

Primary Modes and Predictability of Year-to-Year Snowpack Variations in the Western United States from Teleconnections with Pacific Ocean Climate

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ABSTRACT

Snowpack, as measured on 1 April, is the primary source of warm-season streamflow for most of the western United States and thus represents an important source of water supply. An understanding of climate factors that influence the variability of this water supply and thus its predictability is important for water resource management. In this study, principal component analysis is used to identify the primary modes of 1 April snowpack variability in the western United States. Two components account for 61% of the total snowpack variability in the western United States. Relations between these modes of variability and indices of Pacific Ocean climate [e.g., the Pacific decadal oscillation (PDO) and Niño-3 sea surface temperatures (SSTs)] are examined. The first mode of snowpack variability is closely associated with the PDO, whereas the second mode varies in concert with both the PDO and Niño-3 SSTs. Because these atmospheric-oceanic conditions change slowly from season to season, the observed teleconnections between the Pacific Ocean climate and 1 April snowpack may be useful to forecast 1 April snowpack using data that describe the Pacific Ocean climate in the previous summer and autumn seasons, especially for the northwestern United States.

1. Introduction

In the western United States, snowpack is an important source of runoff and water supply. For example, between 50% and 70% of the annual precipitation in the mountainous regions of the western United States falls as snow and is stored in the snowpack through the winter season and into the spring and summer (Serreze et al. 1999). At many locations in the western United States, 1 April snowpack water contents provide estimates and forecasts of the eventual total annual runoff (Gray and Male 1981; McCabe 1996; Clark et al. 2001).

Relations between large-scale atmospheric circulation and snowpack accumulations in the western United States have been studied in several ways. Cayan (1996) performed a rotated principal component analysis (PCA) of snowpack water contents in the western United States identifying five regions characterized by internally correlated, interannual snowpack variations: the Pacific Northwest, the northern Rocky Mountains, the central Rocky Mountains, the southern Rocky Mountains, and the Sierra Nevada/Great Basin region. Cayan described the variability of snowpack in each of these

regions and related the variability to climate variations. He found that precipitation variations had the strongest influence on springtime snowpack water contents in all regions and that temperature had only a modest effect, except at low-altitude sites. Cayan also determined that anomalously low 1 April snowpacks in each of the regions were related to the Pacific-North American (PNA) circulation pattern (Barnston and Livezey 1987; Leathers et al. 1991)—that is, atmospheric patterns with anomalously strong Aleutian lows and anomalously high pressures over the western United States.

McCabe and Legates (1995) directly addressed relations between atmospheric circulation and the temporal and spatial distributions of 1 April snowpack in the western United States, showing that winter mean 700-hPa height anomalies are significantly related to the temporal and spatial variability of 1 April snowpack in the western United States. In general, above-average 1 April snowpack was found to occur with negative 700-hPa height anomalies over the eastern North Pacific Ocean and the western United States. These anomalies reflect anomalous cyclonic circulations that produce anomalous westerly flows of moist air from the eastern North Pacific Ocean into the western United States and increase winter precipitation and 1 April snowpack. Below-average 1 April snowpacks at most snowcourses

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are related to positive 700-hPa height anomalies over the western United States. The positive anomalies reflect anomalous anticyclonic circulations that prevent intrusion of moist air from the eastern North Pacific Ocean into the western United States, bring subsidence and greater atmospheric stability to the region, and thereby decrease winter precipitation. McCabe and Legates related five winter 700-hPa height anomaly patterns to spatial variability in 1 April snowpack.

Clark et al. (2001) examined the effects of the El Niño–Southern Oscillation (ENSO) phenomenon of the tropical Pacific Ocean on seasonal snowpack evolution in the Columbia and Colorado River basins. Clark et al. found significant effects of ENSO on seasonal snowpack evolution for various parts of these basins and used this information to predict annual runoff. The predictions exhibited only modest skill when based solely on the existence of El Niño or La Niña conditions. Indeed, at almost all sites, predictions based on antecedent snowpack accumulations were more reliable than those based on ENSO information alone. However, combining observations of midwinter snowpack conditions with ENSO indices improved predictions for those basins in which ENSO signals exhibit strong seasonality.

Beyond direct analyses of climatic influences on western snowpacks, other studies have examined relations between climate indices and surface climate of the western United States. Studies by Cayan and Peterson (1989), Redmond and Koch (1991), Kahya and Dracup (1993), and McCabe and Dettinger (1999), among many others, have described relations between surface hydroclimate of the western United States and climate indices such as the Southern Oscillation index (SOI) and tropical sea surface temperature (SST) indices of ENSO phenomena, as well as the Pacific decadal oscillation (PDO; Mantua et al. 1997). Cayan and Peterson (1989) examined the relations between atmospheric circulation and December–August streamflow totals at 30 stream-gauging stations in the western United States, identifying significant correlations between streamflow and winter-mean sea level pressures. They also showed that December–August streamflow in the western United States was significantly correlated with the winter mean SOI and PNA indices. Cayan and Peterson (1989), Redmond and Koch (1991), and Kahya and Dracup (1993) have all shown statistically significant correlations between ENSO indices and precipitation and streamflow in the western United States. As important, some of these studies have shown that antecedent ENSO conditions from the previous summer and autumn are related to winter hydroclimate in many areas. These results suggest the potential for forecasting hydroclimatic conditions of the western United States one to two seasons ahead of time.

The PDO recently has been identified as another important factor that influences the hydroclimate of the western United States (Mantua et al. 1997; Gershunov and Barnett 1998; Latif and Barnett 1998; McCabe and

Dettinger 1999). This interdecadal mode of the Pacific climate system may provide additional predictability for hydrologic and snowpack conditions if its connections to the regional hydroclimate and to ENSO can be understood. Particular attention has been paid to how ENSO and PDO interact (Gershunov and Barnett 1998; McCabe and Dettinger 1999) and modify the expected ENSO hydroclimatic influences in the western United States.

Previous studies have examined the separate effects of PDO and ENSO on winter precipitation in the western United States and have primarily focused on winter precipitation, not snowpack. Because snowpack represents the most significant water resource for many river basins in the western United States, snowpack is the focus of this study. In addition, this study offers new analyses of the relations between snowpack variability in the western United States and the long-term Pacific climate variations associated with ENSO and PDO, individually and combined. The objectives of this study are 1) to identify the largest-scale spatial modes of 1 April snowpack variability in the western United States, 2) to demonstrate that these modes are related to PDO and/or ENSO depending mostly on location of the snowcourses considered, and 3) to demonstrate that forecasts of 1 April snowpack based on atmospheric teleconnections between 1 April snowpack and PDO and/or ENSO exhibit useful skill in many parts of the western United States, even when using PDO and ENSO data from the previous summer and autumn seasons.

2. Methods

a. Snowpack data

The 1 April total snowpack water-equivalent depth (1 April snowpack) observations are used in this study to measure seasonal snowpack accumulations. At most snowcourse locations in the western United States, the snow water equivalent on the ground reaches its peak at about 1 April (McCabe 1996; Serreze et al. 1999; Bohr and Aguado 2001; Clark et al. 2001) and has been found to be highly correlated with annual streamflow in nearby rivers (McCabe 1996). In addition, snowpack is measured most frequently on or near 1 April (Cayan 1996; Clark et al. 2001). The 1 April snowpack is measured primarily by two programs: the U.S. Department of Agriculture (USDA) cooperative snow survey and the California Department of Water Resources. The USDA program is coordinated by the Natural Resources Conservation Service and includes snowcourses in Arizona, Colorado, Idaho, Montana, Nevada, New Mexico, Oregon, South Dakota, Utah, Washington, and Wyoming. The historical 1 April snowpack time series from these two programs were obtained from the Cooperative Institute for Research and Environmental Sciences at the University of Colorado (data obtained from M. Clark and M. Serreze). To examine the full range of temporal and spatial variability in 1 April snowpack, it was de-

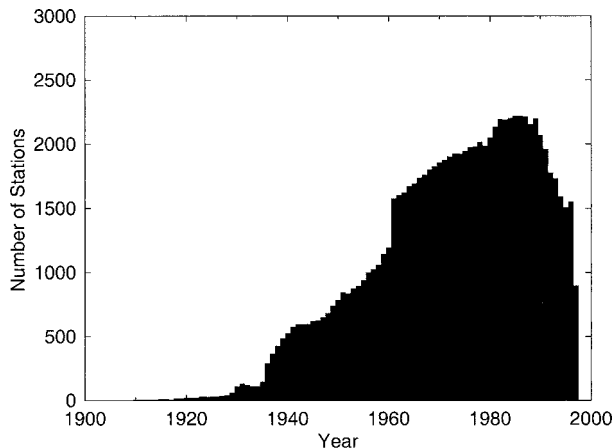


FIG. 1. Number of snowcourses in the western United States by year, 1900–99.

sirable to have a relatively long record of 1 April snowpack data and a relatively large number of observation sites. The number of sites with available 1 April snowpack observations has increased from the early 1900s to a maximum during the 1980s (Fig. 1). Since the 1980s, the number of sites has decreased as the number of snowpack telemetry sites has increased (Serreze et al. 1999; Clark et al. 2001). A set of snowcourses with complete records for as long of a period of record as possible was desired for this analysis. This meant that hundreds of snowcourses could be used for short periods of record or much fewer snowcourses could be used for longer periods of record. It was decided that a 50-yr period of record would provide a long enough period for analysis to examine reliably the variability in snowpack. The snowpack dataset was then searched for the 50-yr period of record with the largest number of snowcourses with complete records. Based on an examination of the dataset, all snowcourses with complete records for the 1941–90 period were used, defining a set of 323 sites for analysis (Fig. 2).

b. Atmospheric pressure and sea surface temperatures

The PDO and Niño-3 indices of Pacific Ocean SSTs have been identified as significant interannual-to-interdecadal driving forces of atmospheric circulation over the western United States (Mantua et al. 1997; McCabe and Dettinger 1999; Clark et al. 2001). Time series of these indices are compared with time series of 1 April snowpack observations in this study. The PDO is an index of SSTs in the North Pacific Ocean, defined by the first component from a PCA of monthly SSTs in the North Pacific Ocean north of 20°N (Mantua et al. 1997). The Niño-3 index is the regional average of SSTs between 5°S and 5°N latitude and between 90° and 150°W longitude. The Niño-3 index reflects the oceanic progress of ENSO. When Niño-3 anomalies are positive,

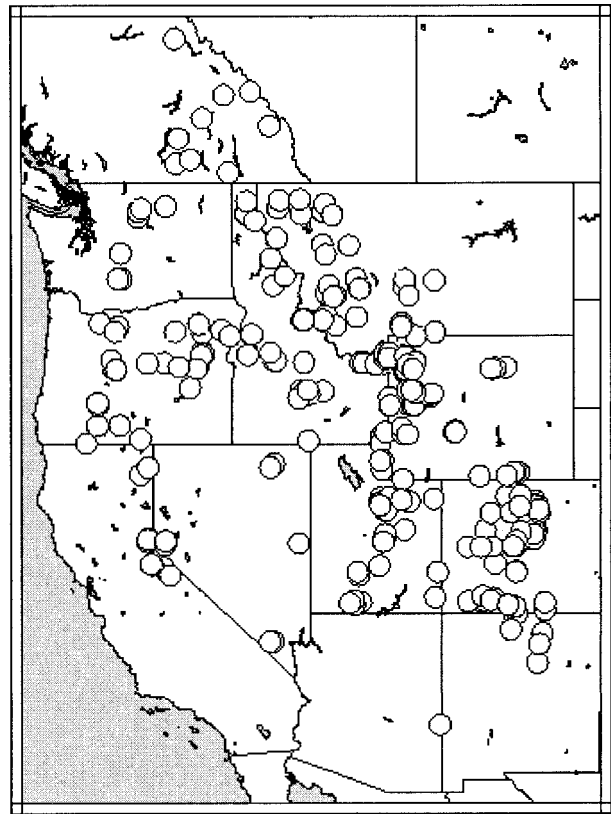


FIG. 2. Snowcourses in the western United States used in this analysis.

El Niño conditions exist, and when Niño-3 anomalies are negative, La Niña conditions exist.

To elucidate the atmospheric connections between 1 April snowpack and PDO and Niño-3, winter-mean (November–March) 700-hPa height anomalies were compared with each. The 700-hPa level was chosen because this atmospheric level provides a good representation of midtropospheric atmospheric circulation above many of the complex, local influences at the earth's surface (Dettinger and Cayan 1992). Several studies have indicated that the 700-hPa level is useful in identifying relations between atmospheric circulation and precipitation (Stidd 1954; Klein 1963; Klein and Bloom 1987; Knox and Lawford 1990; Cayan et al. 1991; McCabe 1994; McCabe and Legates 1995). Monthly 700-hPa height anomalies were derived from gridded daily 700-hPa height series pressure data produced by the National Oceanic and Atmospheric Administration's Climate Analysis Center and were obtained from D. Cayan, Scripps Institution of Oceanography. Winter-mean 700-hPa height anomalies averaged over November–March were chosen for comparison with the 1 April snowpack because it is during these months that the majority of snowpacks in the western United States develops (McCabe 1994; McCabe and Legates 1995).

The atmospheric origins of the snowpack variations

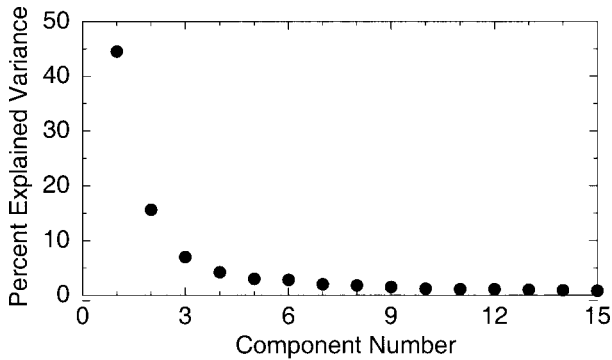


FIG. 3. Percent of explained variance by the first 15 components from a principal component analysis of 1 Apr snowpack data for 323 snowcourses in the western United States for 1941–90.

are explored further by considering the amount of high-frequency variation at midtroposphere as a measure of how storminess varies with ENSO and PDO. The storminess index used here is the same one investigated by Bitz and Battisti (1999) and Dettinger et al. (2000a) and is a November–March average of the monthly standard deviations of the daily high-frequency (2–8 day) variance of 500-hPa height anomalies. The high-frequency pressure variations registered by this measure correspond to increases and decreases in weather variations associated mostly with the passage of storms. Thus a comparison of these storminess measures with the Pacific climate variations will highlight changes in the average locations of storm tracks during the various phases of ENSO and PDO.

c. Data analysis

Principal component analysis is often used 1) to identify groups of intercorrelated variables, 2) to reduce the number of variables being analyzed, and 3) to rewrite a dataset into an alternative form (Johnston 1980). The 1 April snowpack series were subjected to a PCA to identify the primary modes of snowpack variability. The loadings of the principal components were mapped and examined to identify regions of covariant snowpack. Then, to identify relations between snowpack variability and climatic forces, the time series of the component scores were correlated with the PDO and Niño-3 indices. The component-score time series also were correlated with fields of winter 700-hPa height anomalies. The correlations between the component scores and gridded winter 700-hPa height anomalies identify atmospheric-circulation anomaly patterns associated with positive snowpack anomalies in the broad regions weighted by the components (Stidd 1954; Klein 1963; McCabe 1996).

3. Snowpack variability and teleconnections

Based on an analysis of the variance explained by each component resulting from the PCA of the snow-

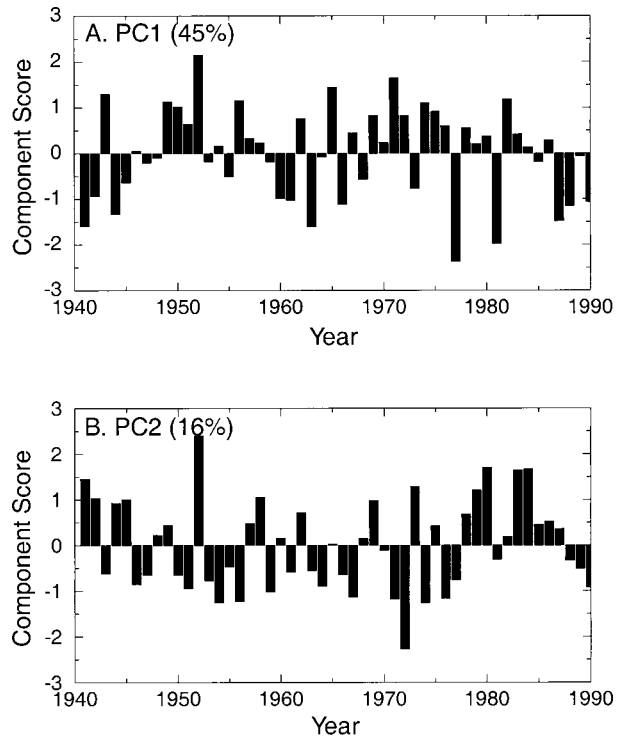


FIG. 4. Time series of component scores for the first two components (PC1 and PC2) from a principal component analysis of 1 Apr snowpack data for 323 snowcourses in the western United States for 1941–90.

pack series, two leading components were retained for detailed analysis (Fig. 3). The two components combine to explain 61% of the total variance in the snowpack dataset, with the first component (PC1) explaining 45% and the second component (PC2) explaining 16% of the total variance (Fig. 4).

The loadings of PC1 on the raw 1 April snowpack data are all positive and statistically significant (at a 95% confidence level) for most of the 323 sites analyzed (Fig. 5a). This result indicates that about one-half of the variability of 1 April snowpack in the western United States takes the form of covariation. Sites in the extreme southern part of the network tend to have small, non-significant loadings for this PC, reflecting the strong tendency for winter precipitation in the southwest to vary in opposition (contrast) to precipitation anomalies in the northwest, in response to ENSO and PDO climate variations (Redmond and Koch 1991; McCabe and Dettinger 1999). This tendency for contrasts of precipitation between the northern and southern regions of the western United States limits the extent to which these southern sites vary (significantly) along with the rest of the network and thus limits their contributions to PC1.

The loadings of PC2 form a pattern of statistically significant positive loadings in the southwestern United States and statistically significant negative loadings in the northwestern United States (Fig. 5b). This loading pattern is similar to the ENSO signal found in seasonal

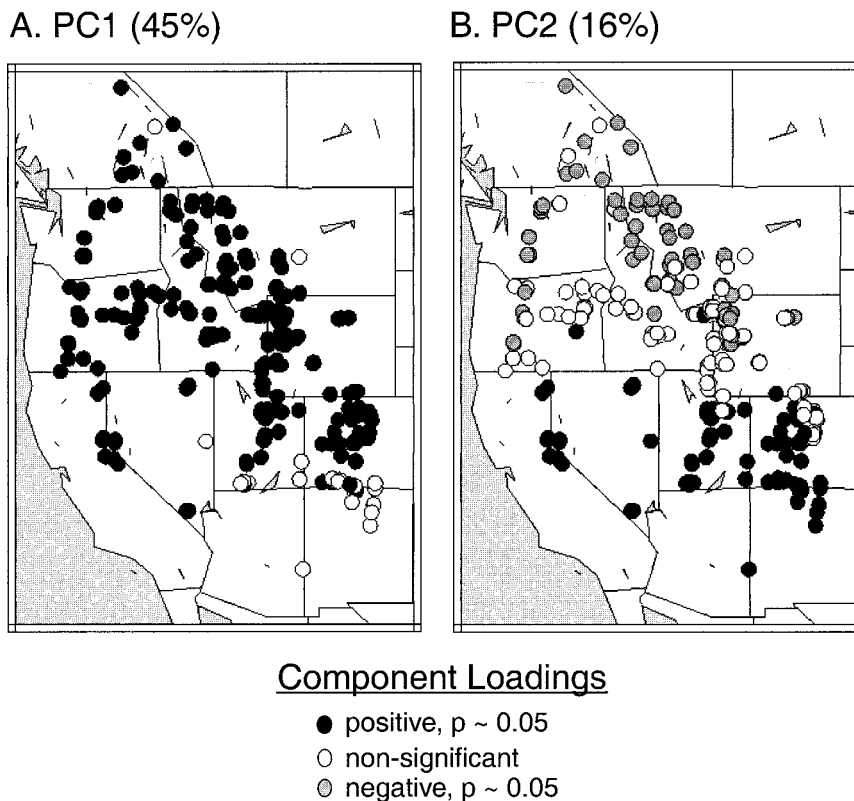


FIG. 5. Loadings of 1 Apr snowpack for 323 snowcourses in the western United States on the first two principal components (PC1 and PC2) from a principal component analysis of the 1 Apr snowpack data for 1941–90. Black-shaded circles indicate statistically significant (at a 95% confidence level) positive loadings, gray-shaded circles indicate statistically significant negative loadings, and nonshaded circles indicate nonstatistically significant loadings.

precipitation anomalies in the western United States (Redmond and Koch 1991; McCabe and Dettinger 1999).

The PC1 time series (Fig. 4a) is characterized by considerable year-to-year variability, with a notable shift from negative values to predominantly positive values early in the period of record (around 1950); PC2 (Fig. 4b) also exhibits considerable year-to-year variability but is most notable for its many negative values through most of the series until 1977 when a switch to positive values occurred. Comparisons between the scores of PC1 and PC2 and winter (November–March) PDO and Niño-3 indicate that PC1 is most closely related to PDO (Fig. 6a), whereas PC2 is equally correlated with PDO and Niño-3 (Figs. 6b,d). This result is interesting in that many previous studies have focused on ENSO indices (e.g., Niño-3 or the SOI) as the primary large-scale driving force for the hydroclimate of the western United States (Redmond and Koch 1991). Our results show that, for 1 April snowpack variability, PDO accounts for a greater part of the variability than does ENSO. The fact that PC2 is equally correlated with Niño-3 and PDO is not surprising, given that PDO and Niño-3 are significantly correlated (correlation coefficient $r = 0.47$). What may be surprising is that PC1, although well correlated with PDO, does not show the charac-

teristic regime shift in 1976–77 (Ebbesmeyer et al. 1991) that is so characteristic of the PDO's interdecadal variation. Something else, perhaps more interannual in character, in PDO is correlating with the PC1 time series.

A frequency-domain analysis of the correlations between the snow PCs and PDO indicates that the PCs differ (especially in their relations with PDO) within interannual frequency bands and show similar low-frequency (decadal to interdecadal) dependencies on PDO. PDO has a strong interdecadal signal and thus is, for practical purposes, nonstationary over the study period (because only one decadal-scale oscillation can be seen over the time period examined). However, PDO is not treated solely as a decadal process in this study. Much of the strength of PDO as a predictor comes not from its decadal character but rather from the fact that it measures North Pacific climate directly, whereas ENSO is a distant and somewhat unreliable—albeit, important—forcing on North Pacific climate. Because North Pacific climate is more immediately related to the winter climate of the western United States than is tropical ENSO, knowing the state of North Pacific climate in any given year ultimately improves predictions of western U.S. winter climate. Thus, the full range of PDO frequencies is used in this study, including interannual

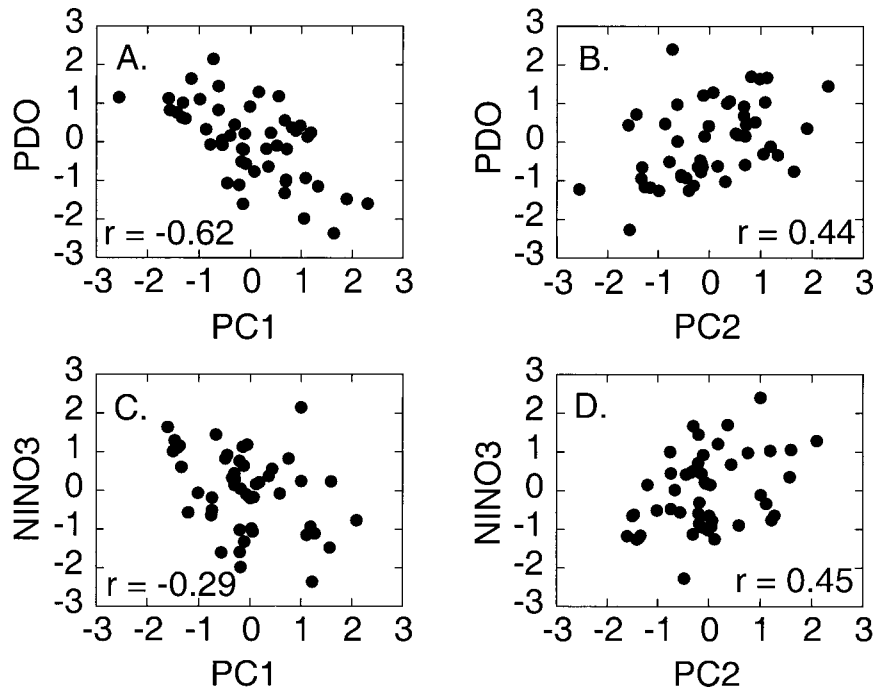


FIG. 6. Comparisons of the first two components (PC1 and PC2) from a principal component analysis of 1 Apr snowpack data for 323 snowcourses in the western United States for 1941–90, with (a) (b) winter (Nov–Mar)-mean Pacific decadal oscillation and (c) (d) winter Niño-3 sea surface temperatures.

and interdecadal modes. The correlations between PDO and the high-frequency (interannual) and low-frequency (decadal and interdecadal) components of PC1 are nearly equal (not shown), so that the connection between PC1 and PDO is not strictly dependent on the nonstationary aspects of PDO over the study period. PC2 follows PDO and ENSO about equally but on different temporal scales; PC2 is correlated with PDO at decadal timescales and with Niño-3 at interannual timescales. Thus PC2's relation to PDO may be compromised by the nonstationarity of PDO, and the finding of equal contributions to PC2 from PDO and ENSO may have to be tempered by this realization.

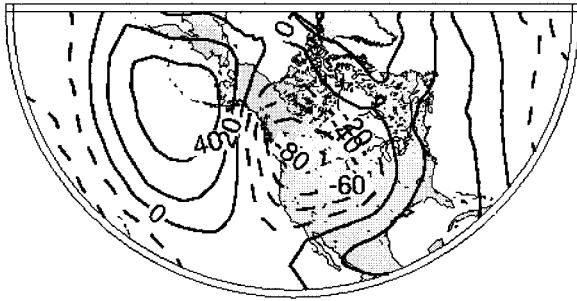
To investigate the atmospheric connections between the Pacific climate indices and the snowpack PCs and to document further the correspondence between Pacific climate modes and the two snowpack PCs, correlations between each of these variables and fields of atmospheric pressure were examined. It is presumed that if PC1 represents important effects of PDO on 1 April snowpack, then these two variables should be associated with similar atmospheric pressure anomalies. The atmospheric signatures of each of the variables were identified by correlating the individual variables with gridded winter 700-hPa height anomalies. The resulting correlation fields map the temporal correlations for each grid point. In such fields, lines of equal correlation are analogous to lines of equal 700-hPa heights associated with positive 1 April snowpack PCs or with positive

Pacific climate indices (Stidd 1954; Klein 1963; McCabe 1996).

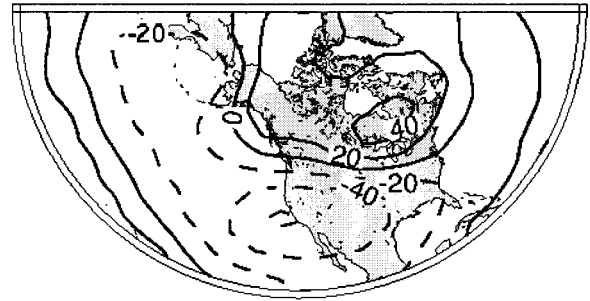
Correlations between the snowpack PC1 series and winter 700-hPa heights are positive over a large part of the North Pacific Ocean, with a center near the Aleutian Islands, and are negative over western Canada. Positive correlations also are present over the southeastern United States (Fig. 7a). This pattern forms the negative of a PNA pattern (Barnston and Livezey 1987). The correlations indicate that, for positive snowpack anomalies in the broad PC1 pattern, anomalously high atmospheric pressures occur over the North Pacific, anomalously low pressures occur over western Canada, and positive pressure anomalies occur over the southeastern United States. The locations of these atmospheric-pressure anomalies represent a weakening of the Aleutian low and the ridge of high pressure that, on average, develop over the North Pacific and western United States, respectively, during winter months. The weakening of these pressure systems directs anomalously zonal flows from the North Pacific Ocean into the western United States, increasing the transport of atmospheric moisture and winter precipitation there.

Correlations between winter $\text{PDO} \times -1$ and 700-hPa heights form a pattern (Fig. 7c) that is very similar to the correlation pattern produced using PC1 scores (because PDO is negatively correlated with PC1, PDO was multiplied by -1 for easy comparison with PC1). The similarity in the correlation fields reflects shared atmo-

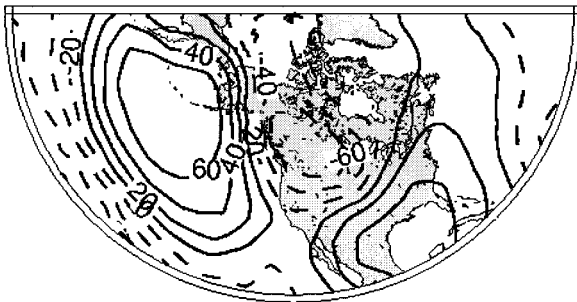
A. Snow PC1



B. Snow PC2



C. PDOx-1



D. NINO3

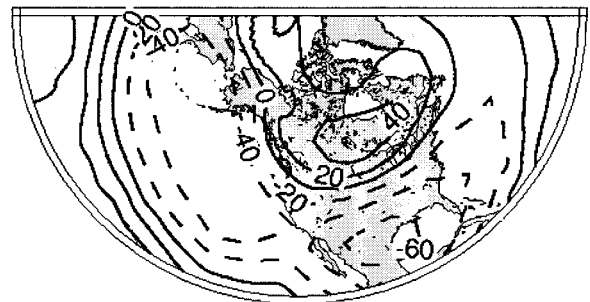


FIG. 7. Correlations (multiplied by 100) between winter (Nov–Mar) 700-hPa heights and component scores from the (a) first (Snow PC1) and (b) second (Snow PC2) principal components from a principal component analysis of 1 Apr snowpack data for 323 snowcourses in the western United States for 1941–90, (c) winter PDO multiplied by -1 , and (d) winter Niño-3 sea surface temperatures. PDO was multiplied by -1 for comparison with the other time series analyzed. The solid isolines indicate positive correlations, and the dashed isolines indicate negative correlations. The contour interval is 20, and the first solid isoline is the zero correlation line.

spheric signatures and suggests a physical link between the two. The PDO corresponds to changes in atmospheric circulations that are translated into snowpack anomalies in the western United States. Furthermore, correlations between winter PDO and 500-hPa storminess (Fig. 8a) indicate that, when the PDO is positive, storm tracks are reduced along the west coast of North America from Alaska to at least as far south as California. Positive PDO is also associated with enhanced storminess in the central North Pacific. These correlations with storminess are consistent with the negative of the atmospheric pressure pattern illustrated in Fig. 7c.

The correlations between the component scores for snowpack PC2 and 700-hPa heights are negative from the North Pacific Ocean across the southern United States to the North Atlantic Ocean and are positive over Canada (Fig. 7b). These atmospheric pressure anomalies indicate that, in years when PC2 is positive, low pressure systems have been displaced to the south such that they track across the southern United States more frequently than under normal conditions. The southward displacement of low pressure systems results in above-average winter precipitation across the southwestern United States and below-average precipitation in the northwestern United States. This pattern of precipitation anomalies is commonly associated with a warm ENSO

condition (e.g., Redmond and Koch 1991). Correlations between winter Niño-3 and winter 700-hPa heights form a pattern (Fig. 7d) that is similar to that produced by the correlations of PC2 with winter 700-hPa heights (Fig. 7b). In a qualitative sense, the correlation pattern for PC2 is more similar to that produced using Niño-3 than the pattern produced using PDO. This result suggests that PC2 may be more indicative of ENSO effects than of PDO effects on snowpack. However, there are some notable differences between the correlation patterns for PC2 and Niño-3. For example, the correlations between 700-hPa heights and Niño-3 are stronger than those for PC2, and the centers of the 700-hPa pressure anomalies represented by the correlations for PC2 are offset from those for Niño-3. The offset for these patterns is greater than the differences in the correlation patterns generated using PC1 and PDO.

The changes in storm tracks associated with PDO and ENSO, inferred from Fig. 7, can be delineated further by using a direct measure of the rapid (on synoptic timescales) pressure changes that accompany stormy weather and storm tracks. One such measure is the 500-hPa storminess index used by Bitz and Battisti (1999) and Dettinger et al. (2000a). Correlations between Niño-3 and 500-hPa storminess (Fig. 8b) are broadly similar to the correlations of storminess with PDO (Bitz and

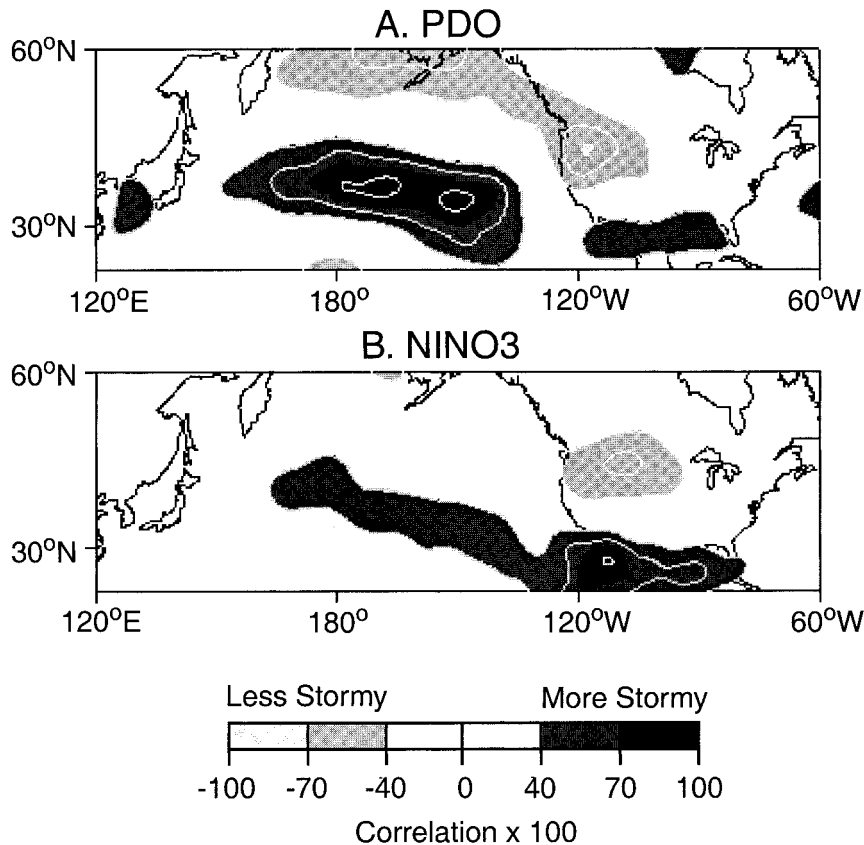


FIG. 8. Correlations (multiplied by 100) between Nov–Mar midtropospheric storminess (500-hPa atmospheric pressure level) and the corresponding (a) PDO and (b) Niño-3 SSTs, 1949–90; storminess is defined here as the anomalous monthly standard deviation of 2–8-day bandpass-filtered daily 500-hPa heights from the National Center for Atmospheric Research–National Centers for Environmental Prediction reanalysis (Kalnay et al. 1996); see Bitz and Battisti (1999) and Dettinger et al. (2000) for a description of this storminess measure. The first contour is 40, and the contour interval is 20. Contours that are significantly different from zero at a 99% confidence level are shaded (the shading interval is 30).

Battisti 1999; Dettinger et al. 2000a) but with locally important differences. Note that storm tracks during positive Niño-3 winters are displaced more or less directly southward over North America, whereas the storm-track displacements associated with PDO are more onshore to offshore in orientation. Furthermore, the PDO storm-track displacements (as mapped by the less-stormy correlation contours in Fig. 8a) extend farther south than do the corresponding displacements in the Niño-3 correlations. These subtle storminess differences help to explain the association of snowpack PC1 with PDO, whereas the broad similarities help to explain the association of PC2 with both PDO and Niño-3 simultaneously.

For consistency with Fig. 7, variations of storminess (defined as in Fig. 8) at the 700-hPa level with PDO and Niño-3 also were analyzed. Resulting correlation patterns (not shown here) are similar to those obtained from the 500-hPa storminess values shown in Fig. 8.

4. Potential for seasonal forecasts

Significant correlations between the snowpack PCs (i.e., PC1 and PC2) and the Pacific climate indices (i.e., PDO and Niño-3) indicate that a large fraction of the variability of 1 April snowpack in the western United States mirrors interannual and interdecadal variations of indices of Pacific Ocean climate. These correlations, together with the fact that these SST-based indices evolve slowly, suggest that the current state of Pacific climate may provide a basis for forecasting 1 April snowpack several seasons in advance. Following this concept, Dettinger et al. (1999, 2000b) have been using PDO and ENSO information to make forecasts of seasonal streamflow probabilities across the conterminous United States.

As a first step to quantifying the relations between 1 April snowpack and the concurrent climate indices, linear correlations between 1 April snowpack at each of the 323 snowcourses and PDO and Niño-3 were com-

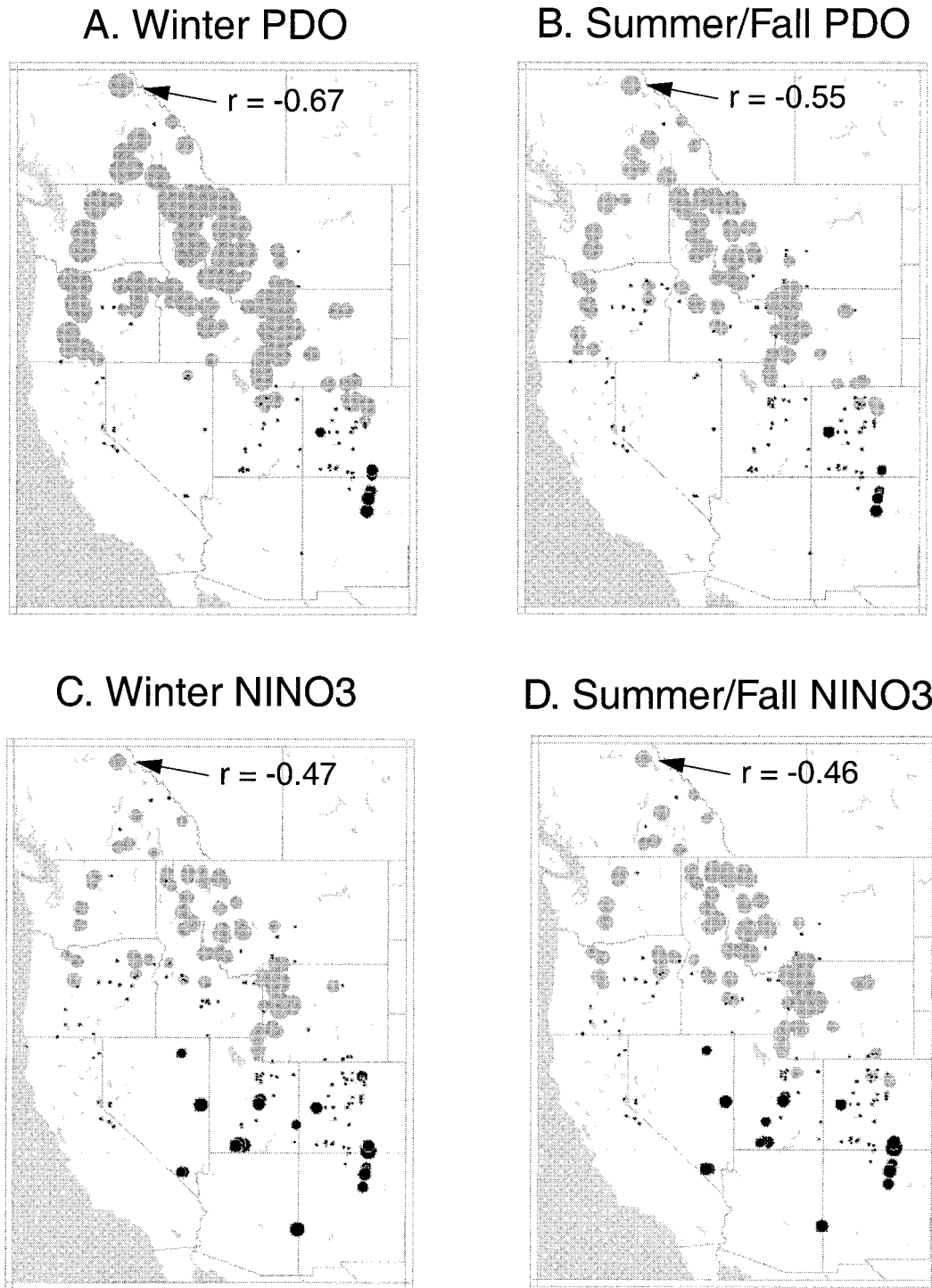


FIG. 9. Correlations between 1 Apr snowpack at 323 stations in the western United States and (a) winter (Nov–Mar) PDO, (b) summer/autumn (Jun–Nov) PDO, (c) winter Niño-3 sea surface temperatures, and (d) summer/autumn Niño-3. Significant (at a 95% confidence level) positive correlations are shaded black, significant negative correlations are shaded gray, and nonsignificant correlations are indicated by small black dots. The size of the symbols indicates the magnitude of the correlations (the value of a significant correlation is indicated for scale).

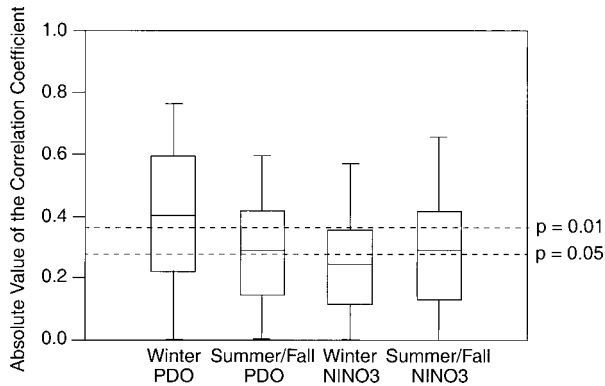


FIG. 10. Absolute values of correlations between 1 Apr snowpack at 323 stations in the western United States and winter (Nov–Mar) and summer/autumn (Jun–Nov) values of the PDO and Niño-3 sea surface temperatures.

puted (Fig. 9). Correlations between 1 April snowpack and PDO and Niño-3 are positive for a few sites in the southwestern United States and negative for numerous sites in the northwestern United States. Correlations between 1 April snowpack and winter PDO are generally more significant than are the correlations with winter Niño-3 (Figs. 9 and 10), consistent with the PCA analysis in the previous section. The correlations between 1 April snowpack and summer/autumn PDO are less significant than those for winter PDO for many sites and are about the same as the correlations with summer/autumn Niño-3 (Fig. 10). In contrast, the summer/autumn correlations for Niño-3 are more significant than those for winter Niño-3 for many sites (Fig. 10). These correlations indicate significant predictive relations between 1 April snowpack and antecedent seasonal values of the Pacific climate indices.

Redmond and Koch (1991) and McCabe and Dettlinger (1999) have shown statistically significant relations between antecedent summer/autumn ENSO and PDO conditions and winter precipitation in the western United States. To examine the predictability of 1 April snowpack using summer/autumn PDO and Niño-3, regressions were performed with 1 April snowpack as the dependent variable and summer/autumn PDO and/or Niño-3 as independent variables. For robustness, the regressions were performed in two steps: 1) regressions were performed to determine the linear relationships between 1 April snowpack at each of the 323 sites and PDO and/or Niño-3 using data for the even-numbered years (one-half of the dataset, 25 yr), and 2) the regression equations computed in step 1 were then used to estimate 1 April snowpack at each site using the data for odd-numbered years. The coefficients of determination r^2 resulting from step 2 were examined to determine 1) whether the amount of variance explained by these indices was statistically significant and 2) which index, or combination of indices, explained the greatest amount of variance in 1 April snowpack for each snowcourse.

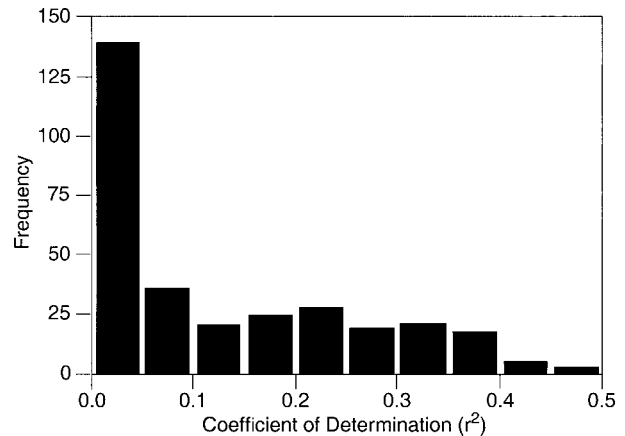


FIG. 11. Histogram of the coefficients of determination r^2 for the regressions of 1 Apr snowpack using summer/autumn (Jun–Nov) values of the PDO and/or Niño-3 sea surface temperatures.

The regression analyses indicate that a statistically significant (at a 95% confidence level) fraction of the variance in 1 April snowpack is explained by the contemporaneous state of one or both of the climate indices at 120 (37%) of the 323 snowcourse stations (Table 1). However, for many sites the fraction of variance explained is not large (Fig. 11). As a first approximation of the “best” predictor of 1 April snowpack for each of the stations, the r^2 resulting from the regressions with PDO, with Niño-3, and with PDO and Niño-3 were compared. The best predictor was identified from the following criteria: 1) the regression r^2 had to be statistically significant at a 95% confidence level, and 2) the regression r^2 had to be at least 0.05 greater than other regression r^2 values that were statistically significant. This analysis indicated that PDO is the best predictor of 1 April snowpack for 79 (24%) of the 323 snowcourses (Table 1 and Fig. 12). PDO and Niño-3 together were the best predictor for 25 (8%) of the 323 snowcourses, and Niño-3 alone was the best predictor for only 16 (5%) of the snowcourses analyzed.

The error in these forecasts also was computed (Fig. 13). For 53 (16%) of the snowcourses, the percent errors are less than 25%; for 101 (31%) of the snowcourses, the percent error is less than 35%. The snowcourses with statistically significantly forecast relations and with the lowest errors are located mostly in the northwestern United States. PDO and/or Niño-3 are not significant (linear) predictors of 1 April snowpack for most of the

TABLE 1. Number of snowcourses modeled best by summer/autumn (Jun–Nov) PDO, Niño-3 SST, PDO and Niño-3 together, or no best model.

Predictor	No. of snowcourses
PDO	79 (24%)
Niño-3	16 (5%)
PDO and Niño-3	25 (8%)
No significant predictor	203 (63%)

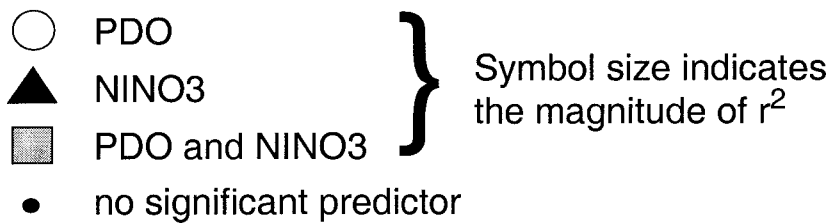
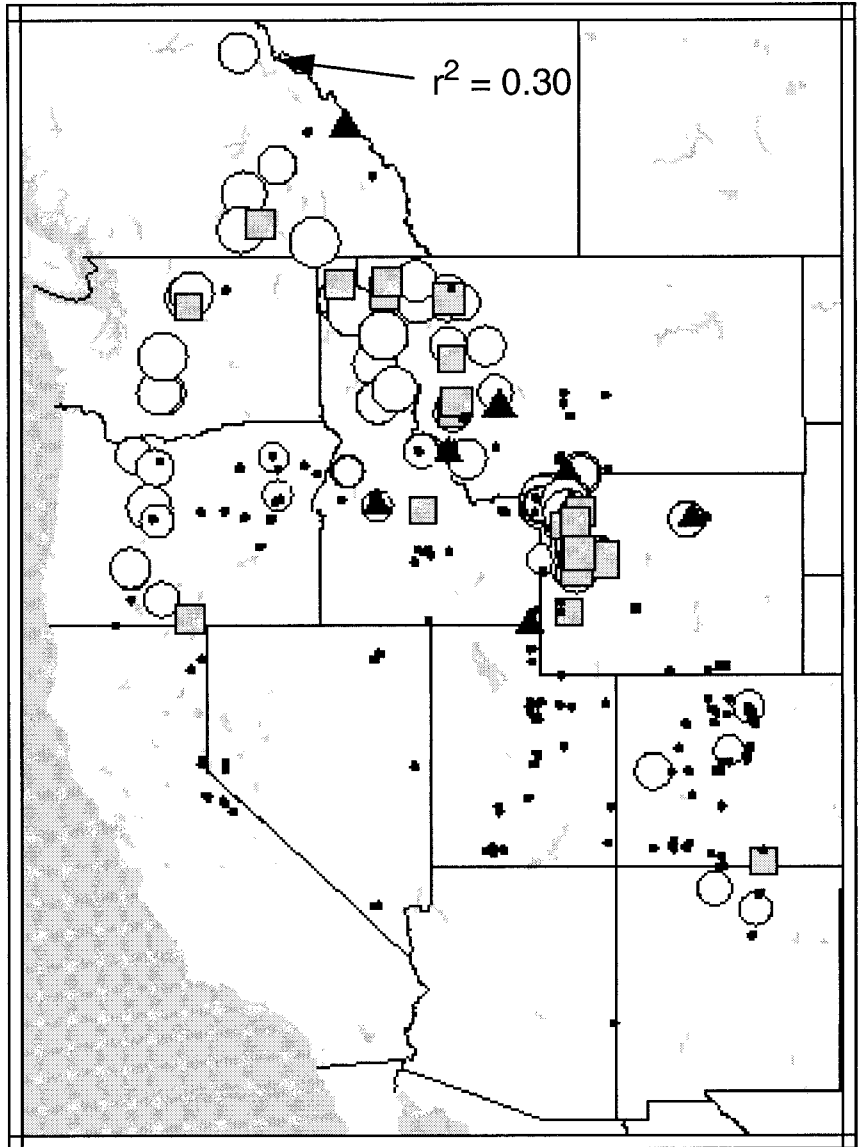


FIG. 12. Most significant (at a 95% confidence level) summer/autumn (Jun–Nov) predictor of 1 Apr snowpack (i.e., PDO and Niño-3 SST). The significance of the predictors was determined from the r^2 resulting from regressions of 1 Apr snowpack with summer/autumn PDO and/or Niño-3. The size of the symbols indicates the magnitude of the r^2 values (the value of a significant r^2 is indicated for scale).

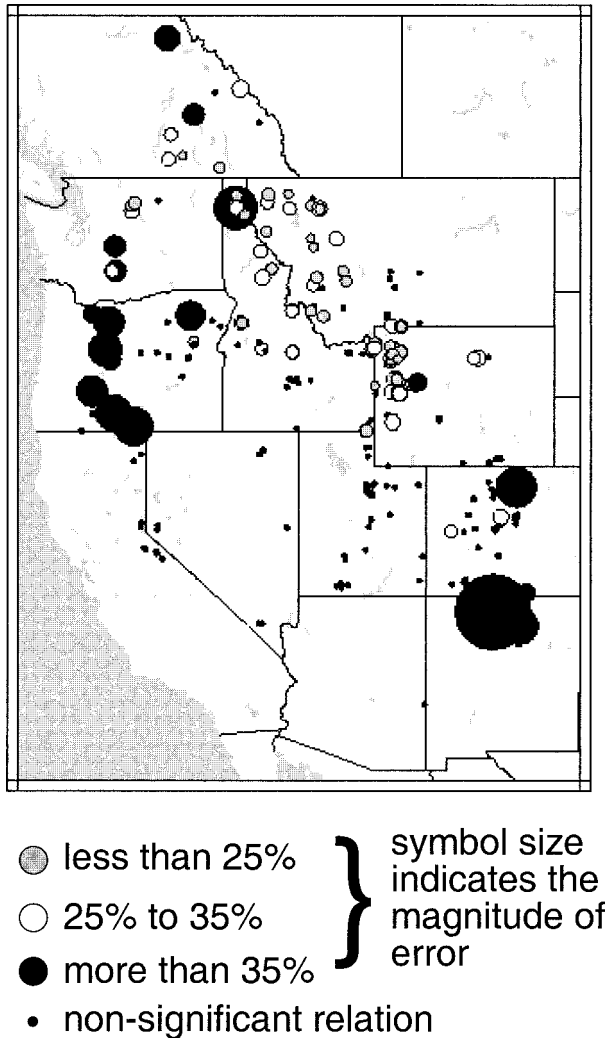


FIG. 13. Percent error in forecasts of 1 Apr snowpack. Error is expressed as the root-mean-square error divided by the observed mean 1 Apr snowpack multiplied by 100.

snowcourses in the southwestern United States (Fig. 12). Of the stations with statistically significant predictive relations, PDO and/or Niño-3 predict readily useful fractions of 1 April snowpack variations (e.g., more than 25% of variance) for about 70 (22%) stations. These stations are exclusively in the northwestern United States and southwestern Canada.

5. Conclusions

The majority of the year-to-year variations (over 61%) of 1 April snowpack in the western United States can be explained by two principal components. The first component explains 45% of the total variability in 1 April snowpack and is highly correlated with PDO. The second component explains 16% of the variability in 1 April snowpack and is correlated with Niño-3 SSTs. These results indicate that PDO, not ENSO, is the pri-

mary driving force of variability in 1 April snowpack in the western United States. Thus, methodologies for forecasting 1 April snowpack variations should include PDO, not just ENSO, variability. Because these atmospheric and oceanic conditions change slowly from season to season, the observed teleconnections between the Pacific Ocean climate and 1 April snowpack may be useful to forecast 1 April snowpack using data that describe the Pacific Ocean climate in the previous summer and autumn seasons, especially in the northwestern United States.

The linkages between PDO and snowpack conditions of the western United States reflect changes in winter storms and precipitation regimes that have historically been associated with year-to-year variations in the North Pacific climate. PDO also is associated with temperature variations over western North America (Dettinger et al. 2000a) that may contribute to year-to-year snowpack differences.

Snowpack variations in the western United States have a strong interannual and a modest interdecadal character (Fig. 4). The ability of the linear methods employed here to predict snowpack variations using PDO therefore have been contingent upon use of seasonal PDO values without any prior filtering to emphasize the interdecadal character of that index. Indeed, in this unfiltered form, PDO reflects important ENSO episodes along with the slower decadal character of the North Pacific climate. This PDO arguably is as much a measure of how the various individual ENSO episodes played out in the North Pacific and, by extension, over North America as it is a measure of interdecadal processes in the extratropical Pacific. Given the greater proximity of the North Pacific PDO index to western North America and its tendency to reflect the strongest ENSO variations, it should be no surprise that it most often outperforms the ENSO indices when predicting snowpack in the western United States.

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