

EXAMINING THE RECENT CLIMATE THROUGH THE LENS OF ECOLOGY: INFERENCES FROM TEMPORAL PATTERN ANALYSIS

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Abstract. Ecological theory asserts that the climate of a region exerts top-down controls on regional ecosystem patterns and processes, across space and time. To provide empirical evidence of climatic controls, it would be helpful to define climatic regions that minimized variance in key climate attributes, within climatic regions—define the periods and features of climatic regimes, and then look for concordance between regional climate and ecosystem patterns or processes. In the past, these steps have not been emphasized. Before we evaluated the recent climate of the northwestern United States, we established a Northwest climatic region by clustering time series of the Palmer Drought Severity Index (PDSI) for the period of 1675–1978, for the western United States. The background climatic regime and anomalies of the recent northwestern U.S. climate were then identified through temporal pattern analysis involving application of correspondence analysis to the same PDSI time series.

Our analysis distinguished 10 distinct periods and four unique types of regimes (climatic signals). Five of the 10 periods (79% of the ~300-year record) were marked by mild and equitable moisture conditions (Pacific regime), the “background” climate of the Northwest. The remaining periods were anomalies. Two periods displayed a high-variance, mixed signal marked by switching between severe to extreme annual to interannual dry and wet episodes (High/Mixed regime; 9% of the record). Two more periods displayed a moderate-variance, mixed signal marked by switching between moderate to severe annual to interannual dry and wet episodes (Moderate/Mixed regime; 5%). Only one period was unidirectional and relatively low variance, marked by persistent yet mild to moderate drought (Low/Dry regime, 7%).

Our method distinguished decadal- to interdecadal-scale regimes, defined regime periods, and detected both mixed and unidirectional anomalies from the background climate. The ability to distinguish the variance, direction, and period of sequential climatic regimes provides a plausible basis for examining the role of past climate within terrestrial ecosystems of the Northwest. For example, we found concordance between the period of the Low/Dry anomaly and a period of tree establishment in the Olympic Mountains of Washington, close alignment between tree growth with the Moderate/Mixed and High/Mixed signals in Oregon, and a mixed fire response to mixed climatic signals in northeastern Oregon. Linking historical climatic regimes to particular ecosystem patterns and processes also aids in the prediction of future ecosystem changes by providing evidence of the kinds of interactions that may be anticipated.

Key words: ARIMA analysis; climate; climatic regime; climatic signal; correspondence analysis; fire regime; mixed and unidirectional anomalies; northwestern United States; Pacific Decadal Oscillation (PDO); regionalization; temporal pattern analysis; TWINSpan.

INTRODUCTION

Ecological theory asserts that the climate of a region exerts top-down control on regional ecosystem patterns and processes, across space and time. Within a climatic region, the amplitude and frequency of climatic patterns, such as the El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO), may vary on interannual, decadal, and longer time scales (Diaz and Markgraf 2000, Mantua et al. 1997, Gedalof and

Smith 2001). Hence, in regions where these climatic patterns were manifested, one would expect corresponding changes in ecosystem responses during specific time periods when the underlying climatic regimes were changing (Grissino-Mayer and Swetnam 2000, Kitzberger et al. 2001). This has been demonstrated for changes in anadromous fish stocks related to shifts in the PDO (Mantua et al. 1997).

Ecological processes may respond differently to climatic variation at each of these scales, depending on the region and ecosystem. Climate affects ecological processes both directly and indirectly, and complex lagging patterns may exist. For example, interannual to

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decadal-scale changes in climatic regimes and ecosystem responses affect the demographic patterns (mortality and natality) of forests and meadows (e.g., Villalba and Veblen 1997, 1998, Swetnam and Betancourt 1998, Woodward et al. 1995). Woodward et al. (1995) found that tree establishment in subalpine meadows in the Olympic Mountains of Washington State was directly related to climate variables such as winter precipitation and the Palmer Drought Severity Index (PDSI).

Fire regimes in semiarid forests and woodlands in the southwestern United States, in Colorado, and in Patagonia, Argentina, appear to be sensitive to climatic regimes characterized by interannual switching from wet to dry conditions on time scales of about two to four years (i.e., periods of high interannual variability). This wet/dry switching and low/high fire activity is often in phase with the ENSO (Swetnam and Betancourt 1990, 1992, Kitzberger and Veblen 1998, Veblen et al. 1999, 2000, Donnegan et al. 2001), and may be related to the importance of fine fuel (e.g., grass and pine needle) growth, accumulation, and moisture content.

In contrast, interannual switching from wet to dry is apparently less important in more productive pine forests of eastern Oregon than in the Southwest, but multi-year (decadal-scale) drought conditions may be more important to fire frequency patterns (Heyerdahl et al. 2002). The influence of warm ENSO events (warm = El Niño, or cool = La Niña, based on the direction of change in sea surface temperatures) on the moisture content of fuels apparently acts to synchronize fire occurrence at regional scales in Oregon and in the Southwest, but the relations tend to be inverse between the regions (Dettinger et al. 1998). Warm ENSO events are typically related to lower than average winter and spring precipitation in the Pacific Northwest and increased fire activity, but higher than average winter–spring precipitation and reduced fire activity in the Southwest (Swetnam and Betancourt 1990, 1992, Heyerdahl et al. 2002).

Information is available on the general relationship between climate and regional ecosystems, but climatologists and fire and forest ecologists seek greater insight into how fire regimes, tree growth, and regeneration vary directly with the climate. Accurate characterizations of the features and the periods of anomalies would advance our knowledge of linkages between regional climatic systems, dynamic vegetation and habitat patterns, and disturbance regimes (Swetnam 1993, Swetnam and Betancourt 1998). To date, little specific information is known of how, for example, fire regime parameters, such as frequency, severity, and extent, have varied with climate over the past several centuries. Bioclimatologists, aware of climatic constraints, would like to develop models that burn regional landscapes under varying climatic scenarios. Developing this capacity has important rami-

fications for allocating carbon and estimating carbon budgets. Our long-term goal was to link temporal patterns of the recent climate to specific ecological processes for the northwestern region of the United States. To develop this type of information, one might begin by correlating past climatic patterns with natural records of ecosystem patterns or processes. For example, fire scars on living and dead trees provide information that is useful to inferring recent historical fire frequency, spatial extent, and severity.

To provide empirical evidence of climatic controls, it would be helpful to define climatic regions that minimized variance in key climate attributes, within climatic regions define the periods and features of climatic regimes, and then look for concordance between regional climate and ecosystem patterns or processes. In the past, these steps have not been emphasized. This lack of definition has made it difficult to correlate temporally referenced changes in ecological patterns and processes with changes in the regional climate. Here, we define a climatic regime as any period in the climate of a region that is quantitatively different from other periods in terms of one or more primary attributes. Climatic anomalies are relatively protracted and unique climatic regimes. A regime generally persists for a period of time that is longer than the time it takes to shift between unique episodes, and is typically measured at decadal to interdecadal or longer time scales.

Knowledge of specific historical changes in climatic regimes is needed to evaluate and understand past and predict future regional ecosystem patterns and processes. A review of the regional climate literature showed that there were many studies of the past northwestern U.S. climate, but there was little agreement among them (Fig. 1), and they did not offer what we needed. The available studies did not: (1) pre-define a climatic region, (2) identify climatic regions that were temporally coherent in terms of the climatic data used, (3) identify specific start and end dates for climatic periods, and (4) identify information on climatic regime characteristics.

Many studies of northwestern U.S. climate have focused on identifying major temperature and precipitation anomalies by their common modes of variance or shared variance patterns, either using principal components analyses (PCA) or factor analyses (FA), respectively (Fig. 1). In these studies, features of anomalies were not estimated, and periods of anomalies were approximated, with the exception of Gedalof and Smith (2001). PCA and FA do not provide the capacity to precisely bound the periods of anomalies or characterize similarities among climatic regimes; hence, it has been difficult to correlate regional climate with dynamic ecosystem patterns and processes. These factors motivated us to develop alternative methods for characterizing and defining the periods and features of northwestern U.S. climatic regimes.

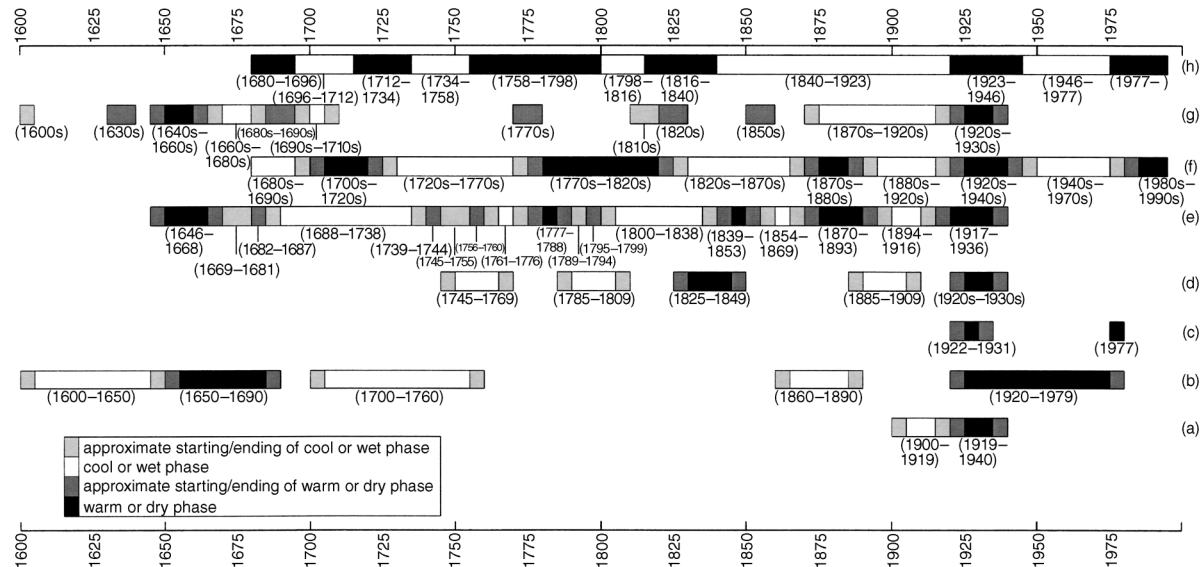


FIG. 1. Results of recent climatological studies in the western and northwestern United States that evaluated changes in temperature and precipitation relations. Shown are putative regime periods and changes from cool to warm, warm to cool, wet to dry, and dry to wet conditions. The studies are referenced by author(s), date of publication, geographic region, and main type(s) of statistical analysis used: (a) Brubaker (1980), Washington state (WA), PCA; (b) Graumlich and Brubaker (1986), WA, regression; (c) Diaz (1983), Oregon (OR), WA, Idaho (ID), variance analysis; (d) Garfin and Hughes (1996), eastern OR, PCA and regression; (e) Keen (1937), eastern OR, tree growth anomalies; (f) Peterson et al. (1999), OR, PCA; (g) Briffa and Jones (1992), northwestern United States, PCA and regression; and (h) Gedalof and Smith (2001), coastal Alaska to southern OR, factor analysis (FA), regression, and intervention analysis.

The problem of pattern detection in spatially referenced data is familiar to ecological research, and we saw an opportunity to apply statistical methods from landscape and community ecology to the challenge of classifying climatic patterns in time. We examine here the application of correspondence analysis (as implemented in TWINSpan; Hill 1979, Jongman et al. 1995) for detection of temporal patterns in proxy climate data.

One aim of ordination and classification analyses in ecology is to group plots or areas into clusters that are most similar in species composition and species abundance. In addition, TWINSpan directly identifies key elements of each group. These key elements directly define the unifying features of any group, or in this application, the features of each climatic regime. Previously, where TWINSpan was used with plant species data, for example, the method considered the species and abundance values of each plot in relation to all other plots, and grouped them according to their similarities. Our idea was to utilize climate data in place of the plant data, use the magnitude of the climatic variables in place of species abundance values, and create what were in effect "species" of climatic factors in place of the usual plant species.

Using proxy time series of the PDSI (Palmer 1965) reconstructed from tree-ring width chronologies, we investigated multi-scale temporal patterns of drought and pluvial conditions for the northwestern United States. The PDSI uses temperature and precipitation

information to gauge relative levels of pluvial and drought conditions. We used the PDSI as an intuitive climate measure because terrestrial plant and animal biogeography, and disturbance processes like fire, are responsive to changes in temperature and moisture regimes. Our objectives were to: (1) quantitatively define a northwestern U.S. climatic region that was marked by a coherent temporal pattern of drought; (2) apply TWINSpan to characterize the background climate, anomalies, and periods of Northwest climate; (3) compare the climate patterns derived by TWINSpan with those resulting from the more commonly used PCA and FA; (4) evaluate relations between temporal patterns of regional climate detected by TWINSpan, PCA, and FA, and climate forcing in the North Pacific basin associated with the Pacific Decadal Oscillation; and (5) consider a few climate–ecosystem linkages in the light of shifting regional climatic regimes.

METHODS

Data source

The data used to identify a study area were instrumental and tree-ring-based PDSI reconstructions from an existing network of grid points representing 18th- to 20th-century drought and pluvial relations for the continental United States (Cook 2000). Proxy reconstructions were developed by Cook et al. (1999) from a network of 388 climatically sensitive tree-ring width chronologies using the point-by-point regression meth-

od. The reconstructions were validated using instrumental PDSI data not used in the original regression modeling (Briffa et al. 1986, Cook et al. 1994, 1999). Verification revealed that reconstructed PDSI was significantly related to instrumental PDSI over the grid (explained variance [R_c^2] = 0.55, squared Pearson correlation [R_v^2] = 0.36, reduction in error in the verification period [RE] = 0.31, coefficient of efficiency over the verification period [CE] = 0.22, $P < 0.05$).

The PDSI was designed to measure a wide range of moisture conditions, standardized to facilitate comparisons between regions and over time (Palmer 1965). The PDSI is based on water balance accounting by which excesses or deficiencies in moisture are determined in relation to average climatic values. The water balance computation is calculated based on precipitation, temperature, and the local available water content of the soil. It is most effective in measuring impacts that are sensitive to soil moisture (Willeke et al. 1994). Drawbacks to the index include underestimation of runoff, all precipitation is treated as rain, and intensity values are arbitrarily selected based on Palmer's initial study area (Alley 1984). However, it is the index most commonly employed to measure moisture conditions within the United States, because it provides information with which to compare current conditions to historical (Alley 1984).

Clustering grid points into climatic regions

Climate studies that strive to identify regime shifts have seldom pre-stratified the historical data by climatic region. The basis for such stratification should be to maximize coherence of temporal pattern in the data among the time series. Consequently, data are often used that may represent blended signals, variation, and regimes of more than a single climatic region (e.g., Garfin and Hughes 1996, Gedalof and Smith 2001). Stratification potentially reduces extraneous variation in relevant subsets of the data.

To isolate a core set of drought reconstructions to best represent the northwestern United States, we used proxy PDSI time series representing the entire western United States (Cook 2000). We used hierarchical cluster analysis (Gauch 1982, McCune and Mefford 1999) to group grid points into similar subgroups (Fig. 2B). The Euclidean distance measure was used along with Ward's method to link samples into clusters. Ward's method minimized distortions in the underlying data space by seeking solutions that minimized variance within clusters, as compared to variance between clusters (McCune et al. 2002).

In the matrix submitted to analysis, rows were grid points, columns were years, and our measure of abundance was the magnitude of the annual PDSI. Grouping of grid points into climatic regions was based on the degree of coherence of the annual PDSI values across the time series. We used forward-stepping linear discriminant function analysis (Tabachnick and Fidell

1989, SYSTAT 1998) to independently evaluate the validity of the climatic regions identified through cluster analysis. We used cross-validation to evaluate the predictive power (robustness) and stability of the discriminant function. To cross-validate the discriminant model, 25% of the years were randomly drawn and set aside as the test set. Classification functions were derived from the remainder. We used four iterations of cross-validation, to confirm that the groups identified by cluster analysis would contain grid points with the most similar temporal pattern of the PDSI, and that clusters were stable.

For each of the grid points in the identified Northwest climatic region, proxy PDSI reconstructions based on tree-ring width chronologies were available for the years 1675–1978, and this constituted the set used in further analysis (Cook et al. 1999, Cook 2000).

Temporal pattern analysis

PCA and FA are often used to look for temporal patterns of climate in time series data of such variables as sea surface temperature or pressure, precipitation, or drought and pluvial relations. These techniques are useful to developing vectors of variables that show a high degree of shared variance, or common modes of variance through time; however, we were concerned about their capacity to detect mixed wet and dry anomalies, which might resemble the background climate, but with a higher level of variance. Also, PCA is most effective if variables considered in ordination are linear with respect to each other, or monotonic with respect to the main gradient of variation (McCune et al. 2002). These conditions are somewhat rarely met in ecological or climatological data, and were not met by the PDSI data.

In contrast to PCA and FA, correspondence analysis, also an eigenanalysis method, is better suited to non-linear and nonmonotonic variables. We used correspondence analysis as implemented in TWINSpan (Hill 1977, 1979, Jongman et al. 1995) because it combined the advantages of ordination with a classification function, allowing direct group formation. TWINSpan was also chosen as a grouping algorithm because the standard ecological application of defining groups of sites according to their similar plant species composition and abundances was analogous to grouping years across an array of grid points according to similar PDSI sign and magnitude. In addition, using TWINSpan allowed for the potential of grouping any year with each of the other years. In multivariate ordination or classification analysis, interactively building alternative groupings of samples while one observes both the variables and the quantitative values that formulate each group provides information on group similarities and differences. This is a valuable characteristic of TWINSpan.

By the method of correspondence analysis, TWINSpan classifies data in a divisive, hierarchical fashion

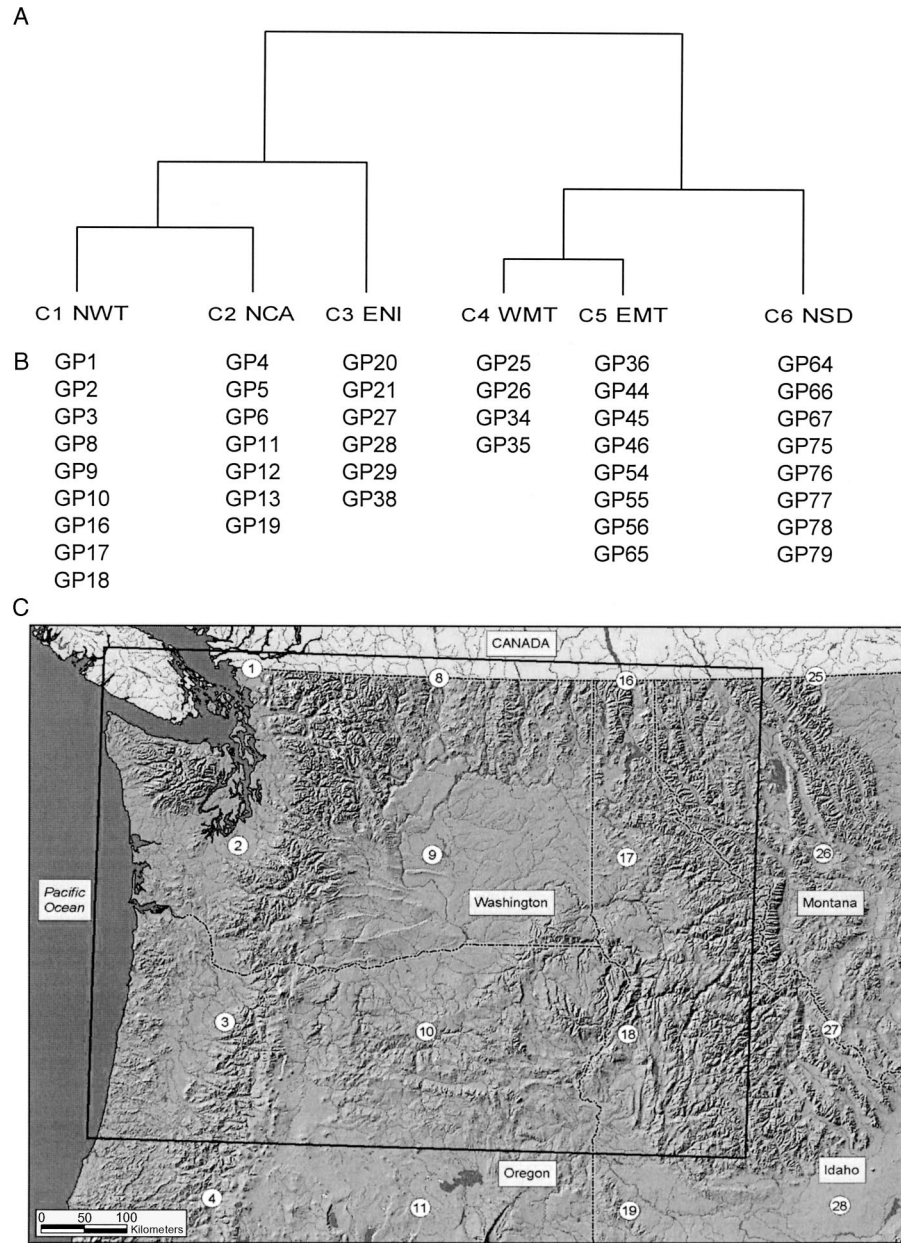


FIG. 2. (A) Dendrogram of quantitatively derived climatic regions shown for the northern half of the western United States. (B) Regions were derived from hierarchical cluster analysis of Palmer Drought Severity Index (PDSI) data and confirmed through discriminant analysis and cross-validation. Cluster names are: NWT, Northwest (consisting of Washington, northern Oregon, and northern Idaho); NCA (northern California, southern Oregon, northwestern Nevada, and southwestern Idaho); ENI (eastern Nevada, southeastern Idaho, and northern Utah); WMT (western Montana and northwestern Wyoming); EMT (eastern Montana and southwestern North Dakota); and NSD (North and South Dakota and northeastern Nebraska). (C) Map of the grid points (GP) of the Northwest Region, showing numbered grid points.

(Jongman et al. 1995, McCune et al. 2002, McCune and Mefford 1999), which results in the first ordination axis expressing the range of the main gradient of variation. In contrast, PCA often fails to express only the range of the main gradient in the first PCA axis, especially with nonlinear data, as it will fit a linear model to nonlinear relationships (McCune et al. 2002). With TWINSpan, the data are initially arranged in ordi-

nation space by reciprocal averaging, and then the ordination is split near the center of gravity via correspondence analysis. This creates the primary dichotomy of samples. Species that are differential to one side of the dichotomy are identified and used to refine the groups initially identified.

TWINSpan output can be graphically represented in a dendrogram, which illustrates the nested hierar-

chical relationships among the groups. TWINSpan has the added feature of identifying key elements for each group (called indicator or differential species). The indicator species name the unifying features of each group. See Hill (1977, 1979), McCune et al. (2002), and Jongman et al. (1995) for more detailed information on classification with TWINSpan.

To comprehensively examine temporal patterns of the recent climate of a single climatic region, we developed methods to directly scale the severity and duration of each anomaly detected among the time series representing that region. First we combined the separate time series representing the northwestern United States into a single matrix. To examine the features of any possible anomalies embedded in the time series, we then filtered the continuous variation seen in the PDSI values by defined drought severity levels. To scale the duration of anomalies, we constructed one-, two-, and 3-decade moving windows (bins), slid each bin forward one year at a time across each time series, and computed the proportion of the years within each bin that fell within the defined drought severity levels. Fig. 3 shows the flow of analysis.

Defining levels of drought and pluvial severity

Using published definitions of dry/wet severity (Palmer 1965, Alley 1984), we defined boundary PDSI conditions that corresponded to four distinct severity levels: mild–extreme (abbreviated as “Mild”), moderate–extreme (“Moderate”), severe–extreme (“Severe”), and extreme (“Extreme”) conditions (Fig. 4). For example, Palmer (1965) defined mild drought years as those having a PDSI value of -1 . In our evaluation, Mild dry years displayed any value of the PDSI ≤ -1 . Mild wet years displayed PDSI values ≥ 1 , and so-called “in-between” conditions fell in the range of PDSI values -1 to 1 . Boundary values for Moderate, Severe, and Extreme drought levels were set in a similar fashion using negative and positive forms of the integers 2, 3, and 4, respectively (Fig. 4). Using these four definitions of drought severity, each original PDSI value was transformed into a presence/absence value, with a 1 given in the portion of the range in which the PDSI value was contained. This partitioned the raw PDSI data into wet, dry, and in-between conditions as defined by the four distinct severity levels.

In addition to categorizing the PDSI values in four separate passes by severity definition, we scaled the temporal window through which Northwest climate would be viewed. Each of the four sets of time series created above was analyzed at three temporal scales: one, two, and three decades. For example, using the transformed presence/absence data for Mild conditions and a one-decade period as a forward moving bin, the proportion of each running decade that displayed Mild dry, wet, and in-between conditions was calculated and assigned to the last year of the running decade. This resulted in a derivative time series for each grid point

where the rows were years, and the columns were the proportion of the years in each one-decade forward moving bin where PDSI was ≤ -1 , ≥ 1 , or -1 to 1 . This process was repeated for each bin size. Once the one- to three-decade forward moving bins were calculated for Mild conditions, we created similar sets of time series for the Moderate, Severe, and Extreme severity levels.

Separate TWINSpan analyses were performed for each unique combination of the four drought severity levels and the three temporal window sizes. The TWINSpan program defaults were used, except custom pseudospecies cut levels were selected (McCune and Mefford 1999). Several different sets of cut levels were examined to evaluate group cohesion. We selected the best TWINSpan classification independently for each set by observing grouping behavior, and identifying groupings and pseudospecies cut levels that minimized borderline and misclassified years.

Validating TWINSpan groups using an external yardstick

For all groups identified by TWINSpan, we used interactive, forward-stepping linear discriminant function analysis (Tabachnick and Fidell 1989, SYSTAT 1998) to evaluate the validity and robustness of the predicted regimes. To cross-validate the discriminant models, 25% of the years were randomly drawn and set aside as the test set. Classification functions were derived from the remainder. We used four iterations of cross-validation with discriminant analysis to evaluate the predictive power and stability of each discriminant model. TWINSpan-identified temporal patterns of the PDSI that were valid after cross-validation were plotted along a timeline.

Refining period boundaries

We constructed a composite diagram consisting of the timelines constructed following each TWINSpan analysis, and noted that the temporal patterns of PDSI anomalies shifted somewhat by combinations of bin size and severity level. Thus far, our method adequately revealed background climate and anomalies, but closely related alternative starting and ending dates could be interpreted for several periods.

We evaluated two boundary detection algorithms to identify the most likely year when regime changes occurred. The first method, TWINSpan Signal Strength analysis, involved examining all representations of the period of an anomaly across combinations of the three bin sizes and four drought severity levels. We could determine the best temporal scaling of the period and the most appropriate severity characterization by observing the severity levels under which an anomaly was present, and by observing the bin size(s) that revealed an anomaly without causing it to bleed forward solely as a function of increased bin size. For example, if an anomaly was present at the Mild severity level, but it

Flow of Analysis

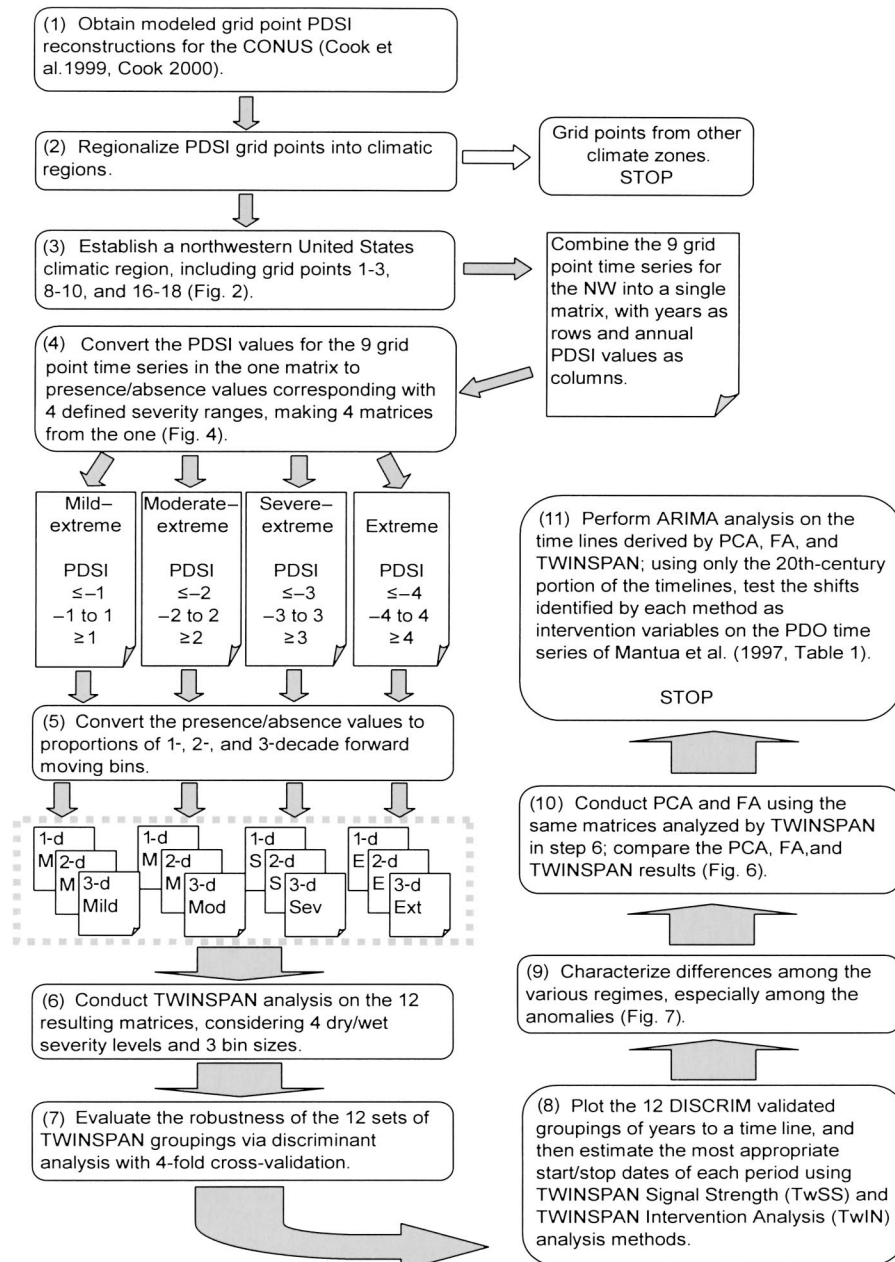


FIG. 3. The flow of analysis used in examining the multi-scale temporal patterns of drought and pluvial conditions for the northwestern United States.

attenuated when severity was defined at the Moderate, Severe, and Extreme levels, we could infer, by subtraction, that the bulk of the anomaly was contributed by mildly dry or wet PDSI values, or those in between. Similarly, if an anomaly was strong at the 1-decade bin size and remained strong while bleeding forward with the 2- and 3-decade bin sizes, the most appropriate temporal scaling occurred at the 1-decade bin size. In nearly all cases, the 1-decade bin size most appropri-

ately scaled the anomalies, and we used periods defined by this bin size.

A second approach, TWINSpan Intervention analysis, involved developing an autoregressive integrated moving average (ARIMA) model (Box and Tiao 1975, SPSS 1999) for the 10-year average variance of the original PDSI time series for the northwestern U.S. climatic region. In this approach, the alternative TWINSpan anomaly start/stop dates were tested for signif-

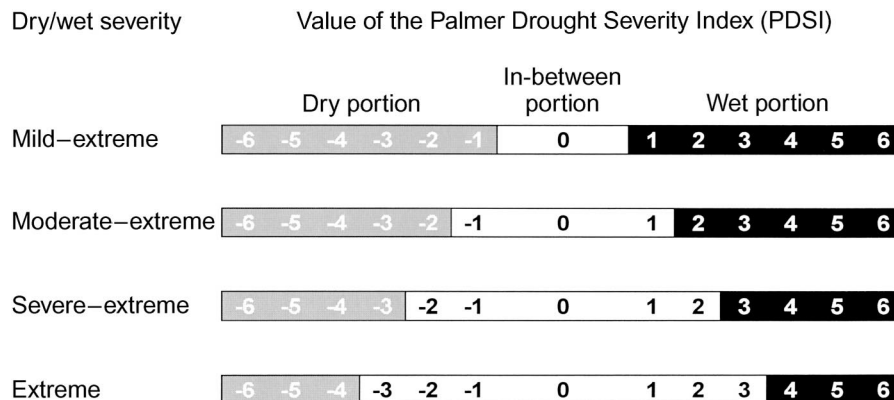


FIG. 4. Four PDSI value ranges are shown that correspond to four previously defined ranges of dry and wet severity (Palmer 1965, Alley 1984). These were used in an iterative fashion to separate years into wet, dry, and in-between conditions, depending upon the severity definition. In the mild–extreme range, PDSI values ≥ 1 were considered wet, values ≤ -1 were considered dry, and all values between 1 and -1 were considered in-between. The moderate–extreme range used ± 2 as the boundaries for the wet, dry and in-between categories; similarly, ± 3 was used for the severe–extreme range, and ± 4 was used for the extreme range.

icance ($P \leq 0.10$) as interventions (Box and Tiao 1975, Box and Jenkins 1976). Models were initially estimated based on the pattern of the autocorrelation and partial autocorrelation functions. The models were then objectively evaluated based on several criteria, including the pattern of the residuals and the residual variance, the Akaike Information Criterion (AIC), and the Schwarz-Bayesian criterion (SBC). The final model had residuals that fit a white noise pattern.

Characterizing climatic anomalies

We characterized the basic features of climatic anomalies by evaluating the “indicator species” that were associated with each side of a TWINSpan division. Recall that these indicator species define the unifying features of any group, which in this case were groups of years. We also characterized differences among the derived types of anomalies by comparing their amplitude or variance level (mean PDSI range), and their composition (the mean percentage of positive and negative PDSI). We compared the composition of each type of anomaly by computing the ratio: [area under the PDSI trace that was above or below the zero axis]/[the sum of the total area under the PDSI trace that was above and below the PDSI = 0 axis] $\times 100$. We compared the variance level among types of anomalies by generating the mean PDSI range of each type of anomaly, which was computed by independently averaging the minimum (min) and maximum (max) PDSI values of each anomaly. Significant differences among the types of anomalies were tested by ANOVA; the Tukey multiple comparison procedure was used to determine which groups were significantly different ($P \leq 0.10$). A two-sample t test was used if there were only two groups being compared (SYSTAT 1998).

Deriving climatic anomalies using PCA and FA

We applied PCA, (McCune and Mefford 1999) and FA (SPSS 1999) to the nine original PDSI grid point reconstructions for the northwestern United States because this was the most appropriate test. Correlation cross-products matrices were used in the PCA and FA, and axes were not rotated. Both Factor 1 (F1) from the FA and Axis 1 (PC1) from PCA explained 67% of the variance among the nine time series, respectively, and were used for all subsequent analyses involving FA and PCA. Climate patterns in F1 and PC1 were explored using methods outlined in Gedalof and Smith (2001). An intervention detection algorithm involving a moving window and a two-sample t test was applied to the time series. Potential shift dates identified through the t test were tested for significance using intervention analysis ($P \leq 0.10$; Box and Tiao 1975).

Climatic anomalies and the Pacific Decadal Oscillation

We obtained the PDO time series, which is nominally the leading eigenvector of monthly sea surface temperature anomalies in the North Pacific Basin (Mantua et al. 1997) from Stephen Hare (International Pacific Halibut Commission, University of Washington, Seattle, Washington, USA). The ARIMA analysis was performed on the series in a manner detailed earlier. The 20th century anomalies identified through PCA, FA, and TWINSpan Signal Strength analysis were each tested as intervention variables on the PDO time series (Box and Jenkins 1976, SPSS 1999).

RESULTS

Identifying a Northwest climatic region

Cluster analysis of PDSI grid points representing the northern half of the western United States yielded six

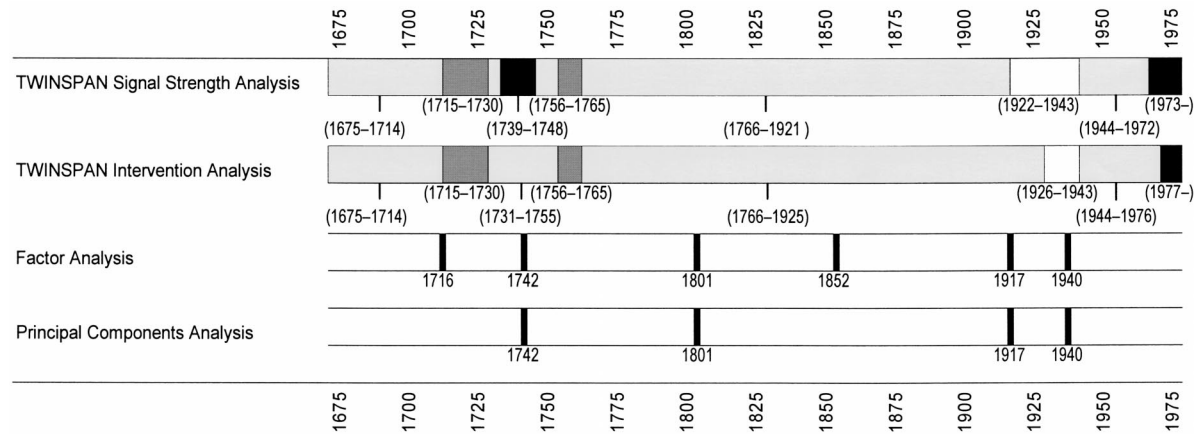


FIG. 5. Temporal patterns of climate signals in the northwestern United States over the 300-year period from 1675 to 1978, by methods tested. Periods identified as a High/Mixed (dark gray) anomaly were marked by high variance, short-duration severe to extreme drought and wetness. Periods identified as a Moderate/Mixed (black) anomaly were marked by moderate variance, short-duration moderate to severe drought and wetness. Periods identified by the Pacific (light gray) condition were marked by a mild and equitable climate. The single period identified by a Low/Dry (white) anomaly was marked by persistent yet low to moderate variance, mild to moderate drought.

groups within an area from Northern California, through Washington State, and extending to the eastern edge of North Dakota and South Dakota (Fig. 2A). Clusters 1–3 combined corresponded with the Northwest region recognized by Karl and Koscielny (1982), and clusters 4–6 combined corresponded with their West North Central region (Fig. 2A, B). In this analysis, subdivisions of these larger areas were recognized as the cohesive climatic regions (Fig. 2A, B). Cluster 1, the Northwest (NWT), consisted of nine grid points 1–3, 8–10, and 16–18 (representing Washington State, northern Oregon, and northern Idaho), and represents the northwestern U.S. climatic region (Fig. 2C).

Identifying climatic anomalies and their temporal patterns

As the name “Pacific” implies, the climate of the Pacific Northwest provides a mild and equitable, if not neutral, background upon which anomalies stand out in sharp relief. All methods tested found robust decadal- to interdecadal-scale anomalies in the Northwest PDSI climate data. The two methods involving TWINSpan as the primary analysis tool showed much similarity with few salient differences (Fig. 5). Two climatic anomalies in the 1700s, 1715–1730 and 1756–1765, were the same for both methods. A third anomaly in the 18th century, occurring from 1739–1748, was identified via TWINSpan Signal Strength analysis, but not by TWINSpan Intervention analysis. Both FA and PCA showed significant shifts in 1742 and 1801. The FA also identified shifts in 1716 and 1852. Neither TWINSpan-based method found any significant decadal-scale or larger anomalies in the 1800s.

Both TWINSpan-based methods found two anomalies in the 20th century, with differences in the starting

dates. The TWINSpan Signal Strength analysis showed the earlier anomaly starting in 1922, while the TWINSpan Intervention analysis identified the starting date as 1926; the anomaly end date was 1943 for both methods. Both the FA and PCA patterns showed significant shifts in 1917 and 1940. Similarly, the TWINSpan Signal Strength analysis showed an earlier starting date for a 1970s anomaly, 1973, while the TWINSpan Intervention analysis identified the starting date as 1977 (Fig. 5). There were no significant shift dates for this period found in either PCA or FA.

The most common climatic regime found was, not surprisingly, that of background mild and equitable conditions, which we termed the Pacific regime. Periods of the Pacific regime ranged in length from nearly one decade (eight years) to >15 decades (156 years). Three distinct types of climatic anomalies were found in the ~300-year climate record, and all were decadal to interdecadal in scale. The most common anomaly was mixed in sign (marked by annual to interannual switching between wet and dry PDSI values), and displayed high variance, indicated by large negative and positive (Severe to Extreme) PDSI values (Fig. 6). We termed it the High/Mixed anomaly. The next most common anomaly was also mixed in sign, and displayed moderate variance indicated by intermediate negative and positive (Moderate to Severe) PDSI values. We called it the Moderate/Mixed anomaly (Fig. 6). The third type of anomaly found was unidirectional, i.e., dry only in sign, and displayed low to moderate variance. We called it the Low/Dry anomaly.

The periods of the anomalies detected by the various analysis methods are compared in Fig. 5. Both the TWINSpan Signal Strength and TWINSpan Intervention analysis methods detected the Low/Dry anomaly

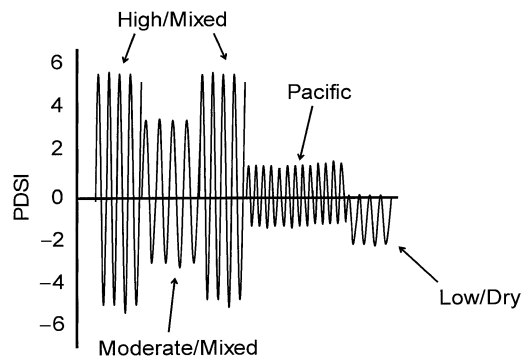


FIG. 6. Schematic drawing of the differences between climatic regimes derived by TWINSpan analysis.

aly. The periods identified were 1923–1943 and 1926–1943, respectively. This anomaly was also detected by PCA and FA, with period dates of 1917–1940.

The TWINSpan Signal Strength and TWINSpan Intervention analysis methods were equally effective in detecting the High/Mixed anomaly; the Moderate/Mixed anomaly of 1739–1748 was identified only by TWINSpan Signal Strength analysis. This was the least conspicuous of the anomalies because the variance level was mostly moderate, with annual to inter-annual switching between moderately wet and dry years. Both the TWINSpan Signal Strength and TWINSpan Intervention analysis methods detected a 1970s Moderate/Mixed anomaly beginning in 1973 and 1977, respectively. The intervention detection algorithms involving PCA and FA did not identify either the High/Mixed or Moderate/Mixed signals effectively, with two periods detected through FA, 1716–1742 and 1801–1852, and only one period detected, 1742–1801 for PCA, which does not correspond closely to any period identified by the TWINSpan-based methods (Fig. 5).

These results suggest that TWINSpan is more sensitive than PCA or FA for detecting mixed climatic anomalies where a change in variance level is the primary descriptor. TWINSpan Signal Strength analysis better detected occurrences of the Moderate/Mixed anomaly than the TWINSpan Intervention method, because the former retains the most information from the original grid point PDSI values. The TWINSpan Intervention method used the 10-year average variance of the grid points as a time series with which to test TWINSpan identified start/stop dates with intervention analysis. PCA and FA both detected shifts based on modes of variance in common among the time series.

Of the methods used, TWINSpan Signal Strength analysis retained the greatest amount of the original information contained in the data, and was more sensitive in detecting variance level and direction of anomalies. The climatic anomalies and background Pacific

periods derived by this method were the only ones further characterized.

Comparing the background climate with the anomalies

Mild and equitable (Pacific) conditions were found in five of 10 observed periods (79% of the record): 1675–1714, 1731–1738, 1749–1755, 1766–1921, and 1944–1972. The High/Mixed type of anomaly was seen in two periods, 1715–1730 and 1756–1765, representing 9% of the record. The TWINSpan Signal Strength method identified two periods displaying the Moderate/Mixed type of anomaly, 1739–1748 and 1973–1978 (5% of the record). The Low/Dry anomaly was found only in a single period, 1922–1943 (6% of the record).

Mean negative PDSI amplitude was significantly different for the High/Mixed type of anomaly compared to all other types of anomalies and the background Pacific climate conditions (Fig. 7A). Mean positive amplitude was also significantly higher for the High/

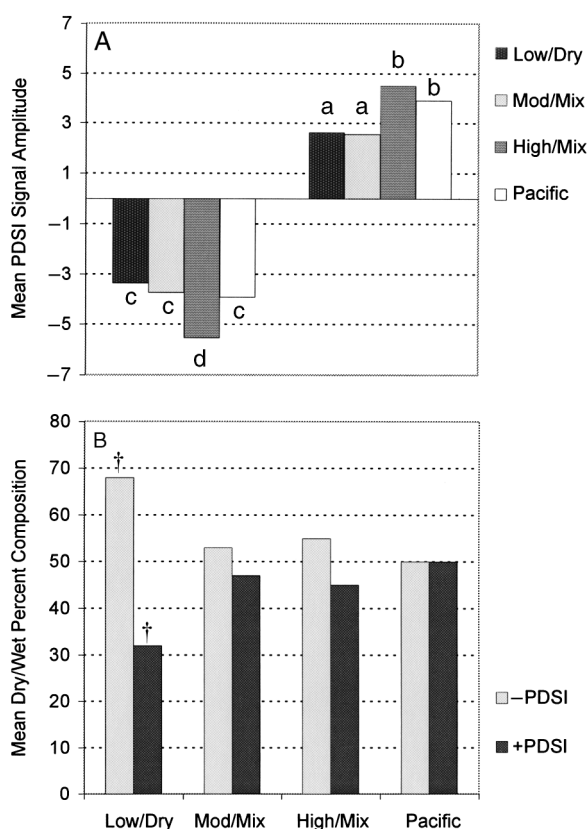


FIG. 7. Characteristics of four types of climate signals: High/Mixed, Moderate/Mixed, Low/Dry, and Pacific. (A) Mean signal amplitude (mean Palmer Drought Severity Index [PDSI] range). Columns with the same letter placed above them are not significantly different from each other. (B) Signal composition, the mean percentage of positive and negative PDSI for each signal type. Columns with daggers (†) placed over them are significantly different from each other ($P \leq 0.10$).

TABLE 1. Comparison of Pacific Decadal Oscillation (PDO) phase shift dates of Mantua et al. (1997) to the dates derived by TWINSpan Signal Strength, principal components analysis (PCA) Intervention, and factor analysis (FA) Intervention methods.

PDO phase shift	Mantua et al. (1997)		TWINSpan Signal Strength		PCA Intervention		FA Intervention	
	Date	P	Date	P	Date	P	Date	P
Cool to warm	1925	0.017†	1922	0.003	1917	0.460	1917	0.460
Warm to cool	1947	0.000	1943	0.000	1940	0.260	1940	0.260
Cool to warm	1977	0.000	1973	0.000				

Notes: Each set of shift dates were tested as intervention variables on the same PDO time series used in Mantua et al. (1997). Intervention analysis methodology follows that of Box and Tiao (1975).

† Value reported here differs from that published in Mantua et al. (1997); however, it is correct (S. Hare, *personal communication*).

Mixed type of anomaly and the Pacific conditions compared to the Low/Dry and Moderate/Mixed types of anomalies. Both findings support the hypothesis that the High/Mixed type of anomaly contained both extreme wet and dry components. No other significant differences were found, yet it is interesting to note that the Low/Dry anomaly had a smaller negative mean amplitude than the other types. This observation supports the hypothesis that the annual drought found in this anomaly was mild yet persistent.

There were no significant differences among anomalies in percentage negative or positive PDSI composition (Fig. 7B). Within the Low/Dry anomaly, the percentage of negative PDSI composition was significantly higher than that of the positive PDSI. No other types of anomalies showed significant differences of this nature. This observation supported the hypothesis that the Low/Dry anomaly lacked a significant pluvial component.

Signal correspondence to the PDO

All methods were tested for correspondence with a known climate index for the northern Pacific basin, the PDO. Table 1 shows the PDO phase shifts, and compares the significance values for shift dates found in the Northwest PDSI data set by method tested, along with the published results of Mantua et al. (1997). The shift dates identified by TWINSpan Signal Strength analysis were significant for all PDO phase shifts. PDO phase shifts past 1977 were not tested because the Northwest PDSI time series ends in 1978. Both 1922 and 1925 were shown to be significant as intervention variables for the PDO cool-to-warm shift, 1943 and 1947 for the warm-to-cool shift, and 1973 and 1977 were both significant as intervention variables in the 1970s cool-to-warm PDO shift. These results show that the effects of the shift in PDO phase on drought (as measured by the PDSI) may occur over several years.

DISCUSSION

Results reported here show that temporal patterns of drought anomalies in the northwestern United States can be recognized at decadal to interdecadal scales us-

ing correspondence analysis, and the pattern of the recent climate consists of at least four distinct types of signals; a backdrop of relatively mild and equitable conditions upon which at least three types of anomalies have occurred. Equitable and mild conditions, the Pacific signal, have been the norm over the past 300 years, occurring about 79% of the time. Three signals represent departures from these conditions. The High/Mixed anomaly was a high variance, mixed signal, dominated by recurring high amplitude, short-duration, severe to extreme annual to interannual dry and wet episodes, with more dry years than wet. The Moderate/Mixed anomaly was similar to the High/Mixed signal, except that dry and wet years were of moderate severity. Persistent mild drought without a significant wet component characterized the Low/Dry anomaly, which was found only in the second quarter of the 20th century.

Comparisons with previous studies

All of the previous studies on Northwest climate detailed in Fig. 1 found a dry period in the vicinity of the 1920s to the 1940s. This period corresponds to the single instance of the Low/Dry anomaly. In other portions of the timeline, there is little agreement among the studies. This may be due, in part, to often large difference in the geographic domain of the analyses; some studies were limited to eastern Oregon (Garfin and Hughes 1996), some looked at Washington (Graumlich and Brubaker 1986), and another at coastal Alaska through British Columbia to Crater Lake, Oregon (Gedalof and Smith 2001). These differences in geographic domain also fortuitously suggested that the Low/Dry anomaly detected by all studies covered several climatic regions.

Change in spatial domain will alter the characteristics of the climate patterns that are detected, because the spatial patterns of climate processes influential to land systems vary in relation to geographic domain (Holling 1992, Ricklefs 1990). For this reason, we suggest that regionalization should normally precede studies such as this one. Where studies present portions of several climatic regions as a single region, there will

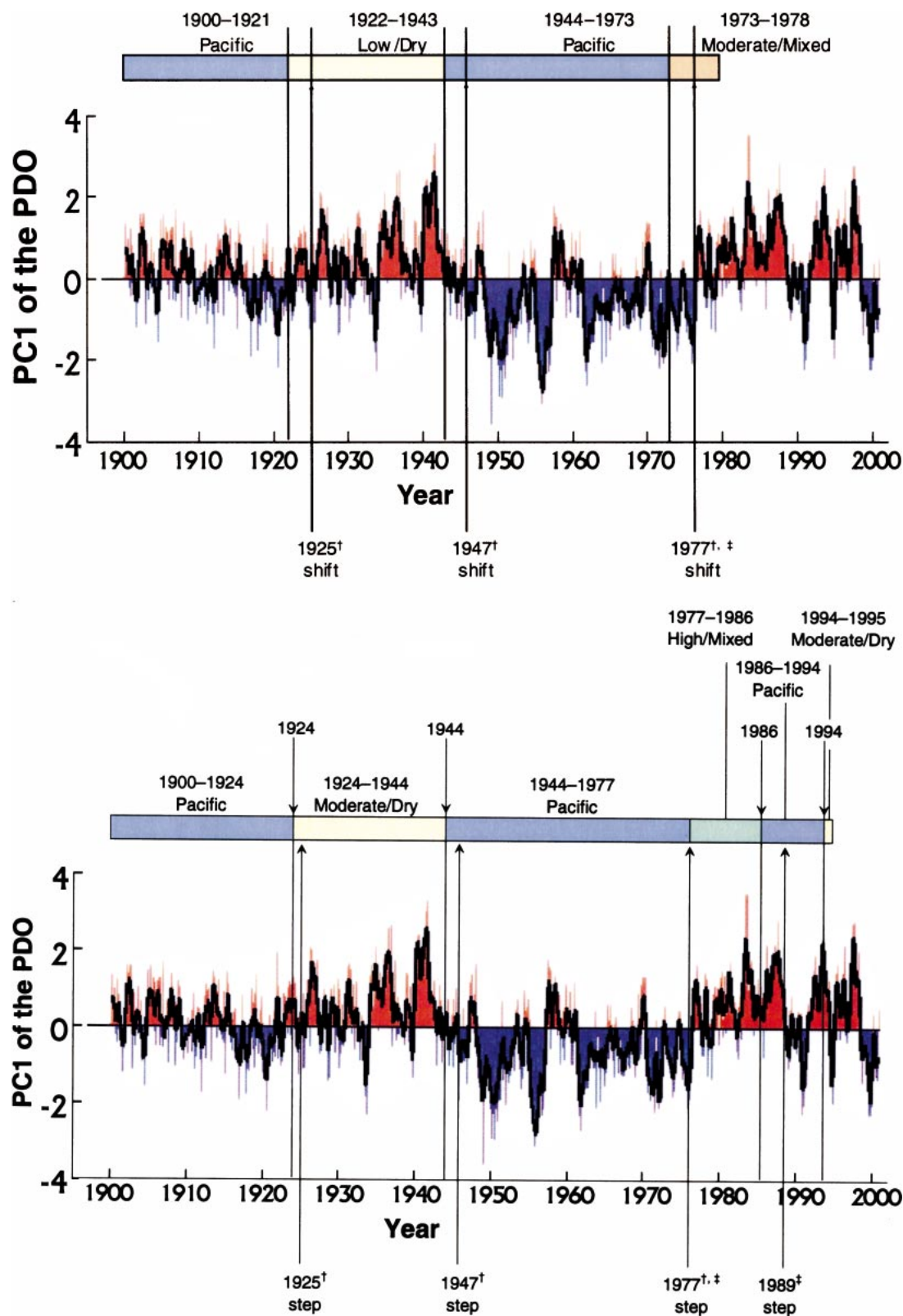


FIG. 8. Correspondence of periods of northwestern U.S. climate, derived from (top panel) tree-ring-based PDSI records for the period from 1900 to 1978 and (bottom panel) instrumental PDSI records for the period from 1900 to 1995, by TWINSpan Signal Strength analysis, with phase reversals of the Pacific Decadal Oscillation (PDO; Mantua et al. 1997). Symbols [†] and [‡] reference PDO steps (phase reversals) identified by Mantua et al. (1997) and Hare and Mantua (2000), respectively.

TABLE 2. Comparison of PDO phase shift dates of Mantua et al. (1997) to the dates derived by TWINSpan Signal Strength analysis of the instrumental Palmer Drought Severity Index (PDSI) time series of Cook (2000) for the northwestern United States.

PDO phase shift	Mantua et al. (1997)		TWINSpan Signal Strength	
	Date	P	Date	P
Cool to warm	1925	0.017†	1924	0.000
Warm to cool	1947	0.000	1944	0.000
Cool to warm	1977	0.000	1977	0.000
Warm to cool			1986	0.021
Cool to warm			1994	0.473

Notes: We tested each set of shift dates as intervention variables on the same PDO time series used in Mantua et al. (1997). Intervention analysis methodology follows that of Box and Tiao (1975).

† Value reported here differs from that published in Mantua et al. (1997); however, it is correct (S. Hare, *personal communication*).

always be unexplainable variation in the signals detected due simply to the mixing of climatic regions and their signals. A study based at the scale of eastern Oregon climate may find patterns and signals more specific to that subregion. A study that includes a spatial domain from southern Oregon to coastal Alaska may find patterns influenced by common and disparate factors from several climatic regions.

In addition to differences influenced by geographic region, the temporal patterns of climate found in other studies may differ with our results due to differences in methods. Most of the previous studies listed in Fig. 1 used PCA, or the related FA, as their base analysis tool. Multivariate methods like PCA and FA are helpful for extracting variance common among sites that may be embedded in time series data. This approach assumes that signals will be expressed in common modes of variance (e.g., a signal will reflect the presence of a wet or dry, or warm or cool regime). PCA and FA identified the Low/Dry anomaly with different start/stop dates than the TWINSpan-based methods. In the 1700s, FA identified one event, 1714–1742, and PCA identified a period from 1743–1801. The FA period combines much of High/Mixed and Moderate/Mixed periods of 1715–1730 and 1739–1748. There is no period in our analysis similar to the 1743–1801 period in PCA. Perhaps PCA- and FA-based methods are more limited in identifying mixed signals that differ from the background climate primarily in their variance level; that is, mixed signals in the Northwest are essentially the Pacific regime with the “volume turned up.”

Gedalof and Smith (2001) used FA to derive results with similarities to ours for the 1700s (Fig. 1h). One period starts in 1712 and ends in 1734, which is fairly close to our 1715–1730 High/Mixed period. Gedalof and Smith (2001) also found a period that started in 1758, close to our 1756 date; however, their period extends to 1798, while we identified a shift in 1765.

Why one portion of what we characterized as an High/Mixed anomaly could be seen through their data and not another may be explained by the fact that the geographic region analyzed by Gedalof and Smith (2001) was well beyond the boundaries of the Northwest climatic region identified in the present study.

The lack of correspondence between our results and those of others in the 1700s and the closer correspondence in the 1900s, suggest that perhaps TWINSpan can better detect pattern that is mixed in sign than can PCA or the related FA. TWINSpan combines ordination (correspondence analysis) with a classification function, while PCA and FA ordinate data based on common modes of variance among the time series. PCA focuses on explaining variance along the plane expressing the greatest variation, which may express more than the main gradient, expecting the data to vary in a monotonic fashion. Correspondence analysis focuses on the main gradient, and presumes that data may vary in a nonmonotonic fashion. PCA is also unsuited to longer gradients and data sets with many zeros, while correspondence analysis exhibits good behavior with sparse matrices (Legendre and Legendre 1998). Our main gradient (time) was quite long, and the data set had many zeros contained within it. TWINSpan identified the decadal-scale pattern, based on similarities both in the magnitude (variance) and sign of events among the time series. In addition, by identifying key indicators for each group, TWINSpan provided basic information on the features of each signal.

Pacific Decadal Oscillation

We correlated climate signal shifts with phase reversals of the PDO and found that our climate signals and periods corresponded significantly in each case with phases of the PDO for the 20th century (Table 1). Periods associated with a Pacific climate signal corresponded well with cool phases of the PDO. The warm phase of the PDO corresponded with a period marked by drought (Fig. 8, top panel). Our results either postulate slightly different shift dates for the phenomenon than previously published, or indicate that the climatic shift, as realized in terrestrial environments, occurs over a short period of years. Our findings also indicate that the PDO has been a primary forcing mechanism for observed drought signal shifts in the northwestern United States, at least throughout much of the 20th century.

Evaluating the instrumental PDSI record

To provide another independent evaluation of our method and observe a somewhat longer period of the recent northwestern U.S. climate, we applied the same TWINSpan methods to the instrumental PDSI time series (Cook 2000) for the same nine grid points representing the northwestern United States, for the period of that record (1895–1995). Using TWINSpan Signal Strength analysis we identified climatic regimes that

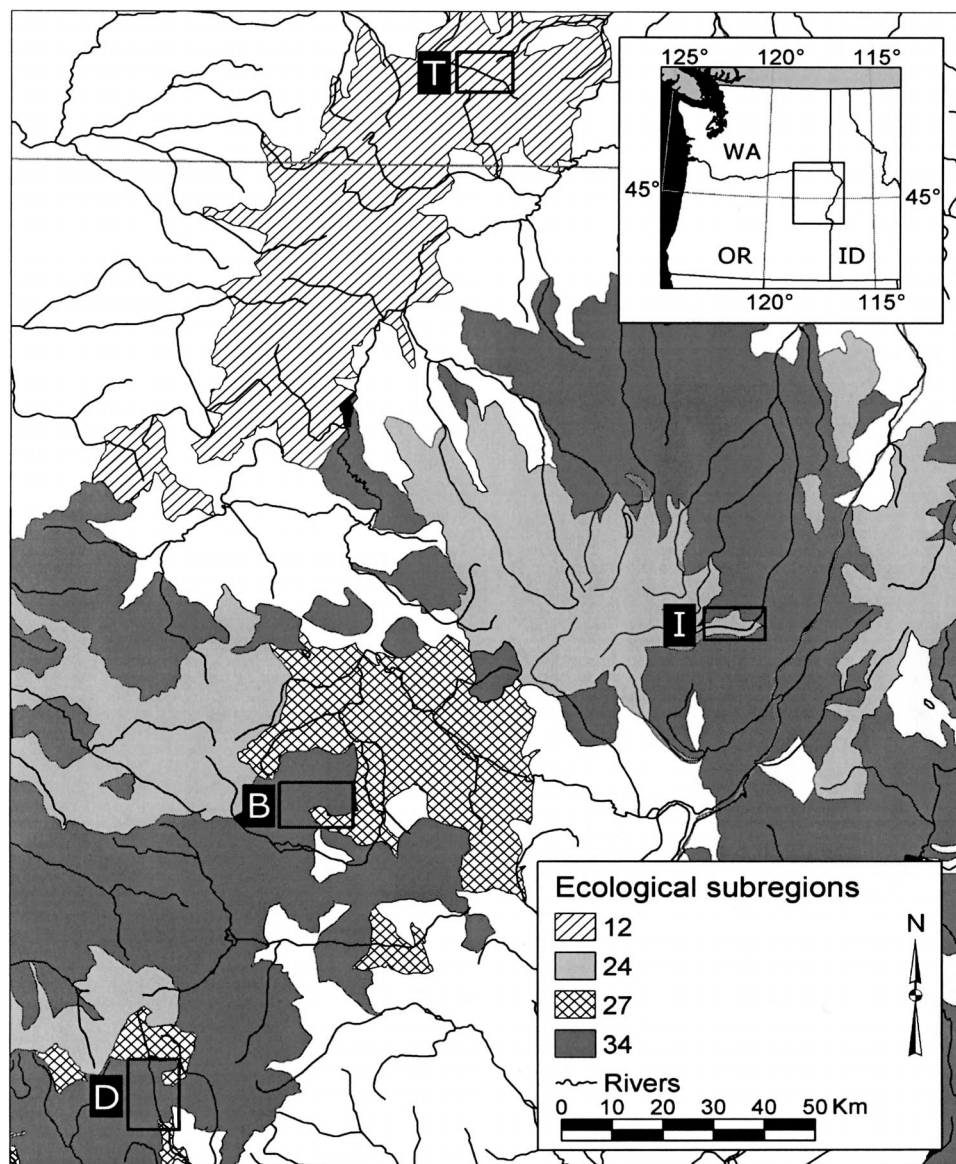


FIG. 9. Ecological subregions of the Blue Mountains of northeastern Oregon (adapted from Hessburg et al. [2000]). Shown are the locations of the Heyerdahl et al. (2001, 2002) fire history study sites. The Tucannon (T) site is located in subregion 12, the Imnaha (I) site is located in subregion 24, and the Baker (B) and Dugout (D) sites are located in subregion 34. The three subregions differ significantly in their potential vegetation and climate attributes (see Table 3).

corresponded well with what we identified from the proxy PDSI records based on tree rings. Periods of the Pacific regime were identified for 1895–1924, 1944–1976, and 1987–1993 (Fig. 8, bottom panel). The period of the Low/Dry anomaly found in the prior analysis was identified again as a period of persistent moderate to mild drought with moderate drought dominating (Moderate/Dry), and it occurred from 1924 to 1944. The Moderate/Mixed period found in the prior analysis was identified again as a mixed signal, but with high rather than moderate variance (High/Mixed), and it occurred from 1977 to 1986. Finally, an additional period of persistent moderate to mild drought with moderate

drought dominating (Moderate/Dry) occurred from 1994 to 1995, the end of the record. The ARIMA analysis was performed on the series as detailed earlier, and the 20th century anomalies identified through TWINSpan Signal Strength analysis were each tested as intervention variables on the PDO time series (Box and Jenkins 1976, SPSS 1999). We correlated climate signal shifts in 1924, 1944, 1977, 1987, and 1994 with phase reversals of the PDO and found that our climate signals and periods corresponded significantly in all but one case with phases of the PDO for the 20th century (Table 2). Periods associated with a Pacific climate signal corresponded well with cool phases of the PDO.

TABLE 3. Potential vegetation and climate attribute composition of selected ecological subregions of the Interior Columbia River Basin and vicinity, USA (Hessburg et al. 2000).

Ecological subregions (ESRs) [†]	Potential vegetation groups								Precipitation		
	AL	CF	CS	DF	DG	DS	MF	WD	VD	D	M
ESR 12		4	2	53	6		31	3		1	83
ESR 24	1	40	1	34	4		19			1	65
ESR 34		3	12	61	12	4	8	1		7	92

Notes: Values are the percentages of the subregion area. Potential vegetation groups are: AL, alpine; CF, cold forest; CS, cool shrubland; DF, dry forest; DG, dry grassland; DS, dry shrubland; MF, moist forest; RK, rock; RS, riparian shrub; WA, water; and WD, woodland. Total annual precipitation classes are: VD (very dry), 0–150 mm/yr; D (dry), 150–400 mm/yr; M (moist), 400–1100 mm/yr; W (wet), 1100–3000 mm/yr; and VW (very wet), 3000–8100 mm/yr. Mean annual temperature classes are: F (frigid), -10° to -1°C ; C (cool), $0-4^{\circ}\text{C}$; W (warm), $5-9^{\circ}\text{C}$; and H (hot), $10-14^{\circ}\text{C}$. Averaged annual daytime solar radiation (flux) classes are: VL (very low), 150–200 W/m^2 ; L (low), 200–250 W/m^2 ; M (moderate), 250–300 W/m^2 ; H (high), 300–350 W/m^2 ; and VH (very high), 350–400 W/m^2 .

[†] ESR 12 is dominated by dry (DF) and mesic (MF) forest potential vegetation types, a moist precipitation regime, warm temperatures, and moderate solar radiation. ESR 24 is dominated by cold (CF) and dry forest (DF) potential vegetation types, a moist to wet precipitation regime, cool temperatures, and high solar radiation. ESR 34 is dominated by dry forest (DF), dry grassland (DG), and cool shrubland (CS) potential vegetation types, a moist precipitation regime, cool to warm temperatures, and high solar radiation. Key distinguishing features are shown in boldface type.

The warm phases of the PDO corresponded with a period marked by a Moderate/Dry anomaly (1924–1944) and one marked by a High/Mixed anomaly (1977–1986) (Fig. 8, bottom panel). The signal shift in 1994 back to a Moderate/Dry anomaly did not correspond significantly with the PDO ($P = 0.47$), suggesting that it was either not the dominant forcing factor for that shift, or that a longer span of years was needed to evaluate shifting as a function of the PDO.

Ecological applications

It has long been understood that the climate of a region plays an important role in regulating the patterns and processes of ecosystems by providing environmental context at different spatial and temporal scales. But for any given climatic region, little is known of the specific mechanisms whereby the climate system controls ecological patterns, processes, and their interactions. The ability to distinguish the characteristics of climatic signals enables ecologists to develop testable hypotheses about the mechanisms of climatic influence.

The climatic signals identified for the Northwest using a TWINSpan-based methodology can be used to re-examine the historical relationships between biological systems and their associated climate. The advantages of having specific start and end dates of anomalies, knowing the basic characteristics of the signals, and being able to detect both mixed and unidirectional signals make TWINSpan a useful tool for fire–climate and climate–plant geographical analyses.

The single period of the Low/Dry anomaly (1922–1943) corresponds well to the 1921–1945 period of strong mountain hemlock (*Tsuga mertensiana*) establishment identified by Woodward et al. (1995). She noted that tree establishment increased during dry periods on normally cool and wet sites. During a drought, these sites are relatively warmer and moist, and apparently more amenable to hemlock regeneration and

establishment. There was no clear correspondence to the identified period of strong subalpine fir (*Abies lasiocarpa*) establishment (1956–1985) with our results; however, examination of the published establishment rates points to the possibility that the period may have actually started in 1945. Woodward et al. (1995) set a tree establishment rate $\geq 5\%$ as the level indicative of a significant establishment episode, and the period 1945–1950 fits this criterion. The establishment rate dropped during the 1951–1955 period, which is possibly why the period of strong establishment was reported as starting in 1956. If however, change in establishment rate started in 1945, then the period more closely corresponds to our Pacific period of 1944–1972.

Our results in the 1700s align closely with those of Keen (1937), who found periods of poor ponderosa pine growth in 1739–1744 and 1756–1760, with adjacent periods of good growth in 1745–1755 and 1761–1776. These periods are closely related to our Moderate/Mixed and High/Mixed periods of 1739–1748 and 1756–1765, with intervening periods of Pacific climate. Because ponderosa pine is drought limited, it is easier to correlate poor growth to moisture limitation than good growth with excess moisture, hence the portions of our mixed signals that are dry fit more closely with the reported growth rates. Keen (1937) did not quantitatively differentiate normal from above-normal growth.

There was no easily seen correspondence between the climate patterns we found in the 1900s and fire patterns in the Blue Mountains (Heyerdahl et al. 2001, 2002). Fire suppression, domestic livestock grazing (by reduction of fine fuels), and other factors in the 20th century had decoupled the influence of climate on fire, and few fires were seen in the 1900s. The climate anomalies we found for the 1700s (High/Mixed and Moderate/Mixed) differed from the background Pacific climatic regime by exhibiting moderate or high variance,

TABLE 3. Extended.

Precipitation		Temperature				Solar radiation				
W	VW	F	C	W	H	VL	L	M	H	VH
16			14	85	1		2	98		
34		4	83	14				2	97	2
1			29	70	1			2	98	1

but like the Pacific regime, they were mixed dry and wet periods. We would postulate a mixed-fire response to mixed signals, and fire frequency and extent appeared to have varied from low to high, both during the 1715–1730, 1739–1748, and 1756–1765 periods of anomalies, and during the intervening periods of Pacific regime at the various study sites (Heyerdahl et al. 2001, 2002).

Recently, Hessburg et al. (2000) developed a quantitative ecoregionalization of the Interior Columbia River basin. Subwatersheds (~5000- to 20 000-ha catchments) were grouped into ecological subregions according to their similar areal composition of geologic features, landform settings, potential vegetation, and several climate attributes. Later, they showed that the subregions of the eastern Washington Cascade Mountain Range readily explained variation in the percentage of subwatershed area in historical fire severity classes (Hessburg et al. 2004). These results suggest that ecoregions can, and perhaps should, be used as pooling strata for studies that explore climate–fire regime interactions, and where direct evidence of top-down spatial control of fire regime is sought.

We stratified the four study locations of Heyerdahl et al. (2001) using the Hessburg et al. (2000) subregions and found that sampling locations of two study sites (Baker and Dugout) fell within subregion ESR 34, sampling locations of another (Tucannon) fell within subregion ESR 12, and those of a fourth site (Imnaha) fell within a third subregion ESR 24 (Fig. 9). These subregions differ quite significantly in their areal composition of potential vegetation and climate attributes (Table 3). ESR 12 is dominated by dry forest (DF) and moist forest (MF) potential vegetation types, a moist precipitation regime, warm temperatures, and moderate solar radiation. ESR 24 is dominated by cold forest (CF) and DF potential vegetation types, a moist to wet precipitation regime, cool temperatures, and high solar radiation. ESR 34 is dominated by DF, dry grassland (DG), and cool shrubland (CS) potential vegetation types, a moist precipitation regime, warm and cool temperatures, and high solar radiation. Based on these ecoregion characteristics, we would expect to find fire frequency highest and mean fire-free intervals shortest in watersheds of ESR 34. An inspection of the fire charts for the Baker and Dugout sites shows that fires at these sampling locations were more than twice as frequent ($P < 0.01$) relative to the other two sites (also

see Figs. 7 and 8a in Heyerdahl et al. 2001). Likewise, we would anticipate that the Tucannon and Imnaha sites would show reduced historical fire frequency owing to the large areas dominated by moist (31%) and cold (40%) forest potential vegetation types, respectively. To provide a direct measure of top-down regional climatic controls on spatial patterns of fire frequency, severity, or extent, we suggest that one would need to first sample forest landscapes by ecoregion or subregion, then stratify the relevant sets of fire chronologies by the periods of anomalies and background regime, and look for quantitative evidence of concordance or interactions.

Conclusions

Application of a community ecology technique, TWINSpan, to the analysis of climate pattern across time was successful. It provided specific period start and end dates and signal characteristics, which facilitates comparison to other ecological data sets. An unexpected finding was that the amplitude or variance level of a climatic anomaly can be a primary descriptor of the climate of a region. Two of the three anomalies identified were mixed signals, coherent in terms of amplitude, while not solely wet or dry in nature. The potential coherence in amplitude implies that perhaps research should focus on both the level and direction of variation. This has implications for both research on climate, and how climate affects ecological processes.

Recommendations for enhanced signal detection

Among the various studies of climatic regimes and temporal variation for the northwestern United States, we found relatively little consistency in results. Where there are similarities in results, there is a similar focus of methods. Following, we highlight four considerations for enhanced signal detection:

- 1) Stratify data into climatic regions prior to pattern analysis. We observed that it made sense to stratify our data into logical climatic regions before we looked for temporal patterns of climatic signals. When we minimized variance within groups in data space, we were more likely to find signals amidst the noise.
- 2) Relax assumptions about the features of climatic signals. We observed that it is useful to relax assumptions about the nature of climatic signals.

Furthermore, it seems prudent to employ a suite of methods in temporal pattern analysis that can detect a broad array of signal types, perhaps even choosing several different quantitative methods that vary by the way they treat patterns of variance in data space.

- 3) Use ordination and classification methods in pattern analysis. We observed that it is sensible to employ methods that look sequentially at time series data *and* that give every year the chance of being grouped with any other year in the time series. This will facilitate identification of comparable signals over time, and will differentiate climatic anomalies from background climate.
- 4) Consider the characteristics of the background climate and how anomalies might stand out. We observed that it was useful to examine characteristics of the background climate and how anomalies might contrast with it. This may influence the multivariate technique employed in temporal pattern analysis.

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