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Future climate analysis -- 10,000 years to 1,000,000 years after present

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ANALYSIS and MODEL COVER SHEET

[X] (1) Analysis **Check all that apply:**
Type of Analysis
[X] Scientific

Intended use of Analysis
[ ] Input to Calculation
[ ] Input to another Analysis or Model
[X] Input to a Technical Document
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Describe Use:
Provide analog stations and estimate the timing for future climate states from 10,000 to 1,000,000 years after present to be utilized as input to models of the infiltration process to assess the performance of the natural and engineered system at Yucca Mountain.

[ ] (2) Model **Check all that apply:**
Type of Model
[ ] Conceptual Model
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Intended use of Model
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QAP-3.3-1 Rev 10/26/00

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01	Minor changes (typos/clarification) throughout text. Rounded the values in Tables 6-1 (pp. 22-23), 6-4 (p. 47) and 6-10 (p. 64). (Table 6-10 is based on the newly rounded values in Table 6-1). Section 6.5.3 was revised to better describe how the timing of future climate in USGS 2000a and this paper differed. Removed the estimated 11% error from Table 6-6 and text because I felt it was not adequately supported. Deleted Table 6-4; and added the Thompson reference Data ID Number to Table 6-3.

QAP-3.3-2 Rev 10/26/00

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ACRONYMS AND DEFINITIONS OF SELECTED TERMS

C	Celsius
DOE	U.S. Department of Energy
ECCENTRICITY	The variation of an ellipse from a circle. Used here as variation in the shape of the earth's orbit
ENSO	El Nino Southern Oscillation
EPA	Environmental Protection Agency
GLACIAL (G)	Glacial state (period of climate with greater effective moisture than today: some combination of cooler and/or wetter climate)
GLACIAL TRANSITION	Period of transition between glacial and interglacial climate states, and period of transition between interglacial and glacial climate states, also called intermediate state
INTERGLACIAL (IG)	Interglacial state (period of relatively warm climate, identical to present-day climate)
INTERMEDIATE (IM)	Period of transition between glacial and interglacial climate states, and period of transition between interglacial and glacial climate states, also called glacial transition state
INTERMEDIATE/ MONSOON (IM/M)	Intermediate/Monsoon state (period of alternating climate states between intermediate and monsoon climates)
ka.	Thousands of years
MONSOON	Monsoon state (period of relatively warm and wet climate)
MAP	mean annual precipitation
MAT	mean annual temperature
NOAA	National Oceanic and Atmospheric Administration
NRC	Nuclear Regulatory Commission
OBLIQUITY	The angle between the planes of the earth's equator and orbit
OCRWM	Office of Civilian Radioactive Waste Management
OIS	Oxygen Isotope Stage
PRECESSION	The slow migration of the earth's axis that traces out a cone over a period of about 26,000 years
QARD	Quality Assurance Requirements and Description
SPECMAP	Spectral Mapping Project
TDMS	Technical Data Management System
TDS	Total Dissolved Solids
TSPA	Total System Performance Assessment

USGS	U.S. Geological Survey
VSMOW	Vienna standard mean ocean water
yr. A.P.	years after present
yr. B.P.	years before present

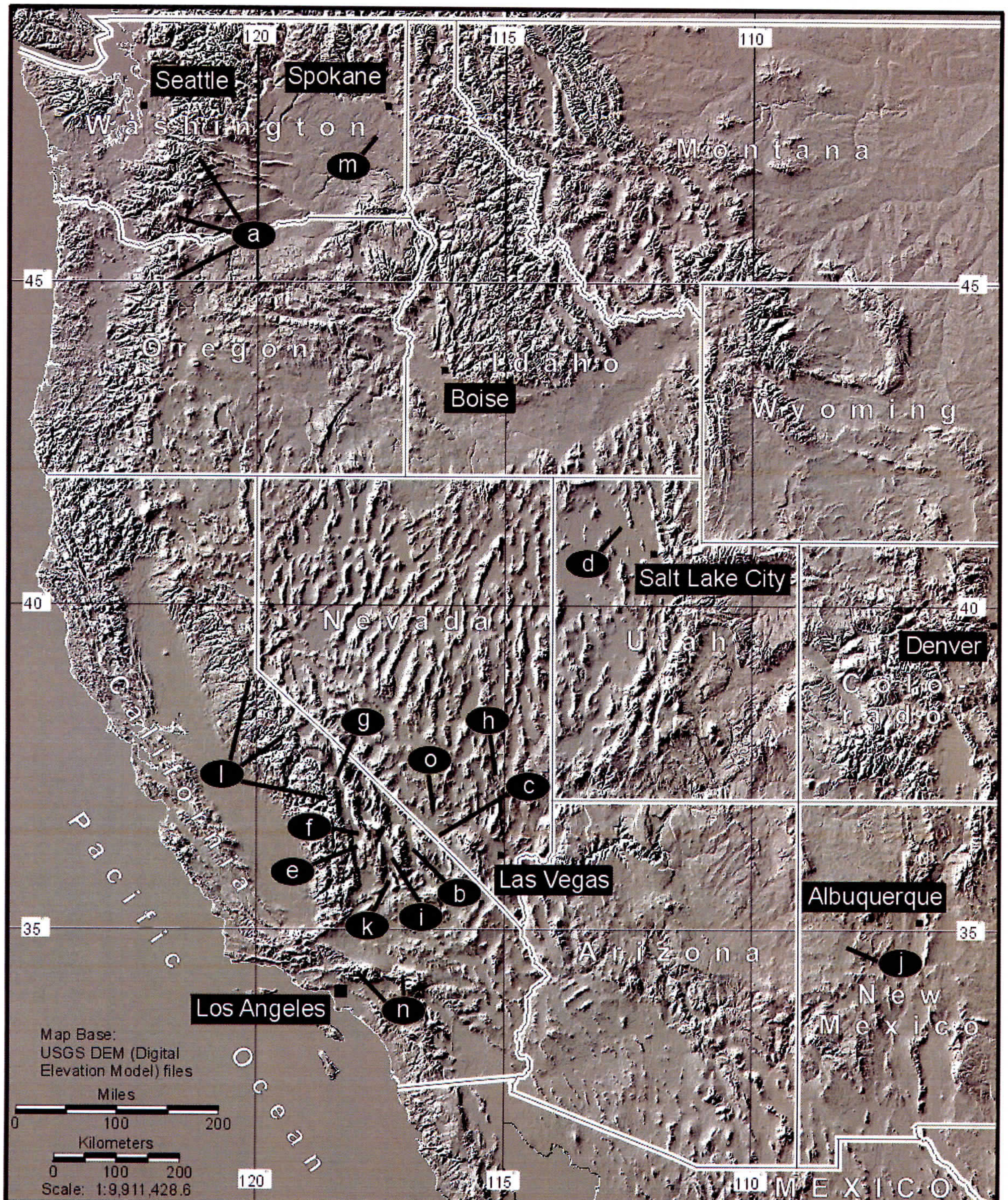
1. PURPOSE

The purpose of this report is to provide quantified estimates of temperature and precipitation and estimate the timing of climate states in the Yucca Mountain, Nevada, area for the period from 10,000 to 1,000,000 years beyond the present. Primary tasks are limited to: 1) selecting modern analog climate stations for three different magnitude glacial stages; and, 2) determining the timing of future climate states using orbital parameter data and Devils Hole and Owens Lake records. These estimates are intended to be used as input to models of the infiltration process to assess the performance of the natural and engineered systems of a potential underground geologic repository for the storage of radioactive nuclear waste.

This report uses the methodology established and the assumptions set forth in USGS 2000a, Sections 5 and 6, which provide predictions of future climate for the next 10,000 years. USGS 2000a (Table 2, p. 66) identified present-day meteorological stations to represent three potential future climate states: modern (interglacial), monsoon, and glacial transition (intermediate) in the Yucca Mountain area. Table 2 of USGS 2000a also includes estimated durations of these climate states. This analysis uses the same approach as USGS 2000a and estimates the duration, magnitude, and timing of climate for the next 1,000,000 years based on the celestial mechanics theory (calculated earth-orbital parameters) and their relation to the Devil's Hole, Nevada, paleoclimatological record and the Owens Lake, California, record (Figure 1-1).

This report identifies four potential future climate states (interglacial, monsoon, intermediate, and full glacial) for the next 1,000,000 years and proposes minor changes in climate predictions for the next 10,000 years from those described in USGS 2000a. This report also identifies present-day meteorological stations that represent the four future climate states, describes a process to estimate the timing of future climate states, and provides timing and duration of climate states for the next 1,000,000 years. The timing and duration of climate states (interglacial, monsoon, intermediate, and full glacial) may be used as part of the process to address the peak dose within the period of geologic stability. The level of confidence obtained by this methodology is suitable for its intended use (40 CFR 197.35).

Although the Environmental Protection Agency (EPA) in 40 CFR Part 197, *Public Health and Environmental Radiation Protection Standards for Yucca Mountain, Nevada*, sets a period of 10,000 years for which the U.S. Department of Energy (DOE) must demonstrate compliance with the proposed radiological standard, both the National Academy of Sciences and the EPA have suggested that estimating climate for the next 1,000,000 years would help in design and licensing decisions. Based on the geologic record, climate is likely to be much wetter and/or cooler beyond 10,000 years after present, when a peak dose would be most likely to occur. It should be noted that the EPA states in 40 CFR Part 197 that the Nuclear Regulatory Commission (NRC) is not to use the additional analysis in determining compliance with 40 CFR Part 197.



a Cascade Range
b Death Valley, Calif.
c Devils Hole, Nev.
d Great Salt Lake Basin, Utah
e Haiwee Reservoir, Calif.
f Owens (dry) Lake, Calif.
g Owens River, Calif.
h Pahranagat Lakes, Nev.
i Panamint Basin, Calif.
j San Agustin Basin, N. Mex.
k Searles (dry) Lake, Calif.
l Sierra Nevada Mountains
m Sprague Lake, Wash.
n Transverse Ranges, Calif.
o Yucca Mountain, Nev.

Figure 1-1. Western United States Showing Localities Discussed in the Text (from USGS 2000a)

2. QUALITY ASSURANCE

The work is subject to the requirements of the University and Community College System of Nevada (UCCSN) Quality Assurance Program of Cooperative Agreement DE-FC-28-98NV12081 (and DE-FC08-98NV12081). The report was prepared and reviewed in accordance with QAP-3.3, *Models*. This report contributes to the analyses and modeling of data for performance assessment and site characterization; it does not directly impact engineering, construction, or operational tasks associated with the Q-list items and natural barriers.

3. COMPUTER SOFTWARE AND MODEL USAGE

No software or models were used in performing this analysis.

The work activities documented in this report depend on electronic media to store, maintain, retrieve, modify, update, and transmit quality-affecting information. As part of the work process, electronic databases, spreadsheets, and sets of files were required to hold information intended for the use to support the potential development of a license application for submittal to the NRC. In addition, the work process required the transfer of data and files from one location to another. File transfers were verified for accuracy and completeness by cyclic redundancy checks using WinZip©. Consequently, all electronic files consisting of source data and results were maintained and processed according to the compliance criteria listed in QAP-3.1, *Control of Electronic Data*.

4. INPUTS

The qualification status of the cited input source data may be confirmed by using the Data Tracking Number (DTN) to access the information in the Technical Data Management System (TDMS).

4.1 DATA AND PARAMETERS

The data sets used in this analysis are summarized in Table 4-1.

Table 4-1. Summary of Data Inputs

Data Inputs	Data Tracking Number
Radiometric Dating and $\delta^{18}O$ Data from Devils Hole, Nevada	GS000200005121.003
Numerical Values of the Elements of the Earth's Orbit from 5,000,000 yr. B.P. to1,000,000 YAP	GS000900005121.004
Vostok Ice Core Deuterium Values	UN0104SPA021SS.001
Western Regional Climate Summaries through December 31, 2000	UN0112SPA021SS.004
Diatom Data from Owens Lake 1984-1992 Cores	GS970708315121.001
Ostracode Data from Owens Lake 1984-1992 Cores	GS970708315121.002
Supplementary Data to Ostracode Data From Owens lake 1984–1992 Cores.	GS991008315121.001
Supplementary Data to Diatom Data From Owens Lake 1984-1992 Cores	GS991008315121.002

These data were used because this analysis provides a rationale for estimating future climate and provides a basis for other analyses and models related to assessing the performance of a potential radioactive-waste repository at Yucca Mountain. The Devils Hole $\delta^{18}O$ record (DTN: GS000200005121.003) is appropriate because it provides a well-dated history of glacial and interglacial events (see discussion in Section 6.4.1) approximately 60 km from Yucca Mountain. The calculated earth orbital parameters (DTN: GS000900005121.004) are appropriate because they establish the pattern and timing of solar radiation on the earth (see discussion in Section 6.4.2). The Vostok, Antarctica record (DTN: UN0104SPA021SS.001) is appropriate because it is a continental record and its curve has the same climate-change sign as the Devils Hole curve (see discussion in Section 6.1). The modern data inputs summarizing the daily observations from the Western Regional Climate Center (DTN: UN0112SPA021SS.004) are appropriate because they furnish temperature and precipitation values to be used as analog climate parameters in modeling net-infiltration estimates (see discussion in Section 6.3.2). The Owens Lake, California, record (DTNs: GS970708315121.001, GS970708315121.002, GS991008315121.001, and GS991008315121.002) is appropriate because it provides a lake and Sierran snowpack history for the last 800,000 years approximately 140 km from Yucca Mountain (see discussion in Section 6.1).

These parameters are all appropriate because they comprise the basis of the calculations needed for the analysis of infiltration at the site. Using identifiable relations between the timing of past climate change and orbital parameters to forecast future climate change is within NRC acceptance criteria (NRC 1997).

4.2 CRITERIA

This report complies with the requirements promulgated in Subpart B, 10 CFR Part 63 (66 FR 55732). Subparts of the regulation that apply to this analysis are those pertaining to the characterization of the Yucca Mountain site (Subpart B, Section 63.15), the compilation of information regarding hydrology of the site in support of the License Application (Subpart B, Section 63.21(c)(1)(ii)), and the definition of hydrologic parameters and conceptual models used in performance assessment (Subpart E, Section 63.114(a)).

4.3 CODES AND STANDARDS

No specific, formally established codes or standards have been identified as applying to this analysis.

5. ASSUMPTIONS

This analysis of future climate is based on the methodology established and the assumptions set forth in USGS 2000a (pp. 19, 21) that provided future climate estimates for the next 10,000 years. The four key assumptions set forth in USGS (2000a, p. 19) also are valid for the analysis documented in this report and are as follows:

1. Climate is cyclical over 400,000-year periods and the earth is entering into the next 400,000-year cycle. Climate cyclicity is important for forecasting future climate because it implies some past climate or aspects of past climate will recur in the future.

2. Past climate change can be timed with an earth-orbital clock of precession and eccentricity, so the timing of future climate change can be estimated from the orbital clock. Timing climate change with a clock that can be set accurately in the future is important for forecasting climate, because it allows for an accurate assessment of future climate durations used as input by Total System Performance Assessment (TSPA) and infiltration (USGS 2000b) models. Cycles of glacial and interglacial climates occur about every 100,000 years.

3. Past glacial/interglacial climates differ from each other, and the nature of particular past climates should repeat themselves in a predetermined order. Thus, the analysis can focus on one particular climate sequence rather than all past climates and need not take the conservative approach of using the climates that generate the highest infiltration as being those expected in the next 10,000 years.

4. Long-term earth-based climate-forcing functions, such as tectonic change, have remained relatively constant over the past 500,000 years or so and will remain constant for the next 10,000 or more years. This is important to climate forecasting because such forcing functions change climate in non-cyclic ways, so if they were not constant the first three assumptions would be invalid (USGS 2000a, p. 76).

Because this report estimates future climate beyond 10,000 yr. A.P. (years after present), processes such as tectonic alteration may impact climate beyond 500,000 years in the future. Assumption 4 is discussed further in Section 6.5.5.

Using the sequence and nature of past climate change as a basis for estimating future climate change should be viewed with caution because the drivers of climate change are not well understood. Furthermore, the methodology used to estimate future climate influences the estimate. Uncertainties are associated with any prediction of future events, particularly estimating future climate for the next 1,000,000 years. Past, future, and linkage uncertainties associated with this project include:

Uncertainty in the past:

- Uncertainty in the paleoecologic record
- Uncertainty in past climate reconstructions
- Uncertainty in understanding the influence of ice sheets
- Uncertainty in the resolution of timing, dating and duration of specific events in the past
- The assumption that past climate can serve as an analog for future climate

Uncertainty in the future:

- Future events that we are unable to predict, especially the indirect effects of human activity on climate and geologic activities such as volcanic eruptions, and tectonic change
- Uncertainty in future climate itself
- Past climate may not repeat in the future
- Astronomical events such as meteor showers, changes in solar activity, etc.

Linkages that we do not fully understand:

- The inherent predictability of climate on all of its time scales
- El Niño Southern Oscillation (ENSO) cycles, effects of solar variability, effects of increased carbon dioxide, and ocean-atmosphere interactions
- The drivers of climate change
- Factors influencing the timing of climate cycles
- The role and mechanisms of global oceanic circulation
- The global effects of land use and land surface variations
- The role of biological processes

Nonetheless, a scientifically reasonable, sound, and defensible methodology can be established to address this problem resulting in a high degree of success. Foremost, the reconstruction of past climate is the only defensible source of future climate information. The well-dated Devils Hole calcite record (DTN: GS000200005121.003) and the Owens Lake sediment core record (DTNs: GS970708315121.001, GS970708315121.002, GS991008315121.001, and GS991008315121.002), both from the Yucca Mountain region, provide robust, terrestrial, local, paleoenvironmental data sets that can be used to reconstruct past climate. Secondly, general climate states (i.e. glacial or interglacial) can be selected from these data to provide "types" of climate that occurred over this interval that have a likelihood of recurring in the future. Third, the reconstructed past-climate interval can be compared to calculated orbital parameters based on celestial-mechanics theory. Correlations among past solar radiation, climate change, and paleoclimate can be identified and projected into the future, establishing the timing and magnitude of future climate-change states. Finally, data from present-day meteorological stations can be selected as analogs to represent past climate states. The record of daily temperature and precipitation measurements from these stations can provide quantitative estimates of future temperature and precipitation values.

Climate for the next 1,000,000 years likely will include many more climate states than the four identified in this report, however, these four climate states represent a reasonable range of variability encountered in the past and are expected to reasonably represent future climate. The future climatic intervals based on the fossil record are considered to provide realistic estimates, and the reduction of potential future climate states to the subset mentioned here simplifies model simulations of net infiltration.

This report documents the development of a climate analysis for the Yucca Mountain area. Although this information is subsequently used as input for modeling of potential groundwater seepage into waste emplacement drifts and radionuclide transport, the analysis documented in this report does not estimate or otherwise directly address any of the Principal Factors, Other Factors, or potentially disruptive processes and events included within the Repository Safety Strategy (CRWMS M&O 2000a).

6. ANALYSIS

The approach used in this analysis of future climate 1) identifies the sequencing, duration and effect of past climate states (glacial, interglacial, monsoon, and intermediate) suggested by the Owens Lake and Devils Hole paleoenvironmental records; 2) selects present-day meteorological stations to represent these past climate states so that the record of daily temperature and precipitation from these stations can represent future temperature and precipitation; 3) compares the relation of the Devils Hole reconstructed climate interval (approximately 568,000 to 60,000 yr. B.P.) to calculated orbital parameters based on celestial mechanics to identify a pattern of past climate; and 4) projects this pattern into the future to establish the nature and timing of future climate change.

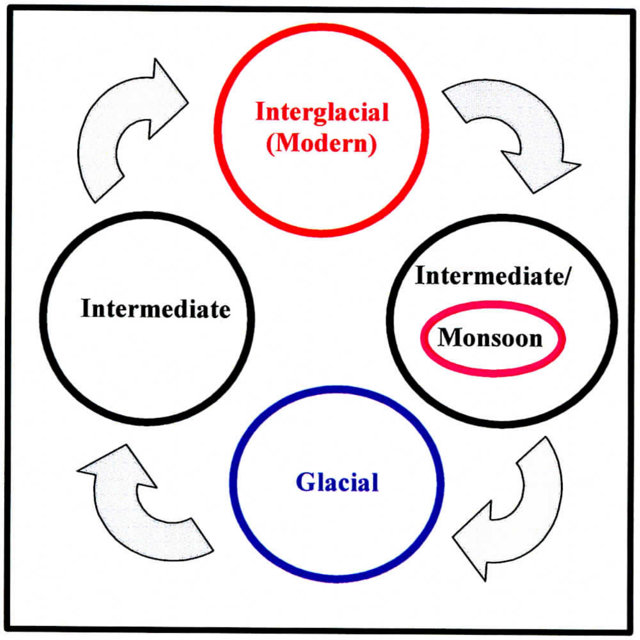
6.1 IDENTIFICATION OF PAST AND PRESENT CLIMATE STATES

The paleoecology and paleoclimate record is better preserved for the last 400,000 years relative to the prior time period, so these later records are used here to determine general past climate states. Climate *states* are defined here as the *type* of dominant climate (glacial, interglacial, monsoon or intermediate) whereas oxygen isotope *stage* (OIS) refers to a period of time associated with a glacial or interglacial climate state. Although usable records exist prior to 400,000 years ago, such as the lake record in the western Great Basin, colluvial boulder deposits in southern Nevada, and the marine isotope record, they are generally not well-dated and may have been influenced by tectonic configurations different than today so their strength lies in comparing their estimated relative magnitudes with comparable younger climate states. These records are discussed in Section 6.2.

The methodology used in USGS (2000a) and in this report identifying past and selecting potential future climate states is based on the ostracode (microscopic bivalve crustacean) and diatom (microscopic algae) assemblages recovered from the Owens Lake sediment core (USGS 2000a, pp. 48-59; Forester et al. 1999, pp. 15-21; CRWMS M&O 2000b, Section 6.3.4.1.2). The 322.9 m long Owens Lake core, extracted in 1992, provides a lake and climate history for the past 800,000 years (Smith and Bischoff 1997, p.1) but only the last 400,000 years is used for this analysis for the reasons listed above.

USGS (2000a, pp. 53-73) identified three potential climate states (periods of time during which a particular "type" of climate is dominant) for the next 10,000 years based on the modern geographic and climatic distributions of the ostracode and diatom assemblages recovered from the Owens Lake core: interglacial, monsoon, and glacial-transition. The interglacial climate state is comparable to our relatively warm modern climate state; the monsoon climate state is characterized by hot summers with increased summer rainfall relative to today; the glacial-transition (or intermediate) climate state has cooler and wetter summers and winters relative to today. Glacial states, which were not included in USGS 2000a, are much cooler and wetter than today. Although USGS (2000a, pp. 46, 48, 54, 67) referred to a glacial-transition climate, this is the same climate state, with the same present-day analog meteorological stations, as what is referred to in this report as the "intermediate climate state". Figure 6-1, based on ostracode and diatom assemblages from the Owens Lake sediment core, shows the cyclical sequence of the four climate states used herein: interglacial to intermediate/monsoon to glacial to intermediate. The monsoon climate state interbedded within the intermediate climate state (designated intermediate/monsoon) may be considered "bursts" of monsoonal activity occurring randomly throughout the intermediate climate state and generally lasting from 300 to 1,000 years.

Figure 6-1. Simplified Climate State Sequence



The modern distribution of ostracodes is related (among other factors) to the total dissolved solids (TDS), the solute composition, and the temperature of the water in which they live (Forester 1983, pp. 437-438; 1985, pp. 13-14; 1986, Figs. 1,2,3 pp. 797-798). Because these variables often are correlated with climate (Forester 1987, pp. 261-267), as in the case of Owens Lake, modern ostracode geographical distributions can be linked to climate, and hence, the atmospheric circulation patterns that affect regional climate. Therefore, change in the ostracode assemblage is often linked to climate change, which may have resulted from a major shift in atmospheric circulation. Figure 6-2 shows how the Owens Lake ostracode assemblages represent effective moisture which is a combination of temperature and precipitation.

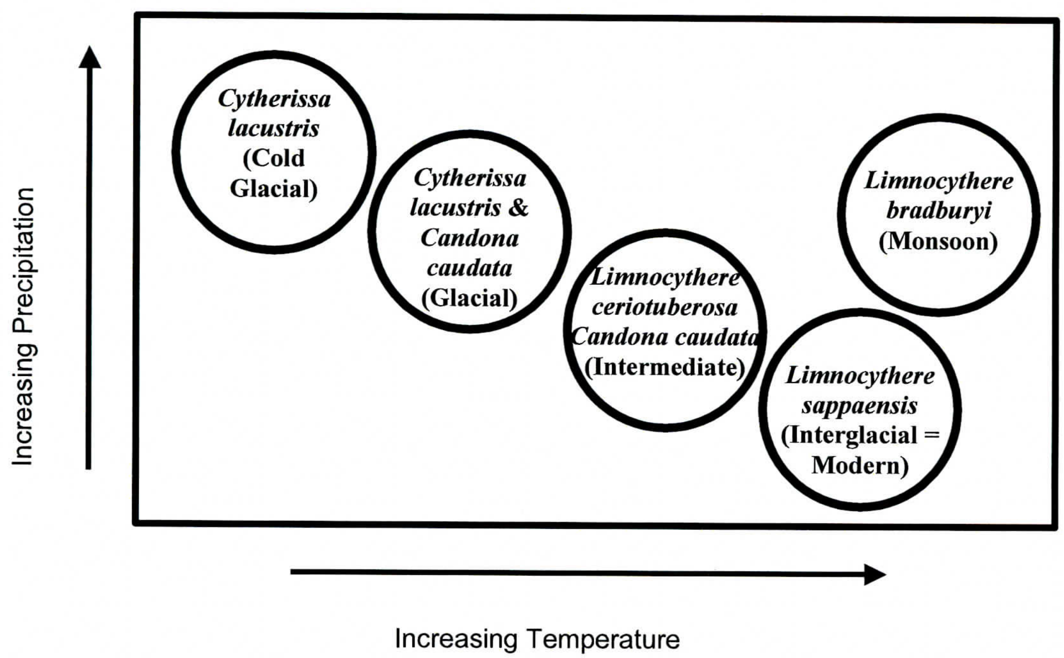
For example, *Limnocythere sappaensis* occurs under current climatic conditions in saline waters. Its presence in the Owens Lake stratigraphic record is correlated with warm, dry, interglacial episodes analogous to current climate and atmospheric circulation patterns (USGS 2000a, pp. 52-53).

Limnocythere bradburyi commonly occurs under current climatic conditions in central Mexico in climates warmer and wetter than the current climate at Owens Lake. Its presence in the Owens

Lake stratigraphic record represents summer monsoon climate episodes at Owens Lake that likely were brought northward from the gulfs of California and/or Mexico (USGS 2000a, p. 56).

Limnocythere ceriotuberosa and *Candona caudata* in the Owens Lake stratigraphic record imply intermediate climates cooler and wetter than modern. These ostracodes occur presently in low salinity water representative of a fill and spill cold-water lake (USGS 2000a, p. 53). Their occurrence in Owens Lake represents climate dominated by polar air masses and westerly airflow, but not as wet and cold as glacial climates at Owens Lake.

Figure 6-2. Climate State and Relative Magnitude Based on the Owens Lake Ostracode Record



Full glacial climates are represented in the Owens Lake record by the occurrence of *Cytherissa lacustris* and *Candona caudata* because the occurrence of these ostracodes imply low salinity water, a fill and spill lake, and cold climates (USGS 2000a, pp. 54 and 73). The modern distribution of *Cytherissa lacustris* is in the Canadian boreal forest and near the Arctic Circle where the climate is dominated by arctic and polar air masses, whereas the modern distribution of *Candona caudata* is in Canada, Alaska, and many locations in the northern continental United States. The modern distribution of these taxa suggests that the intervals containing *Candona caudata* in the Owens Lake record implies glacial climates that were wetter and probably colder than at present. When *Candona caudata* occurs with *Cytherissa lacustris* in the Owens Lake record climate is probably colder with a fresher lake than intervals with only *Candona caudata* (USGS 2000a, p. 54).

The occurrence of these five ostracode taxa from the Owens Lake sedimentary record (see USGS 2000a, Fig 11, p. 50) was used to identify the four basic climate states identified above for the past 400,000 years based on modern ostracode distribution (Table 6-1), which also is linked to atmospheric circulation patterns. The first column in Table 6-1 refers to oxygen isotope stages 12 through 1, with OIS 12 being the oldest and OIS 1 being the youngest. The OIS were established from studies of marine carbonate $\delta^{18}O$ records reflecting change in $\delta^{18}O$ values of ocean water as continental ice sheets expanded and contracted (Imbrie et al. 1984, pp. 288-293; Shackleton and Opdyke 1973, Fig. 7 p. 45, p. 41-44). *Limnocythere sappaensis* represents interglacial episodes (associated with odd-numbered OIS). The duration of all *Limnocythere bradburyi* intervals were identified and equated with monsoon climate. *Candona caudata* and *Cytherissa lacustris* represent glacial (even numbered OIS) climates, and *Limnocythere ceriotuberosa* in the remaining intervals were assigned to the intermediate climate.

The time series indicated in Table 6-1 is based on the Devils Hole $\delta^{18}O$ chronology beginning in OIS 12 through OIS 5 and into 4, where the published Devils Hole data ends. OIS 3 to the present is based on the δ D data from the Vostok Ice Core (Petit et al. 1999, Fig 1, p. 430) because it is also a continental record of climate change and the Vostok curve shows a strong similarity to the Devils Hole curve (Winograd at al. 1992, Fig 3, p. 257). Data sets were combined to complete the time-series analysis by graphically scaling the Vostok record to the Devils Hole curve. The superimposed curves resulted in a near identical agreement through the 60,000 to the 450,000 yr B.P. interval. The timing for the Vostok curve was not adjusted to match the SPECMAP (Spectral Mapping Project) (Imbrie et al. 1984, Table 6 and 7, p. 288-293) or other climate chronologies for the Late Pleistocene. Consequently, the ages for the boundaries between OIS 3, 2, and 1 do not conform precisely to the other Late Pleistocene chronologies. However, the discrepancies between the various climate-change chronologies are small and for the purposes of this exercise have no impact on the information or analysis.

The timing between OIS listed in Table 6-1 was determined by locating the inflection points on the Devils Hole and Vostok isotope records. For example, the age at which the isotope curves change in concavity marked the point between the OIS (glacial to interglacial or visa versa). Once the OIS isotope stage boundaries were delineated in this manner, the age at which the curves reverse direction denote the general center of glacial or interglacial periods. The uppermost peaks in the curve (high points, or more positive $\delta^{18}O$ or δ D values) represent interglacial periods and the troughs represent glacial periods.

The length of time that the glacial or interglacial periods lasted was based on change in the slope of the isotope curves near the reversal peaks or troughs. A one-value cutoff-point designating all glacial or all interglacial periods could not be chosen because each individual glacial or interglacial event had its own set of values particular to the preceding climate interval and factors associated with climate and groundwater mechanisms. However, the estimated duration of glacial and interglacial states based on a change in slope in the Devils Hole isotope curve is generally consistent with the timing of glacial and interglacial onset and duration reported in the literature. Isotope values falling in between the glacial and interglacial periods were designated intermediate or monsoon climate states.

Climate for the next 1,000,000 years will likely include many more climate states than the four identified here. However, these four climate states represent four periods of differing effective moisture, which is some combination of increasing precipitation and decreasing temperature (more effective moisture) or decreasing precipitation and increasing temperature (less effective moisture). For example, the interglacial climate state has the least effective moisture, so infiltration is less than in the glacial climate state which has the greatest effective moisture of these four selected climate states.

Table 6-1. Correlation Between Climate States, Representative Ostracodes, and Oxygen Isotope Stages for the Owens Lake Core for the Last 400,000 Years

Climate State and Representative Ostracode	Interglacial (IG) *Limnocythere sappaensis*			Monsoon (M) *Limnocythere bradburyi*			Intermediate (IM) *Limnocythere ceriotuberosa*			Full glacial (G) *Cytherissa lacustris* *Candona caudata*		
Oxygen Isotope Stage/ sub-stage	**Begin** yr B.P.	**End** yr B.P.	**Duration** years	**Begin** yr B.P.	**End** yr B.P.	**Duration** years	**Begin** yr B.P.	**End** yr B.P.	**Duration** years	**Begin** yr B.P.	**End** yr B.P.	**Duration** years
12							425,000	410,000	15,000			
11	410,000	405,000	5,000									
11				405,000	403,000	2,000						
11	403,000	398,000	5,000									
11				398,000	397,000	1,000						
11	397,000	397,000	0									
			T: 10,000			T: 3,000						
10							397,000	364,000	33,000			
10										364,000	348,000	16,000
10							348,000	336,000	12,000			
									T: 45,000			
9	336,000	323,000	13,000									
9				323,000	323,000	0						
9							323,000	276,000	47,000			
8										276,000	262,000	14,000
8							262,000	247,000	15,000			
7E				247,000	247,000	0						
7E	247,000	246,000	1,000									
7E				246,000	245,000	1,000						
7E	245,000	244,000	1,000									
7E				244,000	244,000	0						
7E	244,000	243,000	1,000									
7E				243,000	242,000	1,000						
7E	242,000	235,000	7,000									
7E				235,000	234,000	1,000						
7E	234,000	232,000	2,000									
7D							232,000	225,000	7,000			
7D										225,000	219,000	6,000
7C							219,000	210,000	9,000			
7C				210,000	210,000	0						
7C							210,000	201,000	9,000			
7B										201,000	200,000	1,000
7A							200,000	184,000	16,000			
			T: 12,000			T: 3,000			T: 41,000			T: 7,000
6										184,000	147,000	37,000
6							147,000	140,000	7,000			
5E				140,000	138,000	2,000						
5E	138,000	119,000	19,000									
5D							119,000	109,000	10,000			
5C	109,000	95,000	14,000									
5B							95,000	81,000	14,000			

Climate State and Represen-tative Ostracode	Interglacial (IG) *Limnocythere sappaensis*			Monsoon (M) *Limnocythere bradburyi*			Intermediate (IM) *Limnocythere ceriotuberosa*			Full glacial (G) *Cytherissa lacustris* *Candona caudata*		
Oxygen Isotope Stage/ sub-stage	**Begin yr B.P.**	**End yr B.P.**	**Duration years**	**Begin yr B.P.**	**End yr B.P.**	**Duration years**	**Begin yr B.P.**	**End yr B.P.**	**Duration years**	**Begin yr B.P.**	**End yr B.P.**	**Duration years**
5A	81,000	81,000	0									
5A				81,000	80,000	1,000						
			T: 33,000			T: 3,000			T: 24,000			
4							80,000	70,000	10,000			
4										70,000	60,000	10,000
4							60,000	58,000	2,000			
									T: 12,000			
3	58,000	56,000	2,000									
3							56,000	34,000	22,000			
2							34,000	24,000	10,000			
2										24,000	24,000	0
2							24,000	23,000	1,000			
2										23,000	22,000	1,000
2							22,000	21,000	1,000			
2										21,000	20,000	1,000
2							20,000	19,000	1,000			
2										19,000	19,000	0
2							19,000	18,000	1,000			
2										18,000	18,000	0
2							18,000	12,000	6,000			
									T: 20,000			T: 2,000
1	12,000	0	12,000									

yr. B.P. = years before present
DIN: 021SS.013

Data Source: Radiometric Dating and $\delta^{18}O$ Data from Devils Hole, Nevada (GS000200005121.003); Vostok Ice Core Deuterium Values (UN0104SPA021SS.001; Ostracode Data from Owens Lake 1984-1992 Cores (GS970708315121.002); Supplementary Data to Ostracode Data From Owens lake 1984-1992 cores (GS991008315121.001).

Note: T = total years of sub-stages; yr. B.P. = years before present; numbers rounded to nearest 1,000 years; durations of 0 years = < 500 years

6.2 SEQUENCING, DURATION, AND EFFECT OF PAST GLACIAL STATES

The last 800,000 years includes two full eccentricity cycles each approximately 400,000 years long (USGS 2000a, p. 59-60). Eccentricity as used here is the variation in the shape of the earth's orbit which affects the total radiation received at the top of the Earth's atmosphere. The present climate appears poised to begin another 400,000-year cycle (USGS 2000a, p. 59, 62-63; Loutre and Berger, 2000, p. 64). Based on past precession (the slow migration of the earth's axis that traces out a cone) and eccentricity parameters (GS000900005121.004), it appears that the next 400,000-year cycle will be most similar to the last 400,000-year cycle which began at the transition between OIS 11 and 10, approximately 400,000 years ago (USGS 2000a, p. 62; Loutre and Berger, 2000, p. 64).

Because the hydrology of Owens Lake is closely linked to climate (Smith and Bischoff 1997, p. 144), the limnologic evidence (specifically ostracode occurrence) from Owens Lake was used to determine the sequencing and nature of past glacial climates over the last 400,000 year climate cycle (USGS 2000a, pp. 48-61). Based on this ostracode record, the three full glacial-climate states of different magnitudes specific to OIS (OIS 2/4, OIS 6, and OIS 8/10) were determined. However, paleoenvironmental records representing the older OIS glacial periods (OIS 12, 14, 16, 18, and 20) in the eccentricity cycle occurring between 800,000 and 400,000 years ago indicate OIS comparable in sequence and magnitude to the more recent OIS (USGS 2000a, pp. 60-61). Although the older records are poorly dated and may have been influenced by tectonic configurations and processes that did not affect the younger records, it is still useful to analyze both of these climate cycles to estimate the timing, nature, and duration of future climate states.

Comparison of the relative magnitude of glacial states in the most recent 400,000-year climate cycle (from approximately 400,000 yr. B.P. to present) suggests that OIS 6 (occurring from about 180,000 to 140,000 yr. B.P.) appears to have had the greatest effective moisture (some combination of cooler and/or wetter climate) and the coldest glacial temperatures. The ostracode, *Cytherissa lacustris*, recovered during much of the OIS 6 time period represented in the Owens Lake core, implies that the climate was dominated by polar and arctic air masses. This is because *C. lacustris*' modern distribution is in the Canadian boreal forest and above the Arctic Circle (USGS 2000a, p. 54). Glacial OIS 10 (occurring approximately between 400,000 and 340,000 years ago) and 8 (occurring approximately between 280,000 and 250,000 years ago) were warmer and wetter, relative to the other OIS (USGS 2000a, p. 58), as indicated by the presence of *Candona caudata* and *Limnocythere ceriotuberosa*, and the absence of *Cytherissa lacustris*. The co-occurrence of these ostracodes suggests that the climate was dominated by the mean seasonal or annual latitude of the polar front, with winter-dominated precipitation, but without periods of extended dominance by high-pressure, anti-cyclonic circulation. OIS 4 (occurring approximately between 80,000 and 58,000 years ago) and 2 (occurring approximately between 34,000 and 12,000 years ago) were drier and colder than OIS 10 and 8, but not as cold as OIS 6, given the combined presence of *Cytherissa lacustris, Candona caudata,* and *Limnocythere ceriotuberosa*.

The long climate cycle from 800,000 to 400,000 yr. B.P. shows a similarity in the sequence of relative magnitude of glacial stages OIS (Table 6-2). This similarity supports the third assumption in Section 5 above that a relation exists between the sequence, nature, and magnitude of past climates. Although the Owens Lake ostracode record suggests that the five glacial episodes occurring within the last 400,000 years were very different from one another, their sequence is similar to the sequence of the five glacial episodes in the older long climate cycle.

Table 6-2. Comparison of OIS in the Last Two Long Climate Cycles

Older Long Climate Cycle: ~ 800,000 to ~400,000 yr. B.P.	**Younger Long Climate Cycle: ~400,000 to 0 yr. B.P.**
OIS: characteristics	OIS: characteristics
20: smaller ice sheet than in OIS 6	10: smaller ice sheet than in OIS 6
18: smaller ice sheet than in OIS 6	8: smaller ice sheet than in OIS 6
16: largest lakes in sequence; large ice sheet	6: largest lakes in sequence; large ice sheet
14: smaller ice sheet than in OIS 6	4: smaller ice sheet than in OIS 6
12: large ice sheet; lakes smaller than those in 16	2: large ice sheet; Death Valley Lake smaller here than in 16, and possibly smaller than in 12 and 6.

Data Source: USGS 2000a, p. 60-61.
Note: OIS = oxygen isotope stage

The marine isotope record suggests that glacial OIS 20, 18, 14, 10, 8, and 4 had smaller and/or lower ice sheets than other glacial OIS. This may indicate glacial periods with less effective moisture relative to OIS 16, 12, 6, and 2, creating the record of relatively smaller lakes in Nevada during these periods. (See discussion in USGS 2000a, pp. 60-61). The largest ice sheets recorded by the marine isotope record over the last 800,000-year interval occurred during OIS 24, 16, 12, 6, and 2, although these sheets varied in their relative size. It is possible that the OIS with very large ice sheets could produce climates with greater effective moisture in the vicinity of Yucca Mountain relative to OIS with smaller ice sheets. As continental ice sheets expand in area and become higher in elevation they tend to deflect dry and very cold arctic high pressure air masses south during the entire year (an annual cold/dry climate state) or just during the winter if they retreat northward in summer (Kutzbach et al. 1993, Fig 4.16, Fig 4.17, pp. 56-59). Thus, large ice sheets could result in increased average annual effective moisture over southern Nevada.

The lake record in the western Great Basin suggests that OIS 16 had lakes larger than OIS 12 (Reheis 1999, Fig 3, p. 200; USGS 2000a, p. 61) and in Death Valley OIS 6 had lakes larger than OIS 2 (Ku et al. 1998, Figure 6, p. 272). The OIS 2 lake in Death Valley was large (approximately 70 m deep) but smaller than the OIS 6 lake (at least 175 m deep) (Ku et al. 1998, p. 261). Additionally, Jannik et al. (1991, Fig. 10 p. 1158) suggest that the Owens drainage lakes filled and flowed into Death Valley during parts of OIS 16, 12, 6, but not in OIS 2.

Note that the largest lakes in the Great Basin apparently occurred during the third glacial in both the previous 400,000 year climate cycle (i.e. during OIS 16) and in the most recent 400,000 year climate cycle (i.e. during OIS 6), suggesting high effective moisture generated by some combination of increased precipitation and/or lowered temperature. OIS 16 and 6 were also the coldest glacials in each long climate cycle (USGS 2000a, p. 60). However, OIS 16 (centered about 600,000 yr. B.P. and lasting for approximately 30,000 years) during the 800,000 to 400,000 year before-present-climate-cycle appears to have had greater effective moisture than OIS 6. The OIS 16 lakes identified by Reheis (1999 Fig. 1, p. 197) in the northern Great Basin are much larger and deeper than those from the same basins during OIS 6. Evidence also exists for a large lake during OIS 12, but not as large as the one during OIS 16 (Reheis 1999, Fig. 3, p. 200).

Additional evidence exists that suggests that OIS 16 had very high effective moisture.

- Lake sediments were deposited in Death Valley between 1,000,000 and >760,000 yr. B.P.; from >760,000 to ~665,000 yr. B.P.; and just prior to 510,000 yr. B.P. (Knott 1999, p. 92).

- Lake Clyde, a tectonically dammed lake in the San Joaquin and Sacramento River Valleys of California, over-topped its sill, rapidly incised its outlet, and drained shortly after 660,000 yr. B.P. (Sarna-Wojcicki, 1995 p. 6).

- A large lake existed in the Searles Basin toward the end of OIS 16 that overflowed to the Panamint Basin. An OIS 18 lake also may have overflowed to the Panamint Basin and both of these lakes may have overflowed from the Panamint Basin to Death Valley (Jannik et al. 1991, p. 1146).

- Trout and whitefish recovered only at approximately 700,000 yr. B.P. in the Owens Lake record suggest a freshwater, cool-temperature lake during this time period (Smith and Bischoff 1997, p. 123).

- Colluvial boulder deposits in southern Nevada, suggested to have been produced during periods of greater effective moisture, imply that winter minimum monthly temperatures were 7 to 9° C colder than present. Some of these deposits date approximately 800,000 yr. B.P. and 640,000 to 760,000 yr. B.P. (Whitney and Harrington 1993, p. 1015).

- A regional increase in effective moisture by a factor of 1.2 to 3 in the middle Pleistocene (OIS16) relative to late Pleistocene (OIS 4 and 2) amounts is suggested to have been necessary to create high lake levels (Reheis 1999, p. 196). Reheis (1999, p. 202) also estimates that mean annual temperature (MAT) may have been reduced by 8° C relative to modern.

- Lake Tecopa, in the Amargosa Valley east of Death Valley, began an upward trend in size and depth about 1,000,000 years ago culminating in a high stand about 186,000 yr. B.P. (Morrison 1999, p. 304). Assuming that temperature was at least 10° C colder at 186,000 yr. B.P. (Roberts and Spencer 1995, p. 3941) a value of 20 to 25 cm mean annual precipitation (MAP) was calculated compared to 7 cm MAP at present (Morrison 1999, p. 332).

However, uncertainties exist when suggesting that OIS 16 had the greatest effective moisture. These include:

- A different topographic landscape than at present would result in a different climate response. Tectonic change is probably not constant in this time frame and, hence, may contribute to climates in the older long-climate-cycle time frame in a different way or with different magnitude than those from the younger long-climate cycle or those climate cycles in the future.

- Lake Clyde, a tectonically dammed lake in the Central Valley of California, could have recharged Pacific air masses that could have increased the rain and snowfall on the Sierra Nevada during OIS 16 time (Sarna-Wojcicki 1995, p. 4).

- Increased rainshadow effect from Sierra Nevada uplift might lower precipitation in the Yucca Mountain area and otherwise affect climate over time depending on past storm tracks. The Sierra Nevada may have increased in elevation 300 m in the last 800,000 years (Huber, 1981, p. 26; Winograd et al. 1985, p. 520-521). However, other workers (Small and Anderson 1995, p. 280) suggest that the uplift is an isostatic response to erosion and not tectonic uplift, which could account for 30 to 200 m of uplift per 1,000,000 years.

- A possible shifting of the center of mass of the continental ice sheets from west in the older glacials to east in the younger glacials may have significantly impacted Great Basin climate over this time period.

Because OIS 16 appears to have had the greatest effective moisture of any glacial period over the last 800,000 years, estimates of temperature and precipitation during this time are used as an upper-bound glacial-climate parameter (see Section 6.3.2). Based on the above discussion and despite the possibility of uncertainties associated with these estimates, OIS 16 is considered to be an example of a conservative glacial state. It is believed that these estimates provide an appropriate upper bound approximation of past and future climate parameters.

Analyzing the sequence and magnitude of the last two long climate cycles (800,000 to 400,000 and 400,000 to 0 yr. B.P.) suggests that a general relation exists between the sequence of climate couplets in these adjacent cycles. This would further suggest that these have differed from each other in a systematic way in the past, and that this relation provides a criterion for the selection of particular past climates as analogs for future climates.

6.3 SELECTION OF PRESENT-DAY METEOROLOGICAL STATIONS AS ANALOGS TO PAST CLIMATE STATES

Present-day meteorological stations were selected as analogs for past climate states on the basis of geographic location with respect to atmospheric circulation patterns and length and completeness of record.

6.3.1 Atmospheric Circulation Patterns

The present-day meteorological stations chosen to represent past climate states were selected, in part, based on the limiting hydrologic and physical factors estimated from the modern distributions of fossil ostracode and diatom assemblages recovered from the Owens Lake record (USGS 2000a, p. 68-75). Stations based on geographic location rather than elevation alone were chosen as analog climate localities because geographic location better represents past climate states, given that the shifting atmospheric circulation pattern over time manifests itself more in terms of latitude and longitude than elevation.

Atmospheric circulation affects the position of the polar front, high and low pressure systems and, thus, storm tracks, precipitation, and temperature. This geographic, rather than elevation-oriented manifestation begins with the contrast in temperature between the poles and the equator. This temperature gradient drives westerly winds because cold air is more dense than warm air thus establishing a pressure gradient from the equator (higher pressure) to the poles (lower pressure) in upper air at approximately 18,000 to 20,000 feet above the earth's surface. The rotation of the earth deflects these winds eastward in the northern hemisphere creating the winds we call westerlies (Lutgens and Tarbuck 1998, pp. 167, 172). As the earth's orbital parameters change, solar radiation on the surface of the earth changes, which brings about spatial changes in the rate of heating, which affects the equator-to-pole temperature (pressure) gradient, thus changing climate patterns (Barry and Chorley 1992, pp. 123-135; Imbrie et al. 1992, p. 701).

Maximum high-speed, high-altitude winds embedded within the (relatively) slower westerly flow are called jet streams (Lutgens and Tarbuck 1998, pp. 173-174) and are associated with strong temperature contrasts (fronts) at the surface of the earth and within the tropopause. These temperature contrasts produce greater pressure gradients aloft and therefore faster upper air winds. The jet stream is a ribbon of strong winds resulting from this temperature gradient that reaches maximum speed near the tropopause where the temperature gradient reverses in the stratosphere. The polar front is the transition zone between two air masses where the temperature gradient occurs. The polar front brings colder and stormier weather to areas north of it and when it retreats northward, conditions become warmer and drier on the southern side resulting in a seasonal fluctuation of precipitation.

Upper air troughs (elongate regions of low atmosphere pressure), surface cyclones (areas of low atmospheric pressure characterized by counterclockwise rotation about the center, and converging surface winds and ascending air), and the polar front influence temperature and surface conditions because they direct day by day paths of storms. The larger temperature gradient in the winter relative to summer often causes the polar front to move as far south as 30° north latitude, whereas in the summer it migrates north to an average of 50° north latitude (Lutgens and Tarbuck 1998, p. 173-174). For reference, Yucca Mountain is at about 37° north latitude (Fig. 1-1). This midlatitude zone receives more precipitation as the polar front moves southward in the winter and less precipitation as it moves northward in the summer. Hence, the position of the polar front is a critical factor in determining temporal and geographical shifts in climate. As solar radiation on the earth's surface changes, air temperature and pressure gradients change, thus affecting the position of the polar front. Atmospheric circulation models suggest that the presence of Pleistocene ice sheets over the northern U.S. and southern Canada deflected the polar front southward (Kutzbach et al. 1993, Fig 4.16, Fig 4.17, pp. 56-59), potentially bringing cold and wet weather to southern Nevada for extended periods.

Other important features of atmospheric circulation include upper air and surface cyclones, anticyclones (areas of high atmospheric pressure characterized by diverging and clockwise rotation of winds about the center and subsiding air aloft) and associated zones of low and high surface pressure. Those relevant to past and present climates of southern Nevada are the subtropical high pressure zones located between about 20° and 35° north latitude; the subpolar low pressure zones located between 50° and 60° north latitude; and the polar high located at the north pole. The Pacific High is located over the western North Pacific ocean; the Bermuda high is located over the western part of the North Atlantic ocean; the Aleutian Low is located over the Gulf of Alaska; the Icelandic Low is located over the Northern Atlantic ocean; and the Arctic High is located over the Arctic region. The upper air circulation pattern of troughs and ridges (Rossby waves) affect the location of these high and low pressure systems at the earth's surface (Lutgens and Tarbuck 1998, pp. 175-176; Houghton et al. 1975, pp. 9-10), thus altering their seasonal strength and location.

For example, hot, dry summers with convective summer thunderstorms characterize interglacial (modern) climate in the Yucca Mountain region. Winters are generally dry and warm, and wetter at higher than at lower elevations. This climate regime is dominated by the northward movement and intensification of the subtropical high residing over the area from the late spring to the early fall. From late fall through early spring, the subtropical highs weaken and retreat south which allows Pacific fronts to move across California to Nevada bringing precipitation carried by the prevailing westerlies. Interglacial climates have lower annual precipitation and higher annual temperatures than the other climate states designated herein, except perhaps the monsoon state.

Monsoon climates in the Yucca Mountain area can be characterized by summer rain generated by incursions of moisture originating within subtropical easterlies. Winter precipitation most likely did not dominate the mean annual precipitation during monsoon intervals because winter storms would have been less frequent than modern. Monsoon climate states were most likely warmer and wetter in summer than today with much of the precipitation lost to evapotranspiration and evaporation.

Intermediate climates in the Yucca Mountain area can be characterized by a resident polar front during much of the year resulting in cool, wet winter seasons and warm (but not hot) to cool and dry summers relative to modern. This climate regime would not experience extended dominance by the very cold Arctic high-pressure air, but most likely would have periods dominated by polar air masses and westerly airflow. Summers could have included subtropical high activity with more evaporation than modern, although winters were still dominated by polar-air masses. Effective moisture was greater relative to modern.

Glacial climate states in the Yucca Mountain region had a winter-dominated precipitation regime in both the mountains and the valleys. Arctic highs probably resided over the area much of the year resulting in snowy cold and dry or snowy cold and wet winters. Summers were cool and dry or cool and wet and effective moisture was much greater relative to modern. Subtropical highs were less persistent although polar air masses and westerly airflow probably occurred.

Because of these atmospheric circulation patterns, present-day meteorological stations positioned with respect to the seasonal location of the polar front and associated low and high pressure zones were selected as analogs for past climate. These stations better represent the seasonal distribution of temperature, precipitation, snowfall, and humidity than high-elevation stations in southern Nevada. If stations were selected based on elevation alone, they would represent only modern atmospheric circulation patterns with the same distribution of temperature and precipitation as the present day. Because the analysis documented in this report estimates that modern-like climates occurred only about 12 percent of the time during the past 1,000,000 years (see Section 6.5.3), selection of climate analog meteorological stations based on geographic location rather than elevation is appropriate.

6.3.2 Description of Present-Day Meteorological Stations

Only meteorological stations with relatively complete and long records were considered as analogs for past climates (Figure 6-3, Table 6-3). Stations with periods of record exceeding 50 years and observations greater than 95 percent include Lake Yellowstone, Wyoming; Simpson, Montana; and Chewelah, Rosalia, and Spokane, Washington. Stations with records exceeding 50 years and observations greater than 85 percent include Browning, Montana; Delta, Utah; Nogales, Arizona; and Elko and Beowawe, Nevada. Although both the Hobbs, New Mexico, and Nogales, Arizona temperature observations are only slightly greater than 70 percent, these stations have records exceeding 50 years (1914-2000 and 1892-1948 respectively). The St. John, Washington, observations number greater than 95 percent complete although the record is only 37 years long (1963 to 2000). When averaged with the Rosalia and Spokane data they are considered adequate to represent the upper bound intermediate and lower bound full glacial climates for OIS 8/10. Variables such as mean annual and seasonal air temperature and mean annual and seasonal snow and rainfall from these present-day stations provide daily input for net-infiltration estimates (USGS 2000b, p. 13). Stations were chosen to represent upper (wetter) and lower (drier) bounds rather than means because the net-infiltration and performance-assessment models require bounding conditions to account for uncertainties associated with the paleoenvironmental record and the long time frames for climate predictions.

As summarized on Table 6-3, the present day climate state is represented by regional meteorological stations in the Yucca Mountain area (USGS 2000a, pp. 69-71; USGS 2000b, pp. 58-59). The monsoon climate state is represented by Nogales, Arizona, and Hobbs, New Mexico for an upper bound and the Yucca Mountain regional stations as a lower bound (USGS 2000a, pp. 71-72). The intermediate climate state is represented by three stations in Washington state: Rosalia, St. John, and Spokane for an upper bound, and Beowawe, Nevada, and Delta, Utah, for a lower bound (USGS 2000a, pp. 72-75). (See Figure 6-3.)

The locations of the meteorological stations representing upper and lower bounds for the three magnitudes of glacial climate (Table 6-3) were determined using the same method as outlined in

USGS 2000a(pp. 68-75). Consequently, the number of past climate states and representative meteorological stations were limited to facilitate and simplify model simulations of net infiltration. When possible, stations selected for the analysis in USGS (2000a, Table 2, p. 68) were selected for the current analysis. For example, the stations selected in the current analysis to represent the lower bound of the OIS 8/10 full glacial state are the same as those selected in USGS (2000a) to represent the upper bound of the intermediate climate state.

In USGS (2000a, p. 58) the ostracode data were calibrated relative to Late Pleistocene and present day climate data. The late Pleistocene climate data come from the reconstruction based on packrat middens (Thompson et al. 1999, Table 4, p. 24) and the current climate data comes from Yucca Mountain regional meteorological data (Thompson et al. 1999, Table 4, p. 24). The modern ostracode distribution data comes from Forester (1983, pp. 436-437; 1985, pp. 10-11; 1986, pp. 797-8) and CRWMS M&O (2000b, Sections 6.3.4.1.2 and 6.3.4.2). The OIS 2 estimates for MAP and MAT at Yucca Mountain were 266 to 321 mm and 7.9° C to 8.5° C, respectively (Thompson et al. 1999, Table 4, p. 24; USGS 2000a, p. 58). Therefore, if OIS 10 was wetter and warmer than OIS 2 and 6, it may have had a MAP much greater than 300 mm and a MAT greater than about 8° C. If OIS 6 was colder than, but with a similar MAP to OIS 2, it may have been colder than 8° C with a MAP of 300 mm or higher. With the intermediate climates drier and warmer than OIS 2, but wetter and cooler than present day, MAP for the intermediate climates may have been greater than 125 mm, but less than about 275 mm, and MAT may have been between 8 and 13° C (USGS 2000a, p. 58).

Because the full-glacial OIS 6 climate seems to have had greater effective moisture than OIS 2 with a MAP of 300 mm or greater, and a MAT colder than 8° C, and OIS 16 appeared to have more effective moisture than OIS 6, meteorological stations with values colder and wetter than OIS 2 were sought. Because the ostracode *Cytherissa lacustris*, found in the OIS 6 climate state in the Owens Lake record, lives in regions dominated by polar air masses, such as the Canadian boreal forest and above the Arctic Circle, the northern United States geographic region was chosen for analog meteorological stations.

Cytherissa lacustris is currently found only in a few localities in the United States. It has been collected in Lake Yellowstone, Wyoming, a very fresh and cold lake. Because this region is dominated by polar air masses, it was chosen as the upper bound for the full glacial 6/16 climate state. The annual temperature at this station is very cold (0° C) because of its high elevation and latitude, therefore it may be a very conservative analog (Figure 6-3, Table 6-3). The lower bound stations, Browning and Simpson, Montana, are slightly more in line with estimated OIS 6 temperatures (4.4 and 5.0° C respectively) and average slightly above the estimated 300 mm OIS 2 MAP, even though *Cytherissa lacustris* has not been reported in this locality.

The lower bound for the full-glacial OIS 6/16 climate (the Montana stations) also was chosen for the upper bound of the full-glacial OIS 2/4 because estimates based on packrat middens put the MAP for OIS 2 between 266 and 321 mm and MAT between 7.9° C and 8.5° C (Thompson et al. 1999, Table 4, p. 24). Again, this is a conservative analog as average annual temperatures for these stations are 3-4° C below the OIS 2/4 temperature estimates. Elko, Nevada, was selected for the lower bound for full-glacial OIS 2/4 with a MAP of about 240 mm and a MAT of about 8° C (Table 6-3, Figure 6-3). Elko was selected because it can experience cold, wet, snowy

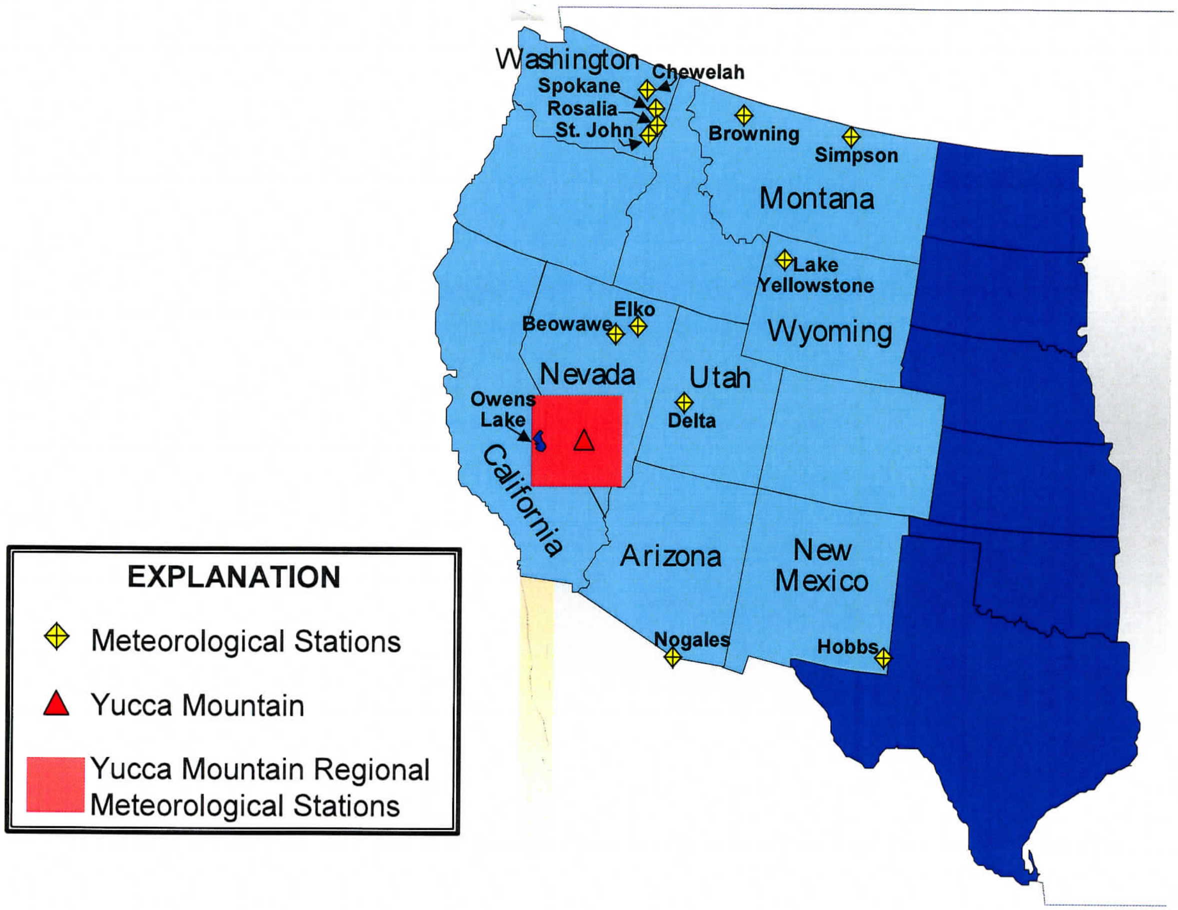


Figure 6-3. Modern Meteorological Stations Used as Future Climate Analogs

Table 6-3. Present-Day Meteorological Stations Selected as Analogs for Climate States

Climate State	Analog Meteorological Stations	Latitude	Longitude	Elevation/m[1]	MAT ° C	MAP mm/yr
Full Glacial, OIS 6/16—Average upper bound[2]	Lake Yellowstone, WY (485345)	44° 33'	110° 24'	2368	0.0	513
Full Glacial OIS 6/16--Average lower bound[2]	Browning, MT (241202)	48° 34'	113° 01'	1329	4.4	380
	Simpson 6NW, MT (247620)	48° 59'	110° 19'	835	5.0	260
Full Glacial, OIS 2, 4--Average upper bound[2]	Browning, MT (241202)	48° 34'	113° 01'	1329	4.4	380
	Simpson 6NW, MT (247620)	48° 59'	110° 19'	835	5.0	260
Full Glacial, OIS 2, 4--Average lower bound[2]	Elko, WB Airport, NV (262573)	40° 50'	115° 47'	1539	7.7	243
Full Glacial, OIS 8, 10--Average upper bound[2]	Chewelah, WA (451395)	48° 15'	117° 43'	509	7.9	537
Full Glacial, OIS 8, 10--Average lower bound[2]	Rosalia, WA (457180)	47° 14'	117° 22'	732	8.3	455
	St. John, WA (457267)	47° 06'	117° 35'	594	9.1	432
	Spokane, WSO Airport, WA (457938)	47° 38'	117° 32'	719	8.9	409
Intermediate—Average upper bound[2]	Rosalia, WA (457180)	47° 14'	117° 22'	732	8.3	455
	St. John, WA (457267)	47° 06'	117° 35'	594	9.1	432
	Spokane, WSO Airport, WA (457938)	47° 38'	117° 32'	719	8.9	409
Intermediate—Average lower bound[2]	Beowawe, NV (260795)	40° 36'	116° 29'	1433	8.8	217
	Delta, UT (422090)	39° 20'	112° 35'	1408	10.1	201
Monsoon—Average upper bound[2]	Nogales Old Nogales, AZ (025922)	31° 20'	110° 57'	1189	17.1	399
	Hobbs, NM (294026)	32° 42'	103° 08'	1103	16.6	409
Monsoon—Average lower bound[3]	Yucca Mountain regional stations			750-2300	13.4	125
Modern or interglacial climate[3]	Yucca Mountain regional stations			750-2300	13.4	125

Output DTN: UN0201SPA021SS.007

Data Sources: Western U.S. Climate Historical Summaries. DTN: UN0112SPA021SS.004; USGS 2000b; Thompson et al. 1999, Table 4, p.24.
Note: MAT = mean annual temperature; MAP = mean annual precipitation; OIS = Oxygen isotope stage

[1] Elevations are above mean sea level

[2] Using DTN: UN0112SPA021SS.004, MAT is calculated by averaging average annual maximum and average minimum temperature (in °F) and then converting to °C; MAP is calculated by converting inches to mm.

[3] Thompson et al. 1999. DIN:021SS.014

winters influenced by either Polar lows or Arctic highs and cool, dry summers resulting from both the presence of cool, westerly flows and the absence of subtropical highs in the region. Presently, *Candona caudata* inhabits localities from Canada south to Pahranagat Lake in southern Nevada (USGS 2000a, p. 54).

The area east of the Cascade mountain range in the state of Washington was chosen for the lower bound full glacial OIS 8/10 analog and the average upper bound analog for the intermediate climate state and because the region 1) is east of a high mountain range in a rain shadow similar to the Yucca Mountain region; 2) is winter-precipitation dominated; 3) is under the influence of the polar front during the winter; 4) is situated near the average position of the polar front throughout the year; and 5) does not experience extended dominance by cold Arctic high-pressure air. Additionally, ostracodes recovered from the full glacial OIS 8 and 10 in the Owens Lake core also occur presently in eastern Washington, supporting the link between distribution and climate. The Spokane, Rosalia, and St. John climate stations were selected to represent the upper bound intermediate (glacial-transition) climate in USGS 2000a (Table 2, p. 66). Because the full glacial OIS 8/10 upper bound needed to be wetter and slightly cooler than OIS 2, Chewelah, Washington, was selected based on geographic criteria and the fact that it has a MAP of approximately 537 mm and a MAT of approximately 8° C (Figure 6-3, Table 6-3).

Beowawe, Nevada, and Delta, Utah, were chosen for the intermediate lower bound climate analogs in USGS 2000a (Table 2. p. 66) and herein because they represent cool, winter wet seasons, warm to cool and dry summers, and lie on the east side of large mountain ranges (see discussion in USGS 2000a, pp. 73-75).

Nogales, Arizona and Hobbs, New Mexico, were chosen as the monsoon average upper bound climate analogs in USGS 2000a (Table 2., p. 66) and herein because the ostracode, *Limnocythere bradburyi* recovered from the Owens Lake record, implies an Owens Lake source water not derived from snowmelt. The presence of this ostracode in Owens Lake can be best explained by an expansion and intensification of the summer rain system (monsoons) from the air masses (USGS 2000a, pp. 71-72).

The monsoon climate analog average lower bound and the modern (interglacial) climate state are represented by the Yucca Mountain regional climate stations. These stations average 13.4° C and 125 mm precipitation per year (Thompson et al., 1999 Table 4, p. 24).

Figure 6-4 portrays the temperature and precipitation values (taken from Table 6-3) for each of the climate state upper and lower bounds. If an upper or lower bound is represented by more than one climate station, the values are averaged to show a general comparison among the climate states. For example, the full glacial OIS 6/16 lower bound Browning and Simpson, Montana, values are averaged. Note that all values are cooler and wetter than modern values except the monsoon temperature upper bound. Infiltration is greater during cooler and wetter climate states.

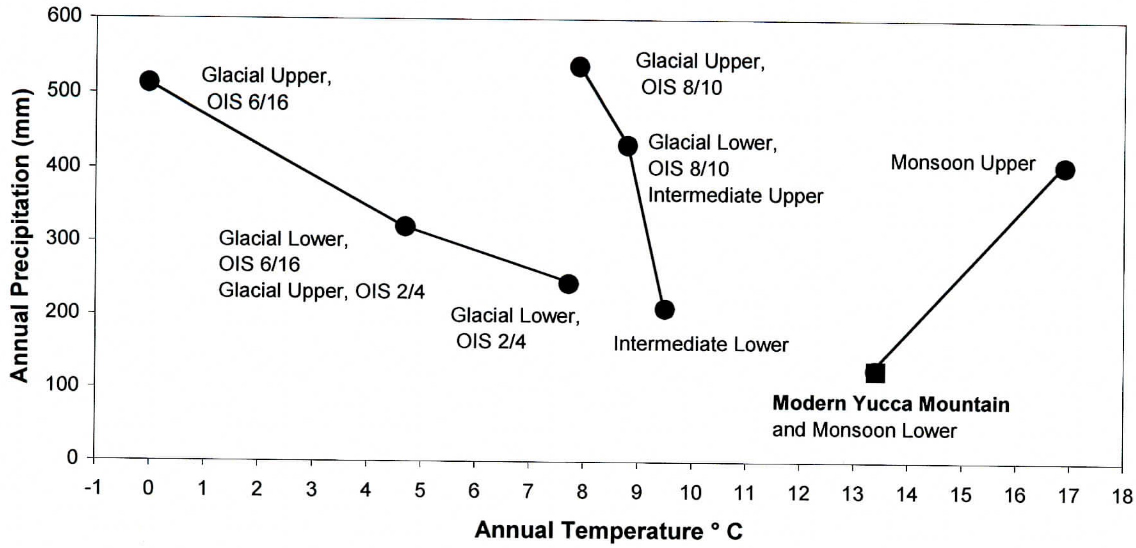


Figure 6-4. Modern Meteorological Station Temperature and Precipitation

6.4 RELATION OF THE DEVILS HOLE CLIMATIC RECORD TO ORBITAL PARAMETERS

USGS (2000a, pp. 35-37) identified a pattern linking the relation between precession, eccentricity, and terminations in glacial and interglacial cycles in the 400,000-year old Devils Hole record. This relation provides the basis for forecasting climate into the future. These datasets also support the first two assumptions discussed in USGS (2000a, p. 19) that 1) climate is cyclical, therefore the past can be used to forecast the future; and 2) a relation exists between the timing of (inter)glacial cycles and the timing of changes in certain earth-orbital parameters. Briefly, the two datasets are described as follows.

6.4.1 Devils Hole Calcite Record

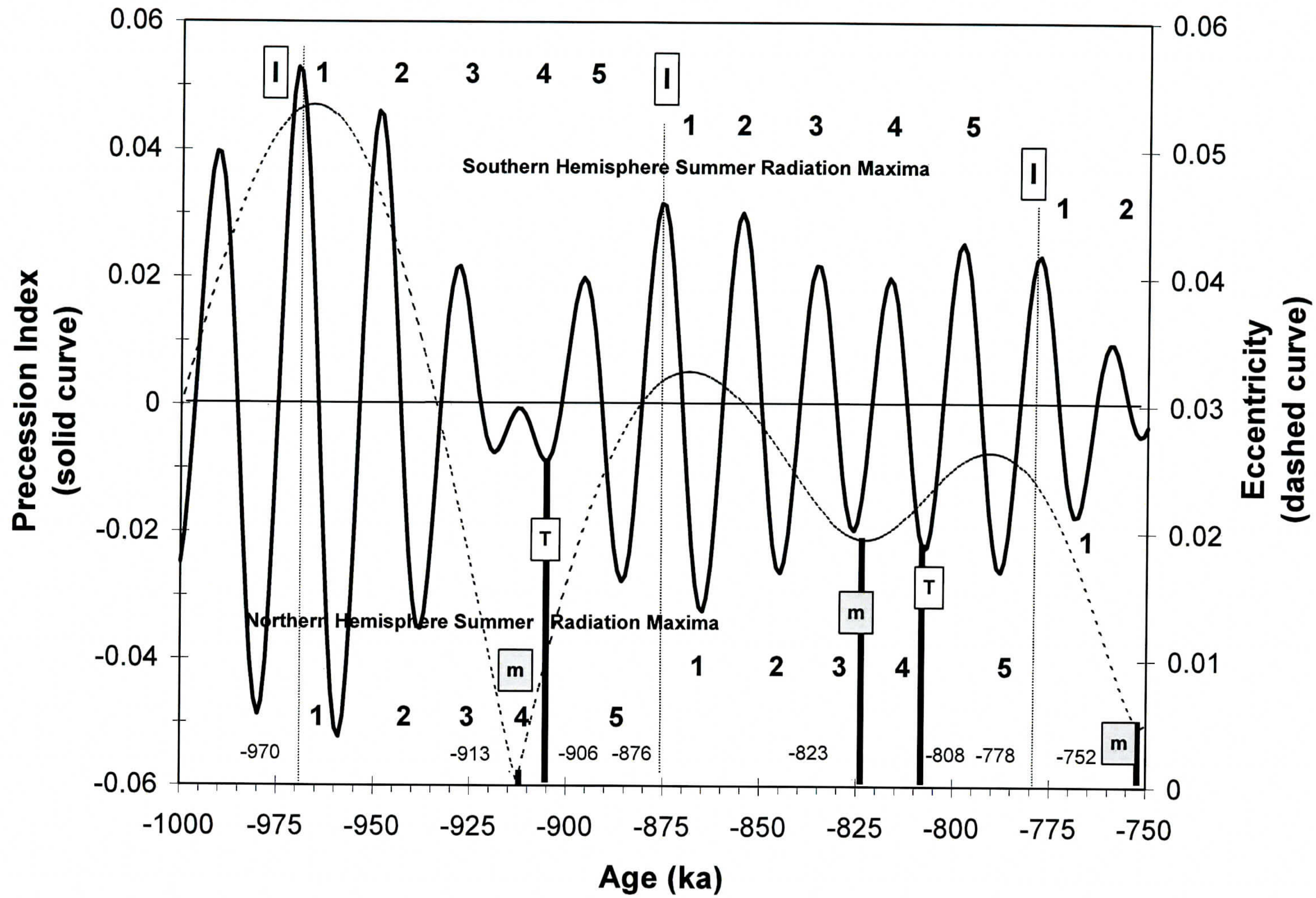
The Devils Hole climatic record is an accurately dated (Ludwig et al. 1992, Table 1 and 2 p. 285-6; Landwehr et al. 1997, pp. 1-2) calcite vein in southern Nevada that records the isotopic signal of groundwater in the recharge area of the regional aquifer (Winograd et al. 1992, p. 255) from approximately 568,000 to 60,000 yr B.P. The isotopic values of the Devils Hole calcite record change relative to the infiltration in the recharge area. This reflects a cyclic change of glacial and interglacial climates in southern Nevada, thus supporting assumption 1 in Section 5 (USGS 2000a, pp. 19, 30).

The Devils Hole record (Landwehr et al. 1997, pp. 1-8) contains the most robust information and most accurate dates about climate change in the region. Therefore, it forms the basis for the comparison and timing of climate change for the current analysis of future climate. The high $\delta^{18}O$ values in the Devils Hole record represent interglacial climates and the low values represent glacial or intermediate climates (USGS 2000a, p. 29).

The timing of the Devils Hole record can be compared to the timing of OIS (based on marine carbonate $\delta^{18}O$ records, Imbrie et al. 1984 Table 7 p. 291-293). Although the OIS and Devils Hole chronology are not completely synchronous, particularly in the timing of the last glacial terminations, similarities between the two records exist (see discussion USGS 2000a, pp. 30-31; 35; 42-44; Winograd et al. 1992, Fig. 3, p. 257; Smith and Bischoff 1997, p. 153).

6.4.2 Orbital Parameters

Past and future timing of the Earth's orbital parameters (obliquity, eccentricity, and precession) can be accurately constructed from celestial mechanics calculations, assuming there are no perturbations from any large bodies passing through the solar system (Hartmann 1994, pp. 307-308). Obliquity, which varies on time scales of about 40,000 years, influences the seasonal cycle in high latitudes (Crowley and North 1991, pp. 134-136), but shows no apparent consistent relation with the Devils Hole record (USGS 2000a, p. 33). However, eccentricity and precession do. Eccentricity and precession for the last 1,000,000 years B.P. are shown in Figure 6-5a through d.



Data Source: DTN: GS000900005121.004

NOTE: I = initiation of transition to glacial climate; T = initiation of transition to interglacial climate; m = minimum eccentricity value; Numbers 1 through 4 or 5 = summer solar radiation maxima. Numbers at the top of graph are summer solar radiation maxima in the southern hemisphere; numbers at the bottom of graph are summer solar radiation maxima in the northern hemisphere. Ages for I, T, and m are shown near bottom of graph. Continuation of diagram is given as Figures 6-5b, 6-5c, and 6-5d.

Figure 6-5a. Relation Between Precession and Eccentricity From 1,000,000 Years Before Present to Present

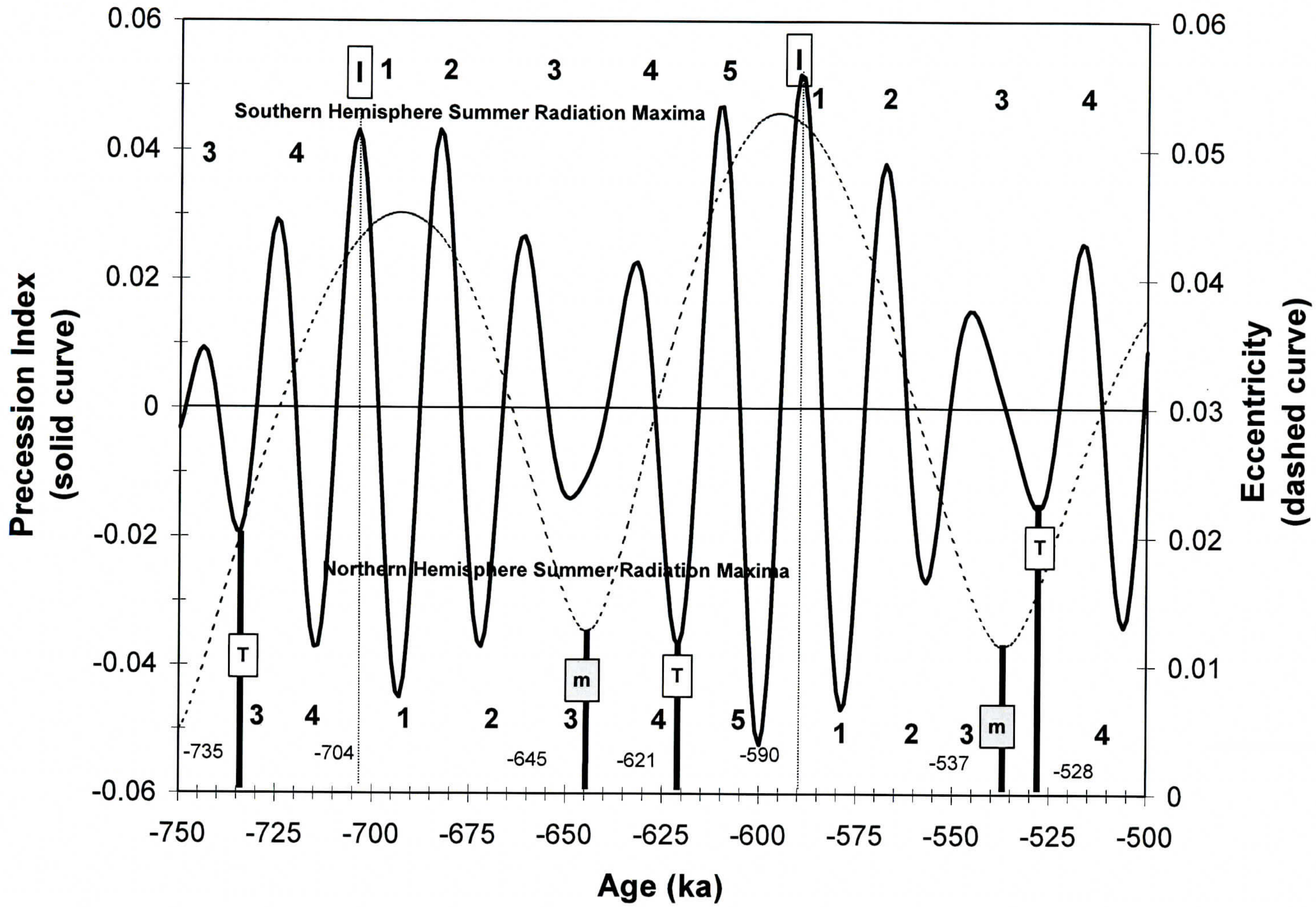
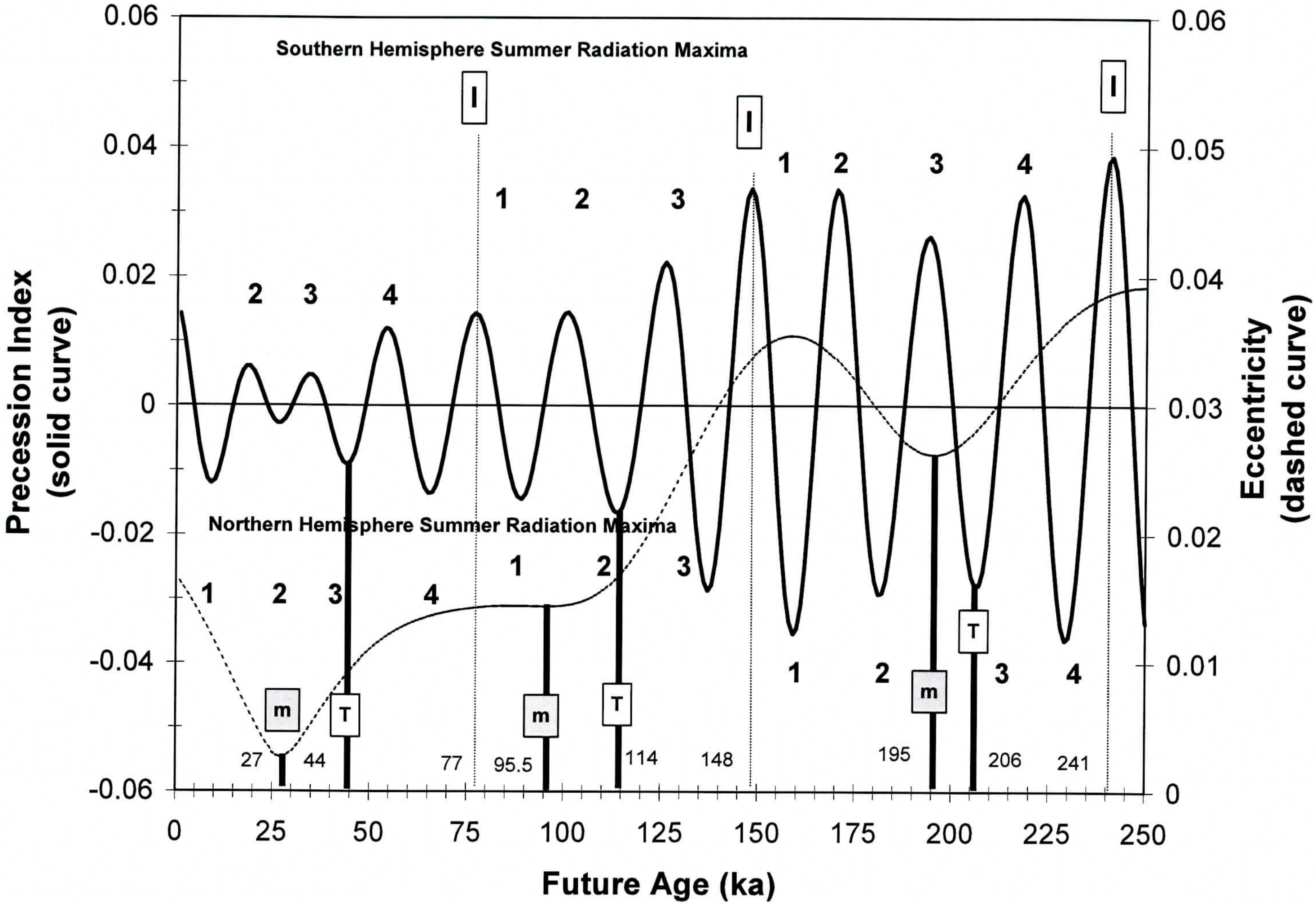


Figure 6-5b. (Continuation of Figure 6-5)

In addition, a "flattening" of the eccentricity cycle occurs at 95,500 yr. A.P. The move from concave down to concave up is minimal and seems to have an effect on the corresponding precession sequence. The precession sequence here is the only one that has three precession peaks, rather than four or five, in the entire 2,000,000-year record evaluated in this analysis. Because no previous pattern for a three-precession cycle sequence was available, the intermediate/monsoon climate states were determined to be one precession cycle shorter (lasting through southern-hemisphere maximum 2 rather than 3). This way, the durations of the glacial and following intermediate climate states were similar to past durations. (See Tables 6-1 and 6-7 for durations.) If the intermediate/monsoon climate state was continued to just beyond the southern hemisphere summer solar radiation maximum as in previous cycles, the glacial, intermediate, and interglacial states would be compressed into 17,000 years in less than one precession cycle.



Data Source: DTN: GS000900005121.004.
NOTE: I = initiation of transition to glacial climate; T = initiation of transition to interglacial climate; m = minimum eccentricity value; numbers 1 through 4 or 5 = summer solar radiation maxima. Numbers at the top of graph are summer solar radiation maxima in the southern hemisphere; numbers at the bottom of graph are summer solar radiation maxima in the northern hemisphere. Ages for I, T, and m are shown near bottom of graph. Continuation of diagram is given as Figure 6-7b, 6-7c, and 6-7d

Figure 6-7a. Relation Between Precession and Eccentricity From Present to 1,000,000 Years After Present

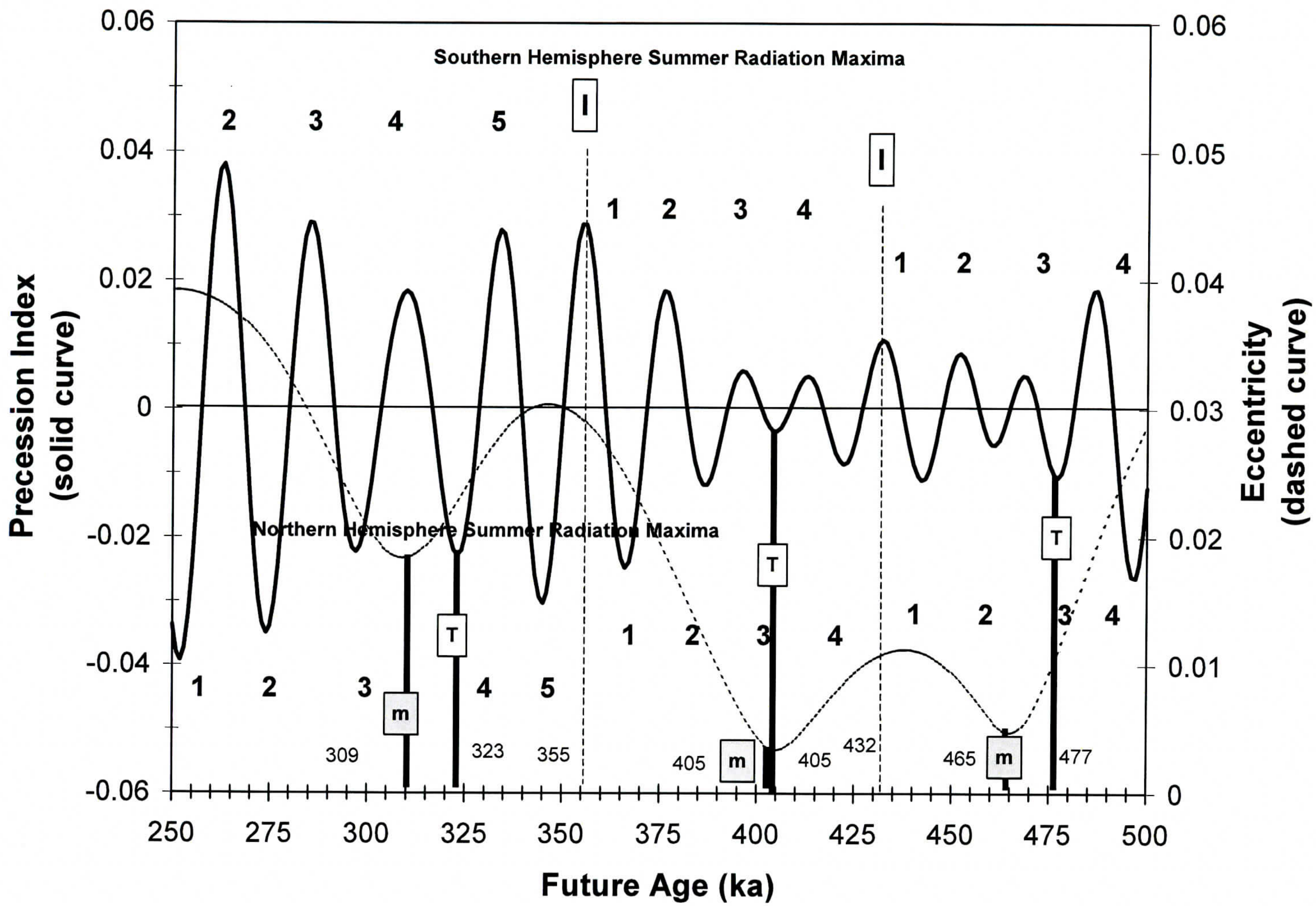


Figure 6-7b. (Continuation of Figure 6-7)

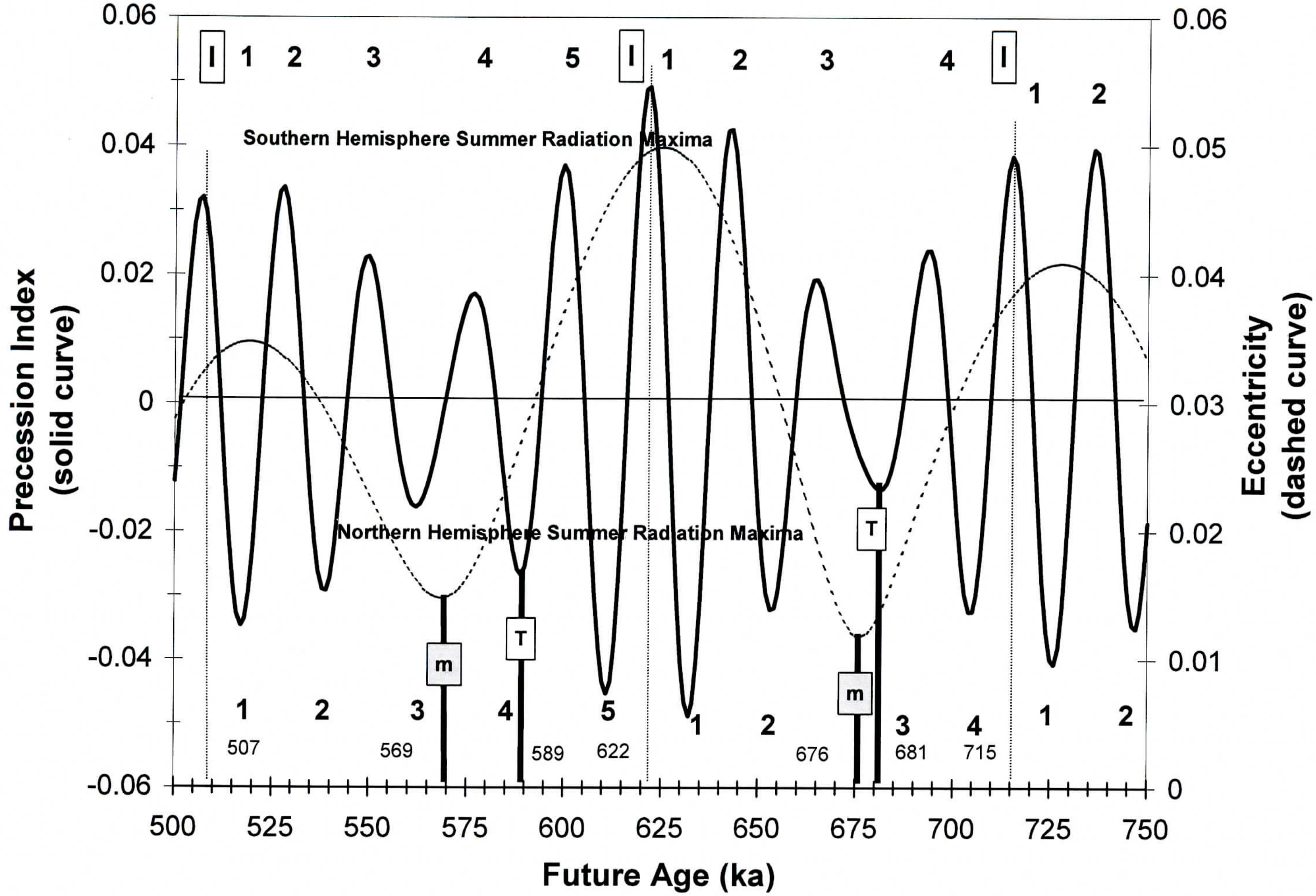


Figure 6-7c. (Continuation of Figure 6-7)

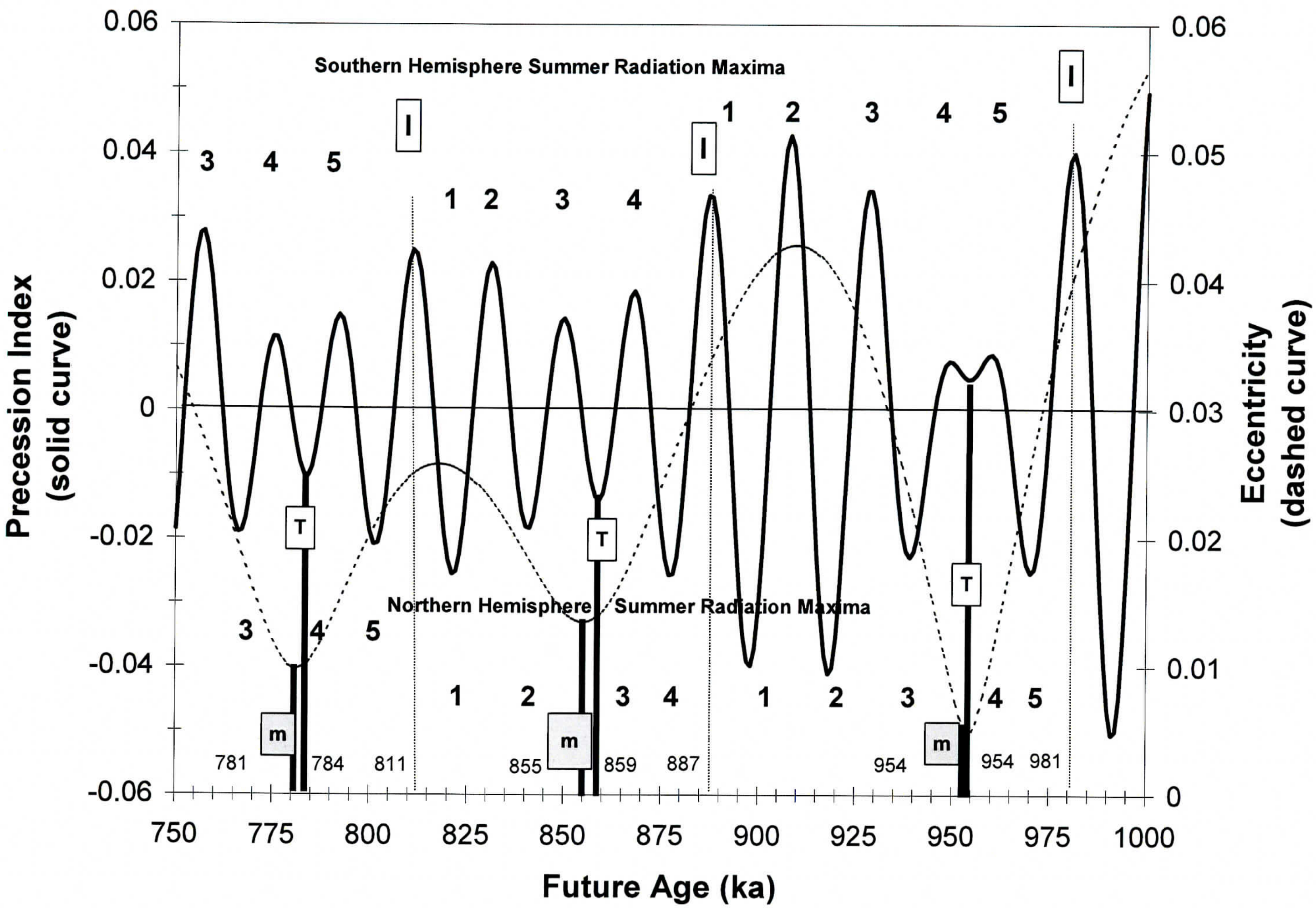


Figure 6-7d. (Continuation of Figure 6-7)

6.5.3 Starting Date and Timing of Future Climate States

The predicted sequence and durations of climate states for the next 1 million years are listed in Table 6-5. This table was generated using values from the precession methodology described in Section 6.5.2 with the values used to generate Figures 6-5 and 6-7. As described in Section 6.1, four climate states are considered to comprise the sequence of climate states during the next million years: intermediate/monsoon (IM/M) alternating between monsoon (M) and intermediate (IM) climate states, glacial (G), intermediate (IM), and interglacial (IG).

The precession methodology to time future climate states was applied to the next 1,000,000 years based on the past/present analog point of about 404,000 years ago established in USGS (2000a, p. 64) using the ostracode sequence in the Owens Lake record and the Devils Hole chronology. The "I" event, at the end of interglacial OIS 11 at 399,000 yr. B.P., is equivalent to the "I" event occurring at –1,000 yr. B.P. in the Devils Hole chronology (USGS 2000a, p. 62). USGS (2000a, pp. 62-64) suggested that the current climate has just passed an inflection point from interglacial to glacial (Figure 6-5d, "I" event at –1,000 yr. B.P.) and that the current interglacial state may soon be nearing a monsoon climate state[1].

The glacial stages in the current analysis are based on the pattern of glacial stages over the last 400,000 years: OIS 10 to 8 to 6 to 4 to 2. Glacial stages that were similar in nature (8 and 10, 8/10, or 6 and 16, 6/16) were combined into one glacial state. OIS 4 and 2 were also combined and designated OIS 4/2 with an OIS 2 magnitude (see Section 6.4.5). The starting point for the future glacial sequence is OIS 10 because the past/present analog point beginning the future climate sequence is OIS 11. Because OIS 10 and 8 are similar in magnitude (warm and wet) the first two glacial stages beginning at 38,000 yr. A. P. and at 106,000 yr. A. P. use OIS 8/10 as an analog. The third glacial at 200,000 yr. A.P. uses OIS 6/16 as an analog. The fourth glacial at 291,000 yr. A.P. uses OIS 4/2 as an analog. The glacial sequence starts over after OIS 4/2 beginning with OIS 8/10.

This analysis differs from that of USGS (2000a, p. 76) in that it suggests the monsoon period began 1,000 years ago and will last 500 years into the future, 1,400 to 1,600 years prior to the USGS estimate. USGS (2000a, p. 64) based the future timing estimates on the repetition of ostracode occurrence at the past/present analog point in the Owens Lake record whereas this analysis bases the timing on the precession methodology.

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[1] The timing of the past/present analog point (~404,000 yr. B.P.) falls within the *Limnocythere bradburyi* event (405,000-403,000 yr. B.P.) in Table 6-1. That is, it appears that *L. bradburyi* arrived "sooner" (by about 1,000 years) than it should have. However, the timing of the past-present analog point was chosen using the isotope values and the timing of the Devils Hole chronology. The past-present analog point had to correspond to a point in the Devils Hole record where the isotopic values were increasing in response to monsoonal flow, after 405,400 yr. B.P. Since the sampling interval of the Devils Hole calcite represents an average time interval of about 1,800 years at 2 σ (Winograd et al. 1992, p. 255), the timing discrepancy falls within this uncertainty.

Table 6-5. Predicted Sequence and Durations of Climate States for the Next 1 Million Years for the Yucca Mountain Region

Dates are mean values, rounded to the nearest 500 years

IM/M = Intermediate and monsoon combination
M = Monsoon
IM = Intermediate
G = Full Glacial
G, 10/8 = OIS 10 and 8 equivalent
G, 16/6 = OIS 16 and 6 equivalent
G, 4/2 = Glacial Stage 2 equivalent
IG = Interglacial (modern)

Climate State	begin (yr A.P.)	end (yr A.P.)	Duration (years)
IG	-12,000	-1,000	11,000
IM/M	**Combination**		
M	-1,000	0	1,000
M	0	500	500
IM	500	18,500	18,000
M	18,500	20,000	1,500
IM	20,000	38,000	18,000
G, 10/8	38,000	49,000	11,000
IM	49,000	65,000	16,000
IG	65,000	77,000	12,000
Duration			**78,000**
IM/M	**Combination**		
M	77,000	78,500	1,500
IM	78,500	91,500	13,000
M	91,500	93,000	1,500
IM	93,000	106,000	13,000
G, 10/8	106,000	120,000	14,000
IM	120,000	137,000	17,000
IG	137,000	148,000	11,000
Duration			**71,000**
IM/M	**Combination**		
M	148,000	149,500	1,500
IM	149,500	174,000	24,500
M	174,000	175,500	1,500
IM	175,500	200,000	24,500
G, 16/6	200,000	213,000	13,000
IM	213,000	229,000	16,000
IG	229,000	241,000	12,000
Duration			**93,000**
IM/M	**Combination**		
M	241,000	242,500	1,500
IM	242,500	266,000	23,500
M	266,000	267,500	1,500
IM	267,500	291,000	23,500
G, 4/2	291,000	329,000	38,000
IM	329,000	345,000	16,000
IG	345,000	355,000	10,000
Duration			**114,000**
IM/M	**Combination**		
M	355,000	356,500	1,500
IM	356,500	378,000	21,500
M	378,000	379,500	1,500
IM	379,500	401,000	21,500
G, 10/8	401,000	409,000	8,000
IM	409,000	422,000	13,000
IG	422,000	432,000	10,000
Duration			**77,000**
IM/M	**Combination**		
M	432,000	433,500	1,500
IM	433,500	451,500	18,000
M	451,500	453,000	1,500
IM	453,000	471,000	18,000
G, 10/8	471,000	482,000	11,000
IM	482,000	497,000	15,000
IG	497,000	507,000	10,000
Duration			**75,000**
IM/M	**Combination**		
M	507,000	508,500	1,500
IM	508,500	531,000	22,500
M	531,000	532,500	1,500
IM	532,500	555,000	22,500
G, 16/6	555,000	595,000	40,000
IM	595,000	611,000	16,000
IG	611,000	622,000	11,000
Duration			**115,000**
IM/M	**Combination**		
M	622,000	623,500	1,500
IM	623,500	647,000	23,500
M	647,000	648,500	1,500
IM	648,500	672,000	23,500
G, 4/2	672,000	688,000	16,000
IM	688,000	704,000	16,000
IG	704,000	715,000	11,000
Duration			**93,000**
IM/M	**Combination**		
M	715,000	716,500	1,500
IM	716,500	738,000	21,500
M	738,000	739,500	1,500
IM	739,500	761,000	21,500
G, 10/8	761,000	788,000	27,000
IM	788,000	801,000	13,000
IG	801,000	811,000	10,000
Duration			**96,000**
IM/M	**Combination**		
M	811,000	812,500	1,500
IM	812,500	832,500	20,000
M	832,500	834,000	1,500
IM	834,000	854,000	20,000
G, 10/8	854,000	864,000	10,000
IM	864,000	877,000	13,000
IG	877,000	887,000	10,000
Duration			**76,000**
IM/M	**Combination**		
M	887,000	888,500	1,500
IM	888,500	910,500	22,000
M	910,500	912,000	1,500
IM	912,000	934,000	22,000
G, 16/6	934,000	957,000	23,000
IM	957,000	970,000	13,000
IG	970,000	981,000	11,000
Duration			**94,000**
IM/M	**Combination**		
M	981,000	982,500	1,500
IM	982,500	1,000,000	17,500
Duration			**19,000**

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Table 6-6 compares the estimated timing[2] between the two analyses. Both USGS 2000a (p. 26) and this report (Table 6-1) confirm the existence of a long duration modern (interglacial) climate state for at least the last 9,000 years. However, three timing differences between the two future estimates occur for the next ~20,000 years:

1. Transition from modern to monsoon, maximum difference is 1,600 years (between 600 and –1,000 years).

2. Transition from monsoon to intermediate, difference is 1,500 years (between 2,000 and 500 years).

3. Presence of a 1,500-year monsoon state occurring between 18,500 and 20,000 in this report.

Table 6-6. Comparison Between the Two Estimates of the Timing of Future Climate States for the Next ~50,000 Years.

USGS (2000a, pp. 48 ,67); USGS (2000b, p. 57)		This report	
Modern	600 yr. A.P. [600]	Interglacial	N/A
Monsoon	600 to 2,000 yr. A.P. [1,400]	Monsoon	-1,000 yr. B.P. to 500 yr. A.P. [1,500]
Glacial-Transition	2,000 to 30,000 [28,000]	Intermediate	500 to 18,500 yr. A.P. [18,000]
		Monsoon	18,500 to 20,000 yr. A.P. [1,500]
		Intermediate	20,000 to 38,000 [18,000]
Glacial	30,000 ending before 50,000 yr. A.P. [<20,000]	Glacial	38,000 to 49,000 yr. A.P. [11,000]

Note: yr. A.P. = years after present; brackets denote duration in years
Source: USGS 2000a, USGS 2000b.

The difference in timing between the two reports is considered to be insignificant for two reasons. First, both estimates use the Devils Hole record chronology. Each Devils Hole sample integrates an average time interval representing about 1,800 years (Winograd et al. 1992, p. 255). Therefore, the differences of 1,600 years and 1,500 years for the first two timing differences are less than the Devils Hole sample resolution of 1,800 years. The duration of the 1,500-year monsoon interval is also less than the Devils Hole sampling error. Since the monsoon is between two intermediate states of long durations (18,500 years), the uncertainties of timing for both the beginning and the end of monsoon are dominated by the uncertainties of the intermediate states. Second, this report estimates the timing of climate states (Table 6-5) to the nearest 500 years (see Section 6.5.4). Therefore the timing of future climate estimated in this report confirms the timing suggested in USGS (2000a, p. 76).

USGS 2000a (Table 2, p. 66) and this report are in relatively close agreement for the onset and length of the next glacial state after the intermediate climate state concludes. USGS (2000a, p.

[2] USGS (2000a, Table 2 pp. 48, 66) reported durations of modern climate for 400-600 years; monsoon climate for 900-1400 years; and glacial transition (intermediate) climate for ~ 28,000 years. However, Table 6-6 uses the time frame selected by USGS 2000b (600 years and 2,000 years A.P.) as the timing for these changes in climate states.

48) estimates the next glacial state will occur from 30,000 to less than 50,000 years after present and this report estimates that it will occur 38,000 to 49,000 years A.P.

Other factors that may impact the timing of these climate states include the standard deviation associated with the Devils Hole ages, the uncertainty of the exact time when the Devils Hole record implies climate is changing, the uncertainty of exactly where the past/present analog point is in the Owens Lake record, and the uncertainty of climate change itself (USGS 2000a, p. 77). The standard deviations about the mean of the Devils Hole ages are, by their nature, an estimate of uncertainty. That estimate was not incorporated into the climate analysis, in part, because the other sources of uncertainty cannot be estimated and hence their relation to standard deviation is unknown.

Comparison of Tables 6-5 and 6-1 indicates that the estimated durations of future climate states based on the precession methodology compare favorably with the estimated durations of past climate states based on the fossil and isotope records. Table 6-7 compares these data showing the durations of glacial and interglacial stages based on the timing of orbital parameters for 2,000,000 years (Section 6.5.2) with OIS 4, 3, and 2 combined (designated OIS 4) and OIS 1 equivalent to OIS 11. This table was generated using values from the precession methodology described in Section 6.5.2 with the values used to construct Figures 6-5 and 6-7. The durations are fairly consistent for both past and future stages. Interglacial states (IG), which are comparable to our relatively warm modern climate state, last between 10,000 and 12,000 years. Monsoon/Intermediate states (M/IM) are highly variable and last 29,000 to 53,000 years. The monsoon/intermediate climate state alternates between hot summers with increased rainfall relative to today (monsoon) and periods of time that have cooler and wetter summers and winters relative to today (intermediate). Glacial states (G) last between 8,000 and 40,000 years, and these states are much cooler and wetter than today. Intermediate states (IM) moving forward in time from glacial to interglacial last between 13,000 and 20,000 years. Notice that the duration of certain climate states for particular OIS are often fairly consistent. For example, the durations of the M/IM state in OIS 11 range from 37,000 to 46,000 years. Similarly, the durations of the IM in OIS 10 range from 13,000 to 16,000 years.

Total durations of each of the major climate states during the past 1,000,000 years and the next 1,000,000 years are listed in Table 6-8 and the percentage durations for the future are shown in Figure 6-8. The values in Table 6-8 are the sums of the rows in Table 6-7 above. For example, the past 1,000,000 years of interglacial climate is the sum of the row of past interglacial climate in Table 6-7.

Table 6-7. Durations of Glacial and Interglacial OIS, in Thousands of Years, for Past and Future Climate Based on the Precession Methodology

OIS ⟶																									
Past	**6**	**7**	**6**	**5**	**4**	**11**	**10**	**9**	**8**	**7**	**6**	**5**	**4**	**11**	**10**	**9**	**8**	**7**	**6**	**5**	**4**	**11**			
IG		10		10		10		11		10		11		10		10		11		11		11			
M/IM		47		45		37		49		53		45		39		50		49		50		1			
G			22		28		11		39		15		26		10		14		38		39				
IM	20		15		15		15		16		16		15		16		18		17		15				
OIS ⟶																									
Future		**11**	**10**	**9**	**8**	**7**	**6**	**5**	**4**	**11**	**10**	**9**	**8**	**7**	**6**	**5**	**4**	**11**	**10**	**9**	**8**	**7**	**6**	**5**	**4**
IG				12		11		12		10		10		10		11		11		10		10		11	
M/IM		38		29		52		50		46		39		48		50		46		43		47			19+
G			11		14		13		38		8		11		40		16		27		10		23		
IM			16		17		16		16		13		15		16		16		13		13		13		

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Table 6-8. Total Years for Each Climate State Based on the Precession Methodology

Climate State	Past 1,000,000 Years		Future 1,000,000 Years	
Interglacial	115,000	12%	118,000	12%
Intermediate/Monsoon	465,000	46%	507,000	51%
Glacial	242,000	24%	211,000	21%
Intermediate	178,000	18%	164,000	16%

Figure 6-8 shows the percentage durations of future climate based on the future durations from Table 6-8. The intermediate/monsoon climate combination is estimated to occur about 51 percent of the time (507,000 years) during the next 1,000,000 years. Monsoon climates may only comprise climate states for less than 3 percent of this time (a total of approximately 33,500 years). Monsoon climate state bounds range from about 13 to 17° C and 125 to 400 mm per year. Eleven glacial stages are estimated to occur over the next 1,000,000 years. They may range between 8,000 and 40,000 years in length and encompass about 21 percent (211,000 years) of the next 1,000,000 years. These glacials will be different in magnitude, varying from relatively warm and wet to cold and dry. The upper bound for the most conservative estimates (OIS 6/16 equivalent) for annual temperature and annual precipitation is 0° C and 513 mm, respectively. The lower bound for the warmest and wettest estimate (OIS 8/10 equivalent) for annual temperature and annual precipitation is approximately 9° C and 430 mm, respectively. The intermediate climate state occurring after each glacial may encompass over 16 percent the total next 1,000,000 years (164,000 years). Intermediate climate state bounds range from approximately 9 to 10° C and 430 to 200 mm per year. Interglacial (modern-like) climate is estimated to occur about 12 percent (118,000 years) of the time during the next 1,000,000 years with temperature and precipitation estimated to be about 13° C and 125 mm per year.

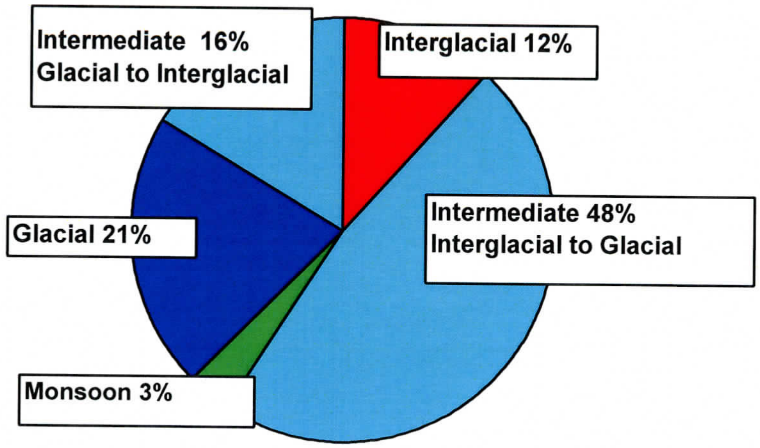

Figure 6-8. Percentage Duration of Future Climate States for the Next 1,000,000 Years

6.5.4 Uncertainty in the Timing of Future Climate

The age uncertainty associated with Table 6-5 is very difficult to estimate. Mean values for the onset and end of climate states were determined based on the precession methodology. These values were reported to the nearest 500 years for three reasons. First, it is meaningless to assign significant digits to future climate durations because the accuracy of those values cannot be validated. Secondly, assigning values within 500-year intervals allows values in the precession methodology to be easily replicated using the methodology outlined in Section 6.5.2. Finally, the error most likely increases farther into the future, so this must be taken into account when assigning values. The above reasons make it problematic and possibly unrealistic, to estimate the error in the timing of future climate states.

Furthermore, because the Devils Hole record itself contains uncertainty, basing timing on the precession cycle with respect to the Devils Hole timing increases the uncertainty in the future climate forecast. The standard deviation on the ages in the Devils Hole chronology, the sampling interval of the Devils Hole record (which incorporates about 1000 years), the questionable direct correlation of the Devils Hole isotope values and change in climate parameters, and lag or lead time in the Devils Hole record relative to regional climate all add error into the correlation of Devils Hole and precession and, therefore, the timing of future climate.

However, estimates can be made by comparing the Owens Lake record with the precession methodology over the last 410,000 years. Table 6-9 compares climate states and durations from the ostracode record from Owens Lake (with the timing based on the Devils Hole chronology;

see Table 6-1) with the timing of climate states based on the precession methodology (see Table 6-7) in an effort to evaluate the uncertainty associated with the onset and duration of climate states. The values in the Owens Lake chronology column are taken from Table 6-1; the values in the precession methodology column are taken from Table 6-7. The difference in years between the Owens Lake record and the precession methodology is noted in the fourth column. The last column is the cumulative difference in years.

Table 6-9. Durations of Climate States Estimated from the Owens Lake Record and Precession for the Last 410,000 Years

OIS	Owens Lake Chronology (duration in years)	Precession Methodology (duration in years)	Difference (years)	Cumulative Difference
11	13,000	49,000	-36,000	
10	61,000	26,000	35,000	-1,000
9	60,000	60,000	0	-1,000
8	29,000	32,000	-3,000	-4,000
7	63,000	60,000	3,000	-1,000
6	44,000	55,000	-11,000	-12,000
5	60,000	61,000	-1,000	-13,000
4/3/2	68,000	54,000	14,000	1,000
1	12,000	12,000	0	1,000

The largest discrepancy occurs in OIS 11 and 10. Misplacement of the Owens Lake chronology boundary between OIS 11 and 10 may account for some of the first timing difference since the cumulative difference for OIS 10 and 11 is only 1,000 years. The remaining large timing differences occur in glacial OIS 6 and the combined OIS 4/3/2. Boundary misplacement among the later OIS may also have occurred because the cumulative difference for the past 410,000 years is 1000 years. A lag in the response time in the Owens Lake chronology to climate change may also contribute to differences in timing. Comparison of the percentages using the Owens Lake record and the precession methodology for past and future climate states is presented in Table 6-10 generated from values in Tables 6-1 and 6-8. The glacial climate state varies by 3 percent. The intermediate/monsoon climate state varies by 9 percent, and the interglacial climate state varies by 8 percent.

Table 6-10. Percentage Comparison of Past and Future Climate State Duration

Climate State	Past 1,000,000 Years Based on Precession Methodology (from Table 6-8)	Last 400,000 Years Based on Owens Lake Ostracodes (from Table 6-1)	Future 1,000,000 Years Based on Precession Methodology (from Table 6-8)
Interglacial	12%	20%	12%
Intermediate and Monsoon	64%	58%	67%
Glacial	24%	22%	21%

6.5.5 Uncertainty in the Analysis

The previous section discusses uncertainty in the timing of the climate states. Additional uncertainties in this approach include uncertainty in the methodology and uncertainty in the earth's future physical processes.

Methodological uncertainty includes the possibility that orbital parameters may simply be correlated with some other factor that causes climate change, such as solar output, or may play a minor role by initiating a mechanism that pushes the climate system over a threshold (USGS 2000a, p. 37). This methodology also assumes that the nature and sequencing of climate states is similar and is repeated over time. If these assumptions are not accepted, then the future climate bounding estimates would depend on a conservative estimate of climate based on the extreme temperature (very cold) and precipitation (very wet) values from the previous 400,000-year cycle instead of values within the extremes (USGS 2000a, p. 48).

The uncertainty in physical processes includes both extra-terrestrial and lithospheric processes. Assumption four in USGS (2000a, p. 19, 76) stated that long–term, earth-based climate forcing functions remained relatively unchanged between 500,000 yr. B.P. and present and will remain unchanged through 10,000 yr. A.P. However, this assumption may not hold true for the current analysis. It is likely that climate change on the million-year time scale is non-cyclic, and, therefore, may not follow the sequential nature of previous climate characteristics (USGS 2000a, p. 48).

Factors which could contribute to climate change over the million-year time scale include solar variability, continental uplift and mountain building, sea level change, volcanic dust in the atmosphere, abyssal ocean circulation, atmosphere-ocean-cryosphere autovariation, and possibly polar wandering and continental drift (Williams et al. 1998, Fig 1.8, p. 9).

Positive and negative feedback mechanisms also could influence the timing of climate change on a shorter time scale. These mechanisms could include input of cosmic material (meteorites); a change in solar radiation; change in ocean basin shape, salinity, or level; changes in land features (orography, vegetation, albedo); and/or changes in atmospheric composition (fossil fuel emissions, aerosols, and volcanic eruptions). Uncertainty also comes from the chaotic nature of the climate system itself.

The relation of the above sources of uncertainty could sum together to create a large uncertainty or cancel each other out to create a smaller uncertainty. Unfortunately, there is no straightforward way of assessing the nature of uncertainty as it might apply to future climate change.

7. CONCLUSIONS

This report identifies four potential future climate states for the Yucca Mountain area: interglacial (modern), monsoon, intermediate, and glacial and estimates their sequence and duration for the next 1,000,000 years. Modern meteorological stations representing these climate states provide daily temperature and precipitation values that can be used in assessing the performance of the natural and engineered system of a potential monitored geologic repository for radioactive waste at Yucca Mountain.

The future climate state sequence described herein moves from interglacial (modern) to intermediate/monsoon to glacial to intermediate. With the exception of the monsoon climate state, the interglacial climate state has a lower annual precipitation and higher annual temperature than the stations selected to represent the other climate states. Hence, glacial and intermediate climate states are predicted to be cooler and wetter than modern and, therefore, would have more effective moisture and lower evaporation rates. Glacial and intermediate climate states are the most important in terms of potential infiltration because they have more effective moisture (a combination of lower temperature and increased precipitation) relative to the other climate states. Thus, precipitation would be stored more readily under these conditions than under current climate conditions.

Temperature in the Yucca Mountain area will be substantially lower than modern in full glacial states and somewhat lower in intermediate climate states. For example, the most conservative estimate (OIS 6/16 glacial analog) mean annual temperature upper bound is 0° C, whereas the modern mean annual temperature at Yucca Mountain is approximately 13° C. Precipitation during glacial states is estimated to be two to four times the modern (125 mm) average annual precipitation. The intermediate climate state average temperature is about 9° C and precipitation is about one-and-three-quarters to three-and-one-half times modern. The monsoon climate state has higher annual temperatures than modern (by possibly as much as 3 to 4° C) and annual precipitation ranging from one to three times modern.

Eleven glacial states and eleven interglacial states are estimated to occur over the next 1,000,000 years. Glacial states are estimated to occur 21-24 percent of this time; interglacial states may occur at least 12 percent of the time; monsoon states may occur 3 percent of the time and intermediate states may occur over 58 percent of the time. The intermediate state is the most common climate state and the modern climate state, interglacial, is the least common climate state and has least effective moisture relative to the other climate states.

Numerous uncertainties exist in estimating future climate. To allow for some of these uncertainties, both upper and lower bounds for each climate state are defined herein, as are three glacial states of differing magnitude. However, climate may be wholly chaotic therefore it might not be cyclic and so the past might not provide a basis to understand the future. Additionally, human activity might enhance chaotic behavior within the climate system. Despite all of the uncertainties, it is contended that the analysis described in this report is reasonable because it is based on a consistent interpretation of available data and, thus, is defensible.

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8.2 CODES, STANDARDS, REGULATIONS , AND PROCEDURES CITED

10 CFR Part 63. Nuclear Regulatory Commission: Disposal of High-Level Radiocative Wastes in a Proposed Geologic Repository at Yucca Mountain, NV. 66 FR 55732. Readily available.

40 CFR Part 197. Environmental Protection Agency: Public Health and Environmental Radiation Protection Standards for Yucca Mountain, Nevada. 66 FR 32074. Readily available.

University and Community College System of Nevada Quality Assurance Program:

QAP-3.1 Control of Electronic Data

QAP-3.3 Models

8.3 SOFTWARE USED

N/A

8.4 SOURCE DATA, LISTED BY DATA TRACKING NUMBER

GS000200005121.003. Radiometric Dating and 18O Data from Devils Hole, Nevada. Submittal date: 03/06/2000.

GS000900005121.004. Numerical Values of the Elements of the Earth's Orbit from 5,000,000 YBP to 1,000,000 YAP. Submittal date: 02/05/2001.

GS970708315121.001. Diatom Data from Owens Lake 1984-1992 Cores. Submittal date: 07/30/1997.

GS970708315121.002. Ostracode Data from Owens Lake 1984-1992 Cores. Submittal date: 07/31/1997.

GS991008315121.001. Supplementary Data to Ostracode Data from Owens Lake 1984-1992 Cores. Submittal date: 10/27/1999.

GS991008315121.002. Supplementary Data to Diatom Data from Owens Lake 1984-1992 Cores. Submittal date: 10/27/1999.

UN0104SPA021SS.001. Vostok Ice Core Deuterium Values. Submittal date: 04/11/2001

UN0112SPA021SS.004. Western Regional Climate Summaries Through December 31, 2000. Submittal date: 12/13/2001.

8.5 ANALYSES AND MODEL OUTPUT DATA, LISTED BY DATA TRACKING NUMBER

UN0112SPA021SS.006. Predicted Sequence and Durations of Climate States for the Next 1 Million Years for the Yucca Mountain Region. Submittal date: 12/19/2001.

UN0201SPA021SS.007. Mean Annual Temperature and Precipitation for Select Western Regional Climate Locations. Submittal date: 01/11/2002.

021SS.011. Durations of Glacial and Interglacial OIS, in Thousands of Years, for Past and Future Climate Based on the Precession Methodology. Submittal date: 01/30/2003.

021SS.013. Correlation between Climate States, Representative Ostracodes, and Oxygen Isotope Stages for the Owens Lake Core for the Last 400,000 Years. Submittal date: 01/30/2003.

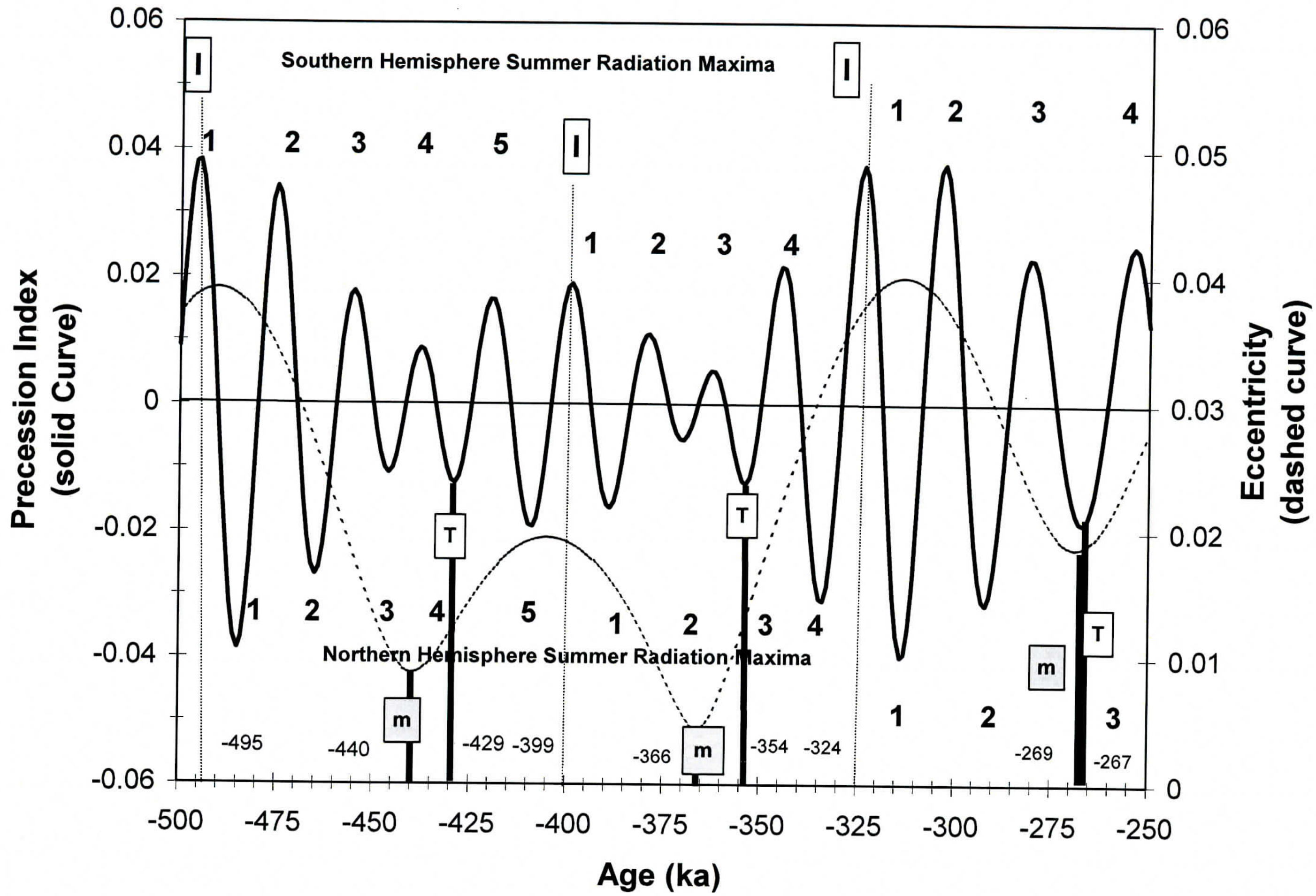


Figure 6-5c. (Continuation of Figure 6-5)

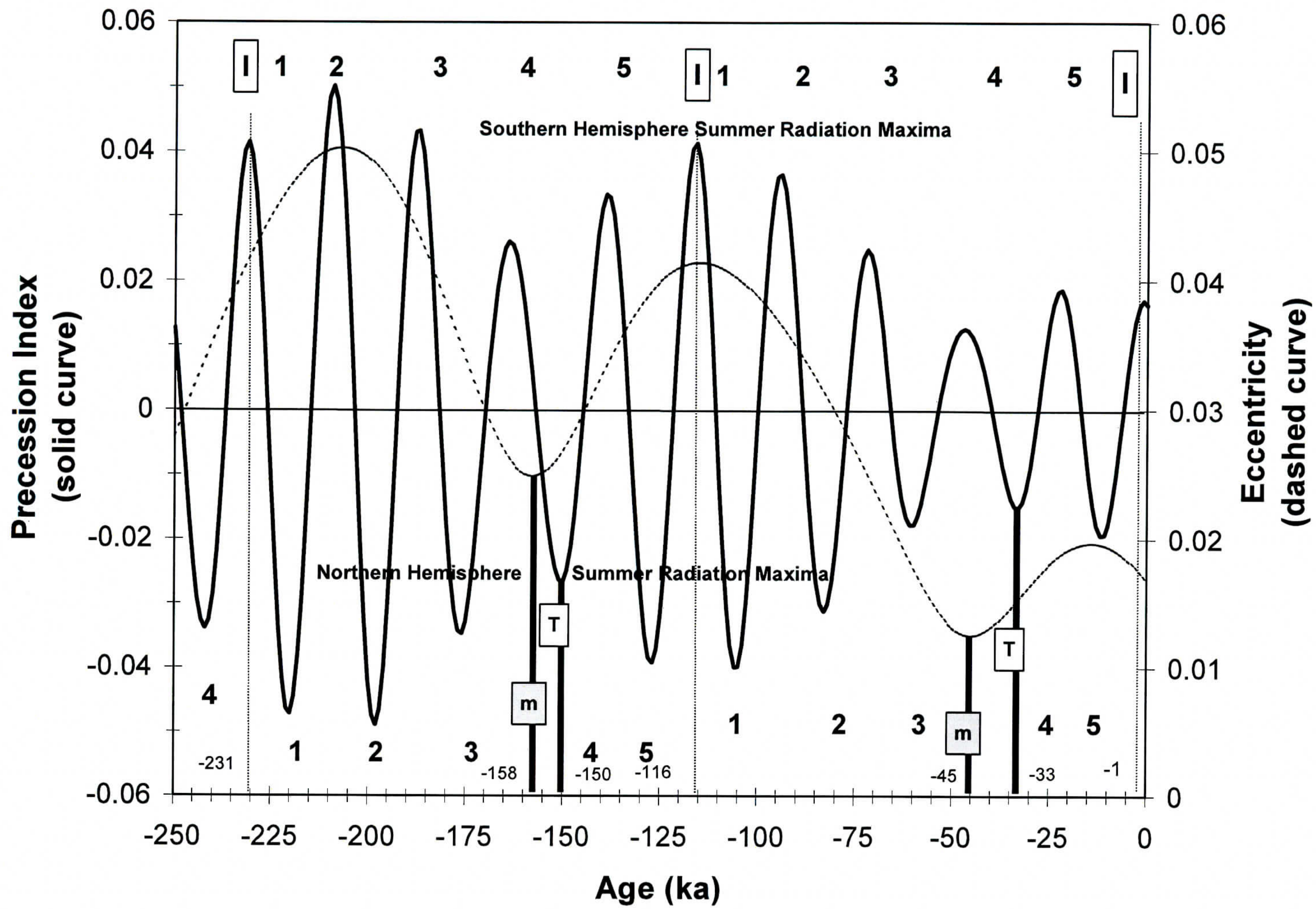


Figure 6-5d. (Continuation of Figure 6-5)

Eccentricity (dashed curve in Figure 6-5 a through d), the degree to which the orbit of the earth departs from a circle (Hartmann 1994, p. 303), affects the annual total radiation received at the top of the earth's atmosphere. It also modulates the amplitude of precession variations (i.e. high eccentricity amplifies the precession effect (Crowley and North 1991, p. 132)). The closer eccentricity (dashed curve in Figure 6-5a through d) is to 0, the more circular the earth's orbit. Eccentricity operates on approximately 100,000- and 400,000-year time scales.

Precession (solid curve in Figure 6-5a through d) affects the distance between the earth and sun for a given season and causes a latitudinal and seasonal redistribution of solar radiation at the top of the atmosphere (Crowley and North 1991, pp. 134-135). Two types of precession factors interplay: axial precession, the wobble of the Earth's axis with respect to the stars; and elliptical precession with the axis of the ellipse itself slowly rotating in the opposite direction of axial precession. A decrease in the earth-sun distance at any given season causes an increase in radiation at that season. For example, perihelion, which is the point where the earth is closest to the sun, occurs presently during winter in the northern hemisphere. Consequently, portions of the winter hemisphere receive as much as 10 percent more solar radiation at present than they will 11,000 years from now when perihelion will occur in the summer (Crowley and North 1991, pp. 134). Precession varies on approximately 19-23,000 year cycles.

Past eccentricity and precession index values are graphed for the last 1,000,000 years in Figure 6-5a through d). Values for precession and eccentricity for the last 1,000,000 yr. B.P. and for the next 1,000,000 yr. A.P., as described in Section 6.5.2, were taken from Berger (1978; 2000 and GS000900005121.004).

In Figure 6-5, the small letter "m" denotes the eccentricity minimum (more circular orbit) and the large letter "T" marks the first northern-hemisphere solar radiation maximum after the eccentricity minimum. Dates for these events are shown toward the bottom of the graph. The precession index peaks near the numbers 1 through 4 or 5 at the top of Figure 6-5a through d indicate summer solar radiation maxima in the southern hemisphere. Conversely, the numbers 1 through 4 or 5 at the bottom of the graph indicate summer solar radiation maxima in the northern hemisphere. The letter "I" marks the second southern-hemisphere precession peak after the "T" event. USGS (2000a, p. 42) suggests invoking a 30,000-year constant measured forward in time from each "T" event to locate the "I" events. Further inspection indicates that using the 30,000-year interval is not necessary because all the "I" events designated in USGS (2000a, Figure 7a-b, pp. 38-39) for the past 400,000 years are located two southern-hemisphere maxima precession peaks forward in time from each "T" event. The span from one "I" event to the next encompasses a "precession sequence". The number of precession peaks in past sequences seems to vary randomly between 4 and 5.

6.4.3 Comparing the Datasets

The timing of full glacials and interglacials during the more recent climate cycle from about 400,000 years B.P. was derived from the $\delta^{18}O$ signature from the Devils Hole calcite vein. When the Devils Hole record is graphed with the orbital data, a pattern of glacial/interglacial cycles with precession and eccentricity emerges (Figure 6-6a through c), thus supporting assumption 2 in Section 5 above. The highest peaks in the Devils Hole $\delta^{18}O$ record are interglacial episodes and the low troughs are glacial periods. The high Devils Hole $\delta^{18}O$ values (interglacials and other warm periods) generally correspond to "I" events (the first southern-hemisphere precession peak in a precession sequence) and the low Devils Hole $\delta^{18}O$ values (glacial periods) generally correspond to "T" events. Generally the letter "I" denotes the terminal inflection point in an interglacial sequence, and the letter "T" denotes the terminal inflection point in a glacial period (USGS 2000a, p. 40). These "I" and "T" events consistently identify all primary inflection points in the available Devils Hole record from 400,000-60,000 yr. B.P. Furthermore, from these primary inflection points (which begin a change to the next climate state) a substantial amount of time elapses before the next climate state is reached, and reversals occur within each general trend.

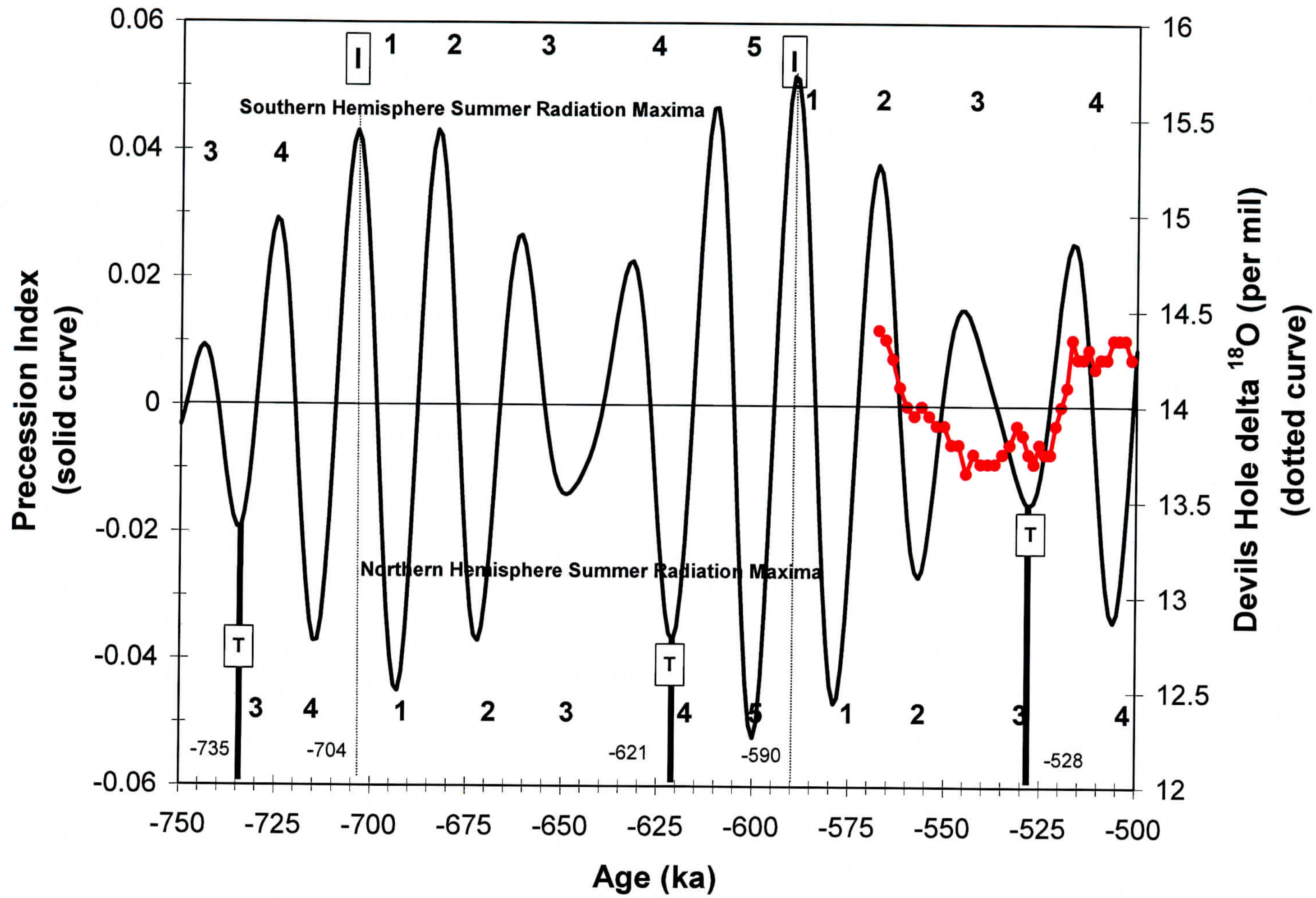
This pattern in the Devils Hole record prior to approximately 470,000 yr. B.P. breaks down. Although glacial period OIS 14 is recorded at the "T" event at about 528,000 yr. B.P., a flattening of the curve occurs across the estimated interglacial climate state. The alteration of the pattern could mean that the glacial interglacial pattern established by the Devils Hole record subsequent to 470,000 yr. B.P. is coincidental, or the earliest part of the Devils Hole record was influenced by a shift in climate, earth processes or some other factor.

The correspondence between the timing of low $\delta^{18}O$ values (cooler and/or wetter conditions in the recharge area) in the latter part of the Devils Hole record and maximum precession (increased summer solar radiation) in the northern-hemisphere summer (Figure 6-6) is perplexing because it suggests that climate begins to get colder when heat is being added to the northern hemisphere. This could imply that 1) there is no causal relationship between these two variables, 2) the variation in the climate system lags or leads precession, or 3) there is a process whereby the moisture necessary to induce a northern-hemisphere glacial period is somehow linked to maximum northern hemisphere precession (see USGS 2000a, p. 46).

6.4.4 Timing Past Climate

The correspondence between the precession-based (Berger 1978, n.p.) and Devils Hole-based timing (Landwehr et al. 1997, pp. 1-8) of glacial and interglacial events is discussed in USGS (2000a, pp. 42-43). The precession ages and the available Devils Hole inflection points are all within 2,500 years or less of each other if ages from Szabo et al. (1994) are used (USGS 2000a, p. 42-43). Factors discussed in USGS 2000a that may account for the difference in timing include 1) age uncertainty in the Devils Hole dates, even though that uncertainty is unusually small; 2) the methodology of selecting a precession value that marks the Devils Hole $\delta^{18}O$ inflection points, if precession values represent a fortuitous correlation with climate change; and 3) the effect of regional climate on the Devils Hole signal itself, if a primary inflection point precedes or follows global change.

The other timing issue involves the correspondence between the SPECMAP chronology (orbitally-tuned) and the Devils Hole (terrestrial-based) record. Winograd et al. 1992 (pp. 255, 257-258) challenged the linkage between the timing of glacial terminations recorded in the Devils Hole record and the SPECMAP chronology (see discussion in CRWMS M&O 2000b Section 6.3.4.1.1). The discrepancies in timing between these two records are not pertinent to this analysis because only the chronology of the Devils Hole record is used in this analysis.



Data Source: DTN: Devils Hole GS000200005121.003, Orbital Data GS000900005121.004

NOTE: Stable isotope data (closed circles) are reported relative to VSMOW.
NOTE: I = initiation of transition to glacial climate; T = initiation of transition to interglacial climate; Ages for I and T are shown near bottom of graph. Numbers 1 through 4 or 5 = summer solar radiation maxima. Numbers at the top of graph are summer solar radiation maxima in the southern hemisphere; numbers at the bottom of graph are summer solar radiation maxima in the northern hemisphere. Continuation of diagram is given as Figure 6-6b.

Figure 6-6a. Relation of Precession to the Devils Hole Stable Isotope Climate Proxy Record During the Last 568,000 Years

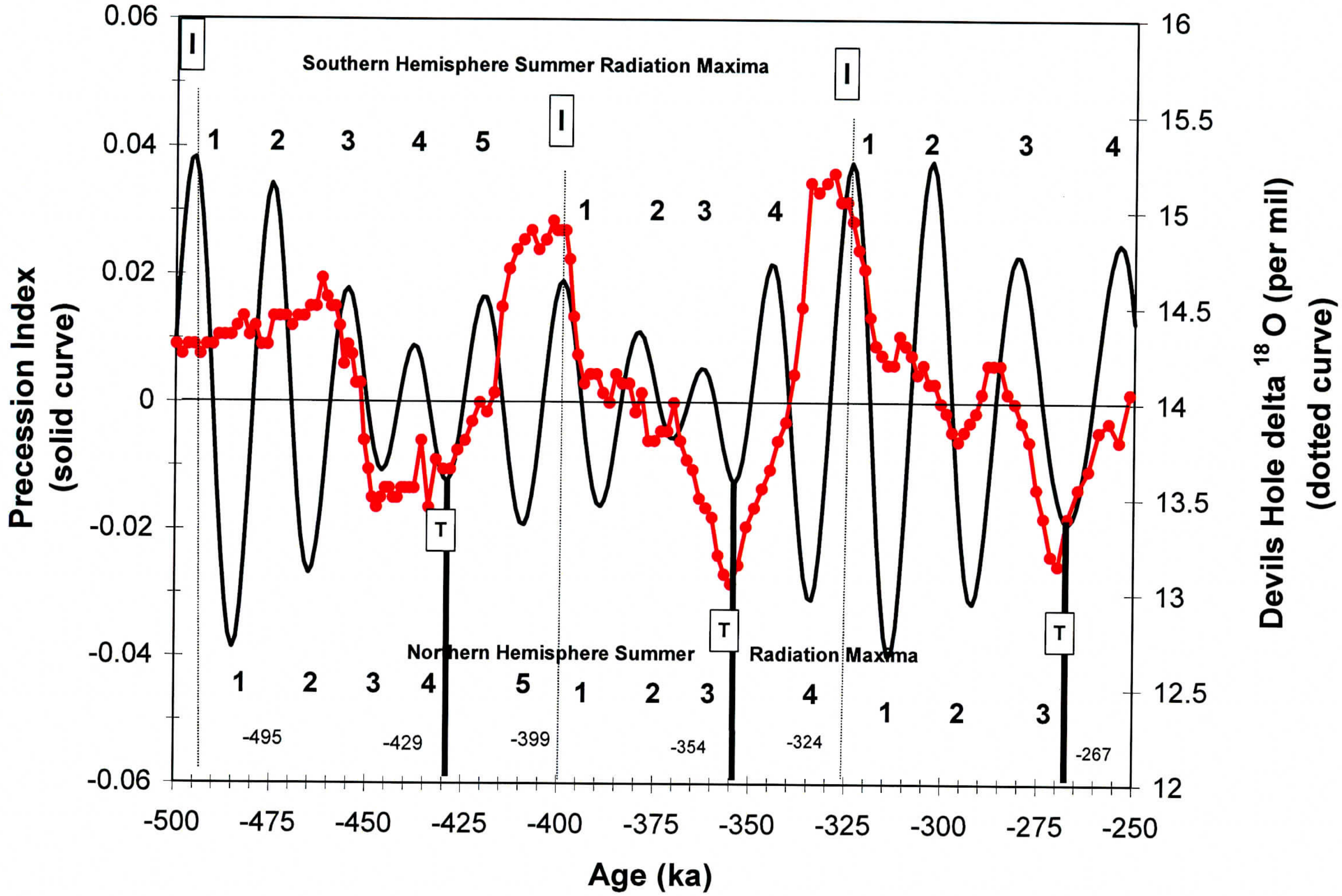


Figure 6-6b. (Continuation of Figure 6-6)

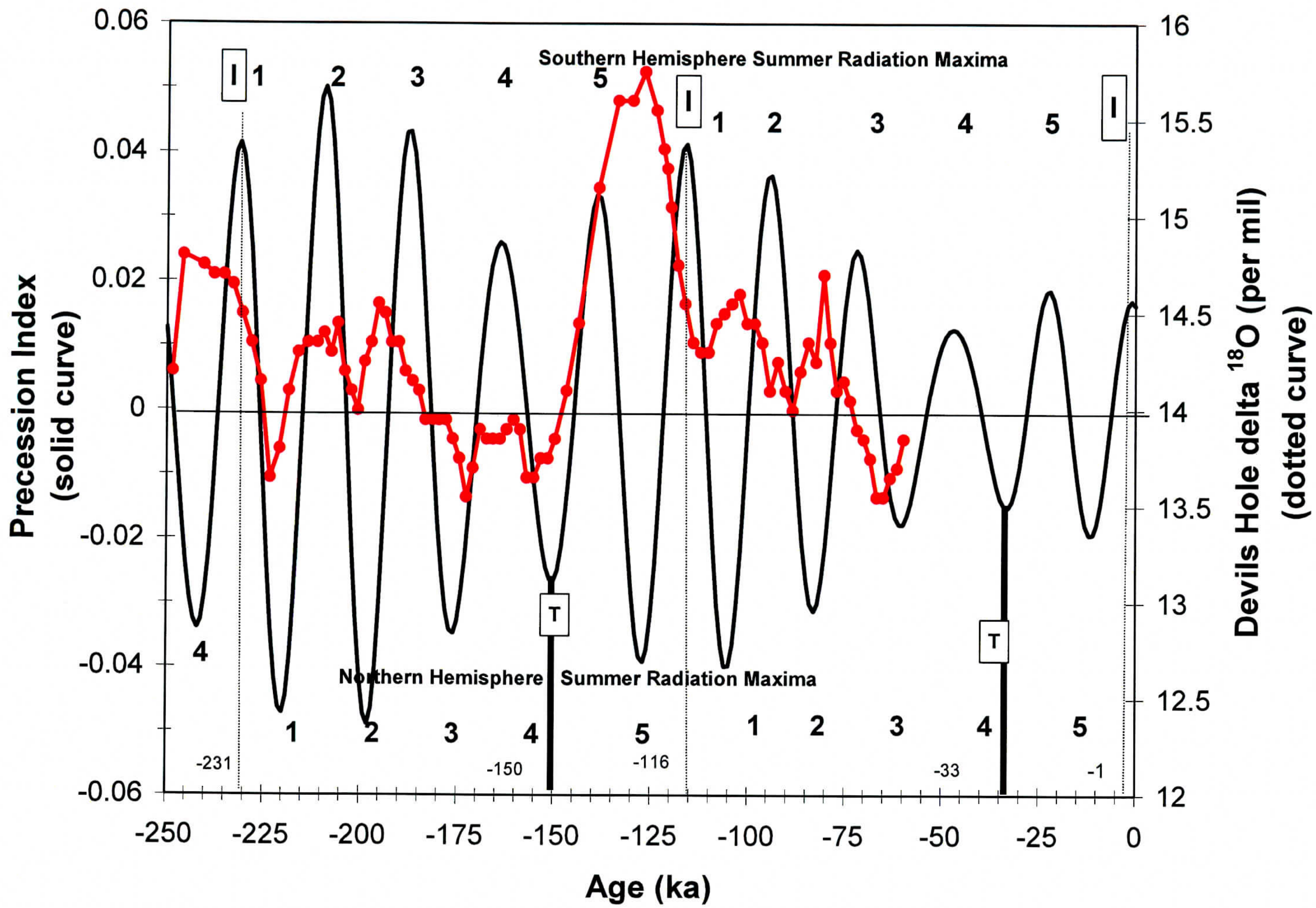


Figure 6-6c. (Continuation of Figure 6-6)

6.4.5 The Pattern of OIS 4 Through 2

The repetitive pattern of the Devils Hole isotope record suggests that OIS 4, 3 and 2 could be combined for the purposes of this analysis. Both the Owens Lake and the Devils Hole records contain patterns that support combining these 3 OIS. Table 6-1 shows a particular pattern during interglacial OIS 7 and 5: cold episodes occur during sub-stages 7d, 7b, 5d, and 5b. These cold reversals (cold episodes in a warming trend) are evident as troughs occurring just after interglacial periods in the isotope record of Devils Hole (Figure 6-6b) in OIS 7 (about 225,000 and 200,000 yr. B.P.) and OIS 5 (about 110,000 and 90,000 yr. B.P.). They generally occur between the Southern Hemisphere solar radiation maxima 1 and 2 and between 2 and 3. Cold periods associated with these sub-stages also appear in other paleoenvironmental records (Woillard 1978, p. 16; Litwin et al. 1999, Fig. 3a, p. 1158; Adam 1988, Fig. 1, p. 85; Shackleton and Opdyke 1973, Fig. 8, p. 47, Fig. 9, p. 48). Troughs also occur after interglacial periods in the Devils Hole record at 560,000 yr. B.P. (OIS 15), at 480,000 yr. B.P. (OIS 13), at 385,000 yr. B.P. and 375,000 yr. B.P. (OIS 11), and at 315,000 and 295,000 yr. B.P. (OIS 9). With the exception of OIS 13 these reversals occur between the Southern Hemisphere solar radiation maxima 1 and 2 and 2 and 3. After the second trough in all of these sequences moving forward in time, the Devils Hole record records a deeper trough, signifying a glacial period (near "T" events on Figure 6-6).

Following the glacial period reversal trough (where the isotope values begin to increase after "T" going forward in time), small cold reversals occur during the final (4^{th} or 5^{th}) cycle of the southern-hemisphere summer radiation maximum in every other precession sequence cycle. For example, a cold reversal occurs at the southern-hemisphere maximum summer radiation peak 5 at approximately 419,000 yr. B.P., and beneath cycle 4 at approximately 254,000 yr. B.P. based on the Devils Hole chronology. OIS 2 occurs during the southern-hemisphere maximum summer radiation peak 5, about 21,000 to 18,000 yr. B.P. OIS 2 fits the pattern of one of these events and, although the latter part of the Devils Hole chronology is not published, one might expect to see the mid-point of a cold reversal about 20,000 years ago.

If the past cyclical pattern shown in the Devils Hole record continues to repeat, the number of glacial and interglacial periods in each precession sequence also supports combining OIS 4, 3, and 2. For example, each precession sequence ("I" to "I" event) beginning about 500,000 and continuing to 60,000 years ago, using the Devils Hole chronology, begins with an event in an interglacial period ("I" event), moves into a glacial period, and then moves toward another interglacial period as it nears the next "I" event (Figure 6-6). If OIS 3, 2 and OIS 1 are defined as separate OIS in the last precession sequence, this sequence would be the only sequence containing three interglacial and two glacial periods. If OIS 4, 3, and 2 are considered one OIS, the previous precession sequences are repeated.

Table 6-4 compares the traditional (inter)glacial sequence with the proposed sequence. This proposed change in the superposition of glacial OIS does not alter the sequence of climate states or their timing because the climate events in OIS 4, 3 and 2 still are included. Only the magnitude of future glacial events is altered beyond 400,000 yr A.P. Both sequences contain eleven glacial OIS and twelve interglacial OIS over the next 1,000,000 years. The interglacial sequence based on the younger long climate cycle beginning approximately 400,000 years ago begins in OIS 11 (equivalent to our present climate state) then moves through OIS 9, 7, 5, 3, and

1 (see Table 6-1 and Section 6.5.3). The climate analysis in this report suggests, however, that OIS 4, 3, and 2 represent OIS 4. The current glacial climate analysis sequence repeats OIS 10, 8, 6, and 4 (which includes OIS 3 and 2) into the future and then starts again with OIS 10.

Table 6-4. Comparison of Past and Future (Inter)Glacial OIS Sequences Combining and not Combining OIS 4,3, and 2

Proposed Past 400,000 Year Sequence Combining OIS 4, 3, and 2	**Traditional Past 400,000 Year Sequence With OIS 3 and 2 (Shackleton and Opdyke 1973, p. 49)**
OIS 11	OIS 11
OIS 10	OIS 10
OIS 9	OIS 9
OIS 8	OIS 8
OIS 7	OIS 7
OIS 6	OIS 6
OIS 5	OIS 5
OIS 4	OIS 4
OIS 3 = OIS 4	OIS 3
OIS 2 = OIS 4	OIS 2
OIS 1 = 11	OIS 1 = OIS 11
Proposed Future 1,000,000 Year Sequence Combining OIS 4, 3 and 2	**Estimated Future 1,000,000 Year Sequence not Combining OIS 4, 3 and 2**
OIS 1/11 continued	OIS 1/11 continued
OIS 10	OIS 10
OIS 9	OIS 9
OIS 8	OIS 8
OIS 7	OIS 7
OIS 6	OIS 6
OIS 5	OIS 5
OIS 4	OIS 4
OIS 1/11	OIS 3
OIS 10	OIS 2
OIS 9	OIS 1/11
OIS 8	OIS 10
OIS 7	OIS 9
OIS 6	OIS 8
OIS 5	OIS 7
OIS 4	OIS 6
OIS 1/11	OIS 5
OIS 10	OIS 4
OIS 9	OIS 3
OIS 8	OIS 2
OIS 7	OIS 1/11
OIS 6	OIS 10
OIS 5	OIS 9

This proposed sequence results in a conservative analysis (greater effective moisture) for the TSPA because glacials with greater effective moisture (i.e. 8/10 and 6/16) replace glacials with less effective moisture (OIS 2 and 4). Periods with more effective moisture are considered more conservative with regard to the TSPA because they have the greatest potential for groundwater infiltration. The proposed sequence also simplifies the specification of estimated future climate states and largely preserves the cycle of precession sequences (see Section 6.5.2) described for the last 425,000 years.

6.5 ESTIMATING THE NATURE AND TIMING OF FUTURE CLIMATE STATES

This section discusses the general pattern of past climate states based on the published Devils Hole isotope record, how this pattern corresponds to orbital precession cycles, and how these two data sets were used to estimate future climate. The Devils Hole isotope record establishes a recurring climate pattern suggesting different climate states ranging from interglacial to glacial stages over the last 568,000 years. The past orbital precession cycles show a pattern of seasonal change in solar radiation.

6.5.1 Nature of Different Climate States

Four general climate states were selected from the Owens Lake record based on ostracode assemblages, and the timing of the climate states was placed into the context of the Devils Hole record (Table 6-1). Next, the Devils Hole isotope values were inspected. Climate trend reversals (peaks and troughs) in the Devils Hole record appear to represent when climate regimes began to be replaced by new atmospheric-climatic conditions (see Smith and Bischoff 1997, p. 155).

The Devils Hole record spans $\delta^{18}O$ values from 13.05 to 15.75 per mil and the average and median $\delta^{18}O$ values are both 14.1 per mil. Therefore, isotope values for some distance on either side of the 14.1 per mil point were designated intermediate climates. The timing of the beginning and end of the intermediate climate states was determined by the end of the glacial and the beginning of the interglacial climate states, respectively, based on the precession sequences.

Monsoon climate states were incorporated into the intermediate states based on the monsoon intervals suggested by the ostracode, *Limnocythere bradburyi*, in the Owens Lake record. The total duration of the monsoon state according to the Owens Lake record was very generally about 3,000 years occurring primarily between the interglacial moving toward glacial climate state. For this report, this 3,000-year duration was divided into two monsoon intervals, each 1,500 years long and these were distributed evenly within the intermediate climate state moving from interglacial to glacial states to estimate future climate. This timing is an artifact of simplifying the record of past climate states and projecting that simplification into the future. Although this is an oversimplification of what the past ostracode record suggests, it captures the climatic event represented by the monsoon intervals while simplifying input to the infiltration model.

The interglacial climates were defined by $\delta^{18}O$ values that increase and reach a plateau following a glacial period in the Devils Hole record (Figure 6-6). Generally, this plateau of $\delta^{18}O$ values is reached about 20,000 to 25,000 years after the glacial primary inflection point USGS (2000a, p. 42).

The glacial climate states were established by visually inspecting the low troughs in the Devils Hole $\delta^{18}O$ record. The magnitude of the glacial OIS was determined by the Owens Lake and other paleoenvironmental records (see Sections 6.1 and 6.2). Visual analysis showed that individual climate states (interglacial, intermediate, and glacial) occurred at similar precession index maxima for the last 400,000 years in the Devils Hole record (see Section 6.4.3 and Figure 6-6b and c). The more recent 400,000-year climate cycle was used for this comparison because terrestrial and extra-terrestrial processes and feedback mechanisms produce greater uncertainty farther back in time (see Section 6.5.5). This correlation facilitated the selection of points on the precession curve for the last 400,000 years to establish the timing of the beginning and the end of these different climate states. This pattern was carried into the next 1,000,000 years using the calculated precession parameter (see Section 6.5.2).

6.5.2 Using Precession to Time Future Climate States

When the precession cycle (Figure 6-5) is compared to the four climate states selected from the Owens Lake (Table 6-1) and Devils Hole records (Figure 6-6), the general pattern for the last 400,000 years is fairly consistent. As described in Section 6.4.2 and as in Figure 6-7a through d, the small letter "m" denotes the eccentricity minimum and the large letter "T" marks the first northern-hemisphere summer solar radiation maximum after the eccentricity minimum. The precession peaks near the numbers 1 through 4 or 5 at the top of Figure 6-7 indicate summer solar radiation maximum in the southern hemisphere. Conversely, the numbers 1 through 4 or 5 at the bottom of the graph indicate summer solar radiation maxima in the northern hemisphere. "I" marks the second southern hemisphere solar radiation maximum after the "T" event. The pattern always moves forward in time.

Figure 6-7 (a through d) shows future precession and eccentricity sequences for the earth's orbit for the next 1 million years. By relating these orbital parameters to the climate records for Owens Lake (Table 6-1) and Devils Hole (Figure 6-6), the following observations and conclusions are evident:

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

2. From the "I" 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.

Figure 6-7 also shows that currently, and for the next 50,000 years, the precession effect is small because of the small eccentricity during this time.