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A red tide of *Alexandrium fundyense* in the Gulf of Maine

D.J. McGillicuddy Jr.[a,*], M.L. Brosnahan [b], D.A. Couture [c], R. He [d], B.A. Keafer [b], J.P. Manning [e], J.L. Martin [f], C.H. Pilskaln [g], D.W. Townsend [h], D.M. Anderson [b]

[a] Department of Applied Ocean Physics and Engineering, Woods Hole Oceanographic Institution, Woods Hole, MA 02543, USA
[b] Biology Department, Woods Hole Oceanographic Institution, Woods Hole, MA 02543, USA
[c] Resource Access International, Brunswick, ME 04011, USA
[d] Department of Maine, Earth, and Atmospheric Sciences, North Carolina State University, Raleigh, NC 27695, USA
[e] National Oceanic Atmospheric Administration, Northeast Fisheries Science Center, Woods Hole, MA 02543, USA
[f] St. Andrews Biological Station, Fisheries and Oceans Canada, St. Andrews, NB, Canada E5B 2L9
[g] School of Marine Sciences, University of Massachusetts Dartmouth, North Dartmouth, MA 02747, USA
[h] School of Marine Sciences, University of Maine, Orono, ME 04469, USA

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ABSTRACT

In early July 2009, an unusually high concentration of the toxic dinoflagellate *Alexandrium fundyense* occurred in the western Gulf of Maine, causing surface waters to appear reddish brown to the human eye. The discolored water appeared to be the southern terminus of a large-scale event that caused shellfish toxicity along the entire coast of Maine to the Canadian border. Rapid-response shipboard sampling efforts together with satellite data suggest the water discoloration in the western Gulf of Maine was a highly ephemeral feature of less than two weeks in duration. Flow cytometric analysis of surface samples from the red water indicated the population was undergoing sexual reproduction. Cyst fluxes downstream of the discolored water were the highest ever measured in the Gulf of Maine, and a large deposit of new cysts was observed that fall. Although the mechanisms causing this event remain unknown, its timing coincided with an anomalous period of downwelling-favorable winds that could have played a role in aggregating upward-swimming cells. Regardless of the underlying causes, this event highlights the importance of short-term episodic phenomena on regional population dynamics of *A. fundyense*.

1. Introduction

Although the term "red tide" is frequently used in reference to harmful algal bloom events, its use to describe blooms of *Alexandrium fundyense* in the Gulf of Maine is largely a misnomer. Concentrations of *A. fundyense* seldom reach levels sufficient to discolor the water, and this species typically constitutes a small fraction of the total phytoplankton biomass. However, there have been some exceptions, including the historic bloom of 1972 during which *A. fundyense* (formerly *Gonyaulax tamarensis*) discolored the water offshore of the northern Massachusetts and New Hampshire coastlines (Hartwell, 1975; Mulligan, 1973; Sasner et al., 1974). *A. fundyense* also discolored water in the Bay of Fundy in 1980, 2003, and 2004 (Martin et al., 2008; Martin and White, 1988).

An unusual "red tide" of *A. fundyense* occurred in the Gulf of Maine in 2009. Initial discovery of the anomaly was serendipitous, taking place on a mooring turnaround cruise prompted by an increase in Paralytic Shellfish Poisoning (PSP) toxicity along the Maine coast in late June–early July. Visual observations of discolored water prompted surface sampling to and from the mooring site, revealing *A. fundyense* concentrations ranging from hundreds of thousands of cells l^{-1} to in excess of one million cells l^{-1}. This triggered a rapid-response sampling effort, both at sea and via aerial survey. Herein we characterize the phenomenology of this event utilizing these observations together with satellite imagery, shellfish toxicity measurements, flow cytometric analysis of samples from the discolored water, as well as cyst fluxes from a nearby sediment trap and a spatial survey of cysts in coastal sediments the following October. Through synthesis of this diverse set of observations, it is clear that this was a significant event not only in terms of coastal shellfish toxicity but also the regional population dynamics of *A. fundyense*.

2. Methods

2.1. Hydrography

Hydrographic profiles and water samples were collected with a standard CTD-rosette system with Niskin bottles. *A. fundyense*

* Corresponding author. Tel.: +1 508 289 2683; fax: +1 508 457 2194.
E-mail address: dmcgillicuddy@whoi.edu (D.J. McGillicuddy Jr.).

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samples were collected by sieving 2 l through a 20 μm Nitex screen that was washed into a 15 ml centrifuge tube and fixed in 5% formalin for <24 h. The samples were then centrifuged, the supernatant removed, and ice-cold methanol added. Samples were stored at −20 °C for later enumeration in the laboratory (Section 2.2 below). An additional 10 l sample of surface water was sieved in the same manner for the purposes of an on-board "live" count. Nutrient samples were filtered through Millipore HA filters, placed immediately in a sea water-ice bath for 5–10 min, and frozen at −18 °C. Concentrations of NO_3+NO_2, NH_4, $Si(OH)_4$ and PO_4 were measured ashore following each cruise with a Bran Luebbe AA3 AutoAnalyzer using standard techniques.

2.2. Moored observations

A McLane Laboratories Inc. autonomous Phytoplankton Sampler (PPS) obtained measurements at 5 m depth from April to September in two contiguous deployments. The mooring was located in the vicinity of the Northeastern Regional Association of Coastal and Ocean Observing Systems (NERACOOS) buoy B at 43° 11′N, 70° 26′W (Fig. 1B). A total of 24 samples were taken per deployment, at a frequency of one every 2–3 days. For each sample, the instrument filters 2 l of seawater onto a 15 μm Nitex screen. The instrument was prepared with 10% formalin dissolved in artificial seawater that was adjusted to be lighter (specific density = 1.018) than the ambient sample seawater. During the automated filtering process, the "light" 10% formalin solution dispensed into the bottom of the filter reservoirs is diluted and displaced upward onto the filter by the heavier ambient sample seawater. This process resulted in a 1/2 reduction in the concentration of preservative to about 5% final. After the instrument was recovered, the preserved >15 μm samples were backwashed off the Nitex screen into a 50 ml centrifuge tube for further concentration and *A. fundyense* cell counting as described in Section 2.3.

2.3. Enumeration of A. fundyense cells and cysts

A. fundyense cells were enumerated from water samples using a species-specific oligonucleotide probe and methods described in Anderson et al. (2005c). Both *A. tamarense* and *A. fundyense* occur in the Gulf of Maine, and these are considered to be varieties of the same species (Anderson et al., 1994; Brosnahan et al., 2010; Scholin et al., 1995). Available molecular probes cannot distinguish between them, and only detailed analysis of the thecal plates on individual cells can provide this resolution—which is not practical for large numbers of field samples. Accordingly, for the purpose of this study, the name *A. fundyense* is used to refer to both forms.

Surface "live" counts consisted of two transects across a Sedgewick-Rafter counting slide using an on-board light microscope at 200x magnification. The slide was loaded with 1 ml of concentrated sieved material (see Section 2.1 above) resuspended to 14 ml. This provided a lower limit of detection of 14 cells l^{-1}. Light microscopy of this kind cannot distinguish *A. fundyense* from the morphologically similar non-toxic species *A. ostenfeldii*, and therefore the live counts can sometimes overestimate *A. fundyense* concentration.

Cysts of *A. fundyense* were collected and enumerated from sediment samples using primulin-staining methods described in Anderson et al. (2005d). Samples were obtained with a Craib corer in dedicated surveys in fall 2008, 2009, and 2010. The sampling pattern consisted of 14 cross-shore transects in the coastal Gulf of Maine and three transects across Georges Bank, for a total of approximately 120 stations. *A. fundyense* cysts from the upper 1 cm of oxygenated sediment are viable for germination (Anderson et al., 2005d) and thus only that vertical fraction of the sediment samples is presented herein.

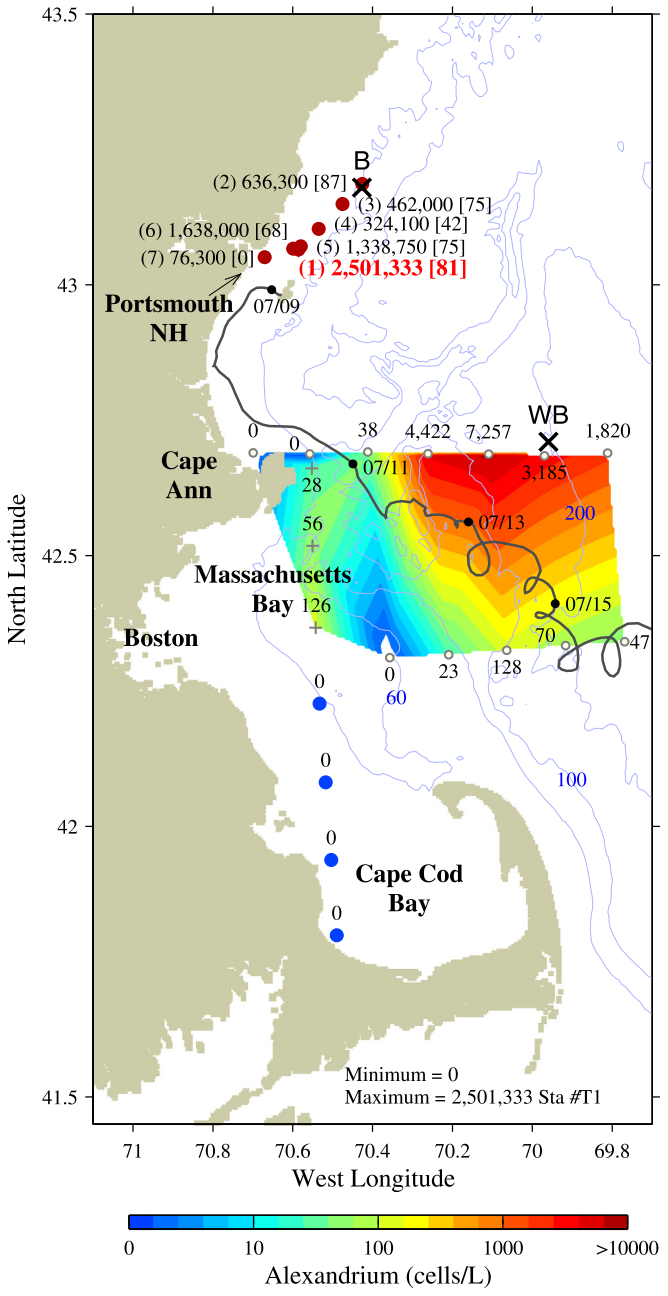

Fig. 1. Dots north of 43°N: surface *A. fundyense* concentrations (cells l^{-1}) observed on July 10, 2009 (whole cell counts). Station numbers (in parentheses) precede the cell counts, and the percentage of planozygotes follows in brackets. Map, dots, and plus signs south of 43°N: surface *A. fundyense* concentrations observed on R/V Tioga 383 July 12, 2009 (live counts). Black crosses indicate the locations of NERACOOS mooring "B" where the McLane PPS sampler was located, and the Wilkinson Basin "WB" sediment trap. Trajectory of surface drifter #97201 released on July 9 is plotted as a gray line, with dates provided every two days along track.

Cyst fluxes were measured in time-series sediment traps (Honjo and Doherty, 1988) deployed on subsurface moorings. See Pilskaln et al. (this issue) for a complete description of these data. Of particular interest to this study are the traps located in Wilkinson Basin located at 42° 43′N, 69° 58′W (Fig. 1, WB). The traps had a baffled surface collection area of 0.5 m^2, and collected time-series samples in thirteen 250 ml volume cups per deployment. Prior to deployment, trap cups were pre-poisoned with an 8% density-adjusted formalin solution in filtered seawater buffered to a pH of 8.0–8.1. Recovery and redeployment of the trap moorings occurred approximately every 5–9 months, with individual cup collection

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