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ASSIGNING CLIMATE VALUES TO MODERN POLLEN SURFACE SAMPLE SITES AND VALIDATING MODERN ANALOG CLIMATE RECONSTRUCTIONS IN THE SOUTHERN CALIFORNIA REGION

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ABSTRACT

In the modern analog technique (MAT), climate characteristics associated with the vegetation producing modern reference pollen assemblages are used to reconstruct the paleoclimates that occurred in association with vegetation producing similar (i.e., analogous) fossil pollen assemblages, based on the assumption that similarity of vegetation implies similarity of climate and other ecological characteristics. Quantitative reconstruction of paleoclimate using the MAT requires attribution of climate values at the modern reference pollen sites. In this paper, climate assignments for temperature and precipitation are determined for forty-one modern reference pollen sites in the southern California cismontane region. Six temperature lapse rates and eleven linear and non-linear equations fitted to precipitation-elevation relationships are used, based on instrumental data from available reporting stations in the region. The climate assignments match well with existing, less spatially-explicit, regional climate analyses and show ability to capture relatively small-scale variations of the region's climate patterns. The quality of the MAT when employed with the combined surface sample/climate data set is examined by reconstructing the modern climate and elevation at the surface sample sites. The general results of this validation analysis show that highly accurate, relatively precise temperature and apparent elevation reconstructions are achievable, while accurate, but somewhat less precise reconstructions of precipitation can typically be expected. When analog selection is largely confined to samples from montane conifer-dominated forests, high quality reconstructions of all the climate and elevation variables can be achieved.

Key Words: southern California, climate, climate reconstruction, paleoclimate, paleoecology, modern analog technique.

Pollen surface samples from lakes, bogs, small forest hollows, small clearings in vegetation, and moss polsters are commonly used as calibration sets to determine modern analogs for fossil pollen assemblages. Similar pollen spectra in modern and fossil samples are interpreted to imply that the vegetation, climate, and other ecosystem characteristics (e.g., forest structure and biomass) of the fossil site in the past were similar to those of its analog sites today (e.g., Maher 1972; Overpeck et al. 1985; Anderson et al. 1989; Anderson 1990; Guiot 1990; Bartlein and Whitlock 1993; Anderson and Smith 1994; Davis 1995; Davis et al. 1998, Peyron et al. 1998; Davis 1999; Davis et al. 2000; cf. Birks 1998 regarding use of modern analogs in European paleolimnology). This method of paleoecological reconstruction is commonly called the modern analog technique, or MAT.

Assigning climate values to surface sample sites in order to implement the MAT for quantitative climate reconstruction is often done using grids of interpolated climate data derived from instrumental records (e.g., Thompson et al. 1998; Bartlein et al. 1998; Minckley and Whitlock 2000). The resolution of these data is typically on the order of 15–25 km per grid-square side. Site-specific estimates are determined using weighted averages of the nearest grid points, interpolated to the sites by using local lapse rates for elevation (Minckley and Whitlock 2000). Although this method is appropriate for use in many circumstances, it is coarse in relation to the fine-scale heterogeneity of environments in the Peninsular and Transverse Ranges of southern California (Wahl 2003). In these mountains, a horizontal distance of 15 km can encompass vertical distances of more than 2000 m, with large associated differences in climate, which makes averages of nearby grid points, even when downscaled using local lapse rates, an overly-smoothed tool. Finer-scale climate estimates have recently become available at 1 km^2 resolution (Daymet U.S. Data Center, University of Montana *http://www.daymet.org*); however, the period of the Daymet data, 1980–1997, determines that key observational records that could be exploited from the study region are not utilized in the construction of the Daymet estimates.* Climate estimates are developed here for the 41 modern pollen surface sample sites reported

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* For example, the data from the Mount San Jacinto WSP and Mill Creek 2 weather stations lie entirely out of the Daymet period of record (cf. Table 1); the Julian Wynola station record loses 19 out of its 28 years of coverage.

TABLE 1. WEATHER STATIONS USED TO ASSIGN CLIMATE VALUES TO SURFACE SAMPLE SITES. Normative Period of Record: 1961–1990. Stations with other periods of records: Escondido, 1961–1979; Escondido 2, 1980–1990; Julian Wynola, 1961–1988; Mill Creek 2, 1961–1967; Mount San Jacinto WSP, 1965–1978.

Station name	County	Latitude	Longitude	Elevation	COOPID #
Alpine	San Diego	32:50	−116:47	528.8	40136
Big Bear Lake	San Bernardino	34:15	−116:53	2069.6	40741
Cuyamaca	San Diego	32:59	−116:35	1414.3	42239
Descanso Ranger Stn	San Diego	32:51	−116:37	1066.8	42406
Escondido	San Diego	33:07	−117:05	200.9	42862
Escondido No 2	San Diego	33:07	−117:06	182.9	42863
Idyllwild Fire Dept	Riverside	33:45	−116:42	1639.8	44211
Julian Wynola	San Diego	33:06	−116:39	1112.5	44418
La Mesa	San Diego	32:46	−117:01	161.5	44735
Lake Arrowhead	San Bernardino	34:15	−117:11	1586.5	44671
Mill Creek 2	San Bernardino	34:05	−117:02	897.0	45629
Mount San Jacinto WSP	Riverside	33:48	−116:38	2567.9	45978
Palomar Mountain Observatory	San Diego	33:23	−116:50	1691.6	46657
Redlands	San Bernardino	34:03	−117:11	401.7	47306

in the companion paper (Wahl 2003), based on mountain-specific temperature lapse rates and linear/non-linear precipitation-elevation equations. These relationships are derived primarily from the available instrumental data in the region (U.S. Department of Commerce, National Oceanic and Atmospheric Administration—NOAA), with additional reference to interpolated precipitation isohyets developed by the U.S. Department of Agriculture (*California Annual Precipitation* map 1999).

In quantitative applications of the MAT, it is possible to rigorously test the reconstruction capabilities of the calibration set in order to validate its use in the MAT procedure (e.g., Overpeck et al. 1985; Guiot 1990; Bartlein and Whitlock 1993; Birks 1998; Davis et al. 2000; Seppä and Birks 2002). In this paper, the MAT is used with the climate values assigned to the surface sample sites to reconstruct each site's modern climate and elevation, based on analogy of pollen spectra, which provides a quantitative test of the likely ability of the surface sample set to be successful in reconstructing paleoclimates in the region. This test is necessarily indirect, but it is logically equivalent to known-data and historical-period goodness of fit tests used to gauge the likely success of prediction models in a variety of disciplines. A key assumption of this procedure is that the modern surface sample set contains potential analogs encompassing the range of vegetation types and climates likely to be encountered during the time period studied at the paleo-reconstruction sites where it is used. The validity of this assumption for the surface sample set examined here, and for its use in reconstructing Holocene vegetation and climate at fossil pollen sites in the cismontane region of the Peninsular and Transverse Ranges, is examined in Wahl (2003).

METHODS

Climate Assignments

The basic climate data set consists of instrumental weather records from all the reporting stations in the NOAA database in the mountain and foothill areas of the study region, which is east of Los Angeles and San Diego (Table 1; Fig. 1 in Wahl 2003). These data were downloaded at *http://www5.ncdc.noaa.gov:7777/plclimprod/plsql/poemain.poe*. One station (La Mesa) nearer the Pacific Ocean coast was also used. The standard period of record is 1961–1990 (for both instrumental temperature/precipitation data and map-derived precipitation data); deviations from this period are noted in Table 1. The data were utilized as the mean during the period of record for each climate variable. Missing values in the record were estimated as the average of the five previous and five following values in the series. When a missing value was less than five years from the beginning or end of the series, the estimation included all values available between the missing value and the end of the series.

The primary method for assigning climate values to the surface samples developed mountain-specific lapse rates for temperature and linear/non-linear precipitation-elevation equations for precipitation; these relationships were applied to the surface sample sites based on their elevation. Six lapse rates each were determined for January and July temperature, and eleven equations were determined for annual precipitation. The extra relationships for precipitation were developed because the instrumental data indicate that rain and snow are more heterogeneous in the region than temperature. For each temperature variable, two lapse rates were determined for the San Bernardino Mountains, two for the Cuyamaca and Laguna Mountains, and one each for the San Jacinto Mountains and Mount Palomar. For precipitation, six equations were determined for the San Bernardino Mountains, three for the Cuyamaca and Laguna Mountains, and one each for the San Jacinto Mountains and Mount Palomar. The number of lapse rates/equations for each mountain group reflects the availability of the data, the geographic extent of the ranges and surface samples, and the topographic complexity of the ranges. All relationships are for the cismontane side (west of the eastern, desert crest) of the coastal mountains. The individual lapse rates and equations are listed in Table 2, along with their assignments to the surface samples.

For temperature, the lapse rates use foothill and montane endpoints. The rates were calculated as the linear change in temperature for change in elevation. For the one near-coastal sample (41), the temperatures of a specific reporting station were used.

For precipitation, three types of calculation were used: a) where only foothill and montane endpoints are available, linear equations were employed; b) in two cases in the San Bernardino Mountains, weighted averages of two linear equations were calculated (the weighting scheme is described in Appendix 1); and c) where the data allow, equations were fitted using information from a foothill station, an intermediate station, and a montane station or high-elevation map location. In these latter cases, four functional types were examined as estimating equations for the precipitation-elevation relationship: linear, exponential, logarithmic, and power functions. With two exceptions, the best fitting of these equations were used. In the first exception, two of the functions fit similarly well and the equation chosen was to be used to extrapolate to elevations well beyond the range of the data points; the second best, linear, fit was chosen since the better fit rose sharply outside of the range of the data. In the second exception, three of the functions fit almost identically well; the second best, linear, equation was chosen as the simpler functional form. Due to its restricted period of record, Mill Creek was used as an intermediate station only when: a) it provided a functional relationship significantly different from that determined by the corresponding foothill and montane endpoints; and b) the average precipitation values for the corresponding endpoints during the Mill Creek period of record were very close to their values during the normative period of record. For the one near-coastal sample, the precipitation value was taken from the *California Annual Precipitation* map (1999).

The temperature lapse rates are based solely on instrumental data. Four of the precipitation equations use precipitation values interpolated from the *California Annual Precipitation* map (1999) to give high-elevation endpoints where no instrumental data are available. The map isohyets were cross-checked against the instrumental data at the Lake Arrowhead, Big Bear Lake, and Cuyamaca station sites.

Validation of the Modern Pollen Surface Sample Set for Use in the MAT Procedure

The basic method of validation used here follows that of Prell (1985), Bartlein and Whitlock (1993), and Davis et al. (2000). In this approach, the modern climate values assigned to the surface sample sites are reconstructed using the same technique that is employed for paleoclimate reconstruction, by selecting analogs for each sample from among the *other* surface samples (the sample whose site conditions are being reconstructed is not allowed to serve as an analog for itself). A weighted average of the climate values associated with the analogs for a particular sample gives the reconstructed climate for the sample; the weights are proportionate to the inverses of the squared chord distances (SCD's) between the pollen assemblages of the target sample and its analogs. The reconstructed climate for each site is then compared to its assigned value. (Mathematically, use of the inverse SCD for weighting determines that the same-sample data must be excluded from the reconstruction procedure, since the inverse of a sample's SCD with itself is 1/0, which is undefined.) Definition of the SCD is given in Wahl (2003), where some of its characteristics and issues concerning its use in the MAT are described. Extended consideration of the SCD and its characteristics for use in the MAT is given in Overpeck et al. (1985), Gavin et al. (2003), and Wahl (in press). The pollen taxa included in the SCD calculations are the same as those used in the companion paper to examine patterns of SCD relationships among the elements of the surface sample set (cf. Fig. 4 in Wahl 2003).) The same procedure was also used to test elevation reconstructions, since reconstruction of the "apparent" elevation of study sites at different times in the past (in terms of the vegetation growing at a site in relation to its modern vegetation) is an important Quaternary paleoecological tool used in montane portions of western North America (e.g., Anderson et al. 2000).

This basic method was extended by reconstructing each of the climate variables and elevation using five different SCD cutoff values for analog selection, 0.15, 0.20, 0.25, 0.30, and 0.35 (a given cutoff value defines the SCD below which two pollen assemblages are considered similar enough to be analogous). Employing a range of SCD cutoffs allows the quality of the reconstructions to be used as a gauge for determining which cutoff level(s) recover maximal climate and elevation information. The range of cutoff values chosen brackets the range of best-performing values determined for this surface sample set in terms of separating like from unlike vegetation (Wahl 2003; Wahl in press). Two thresholds for the minimum number of analogs required to reconstruct were also examined, in order to evaluate the extent to which restricting reconstructions to three or more analogs might eliminate relevant information. The combination of five cutoff values with two levels for the minimum number of analogs gives ten reconstruction scenarios for each of the four climate variables and elevation in a 3-way factorial design.

Samples 21 and 35 (Table 3) were not included

TABLE 2. CLIMATE ASSIGNMENT FORMULAS AND SINGLE-POINT DATA USED TO DETERMINE SURFACE SAMPLE CLIMATE VALUES. *January and July temperature formulas* are rates of change calculated from station values as end-points. The **bold** values are the lapse rates in °C/km elevation. The italicized value before the lapse rate is the low station's temperature; the italicized value subtracted from "Elevation" is the low station's elevation. *Precipitation formulas* are fitted linear, logarithmic, or exponential equations as indicated. The slope values for the linear equations are lapse rates in cm/km elevation, and are highlighted in **bold.** Four high-elevation endpoint values were taken from the *California Annual Precipitation* map (1999), as indicated. *Notes* (1) Mill Creek not used as intermediate station. Fit between endpoints nearly identical to fit with Mill Creek included; explained in text. (2) r^2 for linear form = 0.987. Linear form used instead of exponential fit with r^2 of 0.997; explained in text. (3) Equation fitted with elevation in m; factor 6.90775 (ln 1000) corrects for conversion of m to km. r^2 = 0.945. (4) r^2 = 0.967. (5) r^2 = 0.971. (6) r^2 for linear form = 0.992. Linear form used instead of power function fit with r^2 of 0.999; explained in text.

End- & mid-point stations (names of stations/map sites)	Formula for calculation (°C temp.) (cm precip.)		Associated surface samples (#'s follow Wahl 2003)
	"Elevation" in formulas indicates surface sample elevation in km		
January temp. (monthly mean)			
Redlands-Big Bear Lake	*11.61* + (−**6.576***(Elevation − *0.4017*))		1, 2, 3, 4, 5, 6, 10, 12, 13, 15, 16, 23
Redlands-Lake Arrowhead	*11.61* + (−**7.355***(Elevation − *0.4017*))		7, 8, 9
Idyllwild Fire Dept-Mount San Jacinto WSP	*4.75* + (−**5.062***(Elevation − *1.6398*))		11, 14, 18, 19, 20
Alpine-Cuyamaca	*12.02* + (−**8.369***(Elevation − *0.5288*))		17, 21, 22, 24, 25, 26, 27, 28, 31, 32, 33, 34, 35, 37, 38, 39, 40
Alpine-Julian Wynola	*12.02* + (−**7.336***(Elevation − *0.5288*))		29
Escondido (1 & 2)-Palomar Mountain Observatory	*12.06* + (−**4.028***(Elevation − *0.2009*))		30, 36
La Mesa Station value	13.65		41
July temp. (monthly mean)			
Redlands-Big Bear Lake	*25.79* + (−**4.983***(Elevation − *0.4017*))		1, 2, 3, 4, 5, 6, 10, 12, 13, 15, 16, 23
Redlands-Lake Arrowhead	*25.79* + (−**4.472***(Elevation − *0.4017*))		7, 8, 9
Idyllwild Fire Dept-Mount San Jacinto WSP	*20.38* + (−**4.737***(Elevation − *1.6398*))		11, 14, 18, 19, 20
Alpine-Cuyamaca	*24.30* + (−**3.614***(Elevation − *0.5288*))		17, 21, 22, 24, 25, 26, 27, 28, 31, 32, 33, 34, 35, 37, 38, 39, 40
Alpine-Julian Wynola	*24.30* + (−**2.762***(Elevation − *0.5288*))		29
Escondido (1 & 2)-Palomar Mountain Observatory	*23.25* + (−**0.384***(Elevation − *0.2009*))		30, 36
La Mesa Station value	22.49		41
Annual precipitation			
Redlands (instrumental)-San Bernardino Mt. (map)	(**28.7***Elevation) + 21.051	(1)	5, 6, 15, 16, 23
Redlands-Mill Creek-Lake Arrowhead	(**60.8***Elevation) + 2.5678	(2)	*Not Applicable*: calculated for use with following two rates
70% Redlands-San Bernardino Mt. + 30% Redlands-Mill Creek-Lake Arrowhead	0.7*((**28.7***Elevation) + 21.051) + 0.3*((**60.8***Elevation) + 2.5678)		8, 9, 12
50% Redlands-Mill Creek-Lake Arrowhead + 50% Redlands-San Bernardino Mt.	0.5*((**28.7***Elevation) + 21.051) + 0.5*((**60.8***Elevation) + 2.5678)		7
Redlands-Mill Creek-Big Bear Lake	19.666*((LN Elevation) + 6.90775) − 85.835	(3)	13
Big Bear Lake (instrumental)-Onyx Peak (map)	(**49.9***Elevation) − 45.329		1, 2, 3, 4, 10
Idyllwild Fire Dept (instrumental)-Mount San Jacinto (map)	(**24.3***Elevation) + 26.733		11, 14, 18, 19, 20
Alpine-Descanso Ranger Stn-Cuyamaca	27.24* EXP (0.8*Elevation)	(4)	17, 24, 26, 27, 28, 31, 32, 33, 38, 40

TABLE 2. CONTINUED.

End- & mid-point stations (names of stations/map sites)	Formula for calculation (°C temp.) (cm precip.)		Associated surface samples (#'s follow Wahl 2003)
Alpine-Descanso Ranger Stn-Julian Wynola	29.75*EXP (0.7*Elevation)	(**5**)	29
Alpine-Descanso Ranger Stn (instrumental)-Mt. Laguna (map)	(**25.5***Elevation) + 30.159	(**6**)	21, 22, 25, 34, 35, 37, 39
Escondido (1 & 2)-Palomar Mountain Observatory	(**22.1***Elevation) + 33.330		30, 36
Interpolated map data	27.94		41

in the reconstruction analysis because their pollen representation characteristics cause them to have only spurious analogies with other vegetation types (Wahl 2003). Pollen representation refinements to the analog method (Calcote 1998; Wahl 2003) were not employed to restrict analog selection, so that the pure impact of varying the SCD cutoff level could be assessed. Possible enhancements using this technique are described in the "Discussion" section.

RESULTS

Climate Assignments

The climate values assigned to the surface sample sites are listed in Table 3. Four climate variables were assigned: January average daily mean temperature, July average daily mean temperature, the average of January and July temperature, and annual precipitation. Average January and July temperature is included as an approximation of annual temperature, at the scale of resolution available in some paleoclimate model experiments that have been extensively compared to paleoclimate data (COHMAP members 1988; Thompson et al. 1993). (These experiments simulate climate as "snapshots" of January or July conditions.) The numbering of the samples conforms to the numbering in Wahl (2003, Table 1), where site information for the samples is also given. Figure 1 shows the range of values for each of the assigned variables in graphical form, categorized by the major elevation-related vegetation groups from which the samples were taken; the vegetation groups are described in Wahl (2003). Figure 2 shows the mean and range of variation for each variable for each of the vegetation groups.

The January temperature lapse rates are close to typical measured adiabatic rates of -6–$7°C\ km^{-1}$ for dry air (which exhibit significant localized variation, Wallace and Hobbs 1977). The July temperature lapse rates are closer to the typical humid air adiabatic lapse rate of $\sim -4°C\ km^{-1}$ (Wallace and Hobbs 1977), likely reflecting the greater humidity characteristic of the cismontane region in the late spring and summer. The values for the Escondido (1&2)/Palomar Mountain Observatory temperature lapse rates are unusually low in terms of their absolute value, especially for July, a characteristic noted for other near-coastal large mountains in the region. For example, the lapse rates determined here for Escondido/Mt. Palomar (including precipitation) are highly similar to those observed for the Pasadena (263 m)/Mt. Wilson (1740 m) transect in Los Angeles County (Major 1988, p. 50). Both mountains form imposing scarps of similar elevation only ~50 km from the Pacific Ocean. The summer lapse rates for these mountains may be particularly influenced by the temperature inversion associated with late spring/summer coastal fogs, which typically occurs at elevations including the Mt. Palomar and Mt. Wilson observing stations (University Corporation for Atmospheric Research, Cooperative Program for Operational Meteorology, Education, and Training, "West Coast Fog" module *http://meted.ucar.edu*). In comparison, other regional paleoecological studies that have developed quantitative temperature estimates using lapse rates (Adam and West 1983 in coastal northern California; Anderson et al. 2000 in the interior Southwest) have used values in the typical range for dry adiabatic processes.

Validation

Table 4 and Figures 3 and 4 give the results of the validation tests. Table 4 gives regression results for comparisons of the reconstructed and assigned values. The regressions marked with an asterisk indicate the cutoff scenario(s) with the best reconstructions, as determined by a combination of slope closest to one and intercept closest to zero (together representing the most unbiased, or accurate, estimates) and highest r^2 (representing the most precise estimates). In cases of tradeoffs between slightly higher r^2 and slope slightly further away from one (e.g., January temperature for the 0.25 and 0.30 cutoffs), greater importance was assigned to the slope parameter; i.e., small degradations in precision are considered appropriate to sacrifice for lowering bias to near zero. Figure 3 shows example scatter plots and fitted regression lines for one of the best-case scenarios noted in Table 4 (January temperature).

Comparison of the slope, intercept, and r^2 values across scenarios by use of standard techniques for

TABLE 3. SURFACE SAMPLE SITE ELEVATION AND CLIMATE CHARACTERISTICS. Numbering and vegetation names follow Wahl (2003).

Sample		Main vegetation category	Elevation (m)	Temperature (°C)			Annual Precip. (cm)
				January	July	Jan/July average	
1	Lodgepole/Jeffrey/Fir Forest	**Upper- & mid-Montane Coni-**	2774	−3.99	13.97	4.99	93.09
2	Western Juniper/Lodgepole Forest/Woodland	**fer-dominated Forests**	2746	−3.81	14.11	5.15	91.70
3	Fir/Lodgepole Forest	**(1–20)**	2707	−3.55	14.30	5.38	89.75
4	Fir/Limber/Juniper Woodland		2597	−2.83	14.85	6.01	84.26
5	Fir/Jeffrey/Lodgepole Forest		2499	−2.18	15.34	6.58	92.77
6	Jeffrey/Fir Forest		2481	−2.06	15.43	6.68	92.26
7	Pine/Fir/Oak Forest		2243	−1.93	17.56	7.81	112.18
8	Pine/Fir Forest		2228	−1.82	17.62	7.90	100.91
9	Pine/Fir Forest		2228	−1.82	17.62	7.90	100.91
10	Pine/Western Juniper/Fir Forest		2438	−1.78	15.64	6.93	76.33
11	Lodgepole/Limber Forest		2926	−1.76	14.29	6.26	97.83
12	Pine/Fir Forest		2402	−1.54	15.82	7.14	107.57
13	Pine/Fir Forest		2286	−0.78	16.40	7.81	66.27
14	Lodgepole/Fir Forest		2682	−0.53	15.44	7.46	91.91
15	Fir/Pine Forest–Aspen Grove (> dense with Aspen)		2170	−0.02	16.98	8.48	83.33
16	Fir/Pine Forest—Aspen Grove (< dense with Aspen)		2170	−0.02	16.98	8.48	83.33
17	Pine/Fir/Oak/Cedar Forest		1890	0.63	19.38	10.00	123.56
18	Pine/Alder/Fir Forest		2405	0.88	16.76	8.82	85.17
19	Pine/Fir Forest		2405	0.88	16.76	8.82	85.17
20	Pine/Fir Forest		2402	0.89	16.77	8.83	85.10
21	Manzanita Chaparral	**Lower-Montane Conifer-Oak**	1692	2.29	20.10	11.19	73.31
22	Pine/Oak Forest	**Forests, Meadows, Chaparral**	1829	1.14	19.60	10.37	76.80
23	Oak/Conifer Forest	**(21–33)**	1682	3.19	19.41	11.30	69.32
24	Cedar/Pine/Oak/Fir Forest		1573	3.28	20.53	11.90	95.88
25	Pine/Oak Forest		1554	3.44	20.59	12.02	69.79
26	Oak/Cedar/Pine Forest		1451	4.30	20.97	12.63	86.96
27	Oak/Cedar Stand-in Pine/Oak/Cedar/Fir Forest		1448	4.33	20.98	12.65	86.75
28	Pine/Oak Open Forest Clearing		1439	4.40	21.01	12.71	86.13
29	Oak/Pine Forest		1228	6.89	22.37	14.63	70.28
30	Cedar/Oak/Fir Forest-Burn Site		1573	6.53	22.72	14.63	68.09
31	Meadow–in Pine/Oak/Cedar/Fir Forest		1439	4.40	21.01	12.71	86.13
32	Meadow–in Pine/Oak/Cedar/Fir Forest		1434	4.44	21.03	12.74	85.79
33	Mixed Chaparral–Mt. Mahogany dominated		1384	4.86	21.21	13.04	82.42
34	Sagebrush Steppe (> open phase)	**Steppe, Mixed Chaparral, Oak**	1132	6.97	22.12	14.55	59.03
35	Sagebrush Steppe (> closed phase)	**Woodland**	1125	7.03	22.15	14.59	58.85
36	Oak Woodland (> closed phase)	**(34–39)**	1414	7.17	22.78	14.98	64.58
37	Oak Woodland (> open phase)		1073	7.47	22.33	14.90	57.52
38	Mixed Chaparral		1091	7.31	22.27	14.79	65.20
39	Mixed Chaparral		1061	7.57	22.38	14.97	57.21
40	Chamise Chaparral	**Chamise Chaparral, Sage scrub**	817	9.61	23.26	16.43	52.37
41	Coastal Sage Scrub		244	13.65	22.49	18.07	27.94

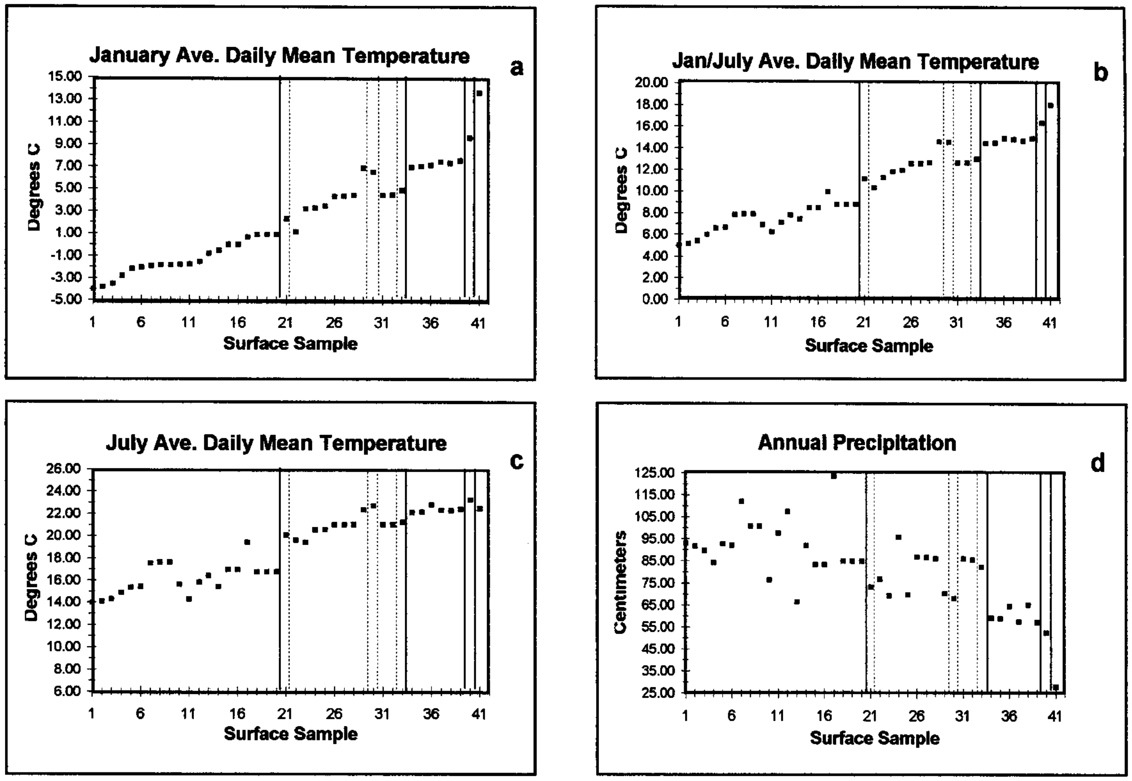

FIG. 1. Temperature and precipitation values for surface samples. Sample numbers conform to Table 3. From left to right, categories set off by heavy dark lines are: 1) Upper- and Mid-Montane Conifer-dominated Forests; 2) Lower-Montane Vegetation; 3) Steppe, Mixed Chaparral, and Oak Woodland; 4) Chamise Chaparral; and 5) Coastal Sage Scrub. Vegetation types within the Lower-Montane category are set off by dashed lines; from left to right these are: manzanita chaparral, conifer-oak forests, a forest burn site, lower-montane meadows, and higher-elevation mixed chaparral.

testing differences between computed parameters is not appropriate since each regression gives the results of the reconstruction procedure for a different population of potential reconstructions (R. D. Cook personal communication). (Different cutoff levels determine different numbers of selected analogs and different absolute weights for each set of chosen analogs.) However, since each parameter reported is an estimate of the expected value of the distribution of that parameter, it is reasonable to evaluate these expected values one against another in a qualitative manner (R. D. Cook personal communication). While these comparisons cannot be subjected to strict confidence interval testing at specified levels of risk, it is more reasonable to accept the reported parameters closest to the defined optima as likely to identify the best reconstruction scenarios than it is to reject comparison entirely and assume that the reported parameters carry no comparative information.

Figure 4 shows the numerical anomalies (reconstructed value minus assigned value) for the individual surface samples, organized by vegetation type. The anomalies for precipitation and elevation are given as percentages, in order to express them in terms of relative measure. The anomaly values for temperature are given in degrees, since relative temperature differences are represented by degree differences, regardless of plus/minus magnitude. The reconstructions in each figure are based on two or more analogs being chosen by a sample. Figure 4a shows anomalies for reconstructions at a SCD cutoff level of 0.20 and Figure 4b shows anomalies at a cutoff of 0.25. These combinations of reconstruction parameters yield the best accuracy and precision for temperature and elevation reconstructions, as discussed below, and also yield the lowest mean anomaly values for these variables. The mean anomalies for precipitation reconstruction also are lowest at the 0.20 cutoff level, although less bias and somewhat greater precision in terms of regression analysis of the reconstructions is obtained at higher cutoffs.

Results are not reported or discussed separately for the average of January/July temperature to avoid redundancy, since the reconstruction performance for this variable is highly similar to that of the other two temperature variables.

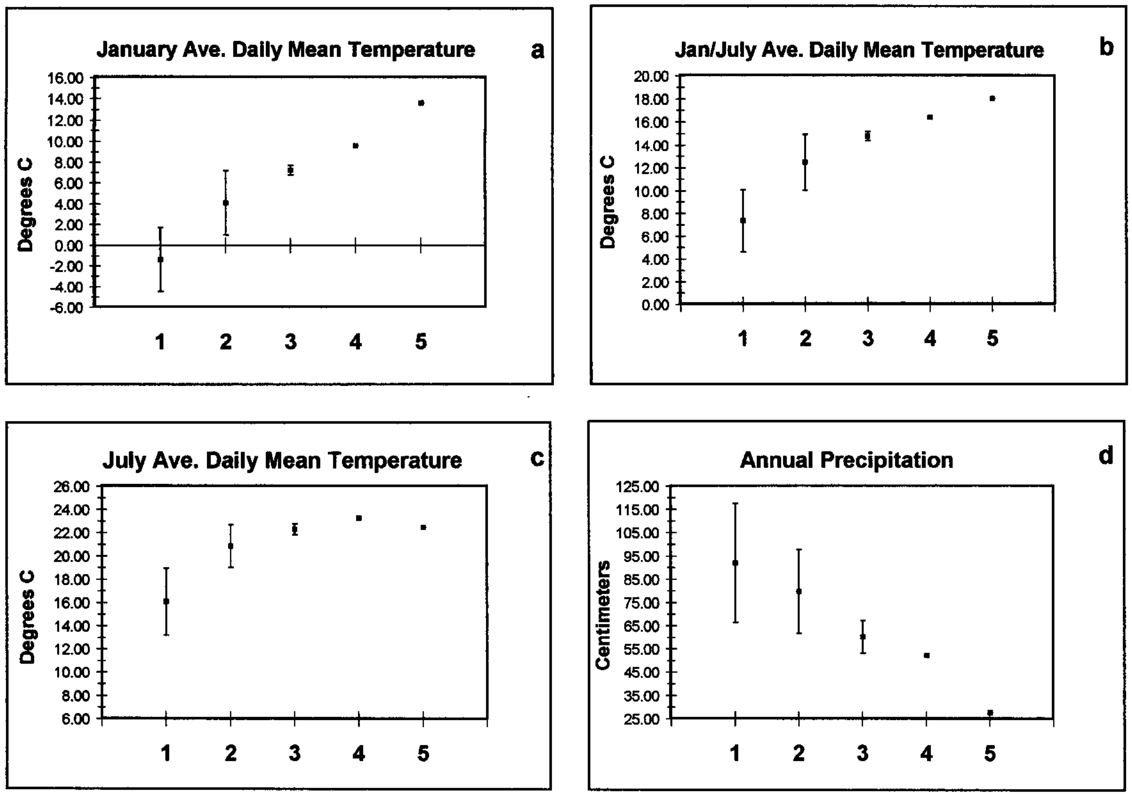

FIG. 2. Climate ranges of vegetation categories. Categories conform to Table 3 and Figure 1: 1) Upper- and Mid-Montane Conifer-dominated Forests; 2) Lower-Montane Vegetation; 3) Steppe, Mixed Chaparral, and Oak Woodland; 4) Chamise Chaparral; and 5) Coastal Sage Scrub. Data points and error bars for 1–3 show the mean and 2× standard deviation for all samples in the category. Data points for 4–5 show the value for the one sample in the category.

DISCUSSION

Characteristics of Assigned Climate Values and Relation to Vegetation

The most salient characteristic of the climate values is the difference between the variances of the temperature and precipitation values within and among vegetation categories. This characteristic is evident in the greater relative spread of the precipitation values in Figure 1, and more analytically in the overlap and width of the 2× standard deviation ranges in Figure 2. Figures 1 and 2 highlight the reduced climatic separation between the mid- and upper-montane conifer-dominated forests and the lower-montane vegetation types of cismontane southern California in terms of precipitation relative to temperature. These data suggest that temperature, rather than precipitation, is the primary climate factor responsible for the dominance of pine-fir forests in the mid- and upper-montane portions of the region—with the complete exclusion of oaks (arboreal and shrub) and lower-montane chaparral at higher elevations. Neilson and Wullstein (1983) relate winter cold and spring freezes to the close association of the northern range limit of *Quercus gambelii* with the " 'polar front' gradient" in northern Utah. The higher elevations of the southern California mountains would be more likely than lower-montane areas to experience temperatures cold enough to damage adult stems unprotected by snow cover and to develop severe frost after conditions warm enough to initiate break from dormancy, analogous to the latitudinal distribution of similar limiting conditions in the northern Great Basin (Neilson and Wullstein 1983).

Overall, January average daily mean temperature is most closely associated with differences in the vegetation of the surface samples (Fig. 2), consistent with the interpretation that winter cold could partially explain the dominance of conifer species in the mid-and upper-montane forests and woodlands. This variable has the least overlap among samples of the five major vegetation categories. In particular, the lower-montane and steppe/mixed chaparral/oak woodland vegetation categories are well distinguished from each other and from the chamise chaparral and coastal sage scrub samples. July temperature separates the lower-montane and steppe/mixed chaparral/oak woodland categories slightly less well than January temperature, and does not separate the lower-montane and steppe/

TABLE 4. VALIDATION RESULTS: REGRESSIONS COMPARING ASSIGNED AND RECONSTRUCTED CLIMATE AND ELEVATION.[a, b]
[a] The best regressions for each climate parameter and elevation (defined as combinations of slope nearest one, intercept nearest zero, and highest r^2—with close tradeoffs between these characteristics decided in favor of the slope parameter) are marked with asterisks. [b] In these regressions, reconstructed values and assigned values are "placed" on the "x" and "y" axes, respectively. This placement follows Bartlein, Webb, and Fleri (1984) and Cook and Weisberg (1999) for comparison of actual values of a variable with estimates of the same variable. (The convention in regression is to place a variable of interest on the "y" axis whose relationship to the conditional distribution of another variable, placed on the "x" axis, is being considered. In "actual vs. estimated" comparisons, the interest is in understanding how the actual [here "assigned"] values—which are not knowable in the real prediction/reconstruction period—are related to the conditional distribution of the estimated [here "reconstructed"] values—which *are* known in the prediction/reconstruction period [Cook and Weisberg 1999].)

Reconstructed parameter	SCD cutoff	Min. # analogs	Slope	Intercept	r^2	n
January temperature (average monthly mean °C)						
	0.15	2	0.8781	0.1222	0.6517	27
	0.15	3	0.8566	0.0925	0.5427	24
	0.20	2	0.9182	0.1993	0.7098	32
	0.20	3	0.9317	0.1308	0.6717	28
	0.25	2	*0.9988	*0.3071	*0.7266	35
	0.25	3	*1.0060	*0.3191	*0.7140	33
	0.30	2 & 3	1.0586	0.2883	0.7545	36
	0.35	2 & 3	1.0570	0.3273	0.7382	36
July temperature (average monthly mean °C)						
	0.15	2	0.9614	0.6014	0.6859	27
	0.15	3	0.9590	0.6425	0.5848	24
	0.20	2	*0.9782	*0.4589	*0.7305	32
	0.20	3	*1.0066	*0.0869	*0.6919	28
	0.25	2	*1.0147	*0.0576	*0.7125	35
	0.25	3	*1.0236	*0.2016	*0.6959	33
	0.30	2 & 3	1.0637	0.9302	0.7306	36
	0.35	2 & 3	1.0670	0.9633	0.7187	36
Precipitation (annual cm)						
all data	0.15	2	0.5333	39.882	0.1447	27
all data	0.15	3	0.6043	33.850	0.1403	24
lowest/highest outliers omitted	0.15	3	0.7077	24.926	0.2562	22
all data	0.20	2	0.6481	30.517	0.1458	32
all data	0.20	3	0.6673	29.323	0.1565	28
lowest/highest outliers omitted	0.20	3	0.7241	24.164	0.2503	26
all data	0.25	2	0.7659	19.942	0.1688	35
all data	0.25	3	0.7658	19.939	0.1687	33
lowest/highest outliers omitted	0.25	3	0.8774	10.105	0.2812	31
all data	0.30	2 & 3	0.8169	15.085	0.1846	36
lowest/highest outliers omitted	0.30	2 & 3	0.9240	5.6360	0.2975	34
all data	0.35	2 & 3	*0.8418	*12.870	*0.1946	36
lowest/highest outliers omitted	0.35	2 & 3	*0.9535	*3.0361	*0.3139	34
Elevation (meters above sea level)						
	0.15	2	0.9992	18.123	0.7165	27
	0.15	3	0.9487	141.52	0.6216	24
	0.20	2	*0.9985	*7.4306	*0.7647	32
	0.20	3	*1.0309	*68.226	*0.7303	28
	0.25	2	1.0438	129.91	0.7523	35
	0.25	3	1.0562	159.69	0.7375	33
	0.30	2 & 3	1.0796	199.14	0.7648	36
	0.35	2 & 3	1.0858	218.99	0.7490	36

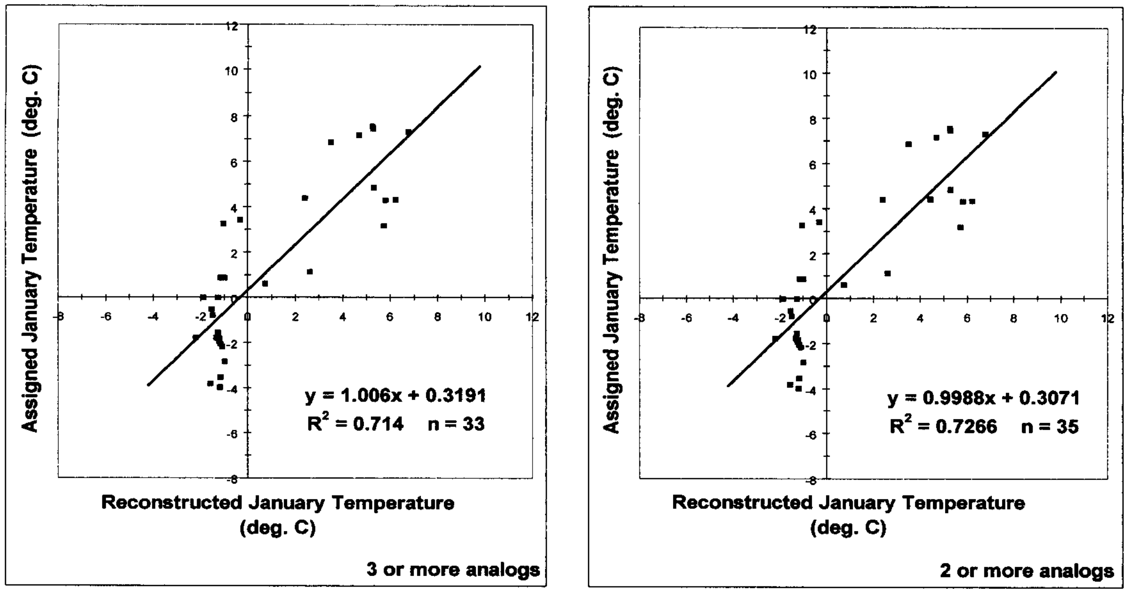

FIG. 3. Validation results: scatter diagrams and regressions comparing assigned and reconstructed January temperature at 0.25 squared chord distance (SCD) cutoff level. Results for July temperature and elevation reconstructions are highly similar.

mixed chaparral/oak woodland categories well from the coastal sage scrub sample. The reversal in July temperature between the chamise chaparral and coastal sage scrub samples goes against the general elevation-temperature relationship in the region, but is an expectable result of the cool, near-coastal fogs that are characteristic in the late spring and summer (*Climates of the States* 1985).

The precipitation value for sample 17 on Mt. Cuyamaca in San Diego County (123.6 cm/yr; Table 3, Fig. 1) is the largest of all the samples, and is unusual for its elevation. The value determined here is consistent with precipitation reported for the higher parts of the Cuyamaca Mountains in the published flora of San Diego County (Beauchamp 1986). It is also worth noting that the Cuyamaca Mountains receive the highest average summer rainfall in the southern California region (Hamilton 1983). The high precipitation at this site has been recognized since pre-historic times; the name Cuyamaca is a Latinization of the Native Californian name for the area, meaning "the place where it rains" (Cuyamaca Rancho State Park Museum, California Department of Parks and Recreation).

Characteristics of MAT Validation of the Modern Pollen Surface Sample Set

Best MAT Cutoff Values and General Characteristics of Climate and Elevation Reconstructions. For January temperature, the best analog-based reconstructions occur at the SCD cutoff level of 0.25 (Table 4). For July temperature, cutoffs of 0.20 and 0.25 both yield the best reconstructions. Elevation is best reconstructed at a cutoff level of 0.20. Overall, the reconstructions for the temperature variables and elevation are very similar in their characteristics. All exhibit nearly zero bias and similarly good precision (r^2 = 0.69–0.76) at their best cutoff values, and give good quality reconstructions for the overall range of cutoffs bounded by 0.20 and 0.35. These variables are also generally characterized by more rapid improvement in reconstruction quality between cutoffs of 0.15 and 0.20 in relation to the decline in quality from the best cutoff(s) to 0.35 (especially in terms of precision for July temperature and elevation).

The range of best cutoff values for temperature and elevation is nearly identical to that determined independently for the surface sample set in terms of discriminating between samples from like and unlike vegetation (Wahl in press). This congruence of results suggests that the pollen assemblages of the surface samples have similar information capacities in terms of the temperature/elevation and vegetation characteristics of the samples. The relatively rapid decline in reconstruction quality at SCD's below the best range and the relatively slow decline above it also parallel the sharp increase in false negatives below the best range and the slow increase in false positives above it in terms of vegetation discrimination (Wahl in press). This characteristic indicates that conservative cutoff levels set below the best range would eliminate important temperature/elevation information, relatively quickly leading to increased imprecision and bias, whereas cutoffs set somewhat above the best range would degrade performance less critically. All of these variables exhibit improved precision when the min-

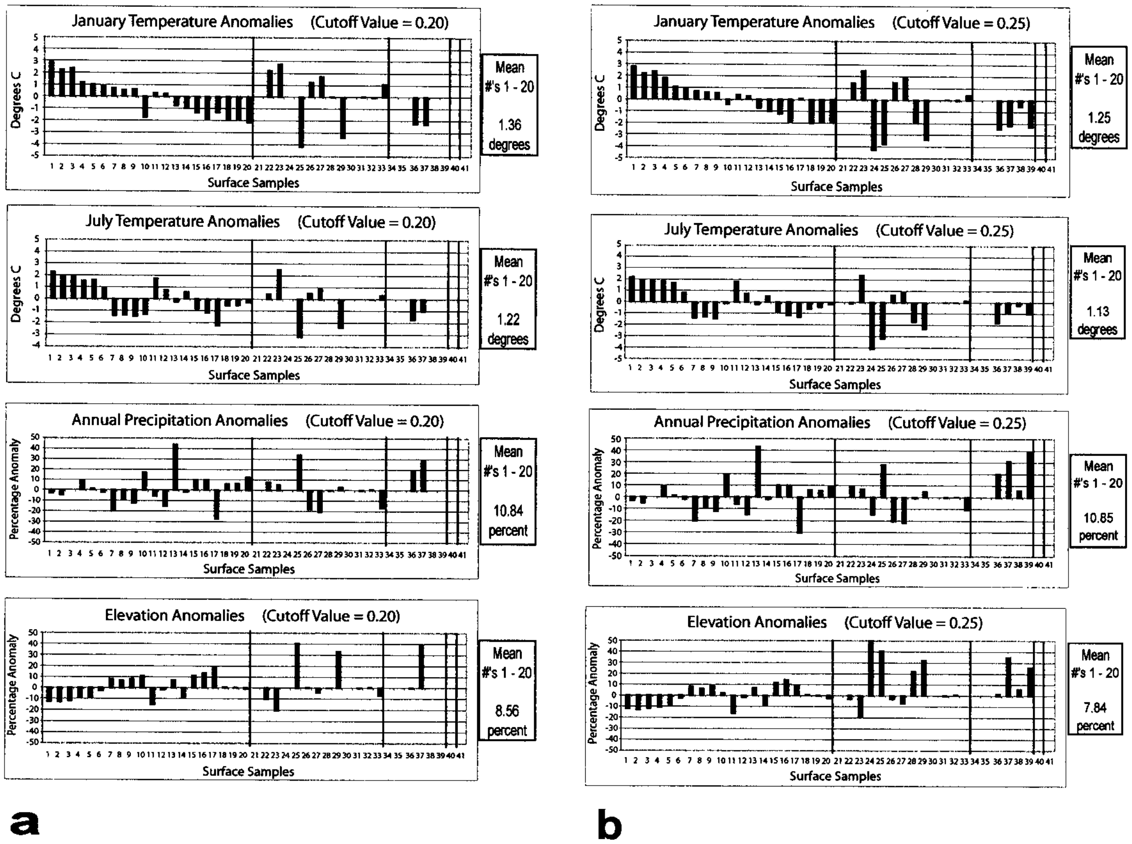

FIG. 4. Reconstruction anomalies (reconstructed value minus assigned value) for the individual surface samples, organized by vegetation type. (a) Anomalies at a squared chord distance (SCD) cutoff value of 0.20; (b) anomalies at a SCD cutoff value of 0.25. Reconstructions are based on 2 or more analogs; samples without anomalies were not reconstructed because they had too few analogs. The mean values reported average the absolute values of the anomalies, so that positive and negative values do not cancel each other.

Vegetation categories set off by vertical lines are, from left to right: a) Upper-and Mid-Montane Conifer-dominated Forests (1–20); b) Lower-Montane Vegetation (21–33); c) Steppe, Mixed Chararral, and Oak Woodland (34–39); d) Chamise Chaparral (40); and e) Coastal Sage Scrub (41). Sample numbering and categories conform to Table 3 and Figure 1.

imum number of analogs allowed in reconstruction is set at two instead of three (at the cutoff values for which this comparison is relevant, 0.15–0.25) indicating that important information is also being discarded at the higher minimum requirement.

The most significant limitation for the reconstruction of temperature and elevation is that the reconstructed values at lower temperatures/higher elevations do not reflect the full range of the assigned values. In Figure 3 this phenomenon is shown for January temperature by the relatively large vertical spread of points for a less-wide horizontal spread at lower temperature. The scatter plots for July temperature and elevation look much like those for January temperature. The means of the reconstructed and assigned values in these ranges are nearly identical, however, which contributes to the overall lack of bias in the reconstructions. Based on these validations, paleo-temperature and apparent elevation reconstructions developed with this surface sample set can be expected to be generally unbiased and relatively precise, although the range of lower-temperature/higher-elevation reconstructions can be expected to be slightly compressed in comparison to the true variation of these variables in paleo-history in the study region.

For annual precipitation, the best reconstructions in terms of regression analysis parameters occur at the SCD cutoff level of 0.35, with reasonably low levels of bias but relatively poor precision (Table 4). Even with the highest and lowest outliers eliminated from the regressions, the highest r^2 obtained by any precipitation reconstruction scenario is only 0.31. This reduced precision is expectable from the relatively high degree of variation in precipitation both within and between the mid- and upper-montane conifer-dominated forests and the lower-montane vegetation types in the study region (Figs. 1, 2). In addition, the pattern of increased precision associated with lowering the minimum number of analogs exhibited by the temperature and elevation variables is not apparent for the precipitation reconstructions, at the cutoff values for which this comparison is relevant (0.15–0.25). Because of these characteristics, quantitative reconstructions of paleo-precipitation derived from this surface sample set generally can be expected to be somewhat less precise than those for temperature and elevation. The lowest mean absolute anomaly for precipitation reconstruction occurs at a cutoff of 0.20.

Reconstruction characteristics of vegetation groups and particular samples. The most salient feature of the individual anomalies (Fig. 4) is that most of reconstructions at the best SCD cutoffs (0.20 and 0.25) are within ±2°C for the temperature variables and ±15% for elevation. Precipitation has a greater proportion of large (>±20%) anomalies, as expected, but also has numerous quite small anomalies at these cutoffs, which make its average anomaly relatively small. A second important characteristic is the overall excellent performance of the reconstructions for all the variables (including precipitation) within the conifer-dominated forest category (samples 1–20), even bearing in mind that possible restrictions of analogs with conifer-oak forests (Wahl 2003) were not done in this analysis. Only the precipitation reconstructions for samples 13 and 17 deviate greatly from this pattern. This characteristic is of particular significance for paleoreconstruction, since the predominant selection of analogs by the fossil record for which the surface samples were developed as a calibration set is from the conifer forest group (Wahl 2002; E. Wahl, Holocene paleoenvironmental reconstruction in the southern California Peninsular and Transverse Ranges, *in preparation*). The lowest mean absolute anomalies for the conifer-dominated forest category are shown in Figure 4: 1.25° for January temperature, 1.13° for July temperature, 7.84% for elevation (all at a SCD cutoff of 0.25), and 10.84% for annual precipitation (at a cutoff of 0.20).

Seven samples (13, 17, 24, 25, 29, 37, and 39) have particularly large anomalies in one or more of the reconstructed variables. Within the conifer forest category, sample 13 has erroneously high reconstructed precipitation because it is the site with the lowest assigned precipitation in this group, reflecting a precipitation shadow in the local Big Bear Valley area (Table 3, Fig. 1). The vegetation and pollen representation at this site are typical of the conifer-dominated forests, causing it to select analogs that have significantly higher precipitation. Sample 17 is nearly the opposite case, having the highest precipitation in the entire surface sample set (Table 3, Fig. 1). It necessarily selects analogs with less moisture, causing its reconstructed values to be erroneously low. This is an intractable problem for end-members of a calibration set in this kind of verification test of the MAT.

The greatest inaccuracies are generally associated with three of the conifer-oak forest samples in the lower-montane vegetation category (24, 25, 29). Samples 24 and 25 have relatively high conifer/*Quercus* pollen ratios (Wahl 2003), which cause them to select most of their analogs from the higher, cooler conifer forest category. Since the conifer-oak forests of the region can be reliably distinguished from the conifer-dominated forests on the basis of their *Quercus* pollen representation (Wahl 2003), a potential way to eliminate some of the reconstruction inaccuracy for these samples would be to constrain the set of analogs they are allowed to select—to samples with *Quercus* pollen proportions greater than the maximum *Quercus* proportion among the conifer-dominated forests. Sample 29 reconstructs temperature and elevation poorly because it is the lowest-elevation representative of its group, being essentially in the transition between the lower-montane and steppe/mixed chaparral/oak woodland vegetation categories (Table 3; Wahl 2002). The analogs it selects are mostly higher, cooler conifer-oak forests, with only one analog from the conifer-dominated forests. Because of this pattern of analog selection, the bias in its reconstruction cannot readily be corrected using the constrained-selection approach suggested for samples 24 and 25.

Samples 37 (oak woodland) and 39 (mixed chaparral) have precipitation and elevation reconstructions biased to higher values because they select some of their analogs from higher, wetter sites in the lower-montane vegetation category. A constrained-selection approach might also be employed with these samples for analogies with conifer-oak forest sites, since the latter generally have much higher representation of *Pinus* pollen than the oak woodland and chaparral samples (Wahl 2003).

Summary Considerations and Implications for Paleoenvironmental Reconstruction

The ability of the assigned values to reflect highly local variations of the regional climate—in particular the high precipitation value for Mt. Cuyamaca (sample 17) and the precipitation shadow in the Big Bear Valley area (sample 13)—indicates that the assignment methods are well-calibrated to the region's fine-scale climate patterns. Although the results of the validation procedure show that unbiased and relatively precise paleoclimate reconstructions can be anticipated from use of the new modern pollen data set, especially for the temperature variables, the high precipitation reconstruction errors for sites 13 and 17 (which cannot be reduced by constraining analog selection among vegetation categories) suggest that the information capacity of the MAT using these pollen data is not as fine-grained spatially as that of the underlying climate data. While it would be optimal to have additional fine-grained information capacity in the pollen/MAT tool, it is better that information "further down" in the analytical structure (the climate assignments) has the higher information capacity, as opposed to the reverse. This is true in general for any calibration system—the information content of the system, and thereby its ability to act as an analytical or reconstruction tool, is fundamentally constrained by the signal-to-noise ratio ("noise floor") of its most basic elements. In this case, the pollen-climate relationship developed via the MAT appears to be slightly more limiting to the potential accuracy of paleoclimate reconstructions than do the assignments of climate values to the surface sample reference sites. As such, the climate assignments reported can be expected to provide an empirically sound basis for paleoclimate reconstruction from fossil pollen samples developed in the study region.

The quality of the modern reconstructions in this study is comparable to that obtained in other studies in Europe and northeastern North America by entirely different multivariate methods (Guiot 1990; Bartlein and Whitlock 1993; Seppä and Birks 2002). The relatively lower precision for precipitation reconstruction is also seen in other data sets (Bartlein and Whitlock 1993; Peyron et al. 1998; Davis et al. 2000), and reflects the heterogeneity of the precipitation-vegetation relationship in the surface sample set. Overall, the results of the validation tests indicate that the reconstruction procedure can be confidently applied to Holocene fossil pollen data from the southern California montane region. In particular, when selection of analogs is largely confined to the montane conifer forest group, average absolute anomalies of $<2°$ for temperature, $<10\%$ for apparent elevation, and $<12\%$ for precipitation can be expected. In cases of selection of analogs with mixed representation across vegetation categories (e.g., conifer-dominated forests and conifer-oak forests), constraining analog selection according to the criteria described above and in Wahl (2003) could be considered to achieve the most accurate results.

The congruence of results between this study and those reported in Wahl (in press) in terms of best-performing cutoff values and the asymmetry in degradation of performance on either side of the range of best cutoffs is of particular interest, and has important implications beyond the validation of paleoenvironmental reconstruction methods in the study region. Up to this time, the primary focus for evaluation of appropriate cutoff values in implementations of the MAT with dissimilarity metrics (such as SCD) has been the reduction of false positive analogies (in terms of the vegetation characteristics associated with the pollen samples), which now appears to have been a bias that entails significant risk of "throwing out" relevant climate and vegetation reconstruction information via too-low cutoffs (cf. Wahl in press). The method used in this paper of systematically varying the cutoff level when validating environmental reconstruction calibrations can be an important tool in determining analog identification thresholds that recover maximal climate and apparent elevation information from pollen samples. This method can be readily implemented with existing sample-site climate information, without the need for time- and labor-intensive effort to develop the site-specific vegetation data necessary to examine best-performing cutoffs in terms of distinguishing like from non-like vegetation.

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APPENDIX 1

The weighting scheme used for calculating precipitation values for samples 7, 8, 9, and 12 was developed to account for the lack of nearby precipitation-elevation equations for these four samples, and since the nearest instrumental data (from the Big Bear Lake station) suggest a localized precipitation-shadow effect (cf. the precipitation value assigned to sample 13). The *California Annual Precipitation* map (1999) isohyets are consistent with this interpretation.

The weights used were developed taking into account the following information: a) the annual precipitation value at the Lake Arrowhead reporting station is nearly identical to that interpolated at the lake by the map (103.8 cm from the instrumental data vs. 101.6 cm, or 40 inches, from the map); and b) the annual precipitation from the map for a high-elevation endpoint on San Bernardino Mountain is also 40 inches. With the elevations of the

Lake Arrowhead and San Bernardino Mountain endpoints used as bracketing values, two intermediate elevations were determined: a) for the location nearest samples 8, 9, and 12 that is transected by the 40-inch isohyet in the map; and b) for the location nearest sample 7 that is transected by the 40-inch isohyet. The relationships between these elevations and the elevations of the Lake Arrowhead and San Bernardino Mountain endpoints were used to determine the weights employed in the precipitation calculations.