

Exploratory analysis of snowpack in Washington State

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Abstract. Snow water equivalent (SWE) is used to measure seasonal snowpack accumulations. The annual maximum SWE and the rate of snowpack accumulation and melt-off determine the volume of spring runoff. In this paper, the objective is to use exploratory analysis to investigate the effect of variation in El Nino-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) on the annual maximum SWE and its associated timing. Traditionally, snowpack was thought to peak around April 1 in the Pacific Northwest. Twenty-five snowpack telemetry (SNOTEL) sites that have more than 20 years of daily records in Washington State were examined first. It was also found that the peaks of snowpack do not occur ten days before and after April 1 in most SNOTEL sites. Then Pearson's correlation coefficient test was applied to examine the relationship between last year's ENSO indices and the current annual maximum SWE and its associated timing for each site. Finally, a simple linear regression model was used to analyze the combined effects of ENSO and PDO as well as their interaction on the annual maximum SWE. Teleconnections between these indices and the annual maximum SWE in Washington State were identified by the exploratory analysis.

1. Introduction

Snow water equivalent (SWE), or the theoretical volume of water contained in a column of snow, is the most common measure used to track snowpack accumulation and meltoff. Currently, the SWE on April 1 is used to estimate the volume of spring and summer runoff for the snowmelt-dominated basins in the Pacific Northwest because previous research showed that SWE reaches its peak around April 1 at most snow course locations in the Western United States (McCabe, 1996; Serreze, et al., 1999; Clark, et al., 2001; Bohr and Aguado, 2001). Since SWE obtained from snowcourse measurements is typically verified by snow surveys undertaken on certain days of the year, these data are discrete measurements and not daily time series, and thus, the actual annual peak of SWE may not be captured by the data. It is therefore worthwhile to validate previous researches of peak SWE by examining some of the SWE data collected by the snowpack telemetry (SNOTEL) system in Washington State.

SWE on April 1 is useful in predicting the volume of spring-summer runoff (Gary and Male, 1981), but the value of SWE collected on that date seldom represents its annual peak value. It will be shown that snowpack on that date is usually undergoing either continued accumulation or meltoff at that time. For water resource managers, the timing of when snowpack reaches its maximum is equally as important as its maximum value because the timing of that peak helps determine when the transition from reservoir flood control operations to seasonal runoff storage operations should occur. It will be shown here that the annual maximum SWE does not occur over the interval from ten days before to ten days after April 1 at most SNOTEL sites investigated. Thus, the SWE measured on April 1 may represent either continued snowpack accumulation or meltoff, and can lead water resource managers to make totally different decisions in reservoir operations.

After examining some of the SWE data in Washington State, an exploratory analysis will be used to investigate the effect of variations of El Nino-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) on the annual maximum SWE and its associated timing. A number of studies have related variations of SWE around April 1 in the western United States to large-scale atmospheric circulation such as ENSO, Nino 3 sea surface temperature (SST) and the Pacific Decadal Oscillation (PDO) (Cayan and Webb, 1992; McCabe, 1994; McCabe and Legates, 1995; Cayan, 1996; Clark et al., 2001; McCabe and Dettinger, 2002). The observed effects of these climatic phenomena on snowpack have provided powerful illustrations of our regional sensitivity to climate, but the combined effects and interactions of these large-scale climate indices on Pacific Northwest SWE remain relatively unexplored.

This paper is organized as follows: in section 2, daily SWE data are screened to locate the peak date; in section 3 the variability between annual maximum SWE and its associated timing and the data described in section 2 are examined through the use of a Pearson's correlation coefficient test; and in section 4 a simple linear regression model is used to investigate the significance of the additive effects and interactions of these climate indices on the annual maximum SWE. The summary and conclusions are given in section 5.

2. Data and variability of SWE

2.1. Snowpack data

The Natural Resources Conservation Service (NRCS) installs, operates, and maintains an extensive, automated system to collect snowpack and related climatic data in the Western United States called SNOTEL (for SNOwpack TELemetry). Since 1979, SNOTEL data have provided a great deal of information about snow conditions at individual locations in Washington State, and have been used for many years to forecast spring runoff using traditional statistical techniques to support the water resource management activities of NRCS and others.

In this study only the SNOTEL sites that have more than 20 years continuous records collected in Washington State were examined to enable a comparison with the effects of large-scale patterns of climate variation like the PDO, which persists for decades (Mantua, et al., 1997). Table 1 lists the 25 sites under study. For detailed information about each site, please visit the website:

http://www.wcc.nrcs.usda.gov/snotel/Washington/washington.html.

(Table 1)

Most of these 25 sites are located in Columbia River Basin and on the west slopes of the Cascades. The elevations of these 25 sites range from 975 to 1981 meters, and they represent snowpack measurements from low to moderate elevation altitudes.

2.2. Variability of SWE

Snowpack is determined by many factors such as wind, air temperature, storm frequency and the amount moisture in the atmosphere, but one of the objectives of this study is to investigate the teleconnections, i.e., the long-distance climatic cause and effect relationships, among selected large-scale atmospheric climatic indices and annual maximum SWE, and to find better predictors to forecast the peak annual SWE at six to nine months lead time. However, before examining the relationship of these large-scale climatic indices with annual maximum SWE and its associated timing, the timing of when the annual maximum SWE occurred in these twenty-five sites should be observed. It was found that the variation of the timing associated with the annual maximum SWE ranges from as early as the middle of December at low elevations to as late as early June at high elevations. Over the period of record considered here, even at the same site, the variation of the magnitude of annual maximum SWE and its associated timing fluctuated dramatically. For example, at the Cougar Mountain SNOTEL site, (elevation 975m) annual maximum SWE varied from 99 millimeters in 2005 to 1039 millimeters in 1997. The timing associated with the annual maximum SWE varied from December 18 in 1995 to April 22 in 1982. Given that a time interval of ten days before and after April 1 has been considered as the traditional "peak time of snowpack around April 1," we found that only 37% of the peak SWE of the 25 sites under examination actually fell into this interval. Further, when the interval is extended to two weeks before and after April 1, only 55% of peak SWE timing fell into that interval. Therefore, a typical measurement of SWE on April 1 may represent that parameter under two different hydrologic processes, either snowpack accumulation or melt-off, depending on the year and location.

Previous studies have demonstrated significant teleconnections between April 1 SWE and climate indices such as SOI, PDO and Niño3 SST (Cayan and Webb, 1992; McCabe and Dettinger, 2002) by either computing the correlations between these indices with April 1 SWE, or performing principle component analysis. This study took a different approach by testing the significance of correlations between the monthly climate indices and annual maximum SWE and its associated timing. In addition, a linear regression model was used to analyze the additive effects and interaction of the climate indices on annual maximum SWE.

3. Statistical test for Pearson's correlation coefficient

A simple statistical test for Pearson's product moment correlation coefficient was performed with SOI and Niño3 SST indices and the SWE data taken from all twenty-five SNOTEL sites listed in Table 1. The test was performed using the current year's maximum SWE and its previous year's climate indices from January through December, month by month. Table 2 lists the months in which SOI and Niño3 SST indices are significantly (p-values ≤ 0.1) associated with the annual maximum SWE, and the most significant correlation coefficients obtained.

It can be seen that prior to June of the previous year, there was no significant correlation between monthly SOI index and annual maximum SWE, and the strongest correlation to the annual maximum SWE occurred in June at the most sites (18 out of 25). The range of the correlation coefficients varied from 0.38 to 0.63. Though there were a few occasions where the correlation coefficients in September and December were larger than that in June, the differences between them were statistically insignificant. Therefore, it appears that the previous June's SOI index has a moderate positive correlation with the current year's maximum SWE at most sites under this study, that is, a large positive (negative) SOI value) in June is likely to yield a larger (smaller) snowpack in the winter.. This shows that the previous June's SOI index is a significant predictor in forecasting the annual peaks of SWE. No significant correlation was found in four out of twenty-five sites, but the correlation coefficients were all positive. This may be due to relatively small sample size (about 20 years) or other reasons unknown.

The correlations between the current year's maximum SWE and the previous year's monthly Niño3 index are only significant in seven out of twenty-five sites and ranged from -0.38 to -0.56. The most significant correlations all occurred in December in these seven sites.

(Table 2)

From the above analysis, one can see that the annual maximum SWE is positively correlated with SOI index in twenty-one out of twenty-five sites, and in most sites the most significant correlation occurred in June. This implies that cold June SSTs in the previous year in the equatorial Pacific may be used to predict greater SWE in most SNOTEL sites in Washington State the following winter. By contrast, annual maximum SWE is negatively correlated with the Niño3 SST index in only seven sites, with the most significant correlation occurring in December. This implies that a warm December in the previous year in equatorial Pacific may be used to predict less snowpack in some locations in Washington State the following year.

Next let's examine the correlation between the timing associated with the annual maximum SWE and monthly SOI and Niño3 SST. There are two ways to look at the timing. One is the timing within each calendar year; and the other the lags between adjacent annual peaks. Since in lags between adjacent annual peaks would be used to forecast the timing of the next peak, the investigation here is focused on the correlations between the lags and the selected climate indices. From Table 3 below one can see that the lags in twenty out of twenty-five sites have significant correlations with the SOI index, and the most significant correlations between the monthly SOI index and the lags, ranging from -0.38 to -0.64, occurred in the first three months of the previous year. (Table 3)

Recall that a large negative value of SOI is related to abnormally warm and drought conditions over much Alaska and the northwestern regions of Canada and the United States, so the negative correlation indicates that a warm episode is likely to shorten the duration until the next peak. The correlations between the lags and Niño3 SST index are only significant in eleven out of twenty-five sites and vary from month to month and from negative to positive depending on location.

From the above analysis one can see that the correlations between the lags and SOI index in the first three months of the previous year are useful information in forecasting the timing of the next peak. How to use the information will be addressed in another paper.

4. Combined effects of the ENSO and PDO on the magnitude of snowpack

From Pearson's test, it is evident that the annual maximum SWE is moderately correlated with the previous June's SOI index. But other studies showed that SOI index is not the only climatic factor that influences snowpack on a year-to-year basis. Some researchers believe that PDO is actually the primary driving force in snowpack variation across the Western region of the United States (McCabe and Dittinger, 2002). So, it is interesting to see the combined effects and the interactions of these climate indices on the annual maximum SWE. Since the interactions between those monthly climate indices are complicated, for practical purposes only the interaction between ENSO and PDO phases on the distribution of the annual maximum SWE were selected for investigation. It is reasonable to assume that the peak of snowpack driven solely by the SOI index is normally distributed, and therefore a simple linear regression model can be used to analyze the combined effects and interaction of ENSO and PDO on the annual maximum SWE.

Let:

$$SWE_{peak} = b + a_1 SOI_{month} + a_2 ENSO_{phase} + a_3 PDO_{phase} + a_4 MUL + \varepsilon \qquad (1)$$

Where, SWE_{peak} is the annual maximum SWE; SOI_{month} is SOI index value in the selected month of the previous year; $ENSO_{phase}$ is ENSO phase and PDO_{phase} is PDO phase, which are described in the previous section; and MUL is the interaction term and is defined as $ENSO_{phase} \cdot PDO_{phase}$. a_i's and b are regression coefficients and ε is the error term.

Recall that the ENSO phase is classified into three categories: warm (coded as 1), cold (coded as -1) and neutral (coded as 0) based on a threshold of ± 0.5 ^{0}C from the running mean of observed SST anomalies in the Niño 3.4 region (4^{0}N – 4^{0}S, 90^0 – 150^{0}W) for a minimum of 6 consecutive months including October, November and December in the previous year. The PDO phase is classified into only two categories: warm (coded as 1) and cool (coded as -1) since only two phases have been present since 1976 to the present time, and it was “warm” from 1976 to 1998 and “cool” from 1999 to the present (JISAO, 2006). Table 4 lists these episodes.

(Table 4)

Because this analysis is largely exploratory, seeking to discover what effects and interactions these climate indices have on the annual maximum SWE, it is reasonable to transform the measurement of SWE to a log scale in order to better fit statistical assumptions of linear models. The monthly SOI indices in the previous year were sequentially put into the regression equation (1) to choose the best model according to the p-value and R^2.

The results are shown in Table 5, from which one can see that the ENSO phase is the most significant factor for twenty three out of twenty-five sites under the study (p-value for partial correlation ≤ 0.05), followed by the interactions of the ENSO and PDO phases and selected monthly SOI index from the previous year. The PDO phase appears to be a significant factor only at six sites. This may be due to the relatively short period of observations since PDO is an inter-decadal phenomenon. But the interactions of the

ENSO and PDO phases are significant in fourteen out of the twenty-five sites under study. From Table 5, one can see that the regression coefficients are all positive for selected monthly SOI indices and for the interaction term. They are negative for the ENSO phase and positive for the PDO phase. The positive coefficient in equation (1) for selected monthly SOI indices implies that a strong negative (positive) monthly SOI index would result in decreasing (increasing) snowpack; the negative coefficient for the ENSO phase implies that in an El Niño water year (warm ENSO phase) the snowapck in the winter would be lower than normal, and in a La Niña water year (cold ENSO phase) the snowpack in the winter would be higher than normal. These analytical results are consistent with the other studies. By contrast, a warm (cool) PDO phase is likely to increase (decrease) the snowpack. This is in opposition to other studies that find during a cool PDO phase the jet stream may steer further north to yield a wetter winter. The interaction of the ENSO and PDO phases are complicated. It will be discussed in the following paragraphs.

When the regression coefficients were estimated for equation (1), the linear model can be can be written as

$$S\hat{W}E_{peak} = \hat{b} + \hat{a}_1 SOI_{month} + \hat{a}_3 PDO_{phase} + (\hat{a}_2 + \hat{a}_4 PDO_{phase}) ENSO_{phase} \qquad (2)$$

All parameters are the same as described before. Note that $\hat{a}_1 > 0$, $\hat{a}_2 < 0$, $\hat{a}_3 > 0$, $\hat{a}_4 > 0$, and $|\hat{a}_2| > |\hat{a}_3|$ for all significant sites in Table 5. From equation (2) four cases can be analyzed. The analysis s based on these coefficients given in Table 5.

Case 1: when the both phases of the ENSO and PDO are cold, equation (2) becomes

$$SWE_{peak} = \hat{b} + \hat{a}_1 SOI_{month} - \hat{a}_3 - (\hat{a}_2 - \hat{a}_4) \tag{3}$$

Since $\hat{a}_2 < 0$ *and* $\hat{a}_4 > 0$, the term $(\hat{a}_2 - \hat{a}_4)$<0, hence $-\hat{a}_3 - (a_2 - \hat{a}_4) > 0$ by $| \hat{a}_2 | > | \hat{a}_3 |$.

Therefore, the interaction term is likely to yield more than normal snowpack for the current year. This indicates that though a cool PDO phase alone tends to weaken the effects of La Niña, its interaction with a cold ENSO phase tends to enhance the effects of La Niña to yield a higher than normal snowpack.

In the rest of the paper the phrase "the effects of La Niña" means higher than normal snowpack; and the phrase "the effects of El Niño" means lower than normal snowpack, except where otherwise specified.

Case 2: when the ENSO phase is cold, but the PDO phase is warm, the equation (2) becomes

$$SWE_{peak} = \hat{b} + \hat{a}_1 SOI_{month} + \hat{a}_3 - \hat{a}_2 - \hat{a}_4 \tag{4}$$

The interaction term may yield more, less or equal than normal snowpack depending on the signs of $(\hat{a}_3 - \hat{a}_2 - \hat{a}_4)$. This indicates that though a warm PDO phase tends to enhance the effects of La Niña, its interaction with a cold ENSO phase tends to weaken the effects of La Niña. If the effect of a warm PDO phase is stronger than that of the interaction, that is $(\hat{a}_3 - \hat{a}_4) > 0$, then the snowpack is likely be higher than normal, but if the effect of the interaction is much stronger than that of the combined effects of a cold ENSO phase and a warm PDO phase, that is $(\hat{a}_3 - \hat{a}_2 - \hat{a}_4) < 0$, then it tends to weaken the effects of La

Niña to yield a lower than normal snowpack. If the effect of the interaction is the same as that of the combined effects of a cold ENSO phase and a warm PDO phase, that is $(\hat{a}_3 - \hat{a}_2 - \hat{a}_4) = 0$, then it cancels out the effects of La Niña to yield a normal snowpack. From Table 5 one can see that the effect of interaction varies from site to site in this case.

Case 3: when the ENSO phase is warm, but the PDO phase is cool, the equation (2) becomes

$$SWE_{peak} = \hat{b} + \hat{a}_1 SOI_{month} - \hat{a}_3 + \hat{a}_2 - \hat{a}_4 \qquad (5)$$

Since $(-\hat{a}_3 + \hat{a}_2 - \hat{a}_4) < 0$, this indicates that a cool PDO phase and its interaction with a warm ENSO tends to enhance the effects of El Niño to yield a lower than normal snowpack in the winter. This has a significant impact on winter recreational activities that are dependent on the snow cover.

Case 4: when both the phases of the ENSO and PDO are warm, then the equation (2) becomes

$$SWE_{peak} = \hat{b} + \hat{a}_1 SOI_{month} + \hat{a}_3 + \hat{a}_2 + \hat{a}_4 \qquad (6)$$

The interaction term may yield more, less or equal to normal snowpack for the current year depending on the signs of $(\hat{a}_3 + \hat{a}_2 + \hat{a}_4)$. Equation (6) indicates that a warm PDO phase and its interaction with a warm ENSO phase both tend to weaken the effects of El Niño. If the effect of a warm PDO phase or the interaction term is stronger than that of a warm ENSO phase, that is either $|a_2| < |a_3|$ or $|a_2| < |a_4|$, then the snowpack is likely be higher than normal in the winter. However, if the effect of a warm ENSO phase is stronger than that of the combined effects of a warm PDO phase and the interaction term, that is $(\hat{a}_3 + \hat{a}_2 + \hat{a}_4) < 0$, then the snowpack is likely be lower than normal in the winter. If the effect of a warm PDO phase and the interaction is the same as that of a warm ENSO phase, that is $(\hat{a}_3 + \hat{a}_2 + \hat{a}_4) = 0$, then the effects of El Niño are canceled out, and the snowpack is likely be normal. From Table 5 one can see that the effect of interaction varies from site to site in this case.

Summarizing the above analysis one can see that ENSO phase has a significant additive effect on the snowpack in most SNOTEL sites in Washington State, while the additive effect of PDO phase on the snowpack is significant at only six sites. This may be due to the relative short monitoring period of SNOTEL data compared to the inter-decadal variation of the PDO. It shows that long-term monitoring data are needed for further investigation. Among these six sites, three are located at low elevations in the Puget Sound basin, one is at the high elevation in the North Cascades, and one is at a high elevation in the Southern Cascade. The interaction between the ENSO phase and PDO phase and the snowpack is significant in fourteen out of twenty-five sites under the study. From the case analysis of the interaction term it is evident that during a La Niña year a cool PDO phase and the interaction term tend to enhance the effects of La Niña based on the data under this study; while during an El Niño year a cool PDO phase and the interaction between them do not appear to weaken the effects of El Niño, but tend to enhance the effects of El Niño. This contradicts the perception that a cool PDO phase should weaken the effects of El Niño.

In Table 5 only the significant coefficients were reported. This is because the independent variables may be correlated, a condition known as multi-collinearity, that is, the highly correlated independent variables are explaining the same part of the variation in the dependent variable. So, the coefficients on individual variables may be insignificant but on the regression as a whole are significant. This is characterized by the p-values of the overall test in regression. From Table 5 one can see that the p-values for the overall test of regression are significant for all sites under the study. The multiple correlations R^2, which are generally of secondary importance unless the main concern is using the regression equation to make accurate predictions, ranged from 0.37 to 0.74. The median R^2 is 0.57.

(Table 5)

5. Summary and conclusion

The forecasts of total volumes of spring-summer runoff in snow-dominated basins in Washington State are an important element to water resource management. They are important in planning water uses and developing operating strategies for reservoir management. These forecasts are largely based on measurements of SWE on April 1. However, by examining more than twenty years of daily SWE time series at twenty-five SNOTEL sites, it was found that the annual maximum SWE did not occur in the interval extending from ten days before to ten days April 1 at more than 60 percent of the SNOTEL sites under consideration. Therefore, the snowpack measured on April 1 may represent two different hydrologic processes - snowpack accumulation or meltoff. In either case, a substantial portion of the total volume of water goes unaccounted for. More importantly, the reservoir operations are totally different for these two different hydrologic processes, hence a reliable forecast of annual maximum SWE and its associated timing, especially in six to nine month lead times, is desirable for water managers across Washington State.

Variability of snowpack in Washington State is reflective of the variability of our regional climate, which in turn is related to large-scale phenomena in the oceans and atmosphere. Understanding the relationship between them is crucial in water resources planning and management, and requires some new systematic methods to assess the effects of climatic variability on the snowpack. The exploratory analysis in this study has clearly shown that the previous June SOI index is significantly correlated with the current year maximum SWE at most SNOTEL sites under investigation. The Niño 3 SST index of the previous December is also significantly correlated to the current year maximum SWE in seven sites. The correlations between the lags of adjacent snowpack peaks and SOI index in the first three months of the previous year are significant, but the correlations between the lags and Niño 3 SST index appear to be site dependent and vary from month to month and from positive to negative. These primary findings were incomplete, but demonstrated that long term daily monitoring of snowpack is necessary and useful. Without such long-term daily time series, the relationships between climate indices such as SOI and Niño 3 SST indices and annual maximum SWE were impossible to establish. As the study continues, one may begin to understand how variations in climate influence the short and long term variability of snowpack in Washington State.

A simple linear regression model was used to investigate the combined effects of climatic phenomena and their interactions on annual maximum SWE. It is clear that a warm episode characterized by a strong negative (positive) monthly SOI value in the previous year is likely to yield lower (greater) than normal snowpack in the current year. The ENSO phase is the most significant climate index to affect snowpack in Washington State. The PDO phase is only significant on the annual maximum SWE in six out of twenty-five sites, but its interaction with the ENSO phase has significant impact on the annual maximum SWE in more than half of the SNOTEL sites under the study. From the regression analysis the interaction term has four different impacts on the snowpack as described in cases 1 through 4 in the last section. When the ENSO phase is cold, a cool phase PDO is likely to enhance the effect of La Niña to yield a higher than normal snowpack; on the other hand, when the ENSO phase is warm, a cool phase PDO does not appear to weaken the effect of El Niño, but to enhance it in the winter. This may have a significant impact on winter recreational activities that depend on the snow cover. However, there is only one warm phase ENSO episode that appeared during 1999 to 2005 during which the PDO phase changed from warm to cool, and it can be seen that the snowpack measured in many SNOTEL sites in the Washington State were at record low values. More data is needed to verify the results.

The teleconnections between the selected climate indices and annual maximum SWE is characterized by the multiple correlation R^2 of the linear regression. The range of R^2 varies from 0.38 to 0.74 with a median 0.57, which represents a moderate correlation among climate indices under the study at more than 50 percent of the SNOTEL sites under consideration. This indicates that the temporal and spatial variation in ENSO and PDO teleconnections may be nonlinear, though a linear regression model was used for the analysis. This issue will be discussed in another paper.

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Table 1. Washington State Snotel Sites

Name	Time Period	Elevation (m)	Name	Time Period	Elevation (m)
Blewett Pass	82-05	1301	Park Creek Ridge	79-05	1402
Bumping Ridge	84-05	1402	Pigtail Peak	82-05	1798
Bunchgrass	84-05	1524	Pope Ridge	82-05	1079
Corral Pass	82-05	1829	Potato Hill	84-05	1372
Cougar Mountair	81-05	975	Rainy Pass	83-05	1457
Fish Lake	84-05	1027	Salmon Meadow	84-05	1372
Green Lake	83-05	1829	Sheep Canyon	84-05	1228
Grouse Camp	83-05	1640	Stampade Pass	83-05	1177
Harts Pass	83-05	1981	Stevens Pass	81-05	1241
Lone Pine	82-05	1158	Surprise Laks	80-05	1295
Lyman Lake	84-05	1798	Upper Wheeler	82-05	1341
Morse Lake	84-05	1646	White Pass	81-05	1372
Paradise	84-05	1561			

Table 2. Correlation Coefficients Between the Annual Maximum SWE and SOI and Niño3 Indices

Name	SOI		Niño3	
	Significant Months	Most Significant Correlation Cofficient	Significant Months	Most Significant Correlation Cofficient
Blewett Pass	Jun	0.38 at June	Not significant	
Bumping Ridge	Jun to Sept, Dec.	0.54 at June	Not significant	
Bunchgrass	Jun	0.56 at June	Not significant	
Corral Pass	Jun, Jul	0.51 at June	Not significant	
Cougar Mountain	Jun to Dec	0.60 at September	Jun to Dec	-0.56 at December
Fish Lake	Jun, Jul, Dec	0.61 at June	Dec	-0.37 at December
Green Lake	Not significant		Not significant	
Grouse Camp	Not significant		Not significant	
Harts Pass	Jun	0.44 at June	Not significant	
Lone Pine	Jun, Jul, Dec	0.49 at June	Not significant	
Lyman Lake	Jun	0.56 at June	Not significant	
Morse Lake	Jun	0.44 at June	Not significant	
Paradise	Jun to Oct, Dec	0.61 at June	Dec.	-0.41 at December
Park Creek Ridge	Jun, Jul, Oct	0.54 at June	Not significant	
Pigtail Peak	Jun to Jul, Sept,Dec	0.55 at June	Not significant	
Pope Ridge	Jun	0.49 at June	Not significant	
Potato Hill	Jun, Jul, Sept, Nov, Dec	0.5 at Dec	Dec	-0.38 at December
Rainy Pass	Jun	0.56 at June	Not significant	
Salmon Meadow	Not significant		Not significant	
Sheep Canyon	Jun to Dec	0.54 at September	Jan to Mar, Oct to Dec	-0.46 at December
Stampade Pass	Jun, Jul, Sept, Oct, Dec	0.63 at June	Dec.	-0.39 at December
Stevens Pass	Jun, Jul, Sept to Dec	0.49 at June	Nov to Dec	-0.42 at December
Surprise Laks	Jun, Jul, Sept, Dec	0.44 at June		
Upper Wheeler	Not significant		Not significant	
White Pass	Jun	0.50 at June	Not significant	

Table 3. Correlation Coefficients of the lags Between the Annual Maximum SWE and Climate Indices

Name	SOI		Niño 3 SST	
	Significant Months	Most significant Coefficient	Significant Months	Most significant Coefficient
Blewett Pass	Feb.	-0.49 at Feb	Not singnificant	
Bumping Ridge	Not significant		Jan. to May	0.64 at April
Bunchgrass	Jan., May	0.44 at May	Not singnificant	
Corral Pass	Not significant		Jan. to Feb., Jun	-0.44 at June
Cougar Mountain	Feb, Aug to Dec	-0.54 at Feb	Not significant	
Fish Lake	Jan., Feb.	-0.45 at Jan.	Feb to Apr	-0.48 at April
Green Lake	Not significant		Not significant	
Grouse Camp	Not significant		Apr to May, Sept	0.43 at September
Harts Pass	Not significant		Not significant	
Lone Pine	Jan., Feb.	-0.36 at Jan.	Jan. to May	0.49 at April
Lyman Lake	Jan., May	-0.59 at Jan.	Not significant	
Morse Lake	Jan.	-0.56 at Jan.	Apr	0.38 at April
Paradise	Jan., Mar.	-0.38 at Mar.	Not significant	
Park Creek Ridge	May	0.44 at May	Not significant	
Pigtail Peak	Jan., Mar.	-0.48 at Jan.	Not significant	
Pope Ridge	Feb., Mar.	-0.48 at Feb.	Nov. to Dec.	-0.40 at December
Potato Hill	Feb.	-0.47 at Feb.	Not significant	
Rainy Pass	Jan.	-0.53 at Jan.	Not significant	
Salmon Meadow	Jan.	-0.43 at Jan.	Oct to Dec	-0.45 at November
Sheep Canyon	Feb.	-0.58 at Feb.	Feb to Apr	0.52 at April
Stampade Pass	May, Aug., Sept.	0.49 at May	Not significant	
Stevens Pass	Jan., Feb.	-0.46 at Jan.	Mar to Apr	0.46 at April
Surprise Laks	Jan., Feb., Mar., Sept.	-0.64 at Jan.	Jan to Apr, nov	0.44 at February
Upper Wheeler	Jun., Jul.	-0.51 at Jun.	Not significant	
White Pass	Not significant		Not significant	

Table 4. ENSO and PDO Phases from 1979 to 2005

Year	ENSO Phase	PDO Phase	Year	ENSO Phase	PDO Phase
1979	neutral	warm	1993	neutral	warm
1980	neutral	warm	1994	neutral	warm
1981	neutral	warm	1995	neutral	warm
1982	warm	warm	1996	neutral	warm
1983	neutral	warm	1997	warm	warm
1984	neutral	warm	1998	cold	warm
1985	neutral	warm	1999	cold	cool
1986	warm	warm	2000	neutral	cool
1987	warm	warm	2001	neutral	cool
1988	cold	warm	2002	neutral	cool
1989	neutral	warm	2003	neutral	cool
1990	neutral	warm	2004	neutral	cool
1991	warm	warm	2005	warm	cool
1992	neutral	warm			

Table 5. Results of Linear Regression Analysis for Combined Effects and Interaction on the Annual Maximum SWE

SNOTEL sites	Selected SOI Month	Significant partial correlation for (a_1) SOI_{month}	(a_2) $ENSO_{phase}$	(a_3) PDO_{phase}	(a_4) MUL	p-value	R^2
Blewett Pass	April	0.07	-0.49	0.24	0.47	<0.01	0.74
Bumping Ridge	December		-0.47		0.50	<0.01	0.68
Bunchgrass	June	0.10	-0.18			0.03	0.45
Corral Pass	January	0.07	-0.33		0.41	<0.01	0.59
Cougar Mountain	November	0.18	0.28	0.24	0.42	<0.01	0.57
Fish Lake	June	0.15	-0.38	0.13		<0.01	0.70
Green Lake	November		-0.39		0.40	0.02	0.46
Grouse Camp	January		-0.38		0.38	<0.01	0.60
Harts Pass	June		-0.24	0.12		0.01	0.50
Lone Pine	December		-0.43		0.45	0.02	0.45
Lyman Lake	June	0.13	-0.20			0.02	0.50
Morse Lake	June		-0.28			0.03	0.47
Paradise	June		-0.23			<0.01	0.57
Park Creek Ridge	January	0.05	-0.39		0.49	<0.01	0.58
Pigtail Peak	June	0.13	-0.29			0.02	0.45
Pope Ridge	June		-0.30			<0.01	0.56
Potato Hill	April	0.07	-0.60		0.49	<0.01	0.71
Rainy Pass	May		-0.23			<0.01	0.57
Salmon Meadow	May		-0.21		0.29	0.05	0.42
Sheep Cayon*	May	7.42	-27.83		12.86	<0.01	0.62
Stampede Pass	June	0.15	-0.42	0.13		<0.01	0.65
Stevens Pass*	June					0.05	0.37
Surprise Lake	April		-0.53		0.55	<0.01	0.48
Upper Whileer	October				0.42	0.02	0.43
White Pass	September		-0.47	0.12	0.54	<0.01	0.61

* means the regression is performed without a log transformation