# IMPLICATIONS OF PACIFIC NORTHWEST CLIMATE PATTERNS ON HARMFUL ALGAL BLOOMS AND THE SUBSEQUENT MARINE BIOTOXINS


By

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ABSTRACT

Implications of Pacific Northwest Climate Patterns on Harmful Algal Blooms and the Subsequent Marine Biotoxins

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Washington state Department of Health records of Paralytic Shellfish Poisoning (PSP) concentrations in shellfish from Sequim Bay in the Pacific Northwest were used to investigate the influence of climate patterns on *Alexandrium catenella* and shellfish toxicity. Sea surface temperatures (SSTs) were regressed against years 1957-2022 and found to be significantly increasing over time. SSTs over 13℃ are known to increase shellfish toxicity so with SST increasing over time, PSP could be expected to increase as well. The Pacific Decadal Oscillation (PDO) and El Nino Southern Oscillation (ENSO) are both positively and significantly correlated with PSP. This is likely because warmer SSTs increase *A. catenella* blooms thus subsequently increasing toxin accumulation in shellfish (PSP). The PDO and ENSO both contribute to SST anomalies and during warm phases this could increase shellfish toxicity.

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# Introduction

Washington state is the country's lead producer of farmed bivalves (e.g., clams, oysters, and geoducks) with an estimated annual harvest of 270 million dollars (Cooley et al. 2017). The shellfish industry brings jobs to over 32,00 people, primarily in rural coastal communities where other industry (and jobs) are lacking (King 2020). The Pacific Northwest is known for its abundance of diverse shellfish and serves as an icon for the region.

An issue that has afflicted the shellfish industry and its stakeholders is the presence of harmful algal blooms (HABs) (Anderson, Cembella, and Hallegraeff 2012). HABs are blooms of phytoplankton that naturally release toxins into the surrounding waters. These toxins can harm marine life or become concentrated in shellfish which poisons and can even kill humans after consumption. When HABs are present it results in the closure of commercial and recreational beaches resulting in less seafood for coastal communities and economic loss for all stakeholders (DOH 2022).

Sea surface Temperature (SST) is known to influence HABs and the subsequent biotoxins (Moore et al. 2010). Investigating what influences SSTs can help us better monitor and even predict HABs. The Pacific Decadal Oscillation (PDO) and El Nino Southern Oscillation (ENSO) are two climate patterns known to influence SST in the Pacific Northwest. These ENSO and PDO-driven changes in SSTs could be influencing HABs and the subsequent shellfish toxicity. Previous research has suggested that PDO does influence shellfish toxicity, but ENSO is still up for debate (Moore et al. 2010).

Understanding HAB dynamics and the factors impacting it can help organizations better monitor and regulate shellfish to ensure public safety. This thesis research studies the impacts of the climate patterns, El Nino Southern Oscillation (ENSO) and Pacific Decadal

Oscillation (PDO) on a specific HAB species (i.e., *Alexandrium catenella*) to provide more insight and predictive capabilities for public health monitoring agencies (e.g., Department of Health). Specifically, this thesis examines the following research question; To what extent does the Pacific Decadal Oscillation (PDO) and El Nino southern Oscillation (ENSO) correlate with shellfish toxicity (Paralytic Shellfish Poisoning) in Washington?

# Literature Review

This literature review will provide key background information needed to understand the dynamic of harmful algal blooms and the mechanisms behind the Pacific Decadal Oscillation (PDO) and the El Nino Southern Oscillation (ENSO). First, we'll start with information on phytoplankton and then more specifically, *Alexandrium catenella* and the subsequent shellfish toxicity (Paralytic Shellfish Poisoning). Then factors influencing *A. catenella*, and the climate patterns (i.e., ENSO and PDO) influencing SSTs. Lastly, we'll look at relevant literature regarding PDO, ENSO and PSP.

Phytoplankton are the most abundant living organism in the ocean and can be found in even a single drop of seawater. They are primary producers that provide more than 45% of the earth's oxygen (Simon et al. 2009)**.** As primary producers, they serve as the basis of all marine food chains. Phytoplankton provides sustenance for everything from microbes and other microscopic organisms to large fish species making them vitally important to the success of all marine ecosystems (NOAA, 2021).

The term phytoplankton refers to photosynthesizers unable to propel themselves against a current (planktos is Greek for "drifter") (NOAA, 2021). There are two main types of phytoplankton, dinoflagellates, and diatoms. Dinoflagellates are defined as a single-celled eukaryote with flagella, most commonly occurring as marine plankton (Simon et al. 2009). While dinoflagellates do have flagella to swim, it's mostly for vertical swimming through the water column (Ralston and Moore 2020). Diatoms are defined as single-celled algae that contain siliceous skeletons (i.e., frustules), which are commonly found in fresh and marine water (Simon et al. 2009). An important distinction is that dinoflagellates are motile while diatoms are not, allowing dinoflagellates to swim in search of nutrients, light, etc. which can be a major advantage in certain environments throughout the year (Moore et al. 2010). For example, once the surface layer is depleted of nutrients, dinoflagellates can move lower in the photic zone where more nutrients are available. There they can continue to photosynthesize utilizing the nutrients and space where there is less competition (Ralston and Moore 2020). This leads to a cyclical nature of diatom or dinoflagellate dominated times of the year due to the seasonality of environmental conditions (Alpine and Cloern 1992).

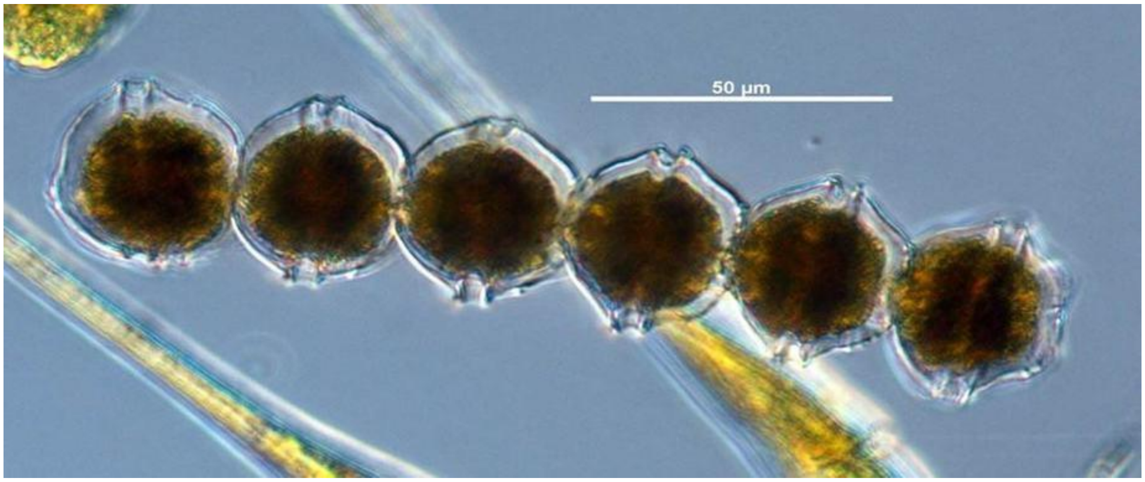
### Problem Description

While phytoplankton species provide many benefits for marine ecosystems, there are also negative consequences of phytoplankton. Some phytoplankton such as *Alexandrium catenella* (i.e., a common dinoflagellate in PNW marine waters) are known as harmful algal bloom (HAB) species because they naturally release biotoxins that are harmful to other life (Fig. 1) (Trainer et al. 2003). There are dozens of dinoflagellate and diatom species that release biotoxins posing threats to different types of life. These marine biotoxins are directly related to the success of harmful algal blooms (Moore et al. 2010). HAB biotoxins naturally bioaccumulate in filter-feeding organisms such as shellfish since they are directly consuming the algal species (Trainer et al. 2003). These biotoxins do not harm shellfish, but when consumed by other animals such as mammals and birds, it can have harmful impacts on them (Anderson, Cembella, and Hallegraeff 2012). *A. catenella* releases a toxin known as saxitoxin which is a neurotoxin that accumulates in shellfish throughout the year (mostly in summer and fall in the PNW). This can be extremely harmful to animals when consumed if the shellfish have accumulated high concentrations.

Marine biotoxins have been in the Pacific Northwest (PNW) as far back as the 18th century where written records were found describing shellfish poisoning (Anderson 1998).

Anecdotal evidence suggests marine biotoxins and shellfish toxicity has been around much longer and well known to tribes within Washington State (DOH 2022). The Washington State Department of Health has been testing for shellfish toxicity since the 1950s (DOH 2022). Several biotoxins have appeared in Washington's waters over time that were once not here (Fig. 2). This is attributed to warming and anthropogenic nutrient input allowing for phytoplankton to thrive (Van Dolah 2000).

FIGURE 1.
*ALEXANDRIUM CATENELLA*




*Note*. *Alexandrium catenella* cell chain under microscope (Mantua et al. 1997).

### ***Alexandrium catenella*** **– Paralytic Shellfish Poisoning**

*A. catenella* is a dinoflagellate with a unique life cycle (Fig. 3). *A. catenella* can occur as a single cell or as a chain of cells (Fig. 1). It is the main HAB species associated with Paralytic Shellfish Poisoning (PSP) via its release of saxitoxin (Trainer et al. 2003). While saxitoxin is the main neurotoxin responsible for PSP, there are many chemically similar structures that also contribute. Collectively, this group of neurotoxins is referred to as saxitoxins (STXs). Neurotoxins are described as poisons that act on the nervous system and disrupt the normal function of nerve cells. STXs bind strongly to site 1 on the voltage-dependent sodium channel, inhibiting channel conductance which blocks neuronal activity (Van Dolah 2000). The main area of STXs action in humans is the peripheral nervous system which leads to the rapid onset of symptoms (within ~1 hour) (Van Dolah 2000). Symptoms of Paralytic Shellfish Poisoning include tingling of the fingers and lips, difficulty breathing, loss of muscle control, and respiratory muscle paralysis leading to death (Van Dolah 2000). It is important to note that biotoxins cannot be destroyed or cooked out of shellfish and are structurally stable (DOH 2022).

These toxins released by *A. catenella* can be directly accumulated by algal-feeding fish or via consumption of phytoplankton-consumers (e.g., consumption of shellfish) (Dyhrman et al. 2010). PSP is known to affect humans, marine mammals, fish, and birds. There are also PSP cases that resulted in the death of Humpback whales. (Van Dolah 2000). Globally, almost 2,000 cases of PSP in humans per year are reported. Of those 2,000 cases, roughly 300 are lethal (Van Dolah 2000). This highlights the intensity of the illness and the importance of monitoring it. Lethal cases have dropped dramatically since and continue to drop as regulatory bodies expand and monitor biotoxins like PSP.

*A. catenella* releases saxitoxin consistently no matter the environment which is important to recognize as other species don’t always release their respective biotoxins. As noted previously, the release of toxins is directly related to the concentration of HAB, but there are many factors that contribute to the success of HAB and their relative toxicity. It is important to understand these factors contributing to *A. catenella* blooms and their relative toxicity to better monitor the presence and concentration of biotoxins in shellfish. In doing so, protection of humans and animals from PSP exposure can be more effective.

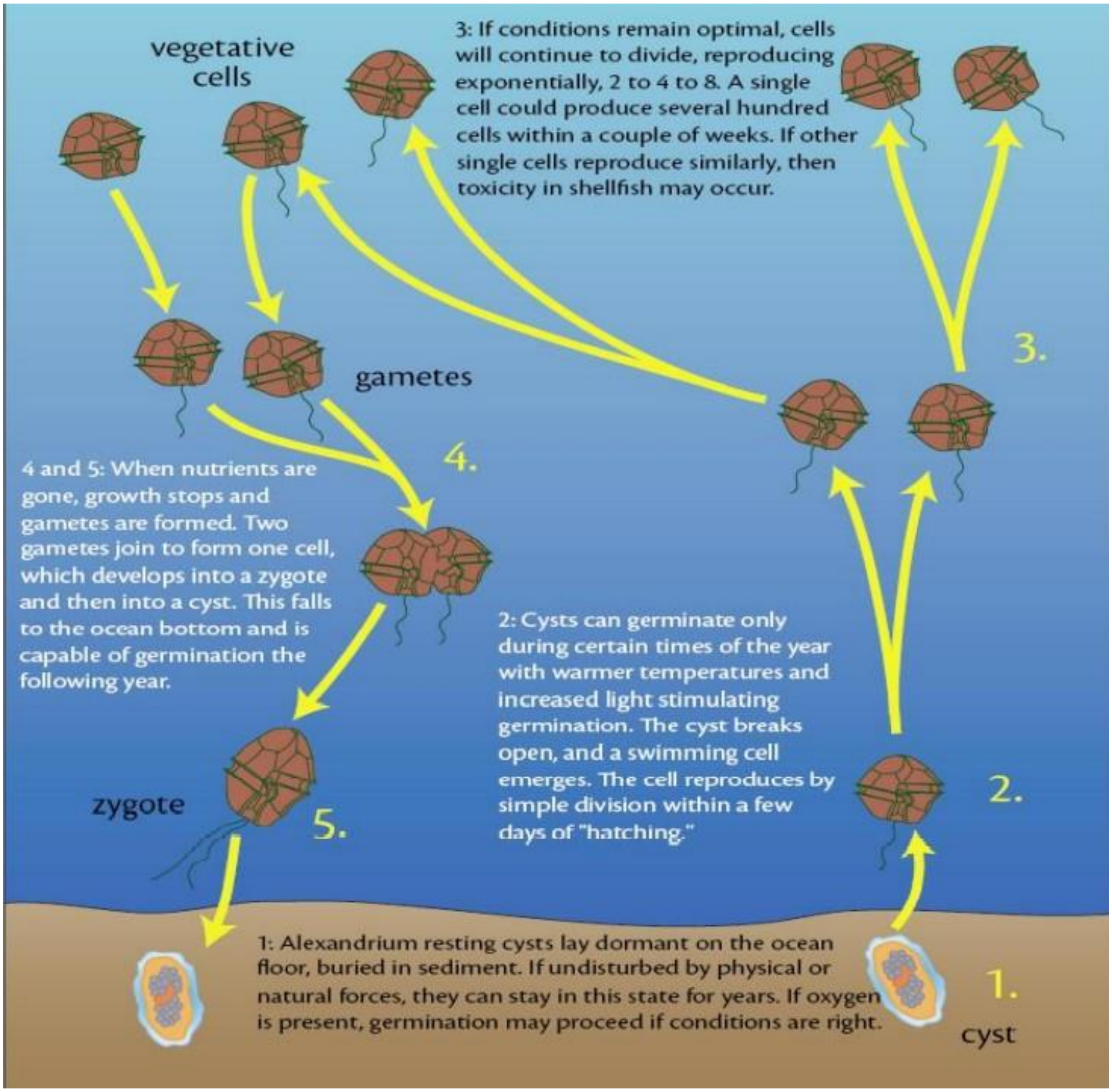
### *Alexandrium catenella* Life Cycle

Environmental drivers impact each stage of the *A. catenella* life cycle so understanding its life cycle is necessary in understanding how environmental conditions will impact their population dynamics (Anderson 1998).

Dormancy is the resting state and initial stage of the life cycle where *A. catenella* can remain for hours to months or even years depending on the environmental conditions (Fig. 2) (Anderson, Estrada, and Pitcher 2005; Anderson 1998). The cysts will remain in the sediment until conditions are ideal for germination. Germination is dependent on certain environmental factors, so it is usually constrained to certain times of the year. Late spring through fall when there are warmer temperatures and increased sunlight, the cysts will germinate. If the conditions are optimal for growth, then the cells will reproduce exponentially. Cell reproduction is via simple cell division which can occur rapidly. This is when harmful algal blooms and subsequent toxicity in shellfish occurs (Anderson 1998; Anderson, Estrada, and Pitcher 2005; Anderson, Cembella, and Hallegraeff 2012). These vegetative cells will continue to grow and divide until nutrients are gone. Once the nutrients have been depleted, *A. catenella* cells will form gametes. Gametes will combine to form zygote cells and then cysts. The cysts then fall onto the ocean floor and await germination once again (Anderson 1998). In the PNW, *A. catenella* typically blooms in early summer and early fall, but there is some variability from year to year (Anderson 1998). In late fall and winter, *A. catenella* tend to lay as dormant cysts until the warmer seasons arrive. Each stage of the life cycle is influenced by the surrounding physical properties. The environmental conditions dictate whether *A. catenella* cells will continue to proliferate or fall off into the deep as dormant cysts.

FIGURE 2.

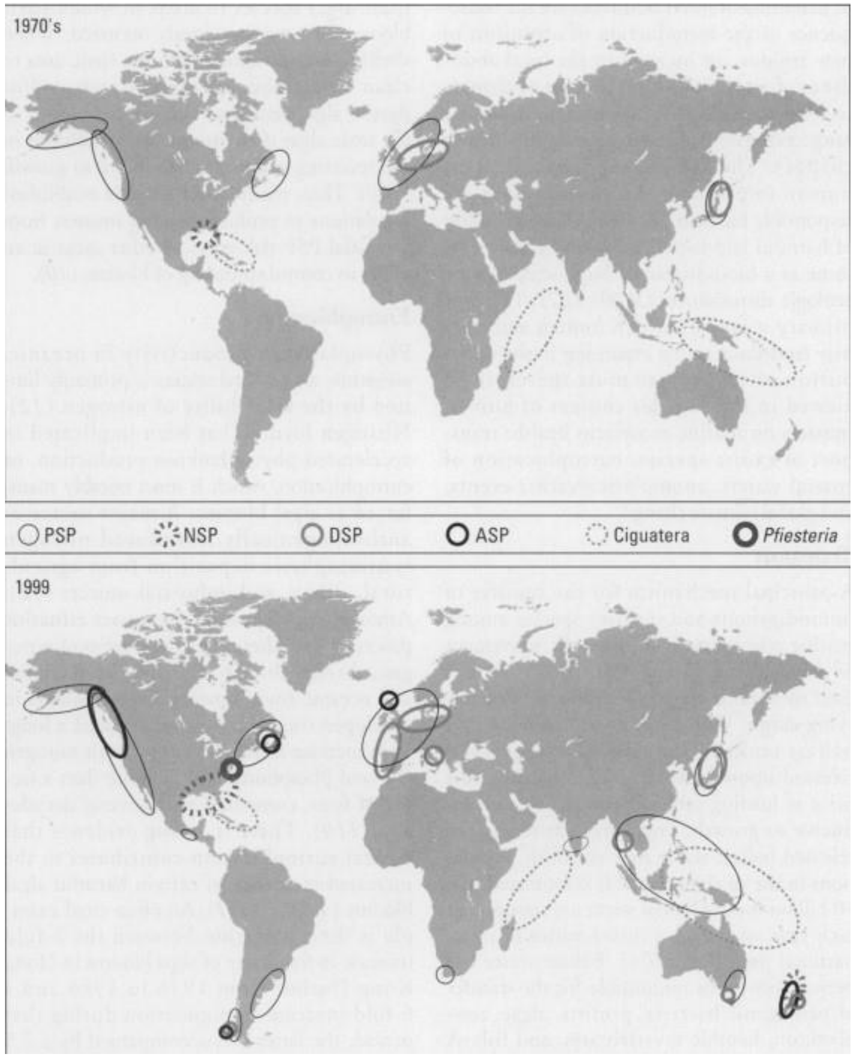
LIFE CYCLE OF *ALEXADNRIUM SP*.




*Note.* Life cycle of *Alexandrium sp.* (Anderson, Estrada, and Pitcher 2005).

FIGURE 3.

HARMFUL ALGAL BLOOMS (1970 VERSUS 1999)




*Note.* Comparison of harmful algal bloom (HAB) toxin levels around the world between 1970 and 2000. The encircled areas indicated where toxin levels were concentrated enough to have negative impacts on human life (Van Dolah 2000).

## Environmental Conditions and Drivers

Many factors influence the overall success of algal blooms. The main factors involved are oxygen, nutrient availability, sunlight, temperature, turbulence, and salinity. Climate and weather patterns (e.g., El Nino Southern Oscillation and Pacific Decadal Oscillation) also contribute to and alter these factors influencing algal bloom dynamics (see pages 13-18). For now, we will look at the impact of environmental and physical conditions on *A. catenella* so that we can then extrapolate to larger scale climate patterns.

Oxygen must be present for *A. catenella* cysts to germinate. Cysts can stay in sediment for years if conditions are not optimal (i.e., no oxygen) unless disturbed by physical or natural forces (Anderson 1998). Nutrient availability has been a main concern in recent years due to the excess nutrient input from urban and agricultural runoff (Fig. 3). This excess of nutrients allows for larger algal blooms resulting in eutrophication and release of toxins (Fig. 3) (Garneau et al. 2011). Phytoplankton are photosynthesizers so sunlight intensity can limit or induce growth. Along with sunlight, temperature is a major factor affecting phytoplankton growth. In general, warmer temperatures correlate with larger and more rapid algal blooms (Wells et al. 2015). The toxicity of *A. catenella* is also connected to water temperature. Between temperatures 10°C and 12°C, *A. catenella* produces the most saxitoxins (STXs). These SSTs are usually during spring and fall in the PNW. When below or above this range, toxin production is significantly lower in *A. catenella* (Navarro, Muñoz, and Contreras 2006). It is important to note that *A. catenella* still releases saxitoxin in any environment it can survive. This trend has been shown in other toxic algal species as well (Navarro, Muñoz, and Contreras 2006; Tatters et al. 2013).

*A. catenella* is known to thrive in stratified bodies of water where winds are weak, and turbulence is low. As mentioned earlier, this is partly because the cells can swim through the thermocline in search of nutrients and sunlight giving it an advantage over non-motile cells (i.e., diatoms) (Ralston and Moore 2020). Turbulence is a major component known to negatively affect dinoflagellate blooms (Smayda 1997). The three main mechanisms impacting dinoflagellate blooms via turbulence are physical damage, physiological impairment, and behavioral modification (Smayda 1997). Turbulence may affect *A. catenella* through these mechanisms in a variety of ways. Physical damage (torn or ripped cells) may happen during intense periods of wind typically during late fall and winter (Sullivan and Swift 2003). *A. catenella* cells may be transported lower in the photic zone (where less light penetrates) or completely below the photic zone via turbulence killing off any viable cells since photosynthesis would not be possible (Sullivan and Swift 2003). This would be an example of physiological impairment. Turbulence could also have potentially positive effects on *A. catenella* via turbulence mechanisms resulting in behavioral modification. For example, nutrients could be transported above the thermocline via turbulence negating the need for *A. catenella* cells to swim in search of nutrients thus saving energy that could be used for cell division. Turbulence could also help suspend *A. catenella* in the photic zone negating the need for it to swim if conditions are optimal thus saving energy (Sullivan and Swift 2003).

Climate change is predicted to cause further warming of the ocean's temperatures and elevated anthropogenic carbon dioxide concentrations is expected to increase ocean acidification (Cooley et al. 2017). Warmer temperatures and higher $CO_2$ levels are expected to impact *A. catenella* in a variety of ways. Generally, warmer temperatures and higher $CO_2$ levels are expected to increase opportunities for photosynthesis thus an increase in algal blooms (Navarro, Muñoz, and Contreras 2006). This increase in algal blooms could have negative impacts via eutrophication and/or toxin production. An increase in HAB toxins has already been shown, but the causation is still up for debate (Fig. 3) (Van Dolah 2000). The most notable attributions to explain the increase of biotoxins over time are the influx of anthropogenic nutrients and warmer sea surface temperatures (SST).

Increased $CO_2$ levels have been found to increase the cellular toxicity of *A. catenella* (Tatters et al. 2013). This is likely due to an increase in the cells photosynthetic rates. The most toxic scenario in the Tatters et al. experiment was an environment with high $CO_2$, "low" temperature (15°C), and low phosphate levels further highlighting the complexity of HAB dynamics (Tatters et al. 2013). While increasing SSTs will likely lead to an increase in HABs, the warmer temperatures could potentially offset added cellular toxicity from $CO_2$. Continuing to investigate how these environmental drivers impact *A. catenella*, we can extrapolate to larger climate scale patterns and the implications involved with *A. catenella* and HAB dynamics. For example, we can investigate the impact of El Nino Southern Oscillation or Pacific Decadal Oscillation on *A. catenella*. In doing this, we can then better predict potential shellfish toxicity and better manage shellfish safety and public health.

# Climate Patterns – ENSO and PDO

## El Nino Southern Oscillation

The El Nino-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) are climate patterns that result in variable weather conditions in the Pacific Northwest (Moore et al. 2010). They produce changes in the local surface winds, air temperatures, and precipitation patterns (Moore et al. 2010). There are three phases of the ENSO: 1) warmer than average tropical Pacific Ocean temperatures (El Nino), 2) colder than average tropical Pacific Ocean temperatures (La Nina), and 3) a neutral phase where conditions are typical or near the average. Essentially, a change in the trade winds leads to the different phases of ENSO in the PNW. For example, stronger than average Eastern Trade Winds will push warm surface water farther allowing for more upwelling of deep colder water (Newman, Compo, and Alexander 2003). This would be an example of the La Nina phase associated with colder SSTs. Weak Trade Winds result in warmer SSTs since less upwelling can occur. This would be the El Nino phase associated with the warmer SSTs. The different phases of ENSO can last up to 3 years, but typically are 1 to 2 years (Newman, Compo, and Alexander 2003).

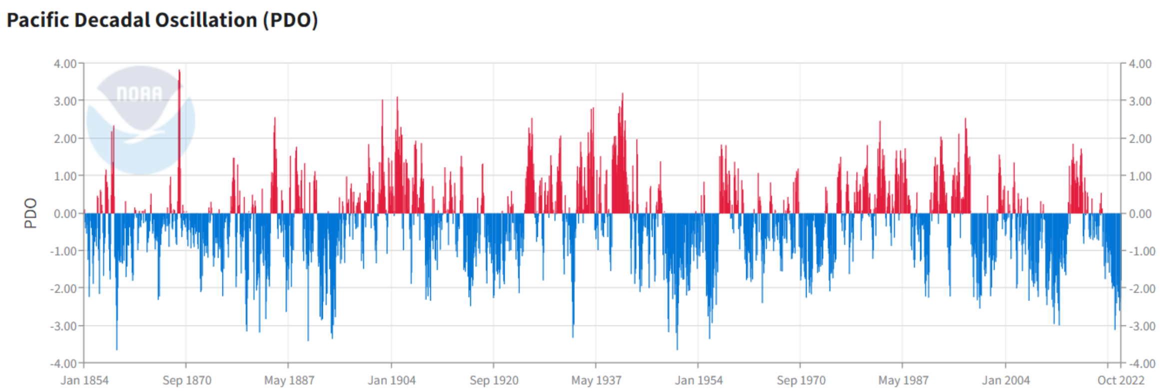
The Pacific Decadal Oscillation is known to be influenced by the phases of ENSO along with changes in atmospheric pressure (Moore et al. 2010). Since ENSO and PDO are known to cause variabilities in weather (especially SSTs), it's important to look at how these changes impact HAB dynamics like *A. catenella*. Understanding the factors that will lead to *A. catenella* blooms could essentially predict shellfish toxicity, which would be invaluable for the regulation and safety of the shellfish industry.

## Pacific Decadal Oscillation

The Pacific Decadal Oscillation (PDO) is known as the most consistent pattern of monthly North Pacific SST variability (Mantua and Hare 2002). The mechanisms responsible for this SST variability are still under ongoing research, but some climate cycles and causes are becoming more clear (Newman et al. 2016). The observed effects of the PDO are not via a single phenomenon, but instead the combination of many physical processes. The main physical processes known to force the different PDO phases (i.e., warm and cold) are variability in the Aleutian low, El Nino-Southern Oscillation (ENSO), and oceanic zonal advection anomalies in the Kuroshio-Oyashio Extension (Newman, Compo, and Alexander 2003). Low atmospheric pressure over the Aleutian Islands results in warm waters being transported to the coast of North America via ocean currents. These warmer waters contribute to higher SSTs in the PNW and are an example of a warm phase of the PDO. Wind-forced changes in the Kuroshio-Oyashio current system result in oceanic waves moving westward leading to SST anomalies as well(Newman et al. 2016). These separate mechanisms and their contribution to SST variability and anomalies in the PNW are what make up the PDO. The impact of these physical processes on PDO variance is frequency dependent. At decadal time scales, all three physical processes account for relatively similar amount of variance in the PDO index (Newman, Compo, and Alexander 2003). The similar impact on PDO variance from the different physical processes further supports this idea of multiple physical processes combining into the observed SST anomalies collectively categorized as the different PDO phases.

The PDO is most easily described as long-lived ENSO-like patterns of climate variability (Zhang et al. 1997). Extremes of the PDO phases are noted by variations in the Pacific Basin and the North American climate. These phases are known as warm or cold denoted by the warm or cold anomalies in sea surface temperatures (SST) along the Pacific Coast (Mantua and Hare 2002). When SSTs are warmer than average along the Pacific Coast and sea level pressures are below average over the North Pacific, the PDO is in a positive phase denoted by a positive value (red line) using the PDO index (Fig. 4). When the SSTs are cooler than average along the Pacific Coast and sea level pressures are above average over the North Pacific, the PDO is in a negative phase denoted by a negative value (blue line) using the PDO index (Fig. 4).

FIGURE 4.
PDO INDEX

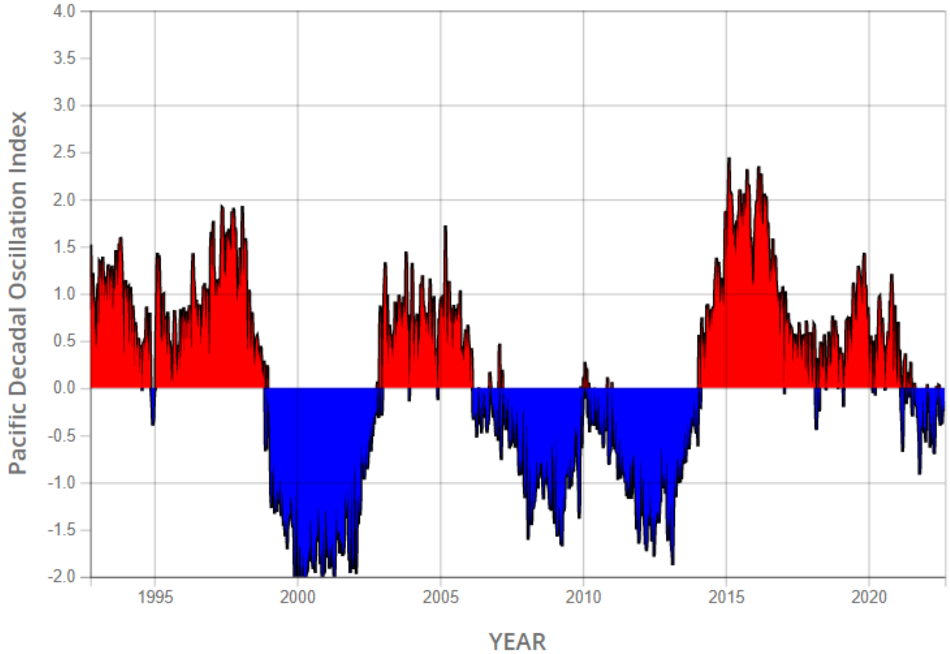



*Note.* PDO index overtime provided by NOAA. PDO on the x-axis, time on the y-axis from 1854 to current. (NOAA 2022.)

ENSO-forced variability of the PDO phases has been shown over the years (Fig. 5). La Nina (i.e., cold phase of the ENSO) can exacerbate the cold phase of the PDO and El Nino (i.e., warm phase of the ENSO) can exacerbate the warm phase of the PDO. The warmer (or cooler) than average ocean temperatures as result of the Trade Winds moving northward influencing the atmosphere and sea surface temperatures (Mantua and Hare 2002).

FIGURE 5.

ENSO-DRIVEN PDO




*Note.* PDO index on the y-axis, time in years on the x-axis. Red shading represents El Nino phase, blue shading represents La Nina phase (NOAA 2022.)

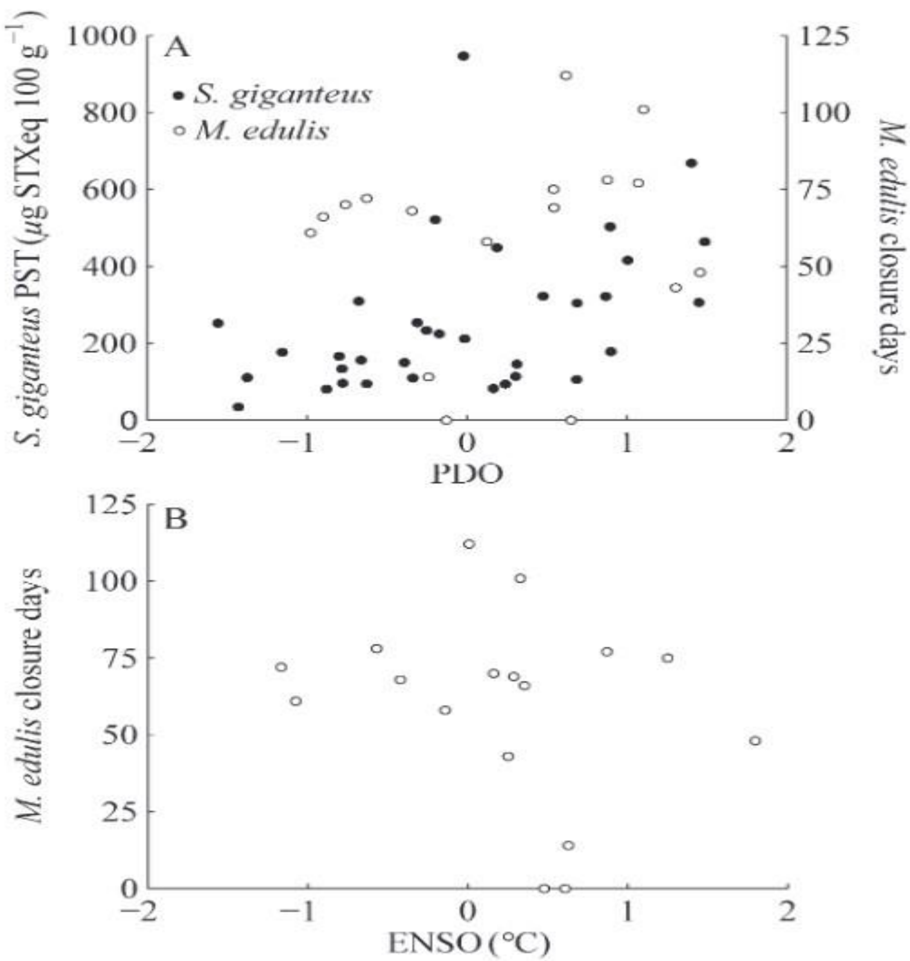
**ENSO, PDO, and Shellfish Toxicity**

As mentioned, the ENSO and PDO are most known as the source of consistent and cyclical sea surface temperature anomalies here in the PNW (Mantua and Hare 2002). This can have major impacts on *A. catenella* populations as they are sensitive to these kind of fluctuations (Schneider and Cornuelle 2005). The influence of warm and cold phases of the PDO and ENSO on *A. catenella* could provide some insight on future PSP concentrations in shellfish (Moore et al. 2010; Newman, Compo, and Alexander 2003; Newman et al. 2016). For example, a positive relationship was found between *Saxidomus giganteus* (Butter Clam) toxicity and PDO index, although it was not significant ($p = 0.12$, Fig. 6) (Moore et al. 2010). This relationship does follow the trend of warmer SSTs allowing for larger HABs, thus subsequent biotoxin production and assimilation. A significant and positive relationship was found between number of days SST

> 13 °C and *S. giganteus* toxicity, further supporting this trend (Fig. 7) (Moore et al. 2010). However, there was no significant relationship found between *Mytilus edulis* (Blue Mussel) toxicity in the Moore study. This could be due to *S. giganteus'* ability to store toxins for longer providing a more representative sample of the toxins present (Moore et al. 2010).

FIGURE 6.

SHELLFISH TOXICITY AND CLOSURE DAYS

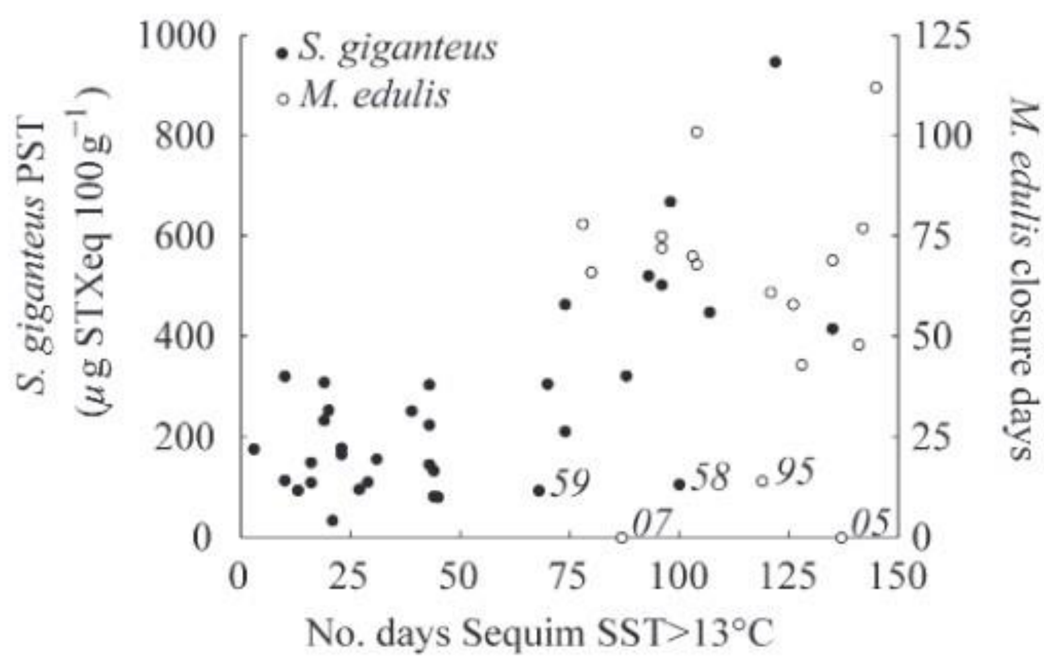



*Note.* (A) PDO index plotted against *Saxidomus giganteus* (Butter Clam) toxicity and *Mytilus edulis* (Blue Mussel) closure days from 1957-2007. (B) ENSO index plotted against Blue Mussel closure days from 1957-2007 (Figures taken from Moore et al. 2010).

Shellfish toxicity is thought to vary with the Pacific Decadal Oscillation along with number of days over 13 °C (a known threshold for increases in shellfish toxicity in the PNW), but ENSO is still not considered a causing factor (Moore et al. 2010). ENSO is known to influence the phases of the PDO. As such, further research exploring the relationship between the ENSO index and shellfish toxicity is warranted.

FIGURE 7.

SHELLFISH TOXICITY AND SST




*Note*. Number of days sea surface temperature (SST)>13 °C plotted against *Saxidomus giganteus* (Butter Clam) toxicity and *Mytilus edulis* (Blue Mussel) closure days (Figures taken from Moore et al. 2010).

The SST warm anomalies via ENSO tend to be during winter in the PNW and do not persist into summer and fall when shellfish typically accumulate toxins. In contrast, SST warm anomalies via positive PDO phases in the winter and spring typically do persist into the summer and fall when shellfish are accumulating toxins (Moore et al. 2010). This difference in temperature seasonality is likely the main explanation for the implied relationship between the PDO index and shellfish toxicity, and the non-relationship between ENSO index and shellfish toxicity (Moore et al. 2010).

## Thesis Statement – Research Question

It is documented that the PDO influences SST and SST variability influences shellfish toxicity (Fig. 6 and 7). ENSO also influences the PDO, so it is possible that ENSO influences SST and the subsequent shellfish toxicity. This thesis examines the following research question; To what extent do the Pacific Decadal Oscillation (PDO) and El Nino southern Oscillation (ENSO) correlate with marine biotoxins (i.e., paralytic shellfish poisoning causing saxitoxin) in the Pacific Ocean along the Washington coast?

# Methods

This thesis research involves the analysis of El Nino Southern Oscillation and Pacific Decadal Oscillation influence on Paralytic Shellfish Poisoning (P.S.P) concentrations in shellfish in Sequim, WA from 1957 through 2022. Descriptive statistics and data visualizations were also produced for sea surface temperatures (SSTs) over time, PDO over time, ENSO over time, and P.S.P over time.  Statistical Analyses were performed to determine if there is a relationship between P.S.P concentration in shellfish and Pacific Decadal Oscillation and/or El Nino Southern Oscillation. Pearson’s correlations and simple linear regression were the analyses used in this study following the methods of Moore et al. 2010 to examine the relationship between PDO, ENSO, and shellfish toxicity (Moore et al. 2010). Moore et al. used the same dataset presented in this study to examine these relationships between 1957-2007, and this study reanalyzes this data, extending it through 2022 to understand the impacts of recent climate patterns on PSP concentrations in Sequim, WA.

## Data Sources

All data used for this thesis research was gathered from public databases. Such as the Department of Health, National Oceanic and Atmospheric Administration, Department of Fisheries and Oceans Canada, and National Centers for Environmental Information. Each dataset is described in further detail below.

## El Nino Southern Oscillation (ENSO) Index

The ENSO index used in this thesis research is from NOAA’s Physical Science Laboratory database (Rayner 2003). The index is calculated from SST anomalies averaged over the NINO 3.4 region (5°North-5°South;170-120°West) (Fig. 8). The SST anomalies used to calculate the ENSO index are from the monthly NOAA Extended Reconstructed SST (ERSST) v5 at NOAA's Physical Science Laboratory (NOAA 2023). NINO 3.4 (Fig. 8) region is known to correlate well with teleconnections to the west coast of North America (Rayner 2003) . Essentially, the ENSO Index value is calculated by comparing the three-month running mean of ERSST anomalies against the 30-year average of SSTs.

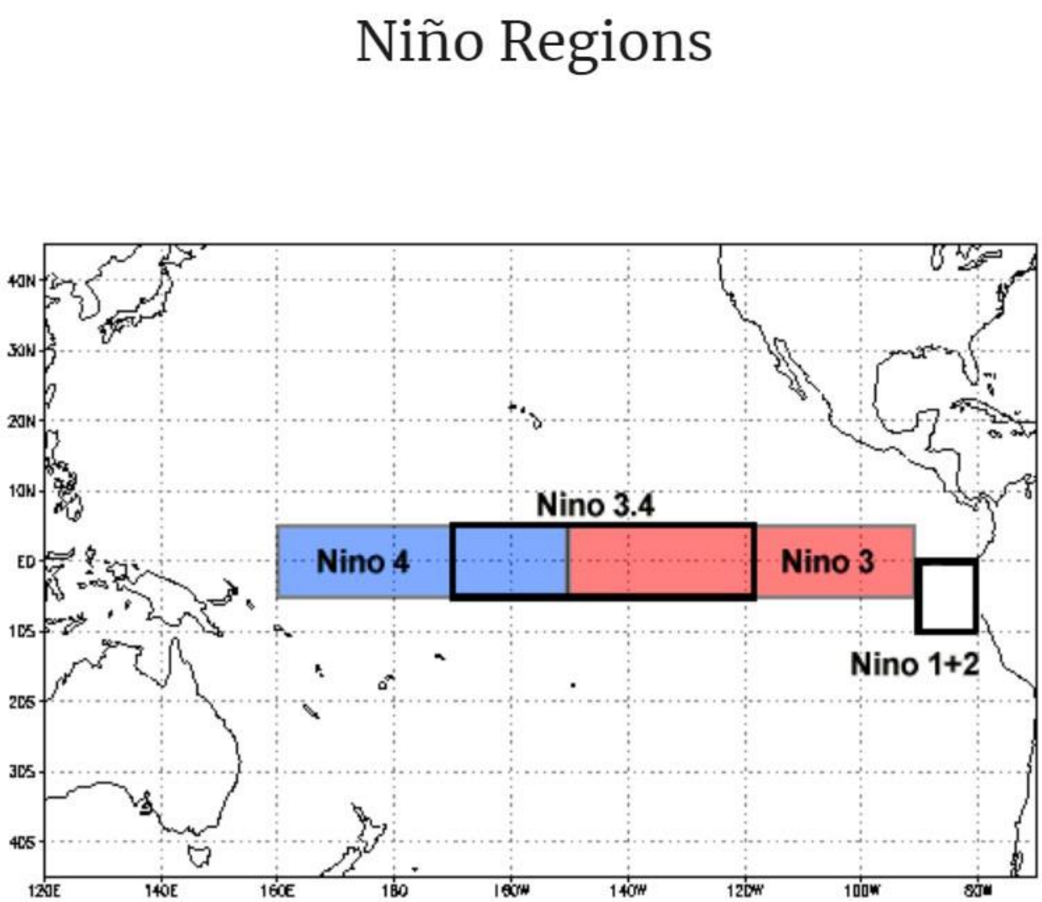
ERSST data calculations explained below (courtesy of NOAA and NCEI 2023).

"The Extended Reconstructed Sea Surface Temperature (ERSST) dataset is a global monthly analysis of SST data derived from the International Comprehensive Ocean–Atmosphere Dataset (ICOADS). The dataset can be used for long-term global and basin-wide studies and incorporates smoothed local and short-term variations. The NOAA Global Surface Temperature (NOAAGlobalTemp) product integrates ERSST data with land surface air temperature from the Global Historical Climatology Network-Monthly dataset to create integrated surface temperature analyses." (NOAA and NCEI 2023).

The SST anomalies are calculated with respect to 1971-2000 climatology. The data sources are from ICOADS 3.0, which combines SST from Argo floats (above 5 meters), Hadley Center Ice-SST version 2 (HadISST2) ice concentration (1854-2015), and NCEP ice concentration (2016-present) (NOAA 2023). ENSO Index data has been collected since 1870 (Fig. 9).

FIGURE 8.

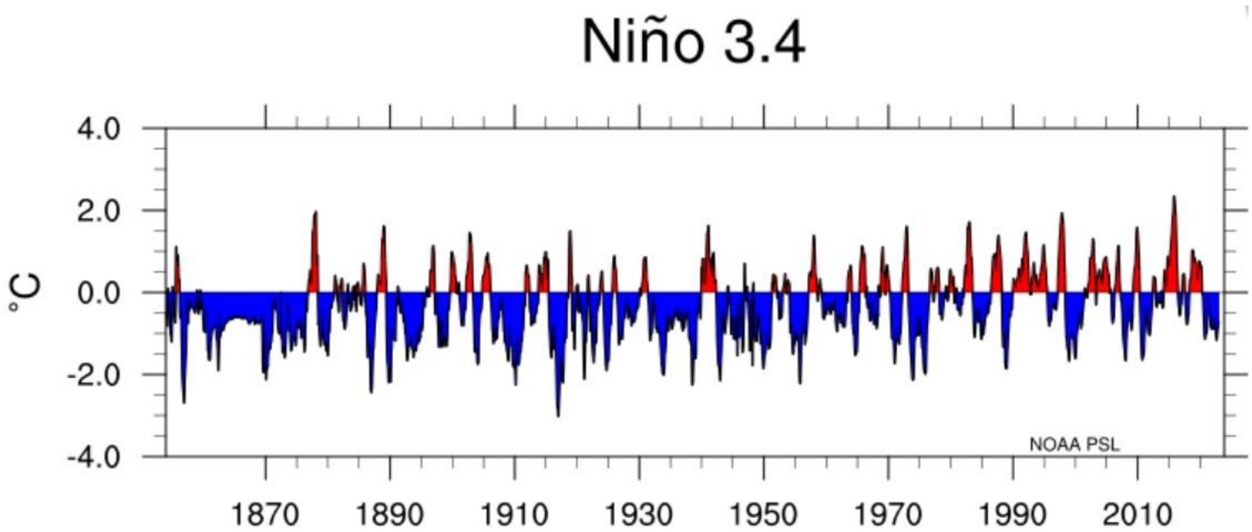
EL NINO SOUTHERN OSCILLATION 3.4 REGION




*Note.* Nino 3.4 region (5°North-5°South;170-120°West) depicted in the figure is where SST anomalies are gathered to calculate the ENSO index used in this research (NOAA 2023). https://www.ncei.noaa.gov/access/monitoring/enso/sst

FIGURE 9.

ENSO INDEX




*Note*. Nino 3.4 Index timeseries; degrees Celsius on the y-axis. (NOAA 2023). https://psl.noaa.gov/enso/dashboard.html

**Pacific Decadal Oscillation**

The PDO index data used in this thesis research is from the National Centers for Environmental Information (NCEI). The exact method of calculation is explained below (courtesy of NOAA and NCEI 2023).

"The NCEI PDO index is based on NOAA's extended reconstruction of SSTs (see ERSST section above). It is constructed by regressing the ERSST anomalies against the Mantua PDO index for their overlap period, to compute a PDO regression map for the North Pacific ERSST anomalies. The ERSST anomalies are then projected onto that map to compute the NCEI index. The NCEI PDO index closely follows the Mantua PDO index." (Mantua 1999).

The SST anomalies for the PDO index values are obtained via Empirical Orthogonal Function (EOF) analysis. Essentially, the orthogonal functions are used to examine variability within the SST data and to analyze relationships with other variables (e.g., ENSO or PDO index) over time. The SST anomalies are departures from the climatological annual cycle from which global mean SST anomalies have been subtracted. This helps remove external influences that could be due to climate change (Mantua and Hare 2002).

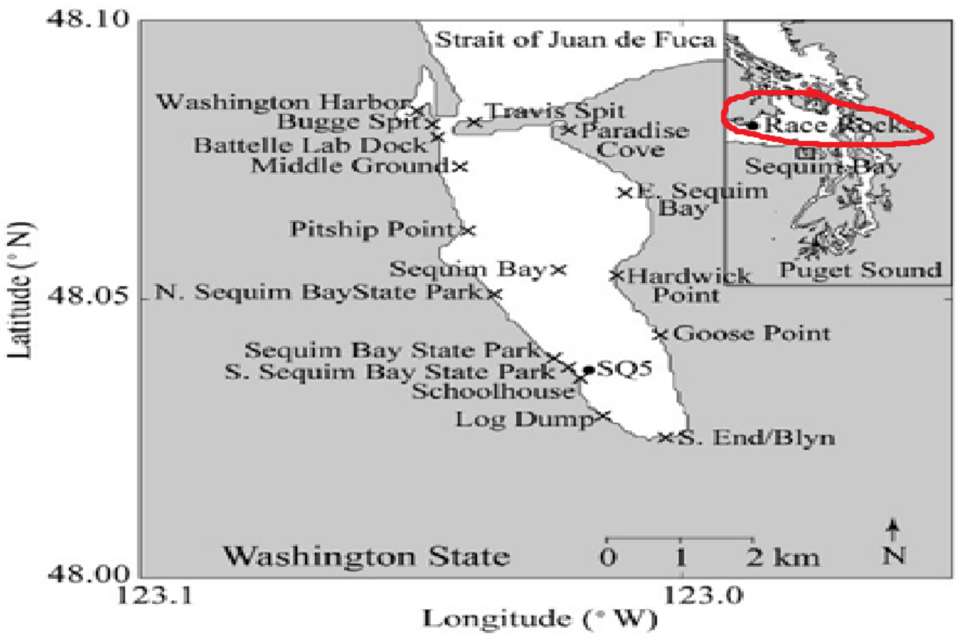
### Sea Surface Temperatures (SSTs)

Sea surface temperature (SST) measurements just north of Sequim Bay were collected and utilized to track temperature averages to compare shellfish toxicity, PDO index, and ENSO index. SST data was collected north of Sequim Bay at Race Rocks (Fig. 10) which is a small rock island located in the Strait of Juan de Fuca with SST measurements that span as far back as 1914 (Moore et al. 2010). Data is collected by the Department of Fisheries and Oceans Canada (DFO) which is responsible for developing and implementing policies and programs in support of Canada's economic and ecological interests in oceans and other waters (Government of Canada 2008). The SST data was transformed to represent Sequim Bay SST by regressing Race Rocks SST to a three-year span (1997-2000) of SST data from Sequim (Moore et al. 2010). The equation for the relationship derived from linear regression analysis is shown below (Moore et al. 2010). Sequim Bay SST anomalies were calculated with respect to the average SST spanning 1971-2001.

$$\mathbf{SST_{Sequim} = -11.5 + 2.3 \times SST_{Race\ Rocks}}$$

FIGURE 10.

HISTORICAL BIOTOXIN SAMPLE SITES




*Note.* Shellfish sample sites for Department of Health from 1957 to current in Sequim Bay, Washington. Sea surface temperatures taken from Race Rocks (circled red) shown in top right portion of the map (Moore et al. 2010).

**Shellfish Toxin Concentrations**

Paralytic Shellfish Poisoning concentrations are monitored by the Washington State Department of Health (DOH). Commercial and recreational shellfish are regularly monitored throughout the year via mouse bioassay to test for saxitoxin concentration in shellfish (henceforth referred to as P.S.P concentration) (DOH 2022). The PSP concentration data has been recorded since 1957 in the DOH database. Concentrations are in micrograms/100grams of shellfish tissue and recorded every week to 2 weeks depending on saxitoxin levels in the area. Shellfish toxicity, PSP concentration, and saxitoxin concentration are all used interchangeably. A PSP index was calculated to use in all analyses in this study. It was calculated by averaging monthly maximums of PSP concentration each year. This was done to better represent average maximum PSP concentrations each year.

The PS concentrations are from sample areas within Sequim Bay located in Sequim, Washington (Fig. 10 and 11). The two sites on the map (Fig. 11) are current sample sites for the Department of Health, but there have been many sites in Sequim Bay since 1957. Previous sites that were once used to collect PSP concentration are shown in Fig. 10 (Moore et al. 2010). All sites were treated as one variable to represent shellfish toxicity from Sequim Bay.

FIGURE 11.

CURRENT BIOTOXIN SITES


*Note.* GIS Map of current DOH biotoxin sites in Sequim Bay (created by Zach Mangus 2022)

Microsoft Excel was utilized to manage and compile data from separate databases. Statistical tests were then run via importing data into R studio (R version 4.2.0). Normality was assessed using the Shapiro Wilks test for normality. All variables were found to be normally distributed except PSP index. The PSP index was log transformed and then found to be normally distributed. Simple linear regression was used to test Sequim Bay SST over time and PSP over time. Pearson's correlation was run for PDO index and shellfish toxicity (maximum average monthly PSP concentrations), ENSO index and PSP concentration, temperature and PSP concentration. Time, ENSO index, and PDO index were the independent variables. The PSP index was consistently the dependent variable.

## Results

Average annual values of SSTs in Sequim Bay are shown in Fig. 12a. There is a positive trend as shown in fig. 12a. Simple line regression for time (years) and temperature (°C) was calculated ($r^2 = 0.31$) indicating a modest positive relationship that was statistically significant ($p = < 0.001$). Sequim SST anomalies were calculated from 1957-2022 (Fig. 12b).

FIGURE 12.A

SST AND SST ANOMALIES

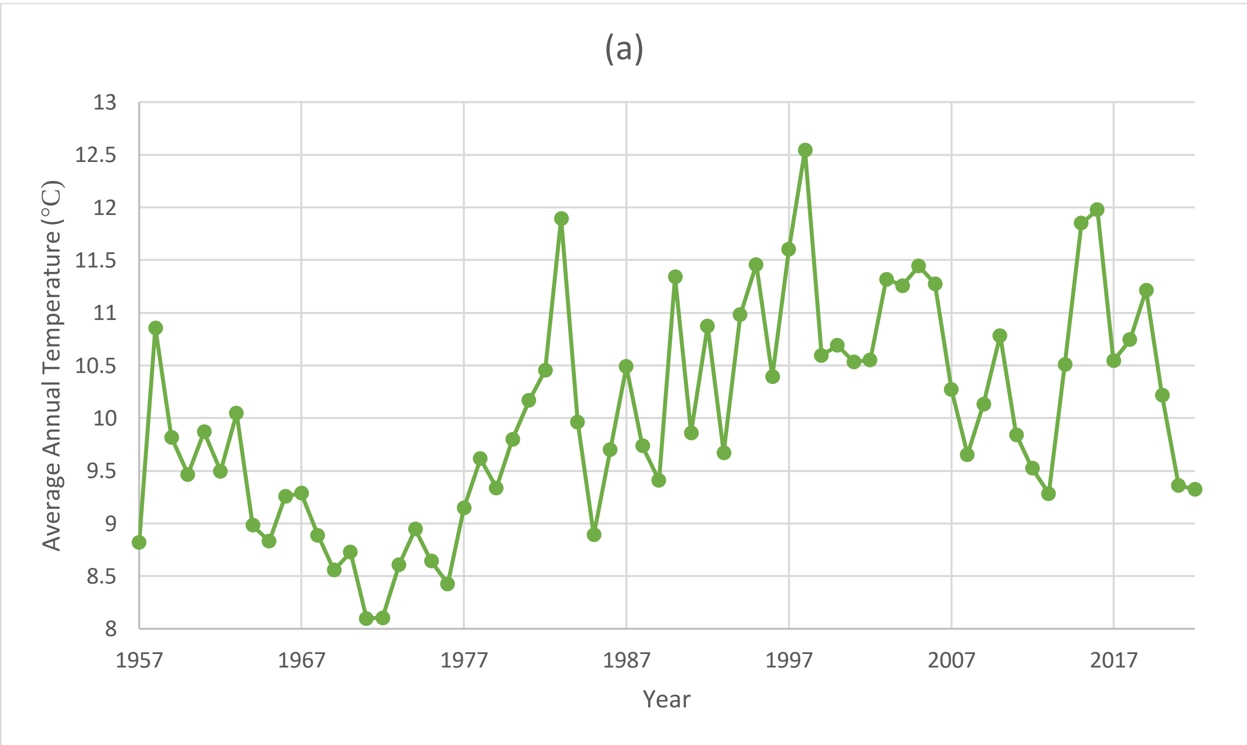
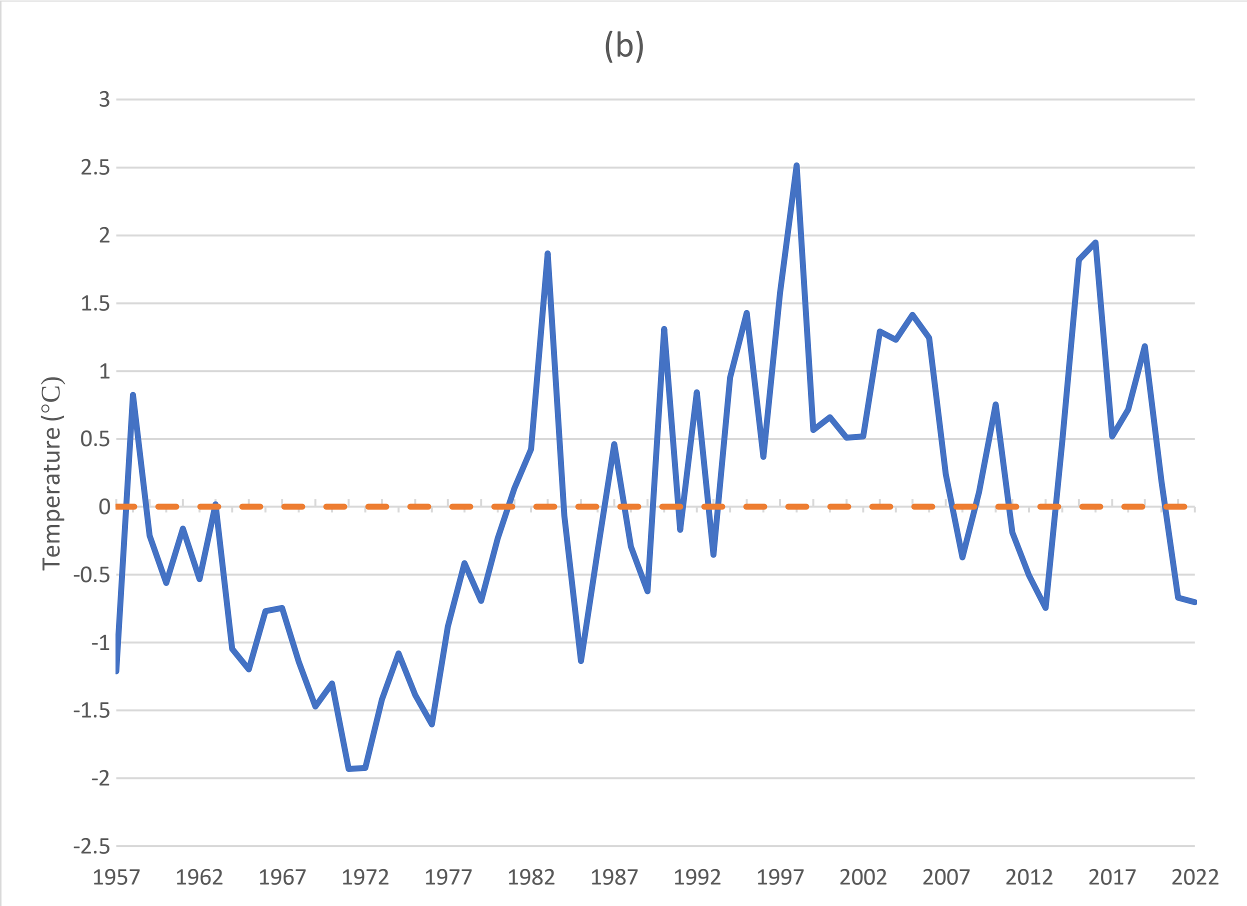


FIGURE 13.B

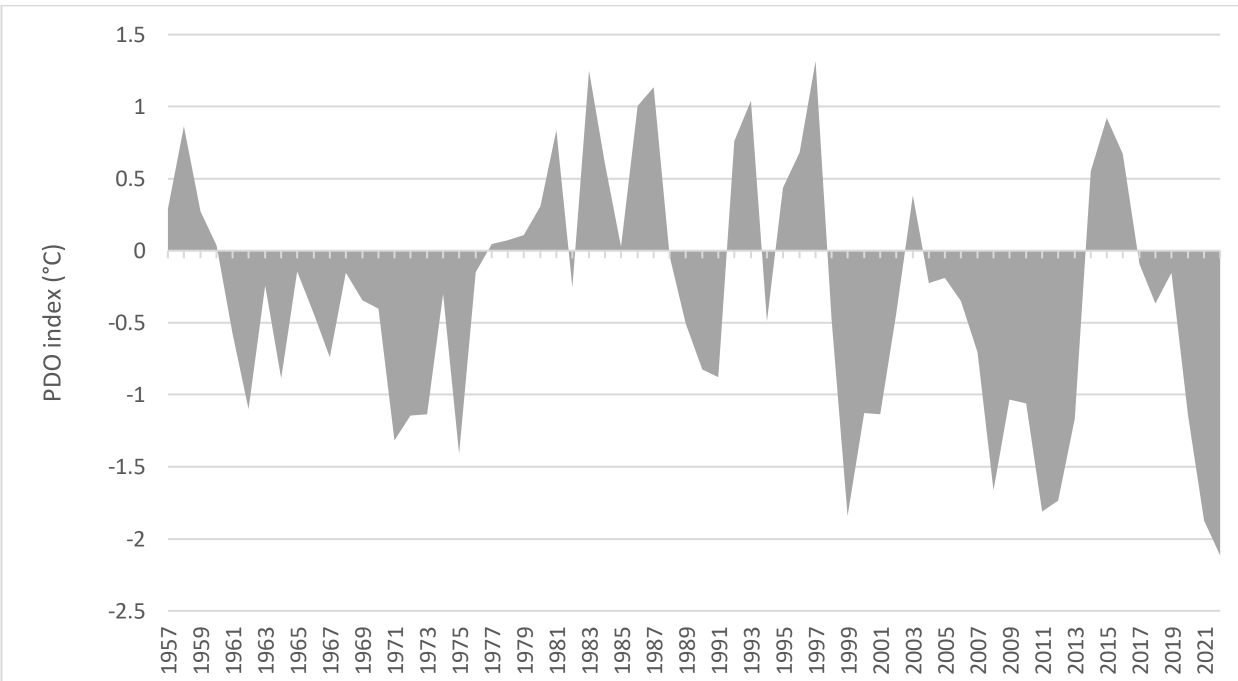



*Note.* (a) Projected Sequim Bay Sea surface temperatures over time from 1957-2022. The y-axis represents years, x-axis represents temperature (°C). The data from 1957 through 2007 was originally published by Moore et al. 2010. (b) Sequim Bay SST anomalies calculated each year from 1957-2022.

The Pacific Decadal Oscillation (PDO) index is shown for each year from 1957 to 2022 (Fig. 13). Cool phases of the PDO are indicated by negative values while warm phases are indicated by positive numbers. Warm or cool phases of the PDO historically persist for decades. For example, a cool phase lasted from 1947 to 1976, and then a warm phase occurred from 1977 to 1998. The longer phases appear to have ceased and shorter more variable phases have taken place since 1998. As shown in fig. 13, we entered a warm phase from 2002 to 2005, a neutral phase from 2006-2007, then a cold phase from 2008 to 2013, and then back to a warm phase from 2014 to 2020. The most recent and current phase has been cold again as depicted with negative values (Fig. 13).

FIGURE 14.

PDO INDEX

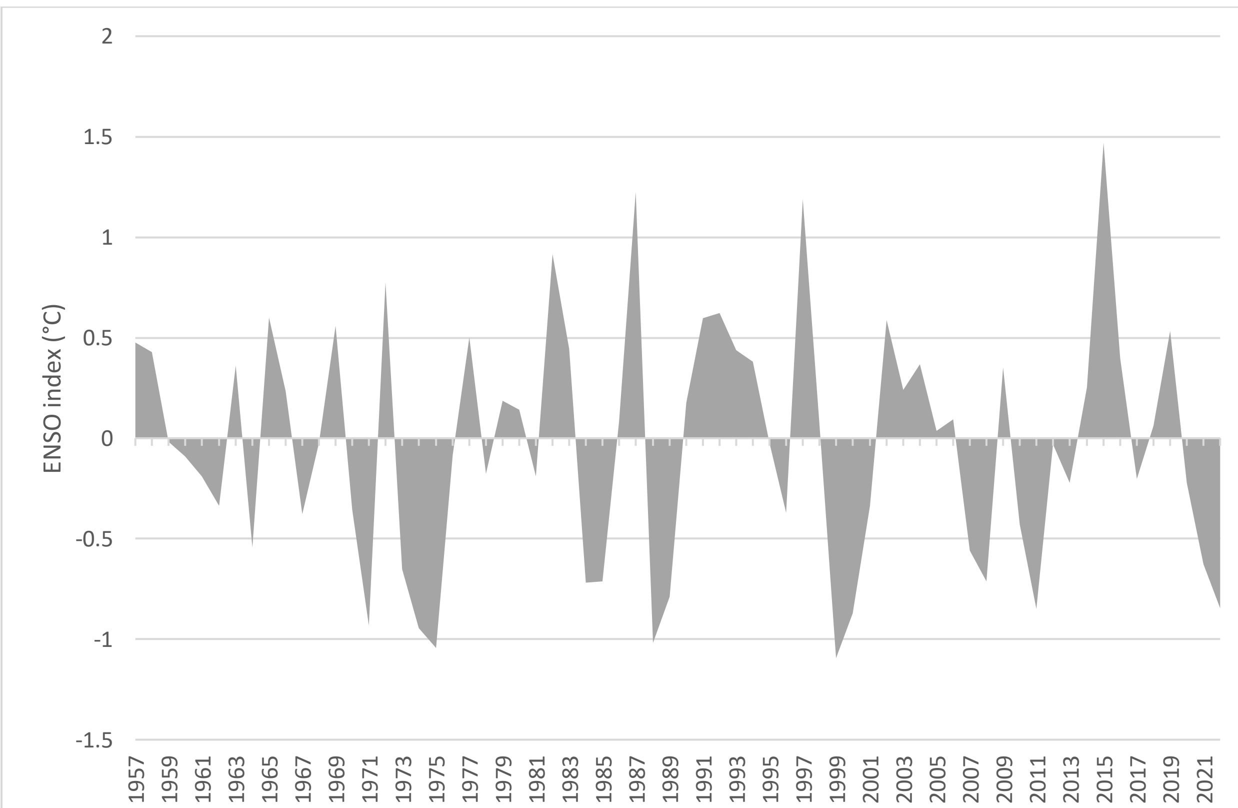



*Note.* The annual Pacific Decadal Oscillation index graphed for each year from 1957-2022. The y-axis displays PDO index in units of °C. The data from 1957 through 2007 was originally published by Moore et al. 2010.

The El Nino Southern Oscillation Index is shown for each year from 1957 to 2022 (Fig. 14). The negative values represent the La Nina phase and positive values represent the El Nino phase of ENSO. Notice the frequency in ENSO phases compared to the PDO. This variability remains relatively consistent over the 65-year time series. An ENSO phase typically only lasts 1-2 years (Fig. 14).

FIGURE 15.

ENSO INDEX

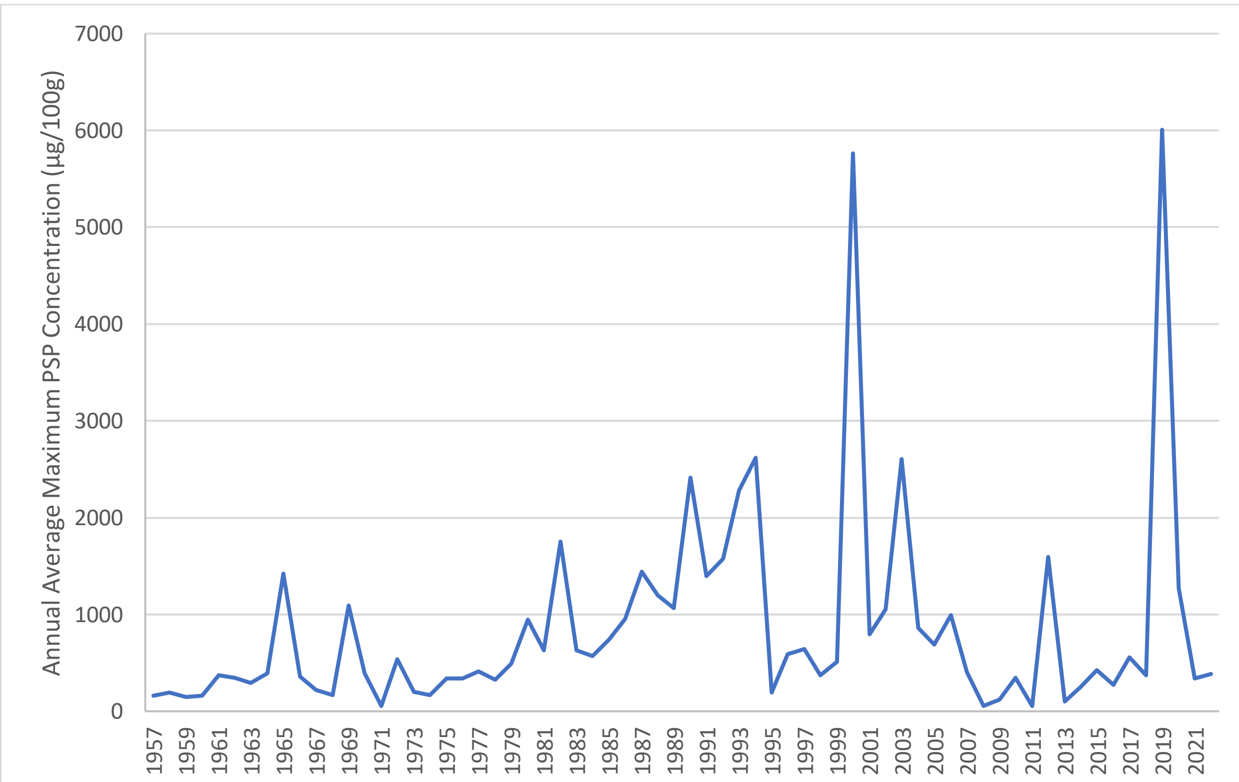



*Note.* The annual El Nino Southern Oscillation Index graphed for each year from 1957-20022. The y-axis is ENSO Index (°C). The data from 1957 through 2007 was originally published by Moore et al. 2010.

Annual average maximum paralytic shellfish poisoning (PSP) was taken for each year and graphed over time (Fig. 15). There is high variability in this time series with a range from 54 µg/100g to 6007 µg/100g and a standard deviation of ~1090. The mean PSP max is ~855 and the median is 456.

FIGURE 16.

DAILY PSP OVER TIME



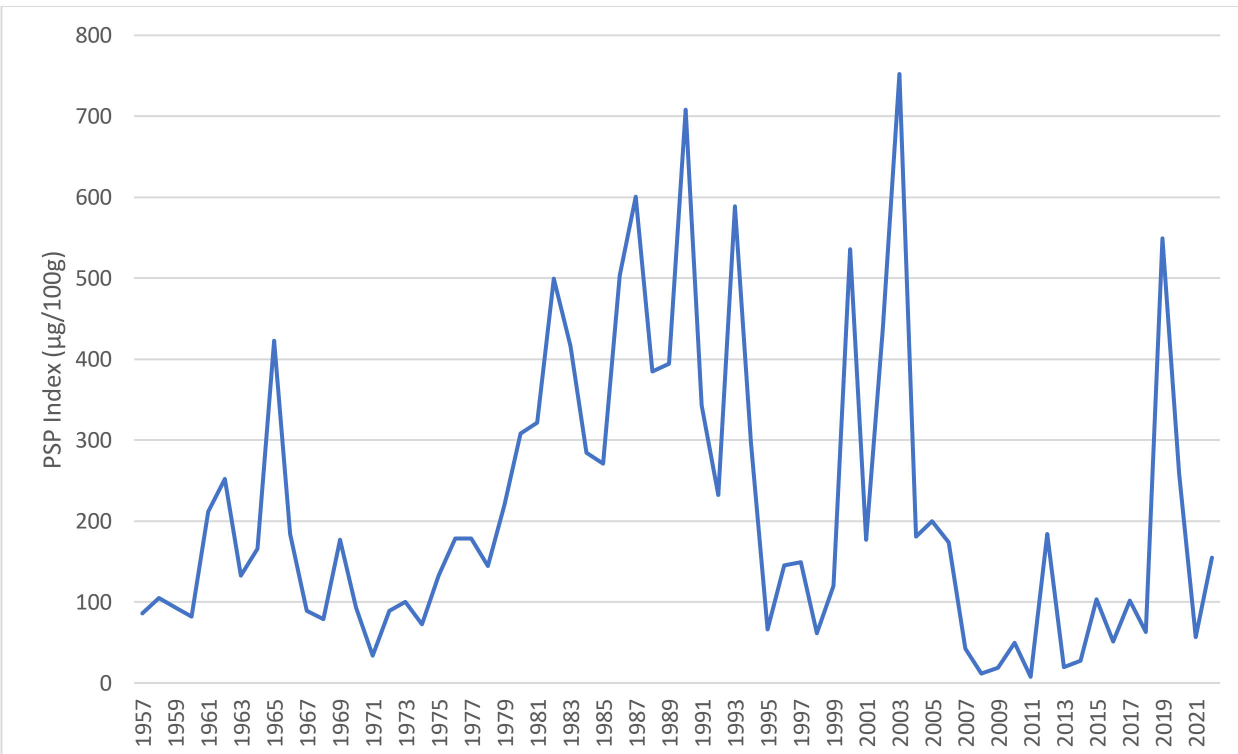

*Note.* The maximum paralytic shellfish poisoning (PSP) toxin concentration for each year from 1957-2022. The y-axis is PSP concentration (µg/100g).

A PSP index was calculated to account for all the variation and graphed over time (Fig. 16). The annual maximum PSP index was calculated by averaging the monthly maximums of PSP for each year.

Daily PSP concentrations were graphed over time from 2015 to 2018 to show the seasonality of *A. catenella* and the subsequent PSP concentration (Fig. 17). As mentioned previously, phytoplankton blooms are dependent on the right circumstances (e.g., temperature, sunlight, nutrients, etc.) and therefore have an innate seasonality. Figure 17 depicts this seasonality as the PSP concentrations spike in spring, summer, and fall each year when *A. catenella* can proliferate due to the ideal environmental factors.

FIGURE 17.

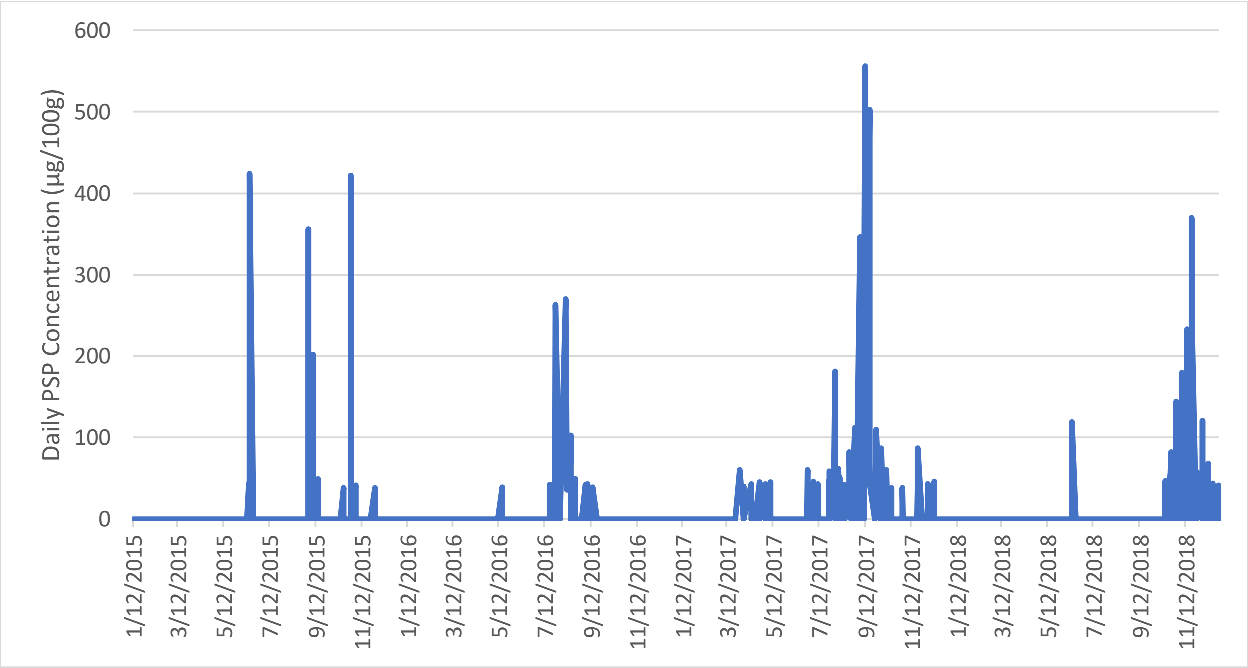
PSP INDEX




*Note.* Annual averaged maximum paralytic shellfish poisoning (PSP) index graphed for each year from 1957-2022. The annual maximum PSP index was calculated by averaging maximum concentrations each month of the year.

FIGURE 18.

SEASONAL PSP

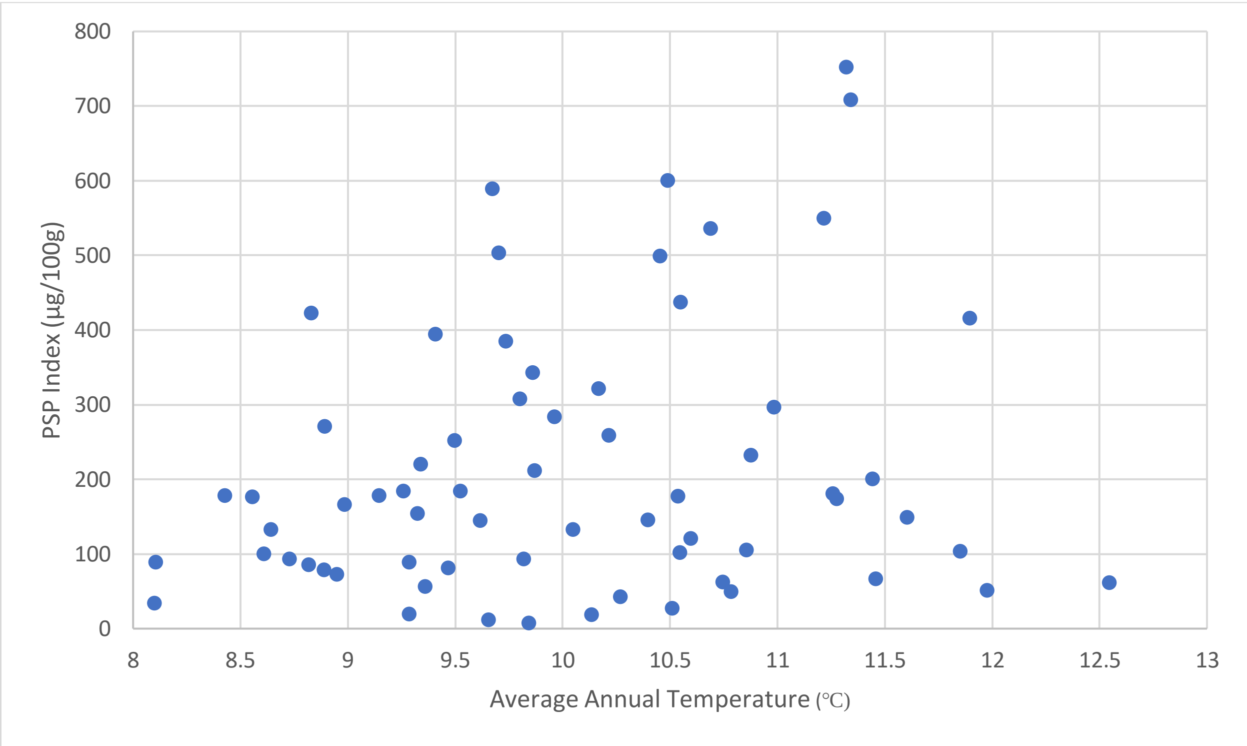



*Note.* Daily paralytic shellfish poisoning (PSP) concentrations graphed over time from 2015-2018. The x-axis is time (day/month/year), the y-axis is PSP concentrations (µg/100g).

Temperature was positively correlated with average annual PSP concentration (Fig. 18), although the relationship was not significant (r = 0.13, p = 0.28).

FIGURE 19.

PSP VERSUS TEMPERATURE

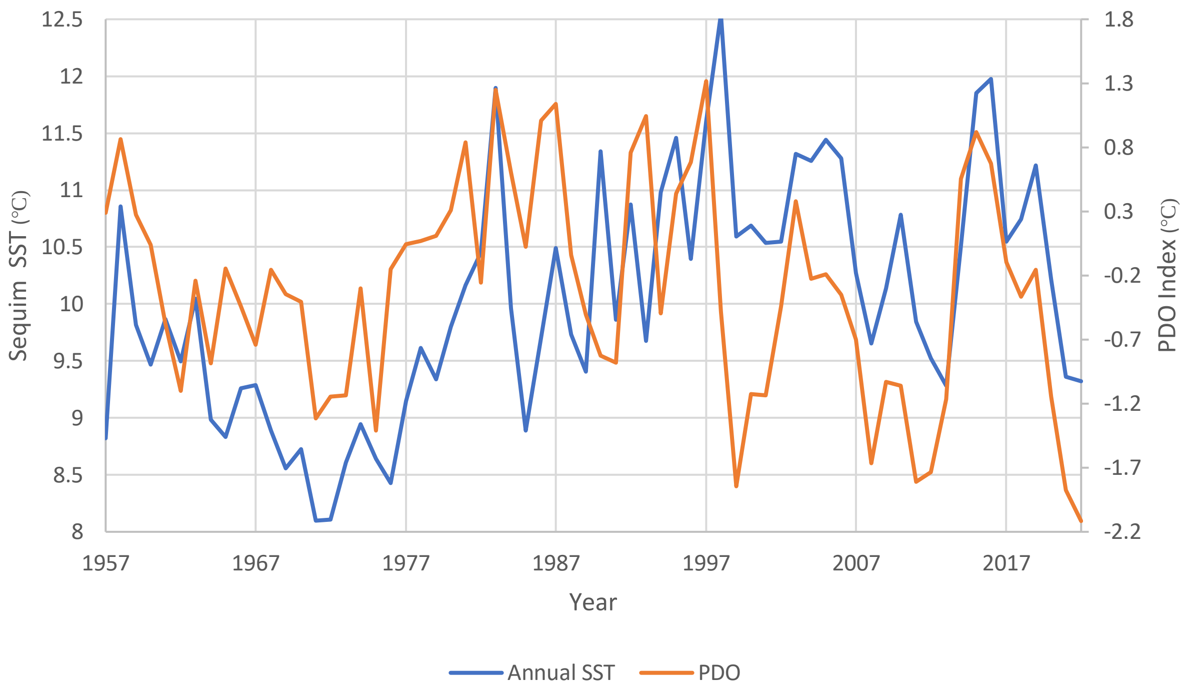



*Note.* The paralytic shellfish poisoning (PSP) index plotted against average annual temperature from each year between 1957 and 2022.

As we can see in Figure 19, Sequim average annual SST follows the average monthly PDO index closely over time. A positive and significant association between Sequim SST and PDO index was observed (r = 0.35, p = 0.003). Sequim SST also follows the ENSO index over time as shown in Figure 20. A positive and significant association was observed (r = 0.36, p = 0.002).

FIGURE 20.

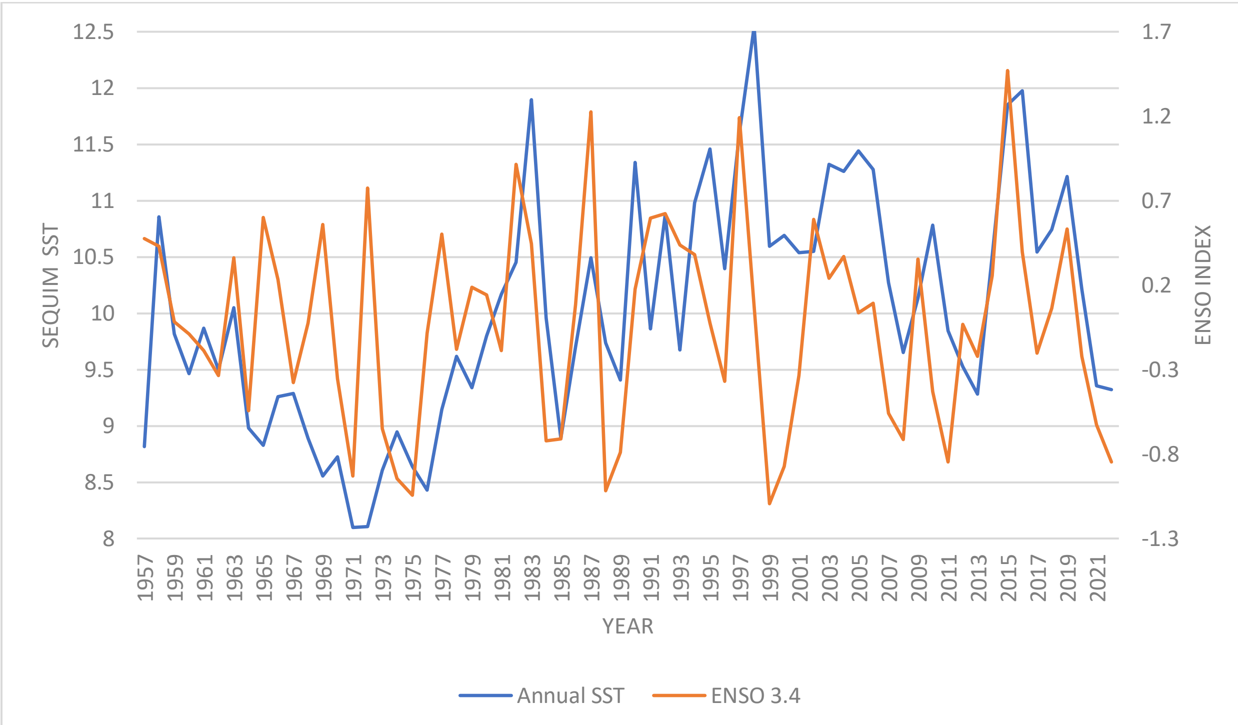
PDO AND SST




*Note.* Annual sea surface temperatures (SST) plotted against the Pacific Decadal Oscillation (PDO) over time from 1957-2022.

FIGURE 21.

ENSO AND SST

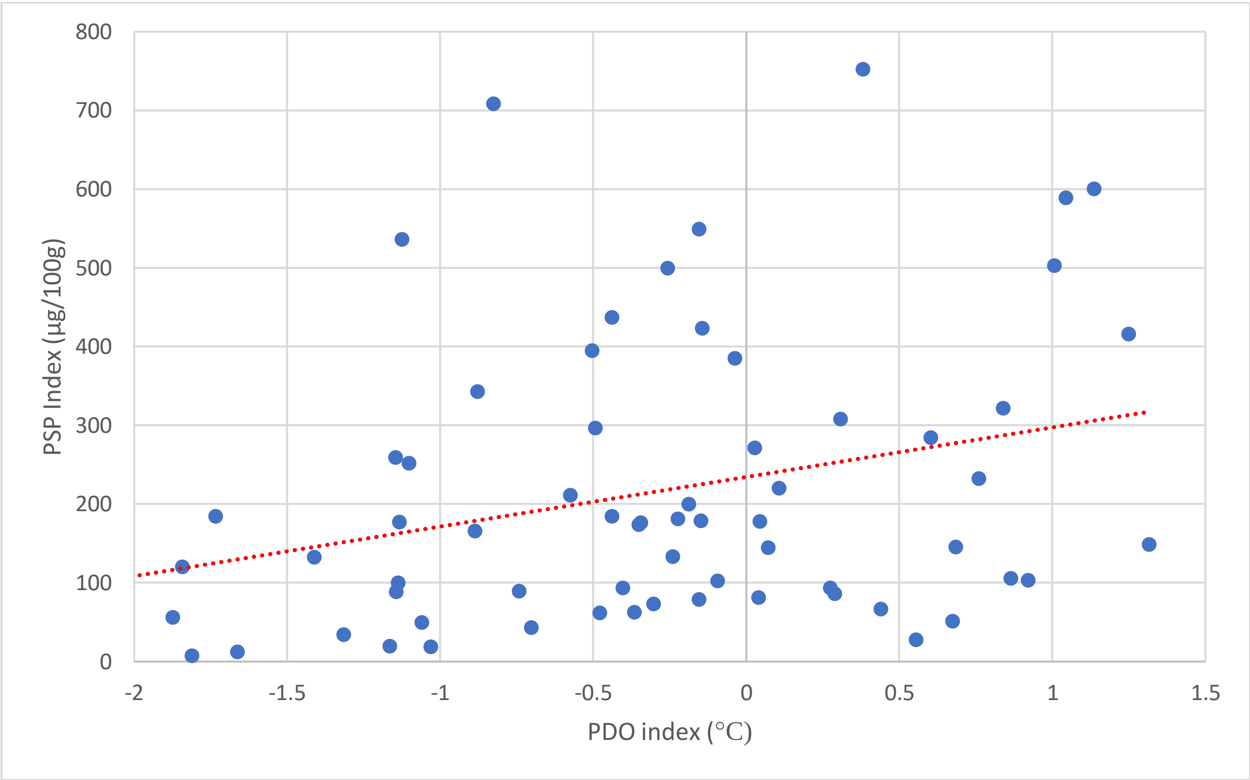



*Note.* Annual sea surface temperatures (SST) plotted against the El Nino Southern Oscillation (ENSO) over time from 1957-2022.

There is a significant and positive relationship between PDO index and PSP concentration (Fig. 21) (r= 0.36, p= 0.003). The relationship between ENSO index and PSP concentration looks similar (Fig. 22), showing a significant and positive relationship (r = 0.27, p = 0.026).

FIGURE 22.

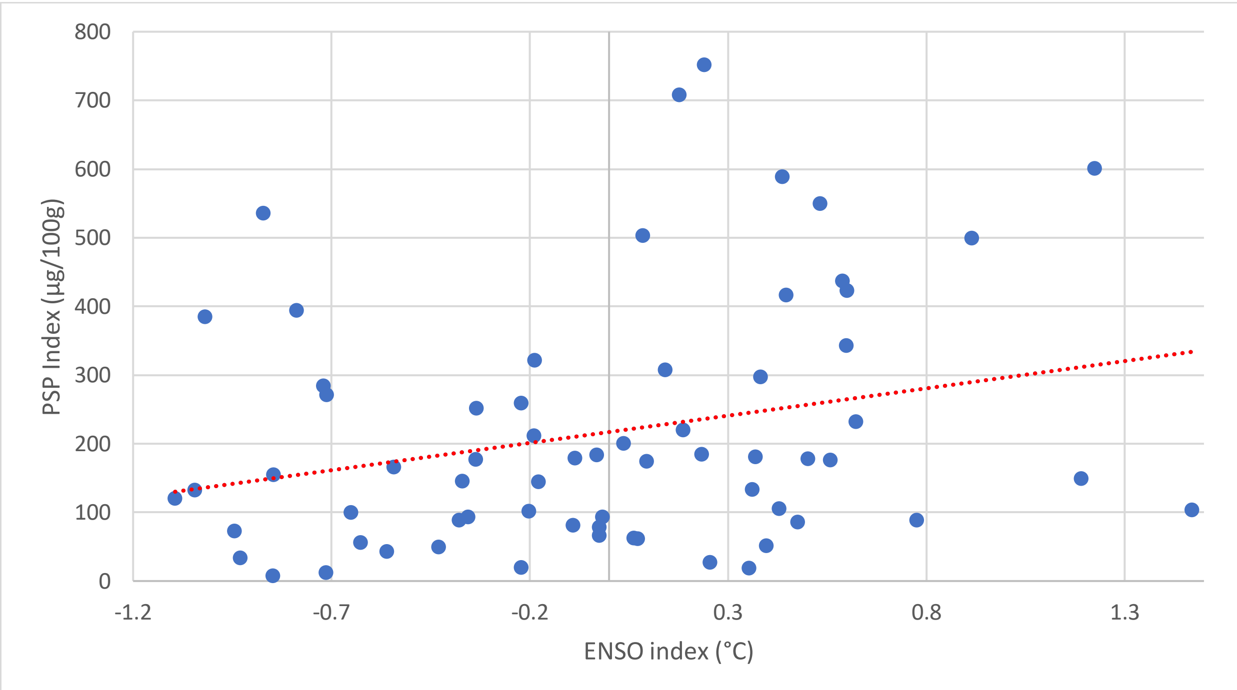
PDO AND PSP




*Note.* The paralytic shellfish poisoning (PSP) index plotted against the Pacific Decadal Oscillation (PDO) from 1957-2022. The data from 1957 through 2007 was originally published by Moore et al. 2010.

FIGURE 23.

ENSO AND PSP




*Note.* The paralytic shellfish poisoning (PSP) index plotted against the El Nino Southern Oscillation index (ENSO) from 1957-2022. The data from 1957 through 2007 was originally published by Moore et al. 2010.

# Discussion

This research suggests that sea surface temperatures (SSTs) in Sequim Bay have increased slightly over the last 65 years (Fig. 12). Higher average sea surface temperatures could contribute to more frequent *A. catenella* blooms and subsequently more shellfish toxicity (paralytic shellfish poisoning). Daily SSTs at or above 13°C have been shown to increase *A. catenella* and paralytic shellfish poisoning (Nishitani and Chew 1984; Moore et al. 2010). The optimum temperature range is known to be 13-17°C for *A. catenella* blooms, so continued SST increases may contribute to more paralytic shellfish poisoning in the future (Tatters et al. 2013).

A limitation of this study is that it employed annual mean SST and correlated it with the PSP index, which utilized annual monthly maximum PSP concentrations. This was done to better represent SST warming trends over time. As such, the annual SSTs used here (~ 8 through 12°C) were below the optimal conditions for *A. catenella* blooms. Mean annual SST still significantly positively correlated with the PSP index, but a more representative SST variable (e.g., number of days SST was greater than 13°C) would likely have statistical significance (Moore et al. 2010). Number of days over 13°C was the temperature variable Moore et al. (2010) used to represent SSTs in Sequim Bay which did result in statistical significance when correlated with PSP concentrations (Moore et al. 2010).

As warming continues, temperatures in the future could persist past the thermal threshold of *A. catenella*, potentially lowering PSP concentrations during certain times of the year (i.e., primarily in the summer). Sequim Bay SSTs typically range between 12°C and 17°C during the summer months. SST maximums in Sequim Bay in the summer don't typically surpass 17°C, but this could change as warming continues. It would likely lead to more seasonality of *A. catenella* and the subsequent shellfish toxicity. This will have to be monitored and studied as SST and PSP concentration data are gathered over time. Monitoring Daily SSTs could prove more beneficial in determining potential PSP concentrations versus using yearly SST means as this study did.

This work aimed to explore the relationship between the Pacific Decadal Oscillation (PDO) and the El Nino Southern Oscillation (ENSO) and their impacts on PSP concentrations. The PDO and ENSO index have previously been shown to be positively correlated with SST as did this study (Moore et al. 2010; Mantua and Hare 2002). Further, previous research has shown that SST anomalies via PDO cycles are strongest from May through August, whereas ENSO tends to influence SST the most in March (Moore et al. 2010). Previous studies have attributed this difference to why PDO has been shown to influence shellfish toxicity, but not ENSO (Moore et al. 2008; 2010).

In this study, PDO and ENSO were both found to have positive and significant relationships with shellfish toxicity (PSP concentration) which is unique compared to the scientific literature (Moore et al. 2010). This difference could be due to the added years in the time series (2010-2022) containing a considerable amount of variability and warmer than average temperatures overall. The years 2014-2016 are especially notable as this was when the PNW experienced a marine heat wave leading to very warm SST later to be named “The Blob” (Shanks et al. 2020). The SSTs during the blob were 16% higher compared to the mean SST of all years (1957-2022). The average SST from the years 1957-2007 compared to the years 2008-2022 were 5% lower. These warmer than average temperatures would have given the opportunity for more *A. catenella* blooms, thus more opportunity for paralytic shellfish poisoning. This could have been the result of the extreme El Nino phase observed in 2015.

ENSO is known to influence SST and SST is known to influence *A. catenella* as previously mentioned. Since SSTs have been increasingly warmer, the ENSO-driven SST anomalies likely lead to more windows of opportunity for HABS and subsequent shellfish toxicity (PSP concentration) due to the increased baseline of warmer SSTs. This could be another explanation for the significant relationship between ENSO and PSP concentration found in this study.

This study also shows the significant relationship between ENSO and PDO as have other studies in the past (Moore et al. 2010; Newman et al. 2016). ENSO is known as one of the main forcing factors on PDO and the subsequent SST anomalies. Since ENSO influences PDO and PDO influences SST and shellfish toxicity, one could deduce that ENSO also influences shellfish toxicity as shown in this study. One could also surmise that since ENSO is known as one of the main forcing variables contributing to the PDO phenomenon then at the very least, ENSO would be an indirect influence of shellfish toxicity knowing that PDO does influence shellfish toxicity.

*A. catenella* is a dinoflagellate meaning it is motile and can swim in search of nutrients, light, or other favorable environmental factors. Since the mechanisms of ENSO phases (e.g., El Nino, La Nina, neutral) impact the environment differently, *A. catenella* bloom dynamics will respond accordingly. For example, during an El Nino phase when Eastern Trade Winds are weak and there is minimal upwelling, less nutrients would be available, but SSTs would be warmer and more ideal for *A. catenella*. Due to their motility, these dinoflagellates could also be able seek out warmer waters where nutrients aren't depleted thus giving them a competitive advantage over other phytoplankton. This is a scenario that would lead to a bloom and subsequently, more shellfish toxicity (PSP concentration).

While this study suggests a positive association between ENSO index and PSP concentration and PDO index and PSP concentration, it's important to note that the correlations were modest. This is likely due to the large number of variables to consider when investigating these relationships among SST, PDO, ENSO, and PSP concentration. Variables like sunlight, nutrient availability, turbidity, salinity, and many other unnamed or unknown variables could not be accounted for in this study. These variables impact *A. catenella* bloom dynamics and the subsequent PSP concentrations, their exact influence is unknown, but they certainly play a role. Including more of these variables (i.e., sunlight, salinity, turbidity, etc.) in future analyses could provide more insight on *A. catenella* bloom dynamics and the subsequent shellfish toxicity.

# Conclusion

Harmful algal blooms and the subsequent toxins have increased over time and continue to expand their presence throughout the world (Van Dolah 2000). Paralytic Shellfish Poisoning is no exception and is a public health issue that will continue to need effective monitoring and regulation. The Pacific Decadal Oscillation (PDO) and El Nino Southern Oscillation (ENSO) are known to cause sea surface temperature (SST) anomalies in the northern Pacific Ocean (Mantua et al. 1997). Warm PDO phases is associated with warmer SSTs and more days of SST >13 ℃ which results in more shellfish toxicity in the Pacific Northwest (Moore et al. 2010). This work suggests a significant relationship between PDO and shellfish toxicity (PSP concentration) and ENSO and shellfish toxicity (PSP concentration).

This calls for more research to further investigate weather patterns and anomalies associated with ENSO that could be impacting *A. catenella* and other HAB dynamics. Future research could also focus on *A. catenella* cell counts instead of PSP concentrations to better represent HAB dynamics. This could provide real-time insights on the number of *A. catenella* cells. *A. catenella* cell counts could be used to estimate the subsequent PSP concentrations in surrounding areas once a threshold was determined for cell counts and its connection to PSP concentrations.

More research on climate change and the continued warming of SSTs associated with climate patterns like ENSO or PDO could also shed more light on this complex story. Understanding the environmental drivers and variabilities that affect *A. catenella* bloom dynamics will allow us to monitor shellfish toxicity more effectively. In doing this, shellfish can continue to be a safe and healthy source of food for all communities.

# References

Alpine, Andrea E., and James E. Cloern. 1992. “Trophic Interactions and Direct Physical Effects Control Phytoplankton Biomass and Production in an Estuary.” *Limnology and Oceanography* 37 (5): 946–55. https://doi.org/10.4319/lo.1992.37.5.0946.

Anderson, Donald M. 1998. “[PDF] Physiology and Bloom Dynamics of Toxic Alexandrium Species, with Emphasis on Life Cycle Transitions.” 1998. https://www.researchgate.net/publication/301838910_Physiology_and_bloom_dynamics_of_toxic_Alexandrium_species_with_emphasis_on_life_cycle_transitions.

Anderson, Donald M., Allan D. Cembella, and Gustaaf M. Hallegraeff. 2012. “Progress in Understanding Harmful Algal Blooms: Paradigm Shifts and New Technologies for Research, Monitoring, and Management.” *Annual Review of Marine Science* 4 (1): 143–76. https://doi.org/10.1146/annurev-marine-120308-081121.

Anderson, Donald M., Marta Estrada, and Grant Pitcher. 2005. “(PDF) The Comparative ‘Systems’ Approach to HAB Research.” 2005. https://www.researchgate.net/publication/33549722_The_Comparative_Systems_Approach_to_HAB_Research.

Cooley, S., J. E. Cheney, R. Kelly, and E. Allison. 2017. “Ocean Acidification and Pacific Oyster Larval Failures in the Pacific Northwest United States.” 2017. https://www.semanticscholar.org/paper/Ocean-acidification-and-Pacific-oyster-larval-in-Cooley-Cheney/74cb9551e1011263d8714ae655c88d62026f4eb6.

DOH. 2022. “Paralytic Shellfish Poisoning (PSP).” Washington State Department of Health. 2022. https://doh.wa.gov/community-and-environment/shellfish/recreational-shellfish/illnesses/biotoxins/paralytic-shellfish-poisoning.

Dyhrman, Sonya T., Sheean T. Haley, Jerry A. Borchert, Bob Lona, Nicole Kollars, and Deana L. Erdner. 2010. “Parallel Analyses of Alexandrium Catenella Cell Concentrations and Shellfish Toxicity in the Puget Sound.” *Applied and Environmental Microbiology* 76 (14): 4647–54. https://doi.org/10.1128/AEM.03095-09.

Garneau, Marie-Ève, Astrid Schnetzer, Peter D. Countway, Adriane C. Jones, Erica L. Seubert, and David A. Caron. 2011. “Examination of the Seasonal Dynamics of the Toxic Dinoflagellate Alexandrium Catenella at Redondo Beach, California, by Quantitative PCR.” *Applied and Environmental Microbiology* 77 (21): 7669–80. https://doi.org/10.1128/AEM.06174-11.

Government of Canada, Fisheries and Oceans Canada. 2008. “Fisheries and Oceans Canada | Pacific Region | Fisheries and Oceans Canada.” November 12, 2008. https://www.pac.dfo-mpo.gc.ca/index-eng.html.

King, Teri. 2020. “Shellfish.” *Washington Sea Grant* (blog). 2020. https://wsg.washington.edu/our-northwest/shellfish/.

Mantua, Nathan, and Steven Hare. 2002. “The Pacific Decadal Oscillation.” *Journal of Oceanography* 58 (February): 35–44. https://doi.org/10.1023/A:1015820616384.

Mantua, Nathan, Steven Hare, Yuan Zhang, John Wallace, and Robert Francis. 1997. “A Pacific Interdecadal Climate Oscillation with Impacts on Salmon Production.” *Bulletin of the*

*American Meteorological Society* 78 (June): 1069–79. https://doi.org/10.1175/1520-0477(1997)078%3C1069:APICOW%3E2.0.CO;2.

Moore, Stephanie K., Nathan J. Mantua, Barbara M. Hickey, and Vera L. Trainer. 2010. "The Relative Influences of El Niño-Southern Oscillation and Pacific Decadal Oscillation on Paralytic Shellfish Toxin Accumulation in Northwest Pacific Shellfish." *Limnology and Oceanography* 55 (6): 2262–74. https://doi.org/10.4319/lo.2010.55.6.2262.

Moore, Stephanie K., Nathan J. Mantua, Jonathan P. Kellogg, and Jan A. Newton. 2008. "Local and Large-Scale Climate Forcing of Puget Sound Oceanographic Properties on Seasonal to Interdecadal Timescales." *Limnology and Oceanography* 53 (5): 1746–58. https://doi.org/10.4319/lo.2008.53.5.1746.

Navarro, J. M., M. G. Muñoz, and A. M. Contreras. 2006. "Temperature as a Factor Regulating Growth and Toxin Content in the Dinoflagellate Alexandrium Catenella." *Harmful Algae* 5 (6): 762–69. https://doi.org/10.1016/j.hal.2006.04.001.

Newman, Matthew, Michael A. Alexander, Toby R. Ault, Kim M. Cobb, Clara Deser, Emanuele Di Lorenzo, Nathan J. Mantua, et al. 2016. "The Pacific Decadal Oscillation, Revisited." *Journal of Climate* 29 (12): 4399–4427. https://doi.org/10.1175/JCLI-D-15-0508.1.

Newman, Matthew, Gilbert P. Compo, and Michael A. Alexander. 2003. "ENSO-Forced Variability of the Pacific Decadal Oscillation." *Journal of Climate* 16 (23): 3853–57. https://doi.org/10.1175/1520-0442(2003)016<3853:EVOTPD>2.0.CO;2.

Nishitani, Louisa, and Kenneth K. Chew. 1984. "Recent Developments in Pralytic Shellfish Poisoning Research." *Aquaculture*, Recent Innovations in Cultivation of Pacific Molluscs, 39 (1): 317–29. https://doi.org/10.1016/0044-8486(84)90274-6.

NOAA. n.d. “El Nino Index Dashboard: NOAA Physical Sciences Laboratory.” Accessed February 7, 2023. https://psl.noaa.gov/enso/dashboard.html.

Ralston, David K., and Stephanie K. Moore. 2020. “Modeling Harmful Algal Blooms in a Changing Climate.” *Harmful Algae*, Climate change and harmful algal blooms, 91 (January): 101729. https://doi.org/10.1016/j.hal.2019.101729.

Rayner, N. A. 2003. “Global Analyses of Sea Surface Temperature, Sea Ice, and Night Marine Air Temperature since the Late Nineteenth Century.” *Journal of Geophysical Research* 108 (D14): 4407. https://doi.org/10.1029/2002JD002670.

Schneider, Niklas, and Bruce D. Cornuelle. 2005. “The Forcing of the Pacific Decadal Oscillation.” *Journal of Climate* 18 (21): 4355–73. https://doi.org/10.1175/JCLI3527.1.

Shanks, Alan L., Leif K. Rasmuson, Jenna R. Valley, Marley A. Jarvis, Carly Salant, David A. Sutherland, Eleanor I. Lamont, MacKenna A. H. Hainey, and Richard B. Emlet. 2020. “Marine Heat Waves, Climate Change, and Failed Spawning by Coastal Invertebrates.” *Limnology and Oceanography* 65 (3): 627–36. https://doi.org/10.1002/lno.11331.

Simon, Nathalie, Anne-Lise Cras, Elodie Foulon, and Rodolphe Lemée. 2009. “Diversity and Evolution of Marine Phytoplankton.” *Comptes Rendus Biologies*, La théorie de Darwin revisitée par la biologie d’aujourd’hui / Darwin’s theory revisited by today’s biology, 332 (2): 159–70. https://doi.org/10.1016/j.crvi.2008.09.009.

Smayda, Theodore J. 1997. “Harmful Algal Blooms: Their Ecophysiology and General Relevance to Phytoplankton Blooms in the Sea.” *Limnology and Oceanography* 42 (5part2): 1137–53. https://doi.org/10.4319/lo.1997.42.5_part_2.1137.

Sullivan, James M., and Elijah Swift. 2003. "EFFECTS OF SMALL-SCALE TURBULENCE ON NET GROWTH RATE AND SIZE OF TEN SPECIES OF MARINE DINOFLAGELLATES [1]." *Journal of Phycology* 39 (1): 83–94. https://doi.org/10.1046/j.1529-8817.2003.02094.x.

Tatters, Avery O., Leanne J. Flewelling, Feixue Fu, April A. Granholm, and David A. Hutchins. 2013. "High CO2 Promotes the Production of Paralytic Shellfish Poisoning Toxins by Alexandrium Catenella from Southern California Waters." *Harmful Algae* 30 (December): 37–43. https://doi.org/10.1016/j.hal.2013.08.007.

Trainer, Vera L, Bich-Thuy L Eberhart, John C Wekell, Nicolaus G Adams, Linda Hanson, Frank Cox, and Judy Dowell. 2003. "PARALYTIC SHELLFISH TOXINS IN PUGET SOUND, WASHINGTON STATE," 11.

US Department of Commerce, National Oceanic and Atmospheric Administration. n.d. "What Are Plankton?" Accessed November 15, 2022. https://oceanservice.noaa.gov/facts/plankton.html.

Van Dolah, F. M. 2000. "Marine Algal Toxins: Origins, Health Effects, and Their Increased Occurrence." *Environmental Health Perspectives* 108 Suppl 1 (March): 133–41. https://doi.org/10.1289/ehp.00108s1133.

Wells, Mark L., Vera L. Trainer, Theodore J. Smayda, Bengt S. O. Karlson, Charles G. Trick, Raphael M. Kudela, Akira Ishikawa, et al. 2015. "Harmful Algal Blooms and Climate Change: Learning from the Past and Present to Forecast the Future." *Harmful Algae* 49 (November): 68–93. https://doi.org/10.1016/j.hal.2015.07.009.