Spatial Variability of Late-Quaternary Paleoclimates in the Western United States

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Paleoclimatic interpretation of proxy data is complicated sometimes by the appearance of heterogeneous patterns of climatic responses across networks of sites. Modern climate analogues for the western United States, similar to those patterns of atmospheric circulation of 18,000 and 9000 yr B.P., were examined in order to explain such patterns of spatial heterogeneity. Modern analogues were defined by comparing modern atmospheric circulation patterns with those simulated by general circulation models. Maps of temperature and precipitation anomalies of the modern analogues reveal patterns of spatial heterogeneity, which resemble the patterns of effective moisture compiled from paleoclimatic data. January 1957 was found to be a reasonable 18,000 yr B.P. analogue, and it features isolated areas of increased wetness in the northern Great Basin and increased dryness in the Northwest interior. Analogues for 9000 yr B.P. from a composite of 11 Augusts display patterns of spatial heterogeneity of effective moisture over most of the mountainous areas. The analogues suggest that spatial heterogeneity of climate is the rule rather than the exception over much of the western United States, with the climatic anomalies at any particular time representing the outcome of the mediation of large-scale atmospheric circulation controls by smaller scale topographic features.

INTRODUCTION

The interpretation of paleoclimatic data is often complicated by the appearance of site-to-site differences in climate reconstructions that only seem indirectly related to macroclimatic patterns. In the western United States, changes in large-scale atmospheric circulation appear to explain the broad-scale patterns of effective moisture that varied through the late Quaternary (Thompson et al., 1993). Paleoclimatic data, however, also indicate that smaller scale variations of effective moisture occurred within parts of the mountain and plateau regions, particularly at 9000 yr B.P. (Fig. 1; Davis and Sellers, 1987; Thompson et al., 1993). Analytical methods are needed to show whether these smaller scale variations are consistent with shifts in broad-scale atmospheric circulation or are just the result of noise or nonclimatic factors influencing the data. Spatial heterogeneity of climate at the regional scale may arise from both climatic and nonclimatic sources, including: (1) small-scale climatic variations, defined as different-surface climatic responses at adjacent sites to the same larger scale climatic forcing; (2) local nonclimatic factors such as substrate and disturbance regimes that may modify the response of paleoclimatic indicators to large-scale climatic variations; (3) uncertainties in the quality of dating control that may result in the grouping of records of different age, giving the impression of a spatially heterogeneous record at a particular time; and (4) uncertainties in the climatic interpretations drawn from the paleoclimatic evidence, again giving the impression of spatial heterogeneity.

Whitlock and Bartlein (1993) and Whitlock et al. (1995) proposed that the smaller scale climatic variations account for a larger portion of the spatial heterogeneity than the nonclimatic sources for the Yellowstone National Park region of the northern Rocky Mountains. They ascribed this heterogeneity to the way in which the influence of large-scale circulation controls is locally mediated by topography. Whitlock and Bartlein (1993) and Whitlock et al. (1995) suggested that spatially heterogeneous patterns of paleoclimatic variations therefore may be consistent with large-scale circulation patterns, and that similar heterogeneous responses to simple large-scale forcing probably also exists in other parts of the western United States.

General circulation models (GCMs) and “mesoscale” models or regional climate models (RCMs) provide a means for understanding the climatic controls that operated in the past (COHMAP Members, 1988; Hostetler et al., 1994). GCMs have sufficient resolution to describe variations in large-scale atmospheric circulation patterns (Kutzbach, 1987; Kutzbach et al., 1993), but they cannot accurately simulate smaller-scale circulation features and their interactions with topography that may explain some of the spatially varying climatic changes in the western United States. Higher resolution RCMs portray topography more realistically than GCMs but still greatly smooth the terrain relative to the actual landscape. Therefore, a strictly model-based approach cannot yet fully identify the hierarchy of climatic controls that may have led to patterns of
spatial heterogeneity over the western United States during the late Quaternary.

The analysis of modern analogues offers an attractive way to understand atmospheric circulation and surface climate variations of the past (Barry, 1981). Such analyses are based on the assumptions that the range of modern conditions contains extreme events that may have been more frequent in the past and that the climatic processes work in the same way during the present and past. Modern analogues have been used to explain paleoclimatic variations at the regional scales (e.g., Nicholson, 1978; Diaz and Andrews, 1982; Hostetler and Benson, 1990), but they have not yet been applied to smaller spatial scales. For the western United States, the modern record has advantages in spatial resolution over that provided by GCMs, RCMs, and networks of paleoclimatic data, because the network of meteorological stations is much denser. Modern climate analogues for the western United States, therefore, can be compared with reconstructions from proxy data in order to suggest why spatial heterogeneity in the reconstructions may occur.

The objective of this paper is to examine modern climate analogues of the western United States for 18,000 and 9000 yr B.P. The study area of this paper includes the United States west of 93°W in order to cover a diverse range of spatial climatic controls and scales. The times 18,000 and 9000 yr B.P. provided ideal scenarios for testing the reliability of modern climate analogues because external climatic controls at those times were much different than today (COHMAP Members, 1988). Because some boundary conditions (e.g., ice-sheet size and insolation) during the late Quaternary were dramatically different from those today, perfect modern analogues obviously do not exist. However, partial analogues provide information on the climatic controls and processes that may have operated at spatial scales at and below the regional scale (Barry, 1983; Crowley, 1990). The modern analogues were selected on the basis of having broad-scale atmospheric circulation patterns similar to those believed to have occurred in the past. The selection was achieved by matching circulation patterns simulated by GCMs with those in the instrumental record. Thus, the modern analogues are selected climatic extremes of these modern circulation patterns, expressed as monthly analogues (e.g., abnormally cold Januaries). These modern analogues reveal patterns of surface climate that are consistent with large-scale circulation patterns and also provide finer resolution that show patterns of spatial heterogeneity.

The purpose of our analogue analysis is not to reconstruct a circulation pattern that prevailed in the past nor to reconstruct surface temperature or precipitation; rather, our purpose is to offer insights into the details of the smaller scale responses to large-scale climatic controls. Also, the modern analogues are not designed to assess shifts in seasonality of paleoclimate; they cannot do so because monthly analogues do not correspond directly with annual indicators of paleoclimate. However, the monthly analogues can clearly represent the anomalous character of spatial climatic variability at 18,000 and 9000 yr B.P. as compared to today, and the patterns of atmospheric circulation as represented by the analogues likely predominated during most of the course of the annual cycle. Thus, modern climate analogues can be used to explore and infer meso- and microscale climatic features that are recorded by paleoclimatic evidence from proxy data.
DATA AND METHODOLOGY

Types of Data

The paleoclimatic data used in this study were derived from subjectively interpreted field data for 18,000 and 9000 yr B.P., based on packrat middens, lake-level, and fossil pollen sites (Fig. 1). The data are presented in terms of anomalies of effective moisture relative to modern values. Most of the interpretations were derived by Thompson et al. (1993), with 49 sites for 18,000 yr B.P. and 110 sites for 9000 yr B.P. Sites from this data set were augmented with 9 sites for 18,000 yr B.P. and 20 sites for 9000 yr B.P. in the Great Plains. Overall, 18 new pollen, lake-level, and plant macrofossil sites were added to the Thompson et al. (1993) data set for 18,000 yr B.P., and 63 new sites were added to the data set for 9000 yr B.P. (refer to Mock (1994) for a list of these sites). As a consequence of the diversity of terrain in the western United States, the addition of even a few paleoclimatic sites in a small region can greatly aid in paleoclimatic interpretation (Whitlock and Bartlein, 1993).

Three types of data were analyzed in this study, paleoclimatic evidence from geological and biological records as described above, atmospheric circulation data, and surface climate data. Atmospheric circulation and surface climate data span the entire length of the modern instrumental period and thus can be used to illustrate a range of circulation regimes. The 500-mb level was selected for examining atmospheric data. This level is commonly used by the climatologist to study upper-level flow as it relates to surface weather and climate, and the level lies above the friction layer where flow is influenced by boundary layer processes and topography. Circulation data for the 500-mb level were obtained from CD-ROM (Mass, 1993). The circulation data are expressed as heights (in meters) of the 500-mb level, with lower heights indicating regions of lower pressure and troughs and higher heights representing areas of higher pressure and ridges. These data were analyzed for a region spanning the western Pacific to the eastern Atlantic in order to describe adequately large-scale climatic controls for the study area. The data are expressed as monthly averages and cover the period from 1946 to 1988. The surface climate data include sites from the Historical Climatology Network (HCN). This network consists of 500 stations within the western United States, with monthly temperature and precipitation data covering the period from 1948 to 1988 (Wallis et al., 1991).

Identification and Analysis of 18,000 and 9000 yr B.P. Analogues

The analogue analysis consists of two parts, identification of the appropriate analogues in the modern record that resemble the paleoclimates under consideration, and summarization of the circulation and surface climatic data to understand the hierarchy of climatic controls and associated surface responses. The identification of the appropriate modern analogues involved three steps. First, the key features of the circulation of paleoclimate under consideration were inferred from large-scale circulation patterns simulated by GCMs. Results from the National Center of Atmospheric Research Community Climate Model 0 (NCAR CCM 0) was used in this study because they have been the most extensively documented and used (COHMAP Members, 1988; Kutzbach et al., 1993), but results from other GCMs were used as well (e.g., Broecker and Manabe, 1987; Mitchell et al., 1988). Second, occurrences of large-scale circulation patterns similar to the paleoclimate of interest were sought in the modern record. The search for similar patterns was assisted by the use of circulation indices, which summarize a particular regional atmospheric circulation pattern to a single number (Yarnal, 1993). These indices show, objectively, how strongly a particular circulation pattern (e.g., a meridional jetstream) is expressed in each month or season in the modern record. Circulation indices can be derived from values of upper-level heights at a few locations (e.g., Pacific North American indices from Leathers et al., 1991) or based on the latitudinal positions of selected atmospheric circulation features (e.g., the subtropical ridge indices from Carleton, 1987). Third, the key large-scale patterns were examined for every potential modern analogue because the similarity of large-scale patterns between some potential analogues can differ substantially, despite being expressed in a similar manner in terms of its circulation index. Any analogues that deviated from the key large-scale circulation patterns as simulated by GCMs were regarded as outliers and eliminated from the list of potential analogues.

The circulation patterns and surface climatic responses for the modern analogues were summarized by anomaly maps of circulation, temperature, and precipitation. If the number of remaining modern analogues was ten or greater, composite anomaly maps were constructed. Such anomaly maps provide useful information in depicting spatially the patterns of climatic features that lead to climatic extremes (Yarnal, 1993). Composite anomaly maps provide a quantitative method for illustrating the differences between averaged values of selected climatic extremes (the appropriate modern analogues) and climatic normals. If only a few appropriate analogues existed, then circulation, temperature, and precipitation anomalies for each analogue were examined individually. Prior to constructing composite anomaly maps of precipitation, the precipitation data were standardized by dividing monthly precipitation values at a station by its annual average, thereby enabling comparisons to be made of precipitation anomalies among stations in complex terrain (Tang and Reiter, 1984). Temperatures were expressed as departures from normal. Surface climatic anomalies of the modern analogues were then compared with spatial networks of effective moisture derived from paleoclimatic evidence, enabling conclusions on the predominant climatic controls that operated in the past to be drawn.
RESULTS

18,000 yr B.P. Paleoclimate

GCM simulations using the NCAR CCM 0 for 18,000 yr B.P. illustrate the response of surface climates in the western United States to larger ice sheets, higher aerosol concentration, lower sea-surface temperatures, and lower carbon dioxide concentrations. NCAR CCM 0 simulates reasonably accurate patterns of present-day upper-level winds over North America (Pitcher et al., 1983), thus it may simulate accurate patterns for the past. The split and southward displacement in the polar jet stream at 18,000 yr B.P. during January is the most distinctive feature simulated by all GCM simulations of the 18,000 yr B.P. climate, with increased southwesterly flow into the southwestern United States (e.g., Broccoli and Manabe, 1987; Kutzbach et al., 1993). This pattern is less apparent for July, suggesting that changes during midwinter (January) characterize the major differences between 18,000 yr B.P. and today’s climates. An upper-level trough, associated with the increased southwesterly flow from the split in the polar jetstream, was responsible for the simulation of a mild (but still ca. 5°C cooler than today) and wet climate in the American Southwest (Kutzbach, 1987). The simulations also suggest that the Pacific Northwest was drier as a result of a glacial anticyclone centered in western Canada. Similar patterns of circulation features and surface responses are simulated by other GCMs (e.g., Broccoli and Manabe, 1987).

Monthly extremes of PNA (Pacific North American Teleconnection) indices from the modern record were examined to find occurrences of large-scale patterns similar to an 18,000 yr B.P. paleoclimate. The PNA index represents the strength of the ridge–trough–ridge pattern (or high–low–high pattern of atmospheric pressure) of upper-level flow over North America (Leathers et al., 1991). Large, negative PNA indices indicate increased ridging in the Gulf of Alaska and increased troughing (or low pressure) bringing an increased frequency of storms into the American Southwest, a pattern similar to the 18,000 yr B.P. simulated pattern (Kutzbach et al., 1993). Januarys with PNA indices larger than one standard deviation below the mean (relative to the period from 1947 to 1989) were chosen as potential modern analogues. January PNA indices were used in this study because this is the month when the PNA pattern is most clearly defined (Leathers et al., 1991).

Negative PNA extremes from eight Januaries were used to construct 500-mb anomaly maps. The examination of each of the eight Januaries yields three months that show the characteristic features of the 18,000 yr B.P. January simulations (January of 1949, 1957, and 1969). This finding is not surprising, because the PNA indices for these are the lowest of the eight months. The pattern for January 1957 is clearly, and by far, the most consistent with GCM simulations of an 18,000 yr B.P. winter climate (Fig. 2A). A split flow at upper levels off the west coast is evident along with a trough extending over eastern North America. Although positive 500-mb height anomalies are evident over the Gulf of Mexico, anomalies are weak, and northwesterly flow predominated aloft over most of the Great Plains region during January 1957. The 500-mb circulation for January 1957 differed most from the other months by having positive anomalies extending eastward into Alberta and negative anomalies extending into New England (Stark, 1957). The catalog of daily sea-level pressure pattern types, derived by Barry et al. (1977), shows that January 1957 has 10 days with a high pressure centered over western Canada that is similar to the NCAR CCM 0 simulation of the glacial anticyclone in northern North America. Consequently, January 1957 was selected as the best potential 18,000 yr B.P. analogue.

Surface temperature and precipitation data are consistent with the selection of January 1957 as being the closest analogue to an 18,000 yr B.P. climate. Air temperature departures

FIG. 2. (A) 500 mb anomaly map for January 1957; (B) 500 mb composite anomaly map of 11 August STR extremes. Units are in geopotential meters, dashed lines indicate negative anomalies, and solid lines indicate positive anomalies.
FIG. 3. (A) Temperature departures (°C) and (B) precipitation percentiles for January 1957.

for January 1957 were negative throughout most of the region (Fig. 3A). Although slightly positive departures of up to 2°C are evident over the Southwest, the temperature gradient from north to south was relatively large and consistent with GCM simulations.

The precipitation-percentile map for January 1957 was mapped using a criterion defined by the National Meteorological Center: values less than the 10th percentile indicate very dry conditions, 10th–30th percentiles indicate dry conditions, 30th–70th percentiles indicate no significant anomaly, 70th–90th percentiles indicate wet conditions, and values greater than the 90th percentile indicate very wet conditions. The precipitation-percentile map shows the Southwest was wet as a result of increased southwesterly flow that brought moisture from the eastern Pacific into the region (Fig. 3B). Relatively dry conditions in New Mexico and Texas suggest that moisture from the Gulf of Mexico played less of a role than normal during January 1957. Easterly winds were prevalent in the Pacific Northwest and brought cold and dry conditions. Overall, the large-scale precipitation response for January 1957 is also consistent with anomaly signs suggested in GCM simulations.

Smaller scale precipitation responses during January 1957 are also clearly evident over parts of the western United States. Northwesterly winds were predominant in the northern and central Great Plains during January 1957, creating generally dry and cold conditions. However, the precipitation-percentile map indicates that the dry conditions also extended westward through the Rawlins Gap, Wyoming, into the Snake River Plain, Idaho. This low-elevation pathway is responsible for creating localized weather conditions that can differ from that of surrounding regions (Tang and Reiter, 1984). Wind directions during January 1957 illustrate that some cold and dry air from the northern Great Plains was funneled through these lower elevation gaps, causing the localized cold and dry conditions farther west. Storms that traveled the region from the west occasionally enhanced the westerly push of air through these lower elevation gaps. This air eventually rose over colder air trapped in the valleys of Oregon and Washington east of the Cascades, and thereby created wetter conditions there as compared to the coast. Some stations in the northern Rocky Mountains experienced wet conditions as a result of occasional periods of easterly flow that enhanced orographic effects on the eastern side of the northern Rocky Mountains.

The effective moisture map for 18,000 yr B.P. derived from paleoclimatic evidence shows a large-scale contrast between dry conditions in the Pacific Northwest and southern Idaho, and wet conditions in the Southwest (Fig. 1A). However, the data for 18,000 yr B.P. also suggests a further northward extent of increased wetness into Oregon and Nevada than what GCM simulations imply (e.g., Kutzbach 1987). The dry conditions in southern Idaho and the greater northward extent of wetness may be the result of smaller scale climatic controls operating in a similar manner as discussed above for January 1957. Evidence from frost wedges and lemmings of assumed late-glacial age in the valleys of central Wyoming and southern Idaho support the notion that cold and dry air funneled through the Rawlins Gap and Snake River Plain (Mears, 1981; Mead and
Mead, 1989). Evidence of the northern bog lemming in the northern Great Basin during the last glacial maximum also confirms the implications of a strong north–south temperature gradient and locally mesic conditions from topographic diversity (Mead et al., 1992).

Pollen evidence for 18,000 yr B.P. also indicates that greater effective moisture as compared with today occurred far inland and eastward into the southern Great Plains, perhaps because of strong southwesterly flow of the southern branch of the polar jet stream in a similar manner to January 1957. Vertebrate faunas in the Edwards Plateau of Texas suggest cool moist summers and mild winters (Toomey et al., 1993). Insect fossil evidence also indicates equable paleoclimates during 18,000 yr B.P. in the northern Chihuahuan desert of Texas and New Mexico (Elias and Van Devender, 1992). Wells and Stewart (1987) inferred from land snails and from macrofossils of spruce and limber pine that greater effective moisture also resulted in the central plains of western Kansas and southwestern Nebraska at 18,000 yr B.P.

9000 yr B.P. Paleoclimate

The 9000 yr B.P. climate, simulated by NCAR CCM 0, is characterized by increased summer-monsoonal precipitation over much of the American Southwest and Rocky Mountain region as a result of increased summer insolation, greater continental warming, and thus a stronger onshore flow. NCAR CCM 0 also simulated drier conditions for the Pacific Northwest as a result of a strengthened Pacific subtropical high. Similar patterns are also simulated by other GCMs (e.g., Mitchell et al., 1988). The output of NCAR CCM 0 shows that an upper-level anticyclone (subtropical ridge) over the Colorado Plateau is associated with the increased summer-monsoonal activity, and that a stronger Pacific subtropical high is responsible for the dry conditions in the Pacific Northwest (Kutzbach, 1987). A strong subtropical ridge causes increased monsoonal activity by providing stable conditions aloft, which favors the buildup of strong convective storms. The selection of 9000 yr B.P. analogues was based on extremes of the subtropical ridge (STR) summer monsoon index, which describes a pattern similar to the simulated 9000 yr B.P. climate. The STR index measures the frequency of the subtropical ridge over the southwestern United States during summer (Carleton, 1987). Positive STR indices are associated with wetter summers in the Southwest due to northward movements of the upper-level subtropical ridge. For summers with STR indices greater than the 75th percentile (1945–1987), Augusts were chosen as potential 9000 yr B.P. analogues because they represent the peak of the Southwest monsoon season when monsoonal precipitation occurs farthest to the north.

STR extremes yielded eleven appropriate analogues for 9000 yr B.P. as opposed to the single appropriate analogue for 18,000 yr B.P.; thus, this number is large enough to construct composite anomaly maps of 500-mb heights, temperature, and precipitation. The 500-mb composite map for months with extreme positive STR indices shows an area of positive height anomalies over the West and an area of negative anomalies off the Pacific Northwest coast (Fig. 2B). Although the anomalies are small, they are still relatively large as compared to those over North America and the adjacent oceans, and thus clearly illustrate abnormal summer conditions. The positive height anomalies correspond to the stronger subtropical ridge over the Southwest simulated by the NCAR CCM 0. The negative height anomalies represent the influence of more frequent upper-level troughs passing through the region from the west.

The temperature-departure composite map for 9000 yr B.P. indicates warm anomalies throughout most of the continental interior, and some negative anomalies along the Pacific coast and in southern Arizona, generally consistent with GCM simulations (Kutzbach, 1987) that show greater surface heating in the interior at the regional scale (Fig. 4A). Negative anomalies along the coast in the temperature composite map also suggests an onshore flow that is stronger than normal. The precipitation composite map (Fig. 4B) shows wet conditions that extend from the Southwest northward through Nevada, Utah, Colorado, along the coast of California, and dry conditions over the southern Great Plains due to the influence of the subtropical ridge. Dry conditions are also evident in most of the Pacific Northwest and in the Snake River Plain. These conditions result from a strong Pacific subtropical high, which creates stronger westerly flow through low-level topographic gaps, thus preventing the northerly spread of the subtropical ridge and limiting the northern extent of the summer monsoon (Tang and Reiter, 1984).

A mixture of wet and dry conditions is evident in the northern Rocky Mountains near Yellowstone National Park, in eastern Washington, and in eastern Colorado (Fig. 4B). The spatial heterogeneity of precipitation is the result of the influence of smaller scale terrain features on the synoptic-scale circulation features (Tang and Reiter, 1984; Whitlock and Bartlein, 1993; Whitlock et al., 1995). In the central and northern Rockies, localities that normally have a summer precipitation maximum are wetter than normal, whereas localities that normally have a winter precipitation maximum and summer precipitation minimum are more susceptible to westerly flow and are drier than normal. In the mountains of Colorado, some stations exhibit negative anomalies because they are shielded from the effects of the western side of the subtropical ridge. Spatial heterogeneity in the interior Pacific Northwest may be the result of upper-level troughs that can occasionally cause locally heavy precipitation when associated with strong, westerly flow (Hill, 1993).

The 9000 yr B.P. effective moisture map, derived from paleoclimatic evidence, shows a wet Southwest and dry Northwest, which is generally consistent with the NCAR CCM 0 simulation and the precipitation composite map of the 9000 yr B.P. analogues (Figs. 1B and 4B). At 9000 yr B.P., the drying in the Northwest spreads into southwestern Canada, indicating the possible influence of an expanded Pacific subtropical high and a stronger onshore flow, which causes subsidence east of the North American Cordillera.
The pattern of moisture anomalies is remarkably similar between the modern analogues and the paleoclimatic evidence, with spatially heterogeneous areas in the Yellowstone National Park region, eastern Washington, parts of Colorado, and the eastern Cascades. Smaller-scale climatic controls, similar to those that operate today, probably played an important role in creating the 9000 yr B.P. pattern. The map of paleoclimatic evidence also shows a wet western Great Basin in contrast to the dry conditions along the eastern Sierra Nevada. This may be the result of lower-level divergence that occurred more frequently east of the Sierra Crest due to intense summer heating, a situation that produces drier conditions there as opposed to locations nearby and to the east (Hill, 1993). Additional modern climatic data in the eastern Sierra Nevada, however, are needed to examine further this aspect of lower-level divergence in that region. Dryness over the southern Plains is not clearly evident in the paleoclimatic data map, but paleoclimatic data coverage in that region is sparse. Also, tropical systems from the Atlantic may have been more frequent, and a stronger winter storm track may have extended through the region, creating wetter conditions. Nevertheless, the modern analogues for 9000 yr B.P. clearly illustrate the important role of topographic climatic controls as they interact with larger scale ones.

CONCLUSIONS

The modern climate analogue for 18,000 yr B.P. (January 1957) clearly depicts the dry-Northwest/wet-Southwest contrast, which is consistent both with GCM simulations and with paleoclimatic evidence. The analogue provides additional information on climatic processes that occur at smaller spatial scales. It suggests a more northward extension of wetness into the northern Great Basin that was not simulated by the NCAR CCM 0. This northern extension is implied by paleoclimatic evidence that is consistent with the circulation pattern of the modern analogue. The modern analogue also illustrates the possibility at 18,000 yr B.P. that smaller scale climatic controls may have caused localized areas of increased wetness in the eastern slopes of the northern Rocky Mountains and perhaps the interior Pacific Northwest, and localized areas of increased dryness through the Snake River Plain and Rawlins Gap.

The modern climate analogue for 9000 yr B.P. suggests that smaller scale climatic controls play an even stronger role on the spatial patterns of summer climate. In addition to illustrating the general dry-Northwest/wet-Southwest contrast, the analogue indicates the important role of topographic controls on precipitation at the smaller scale. The moisture pattern of the 9000 yr B.P. analogue shows remarkable similarities to the effective moisture map derived from paleoclimatic evidence, with locations in the central Rocky Mountains, parts of Colorado, parts of the Sierra Nevada, and parts of the Pacific Northwest exhibiting similar heterogeneous patterns in the past and present. Because wetter conditions at 9000 yr B.P. were restricted to locations that presently have a summer precipitation maximum, the seasonality of precipitation at 9000 yr B.P. probably was similar to that of today, with changes occurring primarily in the amplitudes of the annual march of precipitation.
The modern climate analogues for 18,000 and 9000 yr B.P. paleoclimates of the western United States have several important implications regarding paleoclimatic interpretation. The analogues suggest why differences between GCM simulations and paleoclimatic reconstructions from proxy data may occur; they provide a method for looking at smaller scale climatic processes and allow a more-detailed paleoclimatic analysis by linking large-scale climate features to regional- and local-scale proxy evidence of past climate. Spatial heterogeneity in climate patterns over western North America that result from the influence of smaller scale climatic controls appears to be the rule instead of the exception, as illustrated by both the modern climatic and paleoclimatic analyses. Interpretation of a dense network of paleoclimatic evidence in climatic terms must therefore consider the role of local and regional climatic controls in addition to changes in larger scale circulation controls. The analysis of modern climate analogues can also aid in the interpretation of spatial climatic variations as shown by tree-ring evidence in the western United States for the past several hundred years, and the method used in this study can also be extended to other parts of the world where surface climates are spatially heterogeneous.

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