Changes in climate relate to long-term shifts in Puget Sound shrimp abundances

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**Abstract**

In 2013 through 2016, a severe marine heatwave in the North Pacific coupled with a particularly strong El Niño event caused widespread and lasting changes to the marine ecosystem across the Pacific coast of North America. Dubbed ‘the blob’, the event has led to a range of research exploring how marine communities changed in the face of a rapidly warming ocean surface. Yearly trawl data from 2000-2019 was used to quantify long term trends in the abundance of shrimp in central Puget Sound. The results indicate that yearly shrimp abundance is closely correlated with the Oceanic Niño Index, and in particular with the marine heat wave and strong El Niño that simultaneously occurred between 2013-2016. The abundance of shrimp increased dramatically in 2014 and has remained at a high level since. The largest commercial haul of Washington coast pink shrimp ever recorded also occurred in 2014. Increases in abundance were only observed at deeper trawl depths, indicating that in addition to increasing in abundance, shrimp may be altering their diel vertical migrations in response to unfavorable temperatures in surface waters.

**Keywords: climate change, shrimp, Pandalus jordani, pink shrimp, Puget Sound, abundance**

I**ntroduction**

Across the North Pacific there are numerous genera of shrimp distributed in coastal waters from Baja California to the Chukchi Sea in Northern Alaska (Campos et al. 2012; Komai 1999; Zhang and Fong 2021). In Washington State, shrimp are an important commercial and recreational fishery, and an abundant resource. Recreational shrimping exists throughout Puget Sound and the coast, while a large, stable, and long-term commercial fishery for Pandalus jordani (pink shrimp) has existed on the coast of Washington since the 1950’s (Washington Department of Fish and Wildlife). The pink shrimp fishery is viewed locally as extremely productive and sustainable, with no indication that fishing pressure has a negative effect on the total population (Washington Department of Fish and Wildlife). There have been record pink shrimp landings in recent years, with the largest landing in the history of the fishery occurring in 2014 with 30.6 million pounds of recorded catch; (the 25 year average is 8.6 million pounds annually) (Washington Department of Fish and Wildlife). These wild swings in shrimp landings are not well understood.

Parsing out and understanding the reasons for the observed shifts in marine community composition and abundance is critically important. Understanding why these shifts have occurred, and predicting the direction and magnitude of future shifts will help fisheries managers better understand and prepare in the face of rapidly changing ocean conditions. One way to do this is to examine how shrimp and other marine species have reacted to previous shifts in climate over year or multi-year time scales. A well-known and popular study topic is the infamous ‘warm blob’ event that occurred off the west coast of the US from Alaska to Oregon in 2014 and 2015 in conjunction with an extremely strong El Niño cycle. Sea surface temperatures in the North Pacific were an average of 3.9 degrees Celsius warmer than the historical average (NOAA climate predication center).

These recently changing environmental conditions have resulted in shifts in shrimp and other marine invertebrate populations (Brodeur et al. 2019; Peterson et  al. 2017; Sakuma et  al. 2016). In recent years, these changes have been extreme, highly variable, seemingly contradictory; and in some cases not well understood (Morgan et al. 2019). For instance: there was a large observed decrease in the abundance of shrimp, krill, and other crustaceans in the surface and midwaters off the Washington coastline during the 2014-2015 blob event, in conjunction with an explosion in the abundance of warm-water gelatinous organisms (Brodeur et al. 2019; Sakuma et al. 2016), and a decline in marine biomass of salmon (Cheung and Frölicher 2020) associated with a lack of quality marine prey (Daly and Brodeur 2017). The invertebrate community still has not returned to historical levels of abundance and composition, and the shift may be semi-permanent (Brodeur et al 2019). These changes may be due to a decline in absolute abundance, or a shift in habitat usage (Brodeur et al 2019). Pink shrimp for example move up in the water column at night to feed, but may have begun to avoid surface waters that were unfavorably warm.

This event, and the many observed ecosystem responses, gives a preview of potential future baseline conditions under predicted climate change scenarios. Average air temperatures in the Pacific Northwest are expected to increase by 1.8°C - 5.4°C by the 2080s (compared to the 1980s), and summer precipitation is expected to decrease by about 10% (IPCC 2007; National Climate Assessment 2014). To study how shrimp populations in Washington have been affected by past changes in climate and in sea surface temperature, We used 20 years of trawl data collected by the University of Washington in central Puget Sound to examine shrimp abundance at multiple depths and across several El Niño/La Niña climate cycles. This study attempted to examine the following questions:

1. Has shrimp abundance in central Puget Sound changed over time?
2. Has shrimp abundance in central Puget Sound changed across different sampling depths over time?
3. Has shrimp abundance in central Puget Sound changed over time in tandem with large-scale climate shifts?

**Methods**

Study Area

Port Madison is a small bay located on the west/central shore of Puget Sound along the Northern shore of Bainbridge Island (figure 1). The Puget Sound itself is a complex and highly productive ecosystem within the Salish Sea, consisting of several large, environmentally distinct sub-basins (Ruckelshaus et al. 2007). Within Port Madison, depth varies greatly, with average depth decreasing rapidly across a relatively short distance. The large variation in depth within a single bay allows trawl surveys to be conducted at varying depths within a single geographic area.

Sample Collection

Benthic trawl surveys were conducted in Port Madison between 1999 and 2019 with students and faculty from the University of Washington School of Aquatic and Fisheries Sciences. The intent of the trawls was to collect a snapshot of the community composition of nearshore fish and invertebrates. Surveys were conducted over the course of two days in mid-May of each year, with depths of 10, 25, 50, and 70 meters sampled (figure 2). Within the two day yearly sampling effort, a survey boat conducted trawls in 5 different shifts a few hours apart from each other: “afternoon”, “evening”, “night”, “early morning”, and “mid-morning”. Afternoon trawls began shortly after 14:00, evening trawls began shortly after 19:00, night trawls began shortly after 0:00, early morning trawls began shortly after 05:00, and morning trawls began shortly after 10:00. Each shift conducted four trawls in the same approximate locations: one at each depth of 10m, 25m, 50m, and 70m.

Each trawl survey used a Southern California Coastal Water Research Program otter trawl. The net measured 3.5m wide, 1m high, with a 35mm mesh size. For each trawl, the otter trawl was deployed and towed on the sea bed for approximately 370m before being retracted. All captured fish and invertebrates were placed in live wells before being identified to the lowest taxonomic level possible, measured, and released. Metadata consisting of the current tide, time of capture, capture depth, and date were recorded with every individual. Two species of shrimp sampled: *Pandalus eous* and *Pandalus jordani* were not distinguished from each other in the trawl, and were grouped together. In subsequent sections these will be referred to simply as *Pandalus eous/jordani*.

Data Analysis

In order to pair environmental metadata to each specific observation, a unique “sampling event” ID was created for every single trawl. This sampling event ID consisted of the sample date, sample time, and sample depth. Each individual trawl observation was paired with its unique sampling event ID. Using this sample event ID, the catch per unit effort (CPUE) and El Niño/ La Niña Intensity Index (ONI) values were assigned to each individual species observation. CPUE was calculated by multiplying the otter trawl net width (3.5m) by the length of the individual trawl (on average 370m, range: 367m-538m). Catch numbers by species from each trawl was then divided by the total trawled area to get the number of individuals per square meter for each trawl.

Shrimp species were analyzed as an aggregate, before being separated into individual species. Species which had minimal catch numbers (<1000) were excluded from the analysis. All trawl data from 1999 was also excluded since detailed CPUE data was not collected in that year. CPUE of a total of five individual species of shrimp were analyzed: *Crangon alaskensis, Pandalopsis dispar, Pandalus danae, Pandalus platyceros,* and *Pandalus eous.*

El Niño/ La Niña Intensity Index values were taken from [NOAA’s Climate Prediction Center](https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php). Oceanic Niño Index values were averaged over the previous 12 months from each year’s sampling effort and added to the shrimp data by year. Based on ONI conditions, catch data of each shrimp species was separated by year into three groups: “El Niño conditions”, “La Niña conditions”, and “no signal” based on the average ONI values of the previous 12 months prior to each yearly sampling effort. ONI values at or above 0.5 are defined as El Niño conditions by NOAA, indicating temperatures are warmer than average. ONI values at or below -0.5 are defined as La Niña conditions, indicating temperatures are cooler than average. Values that fall between -0.5 and 0.5 are defined as having neither condition present. This categorical classification was the primary variable examined, and was used in leu of the average ONI values in order to lump years into groups based on similar climate conditions.

For each shrimp species, statistical analysis was conducted to determine if there was a significant difference in CPUE between years in which El Niño, La Niña, or neither condition was present. One-way ANOVAs were used to determine statistical significance (p = 0.05) followed by Post Hoc Tukey tests to quantify where statistical differences, if any, exist among the three climate regimes and the CPUE of each shrimp species. The R base function “aov” was used to perform the ANOVA tests, and the “HSD.test” function within the R package “agricolae” was used to perform Post Hoc Tukey tests. After performing ANOVA and Tukey Tests, a linear mixed effects model was performed for each species of shrimp. The R package “lme4” was used to perform mixed effects models for each species using the “glmer” function. Capture depth and the time of day at capture were input as random effects in the model. The Oceanic Niño Index phase of the previous 12 months was input as a fixed effect in the model.

**Results**

Data processing

The majority of the 25 taxa of shrimp sampled did not contain enough individuals to conduct a sufficiently powerful statistical analysis. Of those that did have sufficient numbers, several groups were only sporadically caught over a few years. A total of five taxa were selected for further examination based upon the following criteria: (1) taxon containing a large number of individuals (n ≥ 1,000) and (2) taxon contained enough individuals caught over a large number of years representing several El Niño/La Niña cycles. All samples from 1999 were excluded from the analysis, because detailed trawl data were not recorded in that initial year of the study. Additionally, approximately half of the samples collected in 2013 were also excluded, as data recording errors in trawl times in that year made many of the samples unusable.

Of the remaining data, five species of shrimp were included in the final statistical analysis: C*rangon alaskensis (n =* 5,393 individuals), P*andalopsis dispar* (n = 1,172), P*andalus eous/jordani* with a total of 7,522 individuals sampled, P*andalus danae* with a total of 1,035 individuals sampled, and P*andalus platyceros* with a total of 4,471 individuals sampled. Across all species, 22,070 individual shrimp were sampled (table 1). Note that the aggregate total analyzed includes all shrimp sampled, not just the 5 species that were separated out for individual analysis.

Data analysis

ANOVA and post-hoc Tukey Tests (p ≤ 0.05) were performed for each species, as well as for the combined aggregate of all shrimp captured in the study. Consistently across the study, the vast majority of shrimp were caught in the 50m and 70m depth trawls (figure 5). Both the combined aggregate of all shrimp caught, as well as the five individual species analyzed, showed an identical response in catch per unit efforts across the three Oceanic Niño Index conditions (El Niño, no signal, and La Niña). The highest catch per unit effort occurred in years with El Niño conditions, followed by median catch per unit efforts in years with no Oceanic Niño Index signal, and the lowest catch per unit efforts in years with La Niña conditions (figure 3, figure 4, table 2, table 3). However, only the combined aggregate of all shrimp species, as well as P*andalus eous/jordani* and P*andalus platyceros* had statistically significant catch per unit effort differences between the climate conditions. In all three cases, years with El Niño conditions present were significantly different than years with La Niña conditions or years with no signal. There were no significant differences between years with La Niña conditions and years with no signal among any species. However, the average catch per unit effort in years with La Niña conditions were lower than years with no Oceanic Niño Index signal in every single case (table 2).

A final analysis was carried out on the data using a linear mixed effects model to account for differences in the depth and timing of catch that may have confounded the results. The linear mixed effects model found significant differences (p ≤ 0.05) in shrimp catch per unit effort in all three Oceanic Niño Index phases (table 3). For more information on the analysis, please refer to the appendix(shrimp\_code). For the purposes of reproducibility, all of the R code used to complete the analysis and produce the figures is included in the accompanying appendix.

**Discussion**

There was a clear and statistically significant relationship between shrimp relative abundance and Oceanic Niño Index phase, with abundance highest in comparatively warmer El Niño years, and lowest in comparatively cooler La Niña years. Overall, abundance remained relatively low until 2013/2014, when catch per unit effort increased dramatically and remained high for the remainder of the study. The observed differences across the three Oceanic Niño Index phases were largely driven by extreme outliers. However, the sheer number of outliers, and the clear trend of increasing outliers from cooler to warmer years, support the conclusion that the trends observed are indeed significant. The potentially confounding effects of sample depth and sample time were accounted for in a linear mixed effects model, the results of which did not differ from the ANOVA and Post Hoc analysis.

The majority of all data points fell within a fairly narrow range, with the number and the magnitude of outliers increasing in warmer years. Thus, while the averageshrimp relative abundance did not greatly change across the three Oceanic Niño Index phases, the likelihood for massive booms in relative abundance increased substantially during years of average and warmer than average temperatures, with the greatest number and greatest magnitude of relative abundance booms occurring in El Niño years. When individual species were analyzed, the trends for each species mirrored the combined aggregate. However, the trends for only two of the five species were statistically significant. This is likely due to insufficient sample sizes when individual species were separated out.

When comparing catch per unit effort across depths, the majority of shrimp were consistently caught in 50m and 70m trawls. The large shifts in abundance observed in the study were almost entirely driven by changes at these depths. Catch per unit effort at 10m and 25m trawls remained virtually unchanged across the entire study. The trend of increasing shrimp abundance starting in 2013/2014 onward was driven entirely by catch at these deeper depths. Catch per unit efforts at these depths have never returned to pre-2013 levels.

Many of the years with the highest shrimp abundance occurred from 2013-2016, during the intense marine heatwave known as ‘the blob’. Other studies have observed similarly large swings in abundance or composition of marine communities during the marine heatwave. For example: large decreases in the abundance of krill and shrimp (Brodeur et al. 2019; Peterson et  al. 2017; Sakuma et  al. 2016). Whether these community shifts are temporary or semi-permanent are unknown (Brodeur et al. 2019; Morgan et al. 2019). Interestingly, the abundance of shrimp observed in this study have not returned to their pre-blob levels as of the last trawl survey in 2019, despite the fact that the El Niño phase that caused the blob ended in 2016. Indicating that this may be an example of a semi-permanent community shift in response to the blob event. However, the mild El Niño observed in 2018-2019 may have contributed to this.

The universally positive response of these species to warmer than average temperatures signals that they possess a level of adaptability to environmental shifts that may allow them to persist in the coming decades. Deep water thermal refugia in Puget Sound may also allow for behavior changes to avoid unfavorable temperature conditions in shallower surface waters.

In contrast to these conclusions, a study of a different Northeast Pacific marine system, the California Current, there was an observed decrease in the abundance of krill and shrimp in the unusually warm surface and mid waters during the blob event (Brodeur et al. 2019). However, Brodeur et al. (2019) noted that their trawl surveys were conducted in the warmer upper layers of water above the thermocline, and thus could not ascertain the community composition in deeper layers, which may have not been as affected by the blob. It is important to note that the largest temperature differences as a result of the blob occurred in the top 50-80m of water, with deeper temperatures remaining close to their long term mean along the Washington Coast (Auth et al. 2018; Peterson et al. 2017). Paired acoustic data from the same study showed anecdotal evidence of possible aggregations of euphausiids and other micronekton below the warmer surface layer of water (Brodeur et al. 2019), indicating possible changes in shrimp and krill diel vertical behavior in response to unfavorable temperatures near the surface.

Indeed, this study’s findings suggest the large increase in shrimp abundance during and after the blob years occurred entirely at depths of 50m and greater. lending more support to the theory that shrimp altered their diel vertical migrations in order to avoid potentially harmful water temperatures near the surface. In the case of the Port Madison trawls, this would mean avoiding the shallower areas of the bay entirely. This would help explain the increased abundance of shrimp shown in this paper, which appears contradictory to previous studies showing large shrimp declines over the same period of time along the coast.

As environmental conditions shift over the coming decades, there will be winners and losers among species. Those that are able to tolerate or even thrive in warmer, more acidic waters may expand their ranges and increase in abundance. While the species studied here showed a positive response in abundance during periods with warmer than average temperature, it is important to note that temperature is not the only condition predicted to change in the coming decades. Predicted changes in ocean acidity under future climate change scenarios (Caldeira and Wickett 2005; Cao and Caldeira 2008; Orr et al. 2005; Steinacher et al. 2009) may very well offset or even reverse the trends seen in this study.

**Management Implications**

Several of the species studied here are important for recreational and/or commercial harvest. While the ultimate effect that climate change will have on these species is unclear, judging by the strong response to increased average water temperatures, it is clear that a shift in abundance will likely occur in the coming decades as average sea surface temperatures begin to mirror what currently would be considered above average or extreme. The specific mechanistic effects causing the increased number and magnitude of shrimp abundance booms during El Niño years is not clear, and was not examined in this study. Further work to quantify specific responses to predicted environmental changes is warranted and important, in order to better predict future changes to a number of important shrimp fisheries.

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**Citations**

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Map

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Figure 1. Map of the Puget Sound and it’s sub-basins. The approximate location of the Port Madison Trawls is marked by a red star. Figure modified from an original: creative commons, “Map of Puget Sound and its main basins”, user “Pfly”



Figure 2. Contour map of the bathymetry of Port Madison. Starting and ending locations of the four trawls are marked in green. Figure taken from: Port Madison, Puget Sound SOP.

Graphical user interface

Description automatically generatedFigure 3. Boxplots of the three Oceanic Niño Index phases compared to the combined aggregate catch per unit effort (# shrimp/m2) of all species as well as the five individual species analyzed. Letters above each boxplot indicate statistically significant differences.

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Figure 4. Raincloud plot of combined aggregate catch per unit effort (#shrimp/m2) across the three Oceanic Niño Index phases and across all shrimp species. Box and whisker plots below each ‘cloud’ show quartiles. Clouds help illustrate the variability and many outliers in the data.

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Figure 5. Boxplots of the combined aggregate catch per unit effort (# shrimp/m2) of all species across all years of the study (top). Boxplots of the combined aggregate catch per unit effort (# shrimp/m2) of all species across all years of the study at deeper depths(middle). Boxplots of the combined aggregate catch per unit effort (# shrimp/m2) of all species across all years of the study at shallower depths(bottom).

Table 1. Catch numbers for the combined aggregate of all shrimp species and the five species analyzed.

|  |  |
| --- | --- |
| **species** | **total catch** |
| *Crangon alaskensis* | 5,393 |
| *Pandalopsis dispar* | 1,172 |
| *Pandalus eous/jordani* | 7,522 |
| *Pandalus danae* | 1,035 |
| *Pandalus platyceros* | 4,471 |
| *all species sampled* | 22,070 |

Table 2. Catch per unit effort (CPUE)(# shrimp/m2) for the combined aggregate of all shrimp species and the five species analyzed for each of the Oceanic Niño Index (ONI) phases. Letter denote statistically significant differences in catch per unit effort between the other ONI phases.

|  |  |  |  |
| --- | --- | --- | --- |
| **species** | **La Niña CPUE** | **no signal CPUE** | **El Niño CPUE** |
| *Crangon alaskensis* | 0.013 a | 0.017 a | 0.021 a |
| *Pandalopsis dispar* | 0.007 a | 0.015 a | 0.023 a |
| *Pandalus eous/jordani* | 0.018 a | 0.052 ab | 0.078 b |
| *Pandalus danae* | 0.002 a | 0.007 a | 0.019 a |
| *Pandalus platyceros* | 0.008 a | 0.021 a | 0.072 b |
| *all species sampled* | 0.012 a | 0.021 a | 0.035 b |

Table 3. Results of Linear mixed effects model. Random effects in the model were: Time of day of sampling (afternoon, evening, night, early morning, and morning) and sampling depth (10m, 25m, 50m, and 70m). Fixed effects in the model were the Oceanic Niño Index phase (El Niño, La Niña, or no signal). Estimate indicates the direction of the trend for each fixed effect. P values ≤ 0.05 were considered significantly different. The “lmer” function within the R package “lmerTest” was used to run the model. Asterisks are used for quick reference to denote statistical significance. The following formula was used in the model:

*Linear mixed effects model = shrimp CPUE ~ Oceanic Niño Index phase(****fixed****) + (1|sampling depth(****random****) + (1|time of day(****random****))*

|  |  |  |
| --- | --- | --- |
| **Fixed Effects (ONI)** | **estimate** | **p value** |
| La Niña | -0.024504 | 0.000004\* |
| no signal | -0.015565 | 0.000619\* |
| El Niño | 0.030535 | 0.004667\* |