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Linking the pacific decadal oscillation to seasonal stream discharge patterns in Southeast Alaska

E.G. Neal[a,*], M. Todd Walter[b,1], C. Coffeen[a,c]

[a]US Geological Survey, Water Resources Division, Juneau, AK 99801, USA
[b]Biological and Environmental Engineering, Cornell University, Ithaca, NY 14852-5701, USA
[c]Environmental Sciences, University of Alaska Southeast, 11120 Glacier Hwy, Juneau, AK 99801, USA

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Abstract

This study identified and examined differences in Southeast Alaskan streamflow patterns between the two most recent modes of the Pacific decadal oscillation (PDO). Identifying relationships between the PDO and specific regional phenomena is important for understanding climate variability, interpreting historical hydrological variability, and improving water-resources forecasting. Stream discharge data from six watersheds in Southeast Alaska were divided into cold-PDO (1947–1976) and warm-PDO (1977–1998) subsets. For all watersheds, the average annual streamflows during cold-PDO years were not significantly different from warm-PDO years. Monthly and seasonal discharges, however, did differ significantly between the two subsets, with the warm-PDO winter flows being typically higher than the cold-PDO winter flows and the warm-PDO summer flows being typically lower than the cold-PDO flows. These results were consistent with and driven by observed temperature and snowfall patterns for the region. During warm-PDO winters, precipitation fell as rain and ran-off immediately, causing higher than normal winter streamflow. During cold-PDO winters, precipitation was stored as snow and ran off during the summer snowmelt, creating greater summer streamflows. The Mendenhall River was unique in that it experienced higher flows for all seasons during the warm-PDO relative to the cold-PDO. The large amount of Mendenhall River discharge caused by glacial melt during warm-PDO summers offset any flow reduction caused by lack of snow accumulation during warm-PDO winters. The effect of the PDO on Southeast Alaskan watersheds differs from other regions of the Pacific Coast of North America in that monthly/seasonal discharge patterns changed dramatically with the switch in PDO modes but annual discharge did not. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

The Pacific decadal oscillation (PDO) is a pattern of Pacific climate variability that has been shown to have regional climate signatures similar to those associated with the El Niño/Southern Oscillation (ENSO) (Mantua et al., 1997; Zhang et al., 1997). PDO ‘regimes’ typically persist for 2–3 decades while ENSO events last from 6 to 18 months. The PDO index defined by Mantua et al. (1997) is a November–March average of the leading monthly principal component from a principal component analysis of Pacific Ocean sea-surface temperatures (SST) above 20°N latitude. This report refers to the PDO in terms of warm and cold phases as they relate to variations in

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* Corresponding author. Tel.: +1-907-586-7216x22.
E-mail addresses: egneal@usgs.gov (E.G. Neal), mtw5@cornell.edu (M. Todd Walter).
[1] Tel.: +1-607-255-2488; fax: +1-607-255-4080.

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southeast Alaskan temperature. The warm phase, indicated by positive polarity in the PDO index, is associated with anomalously cool Central-North-Pacific SSTs and warm SSTs along the Pacific Northwest (PNW) coast. The cold phase, indicated by negative polarity in the PDO index, occurs when the SST anomalies are reversed. Accompanying the anomalies in SST are corresponding anomalies in sea level pressure and wind stress in the North Pacific.

Variations in a number of environmental processes have been linked to the PDO including salmon productivity (Mantua et al., 1997; Hare et al., 1999), glacial mass balances (Bitz and Battisti, 1999; Hodge et al., 1998), regional drought (Nigam et al., 1999), and streamflow patterns (Hamlet and Lettenmaier, 1999; Nigam et al., 1999).

Like ENSO, the effects of the PDO are locally specific in that during each phase some regions experience droughts and other receive relatively high precipitation (Nigam et al., 1999). Variations in regional mean annual temperatures can also be expected to vary depending of the phase of the PDO. Southeast Alaskan temperatures observed during the warm-PDO (1977–1998) were higher than during the cold-PDO (1947–1976). Juneau's average annual temperatures were 5.6 and 4.3° for the warm- and cold-PDOs, respectively. Winter temperatures, in particular, were 2 °C warmer during the warm-PDO, which corroborates the measured average annual snowfall at Juneau, which was 35% lower during the warm-PDO (2048 mm) than during the cold-PDO (2915 mm) (significant at $\alpha = 0.1$).

Correlations between the PDO and streamflow are certain enough in the PNW that Hamlet and Lettenmaier (1999) suggest using PDO in Columbia River streamflow forecasting. Most hydrological linkages to the PDO have shown periodic fluctuations in average annual streamflow that are synchronous with PDO switches. For the PNW, it appears that cold-PDO phases generally correlate with above average annual streamflow and warm-PDO phases correlate with below average annual streamflow (Hamlet and Lettenmaier, 1999; Nigam et al., 1999). Hamlet and Lettenmaier (1999) showed that the largest changes in streamflow in the Columbia River in Washington were associated with the summer (May–July).

The objective of this study was to identify, characterize, and explain flow variations in Southeast Alaskan streams associated with changes in the PDO. Because Southeast Alaska has a sparse distribution of gauging stations and few gauging stations with long-term streamflow records, the scope of this study is limited to six watersheds during the period 1947–1998. Although some debate continues regarding recent changes in the polarity of PDO, it is widely acknowledged that the climate system over the North Pacific Ocean was observed to shift its basic state abruptly during the winter of 1976–1977 (Trenberth, 1990; Miller et al., 1994; Mantua et al., 1997) resulting in a shift from a cold- to a warm-PDO. Previous PDO switches may have occurred in 1947 and 1925 (Minobe, 1997; Mantua et al., 1997).

2. Regional characteristics and methods

Southeast Alaska's weather is characteristically Maritime. The region's steep mountains are an orographic barrier to weather patterns that generally move landward from the Pacific; this results in year round storms and relatively high annual precipitation ($>1000\ \mathrm{mm\ yr^{-1}}$). Snow occurs frequently in all areas during the winter months with typical accumulations of 1 m to >5 m depending on elevation. Due to the steep topography and wide range of elevations, precipitation is highly variable within the region with substantially more precipitation at higher elevations. Average summer temperatures are around 18 °C and winter temperatures are about −4 °C; temperatures vary with elevation, latitude, and proximity to the coast. Coastal areas experience slightly warmer winters and cooler summers. Temperature extremes are associated with continental air masses from Northern Canada. Much of Southeast Alaska is temperate rainforest and, though many are rapidly receding, glaciers are one of the region's defining characteristics.

Southeast Alaska has a sparse distribution of streamflow gauging stations and few gauging stations with long-term streamflow records. Streamflow data collected by the US Geological Survey (USGS) for six watersheds in Southeast Alaska were divided into cold-PDO (1947–1976) and warm–PDO (1977–1998) data subsets. Insufficient streamflow data prevented meaningful investigation prior to 1947. The watersheds range in size from 15 to 220 $\mathrm{km^2}$

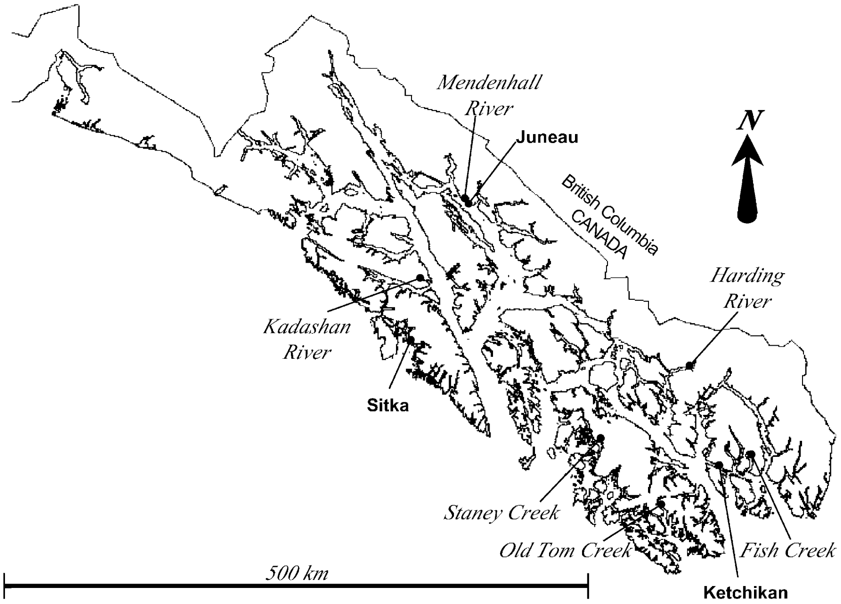

Fig. 1. Location of stream gaging stations in Southeast Alaska.

and represent a wide spatial extent of Southeast Alaska (Fig. 1). With the exception of Staney Creek, none of the watersheds examined have undergone significant human alteration. Physical characteristics for each watershed are shown in Table 1. We compared deviations in warm- and cold-PDO average streamflows from the long-term mean using standard statistical methods. Annual, monthly, and seasonal averages were investigated. Note that annual records were taken as water years, October–September. For notational simplicity, we used the term 'summer' throughout this paper to describe the period during which snowmelt contributions are typically significant to regional streamflow; specifically May–July. Similarly, 'winter' refers to the entire fall and winter season when precipitation commonly falls as snow, specifically December–March.

3. Results

Time series of summer flows (March–July) were developed to check that the 1977 PDO-shift correlated with the shifts in streamflow patterns. Fig. 2(a) shows the time series for the PDO-index from 1947 to 1998. Fig. 2(b) shows the differences between mean summer discharges for each year from 1947 to 1998 and the mean long-term (1947–1998) summer discharge of Fish Creek. The PDO-shift in summer streamflows in 1977 corresponds with the beginning of a pattern of low summer flows that persist through 1998 (Fig. 2). The 1977 PDO shift was previously noted by Mantua et al. (1997). Similar shifts are apparent for all the watersheds, although somewhat less obviously for the two largest watersheds (data not shown). The two largest streams (Mendenhall River and Harding River) have larger, glaciated, and more elevated basins and though they do not exhibit such apparent shifts in summer streamflow, they do exhibit an obvious switch in winter discharge beginning in 1977. In fact, all basins exhibited increase in winter streamflow following the 1977 PDO regime shift (data not shown). Climatic activity in Southeast Alaska is complex and it is probable that other factors also influenced the observed changes in seasonal streamflow patterns. Other climate indices have been shown to correlate with climatic variations in western North America and some of these, like ENSO, appear to interact systematically with the PDO (Mantua et al., 1997). However, we have not yet found any consistent correlations between these other indices and the types of streamflow patterns discussed in this paper.

Table 1
Physical characteristics of the watersheds

Watershed (station number)	Gage location (latitude, longitude)	Max./mean elevation[a] (m)	Drainage area (km^2)	Period of record	Basin coverage
Old Tom Creek (15085100)	55 23′ 44″, 132 24′ 25″	632/305	15.3	1949–1998	4% of basin is lakes, 85% forested
Kadashan River (15106920)	57 39′ 46″, 135 11′ 06″	808/311	26.4	1968–1978, 1980–1998	1% of basin is lakes, 94% forested
Fish Creek (15072000)	55 23′ 31″, 131 11′ 38″	1219/314	83.1	1915–1936, 1938–1998	14% of basin is lakes, 72% forested
Staney Creek (15081497)	55 48′ 05″, 133 06′ 31″	876/269	131.1	1964–1981, 1989–1998	94% Forested
Harding River (15022000)	56 12′ 48″, 131 38′ 12″	1615/732	174.6	1951–1998	9% Glacially covered, 1% of basin is lakes, 40% forested
Mendenhall River (15052500)	58 25′ 47″, 134 34′ 22″	2134/994	220.4	1965–1994, 1996–1998	54% Glacially covered[b] 3% of basin is lakes, 8% forested

[a] All watersheds discharge near sea-level.

[b] Most recent estimate by Motyka et al. (2001); a slightly earlier manuscript (Jones and Fahl, 1994) reports 66% glacier coverage in the Mendenhall Watershed.

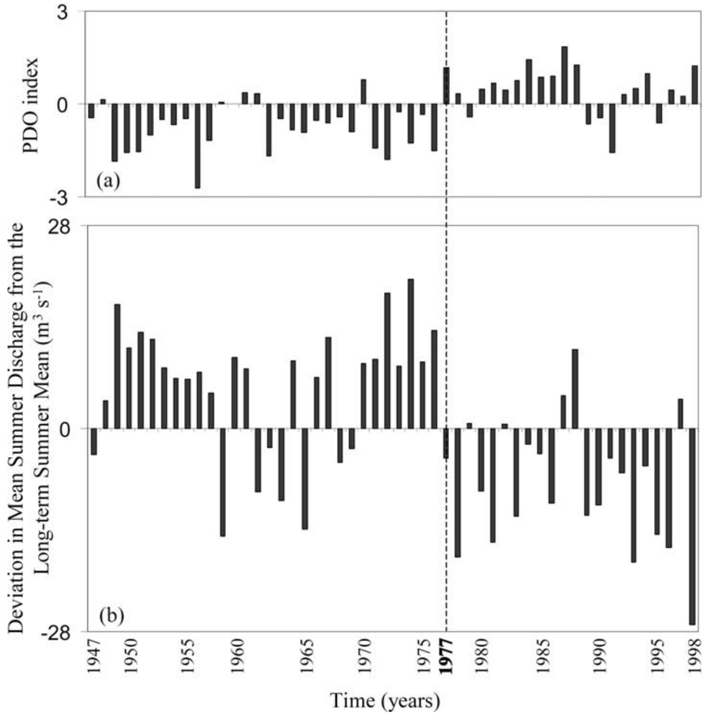

Fig. 2. Time series of the PDO index (a) and summer flow deviations from the long-term mean summer deviations for Fish Creek (b). The dashed line shows 1977, the widely published date of the most recent PDO shift (a).

Table 2 shows the average annual streamflows for the entire record and for the warm- and cold-PDO cycles. Unlike similar studies in the PNW (Nigam et al., 1999; Hamlet and Lettenmaier, 1999), most of these Southeast Alaskan watersheds showed no significant ($\alpha = 0.1$) differences in annual average discharge between the PDO cycles. The exception was the Mendenhall River, which had significantly ($\alpha = 0.1$) higher warm-PDO annual average streamflow than cold-PDO streamflow. There was little consistency in the overall character of the annual streamflows; three watersheds showed higher warm-PDO flows than the cold ones and two showed lower warm-PDO flows than the cold ones. The watersheds that showed small increase in annual streamflow were consistent with observed differences in precipitation in Juneau and Sitka between the two PDO modes. Juneau's average annual cold- and warm-PDO precipitation were 137 and 147 cm, respectively, and Sitka's were and 203 and 235 cm, respectively. The precipitation change was significant ($\alpha = 0.1$) at Sitka, but not at Juneau.

Table 2
Average/standard deviation of annual streamflow for the entire period and for the cold-PDO, warm-PDO (units: $m^3\ s^{-1}$)

	Entire record (1947–1998)	Cold-PDO (1947–1976)	Warm-PDO (1977–1998)
Old Tom Creek	1.16/0.19	1.08/0.15	1.26/0.20
Kadashan River	1.8/0.26	1.8/0.21	1.74/0.39
Fish Creek	11.9/1.59	12.1/1.41	11.5/1.91
Staney Creek	10.3/0.31	10.3/0.10	10.3/0.22
Harding River	20.9/2.46	20.9/1.99	21.1/2.95
Mendenhall River	32.8/5.05	30.6/2.91	34.0/5.61

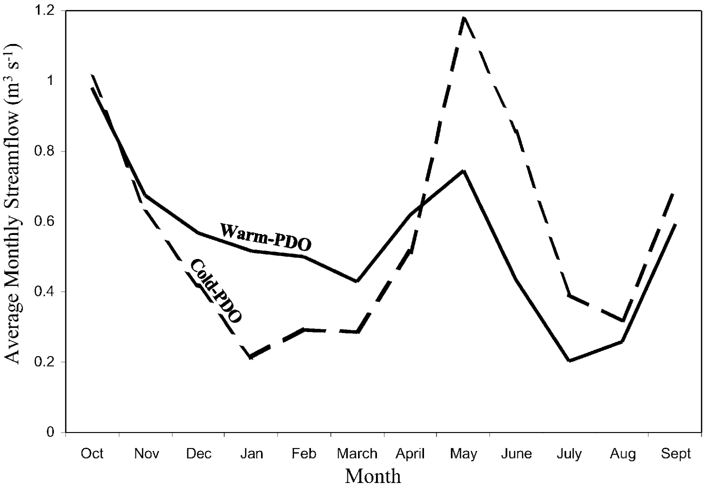

Fig. 3. Kadashan River monthly average streamflow for the warm- and cold-PDO cycles. The dashed line corresponds to the cold-PDO and the solid line to the warm-PDO.

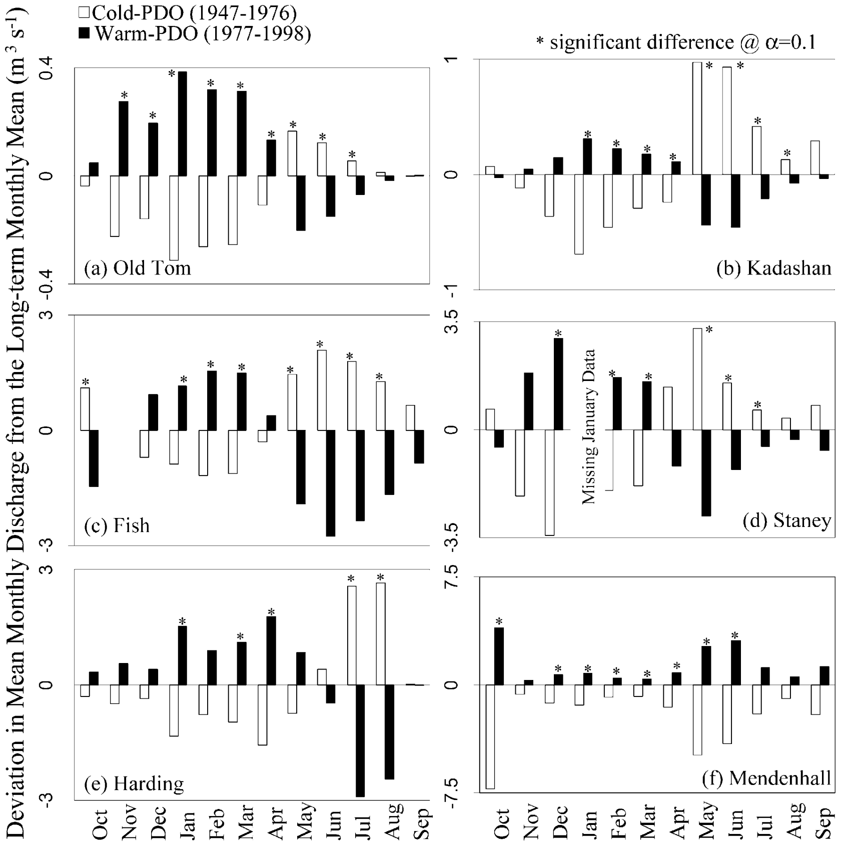

Fig. 4. Mean monthly flow differences between the long-term (1947–1998) mean and each PDO mode (open, old-PDO; solid ,warm-PDO) for all watersheds. The * indicates significant differences between the monthly warm-PDO and cold-PDO flows at $\alpha = 0.1$.

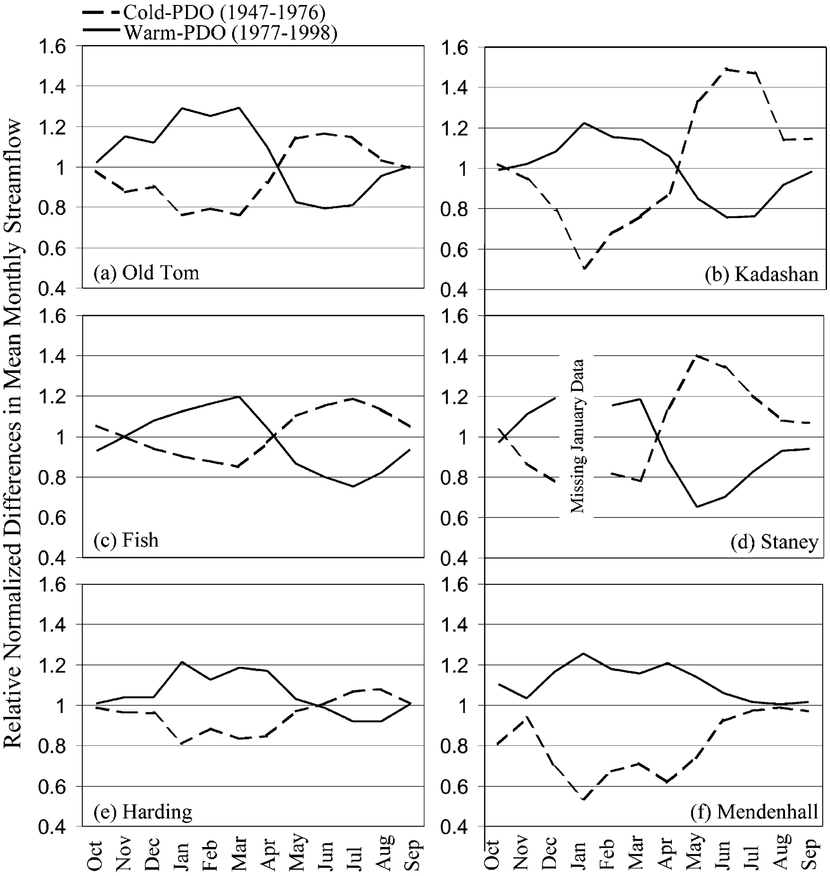

Fig. 5. Relative, normalized mean monthly flow differences (RND) for each PDO mode (dashed, cold-PDO; solid, warm-PDO) for all watersheds.

Although the average annual streamflows show no substantial difference between PDO modes, significant differences exist in the seasonal patterns of discharge. Fig. 3 shows the average annual cold- and warm-PDO hydrographs for the Kadashan River as an example. The summer streamflow is lower for the warm-PDO than for the cold-PDO and the winter flow is higher for the warm-PDO than for the cold-PDO. Fig. 4 shows the differences between the overall (1947–1998) mean monthly discharge and the mean monthly discharge for each PDO cycle for all the watersheds. All the watersheds showed higher winter and early spring discharges during the warm-PDO than during cold-PDO. For all the watersheds except the Mendenhall River, this relationship is reversed in the summer such that the summer warm-PDO discharges were lower than the cold. Over 60% of the monthly flow differences between the PDO modes were significant ($\alpha = 0.1$). The seasonal reversal in flow behavior, i.e. where the data in Fig. 4 change from positive to negative, typically occurred in the spring and again in the fall. In general, the larger basins that include high-elevation areas switch later in the spring and earlier in the fall than the smaller low-elevation basins. The near symmetry shown in Fig. 4 illustrates the consistency in annual discharge between PDO regimes.

The monthly flow differences between the PDO modes are even more apparent in Fig. 5, which shows the relative normalized differences (RND)

$$\mathrm{RND} = \frac{Q_i - Q}{Q} \tag{1}$$

where Q_i is the mean monthly streamflow within a

PDO mode and Q is the long-term (1947–1998) mean monthly discharge. Particularly apparent in Fig. 5 is that the relative differences for the two largest watersheds are most substantial during the winter and early spring, whereas the relative differences for the remaining watersheds are large in both the winter and summer flow periods. Note that Fig. 5 addresses flow seasonality but not volume.

Generalizing flow behavior on a seasonal basis, all the watersheds exhibited significantly ($\alpha = 0.1$) higher average winter (December–March) streamflow for the warm-PDO than for the cold-PDO. Winter streamflow differences between PDO regimes ranged from 26% in Fish Creek to 81% in the Mendenhall River. Five of the six steams showed lower summer (May–July) streamflow during warm-PDO than during the cold-PDO with differences ranging from 5% in the Harding River to 48% in Staney Creek. Differences in summer streamflow were significant ($\alpha = 0.1$) in the four smallest systems. The Mendenhall River's summer streamflow was 12% higher during the warm-PDO than during the cold. The two largest watersheds showed smaller differences in summer flow between the two PDO modes. The Mendenhall had uniquely high average warm-PDO summer flow.

4. Discussion

Climate conditions in southeast Alaska are such that small changes in winter temperatures have profound effects on seasonal streamflow regimes. Slight increases in winter temperatures result in a larger percentage of winter precipitation falling as rain, which runs-off immediately to produce higher-than-normal winter streamflow. Colder winters, on the other hand, result in more precipitation falling as snow, which does not run-off until summer, producing higher-than-normal summer streamflow. The streamflow results of this study are consistent with regional climatic trends. Both summer and winter temperatures in Juneau were significantly ($\alpha = 0.1$) higher for the warm-PDO; winter temperatures were 2 °C warmer, and the summer temperatures were 1 °C higher. These temperature observations corroborate the measured average annual snowfall at Juneau, which was 35% lower during the warm-PDO (2058 mm) than during the cold-PDO (2915 mm) (significant at $\alpha = 0.1$).

For the Kadashan River during the warm-PDO (Fig. 3), lower snowfall combined with similar, or slightly higher overall precipitation resulted in higher winter streamflows than for the cold-PDO. Figs. 4 and 5 demonstrate relatively high warm-PDO winter streamflows for all the watersheds, independent of any characteristics shown in Table 1. Furthermore, low summer-snowpack due to lower snowfall during the warm-PDO winter resulted in relatively small snowmelt contributions to summer streamflow and thus lower overall warm-PDO summer discharge than cold-PDO summer discharge (Figs. 3–5). Moore (1996) and Moore and McKendry (1996) noted similar snowfall-related trends and streamflow response in coastal British Columbia. Figs. 4 and 5 indicate that this summer trend is consistent over all the watersheds with the exception of the Mendenhall River.

It is interesting that the annual discharges from the study watersheds (excluding the Mendenhall) were relatively constant (Table 2, Fig. 3) despite generally higher rainfall during the warm-PDO than during the cold-PDO. One explanation for this apparent disparity may be increased evapotranspiration (ET) during the warm-PDO than during the cold-PDO. Indeed, the higher air temperature associated with the warm-PDO indicates increased energy available for ET and Bauer and Mastin (1997) showed that ET in the PNW was most strongly controlled by air temperature and advection. Using the Blaney–Criddle equation (Soil Conservation Service, 1970) to correlate seasonal ET and air temperature, Juneau's estimated average warm-PDO ET is 6–13 cm yr^{-1} higher than the cold-PDO ET, which is similar to the observed, 10 cm yr^{-1} increase in Juneau precipitation between the two cycles. The range of estimated ET accounts for various estimates of the Blaney–Criddle parameters.

The Mendenhall River is unique in this study in that one of its principle sources is meltwater from the Mendenhall Glacier (Motyka et al., 2001) and in that it has an elevated basin with respect to other streams examined (Table 1). The Mendenhall Glacier covers about 54% of the Mendenhall River's drainage area and as much as 50% of the average summer discharge in the Mendenhall River can be attributed to seasonal melting of the glacier ice and snow (Motyka et al., 2001). The Nugget Glacier also contributes additional meltwater to the Mendenhall River. The large portion of discharge associated with glacial meltwater combined with higher summer temperatures and relatively high watershed elevation attenuates the summer discharge response observed in the other watersheds that resulted from reduced warm-PDO winter snowfall. In essence, the Mendenhall's spring/summer discharge is not as sensitive as the other rivers to low winter snowfall for any particular year or even tens of years because of the large volume of water stored in its glacier and enhanced snowfall accumulation at relatively high elevations.

While differences in summer steamflow on the Mendenhall River do not follow the same trends as the other five steams it is interesting that the largest increase in Mendenhall River summer streamflow appear to begin in 1989 (data not shown) indicating an increase in melting rates of the Mendenhall Glacier. This is consistent with the findings by Hodge et al. (1998) who measured large decreases in the mass balance of coastal Alaska's Wolverine Glacier beginning in 1989 and continuing through 1995.

The Harding River also has a substantial glacial contribution to streamflow and drains a relatively large and elevated region similar to the Mendenhall River (Table 1). There are similarities between these two large, glacially fed watersheds with respect PDO-linked flow response (Fig. 5). Harding and Mendenhall both have much greater RNDs for their winter flows than during the rest of the year. The other watersheds exhibit equally strong, though opposing RND shifts in both winter and summer.

5. Conclusion

This investigation demonstrates that patterns of monthly discharge in Southeast Alaskan streams change with PDO modes. Unlike other places in the PNW, Southeast Alaskan streams show little change in annual discharge despite obvious and significant changes in their flow behavior throughout the year. In general, the non-glacially-fed watersheds demonstrated relatively high winter flow and corresponding low summer flow during the warm-PDO, with a reversal of this pattern during the cold-PDO. Watersheds with significant glacial source-water exhibited increases in warm-PDO streamflow for all months relative to cold-PDO flows.

The changes in streamflow patterns are primarily a result of temperature differences between PDO modes, which strongly influence the form of winter precipitation in southeast Alaska. During the warm-PDO, the warmer winter temperatures result in enhanced wintertime rainfall and decreased snowfall, which, in turn, results in relatively high winter rainfall-run-off and relatively low summer run-off from snowmelt. Many of the island and coastal streams in southeast Alaska have the potential for significant alteration of streamflow patterns as a result of small changes in winter temperatures.

Identifying significant changes in streamflow behavior has potential ramifications for a wide range of activities that are linked to streamflow such as water resource management, hydrological forecasting, and fisheries management. Because the regional stream gage density is exceedingly low in Southeast Alaska, management and design decisions are often based on short periods of streamflow data that may not reflect differences in flow patterns relating to the PDO. Several additional hydrologically and ecologically significant parameters are likely to have significant differences between PDO modes. These findings are particularly important to Southeast Alaska because they demonstrate the prevalence of long-term trends that are foundational to making meaningful management decisions associated with water resources.

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