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Large-scale bloom of *Akashiwo sanguinea* in the Northern California current system in 2009

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ABSTRACT

Significant seabird mortality on the Oregon (OR) and Washington (WA) coast in 2009 has been attributed to a massive bloom of the dinoflagellate *Akashiwo sanguinea* (K. Hirasaka) G. Hansen & Ø. Moestrup. Initial, albeit limited, observations suggested this bloom began in WA and reached OR waters through southward transport. Here, we explore a combination of remote sensing products and an exceptional latitudinal dataset of plankton counts collected in the surfzone and offshore in OR and WA coastal waters. Records of satellite ocean color for this period support the new finding that blooms were concurrent in OR and WA waters, with no evidence for latitudinal propagation as had been previously suggested. Plankton analyses further indicate that there was a rapid and synchronized increase of *A. sanguinea* between late August and mid-September of 2009 along wide swaths of the OR and WA coasts. Bloom onset occurred during a prolonged quiescent and warm period in late August–early September, near the end of the March–October upwelling phase. An upwelling event in October likely contributed to foam production through vertical mixing of *A. sanguinea* rich waters. Bloom intensity peaked earlier and at higher levels in WA waters as compared to OR with cell concentrations exceeding 1.5×10^6 cells L^{-1} (WA) and ~350,000 cells L^{-1} (OR). In OR samples, *A. sanguinea* cells comprised upwards of 90% of dinoflagellate cell counts and ~30% of total phytoplankton cells. At some locations, *A. sanguinea* persisted well into November–December of 2009, during which time satellite sea surface temperature records indicated anomalously warm surface waters (up to ~5 °C greater than climatological means). Taken together, the data reveal a HAB event of a magnitude unprecedented in over a decade of observations. We hypothesize that these blooms originated from either a cryptic cyst bed and/or a pelagic seed bank of viable vegetative cells.

1. Introduction

The productive waters off of the U.S. Pacific Northwest (PNW) coast are representative of a classic Eastern boundary current system: the region is characterized by strong, seasonal upwelling, rich biological productivity, rapid biogeochemical cycling and high perceived rates of carbon export to the open ocean and underlying sediments (Barth and Wheeler, 2005; Hales et al., 2006). In this northern stretch of the California Current, winds predominantly blow equatorward alongshore from May to September, drawing dense, nutrient-rich, offshore subsurface waters shoreward and upward into the coastal euphotic zone. These intermittent upwelling events stimulate phytoplankton blooms that draw down surface water CO_2 levels and ultimately sustain and fuel upper trophic levels (Chase et al., 2007; Hales et al., 2006; Kudela et al., 2008; Landry and Hickey, 1989). In contrast, from October to March, conditions in the PNW are predominantly downwelling favorable: the water column is well-stratified, the standing stock of primary producers is low (surface chlorophyll $\leq 1\ \mu g\ L^{-1}$), and

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productivity is presumed to be light or nutrient limited (Hales et al., 2006; Kudela and Peterson, 2009; Wetz et al., 2004). Clear shifts in phytoplankton community composition are observed over this seasonal progression: diatoms are favored during nutrient-rich upwelling phases, whereas the relative abundance of dinoflagellates increase in the nutrient-deplete and stratified summer periods and during the relaxation phases that interrupt upwelling events (Smayda and Trainer, 2010). These successional patterns are neither regular nor smooth; upwelling is of varying intensity and magnitude as are the duration of relaxation events. As a consequence, the relative composition of phytoplankton communities favored by these contrasting conditions (e.g. colder, nutrient-rich, and well-mixed versus warmer, nutrient-poor, and more stratified) can vary widely at sub-seasonal, seasonal and inter-annual scales.

Large scale shifts in climatic forcing can also impact phytoplankton community composition in upwelling regimes, at times in ways that favor harmful algal blooms (Hallegraeff, 1993; Smayda, 2000). In the California Current system in particular, unprecedented blooms of dinoflagellates have been observed in the last decade. Plankton sampling is inherently discontinuous and therefore limited in space and time, nonetheless these blooms have tentatively been linked to climate anomalies. Dinoflagellates commonly found in these coastal upwelling regions include toxigenic, cyst-forming species such as *Alexandrium catenella* as well as non-toxic species such as *Akashiwo sanguinea* (K. Hirasaka) G. Hansen & Ø. Moestrup (Kudela et al., 2005; Smayda, 2002; Trainer et al., 2010). In Monterey Bay, California, in situ data collected between 2000 and 2006 suggests that phytoplankton community structure shifted from a regime dominated by diatoms to one dominated by two genera of toxic dinoflagellates: *Alexandrium* and *Dinophysis* (Jester et al., 2009). Expanding on these data, Kudela et al. (2010a,b, 2011) report a strong correlation between dinoflagellate abundance and decadal climate indices favoring water column stratification, shallowing mixed layers, and weak upwelling.

Aperiodic climate anomalies have also led to blooms of what Smayda and Trainer (2010) call 'irregularly bloom-forming dinoflagellates', i.e. those organisms that aperiodically appear to dominate phytoplankton community structure. Specifically, blooms of *Akashiwo sanguinea* have been reported in the relatively well-monitored regions of the Pacific Northwest and the California coast (Cloern et al., 2005, 2007; Du et al., 2011; Jessup et al., 2009). In 2004, a large *A. sanguinea* bloom was observed in San Francisco Bay and attributed to an upper-atmosphere high-pressure anomaly following a summer of weak coastal upwelling; this species had not been detected at such levels in nearly three decades of observation in the region (Cloern et al., 2005). *A. sanguinea* cells are large (40–75 μm long), highly motile, and capable of vertical migration. The species is tolerant to a wide range of temperatures and salinities and characterized by relatively high growth rates (maximum growth rate of 1.13 divisions day^{-1}) (Burkholder et al., 2008; Kudela et al., 2010a,b; Matsubara et al., 2007; Smayda, 2000; Tomas, 1997). While not directly toxic, this organism is detrimental to seabirds and other animals (Botes et al., 2003; Jessup et al., 2009; Nightingale, 1936).

In November of 2007 in Monterey Bay, discolored (yellow-green) sea foam concentrated on the coastal shorelines was linked to strong physical mixing following an *Akashiwo sanguinea* bloom. When analyzed via spectrometry this proteinaceous foam demonstrated mycosporine-like amino acids (MAA) absorption features (Jessup et al., 2009). Seabirds coated in this foam were found to be severely hypothermic. *A. sanguinea* blooms and sea foam have been described elsewhere in the region (e.g. San Francisco Bay, inlets of the Juan de Fuca Strait and more recently off Newport, Oregon (Cardwell et al., 1979; Cloern et al., 2005; Du et al., 2011; Voltolina, 1993)), but Jessup et al. (2009) was the first study to causally link *A. sanguinea*, foam production and seabird mortality. *A. sanguinea* (also known as *Gymnodinium splendens*, Lebour or *Gymnodinium sanguineum*, K. Hirasaka) have also been documented as harmful to abalone larvae and spat (Botes et al., 2003), Pacific oysters (*Ostrea lurida* and *Crassostrea gigas*) and manila littleneck clams (Cardwell et al., 1979; Nightingale, 1936; Woelke, 1961), possibly through surfactant production albeit the exact mechanism has not been documented.

In October–November of 2009, for the first time since 2001 when regular phytoplankton monitoring began in Oregon's (OR) coastal waters, a large bloom of *Akashiwo sanguinea* was detected (Du et al., 2011). High levels of *A. sanguinea* were also observed in Washington (WA) coastal waters in September 2009 (unpublished data, http://www.pacoos.org/QuarterlyClimaticEcol.html). As in the Monterey Bay event, this bloom was linked to widespread mortality of seabirds (Phillips et al., 2011). The first reports of seabird deaths were noted in mid-September, with nearly a thousand birds washing up on beaches in WA (Julia Parrish, personal communication). In early October, dead birds began to wash ashore on OR beaches (Sharnelle Fee, Director of the Wildlife Center of the North Coast, personal communication). Over 700 birds noted as 'weak, stressed, and starving' were collected from OR beaches; Red-throated Loons, Western Grebes and Common Murres represented the greatest proportion of the dead (Phillips et al., 2011). Many of these birds were in a primary molt stage during which time they are essentially flightless and have only basic or winter plumage; at this stage they are more susceptible to oiling events (Phillips et al., 2011).

The report of Du et al. (2011) was limited to data collected off the central OR coast along the Newport, OR Hydrographic Line (44.6° N) between August 27th and December 1st, 2009. Given that unpublished reports for WA (at ~47° N) reported a maximum of *Akashiwo sanguinea* cells in September and that the bloom did not peak off Newport, OR until October, Du et al. (2011) hypothesized that this bloom had originated off of WA and propagated southward. Since this early report a research project funded by the National Oceanic and Atmospheric Administration, MOCHA (Monitoring Oregon Coastal Harmful Algae), has compiled a much more extensive dataset of phytoplankton community composition for 2009. This dataset includes two large transect cruises spanning WA-OR coastal waters in August–September of 2009, regular monthly monitoring of nearshore and surfzone locations, and analyses of remote sensing products and data from regional partners in the Olympic Region Harmful Algal Bloom (ORHAB) monitoring program. Here, we evaluate this broad data set to more thoroughly describe the onset, duration and demise of a bloom of *A. sanguinea* spanning the WA and OR coastal margins. Cell count data are combined with upwelling indices, regional climate metrics, and satellite imagery to determine whether the bloom off OR was part of a synchronous coast-wide event, or showed timing and connectivity more consistent with the hypothesis that the bloom began off of WA and was transported south into OR waters. Better understanding of these bloom origins and dynamics should help regional monitoring agencies evaluate the potential threat posed by *A. sanguinea.*

2. Materials and methods

2.1. Coastal and surfzone sampling

Water samples for quantitative and qualitative analysis of *Akashiwo sanguinea* and the overall diatom and dinoflagellate community were collected in the surf zone and at offshore stations along the OR and WA coasts (spanning 38.25–48.33° N) during 2009. Offshore samples were collected during two