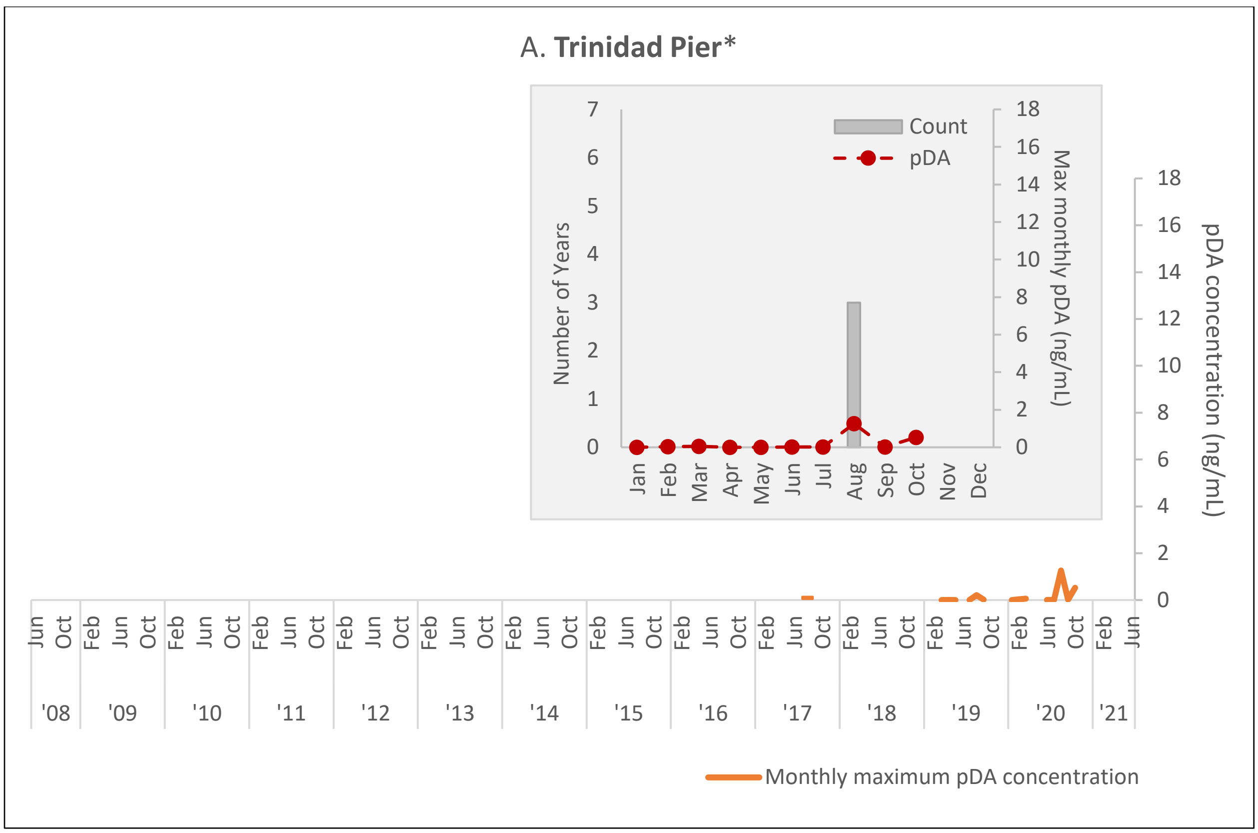
MARINE HARMFUL ALGAL BLOOMS

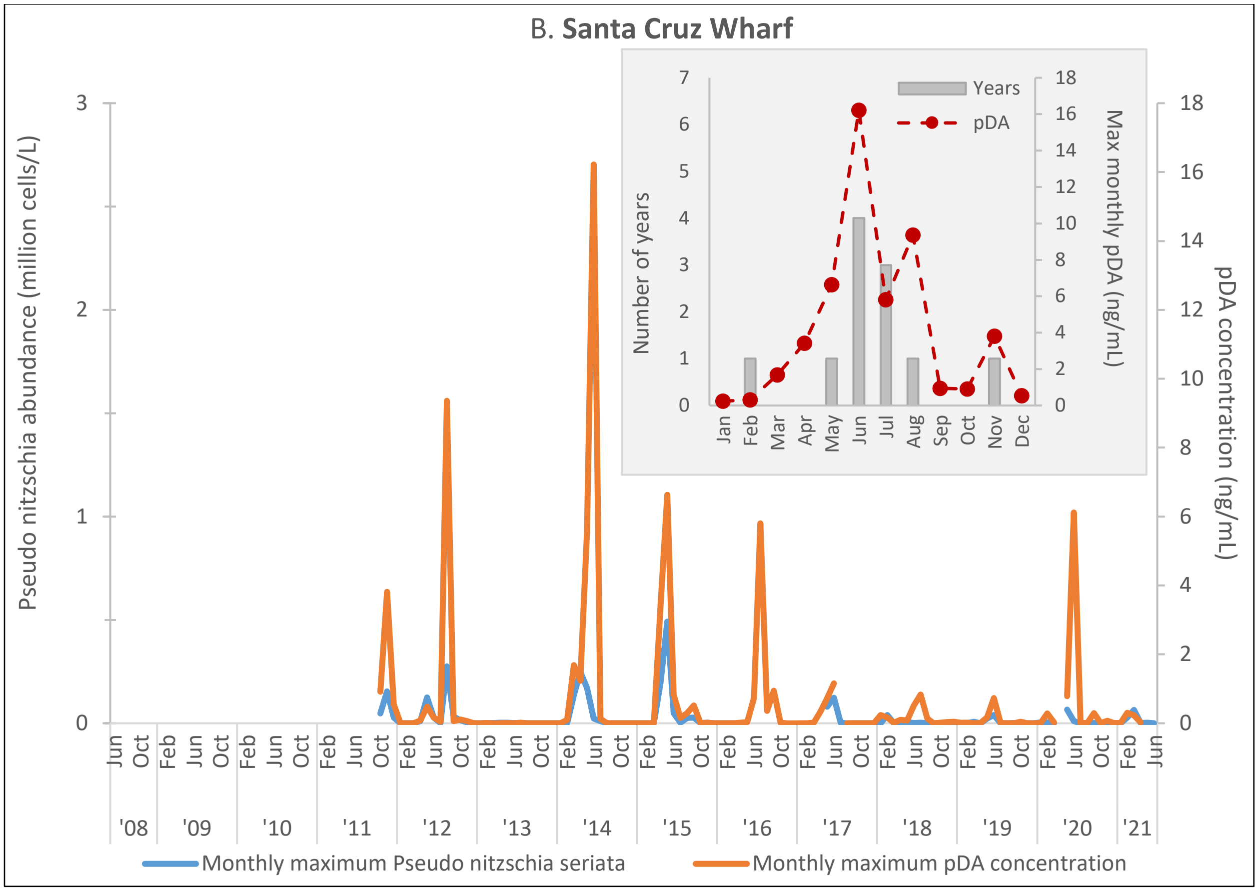
Patterns of blooms of certain types of algae in California coastal waters have been changing. While no trend is evident, blooms are known to be influenced in part by warming ocean temperatures. For example, red tide-forming dinoflagellates have been appearing more frequently since 2018. These harmful algal blooms (HABs) can produce biotoxins or otherwise disrupt marine ecosystems. Pseudo-nitzschia spp., a diatom which produces the toxin domoic acid, has been of particular concern due to its impacts on marine wildlife and fisheries in California.

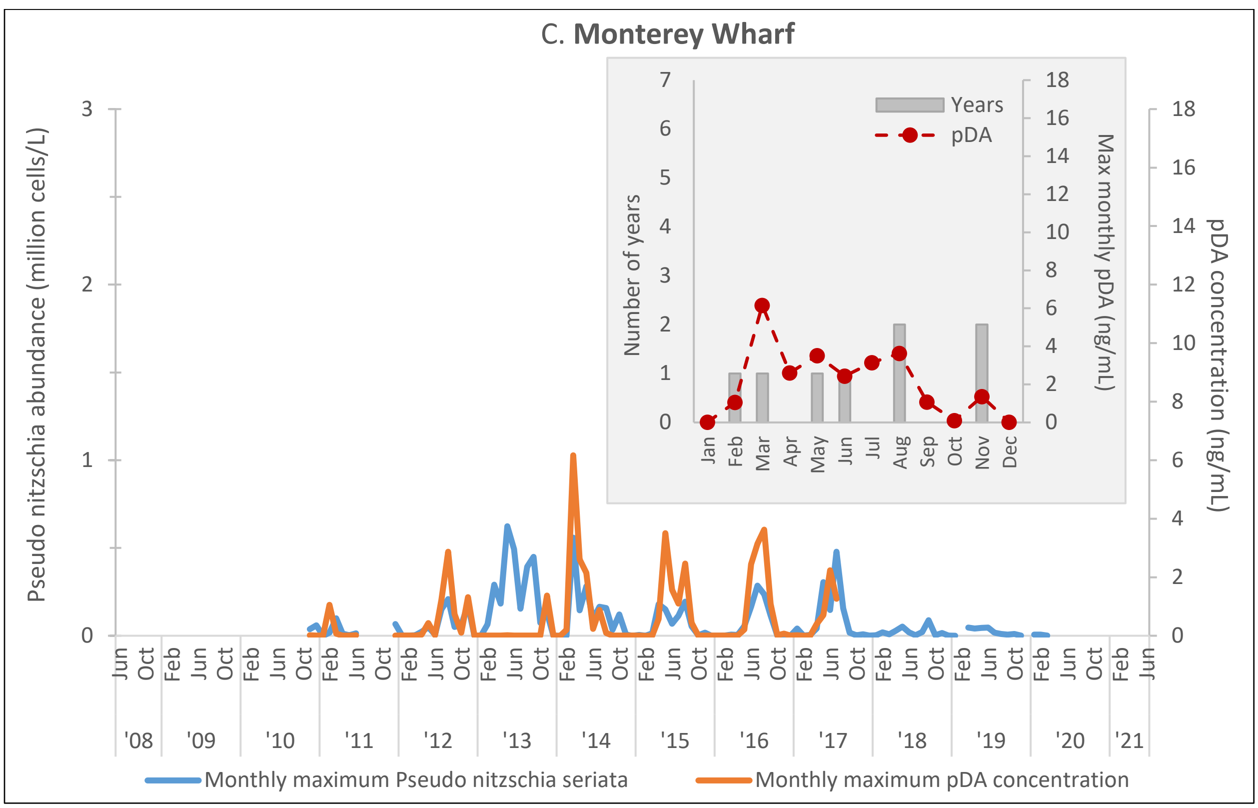
Figure 1. Monthly maximum *Pseudo-nitzschia* seriata abundance and particulate domoic acid (pDA) concentrations

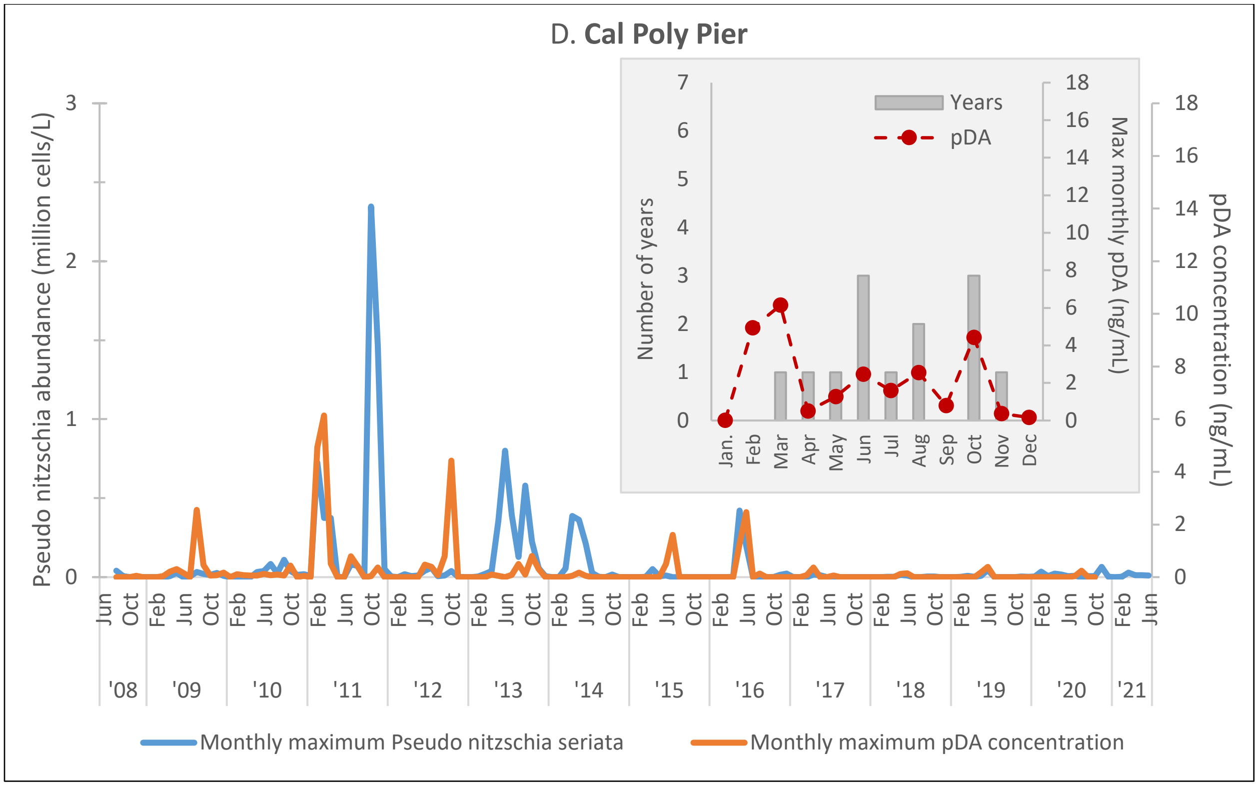
The eight graphs (Figure 1 A, Trinidad Pier to H, Scripps Pier) from the Harmful Algal Bloom Monitoring Alert Program (HABMAP) stations are displayed north to south. Gaps in the line graphs indicate no data were collected during that period. Inset graphs display the annual maximum pDA by month (across all years, line) and the number of years in which the annual maximum occurred in a given month (count, column). Pseudo-nitzschia seriata does not refer to a specific species (which cannot be visually distinguished) but to the larger, typically more toxic size of Pseudo-nitzschia.

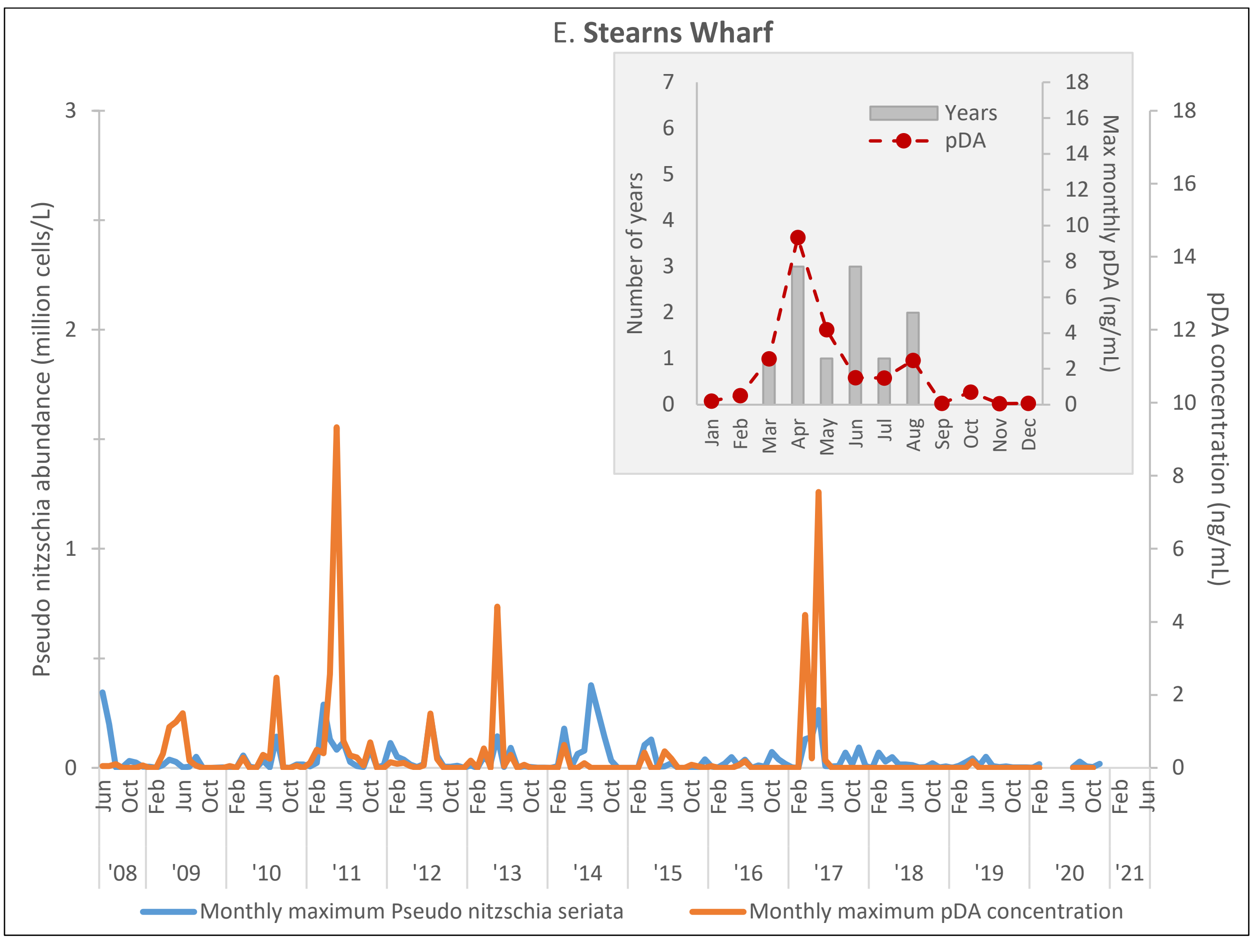


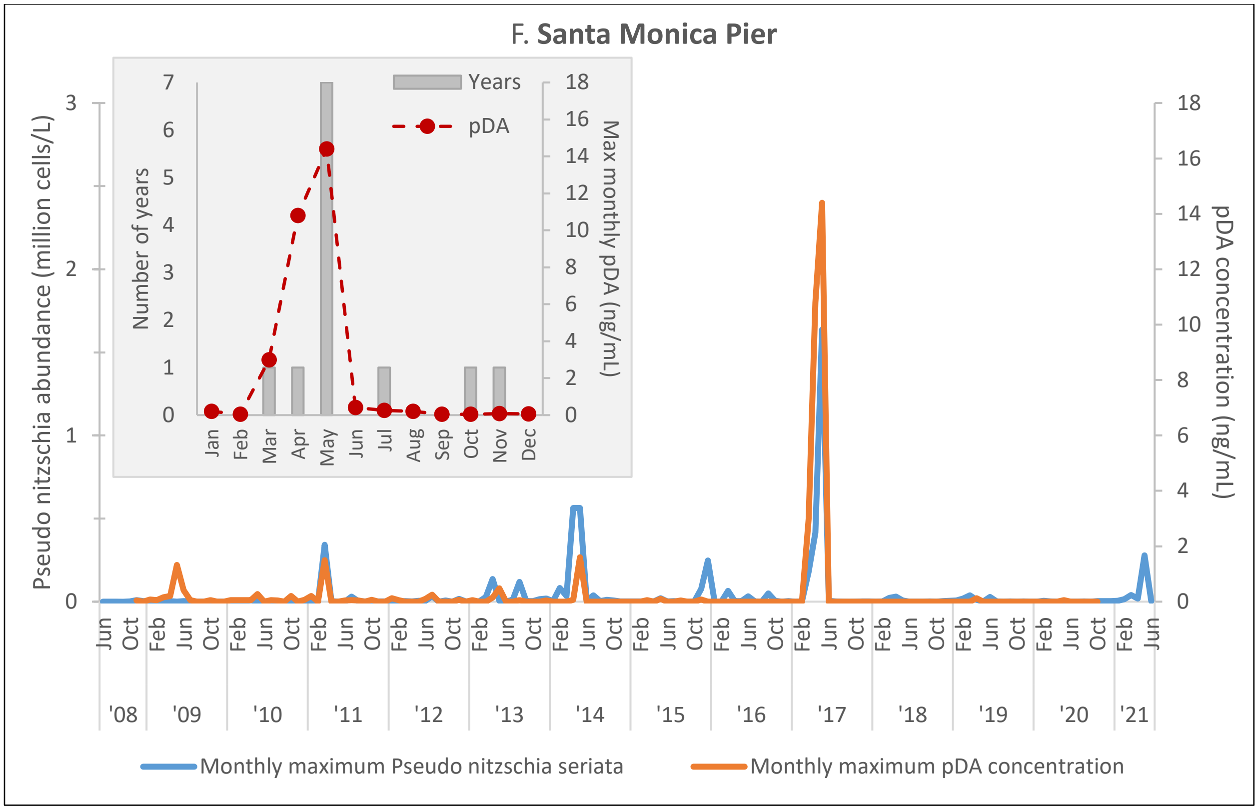
**Note: No cell counts are available, and pDA was intermittently collected starting in 2017.*

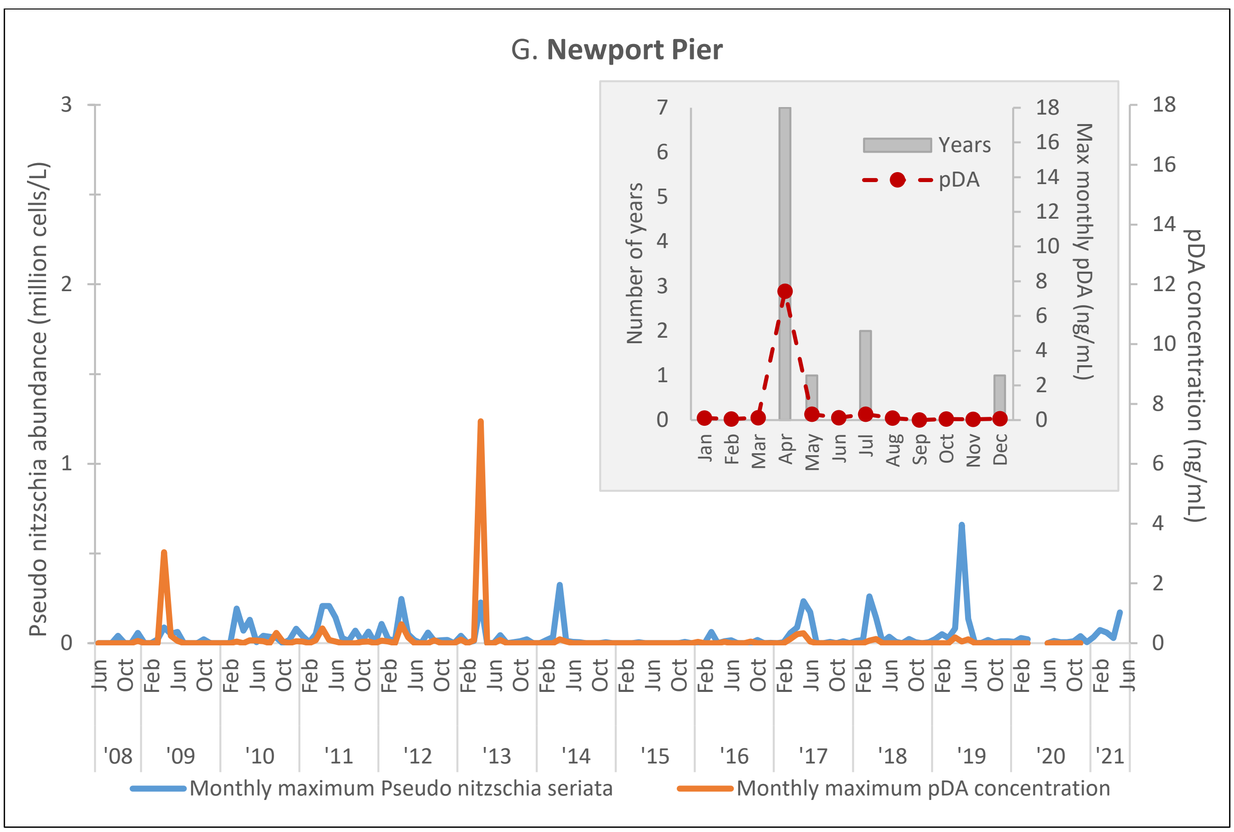

B. Santa Cruz Wharf
Pseudo nitzschia abundance (million cells/L)
pDA concentration (ng/mL)
Number of years
Max monthly pDA (ng/mL)
Years
pDA
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
'08 '09 '10 '11 '12 '13 '14 '15 '16 '17 '18 '19 '20 '21
Monthly maximum Pseudo nitzschia seriata
Monthly maximum pDA concentration

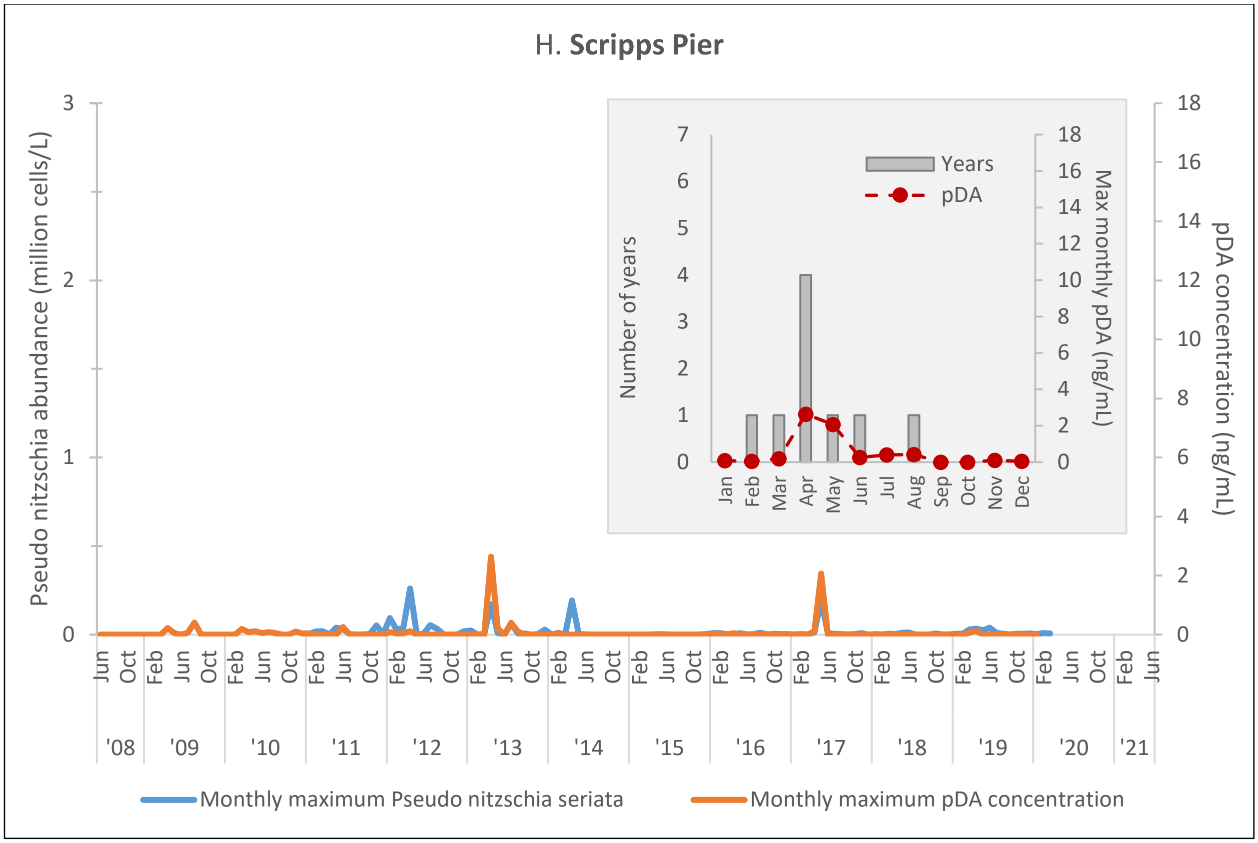

C. Monterey Wharf
Pseudo nitzschia abundance (million cells/L)
pDA concentration (ng/mL)
Number of years
Max monthly pDA (ng/mL)
Years
pDA
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
'08 '09 '10 '11 '12 '13 '14 '15 '16 '17 '18 '19 '20 '21
Monthly maximum Pseudo nitzschia seriata
Monthly maximum pDA concentration


D. Cal Poly Pier
Pseudo nitzschia abundance (million cells/L)
pDA concentration (ng/mL)
Number of years
Max monthly pDA (ng/mL)
Years
pDA
Jan. Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
'08 '09 '10 '11 '12 '13 '14 '15 '16 '17 '18 '19 '20 '21
Monthly maximum Pseudo nitzschia seriata
Monthly maximum pDA concentration


E. Stearns Wharf
Pseudo nitzschia abundance (million cells/L)
pDA concentration (ng/mL)
Number of years
Max monthly pDA (ng/mL)
Years
pDA
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
'08 '09 '10 '11 '12 '13 '14 '15 '16 '17 '18 '19 '20 '21
Monthly maximum Pseudo nitzschia seriata
Monthly maximum pDA concentration


F. Santa Monica Pier
Pseudo nitzschia abundance (million cells/L)
pDA concentration (ng/mL)
Number of years
Max monthly pDA (ng/mL)
Years
pDA
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
'08 '09 '10 '11 '12 '13 '14 '15 '16 '17 '18 '19 '20 '21
Monthly maximum Pseudo nitzschia seriata
Monthly maximum pDA concentration


G. Newport Pier
Pseudo nitzschia abundance (million cells/L)
pDA concentration (ng/mL)
Number of years
Max monthly pDA (ng/mL)
Years
pDA
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
'08 '09 '10 '11 '12 '13 '14 '15 '16 '17 '18 '19 '20 '21
Monthly maximum Pseudo nitzschia seriata
Monthly maximum pDA concentration



What does the indicator show?

Figures 1 and 2 present data collected at nearshore sampling locations in California for two groups of phytoplankton that cause marine harmful algal blooms (HABs): diatoms and dinoflagellates. The data are from sampling locations that comprise the Harmful Algal Bloom Monitoring Alert Program (HABMAP) (see Figure 3 for locations; data for Bodega Pier are not available). Data for Santa Cruz Wharf in Figure 2A include earlier years not reported as part of HABMAP.

Source: Kudela Lab, UC Santa Cruz

Marine HABs in California are generally due to diatoms, such as Pseudo-nitzschia (left), or dinoflagellates, such as Alexandrium (center) and Akashiwo (right) (UCSC, 2022).

Figure 2. HAB organism abundance and toxin levels at selected locations.

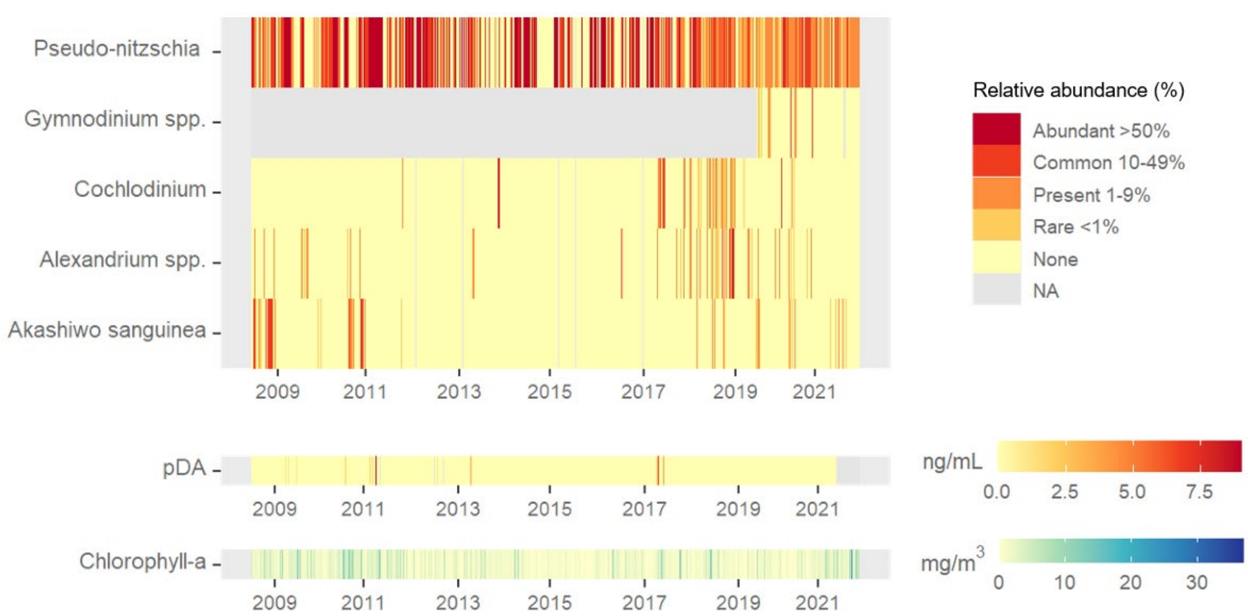
Relative abundance index of Pseudo-nitzschia seriata and several dinoflagellates ("red tide" forming taxa: Alexandrium, Cochlodinium, Gymnodinium, Akashiwo), along with concentrations of dissolved domoic acid (dDA, measured with SPATT, Solid Phase Adsorption Toxin Tracking) (A, Santa Cruz) or particulate domoic acid (pDA) (B, Stearns and C, Newport) and chlorophyll-a concentrations. See Figure 3 for sampling locations.

A. Santa Cruz Wharf

Source: Radan, 2021 and Kudela pers. comm., 2021

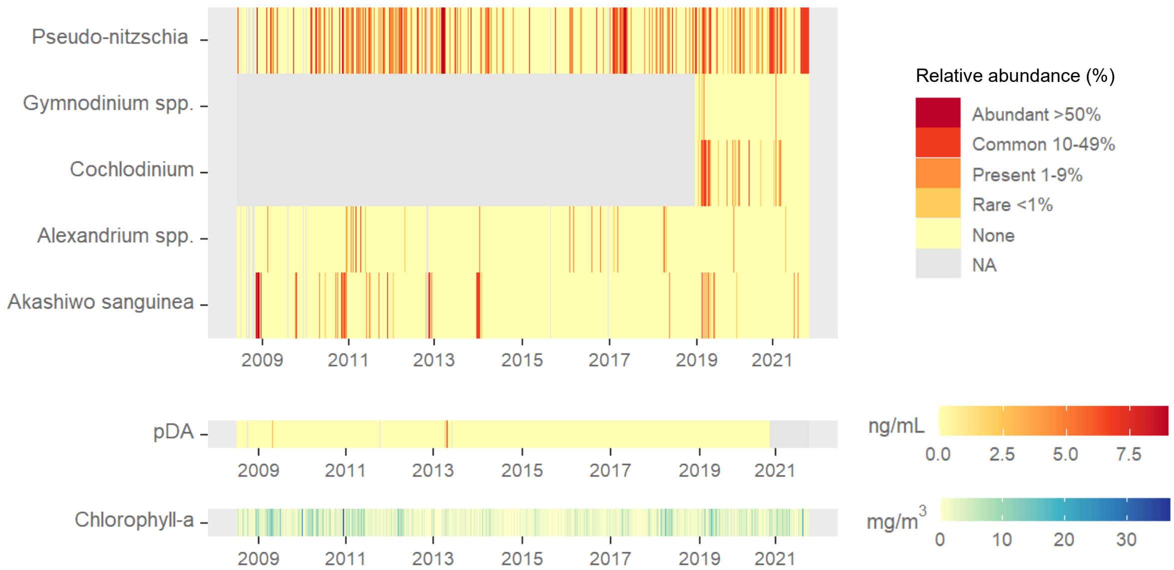
Note: The scale for chlorophyll-a for Santa Cruz Wharf is different from the scale for Stearns Wharf and Newport Beach Pier.

B. Stearns Wharf



Source: HABMAP/SCCOOS, 2021

C. Newport Beach Pier



Source: HABMAP/SCCOOS, 2021

Figure 3. Location of HABMAP sampling locations

Source: SCCOOS, 2021

Figure 1, graphs A through H present monthly maximum cell count values for the diatom *Pseudo-nitzschia* seriata size class and for concentrations of domoic acid, the toxin it produces. *Pseudo-nitzschia* "seriata" does not refer to the actual species (which cannot be distinguished by light microscopy) but rather the larger size class of *Pseudo-nitzschia*, which is generally a more toxigenic group of species. The graphs present concentrations of particulate domoic acid or pDA, which is the intracellular domoic acid concentration in the bulk phytoplankton pool. Accumulation of domoic acid in fish and shellfish is thought to be primarily through ingestion of *Pseudo-nitzschia* cells containing intracellular DA.

There is considerable variability in both cell count and toxin concentration across and within sampling locations. *Pseudo-nitzschia* seriata abundance and pDA concentrations were lowest at the two sites located farthest south, Newport Pier and Scripps Pier, where sea surface temperatures are generally warmer than in the central and north coast. This is consistent with findings that high abundances of *Pseudo-nitzschia* have not been reported in the Southern California Bight when temperatures are above 20 degrees Celsius (°C) or 68 degrees Fahrenheit (°F), and that no substantive concentrations of pDA have been found above 19 °C

(66.2 F; Smith et al., 2018). There are also low pDA concentrations at the northernmost site, Trinidad, however data for this station are limited with no *Pseudo-nitzschia* seriata cell counts nor pre-2017 pDA data publicly available for Trinidad Pier. In general, peak *Pseudo-nitzschia* seriata abundance and pDA concentrations aligned, but there were some exceptions. For example, at Cal Poly Pier a large *Pseudo-nitzschia* seriata bloom event occurred in October 2011 without a corresponding peak in pDA concentrations; conversely, in October 2012 a relatively large spike in pDA concentrations was accompanied by comparatively low *Pseudo-nitzschia* seriata cell counts.

Across all sites, *Pseudo-nitzschia* seriata and pDA concentrations were lowest during the winter months (December to February). For most locations, the highest pDA concentrations occurred during the spring months (March to May), and the highest *Pseudo-nitzschia* seriata abundance during the spring and summer months (March to August). A seasonal signal is most evident at the southern stations – Scripps Pier, Newport Pier and Santa Monica Pier – where highest values for *Pseudo-nitzschia* seriata abundance and pDA concentrations were most common in the spring (April for the former two, and May for the latter). For Cal Poly Pier, the monthly maximum pDA most frequently occurred in June and October; however, the overall monthly maximum pDA across all years was in February and March, driven by a large pDA spike during those months in 2011.

The results of weekly HABs sampling at three of the monitoring sites are presented in Figure 2. Changes over time in the relative abundance of *Pseudo-nitzschia* seriata and the most commonly observed red tide-forming dinoflagellates (*Alexandrium, Cochlodinium, Gymnodinium* and *Akashiwo*) are presented as heatmaps. The colors represent the relative abundance index (RAI) for each species. This is the percentage of a species of interest compared to all other phytoplankton species in a given sample, reported as five categories/ranges: (1) none; (2) rare, less than 1 percent; (3) present, 1 to 9 percent; (4) common, 10 to 49 percent; and (5) abundant, greater than 50 percent (Radan, 2021). A longer time series of HABs is available from the Santa Cruz Wharf, where weekly sampling data for phytoplankton composition extends back to 2002 (Figure 2A). Data from Solid Phase Adsorption Toxin Tracking (SPATT) samplers are included from 2008 to present. SPATT samplers measure dDA over the seven-day deployment, integrating fluctuations due to water movement. As with the shorter time-series, there was no trend in the abundance of *Pseudo-nitzschia*, while the red tide dinoflagellates seem to be appearing more frequently since 2018.

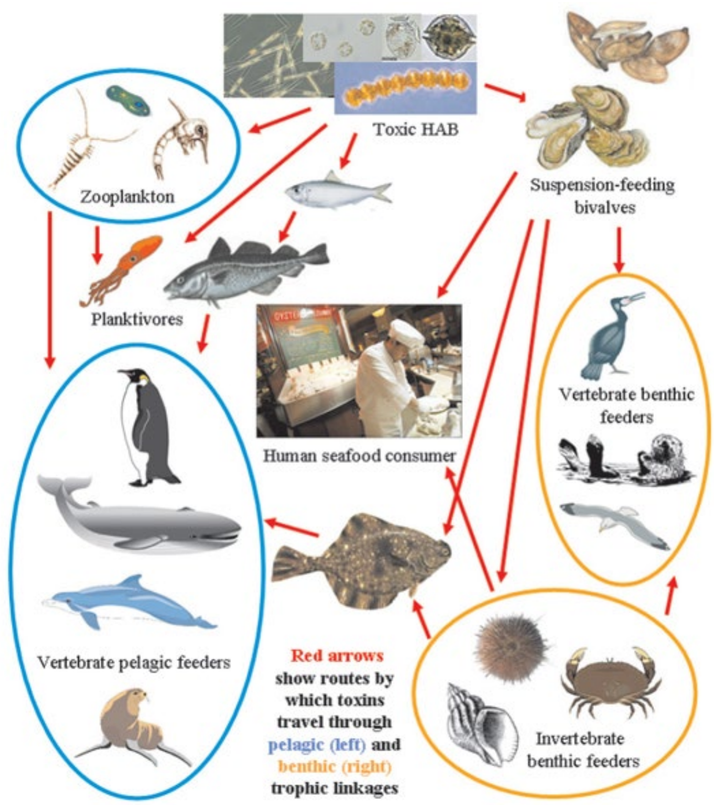
At Stearns Wharf, *Pseudo-nitzschia* seriata has been observed more often than not over the past 13 years, including at “abundant” levels in consecutive sampling periods prior to 2018 (Figure 2B); the diatom appears more frequently and at higher abundances at this location compared to Santa Cruz Wharf. Dinoflagellates were observed only intermittently over the same time period, and at “abundant” levels in only a few samples (monitoring for *Gymnodinium* spp. did not begin until 2019); these organisms occurred less frequently at this location compared to Santa Cruz Wharf. At

Newport Beach Pier (Figure 2C), both groups of HABs occurred less frequently and at lower levels than at either Santa Cruz Wharf or Stearns Wharf. Chlorophyll a concentrations at all three sites site are variable, and at times are high when *Pseudo-nitzschia* and red tide-forming organisms are relatively low. This indicates that other phytoplankton are present in high concentrations.

Why is this indicator important?

HABs can adversely affect marine organisms and their habitats. The diatoms and dinoflagellates associated with HABs can produce toxins that can move up the food chain (see Figure 4), and cause illness or death in fish, marine mammals and seabirds.

Figure 4. How HAB toxins move up the food chain

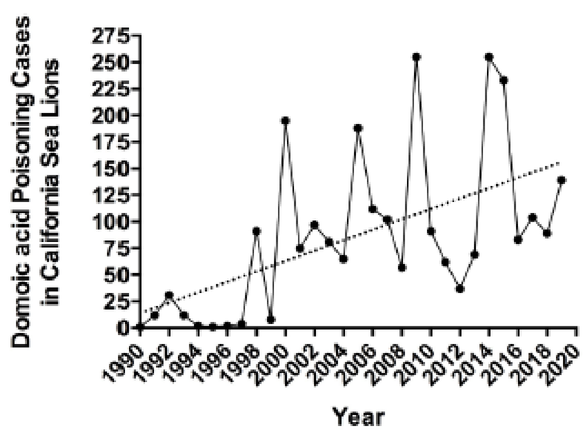


Source: [US National Office for Harmful Algal Blooms 2021]

Out of the roughly 50 different diatom *Pseudo-nitzschia* species, over 25 are known to produce domoic acid at differing concentrations (Bates et al., 2018). Ingestion of *Pseudo-nitzschia* cells containing domoic acid can result in its accumulation in mussels, oysters, clams, other filter-feeding organisms, and planktivorous fish such as sardines and anchovies. Other species may be exposed to domoic acid by feeding on toxin-contaminated organisms or residual cells and through domoic acid in sediment. Anchovies in particular are the dominant vectors of domoic acid and often have far higher concentrations of the toxin than bivalves and benthic feeders (Bernstein et al., 2021). This indicates that anchovies play a large role in aiding in the transfer of domoic acid up the food chain and are good indicators of domoic acid occurrence offshore. Human consumption of fish and shellfish containing domoic acid can result in Amnesic Shellfish Poisoning. Health impacts include symptoms such as nausea, vomiting, and diarrhea at lower doses and seizures, coma, irreversible memory loss at higher doses (OEHHA, 2021). To protect the public from exposures to domoic acid through seafood consumption, California fisheries are closed or have delayed opening when domoic acid is measured in razor clams, lobsters, crab and other seafood above the specified regulatory action limits (>30 ppm for crab viscera, ≥ 20 ppm for all other samples; FDA, 2021). Current biotoxin-related fishery closures are posted by the California Department of Fish and Wildlife.

Marine wildlife that consume domoic acid-contaminated organisms also exhibit signs of neurotoxin exposure. In California, domoic acid was first recognized as a threat to marine mammals in 1998 when hundreds of California sea lions stranded along beaches in central California exhibiting seizures, head weaving, and other neurological signs (Scholin et al. 2000). Retrospective analyses of veterinary records at The Marine Mammal Center in Sausalito revealed cases of domoic acid poisoning since 1990 (see Figure 5; Anderson et al., 2021). Cases increased beginning in 1998 with a notable spike in 2015 coinciding with a widespread coastal bloom. Toxin concentrations in bivalve and fish vector species, while high enough to cause documented illness and mortality in marine mammal and seabird predators, have not been associated with acute health impacts or die-offs among these vectors (Anderson et al., 2021). Between March and November 2015, domoic acid was detected in whales, dolphins, porpoises, seals, and sea lions ranging from southern California to northern Washington—the largest geographic extent of domoic acid detection in marine mammals ever recorded globally (McCabe et al., 2016).

Figure 5. California Sea Lions diagnosed with domoic acid poisoning



Source: Figure 7 from Anderson et al. 2021

Annual number of cases recorded at The Marine Mammal Center in Sausalito CA. Dotted line shows the significant regression ($p<0.05$).

For California, adverse impacts from marine HABs are also associated with blooms of dinoflagellates, which typically occur in the fall. Dinoflagellates are phytoplankton that can swim via their two flagella. As a result they can migrate vertically in the water column, while other phytoplankton such as diatoms cannot. When conditions are favorable, one or more populations of dinoflagellate may begin growing exponentially, resulting in up to millions of cells per liter of seawater. This 'bloom' can alter the appearance of water color to red, orange, or brown (Dierssen et al. 2006), hence these organisms are considered “red tide formers.” As with many HABs, visible indications of a bloom do not distinguish whether toxins are also present. The majority of red tides in California are nontoxic (Kudela et al., 2015); conversely, toxins may be present in the absence of water discoloration.

In the United States, dinoflagellates known to produce saxitoxins – also known as paralytic shellfish toxins (PSTs) – are in the genera *Alexandrium, Gymnodinium,* and

Pyrodinium. Alexandrium is one of the extremely toxigenic genera: a couple hundred cells in a liter of water can cause unhealthy concentrations of toxins even if no bloom is visible (CDPH 2021). PSTs can lead to numerous health impacts, including facial numbness, nausea, vomiting, respiratory failure and death (Anderson et al., 2021). PSTs were recognized as a serious health risk in California in 1927 when a major outbreak near San Francisco led to more than 100 illnesses and multiple deaths (Price et al., 1991). This led to the establishment of a monitoring program for PSTs in shellfish, the first in the U.S.

Other impacts of marine HABs include fish kills by clogging or lacerating fish gills, *Akashiwo* bloom-derived seafoam destroying the waterproofing of seabird feathers, and indirect effects including dying phytoplankton depleting oxygen or large blooms reducing light penetration (UCSC, 2021).

In addition to the human health and wildlife impacts of HABs, the economic impact of HABs is significant. The closure of commercial and recreational fisheries can cause significant economic loss. When the Dungeness crab season was delayed by several months due to a West Coast-wide algae bloom, the estimated economic loss was over $43 million (Holland and Leonard 2020).

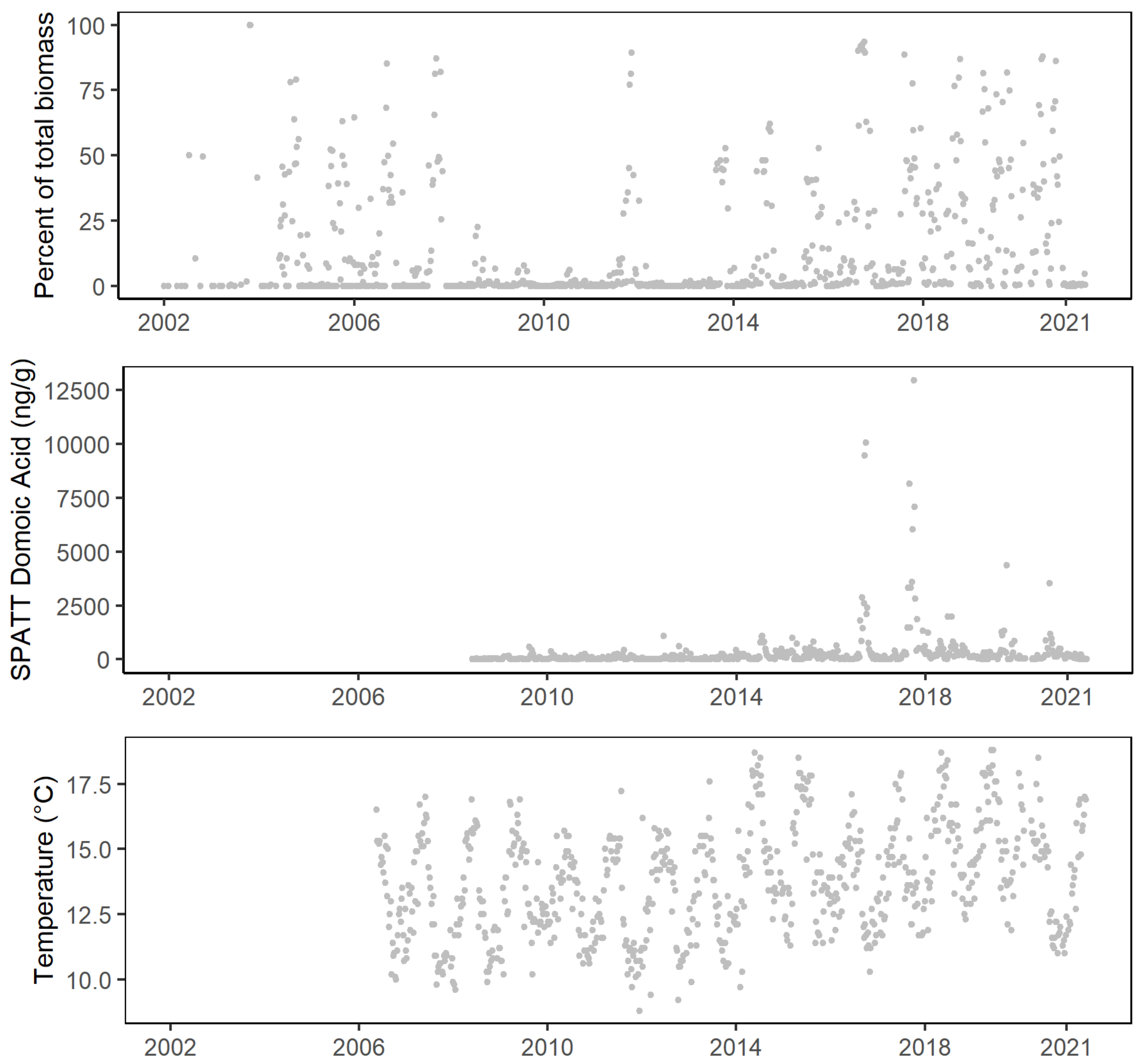
What factors influence this indicator?

Globally, observational and experimental evidence show that shifts in marine HABs distribution, increased abundance, and increased toxicity of marine HABs in recent years have been partly or wholly caused by warming and by other, more direct human drivers (Bindoff, et al., 2019). Marine HAB patterns in California have been associated with multiple factors including both natural and anthropogenic nutrient loading, decadal oscillations, and events such as marine heat waves. With climate change, California coastal waters have warmed over the past century (see *Coastal ocean temperature* indicator), and marine heat waves, such as the one which affected the West Coast of the United States from 2014 to 2016, have become more frequent over the 20th century, and more intense and longer in duration since the 1980s (IPCC, 2021).

All phytoplankton are influenced by light, temperature, nutrients, and physical forcing such as upwelling/downwelling which modulates (e.g.) temperature, salinity, and physical mixing. Water temperature, salinity, upwelling, advection are factors used in the California Harmful Algae Risk Mapping (C-HARM) model to estimate probability of *Pseudo-nitzschia* abundance above 10,000 cells/L and cellular and pDA production above their respective thresholds (see Anderson et al. 2009, 2011, 2016 for more details). C-HARM model predicts these probabilities at the current time ("nowcast") and three days into the future ("forecast") (see https://sccoos.org/california-hab-bulletin/).

Figure 6 presents time series for dinoflagellates, dDA, and temperature in Santa Cruz Wharf. Analyses indicated that both dinoflagellates abundance and dDA concentrations were positively correlated with temperature (not shown; Kudela pers. comm. 2021). These results indicate that with warming oceans, domoic acid concentrations and dinoflagellate abundance, particularly within Central and Northern California, will increase.

Figure 6. Santa Cruz Wharf relative abundance index of several "red tide" forming taxa combined (*Alexandrium*, *Cochlodinium*, and *Gynmnodium/Akashiwo*) compared to overall total phytoplankton biomass (top panel), dissolved domoic acid with Solid Phase Adsorption Toxin Tracking (SPATT) (middle panel), sea surface temperature (bottom panel) data over time.

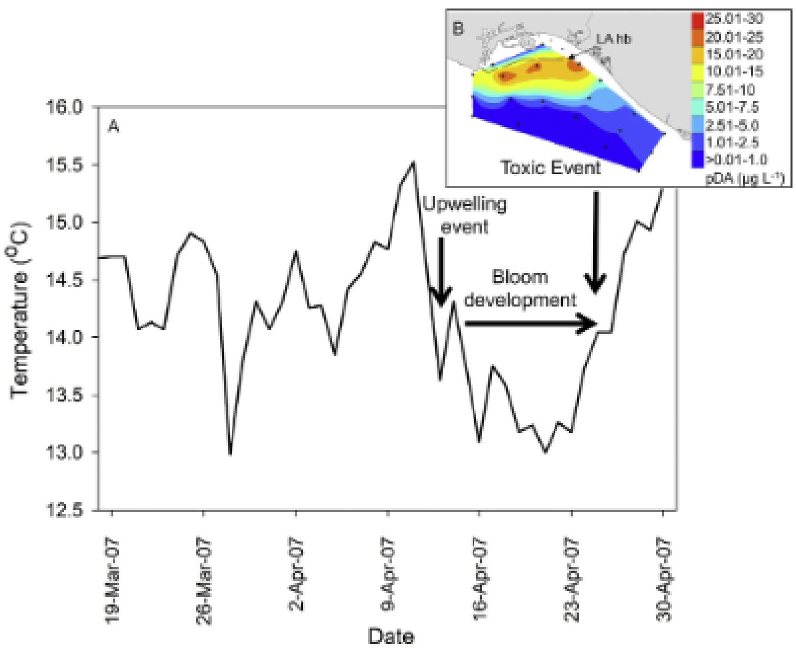


Source: HABMAP and Kudela pers. comm. 2021

A recent analysis of the increase in dinoflagellates concluded that the primary driver at the event-scale is changes in the intensity and direction of local winds (Fischer et al. 2018). It is unclear whether long-term increases in temperature and upwelling intensity will favor or inhibit dinoflagellate blooms, and inter-annual variability is still the dominant pattern in this record. However, the correlation between increasing sea surface temperature, dinoflagellate blooms, and dDA suggest that some HAB species will become increasingly problematic in these Northern and Central California regions in the near future, at least until the apparent thermal maximum (20 °C) for domoic acid production is reached (Fischer et al. 2018; Smith et al. 2018).

Kudela et al. (2003) looked at the correlation between nutrient runoff and *Pseudo-nitzschia* bloom events in Monterey Bay, and did not find a relationship between the two. Lane et al. (2009) developed several models for *Pseudo-nitzschia* in Monterey Bay and Pajaro River discharge was a key negative factor in the Fall-Winter model, meaning discharge resulted in fewer fall blooms. However, Kudela et al. (2008) suggests that urea may be a key variable in bloom events associated with runoff; higher urea concentrations at the Santa Cruz Wharf correlate with higher *Pseudo-nitzschia* abundance. Urea is not often measured in water quality samples, and the lack of this data may be the reason past studies in California have not found a positive correlation between nutrient runoff and blooms.

Figure 7. Influence of upwelling on subsequent bloom of *Pseudo-nitzschia* in Southern California. Data from San Pedro, CA in Spring of 2007



Source: Smith et al., 2018

Umhau et al. (2018) studied the role of upwelling in occurrences of *Pseudo-nitzschia* and pDA in the Santa Barbara Basin. At Stearns Wharf and Goleta Pier, *Pseudo-nitzschia* abundance and pDA concentrations were higher during upwelling versus non-upwelling periods, but due to high variability, these relationships were not significant for the offshore stations. Smith et al. (2018) provides another example of the relationship between upwelling of nutrient-rich water into the nearshore environment and subsequent *Pseudo-nitzschia* bloom in Southern California (see Figure 7).

Warmer sea surface temperatures and upwelling are also shown to be correlated with elevated domoic acid concentrations; within Northern California, maximal domoic acid events coincided during warm periods with upwelling (McKibben et al., 2017).

Furthermore, *Pseudo-nitzschia* and domoic acid are also found within the water column and marine sediment (Umhau et al., 2018). The subsurface populations are believed to act as a seeding population; during upwelling events this population may cause surface blooms (Smith et al., 2018). During the spring of 2015, the largest outbreak of domoic acid was recorded along the west coast. This event coincided with a marine heatwave and the start of the seasonal upwelling period (McCabe et al., 2016). During this marine heatwave, a research cruise that samples waters off the coast of Trinidad found high concentrations of domoic acid and *Pseudo-nitzschia* in water, and record high domoic acid concentrations within razor clams (McClatchie et al., 2016). While warmer water conditions generally favor marine HABs, there appears to be an upper maximum for current strains of *Pseudo-nitzschia* (20°C; Smith et al., 2018) such that in typical years, water temperatures in some areas of Southern California, such as Scripps Pier, may exceed this threshold. In 2015-2016, most impacts were seen north of Los Angeles County, suggesting a northward shift of suitable habitat for toxin-producing *Pseudo-nitzschia* species (McCabe et al., 2016).

More specific factors that are associated with toxin production are certain nutrients and nutrient ratios. Silicate and phosphorus limitations are the two factors most consistently correlated with pDA (Smith et al., 2018). The ratio between silicate and phosphorous also is significantly correlated with pDA, however this correlation is not significant across all years (Anderson et al., 2013). A change in the silica concentrations within upwelling waters of Southern California was associated with an increase in *Pseudo-nitzschia* bloom frequency (Bograd et al., 2015).

Ocean circulation patterns also may influence algal blooms. As the name implies, Pacific Decadal Oscillation (PDO), occurs on a decadal cycle, and the positive phase typically brings lower biological productivity in California. PDO mainly influences sea surface height anomalies (SSHa) and sea surface temperature anomalies (SSTa). PDO has a larger influence on marine life north of San Francisco. The North Pacific Gyre Oscillation (NPGO) also occurs on decadal time scales, affecting SSTa and SSHa, with most influence on regions south of San Francisco. A positive NPGO is associated with an increase in upwelling-favorable winds. El Niño Southern Oscillation consists of two phases – El Niño and La Niña – and occurs on timescales from months to years. El Niño is associated with a warming phase, where California ocean temperatures are typically warmer while La Niña is associated with a cooling phase. In Southern California, PDO has no significant effect on pDA production, while median pDA production increased during periods of negative North Pacific Gyre Oscillation (Smith et al., 2018). Furthermore, pDA production increased during La Niña in Southern California (Smith et al., 2018). These observations suggest that the warm waters within Southern California may exceed the upper temperature limits for *Pseudo-nitzschia* and domoic acid. Within Northern California where water temperatures are generally below the apparent thermal maximum, researchers found that domoic acid concentrations were positively correlated with a positive PDO and El Niño (McKibben et al., 2017). Research near Cal Poly Pier found a significant relationship between PDO and phytoplankton composition, with diatoms and dinoflagellates found to be the dominant phytoplankton in the fall during periods of negative and positive PDO phases, respectively (Barth et al., 2020).

Technical Considerations

Data characteristics

Phytoplankton and pDA data were obtained via the Environmental Research Division's Data Access Program (ERDDAP) in July 2021. SPATT dDA data for Santa Cruz was obtained from Dr. Kudela.

Weekly phytoplankton samples are collected by the Harmful Algal Bloom Monitoring and Alert Program (HABMAP) at nine pier locations throughout California; seven of these stations have historical data. In addition to phytoplankton, water quality samples are taken to measure: algal toxins, temperature, salinity, and nutrients. Surface water samples were taken from each station and a 100-mL water sample preserved to analyze phytoplankton abundance. To calculate the relative abundance index, the Utermöhl method was used to subset the sample and count phytoplankton under a dissecting microscope. The phytoplankton were categorized into nine genera: *Alexandrium*, *Ceratium*, *Cochlodinium*, *Dinophysis*, *Gymnodinium*, *Lingulodinium*, *Prorocentrum*, *Pseudo-nitzschia* delicatissima group, and *Pseudo-nitzschia* seriata group, and two “other” groups, namely other diatoms and other dinoflagellates. Since *Pseudo-nitzschia* is difficult to visually identify to species with light microscopy, the genus is broken up into two groups based on size class. *Pseudo-nitzschia* seriata is the larger and more toxigenic group while *Pseudo-nitzschia* delicatissima is the smaller and typically non-toxigenic group. Relative abundance was calculated by looking at the abundance of the genera compared to the total phytoplankton population (Barth et al., 2020). The relative abundance is then reported as: (1) none; (2) rare, less than 1 percent; (3) present, 1 to 9 percent; (4) common, 10 to 49 percent; and (5) abundant, greater than 50 percent (Radan, 2021).

Grab water samples were filtered and the domoic acid content of all material collected on the filter was analyzed for pDA. Grab samples represent the pDA within the sample at the time of collection. There is a more robust and broadly available dataset for pDA than for dDA via SPATT. Between 2001 and 2008, pDA concentrations were measured using liquid chromatography-tandem mass spectrometry (LC-MS/MS). From 2008 to the present, pDA concentrations were measured using a domoic acid specific enzyme-linked immunosorbent assay (Danil et al., 2021).

SPATT samplers were deployed for seven days and the dDA adsorbed onto the resin at the time of collection was analyzed using LC-MS (Lane et al., 2010). SPATT samplers provide a cumulative measure of domoic acid dissolved in water during the sampler deployment period.

Strengths and limitations of the data

Most of the long-term, consistently collected marine HAB data for California is for surface waters from near-shore structures in Central and Southern California. The HABMAP nearshore station data included above are robust, collected at consistent intervals, and with similar methods since 2008, providing a valuable time series dataset for those areas that is publicly available. The limited publicly available data for Northern California (i.e., Trinidad Pier and Bodega Bay) makes it difficult to analyze trends in that region.

Furthermore, these nearshore, surface water data may not be representative of what is happening offshore or in deeper waters. Umhau et al. (2018) found that offshore stations often had higher domoic acid concentrations than nearshore stations. These nearshore data do not always correspond with C-HARM predictions for the open coast. C-HARM output may be more closely correlated with marine mammals that strand along the coast due to "domoic acid toxicosis" (Anderson et al., 2016). In addition, species such as lobster and crabs that feed on the ocean bottom offshore and are mobile may accumulate domoic acid differently from attached, shoreline bivalve species. For example, Bernstein et al. (2021) found that anchovies had higher domoic acid concentrations than mussels.

As noted above, the *Pseudo-nitzschia* abundances are for two size classes (not individual species) due to the lack of microscopic species-specific identifiers. Availability of rapid, low-cost genetic identification of *Pseudo-nitzschia* species may inform potential relationships between individual *Pseudo-nitzschia* species abundance and domoic acid concentrations and changes with environmental conditions such as temperature and nutrients (Lema et al., 2019).

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