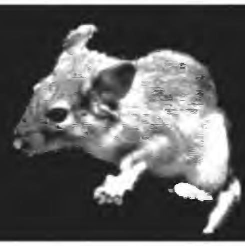

QUANTITATIVE PALEOCLIMATIC RECONSTRUCTIONS FROM LATE PLEISTOCENE PLANT MACROFOSSILS OF THE YUCCA MOUNTAIN REGION

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INTRODUCTION

Plant macrofossil assemblages recovered from packrat (*Neotoma*) middens of late Pleistocene age from the present-day Mojave Desert of southern Nevada contain plant species that today live at higher elevations and/or farther north than the midden collection sites. Previous reconstructions of late Pleistocene climates from packrat midden assemblages in this region (Spaulding, 1985) assessed the minimum climatic differences from today by estimating the present-day climatic differences between the fossil midden sites and the nearest current occurrences of key plant species recovered from the Pleistocene middens. From this approach Spaulding (1985) concluded that although late Pleistocene temperatures were considerably below those of today, only modest increases in precipitation (relative to today) were necessary for these plant species to survive in the current Mojave Desert during the late Pleistocene.

Spaulding's approach provided "state-of-the-art" results from an intensive careful examination of the best data available at the time. However, data and techniques developed since the mid-1980s suggest that there are two possible short-comings to this approach: 1) the use of lowest elevational and (frequently) most southerly occurrences of key plant species results in minimal estimates of the differences between Pleistocene and present-day climates, and 2) the instrumental climate data set available to Spaulding was limited in duration, non-standard in its method of collection, and indicated a modern climate wetter than the long-term historic mean, which resulted in relatively small apparent differences between late Pleistocene and present-day mean annual precipitation levels. In this report we use a more standard (close to the long-term mean) modern calibration period and a modern plant distribution data set that permits us to identify modern analogues for the Pleistocene vegetation. This reexamination permits a more robust reconstruction of the past climate, and results in estimates of mean annual temperature for the glacial maximum at Yucca Mountain that are 1.0° to 1.4° C warmer than those of Spaulding, and estimates of mean annual precipitation that are 60 mm or more higher than his.

METHODS

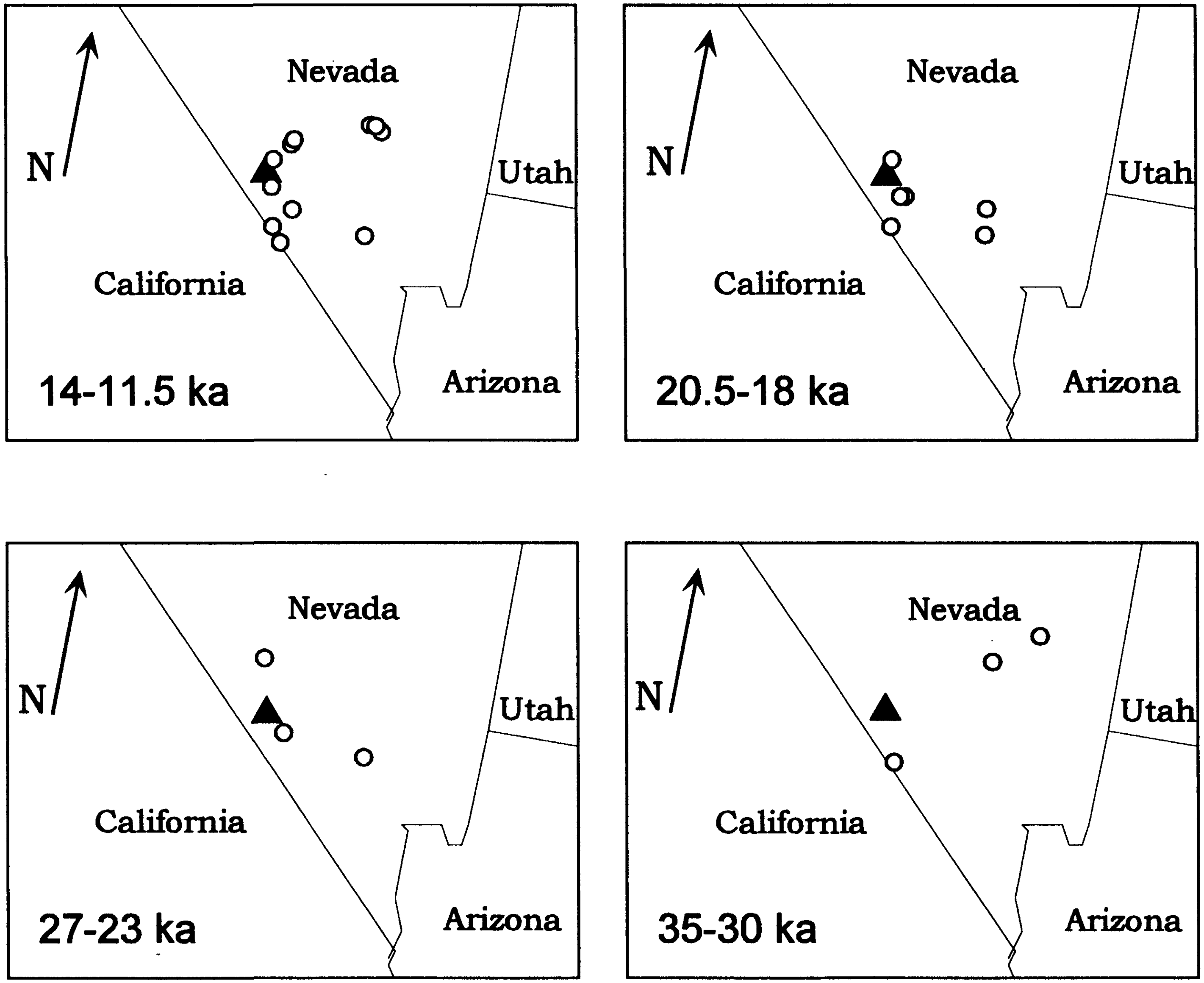
In this report we use present-day climatic and vegetational data from across North America to estimate past temperature and precipitation values from plant macrofossil assemblages preserved in ancient packrat middens from southern Nevada. Our approach involves: 1) compiling a comprehensive list of plant macrofossil assemblages from late Pleistocene packrat middens of the region, 2) employing a ~25 km grid of present-day climate and plant distributions in North America (Thompson and others, 1999), and 3) applying numerical analysis that compared the North American data with the packrat middens to produce estimates of past climates. The following text describes each of these aspects in greater detail.

Plant Macrofossil Assemblages from Packrat Middens.

Previous studies (e.g. Spaulding, 1985; Wigand and others, 1995) recovered numerous packrat middens from southern Nevada dating to the most recent period of continental glaciation during the late Pleistocene (~40,000 to 12,000 yr B.P. [~40 to 12 ka]). This report focuses on quantitative paleoclimatic interpretations of the plant macrofossil assemblages reported by Spaulding and Wigand, with particular emphasis on reconstructions of the climate from the last glacial maximum (LGM, ~18 ka). In addition to this interval, we also estimated the past climates for each of four intervals of the late Pleistocene (35 -30 ka, 27 -23 ka, 20.5 -18 ka, and 14-11.5 ka) that a panel of scientists from the Desert Research Institute (DRI), Dames and Moore (D&M), DOE, University of Colorado (CU) and the USGS selected as key times in the paleoclimatic history of the Yucca Mountain region (Figure 1). These time periods were selected based on previous paleoclimatic studies involving packrat middens, ostracodes, and other data sets that suggested that the climatic characteristics of each period were different. Initially, the period from 35-30 ka was thought to be the wettest interval of the late Pleistocene, and the 20.5 to 18 ka the coldest.

Presence-absence information on all of the plant species identified from 39 packrat middens in this region (Figure 1) were compiled by DRI and USGS researchers. The presence-absence approach places equal weight on the occurrences of all species,

Figure 1. Locations of packrat middens (circles) used in this study by time period. The location of Yucca Mountain is shown as a filled triangle on each map.



rather than placing more (or less) emphasis based on the apparent abundance of a given species. This approach seems warranted, as there is no strong evidence that the abundance of a given plant species in a packrat midden assemblage reflects the actual abundance on the landscape surrounding the midden.

The late Pleistocene packrat middens from the Yucca Mountain region were collected from sites where today the plant cover is dominated by creosote bush (*Larrea divaricata*) and other plants adapted to the hot and dry current Mojave Desert. In contrast, packrat midden data indicate that during the late Pleistocene these sites hosted plants that today grow farther north and/or at higher elevations (including limber pine [*Pinus flexilis*], white fir [*Abies concolor*], Utah juniper [*Juniperus osteosperma*], big sagebrush [*Artemisia tridentata*], and shadscale [*Atriplex confertifolia*]; Figure 2). Collectively the modern distributions of these plant species imply that the late Pleistocene climate was cooler and wetter than that of today.

Present-Day Climate and Plant Distributions.

As part of other research (Thompson and others, 1999), we estimated the present-day climate of North America for each of 31,363 points on a 25-km equal-area grid covering the continent (Bartlein et al, 1994). We then digitized maps of the current distributions (from published sources, including: Benson and Darrow, 1981; Critchfield and Little, 1966; Little, 1971, 1976; and Yang, 1970) of more than 300 major trees and shrubs and aligned these distributions with the 25-km grid. This procedure provides the basis for direct comparisons between the distributions of plant species and climatic parameters and is the foundation for the paleoclimatic reconstructions in this report. In addition to the plant taxa presented in Thompson and others (1999), the panel of DRI, D&M, DOE, and USGS scientists determined that additional maps (not available from previous publications) were required for the modern ranges of twelve additional plant taxa that were common in late Pleistocene packrat middens from the Yucca Mountain region (Table 1). USGS and DRI personnel worked together to compile this information, and USGS contractors digitized the maps and entered this information into the dataset for paleoclimatic analysis.

Figure 2. The present-day distributions of four key plant species (Pinus flexilis [limber pine], Juniperus osteosperma [Utah juniper], Abies concolor [white fir], and Atriplex confertifolia [shadscale]) recovered from late Pleistocene packrat middens in the Yucca Mountain region.

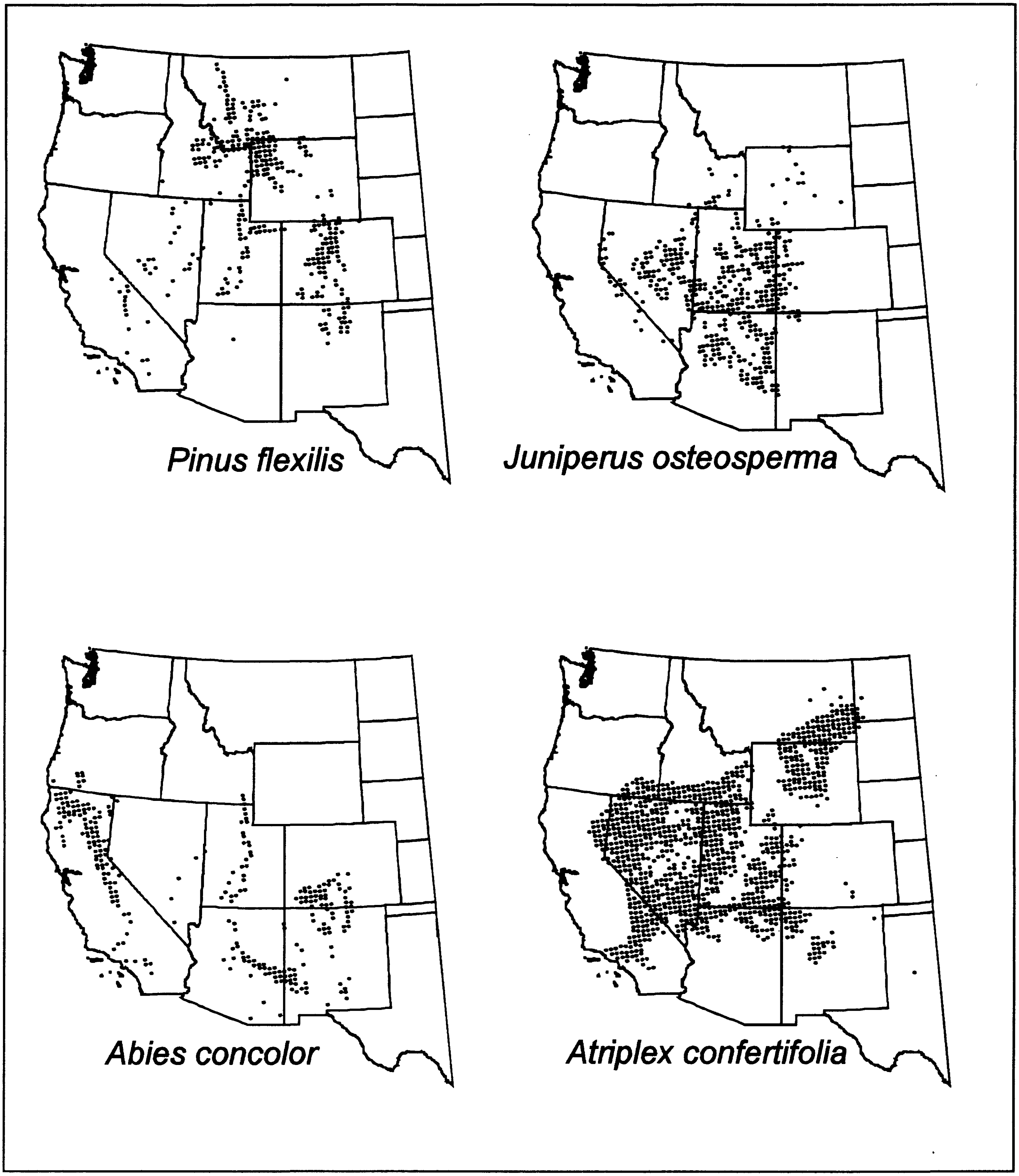


Table 1. Plant species for which maps were compiled by the USGS and/or DRI and digitized by the USGS.

Scientific Name	Common Name
Ambrosia dumosa	white bur sage
Atriplex canescens	four-wing saltbush
Cercocarpus intricatus	little-leaf mountain mahogany
Chamaebatiaria millifollium	fernbush
Chrysothamnus nauseosus	rabbit brush
Colegyne ramosissima	blackbrush
Ephedra nevadensis	boundary ephedra
Ephedra viridis	green ephedra
Fallugia paradoxa	Apache plume
Purshia tridentata	antelope brush
Symphoricarpos longiflorus	snowberry
Symphoricarpos oreophilus	snowberry

Table 2. Present-day and Late Glacial Maximum (LGM) climatic estimates for approximately 5000 ft (1524 m) elevation in the Yucca Mountain area (based on plant macrofossils from packrat middens).

	Annual Temperature	Annual Precipitation
PRESENT DAY		
This study	13.4° C	125 mm
Spaulding, 1985	13.5° C	189 mm
LAST GLACIAL MAXIMUM		
This study	7.9 to 8.5° C	266 to 321 mm
Spaulding, 1985	6.5 to 7.5° C	246 to 265 mm

Estimation of Climatic Parameters from Vegetation Data.

The inventory of fossil plant remains recovered from each packrat midden was compared with the plant list from each North American grid point to identify those grid points whose present-day vegetation is similar to the late Pleistocene vegetation found in the packrat midden (these modern sites are hereafter referred to as "analogues" for the Pleistocene packrat middens). The modern temperature and precipitation values at the analogue sites provide estimates for past climates in the region surrounding Yucca Mountain. We used the latter information to identify climatic patterns for selected past time periods by mapping the paleoclimatic estimates from multiple packrat midden fossil localities, and by plotting them against the geographic locations and elevations of the packrat midden sample sites. Climatic values for the late Pleistocene of Yucca Mountain were estimated by using the climate-elevation relations derived from this approach.

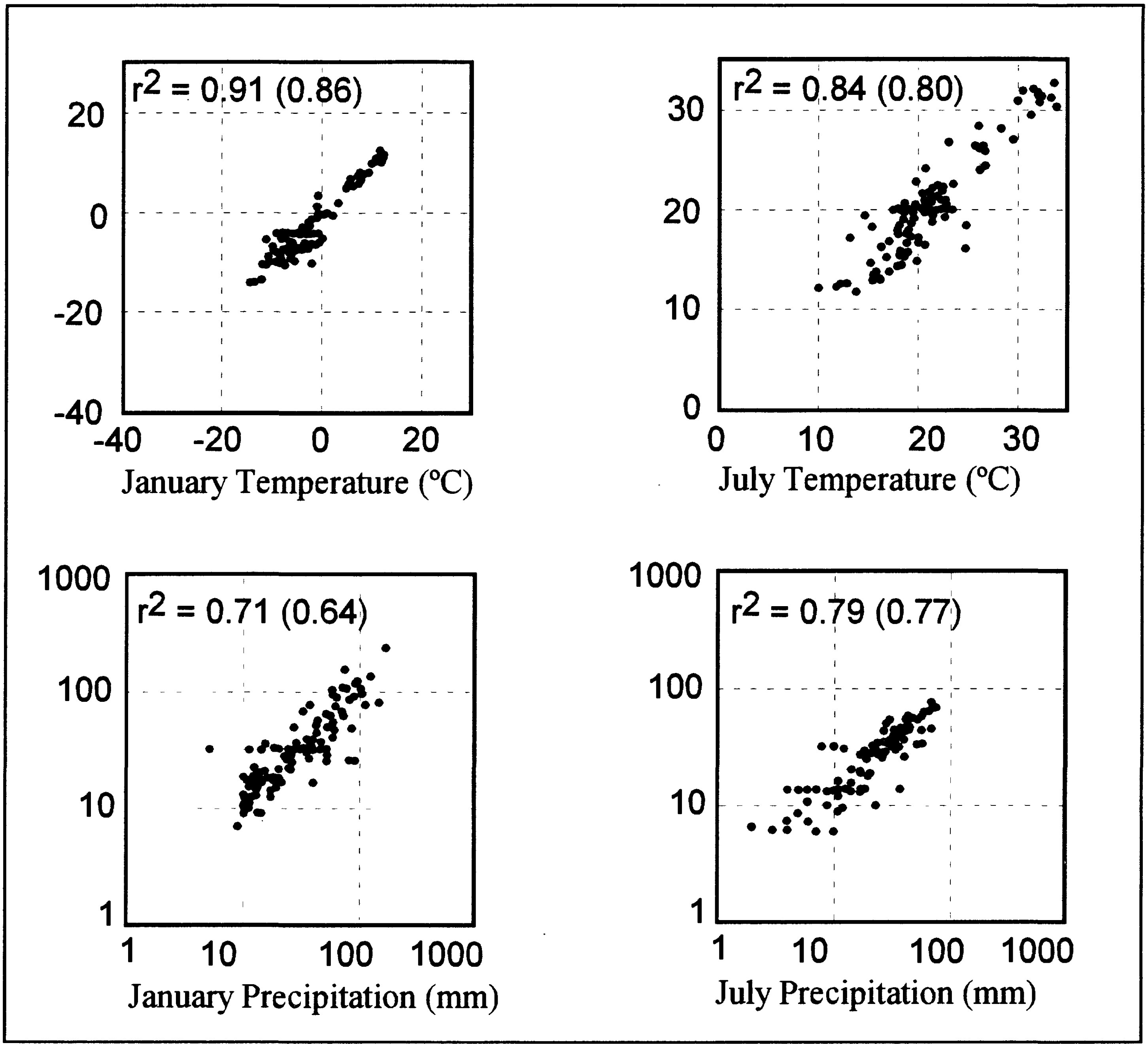
Modern analogue techniques, methods that identify sites where plants found in fossil assemblages are living today, are widely used to reconstruct past climates in eastern North America and Europe (for examples, see Overpeck and others, 1985 and Guiot, 1990). The fossil and the gridded modern vegetation data in this study are both presence-absence data. In order to obtain a measure of similarity between modern and fossil presence-absence data, we used the binary Jaccard matching coefficient (Jaccard, 1908; Schweitzer, 1994) to compare each packrat midden plant assemblage with each gridpoint within the modern data set. The Jaccard coefficient provides a measure of how similar each modern gridpoint assemblage is to the fossil assemblage, with a value of 0.0 indicating no shared species between the modern and fossil assemblages and a value 1.0 indicating that the two assemblages have exactly the same list of species.

The Jaccard matching coefficient identifies modern sites that have vegetation that resembles (to varying degrees as measured by this coefficient) the Pleistocene vegetation recorded in the packrat midden samples. Some of these potential analogues may include some of the taxa in the fossil assemblage, whereas other potential analogues may lack these but include other taxa present in the fossil assemblage. To provide paleoclimatic estimates from fossil plant assemblages under these circumstances, we used weighted averages of climatic parameters from a large number of possible analogues for each fossil sample. To accomplish this, we had to make three decisions: 1) what is the threshold value for the Jaccard coefficient below which we do not consider the modern vegetation analogue to be similar enough to the fossil vegetation to be included in the analysis? 2) how many possible analogues above a threshold value should be included in each paleoclimatic estimate?, and 3) how should we weight the climatic information from each analogue so that the information from the least similar modern samples (in comparison with the fossil assemblage under consideration) does not overshadow the information from the most similar modern samples? There are no firm guidelines for any of these questions, so we experimented with different values for each of these three parameters and then objectively judged the results by comparing climates at a suite of modern gridpoints with those estimated by our method (see below).

Based on our experiments, we discarded potential modern analogues with Jaccard coefficients less than 0.3, and then selected the 200 analogues with the highest Jaccard coefficients above that value (if there were fewer than 200 analogues above that value, we used all of them). As higher Jaccard coefficients imply greater similarity between the modern and fossil vegetation than do low coefficients, we weighted the climatic data from the analogues by the ratio of the cubes of their Jaccard coefficients. Hence the climatic data from a modern sample with a Jaccard coefficient of 0.9 would be weighted approximately six times the data from a sample with a coefficient of 0.5 ($0.9^3 = 0.73$; $0.5^3 = 0.13$; $0.73/0.13 = 5.62$). This ensures that the modern sites with the greatest similarity contribute the most information to a given paleoclimatic estimate, while also allowing a broad examination of the potential climates that could account for the fossil vegetation.

We used the method described above with the present-day vegetation to estimate the modern climate at each of 80 grid points from the western interior of the United States where weather stations occur near the grid points (Figure 3). Regression analysis of the observed versus estimated January, July, and annual temperature at the grid points yielded r^2 values of 0.84 to 0.91 for temperature, indicating that, at least in the present-day situation, this method provides very reliable estimates of temperature. The comparisons of observed and estimated modern January, July, and annual precipitation provided r^2 values of 0.70 to 0.79 for precipitation and 0.71 to 0.80 for the log of precipitation. This

Figure 3. Comparison of observed (x-axis) and estimated (y-axis) present-day climate normals for January and July temperature and precipitation based on the gridded vegetation at 80 grid points in the interior of the western United States (r^2 values in parentheses indicate the comparison between observed climate at weather stations near the grid points and the predicted value for the grid points).



indicates that our method produces somewhat less robust, but still acceptable, estimates of precipitation.

ANALOGUE-BASED PALEOCLIMATIC RECONSTRUCTIONS

Modern Analogues for Pleistocene Vegetation and Climatic Differences from Today.

Using the method described above, the fossil data from packrat middens were compared to our North American grid to locate the best modern analogues for the late Pleistocene vegetation. Figure 4 provides an example of the geographic and climatic spread of the modern analogues (before averaging) for a 13,740 yr B.P. packrat midden from southern Nevada. As seen in this figure, most of the modern analogues for this sample (and for other late Pleistocene middens from the Yucca Mountain region) lie in the steppe and woodland regions of the central Great Basin, and to a lesser extent, the Colorado Plateau. The climates of these analogue sites are cooler and wetter than the modern climates at this fossil-midden site (and at other midden sites).

We estimated the modern temperature and precipitation at each packrat midden site using the same techniques we used to assign climatic values to our North American grid points (Thompson and others, 1999). "Anomalies" for each climatic parameter at each site were then calculated by taking the difference between the estimated modern climatic parameters at the packrat collection site and the late Pleistocene estimates.

RECONSTRUCTION OF LATE PLEISTOCENE CLIMATES

Reconstructed Climates Through Time. The proposed site of the nuclear waste repository at approximately 5000 ft (1524 m) elevation at Yucca Mountain was apparently at or near the lower elevational limits of *Pinus flexilis* (Figure 5), indicating that relatively moist forest environments did not extend below this elevation during the last ~40,000 years. However, climate did vary through the late Pleistocene, and to quantify these changes we analyzed suites of packrat midden assemblages grouped by the

Figure 4. Example of the present-day analogues (from the modern climate grid) for a late Pleistocene packrat midden plant macrofossil assemblage from near Yucca Mountain. The map on the left illustrates the geographic placement of the analogues (characterized by their degree of similarity to the midden assemblage as determined by the Jaccard coefficient). The central and right-hand panels illustrate the placement of the estimated present-day climate (filled square), potential analogues (circles, characterized by degree of similarity), and estimated past climate (filled triangle) in respect to January and July Temperature (central panel) and January and July Precipitation (on logarithmic scale in right-hand panel).

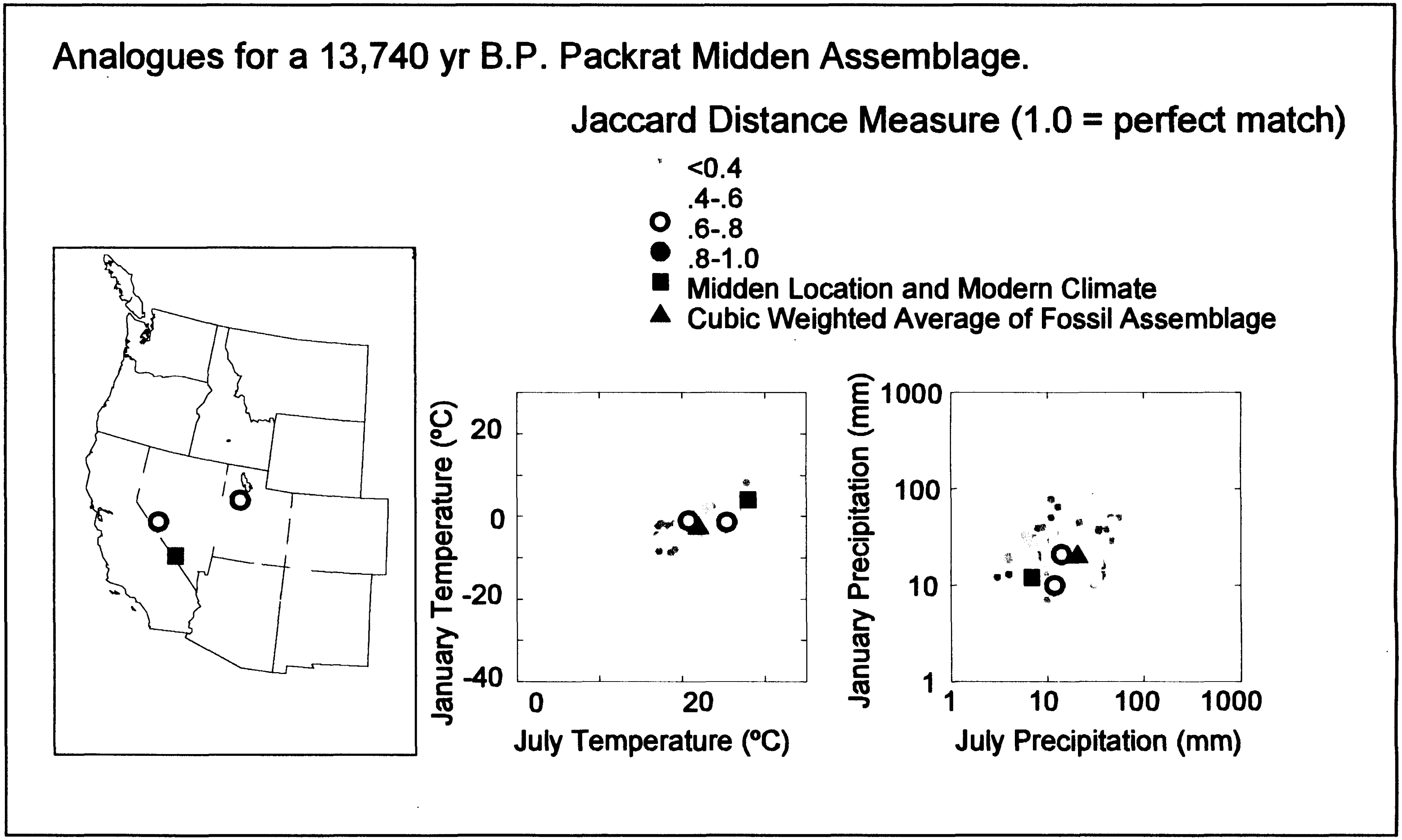


Figure 5. The occurrence of limber pine (Pinus flexilis) in packrat middens from the Yucca Mountain region during the late Pleistocene (plotted by age on the horizontal axis and elevation on the vertical axis). Filled circles indicate that limber pine was present, open circles indicate that it was absent. As illustrated here, the site of the proposed repository at approximately 1524 m elevation at Yucca Mountain was at (or below) the lower limit of limber pine through the late Pleistocene.

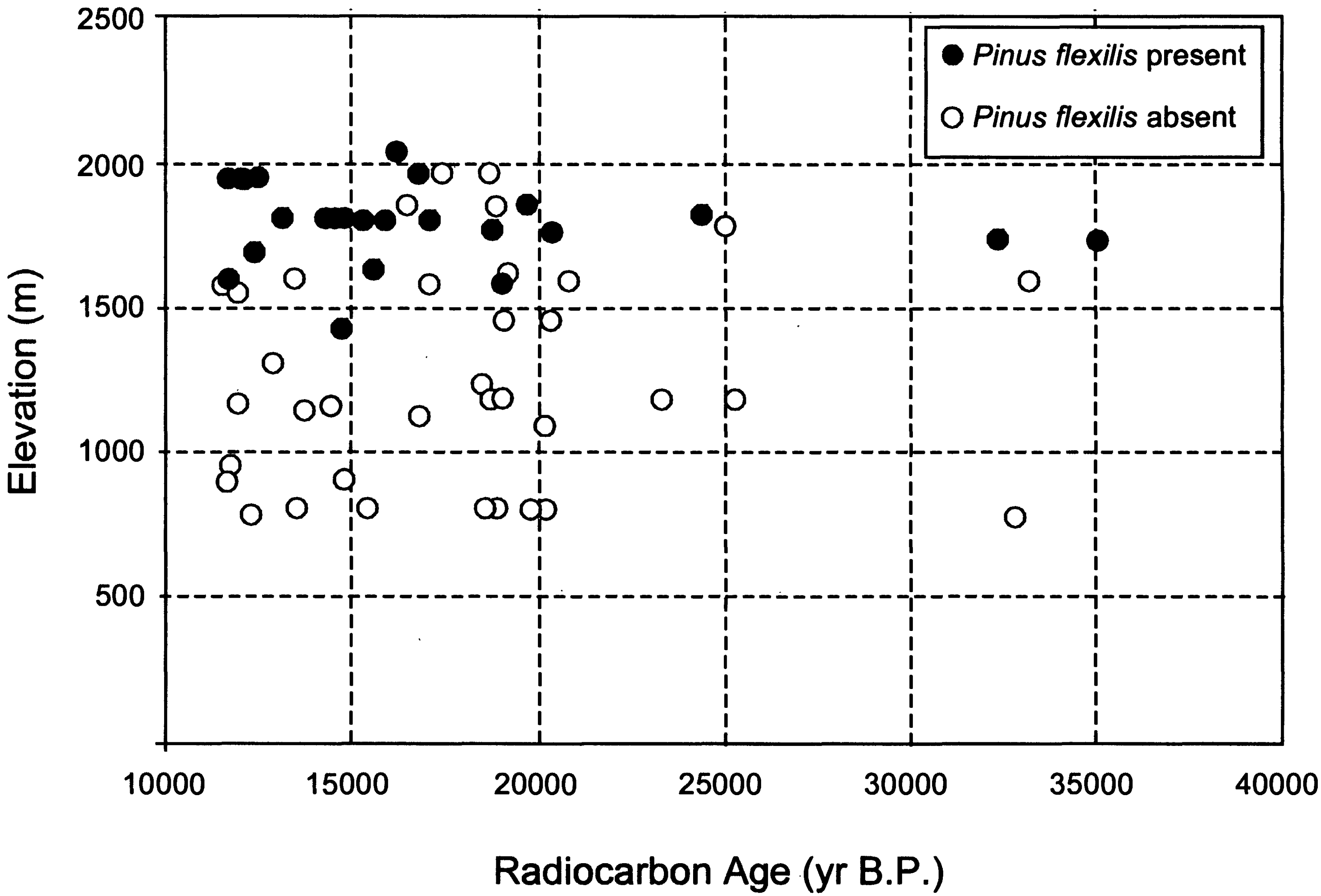
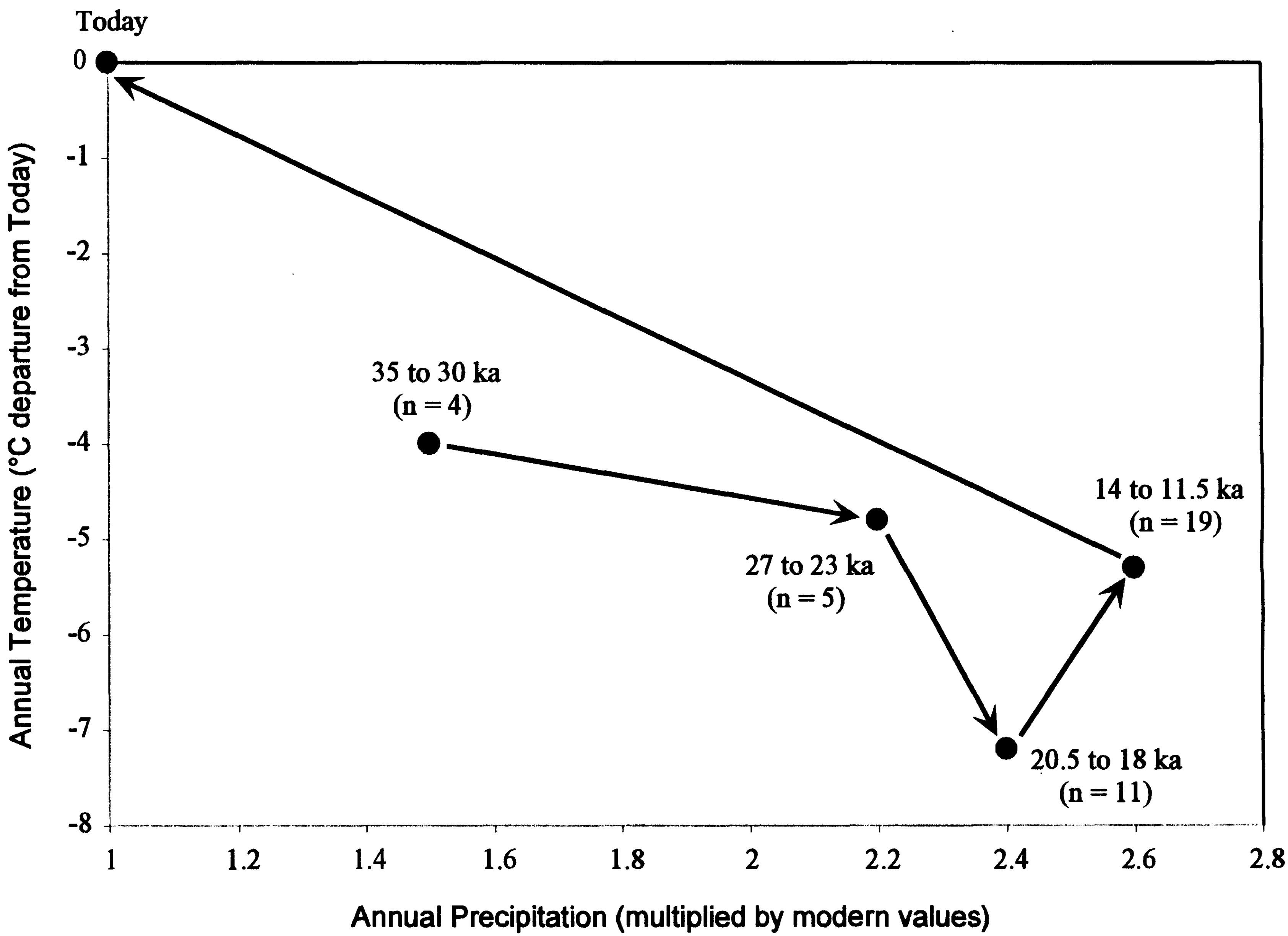


Figure 6. Average paleoclimatic changes inferred from packrat middens in the Yucca Mountain region for four intervals of late Pleistocene time. Arrows indicate the apparent directions of change through time; n = number of assemblages. As discussed in the text, elevation apparently influences the degree of temperature and precipitation change through time, and this effect is not taken into account in this figure.



time periods selected by the advisory panel (discussed above). Comparisons between time periods may be misleading, as the number of samples and the elevational range vary greatly between periods. Setting aside these potential problems, the analogue-based reconstructions suggest that the paleoclimate from 35 to 30 ka was approximately 4° C colder than today in the Yucca Mountain region, and mean annual precipitation was one and one-half times greater than today (Figure 6). The climate apparently cooled and became wetter through 27 to 23 ka, culminating in the coldest period during the late Wisconsin during the Last Glacial Maximum (LGM; 20.5 to 18 ka). Climatic conditions warmed somewhat by 14 to 11.5 ka, which was the period of the highest level of reconstructed precipitation during the late Pleistocene. In the following text we concentrate on reconstructions of the LGM (Table 2) when the estimated climate was the coldest and mean annual precipitation was significantly greater than that of the present-day.

Reconstructed Climates Versus Elevation. Maps of the reconstructed climate reveal differences in the size of the anomalies (difference between modern and reconstructed past climate parameters) within short distances, apparently due to the influence of the high physiographic relief of southern Nevada. For the LGM, there are very strong relationships between elevation and the amplitude of the temperature difference from today ($r^2 = 0.97$ for January, 0.96 for July, and 0.98 for annual temperature). There are weaker, but still strong relations for precipitation anomalies versus elevation ($r^2 = 0.51$ for January, 0.82 for July, and 0.88 for annual precipitation) for the late glacial period (14 to 11.5 ka). These paleoclimatic reconstructions imply that during the late Pleistocene the gradients of decreasing temperature and increasing precipitation with rising elevation were more gradual than those of today in southern Nevada. Subsequent analyses of packrat midden assemblages from farther south in the Mojave Desert to as far north as the Bonneville basin indicate that these apparent shallower-than-modern relations between increasing elevation with decreasing temperature and increasing precipitation occurred during the LGM throughout this region.

Compilations of paleoclimatic proxy data and numerical model simulations of past climates (Thompson and others, 1993) both provide support for the hypothesis that the westerlies were displaced southward from their modern position into the southwestern United States during the late Pleistocene. The persistence through the year of a strong pole-to-equator temperature gradient at that time also caused the westerlies to be much stronger during the summer season than they are today. These factors would have led to more frequent cyclonic storms in the Yucca Mountain region throughout the year, enhanced cloudiness, and a replacement of convective precipitation regime by frontal storms that provide precipitation across the elevational range. This change in storm patterns would have reduced the rate of change (relative to today) of decreasing temperature with rising elevation and the generally wetter climate would also lower the temperature lapse rate.

Paleoclimatic Inferences from Missing Plant Species During the Late Pleistocene. As discussed above, the late Pleistocene occurrences of limber pine (*Pinus flexilis)*, Utah juniper (*Juniperus osteosperma*), and other montane and steppe plants in modern desert environments suggest cooler than modern temperatures, and greater moisture availability than today (Spaulding, 1985). Spruce (*Picea engelmannii, P. pungens*), lodgepole pine (*Pinus contorta*), subalpine fir (*Abies lasiocarpa*), prostrate juniper (*Juniperus communis*) and other boreal plants have not been found in packrat middens in southern Nevada, suggesting that the late Pleistocene climate was not cold or wet enough for these boreal plants. On the other hand, Pleistocene-age middens from the Yucca Mountain area lack evidence of ponderosa pine (*Pinus ponderosa*), Douglas-fir (*Pseudotsuga menziesii*), and other montane trees that live today in the mountains of southern Nevada. Their absence, and the rarity of single-needle pinyon pine (*Pinus monophylla*), may suggest that Pleistocene climates were too cold for those plants. Similarly, the absence of the now widespread creosote bush (*Larrea divaricata*) suggests that late Pleistocene temperatures were much colder than those of today (Spaulding, 1985). In this section we address the question: do our paleoclimatic estimates (if correct) provide an adequate explanation for the absence of these forest and desert plants?

The present-day climatic and plant distributional data in Thompson and others

(1999) provide the basis for examining the apparent climatic meaning of the late Pleistocene absences of key plant species in the Yucca Mountain Region. As illustrated in Figure 7, our reconstructed LGM January temperatures were apparently too cold for the survival of *Larrea divaricata* (in accordance with Spaulding's [1985] interpretation) or *Juniperus californica*. Conversely, winter temperatures were apparently too warm for *Picea pungens*, *Picea engelmannii*, *Abies lasiocarpa*, *Juniperus communis*, and *Pinus flexilis* (which, as illustrated in Figure 5, was apparently near its lower elevational limits here during the LGM). The subsequent figures provide similar illustrations of the reconstructed climates compared with the apparent tolerances of these species in respect to July and annual temperature (Figures 8 and 9), and to January, July, and annual precipitation (Figures 10 to 12). These figures collectively indicate that many of the 'absent' taxa presently live under climatic conditions that differ in at least one aspect of seasonal or annual temperature or precipitation from the analogue-based reconstruction of the LGM climate.

Table 3 summarizes the overall patterns observed in these figures, and as seen here, both temperature and precipitation were important in excluding many of these taxa. However, the reasons for the exclusions of *Pinus edulis*, *Pinus longaeva*, and *Pinus monophylla* are unclear. On the other hand, all three of these species lived in or near southern Nevada during parts of the late Pleistocene, so it is not surprising that the reconstructed climates would apparently permit their growth near Yucca Mountain.

EVALUATION OF CLIMATIC ANOMALIES FOR THE LGM

As discussed above, Spaulding (1985) estimated climatic anomalies for the late Pleistocene based on the present-day southern-most and/or lowest elevational occurrences of key plant species that were recovered from packrat middens in the Yucca Mountain region. Tables 2 and 4 illustrate the differences between Spaulding's and our paleoclimatic reconstructions for the LGM (interpolated to the 5000 ft [1524 m] elevation of the proposed repository). Although our results indicate somewhat warmer and wetter conditions than Spaulding's, the absolute differences between the two approaches are not

Figure 7. Present-day correspondences between mean January temperature and the distribution of selected tree and shrub species from western North America (data are the 10% to 90% distributional limits from Thompson and others, 1999). The 17 species on the left are species that do not occur in late Pleistocene packrat midden assemblages from the Yucca Mountain region (although *Juniperus scopulorum*, *Pinus monophylla*, *Pinus longaeva*, and *Pseudotsuga menziesii* and have been recovered in the broader southeastern California/southern Nevada /southwestern Utah area). The 4 species on the right have been recovered from multiple midden assemblages in the Yucca Mountain region (although *Pinus flexilis* was apparently at or near its lowest limits at the elevation of the proposed repository). The gray band represents the range of paleoclimatic estimates for the Last Glacial Maximum from the modern analogue analysis.

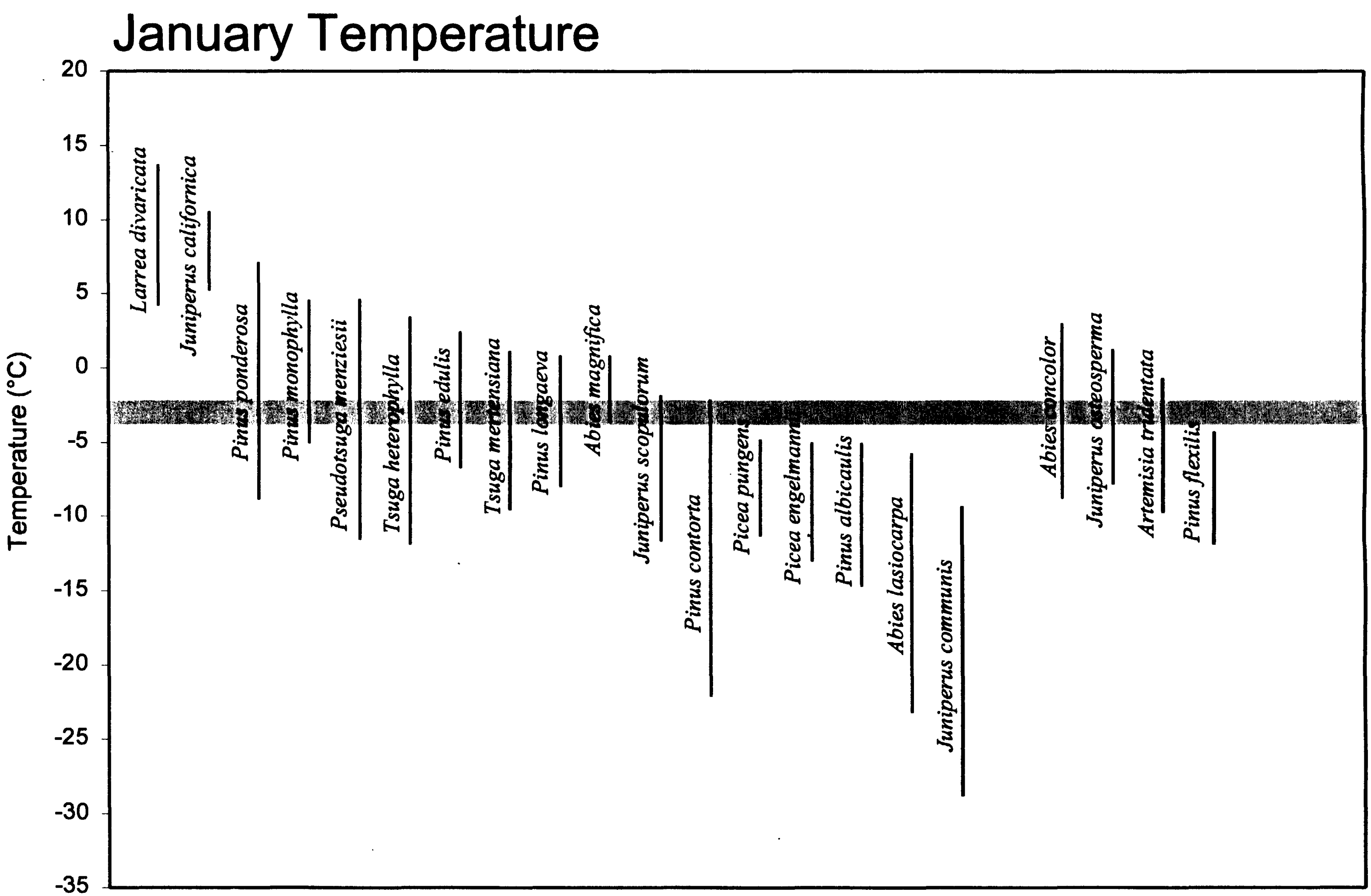


Figure 8. Present-day correspondences between mean July temperature and the distribution of selected tree and shrub species from western North America (see caption for Figure 7 for a more complete explanation).

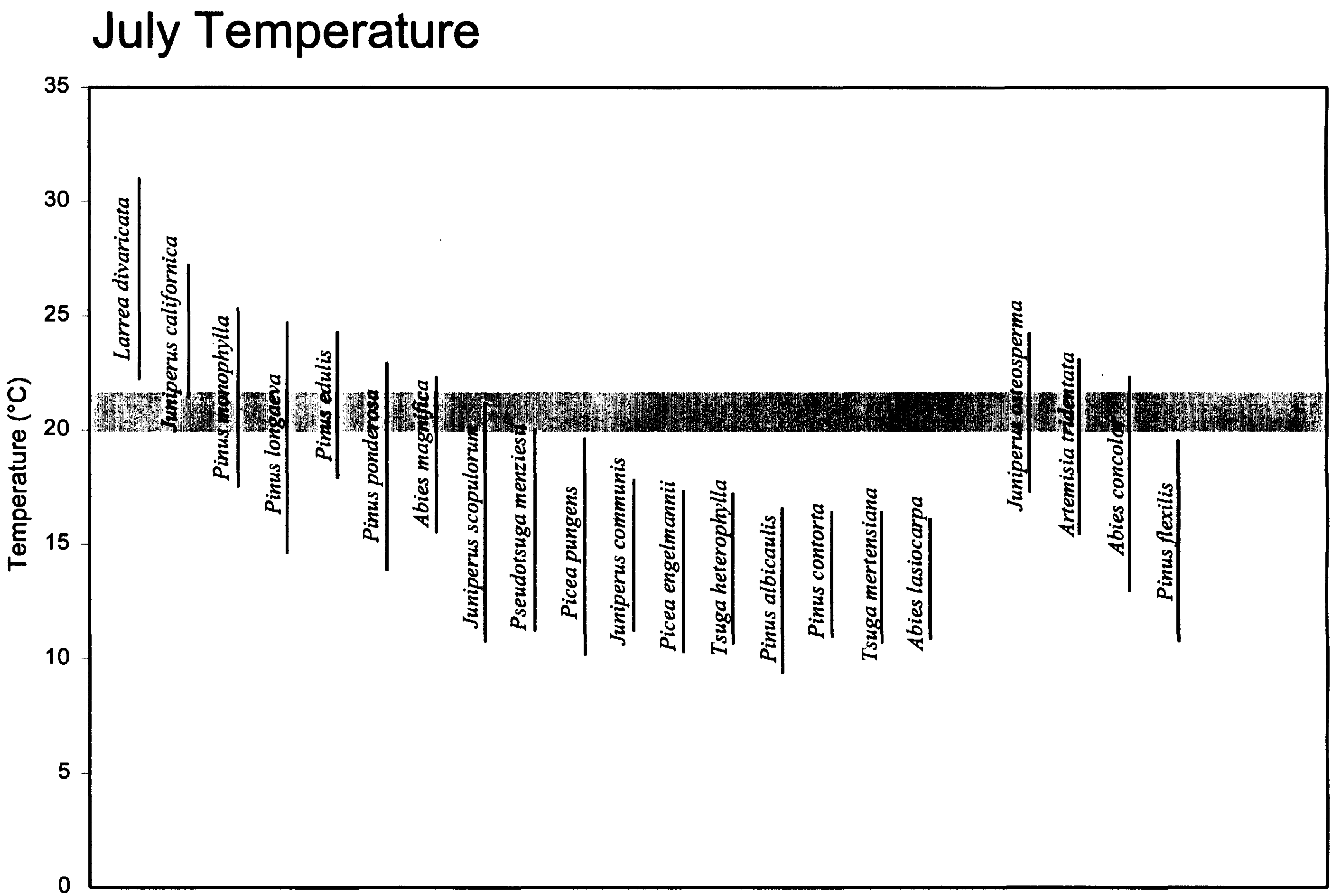


Figure 9. Present-day correspondences between mean annual temperature and the distribution of selected tree and shrub species from western North America (see caption for Figure 7 for a more complete explanation).

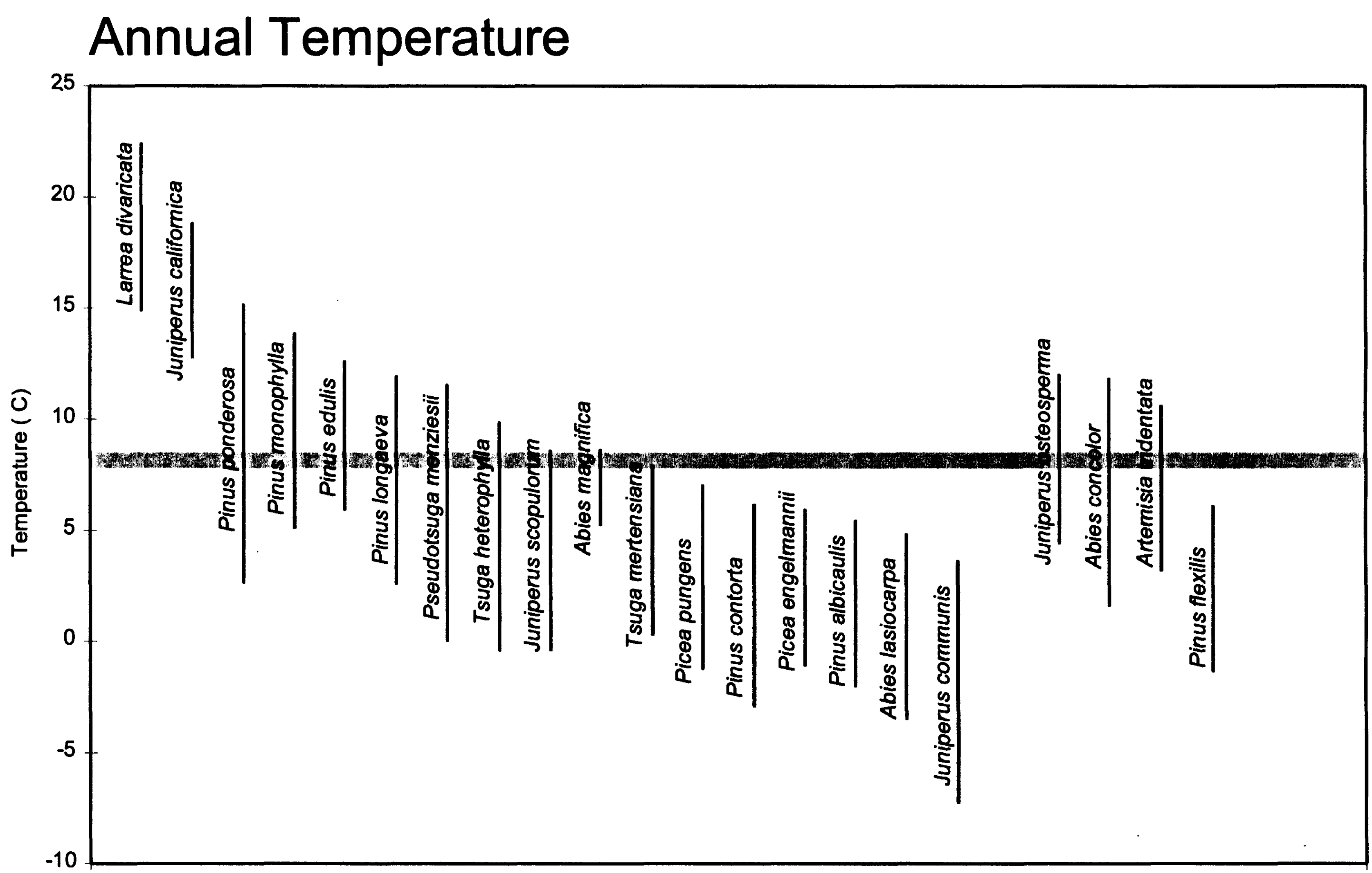


Figure 10. Present-day correspondences between mean January precipitation and the distribution of selected tree and shrub species from western North America (see caption for Figure 7 for a more complete explanation).

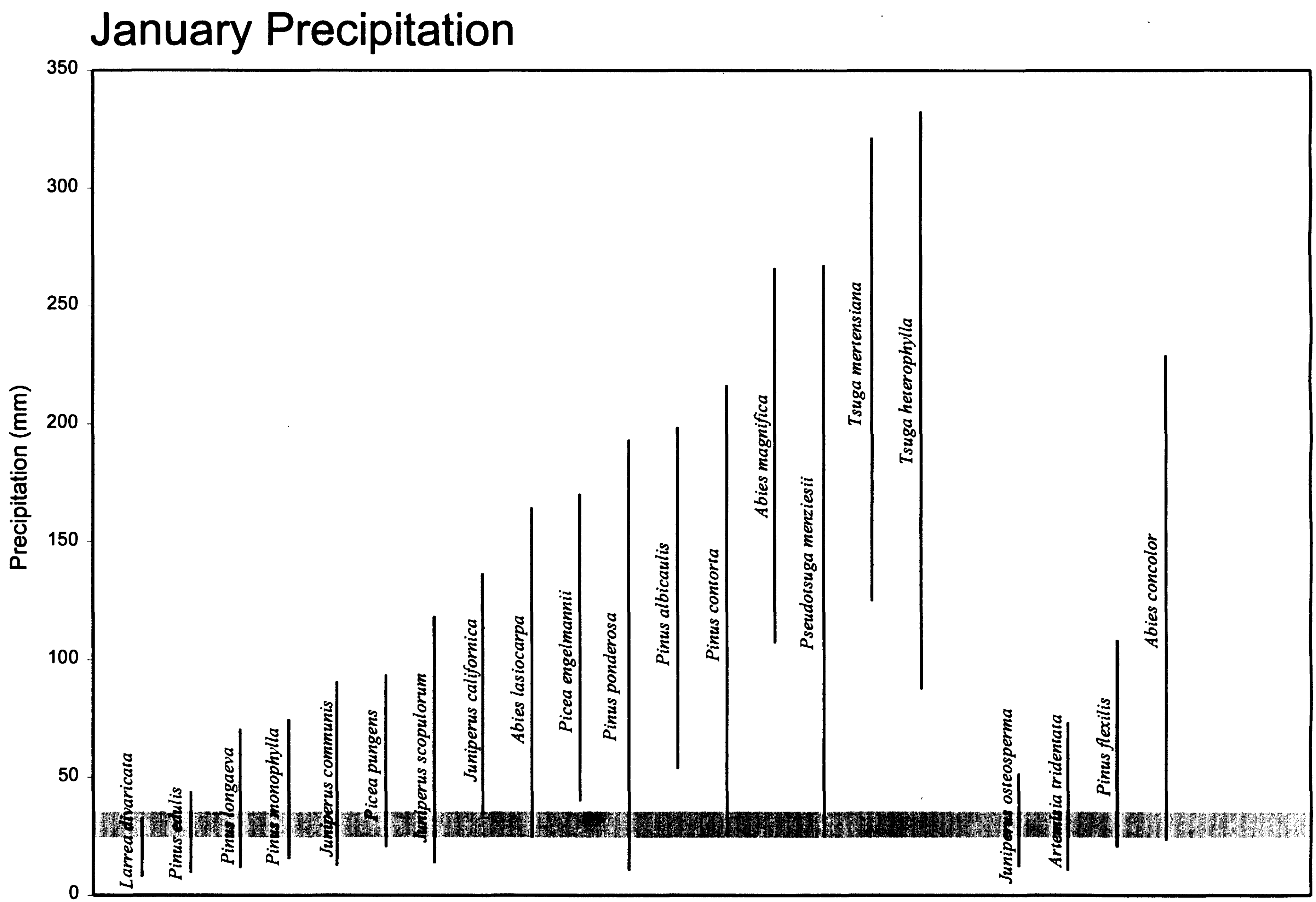


Figure 11. Present-day correspondences between mean July precipitation and the distribution of selected tree and shrub species from western North America (see caption for Figure 7 for a more complete explanation).

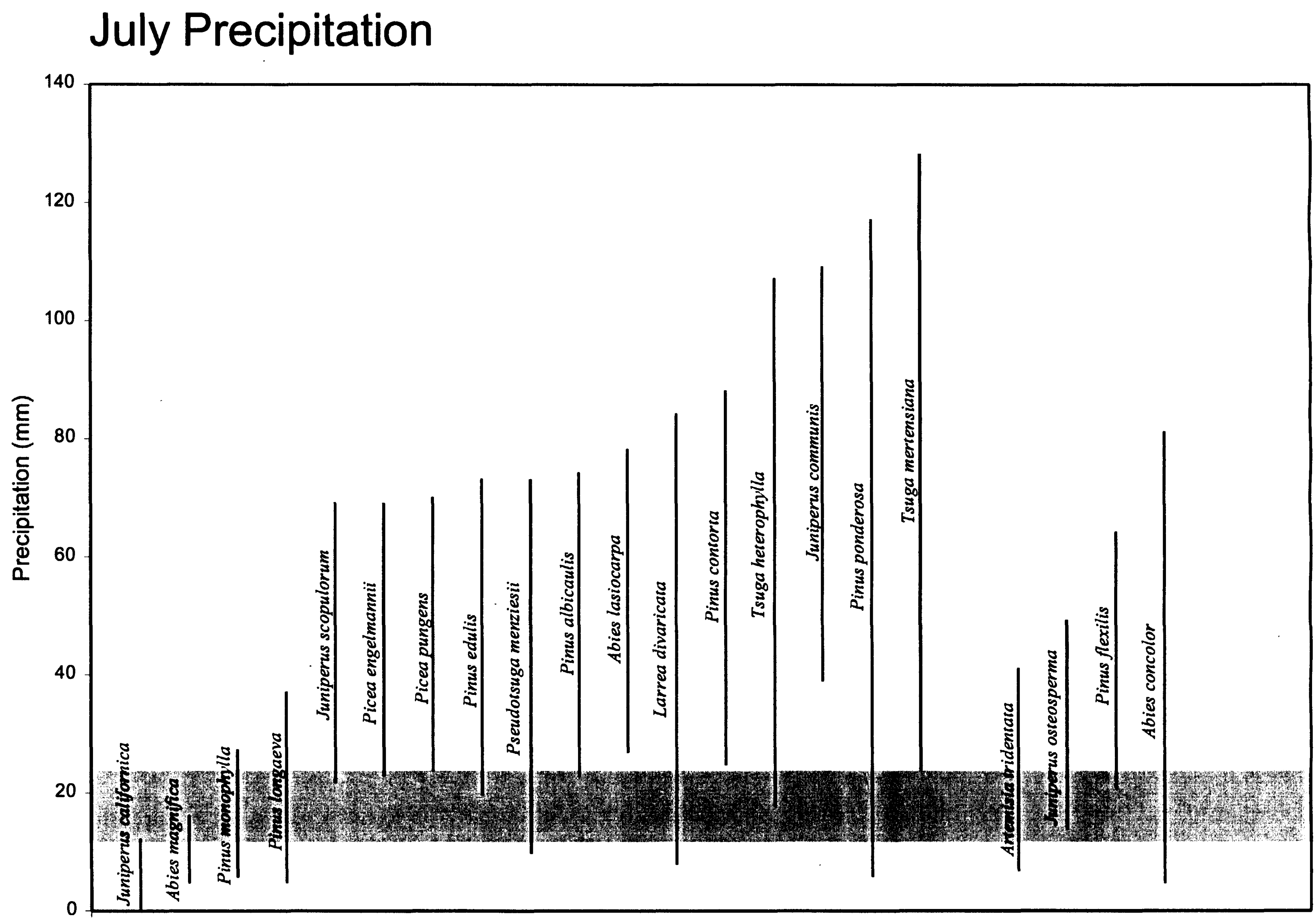


Figure 12. Present-day correspondences between mean annual precipitation and the distribution of selected tree and shrub species from western North America (see caption for Figure 7 for a more complete explanation).

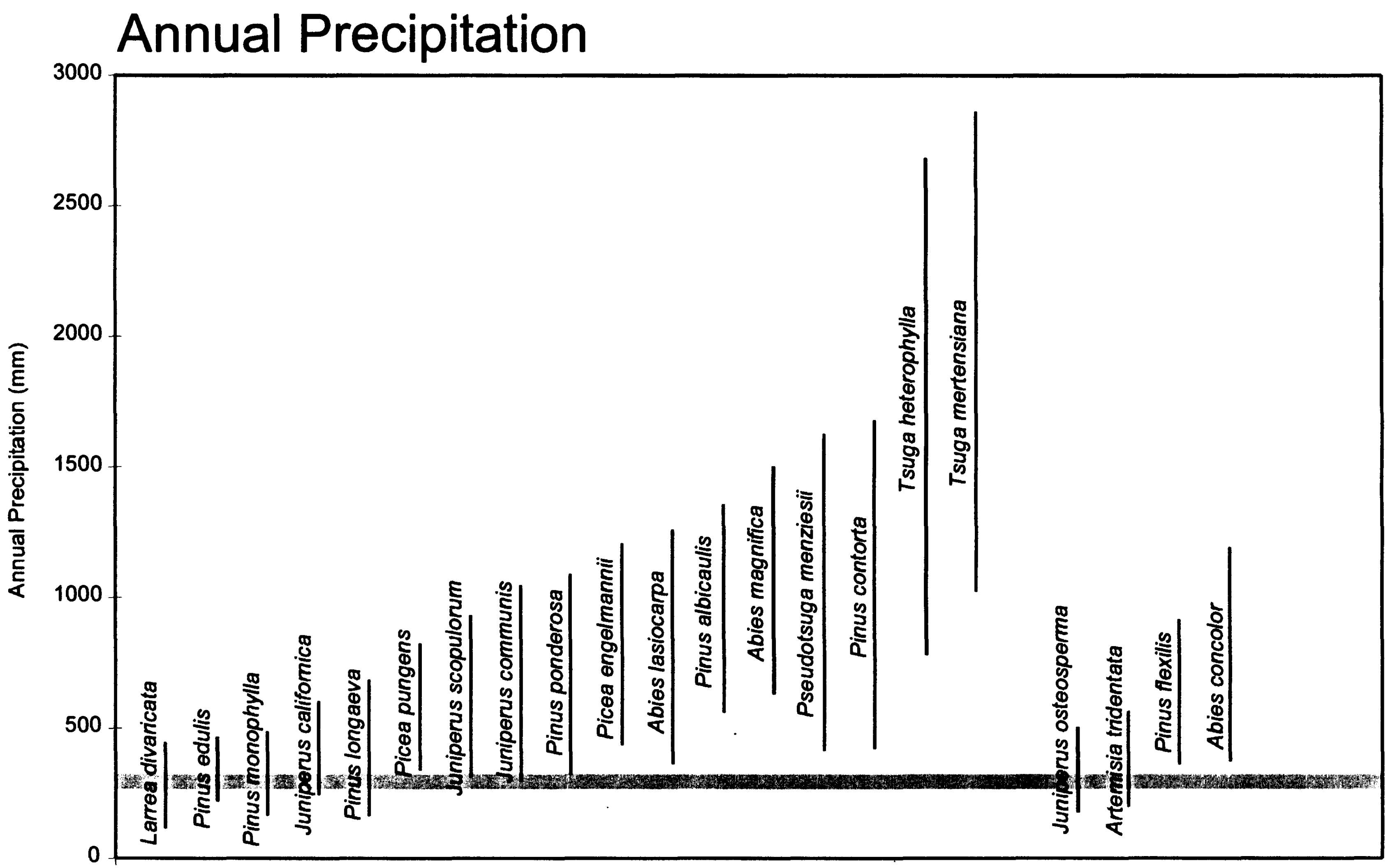


Table 3. Climatic factors that may have excluded selected taxa from the Yucca Mountain region during the late Pleistocene.

	TEMPERATURE			PRECIPITATION		
	January	July	Annual	January	July	Annual
**Abies concolor*						D
Abies lasiocarpa	H	H	H		D	D
Abies magnifica				D		D
Juniperus californica	C	M	C	M	W	
Juniperus communis	H	H	H		D	M
^*Juniperus scopulorum*					M	M
Larrea divaricata	C	C	C			
Picea engelmannii	H	H	H	D	M	D
Picea pungens	H	H	H		D	D
Pinus albicaulis	H	H	H	D	M	D
Pinus contorta		H	H		D	D
Pinus edulis						
**Pinus flexilis*	H	H	H			D
^*Pinus longaeva*						
**Pinus monophylla*						
Pinus ponderosa						D
**Pseudotsuga menziesii*		M				D
Tsuga heterophylla		H		D		D
Tsuga mertensiana		H	M	D	D	D

KEY:

H = too hot for species, C = too cold, D = marginal, W = too wet, M = marginal

* = present near Yucca Mountain during part of the late Pleistocene

^ = present regionally during the late Pleistocene

	TEMPERATURE			PRECIPITATION		
	January	July	Annual	January	July	Annual
Reason for exclusion:						
too warm or dry	6	10	8	6	8	14
too cold or wet	2	1	2	1	1	0

Plants for whom reason of exclusion unclear: Pinus edulis, Pinus longaeva, Pinus monophylla

Table 4. Reconstructed LGM climates and climatic anomalies based on the present-day climate estimates used in this report contrasted with the present-day values used by Spaulding (1985).

	Estimated Values	Reconstructed Values		Anomalies based on Spaulding Modern Values		Anomalies based on This Report Modern Values	
	MODERN	LGM Minumum	LGM Maximum	LGM Minumum	LGM Maximum	LGM Minumum	LGM Maximum
Mean Annual Temperature	°C	°C	°C	°C	°C	°C	°C
Spaulding	13.5	6.5	7.5	7	6	6.9	5.9
This Report	13.4	7.9	8.5	5.6	5	5.5	4.9
Mean Annual Precipitation	mm	mm	mm	mm	mm	mm	mm
Spaulding	189	246	265	57	76	121	140
This Report	125	266	321	77	132	141	196
Multiplier for Annual Precipitation				Mod. X	Mod. X	Mod. X	Mod. X
Spaulding				1.3	1.4	2.0	2.1
This Report				2.1	2.6	1.4	1.7

Mod. X = Modern mean annual precipitation multiplied by this number great for either mean annual temperature (6.5° C versus 7.5 ° C) nor for mean annual precipitation (246 – 265 mm versus 266 – 321 mm). As discussed in greater detail below, the differences between these estimates are substantially less than the variability observed during the historic period.

Importance of Historical Climatic Baseline Data. Although the absolute differences between our estimates and those of Spaulding (1985) are small, the calculated anomalies for precipitation are large. As shown in Table 4, Spaulding's anomalies for LGM mean annual precipitation (based on Beatly's historic climate data) are 57 to 76 mm, which indicates precipitation at levels 1.3 to 1.4 times historic values. In contrast, our LGM mean annual precipitation anomalies (based on our historic climate normals) are 141 to 196 mm, which implies LGM precipitation at levels 2.1 to 2.6 times historic values. These comparisons point out the importance of the modern climatic baseline data in the assessment of the differences between present-day and late Pleistocene climates. As discussed above, our baseline is based on the climate "normals" for the period 1951 to 1980, with the great majority of our data obtained from U.S. Weather Service calculations of these "normal" values. Thus these data provide a baseline that is continental in scale, that is based on three decades of records, and that conforms to the U.S. Weather Service standards. However, this data set does not provide detailed coverage in proximity to Yucca Mountain. In contrast, Spaulding (1985) employed a modern baseline derived from data on the Nevada Test Site collected by Beatly (1975, 1976) for the period 1963 to 1972. This dataset provides more local data, but was collected with non-standard methods (which may over-estimate precipitation) for only a decade.

For the analyses in this report we interpolated the modern climate estimates to the elevation of the proposed repository at 5000 ft (1524 m). Although the two data sets have very similar mean annual temperature estimates for this elevation (Tables 2 and 4) Spaulding's estimates of modern mean annual precipitation are significantly higher than ours. The National Oceanic and Atmospheric Administration (NOAA) provides historic climatic data by divisions within each state (NCDC, 1994; Karl and others, 1986), and (unfortunately) Yucca Mountain is located on the boundary between Nevada Divisions 3 and 4. These data indicate that annual temperature varied relatively little between 1950 and 1972 (the combined period of the Spaulding and our baseline data; Figure 13). However, precipitation increased almost monotonically over this interval, with the result that our baseline (1951 to 1980) for annual precipitation falls near the long-term historic mean, whereas that employed by Spaulding (1963 to 1972) covers a much wetter period (and, in addition, Beatly's measurements may overestimate precipitation, Figure 14). The differences in precipitation estimates in the modern baselines employed by Spaulding (1985) and in this report greatly influence the calculated anomalies for the LGM (Table 4). In fact, the differences in these anomalies is influenced more by the differences in the modern baseline data than by differences in the estimation of late Pleistocene climates (Figure 15).

Comparison of Reconstructed LGM Climates With Historical Climatic Variations. As discussed above, Yucca Mountain is located on the boundary between NOAA Nevada Climatic Divisions 3 and 4. Over the past century, historic variations in precipitation in both of these divisions have reached levels (on an annual basis) as high as those reconstructed for the LGM (Figure 16). However, temperatures have remained above the LGM estimates throughout the historic period, although rare years in Nevada Division 3 have approached the mean annual temperature reconstruction for the LGM at Yucca Mountain (Figure 16). These individual years are labeled on the scatterplot on Figure 17, where it can be seen that in many years between 1897 and 1917 in Nevada Division 3 the annual temperatures approached the mean annual temperatures reconstructed for Yucca Mountain for the LGM. Several of those years (particularly 1901, 1904, 1905, 1906, and 1913) also had precipitation levels comparable to those reconstructed for the LGM. These years include both El Niño and La Niña years (Cayan and Webb, 1992), although the amplitude of the difference between these patterns was apparently smaller than in recent years. The first ~15 years of this century are estimated to have been among the coldest and wettest of the last 400 years in the Intermountain basins and Southwest Deserts (Fritts and Shao, 1992, p. 279-280), although precipitation levels of similar

Figure 13. Historic variations in annual temperature depicted as 10-year running means. Data are from NOAA compilations of instrumental weather data for Nevada regions 3 and 4 (see inset map). The modern mean annual temperature estimates for Yucca Mountain (5000 ft, 1524 m elevation) from Spaulding (1985) and this report are shown on the right. The mean annual temperature reconstructions for the Last Glacial Maximum (LGM) from Spaulding (1985) and this report are shown as gray bands on the lower part of the figure.

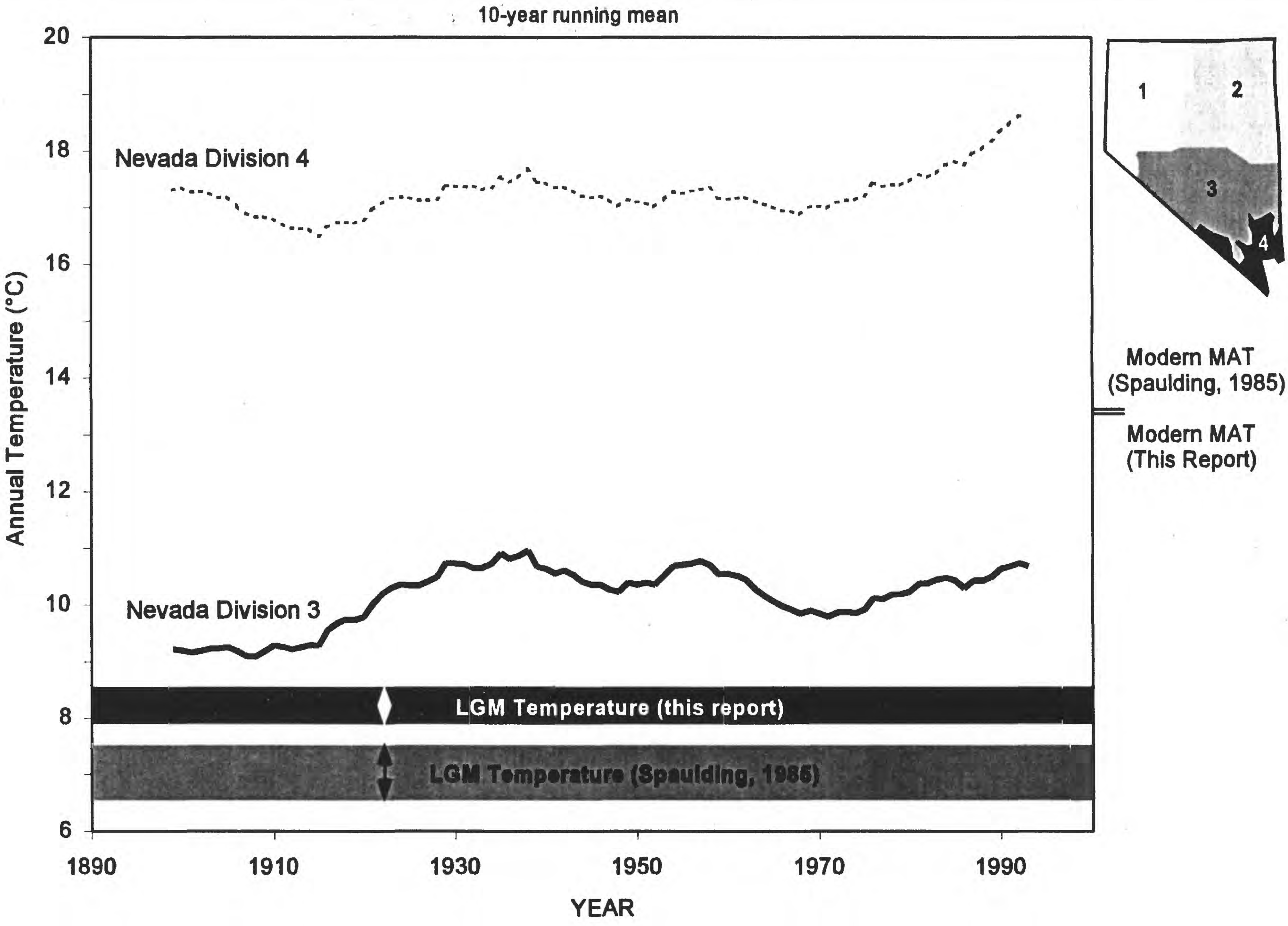


Figure 14. Historic variations in annual precipitation depicted as 10-year running means. Data are from NOAA compilations of instrumental weather data for Nevada regions 3 and 4 (see inset map). The modern mean annual precipitation estimates for Yucca Mountain (5000 ft, 1524 m elevation) from Spaulding (1985) and this report are shown on the right. The mean annual precipitation reconstructions for the Last Glacial Maximum (LGM) from Spaulding (1985) and this report are shown as gray bands on the upper part of the figure.

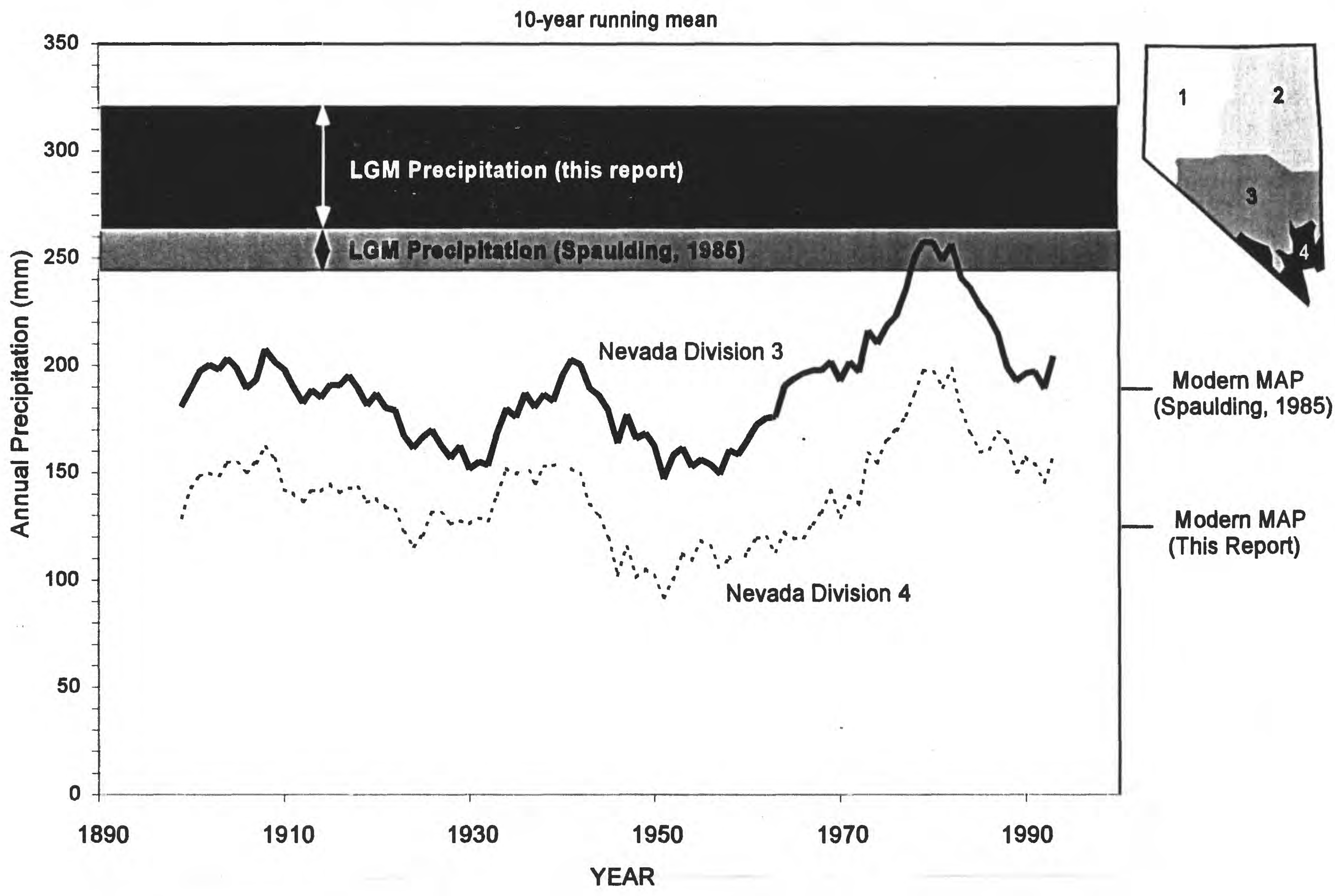


Figure 15. Comparisons of estimates of the modern and Last Glacial Maximum (LGM) climates at Yucca Mountain. Spaulding (1985) inferred a smaller difference in precipitation between today and the LGM than in this report, in part because his estimate of modern precipitation is higher than the one used here.

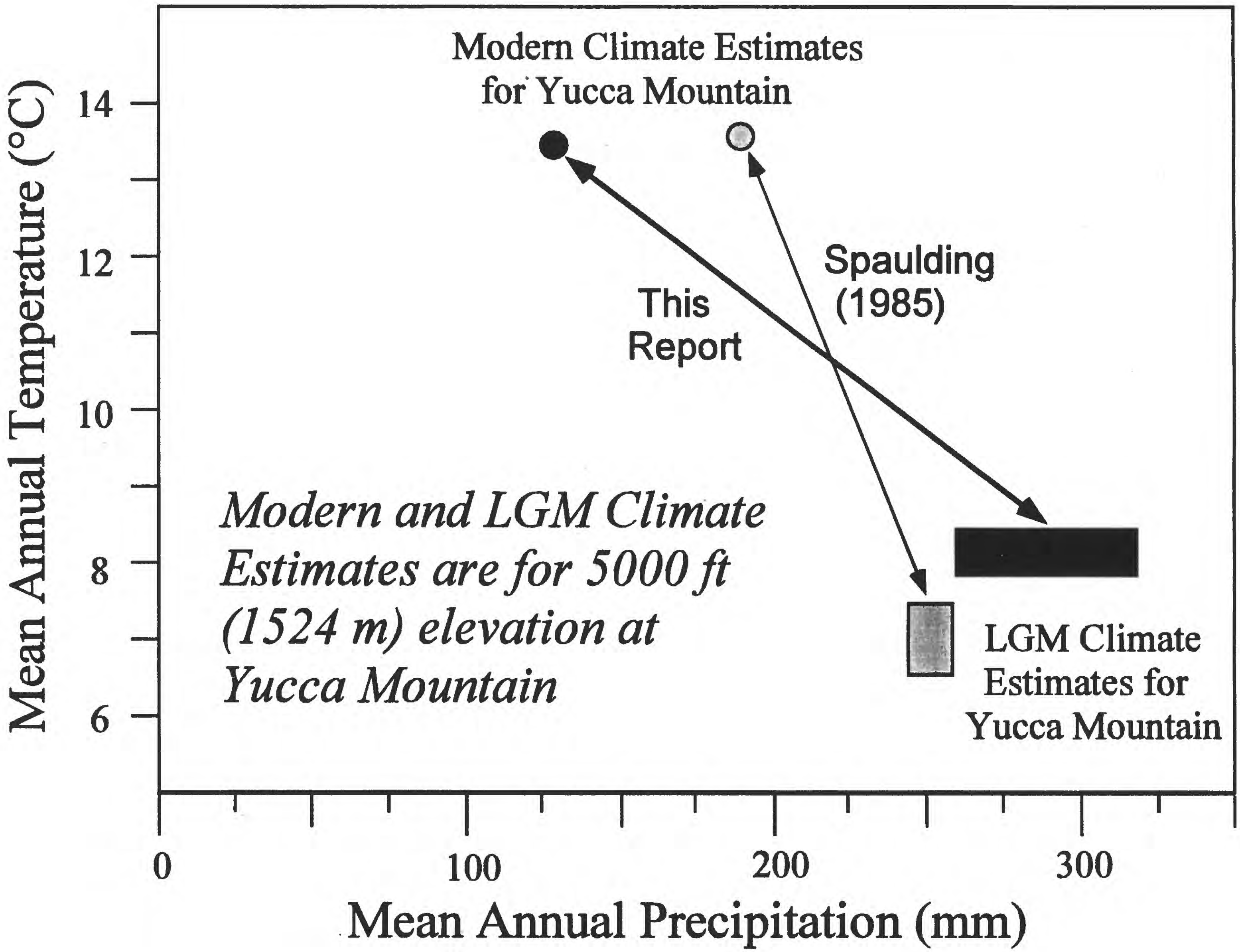


Figure 16. Annual precipitation and annual temperature for the period from 1895 to 1998 for Nevada regions 3 and 4 (see inset map on Figure 13 for the definition of these NOAA regions) characterized by the number of years when precipitation or temperature fell within given ranges. The analogue-based estimates for the Last Glacial Maximum (LGM) are shown as vertical bars. Over the past century there have been years in both regions when precipitation was as great as that reconstructed for the LGM. There have also been a few years when temperatures in region 3 were cool enough to approach those estimated for the LGM.

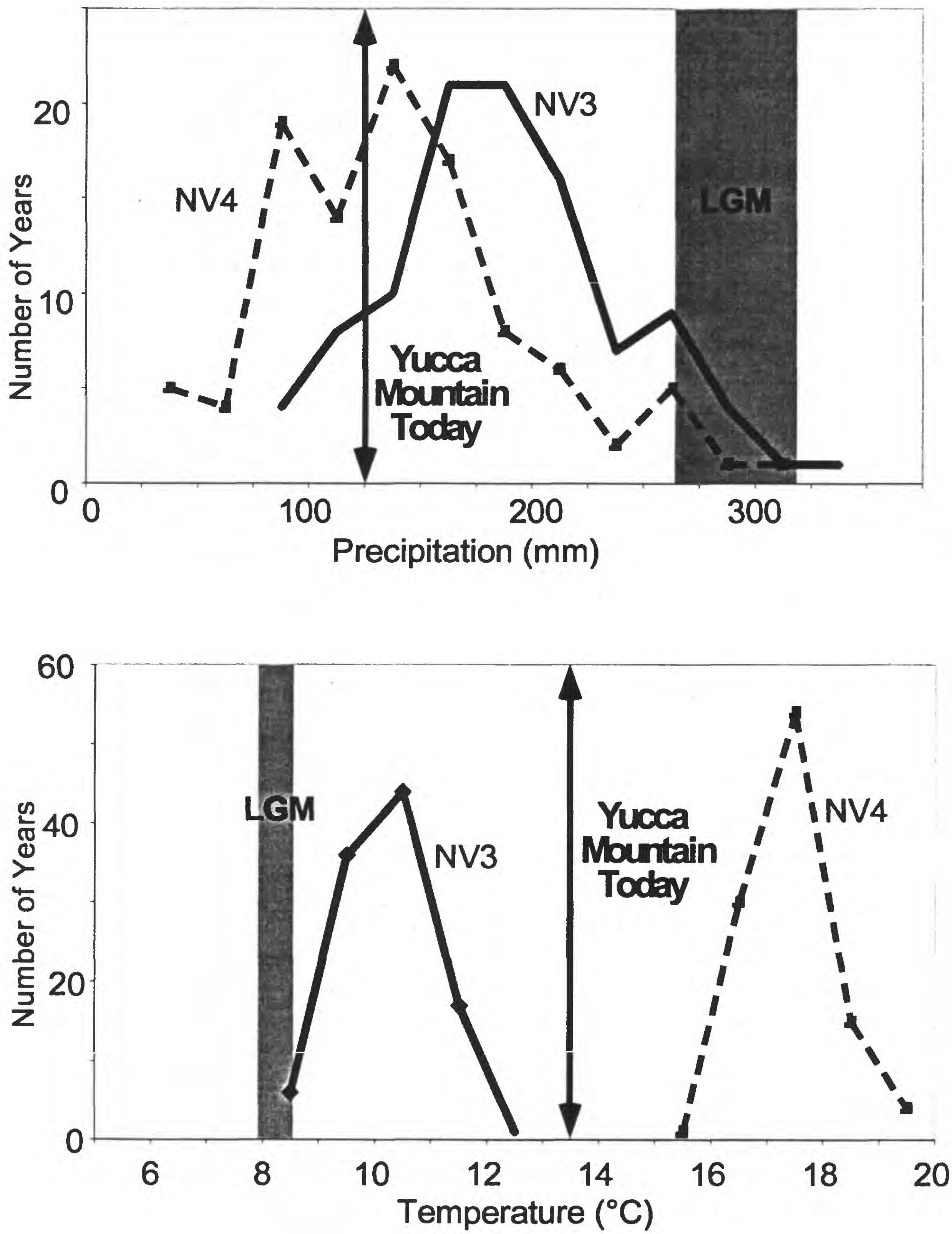


Figure 17. Comparison of historic climates in NOAA Nevada regions 3 (filled circles) and 4 (open circles) compared with modern and LGM climate estimates for Yucca Mountain. Selected years in region 3 are labeled. As shown here, there were several years in the first part of this century (notably: 1901, 1904, 1905, 1906, 1913) when the climate of region 3 was as wet, and nearly as cold, as the LGM reconstructions (at least as viewed on an annual basis - the seasonal climates could still be quite different than those of the LGM).

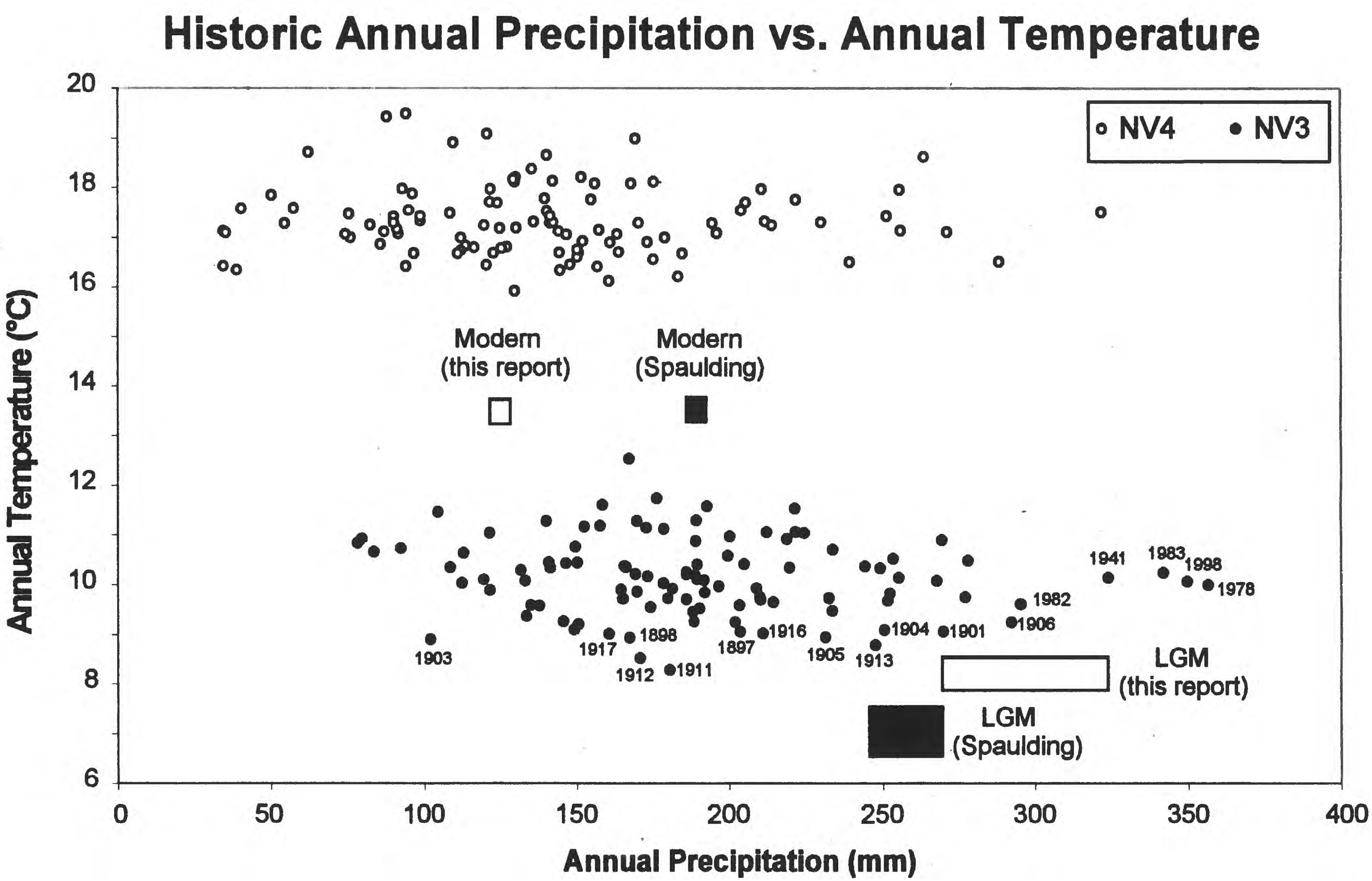
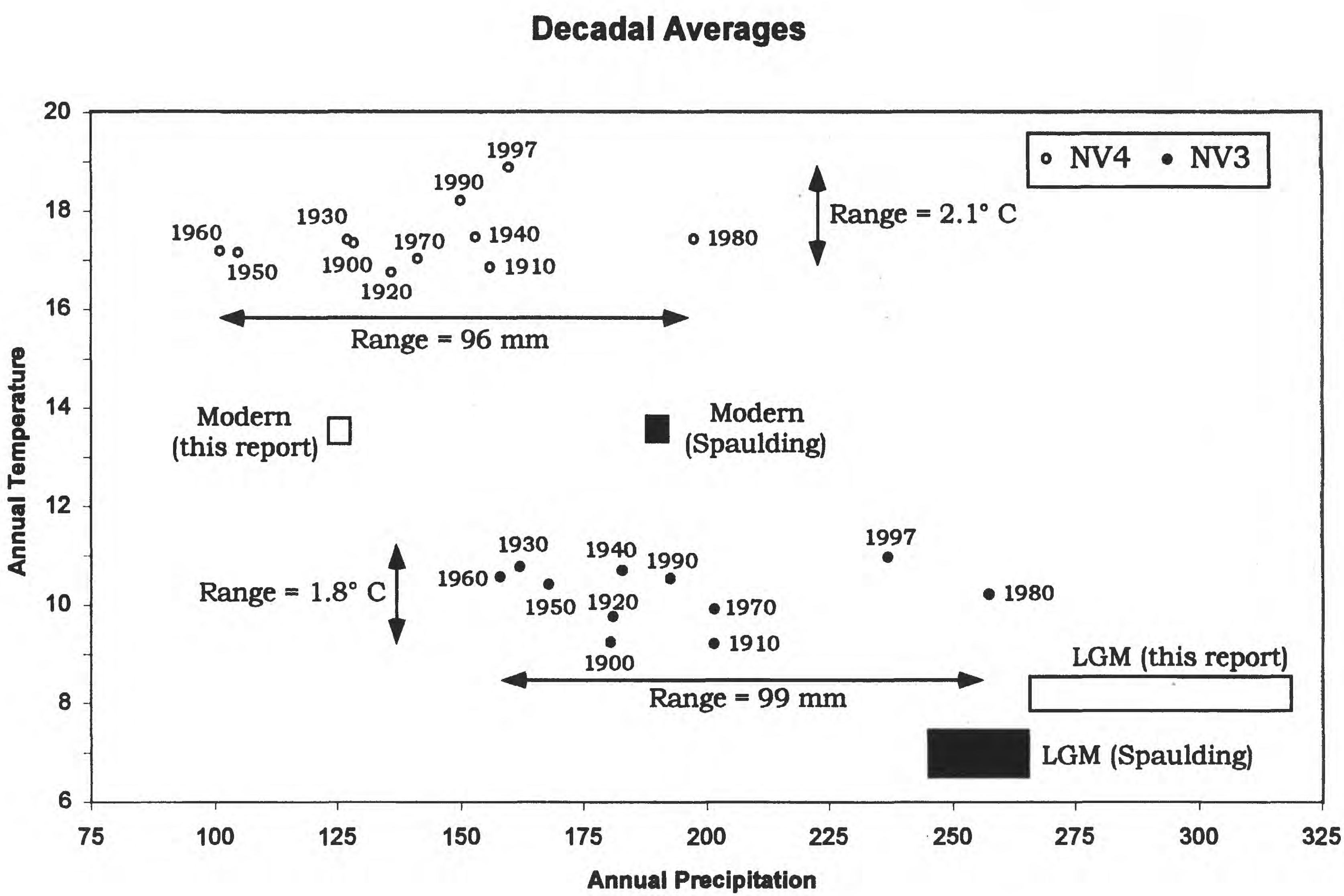


Figure 18. This figure illustrates the same data as in Figure 17, but portrayed as decadal averages plotted by their mid-points. The decades represented by the points at 1900 (1895-1904) and 1910 (1905-1914) are the coldest on record in region 3, whereas 1980 (1975-1984), which encompasses the large-scale El Niño of the early 1980s, is the wettest on record. As shown here, the range in annual temperature over the past century has been 1.8° C in region 3 and 2.1° C in region 4, whereas the variability in annual precipitation has been 99 mm in region 3 and 96 mm in region 4.



amplitudes have been common in Nevada Division 3 through the latter half of the Holocene (Hughes and Graumlich, 1996). Examination of the synoptic climatology of the early part of this century in the Southwest could provide insights into the nature of Pleistocene climates, but is outside the scope of this report.

Although individual years in the historic period had conditions that approached those reconstructed for the LGM, on a decadal basis the climate of Nevada Division 3 has remained warmer and (generally) drier than that of the LGM (Figure 18). The range of inter-decadal variability over the past century has been ~2° C and ~97 mm in Nevada Divisions 3 and 4, exceeding the differences in LGM estimates between Spaulding (1985) and this report.

Potential influences of changes in atmospheric chemistry on plant communities. Atmospheric carbon dioxide concentrations during the late Pleistocene were greatly reduced relative to pre-industrial Holocene levels, and during the LGM they were as low as ~190 ppmv (versus ~280 ppmv during the Holocene, Barnola and others, 1987). In addition to its effects on global climates, this change in atmospheric chemistry may have had influences on the physiology of plants, their elevational distributions, and the sensitivity of plant species and communities to climatic variations (Ehleringer and others, 1997). Woodward (1987) demonstrated that stomatal density decreased during the last 200 years in a variety of species due to the increased availability of carbon dioxide in the atmosphere following the industrial revolution. Van de Water and others (1994) demonstrated that fossil needles of *Pinus flexilis* in the Southwestern United States had 17% greater stomatal density during the LGM than at 12,000 years ago (by which time atmospheric carbon dioxide had increased 30% over LGM levels). By their calculations, water-use efficiency for this species would have been ~15% lower at the LGM than at 12 ka, assuming constant temperature and humidity.

Ecophysiological modeling by Jolly and Haxeltine (1997) suggests that much of the lowering of upper treelines in East Africa during the LGM could be directly caused by the lower concentrations of atmospheric carbon dioxide. They also found that some vegetational assemblages increased their climatic tolerances under lower levels of carbon dioxide. At this point we have no way to assess how well this concept applies to the Yucca Mountain region, but the stability through time of the limber pine/Utah juniper woodland (as other indicators of climate changed through time) could conceivably be due to changes in climatic sensitivity of vegetation related to changes in atmospheric chemistry. Using the African model, it is possible that the apparent changes in lapse rates for temperature could be due (at least in part) to an expanded range of climatic tolerance of woodland vegetation (relative to today). In any case, the increased stomatal density should have decreased water-use efficiency for most plants during the LGM, and hence they would require greater-than-modern levels of precipitation to sustain themselves. Hence, our estimates of late Pleistocene precipitation may be too low, especially for the LGM.

PRIMARY CONCLUSIONS.

1) For 5000 ft (1524 m) at the Yucca Mountain repository we estimate that mean annual temperature (MAT) and precipitation (MAP) differed from our modern baseline data as follows:

   35 to 30 ka: MAT = ~4° C colder than today, MAP = 1.5X modern levels;
   27 to 23 ka: MAT = ~5° C colder than today, MAP = 2.2X modern levels;
   20.5 to 18 ka: MAT = ~8° C colder than today, MAP = 2.4X modern levels;
   14 to 11.5 ka: MAT = ~5.5° C colder than today, MAP = 2.6X modern levels

2) The selection of historic baseline data has strong influence on the perceived differences between Pleistocene and "modern" climates. The baseline data used by Spaulding (1985) was significantly wetter than either the baseline employed in this report or the long-term historic mean. Consequently, Spaulding's estimates of the difference between late Pleistocene and "modern" precipitation levels is much lower than ours.

3) It is difficult to assess the potential effects of decreased atmospheric carbon dioxide concentrations during the late Pleistocene on the physiology of various plant species. However, it is plausible that nearly all species required higher levels of moisture than they do under higher concentrations of carbon dioxide during the 20th century. Consequently, our estimates of late Pleistocene precipitation levels may be too low.

4) During the early part of this century there were several years when the climate of the region adjoining Yucca Mountain on the north approached the annual temperature and moisture conditions reconstructed for the LGM at Yucca Mountain. Inter-decadal variability in the historic climate record is greater than the differences in the LGM reconstructions of Spaulding (1985) and this report.

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