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Chapter 5

CLIMATOLOGY AND METEOROLOGY

Nuclear Waste Policy Act
(Section 113)

E

Consultation Draft

Site Characterization Plan

Yucca Mountain Site, Nevada Research and Development Area, Nevada

Volume II

PART A

January 1988

U.S. Department of Energy
Office of Civilian Radioactive Waste Management
Washington, DC 20585

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CLIMATOLOGY AND METEOROLOGY

INTRODUCTION

Past, present, and future climatic conditions at Yucca Mountain need to be characterized in order to design and predict the performance of a geologic repository. Meteorological conditions, or weather forecasts, must be considered in engineering design, surface facilities placement, and radiological safety assessment, and will serve as input to investigations, including rainfall-runoff assessments, to be performed during site characterization. Climatology involves the study of long-term manifestations of weather. Further evaluation of the site must address the potential for climatic changes that could alter the long-term waste isolation capability of the site. This chapter describes and evaluates data on the existing climate and site meteorology, and outlines the suggested procedures to be used in developing and validating methods to predict future climatic variation.

This chapter addresses the following performance and design issues:

Issue	Short title
1.1	Total system performance (Section 8.3.5.13)
1.6	Ground-water travel time (Section 8.3.5.12)
1.8	NRC siting criteria (Section 8.3.5.17)
1.9	Higher-level findings (postclosure) (Section 8.3.5.18)
1.10	Waste package characteristics (postclosure) (Section 8.3.4.2)
1.11	Configuration of underground facilities (postclosure) (Section 8.3.2.2)
1.12	Seal characteristics (Section 8.3.3.2)
2.1	Public radiological exposures--normal conditions (Section 8.3.5.3)
2.2	Worker radiological safety (Section 8.3.5.4)
2.3	Accidental radiological releases (Section 8.3.5.5)
2.5	Higher-level findings--preclosure radiological safety (Section 8.3.5.6)
2.7	Repository design criteria for radiological safety (Section 8.3.2.3)

The information in this chapter will also be used by the geohydrology, geochemistry, climate, erosion, meteorology, population density, offsite installations, surface characteristics, and preclosure hydrology testing programs. Connections between climatology and meteorology and these issues and testing programs will be identified, and plans for the collection of additional data will be referenced to sections of Chapter 8.

Meteorological data have been collected from monitoring stations operated by the National Weather Service, and at stations on the Nevada Test Site (NTS) and Yucca Mountain. Key meteorological data that indicate local climate are temperature, precipitation, and atmospheric moisture, and to a lesser extent, wind speed and wind direction. Data from a range of elevations are needed to describe the site climate (Figure 5-1). Table 5-1 provides specific information (elevation, period of record, etc.) on each of these stations. Some of the parameters listed in Table 5-1 for the site monitoring program are not specifically related to climate determinations or design considerations but have been included because they will be used in subsequent permitting and licensing activities that are not directly related to site characterization. The environmental monitoring and mitigation plan (EMMP) is being developed to ensure that site characterization activities will not result in significant adverse environmental impacts. The EMMP will describe how the site-specific meteorological data will be used in determining impacts associated with site characterization. The meteorological data will also be needed in obtaining permits, as outlined in the environmental regulatory compliance plan (ERCP).

Section 5.1 describes the recent local climate based on temperature, precipitation, upper air, surface winds, atmospheric moisture, and severe weather data collected at the monitoring stations. However, climatic classifications and climatological summaries only provide a general, time-averaged indication of the meteorological conditions at any given point. Because local meteorological data are needed for several of the investigations (e.g., hydrologic studies described in Chapter 3) and because of the uncertainty associated with applying non-site-specific data to Yucca Mountain, climate information must be supplemented with site-specific meteorological data. The meteorological monitoring program at Yucca Mountain is designed to provide such data (refer to Section 8.3.1.12 or the Meteorological Monitoring Plan (SAIC, 1985) for more information on the program).

Fully assessing the Yucca Mountain site as a potential repository must, however, go beyond the essentially short-term operational-phase concerns related to site meteorological conditions. The performance of the repository system over the next 10,000 yr, including climatic variations, will be included in the assessment as required by 10 CFR Part 60. In addition, 10 CFR Part 960 requires a determination of climatic changes over the next 100,000 yr. To address the performance and design issues listed at the beginning of this chapter, the objective of the climate assessment described in Section 5.2 is to provide climatic data that will be used to estimate infiltration parameters. In turn, these hydrologic infiltration parameters will be used to estimate the resulting effects on the nature and rates of erosion and on the hydrologic and geochemical characteristics at Yucca Mountain.

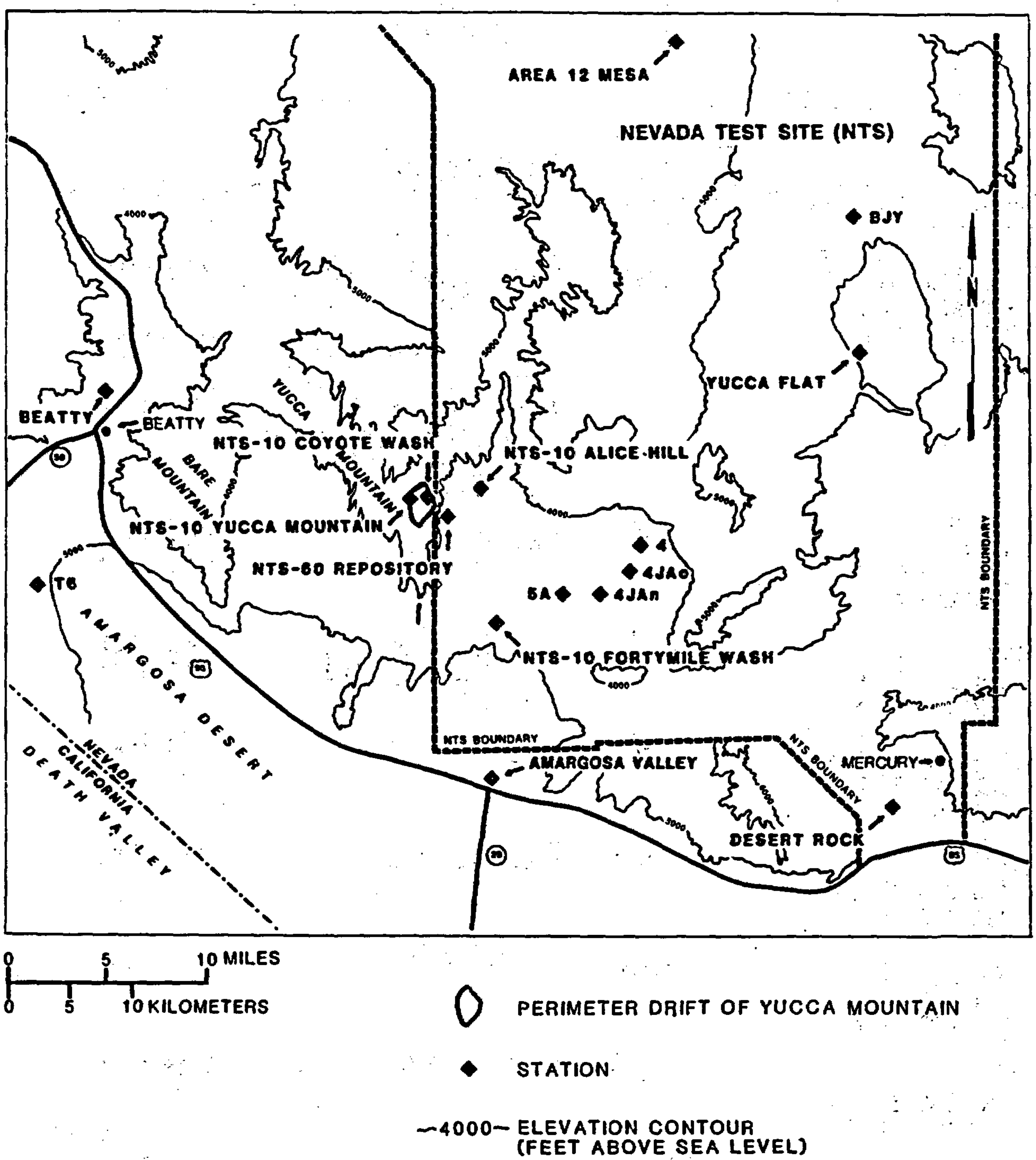


Figure 5-1. Meteorological monitoring stations in the vicinity of Yucca Mountain. Stations NTS-10 Yucca Mountain, NTS-10 Coyote Wash, NTS-10 Alice Hill, NTS-10 Fortymile Wash and NTS-60 Repository are operated as part of the NNWSI Project. Stations at Yucca Flat, Beatty, Desert Rock, and Amargosa Valley are or were operated by the National Weather Service. Stations T-6, Area 12 Mesa, BJY, 4, 4JAn, 4JAo, and 5A were or are operated in conjunction with various NTS activities. Stations YA (too close to NTS-60 Repository to be shown on this map) and YR (too close to NTS-10 Yucca Mountain to be shown on this map) were also operated as part of the NNWSI Project.

Table 5-1. Information on meteorological monitoring stations in the vicinity of Yucca Mountain

Station and location[a]	Elevation in meters above MSL[b]	Meteorological parameters	Period of record
Yucca Flat (UCC)[c] 680,875 ft E 803,600 ft N	1,196	Temperature, relative humidity, precipitation at surface	1962-1971
		Wind speed and wind direction at surface	1961-1978
		Wind speed, wind direction, temperature, relative humidity at upper levels	1957-1964
Beatty[c] 481,250 ft E 795,830 ft N	1,006	Temperature, precipitation	1922-1960 1931-1960
BJY[d] 679,100 ft E 842,300 ft N	1,241	Precipitation, wind speed, wind direction	1960-1981 1957-1964
Desert Rock (DRA)[c] 686,719 ft E 682,790 ft N	1,005	Precipitation	1963-1981
4JAn[d] 610,605 ft E 740,840 ft N	1,043	Precipitation	1967-1981
4JAo[d] 617,000 ft E 748,000 ft N	1,100	Precipitation	1957-1967
T6[d] 458,789 ft E 745,662 ft N	992	Precipitation	1958-1964
Area 12 Mesa[d] 631,450 ft E 889,090 ft N	2,280	Wind speed, wind direction	1957-1964
4[d] 620,000 ft E 752,000 ft N	1,138	Wind speed, wind direction	1956-1962

Table 5-1. Information on meteorological monitoring stations in the vicinity of Yucca Mountain (continued)

Station and location[a]	Elevation in meters above MSL[b]	Meteorological parameters	Period of record
5A[d] 599,150 ft E 742,050 ft N	1,111	Wind speed, wind direction	1958-1966
YA (Yucca Alluvial)[e] 569,722 ft E 761,794 ft N	1,128	Precipitation	1983-1984
YR (Yucca Ridge)[e] 559,238 ft E 763,555 ft N	1,469	Precipitation	1983-1984
Amargosa Valley[c] 578,819 ft E 689,580 ft N	817	Temperature	1949-1976
NTS-60 Repository[f] 569,127 ft E 761,795 ft N	1,143	Wind speed, wind direction, standard deviation of wind direction, temperature, temperature difference, net radiation, standard deviation of vertical wind speed, precipitation, dew point	December 1985-present
NTS-10 Yucca Mountain[f] 558,862 ft E 766,434 ft N	1,463	Wind speed, wind direction, standard deviation of wind direction, temperature, relative humidity, precipitation	December 1985-present
NTS-10 Coyote Wash[f] 562,876 ft E 766,195 ft N	1,274	Wind speed, wind direction, standard deviation of wind direction, temperature, relative humidity, precipitation	December 1985-present

Table 5-1. Information on meteorological monitoring stations in the vicinity of Yucca Mountain (continued)

Station and location[a]	Elevation in meters above MSL[b]	Meteorological parameters	Period of record
NTS-10 Alice Hill[f] 576,810 ft E 769,661 ft N	1,234	Wind speed, wind direction, standard deviation of wind direction, temperature, relative humidity, precipitation	December 1985-present
NTS-10 Fortymile Wash[f] 580,882 ft E 733,230 ft N	953	Wind speed, wind direction, standard deviation of wind direction, temperature, relative humidity, precipitation	December 1985-present

[a]All coordinates are based on the Nevada Central grid.
[b]MSL = mean sea level.
[c]Site operated by the National Weather Service.
[d]Site operated in conjunction with various NTS activities.
[e]Site previously operated as part of the NNWSI Project.
[f]Site operated as part of the Yucca Mountain meteorological monitoring program.

The data set will consist of seasonal averages of air temperature, relative humidity, cloud cover, surface wind speed, and the type, amount, duration, and intensity of precipitation. Plans for collection of such data are given in Sections 8.3.1.5 and 8.3.1.12. Using these and other data sets as input, potential changes in the rate of infiltration (flux) will be estimated.

To estimate the range and recurrence intervals of future climatic variations and the impact that the variations would have in the vicinity of Yucca Mountain, the nature and potential effects of paleoclimatic variation over the Quaternary Period must be evaluated as required by 10 CFR 960.4-2-4 and 10 CFR 60.122. Because records of Quaternary climate do not exist, climatological proxy data, derived primarily from geologic investigations of past biota and lakes, must be relied upon.

The use of paleobotanic proxy data relies on the fact that climate influences the type and amount of vegetation in an area and also influences the altitudinal range of various types of vegetation. The use of paleohydrologic proxy data is based on the fact that the climate has a significant influence on surface-water systems. In principle, knowledge of past changes in plant distributions and of changes in lake levels and water chemistry will provide the basis for reconstructing the underlying casual climatic variations.

Section 5.2 discusses the availability of published proxy data and describes a general strategy for using these data in the reconstruction of past climatic variations and in the characterization of future climates. The climatic interpretation of the proxy data involves the following steps:

1. Using transfer functions or response surfaces to correlate statistically present-day meteorological data and plant distributions.

2. Obtaining dated records of paleobotanic variations through the analysis of plant macrofossils from pack rat middens and of fossil pollen from cores of lacustrine sediment.

3. Applying the transfer functions, response surfaces, or both to the paleobotanic time series to obtain estimates of past climatic variations.

4. Constructing climatic descriptions (synoptic snapshots) for critical time periods for the region over which the paleobotanic data are available.

5. Validating these climatic reconstructions with information for the paleolimnological data.

6. If possible, subjecting paleoclimatic time series to appropriate forms of spectral or statistical analyses to determine the frequencies of climatic variations.

The paleobotanical and paleolimnological data, and the associated paleoclimatic reconstructions, have three main applications:

1. Documentation. The reconstructions of past climatic variations based on the proxy data will serve to document the extent of past climatic variations in the vicinity of Yucca Mountain. These past climatic variations will illustrate the probable future climatic conditions that may occur under boundary conditions of the climate system similar to those that have occurred in the past.

2. Input to hydrologic studies. The climatic interpretations derived from proxy data will provide information such as estimates of precipitation, temperature, and seasonality for studies on the paleohydrology of the Yucca Mountain region. The relationship(s) established among past climatic variations and the resultant hydrological changes will be used in the prediction of future hydrologic variations.

3. Model validation. Mathematical models must be validated before they can be used to predict future climatic variations or scenarios. In

other words, their performance in simulating the climate must be measured under conditions other than those used to formulate or calibrate the models. The paleobotanical and paleolimnological records will provide tests of simulations of past climatic variations.

The future climate model and its assumptions are discussed in Sections 5.2 and 8.3.1.5.1.

The uncertainty associated with data presented in Chapter 5 is primarily related to inherent inaccuracies in measurements and an insufficient number of samples and gaps in the paleoclimatic record. The testing, sampling, and modeling plans discussed in Sections 8.3.1.2, 8.3.1.5, and 8.3.1.12 are structured (1) to reduce these data uncertainties associated with the paleoclimatic and modern meteorological data and (2) to improve modeling of future climate. Uncertainties associated with data presented in this chapter include:

1. Modern meteorological data--the historical records cover only limited time periods and limited areal and elevational ranges.

2. Modern ecological data--the data do not sufficiently cover the necessary elevational and geographic ranges required for developing climate-proxy data calibration equations.

3. Paleoclimatic proxy data--these data are found in very restricted depositional environments and cover limited temporal and spatial ranges. In addition, limited abundance of these proxy data in the Great Basin and especially in the Yucca Mountain area results in gaps in the record, increasing the uncertainty associated with paleoclimatic reconstructions.

4. Age assignments for pack rat middens, lake cores, and pollen samples --radiometric dating techniques introduce uncertainty with increasing age, decreasing sample size, and contamination.

5. Modeling--both global climate models and regional models rely on input in the form of boundary conditions that are either estimated or else provided by other modeling activities that have their own levels of uncertainty. The models contain many assumptions and simplifications that limit their resolution.

These, and any other areas of uncertainty will be reduced through further data collection, additional dating techniques, and model sensitivity studies described in Sections 8.3.1.2, 8.3.1.5, and 8.3.1.12.

5.1 RECENT CLIMATE AND METEOROLOGY

Although a major emphasis throughout the site characterization process will be on assessing the ability of the selected host rock to contain stored wastes, the climate and site-specific meteorology of the Yucca Mountain area can influence some important aspects of repository development. The design and operation of the repository must consider climatic influences to ensure that surface facilities are capable of withstanding expected meteorological conditions (e.g., the design of the ventilation system). The potential for flooding must also be considered in the siting of surface facilities. In addition to these short-term design considerations, defining the existing climatic conditions establishes the basis for comparing the future and past climates with the present climate. Further, establishing the existing climatic conditions and the infiltration rates associated with these conditions is important in evaluating whether climatic variations will affect infiltration rates and subsequent rises or declines in the water table in the Yucca Mountain area. The sections that follow provide both a general description of the climate of the Yucca Mountain area (Section 5.1.1) and discussions of specific atmospheric parameters that are important in establishing the climatic conditions at Yucca Mountain (Sections 5.1.1.1 through 5.1.1.6).

5.1.1 CLIMATE

Long-term site-specific climatological data for Yucca Mountain are not presently available. Five monitoring stations have been established but the period of record is less than 2 yr. Therefore, data from two weather stations near Yucca Mountain that were operated by the National Weather Service (NWS) have been used to provide a general description of the climate in the area (Figure 5-1). One of these stations is located approximately 32 km northeast of the Yucca Mountain site in Yucca Flat, a broad alluvial basin. The other station is near Beatty, Nevada, approximately 24 km west of the Yucca Mountain site. Supplemental information collected at various other locations on the Nevada Test Site covering varying time periods is also available and has been used to describe the climate of the Yucca Mountain site for comparative purposes. A meteorological monitoring program, described in Sections 5.1.3 and 8.3.1.12, will provide site-specific data on the meteorological conditions that are likely to influence site characterization activities or repository development.

The Yucca Mountain site is situated in an area bordering two NWS climatological zones of Nevada: south central and extreme southern (Bowen and Egami, 1983b). The distinction between these two classifications is governed mostly by elevation. Lower elevations in the vicinity of Yucca Mountain experience conditions typical of southwestern desert zones within the United States that are characterized by hot summers, mild winters, and limited amounts of precipitation. Higher elevations have less severe summer temperatures and greater but still limited amounts of precipitation. The general climatological classification of midlatitude desert, in a modified Koeppen system presented in Critchfield (1983), also can be used to describe conditions in and around the Yucca Mountain site. Midlatitude desert areas are far removed from windward coasts and are dominated by tropical and polar air masses. For areas classified as midlatitude desert, summers are dominated by continental tropical air masses and winters are dominated by continental polar air masses. Large annual and diurnal fluctuations in temperature are characteristic of midlatitude desert areas, as is significant variability in precipitation from year to year.

The major air masses affecting the weather of the Yucca Mountain area during winter months originate either over the Pacific Ocean or over polar continental regions. Most of the moisture carried by the Pacific air masses does not reach the Yucca Mountain area because the physical (orographic) lifting effect of the Sierra Nevada forces the air masses to higher elevations as they move eastward, thus cooling the air masses and lowering their ability to hold moisture. The moisture that cannot remain in the vapor phase, due to this cooling, falls as precipitation on the western slopes of the Sierra Nevada. When an air mass has passed the ridge of the mountains, it descends along the eastern slopes and warms again, creating what is called a rain shadow in the lee of the Sierra Nevada (Wallace and Hobbs, 1977). Yucca Mountain and the surrounding areas lie within this shadow. Polar continental air masses bring cold, dry air into the area but are not as common a winter phenomenon as are the Pacific air masses.

A thermally induced area of low pressure is created during the summer months over most desert regions (Wallace and Hobbs, 1977) and prevails over the southwestern United States during summer. Although this thermal low is generally associated with weak cyclonic motion (Huschke, 1959), it brings south to southwesterly winds to the Yucca Mountain area. However, this circulation pattern is essentially nonfrontal. Although summer is generally the driest time of the year, this circulation pattern can bring tropical moisture originating over the Pacific Ocean off the lower coast of California to the area, which in combination with the strong solar insolation during the summer can create thunderstorm activity. Another less frequent summer circulation pattern that brings moisture to the area is a semipermanent subtropical high-pressure system called a Bermuda High (Huschke, 1959). If this system becomes well developed, it can bring moisture from the Gulf of Mexico to the Yucca Mountain area with southeasterly winds, again resulting in thunderstorm activity.

In addition to these synoptic-scale climatic influences, the rugged terrain of the Yucca Mountain area can create micrometeorological variations of a given parameter within relatively short distances. Drainage winds are an example of this phenomenon. These terrain-dependent winds can locally affect wind speed, wind direction, and temperature (Eglinton and Dreicer, 1984), and are most pronounced under calm (synoptic-scale) conditions during cloudless nights (Huschke, 1959). The ground surface quickly cools under these conditions by radiating its heat into the atmosphere. Air very near the surface is subsequently cooled. This cooler, denser air then drains down the terrain. In closed topographic basins such as Yucca Flat, the cold air essentially fills the basin and can significantly lower the temperature in the basin with respect to temperatures at the rims of the basin. The temperature inversion (temperature increasing with height) thereby created can limit effective atmospheric dispersion within the basin. However, these conditions generally dissipate quickly after sunrise as the ground surface is heated by the sun.

Another example of micrometeorological variations induced by the terrain is the variability in precipitation amounts between stations at different elevations and between those with differing exposure to prevailing storm tracks or occurrences. This issue is dealt with in detail in Sections 8.3.1.2 and 8.3.1.12, which outline plans for a precipitation monitoring network designed to characterize the influence that storm location and precipitation amounts would have on runoff and infiltration.

Table 5-2 provides a general outline of the climatic conditions experienced at Yucca Flat during the 10-yr period from 1962 to 1971 (Bowen and Egami, 1983a). Three important parameters at the Yucca Mountain site that will probably differ from the Yucca Flat summary are temperature minimums, wind speeds, and direction. Also, precipitation amounts are expected to be greater at Yucca Mountain because of its higher elevation (1,463 m at the NTS-10 Yucca Mountain station versus 1,196 m at the Yucca Flat station). These parameters are expected to exhibit terrain influences that will be characterized through analysis of the data collected in the site meteorological monitoring program.

The link between synoptic-scale processes and their effect on site-specific meteorology is not known at this time because the data are not yet available. The multitower monitoring program implemented at Yucca Mountain (Section 8.3.1.12) is designed specifically to collect data that can be used to characterize the relationships between site conditions and regional weather systems. Plans for collecting regional data and establishing this relationship are presented in Section 8.3.1.12. In addition, the monitoring program will provide general data on terrain influences and specific data on drainage winds.

Terrain influences are an important factor to consider in site meteorology (Quiring, 1968). Such influences can result in wide variations of any particular parameter within relatively small differences in location or elevation. The temperature at the site is expected to fluctuate between wide limits under predominantly clear skies and low relative humidities. Summer temperatures in excess of 100°F (38°C) are expected to be common, as are winter temperatures below 32°F (0°C). Although extreme lows may reach below 0°F (-18°C), such occurrences are not common (Quiring, 1968).

Precipitation is expected to be minimal but flash flooding, due to thunderstorm activity, may occur irregularly. Normal precipitation patterns for the area indicate a relative maximum in January or February dropping to a low in June. A secondary peak occurs in July and August (or both) with a secondary low in October. However, significant storm events can disrupt this pattern. Snow does occur in the area, particularly at elevations higher than those at Yucca Mountain.

Predominantly northerly winds prevail because of synoptic influences in the fall and winter months, but south to southwesterly winds become dominant during the spring and summer. If the mountain-valley winds experienced elsewhere in the vicinity of Yucca Mountain (Quiring, 1968) occur at the site as expected, the winds during daylight hours will almost always be upslope during the warmest part of the day and will vary in direction, depending on the orientation of the terrain.

Records of meteorological parameters that together describe the climate of the region include temperature, precipitation, atmospheric moisture, surface wind speed and direction, upper air wind speed and direction, and severe weather phenomena. Each of these variables is discussed in detail in the sections that follow.

Table 5-2. Climatological summary for Yucca Flat, Nevada, 1962 to 1971[a] (page 1 of 2)

	TEMPERATURE[b] (°F)							DEGREE DAYS		PRECIPITATION[b,c] (INCHES)											
	AVERAGES			EXTREMES				(Base 65°)									SNOW				
MONTH	DAILY MAXIMUM	DAILY MINIMUM	MONTHLY	HIGHEST	YEAR	LOWEST	YEAR	HEATING	COOLING	AVERAGE	GREATEST MONTHLY	YEAR	LEAST MONTHLY	YEAR	GREATEST DAILY	YEAR	AVERAGE	GREATEST MONTHLY	YEAR	GREATEST DAILY	YEAR
JAN	52.1	20.8	36.5	73	1971	-2	1970	877	0	.53	4.02	1969	T	1971+	1.25	1969	0.9	4.3	1962	4.3	1962
FEB	56.7	25.8	41.3	77	1963	5	1971+	662	0	.84	3.55	1969	T	1967+	1.16	1969	1.9	17.4	1969	6.2	1969
MAR	60.9	27.7	44.3	87	1966	9	1969	634	0	.29	.60	1969	.02	1966	.38	1969	2.0	7.5	1969	4.5	1969
APR	67.8	34.4	51.1	89	1962	13	1966	411	1	.45	2.57	1965	T	1962	1.08	1965	0.7	3.0	1964	3.0	1964
MAY	78.9	43.5	61.2	97	1967	25	1967	147	38	.24	1.62	1971	T	1970+	.86	1971	0	T	1964	T	1964
JUN	87.6	49.9	68.8	107	1970	29	1971+	35	154	.21	1.13	1969	T	1971	.45	1969	0	0		0	
JUL	96.1	57.0	76.6	107	1967	40	1964+	0	366	.52	1.34	1966	0	1963	.77	1969	0	0		0	
AUG	95.0	58.1	76.6	107	1970	39	1968	1	368	.34	1.04	1965	0	1962	.35	1971+	0	0		0	
SEP	86.4	46.7	66.5	105	1971	25	1971	51	103	.68	2.38	1969	0	1968+	2.13	1969	0	0		0	
OCT	76.1	36.9	56.5	94	1964+	12	1971	266	9	.13	.45	1969	0	1967+	.42	1969	0	T	1971	T	1971
NOV	61.8	27.6	44.7	82	1962	13	1966	602	0	.71	3.02	1965	0	1962	1.10	1970	0.5	4.8	1964	2.3	1964
DEC	50.7	19.9	35.3	70	1964	-14	1967	914	0	.79	2.66	1965	T	1969+	1.31	1965	2.3	9.9	1971	7.4	1971
ANN	72.5	37.4	54.9	107	AUG 1970+	-14	DEC 1967	4600	1039	5.73	4.02	JAN 1969	0	SEP 1968+	2.13	SEP 1969	8.3	17.4	FEB 1969	7.4	DEC 1971

Table 5-2. Climatological summary for Yucca Flat, Nevada, 1962 to 1971[a] (page 2 of 2)

MONTH	RELATIVE HUMIDITY (%) HOUR (PACIFIC STANDARD TIME) 04	10	16	22	WIND[b,d] (SPEEDS IN MPH) AVERAGE SPEED	PEAK SPEED	YEAR	RESULTANT (DIR/SP) 23-02 PST	11-14 PST	STATION PRESSURE (INCHES) AVERAGES	HIGHEST	LOWEST	(e) AVERAGE SKY COVER SUNRISE TO SUNSET	AVERAGE NUMBER OF DAYS[f] SUNRISE TO SUNSET CLEAR	PARTLY CLOUDY	CLOUDY	PRECIPITATION .01 INCH OR MORE	.10 INCH OR MORE	.50 INCH OR MORE	1.00 INCH OR MORE	1.0 INCH OR MORE OF SNOW	THUNDERSTORMS	TEMPERATURE MAXIMUM 90° F. OR MORE	32° F. OR LESS	MINIMUM 32° F OR LESS	0° F OR LESS
JAN	67	49	35	60	6.6	58	1965	233/0.7	135/2.6	26.10	26.54	25.42	4.9	13	8	10	2	1	*	*	*	*	0	1	29	*
FEB	67	45	32	56	6.9	52	1967	275/1.1	118/2.7	26.05	26.42	25.56	5.0	11	8	9	3	2	*	*	1	0	0	*	23	0
MAR	58	31	23	44	8.4	55	1971	240/1.8	186/4.5	25.99	26.43	25.48	4.8	12	9	10	3	1	0	0	1	1	0	0	24	0
APR	52	27	21	38	9.1	60+	1970#	250/2.2	196/5.1	25.96	26.39	25.50	4.5	13	9	8	3	1	*	*	*	1	0	0	12	0
MAY	46	22	17	31	8.3	60+	1967	260/1.5	179/7.2	25.94	26.39	25.47	4.3	14	11	6	2	1	*	0	0	1	4	0	2	0
JUN	39	19	14	26	7.9	60+	1967	272/1.9	185/8.2	25.92	26.20	25.56	3.0	19	7	4	2	1	0	0	0	2	14	0	*	0
JUL	40	20	15	28	7.5	55	1971	278/0.9	165/12.0	26.00	26.19	25.68	3.0	19	9	3	3	2	*	0	0	4	29	0	0	0
AUG	44	23	16	30	6.7	60+	1968	222/1.5	182/12.0	26.00	26.22	25.71	3.0	20	8	3	3	1	0	0	0	4	27	0	0	0
SEP	43	21	17	32	7.0	52	1970	281/1.3	163/6.4	26.00	26.36	25.56	2.1	22	6	2	2	1	1	*	0	2	11	0	1	0
OCT	46	24	19	36	6.8	60	1971	286/1.3	138/3.7	26.06	26.40	25.52	2.9	20	7	4	1	1	0	0	0	*	2	0	9	0
NOV	61	39	31	52	6.1	51	1970	234/1.2	152/4.1	26.08	26.58	25.64	4.8	13	7	10	3	2	*	*	*	*	0	0	23	0
DEC	68	50	41	64	6.6	53	1970	288/1.9	109/1.0	26.07	26.59	25.49	4.6	14	8	9	3	1	1	*	1	*	0	1	29	1
ANN	53	31	23	41	7.4	60+	APR 1970#	—	—	26.01	26.59	25.42	3.9	190	97	78	30	14	3	1	3	14	87	2	152	1

[a]Source: Bowen and Egami (1983a). Blanks indicate not applicable.
[b]# = most recent of multiple occurrences.
[c]T - trace (amount too small to measure).
[d]Average and peak speeds are for the period December 1964 through May 1969. The directions of the resultant wind are from a summary covering the period December 1964 through May 1969.
[e]Sky cover is expressed in the range from 0 for no clouds to 10 when the sky is completely covered with clouds. Clear, partly cloudy, and cloudy, are defined as average daytime cloudiness of 0-3, 4-7, and 8-10, respectively.
[f]* = one or more occurrences during the period of record but average less than one-half day.

5.1.1.1 Temperature

Temperature in the site vicinity varies widely on both a diurnal and annual basis (Quiring, 1968; Eglinton and Dreicer, 1984). Temperature data from the 10-yr climatological summary for Yucca Flat and the 39-yr (1922 to 1960) period of record at Beatty are presented in Table 5-3. These data suggest that Beatty is generally warmer and experiences higher maximum temperatures and less severe minimum temperatures than Yucca Flat. Temperature at the Yucca Mountain site is expected to closely resemble the Yucca Flat data. General temperature cycles and ranges of expected temperature values for the Yucca Mountain site are discussed below.

The lowest temperatures generally occur during the months of November through March. During this period minimum temperatures of $\leq$32°F (0°C) occur on 85 percent of the days at Yucca Flat and 57 percent of the days at Beatty. On an annual basis, Yucca Flat experiences 152 days (42 percent) with minimum temperatures $\leq$32°F (0°C) and Beatty experiences 88 days (24 percent) in the same range. The lowest average monthly temperature of 35.3°F (1.8°C) at Yucca Flat occurs in December, which is also the month that has the lowest average daily minimum temperature of 19.9°F (-6.7°C) and the lowest recorded temperature (for the 10-yr summary period) of -14°F (-26°C). Although temperatures below 0°F (-18°C) do occur, they are infrequent and commonly occur on less than 1 percent of the days from November through March. For Beatty, the data suggest that January is the coldest month, averaging 40.6°F (4.8°C) with an average daily minimum of 26.7°F (-2.9°C). However, the lowest temperature recorded at Beatty of 1°F (-17°C) occurred during February. Differences in both magnitude and duration of low temperatures between these recording stations are probably due to the drainage flow conditions present at the Yucca Flat site (as discussed previously), which are also expected to occur at the Yucca Mountain site. Despite the apparent frequency of temperatures below 32°F (0°C), daily maxima during the winter months remain quite mild, averaging at least 50°F (10°C).

Summer temperatures at these two recording stations reach relatively extreme levels but are comparable to temperatures observed elsewhere on the NTS (Quiring, 1968). The hottest months for both Beatty and Yucca Flat are June, July, and August, during which daily maximum temperatures $\geq$90°F (32°C) occur on 76 percent of the days at Yucca Flat and on 87 percent of the days at Beatty. The highest temperature recorded at Beatty was 114°F (46°C) and occurred in July, which has an average daily maximum of 99.5°F (37.5°C). The highest temperature recorded at Yucca Flat is 107°F (42°C). Although this maximum temperature has occurred in June, July, and August, the warmest month overall is July, with an average daily maximum of 96.1°F (35.6°C) and a monthly average of 76.6°F (24.8°C).

Data from Amargosa Valley, Nevada (formerly Lathrop Wells), for the period 1949 to 1976 are presented in Nichols (1986) and are quite similar to data from Beatty and Yucca Flat. The Amargosa Valley monthly minimums occur in January (as at Beatty) with an average daily minimum temperature of 27°F (-3°C). As at Yucca Flat and Beatty, summer temperatures at Amargosa Valley peak in July with an average daily maximum of 99°F (37°C).

Substantial temperature differences between average daily maximum and average daily minimum are characteristic of the area due to high insolation

Table 5-3. Yucca Flat and Beatty temperature data[a]

Month and Station[b]	Temperature °F Average daily maximum	Highest daily	Average daily minimum	Lowest daily	Monthly average
January					
Yucca Flat	52.1	73	20.8	-2	36.6
Beatty	57.5	78	26.7	7	40.6
February					
Yucca Flat	57.7	77	25.8	5	40.3
Beatty	58.2	80	24.6	1	43.9
March					
Yucca Flat	60.9	87	27.7	9	44.3
Beatty	65.6	85	33.9	16	49.7
April					
Yucca Flat	67.8	89	34.4	13	51.1
Beatty	74.0	98	41.0	17	57.5
May					
Yucca Flat	78.9	97	43.5	25	61.2
Beatty	82.0	103	47.9	26	65.2
June					
Yucca Flat	87.6	107	49.9	29	68.8
Beatty	92.3	112	55.5	33	74.0
July					
Yucca Flat	96.1	107	47.0	40	76.6
Beatty	99.5	114	62.1	36	80.8
August					
Yucca Flat	95.0	107	58.1	39	76.6
Beatty	97.2	113	59.9	41	78.6
September					
Yucca Flat	86.4	105	46.7	25	66.5
Beatty	90.5	109	53.4	34	72.0
October					
Yucca Flat	76.1	94	36.9	12	56.5
Beatty	77.4	98	43.6	22	60.5
November					
Yucca Flat	61.8	84	27.6	13	44.7
Beatty	65.3	86	33.5	10	49.4
December					
Yucca Flat	58.0	70	19.9	-14	35.3
Beatty	56.3	80	28.0	4	42.2
Annual average					
Yucca Flat	72.5	107	37.4	-14	54.9
Beatty	76.4	114	42.9	1	59.5

[a]Source: Eglinton and Dreicer (1984).
[b]Yucca Flat period of record: 1962 to 1971; Beatty period of record: 1922 to 1960.

rates and generally low relative humidities. For the data presented in Table 5-3, the Yucca Flat temperature difference between maximum and minimum values of 39.7 Fahrenheit degrees (22.1 Celsius degrees) in September is the most pronounced, but it differs only slightly from the smallest difference of 30.8 Fahrenheit degrees (17.1 Celsius degrees) in December. In comparison, the Beatty data indicate only a slightly more moderate maximum difference of 37.4 Fahrenheit degrees (20.8 Celsius degrees) in July to a minimum of 28.3 Fahrenheit degrees (15.7 Celsius degrees) in December. As with previously discussed phenomena, the wide temperature range at Yucca Flat is probably due to its location in a basin, where the daily minimum temperatures are lower than at Beatty.

Although the exact relationship between the recording stations and Yucca Mountain is not known, general trends can be inferred from the known data. Summer temperatures in excess of 100°F (38°C) should be expected. Winter minimum daily temperatures below 32°F (0°C) will be relatively common, but temperatures below 0°F (-18°C) will be infrequent. There will probably be substantial temperature ranges, with cool summer nights and mild winter daily maximums during most years.

5.1.1.2 Precipitation

Precipitation in the Yucca Mountain area is associated with two distinct atmospheric circulation patterns. The first of these patterns creates winter frontal passages that are associated with Pacific air masses moving toward the area from the west. Approximately 50 percent of the precipitation in the vicinity of Yucca Mountain occurs as a result of these systems during the months of November through April, even though the entire area lies in the rain shadow of the Sierra Nevada. The second type of circulation pattern that occurs in the area creates a secondary peak in precipitation in the late summer (July and August) and is a result of thunderstorm activities. These storms have a much greater flood potential than the frontal precipitation that occurs during the winter months because the storms can release significant amounts of moisture in relatively short periods of time.

The low pressure area that typically dominates the southwestern United States during the summer results in south to southwesterly winds in the Yucca Mountain area that can transport moisture-laden air into the area. The convective activity associated with this moist air flow can result in strong (intense), isolated downpours throughout the area. If the ground surface cannot absorb this moisture quickly, runoff and flooding can occur. Flooding potential is high; a large number of variables influence thunderstorm activities and govern precipitation types, amounts, and intensity, and individual storms generally complete a thunderstorm cycle in about 2 h (Huschke, 1959).

Specific precipitation amounts for the seven stations located in the vicinity of Yucca Mountain that are considered most representative of conditions at the NTS are presented in Table 5-4 (Eglinton and Dreicer, 1984). Monthly and annual average and maximum precipitation amounts at these stations are shown in the table. The data cover periods of record ranging from 5 yr at tower T6 to 29 yr at Beatty (see Figure 5-1 for locations).

Table 5-4. Monthly and annual average and maximum precipitation for sites in the vicinity of Yucca Mountain[a]

	Precipitation (in.)[b,c]													
	BJY 1,241 mMSL (1960-1981)		Yucca Flat 1,196 mMSL (1962-1971)		Desert Rock 1,005 mMSL (1963-1981)		4JAn 1,043 mMSL (1967-1981)		4JAo 1,100 mMSL (1957-1967)		T6 992 mMSL (1958-1964)		Beatty 1,006 mMSL (1931-1960)	
Month	Avg.	Max.	Avg.	Max.[d]	Avg.	Max.	Avg.	Max.	Avg.	Max.	Avg.	Max.	Avg.	Max.
January	0.76	3.41	0.53	4.02	0.64	2.15	0.63	2.29	0.27	0.62	0.37	0.88	0.60	NA[e]
February	0.87	3.42	0.84	3.60	0.78	2.57	1.08	3.45	0.39	1.01	0.59	1.20	0.70	NA
March	0.73	3.58	0.29	3.50	0.70	3.08	0.83	3.00	0.16	0.35	0.16	0.30	0.48	NA
April	0.34	2.40	0.45	2.70	0.33	1.45	0.18	0.63	0.34	1.91	0.10	0.45	0.47	NA
May	0.33	2.02	0.24	1.62	0.35	1.57	0.31	1.41	0.11	0.28	0.15	0.48	0.23	NA
June	0.21	1.22	0.21	2.66	0.14	0.56	0.13	0.67	0.07	0.26	0.14	0.55	0.09	NA
July	0.48	1.54	0.52	1.87	0.34	1.46	0.35	1.50	0.19	0.48	0.50	2.29	0.20	NA
August	0.45	2.38	0.34	2.52	0.52	1.57	0.31	1.97	0.25	0.71	0.22	0.54	0.20	NA
September	0.53	1.89	0.68	2.38	0.38	2.28	0.28	2.13	0.47	1.68	0.50	1.62	0.19	NA
October	0.36	1.49	0.13	1.69	0.25	1.05	0.32	1.42	0.21	0.63	0.22	0.76	0.30	NA
November	0.50	2.37	0.71	3.02	0.50	2.07	0.33	1.22	0.54	1.67	0.61	1.49	0.43	NA
December	0.57	2.61	0.79	2.66	0.46	2.45	0.33	1.78	0.63	3.03	0.44	1.14	0.58	NA
Annual	6.03	12.13	5.73	14.05	5.39	10.08	5.08	11.62	3.63	8.06	4.00	4.61	4.47	NA

[a] Source: Eglinton and Dreicer (1984). The locations of the monitoring stations are shown on Figure 5-1.
[b] All values are monthly or annual averages. To convert in. to mm, multiply by 25.4.
[c] mMSL = meters above mean sea level; Avg.=average; Max.=maximum.
[d] Period of record is 1958-1981.
[e] NA = not available.

The maximum 5-yr average precipitation amount of 6.03 in. (153 mm) occurred at tower BJY, and the minimum of these stations was 3.63 in. (92 mm) at tower 4JAo. All the stations follow the characteristic annual precipitation cycle with a winter peak, an early summer minimum, a secondary peak in late summer followed by a secondary minimum in October. This cycle is clearly illustrated in Figure 5-2, which shows precipitation amounts for each month, based on the average data presented in Table 5-4. The maximum values for each month do not exhibit the same annual cycle evident in the monthly averages. Instead, these data indicate that maximum precipitation generally occurred during winter months with maximums for the various towers having occurred in January, February, March, July, and December (Table 5-4). This variability is indicative of individual frontal systems or storms having occurred during these months.

While the data presented thus far are a reasonable indication of overall precipitation cycles, estimating precipitation at the Yucca Mountain site requires further analysis. The major variable that must be considered is elevation as noted by several investigators (Quiring, 1983; Nichols, 1986). A common means of estimating the precipitation at an elevation where no data are available is to perform linear, loglinear, or exponential regressions using precipitation and elevation data from locations in the vicinity of the site in question. Eglinton and Dreicer (1984) have performed such an analysis using data from 14 stations near Yucca Mountain. At the elevation of the surface facilities, 1,143 m above mean sea level, the regression analysis predicts an annual precipitation of 160 mm. Quiring (1983) performed a similar regression analysis for 11 stations located in various parts of the NTS. His information suggests that at the surface facility elevation, approximately 150 mm of precipitation can be expected annually. While these two analyses are in close agreement with regard to the expected amount of precipitation, site-specific data for various locations and elevations are needed to fully evaluate precipitation in the vicinity of the site.

For the operation phase of the repository and during site characterization, the precipitation resulting from short-term thunderstorms of high intensity is a consideration in design and placement of surface facilities, including those for the exploratory shaft, because these storms can lead to flash flooding (sheet flow, stream flow, and debris flow). Data from two monitoring stations that were operated at the Yucca Mountain site from late 1982 until October of 1984 provide some indication of the amount and intensity of precipitation that has occurred at Yucca Mountain (Chu, 1986). The data, however, represent conditions for only approximately 2 yr. Thus, it is impossible to establish trends or develop corollaries between the short-term data and the long-term conditions at Yucca Mountain. The data are included only as an indicator of the potential thunderstorm-related precipitation. One of the monitoring sites, called Yucca Alluvial (YA), was near the location proposed for the surface facilities, and the other site, called Yucca Ridge (YR), was slightly east of the ridge of Yucca Mountain.

The most significant storm event recorded during the 2-yr period occurred on July 21, 1984. On that date, the YA site recorded a 24-h total precipitation amount of 2.54 in. (64.5 mm), 1.75 in. (44.5 mm) of which fell in 1 h. The YR site registered a similarly significant amount of precipitation of 2.73 in. (69.3 mm) for the 24-h period and an hourly maximum of 1.37 in. (34.8 mm). With a predicted annual average of between 6.30 and

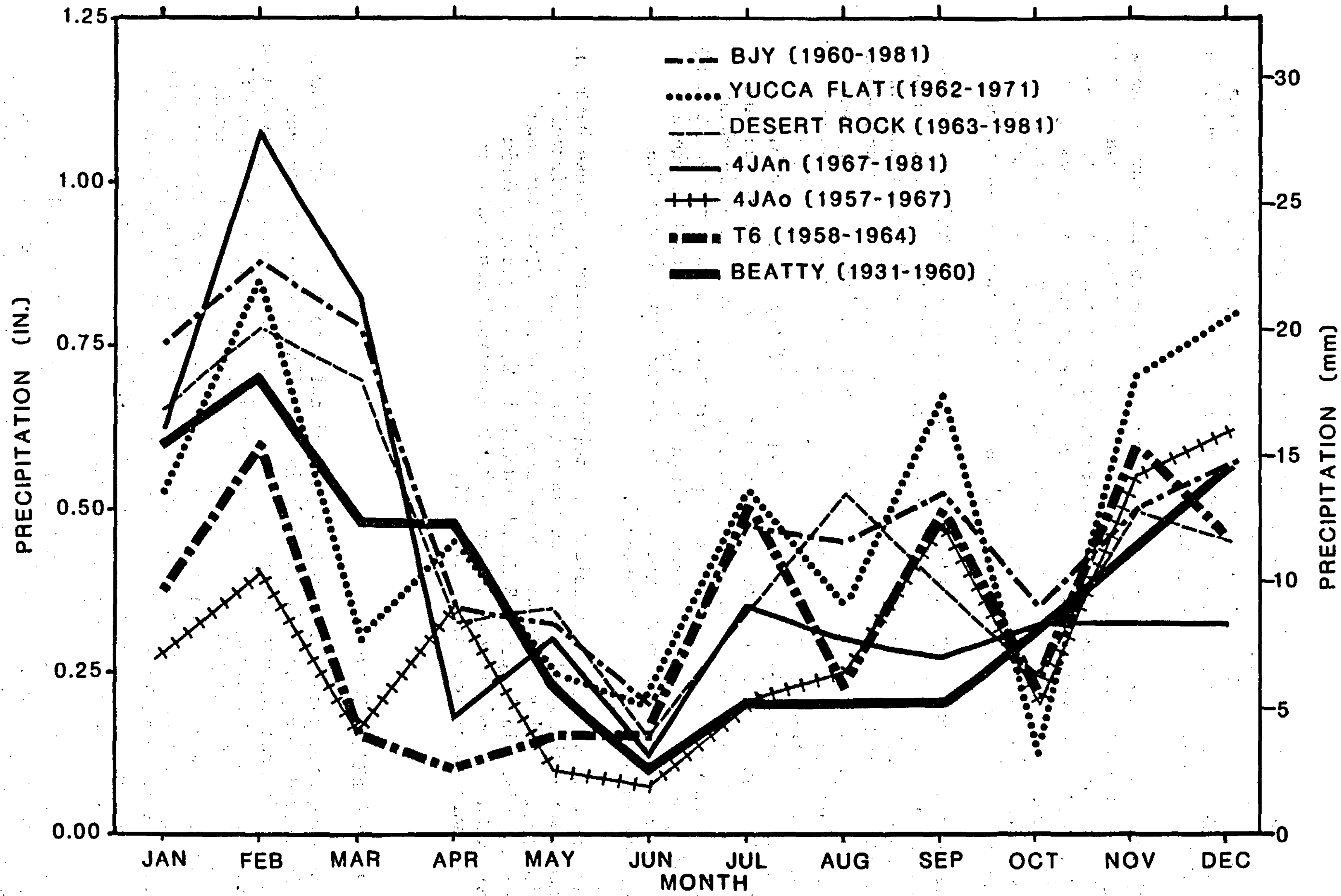


Figure 5-2. Monthly average precipitation (in inches) for stations in the vicinity of Yucca Mountain (modified from Eglinton and Dreicer, 1984).

5.70 in. (160 and 145 mm), the individual storm represents a significant and high-intensity event. Several less significant events were recorded during the 2-yr period, in most instances affecting both of the monitoring sites. However, there were occurrences in which one of the sites received precipitation and the other received less, or none at all.

The Yucca Mountain area does receive precipitation in the form of snow, but such occurrences are uncommon (Nichols, 1986). Yucca Flat averages only about 2 in. (50 mm) of snow per month during the winter months. The snow that does fall persists for only a few hours. The greatest daily amount of snowfall recorded at Yucca Flat is 7.4 in. (188 mm), which occurred in December 1971. Snow is not important in terms of overall precipitation amounts but should be considered in the design of the surface facilities.

Because the repository would be located in the unsaturated zone beneath Yucca Mountain, evaluation of the long-term ability of the site to contain stored waste must include a determination of how much of the precipitation falling at the surface infiltrates as potential recharge to the ground water. While thunderstorms are significant events and potentially damaging, they occur in the summer months when soil moisture is low and potential evapotranspiration is high and thus are not likely to result in significant ground-water recharge (Nichols, 1986). The most likely events leading to infiltration that exceed soil moisture deficit and evapotranspiration and could thus lead to percolation through the repository horizon would occur during the winter months. A series of precipitation events with no intermediate drying-out period would represent high-recharge potential (Nichols, 1986). A discussion of hydrologic infiltration and flux through the unsaturated zone is found in Chapter 3.

A more comprehensive precipitation monitoring network is needed both in the immediate vicinity of Yucca Mountain and in sections of the Fortymile Wash drainage to fully evaluate the recharge potential. Plans for such a network are given in Sections 8.3.1.2 and 8.3.1.12, and geohydrologic investigations needed in conjunction with this precipitation data are discussed more completely in Section 3.7.

5.1.1.3 Atmospheric moisture

The same processes that restrict precipitation in the vicinity of Yucca Mountain provide for generally low relative humidity throughout the year. The general diurnal and annual cycle of relative humidity for the area can be derived from the data contained in the climatological summary for Yucca Flat shown in Table 5-2. On the basis of the Yucca Flat data, relative humidity is expected to reach a minimum monthly average of approximately 25 percent in June or July and reach a maximum of around 55 percent in December. Diurnal trends (also shown in Table 5-2) are for the highest relative humidity to occur during the early morning and late evening hours, with the lowest relative humidity occurring in the afternoon hours.

Although relative humidity, a temperature-dependent variable, is commonly used as an accepted measure of atmospheric moisture, it can be a somewhat misleading indicator. A less temperature-dependent indicator of atmospheric moisture is the wet-bulb temperature or depression, which can either be measured directly or derived from relative humidity and dry-bulb temperature data using a psychrometric chart for the elevation. Because the wet-bulb temperature is always less than or equal to the ambient (dry-bulb) temperature (Huschke, 1959), the difference between the dry-bulb temperature and the wet-bulb temperature is referred to as the wet-bulb depression.

The monthly average relative humidity at hour 1600 and the maximum average temperature data given in the climatological summary for Yucca Flat (Table 5-2) have been used to calculate approximate wet-bulb depression values expected to occur in the vicinity of the Yucca Mountain site. These wet-bulb depression data were calculated using a psychrometric chart given in Weast (1972). The data are shown in relation to the ambient temperature and humidity values for Yucca Flat in Table 5-5. As shown in the table, the wet-bulb depression varies inversely with the relative humidity.

5.1.1.4 Wind speed and direction

Yucca Mountain lies in a geographical region of generally linear mountain ranges that dissect alluvial piedmont valleys with rugged, complex terrain features, as described in Chapter 1. Wind speeds and, more importantly, wind direction will be heavily influenced by the site-specific terrain features. Therefore, extrapolation of wind data from other sites to Yucca Mountain may not be as accurate as extrapolation of other meteorological parameters.

An analysis of winds at four locations on the NTS by Quiring (1968) provides data on conditions that might be experienced at Yucca Mountain. Two of the monitoring towers (4 and 5A) used for this study were located in Jackass Flats, 18 km to the east of the Yucca Mountain site. The third tower (BJY) was located in the middle of Yucca Flat, 12 km north of the Yucca Flat weather station. The fourth tower used in the study was placed high on a mesa overlooking Yucca Flat and is referred to as the Area 12 Mesa tower. The locations of the towers are shown in Figure 5-1.

Data from the towers indicate that wind direction is influenced primarily by two general types of atmospheric activity. First, large-scale pressure systems govern seasonal variations in wind direction and produce predominantly northerly winter winds and predominantly southerly summer winds. Secondary to the overall patterns are terrain-induced wind flow patterns and the effects of ground surface heating and cooling. The influence of these effects is evident in the diurnal wind flow reversal from up the terrain during the day to drainage flow at night (Quiring, 1968). The directions associated with these flows are an artifact of the terrain in the vicinity of the tower. The tower overlooking Yucca Flat was high enough above the valleys and basins to be less influenced by the daily flow-reversal patterns.

Wind speeds associated with the various flow patterns in the Yucca Mountain area are highest during the midafternoon hours and reach minimum speeds both shortly after sunrise and shortly after sunset. This pattern is also due to the terrain influences in which minimum wind speeds represent

Table 5-5. Wet-bulb depression values calculated for Yucca Flat

Month	Relative humidity at hour 1600 (%)	Average daily maximum temperature[a] °F	(°C)	Wet-bulb depression F°	(°C)	Wet-bulb temperature °F	(°C)
January	35	52.1	(11.16)	10.7	(5.94)	41.4	(5.22)
February	32	57.7	(14.28)	14.0	(7.78)	43.7	(6.50)
March	23	60.9	(16.06)	16.1	(8.95)	44.8	(7.11)
April	21	67.8	(19.89)	18.9	(10.50)	48.9	(9.39)
May	17	78.9	(26.06)	24.2	(13.45)	54.7	(12.61)
June	14	87.6	(30.89)	28.8	(16.00)	58.8	(14.89)
July	15	96.1	(36.11)	32.4	(18.50)	63.7	(17.61)
August	16	95.0	(35.00)	30.6	(17.00)	64.4	(18.00)
September	17	86.4	(30.22)	27.0	(15.00)	59.4	(15.22)
October	19	76.1	(24.50)	22.5	(12.50)	53.6	(12.00)
November	31	61.8	(16.56)	14.3	(7.95)	47.5	(8.61)
December	41	58.0	(14.44)	16.8	(9.33)	41.2	(5.11)

[a]Source: Eglinton and Dreicer (1984).

flow reversals or directional changes, and maximum speeds correspond to periods when intense surface heating initiates upgradient air movement. This pattern is common to the data collected from three of the four towers covered in Quiring's (1968) study during all months of the year. The exception to this pattern is the data collected from the tower located on the basin rim. At this tower location, wind speed minimums occur during afternoon hours in November through February.

Surface wind data from the Yucca Flat station have been summarized by frequency of occurrence for the period 1961 to 1978 (DOC, 1986) and show patterns quite similar to the towers evaluated in Quiring's (1968) study. Although not site specific, these data should be indicative of conditions occurring at Yucca Mountain because of the physical similarity between the two locations. The U.S. Department of Commerce (DOC, 1986) data, summarized by season and year, are shown in Figure 5-3 as wind rose plots.

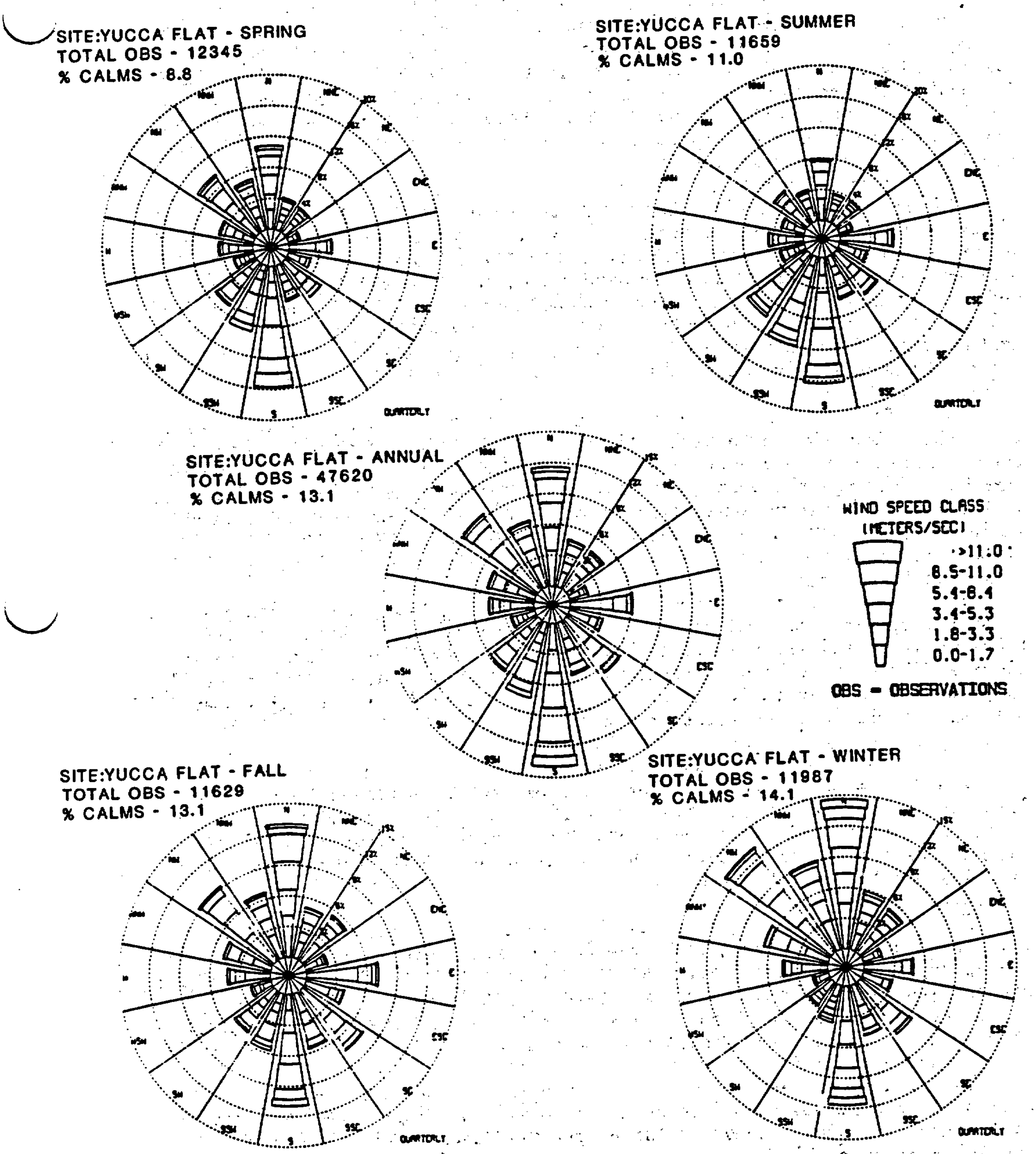


Figure 5-3. Seasonal and annual surface wind distributions for Yucca Flat (1961-1978). Note: scale is not the same for all distributions. Based on data from DOC (1986).

The spring (March through May) distribution shows that winds from the south occur most frequently and account for 15.7 percent of the observations during the season. Winds from the north also occur quite regularly, accounting for 10.8 percent of the spring observations. Overall, winds from the south through the southwest and northwest through north are dominant during the season, with nearly 60 percent of the recorded observations having occurred in one of these six directions.

The summer season (June through August) distribution is again dominated by winds from the south, accounting for 16.3 percent of the distribution. Winds from the south through southwest are clearly the most common during the summer months and represent 38.3 percent of the total observations. The northerly component of the summer wind flow pattern is not nearly as pronounced as in the spring distribution, with winds from the north accounting for 8.0 percent of the observations. This northerly component in the summer months is most likely due to the nighttime drainage winds at this site, which were discussed previously.

Winds from the north during the fall (September through November) were most common and were observed 13.0 percent of the time, with winds from the northwest through the north accounting for 28.9 percent of the observations. There is also a strong southerly element of the fall wind rose, representing 11.0 percent of the recorded observations. The fall data show a general variability in wind direction that is not as evident in the other seasonal distributions.

The winter (December through February) distribution shows a predominance of northerly winds that alone account for 14.5 percent of the total observations. Winds from the northwest through north are the most common observations and account for 36.7 percent of the total distribution. The southerly component evident in the fall wind rose is also significant during winter months, occurring 11.6 percent of the time.

On an annual basis, winds from the south occur somewhat more frequently than winds from the north (14.0 percent from the south versus 11.6 percent from the north). Excluding these two dominant wind flow quadrants, the balance of the annual wind rose exhibits a relatively uniform distribution, somewhat skewed to the northwest and southwest due to the terrain in the vicinity of the Yucca Flat tower.

Wind speeds occurring at Yucca Flat are generally less than 12 mph (5.4 m/s) during all seasons, with generally higher wind speeds occurring in the spring and somewhat lower wind speeds (overall) occurring in the fall and winter seasons. Although there will be differences between the data collected at Yucca Flat and conditions at Yucca Mountain, the general seasonal trends and variability are assumed to be similar.

The wind speeds and directional variability at the Yucca Mountain site will be thoroughly evaluated through the monitoring program that has been implemented at Yucca Mountain. The program is described in the Meteorological Monitoring Plan (SAIC, 1985) in detail and discussed in Section 8.3.1.12. The general information evaluated thus far, however, indicates that although extreme wind phenomena (discussed in Section 5.1.1.6) are potentially damaging, they do not present obstacles to design, construction, or operation of the proposed repository.

5.1.1.5 Upper air data

Data on meteorological conditions, specifically wind speed and direction, at levels above those measured by the various towers on the NTS are useful in assessing the possibility of long-range transport of potential repository emissions. Data collected at the Yucca Flat weather station from 1957 to 1964 and summarized in Quiring (1968) provide upper air wind data. The upper air data from the Yucca Flat weather station are for midseason months only (January, April, July, and October). Times of collection begin at 0400 Pacific standard time (PST) and end at 1600 PST at 3-h intervals, and it is assumed that the midseason data represent an entire season.

Data at 5,000 ft (1,524 m) above mean sea level (328 m above ground level) are similar to surface observations and are shown in Table 5-6, and are plotted as wind roses in Figure 5-4. Winds from the northwest through northeast during winter (January) are shown to occur 60.3 percent of the time, with average speeds of approximately 12 mph (5.4 m/s). Summer patterns at the 5,000-ft (1,524 m) level are virtually opposite the winter data, with southeasterly to southwesterly winds occurring 74.9 percent of the time at average speeds of about 13 mph (5.8 m/s). Spring southerly (southeast through southwest) winds occur somewhat more frequently than do northerly (northwest through northeast) winds, 46.2 percent versus 36.1 percent. Fall patterns balance just slightly opposite the spring data, with 44.5 percent northerly winds compared with 39.4 percent southerly winds. On an annual basis, the seasonal north-to-south change in wind direction is about equal: 43.5 percent of the time from the north (northwest through northeast) and 41.2 percent of the time from the south. Data at 6,000 ft (1,829 m) above mean sea level (633 m above ground level) presented in Table 5-7 and shown in Figure 5-5 show patterns similar to the data at the 5,000-ft (1,524-m) levels, but they are considered to be more synopotically influenced than at lower levels.

5.1.1.6 Severe weather and obstructions to visibility

Occurrences of severe weather are superimposed on the average or normal climatic conditions in the Yucca Mountain area. These events generally include thunderstorms and associated lightning and flash flooding, hail storms, tornadoes, straight-line extreme winds, sandstorms, temperature extremes, freezing rain, and fog. The most important of these phenomena, with respect to development of Yucca Mountain as a repository, are the thunderstorm-derived conditions such as high winds, hail, and flash flooding.

Tornadoes, a possible source of high winds, are considered rare in Nevada but have been observed within a radius of 250 km of Yucca Mountain (Eglinton and Dreicer, 1984). The most severe of these tornadoes was classified as F-0 on the Fujita tornado intensity scale. This scale was developed to classify tornado intensity and maximum wind speed based upon the extent of

Table 5-6. Yucca Flat upper air data for 5,000 ft (1,524 m) above mean sea level (328 m above ground level)[a]

Direction[b]	Winter (%)	Winter Avg. speed (m/s)	Spring (%)	Spring Avg. speed (m/s)	Summer (%)	Summer Avg. speed (m/s)	Fall (%)	Fall Avg. speed (m/s)	Annual (%)	Annual Avg. speed (m/s)
N	21.8	5.6	9.8	5.7	3.2	5.9	13.5	6.3	14.2	5.8
NNE	14.9	5.5	8.7	5.1	1.6	4.1	13.1	5.5	11.2	5.4
NE	7.9	5.0	5.6	4.6	1.5	1.5	8.9	4.8	6.7	4.8
ENE	2.9	3.2	2.9	3.5	1.7	0.6	4.9	3.6	3.2	3.4
E	1.5	2.6	1.5	2.0	1.2	1.7	1.3	2.8	1.4	2.4
ESE	1.7	2.0	2.3	2.4	2.5	2.5	2.7	2.8	2.2	2.5
SE	1.9	4.7	3.5	3.2	4.6	3.6	3.6	3.2	3.1	3.1
SSE	3.0	3.6	6.1	5.0	9.0	4.9	5.9	4.6	5.4	4.6
S	6.4	5.0	12.0	7.5	18.3	6.5	12.6	6.4	11.1	6.4
SSW	9.0	5.8	15.1	8.4	26.5	6.9	10.9	7.2	13.2	7.2
SW	6.4	5.4	9.5	7.8	16.5	6.7	6.4	6.7	8.4	6.7
WSW	3.5	4.0	3.8	4.7	5.8	5.0	2.7	4.3	3.6	4.5
W	1.7	3.1	2.0	3.5	2.6	2.8	1.5	3.3	1.8	3.2
WNW	2.4	2.8	4.5	5.9	1.2	3.0	2.3	3.3	2.7	4.1
NW	5.1	4.5	5.3	6.2	1.7	3.3	3.1	3.6	4.1	4.7
NNW	10.6	5.2	6.7	6.2	2.8	3.8	5.9	4.9	7.3	5.3
Calm	1.4	NA[c]	1.4	NA	1.2	NA	1.9	NA	1.5	NA

[a]Calculated from Quiring (1968).
[b]Winds blow from indicated direction.
[c]NA = not applicable.

resultant damage. An F-0 tornado on this scale is classified as a very weak tornado; it has winds of between 40 and 72 mph (18 and 32 m/s), a path length of less than 1 mi (1.6 km), and a path width of less than 17 yd (16 m) (Ludlum, 1982). Dust devils, which are small whirlwinds containing sand or dust, occur in and around the Yucca Mountain site during the summer months. Dust devils occasionally develop wind velocities in excess of that associated with an F-0 tornado, but they dissipate rapidly (Eglinton and Dreicer, 1984).

Lightning is frequently associated with thunderstorm activity but, because cloud-to-cloud lightning occurs nearly 10 times as frequently as cloud-to-ground lightning, strikes of consequence (i.e., resulting in measurable damage) in Nevada only average 18 per yr (Eglinton and Dreicer, 1984). However, the sparse observational network may reflect a somewhat lower frequency of occurrence than actually might be experienced at the Yucca Mountain site.

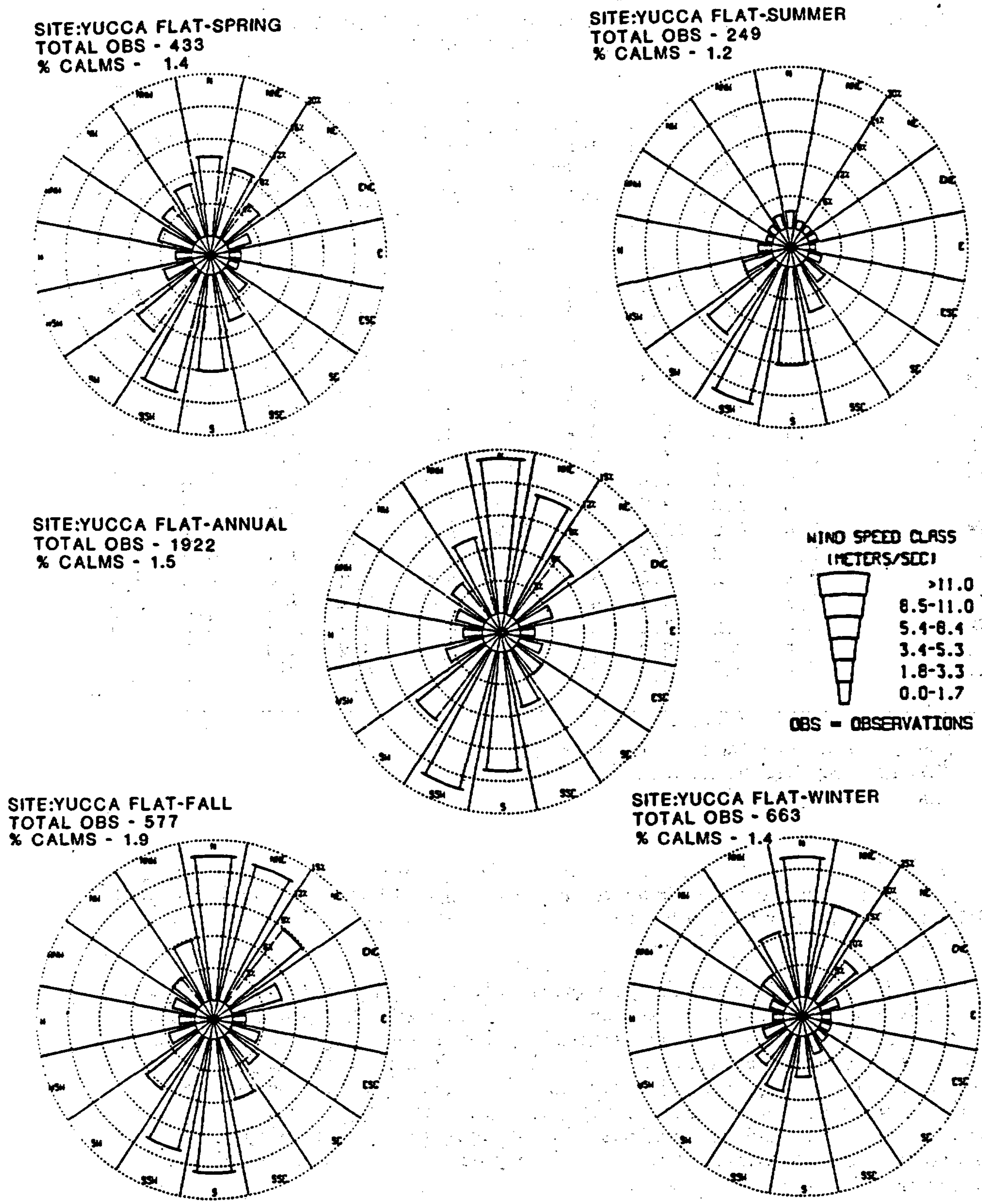


Figure 5-4. Seasonal and annual wind distributions at 5,000 ft (1,524 m) above mean sea level (328 m above ground level) for Yucca Flat (1957 to 1964). Note: Scale is not the same for all distributions. Based on data from Quiring (1968).

Table 5-7. Yucca Flat upper air data for 6,000 ft (1,829 m) above mean sea level (633 m above ground level)[a]

	Winter		Spring		Summer		Fall		Annual	
Direction[b]	(%)	Avg. speed (m/s)	(%)	Avg. speed (m/s)	(%)	Avg. speed (m/s)	(%)	Avg. speed (m/s)	(%)	Avg. speed (m/s)
N	15.3	7.6	7.4	7.8	1.8	6.7	10.8	5.9	10.4	7.1
NNE	17.0	6.8	8.6	5.7	1.6	5.9	14.0	6.6	12.2	6.3
NE	10.7	6.2	6.5	4.7	1.3	4.0	10.2	6.2	8.4	5.7
ENE	4.4	4.6	4.2	3.5	1.1	1.7	5.7	4.8	4.3	4.3
E	1.4	2.2	1.4	1.7	0.6	1.0	1.5	3.5	1.3	2.5
ESE	1.3	2.8	2.1	2.7	1.7	3.4	2.3	3.1	1.8	3.0
SE	1.4	3.0	1.9	3.1	2.9	4.8	3.2	3.6	2.3	3.6
SSE	2.4	4.8	3.6	6.3	7.4	6.0	5.4	5.0	4.2	5.5
S	5.9	7.1	11.9	8.2	21.1	6.8	10.4	7.1	10.6	7.3
SSW	9.8	7.3	19.7	8.3	31.2	7.4	13.7	7.4	16.0	7.6
SW	6.8	6.6	12.4	7.7	18.8	7.1	8.4	6.9	10.1	7.1
WSW	3.6	4.6	4.2	5.1	5.5	5.0	3.0	4.7	3.8	4.8
W	2.9	4.2	1.5	5.8	2.6	4.3	2.2	3.5	2.4	4.2
WNW	3.7	4.2	4.5	6.4	1.0	3.6	2.2	5.2	3.1	5.1
NW	5.4	5.2	4.9	6.5	0.6	3.4	2.4	4.8	3.7	5.5
NNW	8.9	6.3	5.6	6.8	0.9	4.9	4.2	5.0	5.7	6.1
Calm	0.6	NA[c]	0.0	NA	0.0	NA	0.9	NA	0.5	NA

[a]Calculated from Quiring (1968).
[b]Winds blow from indicated direction.
[c]NA = not applicable.

Hail is a variety of thunderstorm activity that can have quite damaging effects, but only one occurrence is expected annually at Yucca Mountain (Eglinton and Dreicer, 1984).

Obstructions to visibility in the vicinity of Yucca Mountain could temporarily disrupt activities at the proposed repository. The most likely conditions that could obstruct visibility appreciably are sandstorms or fog. The conditions conducive to fog formation occur only about twice a year in this area of Nevada and sandstorms of sufficient magnitude to reduce visibility occur only a small fraction of the time (Eglinton and Dreicer, 1984). More detailed discussions of obstructions to visibility as they relate to safe operation of the repository will be included in the environmental impact statement.

Predictions of severe weather needed in design considerations are generally derived by extrapolating past recorded data. The associated probability of occurrence of an event is then calculated based on the frequency of occurrence of the event during the period of record. Of most importance in

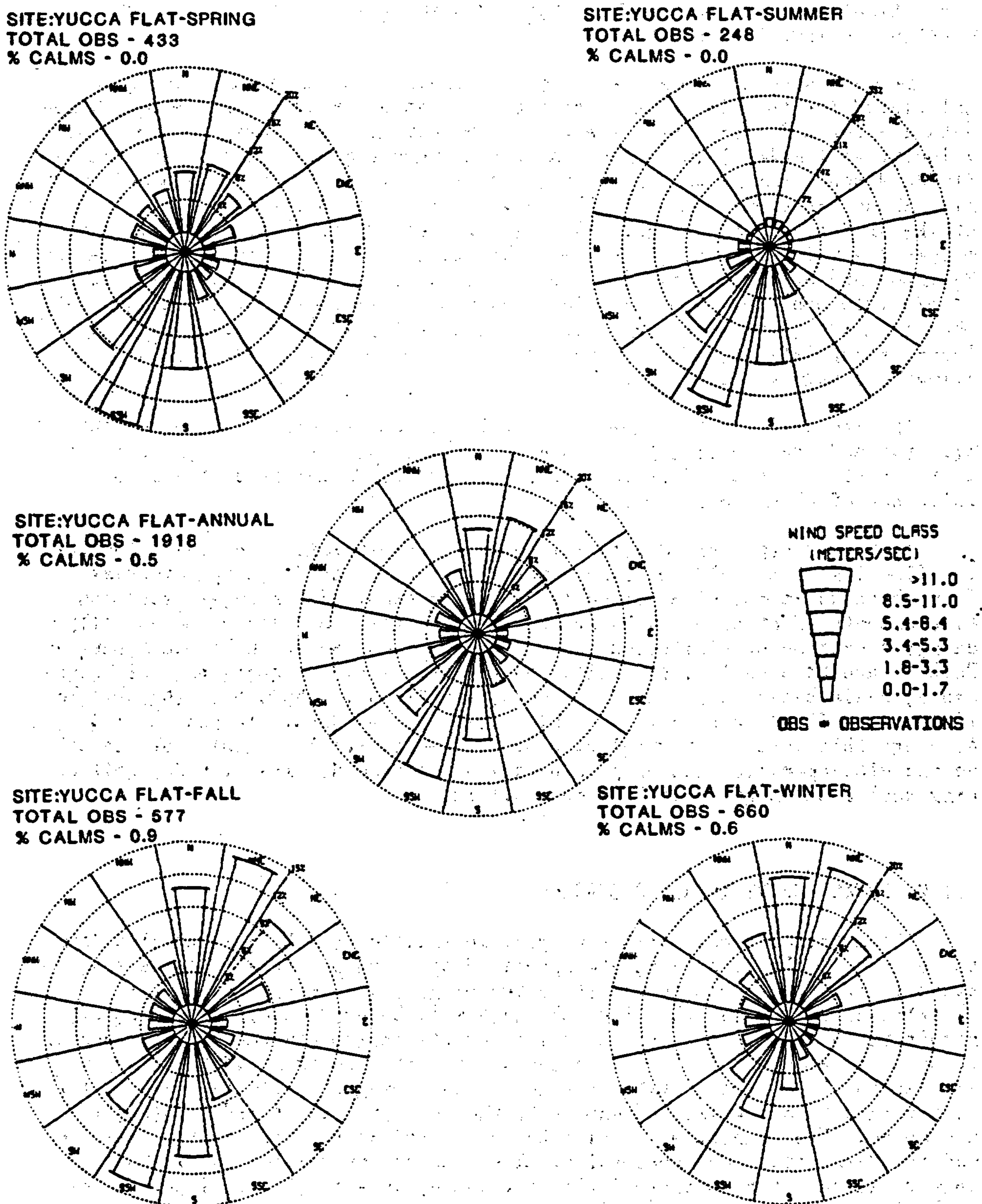


Figure 5-5. Seasonal and annual wind distributions at 6,000 ft (1,829 m) above mean sea level (633 m above ground level) for Yucca Flat (1957 to 1964). Note: Scale is not the same for all distributions. Based on data from Quiring (1968).

designing the surface facilities of the proposed repository at Yucca Mountain are estimates of extreme winds, temperature maximums and minimums, and extreme precipitation events.

Extreme wind speeds and associated probabilities of occurrence have been calculated for the NTS and are presented in Table 5-8 (Quiring, 1968). These data are for a fastest mile of wind, which represent an average highest wind velocity as 1 mile of air passes the measurement point. Eglinton and Dreicer (1984) discuss the potential for both straight-line winds and tornadic (cyclic) winds expected to occur at Yucca Mountain. The probability of a tornado strike at Yucca Mountain, given in Eglinton and Dreicer (1984), is approximately 7.5×10^{-4} in any given year. The maximum design wind speeds cited in Eglinton and Dreicer (1984) for the NTS are a straight-line wind speed of 94 m/s (210 mph) and a tornadic (cyclic) wind speed of 28 m/s (63 mph). Both phenomena are given as having a probability of 1×10^{-6} of occurring in 1 yr. These extrapolations, however, do not take into account the possibility of climatic change in the future.

The probability of occurrence of extreme temperatures, also given in Eglinton and Dreicer (1984), is shown in Table 5-9. These data are estimated on the basis of measured extreme temperatures but do not account for the influence of climatic change.

Another design consideration is extreme precipitation and the potential for flooding that could occur as a result. Because the flooding potential from short-duration, high-intensity storms is high, 24-h average precipitation amounts (Section 5.1.1.2) are not a realistic indicator of potentially damaging extreme precipitation and subsequent flood events at Yucca Mountain. Both 1- and 24-h maximum precipitation and associated probabilities of occurrence, again based on measured extremes, are given in Table 5-10 (Hershfield, 1961). The flooding potential is discussed in more detail in Section 3.2. Although this sort of extrapolation of extreme events is useful, more detailed and site-specific data on precipitation are needed. The plan for collecting such data is given in Section 8.3.1.12.

5.1.2 LOCAL AND REGIONAL METEOROLOGY

The meteorological monitoring program (Section 5.1.3) will provide data to be used in characterizing atmospheric dispersion processes. Aside from establishing the link between site meteorology and general (long-term) climatic conditions at the site, the data will be used in satisfying permit requirements and as input to the environmental impact statement. In general, meteorological conditions experienced at the site are expected to be quite similar to those of the stations used in describing the climate. Winds will be governed to a significant extent by the terrain with regard to direction and speed. The highest winds will be associated with winter frontal passages and thunderstorms. One meteorological parameter not previously discussed, because it is not a characteristic of climate, is atmospheric dispersion or stability. A discussion of this parameter follows.

Atmospheric stability is an important parameter with respect to dispersion of emissions (e.g., particulates and exhaust gases) from the proposed

Table 5-8. Annual extreme wind speed at 30 ft (9.1 m) above ground level and probability of occurrence for Yucca Flat, Nevada[a]

Probability of occurrence in 1 yr	Fastest mile[b]	
	mph	m/s
0.5	48	21
0.2	55	25
0.1	61	27
0.02	75	33
0.01	82	37

[a]Source: Quiring (1968).
[b]Fastest mile is defined as an average highest wind velocity as 1 mile of air passes the measurement point.

Table 5-9. Extreme maximum and minimum temperatures and probability of occurrence for Beatty, Nevada[a]

Probability of occurrence[b] in 1 yr	Temperature (°C)	
	Maximum	Minimum
1.0	40.2	-6.6
0.5	42.3	-10.2
0.2	43.6	-12.3
0.1	44.4	-13.7
0.05	45.2	-15.1
0.04	45.5	-15.4
0.02	46.2	-16.8
0.01	47.1	-18.1
0.005	47.8	-19.4
0.002	48.8	-21.2
0.001	49.6	-22.4
0.0001	52.2	-26.8

[a]Source: Eglinton and Dreicer (1984).
[b]These probabilities of occurrence do not reflect potential climatic changes.

Table 5-10. Maximum 1- and 24-h precipitation and probability of occurrence for Yucca Flat[a]

Probability of occurrence in 1 yr	Maximum precipitation 1 h in.	mm	24 h in.	mm
1.0	0.30	7.6	0.75	19.1
0.5	0.40	10.2	1.00	25.4
0.2	0.60	15.2	1.25	31.8
0.1	0.70	17.8	1.50	38.1
0.04	0.80	20.3	1.75	44.5
0.02	0.90	22.9	2.00	50.8
0.01	1.00	25.4	2.25	57.2

[a]Source: Hershfield (1961).

repository and has been analyzed using estimates of cloud cover, ceiling height, and net solar radiation for the 18-yr period of record at Yucca Flat (DOC, 1986). Annual average stability distributions similar to the data presented in Figure 5-3 can be constructed for only those occurrences of wind speed and direction falling into each of the six Pasquill stability classes (A through F). Stability class A defines an extremely unstable (highly convective) atmosphere, class B is for unstable conditions, class C is slightly unstable, class D is neutral, class E is slightly stable, and class F is stable. Wind roses for each of these stability classes are shown in Figures 5-6 (A through C) and 5-7 (D through F). The most significant features of the stability distributions are summarized in Table 5-11 and discussed in the following paragraphs.

Class A stability was most frequently associated with winds from the east, while winds from the east through southeast were most frequently associated with class B stability. For class C stability, winds from the south were the most common occurrence, but winds from the southeast through the southwest were also quite frequently associated with class C stability. Occurrences of class D stability were the second most commonly observed stability classification and were commonly associated with winds from the north and the south through southwest. The distribution for class E stability indicates that there is a distinct shift from the generally southerly winds associated with the unstable and neutral stability classifications (classes A through D) to predominantly northwesterly winds for class E and class F. Stable atmospheric conditions (class F) were the most commonly observed stability class and the distribution clearly shows the predominance of winds from the west through the north. Because stability classes E and F are both associated with relatively light winds, the predominance of winds from the west through the north for these classes is most likely due to drainage winds at this site that develop under synoptically calm conditions.

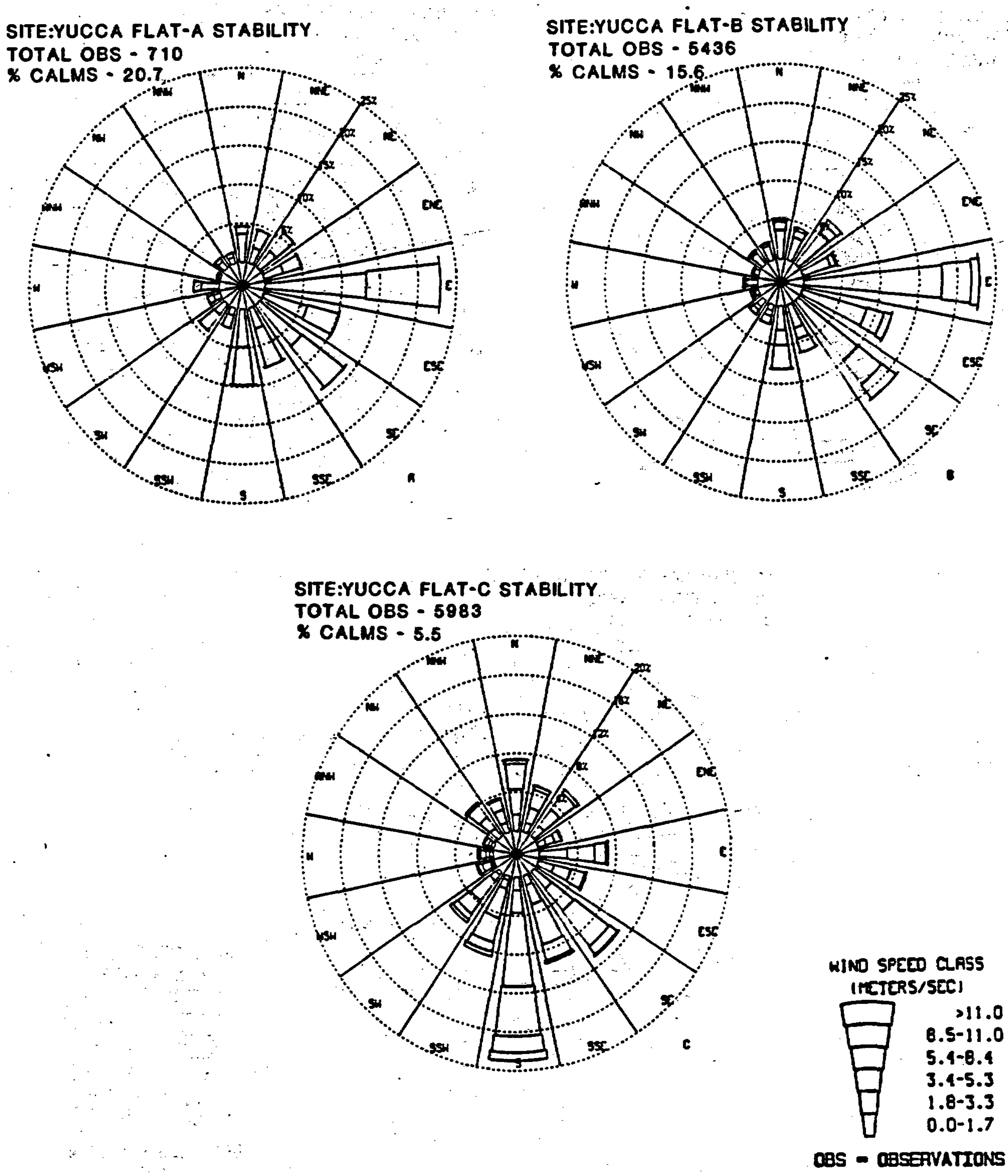


Figure 5-6 Distribution for Pasquill stability classes A, B, and C for Yucca Flat (1961 to 1978). A = extremely unstable, B = unstable, C = slightly unstable. Note: Scale is not the same for all distribution. Based on data from DOC (1986).

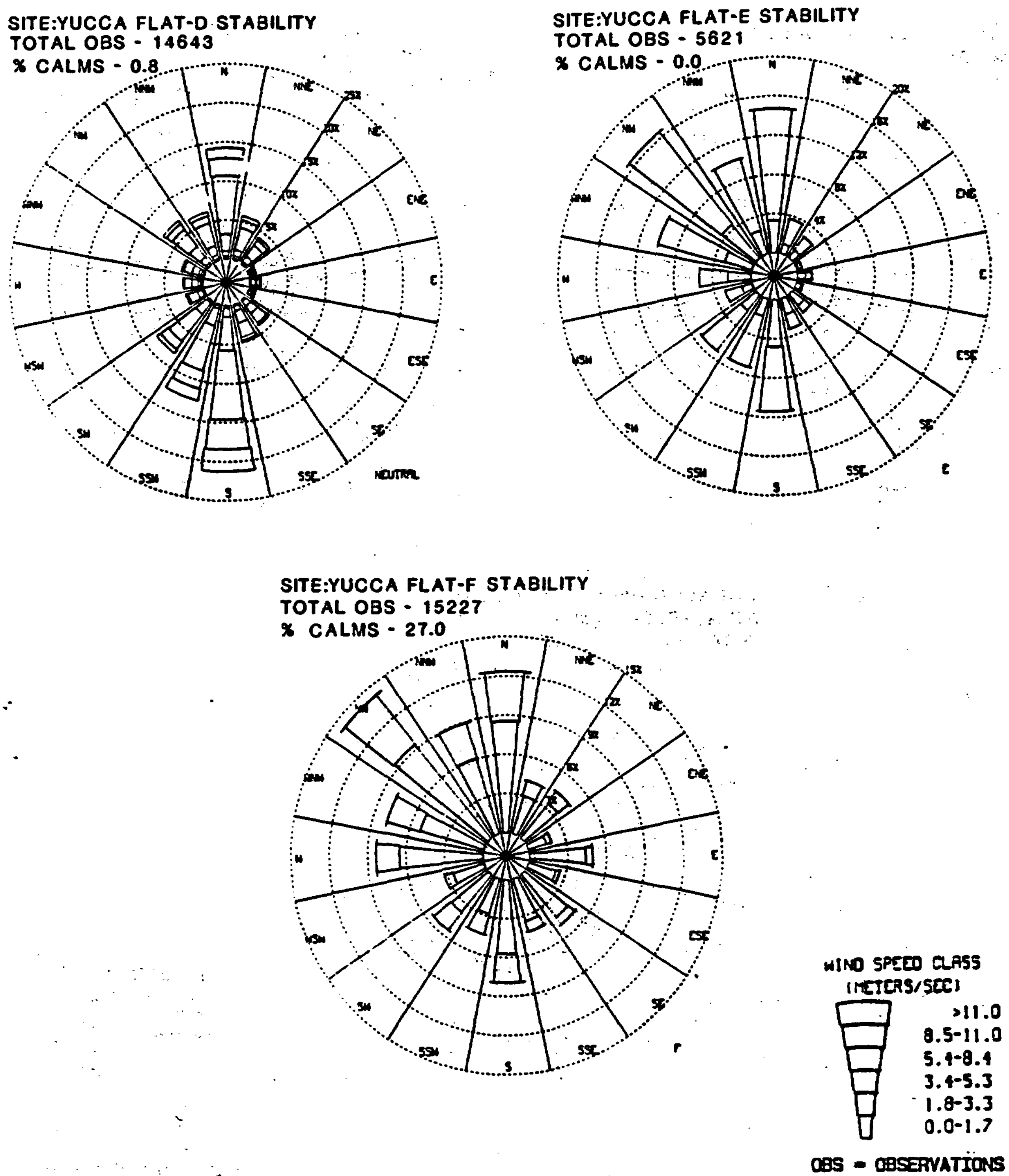


Figure 5-7. Distribution for Pasquill stability classes D, E, and F for Yucca Flat (1961 to 1978). D = neutral, E = slightly stable, F = stable.

Table 5-11. Yucca Flat Pasquill stability class distributions for the period 1961 to 1978[a]

Stability class[b]	Percentage of total observations	Predominant direction[c]	Percentage of stability class observations	Predominant quadrant[c]	Percentage of stability class observations
A	1.5	E	22.9	E-S	64.5
B	11.4	E	22.9	E-SE	51.0
C	12.6	S	19.0	SE-SSW	47.8
D	30.7	S	21.2	S-SW, N	42.0, 14.2
E	11.8	NW	16.6	WNW-N, S-SW	51.4, 25.8
F	32.0	NW	14.2	W-N	51.7

[a]Source: DOC (1986).
[b]A = extremely unstable, B = unstable, C = slightly unstable, D = neutral, E = slightly stable, F = stable.
[c]Wind blows from indicated direction.

In summary, neutral and stable conditions (classes D, E, and F) were by far the most commonly experienced at Yucca Flat and account for 74.5 percent of the total observations. Stable conditions tend to be dominated by winds generally from the northwest, while neutral conditions had a significant south to southwesterly component in addition to a strong northerly component. Unstable conditions (classes A, B, and C) occurred only 25.5 percent of the time, had virtually no northerly component, and were dominated by winds from the east through the south, with the most unstable classes having a stronger easterly element than the slightly unstable category.

Determining the stability distributions is important from the standpoint of evaluating the potential impacts of particulate and gaseous emissions from the repository. The data are required as input to the dispersion models that will be used in acquiring permits for both the site characterization activities will be discussed in the environmental monitoring and mitigation plan and the repository (through the environmental impact statement (EIS) process). Although these data from Yucca Flat provide a preliminary indication of stability and dispersion characteristics of the area, site-specific data are needed. Determination of atmospheric stability was a significant consideration in development of the meteorological monitoring program being operated at Yucca Mountain (Section 5.1.3) and will be fully evaluated throughout site characterization activities.

5.1.3 SITE METEOROLOGICAL MEASUREMENT PROGRAM

A monitoring program was operated at Yucca Mountain for approximately 2 yr. It consisted of two 10-m towers instrumented to collect data on temperature, wind speed and direction (3-m and 10-m levels), relative humidity, insolation, ground surface infrared radiation, soil temperature, precipitation, and barometric pressure. The towers were installed to collect preliminary meteorological data and were decommissioned at the end of October 1984. However, most of the data from this program are still being reduced and are not available.

A new, extended monitoring program has been designed to collect data on both synoptic-scale meteorological influences and specific terrain-induced perturbations. The program includes four 10-m towers designated NTS-10 plus an area designation (Yucca Mountain, Coyote Wash, Alice Hill, and Fortymile Wash) and one 60-m tower designated NTS-60 Repository. The locations of the towers are described in Table 5-1 and shown in Figure 5-1. The 60-m tower is placed near the proposed surface facility location, and the other 4 towers are placed at various locations in the vicinity of Yucca Mountain. Wind speed, wind direction, and standard deviation of wind direction (sigma-theta) data will be collected at each of the 4 remote sites at the 10-m level and at both the 10- and 60-m level at the main site. All the sites are instrumented to collect data on precipitation, relative humidity (dew point at the main site), and ambient temperature. In addition, the 60-m tower instrumentation includes a net radiation sensor (for solar and terrestrial radiation), a vertical wind speed sensor, and circuitry for determining the temperature difference between the 10- and 60-m levels. Most of these parameters are recommended or required to be monitored for regulatory compliance (EPA, 1980). In addition, the hourly average wind speed, wind direction, and temperature data are required as input to dispersion models that will be used in assessing the ambient air quality impacts of the proposed activities. The sigma-theta, vertical wind speed, temperature difference, and net radiation data can all be used to determine atmospheric stability, which is a very important factor in determining ambient impacts through dispersion modeling. The relative humidity and dew point will be used for climatological comparisons, as will the precipitation data. The precipitation data will also be used as input to other studies that will be conducted during site characterization. The other programs are the infiltration studies and the surface water hydrology investigations.

The instruments used to collect data on the various meteorological parameters will meet the following specifications:

1. Wind direction: ±3° of true azimuth (including sensor orientation error) with a starting threshold of less than 0.45 m/s.

2. Wind speed: ±0.22 m/s for speeds above the starting threshold of 0.45 m/s but less than 11.1 m/s, and ±5 percent of true speed, not to exceed 2.5 m/s, at speeds greater than 11.1 m/s.

3. Sigma-theta: wind-vane damping ratio of between 0.4 and 0.6 (inclusive) with a 15° deflection and delay distance not to exceed 2 m.

4. Dry-bulb temperature: ±0.5°C.

5. Temperature difference (between levels): ±0.003°C/m.

6. Radiation (solar and terrestrial): ±5 percent.

7. Precipitation: resolution of 0.25 mm with a recorded accuracy of ±10 percent of total accumulated catch.

8. Relative humidity: ±6 percent.

9. Dew point temperature: ±1.5°C.

10. Time: within 5 min of actual time for all recording devices.

These specifications apply to digital systems; analog backup systems can deviate by up to 1.5 times these values.

The monitoring program will be run in accordance with quality assurance regulations, rules, and guidelines developed to ensure the validity and traceability of all collected data. This and other information regarding the monitoring program is contained in the Meteorological Monitoring Plan (SAIC, 1985), which is discussed in Section 8.3.1.12.

Air quality monitoring, although not directly related to site characterization, may be needed to fulfill permitting requirements for both the site characterization activities and repository development. The environmental monitoring and mitigation plan will contain information on those aspects of site characterization that may require air quality data, and the environmental impact statement (EIS) process will define air monitoring needs with respect to repository development.

5.2 LONG-TERM CLIMATIC ASSESSMENT

An assessment of the long-term climate in the Yucca Mountain area is necessary to resolve several issues. The nature and rates of change in past climates must be understood to allow the prediction of future climate conditions. An understanding of future climate conditions is needed to evaluate the potential effects of climatic change on the location and rates of erosion and on the hydrologic and geochemical characteristics in the vicinity of the Yucca Mountain site. The hydrologic system may be especially susceptible to changes in climate. This section discusses the present understanding of the nature and rates of past climate change and discusses the strategy for developing scenarios for future climatic variations. These scenarios can be used to evaluate anticipated and unanticipated future climate conditions that can be used to assess the potential changes in the hydrologic characteristics in the vicinity of Yucca Mountain (Section 8.3.1.5.2). These estimates of future climate conditions will also be used to determine potential changes in the location and rates of erosion (Section 8.3.1.6.2) at Yucca Mountain.

Paleoclimatic reconstructions discussed in this section focus on the latter part of the Quaternary Period. Figure 5-8 shows the relationship of the geologic time periods discussed in this chapter. The Quaternary Period includes the last 1.6 million years and is subdivided into the Pleistocene

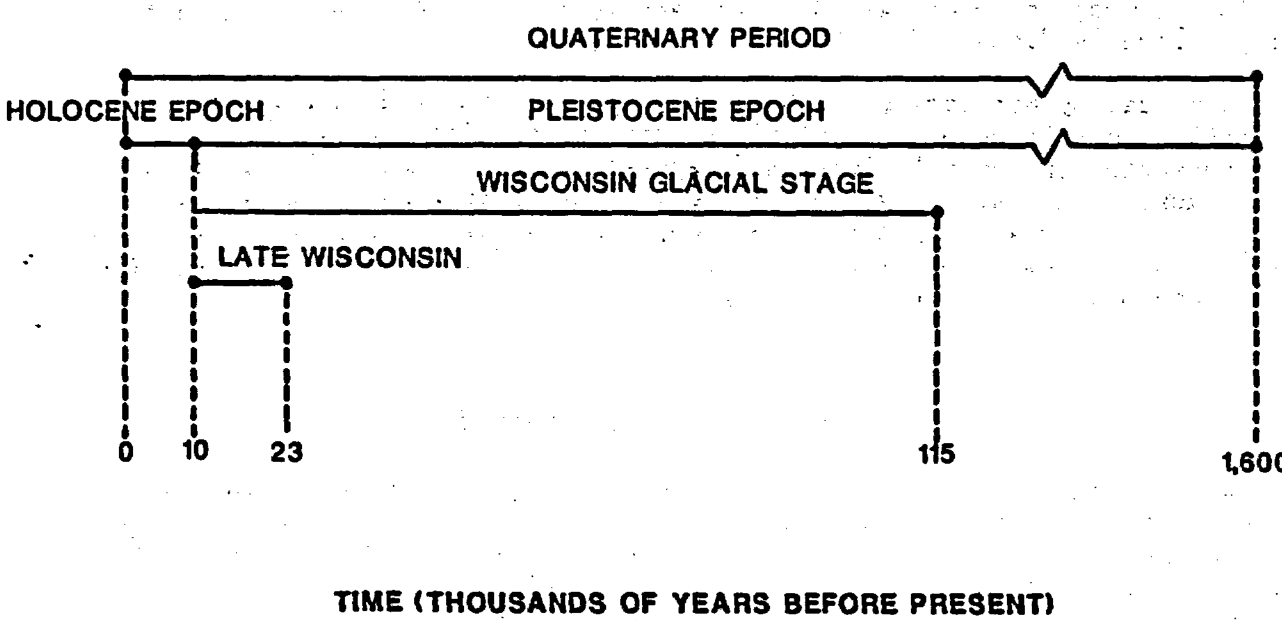


Figure 5-8. Time lines indicating geologic time periods discussed in text. Based on data from GSA (1983).

Epoch (from 1.6 million to 10,000 yr ago) and the Holocene Epoch (from 10,000 yr ago to the present). Further subdivisions of the Pleistocene Epoch are based on periodic glacial advances and recessions. The most recent of these glacial advances, known in North America as the Wisconsin Stage, is important in the reconstruction of the paleoclimatic history of the Yucca Mountain site because the conditions that accompanied this glacial regime may represent the factors that will affect future hydrologic conditions at the NTS, should the Holocene close with a return to a global glacial period. Paleoclimatic investigations must extend back at least to the previous interglacial period (known in North America as the Sangamon) in order to provide a climatic analog for possible future climate states that are warmer than those of today, which could occur in a carbon-dioxide-enhanced world.

Because it is the most recent glacial and pluvial event in the earth's history, the Wisconsin has been intensively studied and is the best understood of the glacial and interglacial stages that make up the Pleistocene. The beginning of the Wisconsin is correlated by Ruddiman and McIntyre (1981) with the 5d-5e boundary of the deep-sea oxygen isotope record, which occurred about 115,000 yr ago. During the late Wisconsin (23,000 to 10,000 yr ago) more than 100 closed basins in the northern and western Great Basin contained lakes (Smith and Street-Perrott, 1983), while in the southern Great Basin, at Yucca Mountain, a marked increase in the area of woodland species of vegetation suggests more available moisture and a general decline in temperature (Spaulding and Graumlich, 1986).

In the following sections, climate variation during the Quaternary Period will be discussed. Because past climatic variability is probably the best indicator of future climatic conditions, understanding this climatic variability is important in assessing future climatic variation. Ensuing sections are structured in terms of three principal topics: paleoclimatology (Section 5.2.1), future climate variation (Section 5.2.2), and paleoclimatic variations and their relation to the Yucca Mountain site (Section 5.2.3).

5.2.1 PALEOCLIMATOLOGY

5.2.1.1 Quaternary global paleoclimate

Climate varies on all temporal and spatial scales, ranging from interannual variations at a particular location related to atmospheric circulation anomalies, to the very long period variations at the global scale related to the evolution of the atmosphere and lithosphere (Webb et al., 1985). An understanding of climate variation on the global scale is necessary for the prediction of local climate. This is because climate at any point on the earth's surface is the result of processes that occur over the entire global area.

In assessing the environmental stability of a particular location, the key climatic variations are those that occur on the time scale of centuries to 100,000 yr (Crowley, 1983). During the Quaternary, the principal climatic variations at such time scales have been those associated with the repeated fluctuations between glacial and interglacial conditions.

The glacial cycles of the Quaternary are part of a long period of cooling, commencing in Late Cretaceous time (Lloyd, 1984). During the past 80 million yr, global average temperature declined, and first Antarctica and later Greenland, North America, and Europe became glaciated. Glaciation of the northern hemisphere probably began about 3.2 million years ago (Crowley, 1983), with clear evidence about 2.5 million years ago for glaciation on land areas contributing sediments to the North Atlantic (Shackleton et al., 1984).

The global volume of glacial ice has varied continuously throughout the Quaternary, but with characteristic quasi-periodicity correlated with variations of the earth's orbital elements, i.e., eccentricity (about 100,000 yr), obliquity (about 40,000 yr), and precession (about 20,000 yr) (Hays et al., 1976; Imbrie et al., 1984). During the past 120,000 yr, global ice volume increased from the low values of the last interglacial (125,000 to 118,000 yr before present) to the high values of the last glacial maximum about 18,000 yr ago, then decreased to approximately its present level by 6,000 yr ago. The paleoclimatic record of the past 18,000 yr provides an illustration of the extremes of climate to be expected in a single glacial to interglacial transition but does not necessarily indicate the full range of conditions that might occur in an interglacial to glacial transition (Spaulding, 1983).

At 18,000 yr before present, global average temperatures were lower than at present, and large ice sheets covered parts of North America and Europe (Denton and Hughes, 1981). Consequently, sea levels were lower, exposing much of the continental shelves (Bloom, 1983). Sea surface temperatures as a whole were lower, and extensive sea ice formed in the northern oceans (CLIMAP Project Members, 1981). Eighteen thousand years ago vegetation and the hydrologic cycle differed markedly from those of today (Street-Perrott and Harrison, 1984). The Laurentide ice sheet in eastern North America reached its maximum extent about this time, while the Cordilleran ice sheet in the Northwest approached its maximum by 15,000 yr B.P. (Mayewski et al., 1981; Waitt and Thorson, 1983).

In the North Pacific Ocean adjacent to western North America about 18,000 yr ago, sea-surface temperatures were more than 4 Celsius degrees lower than today over large areas, and oceanic circulation was altered as well (Imbrie et al., 1983). Land temperature declines ranged from 0 to 10 Celsius degrees during the last glacial maximum (Von Neumann, 1960). In southern Nevada, average annual temperatures were 6 to 7 Celsius degrees lower than the current average annual temperature (Spaulding, 1985). Experiments with climate simulation models (Section 5.2.2.2) suggest that 18,000 yr ago the expanded ice sheets, extensive sea ice, and colder oceans greatly influenced atmospheric circulation around North America (Gates, 1976b; Manabe and Broccoli, 1985; Kutzbach, 1985; Kutzbach and Wright, 1985). For example, to simulate the climate of 18,000 yr ago, Manabe and Broccoli (1985) used a Geophysical Fluid Dynamics Laboratory general circulation model coupled with a static mixed-layer ocean model (in which the sea surface temperatures were predicted by the model), and Kutzbach and Wright (1985) used the National Center for Atmospheric Research Community Climate Model (NCAR CCM) (in which sea surface temperatures were prescribed using the reconstructions by CLIMAP Project Members, 1981). Both models simulated similar changes in the atmospheric circulation across North America (relative to today) resulting from the imposition in the models of the Laurentide ice sheet, including (1) a split in the jet stream in the upper atmospheric flow, with one weaker branch crossing the continent to the north of the ice sheet, and a second stronger branch crossing the continent from southwest to northeast to the south of the ice (Kutzbach and Wright, 1985); (2) the development of a strong ridge over western North America and a deep trough over eastern North America in the upper atmospheric circulation; and (3) the development of strong anticyclonic circulation at the surface over northern North America. Kutzbach and Wright (1985) describe the general compatibility between the climate simulated by the NCAR CCM and the geologic evidence for 18,000 yr ago in North America. Vegetation patterns in North America at 18,000 yr B.P. differed considerably from those at present, reflecting the great differences between modern and full-glacial regional climates (Spaulding et al., 1983; Kutzbach and Wright, 1985; VanDevender et al., 1987; SCP Section 5.2.1.2.3). Large-scale changes in regional hydrology also occurred, as is illustrated by the differences in lake levels between 18,000 yr B.P. and today (Smith and Street-Perrott, 1983; Street-Perrott and Harrison, 1984; Benson and Thompson, 1987; Forester, 1987; SCP Section 5.2.1.2.2).

Between 18,000 and 6,000 yr ago, the global ice volume decreased to approximately its present amount, the sea level rose, and the oceans warmed (Kutzbach and Guetter, 1986). Over the same interval the seasonal cycle of solar radiation was amplified (relative to both 18,000 yr ago and today) by the shift in perihelion from January to July, and by changes in the tilt of the axis (Kutzbach, 1981). At 10,000 yr ago, for example, global solar radiation at the top of the atmosphere was about 8 percent greater in summer than today and about 8 percent less in winter (Kutzbach, 1985). Accompanying these changes was an increase in the concentration of carbon dioxide in the atmosphere (Shackleton et al., 1983) in a manner consistent with the changes in global climate during this interval. The amplification of the seasonal cycle of solar radiation has been linked with the intensification of the summer monsoonal circulation of Africa and southern Asia about 9000 yr B.P. Greater monsoonal precipitation at that time is evidenced by the geologic record of lake-level variations in the tropics (Kutzbach and Street-Perrott, 1985). Similar increases in monsoonal rainfall have been postulated for the Yucca Mountain region (Spaulding and Graumilch, 1986), and this possibility will be examined during site characterization.

Astronomical forcing of climate provides a quasi-periodic physical mechanism for the simulation of past and future climate change. The potential causes of the climatic variations of the Quaternary will be discussed in Section 5.2.2.1 as they pertain to the prediction of future climatic variations. In the following sections, the regional expression of the large-scale climatic variations described above will be reviewed.

5.2.1.2 Quaternary regional paleoclimate

Global paleoclimatology contributes to an understanding of regional and site-scale climatic conditions principally by defining the broad chronology and large-scale mechanisms that control or place bounds on local climates. Although the global factors are necessary for long-term climate prediction, they are insufficient because they do not provide the information required from site characterization as discussed in the introduction to this chapter and in Section 5.2.

There are two primary types of geologic data that provide information on regional and site-specific paleoclimatic fluctuations. First, reconstructions of the past extents and hydrological environments of paleolakes and marshes provide an integrated history of hydrologic response to past climates. Second, paleontological evidence of the local terrestrial biological response to paleoclimates not only provides indications of general climatic conditions, but also suggests ranges for specific variables. By applying quantitative relationships derived from comparisons between modern plant distributions and modern climates, paleobotanical data may be evaluated in terms such as temperature extremes, available moisture, and relative moisture contributions by rain and snow.

Whereas paleobotanical data in the form of pack rat middens are available near the proposed repository (Spaulding, 1985), the adequacy of near-site paleolimnological data has not yet been fully assessed. Paleomarsh deposits are available near the southern and western peripheries of the NTS (Haynes, 1967; Quade, 1986), and potentially promising playa sites occur to the north and east. Paleolacustrine data have been obtained from areas farther north, east, and west in the Great Basin, where pluvial lake systems (Figure 5-9) provide an abundance of datable deposits and micropaleontological data. Paleoclimatic investigations associated with the NTS will include efforts to obtain as much data as possible from the immediate proximity of Yucca Mountain. These data will include plant remains, pack rat middens, and microfossils from playa and paleomarsh sediments. To reduce the uncertainty associated with site-specific studies, these local records will be supplemented with, and tested against, regional paleobotanical and paleolimnological records.

The remainder of this section is organized in the following format: Section 5.2.1.2.1 discusses the relationships among lake size (area and volume), climatic parameters, and hydrologic parameters, including historical data on the variability of these parameters; this review is necessary to establish a framework within which the significance of data from paleolakes can be understood. The presently available paleolacustrine data and their application in defining paleoclimates are presented and discussed in Section 5.2.1.2.2. In Section 5.2.1.2.3 the available results of paleobotanical studies in the Great Basin are summarized and compared with modern relationships of vegetation and climate, followed by a discussion of alternative applications to paleoclimate reconstructions. Other lines of paleoclimatic evidence, such as regional glacial features, are presented in Section 5.2.1.2.4. Finally, in Section 5.2.1.2.5, the present understanding of the paleoclimatology of the Great Basin is synthesized.

5.2.1.2.1 Historical lake, climatic, and hydrologic data

Within the Great Basin the most widespread and continuous data pertaining to paleoclimates are derived from studies of Quaternary lakes. However, even if it were possible to reconstruct complete histories of the shoreline altitudes, volumes, sedimentation, and biota of the lakes, the link to paleoclimates would still be indirect. An understanding of the relationship of lake size to the most important climatic parameters, precipitation and evaporation, and to the principal hydrologic parameters, streamflow and

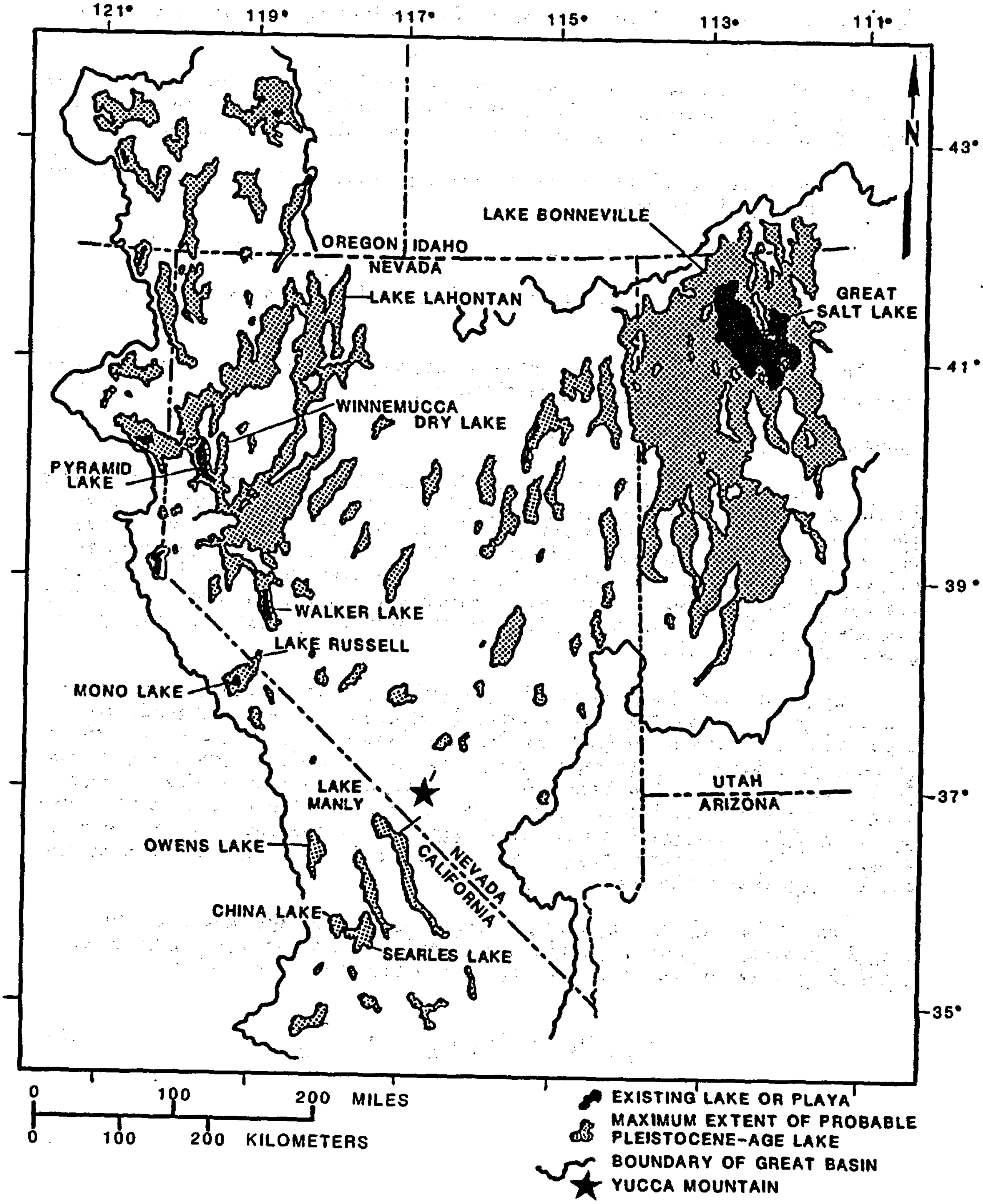


Figure 5-9. Great Basin lakes of presumed Pleistocene age (modified from Spaulding et al., 1983).

ground-water flow, provides a framework for evaluating the significance of paleolacustrine data.

Historical records of precipitation, streamflow, and lake-level fluctuation reflect the hydrologic effects of climate change on large areas. These data, if corrected for the impact of man's activities, can be used to

1. Estimate the short frequency and amplitude of small-scale (<100 yr) changes in climate.

2. Estimate the spatial (area and altitude) variability of climate.

3. Provide data for the creation of synoptic snapshots of climate extremes.

These synoptic snapshots of climate and surface hydrology will serve as test scenarios for modeling future climate (Section 8.3.1.5.1).

Hydrologic balance of lake systems

Lake size is a function of a dynamic equilibrium resulting from changes in the magnitudes of water sources and sinks. The principal water sources for a lake are (1) streamflow into the lake, whether as direct runoff from the watershed or as emergence of ground water to stream channels; (2) precipitation on the lake surface; and (3) ground-water discharge directly to the lake. The principal processes by which water leaves a lake are (1) evaporation from the lake surface, (2) streamflow from the lake, and (3) ground-water outflow from the lake.

The paleolakes that persisted as relatively permanent bodies of water, and therefore provide the best preserved and most continuous record, are those that were contained in large drainage basins. Under these conditions ground-water inflow to the basin and ground-water outflow from the lake can be ignored without a significant loss of precision in water-budget calculations. Further, most but not all of the paleolakes of interest in the region occupied closed topographic basins, eliminating streamflow from the lake as a factor and leaving evaporation from the lake surface as the only process by which water leaves the lake.

For a lake and its surrounding large closed drainage area, the mean-annual hydrologic balance for the steady state can be written in terms of total discharge to the lake and evaporation from the lake surface:

$$(E_L)\ (A_L) = (P_L)\ (A_L) + D_s + D_g \qquad (5\text{-}1)$$

where

E_L = evaporation rate from lake

A_L = area of lake surface

P_L = precipitation on lake

D_s = stream discharge into the lake

D_g = direct discharge of ground water to lake.

A knowledge of man's impact on the hydrologic balance is necessary for the correction of historical records of streamflow and lake levels (Whitaker, 1971; Stauffer, 1985). Figure 5-10 shows the historical and pristine (corrected) records of fluctuations in the water level of the Great Salt Lake for the period from 1851 to 1984. These corrected records can be subjected to spectral analysis to determine the characteristic temporal scales of variation in the hydroclimatological data during the monitored period.

Precipitation and streamflow data

Precipitation data exist for weather stations scattered throughout the western United States (Hershfield, 1961). The data have record lengths of up to 100 yr. Some weather stations located in California and Nevada will be used to provide vegetation-climate calibrations (response surfaces) for future climate prediction (Section 8.3.1.5.1.). Figure 5-11 shows the areal distribution of presently active precipitation and streamflow gaging stations in the basin once occupied by the Pleistocene Lake Lahontan.

The quantity of precipitation that falls directly on the lake basin compared with the inflow from streams varies from basin to basin and is important climatologically. For Lake Lahontan, precipitation that falls directly on the lake surface today is only about 15 percent of the total water input to the basin (Benson, 1986); for Lake Bonneville (Great Salt Lake) on-lake precipitation is about 27 percent of today's total water input (Stauffer, 1985); while for Lake Russell (Mono Lake), on-lake precipitation is about 19 percent of the total water input (Mason, 1967).

The relationship between on-lake precipitation and stream discharge can be examined by comparing precipitation data from a weather station located in the Sierra Nevada (Tahoe City, California), data from a station located on the floor of the Lahontan Basin (Fallon, Nevada), and discharge data for the Carson River that drains a watershed adjoining the Tahoe City site. Discharge data are mainly from gaging stations located upstream of agricultural regions. Figure 5-12 shows the good correlation between the precipitation at Tahoe City and the discharge of the Carson River. The climate (precipitation and temperature) of mountain ranges bordering a lake basin controls, to an extent, the amount of water input to a lake. This is especially true for lake basins such as Lahontan and Mono that lie in rain shadows. This relationship may be relevant to the paleoclimate at Yucca Mountain.

In evaluating the potential effect of climatic change on discharge to closed-basin lakes, it is instructive to examine records of gaged streamflow.

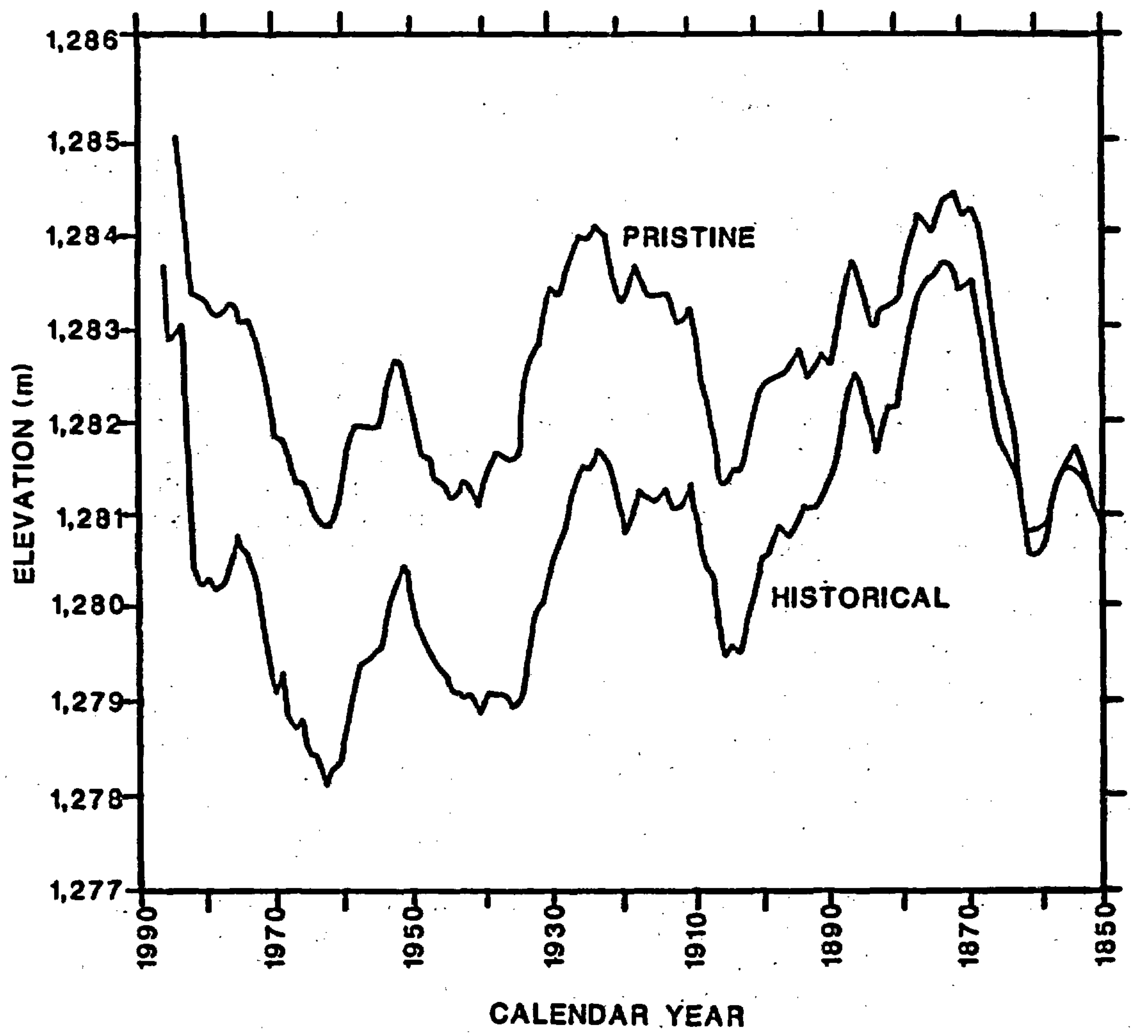


Figure 5-10. Historical and pristine (corrected) records of fluctuations in the level of Great Salt Lake, Utah. Source: Stauffer (1985).

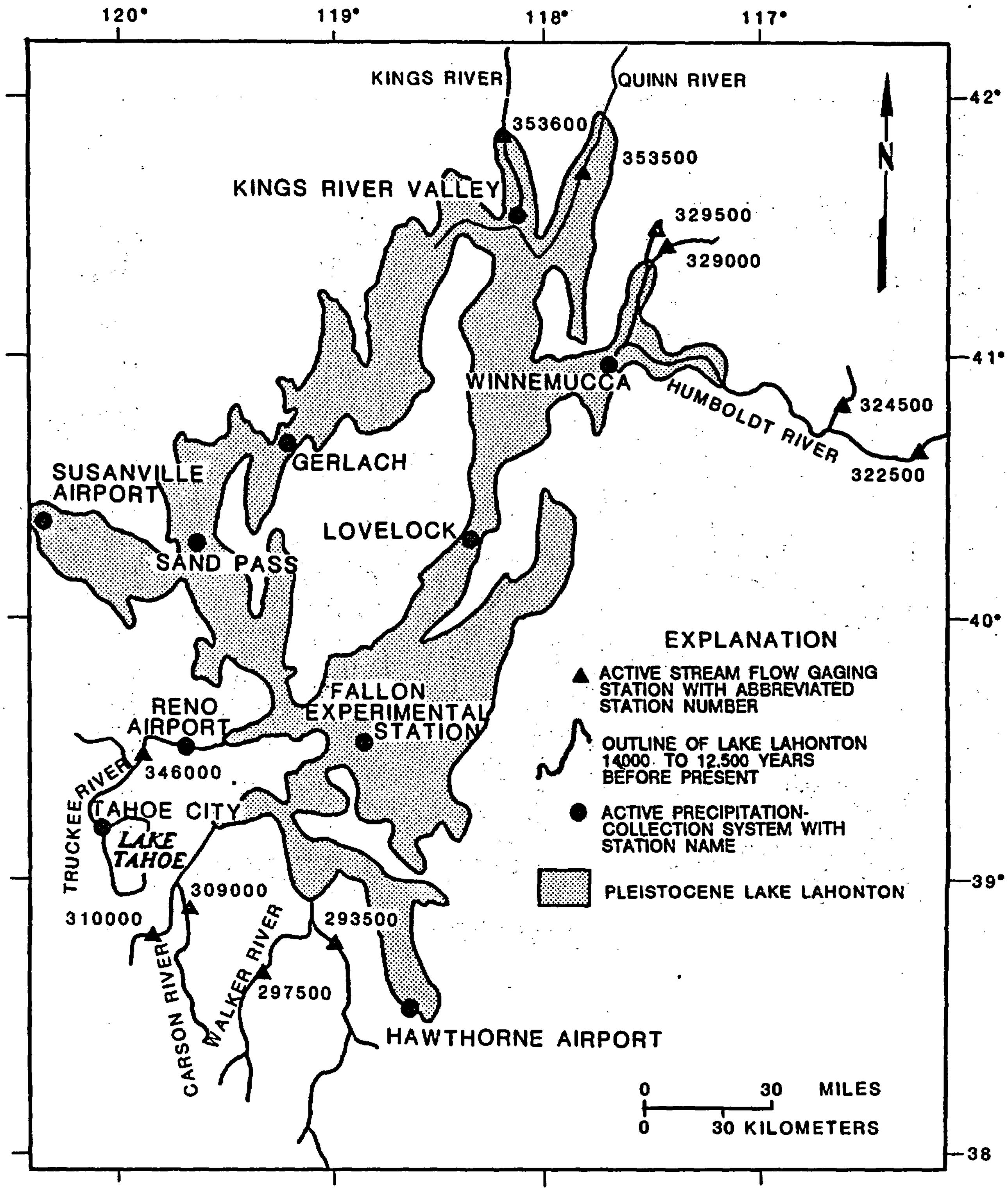


Figure 5-11. Locations of active river streamflow-gaging and precipitation-collection stations. Source: Benson (1986).

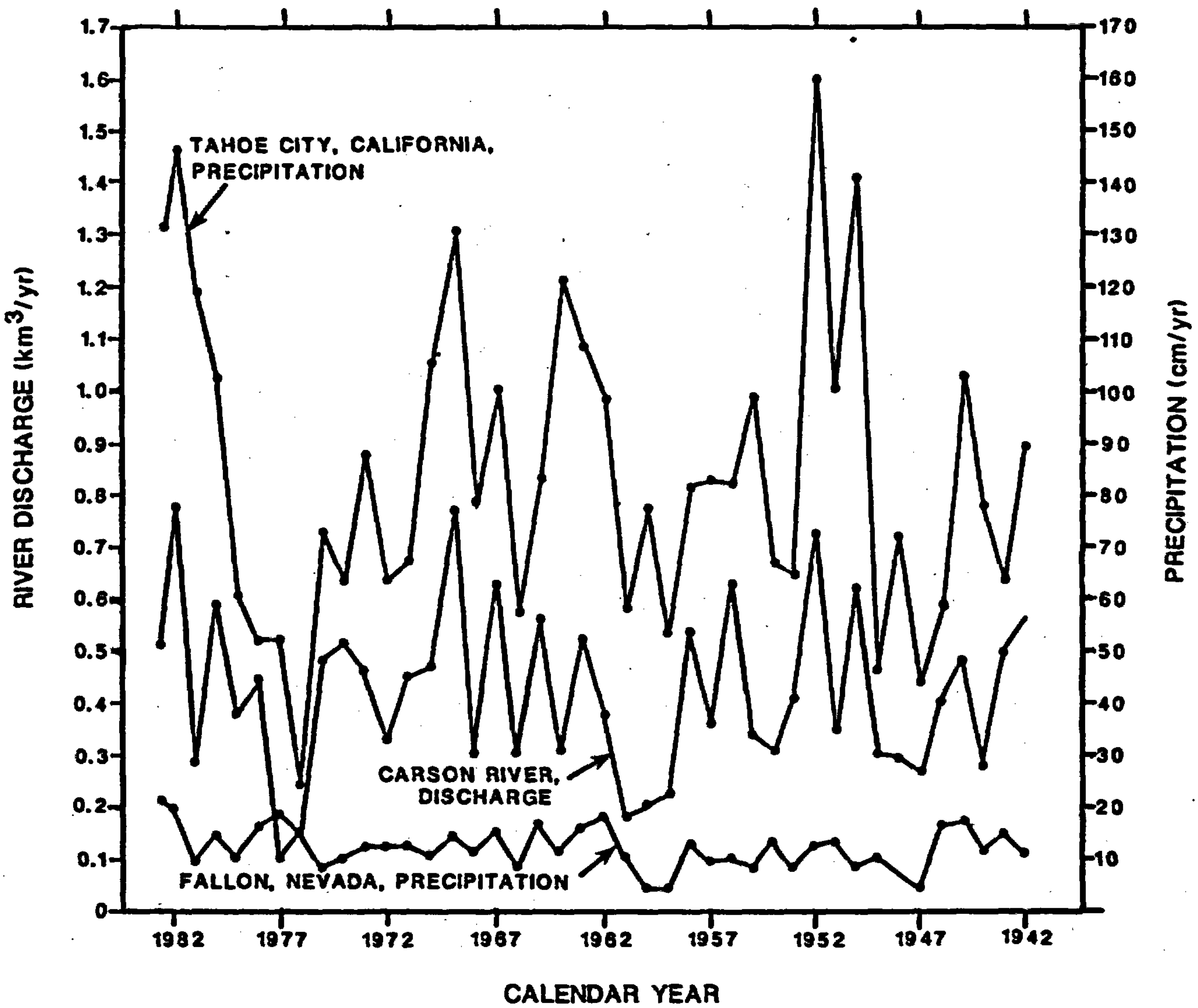


Figure 5-12. Precipitation records for Fallon, Nevada, and Tahoe City, California, compared with Carson River discharge, 1942 to 1983. Streamflow data from Benson (1986).

Gaged streamflow, corrected for consumptive use, is a useful indicator of climate change (Meko and Stockton, 1984). Bartlein (1982) analyzed monthly streamflow over Canada and the United States for the period 1951 to 1970 by means of principal components analysis. He found that 75 percent of the total variance was explained by only 23 large scale anomaly patterns (of 102 potential components) that are, in turn, related to climatic anomalies in atmospheric circulation.

Meko and Stockton (1984) show that carefully selected records of streamflow in the western United States can provide useful information on climatic variation, especially for mountainous areas where high-elevation weather stations are sparse. They found that major low-frequency variations in streamflow have tracked variations in precipitation and temperature, and that secular trends in streamflow in various parts of the West have sometimes paralleled one another and at other times have diverged. This behavior appears to be related to major shifts in regimes of the general atmospheric circulation.

Many semiarid areas now produce up to 10 percent runoff and the most arid areas produce less than 5 percent. When viewing either the past or future, however, it is difficult to estimate how much additional precipitation, lowering of temperature, etc., could increase runoff in terms of either percentage or absolute volume. Langbein et al. (1949) constructed an empirical diagram that allows one to estimate runoff variation in nonarid regions caused solely by temperature or precipitation change. The arid end of this diagram suggests that in an area now averaging 5 percent runoff, an 18 Fahrenheit degree (10 Celsius degrees) drop in temperature (weighted according to precipitation) would increase annual runoff by factors ranging from about 3 to 6; in the same area, a 50 percent increase in precipitation could increase runoff by a factor of about 5. The diagram also implicitly suggests that regions having 15 in. precipitation or less and mean annual temperatures of 60°F (15.6° C) or more produce no runoff until those threshold values are exceeded. Langbein et al. (1949) also notes that drainage areas having similar altitudes and precipitation, but different rock types, exposures, and vegetation, can have runoff percentages that differ by 15 percent or more. Schumm (1965) extends these relations to include areas characterized by 400 mm (15.74 in) or less precipitation, showing that increasing precipitation by 50 percent or more and decreasing temperatures by about 5 Celsius degrees could increase runoff by factors ranging from about 5 to 20. The total sediment outflow from a watershed is a function of soil resistance, basin topography, and plant cover. The outflow reaches a peak at an effective precipitation of about 300 mm (11.8 in.), trailing off at lower values due to increased vegetation cover that protects against erosion (Knighton, 1984). Further discussion of erosion at Yucca Mountain can be found in Chapter 1 and Section 8.3.1.6.

The study of Meko and Stockton (1984) demonstrates that long-term streamflow records corrected for diversion and consumption can be used to reconstruct synoptic climates for the western United States. The results of this study will be combined with further studies presented in Section 8.3.1.5.1 to assist with the reconstruction of past synoptic climates.

Evaporation from lake surfaces

As was discussed in Section 5.2.1.2.1, evaporation is the principal process for water loss from closed lake basins. Therefore, it is essential in paleolacustrine studies to determine the surface area of paleolakes in order to use the equivalence of evaporation to estimate total runoff (surface water and ground water) in the basin.

The most direct means of measuring paleolake area is to trace shorelines by detailed geologic mapping within the context of a well-dated stratigraphy. Studies of cores obtained from lake beds provide information throughout the depositional life of a lake, but single-point depth sampling does little to establish lake area and provides incomplete data on other lake characteristics. Subsurface sampling with good areal distribution and detailed dating and correlation of deposits allow the reconstruction of sedimentary environments from which shoreline positions and paleohydrologic conditions can be estimated. However, studies of this type are very expensive and should be justified only by clear expectations of significant increases to our knowledge of paleoclimates in the southern Great Basin.

Finally, variations in the size of a lake lead to changes in the chemical conditions and thermal structure of the lake. These changes in turn lead to changes in the structure of plant and animal communities confined to the lake environment. The chemistry of minerals precipitated from a lake is also a function of the temperature and the chemical composition of lake water. In some instances, therefore, lake size can be inferred within broad limits from the fossil and mineralogic record preserved within lake sediment.

To estimate the evaporative discharge from paleolake surfaces, factors other than lake size that influence the volume of evaporation must be considered. Many empirical methods have been developed for estimating evaporation from water surfaces using commonly measured meterological parameters, such as humidity or air temperature. Studies by Blaney (1957) concerning evaporation measurements at Lake Mead and Silver Lake are especially relevant to the review of the Yucca Mountain site because these lakes lie less than 200 km to the south. In both areas, annual lake surface evaporation exceeds 2 m. In reconstructing paleoclimates, several authors (Leopold, 1951; Broecker and Orr, 1958; Galloway, 1970; Mifflin and Wheat, 1979) have attempted to estimate the amounts of evaporation from various paleolake systems of probable late Wisconsin age. Approaches to the estimation of evaporation have been based primarily on estimates of maximum atmospheric temperature lowering during the last glacial or pluvial episode. Some authors used the lowering of past treelines as the evidence, while others used the past lowering of snowlines. These data were then used to estimate present and past temperature contrasts by assuming the constancy of lapse rates and the equivalence of free-air and ground-level rates, the mean and monthly distribution of the lowered temperatures, and the total dominance of air temperature over the other factors influencing evaporation rates. Later investigations have shown that these assumptions may lead to significant errors.

For example, Dohrenwend (1984) demonstrated that free-air lapse rates when measured at ground level are not necessarily representative of temperature variation with altitude. He proposed the following generalized model of temperature variation with altitude based on empirical data from eight mountain areas in the western United States: up to 300 m above basin floors, mean annual lapse rates are approximately zero; mean annual lapse rates are -0.057 K/100 m for 300 m to 2,000 m of additional altitude, and -0.76 K/100 m for altitudes greater than 2,000 m above basin floors. However, even if this lapse-rate model is correct, it may not be applicable to times of high lake level and mountain glaciation. During such times, temperature at high altitudes would be influenced by the nearby mass of glacial ice, and temperature above the lake would be influenced by the heat content of water stored in the lake so that both the highstand lake and the mountain glacier would buffer the lapse rate in their immediate vicinity. Thus, extrapolating snowline air temperature estimates to surface air masses located immediately above lakes situated on distant basin floors seems questionable.

Galloway (1970) collected a large base of data relating mean monthly evaporation to mean monthly temperature. As shown on Figure 5-13, for any mean monthly air temperature, the range of mean monthly evaporation is approximately 0.12 m. Although air temperature is an important factor affecting evaporation rates, several studies have shown that other factors are not insignificant. Recent investigations that will continue during the site-characterization phase (Section 8.3.1.2) include studies of the influence of water temperature, humidity, amount and nature of cloud cover, and amount of heat stored in lakes on evaporation rates. Investigations are also evaluating various other methods (covariance, aerodynamic, Dalton, energy-balance, and combination approaches) for calculating evaporation rates. For calculating the sensitivity of evaporation rate to variation in one or more commonly measured climate parameters, the energy-balance method appears the most promising. Each of the heat terms contained within the energy-balance equation has a theoretical or empirical relation to one or more commonly measured climate parameters. The method is theoretically sound, and when applied to computational periods greater than 1 week, satisfactorily estimates evaporation rates that are nearly the same as those obtained from water budget calculations (USGS, 1954). Historically, the energy-balance method has been the standard to which other evaporation computation methods have been compared. Wind speed does not appear explicitly in equations used in the energy-balance method.

Morton (1986) uses a method of computing evaporation that adjusts the humidity of air passing over a lake for the change that occurs as a result of evaporation from the lake surface. Lake size thus becomes a factor. Using the parameters noted above, plus altitude, depth, salinity, and available evaporation data, Morton (1986) calculates evaporation according to three models and compares them with water budget estimates. He lists monthly evaporation estimates for Winnemucca, Pyramid, and Walker lakes in the Lahontan Basin and for Utah and Great Salt lakes in the Bonneville Basin. Averages of the calculated annual rates using the two methods that include data on lake size differ at most by 7 percent from water-budget estimates; calculations using pan evaporation data without lake-size corrections produce estimates that are 51 to 67 percent greater than water-budget estimates. Therefore, pan evaporation data should be reduced by about 30 percent in estimating the evaporation from natural lake surfaces.

Table 5-12 is a compilation of equivalent annual lake-surface evaporation expressed as 70 percent of the pan evaporation values from three locations in Nevada: Boulder City, at the southern extreme; Fallon Experimental Station, near midlatitude Nevada; and Rye Patch Dam, in the northern part of the state. From the range of the mean annual rates (193.44 to 86.93 cm/yr),

Table 5-12. Annual equivalent lake surface evaporation data (calculated from pan evaporation data) in centimeters for three Nevada locations[a]

Year	Boulder City	Fallon Experiment Station	Rye Patch Dam
1984	209.23	87.24	64.15
1983	181.10	94.12	53.91
1981	194.66	103.98	70.62
1978	175.47	98.34	71.60
1977	177.02	107.70	71.51
1976	NA[b]	110.36	65.32
1975	189.78	111.24	75.98
1974	174.82	115.61	81.82
1973	183.13	166.13	81.91
1972	184.70	104.82	84.78
1971	186.30	102.93	72.02
1970	202.80	111.18	60.44
1969	195.29	115.13	65.47
1968	200.72	110.02	64.69
1967	194.06	108.82	67.01
1966	199.19	125.38	102.87
1965	186.38	108.83	61.68
1964	210.26	107.92	69.78
1963	178.70	104.26	74.34
1962	210.68	104.45	80.04
1961	200.91	111.85	71.48
1960	204.16	114.18	93.86
1959	203.22	115.02	73.65
1958	193.86	105.84	81.15
1957	192.72	101.74	87.84
1956	201.43	73.02	87.35
1955	199.12	84.46	97.48
1954	199.40	82.08	100.58
1953	203.75	94.98	94.59
1952	186.05	78.87	93.31
1951	193.77	87.32	115.74
1950	209.32	84.42	112.73
1949	194.68	87.28	109.97
1948	210.31	87.82	72.91
1947	208.25	95.44	112.88
1946	200.53	87.93	113.99
1945	193.33	76.45	111.03
1944	214.44	85.81	117.90
1943	217.29	91.91	129.49
1942	217.96	97.50	128.32
1941	183.41	89.11	122.37
1940	220.47	86.36	78.53
1939	206.79	75.94	NA
Mean annual	193.44	98.46	86.93

[a]Based on data from U.S. Weather Bureau, 1938-1965, and U.S. Department of Commerce, 1966-1984.

[b]NA = not applicable.

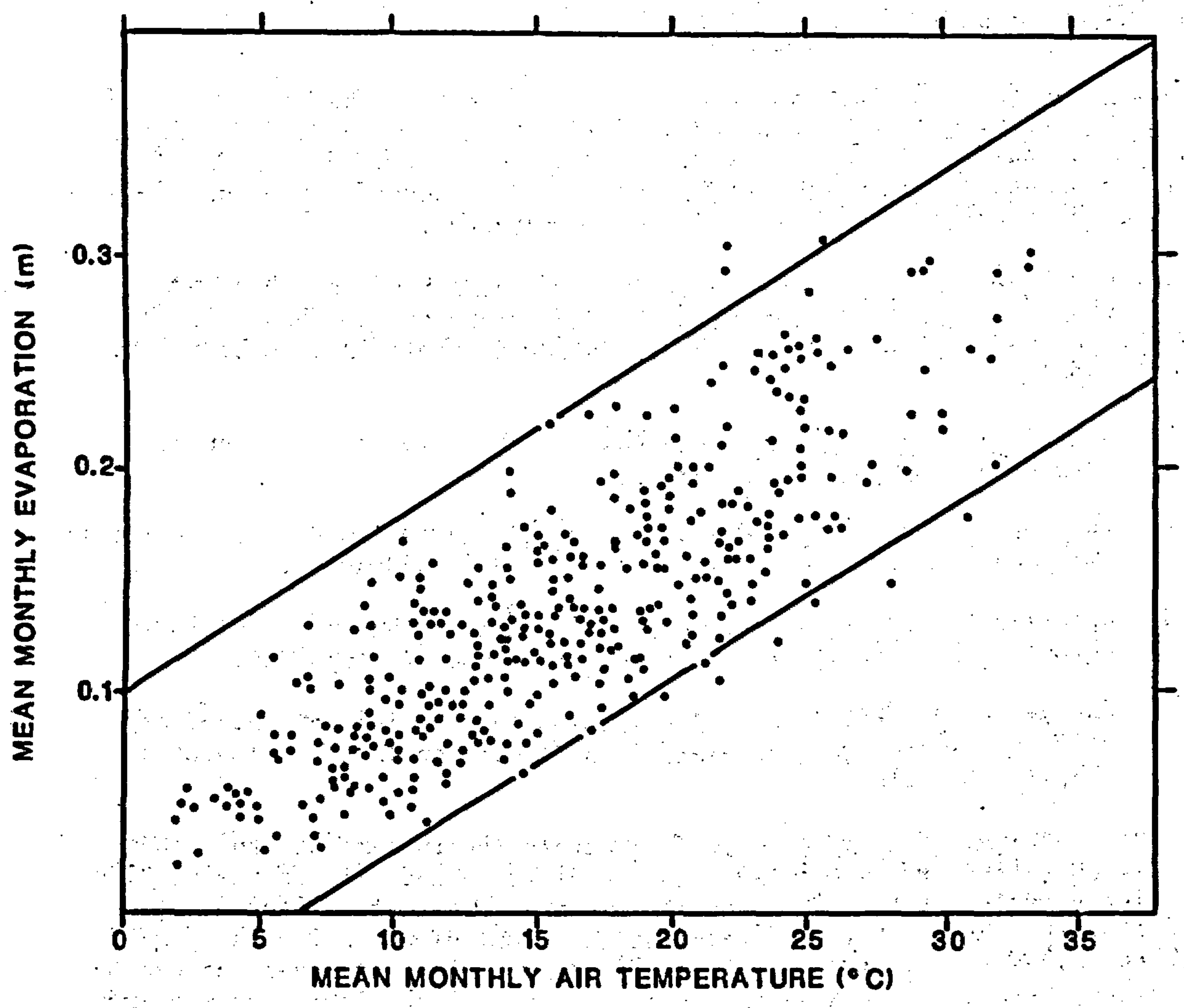


Figure 5-13. Relation of mean monthly evaporation and temperature in the western United States. Source: Galloway (1970).

it is evident that the climatic difference between southern and northern Nevada affects lake evaporation rates.

Using the Pyramid Lake, Nevada, area as a reference lake-climate system, the sensitivity of evaporation rate to change in each of six climate parameters will be investigated: (1) amount of sky cover, (2) type of sky cover, (3) air temperature, (4) water temperature, (5) dew point temperature (humidity), and (6) insolation at the top of the atmosphere.

Using established, empirical relations for components of the energy balance, the response of the calculated evaporation rate to change in the measurable climate parameters allows the following preliminary conclusions (Benson, 1986):

1. Evaporation rate strongly depends on the difference between air temperature and water temperature.

2. The use of insolation values for 12,000 and 18,000 yr ago results in small increases in the calculated rate of evaporation.

3. Relatively large absolute changes in relative humidity result in rather small changes in the calculated rate of evaporation.

4. Change in the fractional distribution and absolute amount of sky cover can bring about a significant reduction in the calculated evaporation rate.

These studies also tentatively demonstrate the fundamental role that reduced evaporation may have played in the creation and maintenance of high-stand closed-basin lakes such as Lake Lahontan. Using precipitation and runoff data for 1969, a particularly wet year, calculations for the period 14,000 to 12,500 yr ago indicate that evaporation must have been reduced to about 40 percent of its present-day value to support the large surface area of Lake Lahontan. Since this result rests on the assumption of a particular discharge rate, more work needs to be done to reconstruct actual discharge rates and thus test the importance of evaporation rate reduction in the creation of large lake systems.

Lake-level data

Historical records of lake-level change can be used to estimate times of climatic extremes. The surface altitudes of most of the lakes in the Great Basin before 1925 are only roughly known. Harding (1965) compiled existing lake-level data for Pyramid, Winnemucca, Walker, Mono, and Great Salt lakes. The data (Figure 5-14) indicate that before 1860 all lakes were at low levels. At that time, lake levels rose rapidly in all basins indicating a marked change in climate. From about 1870 until about 1915 most of the lakes were at high levels. After about 1915, lake levels began to decline, much of which probably can be ascribed to diversion and consumptive use associated with agriculture. The Great Salt Lake record shows a significant recent rise in lake level (Figure 5-14) due in part to an increase in precipitation (Arnow, 1984).

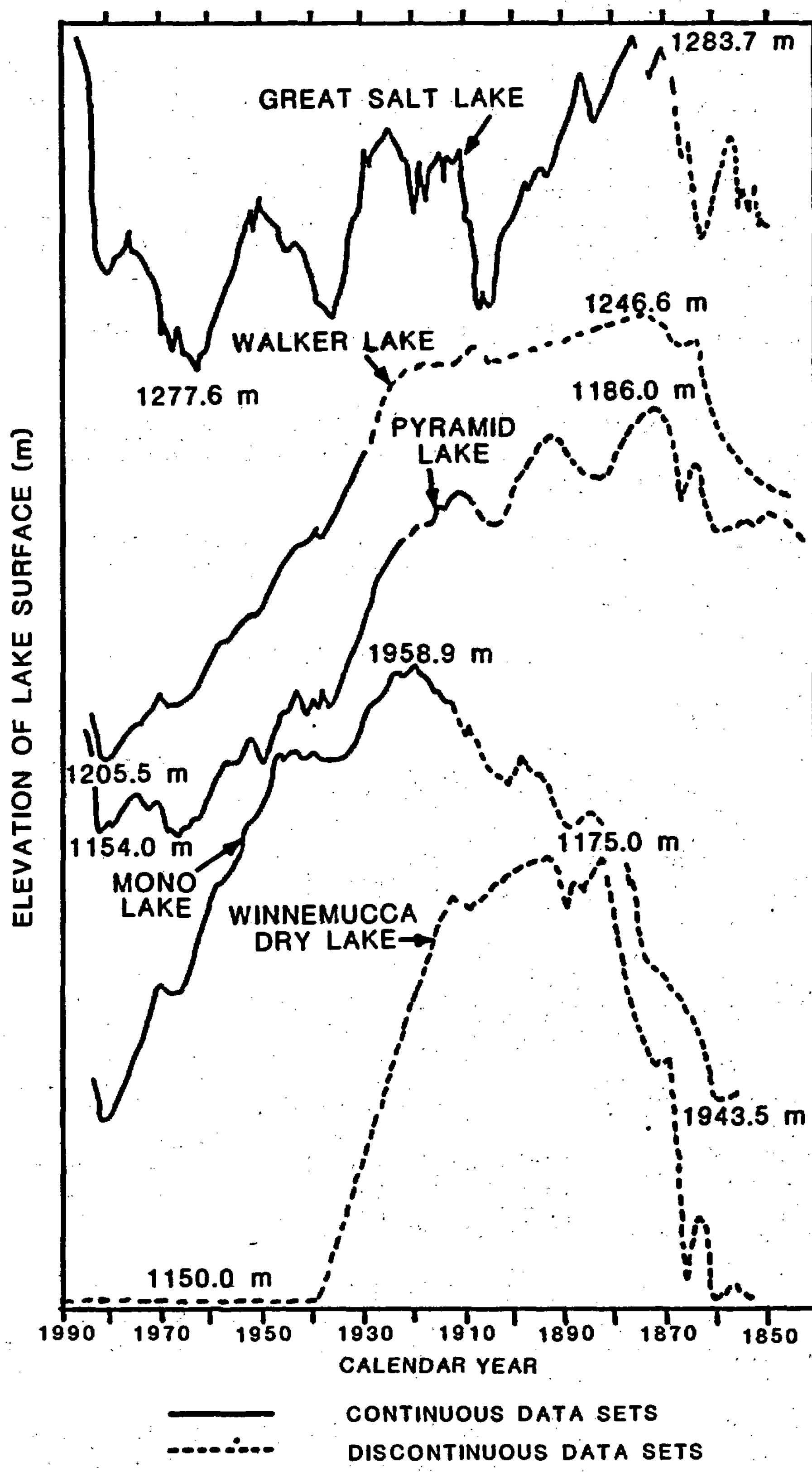


Figure 5-14. Historical fluctuations in the levels of Great Salt, Walker, Pyramid, Mono, and Winnemucca Dry lakes.

5.2.1.2.2 Prehistoric lake-level fluctuations

As discussed in Section 5.2.1.2.1, changes in the sizes of lakes occur as a result of changes in the regional hydrologic balance. The hydrologic balance of the basin in which the lake is located is, in turn, a function of climate. While several criteria can be used to reconstruct past changes in hydrologic balances, paleolake reconstructions may be the most relevant criterion because long-term changes in lake areas, to a large extent, reflect changes in the total amount of runoff (both by surface water and ground water) from the surrounding basins.

Records of prehistoric fluctuations in lake characteristics can be used to

1. Determine the nature of climate variability expressed as the hydrologic balance of a closed-basin surface-water system on the scale of 100 to 100,000 yr.

2. Provide information on the relationships between climatic variations reconstructed from other proxy data (such as paleobotanical records) and the hydrologic system.

3. Provide data necessary to validate climate models.

<u>Dating of paleolake deposits</u>

A chronology of variation in lake size can be obtained through the use of various methods of dating, including radiocarbon, chlorine-36, tephrachronology, uranium series, and magnetostratigraphy. Low lake levels in some closed basins can be identified by changes in the carbonate mineralogy or by the presence of salt layers, which indicate either desiccation or a shallow, saline lake.

Changes in the level and thus the size of a lake for the past 30,000 yr can often be determined by radiocarbon dating of materials, such as tufa or gastropods, deposited near the air and water interface near the paleoshoreline. Sediment cores recovered from the deepest portion of lake basins contain the remains of microscopic lacustrine plants and animals. Variations in the relative abundances and types of these organisms are a function of lake chemistry and physics and, to some extent, size. By examining the biotic content of cores taken from the deepest part of lake basins, it is possible to reconstruct continuous records of lake size over time periods possibly extending back to the beginning of the Quaternary.

Broecker and Orr (1958), Benson (1978), and Stuiver and Smith (1979) have outlined why the radiocarbon activities of lacustrine samples may not always be accurate measures of sample age. The radiocarbon activity can be affected by the following processes:

1. The introduction of carbon-bearing older detritus into a sediment sample, or the solution of that older detrital carbonates after deposition in the lake, altering the apparent age of its water.

2. Precipitation of younger secondary carbonate in the sample.

3. Recrystallization of metastable carbonate phases, exchanging carbonate in the process.

4. Mobilization and reprecipitation of inorganic carbon below the sediment and water interface.

5. Introduction into the lake of waters containing carbon-14, free bicarbonate, and carbonate leached from old carbonate rocks within the watershed (Broecker and Walton, 1959).

6. Nonequilibration between contemporary radiocarbon of the atmosphere and the carbon dissolved in the lake water. For example, Broecker and Kaufman (1965) report that modern Mono and Pyramid lake waters have apparent ages of 1,800 and 800 yr, respectively.

Distribution and age of paleolakes in the Great Basin

The pluvial lake systems in the Great Basin thought to be of Pleistocene age are shown in Figure 5-9. The names and summary hydrographic characteristics of these paleolakes have been given by Mifflin and Wheat (1979).

Only a few of the Great Basin paleolake systems have been sufficiently dated. Nonetheless, most of the radiocarbon dates point toward the existence of lakes in the basins within the last 30,000 yr.

Of the many basins, four of the paleolake systems (Bonneville, Lahontan, Russell, and Searles) have been intensively studied using radiometric dating techniques. Their chronologies for the past 20,000 yr are known well enough for the purpose of model validation. Of these systems, Russell and Searles are close to the Yucca Mountain region and near the same latitude.

Before discussing individual records of lake-level change, it is helpful to consider certain general relations between basinal topography and hydrology that influence the timing of lake-level change. During pluvial maxima, each of the lake systems consisted of a closed basin composed of one or more subbasins, separated from each other by sills (the lowest point on the divide separating adjoining basins or a series of separate basins connected by overflow). Today, some of these subbasins are fed by perennial streams and still contain lakes that rise and fall with changes in climate. Thus, it is the climate in the watershed area of the bordering mountain range that controls surface inflow to a subbasin, not the climate of the basin floor area. The climate of the basin floor area, however, determines the free-surface evaporation rate. The climates of both areas are influenced by the pronounced orographic effect that the Sierra Nevada and other high mountain ranges have on precipitation in the Great Basin (Maxey and Eakin, 1949).

The topography of a basin influences lake-level fluctuations. Lakes in small basins fed by perennial streams will change these levels rapidly in response to changes in moisture storage (influx minus evapotranspiration). Such lake systems are potentially excellent recorders of high-frequency, low-amplitude change in climate on the subregional scale. Lakes that lie in basins with large surface areas fed by perennial streams respond more slowly to changes in moisture storage. Also, the initiation of lake-level rise in a basin that receives surface inflow only when an adjoining basin overflows will lag the onset of lake-level expansion in that adjoining basin by the amount of time it takes the source basin to fill to its sill level. Thus, change in the size (elevation, volume, surface area) of a lake in any particular subbasin or series of basins can be a complicated function of intrabasin climate, extrabasin climate, and basin topography. In settings where adjoining basins coalesce at some level, the combined lakes act as a single body of water responding in an integrated manner to changes in the regional climate.

The records of the four paleolake systems that have been intensively studied are discussed in the following paragraphs.

Lake Bonneville system. Lake Bonneville, located in western Utah (Figure 5-15), had a surface area at its highest stage of about 52,000 km^2, a volume of 7,500 km^3, and a maximum depth of 335 m (Smith and Street-Perrott, 1983); it occupied two main subbasins: Salt Lake subbasin and the Sevier subbasin. Today, runoff contributes about 66 percent, direct precipitation about 31 percent, and ground water about 3 percent of the average influx to Great Salt Lake, the largest present-day manifestation of Lake Bonneville.

Numerous workers have contributed to the knowledge of Lake Bonneville since the classic study of Gilbert (1890). Until recently, the interpretations of Morrison (1965) and Morrison and Frye (1965) were probably cited most frequently, although Eardley et al. (1957), Broecker and Orr (1958), and Broecker and Kaufman (1965) were cited in more complete reviews of the literature. Within the last few years, stratigraphic and chronologic investigations have made extensive use of dating techniques that were not available to earlier studies of Lake Bonneville. These recent studies have given rise to a substantially modified interpretation of fluctuations in the level of Lake Bonneville. The Lake Bonneville chronologies of Currey and Oviatt (1985), Spencer et al. (1984), Scott et al. (1983), and Morrison (1965) are shown together in Figure 5-16. Because of the large distances separating study localities, physically tracing and correlating units is difficult because of disconformities, abrupt facies changes, and similarities in the appearances of deposits from different lake cycles. Scott et al. (1983) relied mainly on analyses of amino acid in shells and radiocarbon dating of wood for correlation, and samples from deposits of uncertain origin were assigned to a specific lake cycle on the basis of the similarity of their alloisoleucine to isoleucine ratios relative to ratios of samples whose relative ages had been determined by other means.

Lake Lahontan system. The Lahontan basin consists of seven subbasins separated by sills of differing altitudes (Figure 5-17). Of the six rivers that terminate in Lahontan subbasins, four (Truckee, Carson, Walker, and Humboldt) presently contribute 96 percent of the total gaged surface inflow (Benson, 1986). The Truckee, Carson, and Walker rivers have their headwaters in the Sierra Nevada, west of the Lahontan basin. The annual flows of these three rivers are highly correlated with each other (Benson, 1986). The Humboldt River has its headwaters in mountain ranges east of the basin. Lake Lahontan, at its highest stage 13,000 yr ago, had a surface area of about 22,300 km^2, a volume of 2,130 km^3 (Benson, 1978), and a maximum depth of 280 m in the Pyramid Lake subbasin (Smith and Street-Perrott, 1983).

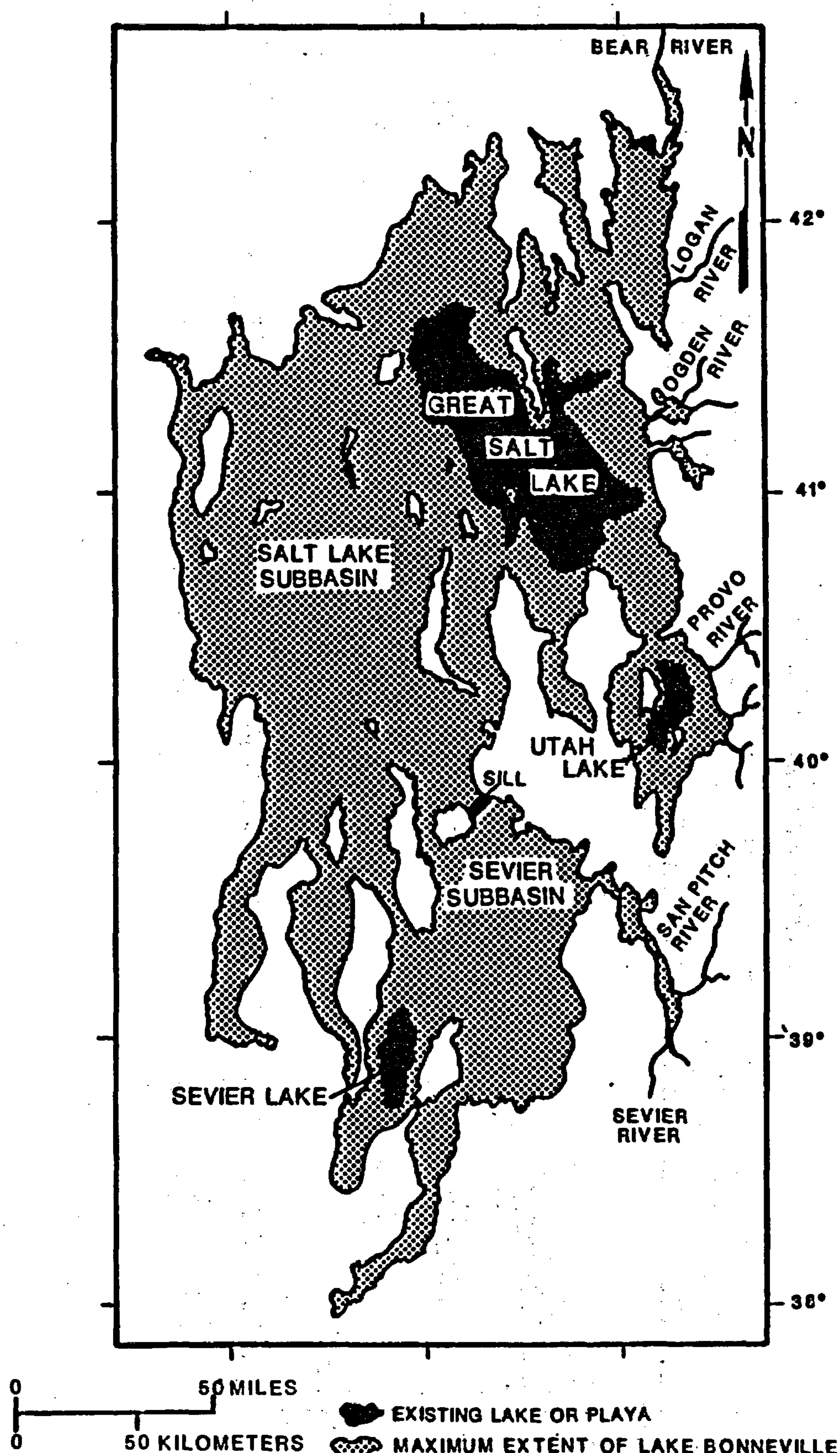


Figure 5-15. Lake Bonneville subbasins. Source: Morrison (1965).

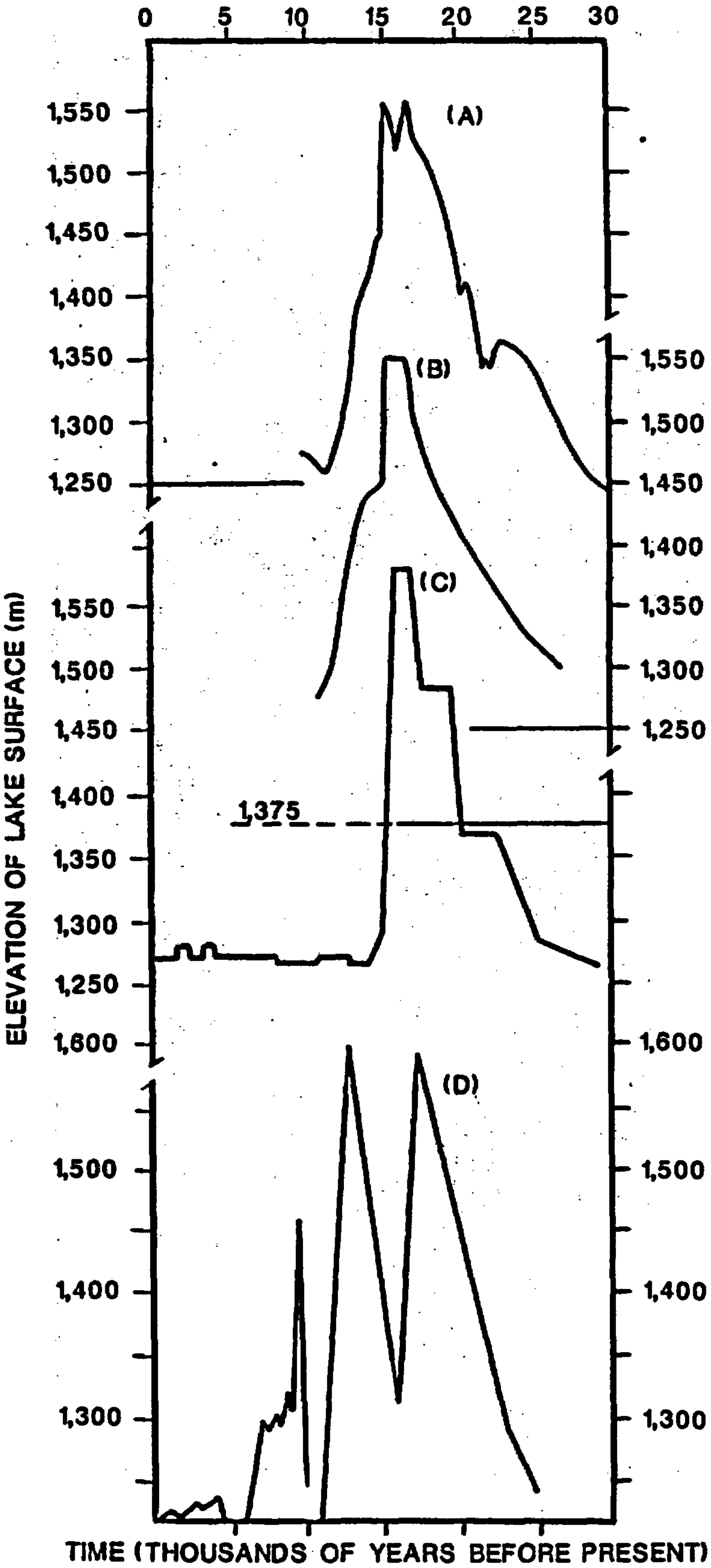


Figure 5-16. The last cycle in the lake Bonneville Basin as interpretated by (a) Currey and Oviatt (1985), (b) Scott and others (1983), (c) Spencer and others (1984), and (d) Morrison (1965).

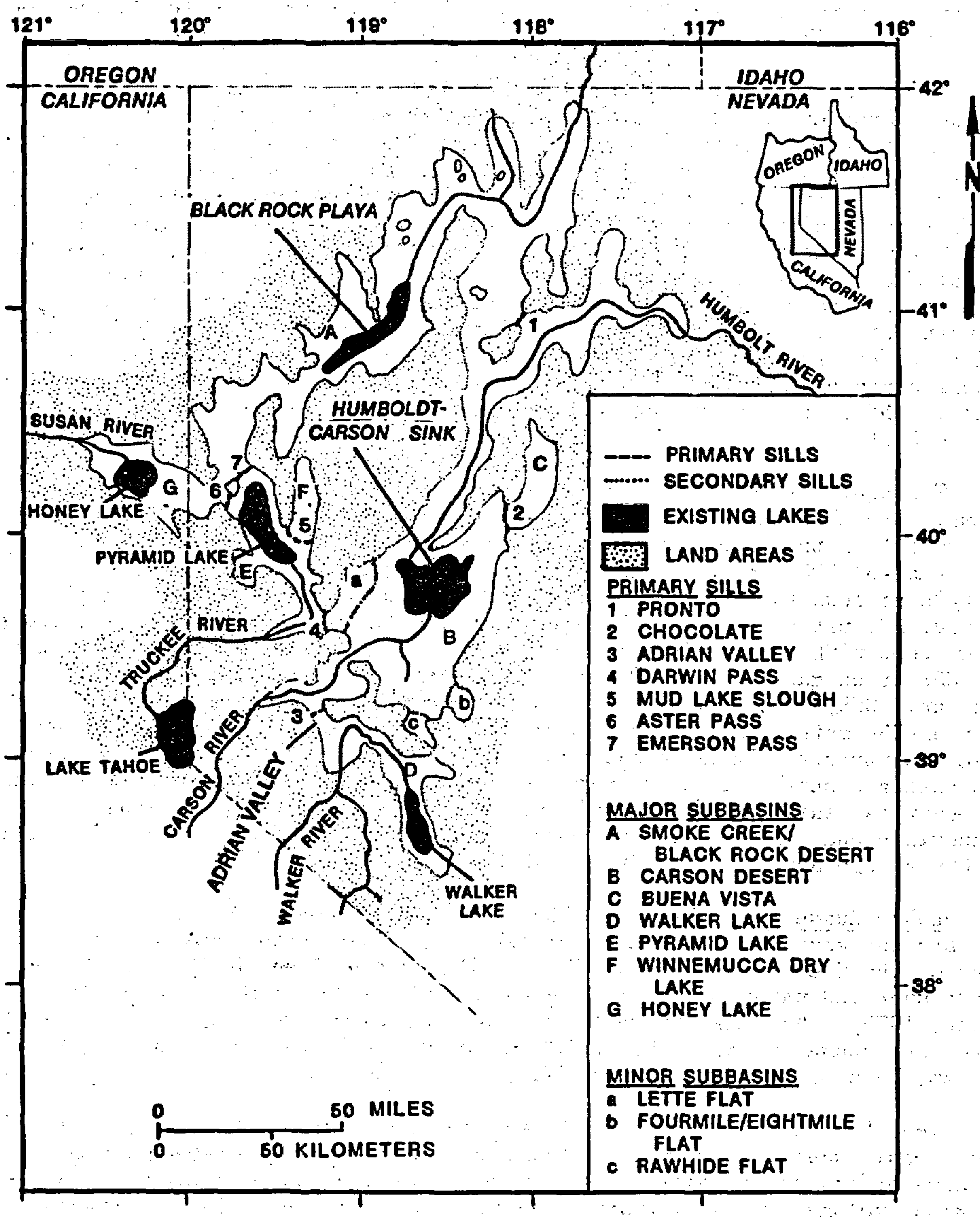


Figure 5-17. Surface extent of Lake Lahontan and geography of its basin 14,000 to 12,500 yr before present (modified after Benson and Mifflin 1986).

The amount of subsurface inflow to present day surface-water bodies in the Lahontan basin is thought to be very small compared with the total amount of water reaching lakes, sinks, and playas in the form of runoff and precipitation (Everett and Rush, 1967). Surface flow accounts for about 85 percent of that total (Benson, 1986).

The first comprehensive study of Lake Lahontan was done by Russell (1885). Broecker and Orr (1958) and Broecker and Kaufman (1965) made the first systematic attempts to assign an absolute time scale to Lake Lahontan history. Morrison and Frye (1965) noted that certain tufa radiocarbon dates were reversed in relation to Morrison's (1964) stratigraphic assignments, which were developed without the benefit of radiocarbon dating. Benson (1978) developed a lake-level chronology for the Pyramid and Walker lake subbasins that used a sample selection procedure that helped to eliminate problems caused by the introduction of secondary carbon into tufa samples. Thompson et al. (1986) presented a chronology for the last Pleistocene lake cycle in the central Lahontan Basin, based on radiocarbon dates and tephrachronology. Their data, together with the data of Born (1972) and Benson (1981), have been used to form the Lahontan lake-level chronology of Figure 5-18.

The age of older lacustrine deposits in the Lahontan Basin is not well known. Broecker and Kaufman (1965) dated several samples of gastropod shells and tufa from those deposits. Radiocarbon activities indicated ages in excess of 34,000 yr. Subsequent age determinations on gastropod shells containing less than 5 percent secondary calcite, using the thorium-230/uranium-234 method, resulted in ages near 120,000 yr. These ages are broadly consistent with thorium-230/uranium-234 ages of about 92,000 and older than 100,000 yr on gastropod shells from the Bonneville Basin (Broecker and Kaufman, 1965). Difficulties associated with applying the thorium-230/uranium-234 method to carbonate samples found in closed basin lake systems preclude strict reliance on age dates determined using this method. However, the data are sufficient to suggest the adoption of a working hypothesis that at least two lake cycles occurred more or less synchronously in both the Bonneville and Lahontan lake basins during the time intervals from 120,000 to 90,000 yr ago and from 25,000 to 12,500 yr ago.

<u>Lakes Russell and Searles</u>. The Owens River system in the late Pleistocene consisted of a chain of lakes occupying a succession of basins east of the Sierra Nevada in California (Figures 5-19 and 5-20). The Owens River supplied water to the lakes downstream from its terminus (Gale 1914; Smith, 1979). When Lake Russell in Mono Basin overflowed, its surplus flowed into the headwaters of the Owens River. Only two of the seven lakes in this system, Russell and Searles, have been studied in detail.

Mono Lake and its ancestral Lake Russell lies in a relatively steep-sided basin separated from Adobe Lake and the Owens River drainage by a sill. Because of its morphology, the lake responds in a sensitive manner to changes in water volume and is potentially an excellent recorder of high-frequency, low-amplitude climatic events that take place in its watershed. Lajoie (1963) made a detailed stratigraphic study of the lake sediments, the chronology of which has been supported by radiocarbon dates on ostracodes and tufa

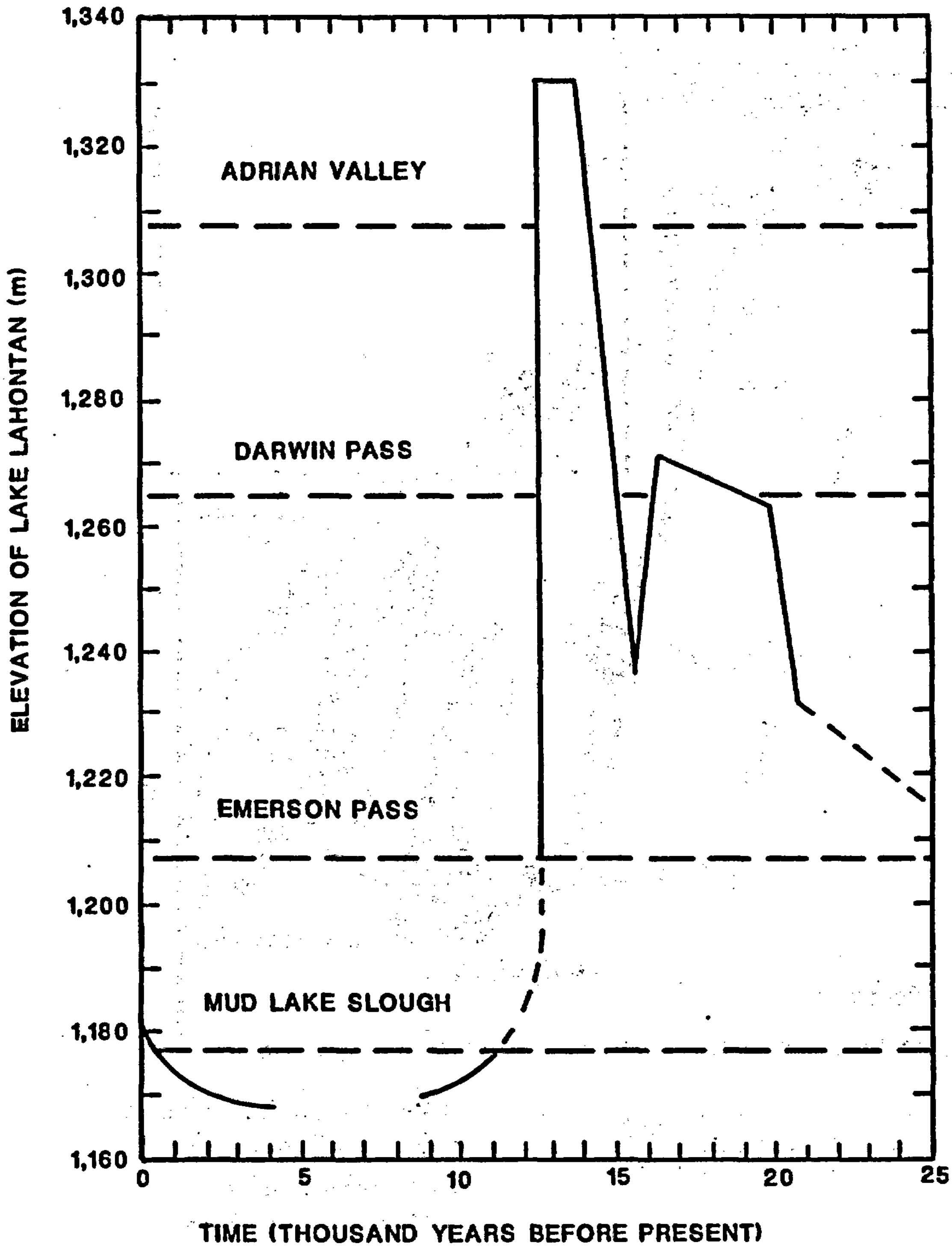


Figure 5-18. Lake Lahontan chronology inferred from data of Born (1972), Benson (1981), and Thompson et al. (1986).

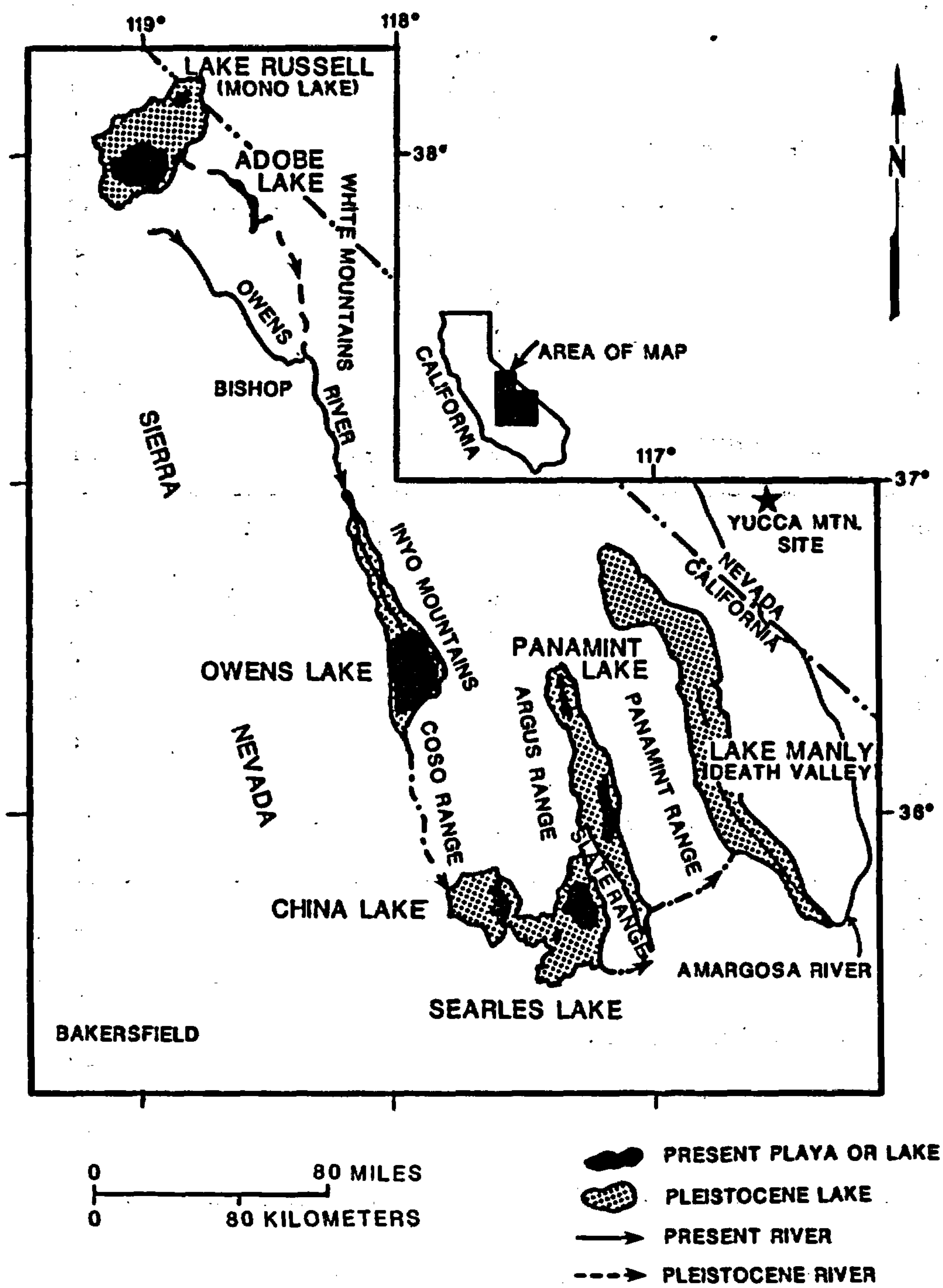


Figure 5-19. Location of lakes in the Owens River system during pluvial periods in the late Pleistocene (modified after Smith, 1979).

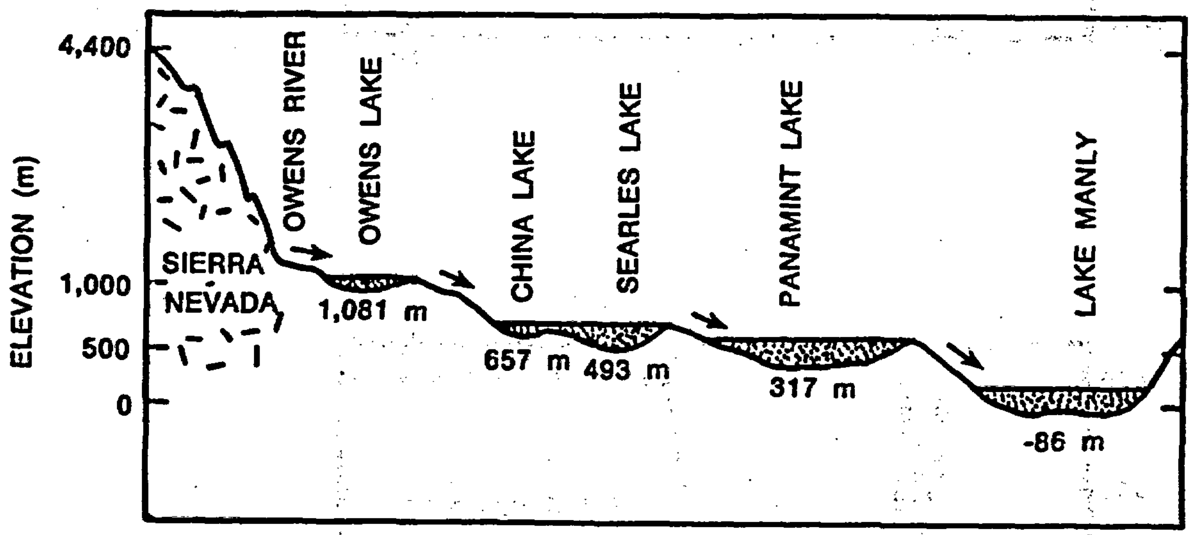


Figure 5-20. Overflow sequence of lakes in the Owens River system (modified after Gale, 1914).

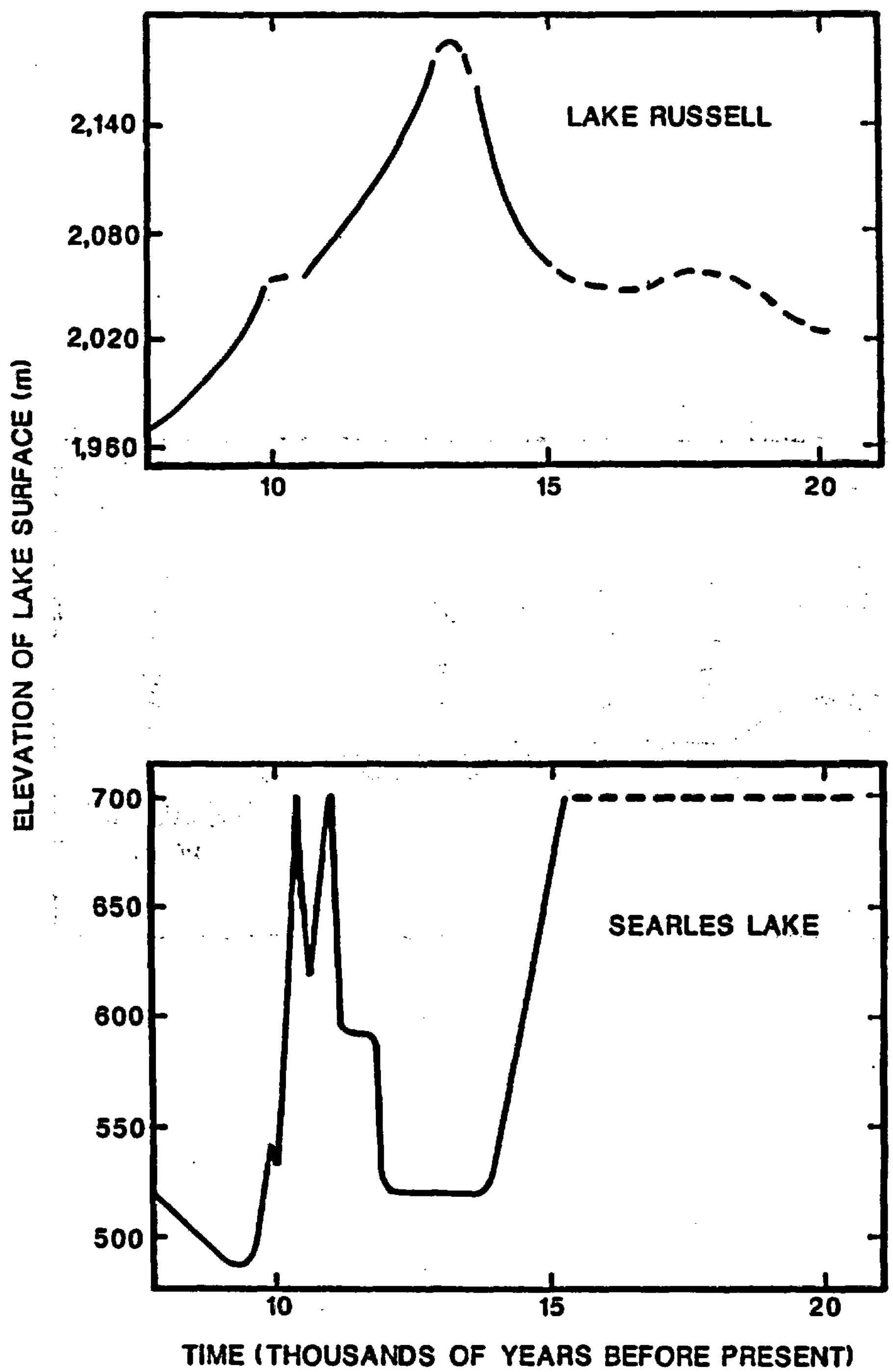


Figure 5-21. Chronologies of lakes in the Russell (Mono) and Searles basins (after Smith and Street-Perrott, 1983, Figure 10-5).

and by tephrachronology. Reconstruction of the lake-level history of Lake Russell for the past 20,000 yr is shown in Figure 5-21. The lake-level chronology depicted in Figure 5-21 is noteworthy in that it closely resembles the Lahontan chronology, Figure 5-18.

The other lake in the Owens River system that has been intensively studied is Searles Lake (Smith, 1979; Stuiver and Smith, 1979). During the late Pleistocene, Searles was third in a chain of lakes that received water from the Owens River. When Owens filled to a level of about 60 m, it overflowed into China Lake; when China Lake filled to a depth of 12 m, it overflowed into Searles Lake; and when Searles Lake reached a level of about 200 m it coalesced with China Lake and overflowed to create a relatively shallow lake in Panamint Valley. During pluvial periods of earlier Pleistocene times, Panamint Lake overflowed into Lake Manly (Death Valley), which was also the terminus of the Mojave and Amargosa rivers (Figure 5-20).

The chronologies of Searles Lake and Lake Russell for the past 20,000 yr are shown in Figure 5-21. The mismatch between the highest stands of Searles Lake and Lake Russell during the time period 20,000 to 11,000 yr ago might be explained in one of the following ways:

1. The data or the data interpretation of one or both of the lake chronologies may be in error.

2. The timing of lake-level fluctuations in the Searles Basin may have been delayed by the cumulative times required for basins upstream in the Owens River system to fill to overflowing or to cease flowing.

3. Both chronologies are basically correct, but there may have been a distinct north-south climate gradient between the watersheds that supply each of the lakes, with each watershed responding to the changing distribution of Pacific sea-surface temperatures in different ways and at different times.

The Searles Lake chronology for the past 30,000 yr, unlike the Russell, Lahontan, and Bonneville chronologies, is based about equally on radiocarbon analyses of samples from both outcropping sediments and core materials, but lacustrine materials of both types carry uncertainties about their carbon-14-based ages. An example from the subsurface record at Searles Lake (Stuiver and Smith, 1979) illustrates the difficulties inherent in all carbon-14 dates from materials deposited in lakes and why differences in chronologies of a few thousand years should not be necessarily viewed as significant. Of the four radiocarbon dates on disseminated organic carbon and wood from the overburden mud (Figure 5-22), Stuiver and Smith (1979) concluded that only the single date on wood was reliable. They reasoned that the unit was deposited in a much smaller lake than were most mud units in this basin, and large areas of older lake beds that contained carbon and carbonate minerals were being eroded, thus contaminating the units being deposited and creating the 3,000-yr discrepancy between the date on wood from this unit (3,520 ± 190 yr) and the older date on detrital carbon from a nearby horizon. A discrepancy having the same magnitude and direction is found between the dates on wood and organic carbon in a mud layer in the Lower Salt (Figure 5-22).

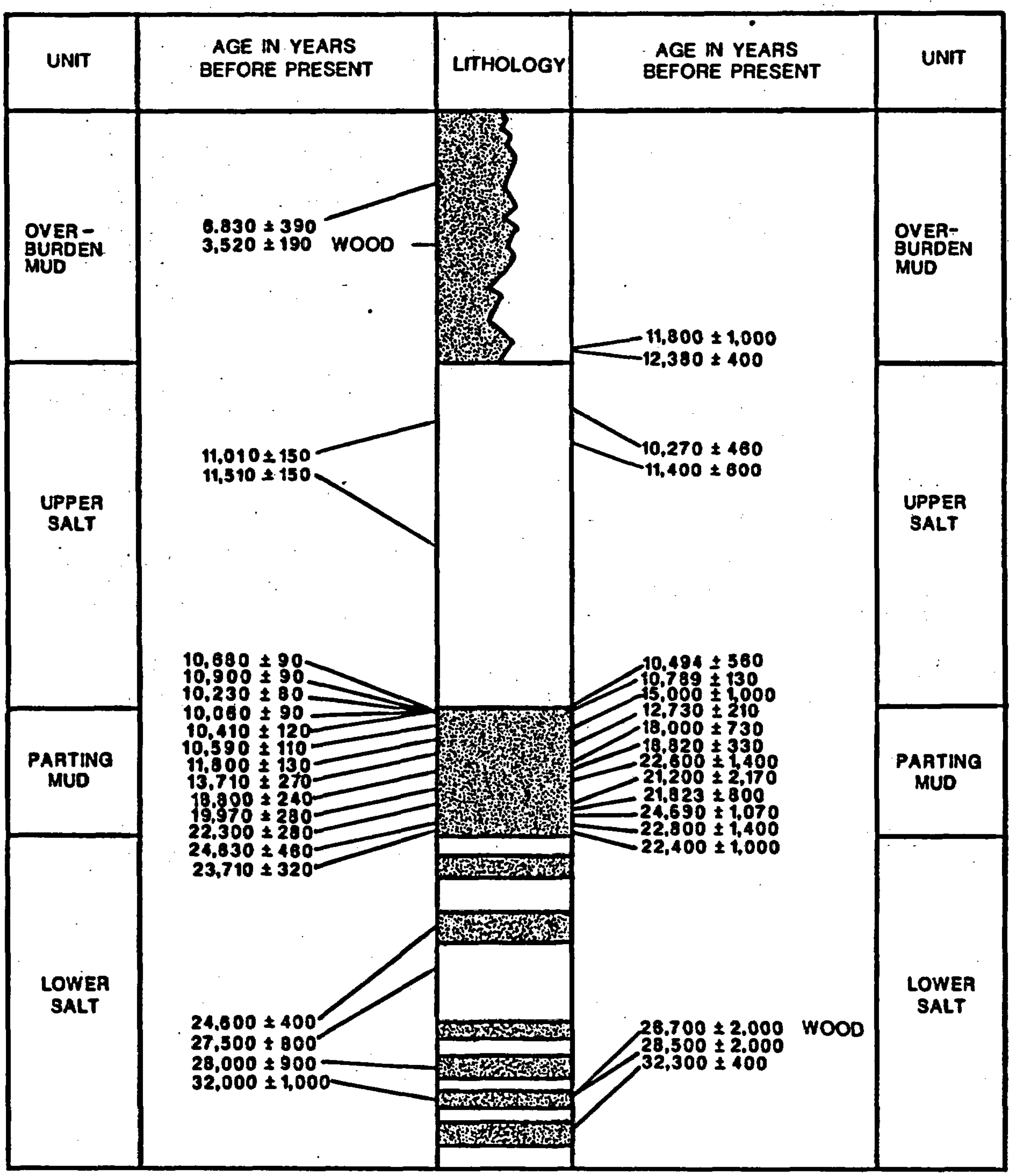


Figure 5-22. Summary of carbon-14 dates on subsurface samples composed of organic carbon and wood from Searles Lake (from Stuiver and Smith, 1979, Figure 30).

Figure 5-21 indicates that Lake Russell experienced a high lake cycle beginning at about 15,000 yr ago and ending about 12,000 yr ago. The lake peaked from about 14,000 to 13,000 yr ago and may or may not have spilled. The Searles record (Smith and Street-Perrott, 1983) shows a strong increase in lake size starting at about 12,500 yr ago. While carbon-14 dates from these areas could be in error, they appear to be substantially correct, and the presence of the brief period of high lake stands between about 12,500 and 10,500 yr ago in Searles is suggested by an episode and age assignment supported by extensive stratigraphic and radiometric dating evidence (Smith and Street-Perrott, 1983).

The broad agreement between the Bonneville, Lahontan, and Russell records--disregarding the differences of a few thousand years in peak stages--suggests that they all occupied a zone that shared a similar climatic history. The similarity between historical records from Great Salt, Walker, Pyramid, Mono, and Winnemucca lakes (Figure 5-14) supports this view. The strong evidence for a different history for lakes in the Owens River system, derived from Searles Lake, creates doubts as to the comparability that should be expected between the climatic histories of the two regions. The similarities in the latitudes (37°) of the Yucca Mountain site and the segment of the Sierra Nevada that contributed most of the runoff to the Owens River system and Searles Lake supports the notion that the Searles Lake history is the better of the pluvial lake records for the evaluation of future climatic change in the Yucca Mountain area.

Death Valley drainage system. During portions of the Pleistocene, Death Valley received surface water flow from the Owens River system (described previously), surface water from the Mojave River drainage, and surface flow and ground water from the Yucca Mountain region. Because of this latter hydrologic tie to the NTS, geologic records from Death Valley are relevant to site characterization activities in paleohydrology, as well as paleoclimatology. Additional discussions are found in Sections 3.7.4.1 and 3.7.4.5.

Because of the poor preservation of shoreline features, relatively little is known about the age and depth of the Pleistocene Lake Manly in Death Valley. Gravel and beach deposits of possible shorelines occur at heights more than 200 m above the basin floor; however, the estimates of the age of these sediments range from Pleistocene (Butler, 1986) to early Wisconsin (Hunt and Mabey, 1966). Radiocarbon dates on organic lake sediments from the last major lake cycle suggest that a deep water lake existed in Death Valley from 26,000 to 10,000 yr B.P. (Hooke, 1972).

In opposition to the above interpretation, Butler (1986) argued that terraces and uplifted alluvial fans in the elevational range from sea level to 120 m have never been covered by lake waters, and thus lake highstands have not occurred in Death Valley since the Pleistocene. However, even if Butler is correct, a lake of up to 86 m in depth could have been present (existing completely below sea level) in Death Valley during portions of the late Pleistocene. Craig (1984) used computer simulations to demonstrate the feasibility of past lake stands in Death Valley, given a range of past conditions of increased runoff or reduced evaporation or both. Dorn et al. (1987) interpreted isotopic evidence from rock varnish on alluvial fans in

Death Valley as indicating the past occurrence during the late Pleistocene of three periods of relatively more humid conditions separated by intervening arid intervals.

The Pleistocene Lake Mojave was present in what are now the Silver and Soda Lake playas in the Mojave River drainage, which drains into Death Valley from the south. Ore and Warren (1971) interpreted geomorphic features and radiocarbon dates on shell and tufa as indicating the following chronology:

1. A major lacustral episode, which reached the overflow level, ending approximately 14,500 yr B.P.

2. A second lacustral episode, which reached the same level, occurring between approximately 13,750 and 12,000 yr B.P.

3. A third lacustral episode, during which, the outlet was downcut, occurring between approximately 11,000 and 9,000 yr B.P.

4. A final lacustral episode, estimated to have occurred between approximately 8,500 and 7,500 yr B.P., was of lesser magnitude and did not overflow the outlet.

Further studies by Wells et al. (1984, 1987) provide additional radiocarbon dates that substantiated the late-Pleistocene portion of the chronology presented above, although these authors suggest that due to bedrock control at the outlet, relatively continuous highstand conditions (with only minor fluctuations in level) occurred between 15,500 and 10,500 yr B.P. These authors also question the dating of the lowest and youngest lake stand, and estimate its age to fall between 10,500 and 8,000 yr B.P. and suggest that it was a short-lived phenomenon (less than a few hundred years in duration). Wells et al. (1987) found evidence of larger than modern flood events in the early and middle Holocene and interpreted these deposits as indicative of intensified monsoonal conditions.

Banks of lake sediments up to 68 m thick are present in the Lake Tecopa basin in the Amargosa River drainage, which flows from the Yucca Mountain area to Death Valley (Sheppard and Gude, 1968). These lake beds are estimated to be of no greater than mid-Pleistocene age and were deposited in alkaline saline waters.

Marshes deposits in Southern Nevada. No evidence has been found of deep water lakes of late Wisconsin age in the Mojave Desert portion of southern Nevada (Mifflin and Wheat, 1979). Instead, the ground-water-fed marshes and wet meadows present in the early historical period were greatly expanded in distribution and in areal coverage. Stratigraphic studies at Tule Springs (Haynes, 1967) and Corn Creek Flat and Indian Springs (Quade, 1985) indicate that marshes and associated shallow lakes reached their maximal extent between 30,000 and 15,000 yr B.P. A progressive desiccation of the marsh-lake complexes occurred between 13,500 and 8,000 to 7,200 yr B.P. After this time perennial water was absent, and the sediments deposited under the moister Pleistocene and early Holocene conditions became dissected. At Corn Springs Flat, the modern water table in the valley center is more than 25 m below the level at 8,500 yr B.P., when it was near the ground surface.

Mehringer and Warren (1976) constructed a radiocarbon-based chronology of changes in marsh coverage and dune migration over the last 5,300 yrs at Ash Meadows, in the Amargosa River drainage south of Yucca Mountain. Peat formation occurred between 5,300 and 4,500 yr B.P. on top of older dune sands. Dune sand covered the site from 4,500 to 4,000 yr B.P., followed by peat development between 3,000 and 2,000 yr B.P. Net deflation occurred between 2,000 and 400 yr B.P., when peat deposition resumed.

Ground water near Yucca Mountain. Radiocarbon dating of ground water in the Amargosa Desert (Claassen, 1985) and at Yucca Mountain (Benson et al., 1983; Benson and McKinley, 1985) indicates that the majority of the recharge that led to the accumulation of these waters occurred between 20,000 and 12,000 to 10,000 yr B.P. Some of the ground-water ages suggest that significant recharge may also have occurred between 35,000 and 30,000 yr B.P. and during the early Holocene. These radiometric dates provide evidence that the paleoclimatic conditions responsible for Pleistocene lake high stands also had significant effects on the hydrologic regime of Yucca Mountain.

Summary of paleolacustrine data

Available information indicates the presence of more than one lake cycle in the Great Basin during the past 150,000 yr. The last cycle that occurred during the late Pleistocene is well documented in the Bonneville, Lahontan, Mono, and Searles basins. Older cycles in both the Bonneville and Lahontan basins are less adequately documented (in terms of absolute age determinations), but one cycle may have occurred 115,000 ± 15,000 yr ago. In Searles basin, the nearly continuous existence of perennial bodies of water, over a period extending from 130,000 to 10,000 yr ago, interrupted by only brief periods of salt deposition, is documented by a wealth of subsurface data (Smith, 1979), supplemented by carbon-14 (Stuiver and Smith, 1979) and uranium-series dating (Bischoff et al., 1985). A large number of basins throughout the Great Basin that today are playas or dry lakes contain shoreline evidence of more than one former lake cycle. Radiocarbon analyses of material from these basins indicate that the youngest shoreline probably corresponds to a lake cycle that occurred in the late Pleistocene. The ages of the older shorelines are not known.

5.2.1.2.3 Time series of prehistorical vegetation change

Paleobotanical data provide the most widespread and continuous records of paleoclimatic change available in this region. Paleobotanical assemblages can be reliably dated, a necessary requirement for modeling. However, since radiocarbon dating is one of the only means of determining ages of most paleobotanical materials, this powerful tool can be applied widely only in studies of late Wisconsin climates (<40,000 yr). Spatial variations in modern climate in the Yucca Mountain region are reflected in the abundances and distributions of plant taxa. Adequate reconstruction of paleobotanical assemblages is, in part; dependent on understanding the variations in the abundance and distribution of modern plant taxa (Spaulding, 1983). Transfer function and response surface techniques will be used to produce quantitative estimates of past precipitation, temperature, and other climatic parameters.

These estimates, in turn, will be used in the testing and validation of climatic models.

Plants react in various ways to variations in climate on many time scales. Annual or seasonal climatic fluctuations affect the growth rates of plants and may be recorded in the width of annual growth rings in mature trees. Dendroclimatological methods have been used to extract climatic data from tree-ring series covering the last 300 to 5,500 yr (LaMarche, 1974) in the western United States. Changes in the patterns of vegetation also reflect larger scale and longer term climatic changes. Pollen and pack rat midden studies have provided proxy paleoclimate data forming the basis for the preparation of maps or tables of vegetation types. These data imply certain ranges of paleoclimate. Longer term (and larger scale) climatic fluctuations can thus be deduced using radiocarbon-dated pollen profiles and pack rat (Neotoma) middens. Paleobotanical data are available from the region surrounding Yucca Mountain as plant macrofossil assemblages from pack rat middens from dry caves and rockshelters and as fossil pollen from lake and marsh sediments. The temporal resolution of the paleoclimatic reconstructions from these data will potentially be limited by the sampling interval for pollen data from lacustrine cores and by the availability of pack rat middens representing the time periods of interest. In the case of palynological data, studies of the pollen content of lake sediments in the Great Basin have had sampling intervals (in temporal terms) of 200 to 1,000 yr (refer to Thompson (1984) for examples). This sampling interval would permit the reconstruction of paleoclimatic fluctuations with a period of 200 to 1,000 yr. The temporal resolution for pack rat midden studies will probably be lower, and it will probably not be possible to confidently reconstruct fluctuations with periods of less than 1,000 yr using pack rat midden data.

Rationale

Studies of past changes in vegetation can be used in the following aspects of paleoclimatology:

1. To determine the nature, range, and frequency of past climatic variability.

2. To provide well-dated paleobotanical time series for the testing and validation of climatic models. These time series provide two types of necessary information:

   a. Long continuous records reflecting low-frequency climatic changes that can be used to reconstruct the slowly varying aspects of climatic change.

   b. A network of sites to test synoptic scale predictions of the more rapidly varying aspects of the models.

Modern vegetation and climate

The sensitivity of plant distributions to geographic and elevational variations in climatic parameters provides a basis for the interpretation of past climatic fluctuations from changes in vegetational records.

The distributions and associations of plant species in the region surrounding Yucca Mountain are greatly influenced by variations in climate, especially temperature and precipitation. For example, the geographic distribution of summer rainfall appears to influence the regional distributions of pinyon pine (Pinus monophylla), Utah juniper (Juniperus osteosperma), ponderosa pine (Pinus ponderosa), and other woodland and montane plants (Houghton et al., 1975). Temperature extremes may also limit the distributions of certain plants. For example, the geographic and elevational limits of many woodland species may be controlled by the extent or duration of winter frosts (Houghton et al., 1975).

On a more local level, plant taxa are segregated into elevational zones that reflect the effects of environmental lapse rates on the elevational distribution of temperature and precipitation (Houghton et al., 1975; Figure 5-23). In the Great Basin the general progression is from shadscale desert on the hot arid valley bottoms, through sagebrush steppe on bajadas and mountain slopes, pinyon-juniper woodland and upper sagebrush grassland at intermediate elevations, to subalpine conifer forest at or near the mountain summits. An exception to this pattern is found in mountain ranges of the northwest Great Basin, where there is even less summer rainfall. Here, sagebrush dominates the entire elevational range. The mountains of the eastern Great Basin that receive more summer precipitation than ranges farther west support ponderosa pine, douglas fir, and other montane plants at middle elevations.

A similar zonation of plant communities occurs in the Mojave Desert. The valley bottoms in this region are lower, hotter, and drier than those of the Great Basin. Mojave desert scrub communities, usually dominated by creosote bush (Larrea divaricata), joshua tree (Yucca brevifolia), and Mojave yucca (Yucca shidigera), occur in these arid settings.

Dendroclimatology

Past variations in tree-ring widths reflect interannual and even seasonal fluctuations in climate on the scale of 10 to 1,000 yr that can be precisely dated to the year or season of occurrence through dendrochronological techniques within a single climatic province (Brubaker and Cook, 1983). A network of 65 carefully selected tree-ring chronologies has been used to reconstruct synoptic scale variations in western climate for the period 1600 to 1960 (Brubaker and Cook, 1983). These reconstructions suggest that while other portions of the northern hemisphere were relatively cool (compared with 20th century means) from 1600 to 1900, the western United States, and in particular the Great Basin, was warmer during this earlier period than during this century (Brubaker and Cook, 1983). An important insight from this research is that the climatic variations in the West may not simply follow mean global or hemispheric trends.

LaMarche (1974) provides another example of paleoclimatic reconstruction from a tree-ring chronology of the bristlecone pines (Pinus longaeva) in the White Mountains of California. LaMarche reconstructed variations in warm-season temperatures over the last 5,500 yr. LaMarche (1974) describes climatic variations qualitatively (e.g., cooler and wetter) but does not quantify the variations from tree-ring data alone. Analysis of mean tree ring

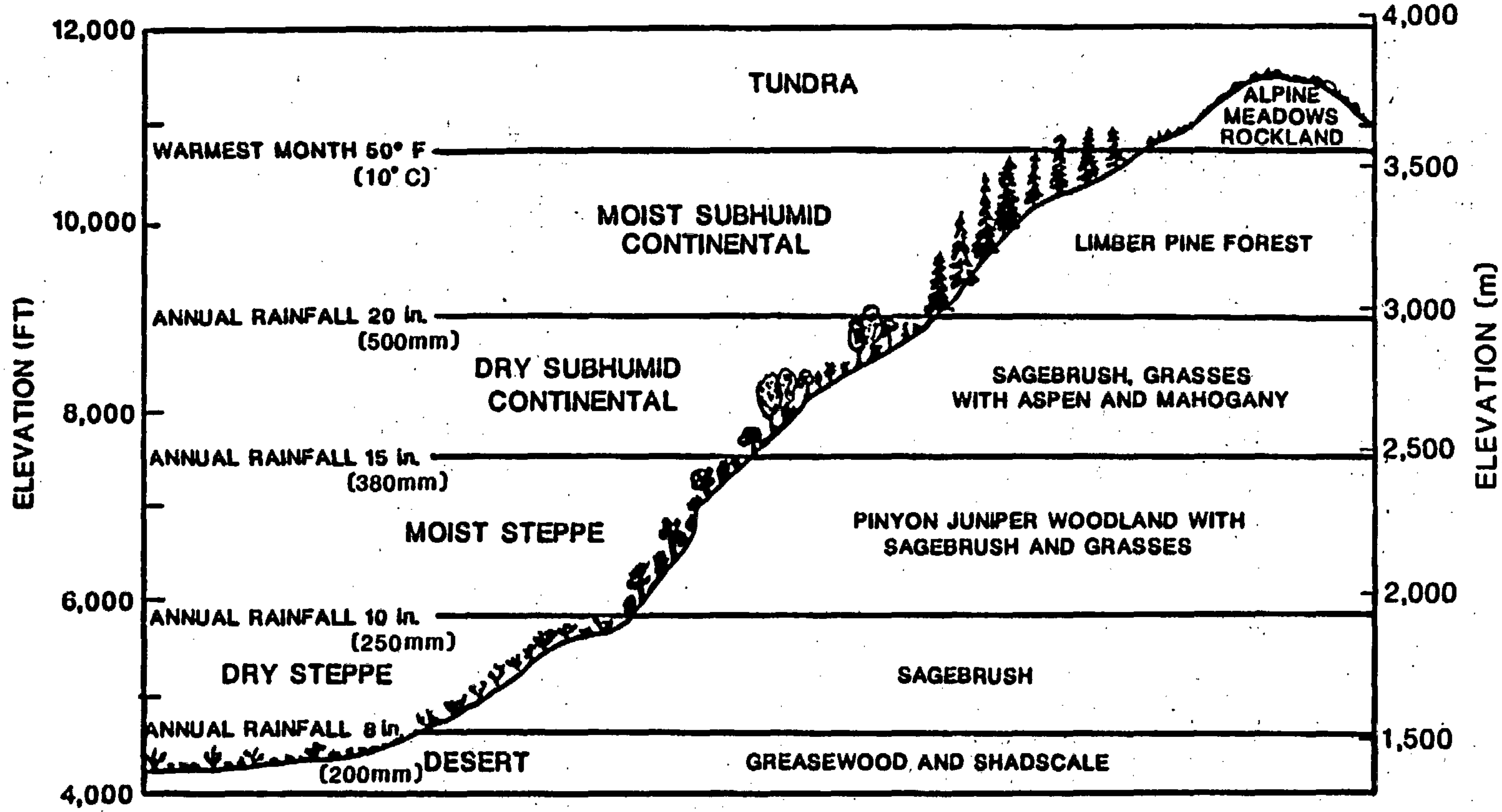


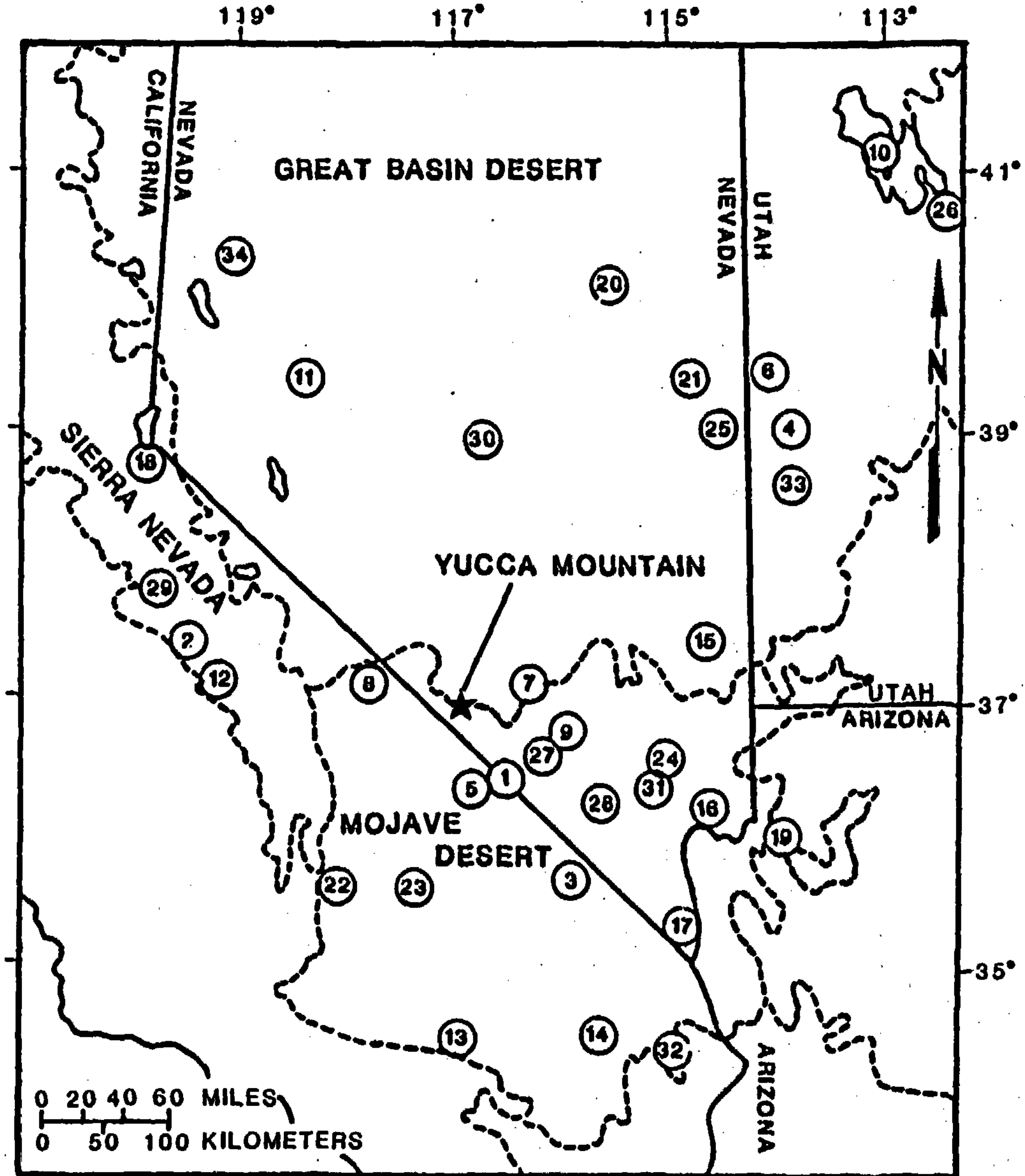
Figure 5-23. Generalized relationships among altitude, precipitation, and the distribution of plant communities for the Great Basin portion of Nevada (modified from Houghton et al., 1975).

widths at the upper tree line suggests periods of relative warmth (compared with the long-term mean) from 3500 to 1300 BC and from 200 BC to 300 with an intervening period of cooler summers. Renewed cooling is suggested after 300 with a brief warm interval at 1200 followed by an extended cool period after 1200. In apparent contrast to the synoptic-scale reconstructions of western climate of Brubaker and Cook (1983), from 1600 to 1960, LaMarche's data from the White Mountains indicate that the last century has been warmer than the preceding few centuries. LaMarche and Mooney (1972) also used remnant tree stumps standing well above the modern tree line in the White Mountains, California, and the Snake Range, Nevada, to demonstrate that (during portions of the middle Holocene) summer temperatures were well above those of today.

Palynology and pack rat midden studies

Fossil pollen in stratigraphic deposits have been extensively used in eastern North America and northern Europe to reconstruct fluctuations in temperature and precipitation over the last 15,000 yr (Webb, 1985). The applicability of the method has been somewhat limited by the relative scarcity of bogs and small lakes, the optimal settings for most types of pollen studies. Nevertheless, substantial paleoclimatological insights have been gained from studies of the fossil pollen contained in sediments deposited in western pluvial lakes, alpine lakes, caves, rockshelters, and alluvium. Pollen records, in general, provide quasi-continuous records of regional vegetational change. While the majority of these studies are restricted to the Holocene, palynological studies of pluvial lake sediments can provide information for the last 40,000 yr.

Pack rat middens are restricted to the semiarid and arid deserts of western North America. In the study of middens, past vegetation is reconstructed from plant remains deposited in rock cavities by rodents of the genus Neotoma (pack rats, wood rats, or trade rats). The plant remains can often be identified to the species level, and the assemblage is believed, based on the contents of modern middens, to represent vegetation growing within a foraging radius of 30 m at the time of accumulation (Spaulding, 1985). Selected plant macrofossils or other materials from each midden are submitted for radiocarbon analysis. The degree of precision of radiocarbon dates for plant macrofossils and other materials from pack rat middens, as with wood and other organic materials, generally increases with decreasing sample age and also with the length of time allowed for the analysis. Because older samples possess less carbon-14 radioactivity than younger samples, a longer period of radioactivity counting is required to gauge the carbon-14 content of an older sample with the same precision that would result from a shorter counting period with a younger sample. The precision of radiocarbon dates for wood and plant macrofossils is high because the potential for contamination by carbon from outside the sample system is low. The energy required for the replacement of carbon in organic compounds is high. Where more precision in dating is required or where the accuracy of a given date is in question, multiple samples from the same midden are submitted for radiocarbon dating. The paleobotanical data from the individual midden assemblages are compiled to create time series of vegetational change from a given area and vegetational setting. Replication of pack rat chronologies from sites with similar settings ensures that site-specific phenomena do not introduce bias into the interpretation of the data set.



1. AMARGOSA DESERT
2. BALSALM MEADOW
3. CLARK MOUNTAIN
4. CONFUSION RANGE
5. DEATH VALLEY
6. DEEP CREEK RANGE
7. ELEANA RANGE
8. EUREKA VALLEY
9. FRENCHMAN FLAT
10. GREAT SALT LAKE (LAKE BONNEVILLE)
11. HIDDEN CAVE
12. KING'S CANYON
13. LUCERNE VALLEY
14. MARBLE MOUNTAINS
15. MEADOW VALLEY WASH
16. MUDDY MOUNTAINS
17. NEWBERRY MOUNTAINS
18. OSGOOD SWAMP
19. RAMPART CAVE (WESTERN GRAND CANYON)
20. RUBY MARSHES
21. SCHELL CREEK RANGE
22. SCODIE MOUNTAINS
23. LAKE SEARLES
24. SHEEP RANGE
25. SNAKE RANGE
26. SNOWBIRD BOG
27. SPECTER RANGE
28. SPRING RANGE
29. CLEAR LAKE
30. TOQUIMA RANGE
31. TULE SPRINGS
32. TURTLE MOUNTAINS
33. WAH WAH RANGE
34. WINNEMUCCA LAKE

Figure 5-24. Locations of study sites for pollen and pack rat midden investigations discussed in text.

Palynological and pack rat midden studies can be used together to construct a regional network of time series of vegetational change spanning the last 45,000 yr. Figure 5-24 shows the locations where palynological and pack rat midden data have been collected. Table 5-13 compiles the results of these studies of vegetational assemblages and inferred paleoclimate conditions for the Great Basin, Mojave Desert, and Sierra Nevada at different times in the Pleistocene and Holocene. The table summarizes some of the interpretations resulting from paleoclimate research in these areas.

Table 5-14 is a compilation of vegetative cover and inferred climatic conditions in the Yucca Mountain area over the past 45,000 yr. It illustrates a correlation between variation of species with elevation over time and variation in temperature and precipitation.

The climatic inferences presented in Table 5-14 are slightly different from those discussed in Table 5-13 for some of the site locations. These differences are due to slightly different interpretations by the various workers. As more data are collected during site characterization, these differences are expected to be reduced.

Summary of paleovegetation changes

During the Wisconsin glacial period, greater than 40,000 to 11,000 yr ago, sagebrush steppe ranged over larger elevation and area than today in the Great Basin. It expanded into the Sierra Nevada and Wasatch mountains and descended southward into the modern Mojave Desert. Shadscale and other xerophytic steppe plants were common in this regime, particularly in the Mojave region. The modern Sierran forests, Great Basin pinyon-juniper woodlands, and southwestern ponderosa pine forests were absent or restricted in extent. In the Great Basin region, xerophytic subalpine conifers grew on rocky substrates as low as the local current base level, surrounded by steppe vegetation on fine valley-bottom soils. In the Mojave Desert, subalpine conifers grew on the lower mountain slopes, where pinyon-juniper and juniper woodlands now grow. Patches of treeless desert scrub were present in the most xeric settings in and near Death Valley. This was not modern Mojave Desert vegetation of the region, though some Mojave plants, such as joshua tree, were present. Creosote bush was absent, and shadscale, sagebrush, and other Great Basin plants grew in its place.

The transition to Holocene conditions occurred after 11,000 yr ago. The lower elevation limits of junipers and sagebrush were below those of today until 9,000 to 8,000 yr ago. By 7,000 to 6,000 yr ago, the lower boundary of these plants moved upslope, creosote bush arrived within its modern range in the Mojave Desert, and pinyon pines dispersed into the Great Basin. While minor changes in vegetation occurred after 6,000 yr ago, the modern communities were in place by this time.

The late Wisconsin vegetation was characterized by a greater coverage (relative to today) of cold-dry steppe species (sagebrush and shadscale) and the elevational depression of cold-tolerant xerophytic conifers (bristlecone pine, limber pine, Utah juniper). This suite of plants reflects cooler temperatures than present and low to moderate rainfall with a pronounced dominance of cool-season precipitation.

Table 5-13. Summary of palynological and pack rat midden data from the Great Basin, Mojave Desert, and Sierra Nevada with inferred climatic changes (page 1 of 8)

Location[a]	Evidence	Age	Vegetational assemblage	Inferred climatic conditions
		WESTERN GREAT BASIN		
Lake Lahontan basin (11,35)	Pack rat middens	12.1 to 11.5 thousand yr ago	Western juniper, sagebrush, and other Great Basin shrubs at lower than modern elevation limits (Thompson et al., 1986).	Semiarid, with dominance of cool-season precipitation and little or no summer precipitation. Summer temperatures cooler than present, but winter temperatures may not have been much colder (Thompson, 1984).
		CENTRAL GREAT BASIN		
Toquima Range (30)	Pollen, pack rat middens	6 thousand yr ago to present	Early Holocene sagebrush steppe with aspen replaced by pinyon-juniper woodland (Thompson and Hattori, 1983).	Early Holocene assemblages may reflect dry conditions with cooler than modern summer temperatures. Differences between middle Holocene and modern woodland plant associations reflect moisture conditions or higher proportion of summer rainfall (or both) from 6 to 3 thousand yr ago.
Ruby Marshes (20)	Pollen	35 to 8 thousand yr ago	Expansion of sagebrush steppe in the valleys; reduction of tree cover (Thompson, 1984).	Probably reflects relatively cold and dry conditions with strong predominance of winter precipitation.
		7 to 5 thousand yr ago	Expansion of shadscale steppe; establishment of pinyon-juniper woodland.	Suggests warmer and perhaps drier than modern conditions. (Thompson, 1984).

Table 5-13. Summary of palynological and pack rat midden data from the Great Basin, Mojave Desert, and Sierra Nevada with inferred climatic changes (page 2 of 8)

Location[a]	Evidence	Age	Vegetational assemblage	Inferred climatic conditions
		EASTERN GREAT BASIN		
Mountain ranges of east-central Nevada and west-central Utah: Schell Creek (21), Snake (25), Deep Creek (6), Confusion (4), and Wah Wah (33) ranges.	Pollen, pack rat middens	> 40 to 11 thousand yr ago (late Wisconsin)	Absence of many woodland plants common in modern assemblage. Occurrence of relatively xeric subalpine conifers, including bristlecone pine (Pinus longaera), limber pine (Pinus flexilis), Englemann spruce (Picca englemanni), and prostrate juniper (Juniperis communis), at elevations as much as 1,000 m below their modern limits (Thompson and Mead, 1982; Thompson, 1984).	Suggests late Wisconsin climate colder than modern, and relatively dry with little summer precipitation.
		11 thousand yr ago to present	Subalpine conifers (except for limber pine) reduced at low elevation xeric sites. Quaking aspen (Populus tremuloides), Rocky Mountain maple (Acer glabrum), and other mesophytic montane shrubs increase in abundance. Woodland junipers well established by 7.4 thousand years ago, pinyon-juniper woodland by 6.1 thousand years ago.	Indicates early Holocene climate warmer than late Wisconsin, but still cooler than modern climate. No evidence for major fluctuations in assemblage over last 6.0 thousand years, indicating prevalence of modern climatic conditions during this period.

Table 5-13. Summary of palynological and pack rat midden data from the Great Basin, Mojave Desert, and Sierra Nevada with inferred climatic changes (page 3 of 8)

Location[a]	Evidence	Age	Vegetational assemblage	Inferred climatic conditions
Meadow Valley Wash (15)	Pack rat middens	20.1 to 12.6 thousand yr ago	Montane conifers (such as limber pine and Douglas Fir (*Pseudotsuga menziesii*)) grew at relatively low elevations (Wells, 1983).	Paleoclimatic interpretation similar to Snake Range region, with cold-dry late Wisconsin conditions yielding to early Holocene cool-dry conditions. Middle and late Holocene conditions were relatively warm. Summer rainfall probably low during late Wisconsin and early Holocene, increasing to near-modern levels by 6 thousand yr ago.
		12.6 to 8.9 thousand yr ago	Montane conifers replaced by Utah juniper and Campbell's oak (Thompson and Mead, 1982).	
		6.6 thousand yr ago	First appearance of pinyon pine.	
Lake Bonneville (10)	Pollen	≈20 to 15 thousand yr ago	Sagebrush, pine, and spruce important in regional vegetation during period of high lake levels.	Probably reflect relatively cold and dry climatic conditions.
Wasatch Mountains: Snowbird Bog (26)	Pollen	12.3 to 8 thousand yr ago	Coniferous forest restricted, arid sagebrush steppe expanded at high elevations; alpine meadows on moist canyon bottoms. Establishment of coniferous forest at about 8 thousand yr ago (Madsen and Curry, 1979).	Cooler than average temperatures and slightly lower than average precipitation (Madsen and Curry, 1979).
		EASTERN MOJAVE DESERT		
Western Grand Canyon: Rampart Cave (19)	Pack rat middens	33.6 to 8.5 thousand yr ago	500-1,500 m xerophytic pinyon-juniper woodlands (Wells, 1983).	Not determined.
		10 to 9 thousand yr ago	Desert shrubs descended to 530 m (Wells and Berger, 1967).	Warm desert conditions.

Table 5-13. Summary of palynological and pack rat midden data from the Great Basin, Mojave Desert, and Sierra Nevada with inferred climatic changes (page 4 of 8)

Location[a]	Evidence	Age	Vegetational assemblage	Inferred climatic conditions
Colorado River Valley: Turtle Mountains (32) Marble Mountains (14)	Pack rat middens	16.9 to 9.9 thousand yr ago	Juniper woodlands descended as low as 258 m, persisting as low as 425 m to at least 9.9 thousand yr ago (Wells and Berger, 1967; Wells 1983).	Indicates late Wisconsin and early Holocene climates of this region cooler and moister than modern conditions. Trend toward increasing aridity, warmth, or both, began by 14 thousand yr ago and accelerated after 11 thousand yr ago.
Newberry Mountains (17) (southernmost Nevada)	Pack rat middens	Late Wisconsin	Descent of pinyon-juniper-oak woodlands to 730-850 m.	Not determined.
Las Vegas Valley: Tule Springs (31)	Pollen	> 30 to modern	Presence of sagebrush and junipers as low as 700 m (Mehringer, 1967). Sagebrush pollen decreased in abundance after 11 thousand yr ago, and Mojave Desert vegetation in place by 7 thousand yr ago.	Wisconsin climate relatively cold and perhaps not much wetter than present, with little summer rainfall. Increase of warmth and aridity before 11 thousand yr ago, but conditions cooler and wetter than modern until about 9 thousand yr ago.
Clark Mountain (3), Sheep (24) and Spring (28) Ranges, Muddy Mountains (16)	Pack rat middens	Late Wisconsin	Presence of bristlecone pine and other subalpine plants as low as 1,500 to 1,700 m; pinyon-juniper woodlands below subalpine assemblage, with pinyon pine (Pinus momophylla) as low as 1,600 m and juniper (Juniperus osteosperma) below 1,900 m. Shadscale up to 320 m above present limits (Spaulding, 1981). Woodland plants at low elevations in Sheep Range until at least 9.4 thousand yr ago.	Late Wisconsin middens indicate higher than modern precipitation levels (Mehringer and Ferguson, 1969).

Table 5-13. Summary of palynological and pack rat midden data from the Great Basin, Mojave Desert, and Sierra Nevada with inferred climatic changes (page 5 of 8)

Location[a]	Evidence	Age	Vegetational assemblage	Inferred climatic conditions
Amargosa Desert (1)	Pack rat middens	Wisconsin to 9 thousand yr ago	Modern Mojave desertscrub preceded by mixture of Great Basin, Mojave, and woodland plants during Wisconsin; assemblages ranged from treeless Great Basin desertscrub to juniper to (rare) pinyon pine. Junipers absent by 9.3 thousand yr ago, and cacti and other succulents became abundant. Arrival of creosote bush (Larrea divaricata) by 9.3 thousand yr ago. Persistence of other plants not present today: Utah agave (Agave Utahensis) and beavertail cactus (Opuntia basilarus).	High abundance of succulents in latest Wisconsin and early Holocene middens may indicate higher than modern summer rainfall levels.
Frenchman Flat (9)	Pack rat middens	40 to 10 thousand yr ago	Abundance of juniper and pine between 1,200 and 1,500 m (Wells and Jorgenson, 1964).	Climate significantly less arid than at present (Wells and Jorgenson, 1964).
		10 to 9 thousand yr ago	Descent of xerophilous juniper woodlands to 1,100 m (600 m below present woodland limit). Coexistence with desert or semidesert shrubs throughout lowered elevation range (Wells and Berger, 1967).	Climate relatively cooler and not much wetter than present during period of 10 to 9 thousand yr ago.

Table 5-13. Summary of palynological and pack rat midden data from the Great Basin, Mojave Desert, and Sierra Nevada with inferred climatic changes (page 6 of 8)

Location[a]	Evidence	Age	Vegetational assemblage	Inferred climatic conditions
Eleana Range (7)	Pack rat middens	17.1 to 13.2 thousand yr ago	Limber-pine (Pinus flexilis) woodland with Great Basin Desert and woodland shrubs as important understory species.	Later glacial trend toward effectively drier conditions, starting at about 16 thousand yr ago and well under way at 13 thousand yr ago. Change to drier climate between 13.2 and 11.7 thousand yr ago.
		11.7 to 10.6 thousand yr ago	Shift to woodland dominated by juniper, pinyon pine, and prickly pear species present in modern nearby woodland. (Spaulding, 1985).	
Specter Range (27)	Pack rat middens	32 to 18.7 thousand yr ago	Middle Wisconsin juniper or juniper-shadscale woodland. Pinyon pine-juniper woodland during Wisconsin maximum. (Spaulding, 1985).	At 30 thousand yr ago, average annual precipitation higher than present, temperature relatively lower.
		WESTERN MOJAVE DESERT		
Death Valley (5)	Pack rat middens	19.6 to 13.1 thousand yr ago 11.2 to 9.1 thousand yr ago	Utah juniper grew from 1,200 to 1,500 m below present limits from 19.6 to 13.1 thousand yr ago. Lowest elevations from this period have traces of juniper mixed with Joshua tree (Yucca brevifola) and Whipple's Yucca (Yucca whipplei). Latter not found at present in Death Valley. Junipers absent from lowest elevations by 11.2 thousand yr ago but persisted below present limits into early Holocene.	Past occurrence of Whipple's Yucca may reflect very mild winter temperatures and substantial winter rain. Junipers receded from lowest elevations by 11.2 thousand yr ago, presaging trend to progressive warmth and aridity from 11.2 to 9.1 thousand yr ago.

Table 5-13. Summary of palynological and pack rat midden data from the Great Basin, Mojave Desert, and Sierra Nevada with inferred climatic changes (page 7 of 8)

Location[a]	Evidence	Age	Vegetational assemblage	Inferred climatic conditions
Eureka Valley, CA (8)	Pack rat middens	14.7 to 5.4 thousand yr ago	Present creosote bush and shadscale (Atriplex confertifolia) area occupied by Utah juniper and limber pine at 14.7 thousand yr ago; also present then were sagebrush, shadscale, and other Great Basin shrubs. Limber pine apparently absent by 10.7 thousand yr ago, while juniper continued to persist well below present limits. Woodland species absent by 8.3 thousand yr ago. Creosote bush and other modern Mojave Desert species began to appear by 5.4 thousand yr ago, and were abundant by 3.9 thousand yr ago.	Changes in plant assemblages apparently reflect a trend toward increasing aridity from 10.7 to 5.4 thousand yr ago.
Far western and southwestern Mojave Desert: Lucerne Valley (13), Lake Searles (23), Scodie Mountains (22)	Pollen, pack rat middens	Late Wisconsin to 7.8 thousand yr ago	Woodland and steppe preceded desertscrub at low elevations during late Wisconsin and early Holocene (Leopold, 1967; Wells and Berger, 1967; Van Devender and Spaulding, 1979). Pinyon-juniper woodland present in Lucerne Valley until at least 11.8 thousand yr ago, while juniper persisted below its modern limits until 7.8 thousand yr ago. Creosote bush and other modern desertscrub species established by 5.9 thousand yr ago.	Late Wisconsin colder than modern conditions; warming and aridification began after 11.8 thousand yr ago and reached modern conditions between 7.8 and 5.9 thousand yr ago.

Table 5-13. Summary of palynological and pack rat midden data from the Great Basin, Mojave Desert, and Sierra Nevada with inferred climatic changes (page 8 of 8)

Location[a]	Evidence	Age	Vegetational assemblage	Inferred climatic conditions
		SIERRA NEVADA		
Sierra Nevada: Osgood Swamp (18), Clear Lake (29), Balsam Meadows (2)	Pollen	Late Wisconsin	Sierran montane forests restricted in distribution; replaced in modern time by sagebrush and other steppe species in association with scattered pines and perhaps junipers (Adam, 1967; Davis et al., 1985).	Climate passed from glacial conditions into warmer postglacial conditions about 10 thousand yr ago and cooling within the last 2,900 yr (Adam, 1967).
		10.5 thousand yr ago to present	Steppe replaced by forest by 10.5 to 9.5 thousand yr ago at Osgood Swamp and Swamp Lake, while it may have persisted as late as 7.0 thousand yr ago at Balsam Meadows (Davis et al., 1985). Pine forests were more widespread than today in the Sierra Nevada from 7.0 to 3.0 thousand yr ago (Davis et al., 1985).	Dry from 10 to 7 thousand yr ago and cool and moister from 3 thousand yr ago to present (Davis et al., 1985).
Kings Canyon (12)	Pack rat middens	45 to 12.5 thousand yr ago	Modern oak and chapparal vegetation preceded by more xerophytic and cold-adapted species, including single-needle pinyon pine (Pinus monophylla), western juniper, and ponderosa pine (Pinus ponderosa) (Cole, 1983).	Pleistocene conditions in southern Sierra Nevada were colder and drier than today. Precipitation during the late Wisconsin not much greater than at present (Cole, 1983).

[a]Numbers in parentheses following location names correspond to those on Figure 5-24.

Table 5-14. Vegetative cover and inferred climatic regime of the Yucca Mountain region[a]

Yr B.P.[b]	Vegetation: Lower elevations (790-1200 m[c])	Vegetation: Intermediate elevations (1200-1800 m)	Vegetation: Higher elevations (1800-2100 m)	Inferred climatic regime: Temperature (°) (compared to modern): Winter	Temperature: Summer	Temperature: Annual	Precipitation (% change from modern): Winter	Precipitation: Summer	Precipitation: Annual	Remarks
5,000	Modern desert scrub	Modern desert scrub	Woodland	--[d]	--	--	--	--	--	Minor fluctuations
10,000	Amargosa: Utah agave, juniper creosote	Desert scrub expansion	Woodland dominated by juniper, pinyon pine, prickly pear	-1 to -2	+1 to +2	0	0	+50	+10 to +20	Trend toward drier conditions and increasing temperatures
18,000	Specter Range: pinyon-juniper woodland	Sheep Range: transition to subalpine-conifer woodland	Sheep Range: subalpine conifer woodland	-6	-7 to -8	-6 to -7	+60 to +70	-40 to -50	+30 to +40	Global glacial maximum at 18,000 ± 3,000 yr BP
30,000	Specter Range: open juniper-shad scale woodland	Sheep Range: Utah juniper	Sheep Range: juniper woodland with prickly pear, sage, mountain mahogany	--	--	-3 to -6	--	--	+10 to +25	
37,800	No record	No record	No record	--	--	-5	--	--	+20	Cooling trend
38,700	No record	No record	Increase in juniper decline of steppe shrubs	--	--	-1 to -2	+25 to +50	-40	+10 to +20	
45,000	No record	Sheep Range: juniper woodland	Elena Range: open juniper woodland	-2 to -3	--	-1 to -3	+20	-60	0	Seasonality of rainfall different, but annual amount approximately the same

[a]Spaulding (1983) and Spaulding et al. (1984).
[b]B.P. = before present.
[c]m = meter(s)
[d]-- = No data.

There is little information on Holocene fluctuations in vegetation across most of this region. It is possible that warmer than modern temperatures or more abundant summer precipitation occurred during some portions of the last 10,000 yr (Antevs, 1948; Martin, 1963; Spaulding et al., 1984; Spaulding and Graumlich, 1986). This will be examined during site characterization as more data are collected within the Great Basin.

Paleoclimatic applications of paleobotanical data

The interpretation of palynological and pack rat midden records in climatic terms requires information on the modern relationships between vegetation and climate. Given such relationships, under certain assumptions it is possible to infer the nature of the climatic variations responsible for the vegetation changes recorded by the fossil evidence. The general assumption underlying the drawing of these inferences is "that past temporal changes in the abundances of a set of pollen types reflect climatic changes equivalent to those responsible for spatial variation in the abundances of the same taxa on the contemporary landscape" (Howe and Webb, 1983). This general assumption can be expanded to more-specific ecological and statistical assumptions.

The specific ecological assumptions are as follows (Bartlein et al., 1984):

1. The modern vegetation data is in equilibrium with the modern climate at the temporal and spatial scales of interest. Given this assumption, the modern vegetation will adequately reflect the modern climate.

2. The variations in the paleoecological record being interpreted are ultimately attributable to climatic variations.

It is not possible to test either assumption in practice, but by proper selection of the temporal and spatial scales of interest, violations of the assumptions can be minimized (Prentice, 1983). The scales of interest for the Yucca Mountain repository will imply an assumption that the modern vegetation-climate relationships can be extrapolated back through Quaternary time over the Great Basin.

The specific statistical assumptions are (1) the statistical model used is specified correctly and (2) the parameters of that model are estimated in an appropriate fashion.

Two data bases are thus required for paleoclimatic reconstruction: (1) a data base of modern combined vegetation and climatic data and (2) a data base of fossil vegetation data. The first data base is used to construct baseline relationships between vegetation and climate to determine, for example, the environmental requirements of individual taxa. The relationships are then applied to the fossil data, either to interpret them in climatic terms, or to permit comparison of the observed fossil record with that simulated by differing paleoclimatic scenarios.

Relationships between modern vegetation and climate are also required for the paleobotanic validation of climate simulation models (Webb, 1980).

To judge the ability of a model to correctly simulate the past climate, modern vegetation-climate relationships are used to transform model simulations of past climates into estimates of past vegetation, which can then be compared with the observed fossil record (Webb, 1980). The collection and the analysis of both modern and fossil vegetation data therefore contribute to both climatic reconstruction and the validation of climate models that may be applied for predicting future climates.

It is possible to construct relationships between modern climate and vegetation in both a qualitative and a quantitative fashion. The following sections discuss these two methods. Both methods rest on the two basic ecological assumptions listed previously.

<u>Qualitative relationships</u>. Thus far, paleoclimatic estimates from vegetation data from the arid West have been based on qualitative comparisons of modern plant distributions with climatic parameters. These methods involved

1. Comparisons of maps of species distributions with maps of climatic parameters. Past changes in the species distribution are assumed to reflect changes in the subjectively correlated climatic variable. Modern plant distributions are poorly mapped in the West, limiting the applicability of this method. Additionally, without means of assessing whether there is a mechanism linking the distribution of a given species with a certain climatic parameter, these mapped comparisons may be misleading.

2. Identifying analog sites that have modern vegetation similar to the fossil vegetation assemblage. The modern climate of the analog site is then assumed to be representative of the climate at the time that the fossil assemblage was deposited (Spaulding, 1985). The utility of this method is limited in that a wide array of modern climatic sites may be suitable analogs, depending upon the criteria for matching the fossil and modern vegetation assemblages.

3. Calculating the amount of elevational depression of a given plant species relative to its modern limits and using the modern environmental lapse rates to estimate the amount of climatic difference represented by this depression (Spaulding, 1981). This method is difficult to apply in that different species experienced widely varying amounts of elevational depression in the past. More importantly, as discussed in the previous section on lake levels, it is very difficult to independently estimate past lapse rates.

<u>Quantitative approaches</u>. There are two related approaches for constructing statistical relationships between modern vegetation and climate data: (1) a transfer function approach (Webb and Bryson, 1972; Bartlein et al., 1984), in which individual climate variables are expressed as a function several vegetation predictor variables (e.g., the percentages of different pollen types) and (2) a response function approach (Bartlein et al., 1985), in which the relative abundance or presence/absence of individual taxa are expressed as nonlinear functions of one or more environmental variables. In addition, forest simulation models have been used to generate vegetational assemblages consistent with a particular set of values of controlling climate

variables (Solomon and Webb, 1985). Such models incorporate the development of a response function for vegetation-climate relations.

The transfer function approach usually makes use of a multiple regression analysis to construct a relationship between a particular climate variable and a number of predictor variables--generally, the percentages of individual pollen types (Webb, 1980; Bartlein et al., 1984). In practice, a data set of paired observations of modern surface pollen samples and climate is required for calibration of the multiple regression equation. The resulting equation is then applied to fossil pollen data to interpret them in climatic terms.

Several statistical assumptions (in addition to the basic assumptions described earlier) underlie the application of regression analysis; these are described by Howe and Webb (1983) and Bartlein and Webb (1985). Comparisons among some of the different approaches to constructing the statistical relationships have been described by Kay and Andrews (1983). Strategies for identifying and minimizing the sources of uncertainty in the paleoclimatic estimates are given in Bartlein et al. (1984) and Bartlein and Webb (1985). Bartlein and Webb (1985) show how to determine the applicability of the methods in time and space.

In the response function approach, the relative abundance or probability of occurrence of different taxa are expressed as a nonlinear (usually polynomial) function of one or more environmental variables. The resulting functions are usually displayed as response surfaces that show how the abundance or probabilities vary in the space defined by the environmental variables (Bartlein et al., 1985). For the relative abundance data, the response functions are fit using linear regression (Bartlein et al., 1985), while for the presence or absence data, the surfaces are fit using logistic regression (Ter Braak and Barendregt, 1986).

Because response functions illustrate the environmental preferences of different taxa, they can provide guidance in the qualitative interpretation of fossil data in climatic terms. Quantitative reconstruction is possible as well, using response functions of several taxa to determine the environmental conditions necessary to give rise to a particular fossil assemblage (Ter Braak and Barendregt, 1986).

Applications of response functions for climate model validation are relatively straightforward. The relative abundance of different taxa can be estimated by applying response functions to the values of climate variables simulated by climate models. The simulated vegetation variables can then be compared with the observed values. In a typical example, the climate model would be set up to simulate some specific paleoclimate, and the simulated vegetation would be compared with the observed fossil record (Webb et al., 1985).

5.2.1.2.4 Glacial and periglacial records and their relation to lake levels

Isotopic records from deep-sea cores indicate that there have been at least seven high-latitude glacial and seven interglacial periods during the last 730,000 yr (Hays et al., 1976). On land, successive glaciations have obliterated much of the evidence of earlier ice advances and, therefore, the record is fragmentary and heavily weighted toward the last glaciation. Although alpine glaciers did form nearby in the higher portions of the Sierra Nevada and in other Great Basin mountain ranges, there is no evidence suggesting that glacial activity ever occurred on Yucca Mountain. Nivation basins, and other periglacial features of assumed late Wisconsin age have been identified in the mountains near the NTS as far south as the Spring Range (Blackwelter, 1931; Sharp, 1938; Porter et al., 1983; Dohrenwend, 1984). The chronology of the formation of periglacial features is unknown.

Deposits from at least four glaciations of Pleistocene age have been found in the Sierra Nevada, with the last assumed to be correlative with the late Wisconsin in northeastern North America (Porter et al., 1983). Lake deposits impounded behind a natural dam composed of outwash from Sierran glaciers at Tulare Lake, California (Atwater et al., 1986) suggest that this latest Pleistocene glaciation began 26,000 yr ago and ended between 13,000 and 10,000 yr ago. The age of the maximal extent of the Tioga advance is unknown, although Porter et al. (1983) suggested that it was correlative with the last high lake stand at Lake Russell (Mono Lake). The Lake Russell maximum has been estimated to have occurred 14,000 to 13,000 yr ago (Figure 5-21). A radiocarbon date of 10,000 yr ago from lake sediments impounded behind a Tioga-age terminal moraine at Osgood Swamp (Adam, 1967), indicates that deglaciation occurred before this time. Mountain glaciers in eastern Nevada appear to have disappeared by about 13,000 yr ago (Wayne, 1984). A similar age of deglaciation is indicated for the central Wasatch Range of Utah (Madsen and Currey, 1979).

The stratigraphic and radiometric data on lake-glacial correlations are ambiguous, although the weight of the evidence points to glacial recessions occurring well before the Pleistocene lakes reached their highest levels (Benson and Thompson, 1987). The lag times between these phenomena cannot yet be assessed nor can the differences in climate (if any) between the "full-glacial" and "full-lake" phases be deduced.

Over the last 10,000 yr (Holocene time), mountain glaciers in the Sierra Nevada advanced at least four times (Burke and Birkeland, 1983). All were of much smaller magnitude than the Pleistocene glaciers. The oldest of these Holocene glaciations is thought to have occurred between 10,000 and 9,000 yr ago, while the other three advances appear to postdate 4,000 yr before present (Burke and Birkeland, 1983).

5.2.1.2.5 Regional paleoclimatic hypotheses

The various sources of paleoclimatological proxy data reviewed in the preceding sections have been used to formulate hypotheses concerning the nature of past climatic variations in the west. Theories of the nature of Wisconsin-age climates implied by the various data sets are wide-ranging. Galloway (1970), Brakenridge (1978), and Dohrenwend (1984) have argued that the past distributions of cryogenic features imply that full glacial mean annual temperatures in the southwest were from 7 to 11 Celsius degrees colder than those of today, with little or no increase in mean annual precipitation.

Others, such as Snyder and Langbein (1962) and Mifflin and Wheat (1979), have suggested that lake-level reconstructions provide evidence for increased rainfall with a more moderate decrease in mean annual temperatures. Benson (1981) modeled the lake budget for Pleistocene Lake Lahontan in western Nevada and concluded that a reduction in mean annual temperature, coupled with an increase in sky cover, were needed to create and maintain these lakes. Smith and Street-Perrott (1983) calculated streamflow volumes that would offset the estimated evaporation from the maximum cumulative areas of late-Pleistocene lakes in the Owens River system (1,963 km^2), and found inflow volumes to be in the range of 3.5 to 6.5 times present volumes, depending on whether a 5 or 10 Celsius degree lowering of temperatures was assumed. Van Devender and Spaulding (1979) interpreted pack rat midden data as reflecting late-Wisconsin climates characterized by increased precipitation, cool summers, and mild winters. Spaulding (1985) presents evidence that the pack rat midden data from southern Nevada indicates temperatures about 7 Celsius degrees below modern mean annual temperature and more abundant winter rainfall. Wells (1979) interpreted pack rat midden from the late Wisconsin as reflecting increased summer rainfall, with little reduction in mean annual temperature.

Opinions on Holocene climates are equally diverse. Antevs (1948), largely on the basis of studies in the northern Great Basin, argued that the middle Holocene was characterized by hot and dry conditions across the entire western United States. Martin (1963) hypothesized that this was instead a period of enhanced monsoonal summer precipitation throughout much of the southwest. In the NTS region, various studies have supported both of these seemingly conflicting hypotheses. Before construction of the Los Angeles Aqueduct, Owens Lake, west of the Yucca Mountain site, was the only perennial lake supported by the Owens River. Though reduced to a body of water only 10 m deep in the late 1800s and supported by a small fraction of maximum pluvial inflow, it apparently never desiccated to form a bed of salts during Holocene time or any other part of the last million or more years (Smith and Pratt, 1957), implying that no period in the Pleistocene has been significantly more arid than the present. To the north, lakes in the Great Basin were at lower than modern levels during the middle Holocene (Davis et al., 1976; Benson, 1978; Currey, 1980; Thompson, 1984) and upper treelines advanced upslope (LaMarche and Mooney, 1972). Both of these phenomena may indicate relatively high summer temperatures. During the same period in this region, there were changes in plant communities that may indicate higher than modern levels of summer precipitation (Thompson, 1984; Spaulding and Graumlich, 1986).

What is clear from this collection of differing paleoclimatic hypotheses is that the paleoenvironmental data, as they now exist, are inadequate to provide critical tests. Plans to develop a more adequate data base are discussed in Section 8.3.1.5.1.

5.2.2 FUTURE CLIMATIC VARIATION

The paleoenvironmental record for the Quaternary reveals that significant climatic variations have occurred in the past, and similar variations can be expected in the future. It seems clear, for example, that the repeated fluctuations between glacial and interglacial climates during the Quaternary have occurred in response to changes in the seasonal and latitudinal receipt of solar radiation as determined by variations of the earth's orbital elements (Hays et al., 1976). Since the orbital variations will continue in the future, it is very likely that the present interglacial climate will eventually give way to another glacial one.

Deciding whether such variations can significantly affect a repository will require a prediction of the times and intensities at which they will occur in the future. The prediction need not be exact; the decision will rest largely on calculations that, for conservatism, will be based on the most extreme ranges that climatic variations can reasonably be expected to exhibit in the future. The paleoclimatic record can supply the needed data on the range of past variations. Nevertheless, the ranges of past variations can be used with greatly increased confidence if the future variations can actually be predicted from an understanding of the causes of climatic variations as well as the record of their past occurrence.

Study of past climatic variations can provide only the general outlines of future variations on the time scale of 1,000 to 100,000 yr. The orbital variations can explain a considerable portion of the total variance of such large-scale climatic variables as global ice volume, but some variance still remains unexplained (Imbrie, 1985). Further, as will be described below, the link between global-scale variations and local ones is not clear. Moreover, for the near future (the next 10 to 1,000 yr) the large inputs of anthropogenic carbon dioxide and other trace gases into the climate system have the potential of greatly altering future climate. The potential effects of carbon dioxide and other trace gases have recently been reviewed by MacCracken and Luther (1985) and Wang et al. (1986), respectively. Specific forecasts of future climatic variations at a particular location should consider the effect of aerosols, anthropogenic carbon dioxide, and other trace gases, as well as the geologic record.

Methods of predicting climatic variations on the time scale of 1,000 to 100,000 yr do exist. In the following sections, the nature and causes of climatic variations that must be considered in furthering the development of methods for predicting future climates are reviewed, followed by a description of the necessary procedures for predicting future climates.

5.2.2.1 Components of the climate system

The major components of the climate system are the atmosphere, hydrosphere, cryosphere, surface lithosphere, and biosphere; these are linked by flows of mass and energy. The major components may be subdivided further. The hydrosphere, for example, can be subdivided into the oceans, atmospheric vapor, and continental water, while the cryosphere consists of sea ice as well as land ice and snow. The ocean can be subdivided further into the mixed layer and deeper water. Individual components have different thermal characteristics and response times. The atmosphere varies relatively rapidly, the mixed layer of the oceans less rapidly, and the deep ocean and continental ice sheets extremely slowly (Saltzman, 1985).

The state of the climate system at any given time can be described by a large and varied set of climate variables that are observed over temporal scales ranging from 10 yr (in the case of annual values of standard meteorological variables) to 10 million yr (the position of the continents), and over spatial scales from local to global. Individual variables can be classified (Saltzman, 1985) as those that describe (1) the boundary conditions or external controls; (2) the slowly varying components, such as the ice sheets and deep oceans; and (3) the fast-response components, such as the atmosphere.

Boundary conditions include those variables that influence the climate system, but in turn are not influenced by it (Imbrie, 1985). The boundary conditions thus include the incoming solar radiation, the position and size of the continents, and inputs of dust and aerosols from volcanic eruptions, and the inputs of dust and carbon dioxide from human activities.

Depending on the particular temporal and spatial scale of the climatic variation under consideration, additional components of the climate system can be added to the list of boundary conditions. At the scale of 10,000 to 1 million yr, the size (volume, area, and elevation) of the ice sheets and the temperature of the oceans are internal variables of the climate system that respond to the orbital variations. At shorter time scales (i.e., shorter than 10,000 yr), the ice sheets and ocean may be regarded as external controls because their response times are 10,000 yr or longer. At short time scales, the preindustrial concentration of carbon dioxide in the atmosphere and the loading of dust from wind erosion in areas of naturally sparse vegetation can be regarded as external boundary conditions. At longer time scales these variables are more properly regarded as internal variables.

Slowly varying components of the climate system include the ice sheets, ice shelves, tectonic activity, and deep layers of the ocean (Saltzman, 1985). These slowly varying components at a particular time serve as additional boundary condition controls of the fast-response components. The fast-response components include the atmosphere, the mixed-surface layer of the ocean, seasonal snow cover, and the land-surface temperature. These components generate the variations of climate at a particular location on time scales shorter than 1,000 yr.

Since the mid-1800s, the concentration of carbon dioxide in the atmosphere has increased as a result of the burning of fossil fuels and large-scale deforestation. The nature of this increase and its potential climatic effects have been reviewed recently in a series of reports published by the DOE (MacCracken and Luther, 1985). Because this increase in carbon dioxide concentration may be of sufficient magnitude to alter the way in which the climate system responds to changes in other boundary conditions, the effects of this increase may be significant in the prediction of future climates.

5.2.2.2 Climatic variations

It is possible to define three kinds of climatic variations (Imbrie, 1985): (1) forced variations produced by changes in the external controls, (2) free variations generated internally within the climate system, and

(3) resonant interactions that are a combination of the two. Climatic variations thus have two ultimate sources: the external controls of the climate system (or boundary conditions) and the climate system itself.

The specific response of the climate system to changes in its external controls (forced variations) depends on both the nature of the variations in the controls and the state of the climate system itself (Imbrie, 1985). For example, a constant change in solar radiation inputs will likely produce different responses depending on the presence or absence of continental ice sheets (Kutzbach and Guetter, 1984).

Free variations of the climate system can arise from the existence of many pathways for the flow of mass and energy within the climate system, and hence from the existence of many feedback mechanisms. It is not unlikely that significant variations in global climate could be generated by such feedback even under fixed boundary conditions. For example, Saltzman and Sutera (1984) described a climate model that considers the continental ice mass, the marine ice mass, and temperature of the ocean. With no external forcing, the model generated a variation of the ice and ocean with many characteristics of the geologic record, for instance, a dominant period of variation of about 100,000 yr. Such free oscillations of the climate system have been obtained using a number of different climate models (Saltzman, 1985). However, the phase relationships between the continental ice mass and ocean temperature in the model were not consistent with those observable in the real climate system. When the model was forced with realistic variations of solar radiation (such as those produced by the orbital variations), the correct relationships among the variables were obtained (Saltzman et al., 1984). This latter result provides an example of climatic variations produced by resonant interactions between forced and free variations of the climate system represented by the model.

The existence of temporal and spatial hierarchies in both the components of the climate system and also the sources of the climatic variations makes it difficult to assign past climatic change at a particular location to a specific ultimate cause, and consequently difficult to predict future changes. For example, variations of the fast-response components may be generated by variations of the slowly varying components (and by internal variations), and in turn, variations of the slowly varying components may be generated by variations of the boundary conditions (and by internal variations).

Similarly, local climate variations of the kind, for example, that make one winter different from the last, are embedded in hemispheric-scale circulation anomalies (Namias, 1975). Moreover, local variations are indeterminate with respect to larger scale variations. The climate of a particular location has two components: (1) a locational component, governed mainly by the latitude of the place and its position on the continent, which determines the mean values of temperature and precipitation and (2) an advective component, governed by the location of the place relative to the traveling weather systems, which determines the day-to-day variations of the weather. Thus, a variety of atmospheric circulation patterns could be envisaged that would lead to the same local climate variations.

Each level of the temporal and spatial hierarchy contributes additional uncertainty about the ultimate causes of past climate variations at a particular place, and the likely consequences of future variations in the controls of the climate system. The development of climate prediction methods for the time scales of interest must therefore proceed in a top-down fashion, from the larger-spatial, longer-temporal scale controls to the local responses to variations of those controls. Such a hierarchical methodology has not yet been developed.

5.2.2.3 Climate prediction methods

Prediction of future climatic variations on the time scale of 1,000 to 100,000 yr will require a multistep procedure that corresponds to the hierarchy of controls and responses in the climate system, and incorporates studies to validate model simulations. Climate prediction over this time scale can not be said to be operational, however. Thus, an important element of any prediction effort will be the selection and evaluation of the individual models.

As outlined previously, an overall approach to climate prediction would proceed from predictions of variations in the external controls to predictions of the slowly varying components, and then to the fast-response components, and from the global to the local scale. Steps in such a prediction approach include

1. Prediction of boundary conditions.

2. Prediction of the slow-response components.

3. Prediction of the fast-response components.

4. Disaggregation of the predictions of the slow- and fast-response components at the appropriate spatial scale.

5. Model validation studies.

Climate simulation models are typically classified into two categories: (1) statistical-dynamical models (Sellers, 1983) and (2) explicit-dynamical models (Kutzbach, 1985; and references therein). Models in the first category attempt to simulate the long-term, spatially averaged variations of the climate, while those in the second category attempt to simulate day-to-day variations of the weather. Other classifications of climate models are possible (Schneider and Dickinson, 1974; Meehl, 1984).

5.2.2.3.1 Prediction of boundary conditions

The key boundary condition for predicting future climatic variations over the next 100,000 yr is the latitudinal and seasonal distributions of solar radiation. Fortunately, these quantities are predictable over the required time interval. The concentration of carbon dioxide and the dust loading of the atmosphere are also important boundary conditions. The past record of these variables, and their potential predictability over the next

100,000 yr is not well known. Past estimates of volcanic loadings might be made stochastically, based on past summaries of volcanic-loading estimates such as those given by Hirschboeck (1980). The prediction of future loadings from natural (e.g., volcanos, wind erosion) and human-induced (desertification) sources is not likely to be easily implemented. Similarly, the source of past variations of the concentration of carbon dioxide in the atmosphere is not clear at present (Shackleton et al., 1983), and so this variable too may be inherently unpredictable, although it is clear that the concentration of carbon dioxide due to human activities will continue to increase at least into the next century.

While the specific course of future variations of climatic variables may not be predictable, the range of their past variations as deduced from the paleoclimatic record can serve to limit the range of variations expectable in the future.

5.2.2.3.2 Prediction of slowly varying components

The prediction of the slowly varying components of the climate system, such as the global volume of glacial ice and deep ocean temperature, will require the application of models from the statistical-dynamical family of climate models. Saltzman (1985) recognizes two groups of models of the slowly varying components: (1) a quasi-deductive group of models that derives models of, for example, the ice sheets from basic physical principles and (2) an inductive group of models that derives models consistent with observed paleoclimatic records that are required to be only physically reasonable. In other words, the first group proceeds from physical principles to a model of observed paleoclimatic variations, while the second starts with the geologic record and derives a physically reasonable model based on it. The distinction between the two groups arises from the inability of purely physically based models to represent all the facets of the records of the slowly varying components, hence the need for an alternative approach.

Recently, paleoclimatologists have recognized the importance of periodic variations of the earth's orbital motion and of insolation as important controls of the climate during the Quaternary, while admitting the potential for internal variations of the climate system to contribute to overall variations of climate (Saltzman, 1985). The quasi-deductive group of models is represented by a series of models that seek to describe the response of the ice sheets, ice shelves, sea ice, and the deformable bedrock (Oerlemans 1982; Pollard, 1983) to variations in solar radiation.

The inductive group of models is represented by a series of models that attempt to reproduce the characteristics of the observed paleoclimatic record using a geologically consistent, but physically reasonable model (Imbrie and Imbrie, 1980; Saltzman and Sutera, 1984; Saltzman et al., 1984; Imbrie, 1985). The Imbrie and Imbrie (1980) model is often cited as an example of a future climate prediction for its extrapolation of the global ice volume series to 100,000 yr into the future. The intent of the authors cited above in displaying this information clearly seems to have been to illustrate the nature of the temporal response of the output of their model rather than to provide an experimental prediction.

Estimates of ice sheet geometry can be produced with numerical computer models based upon a solution of the two-dimensional, time varying, ice flow law. Examples of such models are now in existence. One has been applied to the reconstruction of the dynamics of the Laurentide ice sheet for the last 100,000 yr (Budd and Smith, 1981) and was based on orbitally induced variations of insolation over the ice sheet. Other reconstructions of continental-scale ice sheets for times during the Pleistocene have been produced by Mahaffey (1976) and Sugden (1977).

The information about glacier configurations at various times have been used as input to model studies of the general circulation of the atmosphere. Such studies have been done for reconstructions of past climates using one-dimensional (flow-line) models of ice dynamics (Hughes et al., 1981; Stuiver et al., 1981). The global ice sheet reconstructions of Hughes et al. (1981) were used to model the atmospheric circulation during the time of the last glaciation and more recent periods in the past 18,000 yr. Other atmospheric general circulation model studies of global climate during an ice age have been provided by Williams et al. (1974), Gates (1976a,b), and Manabe and Hahn (1977).

There are several areas in which further development of models of the slowly varying components of the climate system is required. Most of the models thus far have focused on the ice sheets, and models of the deep ocean are relatively primitive (Saltzman, 1985). The models simulate global climate systems; methods must be sought for disaggregating this output to provide, for example, maps of the detailed spatial patterns of the ice sheets.

5.2.2.3.3 Prediction of fast-response components

Models of the fast-response components of the climate system can be drawn mainly from the explicit-dynamical family of climate models and consist mainly of general circulation models. Atmospheric general circulation models attempt to represent the three-dimensional structure of the atmosphere and to simulate the day-to-day variations of the weather. This is done by solving the basic equations governing the motion of the atmosphere over a three-dimensional grid (Schneider and Dickinson, 1974; Meehl, 1984). In practice, general circulation models provide snapshot views of the atmospheric components (wind, temperature, pressure, precipitation) of the climate system under a fixed, or seasonally varying set of boundary conditions. The potential of these models in climate prediction over the time scale of 100,000 yr lies in their ability to disaggregate global and hemispheric scale variations of the boundary conditions and slowly varying components of the climate system.

Applications of general circulation models for simulating past climatic variations include those by Gates (1976b), Manabe and Hahn (1977), Manabe and Broccoli (1985), and Kutzbach and Guetter (1986). In these applications, the state of the boundary conditions and slowly varying components for ice age conditions were used to initialize the models. General circulation models have also been used to investigate the response of the climate system to anthropogenic increases in the concentration of carbon dioxide in the atmosphere. An extensive review of these models is given by Schlesinger (1984).

An important element of general circulation models in need of further development is the manner in which the oceans are treated. In most paleoclimatic applications, ocean surface temperatures were prescribed, fixed at the CLIMAP Project Members (1981) values for 18,000 yr ago, for example. In Manabe and Broccoli (1985) a mixed-layer ocean was used, but such a model still does not represent heat transport by the oceans (Manabe and Wetherald, 1985). Even with increasing computer resources, fully coupled ocean-atmosphere general circulation models are still too inefficient for routine application (Meehl, 1984).

5.2.2.3.4 Spatial disaggregation of predictions

Although general circulation models are capable of providing three-dimensional simulations of the atmosphere, their spatial resolution is too coarse to provide meaningful results for specific sites (Gates, 1985). The National Center for Atmospheric Research Community Climate Model used by Kutzbach and Guetter (1984), for example, has a spatial resolution of 4.4° latitude by 7.5° longitude. Topographic features that may be quite important mediators of the local climate are thus greatly smoothed.

There are two distinct approaches that may be applicable for disaggregating the simulations produced by general circulation models: (1) an empirical approach based on statistical analysis of observed climate data and (2) a modeling approach using mesoscale meteorological models.

Two different strategies have been proposed for statistically based disaggregation of general circulation model output. Kim et al. (1984) described an approach based on a principal components analysis of time series of climate data observed over a dense network (relative to the resolution of a general circulation model). Often, the first several components will represent the general anomalies over a network. Correlations between those components and model output at a specific grid point could then be sought, and the spatial structure of the components could then be used to disaggregate the grid-point output.

The second statistically based approach involves the construction of regression equations that relate the long-term averages of individual climate variables observed over a calibration network to a set of predictor variables that describe the location and elevation of individual stations in the network (Craig, 1984). Location is described, for example, in terms of the distance from the sea coast, and the nature of upwind topographic barriers. In practice, the equations could be applied to locations within the calibration network where climate station data are not available to (1) interpolate the observed climate values or (2) to estimate values of the climate variables consistent with the general circulation models output using wind patterns as simulated by a general circulation model.

While computationally straightforward, the empirical approaches have several drawbacks. The empirical models do not represent the physical processes that generate local variations of climate in any explicit fashion. For example, they do not explicitly represent the control for the occurrence and abundance of precipitation by the large-scale circulation. The empirical basis, and lack of explicit physics, may limit the usefulness of the statistical models when extrapolation is required, as it is for both paleoclimatic simulations or future climate predictions.

The second model-based approach for the spatial disaggregation of general circulation model simulations makes use of mesoscale meteorological models (Anthes, 1983). Mesoscale meteorological models like general circulation models attempt to explicitly represent the physical processes that govern atmospheric circulation and the surface energy and hydrologic balances. The spatial resolution of regional mesoscale models is generally much finer than that of general circulation models and the representation of the surface energy and hydrologic balances is usually more detailed, as is the representation of topography. In practice, mesoscale meteorological models could be used to spatially disaggregate the output of a general circulation model. This could be accomplished by using the general circulation models output to initialize the mesoscale meteorological model, in much the same way that widely distributed meteorological observations are used to initialize standard numerical weather prediction models. The greater topographic detail, and more realistic representation of the surface processes in the mesoscale meteorological models, permit the simulation of regional and local-scale snapshots of climate variables consistent with the larger-scale patterns of those variables simulated by a general circulation model. One limitation of mesoscale meteorological models, however, is that they use the broadly defined boundary conditions of the general circulation model. If there are assumptions and approximations made in developing these boundary conditions, these assumptions are transferred to the mesoscale meteorological models.

Like general circulation models, mesoscale meteorological models require considerable computing resources. This disadvantage is somewhat outweighed, however, by the physical basis of the models, which should make them more robust than the empirically based models when applied in the context of either paleoclimatic reconstruction or climatic prediction.

In making a choice between using a general circulation model-mesoscale meteorological model approach versus an empirically based approach, these factors as well as others (e.g., amount of data available and requirements made by the hydrologic investigators) need to be considered. This consideration is discussed briefly in Section 8.3.1.5.1 and will be a continuing process throughout site characterization.

5.2.2.3.5 Model validation

An important step in the overall modeling effort will be to measure the performance of the model in order to estimate the uncertainties inherent in the eventual climate predictions. The standard criterion used is how well a model simulates the modern climate. While such measures are useful, the danger always exists that a model may be tuned to perform well with respect to the modern climate.

In the hierarchy of climate simulation methods just described, there are two important sources of uncertainty. The first arises in the simulation, on the basis of boundary conditions, of the slowly varying components, and in turn, simulations of the fast-response components of the climate system. The second source of uncertainty arises in the spatial disaggregation of the fast-response components. These uncertainties may be posed as two questions. As the boundary conditions and slowly varying components evolve through time, will the snapshots simulated by the models of the fast-response components adequately track the actual climate? At a specific time, will the spatial patterns of climate be adequately portrayed by the approach used to disaggregate the simulations of the fast-response components? The paleoclimatic record, containing as it does the output of the ideal climate model, can provide the answers to these questions.

Two model validation exercises can be envisaged, one involving long time series of paleoclimatic data at key locations, and the second using dense networks of data at key times. The first exercise would test the ability of the model to track the actual climate as the boundary conditions and slowly varying components change over the next 100,000 yr. Ideally, continuous paleoclimatic records from key locations extending back to the previous interglacial would be used in this exercise. The second exercise would test the ability of the model to simulate correctly the spatial patterns of climatic variations at an appropriate scale. For this exercise, paleoclimatic evidence will be collected to describe spatial patterns of climatic variations at such key times as the full-glacial, late-glacial, early Holocene, etc. For both exercises, methods such as those described in Section 5.2.1.2.2 would be used to transform the model output into simulations of the various paleoclimatic indicators that would then be compared with the observed fossil record. Plans for investigations to develop and validate climate models to satisfy the needs just discussed are specified in Section 8.3.1.5.1.

The individual elements of this procedure for predicting future climates follow the hierarchical nature of climatic variations in a particular region--from global-scale variations of boundary conditions and the slowly varying components of the climate system, to regional-scale variations of the fast-response components. While individual climate simulation models applicable to this approach exist, no comprehensive attempt at predicting future cli-matic variations has yet been made. For this reason, model validation experiments must be carried out to judge the reliability of the predictions. In addition to providing insight into the nature and extent of past climatic variations, the paleoclimatic record provides the information required for the climate model validation exercises. The use of paleoclimatic data for these purposes involves three broad tasks:

1. A data collection task in which the necessary paleoclimatic data, both geologic and biologic, are collected over appropriate networks where possible (i.e., long records at key locations and dense networks at key times).

2. A modeling task in which relationships are developed to link the various climatic indicators to their climatic controls (e.g., lake hydrologic models (Benson, 1986) and modern vegetation-climate relationships (Bartlein et al., 1985)).

3. An interpretation task in which (1) the geologic or paleoecologic record is interpreted in climatic terms, (2) the nature of past

climatic variations is inferred, and (3) the observed paleoclimatic record is compared with that generated by climate-simulation models.

Successful completion of these three tasks is required to document the range of climate variations experienced in the past, to simulate probable future variations, and to provide input for estimating the impact of the effect of those variations on the surface and ground-water systems in the vicinity of Yucca Mountain.

5.2.3 SITE PALEOCLIMATIC INVESTIGATIONS

Historical and prehistorical climatic, limnologic, hydrologic, and vegetational data obtained from near Yucca Mountain and the surrounding region will be used to increase and supplement the paleoclimatic data base used for characterization of the Yucca Mountain site. Detailed plans designed to obtain these data are presented in Section 8.3.1.5.1 for the following activities.

5.2.3.1 Synoptic characterization of regional climate

Historical meteorological data from the Great Basin will be compiled and summarized to provide synoptic-scale information. These data will be used in calibration activities for vegetation-climate and lake-climate models, as well as in the development of a regional climate model. Information on the stable isotope "signatures" from dated ground water and from modern precipitation networks will be obtained from the geohydrology (Section 8.3.1.2) and meteorology (Section 8.3.1.12) programs used in this activity.

5.2.3.2 Collection and analysis of pollen and pack rat midden macrofossil assemblages from the Great Basin

Recent pollen and vegetational assemblages are being collected and mathematically correlated with climatological data (temperature, amount of precipitation, etc.) using transfer functions and response surface techniques. Pollen and macrofossil suites from lake sediments and pack rat middens are being collected and isotopically dated. The transfer and response surface will be used to extract quantitative estimates of climate variation from the vegetational time series data.

5.2.3.3 Coring and paleontological, sedimentological, chemical, and chronological analyses of lacustrine and marsh deposits

Sediment cores will be obtained from playas, paleomarshes, and lakes near Yucca Mountain and in the surrounding region. The paleontological and sedimentolgical changes recorded in these cores will provide dated time series of (1) changes in size, chemistry, and productivity of lakes and (2) wet phases in now-dry playas and marshes.

5.2.3.4 Development, validation, and application of a generalized model of late-Quaternary climatic variations to predict future climate change at the Yucca Mountain site

A generalized model of late-Quaternary climatic variations in the southern Great Basin will be developed, upon which estimates of the range of future climatic conditions can be based. This generalized model has two elements: (1) the reconstruction of past climatic variations to illustrate the range of potential regional climatic variations, and (2) the development of climate simulation models to estimate the response of the regional climate to future changes in the boundary conditions. Reconstruction of past climatic variations will be based on the paleoecological record (pollen and plant macrofossil), supplemented by paleohydrologic, sedimentologic, and geomorphic data sets. Climate simulation models will be validated with the same data sets to measure the ability of the models to correctly simulate past climatic variations, thereby gauging their potential for simulating future variations. These activities will require data on vegetative cover, lake size, lake temperature, glacier size, stream discharge, and infiltration rate. The validation exercises will demonstrate the degree to which the model can simulate climate change without recourse to arbitrary parametric adjustment.

5.3 SUMMARY

The data discussed thus far in this chapter have established the existing climatic information and discussed why data are needed and identified areas where data are lacking or inadequate. This section provides a synopsis of these points and relates them to performance objectives, conceptual models and bounding conditions, the need for supplemental data, and the quality of the presently available data.

5.3.1 SUMMARY OF SIGNIFICANT RESULTS

The existing climate in the vicinity of Yucca Mountain site, as defined by meteorological data available from sites around Yucca Mountain, is classified as midlatitude desert. Variations of a given meteorological parameter, however, are strongly influenced by elevation, giving rise to wide ranges for parameters within the climatological classification. The most notable general meteorological conditions expected at Yucca Mountain are temperature extremes, particularly during summer months, approaching 50°C; temperature ranges between maximum and minimum of nearly 25 Celsius degrees; and low annual precipitation amounts, less than about 6 in. (150 mm) annually.

Skies are predominantly clear throughout the year, and the average relative humidity is low. Precipitation in the area is limited by the blocking and subsequent rain shadow effect of the Sierra Nevada during winter months, although monthly average precipitation reaches its annual peak during January or February. Precipitation is also generated in the area by summer thunderstorm activity, representing a secondary monthly average peak in July or August. Despite the existence of this well-defined annual cycle, precipitation averages only about 150 mm/yr. Winds from the north dominate during fall, winter, and into early spring, but shift to predominately south to southwesterly in late spring and early summer. Terrain influences somewhat disrupt this annual average cycle, with upgradient winds occurring during daylight hours in almost all months.

Meteorological data are also needed as input to infiltration studies and rainfall-runoff modeling. The existing data set is not site specific enough for these investigations, and does not provide detailed information on precipitation intensity, temporal, or areal variability that is necessary for hydrologic investigations (see Chapter 3 and Section 8.3.1.2 for more on hydrologic studies). Therefore, a site monitoring program that will provide the required data has been implemented and will be operated throughout site characterization.

A secondary purpose of collecting site-specific meteorological data, although not directly related to site characterization, is to fulfill permitting and licensing requirements. The environmental monitoring and mitigation plan and the environmental regulatory compliance plan will contain detailed information on the need and use of the meteorological data in permitting and licensing activities. These activities will ensure that the facilities can be built and operated within regulatory constraints.

These short-term considerations, however, are only one aspect of the repository system-climate interaction that must be considered to ensure long-term waste isolation. Long-term climatological evaluations are summarized in the following paragraphs.

The currently available information indicates the presence of two major lake cycles in the Great Basin during the past 150,000 yr. The last cycle, which occurred during the late Pleistocene, is well documented in the Bonneville, Lahontan, and Mono basins. The older cycle is poorly documented by absolute age determination in both the Bonneville and Lahontan basins, but seems to have occurred 120,000 to 90,000 yr ago. A large number of basins throughout the Great Basin, which today are playas or dry lakes, contain shoreline evidence of two former lake cycles. Radiocarbon analyses of material from the basins indicate that the youngest shoreline probably corresponds to a lake cycle that occurred in the late Pleistocene. The age of the oldest shoreline is not known. In addition to these two cycles thee are indications that other lacustrine high stands may have occurred during the middle Wisconsin (Forester, 1987) and that in some lake basins these lesser known events may have been of larger magnitude that the late Wisconsin high stand. Future needs include more detailed analyses of sediment cores that extend further back in time. Studies of cores dating back to the oxygen isotope stage 5d-5e (Shackleton et al., 1983) are necessary to evaluate glacial-interglacial climatic transitions.

The correlation between prehistoric lake cycles and periods of increased precipitation in the region around Yucca Mountain is not well understood, although the last period of significantly increased precipitation in southern

Nevada may correlate with the timing of the last lake cycle in the northern portion of the Great Basin. Moreover, the relationship between increased precipitation and recharge in the region is not well understood. For this reason the available paleoclimatic data offer insufficient insight into the history of ground-water recharge there. Other data, however, have contributed to the current understanding of recharge; they are discussed in Section 3.7.

Information on the advance and retreat of mountain glaciers within the Great Basin is scant. The few data that do exist indicate that late-Wisconsin mountain glaciation may have been roughly synchronous with the last lake cycle.

Pack rat midden and palynological studies indicate that the sagebrush steppe and other vegetation assemblages that adapted to relatively cold, dry conditions were more widespread, during the period from at least 40,000 to 11,000 yr ago, than today; with the period from approximately 20,000 to 14,000 yr ago representing the maximal difference from modern conditions. Plant species and associations that adapted to warmer temperatures and higher levels of summer rainfall were absent or rare during this period. The Wisconsin-age vegetation appears to reflect reduced temperatures rather than great enhancements of pluvial precipitation. By 11,000 yr ago sagebrush and xerophytic subalpine conifers began to move to higher elevations, reflecting increasing warmth and perhaps aridity. However, in much of the Great Basin and Mojave Desert region it appears that conditions between 11,000 and 7,000 yr ago remained cooler than those of today. The pack rat midden data have been interpreted as indicating that monsoonal summer rainfall reached southern Nevada some time between 11,000 and 5,000 yr ago, and may have been at higher than modern levels for all or part of the period.

The repeated fluctuations between glacial and interglacial climates that occurred during the Quaternary are fundamentally related to variations in the seasonal and latitudinal receipt of solar radiation, as determined by variations of the earth's orbital elements. The orbital variations, which explain a considerable portion of the total variance of large-scale climatic phenomena, will continue to force large-scale climate change. The task that remains is to relate the response of climatic variation in the southern Great Basin to large-scale climatic phenomena. Prediction of future climatic variation over the next 100,000 yr requires a multistep procedure that incorporates the hierarchy of controls and responses in the climate system. The development of climate prediction methods must, therefore, proceed in a top-down fashion, from the larger-spatial, longer-temporal scale controls to the local responses to variation in these controls. The process involves the correlation of present-day vegetational and meteorological data and the application of the correlations to paleobotanic records to extract the prehistoric record of climate variation. The process also uses the paleolacustrine, glacial, and paleobotanic records for model validation.

For the near-future (the next 10 to 1,000 yr) predictions of climate, the effect of large inputs of anthropogenic aerosols, carbon dioxide, and other trace gases into the climate system must be taken into account.

The quality of published data needed for input to the developmental validation of a future-climate model is poor to fair depending on the areal and temporal scales of interest. Climatic, stream-flow, and vegetational data for the region during the past 50 yr are of fair quality and are probably sufficient for modeling applications. Lake-level and vegetational time-series data exist for a limited number of sites in the northern and western parts of the region for approximately the past 20,000 yr, but they are insufficient in the southern Great Basin, particularly in the vicinity of Yucca Mountain. Vegetational, hydrologic, and geologic time-series data are poor to inadequate for times before 20,000 yr ago; the aquisition of this older time-series data will be necessary for future climate modeling efforts.

5.3.2 RELATION TO DESIGN

Design of surface facilities must account for extremely high temperatures in summer months that drop significantly at night. Freezing temperatures must be considered, and the possibility of snow cannot be ignored. The components of the surface facilities that extend above ground must be able to withstand occasional high-speed gusts of wind. Aside from providing human comfort and safety needs, the only other meteorological factor that must be considered in the design of the surface facilities is the assurance that flood potential has been considered. Paleoclimatic influences are not pertinent to design.

5.3.3 IDENTIFICATION OF INVESTIGATIONS AND INFORMATION NEEDS

The primary investigation relative to assessing repository performance in terms of meteorological influences is a comprehensive, site-specific base of meteorological data. The data should include hourly averages of wind speed, wind direction, temperature, and parameters for the determination of atmospheric stability. Ideally, the data should cover as long a time period as possible and should include parameters for comparison with less site-specific but longer-term climatological records (precipitation and relative humidity). The Meteorological Monitoring Plan (SAIC, 1985) (Section 8.3.1.12) provides a means by which this information need can be satisfied.

Additional paleoclimatic data are also needed for site characterization. Continuous paleoclimatic records from key locations extending back to the previous interglacial (about 125,000 yr ago) are needed to test the ability of the climate model to track the actual climate as the boundary conditions and slowly varying components change over the time scale of interest. A more dense network of paleoclimatic records extending back about 20,000 yr is needed to describe spatial patterns of climatic variation for such key times as full glacial, late glacial, and early Holocene. Climatic data at a single key location extending back several hundred thousand years are also desirable for determination of the nature (magnitude, frequency) of climate response to astronomic forcing. Models of future local and global climatic variability are needed to establish an important boundary condition (recharge) of the ground-water system.

Underlying these planned and ongoing studies and, indeed, all paleoclimatic studies in southern Nevada generally and at the Yucca Mountain site specifically, is the need for integrating results and interpretations to produce a coherent picture of paleoenvironmental change. The interpretive, integrative, and data gathering processes must all equally progress in time because the insights gained by this effort will direct future research most efficiently.

5.3.4 RELATION TO REGULATORY GUIDE 4.17

A comparison of the information in Chapter 5 with Regulatory Guide 4.17 (NRC, 1987) shows that none of the information required by the guide has been omitted from Chapter 5, but the chapter does include additional information as follows:

1. An introduction that discusses the general information included in the chapter.

2. A summary (Section 5.3) that provides a link between the data presented in the chapter and the plans described in Chapter 8.

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Chapter 5

REFERENCES

Nuclear Waste Policy Act
(Section 113)

Consultation Draft

Site Characterization Plan

Yucca Mountain Site, Nevada Research and Development Area, Nevada

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U.S. Department of Energy
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Washington, DC 20585

REFERENCES FOR CHAPTER 5

Adam, D. P., 1967. "Late-Pleistocene and Recent Palynology in the Central Sierra Nevada, California," Quaternary Paleoecology, E. J. Cushing and H. E. Wright, Jr. (eds.), Yale University Press, New Haven, Conn., pp. 275-301.

Antevs, E., 1948. "Climatic Changes and Pre-White Man," The Great Basin, with Emphasis on Glacial and Postglacial Times, Bulletin of the University of Utah, Vol. 38, No. 20, pp. 168-191.

Anthes, R. A., 1983. "Regional Models of the Atmosphere in Middle Latitudes," Monthly Weather Review, Vol. 111, pp. 1306-1335.

Arnow, T., 1984. Water-Level and Water Quality Changes in Great Salt Lake, Utah, 1847-1983, Geological Survey Circular 913, Alexandria, Virginia.

Atwater, B. F., D. P. Adam, J. P. Bradbury, R. M. Forester, R. K. Mark, W. R. Lettis, G. R. Fischer, K. W. Gobalet, and S. W. Robinson, 1986. "A Fan Dam for Tulare Lake, California, and Implications for the Wisconsin Glacial History of the Sierra Nevada," Geological Society of America Bulletin, Vol. 97, pp. 97-109.

Bartlein, P. J., 1982. "Streamflow Anomaly Patterns in the U.S.A. and Southern Canada - 1951 - 1970," Journal of Hydrology, Vol. 57, Elsevier Scientific Publishing Company, Amsterdam, The Netherlands, pp. 49-63.

Bartlein, P. J., and T. Webb, III, 1985. "Mean July Temperature at 6,000 Yr B.P. in Eastern North America: Regression Equations for Estimates from Fossil-Pollen Data," Climatic Change in Canada 5: Critical Periods in the Quaternary Climatic History of Northern North America, C. R. Harington (ed.), pp. 301-342.

Bartlein, P. J., T. Webb, III, and E. Fleri, 1984. "Holocene Climatic Change in the Northern Midwest: Pollen-Derived Estimates," Quaternary Research, Vol. 22, pp. 361-374.

Bartlein, P. J., I. C. Prentice, T. Webb, III, 1985. "Climatic Response Surfaces from Pollen Data for Some Eastern North American Taxa," Journal of Biogeography, Vol. 12, pp. 310-1-310-24.

Benson, L. V., 1978. "Fluctuation in the Level of Pluvial Lake Lahontan During the Last 40,000 Years," Quaternary Research, Vol. 9, pp. 300-318.

Benson, L. V., 1981. "Paleoclimatic Significance of Lake-Level Fluctuations in the Lahontan Basin," Quarternary Research, Vol. 16, pp. 390-403.

Benson, L. V., 1986. The Sensitivity of Evaporation Rate to Climate Change--Results of an Energy-Balance Approach, USGS-WRI-86-4148, Water-Resources Investigations Report, U.S. Geological Survey, Denver, Colo.

Benson, L. V., and P. W. McKinley, 1985. Chemical Composition of Ground Water in the Yucca Mountain Area, Nevada, 1971-84, USGS-OFR-85-484, Open-File Report, U.S. Geological Survey, Denver, Colo.

Benson, L. V., and M. D. Mifflin, 1986. Reconnaissance Bathymetry of Basins Occupied by Pleistocene Lake Lahontan, Nevada and California, USGS-WRI-85-4262, Water-Resources Investigations Report, U.S. Geological Survey, Denver, Colo.

Benson, L. V., and R. S. Thompson, 1987. "Lakes - The Physical and Geochemical Record of Great Basin Lakes," North America and Adjacent Oceans during the Last Deglaciation, W. F. Ruddiman and H. E. Wright, Jr. (eds.), Chapter 10, Geological Society of America, Boulder, Colo.

Benson, L. V., J. H. Robison, R. K. Blankennagel, and A. E. Ogard, 1983. Chemical Composition of Ground Water and the Locations of Permeable Zones in the Yucca Mountain Area, Nevada, USGS-OFR-83-854, Open-File Report, U.S. Geological Survey, Denver, Colo.

Bischoff, J. L., R. J. Rosenbauer, and G. I. Smith, 1985. "Uranium-Series Dating of Sediments from Searles Lake: Differences Between Continental and Marine Climate Records," Science, Vol. 227, pp. 1222-1224.

Blackwelder, E., 1931. "Pleistocene Glaciation in the Sierra Nevada and Basin Ranges," Bulletin of the Geological Society of America, Vol. 42, pp. 865-922.

Blaney, H. F., 1957. "Evaporation Study at Silver Lake in the Mojave Desert, California," Transactions, American Geophysical Union, Vol. 38, No. 2, pp. 209-215.

Bloom, A. L., 1983. "Sea Level and Coastal Morphology of the United States Through the Late Wisconsin Glacial Maximum," Late-Quaternary Environments of the United States, Volume 1, The Late Pleistocene, S. C. Porter (ed.), Chapter 11, University of Minnesota Press, Minneapolis, pp. 215-229.

Born, S. M., 1972. Late Quaternary History, Deltaic Sedimentation, and Mudlump Formation at Pyramid Lake, Nevada, Center for Water Resources Research, Desert Research Institute, University of Nevada System.

Bowen, J. L., and R. T. Egami, 1983a. Atmospheric Overview for the Nevada Nuclear Waste Storage Investigations, Nevada Test Site, Nye County, Nevada, NVO-269, Nevada Operations Office, U.S. Department of Energy, Las Vegas.

Bowen, J. L., and R. T. Egami, 1983b. Nevada Nuclear Waste Storage Investigations Site Characterization Activities: Preliminary Atmospheric Assessment of a Nuclear Waste Repository, NVO-258, Nevada Operations Office, U.S. Department of Energy, Las Vegas.

Brakenridge, G. R., 1978. "Evidence for a Cold, Dry Full-Glacial Climate in the American Southwest," Quaternary Research, Vol. 9, pp. 22-40.

Broecker, W. S., and A. Kaufman, 1965. "Radiocarbon Chronology of Lake Lahontan and Lake Bonneville II, Great Basin," Geological Society of America Bulletin, Vol. 76, pp. 537-566.

Broecker, W. S., and P. C. Orr, 1958. "Radiocarbon Chronology of Lake Lahonton and Lake Bonneville," Bulletin of the Geological Society of America, Vol. 69, pp. 1009-1032.

Broecker, W. S., and A. Walton, 1959. "The Geochemistry of C-14 in Fresh-Water Systems," Geochimica et Cosmochimica Acta, Vol. 16, pp. 15-38.

Brubaker, L. B., and E. R. Cook, 1983. "Tree-Ring Studies of Holocene Environments," Late Quaternary Environments of the United States, Volume II, The Holocene, H. E. Wright, Jr. (ed.), University of Minnesota Press, pp. 222-235.

Budd, W. F., and I. N. Smith, 1981. "The Growth and Retreat of Ice Sheets in Response to Orbital Radiation Changes," Sea Level, Ice, and Climatic Changes, Proceedings of the Symposium held December 7-8, 1979, during the 17th General Assembly of the International Union of Geodesy and Geophysics, Canberra, IAHS Publication No. 13, pp. 369-409.

Burke, R. M., and P. W. Birkeland, 1983. "Holocene Glaciation in the Mountain Ranges of the Western United States," Late-Quaternary Environments of the United States, The Holocene, Vol. 2, Chapter 1, H. E. Wright, Jr. (ed.), University of Minnesota Press, pp. 3-11.

Butler, P. R., 1986. "Fluvial Response to Ongoing Tectonism, Lower Amargosa River, Southern Death Valley, California," pp. 17-23.

CLIMAP Project Members, 1981. Seasonal Reconstructions of the Earth's Surface at the Last Glacial Maximum, Map and Chart Series, MC-36, Geological Society of America, Boulder, Colo.

Chu, J. -H., 1986. Atmospheric Phenomena at Yucca Mountain, Nevada Test Site, tabular material.

Claassen, H. C., 1985. Sources and Mechanisms of Recharge for Ground Water in the West-Central Amargosa Desert, Nevada--A Geochemical Interpretation, U.S. Geological Survey Professional Paper 712-F, U.S. Government Printing Office, Washington, D.C.

Cole, K., 1983. "Late Pleistocene Vegetation of Kings Canyon, Sierra Nevada, California," Quaternary Research, Vol. 19, pp. 117-129.

Craig, R. G. with contributions from B. L. Roberts and M. Singer, 1984. Climates and Lakes of the Death Valley Drainage System During the Last Glacial Maximum, unpublished paper, available from the Department of Geology, Kent State University, Kent, Ohio.

Critchfield, H. J., 1983. "Climatic Classification," General Climatology, Chapter 6, Prentice Hall, Englewood Cliffs, N.J., pp. 141-155.

Crowley, T. J., 1983. "The Geologic Record of Climatic Change," Reviews of Geophysics and Space Physics, Vol. 21, No. 4, pp. 828-877.

Currey, D. R., 1980. "Coastal Geomorphology of Great Salt Lake and Vicinity," Utah Geological and Mineral Survey Bulletin, Vol. 116, pp. 69-82.

Currey, D. R., and C. G. Oviatt, 1985. "Durations, Average Rates, and Probable Causes of Lake Bonneville Expansions, Stillstands, and Contractions During the Last Deep-Lake Cycle, 32,000 to 10,000 Years Ago," Problems of and Prospects for Predicting Great Salt Lake Levels, P. A. Kay and H. F. Diaz (eds.), Center for Public Affairs and Administration, University of Utah.

DOC (U.S. Department of Commerce), 1986. Monthly and Annual Wind Distribution by Pasquill Stability Classes, Star Program, 6 Classes, Job No. 01775, National Climatic Data Center, Federal Building, Asheville, N.C.

Davis, J. O., R. Elston, and G. Townsend, 1976. "Coastal Geomorphology of the South Shore of Lake Tahoe: Suggestion of an Altithermal Lowstand," Holocene Environmental Change in the Great Basin, R. Elston (ed.), Nevada Archeological Survey Research Paper No. 6, pp. 41-65.

Davis, O. K., R. S. Anderson, P. L. Fall, M. K. O'Rourke, and R. S. Thompson, 1985. "Palynological Evidence for Early Holocene Aridity in the Southern Sierra Nevada, California," Quaternary Research, Vol. 24, pp. 322-332.

Denton, G. H., and T. J. Hughes, 1981. The Last Great Ice Sheets, J. Wiley and Sons, New York, 484 p.

Dohrenwend, J. C., 1984. "Nivation Landforms in the Western Great Basin and Their Paleoclimatic Significance," Quaternary Research, Vol. 22, pp. 275-288.

Dorn, R. I., M. J. DeNiro, and H. O. Aije, 1987. "Isotopic Evidence for Climatic Influence on Alluvial-Fan Development in Death Valley, California," Geology, Vol. 15, pp. 108-110.

EPA (U.S. Environmental Protection Agency), 1980. Ambient Monitoring Guidelines for Prevention of Significant Deterioration (PSD), EPA-450/4-80-012, Office of Air Quality Planning and Standards, Research Triangle Park, N.C.

Eardley, A. J., V. Gvosdetsky, and R. E. Marsell, 1957. "Hydrology of Lake Bonneville and Sediments and Soils of Its Basin," Bulletin of the Geological Society of America, Vol. 68, pp. 1141-1201.

Eglinton, T. W., and R. J. Dreicer, 1984. Meteorological Design Parameters for the Candidate Site of a Radioactive-Waste Repository at Yucca Mountain, Nevada, SAND84-0440/2, Sandia National Laboratories, Albuquerque, N. Mex.

Everett, D. E., and F. E. Rush, 1967. A Brief Appraisal of the Water Resources of the Walker Lake Area, Mineral, Lyon, and Churchill Counties, Nevada, Water Resources-Reconnaissance Series Report 40, State of Nevada, Department of Conservation and Natural Resources, Carson City.

Forester, R. M., 1987. "Late-Quaternary Paleoclimate Records from Lacustrine Ostracodes," North America and Adjacent Oceans during the Last Deglaciation, W. F. Ruddiman and H. E. Wright, Jr. (eds.), Geological Society of America, Boulder, Colo.

GSA (Geological Society of America), 1983. The Decade of North American Geology 1983 Geologic Time Scale, Vol. 11, pp. 503-504.

Gale, H. S., 1914. "Salines in the Owens, Searles, and Panamint Basins, Southeastern California," Contributions to Economic Geology, Part I.--Metals and Nonmetals Except Fuels, Geological Survey Bulletin 580, U.S. Government Printing Office, Washington, D.C., pp. 251-323.

Galloway, R. W., 1970. "The Full-Glacial Climate in the Southwestern United States," Association of American Geographers Annual, Vol. 60, pp. 245-256.

Gates, W. L., 1976a. "Modeling the Ice-Age Climate," Science, Vol. 191, pp. 1138-1144.

Gates, W. L., 1976b. "The Numerical Simulation of Ice-Age Climate with a Global General Circulation Model," Journal of the Atmosperic Sciences, Vol. 33, pp. 1844-1873.

Gates, W. L., 1985. "Modeling as a Means of Studying the Climate System," Projecting the Climatic Effects of Increasing Carbon Dioxide, M. C. MacCracken, and F. M. Luther (eds.), DOE/ER-0237, U.S. Department of Energy, Washington, D.C., pp. 59-79.

Gilbert, G. K., 1890. "Lake Bonneville," U.S. Geological Survey Monograph 1, 438 p.

Harding, S. T., 1965. Recent Variations in the Water Supply of the Western Great Basin, Archives Series Report No. 16, Water Resources Center Archives, University of California, Berkeley, pp. 99, 107, 145, 159.

Haynes, C. V., 1967. "Quaternary Geology of the Tule Springs Area, Clark County, Nevada," Pleistocene Studies in Southern Nevada, H. M. Wormington and D. Ellis (eds.), Nevada State Museum Anthropological Papers No. 13, Carson City, Nev., pp. 15-104.

Hays, J. D., J. Imbrie, and N. J. Shackleton, 1976. Variations in the Earth's Orbit: Pacemaker of the Ice Ages, Science, Vol. 194, No. 4270, pp. 1121-1132.

Hershfield, B. M., 1961. Rainfall Frequency Atlas of the United States for Durations from 30 Minutes to 24 Hours and Return Periods from 1 to 100 Years, U.S. Weather Bureau Technical Paper No. 40, Department of Commerce, Washington, D.C.

Hirschboeck, K. K., 1980. "A New Worldwide Chronology of Volcanic Eruptions," Palaeogeography, Palaeoclimatology, Palaeoecology, Vol. 29, pp. 223-241.

Hooke, R. L., 1972. "Geomorphic Evidence for Late-Wisconsin and Holocene Tectonic Deformation, Death Valley, California," Geological Society of America Bulletin, Vol. 83, No. 7, pp. 2073-2098.

Houghton, J. G., C. M. Sakamoto, and R. O. Gifford, 1975. Nevada's Weather and Climate, Nevada Bureau of Mines and Geology Special Publication Number 2, Mackay School of Mines, University of Nevada, Reno.

Howe, S., and T. Webb, III, 1983. "Calibrating Pollen Data in Climatic Terms: Improving the Methods," Quaternary Science Reviews, Vol. 2, pp. 17-51.

Hughes, T. J., G. H. Denton, B. G. Andersen, D. H. Schilling, J. L. Fastook, C. S. Lingle, 1981. "The Last Great Ice Sheets: A Global View," The Last Great Ice Sheets, G. H. Denton and T. J. Hughes (eds.), John Wiley & Sons, New York, pp. 263-317.

Hunt, C. B., and D. R. Mabey, 1966. Stratigraphy and Structure, Death Valley, California, General Geology of Death Valley, California, U.S. Geological Survey Professional Paper 494-A, Washington, D.C.

Huschke, R. E. (ed.), 1959. Glossary of Meteorology, American Meteorological Society, Boston, Mass., pp. 581-582.

Imbrie, J., 1985. "A Theoretical Framework for the Pleistocene Ice Ages," Journal of the Geological Society of London, Vol. 142, Northern Ireland, pp. 417-432.

Imbrie, J., and J. Z. Imbrie, 1980. "Modeling the Climatic Response to Orbital Variations," Science, Vol. 207, pp. 943-953.

Imbrie, J., A. McIntyre, and T. C. Moore, Jr., 1983. "The Ocean Around North America at the Last Glacial Maximum," Late Quaternary Environments of the United States, The Pleistocene, S. C. Porter (ed.), Vol. I, Chapter 12, University of Minnesota Press, Minneapolis, pp. 230-238.

Imbrie, J. H., J. D. Hays, D. G. Martinson, A. McIntyre, A. C. Mix, J. J. Morely, N. G. Pisias, W. L. Prell, and N. J. Shackleton, 1984. "The Orbital Theory of Pleistocene Climate: Support from a Revised Chronology of the Marine 18-O Record," Milankovitch and Climates, Part 1, A. Berger, J. Imbrie, J. Hays, G. Kukla, and B. Saltzman (eds.), D. Reidel Publishing Company, pp. 269-305.

Kay, P. A., and J. T. Andrews, 1983. "Re-evaluation of Pollen-Climate Transfer Functions in Keewatin, Northern Canada," Annals, Association of American Geographers, Vol. 73, pp. 550-559.

Kim, J. -W., J. -T. Chang, N. L. Baker, D. S. Wilks, and W. L. Gates, 1984. "The Statistical Problem of Climate Inversion: Determination of the Relationship between Local and Large-Scale Climate," Monthly Weather Review, Vol. 112, pp. 2069-2077.

Knighton, D. A., 1984. Fluvial Forms and Processes, Edward Arnold Publishers, London, pp. 68-71.

Kutzbach, J. E., 1981. "Monsoon Climate of the Early Holocene: Climate Experiment With the Earth's Orbital Parameters for 9,000 Years Ago," Science, Vol. 214, pp. 59-61.

Kutzbach, J. E., 1985. "Modeling of Paleoclimates," Advances in Geophysics, Vol. 28A, pp. 159-196.

Kutzbach, J. E., and P. J. Guetter, 1984. "Sensitivity of Late-Glacial and Holocene Climates to the Combined Effects of Orbital Parameter Changes and Lower Boundary Condition Changes," Annals of Glaciology, Vol. 5, pp. 85-87.

Kutzbach, J. E., and P. J. Guetter, 1986. "The Influence of Changing Orbital Parameters and Surface Boundary Conditions on Climate Simulations for the Past 18,000 Years," Journal of the Atmospheric Sciences, Vol. 43, No. 16, pp. 1726-1759.

Kutzbach, J. E., and F. A. Street-Perrott, 1985. "Milankovitch Forcing of Fluctuations in the Level of Tropical Lakes from 18 to 0 kyr BP," Nature, Vol. 317, pp. 130-134.

Kutzbach, J. E., and H. E. Wright, Jr., 1985. "Simulation of the Climate of 18,000 Years BP: Results for the North American/North Atlantic/European Sector and Comparison with the Geologic Record of North America," Quaternary Science Reviews, Vol. 4, pp. 147-187.

Lajoie, K. R., 1963. Late Quaternary Stratigraphy and Geologic History of Mono Basin, Eastern California, Dissertation, University of California, Berkeley.

LaMarche, V. C., Jr., 1974. "Paleoclimatic Inferences from Long Tree-Ring Records," Science, Vol. 183, pp. 1043-1048.

LaMarche, V. C., Jr., and H. A. Mooney, 1972. "Recent Climatic Change and Development of the Bristlecone Pine (P. longaeva Bailey) Krummholz Zone, Mt. Washington, Nevada," Arctic and Alpine Research, Vol. 4, No. 1, pp. 61-72.

Langbein, W. B., and Others, 1949. Annual Runoff in the United States, Geological Survey Circular 52, U.S. Geological Survey, Denver, Colo.

Leopold, E. B., 1967. "Summary of Palynological Data From Searles Lake," Guidebook For Friends of the Pleistocene Pacific Coast Section, pp. 51-66.

Leopold, L. B., 1951. "Pleistocene Climate in New Mexico," American Journal of Science, Vol. 249, pp. 152-168.

Lloyd, C. R., 1984. "Pre-Pleistocene Paleoclimate: The Geological and Paleontological Evidence, Modeling Strategies, Boundary Conditions, and Some Preliminary Results," Advances in Geophysics, Vol. 26, pp. 35-140.

Ludlum, D. M., 1982. The American Weather Book, Houghton Mifflin Company, Boston, Mass., pp. 93-105.

MacCracken, M. C., and F. M. Luther, 1985. "Projecting The Climatic Effects Of Increasing Carbon Dioxide," Carbon Dioxide And Climate Change: Background And Overview, M. C. MacCracken and F. M. Luther (eds.), DOE/ER-0237, U.S. Department of Energy, Washington, D.C., pp. 3-23.

Madsen, D. B., and D. R. Currey, 1979. "Late Quaternary Glacial and Vegetation Changes, Little Cottonwood Canyon Area, Wasatch Mountains, Utah," Quaternary Research, Vol. 12, pp. 254-270.

Mahaffy, M. W., 1976. "A Three-Dimensional Numerical Model of Ice Sheets: Tests on the Barnes Ice Cap, Northwest Territories," Journal of Geophysical Research, Vol. 81, No. 6, pp. 1059-1066.

Manabe, S., and A. J. Broccoli, 1985. "The Influence of Continental Ice Sheets on the Climate of an Ice Age," Journal of Geophysical Research, Vol. 90, No. D1, pp. 2167-2190.

Manabe, S., and D. G. Hahn, 1977. "Simulation of the Tropical Climate of an Ice Age," Journal of Geophysical Research, Vol. 82, No. 27, pp. 3889-3911.

Manabe, S., and R. T. Wetherald, 1985. "CO2 and Hydrology," Advances in Geophysics, Vol. 28A, pp. 131-157.

Martin, P. S., 1963. The Last 10,000 Years - A Fossil Pollen Record of the American Southwest, University of Arizona Press, Tucson, Ariz., 87 p.

Mason, D. T., 1967. "Limnology of Mono Lake, California," University of California Publications in Zoology, Vol. 83, University of California Press, Berkeley, and Los Angeles, 110 p.

Maxey, G. B., and T. E. Eakin, 1949. Ground Water in White River Valley, White Pine, Nye, and Lincoln Counties, Nevada, Water Resources Bulletin No. 8, State of Nevada, Office of the State Engineer, Carson City.

Mayewski, P. A., G. H. Denton, and T. J. Hughes, 1981. "Late Wisconsin Ice Sheets of North America," The Last Great Ice Sheets, G. H. Denton and T. J. Hughes (ed.), Chapter 2, John Wiley & Sons, New York, pp. 132-158.

Meehl, G. A., 1984. "Modeling the Earth's Climate," Climatic Change, Vol. 6, pp. 259-286.

Mehringer, P. J., Jr., 1967. "Pollen Analysis of the Tule Springs Area, Nevada," Nevada State Museum Anthropological Papers, No. 13, pp. 130-200.

Mehringer, P. J., Jr., and C. W. Ferguson, 1969. "Pluvial Occurrence of Bristlecone Pine (Pinus Aristata) in a Mohave Desert Mountain Range," Journal of the Arizona Academy of Science, Vol. 5, No. 4, pp. 284-292.

Mehringer, P. J., Jr., and C. N. Warren, 1976. "Marsh, Dune and Archaeological Chronology, Ash Meadows, Amargosa Desert, Nevada," Holocene Environmental Change in the Great Basin, R. Elston (ed.), Nevada Archeological Survey Research Paper

8, Reno, pp. 120-150.

Meko, D. M., and C. W. Stockton, 1984. "Secular Variations in Streamflow in the Western United States," Journal of Climate and Applied Meteorology, Vol. 23, American Meteorological Society, pp. 889-897.

Mifflin, M. D., and M. M. Wheat, 1979. Pluvial Lakes and Estimated Pluvial Climates of Nevada, Nevada Bureau of Mines and Geology Bulletin 94, University of Nevada, Reno.

Morrison, R. B., 1964. Lake Lahontan: Geology of Southern Carson Desert, Nevada, Geological Survey Professional Paper 401, U.S. Geological Survey, Washington, D.C.

Morrison, R. B., 1965. "Quaternary Geology of the Great Basin," THe Quaternary of the United States, H. E. Wright, Jr., and D. G. Frey (eds.), Princeton University Press, pp. 265-286.

Morrison, R. B., and J. C. Frye, 1965. Correlation of the Middle and Late Quaternary Successions of the Lake Lahontan, Lake Bonneville, Rocky Mountain (Wasatch Range), Southern Great Plains, and Eastern Midwest Areas, Nevada Bureau of Mines, Report No. 9, 45 p.

Morton, F. I., 1986. "Practical Estimates of Lake Evaporation," Journal of Climate and Applied Meteorology, Vol. 25, pp. 371-387.

NRC (U.S. Nuclear Regulatory Commission), 1987. Standard Format and Content of Site Characterization Plans for High-Level-Waste Geological Repositories, Regulatory Guide 4.17, Washington, D.C.

Namias, J., 1975. "Remarks on the Potential for Long-Range Forecasting," pp. 242-251.

Nichols, W. D., 1986. Geohydrology of the Unsaturated Zone at the Burial Site for Low-Level Radioactive Waste Near Beatty, Nye County, Nevada, USGS-OFR-85-198, Open-File Report, U.S. Geological Survey, Denver, Colo.

Oerlemans, J., 1982. "Glacial Cycles and Ice-Sheet Modelling," Climatic Change, Vol. 4, pp. 353-374.

Ore, H. T., and C. N. Warren, 1971. "Late Pleistocene-Early Holocene Geomorphic History of Lake Mojave, California," Geological Society of America Bulletin, Vol. 82, pp. 2553-2562.

Pollard, D., 1983. "Ice-Age Simulations with a Calving Ice-Sheet Model," Quaternary Research, Vol. 20, pp. 30-48.

Porter, S. C., and K. L. Pierce, and T. D. Hamilton, 1983. "Late-Wisconsin Mountain Glaciation in the Western United States," Late-Quaternary Environments of the United States, Volume I, The Late Pleistocene, S. C. Porter, Jr. (ed.), University of Minnesota Press, pp. 71-114.

Prentice, I. C., 1983. "Postglacial Climatic Change: Vegetation Dynamics and the Pollen Record," pp. 273-286.

Quade, J., 1986. "Late Quaternary Environmental Changes in the Upper Las Vegas Valley, Nevada," Quaternary Research, Vol. 26, pp. 340-357.

Quiring, R. F., 1968. Climatological Data, Nevada Test Site and Nuclear Rocket Development Station, ESSA Technical Memorandum ARL-7, Environmental Sciences Service Administration, U.S. Department of Commerce, Las Vegas, Nev.

Quiring, R. F., 1983. Precipitation Climatology of the Nevada Test Site, WSNSO 351-88, National Weather Service, U.S. Department of Commerce, Las Vegas, Nev.

Ruddiman, W. F., and A. McIntyre, 1981. "Oceanic Mechanisms for Amplification of the 23,000-Year Ice Volume Cycle," Science, Vol. 212, No. 4495, pp. 617-627.

Russell, I. C., 1885. Geological History of Lake Lahontan, a Quaternary Lake of Northwestern Nevada, U.S. Geological Survey Monograph Volume XI, Government Printing Office, Washington, D.C.

SAIC (Science Applications International Corporation), 1985. Meteorological Monitoring Plan for the Nevada Nuclear Waste Storage Investigations Project, Yucca Mountain Site, DOE/NV/10270-5, Las Vegas, Nev.

Saltzman, B., 1985. "Paleoclimatic Modeling," Chapter 8, pp. 341-396.

Saltzman, B., and A. Sutera, 1984. "A Model of the Internal Feedback System Involved in Late Quaternary Climatic Variations," Journal of the Atmospheric Science, Vol. 41, No. 5, pp. 736-745.

Saltzman, B., A. R. Hansen, and K. A. Maasch, 1984. "The Late Quaternary Glaciations as the Response of a Three-Component Feedback System to Earth-Orbital Forcing," Journal of the Atmospheric Sciences, Vol. 41, No. 23, pp. 3380-3389.

Schlesinger, M. E., 1984. "Climate Model Simulations of CO2-Induced Climatic Change," Advances in Geophysics, Vol. 26, pp. 141-235.

Schneider, S. H., and R. E. Dickinson, 1974. "Climate Modeling," Reviews of Geophysics and Space Physics, Vol. 12, No. 3, pp. 447-493.

Schumm, S. A., 1965. "Quaternary Paleohydrology," The Quaternary of the United States, H. E. Wright, Jr., and D. G. Frey (eds.), Princeton University Press, Princeton, N.J., pp. 783-794.

Scott, W. E., W. D. McCoy, R. R. Shroba, and M. Rubin, 1983. "Reinterpretation of the Exposed Record of the Last Two Cycles of Lake Bonneville, Western United States," Quaternary Research, Vol. 20, pp. 261-285.

Sellers, W. D., 1983. "A Quasi-Three-Dimensional Climate Model," Journal of Climate and Applied Meteorology, Vol. 22, Sept., pp. 1557-1574.

Shackleton, N. J., M. A. Hall, J. Line, and C. Shuxi, 1983. "Carbon Isotope Data in Core V19-30 Confirm Reduced Carbon Dioxide Concentration in the Ice Age Atmosphere," Nature, Vol. 306, pp. 319-322.

Shackleton, N., J. Bachman, H. Zimmerman, D. Kent, M. Hall, D. Roberts, D. Schnitker, J. Baldauf, A. 1984. "Oxygen Isotope Calibration of the Onset of Ice-Rafting and History of Glaciation in the North Atlantic Region," Nature, Vol. 307, pp. 620-623.

Sharp, R. P., 1938. "Pleistocene Glaciation in the Ruby-East Humboldt Range, Northeastern Nevada," Journal of Geomorphology, pp. 296-323.

Sheppard, R. A., and A. J. Gude, 3rd, 1968. Distribution and Genesis of Authigenic Silicate Minerals in Tuffs of Pleistocene Lake Tecopa, Inyo County, California, Geological Survey Professional Paper 579, U.S. Government Printing Office, Washington, D.C.

Smith, G. I., 1979. Subsurface Stratigraphy and Geochemistry of Late Quaternary Evaporites, Searles Lake, California, Geological Survey Professional Paper 1043, U.S. Geological Survey, Alexandria, Va., 130 p.

Smith, G. I., and W. P. Pratt, 1957. Core Logs from Owens, China, Searles, and Panamint Basins, California, Geological Survey Bulletin 1045-A, U.S. Government Printing Office, Washington, D.C.

Smith, G. I., and F. A. Street-Perrott, 1983. "Pluvial Lakes of the Western United States," Late-Quaternary Environments of the United States, Volume I, The Late Pleistocene, S. C. Porter (ed.), University of Minnesota Press, pp. 190-212.

Snyder, C. T., and W. B. Langbein, 1962. "The Pleistocene Lake in Spring Valley, Nevada, and its Climatic Implications," Journal of Geophysical Resources, Vol. 67, No. 6, pp. 2385-2394.

Solomon, A. M., and T. Webb, III, 1985. "Computer-aided Reconstruction of Late-Quaternary Landscape Dynamics," Annual Review of Ecology Systematics, Vol. 16, pp. 63-84.

Spaulding, W. G., 1981. The Late Quaternary Vegetation of a Southern Nevada Mountain Range, Ph.D. Dissertation, University of Arizona, Department of Geosciences, Tuscon, Ariz., 271 p.

Spaulding, W. G., 1983. Vegetation and Climates of the Last 45,000 Years in the Vicinity of the Nevada Test Site, South-Central Nevada, USGS-OFR-83-535, Open-File Report, U.S. Geological Survey, Denver, Colo.

Spaulding, W. G., 1985. Vegetation and Climates of the Last 45,000 Years in the Nevada Test Site and Vicinity, U.S. Geological Survey Professional Paper 1329, U.S. Government Printing Office, Washington, D.C.

Spaulding, W. G., and L. J. Graumlich, 1986. "The Last Pluvial Climatic Episodes in the Deserts of Southwestern North America," Nature, Vol. 320, pp. 441-444.

Spaulding, W. G., E. B. Leopold, and T. R. Van Devender, 1983. "The Late Wisconsin Paleoecology of the American Southwest," Late-Quaternary Environments of the United States, Volume I, The Late Pleistocene, S. C. Porter (ed.), University of Minnesota Press, Minneapolis, pp. 259-293.

Spaulding, W. G., S. W. Robinson, and F. L. Paillet, 1984. Preliminary Assessment of Climatic Change During Late Wisconsin Time, Southern Great Basin and Vicinity, Arizona, California, and Nevada, USGS-WRI-84-4328, Water-Resources Investigations Report, U.S. Geological Survey, Denver, Colo.

Spencer, R. J., M. J. Baedecker, H. P. Eugster, R. M. Forester, M. B. Goldhaber, B. F. Jones, K. Kelts, J. Mckenzie, D. B. Madsen, S. L. Rettig, M. Rubin, and C. J. Bowser, 1984. "Great Salt Lake, and Precursors, Utah: the Last 30,000 Years," Contributions to Mineralogy and Petrology, Vol. 86, pp. 321-334.

Stauffer, N. E., Jr., 1985. "Great Salt Lake Water Balance Model," Proceedings of Conference on Problems of and Prospects for Predicting Great Salt Lake Levels, March 26-28, 1985, Salt Lake City, Utah, University of Utah Center for Public Affairs and Administration, Salt Lake City, pp. 168-178.

Street-Perrott, F. A., and S. P. Harrison, 1984. "Temporal Variations in Lake Levels Since 30,000 Yr Bp - An Index of the Global Hydrological Cycle," Geophysical Monograph, Vol. 29, pp. 118-129.

Stuiver, M., and G. I. Smith, 1979. "Radiocarbon Ages of Stratigraphic Units," in Subsurface Stratigraphy and Geochemistry of Late Quaternary Evaporites, Searles Lake, California, G. I. Smith, (ed.), Geological Survey Professional Paper 1043, U.S. Government Printing Office, Washington, D.C., pp. 68-73.

Stuiver, M., G. H. Denton, T. J. Hughes, J. L. Fastook, 1981. "History of the Marine Ice Sheet in West Antarctica during the Last Glaciation: A Working Hypothesis," The Last Great Ice Sheets, G. H. Denton and T. J. Hughes (eds.), John Wiley & Sons, New York, pp. 319-436.

Sugden, D. E., 1977. "Reconstruction of the Morphology, Dynamics, and Thermal Characteristics of the Laurentide Ice Sheet at its Maximum," Arctic and Alpine Research, Vol. 9, No. 1, pp. 21-47.

Ter Braak, C. J. F., and L. G. Barendregt, 1986. "Weighted Averaging of Species Indicator Values: Its Efficiency in Environmental Calibration," Mathematical Biosciences, Vol. 78, pp. 57-72.

Thompson, R. S., 1984. "Late Pleistocene and Holocene Environments in the Great Basin," unpublished Ph.D. Thesis, University of Arizona, Department of Geosciences, Tucson, 256 p.

Thompson, R. S., and E. M. Hattori, 1983. "Packrat (Neotoma) Middens from Gatecliff Shelter and Holocene Migrations of Woodland Plants," Anthropological Papers of the American Museum of Natural History, Vol. 59, pp. 157-167.

Thompson, R. S., and J. I. Mead, 1982. "Late Quaternary Environments and Biogeography in the Great Basin," Quaternary Research, Vol. 17, pp. 39-55.

Thompson, R. S., L. Benson, and E. M. Hattori, 1986. "A Revised Chronology for the Last Pleistocene Lake Cycle in the Central Lahonton Basin," Quaternary Research, Vol. 25, pp. 1-9.

USGS (U.S. Geological Survey), 1954. Water-Loss Investigations Lake Hefner Studies, Technical Report, Geological Survey Professional Paper 269, U.S. Government Printing Office, Washington, D.C., 158 p.

USGS (U. S. Geological Survey), 1960. Compilation of Records of Surface Waters of the United States Through September 1950, Part 10. The Great Basin, U.S. Geological Survey, Water-Supply Paper 1314, U.S. Government Printing Office, Washington, D.C., pp. 24-25, 319-320,323-324, 396-397, 409-410, 415.

USGS (U.S. Geological Survey), 1963. Compilation of Records of Surface Waters of the United States, October 1950 to September 1960, Part 10. The Great Basin, Geological Survey Water-Supply Paper 1734, United States Government Printing Office, Washington, D.C., pp. 8, 210, 213, 267.

USGS (U.S. Geological Survey), 1970- 1984. Water Resources Data for California, Part 1. Surface Water Records, Volume 1: Colorado River Basin, Southern Great Basin, and Pacific Slope Basins excluding Central Valley, Water-Data Reports, published annually, U.S. Geological Survey, Washington, D.C.

USGS (U.S. Geological Survey), 1980- 1984. Water Resources Data for Nevada, published annually, USGS-WDR-NV-80 to 84-1, Water-Data Report, U.S. Geological Survey, Reston, Va.

Van Devender, T. R., and W. G. Spaulding, 1979. "Development of Vegetation and Climate in the Southwestern United States," Science, Vol. 204, pp. 701-710.

Van Devender, T. R., R. S. Thompson, and J. L. Betancourt, 1987. "Vegetation History of the Deserts of Southwestern North America: The Nature and Timing of the Late Wisconsin - Holocene Transition," North America and Adjacent Oceans during the Last Deglaciation, W. F. Ruddiman and H. E. Wright, Jr. (eds.), Geological Society of America, Boulder, Colo., pp. 1-56.

Von Neumann, J., 1960. "Some Remarks on the Problem of Forecasting Climatic Fluctuations," Dynamics of Climate, R. L. Pfeffer (ed.), Pergamon Press, New York, pp. 9-11.

Waitt, R. B., Jr., and R. M. Thorson, 1983. "The Cordilleran Ice Sheet in Washington, Idaho, and Montana," Late Quaternary Environments of the United States, Vol. I, Chapter 3, pp. 53-70.

Wallace, J. M., and P. V. Hobbs, 1977. Atmospheric Science: An Introductory Survey, Academic Press, New York, pp. 71-81.

Wang, W. -C., D. J. Wuebbles, W. M. Washington, R. G. Isaacs, and G. Molnar, 1986. "Trace Gases and Other Potential Perturbations to Global Climate," Reviews of Geophysics, Vol. 24, No. 1, pp. 110-140.

Wayne, W. J., 1984. "Glacial Chronology of the Ruby Mountains - East Humboldt Range, Nevada," Quaternary Research, Vol. 21, pp. 286-303.

Weast, R. C. (ed.), 1972. Handbook of Chemistry and Physics, 53rd Edition, The Chemical Rubber Company, Cleveland, Ohio, p. E-39.

Webb, T., III, 1980. "The Reconstruction of Climatic Sequences from Botanical Data," Journal of Interdisciplinary History, Vol. 4, pp. 749-772.

Webb, T., III, 1985. "Holocene Palynology and Climate," Paleoclimatic Analysis and Modeling, A. D. Hecht (ed.), John Wiley and Sons, New York, pp. 163-195.

Webb, T., III, and R. A. Bryson, 1972. "Late- and Postglacial Climatic Change in the Northern Midwest, USA: Quantitative Estimates Derived from Fossil Pollen Spectra by Multivariate Statistical Analysis," Quaternary Research, Vol. 2, pp. 70-115.

Webb, T., III, J. Kutzbach, and F. A. Street-Perrott, 1985. "20,000 Years of Global Climatic Change: Paleoclimatic Research Plan," pp. 182-218.

Wells, P. V., 1979. "An Equable Glaciopluvial in the West: Pleniglacial Evidence of Increased Precipitation on a Gradient from the Great Basin to the Sonoran and Chihuahuan Deserts," Quaternary Research, Vol. 12, pp. 311-325.

Wells, P. V., 1983. "Paleobiogeography of Montane Islands in the Great Basin Since the Last Glaciopluvial," Ecological Monographs, Vol. 53(4), pp. 341-382.

Wells, P. V., and R. Berger, 1967. "Late Pleistocene History of Coniferous Woodland in the Mohave Desert," Science, Vol. 155, pp. 1640-1647.

Wells, P. V., and C. D. Jorgensen, 1964. "Pleistocene Wood Rat Middens and Climatic Change in Mohave Desert: A Record of Junifer Woodlands," Science, Vol. 143, pp. 1171-1174.

Wells, S. G., L. D. McFadden, T. F. Bullard, B. F. Feilberg, R. L. Ford, J. P. Grimm, J. R. Miller, S. M. Orbock, J. D. Pickle, and J. C. Dohrenwend, 1984. "Late Quaternary Geomorphic History of the Silver Lake Area, Eastern Mojave Desert, California: An Example of the Influence of Climatic Change on Desert Piedmonts," pp. 122-136.

Wells, S. G., L. D. McFadden, and J. C. Dohrenwend, 1987. "Influence of Late Quaternary Climatic Changes on Geomorphic and Pedogenic Processes on a Desert Piedmont, Eastern Mojave Desert, California," Quaternary Research, Vol. 27, pp. 130-146.

Whitaker, G. L., 1971. "Changes in the Elevation of Great Salt Lake Caused by Man's Activities in the Drainage Basin," Geological Survey Research 1971, U.S. Geological Survey Professional Paper 750-D, U.S. Govt. Printing Office, Washington, D.C. pp. D187-D189.

Williams, J., R. G. Barry, and W. M. Washington, 1974. "Simulation of the Atmospheric Circulation Using the NCAR Global Circulation Model with Ice Age Boundary Conditions," Journal of Applied Meteorology, Vol. 13, No. 13, pp. 305-317.

CODES AND REGULATIONS

10 CFR Part 60 (Code of Federal Regulations), 1987. Title 10, "Energy," Part 60, "Disposal of High-Level Radioactive Wastes in Geologic Repositories," U.S. Government Printing Office, Washington, D.C.

10 CFR Part 960 (Code of Federal Regulations), 1987. Title 10, "Energy," Part 960, "General Guidelines for the Recommendation of Sites for Nuclear Waste Repositories," U.S. Government Printing Office, Washington, D.C.