

ENSO and Pacific Decadal Oscillation: their effects on basins of the Puget Sound estuary

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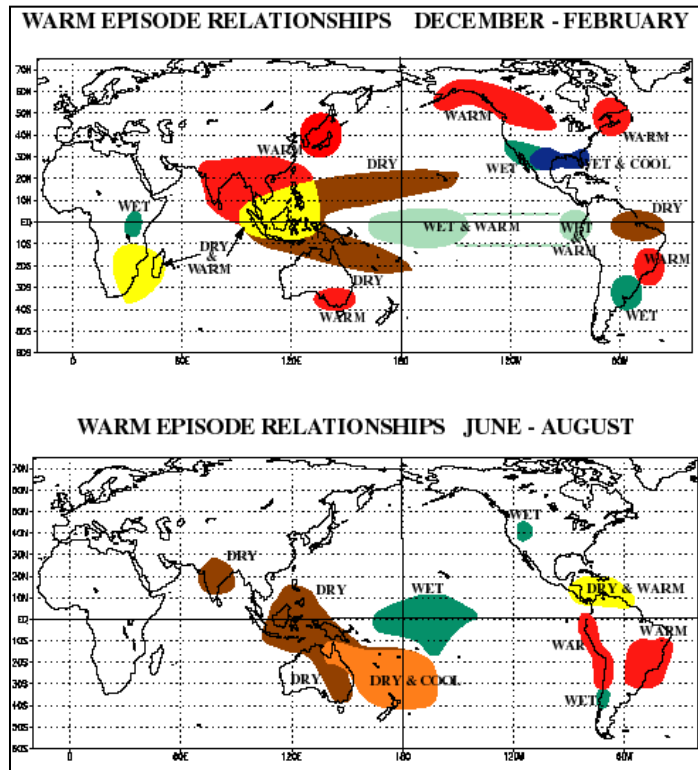
Abstract

Puget Sound in Washington state is one of the largest estuaries in the world and is home to abundant and diverse wildlife and urban communities alike. The different basins of its more 1000 square miles respond uniquely to global climate oscillation patterns like the El Nino Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO). In order to better understand just how quickly and each of the four basins of the Sound respond to these natural patterns, we investigated the relationships between seasonal rainfall and river discharge averages and the indexes that rate the strength of these global weather oscillations. We found there to be very little correlation between the oscillation indexes and rainfall anywhere in the Puget Sound. River discharge rates in the Main and South Basins, which are home to the cities of Seattle and Tacoma, tended to lag behind ENSO and PDO by one to two seasons. The strongest relationships here were between late fall indexes and springtime river discharge. The oscillations were shown to explain nearly half of the seasonal variation in river discharge in these areas. The Whidbey Basin discharge rates took two to three seasons to respond to the indexes and the Hood Basin saw little to no correlation. It was also discovered that averaging the ENSO and PDO indexes into one rating produced a higher correlation for river discharge in all basins but Hood. This knowledge could help to improve our ability to predict changes in snowpack, salinity and other aspects related to freshwater mixing throughout the estuary further in advance.

Introduction

Global weather patterns fluctuate on many different timescales. Around the world, weather patterns change over hours, days, seasons and years. Even slight changes in wind speed and direction in one region can have effects in other areas thousands of miles away. The El Nino

Southern Oscillation (ENSO) is a weather pattern driven by the irregular occurrence of warmer, nutrient-poor surface water in the East equatorial Pacific. This irregularity generally lasts anywhere from two to seven years and dictates climate anomalies around the world (Trenberth, 1997). For example, El Nino conditions, where surface waters in this equatorial region are warmer, result in a warmer winter both across



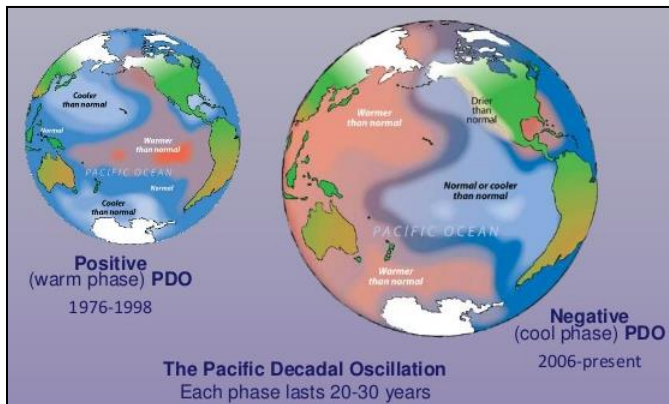
El Nino ('warm episode') global effects in winter and summer.

Southeast Asia and Northwest North America. Billions of people feel the effects of this small climate variation and it is important that they are informed of what climate variations to expect.

Beyond ENSO, there is another climate oscillation that occurs, but on a much longer timescale. The Pacific Decadal Oscillation (PDO) causes sea surface temperature anomalies across the Pacific Ocean and has periods that can last 20-30 years. In its positive phase, sea surface temperatures increase all up and down the east side of the ocean, while temperatures are slightly cooler on the western side. In the past decade or so, we have been experiencing the negative phase, which displays the opposite effects (Newman et al., 2016). This is important to

consider because though the causes of PDO are not fully understood, it is thought that certain effects of this oscillation and ENSO can magnify each other in some areas around the Pacific and beyond. A magnified El Nino is an event the public needs to be informed about as early as possible, because its effects could leave entire countries in droughts or flood zones or create many extensive hazards affecting large-scale infrastructure and transport.

Local governments can prepare for a year of low precipitation or high flood risk. National governments could prepare by funneling resources and funds beforehand to areas they know will be at certain risks, such as areas that will be expecting larger and more frequent hurricanes in that year or the following year. In 1998 in Venezuela, flash floods and landslides killed almost 50,000 people (Cai et al., 2015). The local government was not prepared to support their communities through floods and evacuate them efficiently. That same year, 200 million people



Surface sea temperature patterns of the Pacific Ocean during different phases of the Pacific Decadal Oscillation.

were displaced across China due to similar flood events. If resources, time and effort were invested into these high-risk areas months beforehand, lives could have been salvaged and property potentially saved.

The relationship between ENSO

and PDO is something that has been

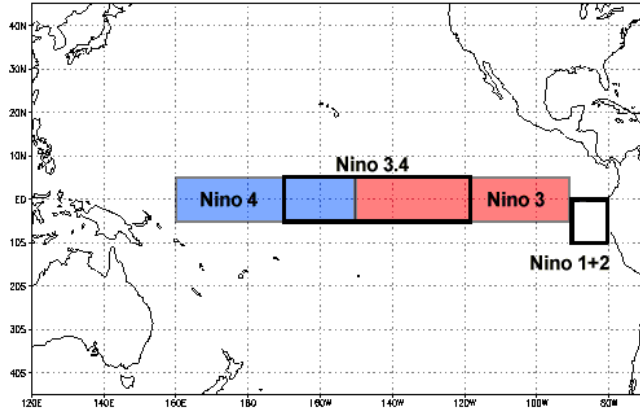
investigated before but is very complicated. Newman et al. (2016) found that ENSO influences PDO on all timescales, though the amount of influence depends on many factors. Atmospheric forcing is the strongest influencer on PDO, and the strength of ENSO's effects in the Northern Pacific depends mainly on the season. Climate variability is still a major restraint on understanding how these two phenomena interact.

The Puget Sound estuary in Washington State is an important and closely studied environment because of the high surrounding population and industrial activity depending on it. With over four million people living around the estuary, even slight changes to its properties or the weather around it could cause major issues. With mountain ranges on both sides of the area, warmer temperatures can have impacts on the snowpack and amount of seasonal river runoff from melting glaciers (Vano et al., 2010). Beyond this, ocean acidification is helping to make it one of the most acidic bodies of water in the ocean (Busch et al., 2014). I want to consider how PDO and ENSO affect weather patterns, and thus oceanographic properties of the water column in the Sound.

Few scientific inquiries into this region regarding climate oscillations have been investigated. The most significant study, Moore et al. 2008, explored ENSO, PDO and Aleutian Low (measures North Pacific atmospheric pressure) index ratings and their correlation to water properties of the Sound. This study focused on the correlation of each of these indexes separately and only looked at their effects on surface temperature and surface salinity around the different basins in the Sound. I looked at a combination of the indexes and their correlation to rainfall and river discharge in each of the basins. I also want to consider the effects of climate change and how future anthropogenic forcing might affect this area as well, especially since global warming is increasing the frequency of extreme El Nino events (Cai et al., 2014). If we can better understand how these processes are affecting the region, we will be better prepared for future El Nino events and we can be more efficient at mitigating the effects of climate change for the millions of people in the area.

Methods

In this study, indexes determined by other sources are used for describing the strength of ENSO and PDO cycles. For ENSO, the index used in this study was the Nino 3.4 (original data found [here](#), or linked in References). This index looks specifically at an area of the central equatorial Pacific from 170W to 120W, which is known as the key region for coupled ocean-atmosphere interactions. This index is generally accepted as the most accurate for predicting climate variations across the continental United States. For PDO, the NCEI index is

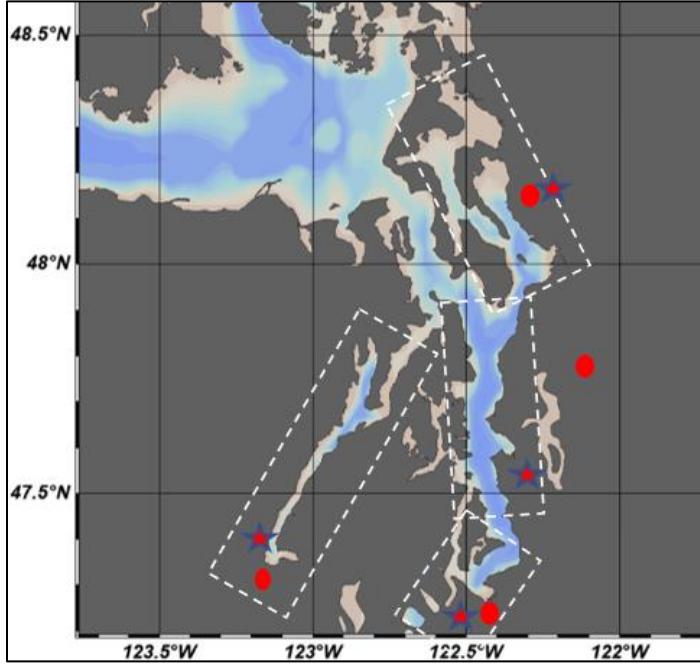


Location differences between Nino indexes. Nino 3.4 represented by clear box with bold lining. (source: NOAA NCDC)

defined by the size of sea surface temperature anomalies in the North Pacific. The index is calculated by NOAA in Seattle, which partners with the University of Washington (original data [here](#), or referenced under Mantua, N).

The data for the indexes was originally reported online, listed as monthly averages. To make the graphs and trends easier to comprehend, these were converted to seasonal averages for each year. Winter was calculated using values for December, January and February, spring was calculated using March, April and May (and so on). All data for rainfall and river output were also originally listed as monthly amounts, total for rainfall and average for river output (in cubic feet per second). These data sets were also converted to seasonal averages. The original data river output data was collected by the USGS (USGS Washington Streamflow Data) and original rainfall data collected by NOAA (NOAA Local Climatological Data). Data for rainfall and river output were collected from four sites around the Puget Sound. Each site is located in one of the

four main basins of the Sound (Main Basin, Whidbey Basin, South Basin and Hood Canal). The data were taken all near their respective river mouths. One index, 'PDO-ENSO Average' (PEA), was created for this study and is a combination of the NCEI PDO and Nino 3.4 indexes. It was



Stars represent locations of river data. Discharge rates were taken from the Snoqualmie River (Main), Skagit River (Whidbey), Skokomish River (Hood) and Deschutes River (South). Rainfall data is represented by the red circles. This data was collected at Cushman Powerhouse (Hood), Olympia Municipal Airport (South), Seattle Boeing Field (Main) and Arlington Station (Whidbey).

calculated by averaging the indexes. The goal of this was to find an index that took the strength of both these oscillatory patterns into account.

To examine possible statistical correlations, a T-test was completed for every pairing of data for each basin. This means that PDO values, ENSO values, averaged values, river output data and rainfall data were all tested with respect to each other. P-values were calculated using a one-tail method

and statistical significance of $p < 0.05$. All data examined was from the years of 1985-2016.

Results

Statistical t-tests were completed between all the seasonal average data sets. A significant p-value was found for 117 of the 448 data set combinations compared. There were 36 significant relationships found in the Main Basin, 38 in the Whidbey Basin, 27 in the South Basin and 16 in the Hood Canal Basin. These relationships are detailed in figures 1a-d in pages 9-11. The results of all 448 data set combinations along with ENSO vs. PDO correlation tests can be found in

Figure 2 of the Appendix. For each of the 117 significant correlations found, a linear regression was performed and a coefficient of determination, r^2 , was calculated. The relationships with a higher r^2 value represent models that explain more variability of the response data around the mean.

The correlation coefficient values for index-discharge relationships are generally much higher than for index-rainfall relationships. Discharge relationships have correlation coefficients as high as 0.46 in the Main Basin, and 0.43 in the South Basin, while only one index-rainfall relationship ever reached a coefficient of 0.2. In Hood Basin, ENSO ratings were not correlated with either rainfall or discharge rate. In South Basin, none of the three ratings used showed a correlation with rainfall in the following seasons.

For ENSO vs. PDO index correlation tests, a significant relationship was found in all 16 tests between ENSO and later PDO seasons. When the test was completed to see if PDO in one season affected ENSO in later seasons, only half as many results showed a significant correlation.

Figure 1: a) Main Basin b) Whidbey Basin c) South Basin d) Hood Basin. All relationships that returned a p-value < 0.05. The measure in the first column is the independent variable and the season it was collected. The third column is the lagging (dependent) variable. Its season always refers to the season after that of the independent variable. Darker rows represent data sets that are from the same season.

Figure 1a – Main Basin

Independent Measure	IM Season	Dependent Measure	DM Season	r ²	Regression Eq.
Rainfall	Winter	Discharge	Winter	0.589	782x+1028
Rainfall	Fall	Discharge	Fall	0.4816	593x+1165
PEA	Winter	Discharge	Spring	0.4653	4464-910x
PEA	Fall	Discharge	Spring	0.4098	4272-767x
PDO	Winter	Discharge	Spring	0.4088	4575-745x
Rainfall	Spring	Discharge	Spring	0.3401	1016x+2170
ENSO	Fall	Discharge	Spring	0.335	4342-592x
ENSO	Winter	Discharge	Spring	0.3282	4305-693x
PDO	Fall	Discharge	Spring	0.3131	4207-622x
PEA	Spring	Discharge	Spring	0.2956	4578-949x
PEA	Summer	Discharge	Spring	0.2908	4363-718x
PDO	Spring	Discharge	Spring	0.2613	4644-626x
PEA	Fall	Discharge	Summer	0.2459	1355-227x
PEA	Winter	Discharge	Summer	0.2383	1391-245x
PDO	Summer	Discharge	Spring	0.2376	4363-491x
ENSO	Fall	Discharge	Summer	0.2272	1376-186x
ENSO	Summer	Discharge	Spring	0.2167	4328-664x
PDO	Winter	Rainfall	Spring	0.2149	2.23-0.31x
PDO	Winter	Discharge	Summer	0.2137	1422-203x
Rainfall	Fall	Discharge	Winter	0.2047	307x+2955
ENSO	Spring	Discharge	Spring	0.1758	4374-857x
ENSO	Winter	Discharge	Summer	0.1641	1348-185x
PDO	Fall	Discharge	Summer	0.1622	1337-171x
PEA	Fall	Rainfall	Spring	0.1587	2.13-0.28x
PEA	Winter	Rainfall	Spring	0.1549	2.17-0.30x
Rainfall	Fall	Discharge	Summer	0.1408	101x+837
PDO	Fall	Rainfall	Spring	0.1357	2.11-0.24x
ENSO	Fall	Rainfall	Spring	0.1167	2.16-0.20x
Rainfall	Spring	Discharge	Summer	0.1013	209x+911
PDO	Winter	Rainfall	Fall	0.0974	5.02+0.51x
PDO	Summer	Rainfall	Spring	0.0971	2.17-0.18x
PEA	Summer	Rainfall	Spring	0.0968	2.17-0.24x
PDO	Fall	Discharge	Fall	0.0957	4204-406x
PEA	Spring	Discharge	Summer	0.0932	1407-201x
Rainfall	Summer	Discharge	Summer	0.085	230x+1121
PDO	Summer	Discharge	Summer	0.0479	1355-85.3x

Figure 1b – Whidbey Basin

IM	IM Sea.	DM	DM Sea.	r ²	Regression Eq.
Rainfall	Fall	Discharge	Fall	0.5726	2628x+1829
Rainfall	Winter	Discharge	Summer	0.41	1693x+4353
PDO	Winter	Discharge	Summer	0.3674	13367-2141x
PEA	Winter	Discharge	Summer	0.3519	13014-2400x
PEA	Fall	Discharge	Summer	0.3387	12644-2141x
Rainfall	Winter	Discharge	Spring	0.2967	1557x+11215
PDO	Spring	Discharge	Summer	0.2956	13673-2018x
PDO	Fall	Discharge	Summer	0.2937	12448-1851x
Rainfall	Fall	Discharge	Winter	0.2854	1248x+10051
PEA	Spring	Discharge	Summer	0.2838	13398-2821x
Rainfall	Spring	Discharge	Summer	0.2613	1898x+6160
ENSO	Fall	Discharge	Summer	0.2456	12831-1558x
PEA	Winter	Discharge	Spring	0.2401	19171-2143x
PDO	Winter	Discharge	Spring	0.2281	19456-1824x
ENSO	Winter	Discharge	Summer	0.1991	12602-1637x
PEA	Fall	Discharge	Spring	0.1981	18778-1773x
PDO	Fall	Discharge	Spring	0.1896	18605-1611x
PEA	Summer	Rainfall	Winter	0.1884	5.03-0.65x
Rainfall	Winter	Discharge	Winter	0.1862	1213x+11271
PDO	Summer	Discharge	Summer	0.1774	12867-1300x
PDO	Summer	Rainfall	Winter	0.1713	5.04-0.47x
ENSO	Winter	Discharge	Spring	0.1541	18800-1556x
PDO	Summer	Discharge	Spring	0.1519	19012-1305x
PEA	Summer	Discharge	Spring	0.1479	18992-1702x
ENSO	Fall	Discharge	Spring	0.1293	18927-1224x
PEA	Fall	Rainfall	Winter	0.1287	4.96-0.48x
ENSO	Summer	Rainfall	Winter	0.1185	5.0-0.55x
ENSO	Spring	Discharge	Summer	0.1151	12703-2103x
PEA	Winter	Rainfall	Winter	0.1125	4.98-0.51x
PEA	Summer	Discharge	Summer	0.1076	12790-1344x
ENSO	Fall	Rainfall	Winter	0.1072	5.00-0.375x
PEA	Spring	Discharge	Spring	0.103	19334-1837x
ENSO	Spring	Rainfall	Spring	0.0998	3.43-0.53x
PEA	Fall	Rainfall	Spring	0.0995	3.44-0.31x
Rainfall	Winter	Discharge	Fall	0.0978	1255x+11279
PDO	Fall	Rainfall	Winter	0.0963	4.92-0.39x
ENSO	Winter	Rainfall	Winter	0.0943	4.89-0.43x
PDO	Spring	Discharge	Spring	0.0931	19468-1224x

Figure 1c – South Basin

IM	IM Sea.	DM	DM Sea.	r ²	Regression Eq.
Rainfall	Fall	Discharge	Fall	0.5189	289x+666
Rainfall	Winter	Discharge	Winter	0.4591	428x+1267
PEA	Winter	Discharge	Spring	0.4378	3938-663x
PDO	Winter	Discharge	Spring	0.4004	4023-554x
PEA	Fall	Discharge	Spring	0.3684	3816-554x
PEA	Spring	Discharge	Spring	0.337	4039-761x
PDO	Winter	Discharge	Summer	0.3313	2186-234x
PDO	Spring	Discharge	Spring	0.3309	4106-529x
PDO	Spring	Discharge	Summer	0.3072	2228-236x
PEA	Winter	Discharge	Summer	0.3026	2147-256x
PDO	Fall	Discharge	Spring	0.3007	3767-464x
ENSO	Winter	Discharge	Spring	0.2944	3823-493x
ENSO	Fall	Discharge	Spring	0.2835	3865-415x
PEA	Summer	Discharge	Spring	0.2773	3883-534x
PEA	Spring	Discharge	Summer	0.2711	2192-317x
PDO	Summer	Discharge	Spring	0.2554	3886-387x
PEA	Fall	Discharge	Summer	0.2525	2107-213x
PDO	Fall	Discharge	Summer	0.2259	2087-187x
PDO	Summer	Discharge	Summer	0.1855	2133-153x
ENSO	Fall	Discharge	Summer	0.1773	2126-152x
ENSO	Summer	Discharge	Spring	0.1706	3855-449x
ENSO	Winter	Discharge	Summer	0.1598	2103-169x
ENSO	Spring	Discharge	Spring	0.1587	3853-612x
Rainfall	Winter	Discharge	Fall	0.1179	219x+1982
PEA	Summer	Discharge	Summer	0.1164	2124-161x
PDO	Winter	Rainfall	Fall	0.1104	6.6+0.70x
Rainfall	Summer	Discharge	Summer	0.0912	160x+1927

Figure 1d – Hood Basin

IM	IM Sea.	DM	DM Sea.	r ²	Regression Eq.
Rainfall	Winter	Discharge	Winter	0.242	18.4x+55.2
Rainfall	Fall	Discharge	Fall	0.2372	20.3x-7.0
PDO	Summer	Discharge	Summer	0.2328	84.0-21.5x
PDO	Spring	Discharge	Summer	0.1636	91.4-21.7x
PDO	Summer	Discharge	Spring	0.1492	136-25.7x
Rainfall	Spring	Discharge	Fall	0.1466	432-48.1x
PEA	Summer	Discharge	Summer	0.1167	82.5-20.22x
PEA	Fall	Rainfall	Spring	0.1037	3.6-0.45x
PDO	Winter	Discharge	Summer	0.1034	85.9-16.4x
PDO	Winter	Rainfall	Fall	0.1003	12.6+1.29x
PDO	Summer	Discharge	Winter	0.099	275-34.3x
PEA	Winter	Rainfall	Fall	0.0977	12.8+1.45x
PDO	Winter	Rainfall	Spring	0.0971	3.77-0.42x
PEA	Spring	Discharge	Summer	0.0931	86.6-23.35x
PEA	Winter	Rainfall	Spring	0.0878	3.7-0.46x
PDO	Spring	Discharge	Spring	0.045	145-18.5x

Discussion

When considering the most effective index rating system for the Puget Sound, we evaluated PDO, ENSO, and PEA, which is an average of the first two indexes. Another common index used to evaluate PDO events is the North Pacific Index (NPI). This index is calculated from average air pressure anomalies over the North Pacific Ocean. Though it is utilized in many ways, it was not considered in this paper. Its relationship with climate in the Puget Sound was already investigated and proven to have far lower statistical significance than the PDO index (Newman et al., 2016).

In the Main Basin, ENSO and PDO had very similar correlation coefficients when testing them against discharge and rainfall data sets. In the Whidbey and South Basins, PDO was a much better predictor than ENSO. But in all three of these basins, PEA had a clearer predictive equation that had much less variation in its model. In Hood Basin, PDO was the most reliable index and outperformed PEA. This is a very clear indicator that these water inputs in the Puget Sound are affected by both oscillatory systems. Random weather trends only account for half of the variation in this data in the Puget Sound. The other half is caused and can be better predicted by a combination of these systems. When PDO and ENSO were tested against each other, it was very clear that ENSO is always influencing PDO in later seasons, and not the other way around. But the strength of both systems is important to consider when looking at how they affect the Sound.

Of the 117 significant relationships found between datasets in this study, 31 were relationships between two datasets in the same season. While these relationships are important, they do not provide any predictive opportunity multiples months in advance. In the following discussion, we will focus on the relationships whose effects lag across seasons.

Throughout all four basins, there were much fewer significant relationships between the indexes and seasonal rainfall totals than the indexes and seasonal river discharge averages. In fact, ENSO index-rainfall relationships were non-existent except for in the Whidbey Basin, and even there the regression coefficients are so low that the equation would not be considered as a reliable predictor of rainfall levels. This is likely due to the fact ENSO and PDO oscillations can have a significant effect on snowpack in the surrounding Cascade and Olympic mountains, and not as much on daily weather around the Sound. This is also interesting because of how ENSO events are described in American media. Words that relate to rain and moisture, such as ‘wet,’ ‘dry,’ or ‘humid,’ are words commonly seen on maps and in the news regarding ENSO weather events. The most reliable rainfall relationship was found comparing winter PDO and spring rainfall in the Main Basin and even in this basin and seasons, river discharge had a relationship with much less uncertainty.

There are many more total significant relationships for index-discharge datasets. This suggests that average river discharge is more easily predictable than rainfall in all basins of the Puget Sound. Better predictability for river discharge makes more sense because this measurement considers not only rainfall totals in the area, but also the amount of melting from snowpack further inland. Discharge amounts are affected by rainfall and temperature, which have a much better relation to sea surface temperature anomalies in the Pacific. Most notably, PDO ratings in both fall and winter had very high correlation coefficients when predicting the amount of river discharge in the spring in the Main and South Basin. In the Whidbey Basin, the river discharge trend tended to lag behind an extra season, meaning the most easily predictable season for river discharge was summer, not spring. In the Hood Basin, there was no one season

that was most easily predictable for any of the variables. PDO arose as the most reliable index to predict changes in the basin, but the lag time for rainfall and discharge is still not clear.

Conclusion

The different basins of the Puget Sound all respond slightly differently to oscillatory weather patterns in the Pacific Ocean. Both the Main Basin, where the city of Seattle is located, and the South Basin lag 1-2 seasons behind PDO and ENSO indexes regarding river input. The indexes are the best predictors for springtime river input and can explain almost half of the variation from the average during this time. The Whidbey Basin lags 2-3 seasons behind the PDO index for river discharge, and this regression model can explain one-third of the variation from average values. The Hood Basin is only affected by PDO, but to an extent of only 10-15%. The rest of the variation of datasets from this basin can be attributed to other local weather patterns and variations. PDO index values tend to lag almost one full season behind ENSO values as well.

For all basins except for Hood, it is clear that both ENSO and PDO influence river input fluxes throughout the seasons. The most helpful index was one that took values from both PDO and ENSO and averaged them into one combined index. This can be a better predictor for how salinity in the water column and overall input amounts will change throughout the Sound moving forward. In the future, analyzing snowpack changes based on these indexes may be helpful in understanding just how ENSO and PDO dynamics can affect the Cascade and Olympic Mountains. It may also be worth the time to test other indexes that combine ENSO and PDO indexes in more robust ways, like offsetting the values by one or multiple seasons to consider PDO's lag time as well. The field of weather and climate variation prediction always needs more

models. This has helped us consider how these oscillations interact with different parts of the Puget Sound. But much more needs to be done to inform our politicians, business owners and fellow citizens of exactly what is to come.

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