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Recent trends in paralytic shellfish toxins in Puget Sound, relationships to climate, and capacity for prediction of toxic events

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ABSTRACT

Temporal and spatial trends in paralytic shellfish toxins (PSTs) in Puget Sound shellfish and their relationships with climate are investigated using long-term monitoring data since 1957. Data are selected for trend analyses based on the sensitivity of shellfish species to PSTs and their depuration rates, and the frequency of sample collection at individual sites. These criteria limit the analyses to the shellfish species *Mytilus edulis* at 20 sites from 1993 to 2007. Blue mussel toxicity is highly variable, but typically exceeds the regulatory limit for human consumption from July to November annually, with most closures occurring early in fall. Using blue mussel data only, we find no robust evidence to suggest that the frequency, magnitude, duration, or geographic scope of PST events in Puget Sound increased between 1993 and 2007. However, there is a significant basin-wide trend for closures to occur earlier in the year. There are no significant correlations between annual indices of mussel toxicity and aspects of the local and large-scale climate. Case studies of daily variations in local environmental factors leading up to exceptionally toxic events identify a combination of conditions that generally precedes most closures from 1993 to 2007. These results suggest that periods of warm air and water temperatures and low streamflow on sub-seasonal timescales may facilitate toxin accumulation in mussels. No relationships were found between water residence times in the surface layer and either streamflow or mussel toxicity. Recommendations are made for future monitoring to improve forecasting of PST risks in Puget Sound, an important region for recreational, commercial, and tribal subsistence shellfish harvesting.

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1. Introduction

Paralytic shellfish toxins (PSTs) are a suite of toxins produced by species of harmful marine dinoflagellates of the genus *Alexandrium*. PSTs, the most potent being saxitoxin, block the conductance of nerve signals by interfering with the sodium channels of excitable cells, thus causing neuromuscular paralysis (Narahashi and Moore, 1968). Like many other dinoflagellates, *Alexandrium* is known to thrive when the water column is vertically stratified and when water temperatures are warm (Nishitani and Chew, 1984). During blooms of *Alexandrium*, shellfish concentrate the toxins in their tissues from the large volumes of water they filter when feeding. We use the word "bloom" here to describe an accumulation of cells at sufficiently high densities to cause concentrations of PSTs in shellfish tissues to exceed the regulatory limit for human consumption. This could be as few as 10 cells ml^{-1} (Nishitani and Chew, 1984). A "bloom" can therefore result from hydrographic processes retaining and concentrating *Alexandrium* cells in a particular location or from in situ growth.

Consumption of contaminated shellfish produces a condition known as paralytic shellfish poisoning (PSP; Gessner and Middaugh, 1995). The first documented cases of PSP in Washington State are from 1942 when the consumption of toxic clams and mussels from the Strait of Juan de Fuca resulted in three fatalities (Quayle, 1969). Nearby on the central coast of British Columbia, four cases of PSP and one fatality were documented in 1793 (Vancouver, 1793). It is generally accepted that blooms of *Alexandrium* in this region are not recent phenomena and that PSTs have been present in the waters off the northwest coast of North America for centuries (Horner et al., 1997).

The presence of PSTs in Washington State coastal waters, including Puget Sound, has been attributed to the species *Alexandrium catenella* (Whedon & Kofoid) Balech. Few direct observations of *A. catenella* cell concentrations exist from this

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region to examine trends in distribution and abundance. However, the Washington State Department of Health (WDoH) monitors for PSTs in shellfish tissues as part of their Biotoxin Monitoring Program. These records reliably date back to 1957, representing one of the longest historical records of PSTs in the United States. Observations of shellfish toxicity are useful because they integrate much of the spatial and temporal variations in PSTs in the water column and can indicate some aspects of *A. catenella* bloom dynamics (Bricelj and Shumway, 1998). However, care should be taken to avoid using shellfish toxicity (or PST event) interchangeably with *Alexandrium* cell density (or harmful algal bloom) as this relationship is complex, largely due to the differing rates of toxin accumulation and depuration by different species of shellfish.

Temporal trends in shellfish toxicity and relationships with climate have mostly been explored on a qualitative level in Puget Sound (e.g., Determan, 1998; Ebbesmeyer et al., 1995; Erickson and Nishitani, 1985; Nishitani and Chew, 1984; Norris-Nishitani et al., 1979; Postel et al., 2000; Rensel, 1993; Saunders et al., 1982; Trainer et al., 2003). A study of decadal patterns of shellfish toxicity indicated that the frequency, magnitude, and geographical scope of PSTs in Puget Sound have increased since the 1950s (Trainer et al., 2003), concomitant with an apparent worldwide increase in the occurrence of harmful algal blooms (Hallegraeff, 1993).

Other studies suggest relationships between shellfish toxicity and large-scale patterns of climate variability (Ebbesmeyer et al., 1995; Erickson and Nishitani, 1985). For example, a shift in the Pacific Decadal Oscillation (PDO) from cool to warm phase in 1977 was locally manifested by persistently warmer air and water temperatures and reduced precipitation and streamflow in the Puget Sound region (Ebbesmeyer et al., 1995; Mantua et al., 1997). This is thought to have contributed to the record levels of PSTs observed in mussels in 1978 and to the spread of *A. catenella* into Whidbey and Main basins (Erickson and Nishitani, 1985; Trainer et al., 2003). However, recent enumeration of cysts from sediment cores suggests *A. catenella* was present in Whidbey basin at least 2 decades prior to this incident (Cox et al., 2008). A relationship between warm phases of the El Niño Southern Oscillation (ENSO, hereafter El Niño) and exceptionally toxic events in Puget Sound, the outer coast of Washington State, and the inland waters of British Columbia has also been suggested (Erickson and Nishitani, 1985), and the retention of PSTs by butter clams, *Saxidomus giganteus*, in an embayment of Puget Sound has been linked to warm/dry climate regimes on decadal timescales (Ebbesmeyer et al., 1995). Rigorous and quantitative analyses are required to determine the statistical significance of these relationships and to develop predictive models of shellfish toxicity.

The mechanisms for these large-scale climate variations to increase shellfish toxicity in the Puget Sound region have not been clearly identified. One hypothesis was that warmer air temperatures and reduced winds that are generally associated with El Niño events lead to prolonged periods of increased water temperatures and thermal stratification of the water column (Erickson and Nishitani, 1985), favoring blooms of *A. catenella* over non-flagellated phytoplankton species. However, a recent assessment of climate influences on Puget Sound oceanographic properties found that El Niño events do not typically cause significant warming or stronger vertical stratification of the water column during summer and fall when shellfish toxicity from *A. catenella* is most commonly observed (Moore et al., 2008). Aspects of the local climate, such as air temperature and streamflow, were found to be more important in determining oceanographic variability in Puget Sound rather than large-scale climate variations like ENSO (Bos et al., 2005; Moore et al., 2008).

The skill and lead times for forecasting shellfish toxicity will be strongly determined by the robustness of relationships with local environmental factors and certain aspects of the large-scale climate. In our analyses, we define local environmental factors to be specific to the Puget Sound basin and to typically vary on daily to seasonal timescales, whereas large-scale climate patterns are hemispheric-scale variations that typically occur on interannual to interdecadal timescales. If PST events are strongly driven by variations in local environmental factors, then advanced warning of shellfish toxicity will be limited by the same factors that limit the prediction of local weather conditions. In contrast, if large-scale climate variations are well correlated with PST events, then advanced warning of shellfish toxicity may be extended. For example, predictability of ENSO variations is possible at lead times up to at least 1 year (Cane et al., 1986).

This study was driven by the desire to better understand PST variations in Puget Sound shellfish and the influence of climate. Specific aims were to apply quantitative statistics to determine (1) potential increases in the frequency, magnitude, duration, and/or geographical scope of PST events, (2) possible relationships between shellfish toxicity, local environmental factors, and aspects of the large-scale climate, and (3) the capacity for predicting PST events. We use a subset of PST observations from a single shellfish species (the blue mussel, *Mytilus edulis*) with continuous and long-term records from the same locations to examine temporal and spatial patterns of variability at sub-seasonal to interannual timescales.

2. Study area

Puget Sound is a deep, fjord-type estuary covering an area of 2330 km^2 in the Pacific Northwest region of the United States (Fig. 1). A double sill at the entrance (i.e., Admiralty Inlet) separates it from the Strait of Juan de Fuca. Whidbey, Main, and Hood Canal basins are the three main branches of Puget Sound (Thomson, 1994). The shallower South Sound is highly branched with numerous finger inlets and is separated from Main basin by a sill at Tacoma Narrows. This study also examines PST variations to the north of Puget Sound in North and Northwest basins; regions encompassing the San Juan Islands and part of the Strait of Georgia, and the southeastern boundary of the Strait of Juan de Fuca, respectively.

Flow within Puget Sound is dominated by tidal currents reaching amplitudes of $\sim$1 m s^{-1} at Admiralty Inlet, and reducing to $\sim$0.5 m s^{-1} in the Main basin (Lavelle et al., 1988). The sub-tidal component of flow reaches $\sim$0.1 m s^{-1} and is driven by density gradients arising from the contrast in salty ocean water at the entrance to Puget Sound and freshwater from river inflows (Lavelle et al., 1988), and by surface winds (Matsuura and Cannon, 1997). Wind-driven flow is strongest in the upper 10 m of the water column, but under weakly stratified conditions can influence currents at depths to 100 m. Annual maxima in freshwater inflows result from periods of high precipitation and snowmelt, with the Skagit River accounting for the majority (Cannon, 1983). The sub-tidal circulation pattern mostly consists of a two-layered flow in Whidbey, Main, and Hood Canal basins, with fresher water flowing northward and exiting the basins at the surface and saltier water flowing southward and entering at depth (Ebbesmeyer and Cannon, 2001). Upwelling at the Tacoma Narrows sill and the absence of major river inflows results in lesser stratified waters in South Sound compared to the other basins, but surface waters generally continue to flow northward and deeper waters flow southward.

3. Shellfish toxicity data

A Biotoxin Monitoring Program for shellfish was first established by the WDoH in the early 1930s. Monitoring efforts initially focused on commercially important species such as the Pacific

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