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Development of a conceptual warning system for toxic levels of *Alexandrium fundyense* in the Bay of Fundy based on remote sensing data

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A B S T R A C T

Harmful algal blooms (HABs) present a potential danger for human health and commercial activities, especially in coastal regions. Observing systems increasingly rely on remote sensors to monitor and possibly predict the locations and intensity of such blooms. Here we present a novel approach for detecting HABs of *Alexandrium fundyense* in the Bay of Fundy, Canada. *A. fundyense* is considered toxic for individuals who consume shellfish when cell abundances adjacent to shellfish harvesting areas are as low as 200 cells·L^{-1}, making it difficult to use direct remote sensing techniques to assess the threat in the early stages of the development of the bloom. Using *in situ A. fundyense* cell abundance measurements, together with satellite observations of sea-surface temperature and the occurrence of diatom-dominated phytoplankton populations, a warning system was developed based on three levels of alerts: green (low abundance of *A. fundyense*), orange (possible threat of *A. fundyense*) and red (high probability of *A. fundyense* concentrations that would result in shellfish toxicity above safe levels for human consumption). Combined information on diatom phenology and variations in sea-surface temperature are key to the timing of *A. fundyense* blooms: our data reveal that the termination of the diatom spring bloom, associated with the warming of the water, can trigger an increase in *A. fundyense* cell abundance. The objective criteria for a HAB warning system was developed and tested in the Bay of Fundy using two different datasets: one to develop the algorithm (data collected between 1998 and 2007) and one to assess its performance (data collected in 2011). The warning system is based on the cautionary principle that a false negative (warning not issued when it should have been) is far more serious than a false positive (warning issued when it should not have been). The overall success of the algorithm when tested on the validation dataset is about 70% using a threshold of 150 *A. fundyense* cells·L^{-1}, with a low occurrence of false negative red alerts (< 8%). The satellite-data-based warning can be used to optimize an *in situ* monitoring system, which can be designed to be more intensive when the warning status is orange or red. This study demonstrates that combined satellite information on phytoplankton phenology and sea-surface temperature can help predict low abundances of toxic *A. fundyense* cells. It also highlights the importance of an integrated approach combining satellite and *in situ* observations to monitor HABs.

1. Introduction

Harmful algal blooms (HABs) continue to be of concern throughout the world and research is focusing on the development of tools for their early detection. Toxic algae occur in all phytoplankton groups, including diatoms (*e.g.*, *Pseudo-nitzschia* spp.), dinoflagellates (*e.g.*, *Alexandrium* spp.) and cyanobacteria (*e.g.*, *Trichodesmium* spp.). This work focuses on a single species, *Alexandrium fundyense*, from a particular location, the Bay of Fundy, eastern Canada.

The dinoflagellates, *Alexandrium fundyense* is known to produce paralytic shellfish poisoning (PSP) toxins in the Bay of Fundy and neighboring Gulf of Maine. PSP toxins can accumulate in shellfish through filter-feeding, and are potentially fatal to vertebrate consumers (Prakash et al., 1971; Martin and Richard, 1996; Hamer et al., 2012). This harmful algal species affects wild fisheries as well as finfish and shellfish aquaculture in the region. *A. fundyense* has been responsible

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for Atlantic salmon (*Salmo salar*) poisoning and mortalities in the Bay of Fundy (Martin et al., 2008), when concentrations reached 2.0×10^5 cells·L^{-1} (Burridge et al., 2010). *A. fundyense* was also responsible for Atlantic herring (*Clupea harengus harengus*) mortalities in 1976 and 1979 (White, 1977, 1980).

A. fundyense is considered to be harmful for vertebrate consumers of shellfish even when cells are present at low densities in natural waters, with counts of 200 cells·L^{-1} being considered to be the level at which toxicity can be detected in shellfish in the Bay of Fundy (Martin et al., 2010; J.L. Martin, pers. comm). Values of around 500 cells·L^{-1} can lead to levels of shellfish toxicity above the threshold accepted for human consumption (80 µg STX equiv. 100 g meat), leading to closures of shellfish harvesting areas (Page et al., 2004, J.L. Martin pers. comm.). Many countries throughout the world, including Canada, have extensive programs to monitor toxins in shellfish to comply with domestic and international regulations that ensure safe products for consumers.

Variables including the timing of the *Alexandrium* spp. blooms (temporal and spatial variations in abundance), and environmental conditions prior to, during, and after these occurrences, are being studied in some areas, to understand the population dynamics of this species. These observations have revealed a complex pattern of seasonal variations, with the species generally beginning to appear in the water column in late spring (May) and subsiding in late summer (July/August) (Martin et al., 2010). There is strong interannual variability in the timing, intensity, and regional distribution of the cells (Page et al., 2004). During the winter resting period, cysts of *A. fundyense* tend to occur in high concentrations in areas of mud/clay bottoms rather than gravel/rocky bottom sediments. A high abundance of resting cysts in the winter does not correlate with large blooms of *A. fundyense* in the summer months (Martin et al., 2014a, 2014b). Many years of observations have shown that *A. fundyense* cells first appear in the water column when the water temperature begins to increase, and the population multiplies exponentially in low-wind and low-light conditions associated with fog (Martin et al., 2014a). The identification of the exact environmental conditions that trigger the occurrences and propagation of *A. fundyense* cells continues to be elusive (Townsend et al., 2005, 2014). These complexities have made it difficult to model and predict *A. fundyense* blooms with a view to minimizing risks to seafood consumers and damage to the aquaculture industries.

It is difficult, if not impossible, to develop a large-scale warning system that relies solely on *in situ* measurements. For instance, automated moorings and buoys, despite measuring water properties with high temporal resolution are not able to capture changes that may occur several kilometers upstream or downstream of their location. This has led to the investigation of the use of satellite remote sensing based on sea-surface temperature to detect blooms of *A. tamarense* in the Gulf of Maine (*e.g.*, Keafer and Anderson, 1993). In other regions of the world, algorithms have been developed to identify HABs using satellite ocean-colour measurements (Sathyendranath et al., 1997; Subramaniam et al., 1999, 2002; Kahru, 1997; Babin et al., 2005; Hu et al., 2010; Tomlinson et al., 2004, 2009). Growing interest in the detection of HABs has led to the creation of an international program (the GlobalHAB programme) that co-ordinates and builds on national, regional and international efforts in HAB research within an ecological and oceanographic context.

In this study we begin with the method of Keafer and Anderson (1993) and consider whether a combination of variables measured by remote sensing could provide information complementary to what we observe from *in situ* measurements. Recently, McGillicuddy et al. (2014) investigated the use of the Medium Resolution Imaging Spectroradiometer (MERIS) ocean colour data to obtain information on *A. fundyense* blooms in the Bay of Fundy. They concluded that satellite-retrieved chlorophyll-a concentration, an index of phytoplankton biomass, could be useful to track the presence of high phytoplankton biomass. Direct observation of the presence of *A. fundyense* at harmful levels using remote sensing remains difficult, especially considering that levels of toxins in shellfish are considered unsafe even at very low cell concentrations (around 500 cells·L^{-1}), when *A. fundyense* is not the dominant species in the water column. Furthermore, in the Bay of Fundy, the optical signature of the species closely resembles that of other common phytoplankton species, including diatoms and other dinoflagellates (M.-H. Forget, unpublished data).

We explore the potential to detect *A. fundyense* indirectly, using indicators of the marine ecosystem that are accessible through remote sensing. In particular we exploit the species succession dynamics evidenced by Townsend et al. (2005) in the Gulf of Maine, where *A. fundyense* blooms tend to follow the decline of diatom blooms. Since *A. fundyense* appears when the temperatures increase after the winter minimum, we also used sea-surface temperature (SST) as a proxy for *A. fundyense* observation. The focus of the study is on *A. fundyense* cells present in the surface waters - we do not address the issue of overwintering *A. fundyense* resting cysts, which can be responsible for some winter time shellfish toxicity – either through re-suspension of cells due to digging activities, wave movement or other disturbances. We also investigate whether using a threshold of 200 *A. fundyense* cells·L^{-1} is a realistic target for a remote sensing approach using our *in situ* dataset to determine the optimum threshold for a warning system.

2. Material and methods

2.1. In situ data

A monitoring program was initiated in 1987 with water samples collected at four/five stations on a monthly basis during the colder months (from November to March each year) and on a weekly basis between April and October to monitor phytoplankton population dynamics, including the toxic algae *A. fundyense* (Martin et al., 2001, 2006, 2014b), among other objectives. From this archive of five stations (see Fig. 1, Martin et al., 2014b), we selected data from the most offshore station, *i.e.*, Wolves station (Fig. 1), between 1998 and 2007 (corresponding to the period of satellite observations), to develop a satellite-based approach to monitor blooms of *A. fundyense*. In 2011, two additional offshore stations were added to the initial sampling plan (stations 46 and 57, Fig. 1, Table 1) to create an *in situ* dataset independent of the data used for algorithm development. These three stations were used because of their offshore location, which made them better suited for satellite observations (*i.e.*, reduced contamination of the marine signal by land) than in-shore stations. We limited the original dataset from early May to mid-July to focus our study on the timing of *A. fundyense* blooms. Station Wolves is located 7.5 and 16.5 km from stations 46 and 57 respectively while station 46 and 57 are separated by 9.5 km.

Sampling was conducted aboard the Canadian Coast Guard Research Vessel, *Viola M. Davidson* and on the Huntsman Marine Science Center vessel *Fundy Spray*. Phytoplankton samples were collected from the water surface by bucket for all three stations. During the summer months a 10 m vertical plankton haul was made with a 20-µm mesh net, 0.3 m in diameter. A subsample was preserved with formalin:acetic acid (1:1 by volume) for plankton identification. Water samples (250 mL) were preserved with 5 mL formalin:acetic acid. Samples were brought back to the laboratory and 50-mL subsamples were allowed to settle in Zeiss counting chambers for 16 h before microscopic examination. All phytoplankton of size > 5 µm were identified and enumerated (as cells·L^{-1}) using a Nikon inverted microscope.

2.2. Satellite data

2.2.1. Satellite datasets for algorithm development

Daily remote sensing reflectance (level 2) data from the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) were downloaded from the NASA ocean-color website (http://oceancolor.gsfc.nasa.gov). Images over the Bay of Fundy covering the *in situ* sampling stations were downloaded