that, even in this arid mountainous region, large scale forcing mechanisms will lead to commensurate annual scale precipitation modifications.

The methodology for this paper is a three-step process: 1) link the records for stations surrounding Yucca Mtn. to other, longer or higher quality, records; 2) relate both sets of records to known climate varying processes; 3) conclude by examining the implications of past changes for the future. The first step includes establishing a quantitative link between the precipitation at the several stations used in this study. The second step includes a quantitative assessment of both the strength and the reliability of the link between precipitation and mechanism.

C.2 THE LOCAL CLIMATE

The target site of Yucca Mtn. in southern Nevada is shown in Figure C.1. The primary winter moisture source is the Pacific Ocean, with moisture trajectories from a relatively low region of the Sierras to the southwest of the Mojave desert. Moisture for summer monsoonal rainfall is usually from the south and southeast. These moisture sources are restricted by very high mountains to the west and south (Sierra Nevadas and adjacent ranges and San Bernardino Mts.), smaller local ranges to the immediate south

(Spring Mts.), and to the east by the vast expanse of the Rockies. The relative heights of the mountains and the narrow range of moisture-bearing wind directions result in an arid climate. Although the moisture comes predominantly from the west and south, the actual groundwater recharge results from precipitation in higher regions to the east and north of Yucca Mtn. (Timber and Shoshone Mts. and Pahute Mesa; U.S. DOE, 1988).

The westward and southward mountain restrictions represent an upstream moisture sink for the Yucca region. However, southern California, on the upstream side of the mountain barriers is also a dry climate. An implication is that the climates of both regions are controlled to some extent by the same large-scale atmospheric processes.

C.3 DATA

Although precipitation records are available for a number of microclimates in the vicinity of Yucca Mtn. (e.g., the Nevada Test Site), they are all of short duration (1-28 years). However, a number of precipitation records for sites in southern Nevada and California extend back to 1900 and even earlier. The stations chosen for this study are Santa Barbara and San Diego, in southern California; Carson City, Austin and McGill in central Nevada; and Beatty, Desert National Wildlife Range (Desert NWR) and Las Vegas. The last three are in the region of Yucca Mtn., southern Nevada. Figure C.1 displays the relative positions of the stations and the Yucca Mtn. site.

The data for San Diego and Santa Barbara are from the work of McGuirk (1982) and represent monthly precipitation from Bulletin W (1926) and the Climate Data Summaries of States. These records are continuous, having had missing data interpolated from the average of the five preceding and following years to provide a conservative correction with respect to any climate signal. Two advantages of the California records are the analysis and careful

checking of the data quality of the coastal stations (McGuirk, 1982) and, especially, the record length at San Diego (123 years).

The Nevada data collected for this study are from the same sources. However, for the Nevada data, missing monthly totals were not replaced, and annual (and cool season) totals for years without the full complement of monthly data were considered unavailable.

Not a single original record was continuous for its entire length. The most significant hiatus occurred at Las Vegas where the station location changed in 1938; since the original and moved records overlapped, it was possible to correct the older Las Vegas record — 1895 through 1937 — to an equivalent record more representative of conditions at the relocated site.

This study used annual and six-month cool season totals of precipitation almost exclusively. The six-month cool season is January, February, and March of the year cited plus October, November, and December of the prior year. Monthly data from the record were summed, and disparate record annual totals were assumed to be clerical errors.

Table C.1 summarizes the length of record for the sites chosen and located in Figure C.1. Table values are annual and cool season, separated by "/". (Note that the annual and cool season record lengths can be different; e.g., the six months of data centered on January 1st of a year may be available for computing a total, while a full 12 months beginning with January of that year may not be.) Also presented in Table C.1 are station descriptive statistics — annual and cool season means and standard deviations. Cool season means were used to examine winter circulation features. The record lengths vary from 123 years at San Diego to only 47 years at Desert NWR, due east of Yucca Mtn.

Nevada annual means (Table C.1) range from about 32 cm to the north (Austin) to less than 11 cm southeast of Yucca Mtn. (Las Vegas and Desert NWR); the standard deviations are typically 30-50% of the means. At least for the Nevada stations, the cool season precipitation is about 50% of the annual means, but somewhat more variable (30-80%) than the southern California stations.

C.4 RESULTS

C.4.1 Station Correlations

Tables 2a and 2b summarize the cross correlations between the observations at each station; Table C.2a is based on annual totals and Table C.2b on 6-month cool season totals. It was anticipated that the observations for at least the Nevada stations would be highly correlated. This assumption was true for the three southern stations, which correlated highly (0.64-0.85). However, the southern stations correlated poorly (0.04-0.41) with the more northern stations; in fact, the northern stations correlated equally poorly with each other as well (0.22-0.41).

The above variations were not anticipated based on previous comparisons of regional precipitation throughout the southwestern U.S. (McGuirk, 1982; Stidd, 1967). The former, based on precipitation correlations for California coastal stations suggests typical correlation magnitudes of about 0.6-0.8 for stations separated by distances typical of those separating the Nevada stations, and given similar climate controls. This latter assumption obviously is not met in the arid desert and mountains of Nevada. Stidd (1967) demonstrated that the annual cycle of Nevada precipitation is controlled essentially by three features: topography, which will not introduce an interannual effect; winter Pacific storm tracks, which dominate the first eigenmode of precipitation; and, the "southwestern monsoon", which is described

by the second and third eigenmodes. The Nevada stations should vary together in the Pacific winter control because all stations, except McGill, have high amplitudes in Stidd's leading eigenmode (72% of the variance). The southern and northern stations correlate poorly in eigenmode amplitudes in the "monsoonal" eigenfunctions (totaling 21% of the variance); thus, the correlation of summer precipitation among all the Nevada stations should be considerably weaker.

This anticipation was determined not to be the case, however. It matters little whether annual totals or only 6-month cool season totals are used. At nearly all stations, the cool season cross correlations are actually smaller (but not statistically so) than correlations based on annual totals. What is observed is that, for annual totals, precipitation at the three southern Nevada stations surrounding Yucca Mtn. correlate more highly with precipitation at San Diego (0.69-0.77) and Santa Barbara (0.60-0.67) than with the northern Nevada stations. Presumably the correlation is higher at San Diego because the mountains are lower between the Nevada stations and San Diego than the mountains toward Santa Barbara. The most important conclusion of these tables is that about half of the variance of precipitation in southern Nevada can be determined from a knowledge of precipitation of southern California coastal stations. This conclusion is true for both annual totals and cool season (winter-dominated) totals.

C.5 INTERANNUAL VARIABILITY OF PRECIPITATION

C.5.1 El Niño Variation

Schonher and Nicholson (1989) relate California precipitation to the occurrence of ENSO. Use of Quinn et al's (1987) ENSO climatology and the present longer precipitation records allows a more definitive correlation between ENSO and precipitation, at least for the more localized southern California and Nevada

region. Rasmusson (1984) used Quinn's data [which later was documented by Quinn et al. (1987)] to classify ENSO intensity on a 1-4 scale, 4 being most intense. Here, we use Rasmusson's (1984) published table, but refer the work to Quinn. Tables 3a and 3b describe annual and cool season precipitation, respectively, for all available events of the Quinn et al. (1987) record. The first three columns give the means for all ENSOs (left), the strongest two ENSO classifications — 3 and 4 (center), and only the most intense ENSOs — 4 (right). The numbers in parentheses give the number of events in the sample. The fourth and fifth columns list climatological information for the entire precipitation record at each station.

For annual precipitation during ENSO occurrence (Table C.3a, all ENSO events) the mean ENSO annual precipitation is higher than the full record mean (annual climatic mean) at all stations. Significance of the means ranges from the 5% to 25% confidence levels, based on a normal distribution of means of equal variance, and using a simple t-test with pooled variance. Only the Desert NWR and San Diego means exceed the 10% level (box enclosed). Significance of moderate to intense ENSO means is similar, with addition of Beatty exceeding the 10% level. However, the category 4 ENSO means (Table C.3a, intense ENSO events) exceed the 10% significance level for all Nevada and California stations, with the California stations, Carson City, Beatty, and Desert NWR exceeding the 5% level. With only two exceptions (Austin and Carson City for moderate [3&4] ENSO only), increasing ENSO intensity is associated with increasing annual precipitation.

The results are more mixed for the cool season (Table C.3b), where precipitation is poorly related to ENSO occurrence (no ENSO means meet the 10% confidence level). The most intense ENSOs, category 4, average wetter than all ENSOs together except at McGill and Carson City. However, in contrast with the annual means, average moderate to intense ENSO does not represent an

increase in cool season precipitation over all events taken together.

Generally, the variation among the ENSO events, as measured by the standard deviation among ENSO events, is larger than the climatological standard deviations; the variance is typically 40% greater for ENSO classifications (comparisons not shown); however, based on a chi-square distribution (conservative for precipitation), only San Diego variance meets an F-test for significantly different variances at the 5% level. Thus, even though the precipitation seems to vary more among ENSO years than among years chosen randomly from climatology, this increased variability is not large in a statistical sense.

In summary, ENSOs are wetter and slightly more variable than average throughout southern California and Nevada. The stronger the ENSO event, the stronger the precipitation signal. Although the signal can be detected in cool season precipitation, both the length of the averaging period and its sequencing with the onset of ENSO effect lead to a much stronger response in annual precipitation totals. The signal is stronger on the California coast (San Diego and Santa Barbara) than near the Yucca Mtn. region. In Nevada, the signal is larger and more persistent in the south, around the Yucca Mtn. region, than it is in central Nevada.

C.5.2 Extreme Values

Most years with large precipitation are associated with ENSO. Table C.4a summarizes all observations in excess of two standard deviations. Six of these observations exceeded the 3-sigma level, and of these, one exceeded 4-sigma (San Diego, 1884). Table C.4b compares these increases of precipitation during extreme years with the average precipitation at each site. In most cases extreme years have a 70-100% increase over the annual mean, with a few years having about a 150% increase. Over two thirds of the

large anomalies occurred during ENSO; over 50% with the strongest ENSO classification. The years 1941 and 1982-3 dominate Tables 4a,b. Although Quinn et al. (1987) note that 1884 may have been among the wettest ENSOs ever observed, only the San Diego and Santa Barbara records extended back to this event in this calculation.

Although the excessively wet months occurred during the normal wet seasons at every station without exception, the extremely wet non-ENSO years were in no case the result of a single wet month. Nine of these ten annual totals were made up of at least four extremely wet months (greater than 2.5 cm); Las Vegas in 1931 had only three such months, but its mean annual precipitation is only 10.97 cm. Except for Beatty in 1978, the wet months of these non-ENSO years were scattered throughout the year; at Beatty, the heavy precipitation was restricted to January through April. Namias (1979) has discussed circulation patterns associated with the non-El Niño 1978 wet year, identifying a weakening of the western North American ridge and persistent low pressure anomaly off the west coast.

Thus, most of the wettest years occur systematically during ENSO. Extremely wet years are not the result of a single catastrophic precipitation event in a single month, but are characterized normally by above average wetness over many months scattered throughout the year.

C.5.3 Winter SSW Variations

Little skill is available for forecasting yearly precipitation anomalies into the future. The best that can be done is to examine the statistical frequency of certain kinds of precipitation patterns and then to relate these patterns to the local station precipitation at the Yucca Mtn. region. McGuirk and Douglas (1988) showed that Sudden Stratospheric Warming (SSW) can affect precipitation anomalies for periods of up to two months; it

may be that these anomalies are of sufficient magnitude to affect the entire year, or at least the six-month cool season. However, Nevada has the weakest response of any of the contiguous U.S. states to SSW, at least in temperature. Additionally, Diaz and Fulbright (1981), in an Empirical Orthogonal Function (EOF) decomposition of U.S. precipitation, distribute Nevada winter precipitation almost uniformly across three of the first four eigenfunctions. This distribution suggests that the factors controlling Nevada precipitation are not simple.

Table C.5 presents the comparison of annual, cool season and winter precipitation over Nevada and southern California for normal climatology and 16 periods of SSW [SSW periods from Labitzke, 1982; McInturff, 1978; Roderick Quiroz, NMC (personal communication)]. At San Diego and around Yucca Mtn., SSW precipitation totals are smaller for winter and annual totals. No signal at all exists for the cool season, which contains precipitation from three or four months which occur before the SSW event. None of the SSW vs. climatology differences are statistically significant. If a physical difference exists in precipitation during SSW events, it does not lead to a meaningful difference in precipitation at Yucca Mtn. To the extent that the Pacific circulation pattern described by Fritts et al. (1979) and discussed by Enzel et al. (1989) is associated with the major circulation disturbances of SSW, this event does not seem to affect precipitation consistently near Yucca Mtn.

C.6 DISCUSSION AND SUMMARY

This paper relates precipitation fluctuations to specific atmospheric circulation changes and climate altering mechanisms, with specific application to precipitation change at Yucca Mtn. north of the Mojave Desert. The analysis included stations around Yucca Mtn., stations farther north in central Nevada, and stations along the southern California Coast. To the extent that

fluctuations in the precipitation records are related to large scale weather or climate fluctuations, the possibilities of climate change can be estimated.

The most significant enhancement of precipitation at Yucca Mtn. documented in this study is due to El Niño. Annual precipitation increases near Yucca Mtn. by about 30%, on average, during strong El Niño events. The majority of statistical outliers in annual precipitation, about 70%, are associated with ENSO events. Individual strong ENSO events show annual local anomalies of precipitation of 2-2.5 times the mean.

Wintertime precipitation enhancement, or decrease, due to stratospheric warming events, is not likely at Yucca Mtn., even though this mechanism is strong in other parts of the U.S. Enzel et al. (1989; 1992) have presented evidence that this may be an important mechanism over longer time scales. At best, estimates from McGuirk and Douglas's (1988) analysis would limit this effect to about twice the monthly precipitation for the one or two months over which the phenomenon acts. Although a related, similar phenomenon (atmospheric blocking) can act longer, its ebb and flow is not now predictable. Even if this mechanism could operate (and this paper suggests that SSW-related blocking has not been significant over the record of study), it might occasionally add several centimeters of precipitation to the annual total.

The extreme-value results of a 70-150% increase in annual precipitation may represent an upper limit to historical variations in this region, as approximately the same values have been obtained for estimates of centennial-scale climate fluctuations of the last few thousand years (Enzel et al., 1989; Stine, 1990) and ice-age changes during the last glacial maximum (e.g., Spaulding et al., 1984; Benson and Thompson, 1987).

It might be conjectured that past changes in lake levels in the Great Basin could represent a more frequent occurrence of the

types of events which represent extreme cases at the present time. For example, Enfield and Cid S. (1991) estimate that the most probable frequency of strong El Niño has fluctuated by about a factor of 1.5 on centennial time scales. However, a doubling of the frequency of occurrence of, say, a mean strong El Niño value of Table C.3a represents only about a 10% increase of annual average precipitation.

Figure C.2 illustrates a comparison of category 3 and 4 ENSO events with our longest station record (San Diego). Note again the change in mean of only about 10%. These results suggest either: 1) that other factors have to be considered to explain decadal-scale fluctuations (e.g., temperature); 2) that hydrological models need to be re-examined; or 3) that increased consideration must be given to lake level changes associated with repetitions of strong El Niños during brief intervals (< 20 years?). Kotwicki and Isdale (1991) have discussed how such episodic variations affect ephemeral lakes in Australia.

Our results may also have implications for the potential Yucca Mtn. repository. Czarnecki (1985) has calculated that a 100% increase in precipitation at Yucca Mtn. would increase the water table 130 m, less than the minimum distance (180 m) between the base of the potential repository and the water table in a recent design given by Rautman et al. (1987). The Czarnecki calculation is subject to uncertainties in the hydrological model; for example, Winograd and Szabo (1988) found only 10 m water table fluctuations in the Pleistocene for the estimated two-fold precipitation increase. When coupled with previously mentioned results from the Little Ice Age and last glacial maximum, our results lend further support to indications that natural variability at Yucca Mtn. has not exceeded a threshold level that could endanger the site.