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The Pacific Northwest Harmful Algal Blooms Bulletin

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ABSTRACT

A bulletin communicating risk of toxic *Pseudo-nitzschia* blooms to shellfish harvest along the open coast of the Pacific Northwest region of the United States (the northeast Pacific Ocean spanning Washington and Oregon) is discussed. This Pacific Northwest Harmful Algal Blooms (PNW HAB) Bulletin is designed for shellfish managers with a focus on the razor clam fishery, but may also be informative to managers of the Dungeness crab fishery since domoic acid accumulation in crabs tends to lag accumulation in razor clams by a couple of weeks. The Bulletin complements beach phytoplankton monitoring programs by alerting coastal shellfish managers about adverse environmental conditions that could be conducive to a toxic *Pseudo-nitzschia* bloom. Beach monitoring programs are effective at determining when toxins have arrived at shellfish beaches, but a risk forecast based on near real-time biophysical information can provide managers with additional forewarning about potential future toxin outbreaks. Here, the approaches taken in constructing the risk forecasts, along with the reasoning and research behind them are presented. Updates to a historical PNW HAB Bulletin are described, as are the current workflow and the individual components of the updated Bulletin. Some successes and failures realized throughout the process are also pointed out for the benefit of the broader community. A self-assessment suggests that when the necessary data sources are available, the PNW HAB Bulletin provides an accurate forecast of risk associated with toxic *Pseudo-nitzschia* blooms. The Bulletin has proven beneficial to coastal shellfish managers by better informing decisions on sample collection, and harvest limits, openings, extensions, and closures.

1. Introduction

1.1. Background

In the California Current System (CCS) along the US west coast, certain species of the marine diatom *Pseudo-nitzschia* produce the neurotoxin domoic acid (Horner et al., 1997; Lelong et al., 2012; Bates et al., 2018). Domoic acid bioaccumulates in shellfish and, if consumed, can cause amnesic shellfish poisoning in seabirds, marine mammals, and humans (Wright et al., 1989; Bejarano et al., 2008). One of the first confirmed cases of domoic acid poisoning in the US occurred in Monterey Bay, California in September 1991 (see Bargu et al., 2012 for a possible 1961 event). In that event, seabirds including brown pelicans (*Pelicanus occidentalis*) and Brandt's cormorants (*Phalacrocorax penicillatus*) were poisoned after they consumed northern anchovies (*Engraulis mordax*) that had foraged on the highly toxic diatom *P. australis* (Buck et al., 1992; Fritz et al., 1992; Garrison et al., 1992; Work et al., 1993). One to two months later, domoic acid was detected in Pacific razor clams (*Siliqua patula*) and Dungeness crabs (*Cancer magister*) in Oregon and Washington (Wekell et al., 1994a, 1994b). That event closed recreational and commercial shellfish harvest but also spurred research and monitoring programs throughout the region.

Since the 1991 domoic acid event, similar outbreaks in Monterey Bay occur nearly every year (Bowers et al., 2018), and often result in numerous seabird (Shumway et al., 2003; Gibble and Hoover, 2018) and marine mammal strandings and deaths (Scholin et al., 2000; McCabe et al., 2016). Off the Pacific Northwest (PNW) coast (Fig. 1), domoic acid events are less regular, but often (though not exclusively) occur when ocean temperatures are elevated, such as during or just after El Niño events or during positive phases of the Pacific Decadal Oscillation (PDO; McCabe et al., 2016; McKibben et al., 2017). While some domoic acid events have been widespread along the PNW coast, toxic blooms of *Pseudo-nitzschia* are most often associated with specific initiation sites or local "hotspots" characterized by retentive currents. Documented examples include the Juan de Fuca eddy region off northwest Washington (Trainer et al., 2002, 2009; MacFadyen et al., 2005, 2008; Fig. 1),

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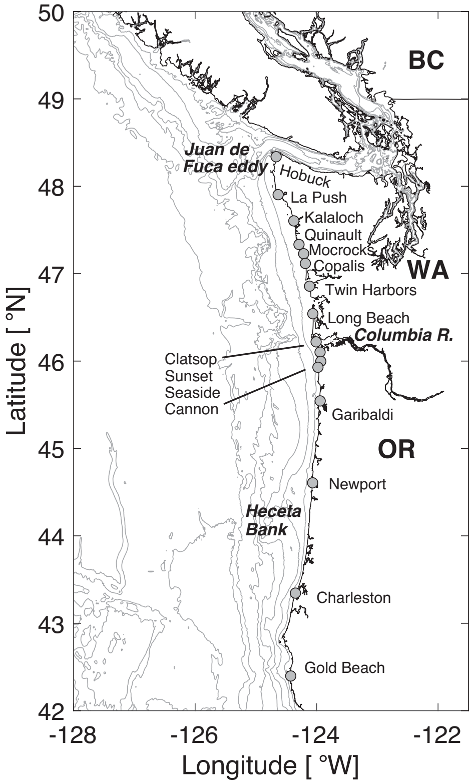

Fig. 1. Map of the Pacific Northwest coast of the United States. Gray lines represent the 50, 180, 500, 1000, 2000, 3000, and 4000 m bathymetry contours, and the coastline is drawn black. Washington (WA), Oregon (OR), and British Columbia (BC), Canada, are indicated as are numerous beach names and important regional features such as the Columbia River, Heceta Bank off central Oregon, and the Juan de Fuca eddy region off northwest Washington. The primary razor clam beaches span the coastline from Kalaloch Beach, Washington, to Clatsop/Cannon area beaches in northern Oregon.

Heceta Bank off central Oregon (Hickey et al., 2013; Fig. 1), Point Conception (Trainer et al., 2000) and Monterey Bay (Scholin et al., 2000) in California, and more recently, the region near Humboldt, California (McCabe et al., 2016; Trainer et al., 2020).

1.2. Regulatory limits on domoic acid concentration in shellfish

Bioaccumulation of domoic acid in shellfish varies dramatically across species. Mussels, such as the blue mussel (*Mytilus edulis*) have high depuration rates so that domoic acid is effectively purged from them in a matter of hours to days (Novaczek et al., 1991, 1992; Wohlgeschaffen et al., 1992; Krogstad et al., 2009; Mafra et al., 2010). Other shellfish such as the King scallop (*Pecten maximus*; Blanco et al., 2002) and the Pacific razor clam (Drum et al., 1993; Horner et al., 1993) can retain domoic acid for months, while Dungeness crab can remain toxic for weeks (Lund et al., 1997). Dungeness crab is the most lucrative seafood fishery on the US west coast, worth more than $170 million annually in ex-vessel value (Pacific States Marine Fisheries Commission Dungeness Crab Report, 2014). Pacific razor clams are also highly prized throughout the PNW, generating an estimated $24 million annually in recreational digger expenditures (2008 dollars; Dyson and Huppert, 2010). Shellfish harvest closures resulting from domoic acid events influence many sectors of the local economy and are known to impose additional negative sociocultural impacts (Weir et al., 2022; Kourantidou et al., 2022). The toxicity of domoic acid and the low depuration rates of these two regionally important species (Dungeness crab and Pacific razor clams) necessitate comprehensive monitoring programs to ensure public safety and further mitigate negative impacts to communities.

Federal regulatory limits on the concentration of domoic acid in shellfish determine whether harvest is allowed. The domoic acid threshold for shellfish meat tissue (including razor clams and Dungeness crab) is 20 ppm, whereas Dungeness crab viscera has a regulatory limit of 30 ppm (US Food and Drug Administration, 2022; Wekell et al., 2004). In Washington, shellfish samples are collected by the Washington Department of Fish and Wildlife (WDFW) and local Tribal Nations and sent to the Washington State Department of Health (WDOH) for domoic acid analysis. In Oregon, the Oregon Department of Agriculture (ODA) conducts the shellfish toxin analyses on samples collected by the Oregon Department of Fish and Wildlife (ODFW). Once available, shellfish domoic acid concentration results are quickly reported back to WDFW, ODFW, and the numerous Tribal Nations who co-manage commercial, public, and tribal subsistence shellfish harvests in their respective states and jurisdictions. Beaches with shellfish domoic acid concentrations over the regulatory limits are closed to harvest.

1.3. Shellfish harvests in Washington and Oregon

In Washington, beaches remain closed to public recreational razor clam harvest until sanctioned harvests, or "openers", are approved by WDOH and WDFW (WDOH, 2023; WDFW, 2023). These harvest periods are scheduled around favorable spring tides during fall, winter, and spring months. Tribal harvests typically coincide with public state harvest periods; one primary exception that occurs prior to public recreational harvests is an annual ceremonial dig in mid to late August by the Quinault Indian Nation (e.g., Kourantidou et al., 2022). Aside from an annual summertime conservation closure period for spawning and settlement at Clatsop area beaches (July 15-September 30), Oregon razor clam harvests generally remain open throughout the year unless shellfish domoic acid concentrations, or other factors, dictate area closures (ODA, 2023; ODFW, 2023). In other words, Oregon beaches are routinely open for razor clam harvest and managers look ahead to potential closures, whereas in Washington, managers open beaches for

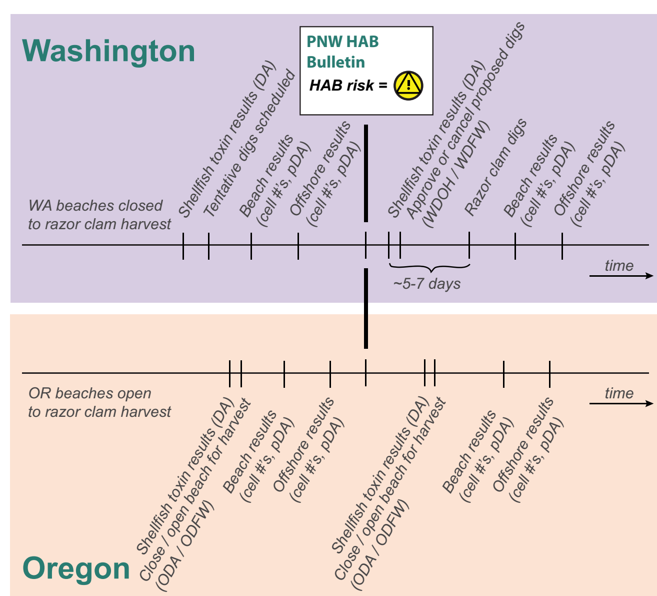

Fig. 2. Schematic of a typical series of events leading up to razor clam harvests in both Washington and Oregon and how the PNW HAB Bulletin fits into the decision-making process by coastal shellfish managers. The specific sequence of events shown on the timeline can change depending on management needs prior to each harvest opening or closure. The following abbreviations are used: cell concentrations (cell #'s), domoic acid (DA), and particulate domoic acid (pDA).

razor clam harvest on a short-term basis (Fig. 2). The commercial Dungeness crab harvest season in Oregon and Washington typically opens December 1 or later, so that it dovetails nicely with the winter razor clam season.

From a risk assessment perspective, this dichotomy in management approaches between Washington and Oregon could be seen to present some difficulty for any single forecast seeking to satisfy both operational modes (Fig. 2). However, since Washington managers seek risk predictions pertaining to scheduled razor clam digs, and Oregon mangers look for "adverse conditions" alerts, aligning risk forecasts with pending digs generally works well for both states. Since the risk forecasts that are discussed herein target razor clam digs, they are also informative to managers of the Dungeness crab fishery; toxification of crabs typically lags that of razor clams by a couple of weeks (D. Ayres, pers. comm.).

1.4. Beach monitoring

To assist shellfish managers in Washington to develop a better understanding of regional HABs a formal collaboration among state, tribal, federal and academic researchers and managers, named the Olympic Region Harmful Algal Bloom (ORHAB) Partnership (https://orhab.uw.edu/; Trainer and Suddleson, 2005), was initiated in 1999. The ORHAB Partnership established a comprehensive monitoring and research program that routinely samples beaches for HAB cells, including *Pseudo-nitzschia, Alexandrium*, and *Dinophysis*, as well as particulate (cellular) domoic acid concentrations. In 2003, ORHAB was successfully transitioned to dedicated state funding via a surcharge on Washington State recreational shellfish licenses. An analogous beach phytoplankton monitoring program is currently operated by ODFW in Oregon, but to date this program has not received sustained support.

These beach phytoplankton and shellfish monitoring programs serve to alert managers about HABs and domoic acid events that are active and beginning to impact shellfish, thereby providing managers with valuable forewarnings. Nevertheless, there is a need for a forecast that can provide coastal managers with additional advance warning about potential HAB events prior to their arrival at shellfish harvesting beaches.

1.5. A domoic acid risk forecast - the PNW HAB Bulletin

An early-warning system referred to as the Pacific Northwest Harmful Algal Blooms Bulletin, hereafter PNW HAB Bulletin, or Bulletin for short, aims to complement beach monitoring programs by alerting coastal shellfish managers about adverse environmental conditions that could be conducive to toxic algal bloom development and/or a toxic bloom's imminent arrival at shellfish beaches. The PNW HAB Bulletin focuses on *Pseudo-nitzschia* blooms and, in support of the razor clam and Dungeness crab fisheries, provides a domoic acid risk assessment to state and tribal co-managers in Washington and Oregon. Although beach monitoring programs are extremely effective at determining when toxins have arrived at shellfish beaches, a risk forecast can provide managers with additional warning about potential future HAB events. The Bulletin, and the early warnings it provides, better inform managers' mitigative actions, such as early harvest or increased harvest limits in anticipation of potential HAB events, or even selective openings in management areas or beaches. As discussed below, it is not uncommon for managers to collect additional samples prior to possible harvest openings based on information provided in the Bulletin.

1.6. Broader context

In the US, a body of regional HAB forecasts are operated by the NOAA National Centers for Coastal Ocean Science (NCCOS; NOAA NCCOS, 2023) with the aim of alerting coastal managers to potential HABs prior to negative impacts. These include forecasts for *Karenia brevis* in the Gulf of Mexico and Florida (Stumpf et al., 2003, 2009); *Alexandrium* spp. in the Gulf of Maine (McGillicuddy et al., 2011); and cyanobacteria in Lake Erie (Wynne et al., 2013). The Southern California Coastal Ocean Observing System (SCCOOS) California HAB Bulletin (SCCOOS, 2023; Anderson et al., 2016) and the PNW HAB Bulletin are in pre-operational status.

A similar, multinational system of HAB forecasting bulletins also exists throughout the European Atlantic (including Scotland, Ireland, England, France, Spain, and Portugal) in support of the aquaculture industry (Davidson et al., 2016). Maguire et al. (2016) provide a concise overview of those efforts along with example bulletins; more recent updates are discussed in Fernandez-Salvador et al. (2021). While the details of each regional approach differ both in the US and in Europe, most rely on the same basic ingredients: in situ samples, a variety of models, and strong partnerships.

In the remainder of this paper, we examine the PNW HAB Bulletin in detail. The goal is to present this regional forecast Bulletin to a broader community, highlighting the approaches taken and some of the successes and failures experienced to date, so that they may inform related efforts in other regions. We begin by briefly documenting the history of the PNW HAB Bulletin before moving on to a description of its current, updated format. We then explain why each component is considered important in the regional HAB risk assessment. Accuracy of the recent series of updated Bulletins is also addressed, and documented examples of management responses to the Bulletin are described, before concluding with some potential elements for future improvement.

2. Origin of the PNW HAB Bulletin

The PNW HAB Bulletin originated in the mid 2000′s as a grassroots collaboration between scientists at the NOAA Northwest Fisheries Science Center, the University of Washington, and state and tribal shellfish managers with funding from the Centers for Disease Control and Prevention. This original Bulletin focused exclusively on the coast of Washington State, as no beach phytoplankton monitoring program existed in Oregon at that time. The fundamental premise behind the Bulletin was that with monitoring of *Pseudo-nitzschia* cells and particulate domoic acid concentrations realized through Washington's ORHAB Partnership, researchers could combine knowledge of regional oceanographic dynamics with weather forecasts to inform coastal shellfish managers of the potential for a domoic acid outbreak (Fig. 3). Openings and closing of shellfish harvests would still adhere to established federal regulatory thresholds on shellfish domoic acid concentrations, but the Bulletin would provide managers with forecasts of risk. Through those risk assessments an increased understanding of the conditions that lead to elevated risk would be conveyed, meaning that managers could get a step ahead on certain mitigative actions and avoid costly shellfish recalls. A vital element in the success of the Bulletin was the cross-team education of managers and researchers that occurred during ORHAB meetings—this education allowed researchers to design the Bulletin for managers' needs as well as position managers to better understand Bulletin figures and text. Bulletin development and current status has been a result of many years of both federal and state government contracts and grants focused on HABs as well as regional ocean currents, nutrient supply, and plankton blooms.

The original Bulletin relied on many of the same key metrics that are utilized in the current Bulletin: *Pseudo-nitzschia* cell abundances at Washington beaches, divided into small and large cell morphologies; recent local wind and seasonal wind metrics; stream flow of the Columbia River, a primary freshwater source in the region; surface ocean currents as measured by a network of high frequency (HF) radar antenna; output from numerical ocean models; and local atmospheric forecasts (e.g., Fig. 3). Each of these elements informed researchers and managers about the atmospheric, and physical and biological oceanographic states. These factors were examined and consolidated into a single page Bulletin that communicated a forecast of risk. Risk of a HAB was categorized in three stages: low, medium, and high, colored green, yellow, and red, respectively, and was assigned based on subject-matter

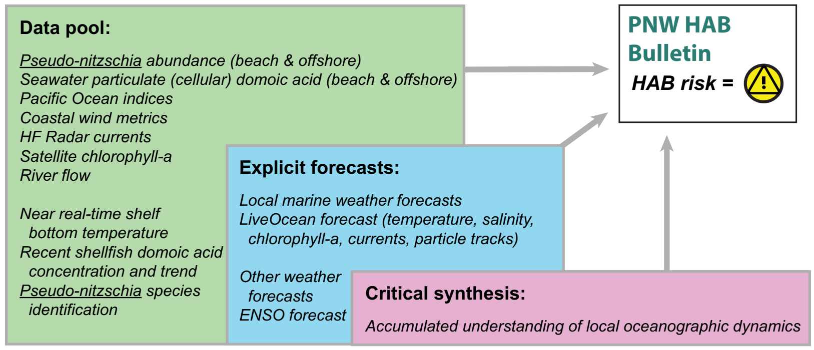

Fig. 3. Components of the risk assessment provided in the current form of the PNW HAB Bulletin.

expert opinion. As discussed in the following section, each of the aforementioned key elements provide information on the state of the coastal ocean and all of them have been retained in the updated version of the Bulletin.

3. Updating the PNW HAB Bulletin

3.1. Simple design

A series of dedicated research projects have led to improved understanding of *Pseudo-nitzschia* HABs in the PNW (Trainer et al., 2002; 2009; MacFadyen et al., 2005, 2008; Hickey et al., 2005, 2013). With support for reintroduction of the PNW HAB Bulletin through a NOAA Monitoring and Event Response for Harmful Algal Blooms Research grant in 2016 came an opportunity for its redesign and its expansion to cover both Washington and Oregon. An initial pilot layout, molded largely after the historical Bulletin but with some enhancement and new elements, was provided to regional shellfish managers in spring 2017. Immediately after that pilot redesign, researchers met with managers for feedback on the design and to solicit their ideas for improvements. At this time, a two-page layout was prescribed along with the essential graphics used in the current Bulletin (Fig. 4).

The basic motivation behind the Bulletin is to provide regional shellfish managers with the same information that researchers use in making an assessment of risk, hence the multiple graphics displayed in the Bulletins (Fig. 4). Website-based versus portable electronic versions were considered throughout the redesign process. The simplicity of a portable electronic version and the ability to download and later access a Bulletin via a mobile device while traveling or while at remote field locations was deemed important. The vertical strip of "Summary" and "Forecast" text on the second page of the new Bulletin allows users accessing the Bulletin from a mobile device to easily scroll through the text in order to read the assessment along with any nuances.

3.2. Construction

Construction of the PNW HAB Bulletin makes use of a simple template in Adobe Illustrator, a graphics-editing program. Multiple graphics and text descriptions are consolidated into the two-page layout that is ultimately distributed to managers and stakeholders as a PDF document via email, similar to other HAB forecasting bulletins (e.g., Stumpf et al., 2003; Wynne et al., 2013; Maguire et al., 2016; Davidson et al., 2021). The Adobe Illustrator template itself retains static overview text and descriptions for each of the graphics, but has customized "Summary" and "Forecast" sections that get updated for each Bulletin. All graphics are also updated for each Bulletin. This is achieved by populating a specified folder with individual images that have standard file names and formats defined in the Adobe Illustrator template. In this way, once the folder has been populated with updated graphics, which may be generated using a variety of software platforms (e.g., Matlab, R, or Python), they automatically appear in the Adobe Illustrator document.

3.3. Communication

An important aspect of the PNW HAB Bulletin is that it facilitates informed communication between researchers and coastal shellfish managers. To date, generally four Bulletins are targeted for both spring and fall razor clam seasons, for an annual total of approximately eight Bulletins. They are typically produced every two to four weeks within a season and are scheduled to coincide with managers' decisions regarding pending razor clam digs (Fig. 2). In other words, Bulletins are released on a schedule. Clearly HABs may occur at any time, so specific "warnings" or "conditions update" communications by Bulletin researchers are also often utilized to inform managers outside of a scheduled Bulletin.

4. Components of the updated PNW HAB Bulletin

An overview of each element of the PNW HAB Bulletin, including a concise description of the relevant science justifying their inclusion, is provided below (Fig. 4).

4.1. Beach sampling data

Beach phytoplankton and domoic acid sampling programs in Washington and Oregon comprise the backbone of the PNW HAB Bulletin (Figs. 2, 4). In Washington, a number of beaches, from Long Beach in the south to Hobuck Beach and Neah Bay in the north, are actively monitored on a once- or twice-per-week basis by members of the ORHAB Partnership (Fig. 1). The ODFW phytoplankton program samples northern Oregon beaches, from Clatsop to Garibaldi, on a weekly basis, and select central and southern Oregon beaches (spanning Newport to Gold Beach) approximately every two weeks using the same protocols as ORHAB (Fig. 1). Water samples are collected for plankton identification including HAB species such as *Pseudo-nitzschia, Alexandrium*, and *Dinophysis*, and filtered for domoic acid analysis, performed by enzyme-linked immunosorbent assay (ELISA) if cell abundances reach certain thresholds (Trainer and Suddleson, 2005). For *Pseudo-nitzschia*, cells are enumerated in small and large size classes, which are distinguished using standard light microscopy, similar to other field monitoring programs (e.g., Cusack et al., 2016). More than 50,000 cells/L of large morphology or more than 1,000,000 cells/L of small morphology *Pseudo-nitzschia* cells lead to presumed increased risk (Table 1) and triggers particulate domoic acid testing. The reason for the size dependent thresholds is simple: large *Pseudo-nitzschia* cells can contain larger amounts of domoic acid than small cells. Large morphology *Pseudo-nitzschia* cells are thus associated with higher risk even though several of the large-sized species present in the region may not produce domoic acid. Although these thresholds may lead to false positives since not all species of *Pseudo-nitzschia* produce domoic acid

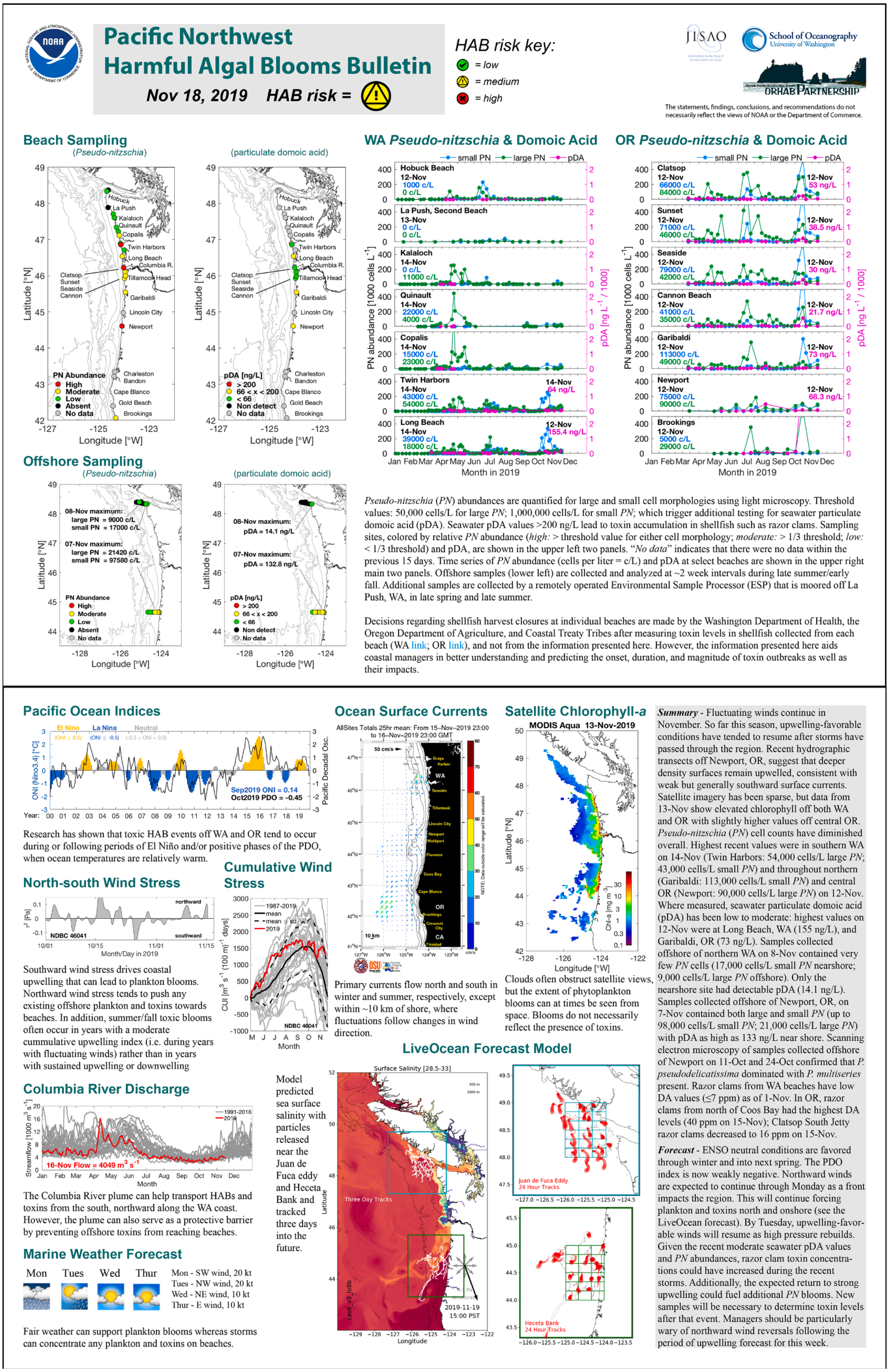

Fig. 4. An example of a PNW HAB Bulletin from 18-Nov-2019. The entire first page (upper half) is devoted to biological observations including *Pseudo-nitzschia* cell abundances and particulate domoic acid concentrations. A quick reference risk assessment (low, medium, high) is provided at the top of the page. The second page (lower half) consists of a number of environmental metrics as discussed in the text, and a weather and an ocean forecast with simulated particle tracks. Summary and Forecast text appear along the right side in the gray box.

Table 1
Elements used to assess risk of a future domoic acid event.

Metric type	Metric
Biological	
	Particulate (cellular) domoic acid >200 ng/L
	Domoic acid concentrations increasing in razor clams
	Detectable domoic acid in California mussels
	Presence of *P. australis*
	Presence of large size *Pseudo-nitzschia* >50,000 cells/L
	Presence of small size *Pseudo-nitzschia* >1,000,000 cells/L
Physical	
	Forecast northward winds or relaxations coupled with biological risk
	Forecast northward winds during established upwelling
	Weak along-shelf currents during established upwelling (retention)
	Columbia River plume tending south and off the shelf (barrier free)
	Seasonally weak summer winds (retention)
	El Niño conditions
	Positive Pacific Decadal Oscillation

(see below), managers have requested that these conservative thresholds be used. Once samples have been analyzed for particulate domoic acid concentrations, values in excess of ~200 ng/L denote elevated risk (Table 1) since razor clams tend to accumulate domoic acid in their tissues when concentrations reach this level (Trainer and Suddleson, 2005).

These two beachside monitoring programs alert managers to developing and ongoing blooms of potential HAB species and particulate domoic acid concentrations. Multiple species of *Pseudo-nitzschia* have been documented in the PNW, including *P. australis, P. multiseries, P. fraudulenta, P. pungens, P. heimii, P. delicatissima, P. pseudodelicatissima, P. cuspidata*, and others (e.g., Trainer et al., 2009). This heterogeneity complicates risk predictions for several reasons: (1) not all *Pseudo-nitzschia* species produce domoic acid; (2) known domoic acid producers do not always produce the toxin; (3) species-level identification is difficult, requiring either molecular probes or expert analysis via scanning electron microscopy (SEM); and (4) multiple species are often present in water samples. In cases where accurate species identification would significantly aid the risk assessment in the Bulletin, sample aliquots are submitted to laboratories for species identification via SEM. Such species identification is often performed for beach samples and for offshore samples alike (see next section). However, since species identification is not yet a routine part of the monitoring program, results are not shown explicitly in graphics; these results are instead incorporated into the "Summary" and "Forecast" sections of the Bulletin. Although SEM is required to accurately identify the majority of *Pseudo-nitzschia* species, experienced taxonomists can often accurately identify the extremely large, and highly toxic, *P. australis* using standard light microscopy. Since *P. australis* usually produces domoic acid, its presence is always associated with presumed elevated risk (Table 1).

4.2. Offshore sampling data

Throughout the CCS, *Pseudo-nitzschia* HABs are known to initiate in specific offshore hotspots. The Juan de Fuca eddy off northern Washington (Trainer et al., 2002, 2009) and Heceta Bank off central Oregon (Hickey et al., 2013) are thought to be the two primary initiation sites in the Pacific Northwest (Fig. 1), although the region near Humboldt, California, has recently led to elevated domoic acid concentrations in southern Oregon (McCabe et al., 2016; Trainer et al., 2020). As beach samples provide knowledge of whether or not species of *Pseudo-nitzschia* and domoic acid have arrived at the coast, offshore samples help to determine whether toxic *Pseudo-nitzschia* are abundant at or near source locations, thereby enabling early warnings to both researchers and managers. In the event that domoic acid or toxigenic species are found offshore, researchers can use knowledge of the regional ocean circulation, as well as numerical weather and ocean circulation forecasts to determine whether or not toxigenic cells are likely to be transported to shellfish beaches in the foreseeable future.

Collaboration with the Makah Tribe and Quileute Tribe via the ORHAB Partnership has enabled samples to be collected by small boats offshore of northern Washington near the Juan de Fuca eddy hotspot in late summer and fall months. After collection, water samples are brought back to local laboratories and analyzed for *Pseudo-nitzschia* abundance and particulate domoic acid concentrations. As with beach samples, results then get reported to the ORHAB Partnership and are incorporated into the PNW HAB Bulletin. A similar collaboration exists with NOAA Northwest Fisheries Science Center and Oregon State University researchers who monitor the Newport Hydrographic Line (NHL) off Newport, Oregon (Fisher et al., 2015; Peterson et al., 2017). This transect is situated just north of the Heceta Bank hotspot that can harbor toxic *Pseudo-nitzschia* blooms (Hickey et al., 2013). In this case, researchers collect samples at NHL stations and they are analyzed for *Pseudo-nitzschia* abundance, particulate domoic acid concentrations, and, at times, species identification. Results are then shared and incorporated into upcoming releases of the Bulletin.

In recent years, a moored Environmental Sample Processor (ESP; Scholin et al., 2009; Doucette et al., 2009) has been deployed at the Northwest Association of Networked Ocean Observing Systems (NANOOS) Ćháʔba· mooring site off northwest Washington (Moore et al., 2021). This instrumentation is located on the outer shelf between the Juan de Fuca eddy and the coast, with deployments targeting the spring and fall razor clamming harvests. Early deployments quantified cell abundances of certain *Pseudo-nitzschia* species as well as particulate domoic acid concentrations, but more recent deployments have focused on quantifying domoic acid only. Results are updated in near-real time to the NANOOS Real-time HABs website (http://www.nanoos.org/products/habs/real-time/home.php) and, as with other offshore samples, are incorporated into the Bulletin.

4.3. Pacific ocean indices

Analyses of historical records of domoic acid concentration in razor clams and *Pseudo-nitzschia* HABs off Washington and Oregon have demonstrated that toxin outbreaks tend to occur during or just after periods of relatively warm ocean temperatures such as El Niño, or positive phases of the PDO (McCabe et al., 2016; McKibben et al., 2017). For this reason, the PNW HAB Bulletin also tracks these two Pacific Ocean indices (Figs. 3, 4; Table 1). It is worth noting that relationships between these metrics and toxic *Pseudo-nitzschia* blooms are not strong farther south off California where additional factors like the North Pacific Gyre Oscillation may play a role (Sekula-Wood et al., 2011; Smith et al., 2018). Such basin-scale metrics also cannot predict specific beaches or stretches of coast that may be subject to a toxic algal bloom. Rather, the recommendation to shellfish managers is that anomalously warm ocean conditions may signal an elevated background state of risk throughout the region. Background perceived risk levels are not lowered during La Niña periods nor during negative phases of the PDO. Although *Pseudo-nitzschia* HABs tend to occur during warm periods, they may also occur after such periods; the 1998 event appears to be one such example (e.g., McCabe et al., 2016). Similarly, domoic acid events have occurred during La Niña periods, such as the fall 2022 events in Oregon and Washington (e.g., PNW HAB Bulletin, 2022).

4.4. Coastal wind data and the marine weather forecast

The development and transport of phytoplankton blooms and their toxins are governed by oceanographic currents. In the PNW, and other coastal upwelling systems in general, the coastal currents, as well as the nutrients that are required for phytoplankton blooms, are primarily influenced by winds along the coast. Coastal winds are seasonal, generally blowing southward along the coast in summer and northward along the coast in winter. The southward winds are weaker and the northward winds are stronger than those at locations farther south in the

CCS (Hickey, 1979; 1989). Ultimately, this along-coast structure in the wind field means that currents and water properties are influenced by both local and remote winds, particularly during summer (Hickey et al., 2006; Connolly et al., 2014; Hickey et al., 2016). The predominantly southward summer winds force offshore surface transport and coastal upwelling of cold, salty, nutrient-rich water, whereas the northward winds that dominate in winter push surface flows northward and shoreward resulting in downwelling. Distinct seasonal transitions, referred to as the spring and fall transitions, mark the changes between the two primary states, and, as their names suggest, occur during spring and fall months (Huyer et al., 1979; Strub et al., 1987; Strub and James, 1988). During summer, winds vary on short time scales (3–10 days) in the PNW. Summer upwelling periods are often interrupted by wind relaxations or periods of northward winds that can reverse along-shelf currents, especially on the inner shelf (Hickey, 1989). Such along-shelf current reversals can occur in as little as 1–2 days (Hickey, 1989). Changes in cross-shelf flows, particularly in the surface Ekman layer, respond to wind variations much more quickly, on the order of a few hours (Winant et al., 1987; Lentz, 1992; Dever, 1997).

The shoreward surface layer transport that occurs during northward wind events has been shown to deliver plankton and any associated domoic acid that may exist offshore to beaches in the PNW (MacFadyen et al., 2005). As discussed earlier, two primary sites are known to seed toxigenic *Pseudo-nitzschia* blooms in the PNW: the Juan de Fuca eddy off northwest Washington (Trainer et al., 2002; MacFadyen et al., 2005, 2009), and Heceta Bank off central Oregon (Hickey et al., 2013). Both sites are defined by underlying topography that promotes retentive currents in summer. In the case of the Juan de Fuca eddy, research has demonstrated that downwelling winds in the summer season concentrate flows in the eddy region whereas upwelling winds allow more water from the eddy region to transit south along the Washington coast (MacFadyen and Hickey, 2010). Thus, under normal summer upwelling conditions, if a toxigenic *Pseudo-nitzschia* bloom exists at the Juan de Fuca eddy, streamers of domoic acid may flow south along the coast and a single storm, or series of storms, could then force the streamer(s) to shore (MacFadyen et al., 2005). Through these mechanisms, MacFadyen et al. (2008) concluded that summers with moderate cumulative upwelling wind stress (i.e. summers with fluctuating rather than persistent upwelling winds) may be more conducive to toxic *Pseudo-nitzschia* blooms in Washington. Fluctuating winds lead to more retention in the Juan de Fuca eddy, yet also allow domoic acid producing *Pseudo-nitzschia* to escape from the eddy and, in turn, be delivered to shellfish beaches (MacFadyen et al., 2008). A similar set of conditions could also apply to the flows at Heceta Bank, Oregon. Wind relaxations are known to lead to shoreward transport in general (Hamilton and Rattray, 1978; Farrell et al., 1991; Austin and Barth, 2002), and northward/onshore flows are well documented between Heceta Bank and the coast during wind relaxations and northward wind reversals (Barth et al., 2005; Hickey et al., 2013).

The PNW HAB Bulletin makes use of these results by tracking both the recent local wind stress spanning the previous two months, as well as the seasonal cumulative wind stress relative to past seasons (Figs. 2 and 3). With this information, researchers and managers can follow the recent wind history, including upwelling- and downwelling-favorable events, as well as its relative seasonal progression in order to estimate the likelihood of toxic *Pseudo-nitzschia* blooms existing at offshore initiation sites. When this information is coupled with relevant biological information and the regional marine weather forecast spanning the upcoming week, an estimate of future risk can be prescribed. Strong northward wind events in summer are associated with elevated risk and such risk is magnified when toxins or toxigenic species are known to exist in the environment (Table 1). Extensive periods of fluctuating winds are also associated with elevated risk, as changes in current direction cause enhanced retention and also subsequent release from HAB hotspots (Table 1), as described by MacFadyen et al. (2008). Moreover, fluctuating winds generally lead to coastal currents with less net along-shelf transport, and thus enhanced regional retention of water and plankton (Table 1). Such periods are identifiable in the Bulletin's cumulative wind stress graphic as extended durations having little cumulative change.

4.5. *Ocean current and temperature data*

In the PNW, *Pseudo-nitzschia* cells are typically found in near-surface water, with maximum abundance at 1–5 m depth (Trainer et al., 2009). Because of this near surface concentration, ocean currents measured by the existing HF radar network (currently spanning Oregon; Kosro, 2005) can provide additional insight on potential transport of *Pseudo-nitzschia* cells and domoic acid. Hickey et al. (2013) used HF radar currents to simulate the transport of particles off Oregon in spring 2005, and demonstrated that the toxic *Pseudo-nitzschia* cells that impacted southern Washington beaches at that time likely originated from Heceta Bank. In the present form of the PNW HAB Bulletin, particle-tracking experiments are routinely completed utilizing output from a regional ocean forecasting model (Section 4.8) rather than with HF radar currents. The HF radar currents are more commonly utilized to help confirm spring and fall transition states, to help visualize potential transport pathways, and as a way to assess the strength of coastal ocean currents (Figs. 3, 4; Table 1). Although not formally displayed in the Bulletin, we also routinely make use of data such as bottom temperature on the shelf from the regional Ocean Observatories Initiative mooring array (https://oceanobservatories.org/) or from ship-based sampling as a way to discern the depth and lateral extent of upwelling, an indication of the availability of nutrients for plankton blooms (Hickey et al., 2006; McCabe et al., 2015). These data also indicate whether or not seasonal transitions have occurred.

4.6. *River flow data*

South of Juan de Fuca Strait, the Columbia River provides the primary source of freshwater to the PNW (Hickey, 1989). Transport of *Pseudo-nitzschia* from offshore to shellfish beaches is complicated by the presence of the Columbia River plume, the strength and location of which are determined by seasonal river discharge, currents, and winds (Hickey et al., 2005; Figs. 3, 4). Prior research has suggested that density fronts associated with the Columbia River plume likely provide a barrier to the onshore transport of toxic cells when at least one branch of the plume is oriented northward (Hickey et al., 2005; Banas et al., 2009b).

As described by Hickey et al. (2005, 2013), during late summer and fall downwelling-favorable events, when regional currents remain southward, but the emerging Columbia plume flows northward on the inner shelf, the Columbia River plume can function as a barrier to the shoreward transport of an offshore toxic *Pseudo-nitzschia* bloom to the Washington coast. Such cells could, however, reach northern Washington beaches prior to the establishment of the newly forming Columbia River plume along the coast (see Fig. 9 of Hickey et al., 2013). During early spring events, when regional currents remain predominantly northward and river outflow is substantial, the Columbia River plume usually extends along the entire Washington coast. In those cases, the plume can facilitate the northward transport of toxic *Pseudo-nitzschia* cells from southern initiation sites such as Heceta Bank, Oregon (Hickey et al., 2013). A similar scenario could also potentially exist immediately after the transition to fall, although at that time of year outflow from the Columbia River is typically low, so that its importance is likely reduced in comparison to spring. Thus, depending on time of year, local wind and current direction, and the magnitude of river flow, the state of the Columbia River plume impacts risk assessments in the Bulletin because it may serve either as an inhibitor or a facilitator to the transport of toxigenic *Pseudo-nitzschia* blooms (Table 1).

4.7. Satellite ocean color data

Using an extensive data set collected aboard six dedicated research cruises spanning four years, Trainer et al. (2009) found satellite-derived remote sensing to be an unsuitable predictor for toxic *Pseudo-nitzschia* blooms off Washington. This contrasts remote sensing successes realized in other regions with other HAB species (e.g., Stumpf et al., 2003; Wynne et al., 2013; Sourisseu et al., 2016). *Pseudo-nitzschia* typically comprise only a small percentage of the phytoplankton community during a bloom (Olson et al., 2008), though blooms dominated by *Pseudo-nitzschia* have been documented (McCabe et al., 2016). Nevertheless, in situ chlorophyll-a concentrations were weakly but significantly correlated with *Pseudo-nitzschia* abundances, and high domoic acid concentrations or *Pseudo-nitzschia* abundances were never observed when in situ chlorophyll-a concentrations were low (Trainer et al., 2009). That is, low chlorophyll-a concentrations are likely indicative of an absence or a correspondingly low concentration of toxic *Pseudo-nitzschia* cells. While toxic *Pseudo-nitzschia* blooms cannot presently be estimated from satellite chlorophyll-a concentrations in the PNW, we are able to use satellite-derived data to discern regions where, and periods when, such blooms are unlikely (Figs. 3 and 4). This conditional finding was utilized successfully by Giddings et al. (2014) to reduce the number of false-positive domoic acid events predicted by their transport model. For the Bulletin, relatively low concentrations of satellite chlorophyll-a thus suggest lower risk of a domoic acid event. Elevated satellite chlorophyll-a concentrations alone, however, do not warrant an increased risk of toxic events.

4.8. LiveOcean forecast

A free-running (without data-assimilation) regional ocean forecasting model, termed LiveOcean (MacCready et al., 2021), is currently employed in the PNW HAB Bulletin to track particles for up to three days into the future (Figs. 3, 4). LiveOcean is based on the Regional Ocean Modeling System (ROMS; Shchepetkin and McWilliams, 2005) and is an outgrowth of a series of former hindcasting models focused on accurate reproduction of the Columbia River plume (Liu et al., 2009; Banas et al., 2009a,b; MacCready et al., 2009) and circulation in the Salish Sea (Sutherland et al., 2011). The model also predicts water properties (ocean salinity and temperature) and chlorophyll, all of which are used in the Bulletin to help assess HAB risk. Giddings et al. (2014) documented the hindcast model's effectiveness at accurately tracking HABs in the PNW. Stone et al. (2022) determined the optimal LiveOcean model beaching thresholds for use in forecasting *Pseudo-nitzschia* events.

A new forecast run is initiated automatically each day in LiveOcean. Output files, and a suite of graphics and animations, are produced and saved. For the Bulletin, particles are seeded in the two known offshore HAB initiation zones (the Juan de Fuca eddy and Heceta Bank) covered by the model domain and are tracked for the three-day span of the forecast. As with other forecasting bulletins (Wynne et al., 2013; Cusack et al., 2016; Pinto et al., 2016; Silva et al., 2016; Davidson et al., 2021), these particle-tracking forecasts are used in conjunction with the additional data sources and the weather forecasts to predict times and locations of potential beaching events. For example, given known toxin concentrations offshore, the LiveOcean forecasts assist researchers and managers to determine if, when, and which beaches may receive toxic cells. Forecast animations are updated daily so that shellfish managers can access them on the LiveOcean website (https://faculty.washington.edu/pmacc/LO/LiveOcean.html) as often as they wish. Importantly, this also allows users to follow predicted ocean conditions and particle beaching events outside of scheduled Bulletins.

4.9. Shellfish domoic acid concentration data

Graphics illustrating domoic acid concentration in shellfish are excluded from the PNW HAB Bulletin. Early in the process of redesigning the Bulletin this option was discussed at length with coastal managers. After all, it is the domoic acid concentration in shellfish that ultimately determines whether shellfish harvest at any given beach is open or closed. Increasing concentrations of domoic acid in razor clams and detectable concentrations of domoic acid in California mussels (*M. californianus*) serve as indicators of elevated risk (Table 1). Coastal shellfish managers closely track shellfish domoic acid concentrations and harvest decisions are made within hours in response to updated results (Fig. 2). The swiftness of those decisions leaves no time to incorporate updated shellfish domoic acid concentration data into Bulletins. Instead, effort is made for each Bulletin to be released to managers just prior to receiving the latest shellfish domoic acid results so that they may consider Bulletin recommendations alongside the updated shellfish domoic acid concentrations (Fig. 2). The Bulletin then provides additional data graphics, interpretations, and advice about the likelihood of increased shellfish domoic acid concentrations associated with *Pseudo-nitzschia* blooms in order to assist managers in their final decisions. Importantly, the Bulletin delivers the only data-based information on future spread, movement, and growth of toxigenic *Pseudo-nitzschia* blooms throughout active razor clam harvest periods.

4.10. Summary and forecast text

The "Summary" and "Forecast" text sections of the Bulletin provide a concise overview of observations and other relevant data since the last Bulletin was issued as well as contextual information related to the future outlook of risk of a domoic acid event. As alluded to previously, these sections also allow for the researchers to incorporate additional supplementary information, such as the results of *Pseudo-nitzschia* species analyses that are not yet a routine part of the Bulletin. Any nuances to the forecast are described herein. In some cases, the assigned Bulletin risk level applies for a few days into the future, but forecast uncertainty may necessitate higher risk at longer time horizons. Similarly, at times, risk is considered higher in one particular spatial area than in others, and such descriptions are detailed here.

Bulletin forecasts are currently the result of qualitative analyses by three regional subject-matter experts. The small number of researchers means that a consensus forecast can be arrived at efficiently, while also decreasing the potential for personal bias by any particular researcher. In practice, a draft Bulletin forecast is generated by a lead researcher one or two days in advance of a target release date, and after iterative discussion amongst the team of three, a final forecast is issued. No quantitative index is currently calculated to determine domoic acid risk levels. To do so would suggest that an explicit set of rules exists that define toxic *Pseudo-nitzschia* blooms. As described previously, many factors are deemed important in the regional HAB problem. Having stated that, and as described in detail throughout this section, a number of core elements do point toward elevated risk that Bulletin researchers often utilize. These factors are summarized in Table 1.

As a result of the complicated multidisciplinary nature of HABs, other HAB forecasting bulletins also rely on qualitative interpretation by subject-matter experts (Cusack et al., 2016; Davidson et al., 2021). As pointed out by Zador et al. (2017), such approaches allow for flexibility such as the rapid incorporation of new knowledge and data types, rather than needing to navigate the slow process of retooling and validating empirical or numerical approaches.

5. Assessment

5.1. Self-assessment

In a basic attempt to address whether or not the PNW HAB Bulletin and its associated communications provide accurate risk assessments, individual Bulletins, Bulletin communications, and their projected risk levels are listed by date in Table 2 along with domoic acid events or harvest closures that occurred within the region. Bulletin

Table 2
Summary of PNW HAB Bulletins and warning communications (denoted with an asterisk), their projected risk (individual and seasonal), and start dates and areas of increased domoic acid concentration in razor clams or harvest closures.

Season Year	PNW HAB Bulletin or Warning Date	Individual Risk Level	Seasonal Risk Level	Razor Clam Domoic Acid Increases or Harvest Closures
Spring 2017	27-Apr (*) 04-May	High High	Elevated	OR closures continued from 2016 04-May south, central WA closures
Fall 2017	19-Aug 26-Sep 25-Oct 21-Nov	Medium Medium Medium Medium	Elevated	25-Aug statewide OR increases 06-Nov north WA increases
Spring 2018	14-Mar 13-Apr 10-May 24-May	Medium Low Low Low	Low	02-Feb south-central OR closure
Fall 2018	03-Sep 20-Sep 04-Oct 18-Oct	Low Medium Medium Medium	Low	31-Aug south OR increases
Spring 2019	18-Mar 28-Mar 14-Apr 12-May	Medium Medium Medium Medium	Elevated	08-Mar north OR closure
Fall 2019	28-Aug 20-Sep 19-Oct 18-Nov	Medium Low High Medium	Elevated	16-Aug south OR closure expanded 01-Nov south central OR closure 13-Dec statewide OR closure
Spring 2020	25-Mar 21-Apr 04-May 19-May	Low Medium Low Low	Low	16-Mar central OR closure
Fall 2020	15-Aug 11-Sep 08-Oct 29-Oct (*)	High Medium Low High	Elevated	21-Oct statewide WA closure 22-Oct central OR closure 30-Oct north OR closure 20-Nov statewide OR closure
Spring 2021	11-Apr 21-Apr 09-May 20-May 07-Jun	Medium Medium Low Medium Medium	Low	None
Fall 2021	20-Aug 12-Sep 27-Sep 11-Oct 22-Oct (*)	Low Medium Medium Low High	Elevated	24-Nov south OR closure
Spring 2022	07-Apr 21-Apr 13-May 26-May	Low Low Low Low	Low	None
Fall 2022	04-Aug (*) 25-Aug 15-Sep 03-Oct 11-Oct (*) 27-Oct (*) 01-Nov	High Medium High High High High High	Elevated	10-Aug north WA increase 05-Sep central WA closure 16-Sep WA postponement 23-Sep north OR closure 30-Sep statewide OR closure 02-Nov statewide WA closure

communications include warning emails or phone calls to managers that were issued outside of scheduled Bulletins; these are denoted with an asterisk in Table 2. Individual Bulletin communications categorize risk in three states: low, medium, and high, as has been adopted in other HAB bulletins (e.g., Davidson et al., 2021). A seasonal risk level, categorized as "elevated" or "low", is also included in Table 2. Here, "elevated" risk was assigned to seasons having at least one individual high-risk rating or all medium ratings. The remaining seasons, having at least one low individual rating, were scored as "low" risk (Table 2). The right-most column of Table 2 lists the areas and start dates of harvest closures resulting from domoic acid, or events with increasing shellfish domoic acid concentrations that may not have resulted in additional harvest closures. The latter events are included because in some cases domoic acid exposure could result in razor clams approaching, but not quite reaching, the 20-ppm closure threshold. Risk during such events is nonetheless high. Additional closures that occur outside active Bulletin periods are not included.

Considering the individual communications in Table 2, the most common assessment within the prior six years was medium ($n = 23$), followed by low ($n = 16$), and high ($n = 12$) risk. Although individual Bulletin communications are provided on a biweekly to monthly basis, each is not necessarily representative of independent conditions. As one example of this, consider events in fall 2022 when high risk was repeatedly communicated (Table 2). In early September 2022, increasing numbers of *P. australis*-like cells began appearing at many beaches, and particulate domoic acid concentrations began increasing at beaches throughout Oregon. By early October, elevated particulate domoic acid concentrations had been confirmed offshore of Oregon, but it took weeks before a storm occurred that was strong enough to deliver toxic cells to the Washington coast. In this case, the same risk remained present for much of the season. If we consider each spring and fall season as independent, then a total of 12 seasons can be evaluated as either "elevated" or "low" risk seasons, as described above.

No new domoic acid events occurred during the active Bulletin periods of spring 2018, fall 2018, spring 2020, spring 2021, and spring 2022 when individual Bulletins communicated low or moderate risk. In contrast, domoic acid events did occur during seasons when Bulletins communicated moderate or high risk (spring 2017, fall 2017, fall 2019, fall 2020, fall 2021, and fall 2022). Thus, at least in this crude seasonal sense, the forecasts provided to date by the Bulletin appear to reasonably reflect domoic acid risk within the region, with "elevated" risk of a HAB predicted roughly half of the time (7 of the 12 seasons). If we consider "elevated" risk as a "positive" and "low" risk as a "negative", then from Table 2, true positives were achieved six times, true negatives occurred five times, and there was a single false positive. No false negatives occurred. Following Anderson et al. (2010) and Anderson et al. (2016) the above designations were used to assign values for accuracy, the probability of detection, a false alarm ratio, the probability of false detection, and bias (Table 3). For comparison, a value of 1 represents high accuracy, high probability of detection, and low bias; a value of 0 is desirable for the false alarm ratio and the probability of false detection. With these definitions, the Bulletin scores well in a seasonal sense: it is highly accurate; there is high probability that it will detect a true domoic acid event; it has a low probability of issuing a false alarm; and it exhibits low bias in its assessments (Table 3). It is important to keep in

Table 3
Seasonal performance metrics for the PNW HAB Bulletin spanning the period of spring 2017 through fall 2022.

Performance Metric	Calculation	Ideal Score	Score
Accuracy	[true positive + true negative] / total	1	0.917
Detection Probability	true positive / [true positive + false negative]	1	1
False Alarm Ratio	false positive / [true positive + false positive]	0	0.143
False Detection Probability	false positive / [true negative + false positive]	0	0.167
Bias	true positive + false positive] / [true positive + false negative]	1	1.167

mind that the Bulletin is not a pure independent prediction system. Rather, it is more analogous to a data-assimilative ocean or weather model - shellfish domoic acid concentrations, particulate domoic acid and *Pseudo-nitzschia* concentrations, and a variety of other data are continually monitored and used in the Bulletin interpretations and rankings. This bio-physical data-based assimilation explains why, to a large extent, the seasonal HAB risk assessments are successful.

Some of the finer detail captured in Table 2 is also instructive and can get overshadowed in the above seasonal depiction. One such example occurred in fall 2020, which proved to be a missed opportunity for the Bulletin. In terms of individual risk rankings, this was the only false negative recorded to date. Prior to a Washington State razor clam harvest closure issued on 21-October, the 8-Oct-2020 Bulletin was given a low-risk rating. This rating occurred even though the Bulletin's forecast text explicitly stated that conditions were conducive to toxigenic *Pseudo-nitzschia* blooms; in hindsight this Bulletin should have been rated as medium risk. Two factors led to the incorrect low-risk ranking: 1) large morphology *Pseudo-nitzschia* cells had been present in large quantities for weeks prior to the event without producing elevated domoic acid concentrations and, 2) there was a lack of updated and comprehensive domoic acid information prior to the Bulletin release (a result of failed equipment and laboratory access restrictions during the COVID-19 pandemic). Had the offshore data collected prior to the 8-Oct-2020 Bulletin contained elevated particulate domoic acid concentrations, the Bulletin would have received a moderate- to high-risk rating. This example highlights the importance of monitoring particulate domoic acid concentrations at both beaches and offshore initiation sites since a model for predicting domoic acid production by *Pseudo-nitzschia* has not yet been implemented for the PNW. Without timely and accurate domoic acid concentration information, risk assessments can be in error. We also stress that the Bulletin is designed to provide a contextual discussion and analysis for managers that strives to capture more than can be communicated by a single risk rating. Assessment of Bulletin successes and failures will continue to be updated as new insights are gained, new data are made available, and the project moves forward.

5.2. Bulletin-guided management actions

State and tribal coastal shellfish managers in Washington and Oregon have repeatedly voiced support for the PNW HAB Bulletin, and report that it is helpful in their decision-making process. Because of the inherent co-education of scientists and managers throughout the tenure of the Bulletin project, managers have also adjusted actions in concert with, or in direct response to, recommendations provided in the Bulletin. We highlight some of those management actions here to illustrate the range of responses that have occurred, and to provide an alternative value assessment of the Bulletin. The examples below do not comprise an exhaustive list.

- Collection of additional samples
  The most common action that coastal shellfish managers have enacted is to collect additional seawater or razor clam samples based on recommendations provided in the Bulletin. Such action typically occurs during moderate- or high-risk scenarios ahead of favorable-tide harvest periods and serves as a first step toward additional actions.
- Continuation of harvests with increased confidence
  Clearly this action can follow the collection of additional samples, but it also may occur during low-risk scenarios. In one such case, the ODFW Shellfish Project Leader expressed gratitude that, based on the information contained in a low-risk Bulletin, additional sample collections were likely not needed prior to a favorable tide series that would be popular for razor clam harvest (Matthew V. Hunter, pers. comm.).
- Extended harvests
  Feedback received from the WDFW Coastal Shellfish Manager described how the Bulletin played a role in their decision to extend the commercial razor clam fishery in Willapa Bay, Washington, in late May 2018: "This gives us confidence to move forward with the extension of our commercial razor clam fishery in Willapa Bay" (Daniel L. Ayres, pers. comm.).
- Modified bag limits
  In anticipation of a domoic acid event, WDFW temporarily increased the razor clam bag limit, for the first time, from 15 to 25 clams per day in spring 2017 (Daniel L. Ayres, pers. comm.).
- Harvest postponement, delay, or closure
  In fall 2017, WDFW delayed razor clam harvest openings, preferring instead to collect additional samples to ensure public safety (Daniel L. Ayres, pers. comm.).
  In fall 2022, harvest was initially postponed by WDFW and then eventually closed. The WDFW Coastal Shellfish Manager remarked, "…late last week we made a difficult decision to delay our Sept. 22 recreational razor clam season opener. The excellent information provided by the PNW [HAB] Bulletin played a major role. While domoic acid levels in razor clams exceeded the action level on only one of four management beaches, the warning signs provided by the data and your analysis in the Bulletin helped us decide to pause and take the time needed to do some additional sampling" (Daniel L. Ayres, pers. comm.).
  The ODFW Shellfish Project Leader described how additional unscheduled samples were collected in fall 2022 based on Bulletin recommendations: "The Bulletin also played a role in Oregon's delay in reopening from the very popular Clatsop Beach fishery from the annual summer conservation closure (July 15-Sept. 30) as the information it provided set in motion additional, unscheduled tissue toxin analysis that indicated domoic acid levels had exceeded the closure threshold. Without the information provided by the Bulletin, the season would have opened on schedule and [would have] been open for almost two weeks before the scheduled tissue toxin analysis would have been completed, … ultimately closing the fishery. The delay in opening the fishery reduced the public's health risk and eliminated the need for [a] product recall" (Matthew V. Hunter, pers. comm.).

6. Summary and future improvements

We have provided a detailed description of the PNW HAB Bulletin, including the philosophy behind it, its origin, its construction, and the components that it relies on to address HAB risk in the PNW, specifically risk associated with toxic blooms of *Pseudo-nitzschia*. While shellfish and phytoplankton monitoring provide essential information to managers about current conditions on beaches, additional forewarning is beneficial. The Bulletin strives to deliver advance notice of domoic acid risk to allow managers additional time to take effective action. The domoic acid risk forecasts have proven skillful and offer valued insight to assist managers' decisions. The hope is that the Bulletin will be transitioned to a sustained-support operational status, so that regional managers may rely on it indefinitely. To conclude, a few salient points are highlighted below.

- The PNW regional ecosystem system is physically and biologically complex, even at the lower trophic level of phytoplankton. A variety of *Pseudo-nitzschia* species exist and *Pseudo-nitzschia* blooms are not always toxic. Moreover, phytoplankton blooms are a regular response to nutrient upwelling, but *Pseudo-nitzschia* typically account for ~10% or less of the resulting phytoplankton community. Fluctuating winds, river plume barriers, and seasonal current changes that are further dependent on remote winds are all part of the environmental setting. Despite these complexities, significant progress has been made in developing risk forecasts for coastal shellfish species.

- Because of this inherent complexity, PNW forecasting solutions cannot rely on singular approaches such as satellite remote sensing of coastal phytoplankton blooms.
- Importantly, and for the same reasons, risk evaluation requires active participation by knowledgeable scientists for reasonably accurate forecasts.
- Bulletin success depends fundamentally on cross education of scientists and managers.
- Forecasting skill depends critically on a PNW coastwide network of biological and physical data collection (including *Pseudo-nitzschia* cell and particulate domoic acid concentrations at shellfish beaches and offshore; coastal wind measurements; river discharge; ocean current data; and satellite chlorophyll-a estimates), weather forecasts, as well as development of a forecasting regional numerical modeling system for the coastal ocean and its rivers and estuaries.

Further enhancement of forecasting skill would require: (1) rapid availability of more sustained offshore particulate domoic acid data; (2) improved atmospheric forecasts that are reliable beyond a 3–5-day horizon, and (3) improved regional circulation models (potentially including assimilation of offshore and larger scale data).

Perhaps the greatest unmet improvement for domoic acid risk forecasts lies in being able to accurately model domoic acid production by *Pseudo-nitzschia*. A much better understanding of the biological and environmental conditions that control domoic acid production is required; links to micro- (Rue and Bruland, 2001; Wells et al., 2005) and macronutrient concentrations (Du et al., 2016) appear promising. If relationships between domoic acid production and such nutrient concentrations could be better established and quantified, researchers might be able to utilize nutrient-phytoplankton-zooplankton-detritus modules or phytoplankton functional group approaches (Rousseaux and Gregg, 2012) in existing regional ocean models (see, e.g., Moreno et al., 2022). Machine learning techniques have also exhibited recent HAB forecasting promise (Grasso et al., 2019; Valbi et al., 2019), so it is possible that they could also offer flexible approaches going forward. The Bulletin could easily incorporate such developments. Until such capabilities are available and tested, additional observations and analyses remain essential. The Bulletin has been deliberately structured to easily incorporate these additional observations, improved understanding, and to make use of the next generation of atmospheric and oceanic models.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Past issues of the PNW HAB Bulletin are available on the ORHAB website (https://orhab.uw.edu/pnw-hab-bulletin/) and the NANOOS website (http://www.nanoos.org/products/habs/forecasts/bulletins.php).

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References

Anderson, C.R., Sapiano, M.R.P., Prasad, M.B.K., Long, W., Tango, P.J., Brown, C.W., Murtugudde, R., 2010. Predicting potentially toxigenic *Pseudo-nitzschia* blooms in Chesapeake Bay. J. Mar. Syst. 83, 127–140. https://doi.org/10.1016/j.jmarsys.2010.04.003.

Anderson, C.R., Kudela, R.M., Kahru, M., Chao, Y., Rosenfeld, L.K., Bahr, F.L., Anderson, D.M., Norris, T.A., 2016. Initial skill assessment of the California harmful algae risk mapping (C-HARM) system. Harmful Algae 59, 1–18. https://doi.org/10.1016/j.hal.2016.08.006.

Austin, J.A., Barth, J.A., 2002. Variation in the position of the upwelling front on the Oregon shelf. J. Geophys. Res. 107, 3180. https://doi.org/10.1029/2001JC000858.

Banas, N.S., Lessard, E.J., Kudela, R.M., MacCready, P., Peterson, T.D., Hickey, B.M., Frame, E., 2009a. Planktonic growth and grazing in the Columbia River plume region: a biophysical model study. J. Geophys. Res. 114, C00B06. https://doi.org/10.1029/2008JC004993.

Banas, N.S., MacCready, P., Hickey, B.M., 2009b. The Columbia River plume as a cross-shelf exporter and along-coast barrier. Cont. Shelf Res. 29, 292–301, 10.106/j.csr.2008.03.011.

Bargu, S., Silver, M.W., Ohman, M.D., Benitez-Nelson, C.R., Garrison, D.L., 2012. Mystery behind Hitchcock's birds. Nat. Geosci. 5 (1), 2–3.

Barth, J.A., Pierce, S.D., Castelao, R.M., 2005. Time-dependent, wind-driven flow over a shallow midshelf submarine bank. J. Geophys. Res. 110, C10S05. https://doi.org/10.1029/2004JC002761.

Bates, S.S., Hubbard, K.A., Lundholm, N., Montresor, M., Leaw, C.P., 2018. *Pseudo-nitzschia, Nitzschia*, and domoic acid: new research since 2011. Harmful Algae 79, 3–43. https://doi.org/10.1016/j.hal.2018.06.001.

Bejarano, A.C., Van Dola, F.M., Gulland, F.M., Rowles, T.K., Schwacke, L.H., 2008. Production and toxicity of the marine biotoxin domoic acid and its effects on wildlife: a review. Hum. Ecol. Risk Assess. 14, 544–567.

Blanco, J., Acosta, C.P., Bermudez de la Puente, M., Salgado, C., 2002. Depuration and anatomical distribution of the amnesic shellfish poisoning (ASP) toxin domoic acid in the king scallop (*Pecten maximus*). Aquat. Toxicol. 60, 111–121.

Bowers, H.A., Ryan, J.P., Hayashi, K., Woods, A.L., Marin III, R., Smith, G.J., Hubbard, K. A., Doucette, G.J., Mikulski, C.M., Gellene, A.G., Zhang, Y., Kudela, R.M., Caron, D. A., Birch, J.M., Scholin, C.A., 2018. Diversity and toxicity of *Pseudo-nitzschia* species in Monterey Bay: perspectives from targeted and adaptive sampling. Harmful Algae 78, 129–141. https://doi.org/10.1016/j.hal.2018.08.006.

Buck, K.R., Uttal-Cooke, L., Pilskaln, C.H., Roelke, D.L., Villac, M.C., Fryxell, G.A., Cifuentes, L., Chavez, F.P., 1992. Autecology of the diatom *Pseudonitzschia australis*, a domoic acid producer, from Monterey Bay, California. Mar. Ecol. Prog. Ser. 84, 293–302.

Connolly, T.P., Hickey, B.M., Shulman, I., Thomson, R.E., 2014. Coastal trapped waves, alongshore pressure gradients, and California Undercurrent. J. Phys. Oceanogr. 44, 319–342. https://doi.org/10.11175/JPO-D-13-095.1.

Cusack, C., Dabrowski, T., Lyons, K., Berry, A., Westbrook, G., Salas, R., Duffy, C., Nolan, G., Silke, J., 2016. Harmful algal bloom forecast system for SW Ireland. Part II: are operational oceanographic models useful for a HAB warning system. Harmful Algae 53, 86–101 j.hal.2015.11.013.

Davidson, K., Anderson, D.M., Mateus, M., Reguera, B., Silke, J., Sourisseau, M., Maguire, J., 2016. Forecasting the risk of harmful algal blooms. Harmful Algae 53, 1–7. https://doi.org/10.1016/j.hal.2015.11.005.

Davidson, K., Whyte, C., Aleynik, D., Dale, A., Gontarek, S., Kurekin, A.A., McNeill, S., Miller, P.I., Porter, M., Saxon, R., Swan, S., 2021. HABreports: online early warning of harmful algal and biotoxin risk for the Scottish shellfish and finfish aquaculture industries. Front. Mar. Sci. 8, 631732 https://doi.org/10.3389/fmars.2021.631732.

Dever, E.P., 1997. Wind-forced cross-shelf circulation on the northern California shelf. J. Phys. Oceanogr. 27, 1566–1580.

Doucette, G.J., Mikulski, C.M., Jones, K.L., King, K.L., Greenfield, D.I., Marin III, R., Jensen, S., Roman, B., Elliott, C.T., Scholin, C.A., 2009. Remote, subsurface detection of the algal toxin domoic acid onboard the environmental sample processor: assay development and initial field trials. Harmful Algae 8, 880–888.

Drum, A.S., Siebens, T.L., Crecelius, E.A., Elston, R.A., 1993. Domoic acid in the Pacific razor clam *Siliqua patula*. J. Shellfish Res. 12, 443–450.

Du, X., Peterson, W.T., Fisher, J., Hunter, M., Peterson, J., 2016. Initiation and development of a toxic and persistent *Pseudo-nitzschia* bloom off the Oregon coast in spring/summer 2015. PLOS One 11, e0163977. https://doi.org/10.1371/journal.pone.0163977.

Dyson, K., Huppert, D.D., 2010. Regional economic impacts of razor clam beach closures due to harmful algal blooms (HABs) on the Pacific coast of Washington. Harmful Algae 9, 264–271. https://doi.org/10.1016/j.hal.2009.11.003.

Farrell, T.M., Bracher, D., Roughgarden, J., 1991. Cross-shelf transport causes recruitment to intertidal populations in central California. Limnol. Oceanogr. 36, 279–288.

Fernandez-Salvador, J.A., Davidson, K., Sourisseau, M., Revilla, M., Schmidt, W., Clarke, D., Miller, P.I., Arce, P., Fernandez, R., Maman, L., Silva, A., Whyte, C., Mateo, M., Neira, P., Mateus, M., Ruiz-Villarreal, M., Ferrer, L., Silke, J., 2021. Current status of forecasting toxic harmful algae for the North-East Atlantic shellfish aquaculture industry. Front Mar Sci 8, 666583. https://doi.org/10.3389/fmars.2021.666583.

Fisher, J.L., Peterson, W.T., Rykaczewski, R.R., 2015. The impact of El Nino events on the pelagic food chain in the northern California Current. Glob. Change Biol. 21, 4401–4414. https://doi.org/10.1111/gbc.13054.

Fritz, L., Quilliam, M.A., Wright, J.L.C., Beale, A.M., Work, T.M., 1992. An outbreak of domoic acid poisoning attributed to the pennate diatom *Pseudonitzschia australis*. J. Phycol. 28, 439–442.

Garrison, D.L., Conrad, S.M., Eilers, P.P., Waldron, E.M., 1992. Confirmation of domoic acid production by *Pseudonitzschia australis* (Bacillariophyceae) cultures. J. Phycol. 28, 604–607.

Gibble, C.M., Hoover, B.A., 2018. Interactions between seabirds and harmful algal blooms. In: Proceedings of the Harmful algal blooms: A compendium desk reference, pp. 223–242.

Giddings, S.N., MacCready, P., Hickey, B.M., Banas, N.S., Davis, K.A., Siedlecki, S.A., Trainer, V.L., Kudela, R.M., Pelland, N.A., Connolly, T.P., 2014. Hindcasts of potential harmful algal bloom transport pathways on the Pacific Northwest coast. J. Geophys. Res. Oceans 119. https://doi.org/10.1002/2013JC009622.

Grasso, I., Archer, S.D., Burnell, C., Tupper, B., Rauschenberg, C., Kanwit, K., Record, N. R., 2019. The hunt for red tides: deep learning algorithm forecasts shellfish toxicity at site scales in coastal Maine. Ecosphere 10 (12), e02960. https://doi.org/10.1002/ecs2.2960.

Hamilton, P., Rattray Jr., M., 1978. A numerical model of the depth-dependent, wind-driven upwelling circulation on a continental shelf. J. Phys. Oceanogr. 8, 437–457.

Hickey, B.M., 1979. The California current system—Hypotheses and facts. Prog. Oceanogr. 8, 191–279.

Hickey, B.M., Landry, M.R., Hickey, B.M., 1989. Patterns and processes of circulation over the Washington continental shelf and slope. Coastal Oceanography of Washington and Oregon. Elsevier Oceanographic Series, Elsevier, Amsterdam, pp. 41–115.

Hickey, B., Geier, S., Kachel, N., MacFadyen, A., 2005. A bi-directional river plume: the Columbia in summer. Cont. Shelf Res. 25, 1631–1656. https://doi.org/10.1016/j.csr.2005.04.010.

Hickey, B.M., MacFadyen, A., Cochlan, W., Kudela, R., Bruland, K., Trick, C., 2006. Evolution of chemical, biological, and physical water properties in the northern California Current in 2005: remote or local wind forcing? Geophys. Res. Lett. 33, L22S02. https://doi.org/10.1029/2006GL026782.

Hickey, B.M., Trainer, V.L., Kosro, P.M., Adams, N.G., Connolly, T.P., Kachel, N.B., Geier, S.L., 2013. A springtime source of toxic *Pseudo-nitzschia* cells on razor clam beaches in the Pacific Northwest. Harmful Algae 25, 1–14. https://doi.org/10.1016/j.jal.2013.01.006.

Hickey, B., Geier, S., Kachel, N., Ramp, S., Kosro, P.M., Connolly, T., 2016. Alongcoast structure and interannual variability of seasonal midshelf water properties and velocity in the northern California Current System. J. Geophys. Res. Oceans 121. https://doi.org/10.1002/2015JC011424.

Horner, R.A., Kusske, M.B., Moynihan, B.P., Skinner, R.N., Wekell, J.C., 1993. Retention of domoic acid by Pacific razor clams, *Siliqua patula* (Dixon, 1789): preliminary study. J. Shellfish Res. 12, 451–456.

Horner, R.A., Garrison, D.L., Plumley, F.G., 1997. Harmful algal blooms and red tide problems on the U.S. west coast. Limnol. Oceanogr. 42, 1076–1088.

Huyer, A., Sobey, E.J.C., Smith, R.L., 1979. The spring transition in currents over the Oregon continental shelf. J. Geophys. Res. 84 (C11), 6995–7011.

Kosro, P.M., 2005. On the spatial structure of coastal circulation off Newport, Oregon, during spring and summer 2001 in a region of varying shelf width. J. Geophys. Res. 110, C10S06. https://doi.org/10.1029/2004JC002769.

Kourantidou, M., Jin, D., Schumacker, E.J., 2022. Socioeconomic disruptions of harmful algal blooms in indigenous communities: the case of Quinault Indian Nation. Harmful Algae 118, 102316 j.hal.2022.102316.

Krogstad, F.T.O., Griffith, W.C., Vigoren, E.M., Faustman, E.M., 2009. Re-evaluating blue mussel depuration rates in 'Dynamics of the phycotoxin domoic acid: accumulation and excretion in two commercially important bivalves. J. Appl. Phycol. 21, 745–746. https://doi.org/10.1007/s10811-009-9410-4.

Lelong, A., Hégaret, H., Soudant, P., Bates, S.S., 2012. *Pseudo-nitzschia* (Bacillariophyceae) species, domoic acid and amnesic shellfish poisoning: revisiting previous paradigms. Phycologia 51, 168–216.

Lentz, S.J., 1992. The surface boundary layer in coastal upwelling regions. J. Phys. Oceanogr. 22, 1517–1539.

Liu, Y., MacCready, P., Hickey, B.M., Dever, E.P., Kosro, P.M., Banas, N.S., 2009. Evaluation of a coastal ocean circulation model for the Columbia River plume in summer 2004. J. Geophys. Res. 114, C00B04. https://doi.org/10.1029/2008JC004929.

Lund, J.K., Barnett, H.J., Hatfield, C.L., Gauglitz Jr., E.J., Wekell, J.C., Rasco, B., 1997. Depuration in dungeness crab (*Cancer magister* Dana 1852). J. Shellfish Res. 16 (1), 225–231.

MacCready, P., Banas, N.S., Hickey, B.M., Dever, E.P., Liu, Y., 2009. A model study of tide- and wind-induced mixing in the Columbia River estuary and plume. Cont. Shelf Res. 29, 278–291. https://doi.org/10.1016/j.scr.2008.03.015.

MacCready, P., McCabe, R.M., Siedlecki, S., Lorenz, M., Giddings, S.N., Bos, J., Albertson, S., Banas, N.S., Garnier, S., 2021. Estuarine circulation, mixing, and residence times in the Salish Sea. J. Geophys. Res. Oceans 126. https://doi.org/10.1029/2020JC016738 e2020JC016738.

MacFadyen, A., Hickey, B.M., 2010. Generation and evolution of a topographically linked, mesoscale eddy under steady and variable wind-forcing. Cont. Shelf Res. 30, 1387–1402. https://doi.org/10.1016/j.csr.2010.04.001.

MacFadyen, A., Hickey, B.M., Foreman, M.G.G., 2005. Transport of surface waters from the Juan de Fuca eddy region to the Washington coast. Cont. Shelf Res. 25, 2008–2021. https://doi.org/10.1016/j.csr.2005.07.005.

MacFadyen, A., Hickey, B.M., Cochlan, W.P., 2008. Influences of the Juan de Fuca Eddy on circulation, nutrients, and phytoplankton production in the northern California current system. J. Geophys. Res. 113, C08008. https://doi.org/10.1029/2007JC004412.

Mafra Jr., L.L., Bricelj, V.M., Fennel, K., 2010. Domoic acid uptake and elimination kinetics in oysters and mussels in relation to body size and anatomical distribution of toxin. Aquat. Toxicol. 100, 17–29. https://doi.org/10.1016/j.aquatox.2010.07.002.

Maguire, J., Cusack, C., Ruiz-Villarreal, M., Silke, J., McElligott, D., Davidson, K., 2016. Applied simulations and integrated modelling for the understanding of toxic and harmful algal blooms (ASIMUTH): integrated HAB forecast systems for Europe's Atlantic Arc. Harmful Algae 53, 160–166. https://doi.org/10.1016/j.hal.2015.11.006.

McCabe, R.M., Hickey, B.M., Dever, E.P., MacCready, P., 2015. Seasonal cross-shelf flow structure, upwelling relaxation, and the alongshelf pressure gradient in the northern California current system. J. Phys. Oceanogr. 45, 209–227. https://doi.org/10.1175/JPO-D-14-0025.1.

McCabe, R.M., Hickey, B.M., Kudela, R.M., Lefebvre, K.A., Adams, N.G., Bill, B.D., Gulland, F.M.D., Thomson, R.E., Cochlan, W.P., Trainer, V.L., 2016. An unprecedented coastwide toxic algal bloom linked to anomalous ocean conditions. Geophys. Res. Lett. 43 https://doi.org/10.1002/2016GL070023.

McGillicuddy, J.D., Townsend, D.W., He, R., Keafer, B.A., Kleindinst, J.L., Li, Y., Manning, J.P., Mountain, D.G., Thomas, M.A., Anderson, D.M., 2011. Suppression of the 2010 *Alexandrium fundyense* bloom by changes in physical, biological, and chemical properties of the Gulf of Maine. Limnol. Oceanogr. 56, 2411–2426. https://doi.org/10.4319/lo.2011.56.6.2411.

McKibben, S.M., Peterson, W., Wood, A.M., Trainer, V.L., Hunter, M., White, A.E., 2017. Climatic regulation of the neurotoxin domoic acid. Proc. Natl. Acad. Sci. U. S. A. 114, 239–244. https://doi.org/10.1073/pnas.1606798114.

Moore, S.K., Mickett, J.B., Doucette, G.J., Adams, N.G., Mikulski, C.M., Birch, J.M., Roman, B., Michel-Hart, N., Newton, J.A., 2021. An autonomous platform for near real-time surveillance of harmful algae and their toxins in dynamic coastal shelf environments. J. Mar. Sci. Eng. 9, 336. https://doi.org/10.3390/jmse9030336.

Moreno, A.R., Anderson, C., Kudela, R.M., Sutula, M., Edwards, C., Bianchi, D., 2022. Development, calibration, and evaluation of a model of *Pseudo-nitzschia* and domoic acid production for regional ocean modeling studies. Harmful Algae 118, 102296. https://doi.org/10.1016/j.hal.2022.102296.

Novaczek, I., Madhyastha, M.S., Ablett, R.F., Johnson, G., Nijjar, M.S., Sims, D.E., 1991. Uptake, disposition and depuration of domoic acid by blue mussels (*Mytilus edulis*). Aquat. Toxicol. 21, 103–118.

Novaczek, I., Madhyastha, M.S., Ablett, R.F., Donald, A., Johnson, G., Nijjar, M.S., Sims, D.E., 1992. Depuration of domoic acid from live blue mussels (*Mytilus edulis*). Can. J. Fish. Aquat. Sci. 49, 312–318.
WDOH, 2023. Shellfish [WWW document]. URL https://doh.wa.gov/community-and-environment/shellfish (accessed 5.23.2023).
NOAA NCCOS, 2023. Harmful algal bloom forecasting [WWW Document]. URL https://coastalscience.noaa.gov/science-areas/habs/hab-forecasts/ (accessed 5.23.2023).
ODA, 2023. Recreational shellfish biotoxin closures [WWW document]. https://www.oregon.gov/oda/programs/FoodSafety/Shellfish/Pages/ShellfishClosures.aspx (accessed 5.23.2023).
Olson, M.B., Lessard, E.J., Cochlan, W.P., Trainer, V.L., 2008. Intrinsic growth and microzooplankton grazing on toxigenic *Pseudo-nitzschia* spp. diatoms from the coastal northeast Pacific. Limnol. Oceanogr. 53 (4), 1352–1368.
ODFW, 2023. Crabbing & clamming [WWW document]. URL https://myodfw.com/crabbing-clamming (accessed 5.23.2023).
Pacific States Marine Fisheries Commission Dungeness Crab Report (2014), Pacific states marine fisheries commission, California department of fish and wildlife, California's living marine resources: a status report, 5 pp. Available at http://www.psmfc.org/crab/2014-2015%20files/DUNGENESS%20CRAB%20REPORT2014.pdf.
Peterson, W.T., Fisher, J.L., Strub, P.T., Du, X., Risien, C., Peterson, J., Shaw, C.T., 2017. The pelagic ecosystem in the northern California Current off Oregon during the 2014-2016 warm anomalies within the context of the past 20 years. J. Geophys. Res. Oceans 122, 7267–7290. https://doi.org/10.1002/2017JC012952.
Pinto, L., Mateus, M., Silva, A., 2016. Modeling the transport pathways of harmful algal blooms in the Iberian coast. Harmful Algae 53, 8–16. https://doi.org/10.1016/j.hal.2015.12.001.
Rousseaux, C.S., Gregg, W.W., 2012. Climate variability and phytoplankton composition in the Pacific Ocean. J. Geophys. Res. 117, C10006. https://doi.org/10.1029/2012JC008083.
Rue, E., Bruland, K., 2001. Domoic acid binds iron and copper: a possible role for the toxin produced by the marine diatom *Pseudo-nitzschia*. Mar. Chem. 76, 127–134.
PNW HAB Bulletin, 2022. PNW HAB Bulletin [WWW Document]. URL https://www.nanoos.org/products/habs/forecasts/bulletins.php (accessed 5.23.2023).
Scholin, C.A., Gulland, F., Doucette, G.J., Benson, S., Busman, M., Chavez, F.P., Cordaro, J., DeLong, R., De Vogelaere, A., Harvey, J., Haulena, M., Lefebvre, K., Lipscomb, T., Loscutoff, S., Lowenstine, L.J., Marin III, R., Miller, P.E., McLellan, W.A., Moeller, P.D.R., Powell, C.L., Rowles, T., Silvagni, P., Silver, M., Spraker, T., Trainer, V., Van Dolah, F.M., 2000. Mortality of sea lions along the central California coast linked to a toxic diatom bloom. Nature 403, 80–84.
Scholin, C., Doucette, G., Jensen, S., Roman, B., Pargett, D., Marin III, R., Preston, C., Jones, W., Feldman, J., Everlove, C., Harris, A., Alvarado, N., Massion, E., Birch, J., Greenfield, D., Vrijenhoek, R., Mikulski, C., Jones, K., 2009. Remote detection of marine microbes, small invertebrates, harmful algae and biotoxins using the environmental sample processor (ESP). Oceanography 22, 158–167.
Sekula-Wood, E., Benitez-Nelson, C., Morton, S., Anderson, C., Burrell, C., Thunell, R., 2011. *Pseudo-nitzschia* and domoic acid fluxes in Santa Barbara Basin (CA) from 1993 to 2008. Harmful Algae 10, 567–575. https://doi.org/10.1016/j.hal.2011.04.009.
Shchepetkin, A.F., McWilliams, J.C., 2005. The regional oceanic modeling system (ROMS): a split-explicit, free-surface, topography-following-coordinate oceanic model. Ocean Model. 9 (4), 347–404. https://doi.org/10.1016/j.ocemod.2004.08.002.
Shumway, S.E., Allen, S.M., Boersma, P.D., 2003. Marine birds and harmful algal blooms: sporadic victims or under-reported events? Harmful Algae 2 (1), 1–17.
Silva, A., Pinto, L., Rodrigues, S.M., de Pablo, H., Santos, M., Moita, T.M., Mateus, M., 2016. A HAB warning system for shellfish harvesting in Portugal. Harmful Algae 53, 33–39. https://doi.org/10.1016/j.hal.2015.11.017.
Smith, J., Connell, P., Evans, R.H., Gellene, A.G., Howard, M.D.A., Jones, B.H., Kaveggia, S., Palmer, L., Schnetzer, A., Seegers, B.N., Seubert, E.L., Tatters, A.O., Caron, D.A., 2018. A decade and a half of *Pseudo-nitzschia* spp. and domoic acid along the coast of southern California. Harmful Algae 79, 87–104. https://doi.org/10.1016/j.hal.2018.07.007.
Sourisseau, M., Jegou, K., Lunven, M., Quere, J., Gohin, F., Bryere, P., 2016. Distribution and dyanmics of two species of Dinophyceae producing high biomass blooms over the French Atlantic shelf. Harmful Algae 53, 53–63. https://doi.org/10.1016/j.hal.2015.11.016.
Stone, H.B., Banas, N.S., MacCready, P., Trainer, V.L., Ayres, D.L., Hunter, M.V., 2022. Assessing a model of Pacific Northwest harmful algal bloom transport as a decision-support tool. Harmful Algae 119, 102334. https://doi.org/10.1016/j.hal.2022.102334.
Strub, P.T., James, C., 1988. Atmospheric conditions during the spring and fall transitions in the coastal ocean off western United States. J. Geophys. Res. 93 (C12), 15561–15584.
Strub, P.T., Allen, J.S., Huyer, A., Smith, R.L., 1987. Large scale structure of the spring transition in the coastal ocean off western North America. J. Geophys. Res. 92, 1527–1544.
Stumpf, R.P., Culver, M.E., Tester, P.A., Tomlinson, M., Kirkpatrick, G.J., Pederson, B.A., Truby, E., Ransibrahmanakul, V., Soracco, M., 2003. Monitoring *Karenia brevis* in the Gulf of Mexico using satellite ocean color imagery and other data. Harmful Algae 2, 147–160.
Stumpf, R.P., Tomlinson, M.C., Calkins, J.A., Kirkpatrick, B., Fisher, K., Nierenberg, K., Currier, R., Wynne, T.T., 2009. Skill assessment for an operational algal bloom forecast system. J. Mar. Syst. 76, 151–161. https://doi.org/10.1016/j.marsys.2008.05.016.
Sutherland, D.A., MacCready, P., Banas, N.S., Smedstad, L.F., 2011. A model study of the Salish Sea estuarine circulation. J. Phys. Oceanogr. 41, 1125–1143. https://doi.org/10.1175/2011JPO4540.1.
Trainer, V.L., Adams, N.G., Bill, B.D., Stehr, C.M., Wekell, J.C., Moeller, P., Busman, M., Woodruff, D., 2000. Domoic acid production near California coastal upwelling zones, June 1998. Limnol. Oceanogr. 45 (8), 1818–1833.
Trainer, V.L., Suddleson, M., 2005. Monitoring approaches for early warning of domoic acid events in Washington State. Oceanography 18 (2), 228–237.
Trainer, V.L., Hickey, B.M., Horner, R.A., 2002. Biological and physical dynamics of domoic acid production off the Washington U.S.A. coast. Limnol. Oceanogr. 47, 1438–1446.
Trainer, V.L., Hickey, B.M., Lessard, E.J., Cochlan, W.P., Trick, C.G., Wells, M.L., MacFadyen, A., Moore, S., 2009. Variability of *Pseudo-nitzschia* and domoic acid in the Juan de Fuca eddy region and its adjacent shelves. Limnol. Oceanogr. 54, 289–308. https://doi.org/10.4319/lo.2009.54.1.0289.
Trainer, V.L., Kudela, R.M., Hunter, M.V., Adams, N.G., McCabe, R.M., 2020. Climate extreme seeds a new domoic acid hotspot on the US west coast. Front. Clim. 2, 571836 https://doi.org/10.3389/fclim.2020.571836.
SCCOOS, 2023. California HAB Bulletin [WWW Document]. URL https://sccoos.org/california-hab-bulletin/ (accessed 5.23.2023).
US Food and Drug Administration, 2022. Fish and fishery products hazards and controls guidance - June 2022 edition. https://www.fda.gov/media/80637/download.
Valbi, E., Ricci, F., Capellacci, S., Casabianca, S., Scardi, M., Penna, A., 2019. A model predicting the PSP toxic dinoflagellate *Alexandrium minutum* occurrence in the coastal waters of the NW Adriatic Sea. Sci. Rep. 9, 4166. https://doi.org/10.1038/s41598-019-40664-w.
WDFW, 2023. Shellfishing regulations [WWW document]. URL https://wdfw.wa.gov/fishing/shellfishing-regulations (accessed 5.23.2023).
Weir, M.J., Kourantidou, M., Jin, D., 2022. Economic impacts of harmful algal blooms on fishery-dependent communities. Harmful Algae 118, 102321. https://doi.org/10.1016/j.hal.2022.102321.
Wells, M.L., Trick, C.G., Cochlan, W.P., Hughs, M.P., Trainer, V.L., 2005. Domoic acid: the synergy of iron, copper, and the toxicity of diatoms. Limnol. Oceanogr. 50 (6), 1908–1917.
Wekell, J.C., Gauglitz Jr., E.J., Barnett, H.J., Hatfield, C.L., Eklund, M., 1994a. The occurrence of domoic acid in razor clams (*Siliqua patula*), Dungeness crab (*Cancer magister*), and anchovies (*Engraulis mordax*). J. Shellfish Res. 13 (2), 587–593.
Wekell, J.C., Gauglitz Jr., E.J., Barnett, H.J., Hatfield, C.L., Simons, D., Ayres, D., 1994b. The occurrence of domoic acid in Washington state razor clams (*Siliqua patula*) during 1991-1993. Nat. Toxins 2, 197–205.
Wekell, J.C., Hurst, J., Lefebvre, K.A., 2004. The origin of the regulatory limits for PSP and ASP toxins in shellfish. J. Shellfish Res. 23 (3), 927–930.
Winant, C.D., Beardsley, R.C., Davis, R.E., 1987. Moored wind, temperature, and current observations made during coastal ocean dynamics experiments 1 and 2 over the northern California shelf and upper slope. J. Geophys. Res. 92, 1569–1604. https://doi.org/10.1029/JC092iC02p01569.
Wohlgeschaffen, G.D., Mann, K.H., Subba Rao, D.V., Pocklington, R., 1992. Dynamics of the phycotoxin domoic acid: accumulation and excretion in two commercially important bivalves. J. Appl. Phycol. 4, 297–310.
Work, T.M., Barr, B., Beale, A.M., Fritz, L., Quilliam, M.A., Wright, J.L.C., 1993. Epidemiology of domoic acid poisoning in brown pelicans (*Pelecanus occidentalis*) and Brandt's cormorants (*Phalacrocorax penicillatus*) in California. J. Zoo Wildl. Med. 24 (1), 54–62.
Wright, J.L.C., Boyd, R.K., de Freitas, A.S.W., Falk, M., Foxall, R.A., Jamieson, W.D., Laycock, M.V., McCulloch, A.W., McInnes, A.G., Odense, P., Pathak, V.P., Quilliam, M.A., Ragan, M.A., Sim, P.G., Thibault, P., Walter, J.A., Gilgan, M., Richard, D.J.A., Dewar, D., 1989. Identification of domoic acid, a neuroexcitatory amino acid, in toxic mussels from eastern Prince Edward Island. Can. J. Chem. 67, 481–490.
Wynne, T.T., Stumpf, R.P., Tomlinson, M.C., Fahnenstiel, G.L., Dyble, J., Schwab, D.J., Joseph Joshi, S., 2013. Evolution of a cyanobacterial bloom forecast system in western Lake Erie: development and initial evaluation. J. Great Lakes Res. Supplement 39, 90–99. https://doi.org/10.1016/j.jglr.2012.10.003.
Zador, S.G., Holsman, K.K., Aydin, K.Y., Gaichas, S.K., 2017. Ecosystem considerations in Alaska: the value of qualitative assessments. ICES J. Mar. Sci. 74 (1), 421–430. https://doi.org/10.1093/icesjms/fsw144.