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Variation in the abundance of *Pseudo-nitzschia* and domoic acid with surf zone type

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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 surf zone hydrodynamics. During two 30-day periods, we sampled *Pseudo-nitzschia* and particulate 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 pDA were 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 1–2 orders of magnitude lower than in samples from 125 and 20 m from shore. Surf zone hydrodynamics affects the ingress of *Pseudo-nitzschia* into surf zones and the exposure of intertidal organisms to HABs on the inner shelf.

1. 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 surf zone 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). Surf zone 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 surf zone 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 surf zone water with

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offshore water and this in turn would limit the ingress of HAB species into the waters over the intertidal zone (Shanks et al., 2010, 2012). 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 surf zone 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 surf zone recirculation associated with rip currents; surf zone 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 surf zone 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 surf zone 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., 2009, 2010; Shanks et al., 2015). Here we compare *Pseudo-nitzschia* spp. (hence forth *Pseudo-nitzschia*) concentrations at these two different 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.

2. Methods

2.1. 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 (Fig. 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. (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 (Fig. 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

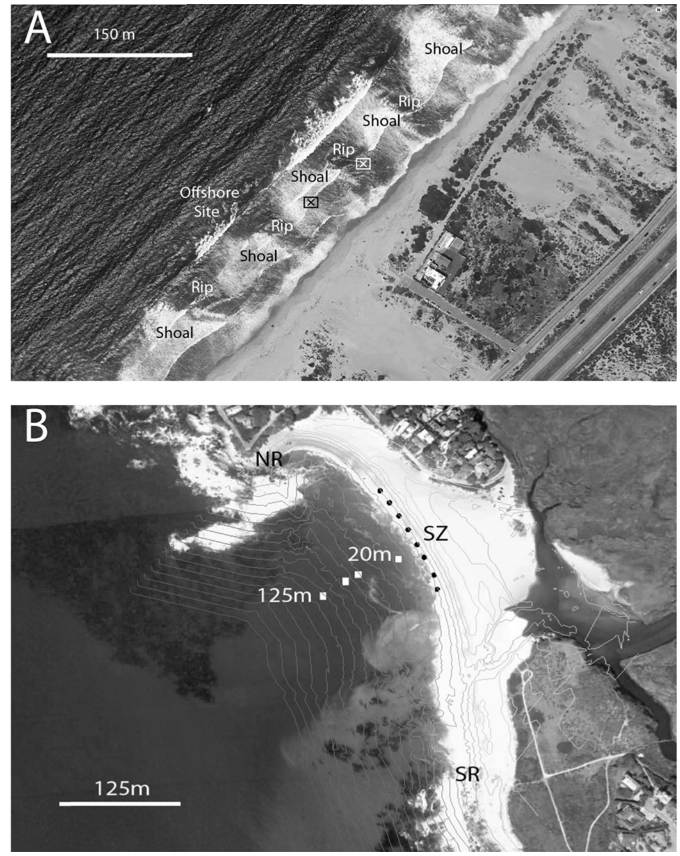

Fig. 1. (A) Sample site at Sand City, California. The surf zone is intermediate characterized by rip currents with deeper channels separated by shallow shoals. Rip channels were spaced ~100 m apart. Surf zone phytoplankton samples were collected at the rip and shoals labeled with X's. The sampled rip 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.

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., 2009, 2010). 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 Fig. 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 (Fig. 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