ANALYSIS OF FACTORS CONTRIBUTING TO UNCERTAINTY IN ESTIMATING FUTURE CLIMATES AT YUCCA MOUNTAIN

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Prepared by

G. Walter

Center for Nuclear Waste Regulatory Analyses
San Antonio, Texas

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ABSTRACT

This report summarizes the approach taken by the U.S. Department of Energy (DOE) to estimate the nature and sequence of future climate, and the uncertainties that may affect these estimates. The approach taken by DOE to estimate future climate conditions at the potential Yucca Mountain high-level waste repository is based on a correlation of paleoclimate conditions with Earth's orbital cycles. Paleoclimate conditions were estimated based on ostracode and diatom assemblages in the Owen's Lake sediment core and a comparison of these assemblages to those seen under present day climate conditions at specific locations throughout the western United States. The timing of paleoclimate changes was then based on temperature variations inferred from the oxygen isotopy of the Devil's Hole calcite core and qualitatively correlated to variations in insolation based on Earth's orbital cycles. Based on this correlation, rules were developed for defining future climate states based on future variations in Earth's orbital eccentricity and precession index. This retrospective approach to estimating future climate conditions is one of the approaches identified in acceptance criteria developed by the U.S. Nuclear Regulatory Commission (NRC, 1997, 2003). The DOE approach projects that the climate in southern Nevada is currently transitioning from an interglacial climate to a sequence of intermediate and monsoonal climates that will culminate in a glacial climate starting about 38,000 years after present.

Research performed within the last five years suggests that the timing of climate changes over the next 100,000 years may be difficult to infer from the patterns of climate change over the last 500,000 years due to the unusually low eccentricity of Earth's orbit and, possibly, the influence of anthropogenic greenhouse gases in the future period. Various types of mathematical and numerical climate modeling have suggested that the transition to the next glacial climate may be substantially delayed. After 100,000 years, the Earth's orbital climate forcing will be stronger, and the influence of greenhouse gases may have diminished so that the Pleistocene climate history may offer a better analog in terms of timing of climate changes. In terms of the characteristics of future climates (i.e., mean annual precipitation and temperature, seasonal weather patterns, and storm intensities), the characteristics inferred from paleoclimate reconstructions and present day analog records may represent the range of climate conditions that could occur in the future, even if the time of these climates cannot be reliably estimated. There remains uncertainty in future climate conditions during the period that anthropogenic effects may result in climates in southern Nevada that do not have analogs with present or Pleistocene climates, such as prolonged El Niño conditions. The nature, likelihood, and duration of such nonrepresentative climate conditions cannot be reliably assessed based on current research. Over longer time periods, the range of conditions inferred from the Pleistocene paleoclimate record may reasonably bound future climate during the period of geologic stability.

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QUALITY OF DATA, ANALYSES, AND CODE DEVELOPMENT

DATA: No CNWRA-generated data are contained in this report.

ANALYSES AND CODES: A Fortran program documented in Scientific Notebook 699 was used to generate the eccentricity and precession index for Earth's orbit. This program utilizes a subroutine obtained from NASA (2005) to compute Earth's orbital cycles.

NASA. "Solar Radiation at Top of Atmosphere." <http://aom.giss.nasa.gov/SOLAR/ORBPAR.SUB> (August 22, 2005).

1 INTRODUCTION

Estimating future climate conditions in southern Nevada is important to understanding the postclosure performance of the potential high-level waste geologic repository at Yucca Mountain because climate strongly affects the rate and volume of water that infiltrates into the unsaturated zone above the repository. The rate and volume of infiltration that becomes deep percolation at the repository level affects the volume of water that is available to contact radionuclides in failed waste packages and carry these radionuclides to the saturated zone, and ultimately to the accessible environment. Climate affects not only the amount of water entering Yucca Mountain itself, but also regional recharge to aquifers and the rate of flow through the aquifer. Climate also can affect the calculation of exposures to radionuclides potentially released from the potential repository through such processes as irrigation rate and evaporative cooler use (Bechtel SAIC Company, LLC, 2003). The purpose of this report is to

- Summarize the U.S. Department of Energy (DOE) approaches to estimate characteristics of future climate states at Yucca Mountain, as well as their sequence and duration

- Reexamine the 1997 U.S. Nuclear Regulatory Commission (NRC) evaluation of methods for estimating future climate change at Yucca Mountain (NRC, 1997)

- Summarize recent research on future global and regional climate change with and without the effects of anthropogenic climate impacts due to the release of greenhouse gases

2 CHARACTERIZATION OF CLIMATE

The primary purpose of studying past, present, and possible future climate at Yucca Mountain has been to support estimates of infiltration of meteoric water into the mountain. Trewartha (1954) defined climate as "... a composite or generalization of the variety of day-to-day weather conditions." The description of a climate state requires defining not only the major features of long-term weather, mean annual precipitation and temperature, but also typical seasonal variations in precipitation, temperature, and characteristics of weather events, such as the duration and intensity of rainfall and snow events. The general aspects of past, present, and possible future climates at Yucca Mountain have been characterized by estimates of mean annual precipitation and mean annual temperature (Bechtel SAIC Company, LLC, 2004; Sharpe, 2002). Meteorological data from the vicinity of Yucca Mountain and from sites in the western United States with present day climates believed to be similar to those of past and future climates were used for analyses requiring more detailed climate characterization (e.g., seasonal distribution of precipitation and storm intensity).

3 APPROACHES TO ESTIMATING FUTURE CLIMATE AT YUCCA MOUNTAIN

This section describes approaches that have been taken by the DOE to estimate the characteristics of future climates, as well as their sequence and duration. It also summarizes findings and recommendations by NRC with respect to the estimation of future climates at Yucca Mountain.

3.1 DOE Approach to Estimating Future Climates

The approach taken by DOE to estimate future climate at Yucca Mountain is described in Sharpe (2002)[1] and Bechtel SAIC Company, LLC (2004). Sharpe (2002) presents an analysis of possible future climates for the period of 10,000 to 1,000,000 years after present. The Bechtel SAIC Company, LLC (2004) report considers only the present to 10,000 years after present, the compliance period specified in 40 CFR Part 197 as promulgated in 2001.

Both of these studies developed estimates of future climates at Yucca Mountain based on a correlation of past climates in the southern Great Basin with cyclical changes in insolation due to Earth's orbital mechanics, the so-called Milankovitch Cycle (e.g., Elkibbi and Rial, 2001; Paillard, 2001). The DOE investigators first established an undated sequence of late Pleistocene climatic conditions by correlating climate conditions to ostracode and diatom assemblages in the Owen's Lake sediment core (Smith and Bischoff, 1997). Climate states over the last 400,000 years were inferred from the geographical and climatic conditions under which these assemblages occur at the present time. Based on this analysis, Bechtel SAIC Company, LLC (2004) described three climate states likely to occur during the next 10,000 years at Yucca Mountain: present-day (interglacial), monsoon, and glacial transition. Sharpe (2002) described six climate states that had occurred during the last 568,000 years and, as will be discussed later, developed a sequence of climate states that could occur during the next one million years. The Sharpe climate states were modern (interglacial), intermediate (similar to the glacial transition climate, but containing a monsoon stage during the transition from interglacial to a glacial climate), and full glacial (consisting of three glacial climates with different mean annual precipitation and temperature). These climate states were assumed to repeat in a fixed sequence, as illustrated in Figure 1. Although Sharpe (2002) included a monsoonal climate only in the transition from interglacial to glacial climate, some paleovegetation studies have indicated monsoonal conditions during the glacial to interglacial transitions (Bull, 1991).

Although the Owen's Lake paleoecology analysis provided a sequence of climate states inferred to have occurred over the last 400,000 years, absolute dates and durations of these climate states are difficult to deduce from the sedimentological record. For this reason, timing of the climate states was derived by correlating the Owen's Lake sequence with the dated oxygen isotope record from the Devil's Hole calcite core (Winograd, et al., 1992). The Devil's Hole calcite core provides a dated record (derived from thorium-230–uranium-234–uranium-238 dating) of changes in the oxygen-18 composition of the calcite extending from approximately 568,000 years before present to 60,000 years before present. The oxygen-18 content of the calcite is correlated with the temperature of precipitation and, presumably, the temperature of recharge water to the aquifer discharging at Devil's Hole, with higher oxygen-18 indicating colder precipitation and recharge. The oxygen-18 record from Devil's Hole was thus used by Sharpe (2002) and Bechtel SAIC Company, LLC (2004) as a dated, but qualitative, indicator of

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[1]A report entitled Future Climate Analysis—10,000 Years to 1,000,000 Years After Present MOD–01–001 REV01 attributed to Sharpe and dated 2003 referenced in Bechtel SAIC Company, LLC (2004) appears to be a revision to Sharpe (2002), but the 2003 report could not be located on the Licensing Support Network. A copy of the report referenced as Sharpe (2003) was located on the website of the Harry Reid Center for Environmental Studies, University of Nevada, Las Vegas (http://hrcweb.nevada.edu/qa/report/MOD–01–001.pdf.). The data in the report is described as unqualified and cannot be used for "quality affective purposes." A review of the 2003 version of the Sharpe report indicates it does not differ in any substantive way from the 2002 version.

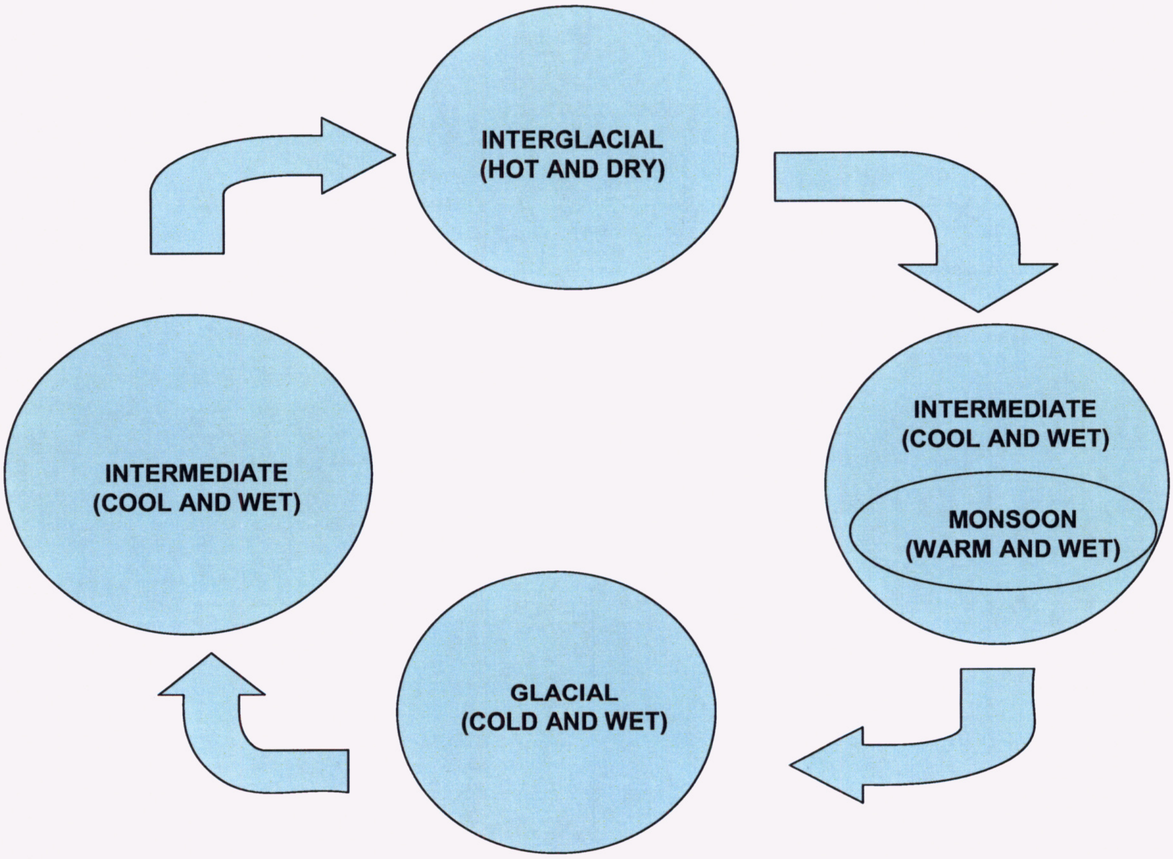

Figure 1. Sequence of Climate States Inferred From Owen's Lake Paleoecology [Modified From Sharpe (2002)]

temperature in the region of southern Nevada containing Yucca Mountain and the recharge area of Devil's Hole. By correlating the sequence of climate states derived from the Owen's Lake paleoecology analysis with the temperature history implied by the Devil's Hole oxygen-18 record, a dated sequence of climate states was developed for the period 568,000 years before present to 60,000 years before present. The timing of the climate sequence from 60,000 years before present to present was dated using isotopic data from the Vostok Ice Core (Petit, et al., 1999).

The dated climate sequence was correlated with changes in the eccentricity of Earth's orbit around the Sun and precession of Earth's axis of rotation (Figure 2) over the past 500,000 years to develop rules for predicting climate transitions in the future from Earth's orbital cycles. These rules are reproduced in the Appendix. The basis used to develop these rules is illustrated in Figure 3 (Sharpe, 2002, Figure 6-6) for the time period 250,000 years before present to present and basically depends on matching climate states with peaks and valleys in the precession index. The precession index is defined as

$$C = e \sin(\omega) \tag{1}$$

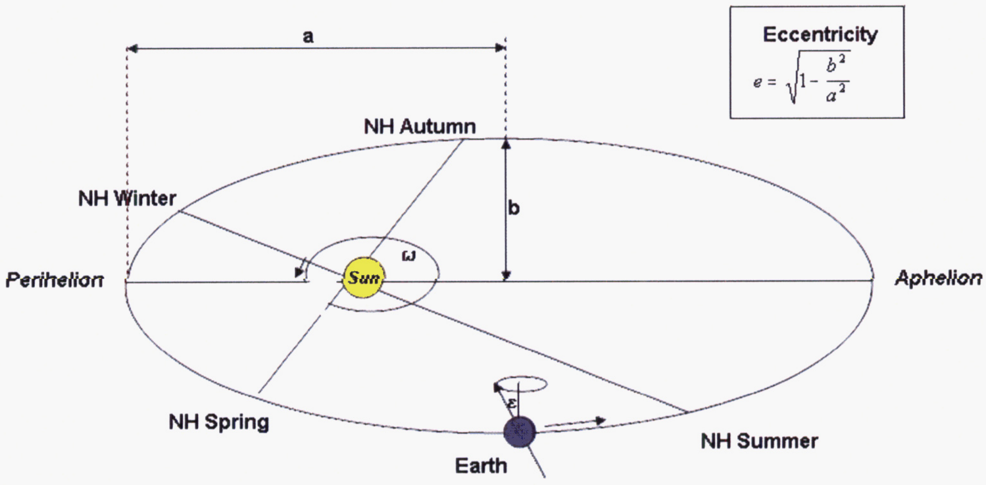

Figure 2. Illustration of Earth's Orbital Parameters Eccentricity (e) and Precession (ω). NH Indicates Northern Hemisphere.

where

C	—	precession index
e	—	eccentricity of Earth's orbit around the Sun
ω	—	longitude of perihelion.

The combined effects of eccentricity and precession largely determine Earth's insolation (i.e., the amount of solar radiation received by the Earth). Eccentricity determines the annual global insolation and precession affects the distribution between the Northern and Southern Hemispheres. Although not immediately obvious, the numbers associated with each peak and valley in the precession index in Figure 3 were derived from the correlation of the timing of transitions between climate states based on the Owen's Lake microfauna assemblages and the Devil's Hole chronology with the precession index (Sharpe, 2002; Bechtel SAIC Company, LLC, 2004). The precession index peak numbers generally start with an inferred end of an interglacial climate and end at the peak immediately preceding the subsequent interglacial. The number of peaks between interglacials typically varies from four to five. The manner in which the precession index is displayed in Figure 3 tends to obscure the correlation between climate and eccentricity and make the rules in the Appendix less than clear when applied to future climate. Furthermore, the rules listed in the Appendix do not appear to have been applied rigorously over the entire paleoclimate record. To clarify the correlation between climate and Earth's orbital cycles implied by the interpretation of Sharpe (2002) and Bechtel SAIC Company, LLC (2004), consider the redepiction of their interpretation shown in Figure 4. This figure shows the eccentricity and precession index obtained from a data file from the National Oceanographic and Atmospheric Administration (2005). In Figure 4, the precessional index is plotted within the envelope of eccentricity, and the climate transitions and precession peaks (valleys) are labeled to correspond to those of Sharpe (2002) in Figure 3. Depicted in this manner, it is clear that the interpretation of Sharpe (2002) and Bechtel SAIC

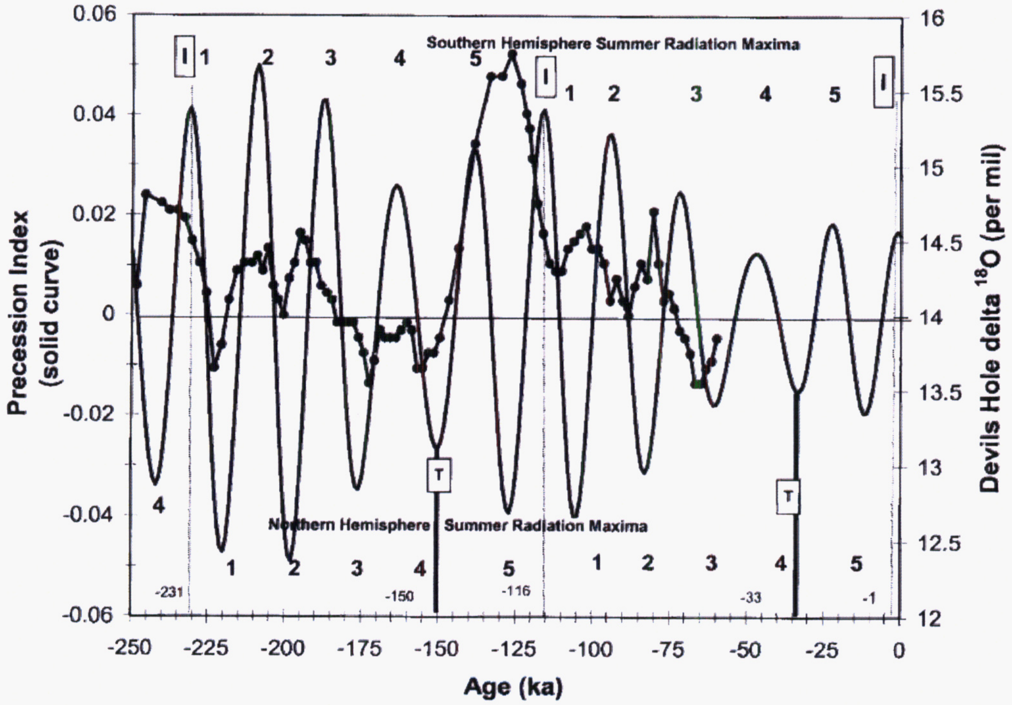

Figure 3. Example of Correlation Between Devil's Hole Oxygen-18 Chronology and Precession Index From Figure 6-6 of Sharpe (2002). The Smooth Curve Is the Precession Index, and the Line With Dots Is the Devil's Hole Oxygen-18 Data. The Boxes With *I* Mark the Date of the Inferred Beginning of a Transition From an Interglacial Climate to Glacial Climate. The Boxes With *T* Mark the Start of a Transition From Glacial to Interglacial Climates. The Numbers Associated With the Peaks and Valleys of the Precession Index Curve Are the Indexes of Precession Peaks Between Interglacial Climates.

Company, LLC (2004) implies a transition from an interglacial to glacial climate (I event) that starts with a precession index peak near a Southern Hemisphere insolation peak corresponding to an eccentricity peak. As illustrated in Figure 4, this triggering precession index peak may be slightly before or after a peak in the eccentricity cycle. The transition from a glacial to interglacial climate (*T* event) starts with a precession index trough near a Northern Hemisphere insolation maximum. This triggering precession event may be slightly before or after a trough in the eccentricity cycle. Based on this interpretation, the glacial cycles have a periodicity of approximately 100,000 years that correlates with the period of Earth's eccentricity, although the climatic changes are actually triggered by the variations in insolation due to the precession index cycle.

Figure 5 shows the extension of the climate interpretation of Sharpe (2002) for 250,000 years after present based on the rules derived from past climates and Earth's orbital cycles. The next 125,000 years represent a relatively infrequent period during which the eccentricity of Earth's orbit is very small and the variations in the precessional index and insolation are correspondingly small. The basis for the number sequence of precession peaks during this

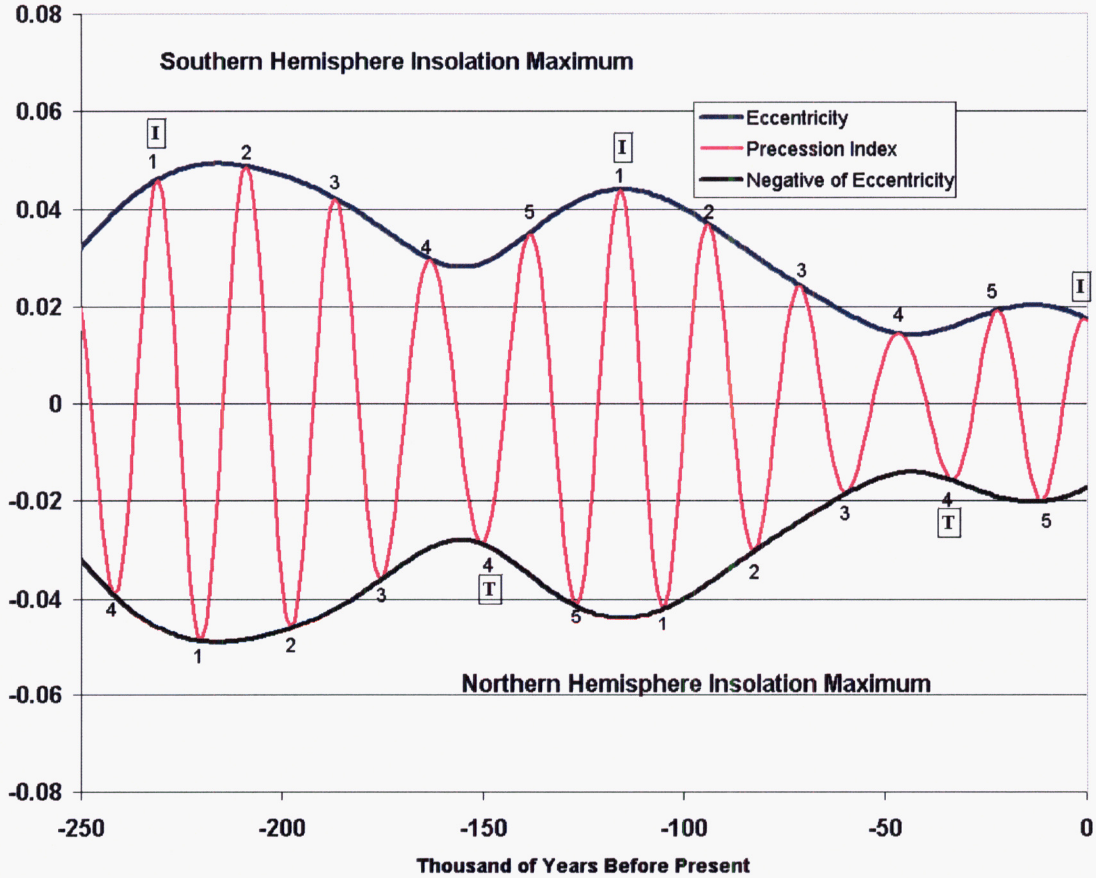

Figure 4. Reconstruction of Sharpe (2002) Climate Sequence for 250,000 Years Before Present to Present Matched With Precession Index and Eccentricity From National Oceanographic and Atmospheric Association (2005). The Negative of the Eccentricity Is Plotted to Highlight That the Precession Index Is a Function of Eccentricity and Falls Within an Envelope Defined by Eccentricity. The Box with *I* Marks the Beginning of the Transition From Interglacial to Glacial Climate According to Sharpe. The Box With *T* Marks the Transition From Glacial to Interglacial Climate.

period by Sharpe (2002) is less obvious than that for the past periods because this future period does not contain a clearly defined eccentricity peak. The result is that the period from 75,000 to 150,000 years after present contains only three peaks. As noted by Sharpe (2002), this is the only period in the 1 million years before and after present with less than four precession peaks according to Sharpe's numbering scheme. Figure 6 shows the same time period with the eccentricity and precession index plotted on the same scale and Sharpe's numbering and climate change indices added. The eccentricity and precession were computed using a simplified solution to the orbital cycles from Berger (1978) obtained from NASA (2005). Figure 6 further illustrates the low amplitude of eccentricity variation during the next 125,000 years and that, despite the presence of a slight eccentricity minimum at approximately 40,000 years after present, there are no clear peaks in eccentricity or the precession index that can be used to

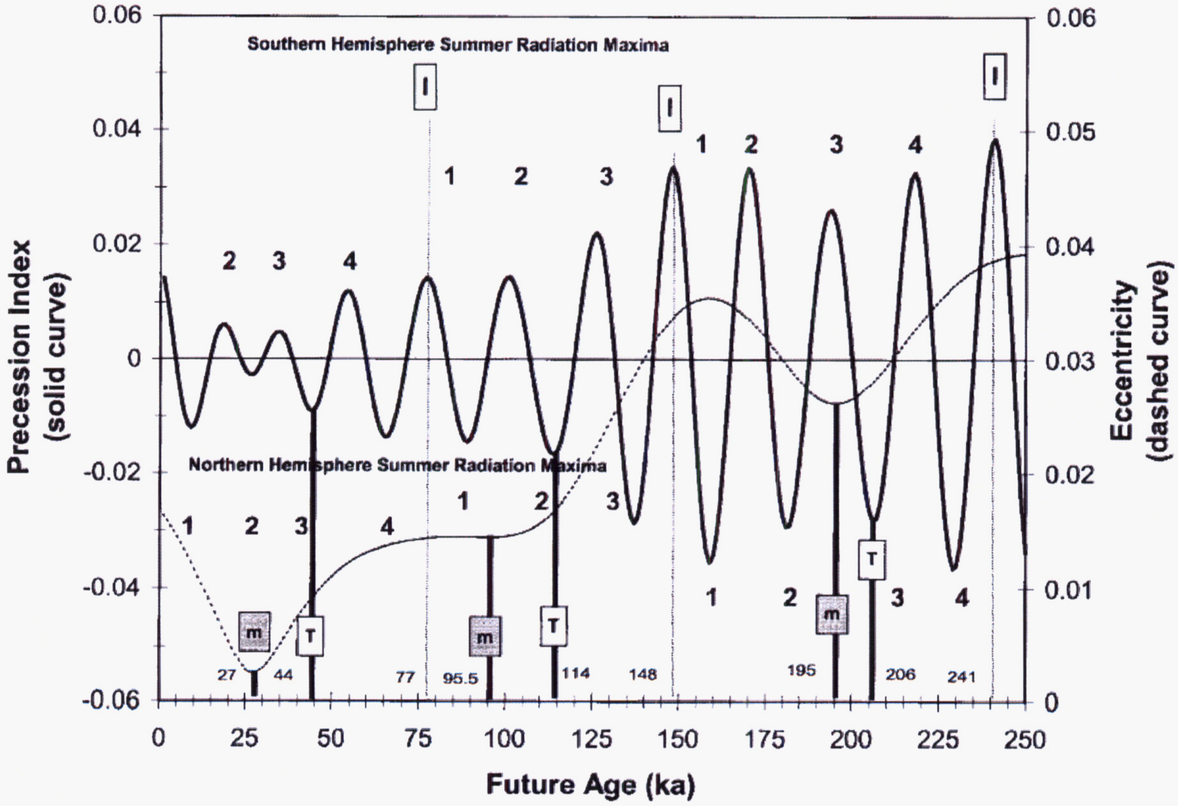

Figure 5. Estimated Future Climates From Sharpe (2002). Boxes With / Indicate Start of Transition From Interglacial to Glacial Climate. Boxes With *T* Indicate Start of Transition for Glacial to Interglacial Climate. Boxes With *M* Indicate Minimum in Northern Hemisphere Summer Insolation.

define the onset of a glacial transition using the paleoclimate analysis and rules of Sharpe (2002). Other estimates of future climate conditions during the next 100,000 years will be discussed in Section 4.

3.2 NRC Issue Resolution Status Report on Methods to Evaluate Climate Change

NRC considered methods for estimating future climates at Yucca Mountain in an Issue Resolution Status Report in 1997 (NRC, 1997). The NRC staff concluded that careful consideration of indicators of past climatic conditions in southern Nevada would provide adequate information to bound the likely range of future climate conditions. The NRC staff also concluded that although anthropogenic influences on climate (i.e., emission of greenhouse gases such as carbon dioxide and methane) could overwhelm natural climate cycles inferred from the past 1 to 2 million years, the anthropogenic influences on climate are likely to diminish over the next few thousand years, allowing natural cycles to be reestablished. This conclusion was consistent with the results of an expert elicitation study on future climate (DeWispelare, et al., 1993) in which three of the five participating experts believed that the principal effects of greenhouse gas emissions would dissipate in 3,000 to 5,000 years. The other two experts believed that the effects would last much longer.

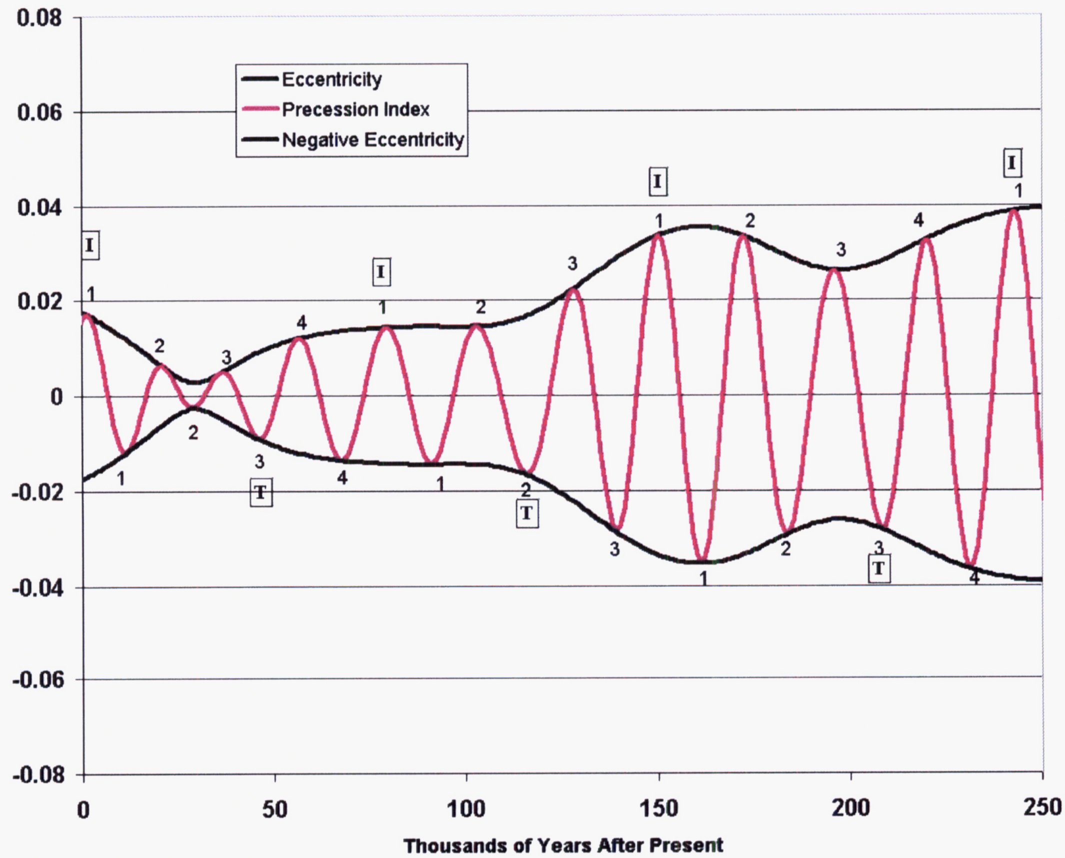

Figure 6. Reconstruction of Sharpe (2002) Climate Sequence for Present to 250,000 Years After Present With Precession Index and Eccentricity Computed From NASA (2005). The Negative of the Eccentricity Is Plotted to Highlight That the Precession Index Is a Function of Eccentricity and Falls Within an Envelope Defined by Eccentricity. The Boxes With *I* Mark the Beginning of Transitions From Interglacial to Glacial Climates. The Boxes With *T* Mark the Transitions From Glacial to Interglacial Conditions.

The 1997 NRC review acknowledged that significant uncertainty existed in the estimation of future climate, including the effects of anthropogenic activities on future climate. The report also acknowledged that the low amplitude of orbital effects on insolation during the next 100,000 years did not have an analog in the paleoclimate records and "Updated solar insolation calculations…should be used to evaluate time periods greater than 50,000–100,000 years after present..." (NRC, 1997, p. 15). Although the NRC report did not attempt to make specific estimates of future climate conditions, it did state that

> The assumption that pluvial [wet and cool] conditions will return to Yucca Mountain during the next 10 kyr has the advantage that useful estimates of future climate can be obtained even though the scientific debate about the causes of climate change continues unabated. (NRC, 1997, p. 15)

Assuming pluvial conditions would return to Yucca Mountain during the performance period of the repository was regarded as reasonably conservative because such conditions would likely increase net infiltration into the mountain and increase seepage at the repository horizon.

The 1997 NRC review also commented on the role of mathematical climate models in estimating future climate. Based on the state of the art at the time, the NRC staff believed that "…attempts to use GCMs [global circulation models] to predict climate changes over tens of thousands of years would almost certainly remain controversial, leading to debate over the competence of one model and data set vs. another" (NRC, 1997, p. 13). Pursuant to this concern about mathematical climate models, the 1997 NRC report provided the following acceptance criterion:

> The staff will not require climate modeling to estimate the range of future climates. If DOE uses numerical climate models, determine whether such models were calibrated with paleoclimate data before they were used for projection of future climate, and that their use suitably simulates the historical record (NRC, 1997, p. 6).

A primarily concern with respect to the use of mathematical climate models was that such models could predict a prolonged period of semi-arid conditions at Yucca Mountain (at least over the next 10,000 years) that would not lead to a reasonably conservative estimate of net infiltration. The acceptance criterion in the Yucca Mountain Review Plan with respect to this point is

> Verify that paleoclimate information is evaluated over the past 500,000 years as the basis for projections of future climate change. For example, confirm that numerical climate models, if used for projection of future climate, are calibrated based on such paleoclimate data (NRC, 2003, p. 2.2-58).

In summary, the preferred approach to characterizing future climate conditions in assessing the performance of the potential repository by DOE and NRC has been to rely on paleoclimate data to estimate the likely range of future climate conditions.

4 EVALUATION OF UNCERTAINTIES AFFECTING FUTURE CLIMATES

As acknowledged by DOE and NRC, estimation of future climate conditions at Yucca Mountain is affected by uncertainty. This uncertainty affects both the characteristics of future climate states (e.g., mean annual precipitation, mean annual temperature, seasonal distribution of precipitation, and storm characteristics) as well as the timing of transitions between climate states. The approach taken by DOE was to construct a future climate sequence based on correlations between paleoclimate interpretations and Earth's orbital cycles, as described in Section 3.1.

This section discusses some of the principal uncertainties associated with this paleoclimatic approach. For the purposes of this discussion, uncertainties associated with the characterization of past climate conditions, such as inferring mean annual precipitation and temperature from proxy data, will not be considered. Rather, only the uncertainties associated with projecting past climates into the future will be addressed. These uncertainties determined

the assumptions required for the projection of future climates by Sharpe (2002) and Bechtel SAIC Company, LLC (2004). The key assumptions, as stated in Sharpe (2002) are

- Climate is cyclical over 400,000-year periods, and Earth is entering into the next 400,000 cycle

- Past climate change can be timed with an Earth-orbital clock of precession and eccentricity so that the timing of future climate change can be estimated from the orbital clock

- Past glacial/interglacial climates differ from each other, and the nature of particular past climates should repeat themselves in a predetermined order

- Long-term Earth-based climate forcing functions, such as tectonic change, have remained relatively constant over the past 500,000 years and will remain constant for the next 10,000 or more years

These assumptions all relate to the ability to identify patterns in past climate changes and to extrapolate these patterns into the future based on their correlation with Earth's orbital cycles.

Sharpe (2002) and Bechtel SAIC Company, LLC (2004) also identified uncertainties affecting future climate projections based on uncertainty in the paleoecological record, past climate reconstructions, and correlations between the climate reconstructions and Earth's orbital cycles. They also acknowledged that discrete events, such as volcanic activity, meteor showers, and tectonic change, could affect the sequence of future climates. Finally, they acknowledged that anthropogenic effects could influence future climate.

The uncertainties associated with the description of past climates based on interpretation of the paleoecological record and the Devil's Hole geochronology are well documented in Sharpe (2002) and Bechtel SAIC Company, LLC (2004). Future research on the paleoclimatology is likely to result in continued refinement of the paleoclimatology of the southwestern United States following multiple lines of evidence. Although such research may affect estimates of the characteristics of past climate states in terms of mean annual precipitation and temperature (e.g., Menking, et al., 2004) and the rate of transitions between climates (e.g., National Academy of Sciences, 2002), the general sequence of climates identified by Sharpe (2002) and Bechtel SAIC Company, LLC (2004) seems well established. Further, because the purpose of this report is to describe uncertainties in the projection of future climates, the following discussion will focus on factors that may limit the retrospective methodology of Sharpe (2002) and Bechtel SAIC Company, LLC (2004) in estimating future climates at Yucca Mountain.

4.1 Correlation With Earth's Orbital Cycles

The methodology used by Sharpe (2002) and Bechtel SAIC Company, LLC (2004) to estimate the sequence and general characteristics of future climates based on correlation of paleoclimate data and interpretations with Earth's orbital cycles was described in Section 3.1. As illustrated in Figures 3, 4, and 5, the interpreted transitions between glacial and interglacial climates correlate closely with peaks and valleys in the eccentricity of Earth's orbit modulated by precession in Earth's axis of rotation. Figure 6 illustrates, however, that the eccentricity of

Earth's orbit is projected to be low during the next 100,000 years and that the amplitude of variations in the precession index will be correspondingly small. The only similar period of low eccentricity and precession index amplitude in the past was centered around 400,000 years before present, as illustrated in Figure 7. As discussed by Paillard (2001), the marine isotope stages (OIS 12 and 11) and other paleoclimate indicators imply significant increases in ice mass during this period of small orbital forcing, in contrast to climate models that rely simply on coupling between the orbital cycles and climate during the Pleistocene. Although both Sharpe (2002) and Bechtel SAIC Company, LLC (2004) identified this period as an analog for the next 100,000 years, careful inspection of Figure 7 indicates that the amplitude of precession index oscillations in the future will be lower than those in the analog period.

Using a relatively simple mathematic model based on threshold couplings between orbital parameters and global ice volume, Paillard (2001) was able to match the timing and relative magnitude of changes in global ice volume (inferred from the marine oxygen-18 record), including those during OIS 12 to OIS 10. The key parameter in his model was the value of minimum Northern Hemisphere insolation (calculated from orbital cycles) that triggered an increase in ice volume. When the Paillard model was applied to the future 200,000 years, two quite different futures resulted depending on the threshold insolation value: one a prolonged interglacial, the other a rapid transition to a glacial climate. The Paillard paleoclimate reproduction, however, did not display the same sensitivity to the threshold value of insolation. Although the Paillard model was relatively simple, the important finding from the Paillard modeling exercise was that the non-linear couplings between insolation and Earth-based processes, such as ice volume and growth/shrinkage rate, can result in complex relationships

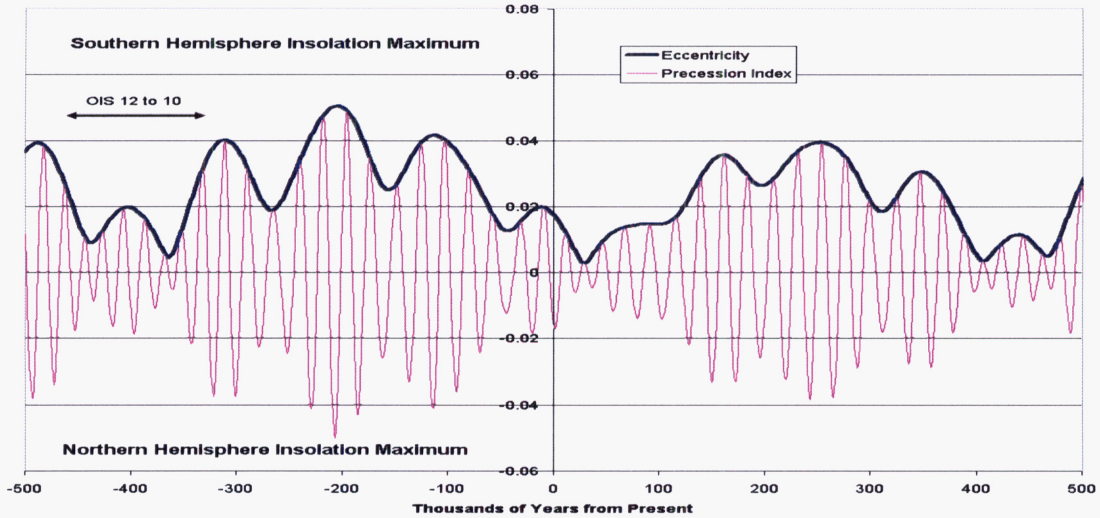

Figure 7. Eccentricity and Precession Index Computed Using NASA (2005) From 500,000 Years Before Present to 500,000 Years After Present. Illustrating Unusually Low Variations in Eccentricity and Precession Index During the Next 100,000 Years and Relationship to Previous Low Period From Approximately 450,000 to 350,000 Years Before Present.

between climate and Earth's orbital cycles. Thus, simple correlations between orbital cycles and paleoclimate conditions may not result in reliable projections of future climates, even in the absence of discrete Earth-based events, such as volcanism, and even when other Earth-based factors are unchanged.

More recently, Berger, et al. (2003) reported the results of past and future climate simulations using the two-dimensional Louvain-la Neuve climate model (LLN 2-D). As opposed to the Paillard simple model, the LLN 2-D model is intermediate in complexity between one- and two-dimensional Energy Balance Models and Global Circulation Models (Bertrand, et al., 2002). For example, the LLN 2-D model includes links between atmospheric dynamics, atmospheric composition in terms of carbon dioxide and sulfate aerosols, ocean circulation and carbon dioxide exchange, land mass properties, and ice mass thermodynamics. Berger, et al. (2003) also discussed the limitations of using the previously mentioned OIS 12 to OIS 10 period as an analog for the next 100,000 years and used the LLN 2-D to investigate possible future climates, with and without anthropogenic effects of greenhouse gases. The results of their simulation of the influence of greenhouse gases will be discussed in Section 4.2.

Berger, et al. (2003) reported two results for two scenarios without anthropogenic increases in carbon dioxide: one holding the carbon dioxide concentration constant at 210 parts per million and the other projecting atmospheric carbon dioxide concentrations reported for the Vostok ice core for the past 130,000 years into the future. In the first scenario, the 210 parts per million by volume value is close to the minimum measured in the Vostok ice core over the past 200,000 years. In the second scenario, carbon dioxide concentrations decrease almost linearly from approximately 300 parts per million by volume at the present (note current carbon dioxide concentrations are approximately 370 parts per million by volume) to 180 parts per million by volume at 130,000 years after present. The constant carbon dioxide simulation resulted in a gradual transition starting at approximately 15,000 years after present to a glacial climate lasting from about 60,000 to 100,000 years after present. The results for this scenario are similar to the climate projection of Sharpe (2002) with the exception that the resulting glacial climate lasts longer in the Berger simulation. The second carbon dioxide scenario (gradually decreasing) caused the current interglacial climate to persist until approximately 50,000 years after present and then to transition to a full glacial climate at 130,000 years after present. Berger, et al. (2003) note that

> … an exceptionally long interglacial under a low eccentricity will place the Earth in a warm mode with the future of the Holocene looking much like the late Pliocene (when low eccentricity prevents any glacial inception) or even earlier warm period like the Pliocene, the Paleocene-Eocene boundary and the Mid-Cretaceous.

Molnar and Cane (2002) have compared the pre-Ice age Pliocene climate to that of a perpetual El Niño. Under El Niño conditions, the desert Southwest experiences higher than normal winter and early spring precipitation (U.S. Geological Survey, 2005), resulting in increased annual precipitation. Berger, et al. (2003) further note, however, that

> ...during these warm epochs (except maybe the late Pliocene), the ocean circulation and the geography were significantly different; that prevents us from using them as "analogues" for predicting the climate over the next hundred thousand years.

The most notable of the changes in ocean circulation and geography mentioned by Berger, et al. (2003) that would make early epochs unrepresentative with respect to future global climate is the closing of the Isthmus of Panama during the Early Pliocene (Soligo, 2005). Philander and Federov (2003) have argued, however, that the cyclical transitions between El Niño from La Niña conditions over the last 3 million years were triggered by a shoaling of the tropical ocean thermocline as a result of a cooler global climate controlled by Earth's orbital cycles. Prior to the Pleistocene cooling, El Nino conditions were dominant in the Eastern Pacific according to Philander and Federov (2003).

In general, the results of Berger, et al. (2003) are similar to those of the Paillard (2001) model in that they suggest that threshold conditions (e.g., global temperature, insolation thresholds, or atmospheric carbon dioxide) control whether or not orbitally induced changes in insolation can initiate ice mass growth and glaciation. A similar conclusion was reached by Archer and Ganopolski (2005) using the CLIMBER-2 numerical model. Pelletier (2003) presented a simple model of late Pleistocene climate variations driven by random global temperature variations rather than orbitallly-driven insolation. His model also required threshold processes to switch the global climate between glacial and interglacial states.

4.2 Anthropogenic Climate Effects

A significant amount of research related to the potential effects of greenhouse gases (primarily carbon dioxide and methane) on global climate has been conducted over the last decade. Much of this work has focused on the dramatic increase in atmospheric carbon dioxide that has occurred over the past approximately 150 years as a result of industrialization and burning of fossil fuels and on climate effects over the next two centuries. Ruddiman (2003), however, has proposed that (i) anthropogenic effects on climate began as early as 8,000 years ago with increased methane emitted from rice paddy farming in Asia and other land use changes and (ii) these anthropogenic releases of methane and carbon dioxide have disturbed the natural sequence of glacial cycles that was largely controlled by Earth's orbital cycles. According to the Ruddiman theory, the pre-industrial releases of greenhouse gases prevented the transition to the next glacial climate that should have begun during the previous few thousand years. The previously mentioned work by Berger, et al. (2003) indicated, however, that even in the absence of anthropogenic effects, an unusually long interglacial period may occur due to the combination of natural increases in carbon dioxide and low orbital forcing for the next 100,000 years. Claussen, et al. (2005) have also proposed that the last three interglacials that were relatively short are not a proper analog for the past few thousand years during which a transition into the next glacial climate would have been predicted based on inference from paleoclimatic sequences.

Arguments over the past effects of anthropogenic greenhouse gas emissions notwithstanding, a significant body of research has been developed that indicates that greenhouse gas emissions will have some effect on the global climate, at least over the next few centuries (e.g., Intergovernmental Panel on Climate Change, 2001; National Academy of Sciences, 2002). The specific nature of these changes and their duration remains a subject of continuing research. As discussed previously, NRC (1997) concluded that the influence of anthropogenic greenhouse gas emissions would dissipate over the next 3,000 to 5,000 years resulting in a return to more natural climate variations. Recent work by Archer[2] has indicated that 25 percent

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[2]Archer, D. "The Fate of Fossil Fuel CO_2 in Geologic Time." *Journal Geophysical Research*. In Press. 2005.

of the anthropogenic carbon dioxide may remain in the atmosphere for thousands of years and 7 percent will remain for 100,000 years. Based on this prolonged residence time of carbon dioxide, Archer and Ganopolski (2005) have simulated a much longer period of anthropogenic influence potentially lasting hundreds of thousands of years, depending on the mass of fossil carbon ultimately emitted.

Although the research discussed suggests the possibility of a prolonged interglacial climate during the next 100,000 years even in the absence of anthropogenic greenhouse gases, global warming due to greenhouse gases could cause the climate in southern Nevada to be modified from current conditions. One such possibility is the initiation of long-term El Niño conditions, as alluded to by Berger, et al. (2003). Although El Niño events are included in the climate records for the analog sites used by Sharpe (2002) and Bechtel SAIC Company, LLC (2004) to describe seasonal and annual precipitation and temperature characteristics for past and future climate states, these records may not properly characterize a prolonged El Niño climate in southern Nevada. Numerical climate modeling by Kim (2005) has also suggested that global warming associated with greenhouse gases could increase the frequency of high precipitation events in the southwestern United States, although the effect simulated by Kim was not attributed to El Niño conditions. Kim's projection only extended over the next 50 years so its relevance to long-term climate conditions that would affect repository performance is uncertain. Hansen, et al. (2005) reported the results of global climate modeling of the effect of greenhouse gas and other anthropogenic atmospheric influences that indicated a general drying climate in the southwestern United States.

Considerable attention has been given to the potential effects of global warming on the thermohaline circulation of the Atlantic Ocean and its effect on global climate (e.g., National Academy of Science, 2002; Wood, et al., 2003). Overpeck, et al. (2005) has suggested that reduction in the size of the Arctic ice sheet will create climate conditions that have not occurred during the last million years. Although various dramatic effects have been attributed to such a possibility, including initiation of glaciation in the near future, the state of the art of global climate modeling leaves significant uncertainty in such predictions. An additional uncertainty in estimating the influence of anthropogenic greenhouse gas emissions on future climate is the unknown role that carbon dioxide sequestration will play in reducing the atmospheric carbon dioxide concentration. Although a variety of carbon dioxide sequestration approaches are currently under consideration (National Academy of Engineering, 2004), the future scope of such sequestration actions and their long-term effect on atmospheric carbon dioxide concentrations is uncertain.

5 SUMMARY AND CONCLUSIONS

The approach taken by DOE to estimate future climate conditions at the potential Yucca Mountain high-level waste repository is based on a correlation of paleoclimate conditions with Earth's orbital cycles. Paleoclimate conditions were estimated based on ostracode and diatom assemblages in the Owen's Lake sediment core and a comparison of these assemblages to those seen under present-day climate conditions throughout the western United States. The timing of paleoclimate changes was then based on temperature variations inferred from the oxygen isotopy of the Devil's Hole calcite core and qualitatively correlated to variations in insolation based on Earth's orbital cycles. Based on this correlation, rules were developed for defining future climate states based on future variations in Earth's orbital eccentricity and precession index. This retrospective approach to estimating future climate conditions was addressed by acceptance criteria developed by NRC. The DOE approach

projects that the climate in southern Nevada is currently transitioning from an interglacial climate to a sequence of intermediate and monsoonal climates that will culminate in a glacial climate starting about 38,000 years after present.

A number of researchers have proposed that the very low eccentricity of Earth's orbit during the next approximately 100,000 years may result in an unusually long interglacial climate, even without the influence of global warming due to greenhouse gas emissions. Qualitatively, such a period of low eccentricity has not occurred since the Late Pliocene, raising questions as to whether truly representative climate analogs can be identified from paleoclimatic reconstructions from the last million years (Berger, et al., 2003). Future climate simulations using various types of mathematical and numerical models suggest that the onset of glacial conditions requires a triggering mechanism, such as changes in insolation due to Earth's orbital cycles, that has a threshold value, such as minimum Northern Hemisphere insolation. If the triggering threshold is not reached due to the low amplitude of insolation variations over the next 100,000 years or elevated global temperatures due to greenhouse gases, the climate could remain in its current interglacial state for at least 50,000 years.

Ruddiman (2003) proposed that anthropogenic greenhouse gases began influencing the global climate as early as 8,000 years ago, overwhelming the influence of Earth's orbital cycles on climate and delaying the transition to a glacial climate. The duration and influence of greenhouse gases remains a matter of intensive research. Archer and Ganopolski (2005) have proposed that 7 percent of the carbon dioxide emitted from fossil fuels could remain in the atmosphere for 100,000 years and moderate the climatic effects of Earth's orbital cycles over the same period. Other effects of greenhouse gases and global warming have been proposed, such as a weakening of the thermohaline circulation in the Atlantic Ocean, a deepening of the thermocline in the Pacific Ocean, and seasonal opening of the Arctic Ocean. The effect of such changes on climate in southern Nevada, should they occur, is uncertain.

In summary, research performed within the last five years suggests that the timing of climate changes over the next 100,000 years may be difficult to infer from the patterns of climate change over the last 500,000 years due to the unusually low eccentricity of Earth's orbit and, possibly, the influence of anthropogenic greenhouses gases. After 100,000 years, the Earth's orbital climate forcing will be stronger, and the influence of greenhouse gases may have diminished so that the Pleistocene climate history may offer a better analog in terms of timing of climate changes. In terms of the characteristics of future climates (i.e., mean annual precipitation and temperature, seasonal weather patterns, and storm intensities), the characteristics inferred from paleoclimate reconstructions and present day analog records may represent the range of climate conditions that will occur in the future, even if the timing of these climates cannot be reliably estimated. The greatest uncertainty in future climate conditions relates to anthropogenic effects that may result in climates in southern Nevada that do not have analogs with present or Pleistocene climates, such as prolonged El Niño conditions. The nature, likelihood, and duration of such nonrepresentative climate conditions cannot be reliably assessed based on current research. Over longer time periods, the range of conditions inferred from the Pleistocene paleoclimate record reasonably bounds future climate during the period of geologic stability.

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APPENDIX

RULES FOR SELECTING CLIMATES BASED ON EARTH'S ORBITAL CYCLES (FROM SHARPE, 2002)

1. The last northern-hemisphere solar radiation maximum in the sequence, #4 or #5, just prior to the "T" event, begins the interglacial climate state. This interglacial state lasts to the "T" event (southern-hemisphere maximum #1).

2. From the "T" event to about halfway between the southern-hemisphere solar radiation maximum #3 and the northern-hemisphere solar radiation maximum #3, the combination of intermediate and monsoon climate states occurs. Two monsoon climate intervals, estimated to last 1,500 years each, are placed at the beginning and in the middle of the duration of the intermediate climate state for the purposes of this analysis. The end of the intermediate climate state is determined to be where the precession curve crosses the 0 precession mark just beyond the southern-hemisphere solar radiation maximum #3.

3. The glacial climate begins where the intermediate climate ends in #2 above. The end of the glacial is where the precession curve crosses the 0 precession mark just forward in time from northern-hemisphere solar radiation maximum precession #3 (if a 4-sequence) or #4 (if a 5-sequence).

4. From the end of the glacial, just forward in time from the northern-hemisphere solar radiation maximum #3 (if a 4-sequence) or #4 (if a 5-sequence), when the precession curve crosses 0, to the last northern-hemisphere solar radiation maximum in the precession sequence (#4 or #5) is the intermediate climate.

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