2. Climate Variability

Abstract

Long historical records of flow in the Columbia River back to about 1860 show that Pacific Northwest (PNW) climate has varied considerably on centennial (century-to-century), decadal (decade-to-decade), and interannual (year-to-year) time scales. Two large scale climate phenomena, the El Niño-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO), explain the broad features of PNW climate variability in the 20th century (e.g. cool season temperature and precipitation variations) along with associated variations in hydrologic variables (snowpack and streamflow) and hydrologic extremes (floods and droughts) in the PNW. The patterns of climate variability, climate extremes, and associated hydrologic variables are likely to be intensified when the PDO and ENSO are in phase (i.e. warm ENSO/warm PDO or cool ENSO/cool PDO). Similarly, the PDO and ENSO strongly influence the climate and hydrology of the Skagit River basin. Variations in air temperature associated with the PDO and ENSO also affect water temperature for the Skagit River.

2.1 Overview of Historical Variations in Pacific Northwest Climate

The impacts of climate variability on hydrologic systems in the Pacific Northwest (PNW) are dominated by cool season (October to March) precipitation, which effectively “recharges” the region’s water systems each year. PNW cool season precipitation and annual river flow have varied considerably on centennial (century-to-century), decadal (decade-to-decade), and interannual (year-to-year) time scales (Mote et al., 2003; Hamlet, 2011). Figure 2.1 shows reconstructed annual flow in the Columbia River at The Dalles from 1958-1998. Annual flow in the Columbia is a good proxy for cool precipitation over the region as a whole (cool season precipitation explains more than 80% of the variance in annual flow), and this relationship is very insensitive to temperature variations (Bumbaco and Mote, 2010). Although trends in annual flow and cool season precipitation in the 20th century (when most observed streamflow and climate records are available) have been relatively small, Figure 2.1 shows that the second half of the 19th century was much wetter than the 20th century in the PNW. In the last 40 years of the 19th century, for example, there were five annual high flow events that were comparable to or larger than the two wettest years on record in the Columbia basin (1974 and 1997). Water year (Oct-Sept) 1894 stands out as an extreme wet year, and produced an instantaneous peak flow in June, 1894 of 1.24 million cfs (USGS peak flow records), almost 25% higher than the highest natural peak flows observed for the Columbia River in the 20th century (May, 1948, 1.01 million cfs). For comparison, the two wettest annual water years in the 20th century, 1974 and 1997, produced estimated natural spring peak flows of about 800,000 cfs, more than 50% below the 1894 peak flow.

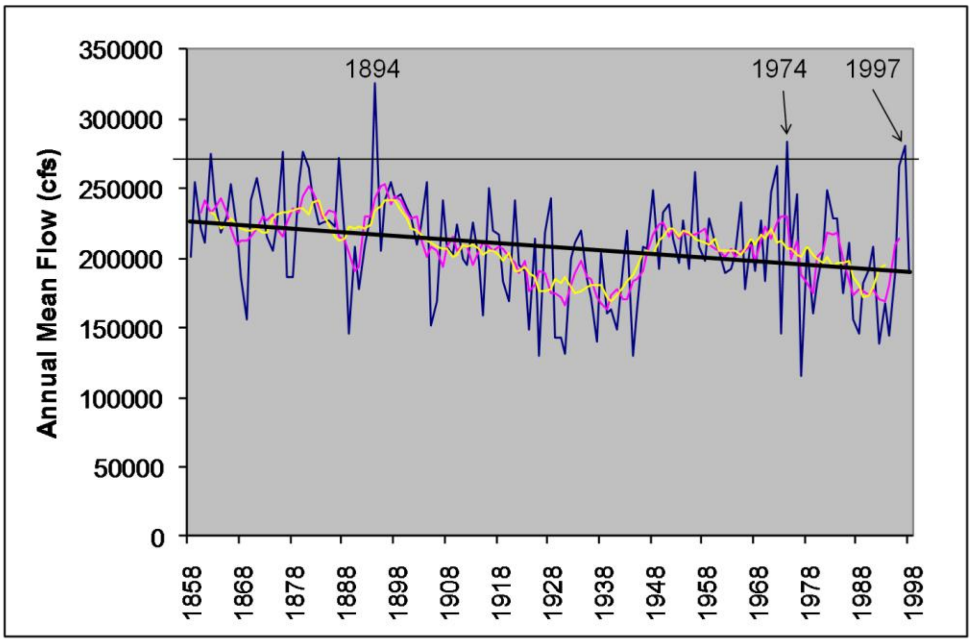

Figure 2.1 Naturalized annual flow in the Columbia River at The Dalles, OR from water years 1858-1998. Flows from water years (Oct-Sept) 1858-1877 are reconstructed from estimates of peak stage from railroad records. Flows from water years 1878-1998 are naturalized data extracted from daily gage records. Magenta and yellow traces show temporally smoothed traces using a five and ten year moving window average respectively (Source: Hamlet, 2011).

Regional summaries of observed precipitation and temperature data show strong 20th century trends in some cases (Figure 2.2). Maximum and minimum daily temperatures in cool season, for example, have exhibited relatively strong warming trends throughout the 20th century. Cool season precipitation, by comparison, has shown relatively little trend. Warm season daily maximum and minimum temperatures show similar patterns to cool season, although minimum temperatures in warm season show stronger trends. Warm season precipitation in the PNW has exhibited strong upward trends over the 20th century. Changes in temperature before about 1970 are believed to be largely related to natural climate variability, whereas changes after 1970 are a mixture of natural (40-65%) and anthropogenic (35-60%) causes (Barnett et al., 2008) (See also Chapter 3). Changes in precipitation over the 20th century have so far not been attributed to anthropogenic climate change, and the dominant hypothesis is that the observed changes are related mostly to climate variability.

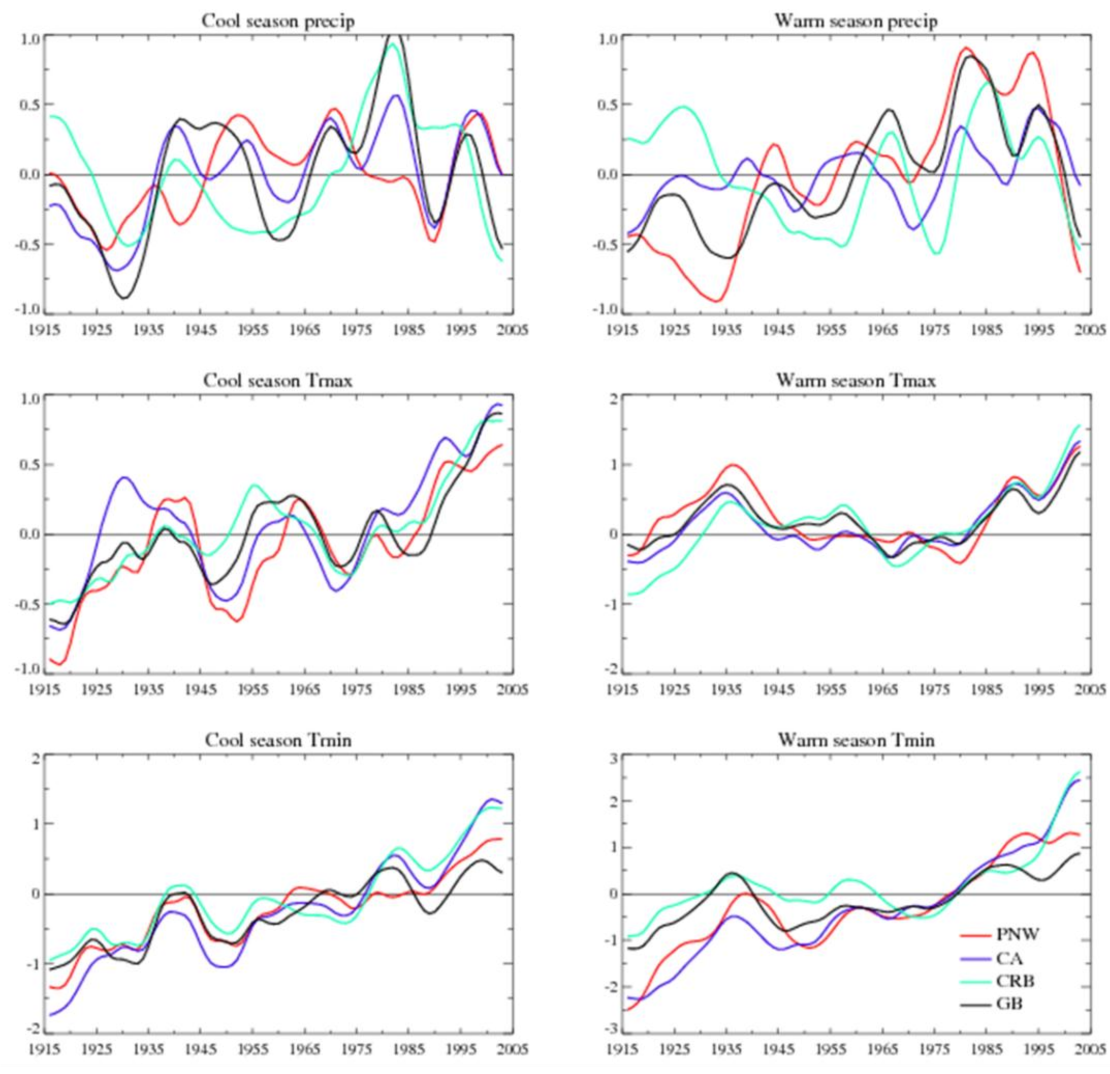

Figure 2.2 A temporally smoothed 20th century time series (1915-2003) of regionally averaged precipitation, maximum temperature, and minimum temperature for the warm and cool season over the western U.S. (Pacific Northwest, California, Colorado River Basin, and Great Basin) (units: standard deviations from the mean) (Source: Hamlet et al., 2007).

2.2 Global Climate Patterns Affecting Pacific Northwest Climate

Two global-scale patterns of climate variability, the El Niño-Southern Oscillation (ENSO) (Battisti and Sarachik, 1995) and the Pacific Decadal Oscillation (PDO) (Mantua et al., 1997), are strongly related to variations in PNW climatological and hydrological variables such as precipitation, temperature, snowpack, and streamflow in the PNW (Piechota et al., 1997; Cayan et al., 1998; Livezey and Smith, 1999; Hamlet and Lettenmaier, 1999; Mote et al., 2003). In this section, we discuss these global climate phenomena and their observed variability over the last 100-150 years.

2.2.1 The El Niño-Southern Oscillation

ENSO is a climate phenomenon directly affecting the tropical Pacific Ocean which impacts regional climate throughout the globe. ENSO is usually defined as a function of wind and sea surface temperatures (SSTs) anomalies (changes from normal conditions) in the tropical Pacific Ocean (Wallace et al., 1998; Battisti and Sarachik, 1995). El Niño (commonly referred to as the *warm phase* of ENSO), refers to the climate conditions characterized by weakened easterly trade winds and unusually warm SSTs in the central and eastern parts of the tropical Pacific. La Niña (commonly referred to as the *cool phase* of ENSO) is essentially the opposite of El Niño and is characterized by warm surface waters pushed far to the west by stronger easterly trade winds and anomalously cold SSTs in the central and easterly parts of the tropical Pacific Ocean (Vecchi and Wittenberg, 2010; Miles et al., 2000). ENSO variations are typically measured via numerical indices such as the Southern Oscillation Index (SOI), which is based on long records of the observed difference in pressure between Tahiti and Darwin, or the Nino3.4 Index (Trenberth, 1997), which is based on SST anomalies in a specific area of the tropical Pacific (covering parts of the Nino3 and Nino4 regions). It is worth noting that although these two indices are broadly equivalent in terms of characterizing historical ENSO events, they are opposite in sign, which sometimes causes confusion. A positive Nino3.4 value corresponds to a negative value of the SOI. For the Nino3.4 index an official definition of ENSO is an anomaly of plus or minus 0.5 ^{o}C (warm or cool respectively) persisting for at least five consecutive and overlapping three month periods. Years which are neither warm nor cool are considered to be ENSO neutral.

ENSO events typically persist for 6 to 18 months and peak in mid-winter (most often in January), when they typically have the greatest effect on regional climate. Warm or cool events have a return interval between two to seven years. ENSO has global impacts, although its effects are regionally specific (Hamlet and Lettenmaier, 1999; Trenberth and Jones, 2007). For instance, ENSO variations (as measured by the Nino3.4 index) are positively correlated with precipitation and streamflow in the U.S. Southwest and Central America and negatively correlated with precipitation and streamflow in the Northwestern U.S. and tropical South America (Gershunov and Barnett, 1998; Hamlet and Lettenmaier, 1999; Cayan et al., 1999; Dettinger et al., 2001; Barton and Ramirez, 2004).

The frequency and amplitude of ENSO have varied considerably over the past 130 years (Folland et al., 2001; Trenberth and Jones, 2007; Wang and Picaut, 2004; Vecchi and Wittenberg, 2010). As shown in Figure 2.3, strong warm and cool ENSO events (measured here by long records of the SOI) occurred about equally often from 1866 to 1925. Strong cool phase events dominate from the mid-1940s to the mid-1970s, after which strong warm phase events have dominated (Folland et al., 2001; Trenberth and Jones, 2007; Wang and Picaut, 2004; Vecchi and Wittenberg, 2010). Since 1976, there was an apparent climate shift to warmer conditions and strong warm ENSO events occurred more persistently (Folland et al., 2001; Trenberth and Jones, 2007; Wang and Picaut, 2004; Vecchi and Wittenberg, 2010), especially from 1990 to 1995, when several weak to moderate El Niño events occurred without alternating with La Niña events (Goddard and Graham, 1997). ENSO variability observed at the end of the 20th century is unprecedented in the record back to 1866. The causes of this unusual variability in ENSO in the last 25 years of the 20th century, including the exceptionally strong El Nino events of 1982/83 and 1997/98, and whether this unusual variability is linked to global warming remains key research questions as noted by Folland et al. (2001) and Trenberth and Jones (2007).

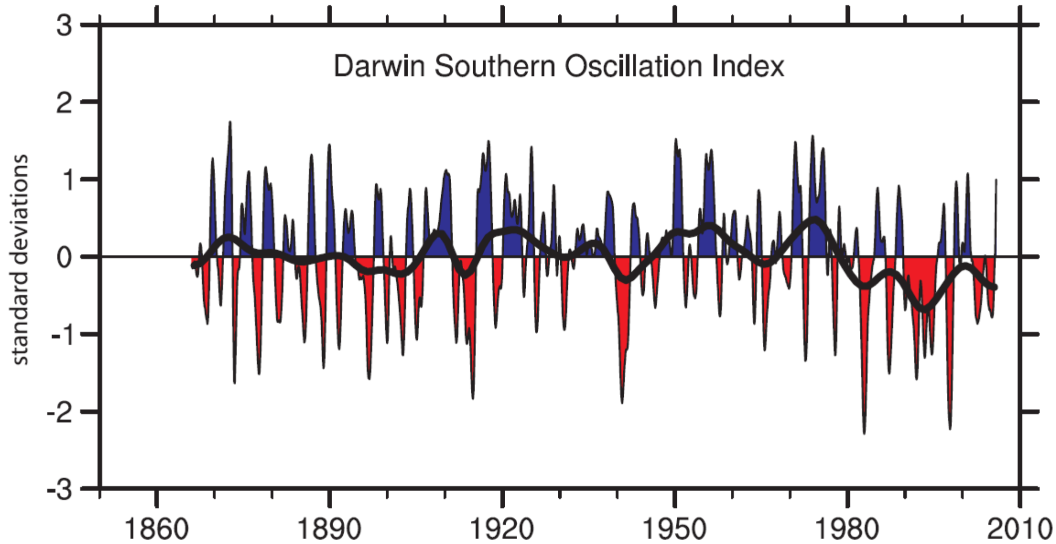

Figure 2.3 The Darwin-based SOI, in normalized units of standard deviation, from 1866 to 2005. The smooth black curve shows decadal variations. Red values indicate positive sea level pressure anomalies at Darwin and thus El Niño conditions (Source: Trenberth and Jones, 2007).

2.2.2 The Pacific Decadal Oscillation (PDO)

The PDO has been described as a long-lived ENSO like pattern of climate variability in the Pacific Basin and North America (Mantua et al., 1997; Miles et al., 2000; Trenberth and Jones, 2007) or as a low-frequency residual of ENSO variability expressing itself on multi-decadal time scales (Trenberth and Jones, 2007; Newman et al., 2003). Newman et al. (2003), for example, demonstrated that simple statistical models representing the persistence of the PDO from year to year combined with an ENSO forcing term could very closely reproduce the variability of the PDO index from one year to the next. In terms of its effects on regional climate, the PDO is different from ENSO in three ways (Miles et al., 2000; Mote et al., 2003; Moore et al., 2008). First, warm and cool PDO events show much longer temporal persistence in comparison with ENSO events. Warm or cool PDO events typically persist for 20 to 30 years while ENSO events persist for 6-18 months. Secondly, the PDO has its most pronounced climatic influence in the central and North Pacific with a more secondary climatic influence in the tropics, while the opposite is true for ENSO. Finally, the observed time series behavior of the PDO is much less well understood than ENSO in part because only a few cycles of the PDO are represented in the relatively short observed climate records available.

The PDO index is based on the Empirical Orthogonal Function (EOF) analysis, a statistical technique which decomposes the spatial and temporal patterns of SST for the Pacific basin north of 20 ^{o} N into a single time series which explains most of the variance in these patterns (Mantua et al., 1997). The PDO index is used in this report primarily to characterize decadal climate variability in the PNW (Hamlet and Lettenmaier, 1999). The PDO had five phases during the 20th century (Figure 2.4): weak warm (positive index values) and cool (negative index values) excursions were present from 1900 to 1924 then predominantly in the warm phase from 1925 to 1946, in the cool phase from 1947 to 1976, and again in the warm phase with several relatively brief excursions to the cool phase (URL 1) from 1977 to the present. It is worth noting that estimates of the PDO in the early 20th century (prior to about 1950) are more uncertain than at the end of the record due to relatively few SST measurements in the early record.

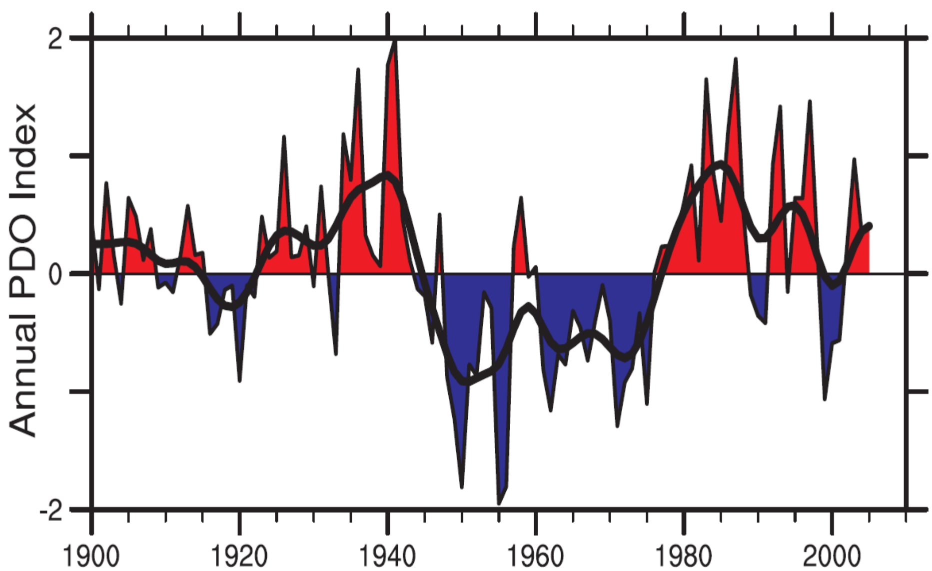

Figure 2.4 Annual time series Pacific Decadal Oscillation (updated from Mantua et al., 1997). The smooth black curve shows decadal variations (Source: Trenberth and Jones, 2007)

2.3 Impacts of ENSO and the PDO on Pacific Northwest Climate and Hydrology

In this section, we discuss regional-scale variations in climatological and hydrological variables associated with ENSO and the PDO. These relationships were created based on the PDO and ENSO definitions defined in Table 2.1. For example, in estimating temperature anomalies associated with warm ENSO years, temperature data from all the warm ENSO years (as defined in the table) were averaged and compared to the same quantities for cool ENSO and ENSO neutral years.

Table 2.1 Retrospective Definitions of Warm, Neutral, and Cool ENSO and PDO Years (Source: Hamlet and Lettenmaier, 2007).

Climate Category	Index Used	Definition
Warm ENSO	NINO 3.4	> 0.5 std. deviations above the mean for DJF mean
ENSO neutral	NINO 3.4	Neither warm nor cool
Cool ENSO	NINO 3.4	< -0.5 std. deviations above the mean for DJF mean
Warm PDO	PDO	> 0.5 std. deviations above the mean for ONDJFM mean
PDO neutral	PDO	Neither warm nor cool
Cool PDO	PDO	< -0.5 std. deviations above the mean for ONDJFM mean

2.3.1 PNW Temperature and Precipitation

Warm ENSO (El Niño) events generally produce warmer and drier winter/spring weather in the PNW (Hamlet and Lettenmaier, 1999; Miles et al., 2000; Mote et al., 2003; Moore et al., 2008), whereas cool ENSO (La Niña) events produce cooler and wetter conditions. As shown in Figure 2.5, warm ENSO years are likely to have higher cool season (Oct-Mar) temperature (about 1°C (1.8 °F) warmer) and lower cool season precipitation (by about 10%) in comparison with cool ENSO years. Cool season temperature and precipitation anomalies (i.e. changes from the mean) associated with the PDO are broadly similar to those shown for ENSO (Figure 2.5). Warm phase PDO shows higher temperature and lower precipitation than cool phase PDO in the cool season (see Figure 2.5). When the PDO and ENSO are in phase (e.g. warm ENSO/warm PDO or cool ENSO/cool PDO), these patterns of climate variability positively reinforce each other. That is, the likelihood of unusually warm and dry winter/spring weather is especially high in years when a warm ENSO event coincides with warm PDO (Gershunov and Barnett, 1998; Miles et al., 2000; Mote et al. 2003). Conversely, cool ENSO/cool PDO years are strongly associated with unusually cool and wet conditions.

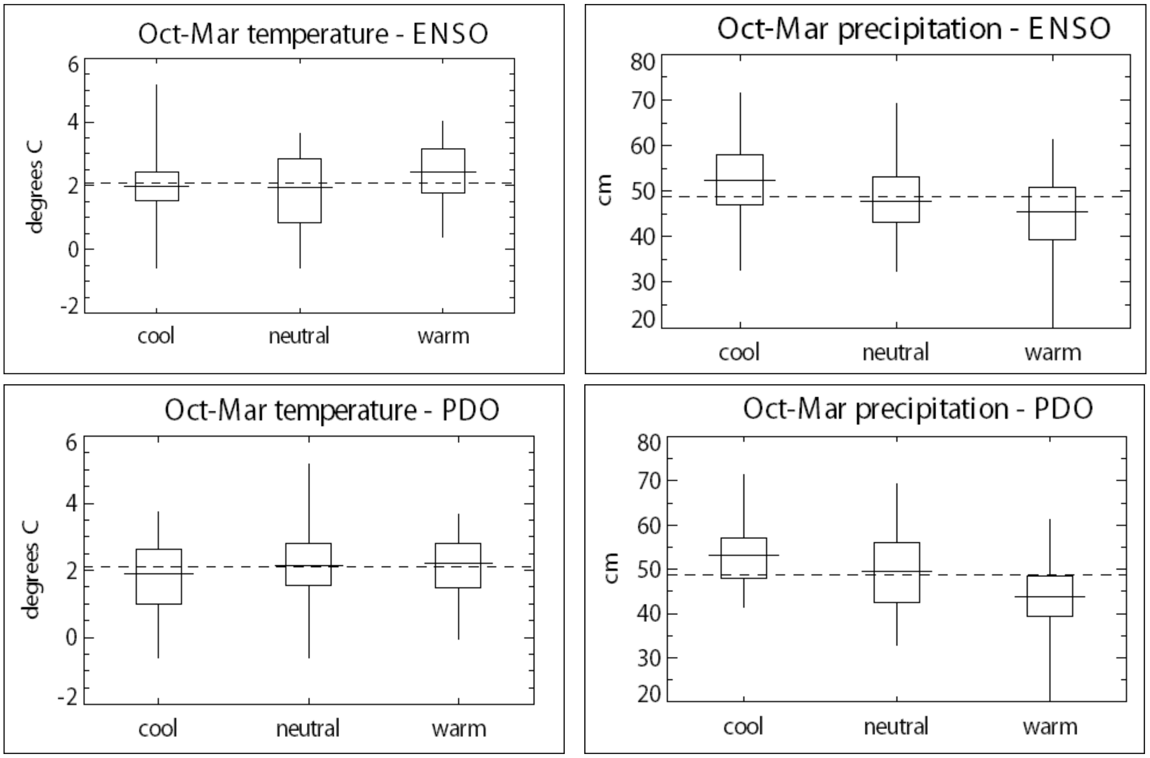

Figure 2.5 Box-and-whisker plots showing the influence of ENSO (top) and the PDO (bottom) on October-March temperature and precipitation (1899-2000) for the PNW. For each plot, years are categorized as cool, neutral, or warm phases. For each climate category, the distribution of the variable is indicated as follows: range of values (whiskers); mean value for the phase category (solid horizontal line); regional mean for all categories combined (dashed horizontal line); 75th and 25th percentiles (top and bottom of box). Area-averaged Climate Division data are used for temperature and precipitation (Source: URL 2).

2.3.2 Effects of the PDO and ENSO on PNW Hydrology

The PDO and ENSO influence temperature and precipitation patterns in the PNW (warm and dry or cool and wet) as mentioned above, and thus these patterns of climate variability also influence hydrologic variables such as snowpack and streamflow in the PNW (Piechota et al., 1997; Cayan et al., 1998; Hamlet and Lettenmaier, 1999; Livezey and Smith, 1999). The effects of climate variability on April 1 snow water equivalent (SWE) in the Western United States have been well documented in previous work (Clark et al., 2001; Hamlet et al., 2005; Mote, 2006). Hamlet et al. (2005) and Mote (2006) examined the separate roles of precipitation and temperature in producing the trends in SWE. They found that the April 1 SWE was negatively correlated with cool season temperature and positively correlated with cool season precipitation in the PNW. Because warm (cool) phases of ENSO and the PDO produce warmer and drier (colder and wetter) winters in the PNW, warm (cool) phases of ENSO and the PDO are associated with lower (higher) SWE as shown in Figure 2.6.

When the PDO and ENSO are in phase (i.e. warm PDO/ El Niño), these April 1 SWE anomalies tend to be enhanced (see Figure 2.6 right). These effects are more pronounced in relatively warm areas in the PNW such as the western slopes of the Cascades because spring snowpack in near-coastal mountain ranges is strongly affected by cool season temperature (Hamlet et al., 2005; Mote et al., 2005; Mote et al., 2007).

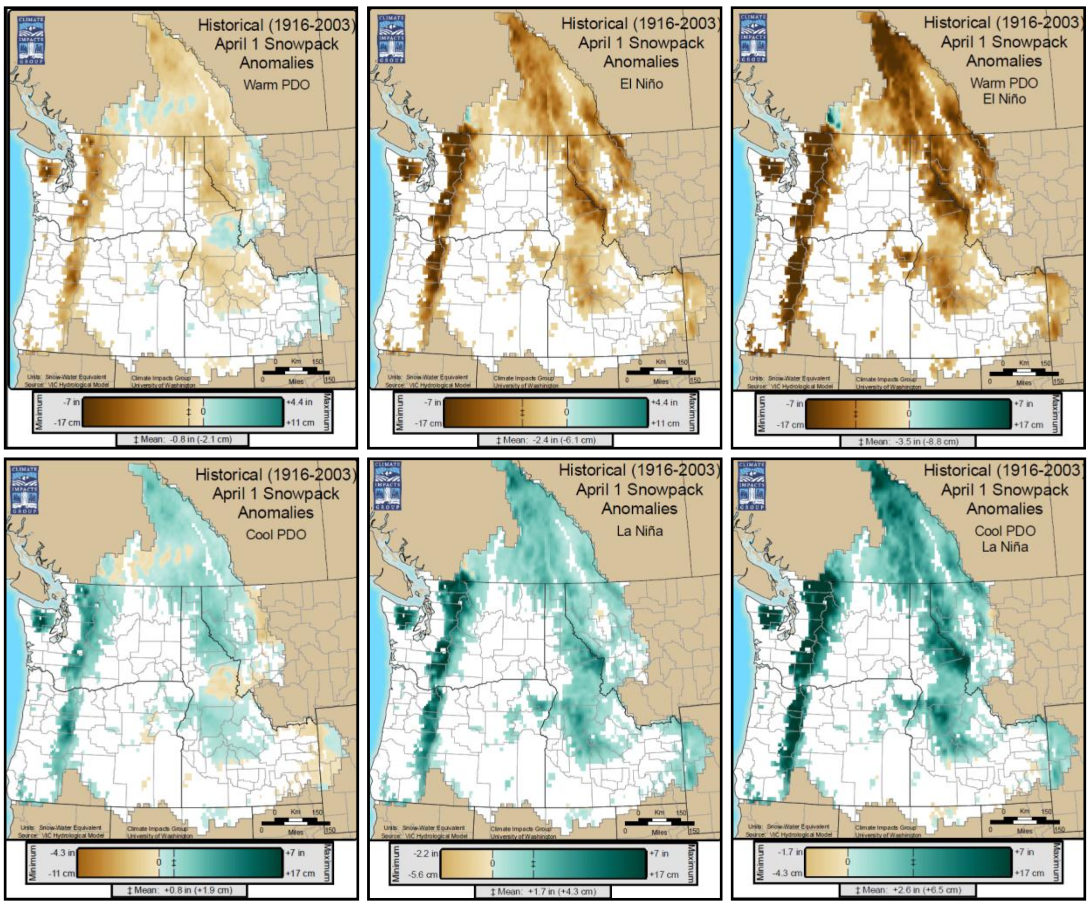

Figure 2.6 Anomalies (i.e. changes from the mean) in April 1 SWE over the 1916-2003 period of record for the Columbia River basin for the PDO phases based on historical epochs (left), for ENSO phases based on Dec-Feb averaged Nino3.4 Index (middle) and for the PDO and ENSO in phase (right). Top panels show warm phase signals, lower panels show cool phase signals (Source: URL 3).

The correlation between streamflow and the PDO and ENSO in the PNW is also well-established (Hamlet and Lettenmaier, 1999; Gershunov and Barnett, 1998; Cayan et al., 1999; Dettinger et al., 2001; Barton and Ramirez, 2004; Miles et al., 2000; Mote et al., 2003). Monthly naturalized streamflow at The Dalles, for example, shows that warm phases of the PDO and ENSO produce lower monthly streamflow in comparison with cool phases of the PDO and ENSO, with the largest response in June (see in Figure 2.7) (Hamlet and Lettenmaier, 1999; Miles et al., 2000; Mote et al., 2003). Coincidence of warm (cool) phases of ENSO and the PDO tends to enhance these streamflow anomalies: cool ENSO/cool PDO produces much higher streamflow in June in comparison with warm ENSO/warm PDO (see lower panel in Figure 2.7).

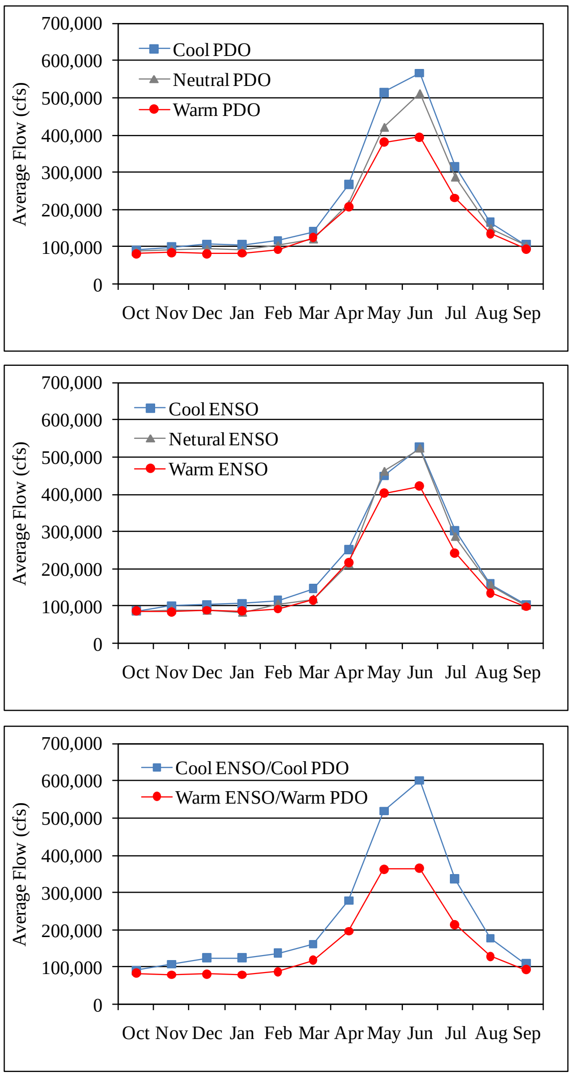

Figure 2.7 Composite monthly naturalized hydrographs for the Columbia River at The Dalles (water years 1931 -1989) for the PDO phases based on the PDO index (top), ENSO phases based on Dec-Feb averaged Nino3.4 Index (middle) and the PDO and ENSO in phase (bottom).

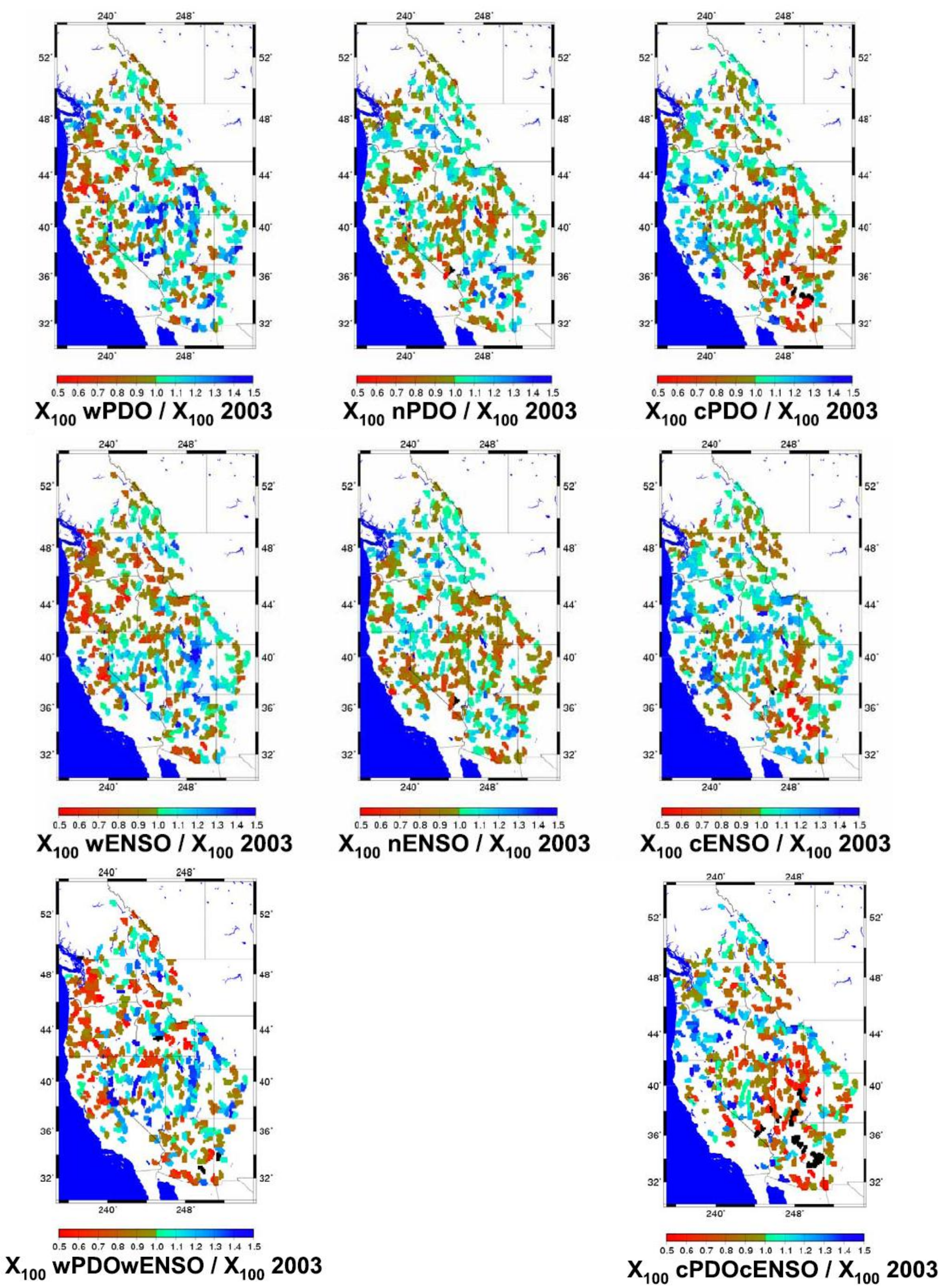

Figure 2.8 Spatial plots of change in s flood risk simulated by a hydrologic model for medium sized river basins (~1700 km^2) across the western U.S. showing the ratio of the estimated 100-year flood for the PDO (top), ENSO (middle) and combined the PDO and ENSO (bottom) to the estimated 100 year flood for all years. (Source: Hamlet and Lettenmaier, 2007).

The incidence of hydrologic extremes such as droughts and floods in the PNW is also influenced by the PDO and ENSO. For example, flood risks are generally higher in the PNW during cool phases of the PDO and ENSO and lower during warm phases of the PDO and ENSO, with large impacts in coastal area (Figure 2.8) (Hamlet and Lettenmaier, 2007). When the PDO and ENSO are in phase, the impacts on changes in flood risks are intensified as shown in the bottom panels in Figure 2.8. Since 1900, five of the six extreme multi-year droughts occurred during the warm phase of the PDO and four of the five highest flow years happened during the cool phase of the PDO (three of them when ENSO was also in its cool phase) (Mote et al., 2003). When these two oscillations are out of phase, observed streamflow tends to vary near the long-term mean (Hamlet and Lettenmaier, 1999; Miles et al., 2000; Mote et al., 2003).

2.4 ENSO and PDO Impacts on the Skagit River Basin's Climate and Hydrology

In this section, we extend the regional analysis presented above to discuss the effects of the PDO and ENSO on the climate and hydrology of the Skagit River basin alone.

2.4.1 Skagit Basin Temperature and Precipitation

Impacts of natural climate variability on temperature and precipitation for the Skagit River are shown in Figure 2.9. Following similar trends over the PNW, warm (cool) phases of ENSO and the PDO produce warmer and drier (cooler and wetter) winter in the Skagit River. When ENSO and the PDO are in phase, the climate anomalies are intensified. Averaged Oct-Mar temperature is 1.4 ^{o}F and 1.7 ^{o}F higher for warm phases of the PDO and ENSO in comparison with cool phases of the PDO and ENSO, respectively. When the PDO and ENSO are in phase, the difference of Oct-Mar temperature between warm and cool phases is significantly increased to 2.8 ^{o}F. Precipitation anomalies are also increased by about a factor of two when the PDO and ENSO are in phase.

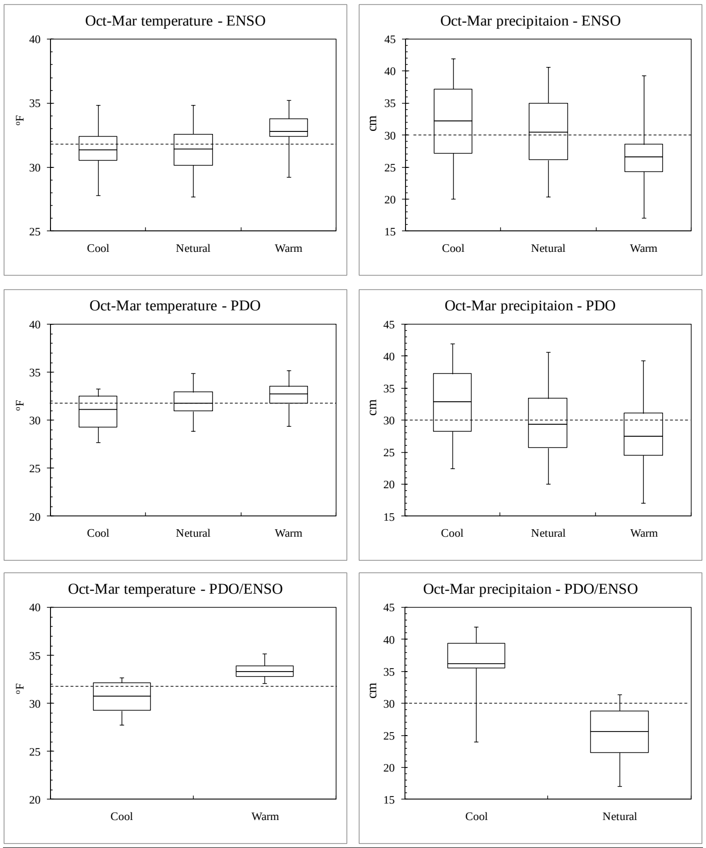

Figure 2.9 Same as Figure 2.5 but the influence of ENSO (top), the PDO (middle) and combined the PDO and ENSO (bottom) on October-March temperature and precipitation (1916-2006) for the Skagit River.

2.4.2 Skagit Basin Snowpack

As mentioned above, the PDO and ENSO have a pronounced influence on snowpack variability in the relatively warm mountain areas on the western slopes of the Cascades (see Figure 2.6). This enhanced sensitivity to both temperature and precipitation is shown in simulations of SWE for the Skagit River basin (Figure 2.10). On average, April1 SWE during warm phases of ENSO and PDO years is 42 % and 58 % lower than those associated with cool phases of ENSO and the PDO, respectively. When the PDO and ENSO are in phase (i.e. warm ENSO/warm PDO or cool ENSO/cool PDO), average April 1 SWE is 86% lower in warm ENSO/warm PDO phase than cool ENSO/cool PDO phase (Figure 2.10). Minor timing shifts in the date of peak SWE are also apparent for warm phase years.

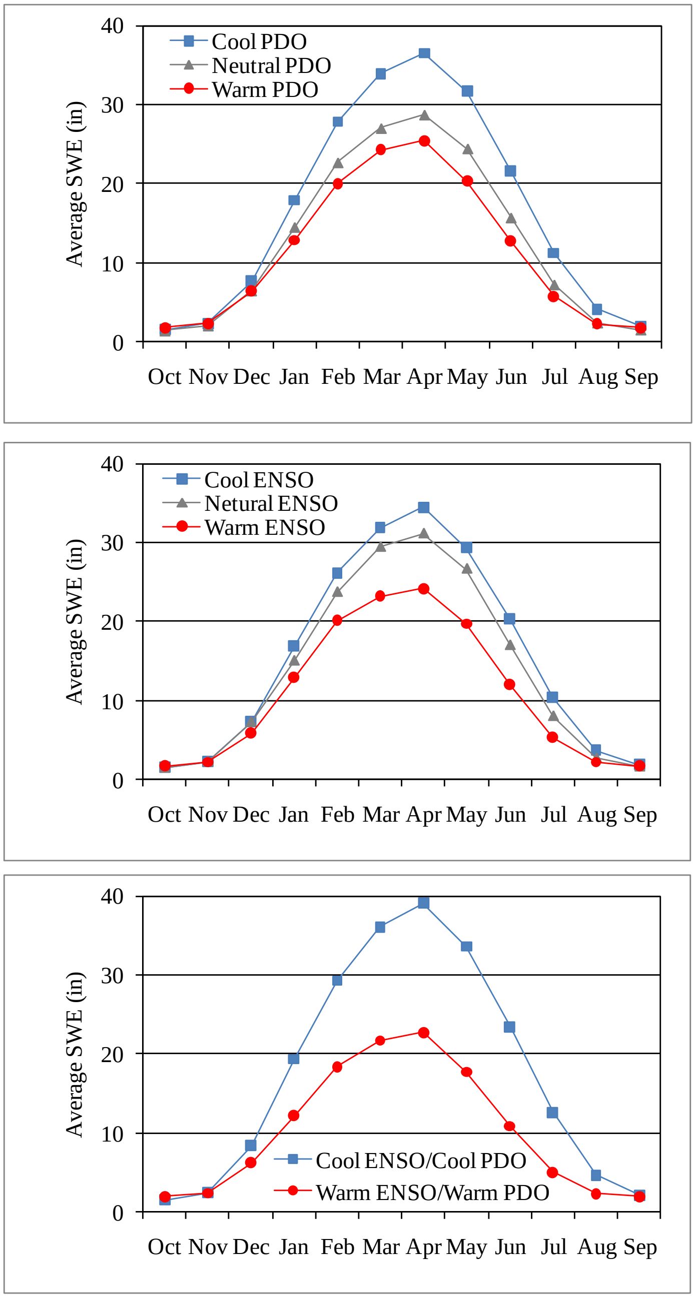

Figure 2.10 Composite monthly simulated snow water equivalent (SWE) for the Skagit River (water years 1916 -2006) for the PDO phases based on the PDO index (top), ENSO phases based on Dec-Feb averaged Nino3.4 Index (middle) and the PDO and ENSO in phase (bottom).

<u>2.4.3 Skagit Basin Streamflow</u>

The PDO and ENSO impacts on streamflow for the Skagit River are illustrated by composite average monthly hydrographs for Ross reservoir near Newhalem (Figure 2.11), for the Sauk

River near Sauk (Figure 2.12) and for the Skagit River near Mount Vernon (Figure 2.13). Monthly naturalized flows for water years 1916-2006 and 1929 -2006 are used for Ross reservoir and for the Sauk River, respectively. Naturalized streamflows are not available for the Skagit River near Mount Vernon, thus streamflows simulated by the Variable Infiltration Capacity hydrologic simulation model (Liang et al., 1994) for water year 1916-2006 are used for the Skagit River near Mount Vernon (URL 4). As shown in Figures 2.11 to 2.13, the responses of annual streamflow to the PDO and ENSO in the Skagit River basin are similar to those experienced in the Columbia River basin, but seasonal responses are somewhat different between the two basins. For both the Columbia River basin and the Skagit River basin, a strong hydrologic response to the PDO and ENSO is observed during summer. In comparison with the Columbia River basin (see Figure 2.7), the Skagit River streamflows show a larger hydrologic response during wintertime (see Figures 2.11 through 2.13). These differences reflect the fact that the Columbia River basin is a strongly snowmelt dominant watershed, whereas the Skagit River basin is warmer and has more temperature sensitive snowpack, which results in a larger streamflow response to precipitation falling as rain in the fall and early winter and a somewhat less pronounced snowmelt peak in spring (Elsner et al., 2010). Thus, winter precipitation anomalies in the Skagit associated with the PDO and ENSO produce a greater streamflow response in the Skagit in the fall and early winter, and warm season flow in the Skagit is more strongly coupled to temperature in cool season. Correlations between Apr-Sep streamflow and Oct-Mar temperature are helpful in quantifying the relationship between cool season temperature and warm season flow. The correlation coefficient between these two variables for the Columbia River at The Dalles is -0.09. By contrast, the correlations for the Skagit River Ross Dam, the Sauk River, and Mount Vernon are -0.38, -0.49 and -0.39 respectively. In other words, Apr-Sep streamflows for the Skagit River are more strongly correlated with cool season temperature in comparison with the Columbia River basin. (Similar relationships between cool season temperature and April 1 SWE are also present in the North Cascades (see Mote, 2006) and, in fact, the sensitivity of SWE to temperature is one of the primary causes of the warm season streamflow anomalies discussed above.) Note also that hydrographs associated with ENSO neutral and cool ENSO years are quite similar to each other.

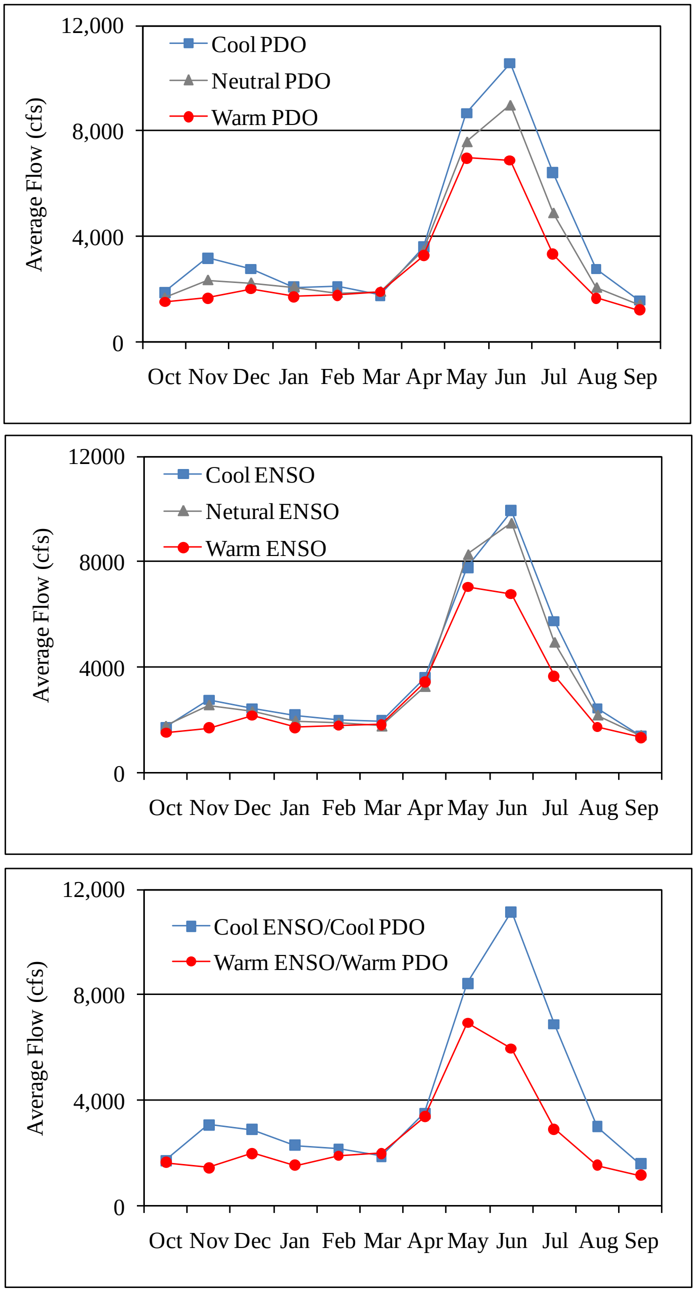

Figure 2.11 Composite monthly naturalized streamflow for Ross reservoir near Newhalem (water years 1916 -2006) for the PDO phases based on the PDO index (top), ENSO phases based on Dec-Feb averaged Nino3.4 Index (middle) and the PDO and ENSO in phase (bottom).

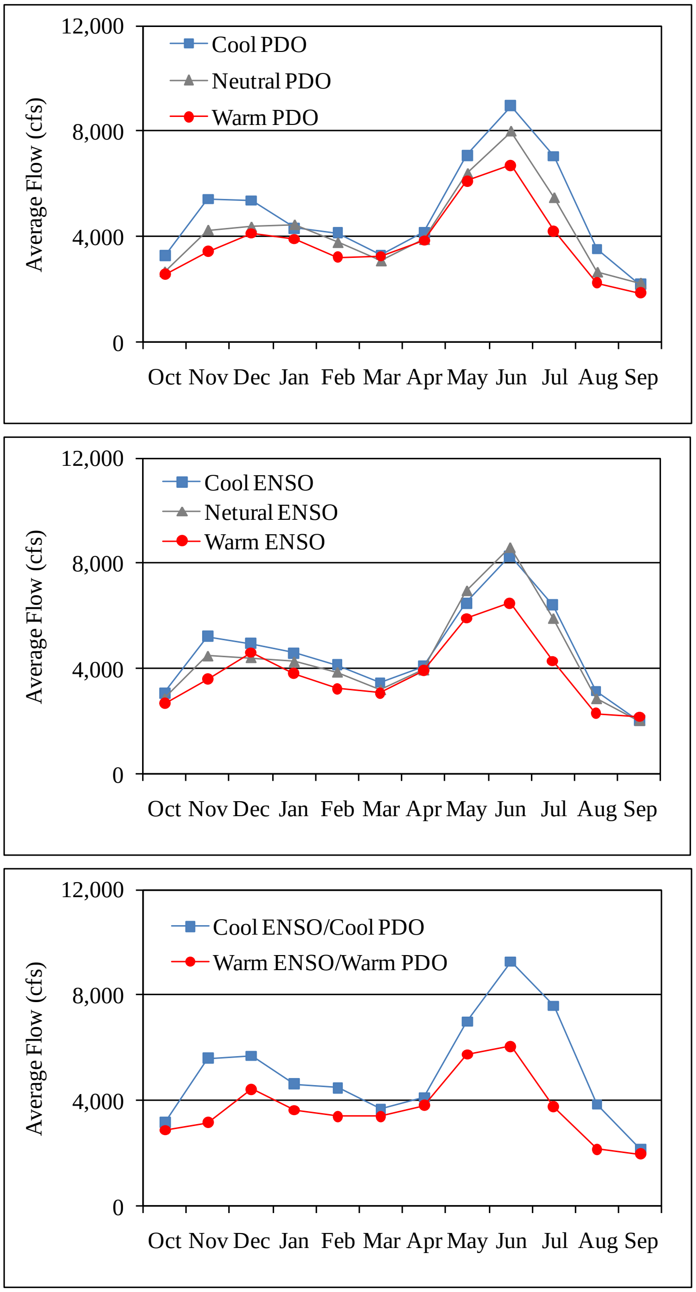

Figure 2.12 Composite monthly naturalized streamflow for the Sauk River near Sauk (water years 1929 -2006) for the PDO phases based on the PDO index (top), ENSO phases based on Dec-Feb averaged Nino3.4 Index (middle) and the PDO and ENSO in phase (bottom).

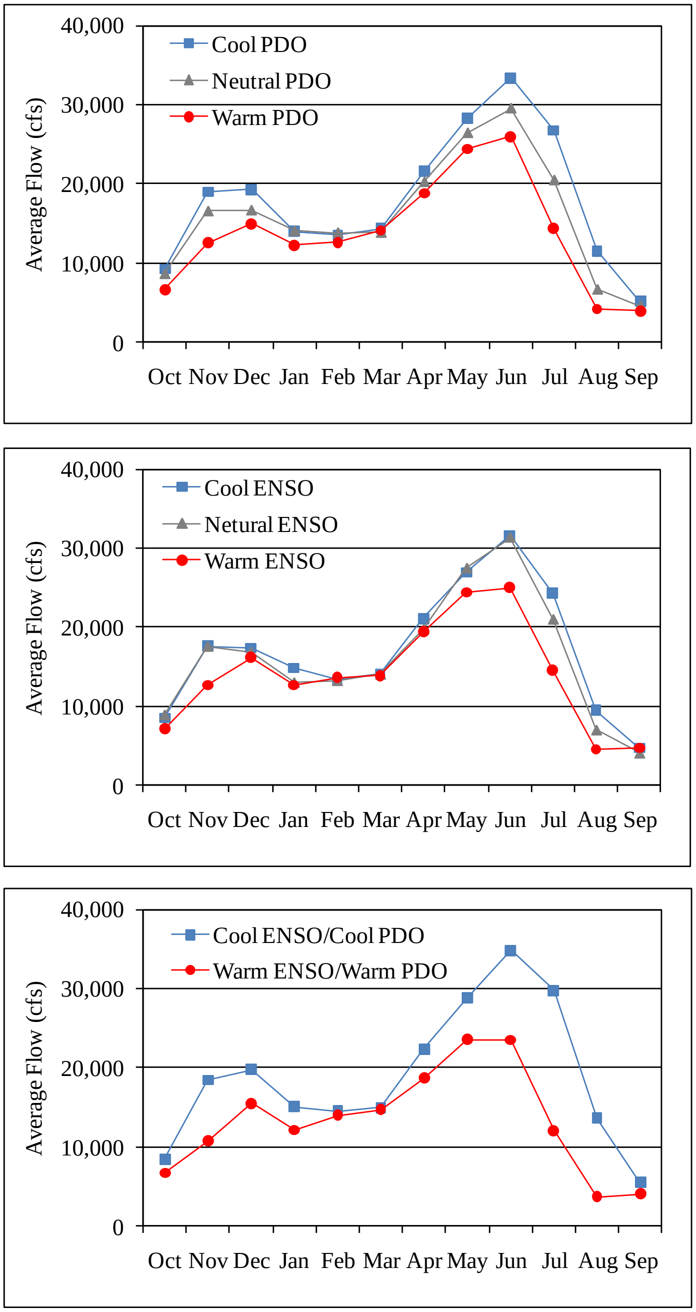

Figure 2.13 Composite monthly raw VIC simulated streamflow for the Skagit River near Mount Vernon (water years 1916 -2006) for the PDO phases based on the PDO index (top), ENSO phases based on Dec-Feb averaged Nino3.4 Index (middle) and the PDO and ENSO in phase (bottom).

2.4.4 Skagit Basin Flood Risk

Retrospective hydrologic modeling studies show that the North Cascades area typically experiences the highest flood risk in cool PDO epochs and ENSO-neutral years in (Figure 2.8) (Hamlet and Lettenmaier, 2007). The same study showed that twentieth century warming trends and increases in cool season precipitation variability that have occurred across the West since about 1975 have strongly increased flood risk in western Washington State. A long unregulated peak flow record is available for the Sauk River near Sauk, WA (a tributary to the Skagit), which shows the expanding variance of peak flows since the mid-1970s associated with the increasing cool season precipitation variance (Figure 2.14). Note also that the four highest peak flow events have all occurred in the last 30 years or so.

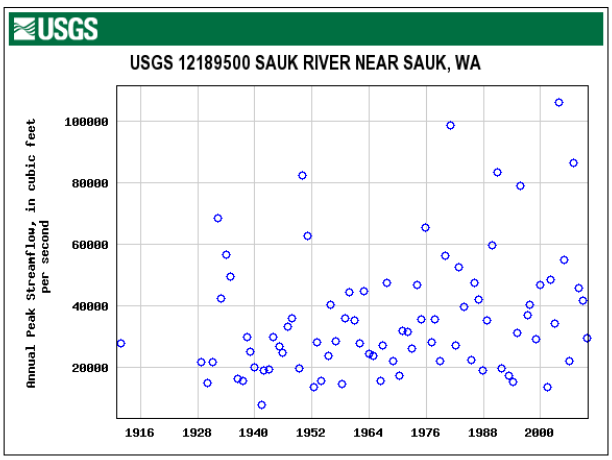

Figure 2.14 Observed instantaneous peak flow in the unregulated Sauk River near Sauk from 1928-2009 (Source: USGS).

The observed increases in precipitation variability, and the associated recent increases in flood risk are currently hypothesized to be related primarily to climate variability, but the observed changes in flood risk may also be related to changing intensity of atmospheric rivers (also called “pineapple express” storms) and warmer temperatures that may have some connection to global climate change (Chapter 3). Neiman et al. (2010), for example, show that many of the largest flood events in western WA in recent decades have been caused by intense atmospheric rivers that deliver both warm temperatures and intense precipitation to the PNW coast. Such storms are hypothesized to increase in intensity with the increased sea surface temperatures in the tropics (the primary source of moisture) and the moisture holding capacity of a warmer atmosphere.

2.4.5 Skagit Basin Water Temperature

The composite weekly water temperature for the Skagit River above Sedro Woolley is shown in Figure 2.15.

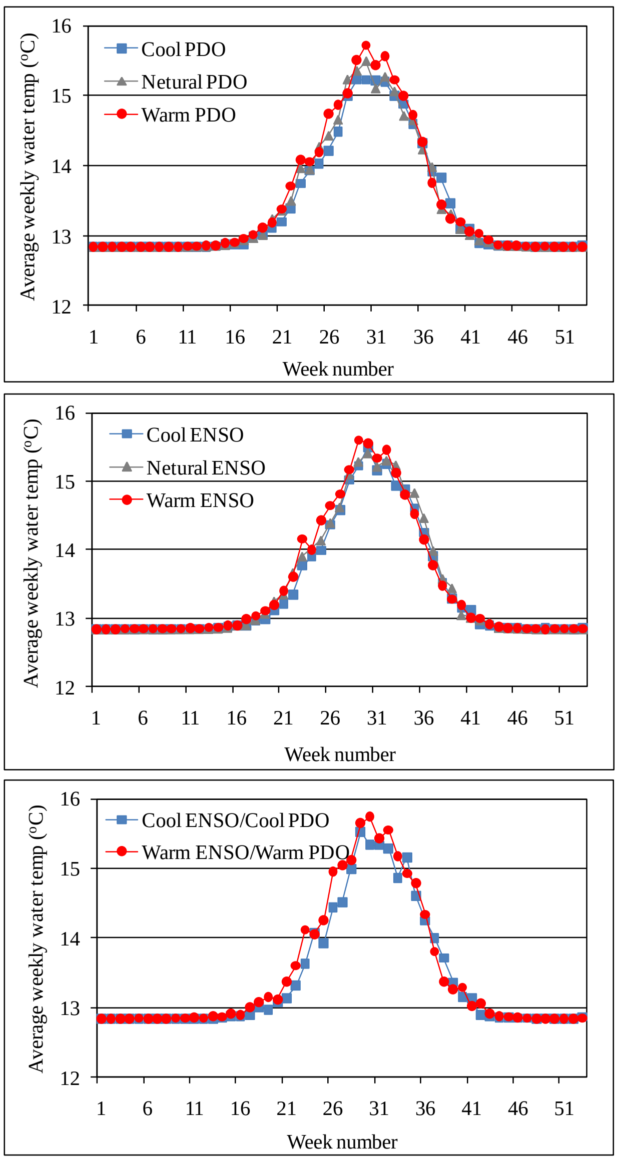

Figure 2.15 Composite weekly water temperature for the Skagit River above Sedro Woolley (water years 1916 -2006) for the PDO phases based on the PDO index (top), ENSO phases based on Dec-Feb averaged Nino3.4 Index (middle) and the PDO and ENSO in phase (bottom) (data source: Hamlet et al., 2010 a).

The warm phase of PDO and ENSO are typically associated with warmer water temperature for the Skagit River. When the PDO and ENSO are in phase, the impacts on water temperature tend to be enhanced.

2.4.6 Heating and Cooling Energy Demand

A heating (cooling) degree day is a measurement which relates a daily average temperature to an index value that is approximately proportional to the energy needed to heat (cool) a home or business (the actual energy use is a function of insulation values, etc.). Heating degree days (HDD) and cooling degree days (CDD) are calculated from the difference between a daily average temperature and a base temperature as follows:

$$HDD = \max(0, 18.33 - t_{avg}) \qquad (1)$$

$$CDD = \max(0, t_{avg} - 23.89) \qquad (2)$$

where t_{avg} is a daily average temperature in degrees Celsius, and 18.33 ^{o}C (65 ^{o}F) and 23.89 ^{o}C (75 ^{o}F) are base temperatures for HDD and CDD, respectively (Hamlet et al., 2010 b). The long term annual average HDD and CDD calculated for historical data (water years 1916 to 2006) for western WA are 3730 ^{o}C (6746 ^{o}F) and 28 ^{o}C (82 ^{o}F), respectively. Figure 2.16 shows special patterns of HDD and CDD in western WA, which vary according to proximity to the coast and elevation. For comparison, observed long-term average heating degree days at Mount Vernon are about 5330 (°F) and cooling degree days (based on the 75° F threshold above) are essentially zero. Thus, energy demand for space heating in the Skagit basin is dominated by heating degree days. Heating degree days are only moderately affected by temperature variability associated with the PDO and ENSO. A warming of 1° C (1.8° F) associated with ENSO, for example, results in about a 10% decrease in heating degree days in the Puget Sound lowlands.

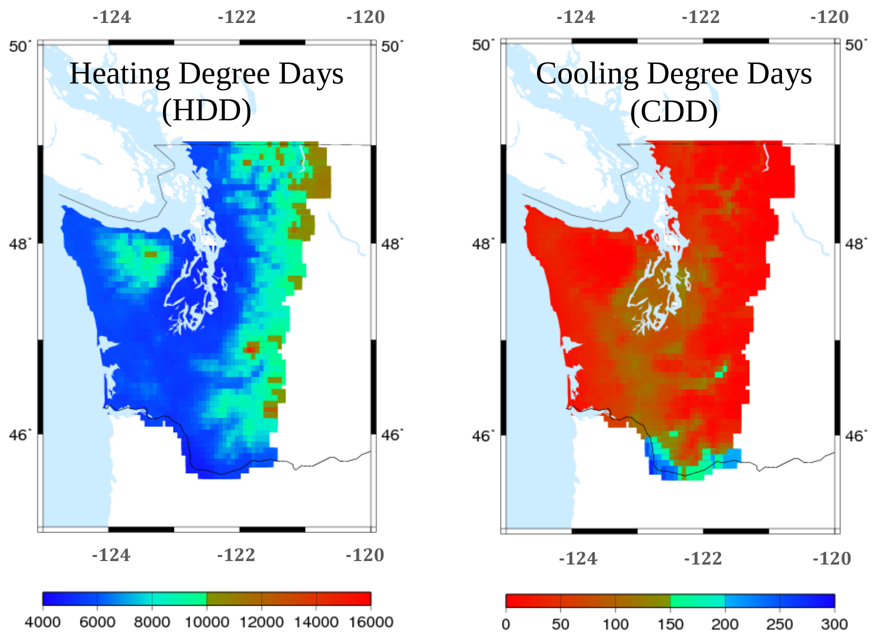

Figure 2.16 Long-term average annual total heating degree days (HDD)(right panel) and cooling degree days (CDD) (left panel) (in ^{o}F) for west Washington (1916-2006). HDD are based on a threshold of 18.33 ^{o}C (65 ^{o}F). CDD are based on a threshold of 23.89 ^{o}C (75 ^{o}F) (Adapted from HDD and CDD databases produced by Hamlet et al., 2010 b).

2.5 Summary and Conclusions

Two large-scale climate phenomena, the El Niño-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO), influence temperature and precipitation patterns in the PNW. These patterns of climate variability also influence hydrologic variables such as April 1 SWE, streamflow, and hydrologic extreme such as droughts and floods in the PNW. Coincidence of warm (cool) phases of the PDO and ENSO tends to enhance the patterns of climate variability and associated anomalies in hydrologic variables and hydrologic extremes. Similarly, the PDO and ENSO have influenced climatological and hydrological variables in the Skagit River basin. Key findings include the following:

- Observed variations in temperature and precipitation in the PNW over the 20th century are mostly related to natural climate variability, although anthropogenic climate change has substantially influenced changes in temperature after 1970 (see also Chapter 3).

- Warm phases of the PDO and ENSO generally produce warmer and drier winter/spring weather over the PNW while cool phases of the PDO and ENSO produce cooler and wetter conditions.
- April 1 SWE is negatively correlated with cool season temperature and positively correlated with cool season precipitation. Therefore, warm phases of the PDO and ENSO are associated with lower April 1 SWE but cool phases of the PDO and ENSO are associated with higher April 1 SWE. The impacts of climate variability on April 1 SWE are pronounced in coastal Washington State which is a relatively warm area.
- Similar to the impacts of climate variability on SWE, warm phases of the PDO and ENSO produce lower streamflows than cool phases of the PDO and ENSO, with largest response in June.
- Coincidence of warm/cool phases of the PDO and ENSO tends to enhance the patterns of climate variability and subsequently the anomalies in hydrologic variables such as SWE and streamflow and the incidence of hydrologic extremes such as floods and droughts.
- Consistent with the impacts of the PDO and ENSO on climate over the PNW as a whole, temperature and precipitation along with associated hydrologic variables and hydrologic extremes for the Skagit River are strongly influenced by the PDO and ENSO.
- Hydrologic variables in the Skagit River correlate better with cool season temperature in comparison with the PNW as a whole. As a result, the PDO and ENSO have a more pronounced influence on snowpack and streamflow for the Skagit River basin in comparison with the PNW as a whole.
- The water temperature for the Skagit River above Sedro Woolley is higher for warm phases of the PDO and ENSO in comparison with cool phases of the PDO and ENSO. The coincidence of warm phases of the PDO and ENSO increases the likelihood of unfavorable summer water temperatures for cold water fish.
- Energy demand for the Skagit River basin is dominated by heating degree days. Heating degree days are only moderately affected by temperature variability associated with the PDO and ENSO.

URL 1: http://cses.washington.edu/cig/pnwc/compensopdo.shtml

URL 2: http://cses.washington.edu/cig/pnwc/clvariability.shtml

URL 3: http://cses.washington.edu/cig/maps/

URL 4: http://www.hydro.washington.edu/2860/

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