U.S. Department of Energy
Office of Civilian Radioactive Waste Management

Performance Assessment - Natural System Future Climate Analysis - 10,000 to 1,000,000 Years After Present

Presented to:
Nuclear Waste Technical Review Board

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YUCCA MOUNTAIN PROJECT

The 10,000-1,000,000 years after present climate forecast

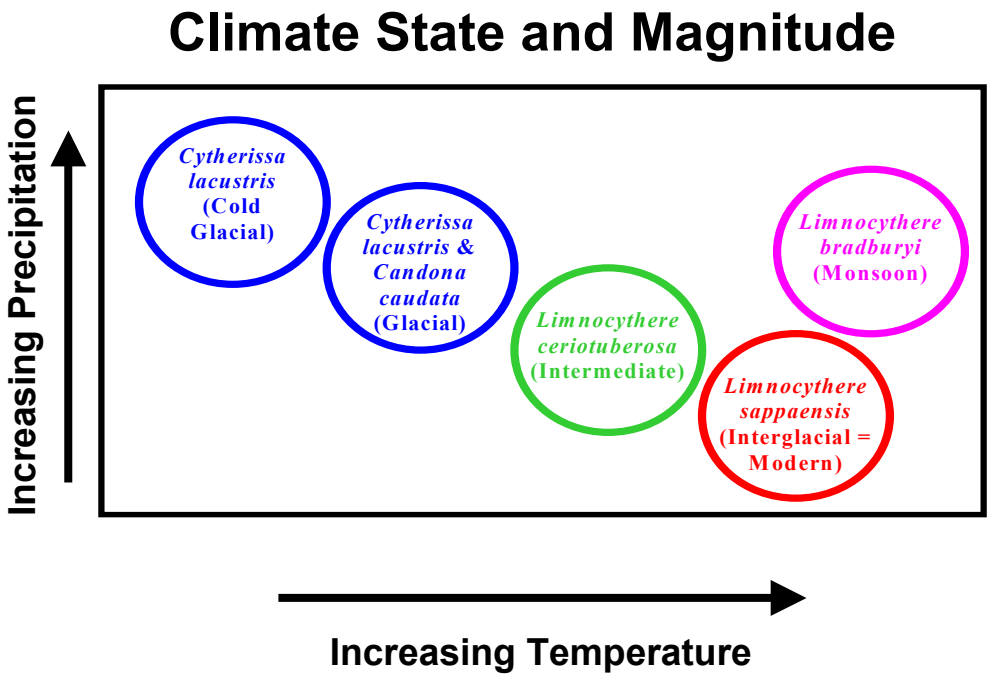
- **Identifies 4 potential future climate states – Interglacial (modern), Glacial, Intermediate/Monsoon, Intermediate**
- **Estimates future climate chronology (timing and duration of different climate states)**
- **Estimates annual temperature & precipitation based on modern meteorological station data (analog sites)**

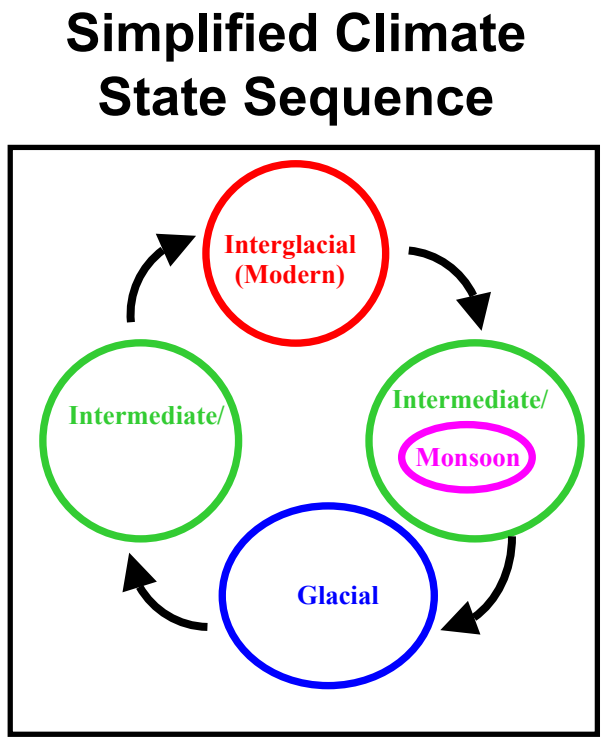
These data are inputs to performance assessment

Comparison with the 0-10,000 year after present climate forecast

	USGS (2000a)	This Analysis
Modern Climate State	0 to 600	N/A
Monsoon Climate State	600 - 2,000	0 to 500
Intermediate Climate State	2,000 to 30,000	500 to 38,000 (includes 1,500 year monsoon state)
Glacial Climate State	30,000 to 50,000	38,000 to 49,000

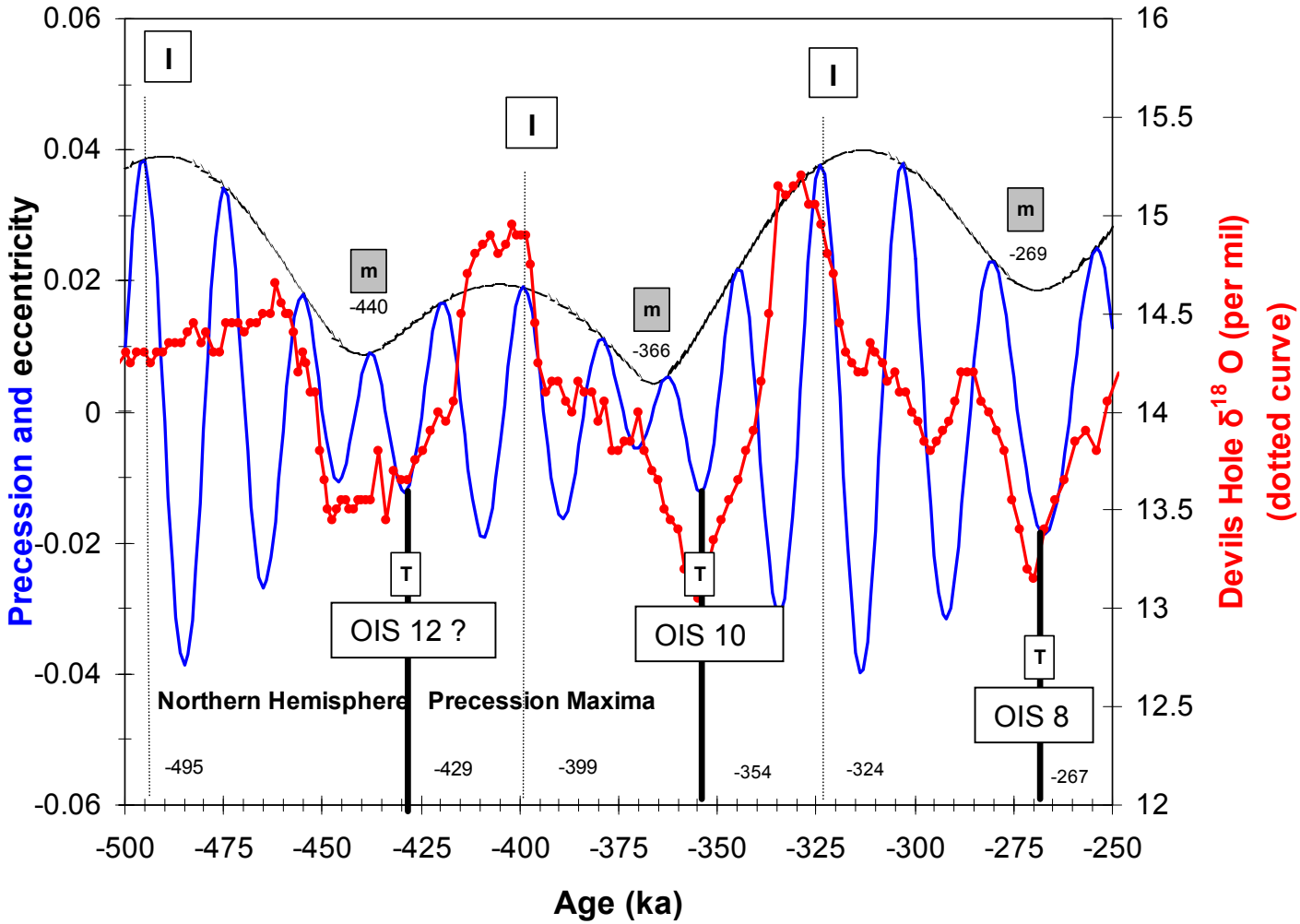
Identification and Magnitude of Climate States





Paleoenvironmental data from Owens Lake, packrat middens, Death Valley, and Las Vegas Valley marsh deposits are also used to calibrate magnitude

Chronology: Devils Hole and Celestial Mechanics



I=initiation of transition to glacial climate

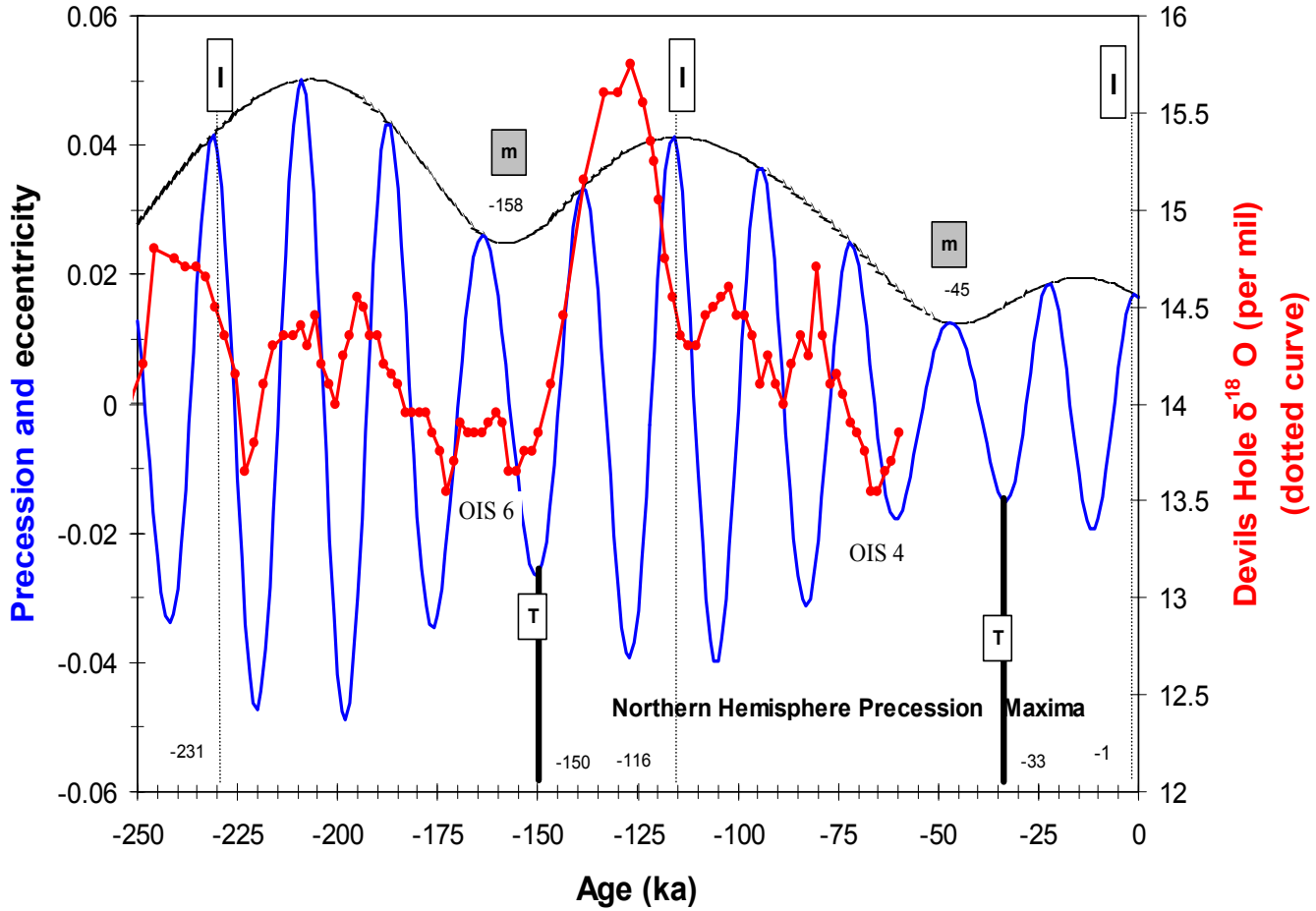
M=eccentricity minima

T=initiation to transition to interglacial climate

OIS=oxygen isotope stage

- Devils Hole climate chronology defines timing of climate change
- Devils Hole chronology compared with celestial mechanics to determine past correlation

Chronology: Devils Hole and Celestial Mechanics



I=initiation of transition to glacial climate

M=eccentricity minima

T=initiation to transition to interglacial climate

OIS=oxygen isotope stage

- Testing this correlation with the penultimate eccentricity cycle (800,000-400,000 years ago) and with other local and regional paleoclimate records

Meteorological stations used as future climate analogs were selected based on

- **Modern atmospheric circulation patterns (seasonal location of the polar front, high and low pressure systems)**
- **Past atmospheric circulation patterns**
- **Geography**
- **Past and modern ostracode and diatom occurrence**

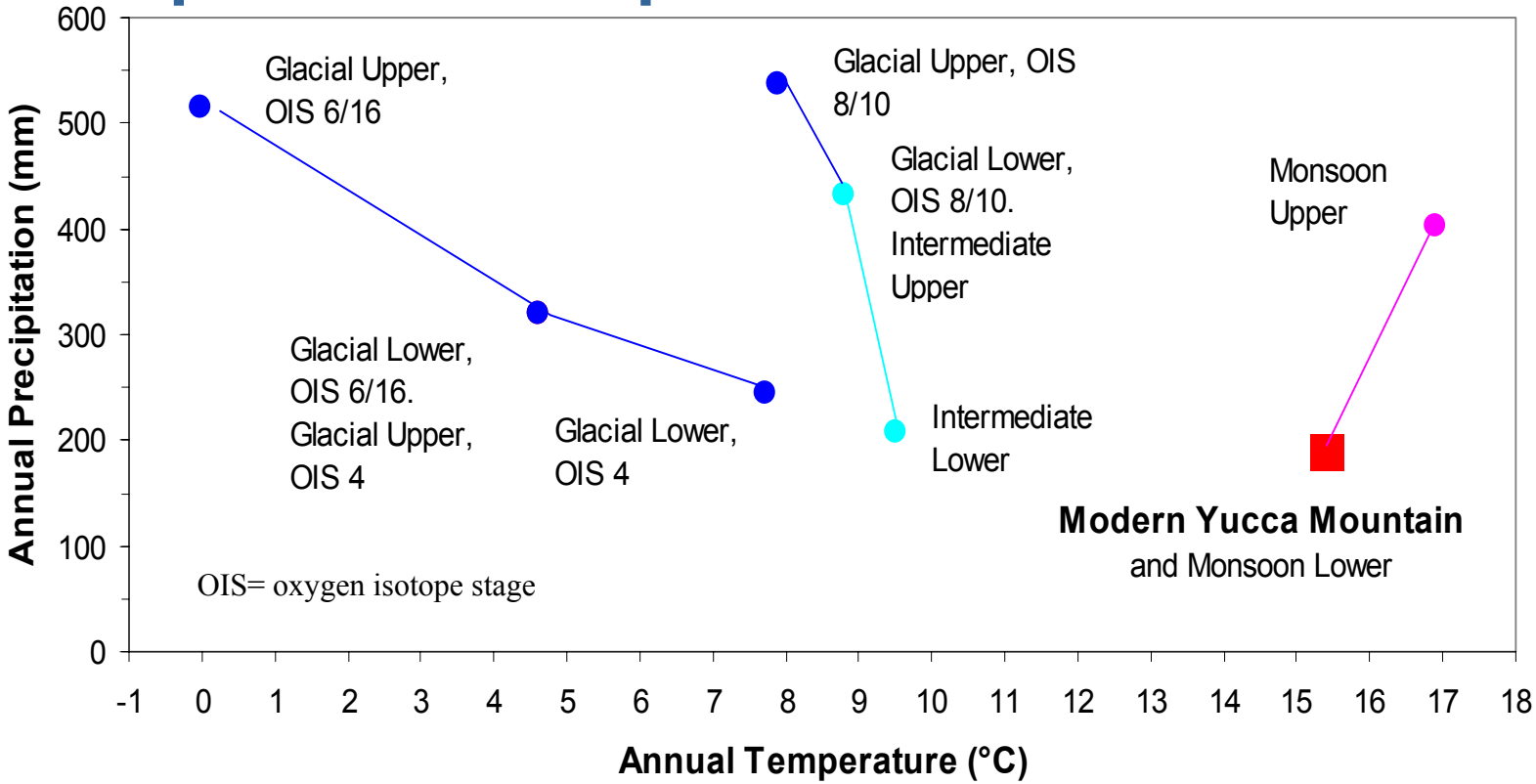
These modern stations define climate histories (temperature and precipitation) for inputs to performance assessment

Modern meteorological stations used as future climate analogs

EXPLANATION

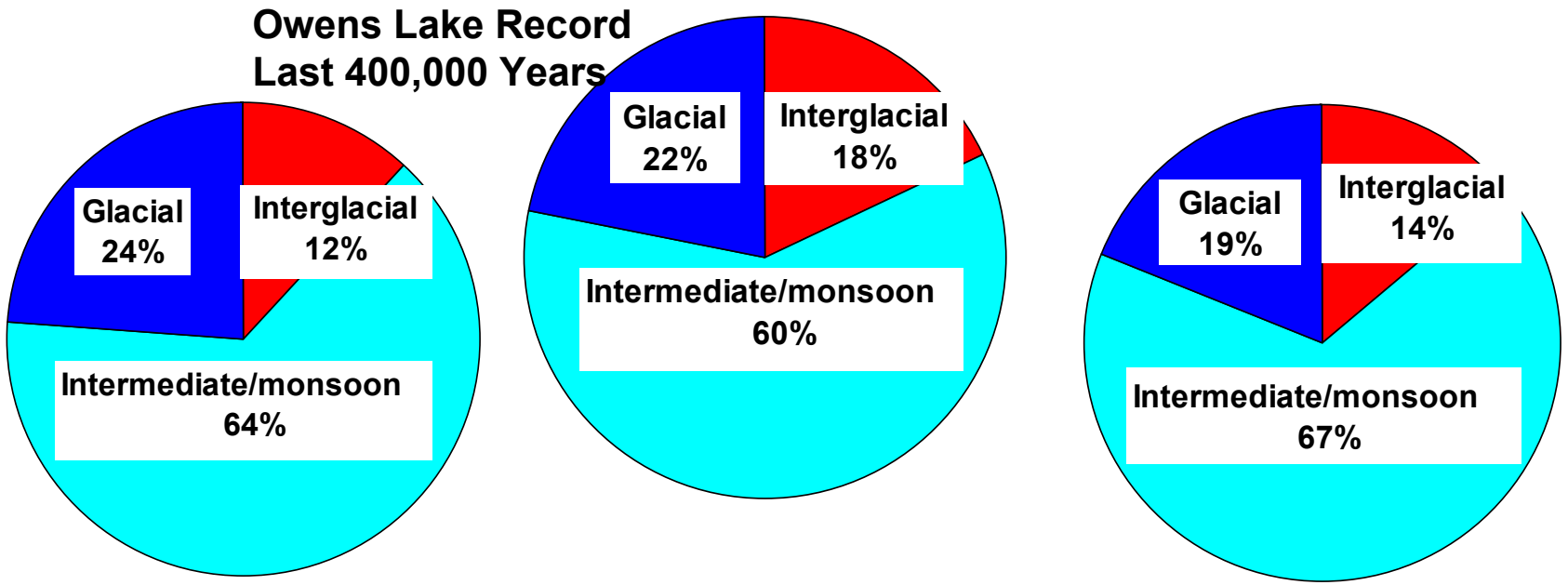
- Meteorological Stations
- Yucca Mountain
- Yucca Mountain Regional Meteorological Stations

Modern Meteorological Station Temperature and Precipitation for inputs to the Infiltration Model



- **All values cooler and wetter than modern values except Monsoon temperature upper bound**
- **These cooler, wetter climates used in the infiltration model**

Climate Duration Validated with Owens Lake Record



Estimated Past States 1,000,000 Years per orbital parameters

Future Climate States 1,000,000 Years per orbital parameters

- Intermediate/monsoon state is most common state
- Interglacial (modern) climate state is the least common state and it has the least effective moisture relative to the other climate states

Glacial State Summary

OIS Stage Analog	Estimated mean annual precipitation	Estimated mean annual temperature	Estimated mean annual precipitation change from modern	Estimated mean annual temperature change from modern
Glacial 6/16 cold, wet	320-515	0-5 °C	130-325 mm increase	11-15 °C cooler
Glacial 8/10 "warm" wet	430-540	8-9 °C	240-350 mm increase	7-8 °C cooler
Glacial 4 cold, dry	245-320	5-8 °C	55-130 mm increase	8-11°C cooler
Modern at YM = 15.4 °C and 189 mm (Hevesi 2000)				

Each glacial period is followed by an intermediate/monsoon and then an interglacial climate state

Forecast Sequence and Duration

Climate State	begin (yr A.P.)	end (yr A.P.)	Duration (years)
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**

Climate State	begin (yr A.P.)	end (yr A.P.)	Duration (years)
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	291,000	329,000	38,000
IM	329,000	345,000	16,000
IG	345,000	355,000	10,000
Duration			**114,000**

-1000 to 355,000 years A.P.

Forecast Sequence and Duration

Climate State	begin (yr A.P.)	end (yr A.P.)	Duration (years)
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**

Climate State	begin (yr A.P.)	end (yr A.P.)	Duration (years)
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	672,000	688,000	16,000
IM	688,000	704,000	16,000
IG	704,000	715,000	11,000
Duration			**93,000**

355,000 to 715,000 years A.P.

Forecast Sequence and Duration

Climate State	begin (yr A.P.)	end (yr A.P.)	Duration (years)
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**

Climate State	begin (yr A.P.)	end (yr A.P.)	Duration (years)
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**

715,000 to 1,000,000 years A.P.

Backup Information

- **Assumptions**
- **Uncertainty**
- **Potential factors not considered**
- **Climate state characteristics**
- **Timing methodology**

Assumptions—same as *Future Climate Analysis*, 2000

- Climate is cyclical, the past is the key to the future
- Relation exists between the timing of long-term climate change and celestial mechanics
- Relation exists between the characteristics of past climates and the sequences of those climates
- Long-term earth-based climate forcing functions have remained relatively unchanged for the last 500,000 years and should remain relatively unchanged for the next several hundred thousand years

Uncertainty

- **Upper and lower bounds for 3 climate state are defined**
- **3 glacial states with different magnitudes estimated**

Potential factors not considered

- **Anthropogenic change (global warming, increased CO_2)**
- **Tectonic activity**
- **Solar variability**
- **Sea level, salinity, circulation change**
- **Atmospheric composition (fossil fuel emissions, aerosols, volcanic eruptions)**

General characteristics of Interglacial (modern) climate state

- Hot, very dry summers with convective summer thunderstorms
- Generally dry, warm winters
- Lower annual precipitation and higher annual temperature than all other climate states except monsoon

General characteristics of Monsoon climate state

- Periods of increased summer rainfall
- Warmer and wetter than today
- Most precipitation falling during summer
- Monsoon states nested in intermediate state.
- Monsoons last for ~ 100-2000 years
- Shifts may have occurred in less that 200 years
- Much precipitation probably lost to evapotranspiration and evaporation

General characteristics of Glacial climate state

- Much greater effective moisture relative to today
- Cold/wet snowy or cold/dry winters
- Cool/dry or cool/wet summers
- Evaporation lower than today
- Evapotranspiration higher than today
- 5 glacial periods occurred over the last 400,000 years
- Differing magnitudes
- Precipitation more readily stored during this climate state

General characteristics of Intermediate climate state

- Transitional periods between glacial and interglacial periods
- Cool, wet winter season
- Warm (but not hot) to cool and dry summers relative to modern
- Winter dominated precipitation with greater effective moisture relative to modern
- Most common climate state occurring 60% of time in last 400,000 years
- Decreased evaporation rate relative to modern
- Precipitation more readily stored than today

Timing Methodology

- The interglacial climate state begins at the last northern hemisphere maxima in the sequence, #4 or #5, just prior to the "I" event. This interglacial state lasts to the "I" event (southern hemisphere maxima #1)
- The intermediate/monsoon climate state begins at the "I" event. The intermediate climate state ends where the precession curve crosses the 0 precession mark just beyond the southern hemisphere maximum #3
- The glacial climate state begins where the intermediate climate ends. The glacial climate state ends where the precession curve crosses the 0 precession mark just forward in time from the northern-hemisphere maxima precession #3 (if 4-cycle) or #4 (if 5-cycle)
- The intermediate climate state begins where the glacial climate ends. The intermediate climate state ends at the last northern hemisphere precession maxima in the precession sequence (#4 or #5)