Variation in the Abundance of *Pseudo-nitzschia* and Domoic Acid with Surf Zone Type

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Running Head: Surfzone Hydrodynamics and *Pseudo-nitzschia*

Abstract

Most harmful algal blooms (HAB) originate away from the shore and, for them to endanger human health, they must be first transported to shore after which they must enter the surf zone where they can be feed upon by filter feeders. The last step in this sequence, entrance into the surf zone, depends on surfzone hydrodynamics. During two 30-day periods, we sampled *Pseudo-nitzschia* andparticulate domoic acid (pDA) in and offshore of a more dissipative surf zone at Sand City, California (2010) and sampled *Pseudo-nitzschia* in and out of reflective surf zones at a beach and rocky shores at Carmel River State Beach, California (2011). At Sand City we measured domoic acid in sand crabs, *Emerita analoga*. In the more dissipative surf zone, concentrations of *Pseudo-nitzschia* and pDAwere an order of magnitude higher in samples from a rip current than in samples collected just seaward of the surf zone and were 1000 times more abundant than in samples from the shoals separating rip currents. Domoic acid was present in all the *Emerita* samples and varied directly with the concentration of pDA and *Pseudo-nitzschia* in the rip current. In the more reflective surf zones, *Pseudo-nitzschia* concentrations were one to two orders of magnitude lower than in samples from 125 and 20 m from shore. Surfzone hydrodynamics affects the ingress of *Pseudo-nitzschia* into surf zones and the exposure of intertidal organisms to HABs on the inner shelf.

Key Words: dissipative, reflective, intermediate, rip current, benthic pelagic coupling, beach morphodynamics, domoic acid, Emerita, *Pseudo-nitzschia*

Introduction

Humans are most often affected by Harmful Algal Blooms (HABs) when they consume contaminated fish and shellfish. Often exposure occurs when shellfish are collected in the intertidal zone by recreational fishers. In most cases, for a HAB to be a health issue, it must enter the waters over the intertidal zone, i.e., the surf zone. Most HABs originate offshore not in the surf zone, to become a health issue they must therefore be transported to the inner shelf and then enter the surf zone.

Coastal water enters the surf zone when water in the surf zone is exchanged with offshore water. The rapidity with which surfzone water is exchanged is in part dependent on the hydrodynamics of the surf zone and this in turn is largely governed by the morphology of the surf zone (Wright and Short, 1984). Surfzone morphology ranges from dissipative to reflective with gradations between the extremes (Woodroffe, 2002). Dissipative to intermediate surf zones are associated with wide, flat beaches with fine sand and the surf zone is wide and generally contains rip currents. More reflective beaches are narrow, steep, with coarse sand, the surf zone is narrow and rip currents are generally not present. The hydrodynamics at more dissipative beaches if rip currents are present are conducive to the efficient exchange of surfzone water with offshore water (Shanks et al., 2010), hence, we predicted that a HAB present in waters seaward of a more dissipative beach with rip currents will more likely be pulled into the surf zone. We hypothesized that hydrodynamics of reflective surf zones, due to the absence of rip currents, limit exchange of surfzone water with offshore water and this in turn would limit the ingress of HAB species into the waters over the intertidal zone (Shanks et al., 2012; Shanks et al., 2010). We predicted that a HAB present in waters seaward of a reflective shore, sandy or rocky, will be less likely to be pulled into the surf zone. If these predictions prove true then monitoring for HABs should, to be conservative, focus on more dissipative shores and we would expect greater bioaccumulation in filter-feeding organisms in these locations.

A first-order question that arises given these hypotheses is: once a HAB enters the surf zone is it evenly distributed there? There are several diatom species which utilize the surf zone as their primary habitat (Garver, 1979). These species have behavioral, morphological, and physiological adaptations which allow them to remain in and exploit the surfzone habitat (Garver and Lewin, 1981). Amongst their behavior is a capacity to change their buoyancy so that they are driven shoreward by the surf and become trapped in the surfzone recirculation associated with rip currents; surfzone diatoms are not evenly distributed in the surf zone, but tend to be concentrated in rip current eddies (Talbot and Bate, 1987b). Coastal phytoplankton, including HAB species, are not surfzone specialists, do not share their adaptations, and are found in the surf zone simply because the coastal waters in which they are living have entered the surf zone. Because these species are not surfzone specialists one might assume that they would be evenly distributed in the surf zone.

We tested these hypotheses by extensive daily physical oceanographic and biological sampling of an intermediate (Sand City, California) and more reflective (Carmel River State Beach, California) surf zone. The physical oceanographic results and models have been described in several previous papers (Fujimura et al., 2013, 2014; MacMahan et al., 2009; Reniers et al., 2010; Reniers et al., 2009; Shanks et al., 2015). Here we compare *Pseudo-nitzschia* spp. (hence forth *Pseudo-nitzschia*) concentrations at thesetwodifferent surf zones and in the adjacent coastal ocean. We viewed phytoplankton as passive tracers and, hence, indicators of the exchange of water between the coastal ocean and surf zone. At Sand City, we were also able to sample domoic acid in the surf zone and inner shelf and in sand crabs (*Emerita analoga*) (hence forth *Emerita*) collected from the beach.

Methods

Intermediate Surf Zone - Sand City, California

In June and July 2010, the hydrodynamics and exchange of phytoplankton between the surf zone and inner shelf were examined during an extensive field experiment on a rip-channeled beach at Sand City (36.615760 N 121.85485 W) at the southern end of Monterey Bay, California (Figure 1). Bathymetry, offshore waves, wind, tidal elevation and currents were measured throughout the field experiment. A detailed description of the physical oceanographic measurements and observations and a model of the hydrodynamics of this surf zone are reported in (MacMahan et al., 2009)and Fujimura et al. (Fujimura et al., 2014), respectively.

At Sand City, from 15 June to 15 July we sampled phytoplankton within the surf zone at low tide and about 50 m seaward of the breaker line in the morning before the sea breeze strengthened making work from a small boat difficult. Initial sampling within the surf zone was limited to samples collected within a rip current (Figure 1). From 6 to 15 July samples were also collected over the shoal just south of this rip current. We assumed turbulence mixed phytoplankton vertically within the surf zone. Within the surf zone, swimmers collected replicate (n=3) 1-L water samples from ~1 m depth. Rip currents at the study site are quite obvious, were present on every day of the study, and remained in the same location throughout the study. A person walking out into the surf zone collected samples from the shoals. The Sand City surf zone and especially the rip current flow regime have been extensively studied (Fujimura et al., 2013, 2014; MacMahan et al., 2009; Reniers et al., 2010; Reniers et al., 2009). At this site, rip currents are apparent as deeper channels oriented perpendicular to shore through which flows a strong current directed offshore. Because of the deeper water in the channels, wave breaking occurs much closer to shore or not at all; this is apparent in Figure 1A. From shore one could see foam within the rip currents being swept seaward. To prevent the swimmers from being swept offshore, they were tethered to shore with a long rope. The shoals separating rip current are equally obvious. They are much shallower, flow was much slower and onshore, and waves broke across the whole shoal. The shoals were shallow enough that a person could walk across them.Offshore samples were collected from a boat a bit south of the sampled shoal and rip current (Figure 1). Offshore the phytoplankton may have been stratified vertically, as was commonly observed during the same time period in northern Monterey Bay (Timmerman et al. 2014). Here we sampled phytoplankton with a 25-µm mesh plankton net. Replicate (n=3) vertical tows were made from the bottom to the surface. The plankton net tow-rope was marked off in meters and the volume filtered by the net was determined from the length of the tow times the surface area of the mouth of the net. The volume of the sample removed from the net cod end was determined by weighting the sample. Samples were preserved in acid Lugols. Phytoplankton were identified to genus and counted on Sedgwick Rafter slides (Sournia 1978).

Surfzone diatoms produce exudates that cause them to adhere to bubble such that they float at the surface (Garver and Lewin, 1981; Talbot and Bate, 1987a, 1987b). This is likely how they become concentrated in rip current recirculation cells (Talbot and Bate, 1987a). Typical offshore phytoplankton taxa can be caught by bubbles rising through the water column (Krichnavaruck et al., 2007) and trapped cells might become concentrated in rip current eddies. Swimmers haphazardly sampled foam within the surf zone by scooping foam into a clean jar. Weighting the jar and sample and subtracting the weight of the jar determined sample volume. These samples were processed like the other phytoplankton samples and the concentration of phytoplankton within the foam samples is reported as *Pseudo-nitzschia* cells/Liter.

To determine pDA concentrations at Sand City, we filtered an aliquot from rip currentsamples collected between 7 and 15 July 2010 and from the offshore vertical plankton tows. From the 1-L rip current samples we filtered a 240 ml aliquot and from the plankton tow samples we removed and filtered from the total sample (sample volume determined by weight) a 10 mlaliquot. pDA was measured from these aliquots. *Emerita* were sampled between 4 July and 15 July 2010 during low tide in the swash zone on the beach above rip channels using a corer (10 cm diam. x 10 cm deep). Three replicate samples were collected each day. Five core samples per replicate were collected and placed in a mesh bag that was rinsed in the surf zone to remove sand. Five to ten individuals,many of which were recent recruits, were selected haphazardly from the samples and frozen for domoic acid analysis. *Emerita*sample weights ranged from 0.62-3.99 g (average 2.17 g, n=12) and the domoic acid concentration in these samples is reported as µg/g of tissue.Analysis of pDA and domoic acid in the *Emerita* were made following standard techniques.Briefly, filters for pDA were sonicated in 10% methanol and processed using Varian solid phase extraction columns following the method of Wang et al. (Wang et al., 2012), with quantification on an Agilent 6130 LC/MS as described in Seubert et al. (Seubert et al., 2014)*Emerita* were processed following the same methods as for shellfish, following Hess et al. (Hess et al., 2005) with quantification as for pDA.

Reflective Surf Zone - Carmel River State Beach, California

In June and July of 2011, the hydrodynamics and distribution of phytoplankton were studied at a steep, highly reflective beach, Carmel River State Beach (CRSB, 36.53789 N; 121.928886 W). Rocks flank the northern and southern ends of this crescent shaped pocket beach (Figure 1). The morphology and hydrodynamics of the study site have been described by Brown et al. (in press) and Shanks et al. (2015) and a model of flow at the site is presented in Fugimura et al. (2013).

Phytoplankton samples were collected daily from 6 June through 15 July 2011. Surfzone samples were collected at the sandy beach (SB) and two rocky intertidal sites at either end of the beach (NR and SR, Figure 1B). During this period we sampled phytoplankton 125 m from shore and, during the last 18 days (starting 28 June) of the time series, we also sampled 20 m offshore (Figure 1B), just outside the breaker line. At the sandy beach surfzone site, phytoplankton was collected with a pump system. A 6-cm dia. hose was attached to pipes jetted into the sand; the hose extended into the surf zone. A gas-powered pump sampled about 240 L of water per min, and replicate (n=3) 1-L phytoplankton samples were collected from this system. Samples were collected within one hour of high tide each day. Depending on wave height, samples were collected within the breakers or just a few meters seaward.

At the two rocky intertidal sites, replicate (n=3) 1-L samples were collected with a well bailer cast with a fishing pole into the surf. At the two offshore sites, samples were collected from a kayak in the morning when winds were light. Replicate (n=3) 1-L phytoplankton samples were collected from ~5 m depth using a stainless steel well bailer. Well bailers are designed to sample water from a well. The well bailer used from the rocky shore consisted of a plastic cylinder with a stopper with a small hole at one end to let air out of the cylinder and a ball valve at the other end. When filling, the ball valve opens allowing water to enter, but when the tube is full the valve closes. The stainless steel well bailer was lowered on a line to depth. A second line was used to open a spring-loaded valve. The valve was held open until the bailer was filled (seconds). In tests during sampling at Sand City there was no significant difference in the concentration of phytoplankton in pump samples and those collected by hand (paired t-test, $P > 0.5$). Phytoplankton samples were preserved and processed as described above for Sand City.

Results

At the Sand City sample site, the concentration of *Pseudo-nitzschia* in the rip current samples (Figure 2) varied with the concentration in the water just seaward of the surf zone ($r^2=0.548$, $n=28$, $P<0.000025$), but *Pseudo-nitzschia* was ~10 more abundant; concentrations in the rip samples were, on most days, above 10^6 cells/L. The concentration of *Pseudo-nitzschia* in the shoal samples (Figure 2) was also significantly correlated with that offshore ($r^2=0.701$, $n=10$, $P<0.003$), but here their concentration was ~100 times lower than offshore and ~1000 times lower than in the rip current samples.

At CRSB, the concentrations of *Pseudo-nitzschia* at the two inner shelf stations, 125 and 20 m from shore, were significantly correlated ($r^2=0.598$, $n=17$, $P<0.00017$) and the abundances were similar (Figure 2). Within the sandy beach surf zone (Figure 1, SZ), the concentrations of *Pseudo-nitzschia* while significantly correlated with concentrations at 125 and 20 m from shore ($r^2=0.706$, $n=27$, $P<0.0005$ and $r^2=0.593$, $n=17$, $p<0.0005$, respectively) were about 10 times lower than in the offshore samples, even those samples collected just 20 m offshore (Figure 2). The concentrations of *Pseudo-nitzschia* in the surf zones associated with the rocky shore to the north and south of the beach sample site (Figure 1, SR and NR) were not significantly correlated with concentrations offshore and concentrations were 10 to 100 times lower (Figure 2).

pDA concentrations were measured at Sand City (Figure 3), but not CRSB. At Sand City, the pDA concentration within the rip current tended to vary with the concentration offshore although the relationship was not significant (r^2=0.446, n=8, P=0.07). The pDA concentration in the rip current was 10 to 100 times higher (average=79 times higher) than offshore and was significantly correlated with the concentration of *Pseudo-nitzschia* in the rip current. Offshore, pDA did not vary with the concentration of *Pseudo-nitzschia* (Figure 4). Assuming all pDA was associated with *Pseudo-nitzschia*cells, we calculated the pDA per *Pseudo-nitzschia* cell (Figure 4). pDA per cell was significantly higher, on average ~2 times higher, for cells in the rip current than offshore (log transformed data, t=2.68, df=15, P=0.0172).

Foam was frequently present in the surf zone at Sand City, but was uncommon at CRSB. *Pseudo-nitzschia* cells were always present in foam at Sand City, but concentrations were highly variable (Figure 5). In some foam samples concentrations were orders of magnitude higher than in the rip current while in other samples concentrations were lower in the foam. *Pseudo-nitzschia* cell concentrations in 40% of the foam samples were > 10 x 10^6 cell/L and were up to 250 x 10^6 cell/L. In four foam samples we measured pDA where it ranged from ~500 to 25,000 ng/L. We have a small number of foam samples, but tentatively, the subjective impression was that the more stable the foam the higher the concentration of *Pseudo-nitzschia* and pDA. For example, the highest concentration of pDA was from very stable foam that was resting on the sand at the edge of wave run up.

Domoic acid was present in all *Emerita* samples (Figure 3) and ranged from 2.2 to 23.7 µg/g of tissue; while only one sample exceeded the 20 ppm (20 µg/g) FDA and California Department of Public Health imposed quarantine limits for domoic acid toxicity in harvested shellfish, the concentrations were comparable to or exceeded previously reported naturally contaminated crabs (Powell et al. 2002; Kvitek et al. 2008). The concentration of domoic acid in *Emerita* appears to vary with the concentration of pDA in the rip current samples, but with a several day lag (Figure 3). Cross-correlations between the two variables found significant correlations only at a lag of 4 days (Figure 6) with around 90% of the variability in *Emerita*explained by the pDA concentrations in the rip current.

Discussion

At the two sampled surf zones, one reflective the other intermediate with rip currents, the abundances of *Pseudo-nitzschia* within the surf zone relative to that in the waters just seaward were quite different. At the reflective surf zone, *Pseudo-nitzschia* was much less abundant in the surf zone than in the waters just seaward; surfzone hydrodynamics appeared to be limiting the ingress of *Pseudo-nitzschia* as well as other coastal phytoplankton taxa into the surf zone(Shanks et al., 2012). At the intermediate surf zone, we observed very high and very low concentrations in the rip current and over the shoals, respectively, relative to just offshore. Here again, surfzone hydrodynamics appears to be affecting the abundance of this HAB taxon in the surf zone.

Within the reflective surf zone, flow is onshore near the surface due to wave breaking and offshore (undertow) within the remainder of the water column (Shanks et al. 2015). Despite the exchange of inner shelf water with surfzone water, the concentration within the surf zone was far lower than just offshore. We hypothesize that the near surface concentration of phytoplankton is low and it is this water and concentration of phytoplankton that enters the surf zone. We did not measure the vertical distribution of phytoplankton and we cannot find measurements of phytoplankton concentrations very near the surface in similar nearshore settings. If turbulence is low enough, phytoplankton may simply sink away from the free surface of the ocean or some taxa may swim away from the surface to avoid harmful light levels or in response to other vertical migration cues (Heaney and Eppley, 1981).

At the more dissipative intermediate surf zone, flow was onshore over the shoals and offshore in the rip currents (MacMahan et al., 2009). Water transported offshore out of the surf zone mixes with innershelf water and some portion is transported back into the surf zone by wave action. Surface drifters released within the Sand City surf zone exited the surf zone via the rip currents, but then were usually transported back into the surf zone over the shoals. Many ultimately became trapped in the eddy formed by the rip current flow system (MacMahan et al., 2009). Because surface drifters float, they do not perfectly follow the movement of water; by floating they can become trapped in an eddy. Surf zone phytoplankton, taxa that preferentially inhabit surf zones, produce mucus, which traps bubbles floating the cells to the surface where they, like surface drifters, become concentrated in the rip current eddy. *Pseudo-nitzschia* cells as well as cells of other coastal phytoplankton taxa were consistently present in the foam sampled from the Sand City surf zone (Shanks et al. unpublished data). We hypothesize that the very high concentrations of *Pseudo-nitzschia* in the rip current samples is due to the interaction of the rip current flow system with floating cells caught by bubbles. Results from a bio-physical model of this surf zone are consistent with this hypothesis (Fujimura et al., 2014).

We can think of two non-mutually exclusive mechanisms that may account for the low concentrations of *Pseudo-nitzschia* in the samples from the shoal. First, if the rip current system is trapping cells in the rip eddy, then over time, cell concentrations within the surf zone may build up in the eddy and drop in the remainder of the surf zone. The second hypothesized mechanism is similar to that proposed above to explain the low abundance of *Pseudo-nitzschia* in the CRSB reflective surf zone. Flow is onshore near the surface over the shoals (MacMahan et al., 2009) and if near surface concentrations of cells are lower than in the water column, then the concentration of phytoplankton in the water entering the surface zone over the shoals may simply reflect the low near surface cell concentration.

Where waves impinge at an angle to a more dissipative surf zone, rip currents do not form, rather an alongshore current is generated within the surf zone (Omand et al., 2011). In this situation, without rip currents, a phytoplankton bloom on the inner shelf didnot enter the surf zone (Omand et al., 2011), a result similar to what we observed at the CRSB reflective surf zone. Without rip currents, dissipative and intermediate surf zones may behave like the sampled reflective surf zone.

Because domoic acid sampling for this study was opportunistic, we only have samples from the rip current and offshore of the surf zone at Sand City. The distribution of pDA mirrored the distribution of *Pseudo-nitzschia*; the concentration of pDA was far higher in the samples from the rip current than in those collected offshore and varied with the concentration of *Pseudo-nitzschia* present in the rip current. In addition, the pDA per *Pseudo-nitzschia* cell was significantly higher in samples from the rip than offshore; perhaps stressful conditions in the surf zone caused enhanced production of domoic acid.

Trainer et al. (Trainer et al., 2010) found concentrations of *Pseudo-nitzschia* during a bloom off Washington to vary from 10^5 to 10^4 cell/L. A downwelling event ultimately transported this bloom to the inner shelf. Peak concentrations of *Pseudo-nitzschia* at the shore within the surf zone of Kalaloch beach ranged from 4 to >15 x 10^6 cells/L. The surf zone at Kalaloch is dissipative with numerous rip currents. The much higher concentrations of *Pseudo-nitzschia* in the surf zone than offshore in the bloom may, as in our observations from Sand City, be due to the concentration of *Pseudo-nitzschia* cells by the rip current system in this surf zone. Shanks et al. (In Review) sampled a number of sites along a short (18 km) length of shore in Oregon. Surf zones at the sample sites varied from more dissipative with rip currents to reflective. Concentrations of *Pseudo-nitzschia* as well as other taxa of coastal phytoplankton were 10 to 100 x higher in more dissipative surf zones than more reflective surf zones.

As a safety precaution, coastal states monitor for HAB taxa and domoic acid by monitoring water and filter feeding organisms from surf zones. Assuming that our observations of the intermediate surf zone at Sand City generally apply to dissipative or intermediate surf zones with rip currents, monitoring samples collected just tens of meters apart could be strikingly different; a sample collected over a shoal could contain a thousand times fewer *Pseudo-nitzschia* cells than one collected in the adjacent rip current. In contrast, *Pseudo-nitzschia* concentrations were much lower in the sampled reflective surf zones. Because surfzone hydrodynamics appears to limit the ingress of coastal phytoplankton into reflective surf zones, monitoring at reflective surf zones may under-represent the degree of potential exposure to HAB toxins. Clearly surfzone hydrodynamics must be considered when designing a monitoring regime. The most conservative sampling regime would focus on sampling the rip current eddy at dissipative and intermediate surf zones.Frolov et al. (Frolov et al., 2010) recommended augmenting existing shore stations with some offshore sites, since decorrelation scales suggest shore stations are only representative of the first ~4 km of water away from the coast. Our findings show that there may be as much, if not more, spatial variability alongshore, but that this variability is predictable and dependent on surfzone hydrodynamics at the shore.

All the *Emerita* samples contained significant levels of domoic acid, up to and exceeding the regulatory limit (20 µg/g) that would trigger a quarantine and closure of shellfish harvesting. *Emerita* inhabits the swash zone and populations are frequently exposed at low tide (Morris et al., 1980). This exposes them to terrestrial predators such as shore birds, crows, and raccoons and these predators may suffer the consequences of consumption of contaminated *Emerita*. Concentrations in the samples were correlated with the concentration of pDA and *Pseudo-nitzschia* in the rip current, but with a lag of 4 days. We can think of no explanation for this lag. Previous sampling of domoic acid in *Emerita* found that concentrations varied with the concentration of *Pseudo-nitzschia*in the coastal ocean, but samples were collected weeks apart while our samples were daily so previously published studies would be unable to detect a four-day lag in contamination. The highest concentration of pDA (25,000 ng/L), which is higher than any value we found in the literature, was from stable foam resting on the beach at the limit of the swash. On that same date (4 July 2010), dissolved DA was also elevated, at 15,050 ng/L. Given where *Emerita* lives, the swash zone, and that they filter feed within this habitat, they may at times be feeding on foam mixed with seawater, which could expose them to very high concentrations of domoic acid.

Depending on the distribution of filterfeeders within a more dissipative surf zone, individuals may be exposed to low or very high concentrations of harmful algal cells. A filterfeeder, e.g., a razor clam, living on a shoal may contain lower levels of contamination than one living nearby but under the rip current eddy. Rip currents can remain fairly fixed in position for extended periods(Inman et al., 1971), hence, if filter feeders also remain in position, they will be exposed to high or low concentrations of phytoplankton for extended periods. This potential variation in the level of contamination should be investigated, but suggests that to pursue the most conservative monitoring, organisms should be sampled from around the rip current eddy.

On the West Coast, mussels and razor clams are monitored for their level of contamination. Mussels, which typically live on rocky generally more reflective shores often do not show contamination with domoic acid even though *Pseudo-nitzschia* is present in coastal waters and producing the toxin (Ferdin et al., 2002b; Scholin et al., 2000). In contrast, species that typically live in more dissipative surf zones, e.g., razor clams and sand crabs, are good sentinels (Altwein et al., 1995; Ferdin et al., 2002b); their contamination varies with the presence of *Pseudo-nitzschia*. Given our observations, differences in the ease and level of contamination between these species may be due to their habitat and the hydrodynamics of the associated surf zone, which can either cause their exposure to *Pseudo-nitzschia* and other HAB taxa in the coastal ocean (e.g., dissipative and intermediate surf zones with rip currents) or isolate them from this exposure (e.g., reflective surf zones or ones without rip currents).

Our results highlight the need to critically evaluate existing shore-based monitoring programs. While shellfish are typically used because they are directly consumed by humans, previous recommendations to add *Emerita* as a sentinel organism (Ferdin et al., 2002a) are supported by our findings. Further sampling based on shoreline morphology is also warranted, and may lead to better understanding of potential exposure and trophic transfer of domoic acid.

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References

Altwein, D.M., Foster, K., Doose, G., Newton, R.T., 1995. The detection and distribution of the marine neurotoxin domoic acid on the Pacific Coat of the United States 1991-1993. Journal of Shellfish Research 14, 217-222.

Ferdin, M., Kvitek, R.G., Bretz, C.K., Powell, C., Doucette, G.J., Lefebvre, K., Coale, S., Silver, M.W., 2002a. Emerita analoga (Stimpson) - possible new indicator species for the phycotoxin domoic acid in California coastal waters. Toxicon 40, 1259-1265.

Ferdin, M.E., Kvitek, R.G., Bretz, C.K., Powell, C.L., Doucette, G.J., Lefebvre, K.A., Coale, S., Silver, M.W., 2002b. *Emerita analoga* (Stimpson) - possible new indicator species for the phycotoxin domoic acid in California coastal waters. Toxicon 40, 1259-1265.

Frolov, S., Ryan, J., Kudela, R.M., Bellingham, J.G., 2010. What is the Right Strategy to Observe Potentially Harmful Algal Blooms off the California Coast?, 2010 Ocean Sciences Meeting, Portland, Oregon.

Fujimura, A., Reniers, A., Claire Paris, C., Shanks, A.L., MacMahan, J., Morgan, S., 2013. Slope-dependent biophysical modeling of surf zone larval transport., Coastal Dynamics 2013, pp. 661-670.

Fujimura, A., Reniers, A., Claire Paris, C., Shanks, A.L., MacMahan, J., Morgan, S., 2014. Numerical simulations of larval transport into a rip-channeled surf zone. Limnology and Oceanography 56, 1434-1447.

Garver, J.L., 1979. A Survey of Surf Diatom Blooms Along the Oregon Coast. University of Washington, Seattle, p. 167.

Garver, J.L., Lewin, J., 1981. Persistent blooms of surf diatoms along the Pacific Coast, U.S.A. I. Physical characteristics of the coastal region in relation to the distribution and abundance of the species. Estuarine, Coastal and Shelf Science 12, 217-229.

Heaney, S.I., Eppley, R.W., 1981. Light, temperature and nitrogen as interacting factors affecting diel vertical migrations of dinoflagellates in culture. Journal of Plankton Research 3, 331-344.

Hess, P., McGovern, E., McMahon, T., Morris, S., Stobo, L.A., Brown, N.A., Slattery, D., 2005. LC-UV and LC-MS methods for the determination of domoic acid. Trends in Analytical Chemistry 24, 358-367.

Inman, D.L., Tait, R.J., Nordstrom, C.E., 1971. Mixing in the surf zone. Journal of Geophysical Research 76, 3493-3514.

Krichnavaruck, S., Oowtongsook, S., Pavasant, P., 2007. Enhanced productivity of *Chaetoveros calcitrans* in airlift phtobioreactors. Bioscience Technology 98, 2123-2130.

MacMahan, J.H., Brown, J., Brown, J., Thornton, E.B., Reniers, A.J.H.M., Stanton, T.P., Henriquez, M., Gallagher, E., Morrison, J., Austin, M., Scott, T., Senechal, N., 2009. Mean Lagrangian Flow Behavior on an Open Coast Rip-channeled Beaches: New Perspectives. Marine Geology, doi:10.1016/j.margeo.2009.1009.1011.

Morris, R.H., Abbott, D.P., Haderlie, E.C., 1980. Intertidal Invertebrates of California. Stanford University Press, Stanford, California.

Omand, M.M., Leichter, J.J., Franks, P.J.S., Guza, R.T., Lucas, A.J., Feddersen, F., 2011. Physical and biological processes underlying the sudden surface appearance of a red tide in the nearshore. Limnology and Oceanography 56(3), 787-801.

Reniers, A.J.H.M., MacMahan, J.H., Beron-Vera, F.J., Olascoaga, M.J., 2010. Rip-current pulses tied to Lagrangian coherent structures. Geophysical Research Letters 37.05.

Reniers, A.J.H.M., MacMahan, J.H., Thornton, E.B., Stanton, T.P., Henriquez, M., Brown, J.W., Brown, J.A., Gallagher, E., 2009. Surf zone surface retention on a rip-channeled beach. Journal of Geophysical Research 114, C10010, doi:10010.11029/12008JC005153. .

Scholin, C.A., Gulland, F., Doucette, G.J., Benson, S., Busman, M., Chavez, p., Cordaro, J., DeLong, R., De Vogelaere, A., Harvey, J., Haulena, M., Lefebvre, K.A., Lipscom, T., Loscutoff, S., Lewensine, L.J., Marin, R.I., Miller, P.E., McLellan, W.A., Moeller, P.D.R., Powell, C.L., Rowles, T., Silagni, P., Silver, M.W., Sparker, T., Trainer, V.L., Van Dolah, F.M., 2000. Mortality of sea lions along the central California coast linked to a toxic diatom bloom. Nature 403, 80-84.

Seubert, E.L., Howard, M.D., Kudela, R.M., Stewart, T.N., Litaker, R.W., Evans, R., Caron, D.A., 2014. Development, comparison, and validation using ELISAs for the determination of domoic acid in California sea lion body fluids. Journal of AOAC International 97, 345-355.

Shanks, A.L., Morgan, S., MacMahan, J., Reniers, A., Brown, J., Ziccarelli, I., 2012. Phytoplankton abundance as an indicator of exchange of surf zone with offshore water at a dissipative and reflective shore and larval transport and settlement, 2012 Ocean Sciences Meeting Salt Lake City, Utah, p. 418.

Shanks, A.L., Morgan, S.G., MacMahan, J., Reniers, A.J.H.M., 2010. Surf zone physical and morphological regime as determinants of temporal and spatial variation in larval recruitment. Journal of Experimental Marine Biology and Ecology 392, 140-150.

Shanks, A.L., Morgan, S.G., MacMahan, J., Reniers, A.J.H.M., Jarvis, M., Brown, J., Griesemer, C., 2015. Transport of Larvae and Detritus Across the Surf Zone of a Steep Reflective Pocket Beach. Marine Ecology Progress Series 530, 103-117.

Talbot, M.M.B., Bate, G.C., 1987a. Rip current characteristics and their role in the exchange of water and surf diatoms between the surf zone and nearshore. Estuarine Coastal and shelf science 25, 707-720.

Talbot, M.M.B., Bate, G.C., 1987b. The spatial dynamics of surf diatom patches in a medium energy, cuspate beach. Botanica Marina 30, 459-465.

Trainer, V.L., Pitcher, G.C., Reguera, B., Smayda, T.J., 2010. The distribution and impacts of harmful algal bloom species in eastern boundary upwelling systems. Progress in Oceanography 85, 33-52.

Wang, Z.J., Maucher-Fuquay, J., Fire, S., Mikulski, B., Haynes, B., Doucette, G., J., R., 2012. Optimization of solid-phase extraction and liquid chromatography-tandem mass spectrometry for the determination of domoic acid in seawater, phytoplankton and mammalian fluids and tissues. . Analytica Chimica Acta 715, 71-79.

Woodroffe, C.D., 2002. Coasts form, process and evolution. Cambridge University Press, Cambridge.

Wright, L.D., Short, A.D., 1984. Morphodynamic variability of surf zones and beaches - a synthesis. Marine Geology 56, 93-118.

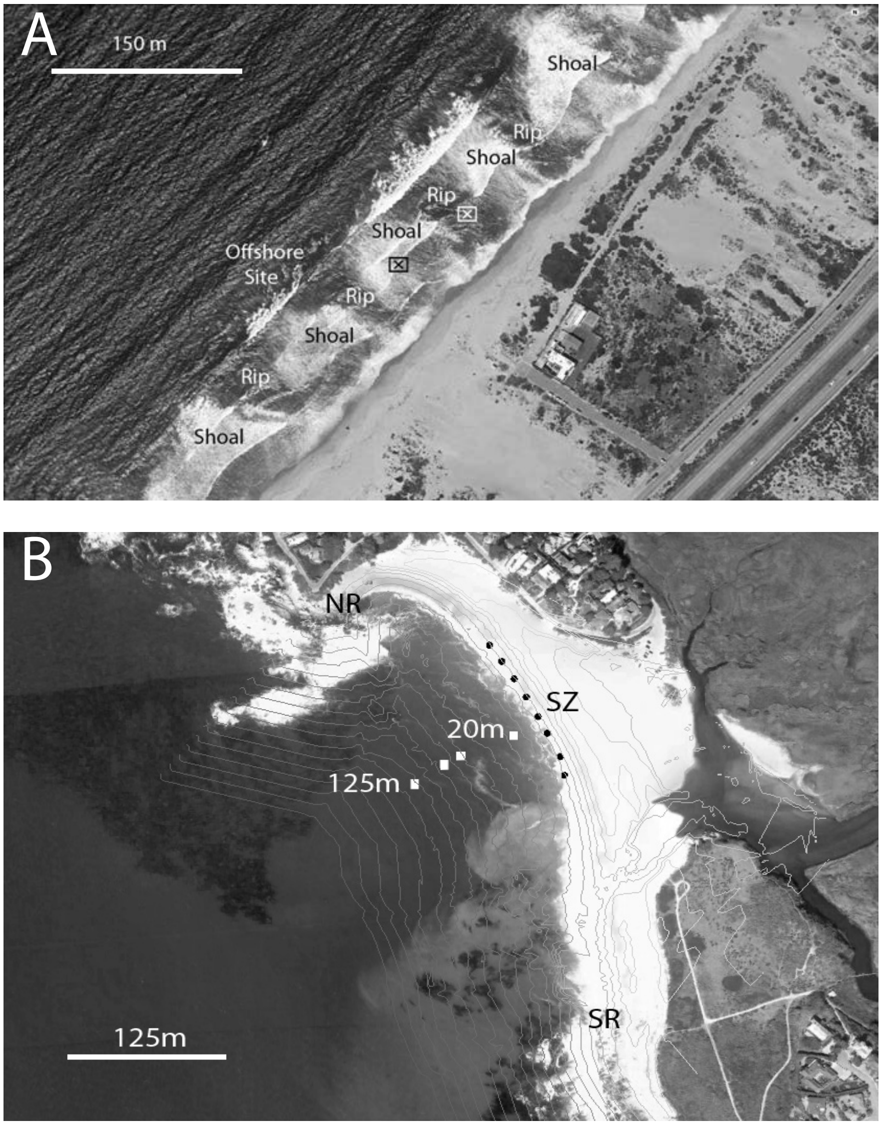


Figure 1. A) Sample site at Sand City, California. The surf zone is intermediate characterized by rip currents with deeper channels separated by shallow shoals. Rip channels were spaced ~100 m apart. Surf zone phytoplankton samples were collected at the rip and shoals labeled with X's. The sampled rip channel and shoals remained fixed in position throughout the month of daily sampling. Offshore phytoplankton samples were collected just outside the surf zone at the "Offshore Site." B) Sample site at Carmel River State Beach, California. Phytoplankton samples were collected within the sandy beach surf zone (SZ), 20 and 125 m seaward of the surf zone (20 m and 125 m, respectively), and in the rocky intertidal zones to the north and south of the beach (NR and SR, respectively). The white squares and black circles indicate locations of hydrographic instruments (Shanks et al. 2015). Images modified from Google Earth.

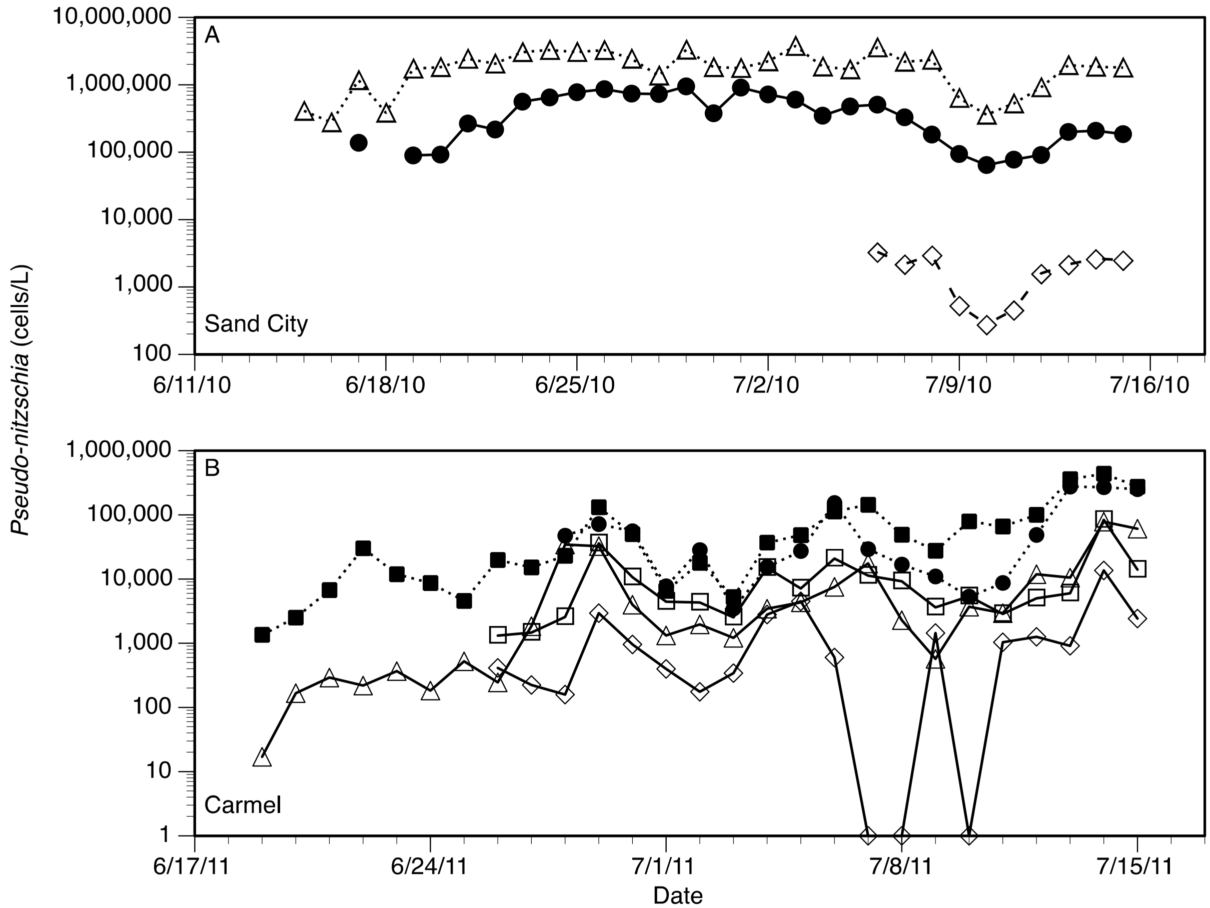


Figure 2. A) Time series of average concentration of *Pseudo-nitzschi*a (cells/L) just offshore of the intermediate surf zone at Sand City, California (filled circles), within a rip current in the surf zone (open triangles), and in water over a shoal between rip currents (open diamonds). B) Time series of average concentration of *Pseudo-nitzschia*(cells/L) 125 m offshore of Carmel River State Beach, California (filled squares), 20 m offshore of the beach (filled circles), within the reflective surf zone of the beach (open squares), within the reflective surf zone to the north (open diamonds) and south (open triangles) of the beach sample site.

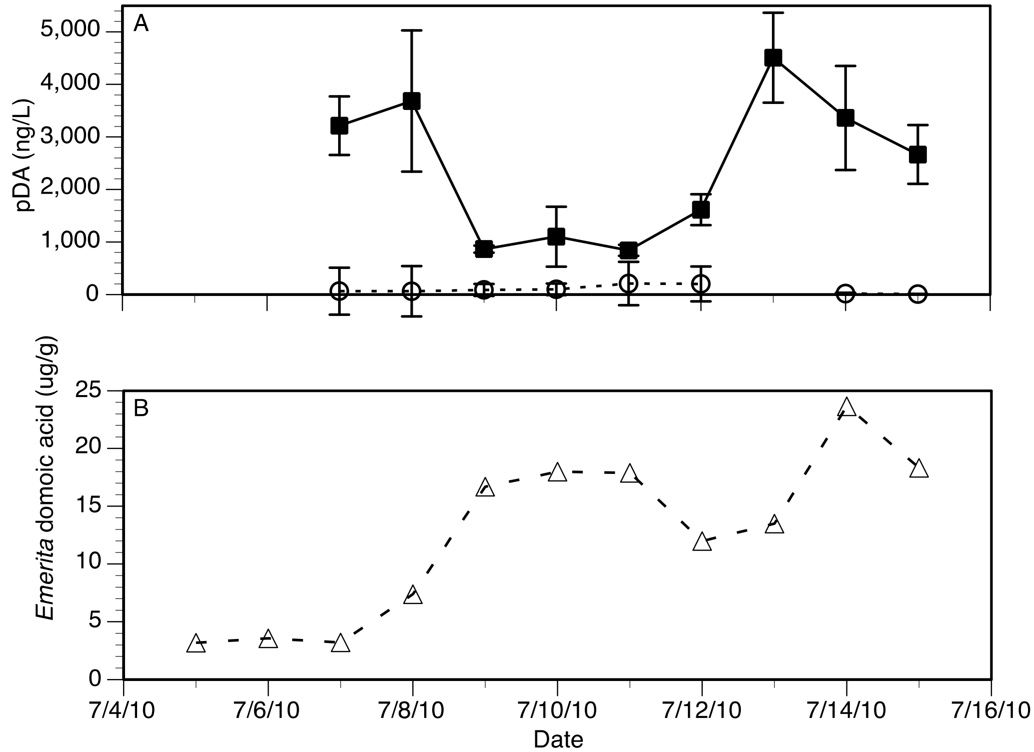
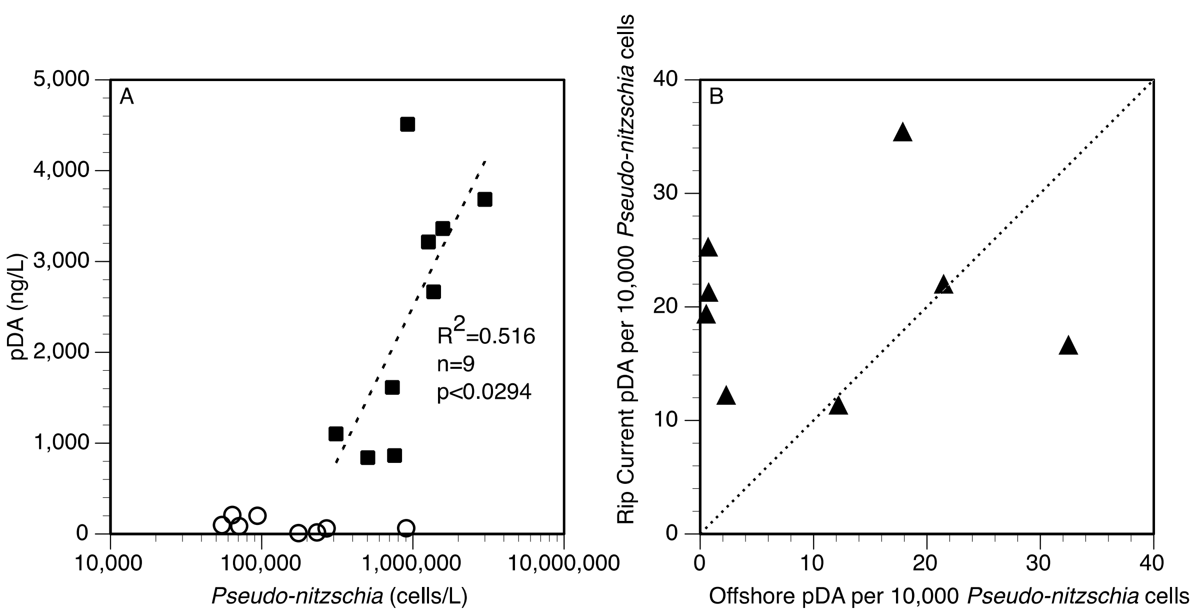


Figure 3. A) Average (± SE) concentration of particulate domoic acid (pDA) in samples collected at Sand City, California from a rip current within the surf zone (filled squares) and just seaward of the surf zone (open circles). B) Concentration of domoic acid in the sand crab *Emerita* sampled at this study site.

Figure 4. A) Correlations between the concentrations at Sand City, California of particulate domoic acid (pDA) and *Pseudo-nitzschia*cells in a surfzone rip current (filled squares) and just seaward of the surf zone (open circles). The dashed line represents the significant relationship between *Pseudo-nitzschia*cell concentration in the rip current and pDA. B) Plot of offshore and rip current pDA per *Pseudo-nitzschia*cell (scaled to 10,000 cells). The dotted line represents a one to one relationship between these variables. pDA was significantly higher per cell (log transformed data, t=2.68, df=15, P=0.0172) in cells from the rip current than offshore.



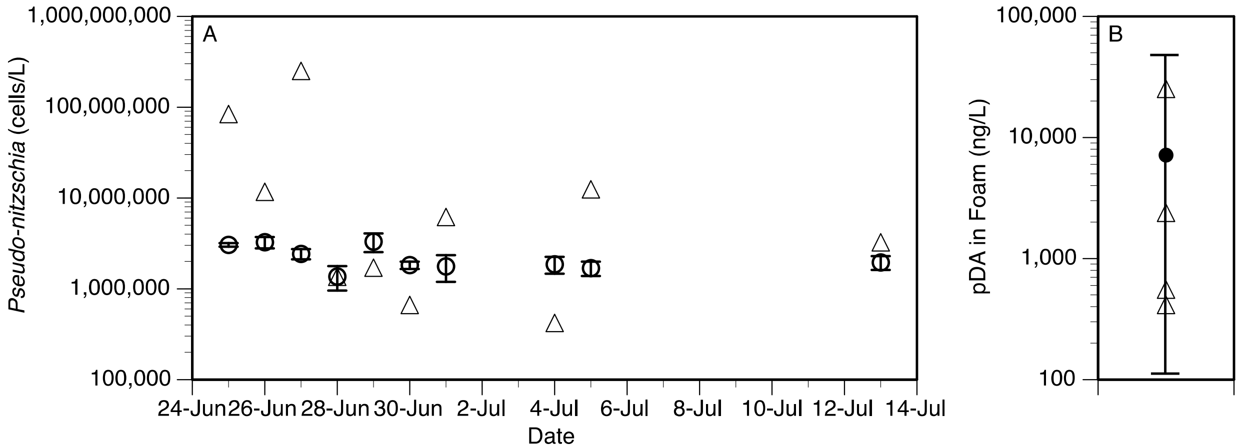


Figure 5. A) Concentration of *Pseudo-nitzschia*(cells/L) in foam samples from the Sand City surf zone (open triangles) and within a surfzone rip current (average ± SE, open circles). B) Particulate domoic acid (pDA) concentrations in four foam samples from Sand City (open triangles) and the average concentration in foam (filled circle, ± SD).

Figure 6. The concentration of particulate domoic acid (pDA) in a rip current at Sand City, California plotted with the domoic acid concentration in *Emerita analoga*collected from this beach. The *E. analoga* data were lagged 4 days. Correlations at lags of 0-3 days were not significant.