JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION
AUGUST AMERICAN WATER RESOURCES ASSOCIATION 2004

VARIATION IN THE RELATIONSHIP BETWEEN SNOWMELT RUNOFF IN OREGON AND ENSO AND PDO[1]

Robin A. Beebee and Michael Manga[2]

ABSTRACT: The value of using climate indices such as ENSO or PDO in water resources predictions is dependent on understanding the local relationship between these indices and streamflow over time. This study identifies long term seasonal and spatial variations in the strength of El Niño Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) correlations with timing and magnitude of discharge in snowmelt streams in Oregon. ENSO is best correlated with variability in annual discharge, and PDO is best correlated with spring snowmelt timing and magnitude and timing of annual floods. Streams in the Cascades and Wallowa mountains show the strongest correlations, while the southernmost stream is not correlated with ENSO or PDO. ENSO correlations are weaker from 1920 to 1950 and vary significantly depending on whether Southern Oscillation Index (SOI) or Niño 3.4 is used. PDO correlations are strong from 1920 to 1950 and weak or insignificant other years. Although there are not consistent increasing or decreasing trends in annual discharge or spring snowmelt timing, there are significant increases in fractional winter runoff that are independent of precipitation, PDO, or ENSO and may indicate monotonic winter warming.

(KEY TERMS: surface water hydrology; snowmelt runoff; climate change; El Niño/Southern Oscillation; Pacific Decadal Oscillation; Oregon.)

Beebee, Robin A. and Michael Manga, 2004. Variation in the Relationship Between Snowmelt Runoff in Oregon and ENSO and PDO. Journal of the American Water Resources Association (JAWRA) 40(4):1011-1024.

INTRODUCTION

Interannual and interdecadal climate variability associated with ENSO and PDO have had significant and related effects on water resources in Oregon and other parts of the Pacific Northwest region of the United States (Barnett *et al.,* 1999; Miles *et al.,* 2000; Taylor and Hannan, 1999). The overall variability in annual water supply correlated with these climate signals is shown by this and other studies to be relatively low (5 to 20 percent) (Dai and Wigley, 2000; Miles *et al.,* 2000). However, surface water is often managed with even smaller margins of error. Hydropower demands compete with flood control, irrigation, industrial and residential water, and wildlife protection flow requirements.

Streams east of the Cascade Mountains (including most of those feeding the Columbia River) are fed primarily by snow that accumulates at high elevation during the fall and winter wet season and melts in the spring and summer. Little precipitation falls during July through September when demand is highest, thus both natural snowpack and reservoir storage are required to maintain surface water supplies (Service, 2004). At the same time, reservoirs must retain enough space throughout the winter and spring to control flood hazards. Thus the timing of snowmelt runoff and floods, modulated by winter and spring temperatures, is as important as the total volume.

Recently, government bodies such as the Natural Resources Conservation Service, Army Corps of Engineers, and local utilities have used ENSO based streamflow predictions to mitigate successfully against floods and droughts (Garen, 1993; Wernstedt and Hersh, 2002). There is other compelling evidence that including the state of ENSO and PDO would result in improved runoff predictions and thus drought and flood mitigation in the Pacific Northwest and elsewhere (Hamlet and Lettenmaier, 1999b; Clark *et al.,* 2001; Jain and Lall, 2001). Despite a wealth of regional studies, relationships between

[1]Paper No. 02099 of the *Journal of the American Water Resources Association* (JAWRA) (Copyright © 2004). **Discussions are open until February 1, 2005.**
[2]Respectively, Hydrologist, U.S. Forest Service, 204 Siginaka Way, Sitka, Alaska 99835; and Associate Professor, Department of Earth and Planetary Science, University of California-Berkeley, Berkeley, California 94720-4767 (E-Mail/Beebee: rbeebee@fs.fed.us).

ENSO and PDO and surface water supply are characterized by temporal and spatial variations that cannot be adequately evaluated without long streamflow and climate records (Wernstedt and Hersh, 2002). This paper describes evidence of both temporal and spatial variations in ENSO and PDO correlations for several physically similar snowmelt dominated drainages in central and eastern Oregon with long discharge records.

OBJECTIVES

The goals of this study are to evaluate long term relationships between the magnitude and timing of runoff in selected snowmelt-dominated basins and large scale circulation indices and to identify trends that cannot be explained by ENSO or PDO and that may relate to regional warming. The following relationships are investigated for each site: (1) correlations between ENSO and PDO indices and annual average streamflow, timing of peak snowmelt, seasonal flow fractions, and magnitude of annual peak floods; and (2) long term trends in annual average flow, snowmelt timing, seasonal flow fractions, and annual peak floods.

Studies of the hydrologic effects of climate variability in the western United States have generally involved spatial averages over several climatic and topographic regions, either through gridding data from many streams of variable drainage size and elevation (e.g., Redmond and Koch, 1991; Cayan *et al.,* 1999; McCabe and Dettinger, 1999, 2002) or using the mainstem of one large system such as the Columbia River (Hamlet and Lettenmaier, 1999a,b; Miles *et al.,* 2000; Clark *et al.,* 2001). Both of these approaches tend to mask the degree of local variability between climate zones, which can be significant (Harshburger *et al.,* 2002; Wernstedt and Hersh, 2002). There is evidence of variation west to east between the Cascades, Wallowa Mountains, and Rockies (McCabe and Dettinger, 2002) and north to south between a warm dry El Niño signal in Washington and northern Oregon and a cold wet El Niño signal in California and Colorado (Cayan and Peterson, 1989; Redmond and Koch, 1991). The approach of using several similar drainages from different climate zones across Oregon allows a detailed look at variations in the magnitude and timing of snowmelt runoff at a spatial scale commensurate with many state and local water management concerns.

Most importantly, studies using a large number of stations generally include only a few with records longer than 50 years. There appear to be several disadvantages to using mainly records beginning in the mid-1940s or later. First, there was a shift from the mostly warm phase to the mostly cool phase in the PDO index around 1945 (Hare and Mantua, 2000). This means that the first half of the time series is in a cool phase and the second half is in a warm phase. Second, studies have shown a muting of the ENSO signal (especially as defined by the Southern Oscillation Index) between 1920 and 1950 (Kirtman and Schopf, 1998; McCabe and Dettinger, 1999), which would be missed using later time series.

ENSO AND PDO IN WESTERN U.S. CLIMATE

ENSO is a tropical phenomenon that affects global sea surface temperature (SST) and climate. During a typical El Niño (warm) event, the low pressure cell centered over the Aleutian chain deepens, shifting the main cyclonic storm track southward and depriving the Pacific Northwest of moisture. Unusually high temperatures follow a warm tongue of ocean water up the Pacific Coast. La Niña (cool) events tend to cause a weakening of the low pressure cell and shift the storm track northward over the Pacific Northwest, drawing cooler coastal waters up the coast of Oregon and Washington and delivering more precipitation (Hoerling and Kumar, 2000). This is a simplified explanation, and the extratropical effects of ENSO are variable (Hoerling and Kumar, 2000). El Niño events tend to correlate with warmer than average temperatures and lower than average runoff in the northwestern United States and colder and wetter than average conditions in the southwestern United States. La Niña events tend to have the inverse effect (Cayan and Peterson, 1989; Redmond and Koch, 1991; Cayan *et al.,* 1999; Miles *et al.,* 2000; Clark *et al.,* 2001). Snowpack and streamflow in the western United States respond more consistently to La Niña than El Niño (Cayan *et al.,* 1999), possibly because during El Niño, circulation anomalies tend to be located east of those in La Niña years, resulting in weaker temperature and precipitation anomalies close to the west coast (Hoerling and Kumar, 2000).

PDO causes precipitation and temperature anomalies in the western United States similar to ENSO (Mantua *et al.,* 1997; McCabe and Dettinger, 1999; Jain and Lall, 2000; Miles *et al.,* 2000) but is defined by SST patterns that predominate in the northern Pacific Basin. The warm phase of PDO is characterized by a strengthened Aleutian low and increased SST along the northwest coast of North America, similar to but stronger than a typical El Niño event. While ENSO changes phase interannually, PDO conditions persist in the same phase for 10 to 30 years, with excursions into the opposite phase for at most two to three years (Mantua *et al.,* 1997). Finally, while ENSO is a reasonably well studied and widely accepted phenomenon with a prediction lead time of several months, the origin and teleconnections of decadal oscillations in the Pacific are disputed (Gu and Philander, 1997; Mantua *et al.,* 1997; Zhang *et al.,* 1997; Barnett *et al.,* 1999; Hunt and Tsonis, 2000; Barlow *et al.,* 2001). Nonetheless, PDO appears to influence Pacific Northwest climate and streamflow as much as ENSO (McCabe and Dettinger, 2002). The PDO index is positively correlated with temperature and negatively correlated with streamflow in the Pacific Northwest, and the following regimes have been identified during the 20th Century: PDO cool phases occurred from approximately 1900 to 1925 and 1945 to 1977, and PDO warm phases have occurred between 1925 and 1945 and since 1977 (Hare and Mantua, 2000). There is debate as to whether PDO changed back to a cool phase in the early 1990s (Miles *et al.,* 2000).

The correlation between ENSO, PDO, and climate has varied over the past century (Gershunov and Barnett, 1998; Kirtman and Schopf, 1998; McCabe and Dettinger, 1999; Folland *et al.,* 2002). McCabe and Dettinger (1999) show that the correlation between ENSO and precipitation in the Pacific Northwest was much stronger before 1920 and after 1950 than during the three decades between 1920 and 1950, which coincide with a PDO warm phase and a divergence in tropical ENSO indices. In addition, the effects of PDO and ENSO appear to be additive when both are in the same phase (Koch and Fisher, 2000; Harshburger *et al.,* 2002). This study shows further evidence that PDO influence has decreased significantly after 1950 as ENSO correlations have strengthened.

DATA SOURCES

Daily discharge and annual peak discharge data from the U.S. Geological Survey (USGS) Water Resources Division for eight watersheds in central and eastern Oregon were used in the analysis herein (Table 1). The gaging stations were selected based on the following criteria: (1) the record begins before 1940 and contains at least 60 complete years of daily streamflow measurements; (2) the drainage area is less than 300 square kilometers; (3) the annual hydrograph is dominated by a spring snowmelt peak; and (4) the watershed upstream of the gaging station is undisturbed by canals, dams, or urbanization. The need for a long record is discussed above. Small drainage areas were chosen to maximize the snowmelt signal, which is diffused in larger drainage basins, and to minimize the effects of human disturbance. Eight watersheds distributed across eastern Oregon met these criteria: Deer Creek and Squaw Creek from the Upper Deschutes Basin of central Oregon; Bear Creek, South Fork Walla Walla River, Lostine River, and Catherine Creek from the Upper Grande Ronde Basin in northeastern Oregon; Strawberry Creek from the Upper John Day Basin of central Oregon; and Trout Creek from the Alvord Lake Basin of southern Oregon/northern Nevada (Figure 1).

Mean annual streamflow was calculated for each station for each water year by averaging daily discharge measurements from October 1 to September 30. The date of peak flow was determined after applying a five-day running average to the discharge record and corresponds to the center of the highest five-day average. No filter was applied to the annual peak recorded discharge data, except that peaks reportedly

TABLE 1. Properties of Streams in Study (locations on Figure 1).

Stream Name	Drainage Basin	Station No.	Area (km^2)	Runoff (m^3/km^2s)	Period of Record	No. of Years	Gage Elevation	Mean Elevation
Strawberry Creek	Upper John Day	14037500	18	0.0198	1925 to 1997*	69	1,496	2,100
Deer Creek	Upper Deschutes	1405200	55	0.0037	1937 to 1997	60	1,378	1,615
Bear Creek	Wallowa	13330500	116	0.0283	1924 to 2000*	63	991	1,800
S.F. Walla Walla River	Walla Walla	14010000	161	0.0311	1908 to 1997*	67	625	1,280
Squaw Creek	Upper Deschutes	14075000	174	0.0170	1908 to 1997*	84	1,064	1,830
Lostine River	Wallowa	13330000	182	0.0303	1912 to 2000*	75	1,936	2,130
Trout Creek	Alvord Lake	10406500	225	0.0020	1932 to 1997	65	1,326	1,830
Catherine Creek	Grand Ronde	13320000	269	0.0125	1912 to 1996*	73	939	1,580

*Indicates missing years in record.

affected by debris flows or outburst floods were not considered. Seasonal discharge fractions consist of the following three month averages, divided by the annual total of monthly averages: fall is September/October/November (SON), winter is December/January/February (DJF), spring is March/April/May (MAM), and summer is June/July/August (JJA). Temperature and precipitation data from stations on Figure 1 are from the U.S. Historical Climatology Network (USHCN). These data have been adjusted to remove biases introduced by station moves, instrument changes, time of observation differences, and urbanization effects. They are available from the U.S. Historical Climatology Network (1996). Additional precipitation data are National Oceanic and Atmospheric Administration (NOAA) Climate Division datasets (Oregon Climate Service, 2002). They represent the average of all reporting stations from the Climate Division for each month of the record. These are not adjusted for long term bias.

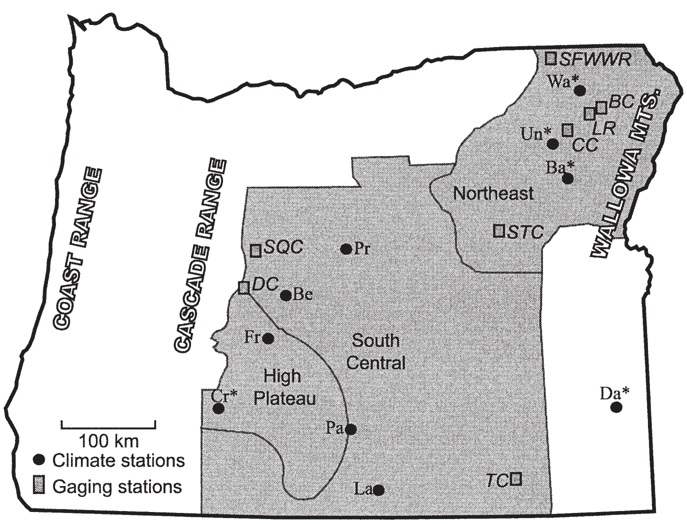

Figure 1. Gaging Stations (squares) and USHCN Climate Stations (black dots) in Central and Eastern Oregon. Gray polygons encompass NOAA climate divisions. DC = Deer Creek, SQC = Squaw Creek, TC = Trout Creek, STC = Strawberry Creek, BC = Bear Creek, CC = Catherine Creek, LR = Lostine River, and SFWW = South Fork Walla Walla River. Temperature stations are La = Lakeview, Pa = Paisley, Cl = Crater Lake, Fr = Fremont, Be = Bend, Pr = Prineville, Ba = Baker City, Un = Union, Wa = Wallowa, and Da = Danner. Those with an asterisk (*) also have precipitation records.

There is no single universally accepted measure of ENSO, and climate correlations vary with index used. Both the atmospheric Southern Oscillation Index (SOI) and an oceanic index, Niño 3.4 are used. The SOI, available from NOAA (2002) is defined as the standardized difference between sea level pressure (SLP) anomalies at Tahiti and Darwin, Australia. The SOI is used in the interest of comparing results from this study to those from other regional studies (e.g., Redmond and Koch, 1991; Cayan *et al.,* 1999; Wolter *et al.,* 1999; Koch and Fisher, 2000; Redmond *et al.,* 2002). The June through September (JJAS) average of SOI is used for all calculations because it correlates best with mean annual streamflow and the date of peak snowmelt in most of the stations. El Niño events are defined in this study as years when the previous June through September average (JJAS) of the SOI is -0.5 or less (one-half a standard deviation below the mean), and La Niña events are defined as those years when JJAS SOI is greater than 0.5. Other years are defined as ENSO neutral. The Niño 3.4 index is also used, and is defined as the smoothed monthly SST anomalies from the Niño 3.4 region of the equatorial Pacific (Trenberth and Stepaniak, 2001). The index is available from the National Center for Atmospheric Research (2002). El Niño events are defined as years when Niño 3.4 averages are greater than 0.4, and La Niña events as less than -0.4. For all calculations, the September/October/November (SON) average is used because it correlates best with mean annual streamflow and date of peak flow in most of the stations. The choice of months used to define the state of ENSO affects seasonal correlations somewhat, but not enough to alter the results of the study.

The PDO index from the University of Washington (Mantua, 2001) is used. PDO is the leading empirical orthogonal function (EOF) of SST variability in the Pacific Basin poleward of 20°N (Mantua *et al.,* 1997). PDO warm events are defined as years when the annual average of the index is greater than 0.5 and PDO cool events as less than -0.5. Other years are defined as PDO neutral. The annual average of all monthly PDO indices is used regardless of whether it is in or out of phase with the decadal scale regime because the interannual component of PDO appears to affect climate in the region at least as strongly as ENSO (McCabe and Dettinger, 2002). Other studies have found significant results splitting the record into predominantly positive or negative PDO regimes (Hamlet and Lettenmaier, 1999a; Miles *et al.,* 2000; Koch and Fisher, 2000).

METHODS AND SIGNIFICANCE TESTS

Undisturbed drainages with long records have advantages over precipitation and snow gages when evaluating the effects of climate variability on water resources. First, surface water is often the greatest concern of water managers. Second, streamflow integrates precipitation and snowmelt over the drainage area and records precipitation from high elevations and rugged topography, where gages are rare (Cayan and Peterson, 1989). Third, the effects of ENSO and PDO are amplified in streamflow compared to precipitation (Cayan *et al.,* 1999). This may be due to the spatial advantage of streamflow mentioned above or because snowmelt runoff depends on both precipitation and temperature. Mean annual discharge reflects total precipitation, date of peak snowmelt reflects spring and summer temperatures, and seasonal runoff fractions represent the balance between precipitation and temperature during the cold-season snow accumulation period and the high evaporation/transpiration period in the summer (Figure 2).

Correlations are tested with two methods. The first is ordinary least squares linear regression, which returns a Pearson product moment correlation coefficient r between 1 (perfectly correlated) and -1 (perfectly negatively correlated). Variables are considered weakly correlated, correlated, and strongly correlated where the test statistic t rejects the null hypothesis with a 90 percent, 95 percent, and 99 percent confidence level, respectively. Linear regression assumes a linear, homoscedastic (variability of y does not change with magnitude of x) relationship between two variables (Hirsch *et al.,* 1993). There is no obvious nonlinearity or heteroscedasticity, but the data are scattered, and there are several factors that would contribute nonlinearity to the relationship between climate indices and streamflow. These include temporal and spatial variability in the strength of ENSO and PDO correlations shown in this study and by Kirtman and Schopf (1998), Hoerling and Kumar (2000), and Jain and Lall (2000) and interannual climate variability that occurs independent of ENSO or PDO. For these reasons correlation coefficients are low and often questionably significant, and linear correlations may not always be appropriate. The significance of Pearson's r is corroborated with Kendall's τ, a nonparametric correlation coefficient. Kendall's τ is found by indexing the two datasets by rank, then correlating by rank rather than actual magnitude. Kendall's τ, like r, ranges from 1 to -1, and significance is determined by a z-test with confidence levels assigned as above. Kendall's τ has the advantage of not requiring linearity or homoscedasticity, is not as sensitive to extreme values as linear regression, and is well suited to river discharge and precipitation data (Kendall and Gibbons, 1990; Hirsch *et al.,* 1993). Hirsch *et al.* (1993) provide mathematical formulas for these parameters. Except as noted, only correlations in which both linear regression and the rank correlation return values significant to at least 90 percent are considered, and only r-values are reported in the tables and graphs.

Long term trends are evaluated using the regression and rank methods above and with plots of cumulative residuals, which do not have any associated significance tests but illustrate the periodicity of variations in time series. The value of the cumulative residual Q_n, n years into the time series is given by

$$Q_n = \sum_0^n \left(Q_i - \overline{Q}\right)$$

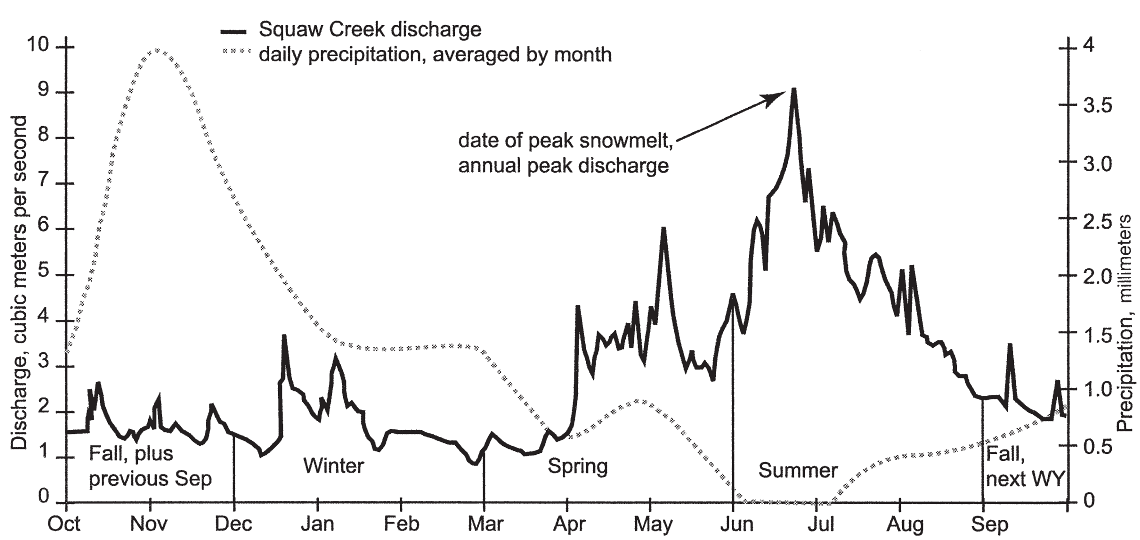

Figure 2. Example of a Snowmelt-Dominated Hydrograph: Daily Discharge of Squaw Creek Near Sisters, Oregon, and Smoothed Monthly Average Precipitation From Sisters, Oregon, Both for Water Year 1962.

where Q_i is the value of the time series at year i and $\bar{Q}$ is the mean value of the time series over the period of record (Hurst, 1951). Low and high points in the cumulative residual plot represent shifts from consistently low years to consistently high years and vice versa. A positive slope indicates that high discharge years are following high discharge years, and a negative slope indicates that lower than average years are following lower than average years.

REGIONAL HYDROLOGIC VARIABILITY

Annual precipitation patterns are variable between the study sites, but in general, precipitation peaks in December or January in central Oregon and in northeastern Oregon in November with a second peak in May and June. Spring snowmelt peaks occur in May for Deer, Catherine, and Trout; in June for Bear, Squaw, Lostine, and South Fork Walla Walla; and in July for Strawberry (Figure 3). The long term average date of peak snowmelt for each stream is positively correlated (r = 0.82) with the average elevation of the drainage area. There is an order of magnitude spread in runoff per unit area shown in Table 1 that is probably due to location with respect to topography and illustrates the variability between climate zones within the semi-arid part of the state.

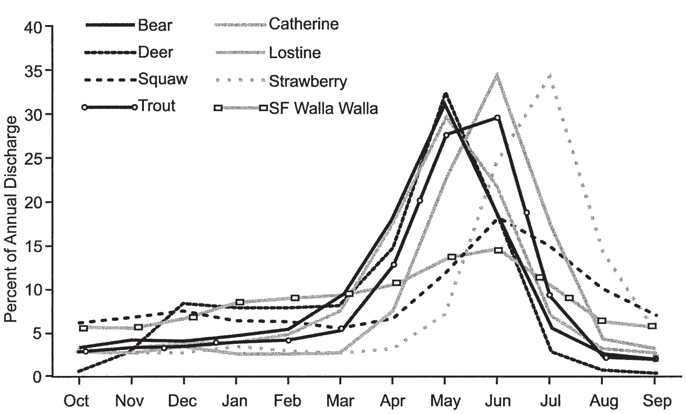

Figure 3. Monthly Flow Fractions, Averaged Over the Period of Record for All Streams in Study Area.

TEMPERATURE AND PRECIPITATION

Because discharge from snowmelt streams depends on both precipitation and temperature, it is useful to determine how these factors have responded to PDO and ENSO. The ten USHCN climate stations used are scattered throughout central and eastern Oregon (Figure 1). Five of these stations have precipitation records as well, but the records are shorter and correlations are poor and inconsistent.

ENSO and PDO are both significantly correlated with mean annual temperature in nearly all of the stations, and neither is consistently correlated with mean annual precipitation (Table 2). Mean annual precipitation averaged over climate divisions correlates better with the indices. ENSO is significant in the Cascades and Northeast climate divisions, and PDO is significant in the Cascades climate division.

Spring and summer temperature and precipitation are better correlated with PDO and ENSO than winter and fall (Figure 4). Again, temperature correlations are more consistent than precipitation.

TABLE 2. Correlation Coefficient Relating Mean Annual Temperature and Precipitation to PDO, JJAS SOI, and SON Niño 3.4 Indices.

Station	PDO	SOI	Niño 3.4
Mean Annual Temperature			
Baker	0.27**	-0.23*	0.26**
Bend	0.36**	-0.21*	0.22*
Lakeview	0.31**	-0.25**	0.21*
Fremont	0.33**	-0.20*	0.22*
Wallowa	0.27**	-0.21*	0.21*
Crater Lake	0.25*	-0.07	0.14
Danner	0.18w	-0.17w	0.21*
Paisley	0.23*	-0.22*	0.14w
Prineville	0.21*	-0.15	0.14
Union	0.31**	-0.24*	0.29**
Mean Annual Precipitation			
Danner	0.07	-0.12	0.1
Union	0.21*	-0.19	0.09
Crater Lake	-0.06	-0.18	0.13
Wallowa	0.01	-0.12	0.09
Baker	0.07	-0.13	0.1
High Plateau	-0.18*	0.20*	-0.23*
South Central	0.07	0.11	-0.11
Northeast	-0.12	0.14w	-0.17*

Note: Double asterisk (**), asterisk (*), and 'w' indicate >99 percent, >95 percent, and >90 percent confidence, respectively. USHCN stations and climate divisions are on Figure 1.

MEAN ANNUAL DISCHARGE

Mean annual discharge responds as expected to PDO and ENSO, decreasing during warm dry phases and increasing during cool wet phases. Correlations

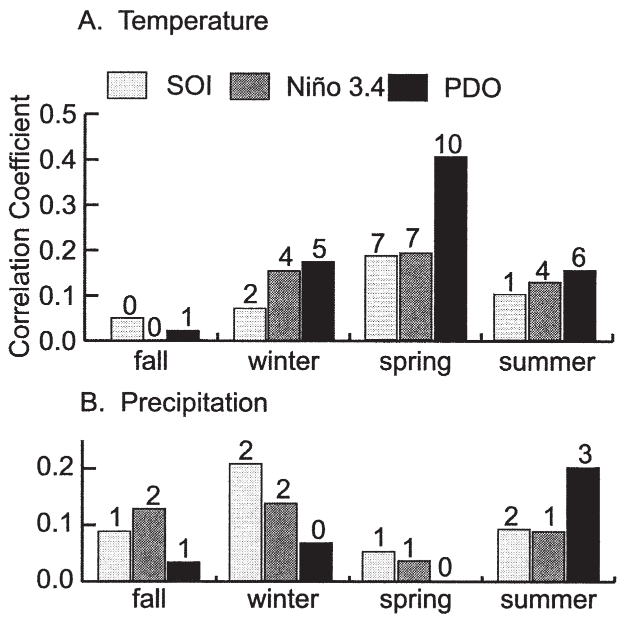

Figure 4. Correlations Between (A) Mean Seasonal Temperature and (B) Precipitation and the Three Climate Indices, Averaged Over All Stations Used in Eastern Oregon. Numbers above bars indicate number of significant (p > 0.05) correlations out of 10 temperature stations and five precipitation stations.

between mean annual discharge and PDO and ENSO indices (Figure 5) are higher and more consistently significant than correlations between climate zone temperature/precipitation data and PDO and ENSO, possibly because the hydrologic cycle amplifies the combined effects of precipitation and temperature or because stream discharge represents a more coherent spatial average over a smaller area than scattered climate stations, or both. Although ENSO correlations are stronger than PDO correlations for most streams, there is spatial and temporal variability in the strength of both relationships.

ENSO correlations for the period of record are strongest in the westernmost stations (Deer and Squaw), lowest in the central stations (Catherine and Strawberry), and insignificant in the southernmost station (Trout). All but Strawberry and Trout are also significantly negatively correlated with PDO for the period of record. Coinciding with the results of McCabe and Dettinger (1999), no sites are significantly correlated with SOI for the years 1920 to 1950, while correlations for data prior to 1920 and after 1950 are substantially higher. However, most streams are significantly correlated with the Niño 3.4 index during 1920 to 1950 (with the highest correlation being $r = 0.72$ for Deer). Correlations between PDO

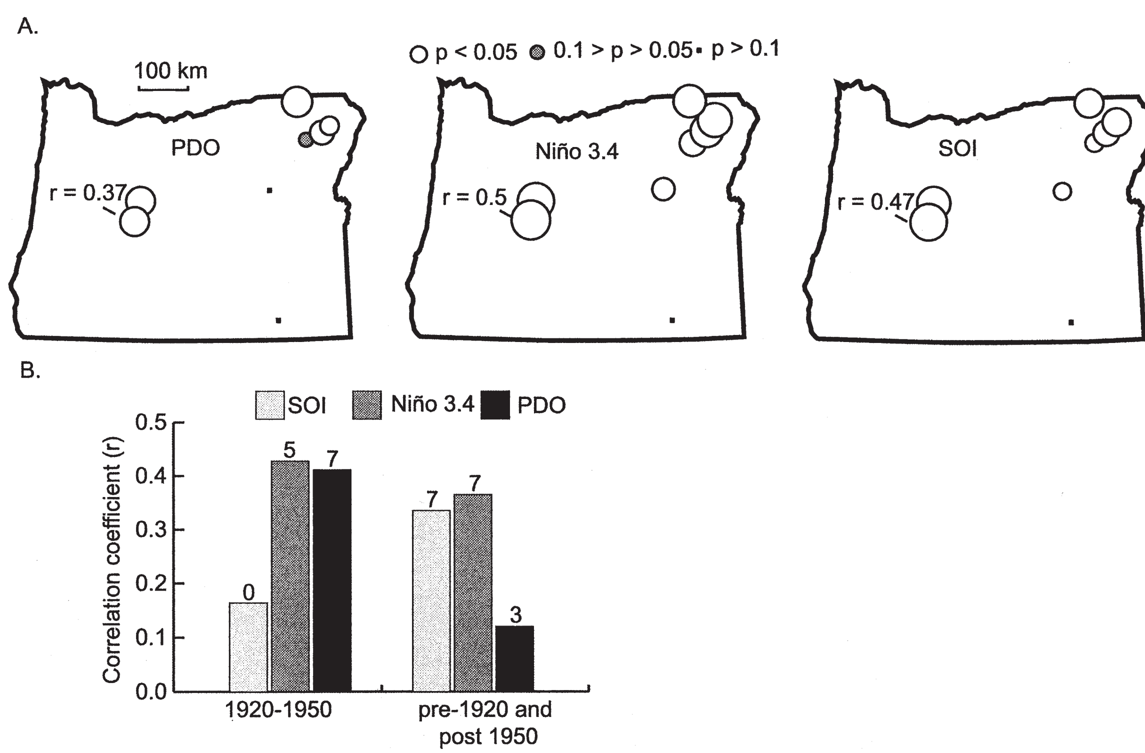

Figure 5. (A) Correlation Between Mean Annual Flow, PDO, Niño 3.4, and SOI for Each Stream. Size of circle is proportional to r-value. (B) Correlations Averaged Over All Eight Streams, and Separated by Period of Record. Numbers above bars indicate number of significant results (p < 0.05) out of eight streams.

and mean annual streamflow show the opposite trend as SOI, with elevated correlation coefficients between the years 1920 and 1950 and lower (or insignificant) correlation coefficients for the years preceding and following this period. Trout's lack of correlation suggests that its southern location is marginal with respect to atmospheric events associated with PDO or ENSO and may be on the hinge between positive anomalies in the north and negative anomalies in the south. This decrease in ENSO effects in southern Oregon has also been seen in coastal rivers (Koch and Fisher, 2000).

The two ENSO indices also diverge on whether La Niña or El Niño affect streamflow to the same extent. Using SOI, split sample analysis supports the observation of Cayan *et al.* (1999) and others that La Niña has a more consistent effect on streamflow than El Niño. In most cases, the percent difference in annual streamflow between La Niña years and SOI neutral years is at least twice the percent difference between El Niño years and SOI neutral years (Figure 6). Using the Niño 3.4 definition, La Niña is dominant in half the streams and El Niño dominant in the other half. Asymmetry in the PDO signal is also inconsistent between sites.

EXTREME LOW AND HIGH WATER YEARS

Droughts and floods are of greater concern to the public than average flow but are by definition rare events. The distribution of PDO and ENSO climate anomalies in drought years (10 lowest mean annual discharges in each stream) and wet years (10 highest) is compared with their distribution throughout the period of record. Using the SOI definition, La Niña (ENSO cool), neutral, and El Niño (ENSO warm) years comprise 23 percent, 47 percent, and 30 percent of the record, respectively (for Niño 3.4 the percentages are 27 percent, 35 percent, and 37 percent) while PDO cool, neutral, and warm years comprise 25 percent, 43 percent, and 32 percent. Out of 80 instances of drought, only three occurred during a PDO cool phase, none occurred during an SOI (ENSO) cool phase, and 13 occurred during a Niño 3.4 (ENSO) cool phase (Figure 7). The extreme wet years were nearly evenly distributed through PDO phases but are dominated by ENSO cool phases as defined by either index.

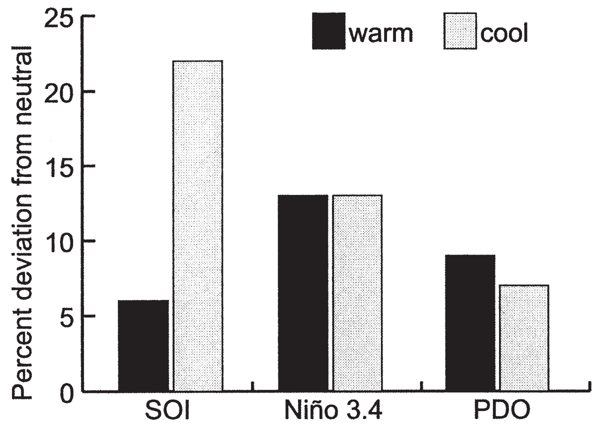

Figure 6. Deviation of Mean Annual Discharge During PDO and ENSO Events From Years When Indices Are Neutral, Averaged Over All Eight Streams.

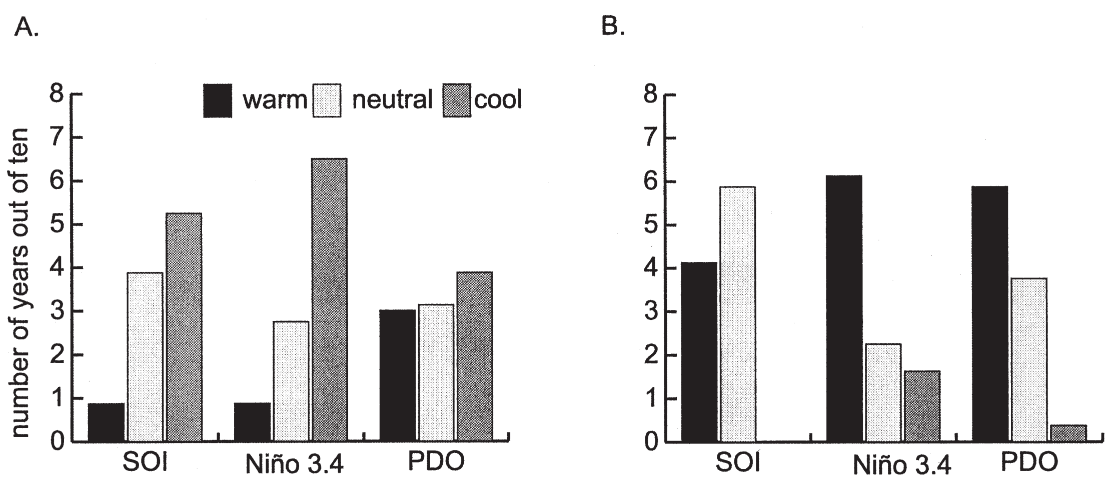

Figure 7. Histograms Showing the Number of Years Out of Ten That the (A) Highest and (B) Lowest Water Years Coincide With ENSO and PDO Phases, Averaged Over All Eight Streams in the Study.

SEASONAL FLOW FRACTIONS

Seasonal fractional runoff reflects the time lag from snow accumulation and is not entirely consistent with climate division temperature and precipitation. The least expected result is that winter runoff fraction does not increase during warm phase years of either ENSO or PDO and in fact decreases in two streams with El Niño, according to the Niño 3.4 index, despite significantly warmer temperatures in some stations, indicating that any increase in winter snowmelt is balanced by decreased precipitation (Figure 8).

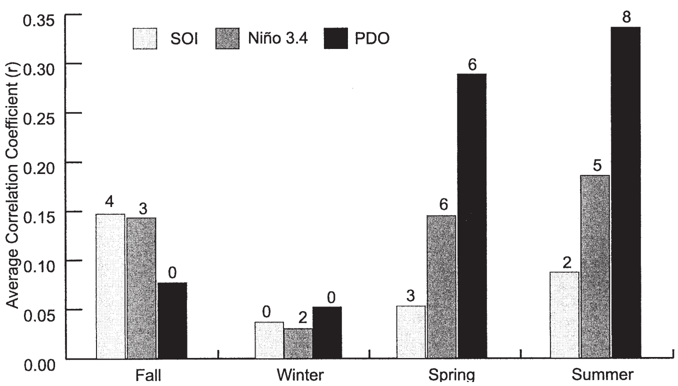

Figure 8. Correlation Coefficients Relating Seasonal Fractional Discharge to PDO, Niño 3.4, and SOI Indices, Averaged Over All Eight Streams. Numbers above bars indicate number of significant results ($p < 0.05$).

Warm season runoff anomalies are more consistent. PDO is strongly positively correlated with spring runoff fraction except for Trout and South Fork Walla Walla and strongly negatively correlated with summer runoff fraction except for South Fork Walla Walla.The temperature data indicate that PDO affects spring temperature; thus high spring flows followed by low summer flows during PDO warm phase events reflect increased early snowmelt runoff (the opposite for cool phase). Niño 3.4 correlations with spring and summer runoff show the same pattern, with increased spring and decreased summer runoff during El Niño events and the opposite during La Niña. SOI correlations with spring and summer flow are insignificant in most streams.

DATE OF PEAK SNOWMELT

The timing of peak spring runoff, which is a major factor in the success of reservoir operations, is significantly earlier during the PDO warm phase and later during the cool phase in all streams but South Fork Walla Walla (Table 3). South Fork Walla Walla drains the lowest elevations and thus derives its spring peak discharge both from snowmelt, which is directly modulated by temperature, and precipitation, which is not. SOI is well correlated with spring temperature but correlates with the date of peak snowmelt less consistently than PDO. Niño 3.4 correlates better with the date of peak snowmelt, though only half the stations show significant correlations. Although PDO correlations with the date of peak snowmelt are consistently higher during the years 1920 to 1950 and lower in other periods, neither ENSO index shows consistent temporal variability. PDO warm events shift the timing of peak snowmelt an average of seven days earlier than PDO neutral events, and PDO cool events shift the peak an average of 6.6 days later than PDO neutral. This generally corresponds to the results of Cayan *et al.* (2001), who found that snowmelt peaks in western U.S. streams have shifted earlier by about two days per decade between 1957 and 1994 (a 7.5 day shift between a PDO cool regime and a PDO warm regime).

ANNUAL PEAK DISCHARGES

Peak discharge records are used to model the statistical distribution of flood magnitude and frequency for dam design and floodplain hazard delineation. For these purposes, floods are generally assumed to be independent and identically distributed and result from temporally stochastic processes. Jain and Lall (2001) challenge this assumption by documenting changes in flood magnitude over time related to PDO and ENSO on the Similkameen River in Washington. In addition to informing flood frequency analyses, the state of ENSO is used to aid in prediction of extreme events. The utility of ENSO as a flood predictor depends on understanding the local effects of ENSO on flooding, which may vary between drainage basins, over time, and with the severity of the event (Wernstedt and Hersh, 2002). Annual peak discharge is used in this study, but others have shown significant ENSO correlations using statistical metrics such as the 90th percentile flows (Cayan *et al.,* 1999).

The highest recorded daily peak discharge each year usually coincides with the snowmelt peak in high elevation drainages but can also be caused by rain on snow events in the winter or spring. Squaw, South Fork Walla Walla, and Deer experience major rain on snow floods. All annual peak floods in the period of record on the other streams occurred during warm season snowmelt. Larger floods occur significantly

TABLE 3. Correlation Coefficients Relation Date of Peak Snowmelt to SOI, Niño 3.4, and PDO Indices.

	All Years			1920 to 1950			Pre-1920 and Post-1950		
	SOI	Niño 3.4	PDO	SOI	Niño 3.4	PDO	SOI	Niño 3.4	PDO
Bear	0.20w	-0.32**	-0.31**	0.14	-0.29w	-0.36*	0.23	-0.37*	-0.21
Catherine	0.14	-0.13	-0.23*	0.18	-0.35*	-0.33w	0.11	-0.06	-0.14
Lostine	0.10	-0.25*	-0.33**	-0.14	-0.32w	-0.35*	0.20w	-0.24	-0.28
Deer	0.18w	-0.29*	-0.38**	0.04	-0.36	-0.57*	0.23w	-0.29*	-0.31*
Squaw	0.10	-0.03	-0.25**	0.20	-0.20	-0.35*	0.05	0.02	-0.20w
SF Walla Walla	-0.18	0.10	-0.14	-0.45	0.45	-0.141	-0.07	0.02	-0.15
Strawberry	0.18w	-0.17w	-0.40**	0.30w	-0.39*	-0.33w	0.11	-0.09	-0.42**
Trout	-0.02	-0.01	-0.19w	-0.45*	0.48	-0.14	0.10	-0.11	-0.21

Note: Double asterisk (**), asterisk (*), and 'w' indicate >99 percent, >95 percent, and >90 percent confidence, respectively. USHCN stations and climate divisions are on Figure 1.

later in the water year in Bear, Catherine, Lostine, and Trout and significantly earlier in Squaw, South Fork Walla Walla, and Deer.

Correlations with flood magnitude vary temporally the same way mean annual discharge does. PDO was significantly more important in determining flood magnitude from 1920 to 1950 (r = 0.76 for Deer Creek) than other years (r = 0.21 for Deer Creek), while both ENSO indices are stronger for the years before 1920 and after 1950, with the exception of Trout and Deer, which show strong flood correlation with Niño 3.4 1920 to 1950. Consistent rank correlations and inconsistent linear correlations between flood magnitude and both ENSO indices and PDO suggest that the relationships may be real but nonlinear (Figure 9).

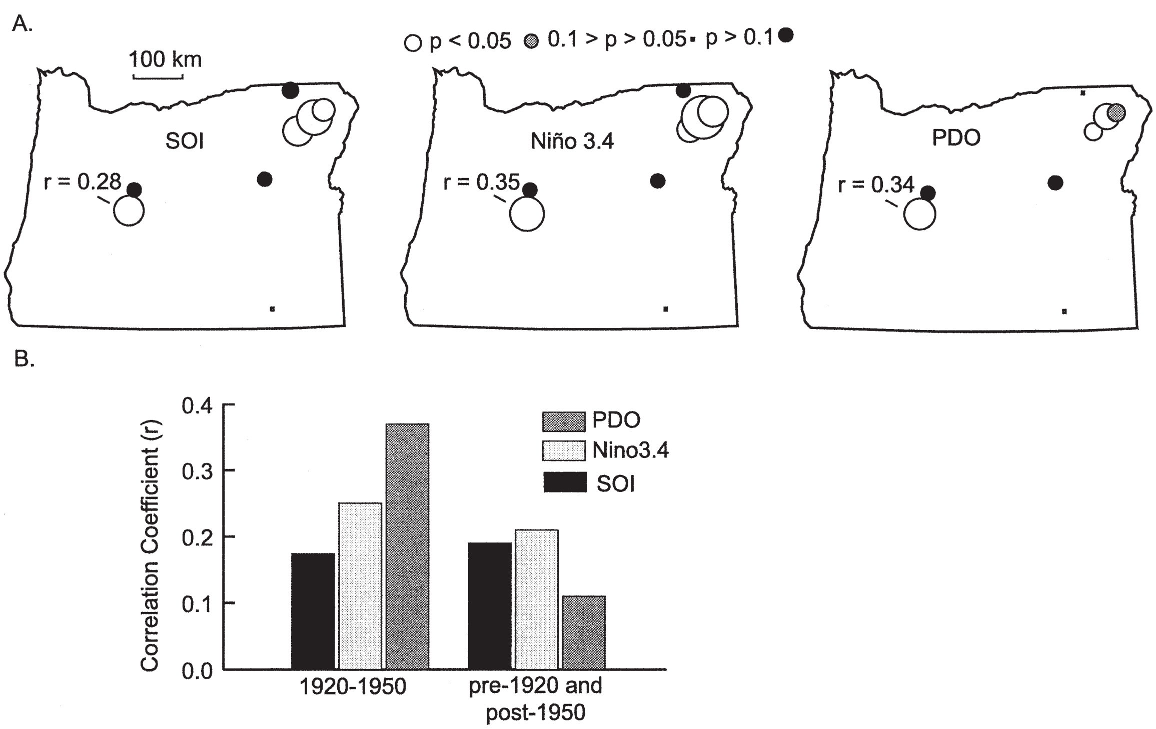

Figure 9. (A) Map Showing Distribution of Significant Correlations Between Annual Peak Discharge, SOI, PDO, and Niño 3.4. Size of circle is proportional to r-value. (B) Bar Graph Showing Correlation Coefficient, Averaged Over All Eight Streams, Between Annual Peak Discharge, PDO, SOI, and Niño 3.4, for Different Periods of Record.

TRENDS IN MEAN ANNUAL STREAMFLOW

A long term increase in mean annual precipitation and temperature is consistent and significant throughout the region (Figure 10). The exception is the westernmost and highest station, Crater Lake, which shows decreasing temperature and precipitation. Despite this, only Bear and Trout show significant increases in streamflow over the period of record. Bear Creek is missing nine years of data, so a regression model based on the adjacent Lostine River was used to fill in the gap. The time series of mean annual

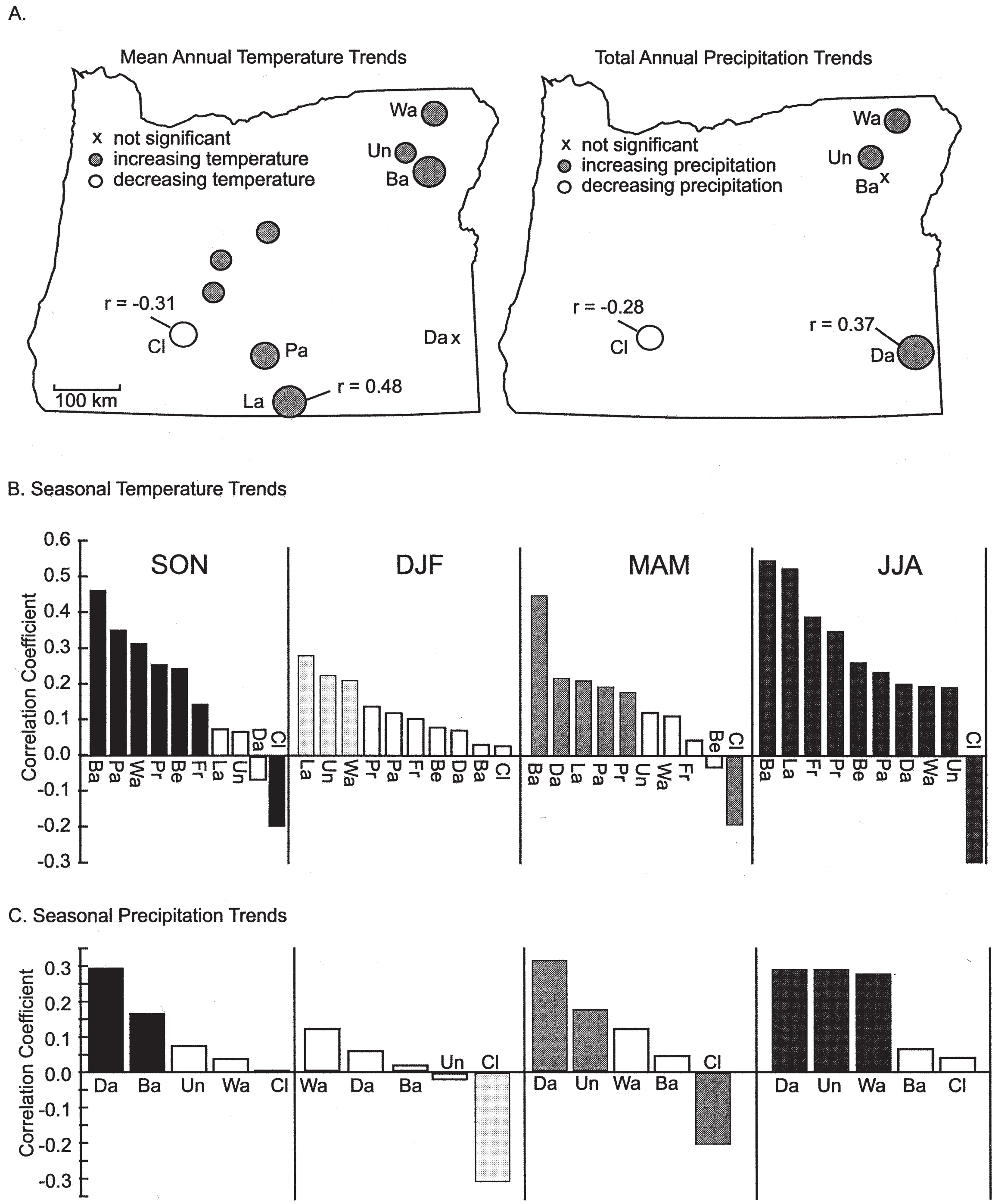

Figure 10. Linear Correlation Between Water Year and (A) Mean Annual Temperature and Precipitation (size of circle is proportional to r-value), (B) Seasonal Temperature, and (C) Seasonal Precipitation Over the Last 100 Years in USHCN Climate Stations. Station abbreviations follow Figure 1. Insignificant correlations are shown without fill in bar graphs.

discharge between the two streams is highly correlated (r^2 = 0.94), with no apparent nonlinearity or heteroscedasticity; thus the regression model is appropriate (Hirsch *et al.,* 1993). With the addition of nine years of modeled discharge data, the trend of increasing discharge in Bear Creek disappeared. Trout Creek, which is not missing any data, may be the only station with a true trend.

Despite spatial differences in correlation with PDO and ENSO, mean annual streamflow in the region has varied coherently over the period of record (Figure 11). Most streams in the study have their lowest inflection points (indicating a shift from consistently lower than average flow to consistently higher than average flow) around the year 1945 (coinciding with a phase shift in PDO) and their highest (indicating a shift from higher than average to lower than average) in either 1976 or 1985. Trend analyses in time series are necessarily sensitive to the beginning and ending point; thus an analysis that uses these streamflow data beginning in the 1940s will suggest a monotonic increase in discharge, while the same analysis using records beginning in the early 1930s will not. The spatial distribution of gaged, undisturbed basins, however, is poor (only eight undisturbed snowmelt dominated basins in the state of Oregon have records currently for longer than 60 years), and this hampers the detection of trends and low frequency climate variability.

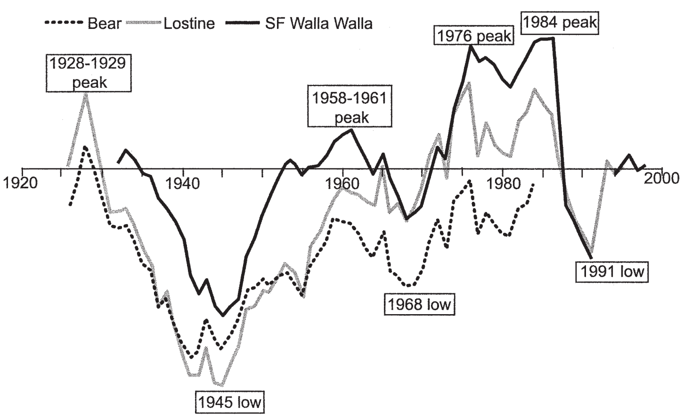

Figure 11. Cumulative Residuals of Mean Annual Discharge for Bear Creek, Lostine River, and South Fork Walla Walla River Showing Coincident Inflection Points. Residuals are dimensionless and scaled to fit on the same graph.

TRENDS IN SEASONAL FLOW FRACTIONS

There are consistent and opposing monotonic trends in winter, spring, and summer runoff (Figure 12), with spring and summer fraction of flow negatively correlated. This is expected in snowmelt streams because summer streamflow represents snow that did not melt in the spring.

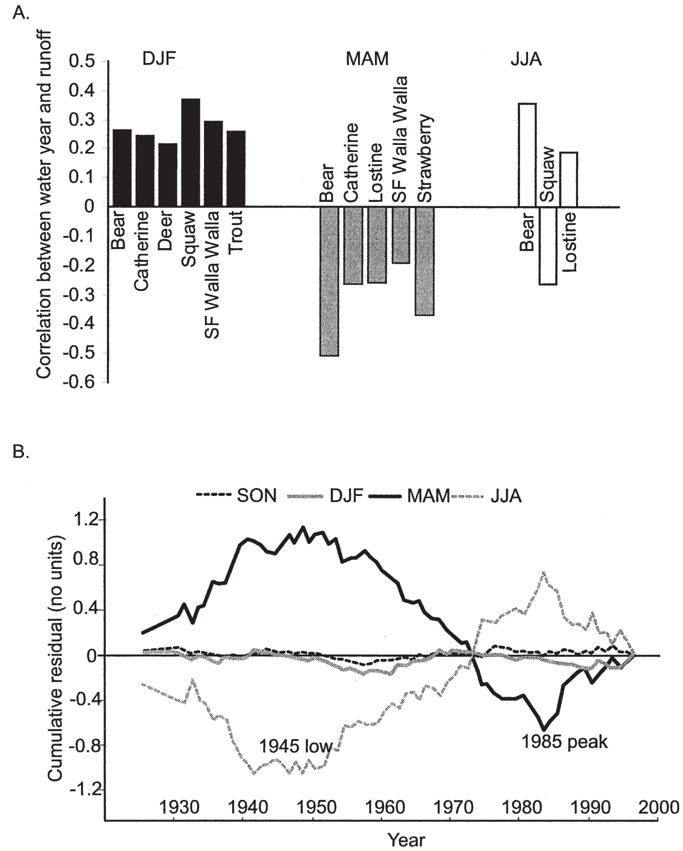

Figure 12. (A) Linear Trends in Seasonal Fractional Discharge Over the Period of Record. Only significant correlations between water year and seasonal discharge are shown. (B) Cumulative Residual of Seasonal Fractional Discharge for Strawberry Creek, Showing Negative Correlation Between Spring and Summer Discharge Fraction.

Although monotonic precipitation increases do not appear in the hydrologic record (except for Trout), monotonic temperature increases seem to. Winter runoff fractions have increased over the period of record in all streams but Strawberry and Lostine, despite a decrease in winter precipitation in all climate zones. This suggests that warmer temperatures are causing more runoff during the winter. Interestingly, winter discharge has not increased significantly during warm phases of PDO or ENSO, suggesting that either they do not affect temperature enough to cause significant snowmelt in the winter, or they coincide with a decrease in total cold season precipitation that is not apparent in the USHCN data. The increase in winter runoff is cannibalized from spring and summer runoff in most streams; thus although the volume of water is not changing over time, the timing of runoff is. This trend is shifting the seasonal surface water supply even more out of phase with demand in the region. Despite the increase in winter runoff, peak snowmelt dates are not occurring significantly earlier in the water year.

CONCLUSIONS

The results of this study indicate that the magnitude and timing of runoff in snowmelt dominated streams in central and eastern Oregon are significantly affected by climatic variability coinciding with PDO and ENSO. Although most aspects of runoff are correlated to some extent with both PDO and ENSO, ENSO signals are strongest in mean annual discharge for all years and in the 10 highest and lowest discharge years in each station. PDO signals are strongest in the date of peak snowmelt runoff, spring and summer runoff, and the magnitude and timing of annual peak discharge events. There is spatial variability in all correlations, which tend to be higher in High Cascades and Wallowa Mountains streams, lower in between, and insignificant in the southernmost stream.

There is significant temporal variability in the effects of PDO as well as ENSO. PDO and ENSO seem to trade dominance, with ENSO much stronger after 1950 and PDO much stronger before 1950. This suggests that long term mean effects of PDO or ENSO on streamflow may not be representative of the current situation for predictive purposes. Correlations between ENSO and streamflow during the period 1920 to 1950 depend on the ENSO index used. In general, the dramatic decrease in SOI correlations is not apparent using Niño 3.4 as a measure of ENSO.

Secular trends not correlated with PDO or ENSO during the period of record include increased precipitation and temperature in USHCN stations in central and eastern Oregon. These are represented in the discharge data as shifts in the timing of runoff but not as increasing or decreasing mean annual flows. The fraction of runoff occurring during the winter increased at most stations during the period of record, and this increase was balanced by a decrease in either spring or summer runoff. Increased winter runoff is probably a result of increased winter temperatures. Cumulative residual plots show that discharge in the study area has increased and decreased consistently among streams, with major inflection points coinciding within one or two years. The appearance of long term trends in the record is sensitive to where the record begins and ends with respect to these inflection points. This reinforces the importance of using the longest and most complete records possible when searching for secular trends in regions that are also affected by low frequency climate cycles such as the PDO.

ACKNOWLEDGMENTS

The authors would like to thank four anonymous reviewers for their thoughtful consideration of this manuscript, especially the two who agreed to review a second version as well. In addition to indicating shortcomings, they pointed out additional sources of information and data that proved useful. This study was funded by NSF Grant EAR-9701768 to Manga.

LITERATURE CITED

Barlow, Mathew, S. Nigam, and E.H. Berbery, 2001. ENSO, Pacific Decadal Variability, and U.S. Summertime Precipitation, Drought, and Stream Flow. Journal of Climate 14:2105-2128.

Barnett, Tim P., D.W. Pierce, R. Saravanan, N. Schneider, D. Dommenget, and M. Latif, 1999. Origins of the Midlatitude Pacific Decadal Variability. Geophysical Research Letters 26(10):1453-1456.

Cayan, Daniel R., S.A. Kammerdiener, M.D. Dettinger, J.M. Caprio, and D.H. Peterson, 2001. Changes in the Onset of Spring in the Western United States. Bulletin of the American Meteorological Society 82(3): 399-415.

Cayan, Daniel R. and D.H. Peterson, 1989. The Influence of North Pacific Circulation on Streamflow in the West. *In:* Aspects of Climate Variability in the Pacific and Western Americas, Geophysical Monograph No. 55. American Geophysical Union, pp. 375-398.

Cayan, Daniel R., K.T. Redmond, and L.J. Riddle, 1999. ENSO and Hydrologic Extremes in the Western United States. Journal of Climate 12:2881-2893

Clark M.P., M.C. Serreze, and G.J. McCabe, 2001. Historical Effects of El Niño and La Niña Events on the Seasonal Evolution of the Montane Snowpack in the Columbia and Colorado River Basins. Water Resources Research 37(3):741-757.

Dai, Aiguo and T.M.L. Wigley, 2000. Global Patterns of ENSO-Induced Precipitation. Geophysical Research Letters 27(9):1283-1286.

Folland, C.K., J.A. Renwick, M.J. Salinger, and A.B. Mullan, 2002. Relative Influences of the Interdecadal Pacific Oscillation and ENSO on the South Pacific Convergence Zone. Geophysical Research Letters 29(13):21-1 to 21-4.

Garen, David C., 1993. Revised Surface-Water Supply Index for Western United States. Journal of Water Resources Planning and Management 119(4):437-454.

Gershunov, Alexander and Timothy P. Barnett, 1998. Interdecadal Modulation of ENSO Teleconnections. Bulletin of the American Meteorological Society 79(12):2715-2725.

Gu, Daifang and S.G.H. Philander, 1997. Interdecadal Climate Fluctuations That Depend of Exchanges Between the Tropics and Extratropics. Science 275:805-807.

Hamlet, Alan F. and D.P. Lettenmaier, 1999a. Effects of Climate Change on Hydrology and Water Resources in the Columbia River Basin. Journal of the American Water Resources Association (JAWRA) 35(6):1597-1623.

Hamlet, Alan F. and D.P. Lettenmaier, 1999b. Columbia River Streamflow Forecasting Based on ENSO and PDO Climate Signals. Journal of Water Resources Planning and Management 125(6):333-341.

Hare, Steven and Nathan Mantua, 2000. Empirical Evidence for North Pacific Regime Shifts in 1977 and 1989. Progress in Oceanography 47:103-145.

Harshburger, Brian, Hengchun Ye, and John Dzialoski, 2002. Observational Evidence of the Influence of Pacific SSTs on Winter Precipitation and Spring Stream Discharge in Idaho. Journal of Hydrology 264:157-169.

Hirsch, Robert M., D.R. Helsel, T.A. Cohn, and E.J. Gilroy, 1993. Statistical Analysis of Hydrologic Data. *In:* Handbook of Hydrology, David Maidment (Editor), McGraw-Hill, Inc., New York New York, pp. 17.1-17.55.

Hoerling, Martin P. and Arun Kumar, 2000. Understanding and Predicting Extratropical Teleconnections Related to ENSO. *In:* El Niño and the Southern Oscillation, H.F. Diaz and V. Markgraf (Editors). Cambridge University Press, Cambridge, United Kingdom, pp. 57-88.

Hunt, A.G. and A.A. Tsonis, 2000. The Pacific Decadal Oscillation and Long-Term Climate Prediction. EOS, Transactions, American Geophysical Union 81(48):581.

Hurst, H.E., 1951. Long-Term Storage Capacity of Reservoirs. American Society of Civil Engineers Transactions 116:770-799.

Jain, Shaleen and U. Lall, 2000. The Magnitude and Timing of Annual Maximum Floods: Trends and Large-Scale Climatic Associations for the Blacksmith Fork River, Utah. Water Resources Research 36(12):3641-3652.

Jain, Shaleen and U. Lall, 2001. Floods in a Changing Climate: Does the Past Represent the Future? Water Resources Research 37(12):3193-3205.

Kendall, Maurice and J.D. Gibbons, 1990. Rank Correlation Methods. Edward Arnold, London, United Kingdom.

Kirtman, Ben P. and Paul S. Schopf, 1998. Decadal Variability in ENSO Prediction. Journal of Climate 11:2804-2822.

Koch, Roy and Austin R. Fisher, 2000. Effects of Inter-Annual and Decadal-Scale Climate Variability on Winter and Spring Streamflow in Western Oregon and Washington. Proceedings of the Western Snow Conference, pp. 1-11.

Mantua, Nathan, 2001 (ongoing updates). PDO Index. *Available at* http://jisao.washington.edu/pdo/PDO.latest. *Accessed in* July, 2003.

Mantua, N.J., S.T. Hare, Y. Zhang, J.M. Wallace, and R.C. Francis, 1997. A Pacific Interdecadal Climate Oscillation With Impacts on Salmon Production. Bulletin of the American Meteorological Society 78:1069-1079.

McCabe, G.J. and M.J. Dettinger, 1999. Decadal Variations in the Strength of the ENSO Teleconnections With Precipitation in the Western United States. International Journal of Climatology 19:1399-1410.

McCabe, G.J., and M.J. Dettinger, 2002. Primary Modes and Predictability of Year-to-Year Snowpack Variations in the Western United States From Teleconnections With Pacific Ocean Climate. Journal of Hydrometeorology 3:13-25.

Miles, Edward L., A.K. Snover, A.F. Hamlet, B. Callahan, and D. Fluharty, 2000. Pacific Northwest Regional Assessment: The Impacts of Climate Variability and Climate Change on the Water Resources of the Columbia River Basin. Journal of the American Water Resources Association (JAWRA) 36(2):399-420.

National Center for Atmospheric Research, 2002. TNI (Trans-Niño Index) and N3.4 (Niño 3.4 Index). National Center for Atmospheric Research Climate Analysis Section. *Available at* http://www.cgd.ucar.edu/cas/catalog/climind/. *Accessed in* July, 2003.

NOAA (National Oceanic and Atmospheric Administration), 2002. Monthly Atmospheric and SST Indices/ Southern Oscillation Index (SOI). National Oceanic and Atmospheric Administration, National Weather Service, National Centers for Environmental Prediction, Climate Prediction Center. *Available at* ftp://ftp.ncep.noaa.gov/pub/cpc/wd52dg/data/indices/soi or http://www.cpc.ncep.noaa.gov/data/indices/index.html. *Accessed in* July, 2003

Oregon Climate Service, 2002. Oregon Climatic Divisions Temperature and Precipitation Data. *Available at* http://ocs.orst.edu/pub_ftp/climate_data/divisions/clim_divs.html. *Accessed in* July, 2003.

Redmond, Kelly T., Yehouda Enzel, P. Kyle House, and Franco Biondi, 2002. Climate Variability and Flood Frequency at Decadal to Millennial Time Scales. *In:* Ancient Floods, Modern Hazards; Principles and Applications of Paleoflood Hydrology, Water Science and Application No. 5. American Geophysical Union, pp 21-45.

Redmond, Kelly T. and R.W. Koch, 1991. Surface Climate and Streamflow Variability in the Western United States and Their Relationship of Large-Scale Circulation Indices. Water Resources Research 27(9):2381-2399.

Service, Robert, 2004. As the West Goes Dry. Science 303:1124-1127.

Taylor, George H., and C. Hannan, 1999. The Climate of Oregon. Oregon State University Press, Corvallis, Oregon.

Trenberth, Kevin E. and David P. Stepaniak, 2001. Indices of El Niño Evolution. Journal of Climate 14:1697-1701.

U.S. Historical Climatology Network, 1996. Monthly Temperature and Precipitation Data (Revision 3) *Available at* http://cdiac.ornl.gov/epubs/ndp019/ndp019.html. *Accessed in* July, 2003.

Wernstedt, Kris and Robert Hersh, 2002. Climate Forecasts in Flood Planning: Promise and Ambiguity. Journal of the American Water Resources Association (JAWRA) 38(6):1703-1713.

Wolter, Klaus, R.M. Dole, and C.A. Smith, 1999. Short-Term Climate Extremes Over the Continental United States and ENSO. Part I: Seasonal Temperatures. Journal of Climate 12:3255-3272.

Zhang, Y., J.M. Wallace, and D. Battisti, 1997. ENSO-Like Interdecadal Variability: 1900-1993. Journal of Climate 10:1004-1020.