Climatic regulation of the neurotoxin domoic acid

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Domoic acid is a potent neurotoxin produced by certain marine microalgae that can accumulate in the foodweb, posing a health threat to human seafood consumers and wildlife in coastal regions worldwide. Evidence of climatic regulation of domoic acid in shellfish over the past 20 y in the Northern California Current regime is shown. The timing of elevated domoic acid is strongly related to warm phases of the Pacific Decadal Oscillation and the Oceanic Niño Index, an indicator of El Niño events. Ocean conditions in the northeast Pacific that are associated with warm phases of these indices, including changes in prevailing currents and advection of anomalously warm water masses onto the continental shelf, are hypothesized to contribute to increases in this toxin. We present an applied domoic acid risk assessment model for the US West Coast based on combined climatic and local variables. Evidence of regional- to basin-scale controls on domoic acid has not previously been presented. Our findings have implications in coastal zones worldwide that are affected by this toxin and are particularly relevant given the increased frequency of anomalously warm ocean conditions.

domoic acid | Pacific Decadal Oscillation | El Niño | Northern California Current | *Pseudo-nitzschia*

The Pacific Decadal Oscillation (PDO) and El Niño Southern Oscillation (ENSO) are recurring patterns of climate variability centered over the northeastern (NE) and equatorial Pacific, respectively, that fluctuate at scales of years (ENSO) to decades (PDO) (1, 2). Distinct, yet also related, these patterns can amplify or dampen each other through atmospheric teleconnection (1, 3). In the NE Pacific, they induce similar spatial patterns of sea surface temperature anomalies during positive (warm) and negative (cool) phases (4). Low-frequency physical variability attributed to the PDO and ENSO modulates large shifts in NE Pacific water temperature, ocean currents, and foodweb dynamics that can persist for months to years (2, 5, 6). Shifts in NE Pacific plankton communities occur as well (7–12); however, climate impacts on phytoplankton ecology in this region are relatively underexplored, largely due to a lack of phytoplankton data at sufficient scales.

Decadal, regional-scale monitoring of domoic acid (DA) in shellfish can be used to investigate climate-scale impacts on phytoplankton ecology. The neurotoxin DA is produced by some species of the diatom genus *Pseudo-nitzschia*. It enters secondary trophic levels when suspension feeders such as shellfish and anchovies ingest toxic *Pseudo-nitzschia* cells. Consumption of these organisms by humans can lead to a serious neurological disorder named Domoic Acid Poisoning (DAP), also termed Amnesic Shellfish Poisoning. DAP symptoms range from gastrointestinal disturbance to seizures, memory loss, or, rarely, death (13, 14).

DA was first identified as a public health threat in 1987 (15). Toxin-producing *Pseudo-nitzschia* spp. and DA have since been identified worldwide with the greatest prevalence in, and most deleterious impacts on, productive eastern boundary upwelling systems (16). Laboratory experiments have found multiple factors that can up- or down-regulate cellular DA synthesis, but there is no consensus regarding whether any one factor or combination of factors lead to predictable DA production in situ (16, 17). DA regulation has primarily been investigated using field observations of discrete bloom events and laboratory-based experiments (17). With some exceptions (e.g., ref. 18), the majority of these studies are based on temporally short or spatially small datasets relative to climate-scale indexes. To protect public health, DA in shellfish has been monitored along the US West Coast since 1991 (19). These records are now long enough to investigate DA regulation at the temporal–spatial scales associated with NE Pacific climate events that have occurred in recent decades, such as El Niño events, PDO transitions, and the 2013–2015 NE Pacific Warm Anomaly (20, 21).

Our research expands on observations of climate-scale regulation of plankton in the Oregon (OR) coastal region of the NE Pacific (e.g., refs. 8–10 and 22). The presence/absence of unique copepod communities is strongly correlated with the PDO (7, 23) and El Niño events (8). Copepods are a robust indicator of water mass transport to the continental shelf off of OR and the strength of the Northern California Current (NCC) (9, 24, 25), a strong seasonal current along the US West Coast. We investigate the relationship between low-frequency climate signals and a 20-y record of DA levels in OR razor clams, then apply these findings to test whether DA levels in Washington (WA) and California (CA) shellfish are also related to warm regimes.

Materials and Methods

Basin-Scale Indices of Warm/Cool Ocean Conditions. The PDO is a monthly proxy of climate variability based on North Pacific sea surface temperature (SST) variability. The Oceanic Niño Index (ONI) is a monthly index based on equatorial Pacific SST anomaly values. A threshold of $\pm 1\ ^{\circ}C$ separates moderate to strong El Niño (warm) events from weak ones. Both indexes were acquired for 1991–2015 (*SI Materials and Methods*).

Significance

We investigate regulation of domoic acid, a potent marine phycotoxin, at the climate scale. Due to the threat domoic acid can pose to public health, marine wildlife, and coastal economies, decades of laboratory experiments have examined controls on domoic acid production without reaching consensus on reliable toxin-producing conditions. Our findings reveal an association between domoic acid in shellfish and climate-scale warm ocean conditions, a unique, large-scale perspective relative to previous work.

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