Seasonal versus transient snow and the elevation dependence of climate sensitivity in maritime mountainous regions

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[1] In maritime mountainous regions, the phase of winter precipitation is elevation dependent, and in watersheds receiving both rain and snow, hydrologic impacts of climate change are less straightforward than in snowmelt-dominated systems. Here, 29 Pacific Northwest watersheds illustrate how distribution of seasonal snow, transient snow, and winter rain mediates sensitivity to 20th century warming. Watersheds with >50% of their area in the seasonal snow zone had significant ($\alpha \leq 0.1$) trends towards greater winter and lower summer discharge, while lower elevations had no consistent trends. In seasonal snow-dominated watersheds, runoff occurs 22–27 days earlier and minimum flows are 5–9% lower than in 1962, based on Sen's slope over the period. Trends in peak streamflow depend on whether watershed area susceptible to rain-on-snow events is increasing or decreasing. Delineation of elevation-dependent snow zones identifies climate sensitivity of maritime mountainous watersheds and enables planning for water and ecosystem impacts of climate change. **Citation:** Jefferson, A. J. (2011), Seasonal versus transient snow and the elevation dependence of climate sensitivity in maritime mountainous regions, *Geophys. Res. Lett.*, *38*, L16402, doi:10.1029/2011GL048346.

1. Introduction

[2] In snowmelt-dominated watersheds, the effects of climate change are being felt as shifts in snow accumulation, spring runoff, and summer low flows [*Hidalgo et al.*, 2009; *Stahl et al.*, 2010; *Stewart*, 2009], and water supplies will be more dramatically affected in the current century than they were in the last one [*Adam et al.*, 2009]. However, the hydrologic impacts of climatic change in areas which receive both winter snow and rain are poorly understood.

[3] Mountain ranges along coasts have strong elevational temperature gradients that control phase of precipitation, and many such areas receive abundant winter precipitation. Mountainous areas in maritime climates occur in the Pacific Northwest, New Zealand, Tasmania, southern Chile, the Pyrenees, Scotland, and the Turkish Black Sea coast. In these areas, lower altitude portions of watersheds may receive winter rain, while at high altitude seasonal snow accumulates. Intermediate elevations are occupied by a transient snow zone, where snow falls and melts more than once per winter [*Harr*, 1981]. This zone plays in an important role in flood generation, as most rain-on-snow events occur therein [*Harr*, 1981]. Modeling studies suggest that streamflow from intermediate elevation watersheds is more sensitive to historical and projected warming than watersheds at higher or lower elevations [*Cuo et al.*, 2009; *Knowles and Cayan*, 2004].

[4] Insight into how on-going climatic changes are impacting stream hydrology in maritime mountainous areas is important for effectively managing water resources for human populations and for projecting impacts to aquatic and estuarine ecosystems. This paper uses historical streamflow records from the US Pacific Northwest (PNW) to explore the elevation-dependence of watershed climate sensitivity, with a primary goal of understanding how the distribution of transient versus seasonal snow mediates hydrologic response to warming.

[5] In the PNW, rivers originate in the coastal cordillera of the Cascades, Olympics, and Coast Ranges. These mountains rise from near sea level to peak elevations of 1000 to >4000 m, and trap much of the moisture from air masses moving off the Pacific Ocean. Temperatures in the maritime PNW have increased by 0.9°C since 1920, while precipitation changes have been minor [*Mote*, 2003], and spring snowpack in the Cascades declined by at least 23% between 1930 and 2007 [*Stoelinga et al.*, 2010]. Low elevation sites have experienced the most dramatic losses in spring snow water equivalent [*Mote*, 2006], and the maritime PNW has experienced greater declines than the rest of the western US in the fraction of winter precipitation falling as snow [*Knowles et al.*, 2006]. *Nolin and Daly* [2006] mapped areas of "at risk" snow in the PNW, finding that 12.5% of snow in the Washington Cascades, 21.8% in the Oregon Cascades, and 61% in the Olympics would convert to winter rainfall with 2°C warming.

2. Datasets and Analyses

[6] Discharge data from USGS gages located west of the Cascade crest in Oregon and Washington were considered for analysis. Records analyzed met the requirements of the Hydro-climatic Data Network (HCDN) [*Slack et al.*, 1993], by being a HCDN gage or being nested within a HCDN watershed. Records were continuous for one or both of the two periods of analysis: water years 1940–2007 and 1962–2007 (water year begins October 1 of the preceding calendar year). These periods were selected to simultaneously maximize record length and the number of gages. For 1940–2007, 23 gages were identified, and for 1962–2007, 29 gages were identified (Figure 1 and Table S1 in the auxiliary material).[1]

[7] Watershed boundaries were delineated from 1/3 arc-second digital elevation models (DEMs) of the National Elevation Dataset [*Gesch et al.*, 2002; *Gesch*, 2007].

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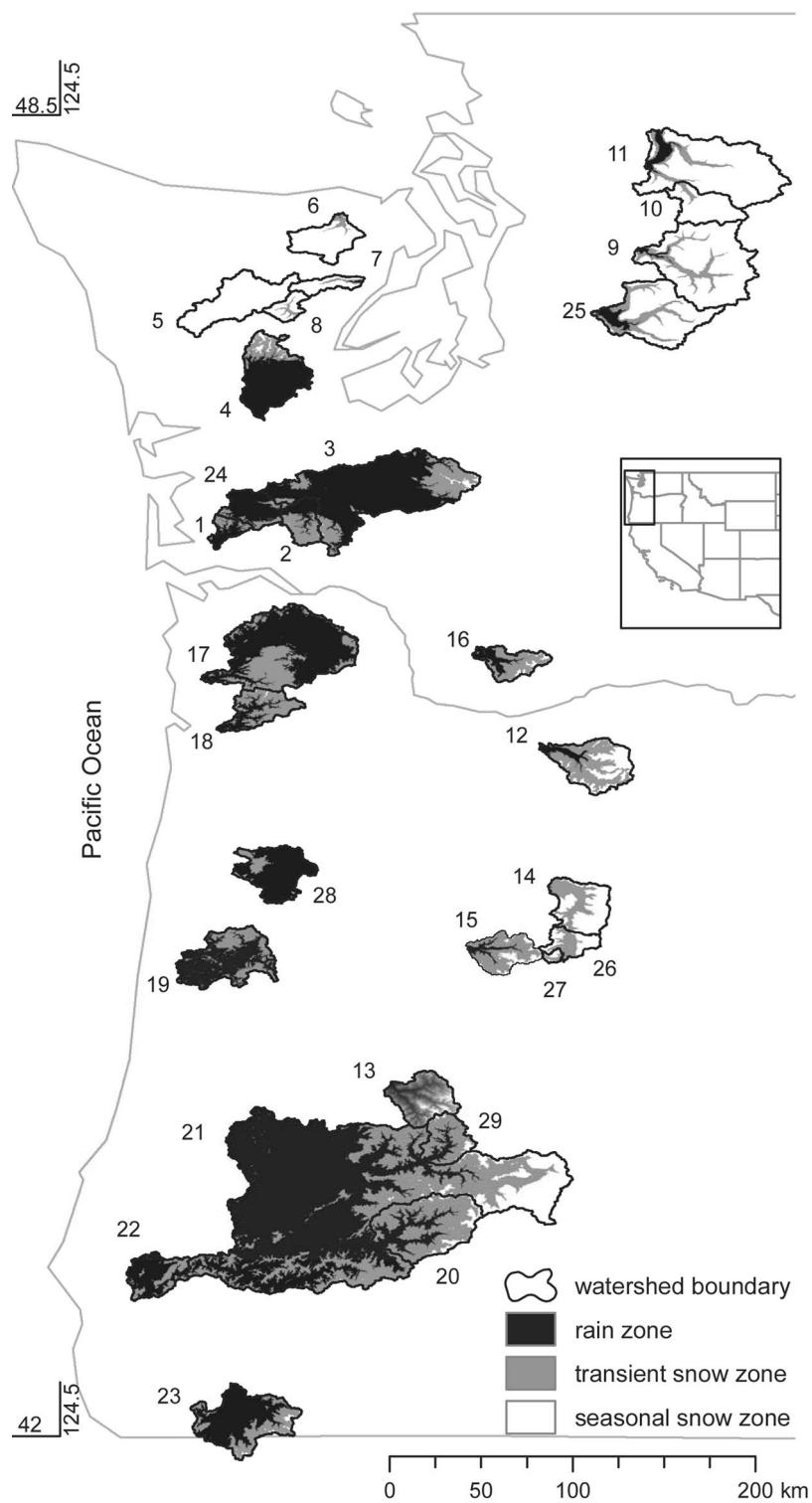
Figure 1. The 29 study watersheds, showing the distribution of rain-, transient snow-, and seasonal snow-dominated zones, delineated from SNOTEL and literature-based values.

Watershed hypsometry was calculated in 10-m elevation bands from the DEMs. Glacier covered area in each watershed was calculated based on digitized glacier outlines from 1:100,000 US Geological Survey maps (obtained from Portland State University at http://www.glaciers.pdx.edu/).

[8] The elevations at which seasonal snow zone (SSZ), transient snow zone (TSZ), and rain zone dominantly occur during the winter vary with latitude in the PNW, and two methods were used to delineate these zones in the study watersheds. First, data from SNOTEL stations (http://www.wcc.nrcs.usda.gov/snow/) located west of the Cascades and existing literature references [*Christner and Harr*, 1982; *Connelly*, 1992; *Grant et al.*, 2008; *Harr*, 1986; *Kattelmann and Ice*, 2004] were used to estimate the boundary between

each zone, and a visual best fit line was used to discriminate between seasonal and transient snow (Figure S1). The percent of watershed area within the SSZ, TSZ, and rain zone were calculated from watershed hypsometry and latitude-dependent elevation ranges for each zone. Each watershed was assigned the latitude of the geographic centroid, and no watershed spanned more than 1° latitude. Second, the Parameter-elevation regressions on independent slopes model (PRISM) provided a dataset of mean monthly minimum temperature, averaged for January through March 1971–2000 (JFM_{min}) [*Daly et al.*, 1994, 2002]. A threshold JFM_{min} of 0°C was chosen to approximate the boundary between the TSZ and rain zone, while −2°C was chosen to approximate the boundary between SSZ and TSZ. There is no previously defined temperature threshold between the TSZ and SSZ, but −2°C threshold is consistent with *Nolin and Daly's* [2006] definition of "at risk" snow and with areas that will become rain-dominated by projected temperature increases in the region in the next 30–40 years [*Mote and Salathe*, 2010].

[9] Daily discharge data was used to calculate mean discharge for each water year and to determine the percent of annual discharge occurring in each of four periods: October–December (autumn), January–March (winter), April–June (spring), and July–September (summer). The day of the water year at which a given percentage of annual discharge has occurred is the daily quantile of flow (DQF), following *Moore et al.* [2007]. For 1962–2007, I calculated the DQF_{25}, DQF_{50}, and DQF_{75}, or the day after October 1 by which 25, 50, and 75% of the annual discharge had occurred.

[10] The non-parametric Kendall's tau test for trend, following the Theil-Sen approach [*Sen*, 1968] and removing the lag-1 autocorrelation [*Yue et al.*, 2002], was used to identify gages with statistically significant trends in annual, seasonal, DQFs, and annual maximum (peak) streamflows. This approach was also used to identify trends in annual precipitation for eight National Weather Service Cooperative Observer (COOP) stations in the study area (Table S2). DQFs were also compared to water year discharge using linear regression. The significance level ($\alpha = 0.1$) was chosen for comparison to previous studies [e.g., *Luce and Holdren*, 2009; *Stewart et al.*, 2005]. Using the method of *Benjamini and Hochberg* [1995] to control the false discovery rate that may result in significant relationships as a result of chance, an adjusted significance level of 0.016 was calculated, based on 486 tests and a chosen significance level of 0.1. With an unadjusted $\alpha = 0.1$, there were 149 statistically significant relationships identified, with 69 of the significant relationships between DQF and discharge. Using the adjusted $\alpha = 0.016$, 79 significant relationships occurred, with 51 of them between DQF and discharge. In this study, the potential for spurious identification of individual trends is less important than gaining an overall sense of how watershed elevation distribution mediates climate sensitivity, so the unadjusted significance level is used to quantify trends in the following discussion.

3. Results

[11] The 29 study watersheds ranged in area from 42 to 9539 km^2, with geographic centroids from 42.1 to 48.2°N and mean elevations from 153 to 1432 m (Table S1). All watersheds spanned more than one snow zone (Figure 1). Glacier covered area accounted for <2% of any the 10 study watersheds with glaciers, so their effects on seasonal and peak streamflows are considered negligible. Seven out of eight precipitation stations had no significant annual precipitation trends (Table S2), and only one of 29 watersheds exhibited a significant trend in annual discharge.

[12] Twenty four of the 29 watersheds were classified similarly by the two methods of apportioning watershed area (Figure S2). Twelve watersheds were dominantly in the SSZ, 3 were dominantly in the TSZ, and 9 watersheds were in the RZ. In 4 watersheds the SNOTEL/literature method placed the majority of watershed area in the TSZ, while the PRISM data was largely $JFM_{min} > 0$°C. The southernmost watershed had the majority of its area in the rain zone by the SNOTEL/literature method, but had 55% of its area between JFM_{min} of −2 and 0°C by the PRISM data. On average, the SNOTEL/literature method apportioned 1% more area to the SSZ and 15% more area to the TSZ than the PRISM method. The largest discrepancies were in the Olympics, where less land area was above the −2°C isotherm than suggested by the SNOTEL/literature values and in the central Oregon Cascades, where the reverse was true.

[13] Percent of the watershed in the SSZ is a strong control on the seasonal distribution of discharge (Figure 2), explaining almost 93% of the variation in the proportion of winter streamflow. In the spring and summer, the amount of watershed in the SSZ explains ~80% of the variation in streamflow across watersheds, as precipitation inputs decline, but snowmelt sustains discharge. There is less variation in autumn discharge, probably resulting from storage of precipitation in snowpack at higher elevations and in soil at lower elevations. Similar results were obtained when seasonal streamflow was plotted against watershed area with $JFM_{min} < -2$°C. Watershed area in the SSZ also influences the correlation between winter precipitation and winter discharge on an interannual basis. Watersheds with ≤20% of their area in the SSZ, had Pearson's correlation coefficients between winter discharge and winter precipitation at the best-correlated COOP station (Table S2) from 0.79 to 0.90 (average: 0.84). For SSZ-dominated watersheds, the correlation coefficients were lower (0.56–0.80; average: 0.68).

[14] Sensitivity to period of analysis was assessed by comparing the number of significant seasonal trends for 1940–2007 and 1962–2007. More than 40% of all seasonal trends identified as statistically significant for 1940–2007 (n = 22) were also significant in 1962–2007, while 69% of the significant trends for 1962–2007 (n = 13) were also significant for the period beginning in 1940. Therefore, while the identification of trends is somewhat sensitive to the chosen period of analysis, a substantial percentage of trends are identified across both periods. Six additional gage records available in 1962–2007 produced four significant trends, so the total number of significant seasonal trends for that period is 17. Thus, there are fewer significant trends in the shorter period, despite a greater number of records available for analysis than for 1940–2007. The longer period also offers the advantage of spanning more multi-year climate cycles (e.g., El Niño-Southern Oscillation). A longer period of record but fewer stations appears to provide a better sense of historical hydroclimatic trends than a shorter record with more stations, if there is adequate spatial coverage.
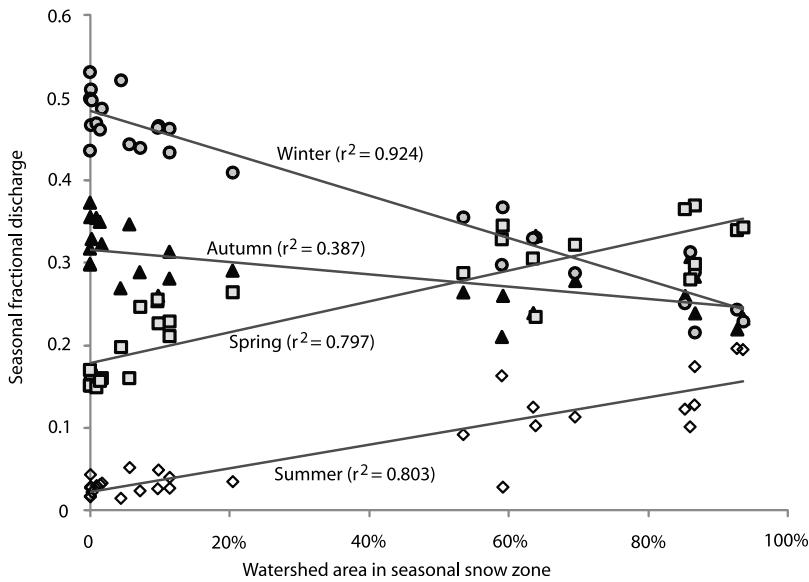
Figure 2. Seasonal distribution of stream discharge as a function of the percent of watershed area in the SSZ, as derived from the SNOTEL and literature-based values. Fractional discharge is calculated as the proportional of total annual flow, based on average data for 1962–2007, occurring in winter (circles), spring (squares), summer (diamonds), and autumn (triangles).

[15] Fourteen watersheds exhibited no significant seasonal trends, and all but one of those watersheds had <12% of its area in the SSZ and <16% with $JFM_{min} < -2°C$. Geographic centroids of the 14 watersheds ranged from 42.1°N to 47.2°N, covering all but the northernmost 1° of the study area. The absence of seasonal streamflow trends in rain and transient snow dominated watersheds across these latitudes suggests that historical climate change has not significantly influenced the seasonal distribution of precipitation or evapotranspiration. Most of the 15 watersheds where significant seasonal streamflow trends were observed are SSZ-dominated, so historical temperature changes affecting the partitioning of rain versus snow and the timing of snow melt are inferred to be the major drivers of trends in seasonal streamflow.

[16] Every SSZ-dominated watershed with a record beginning in 1940 (n = 9) exhibited a trend in the proportion of annual discharge occurring during winter (i.e., winter fractional discharge) (Figure 3 and Table S1). All of these watersheds had a 5–8% increase in winter fractional discharge between 1940 and 2007. Of the three SSZ-dominated watersheds with shorter records, Smith River exhibited a significant increase in winter fractional discharge, while the McKenzie and Snoqualmie Rivers did not. Five watersheds in which the SNOTEL/literature-based SSZ covers 53–93% of the area had statistically significant 4–5% decreases in the spring fractional discharge between 1940 and 2007 (Figure 3 and Table S1). Increases in winter fractional discharge and decreases in the spring are consistent with increasing incidence of rain and transient snow at increasingly higher elevations. No significant warming influence is expected in watersheds without much seasonal snow, as they have always had winter discharges reflective of winter precipitation, as shown by the strong correlation between discharge and COOP station precipitation.

[17] There were statistically significant 1–5% decreases in summer fractional discharge in eight SSZ-dominated watersheds during 1940–2007 (Figure 3 and Table S1). The

Sandy River did not experience a significant decline in summer discharge. Two of three SSZ-dominated streams with shorter records also exhibited significant decreasing trends of similar magnitude. Watersheds with less than 50% of their land area in the SSZ have not experienced warming-driven change in summer discharge distributions. Watershed area in the TSZ does not seem to influence trends in summer streamflow, probably because snow in the TSZ melts before July 1 and summer flows in these watersheds are a function of available baseflow [*Tague and Grant*, 2004].

[18] Average timings of DQF_{50} and DQF_{75} are highly dependent on the amount of watershed area in the SSZ (Table 1), with SSZ-dominated streams having more of their streamflow later in the year. The number of days between DQF_{25} and DQF_{50}, and between DQF_{50} and DQF_{75} also increases as area in the SNOTEL/literature-based SSZ increases. DQF_{25}, which occurs from mid-December to mid-January on average, occurs with fairly consistent timing across watersheds, regardless of area in the SSZ. DQF_{25} is likely a function of autumn precipitation, which generally occurs as rain or transient snow at all but the highest elevations. DQF findings are consistent with the seasonal discharge distributions (Figure 2), with both sets of indices showing that as watershed area in the SSZ increases, discharge is distributed more evenly throughout the year.

[19] Statistically significant linear relationships between annual discharge and DQFs occurred in all 18 streams with <59% of their watersheds in the SSZ, but not in all streams with >59% of their area in the SSZ (Table 1). In almost all cases, annual discharge was inversely related to DQF timing (i.e., in wetter years, DQFs occurred earlier). In rain and transient snow-dominated watersheds, runoff is generated by multiple precipitation events, which dominantly occur in the first half of the water year. In dry years, there are fewer precipitation events, resulting in a more even distribution of precipitation across the year, with a consequent shift toward later DQFs. The number of streams with statistically sig-
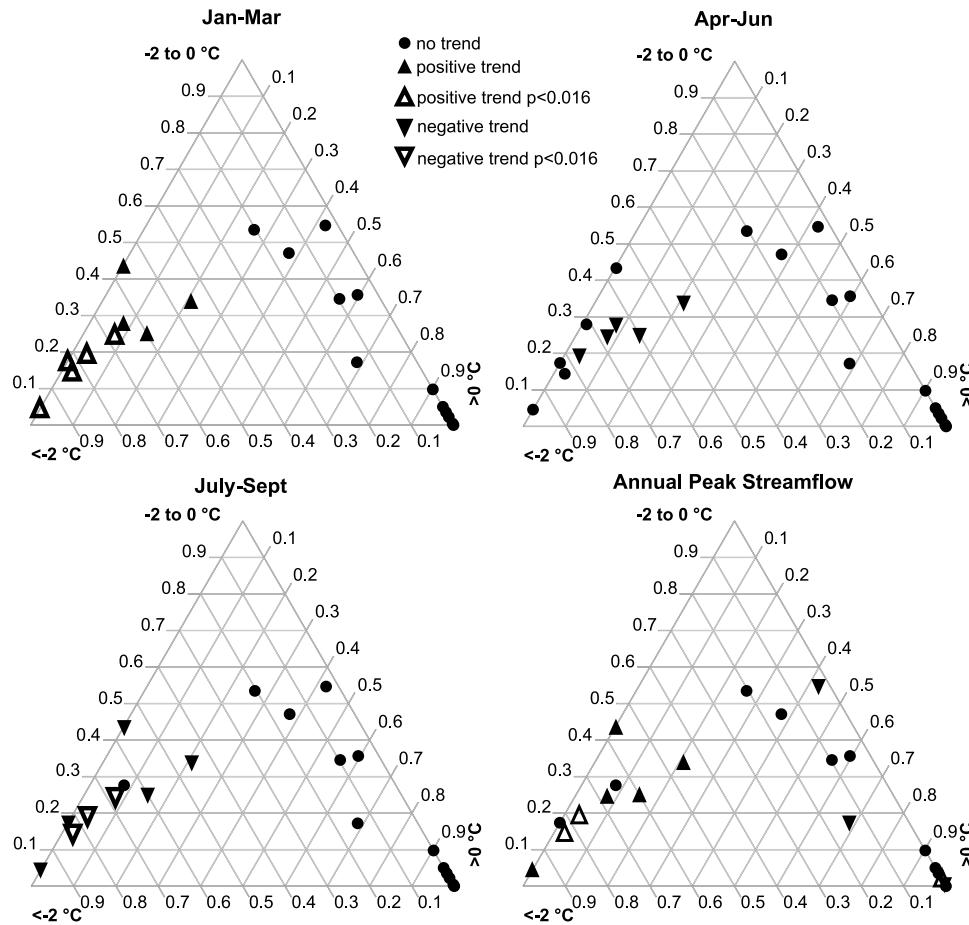
Figure 3. Significant trends (p < 0.1) and adjusted significant trends (p < 0.016) in seasonal and peak streamflows for 1940 to 2007, plotted against percent of watershed area in each of the PRISM-based JFM_{min} classes. In each panel, plotting positions are the same, since they are invariant properties of each watershed, but the symbol represents the significance of the trend for a season (January–March, April–June, July–September) or annual peak streamflow.

nificant relationships between discharge and DQF decreased from DQF_{25} to DQF_{50} to DQF_{75}. In those streams where a statistically significant relationship occurs, DQF_{75} has the strongest relationship with annual discharge, because its occurrence between mid-March and mid-June, after the bulk of the winter precipitation, makes it less sensitive to the timing of individual events.

[20] In most SSZ-dominated watersheds, DQF_{50} and DQF_{75} are insensitive to mean discharge, and their timing likely reflects the timing of snowmelt. In three SSZ-dominated watersheds, there is a statistically significant, but very weak positive relationship between annual discharge and DQF_{75}. A positive relationship between DQF and discharge is the result of wet years accumulating greater snowpack that takes longer to melt [Moore et al., 2007].

[21] The influence of warming on snowmelt timing is evidenced by significant shifts in the DQFs of SSZ-dominated watersheds. In six watersheds, DQF_{50} moved an average of 27 days earlier between 1962 and 2007, and, in eight watersheds, DQF_{75} shifted an average of 22 days earlier in the same period. In those watersheds, the DQF_{75} shift is more than the standard deviation of DQF_{75}. As DQF_{75} occurs earlier, late summer discharge becomes lower, even if total discharge remains the same, because the last 25% of discharge gets distributed over a greater number of days. In

each of the watersheds where a significant negative DQF_{75} trend was identified (n = 8), the minimum discharge between September 1 and November 30 has decreased relative to the water year mean discharge by 5–9% (p < 0.021) since 1962, based on the Sen's slope over the time period. Thus, as snowmelt occurs earlier and the summer recession lasts longer, the lowest flows, at the end of the summer

Table 1. Relationships Between DQF, Annual Discharge, and Water Year, 1962–2007

	Sign	DQF_{25}	DQF_{50}	DQF_{75}
Range in average DQF (days)		34	82	99
r^2 between average % of watershed in SSZ[a] and average DQF		0.22	0.75	0.9
Number of significant regressions with discharge[b]	−	25	23	18
	+	0	0	3
Average r^2 of significant regressions with discharge[b]	−	0.15	0.21	0.27
	+	0	0	0.07
Number of significant temporal trends[b]	−	1	6	8
	+	0	2	1
Average shift in DQF for significant temporal trends[b]	−	−19	−25	−22
	+	0	11	15

[a]SSZ as determined by the SNOTEL/literature method.
[b]Significant trends with both positive and negative slopes were observed. The notation distinguishes between the number and slope of significant trends by sign.

recession, become even lower. Given the strong relationships between discharge and DQFs in the rain and transient snow dominated watersheds, it is not surprising that there were few statistically significant temporal trends in these areas. Two non-SSZ-dominated streams had significant trends toward later DQF_{50} and DQF_{75}, but other watersheds with similar elevation distributions and centroid latitudes did not exhibit significant trends.

[22] Eleven watersheds exhibited statistically significant trends in annual maximum (peak) streamflows in 1940–2007 (Figure 3 and Table S1). Increasing peak streamflows were observed in seven of nine SSZ-dominated watersheds, probably corresponding to more frequent rain-on-snow events at higher elevations. Ten of 14 TSZ- and rain-dominated watersheds had no significant trends. Three watersheds had decreasing peak streamflows, possibly corresponding to decreasing incidences of rain-on-snow as snow becomes restricted to smaller areas in these watersheds. Results were similar for 1962–2007. Hydrologic modeling by *Hamlet and Lettenmaier* [2007] indicated that SSZ-dominated basins had decreasing flood risk as a result of historical warming, because of overall declines in spring snowpack, while TSZ-dominated basins had increased flood risks, and rain-dominated basins had unchanged risks. Methodological differences between that paper and this analysis may explain some of the apparent discrepancy in results, but both analyses suggest that a key control on flooding is the amount of the watershed susceptible to rain-on-snow events or rain at elevations where snow formerly would have occurred. Where warming increases the percent of the watershed impacted by rain-on-snow events, flood magnitude increases, but where warming decreases the percent of the watershed impacted by rain-on-snow, flood magnitude decreases.

4. Discussion

[23] In the maritime PNW, streams with greater than 50% of their area in the SSZ consistently show changes in seasonal and peak streamflow hydrology in association with historical climate trends. Even if much of the watershed area lies within the TSZ, watersheds with less than 50% seasonal snow are relatively immune to the effects of warming temperatures on seasonal hydrology. Given the distribution of gages used in this analysis, it is possible that watersheds with >20% and <50% of their area in the SSZ or >20 and <45% of their area with $JFM_{min} < -2°C$ have experienced some hydrologic impacts from warming temperatures. However, a 50% SSZ threshold seems to provide a good rule-of-thumb choice for identifying maritime mountainous watersheds sensitive to climatic warming. The identification of SSZ-dominated watersheds was similar in the SNOTEL/ literature and PRISM methods, suggesting that the availability and choice of datasets for classification is not a major control on the results obtained.

[24] If, as predicted, warming continues to be the dominant climate change in the PNW [*Mote and Salathe*, 2010], discharge from watersheds with substantial seasonal snow will continue to show climatic impacts until they have <50% of their area in the SSZ. At some point below this threshold, it is expected that the seasonal streamflow distribution will be relatively time-invariant. Future warming could alter evapotranspirative water use and affect seasonal fractional

discharge, but the historical record suggests that such effects are not yet significant.

[25] SSZ-dominated and groundwater-fed [*Jefferson et al.*, 2008] watersheds generate most streamflow during summer months, and it is in these watersheds where increasing winter and peak streamflows and declining spring, summer, and minimum flows will alter aquatic ecosystems and water supplies for irrigation, industrial use, and urban development. Declining late summer low flows are perhaps the most serious water resources concern. With 5–9% decreases in minimum flows over the past 50 years, and a parallel trend of the driest 25% of years becoming increasingly dry [*Luce and Holdren*, 2009], aquatic ecosystems and water supplies are increasingly likely to be stressed during late summer. Future warming will exacerbate that stress.

[26] Calculation of the watershed area within the SSZ, TSZ, and rain-dominated zones allows the approximate identification of seasonal and peak streamflow sensitivity to projected warming and is useful for focusing scientific, adaptation and mitigation resources on areas most sensitive to on-going climate changes. However, many watersheds occur at rain-and transient snow-dominated elevations and have strong relationships between precipitation timing and discharge. Thus, uncertainty in projections of precipitation amount and seasonality limit the ability to plan for climate change impacts in parts of maritime mountainous regions without seasonal snow.

5. Conclusions

[27] In watersheds receiving a mixture of winter rain and snow, the percentage of the watershed in the seasonal snow zone is the most important determinant of the seasonal streamflow distribution and the sensitivity to climatic warming. Trend analysis strongly indicates that the maritime PNW has seen a regional shift toward increasing winter discharge and decreasing summer discharge in seasonally snow dominated watersheds. The amount of watershed area in the transient snow zone does not influence the response of seasonal and peak streamflows to climate change. While this work focused on the PNW, the role of watershed elevation distribution in mediating climate sensitivity may be similar in other maritime mountainous regions.

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