Western US streamflow and atmospheric circulation patterns during El Niño-Southern Oscillation

Thomas C. Piechota, John A. Dracup, Robert G. Fovell

Abstract

Using principal component analysis (PCA), cluster analysis, and jackknife analysis, we investigated the spatial and temporal modes that dominate streamflow variability in the western US in response to El Niño-Southern Oscillation (ENSO) events. Spatial variability was investigated with data only from ENSO years and with rotated PCA on 79 streamflow stations in the western United States. Eight regions, or clusters, were thus pinpointed as areas where streamflow tends to co-vary similarly following ENSO events; traditional cluster analysis confirmed the identification of these regions. The ENSO response in streamflow was then further evaluated by forming an aggregate ENSO composite for each region.

Temporal variability of western US streamflow in the PCA-identified regions was evaluated with a 'T-mode' PCA that isolated the different responses in streamflow following ENSO events. The T-mode PCA breaks the 13 ENSO events that occurred from 1932 to 1993 into five subsets. It is interesting to note that the events in the dominant mode, PC1(+), occurred before 1976, and next mode, PC2(+), included events prior to 1976.

Finally, we investigated the atmospheric circulation patterns over the North Pacific Ocean and much of North America that are associated with the various US streamflow responses. The circulation patterns vary according to the prescribed ENSO forcing. The results of this study contribute to a better understanding of the varied ENSO-streamflow relationship in the western US and the use of ENSO for long-range streamflow forecasting. © 1997 Elsevier Science B.V.

Keywords: Western US streamflow; Principal component analysis (PCA); Cluster analysis; Jackknife analysis; Atmospheric circulation patterns
1. Introduction

Numerous studies have linked anomalous streamflow patterns in the western US with the El Niño-Southern Oscillation (ENSO)—an ocean-atmospheric phenomenon in the tropical Pacific Ocean (e.g. Cayan and Peterson, 1989; Redmond and Koch, 1991; Cayan and Webb, 1993; Kahya and Dracup, 1993; 1994; Dracup and Kahya, 1994; Piechota and Dracup, 1996). An El Niño event occurs when the warm water pool, usually located in the western tropical Pacific Ocean, moves eastward toward the coast of Peru. Fluctuations in the high and low pressure centers in the equatorial Pacific (an atmospheric phenomenon known as the Southern Oscillation) correspond with this eastward movement and the ensuing El Niño events. The Southern Oscillation and its recognized interaction with ‘El Niño’ has come to be designated as ENSO (Rasmusson and Wallace, 1983).

Some 4–6 months later, in response to an ENSO event, hydroclimatic anomalies in temperature, precipitation, and streamflow occur in the western US. Thus, an ENSO indicator, such as the Southern Oscillation Index, can be useful in forecasting changes of climate and streamflow in parts of the US. Today, with increasing accuracy, the onset of an ENSO event is being forecast a year in advance. As the ENSO–streamflow lag relationship becomes better documented, ENSO forecasting of streamflow could be yet longer in range. Streamflow forecasts are important for water allocation among competing water users (e.g., industrial, agricultural, domestic, environmental).

Studies have shown that, on the average, the Pacific Northwest responds with below normal streamflow in the year after the warm phase (El Niño) of the ENSO cycle (Kahya and Dracup, 1993), while, on the average, parts of the Southwest experience the opposite response. However, these responses are not consistent. For example, Kahya and Dracup (1993) noted that seven of the nine El Niño events corresponded with below normal streamflow in the Pacific Northwest in the year after the El Niño event. In the Southwest US, Kahya and Dracup (1994) noted that the streamflow response is most pronounced during Type 1 El Niño events (Fu et al., 1986), when strong ocean warming occurs in the central and eastern Pacific. Namias and Cayan (1984) noted that the different climatic responses seen in North America during ENSO events created a problem when using ENSO activity in long range forecasting. The use of ENSO for streamflow forecasting is probably most dependable when forecasting for the Pacific Northwest area, since the streamflow response to ENSO is fairly consistent and it is easier to predict the ENSO event than to predict the type of the ENSO event.

The purpose of this study was to investigate specifically the spatial and temporal variability of western US streamflow following ENSO events. Numerous studies have identified western and other regions in the US that have a strong response to ENSO, but the study presented here uses objective methods to delineate these regions. And although it is well documented that the streamflow response is not the same for all ENSO events, no studies have evaluated the varying streamflow responses to ENSO found in the western US. In meeting our objectives, two applications of principal component analysis (PCA) have been used (1) to identify the homogeneous regions of streamflow variability and (2) to identify the dominant modes of western US streamflow during ENSO (i.e. the most common responses in streamflow during ENSO). Finally, the large scale circulation patterns associated with each mode have been evaluated with 700-mb height data over the North Pacific and North America.
2. Data

Within a river basin, hydrologic processes are integrated into streamflow data; thus, streamflow data provide a natural filter for precipitation data, which are highly variable in space and time, making streamflow data particularly useful for purposes of this study. Monthly streamflow records (1932–1988) from 79 western US streamflow stations that are relatively free of upstream regulations or diversions were extracted from the US Geological Survey Hydroclimatic Data Network, HCDN (Slack and Landwehr, 1992). These data were updated to 1993 using the individual state data bases available on the Internet. The 62-year time period, 1932–1993, was chosen after reviewing the HCDN data; this time period represents a compromise between length of record and number of stations. The spatial distribution of the 79 stations is shown in Fig. 1. Streamflow data in the US is commonly expressed in ‘water years’ which commence in October. The records extracted for this study start in October of 1931 and end in September of 1993.

The magnitude of the monthly streamflow values varies greatly among the stations, due to both the different climatic regions in the western US and the different drainage basin characteristics associated with each streamflow station. Most of the drainage basins are medium to small sized (<1000 km²) and are located in middle to high elevations (>500 m).

The magnitude variation among stations was not important to this study and could mask the underlying temporal coherences we sought to identify. Therefore, the raw streamflow data were first logarithmically transformed to enhance normality and then standardized by the monthly mean and standard deviation. The standardized streamflow for each station closely follows a normal distribution.

Fig. 1. Location of the selected streamflow stations in the western US for the water years 1932–1993.
Table 1
List of the 13 ENSO events used in this study (after Rasmusson and Carpenter, 1983)

<table>
<thead>
<tr>
<th>ENSO event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1932</td>
</tr>
<tr>
<td>1939–1940</td>
</tr>
<tr>
<td>1941</td>
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<tr>
<td>1951</td>
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<td>1953</td>
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<td>1957</td>
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<td>1972–1973</td>
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<td>1976</td>
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<td>1982–1983</td>
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<tr>
<td>1986</td>
</tr>
<tr>
<td>1991</td>
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</tbody>
</table>

The emphasis in this study was on the ENSO events defined in Rasmusson and Carpenter (1983). During 1932 to 1993, there were 13 ENSO events (see Table 1). In cases where ENSO conditions occurred in 2 consecutive years, the first year was used to define the event. It should be noted that the strength of each ENSO event (e.g. the magnitude of the SOI (Southern Oscillation Index) is not incorporated into the analysis and all ENSO events are given equal weight.

3. Background

Eigentechniques (e.g. principal components, factor analysis) have been used extensively in the meteorological community for data reduction, grouping of variables, and the identification of coherent modes in atmospheric fields (e.g. Richman, 1986). Principal component analysis (PCA) transforms a set of intercorrelated variables into a new set of mutually uncorrelated variables (principal components, PCs) that are linear combinations of the original variables. The first analysis, commonly termed a 'unrotated PCA,' attempts to place a large portion of the total variance in the first PC (dominant mode), and successive PCs claim a smaller portion of the variance. Subsequent rotation of these PCs creates a new set of PCs that may be more readily interpreted. Rotated PCA is sometimes used for the regionalization of stations (e.g. Richman and Lamb, 1985) and as a means of preprocessing data prior to cluster analysis (Fovell and Fovell, 1993). A thorough description of PCA, including reasons for rotation, is provided in Richman (1986). The application of these techniques in the present study is discussed in Section 4.

Various hydrologic studies have investigated streamflow patterns in the US using eigentechniques. Bartlein (1982) identified the basic anomaly patterns of streamflow and homogenous hydrologic regions in the US and southern Canada using unrotated and rotated PCA on 20 years of monthly streamflow records. The spatial and temporal patterns in US streamflow were identified by Lins (1985a,b) using the same type of analysis on 48 years of annual streamflow records. Guetter and Georgakakos (1993)
performed a rotated factor analysis on river outflow in the US (1939–1988) to identify coherent regions of streamflow. Factor analysis decomposes the covariance matrix, and the new components are not assumed to be linear combinations of the original variables, as is the case in PCA.

In the present study, regionalization of streamflow stations in the western US was performed with rotated PCA. We were interested only in the spatial variability in response to ENSO events; therefore, the streamflow records were extracted for defined ENSO events only. Other studies have employed the entire streamflow record. By including only the data from ENSO events, we were able to isolate the different responses that follow ENSO events as seen in western US streamflow levels. Had the entire record been used, the ENSO response would have been only one of the various modes of streamflow variability for the entire record. An unrotated PCA was used to investigate the different temporal responses (modes) in streamflow following ENSO events. No other studies have used these approaches to investigate the different responses of streamflow to ENSO. The two applications of PCA used here are referred to as ‘S-mode’ and ‘T-mode’ by Cattell (1952), and a more thorough description of each application follows.

4. Spatial variations

4.1. Regionalization

The first part of this study attempts to isolate groups of stations that have a similar ENSO response in streamflow. Two approaches were used: (1) S-mode PCA and (2) group average linkage cluster analysis.

4.1.1. S-mode PCA

An S-mode PCA is typically performed on a \( n \times p \) data matrix to isolate subgroups of stations that tend to co-vary similarly, where \( p \) is the number of stations and \( n \) is the number of observations. Since we were interested only in the streamflow patterns in response to ENSO events, the number of observations \( (n) \) was reduced to the number of ENSO events (13) times a 24-month period that starts at the beginning of the ENSO year and ends in the year after. It was seen in earlier studies (e.g. Kahya and Dracup, 1993) that the streamflow patterns in certain regions of the US are anomalous during this 24-month period. In the present study, 79 stations \((p)\) represent the western US, and 312 observations at each station represent the streamflow response to ENSO. Thus, the S-mode PCA was performed on the 79 x 79 station correlation matrix.

The first six components of the unrotated PCA solution have eigenvalues of 27.2, 13.5, 6.6, 5.5, 4.0, and 2.3. These six components together account for 74.8% of the total variance \((59.1/79)\). At this point, it is common to truncate the remaining components that are statistically insignificant. The truncation level is found through several truncation tests (e.g. Rule ‘N’ Horn’s Test). However, all components were retained in study, and Varimax orthogonal rotation was performed on all 79 PCs.

There were several reasons for rotating the non-truncated solution. First, the non-truncated solution does not require a prior assumption of the number of components to
retain. In the truncated PCA, the solution must be specified (i.e. number of PCs, or clusters) so the analysis can be completed. Next, the structure of the clusters is highly dependent on the number of components that are retained. By specifying the number of components to retain, the grouping of stations is constrained and each station must fit into one cluster. Finally, by retaining all of the components, the number of stations with weak, 'fuzzy' PC loadings is minimized. The non-truncated solution does not force isolated stations into predefined clusters. This approach permits a single isolated station to have a high PC loading in a higher order PC which may not necessarily be a cluster.

A preliminary analysis that used only the first six components (truncated PCs) and subsequent rotation revealed six regions that were composed of all 79 stations. This forced clustering of the stations was unsatisfactory for the purposes of this study—to isolate clusters of stations with similar streamflow characteristics during ENSO events. A comparison of the two analyses shows similar clusters for the Pacific Northwest; however, the Southwest contains more clusters when the non-truncated solution was used. The truncated solution uses two clusters in the Southwest and the non-truncated solution uses four clusters to define the different regions in the Southwest.

The solid and dashed lines in Fig. 2 outline regions where the PC loadings, for each PC, are at least 0.7 and 0.6, respectively. Since standardized streamflow data are used, the amount of variance explained by each component at each station is found as the square of the PC loading, and the sum of the squares is unity. Thus, a PC loading of 0.7 represents 49% of the variance, and the regions identified with the solid line in Fig. 2 are areas where at least 49% of the variance is accounted for in the corresponding PC. These are areas where the streamflow response to ENSO events is spatially homogeneous for two or more stations. There is a certain amount of bias in this analysis due to irregularly spaced data, as discussed in Karl et al. (1982). The regions identified here tend to be in data-rich regions. However, the option of interpolating the data on to a regularly spaced grid may also introduce a large amount of bias, since, for many areas of the western US, streamflow data are not available.

4.1.2. Cluster analysis

Group average linkage cluster analysis is another method for identifying regions with similar streamflow characteristics. The group average linkage algorithm uses the smallest Euclidean distance between stations and accounts for the number of stations already absorbed into the clusters. The Euclidean distance is a measure of the dissimilarity between two pairs of objects, \( i \) and \( j \), in an \( n \times p \) data matrix. It is computed as:

\[
d_{ij} = \left[ \sum_{k=1}^{p} (x_{ki} - x_{kj})^2 \right]^{1/2} \tag{1}
\]

where \( p \) is the number of variables. One practical problem with the Euclidean distance shown in Eq. (1) is that the number of members in each object (cluster) are not accounted for. The group average linkage algorithm accounts for the number of stations by computing the Euclidean distance between a new cluster AB and cluster C \((d_{AB-C})\) as:

\[
d_{AB-C} = (N_A d_{AC} + N_B d_{BC})/(N_A + N_B) \tag{2}
\]

where \( N_A \) and \( N_B \) are the number of members in clusters A and B, and \( d_{AC} \) and \( d_{BC} \) are the
Fig. 2. Regionalization of western US streamflow during ENSO events based on S-mode PCA and average linkage cluster analysis. The solid and dashed lines are the region boundaries based on the 0.70 and 0.60 PC loading isopleths, respectively, for individual PCs. The symbols at each station correspond to the 13-cluster solution of the average linkage cluster analysis. Stations noted with a 'I' symbol are isolated clusters with only one station.

Euclidean distances between clusters A and C, and B and C, respectively. Fovell and Fovell (1993) provide a detailed description of group average linkage cluster analysis and other cluster analysis algorithms.

The symbols in Fig. 2 represent the different clusters to which each station belongs from the 13-cluster solution. The 13-cluster solution is one solution chosen after evaluating the pseudo-$F$ and pseudo-$r^2$ statistics described in the documentation for SAS Institute (1985, p. 268). Other solutions were noted for the 7- and 18-cluster levels; however, evaluation of the spatial patterns revealed that the 13-cluster solution was most similar to the S-mode PCA patterns. These similarities are seen in Fig. 2, where the PCA Regions 1 through 8 generally include stations that belong to one cluster (i.e. same symbols in each region).

4.1.3. Consensus regions

Evaluation of Fig. 2 shows that the results of the S-mode PCA are corroborated by the group average linkage cluster analysis results. At this point, the regions where the PC loadings are at least 0.7 are identified as regions where streamflow patterns co-vary
similarly in response to ENSO events. It is important to note here that the purpose of this analysis is to identify homogeneous regions in the western US where the streamflow response to ENSO is broad on a spatial scale. By including only those stations with a 0.7 PC loading, stations with weak PC loadings were not forced into defined clusters, as is the case in group average linkage cluster analysis. Furthermore, the use of PC loadings was an objective criterion for establishing homogeneous regions where at least 49% of the variance was explained in the stations. The criterion established here is somewhat arbitrary; however, we feel confident that the stations within these regions have similar streamflow patterns during and after ENSO events. Finally, the criterion used here is more stringent than that used by Richman and Lamb (1985), who took a 0.4 loading level to regionalize climate stations using summer rainfall in the central US.

Thirty stations are not associated with the eight regions in Fig. 2. These stations all have PC loadings that are less than 0.7, or less than 49% of the variance. The majority of the eliminated stations are in a region covering all of Colorado, southern Utah, southern Idaho, Nevada, and northern Arizona.

4.2. Regional aggregate composites

Within the eight identified regions, the standardized streamflow data are aggregated to form 36-month ENSO composites. A 36-month composite is chosen so the entire streamflow response before, during, and after an ENSO event can be evaluated. Each 36-month composite begins in January of the year before the ENSO event and ends in December of the year after the ENSO event. Using common conventions, the ENSO year is designated by (0), while the year before is (−) and the year after is (+). These composites represent the regional streamflow response. The statistical significance of the standardized streamflow anomaly for each month (i.e. statistically different from randomly formed composites) is determined from a bootstrap resampling procedure used by Piechota and Dracup (1996). The procedure involves the random formulation of 500 aggregate composites and the computation of the monthly mean and standard deviation. Using the t-statistic, critical values are then computed to test whether the anomaly in the ENSO aggregate composite is significantly different from the randomly formed aggregate composite. Using this procedure, it was found that a streamflow anomaly that is greater than +0.267 or less than −0.267 is significantly different from the long-term average of each month in the composite at the 95% confidence level. If 4 consecutive months are significant at a 95% level, then those months are identified as being a significant response to ENSO.

An examination of the aggregate composites for the eight regions reveals four regions that have statistically significant anomalies for 4 or more months. The aggregate composites for these four regions are shown in Fig. 3. The Pacific Northwest (Region 2) and northern Rockies (Region 5) experience above normal runoff during much of the ENSO year and below normal runoff in the spring-summer of the year after the ENSO event (see Fig. 3. A 36-month ENSO aggregate composite for (a) Region 2, (b) Region 3, (c) Region 5, and (d) Region 8. These are regions where streamflow is consistently above or below the mean. Streamflow data are standardized by station mean and standard deviation. The 36-month composite starts at Jan.(−) and continues until Dec.(+). The horizontal line is the threshold for anomalies significant at the 95% confidence level.)
Fig. 3(a) and (c)). These results are similar to those of Kahya and Dracup (1993); however, the regions used here were based on an analysis (i.e. PCA) different from that of Kahya and Dracup, who worked with harmonic analysis. In the Southwest (Regions 3 and 8), runoff tends to be above normal in the latter part of the ENSO year and during the winter of the year after the ENSO event (see Fig. 3(b) and (d)). The streamflow anomalies that occur in the latter part of the ENSO year and the year after ENSO suggest that summer ENSO conditions may be an indicator of streamflow patterns in the following year.

4.3. Investigation of individual ENSO events

The different responses in the Northwest and Southwest streamflow during individual ENSO events is investigated herein. We use Region 2 to represent the Northwest and Region 3 to represent the Southwest. The statistically significant seasons from the Northwest and Southwest aggregate composites (Fig. 3(a) and (b)) are used to form index time series (ITS). The ITS is the average of the monthly values for the identified season for each ENSO event in the time series. The change in the statistical significance of each ITS value is evaluated with a Jackknife procedure (Efron, 1982). Each ENSO event (i.e. ITS value) is removed one at a time, and the change in the overall response (i.e. the average ITS for the remaining ENSO events) is evaluated. Figs. 4 and 5 present the ITS values for each ENSO event in the Northwest and Southwest, respectively.

For Region 2 (Fig. 4(a)), ten of the 13 ENSO events are associated with below normal streamflow in the spring-summer of the year after ENSO. The change in the average ITS is evaluated by individually removing and replacing the ENSO events (Fig. 4(b)). Note that when the 1932 or 1953 ENSO event is removed, the significance level of the average ITS increases to approximately 99%. This suggests that these events are significantly different from the 'average' ENSO response.

In the Southwest (Fig. 5(a) and (b)), nine of the 13 ENSO events are associated with above normal streamflow in the second half of the ENSO year and in the winter of the year after ENSO. The removal of the 1932, 1939, 1951, 1953, or 1976 ENSO events increases the significance level of the overall ITS. It is noteworthy that the ENSO events of 1932 and 1953 had significantly different responses from the responses expected in both the Northwest and Southwest.

The analysis performed for Regions 2 and 3 was also performed for Region 5; however, the average ITS value was not statistically different from the long-term average (at the 90% confidence level). Thus, the results are not shown here.

5. Temporal variations

The temporal variability of western US streamflow in response to ENSO events is investigated here by performing a T-mode unrotated PCA on a p × n data matrix where n is the number of observations and p is the number of stations. To facilitate T-mode analysis, the high number of observations (312) used in the S-mode analysis (see Section 4.1.1) is reduced by using seasonal values of streamflow for the second half of the ENSO year and for the entire year after ENSO. Thus, the number of observations (n) is
Fig. 4. (a) An index time series (ITS) of the streamflow in Region 2 (Pacific Northwest) during ENSO events for the identified seasons in Fig. 3(a). Each bar represents the average standardized streamflow for the specified season for each ENSO event. (b) The change that occurs in the average (of all ENSO events) ITS when one individual ENSO event is removed. The subsets correspond to the removal of the ENSO events in (a).
Fig. 5. (a) An index time series (ITS) of the streamflow in Region 3 (Southwest) during ENSO events for the identified seasons in Fig. 3(b). Each bar represents the average standardized streamflow for the specified season for each ENSO event. (b) The change that occurs in the average (of all ENSO events) ITS when one individual ENSO event is removed. The subsets correspond to the removal of the ENSO events in (a).
78 (six seasons times 13 ENSO events), and the number of stations (p) is 79. Considering several truncation tests (e.g. Rule ‘N,’ Horn’s Test) and the scree plot of the components from the PCA, it was decided that only the first five components would be evaluated as significant PCs. These PCs represent the different modes of streamflow variability in response to ENSO. After evaluating the pairwise plots of the first five PCs for both the unrotated and rotated solutions, the unrotated solution was favored over the rotated solution. The rotated solution did not seem to enhance the unrotated PC loadings significantly.

The assignment of the ENSO event to a particular component is accomplished by computing the average of the PC loadings from the six seasons in each ENSO event. The PC loadings for the six seasons that represent an ENSO event were averaged to find the overall loading of each ENSO event for each PC. The largest average loading was used to assign a particular ENSO event to a PC. Using this approach, the ENSO events of 1941, 1957, 1965, 1969, and 1972 were associated with PC1(+), the dominant mode. There are large negative loadings on PC1(−) for the years 1932 and 1953. This suggests that 1932 and 1953 are 2 years when the streamflow response is opposite to the dominant mode. The large positive loadings in PC2(+) represent the ENSO events of 1976, 1986, and 1991. A summary of the PCA and the retained components is shown in Table 2.

The years identified in PC1(−) and the results of the Jackknife analysis on the regional ITS values suggest that the ENSO events of 1932 and 1953 are significantly different (opposite) from the ‘normal’ ENSO response, PC1(+). It is also noteworthy that the ENSO events in PC1(+) are all pre-1976 and the ENSO events in PC2(+) are all post-1976. Some studies hypothesize a shift occurring in the climate regime in 1976 (Trenberth, 1990; Ebbesmeyer et al., 1991). While the shift in ENSO groupings seen here is based on only 13 ENSO events, the separation of the ENSO events into two categories, PC1(+)

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**Table 2**

PCA loading patterns based on a T-mode PCA. The crosses are the ENSO events associated with the principal component (PC) of that column

<table>
<thead>
<tr>
<th>ENSO event</th>
<th>Variance claimed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>25.0%</td>
</tr>
<tr>
<td>PC1(+)</td>
<td></td>
</tr>
<tr>
<td>PC1(−)</td>
<td></td>
</tr>
<tr>
<td>PC2(+)</td>
<td></td>
</tr>
<tr>
<td>PC2(−)</td>
<td></td>
</tr>
<tr>
<td>PC3</td>
<td></td>
</tr>
<tr>
<td>1932</td>
<td>×</td>
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<tr>
<td>1939</td>
<td>×</td>
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<tr>
<td>1941</td>
<td>×</td>
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<td>1986</td>
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<td>1991</td>
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</tbody>
</table>
Table 3
Comparison of ENSO groupings based on western US streamflow (PCA) and Fu et al. (1986) groupings based on zonal SST distributions

<table>
<thead>
<tr>
<th>ENSO event</th>
<th>Streamflow principal component</th>
<th>Fu et al. (1986) ENSO types</th>
</tr>
</thead>
<tbody>
<tr>
<td>1941</td>
<td>PC1(+)</td>
<td>N/A</td>
</tr>
<tr>
<td>1957</td>
<td>PC1(+)</td>
<td>1</td>
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<tr>
<td>1965</td>
<td>PC1(+)</td>
<td>1</td>
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<tr>
<td>1969</td>
<td>PC1(+)</td>
<td>2</td>
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<tr>
<td>1972</td>
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<tr>
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<td>PC1(-)</td>
<td>N/A</td>
</tr>
<tr>
<td>1953</td>
<td>PC1(-)</td>
<td>N/A</td>
</tr>
<tr>
<td>1976</td>
<td>PC2(+)</td>
<td>3</td>
</tr>
<tr>
<td>1986</td>
<td>PC2(+)</td>
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<td>N/A</td>
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<tr>
<td>1982</td>
<td>PC2(-)</td>
<td>1</td>
</tr>
</tbody>
</table>

and PC2(+), is probably not serendipitous and may be a manifestation of the shift in climate regimes.

A study by Fu et al. (1986) noted three major patterns of the zonal distribution of sea surface temperatures from 1940 to 1983 in the equatorial Pacific during ENSO events. These patterns are used to classify some of the historical ENSO events into three types: Type 1—1957, 1965, 1972, and 1982; Type 2—1963 and 1969; and Type 3—1976. The 1963 ENSO event was not identified as an ENSO year by Rasmusson and Carpenter (1983) and was not included in the study presented here. The three major classifications do not include all of the ENSO events that occurred from 1940 to 1983. Some ENSO events may instead be a combination of different patterns. Table 3 compares the different responses in streamflow following ENSO events with the three classifications made by Fu et al. (1986). Due to the short data set found in the Fu et al. study, not all of the ENSO events in our study can be compared with those in the different classifications. Nonetheless, the dominant mode of streamflow variability, PC1(+), seems to correspond to Type 1 ENSO events. It was noted earlier that Type 1 ENSO events are characterized by strong ocean warming in the central and eastern tropical Pacific.

6. Large scale circulation patterns

The anomalous streamflow conditions noted for the western US should correspond to anomalous large scale circulation patterns over the North Pacific and North America. The western streamflow anomaly will, however, lag in its correspondence because much of the streamflow in the western US is the result of snowmelt.

These large scale circulation patterns are studied here with 700-mb (hPa) height data obtained from Scripps Institute of Oceanography, San Diego, California. The 700-mb heights generally describe the large scale circulation (winds) at about 3 km above mean sea level in a near-geostrophic atmosphere (Dettinger and Cayan, 1995). The 700-mb height anomalies (m) are presented on a 5° staggered grid for the region 20–70°N and
Fig. 6. Seven-hundred-mb (hPa) height anomalies (m) for the 1957, 1965, 1969, and 1972 ENSO events (PC1(+)). Height anomalies are given for the (a) summer (July–September) and (b) autumn (October–December) of the ENSO year (0) and the (c) winter (January–March) and (d) spring (April–June) of the year after the ENSO year (+). Regions are shaded where the anomalies are significantly different than zero at the 99% confidence level. The height anomalies are the deviation from the long-term mean.
Fig. 7. Seven-hundred-mb (hPa) height anomalies (m) for the 1953 ENSO event (PC1(-)). Height anomalies are given for the (a) summer (July-September) and (b) autumn (October-December) of the ENSO year (0) and the (c) winter (January-March) and (d) spring (April-June) of the year after the ENSO year (+). Regions are shaded where the anomalies are significantly different than zero at the 99% confidence level. The height anomalies are the deviation from the long-term mean.
180°–60°W for the time period 1947–1993. Therefore, only the ENSO events after 1947 have been evaluated in this section.

In the T-mode PCA, the ENSO events were classified into five groups (modes) based on the PC loadings (see Table 2). The first four modes were evaluated here by creating composite 700-mb height anomalies of each mode for the second half of the ENSO year (0) and for the first half of the year after the ENSO year (+).

Fig. 6 is the composite 700-mb height anomalies for the ENSO events in PC1(+). The major anomalous circulation pattern is seen in the winter (+), when low pressure hovered over much of the Pacific and the Southeast US and high pressure over much of Canada. This is the classical Pacific North American (PNA) pattern that Horel and Wallace (1981) first linked to fluctuations in the Southern Oscillation.

The opposite response to PC1(+) is noted in PC1(−) and includes the ENSO events of 1932 and 1953. Fig. 7 presents the 700-mb composites for this group of events. Since the 700-mb height data start in 1947, only the 1953 data were used. Large negative height anomalies occurred in the autumn (0) near the Aleutian Islands; however, this area of low pressure (an intensified Aleutian Low) disappeared in the winter(+). In the winter(+), much of the northern Pacific and the continental US had positive height anomalies (high pressure). The presence of high pressure corresponded with warm-dry conditions throughout much of the US and was expected, since PC1(−) is the opposite response to the dominant mode, PC1(+). It should be noted that the anomalies shown in Fig. 7 are based on only one ENSO event; however, it is hypothesized that addition of more PCI(−) ENSO events could follow the general patterns shown in Fig. 7.

Fig. 8 presents the 700-mb composites for PC2(+) which includes the ENSO events of 1976, 1986, and 1991. The spatial patterns seen here are similar to PC1(+); however, the anomalies in PC2(+) are much larger in magnitude. The magnitude of the Aleutian Low in the winter(+) is approximately doubled. The other difference between PC1(+) and PC2(+) is seen in the anomalous 700-mb heights in the autumn in the PC2(+) composites that are not present in the PC1(+) composites. This anomalous circulation in the autumn suggest that winter conditions may start earlier than usual during PC2(+) ENSO events. The high pressure over Canada and low pressure over the North Pacific during the autumn persisted into the winter (+). As noted earlier, the separation of the ENSO events into pre-1976 and post-1976 may reflect a climate shift in 1976. The intensification of the pressure anomalies over the North Pacific seen in Fig. 8 were also noted by Trenberth (1990) who found an intensification of sea level pressures over the North Pacific when the data were broken into subsets based on pre- and post-1976 dates.

The 700-mb composite for PC2(−) is shown in Fig. 9 and includes the ENSO events of 1951 and 1982. The large anomalous patterns in the winter(+) generally reflect low pressure over much of the western US and high pressure over eastern Canada. The low pressure in the North Pacific and high pressure over Canada are similar to the winter time circulation patterns seen in Fig. 6 and Fig. 8; however, the spatial extent of the low pressure area included western Canada and the Northwest US. In the Northwest, it is typical to have warm-dry conditions during most ENSO events; however, the circulation patterns in Fig. 9 suggest that the Northwest was cold-wet during the 1951 and 1982 ENSO events. Indeed, the 1982 ENSO event was followed by positive streamflow anomalies throughout the western US. It is noteworthy that the 1982 ENSO event was one of the
Fig. 8. Seven-hundred-mb (hPa) height anomalies (m) for the 1976, 1986, and 1991 ENSO events (PC2(+)). Height anomalies are given for the (a) summer (July–September) and (b) autumn (October–December) of the ENSO year (0) and the (c) winter (January–March) and (d) spring (April–June) of the year after the ENSO year (+). Regions are shaded where the anomalies are significantly different than zero at the 99% confidence level. The height anomalies are the deviation from the long-term mean.
largest on record and the widespread impacts are well documented. Therefore, the composite in Fig. 9 may be dominated by the 1982 ENSO event. A comparison of the 1952 winter 700-mb height anomalies with the 1983 winter 700-mb height anomalies (Fig. 10) clearly shows that the 1982 ENSO event is dominant in the overall composite for PC2(−) in Fig. 9.

7. Conclusions

This study has identified the spatial and temporal patterns in the western US streamflow in response to ENSO events. Using 52 years of streamflow data (1932–1993) from 79 stations, two applications of PCA were used for regionalizing stations and identifying the variability of the western US streamflow response to ENSO.

The S-mode rotated PCA identified eight homogeneous regions where at least 49% of the variance was explained at each station by one PC. The eight regions encircle the western US, but the central areas are relatively undefined. The absence of high PC loadings in the central region suggests that these streamflow stations are isolated from the homogeneous regions identified with the first eight PCs. This does not suggest that the ENSO response is weak at these stations. The response in the identified regions is corroborated with results from a group average linkage cluster analysis. Further analysis within the eight regions reveals that the strongest streamflow anomalies occur in the Northwest and Southwest. Within these two regions, it is encouraging, for forecasting purposes, that the streamflow anomalies occur after the onset of the ENSO event.

The temporal variability of streamflow was investigated with a T-mode unrotated PCA. The first three PCs explain more than 50% of the variance in western US streamflow in response to ENSO events. The most common response, the dominant mode, is seen in PC1(+), which includes the ENSO events of 1941, 1957, 1965, 1969, and 1972. An opposite response is seen in PC1(−), which includes the ENSO events of 1932 and 1953. These two ENSO events were also noted as being 'different' in a jackknife analysis of the streamflow data in the Northwest and Southwest.

The atmospheric circulation patterns associated with the different ENSO groups were evaluated with 700-mb height anomalies throughout the North Pacific and North America. The circulation patterns during the years identified in PC1(+) are representative of a PNA pattern with a strong southerly displaced jet stream and ridging over much of Canada. These anomalous circulation patterns were not present during the 1932 and 1953 ENSO events, when pressure was slightly above normal over much of the North Pacific and North America during the winter. The circulation patterns during the 1976, 1986, and 1991 ENSO events, PC2(+), are similar to those during PC1(+); however, the magnitude of the anomalies is much larger. Furthermore, all of the ENSO events in PC2(+) occurred after 1976 and the events in PC1(+) before 1976. This may reflect a shift in climate regimes that others have noted. Finally, the circulation patterns during 1951 and 1982, PC2(−), represent wet-cold conditions throughout much of the western US. This contrasts with the opposite responses seen in the north and south following typical ENSO events.

Understanding ENSO conditions may some day allow us to forecast streamflow levels far into the future for certain parts of the western US (e.g. Pacific Northwest); however, the
Fig. 9. Seven-hundred-mb (hPa) height anomalies (m) for the 1951 and 1982 ENSO events (PC2(-)). Height anomalies are given for the (a) summer (July–September) and (b) autumn (October–December) of the ENSO year (0) and the (c) winter (January–March) and (d) spring (April–June) of the year after the ENSO year (+). Regions are shaded where the anomalies are significantly different than zero at the 99% confidence level. The height anomalies are the deviation from the long-term mean.
varying responses seen to ENSO events require further evaluation. The work presented here identifies the different responses and the associated large scale circulation patterns. Future work on long range streamflow forecasting should incorporate the different ENSO responses and focus on those regions most influenced by ENSO. Given a sufficient length of record, evaluation of different ENSO indicators (e.g. SSTs (sea surface temperatures) SOI, outgoing long-wave radiation, zonal winds) may shed light on the occurrence of the different type of ENSO events and the corresponding changes in the large scale circulation in the extratropical regions.

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Fig. 10. Seven-hundred-mb (hPa) height anomalies (m) during the winters of (a) 1952, and (b) 1983. Regions are shaded where the anomalies are significantly different than zero at the 99% confidence level. The height anomalies are the deviation from the long-term mean.
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