Harmful Algae 10 (2011) 521–529

Contents lists available at ScienceDirect

Harmful Algae

journal homepage: www.elsevier.com/locate/hal

# Past trends and future scenarios for environmental conditions favoring the accumulation of paralytic shellfish toxins in Puget Sound shellfish

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ARTICLE INFO

*Article history:*
Received 18 December 2010
Received in revised form 4 April 2011
Accepted 4 April 2011
Available online 15 April 2011

*Keywords:*
*Alexandrium catenella*
Climate change
Harmful algal bloom window of opportunity
Paralytic shellfish toxins
Paralytic shellfish poisoning
Puget Sound

ABSTRACT

The risk of harmful algal blooms (HABs) of the dinoflagellate *Alexandrium catenella* in Puget Sound, Washington State, can be assessed by identifying and predicting climate and environmental conditions that are favorable for bloom development and the accumulation of paralytic shellfish toxins (PSTs) in shellfish. When these favorable conditions occur in combination, a harmful algal bloom window of opportunity (HAB-WOO) exists for *A. catenella*. The original HAB-WOO was identified by Moore et al. (2009) for the time period 1993–2007. In general, it showed that warm air and water temperatures, low streamflow, low winds, and small tidal variability precede PST events. Here, we use the HAB-WOO model to examine (i) changes in the annual HAB-WOO duration over the period from 1967 to 2006, and (ii) the potential effect of future climate change on HAB risk through the late 21st century. The annual HAB-WOO duration increased between 1978 and 2006, as did the frequency and geographic extent of PST events. Two step-like changes occurred in 1978 and 1992 with higher annual values attained by the HAB-WOO compared to previous years. The 1978 step change may be related to the 1977 reversal of the Pacific Decadal Oscillation from cool to warm phase. Climate change projections from global climate models and regionally downscaled climate models for the Pacific Northwest are used to evaluate scenarios for the future HAB-WOO. Under a moderate greenhouse gas emissions scenario (i.e., A1B), the annual HAB-WOO for *A. catenella* in Puget Sound is projected to increase by an average of 13 days by the end of the 21st century. Furthermore, the annual HAB-WOO may begin up to 2 months earlier in the year and persist for up to 1 month later in the year compared to the present day. This research provides managers, health authorities, and shellfish growers in Washington State with critical information for anticipating climate impacts on toxic HABs in the Pacific Northwest now and in a future warmer climate.


## 1. Introduction

Puget Sound is a deep, fjord-type estuary in the Pacific Northwest region of the United States that supports extensive recreational, commercial, and tribal subsistence harvesting of shellfish (Fig. 1). The Sound covers an area of 2330 km$^2$and has an average depth of 62 m, but depths exceed 200 m in the Main Basin (McGary and Lincoln, 1977). Flow within Puget Sound is dominated by tidal currents reaching amplitudes of $\sim$1 m s$^{-1}$ where it opens to the Strait of Juan de Fuca, and reducing to $\sim$0.5 m s$^{-1}$ to the south 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 between 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). This pattern of flow is mostly two-layered with fresher water flowing northward and exiting the Sound at the surface and saltier water flowing southward and entering at depth (Ebbesmeyer and Cannon, 2001). Wind-driven flow is strongest in the upper 10 m of the water column, but under weakly stratified conditions can influence currents to depths of 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).

Shellfish in Puget Sound can become contaminated with toxins produced by harmful algal blooms (HABs) that predominantly occur during the summer. One such HAB species is the marine dinoflagellate *Alexandrium catenella* (Whedon & Kofoid) Balech. *A. catenella* produces a suite of potent neurotoxins that are

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1568-9883/$ – see front matter 
doi:10.1016/j.hal.2011.04.004

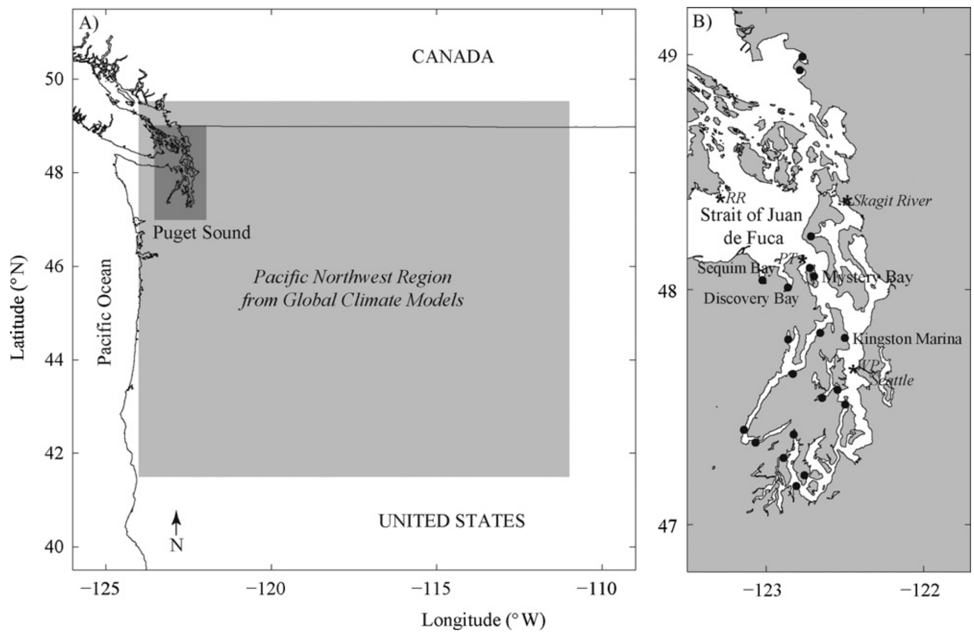


**Fig. 1.** Map showing (A) the Pacific Northwest region between 124–111°W and 41.5–49.5°N that is used to calculate average air temperature and precipitation values from global climate models and (B) the locations of the Washington State Department of Health's blue mussel monitoring stations in Puget Sound and locations where environmental parameters comprising the HAB-WOO are measured. These are Race Rocks (*RR*), Port Townsend (*PT*), the Skagit River, Seattle, and West Point (*WP*).

collectively known as paralytic shellfish toxins (PSTs). These toxins interfere with the sodium channels of excitable cells, thus blocking the conductance of nerve signals and causing neuromuscular paralysis (Kao, 1993). Human consumption of shellfish contaminated with PSTs causes a potentially life threatening condition called paralytic shellfish poisoning (PSP) (Kao, 1993). The first documented case of PSP in Washington State coastal waters was in 1942 when toxic clams and mussels harvested from the Strait of Juan de Fuca were consumed resulting in three fatalities (Quayle, 1969). In 1978, PSTs were first detected in shellfish from Whidbey Basin inside Puget Sound (Trainer et al., 2003). PSTs are now regularly detected in shellfish at concentrations that exceed the regulatory limit for human consumption (i.e., 80 μg STX-eq 100 $g^{-1}$ shellfish meat) in all of Puget Sound's basins except for Hood Canal.

This pattern of increasing HABs in Puget Sound is consistent with an apparent worldwide trend (Hallegraeff, 1993; Van Dolah, 2000; Glibert et al., 2005). Global increases in the frequency, duration, and geographic scope of some HABs have been attributed to anthropogenic nutrient enrichment of coastal waters (Anderson et al., 2002), introduction of non-indigenous harmful algal species via ships' ballast water (Hallegraeff and Bolch, 1991; Hallegraeff and Gollasch, 2006), and changing climate patterns (Moore et al., 2008b; Hallegraeff, 2010). In Puget Sound, the observed increase in shellfish closures due to blooms of *A. catenella* has been linked to increased population size in the greater Seattle area (Trainer et al., 2003) – but with no proven link to anthropogenic factors, the occurrence of water temperatures above 13 °C and stratified water column conditions (Nishitani and Chew, 1984), and warm and dry climate regimes associated with the warm phases of the Pacific Decadal Oscillation (PDO) (Ebbesmeyer et al., 1995; Moore et al., 2010) and El Niño Southern Oscillation (ENSO) (Erickson and Nishitani, 1985; but see Moore et al., 2009 and Moore et al., 2010 for an alternative interpretation).

Most recently, a specific combination of weather and environmental conditions was found to precede toxic events in Puget Sound (Moore et al., 2009). When this combination of conditions occurs, a harmful algal bloom window of opportunity (i.e., HAB-WOO) is said to exist for *A. catenella* and there is greater risk for shellfish becoming contaminated with PSTs. The combination of conditions that comprise the HAB-WOO was identified during the 20 days preceding 5 exceptionally toxic events that occurred over a 15-year time period from 1993 to 2007. These events were identified using historical data from monitoring conducted by the Washington State Department of Health (WDoH) and occurred in October 1996, September 2000, November 2002, September 2004, and September 2006. A window of opportunity for *A. catenella* was shown to occur on days when each of the weather and environmental conditions are within 1.5 standard deviations of the mean value for the 20 days leading up to the exceptionally toxic events. In general, warm air and water temperatures, weak winds, low stream flow and small tidal height variability favored the accumulation of PSTs in the blue mussel, *Mytilus edulis* (Moore et al., 2009). Larger annual HAB-WOOs mean that there are more days when weather and environmental conditions are favorable for toxic events.

There is mounting evidence to suggest that HABs will be impacted considerably by anthropogenic climate change (Moore et al., 2008b; Hallegraeff, 2010). Of great concern to human health is the expansion of harmful algal species to new locations that are unprepared for the potential impacts (Hallegraeff, 2010; Backer and Moore, 2011). There is a pressing need for climate to be considered and incorporated into future research, monitoring efforts, and policy development to mitigate the impacts of HABs and the toxins they produce. As highlighted by Hallegraeff (2010), studies are required that consider the complex interactions that are possible under future climate scenarios, rather than focusing on single environmental factors. The HAB-WOO model is unique because it can simultaneously examine the effect of changes to multiple environmental factors, while accounting for the influence of other environmental parameters that are known to be important for HABs.

The annual HAB-WOO was identified using a 15-year time period from 1993 to 2007 (Moore et al., 2009). If we assume that the same weather and environmental conditions that comprise the HAB-WOO will still be favorable for the development of toxic events in the future, this relationship can be used to assess future HAB-risks arising from toxic blooms of *A. catenella* in Puget Sound.