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Categorizing the severity of paralytic shellfish poisoning outbreaks in the Gulf of Maine for forecasting and management

Judith L. Kleindinst [a],*, Donald M. Anderson [a], Dennis J. McGillicuddy Jr.[a], Richard P. Stumpf [b], Kathleen M. Fisher [c], Darcie A. Couture [d], J. Michael Hickey [e], Christopher Nash [f]

[a] Woods Hole Oceanographic Institution, Woods Hole, MA 02543, USA
[b] NOAA National Centers for Coastal Ocean Science, Silver Spring, MD 20910, USA
[c] NOAA Center for Operational Oceanographic Products and Services, Silver Spring, MD 20910, USA
[d] Darcie A. Couture, Resource Access International, Brunswick, ME 04011, USA
[e] Massachusetts Division of Marine Fisheries, New Bedford, MA 02740, USA
[f] New Hampshire Department of Environmental Services, Concord, NH 03302, USA

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ABSTRACT

Development of forecasting systems for harmful algal blooms (HABs) has been a long-standing research and management goal. Significant progress has been made in the Gulf of Maine, where seasonal bloom forecasts are now being issued annually using *Alexandrium fundyense* cyst abundance maps and a population dynamics model developed for that organism. Thus far, these forecasts have used terms such as “significant”, “moderately large” or “moderate” to convey the extent of forecasted paralytic shellfish poisoning (PSP) outbreaks. In this study, historical shellfish harvesting closure data along the coast of the Gulf of Maine were used to derive a series of bloom severity levels that are analogous to those used to define major storms like hurricanes or tornados. Thirty-four years of PSP-related shellfish closure data for Maine, Massachusetts and New Hampshire were collected and mapped to depict the extent of coastline closure in each year. Due to fractal considerations, different methods were explored for measuring length of coastline closed. Ultimately, a simple procedure was developed using arbitrary straight-line segments to represent specific sections of the coastline. This method was consistently applied to each year’s PSP toxicity closure map to calculate the total length of coastline closed. Maps were then clustered together statistically to yield distinct groups of years with similar characteristics. A series of categories or levels was defined (“Level 1: Limited”, “Level 2: Moderate”, and “Level 3: Extensive”) each with an associated range of expected coastline closed, which can now be used instead of vague descriptors in future forecasts. This will provide scientifically consistent and simply defined information to the public as well as resource managers who make decisions on the basis of the forecasts.

1. Introduction

Development of forecasting systems for harmful algal blooms (HABs) has been a long-standing research and management goal. In most locations, however, there is considerable interannual variability in algal abundance and distribution, and therefore also in toxicity (e.g., Anderson et al., this issue-a; Horner et al., 1997; McGillicuddy et al., 2005b; Thomas et al., 2010) presenting challenges in forecasting HAB events and their impacts.

In southwest Florida (U.S.), blooms of *Karenia brevis* have been a recurrent problem for decades (Steidinger, 2009). Using a combination of satellite imagery, wind predictions, in situ observations, and a model derived from historical observations, a forecast system was developed by the National Oceanic and Atmospheric Administration (NOAA) and the state of Florida (Stumpf et al., 2009). These short range (3–4 days) forecasts provide information on possible impact levels (very low to high) based on *K. brevis* cell concentrations and wind speed and direction, which are used to predict bloom intensification and potential transport along the coast. The expected impacts include possible human respiratory problems, presence of dead fish or marine animals, and shellfish harvesting closures. The forecasts include areas of impact by county and sometimes by water body such as specific bays.

In the Baltic Sea, where cyanobacterial blooms are a problem each year, researchers have developed a model using nutrient

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* Corresponding author. Tel.: +1 508 289 2745; fax: +1 508 457 2027.
E-mail addresses: jkleindinst@whoi.edu (J.L. Kleindinst), danderson@whoi.edu (D.M. Anderson), dmcgillicuddy@whoi.edu (D.J. McGillicuddy Jr.), Richard.Stumpf@noaa.gov (R.P. Stumpf), ktfish12@gmail.com (K.M. Fisher), Darcie.Couture@att.net (D.A. Couture), Michael.Hickey@state.ma.us (J. Michael Hickey), Chris.Nash@des.nh.gov (C. Nash).

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input from the previous winter to predict the biomass of cyanobacteria present the following summer (Kiirikki et al., 2006; Roiha et al., 2010). The Finnish Meteorological Institute runs simulations with a second model using the same initial (winter) nutrient concentration fields and issues a final forecast based on runs of the two models, as well as on the monitored development of the dissolved inorganic nitrogen (DIN)/ dissolved inorganic phosphorus (DIP) -ratio during spring (Heikki Pitkänen, Finnish Environment Institute, personal communication). The model has been used as a tool in estimating the risk of cyanobacterial blooms for the Baltic Sea. Four bloom risk categories (low, moderate, considerable, and high) are used to characterize the risk of impacts. Seasonal forecasts are posted on the Baltic Sea Portal website (Finnish Environment Institute; http://www.itameriportaali.fi/en/itamerinyt/levaennuste/en_GB/levaennuste/).

Blooms of the toxic dinoflagellate *Alexandrium fundyense* have been recurrent and widespread events in the Gulf of Maine for many decades (Anderson, 1997; Anderson et al., 2005a) causing shellfish harvesting closures along the coastlines of Maine, New Hampshire and Massachusetts, as well as Atlantic Canada. In 1972 a massive *A. fundyense* bloom occurred in this region causing closures from Maine to Massachusetts due to the presence of PSP toxins in shellfish (Hartwell, 1975; Mulligan, 1975). Following that outbreak, comprehensive statewide shellfish monitoring programs were implemented or expanded to protect public health in the region by limiting or restricting harvesting in areas experiencing PSP toxicity in shellfish (Bean et al., 2005; Hurst, 1975; Shumway et al., 1988). This region experiences considerable interannual variability in *A. fundyense* blooms and associated toxicity in shellfish (Anderson et al., this issue-a; Bean et al., 2005; McGillicuddy et al., 2005b; Thomas et al., 2010) posing a significant challenge to the resource managers responsible for these monitoring programs.

Conceptual models of *A. fundyense* bloom dynamics in the Gulf of Maine (Anderson et al., 2005b; McGillicuddy et al., 2005a) include key features such as two large cyst “seedbeds”—one in the Bay of Fundy and the other offshore of mid-coast Maine (Anderson et al., this issue-b). Cysts germinate from the Bay of Fundy seedbed, causing localized blooms in the bay that are self-seeding with respect to future outbreaks in that area. The blooms also contribute to populations in the eastern section of the Gulf as some cells escape the Bay of Fundy and enter the eastern segment of the Maine Coastal Current where they form blooms. Some *A. fundyense* cells travel south and west with that current, while others are either removed due to grazing or mortality, or deposited as cysts in the mid-coast Maine seedbed. In subsequent years, these latter cysts (combined with cells originating from the Bay of Fundy) inoculate blooms that cause toxicity in western portions of the Gulf and possibly offshore waters as well (Anderson et al., 2005b; McGillicuddy et al., 2005a).

Building from this conceptual understanding of bloom dynamics, models have been developed for this region that have skill in simulating blooms of *A. fundyense* (He et al., 2008; McGillicuddy et al., 2005a; Stock et al., 2005). This model is now being used for both short- and long-term forecasts (Anderson et al., 2012; Li et al., 2009; McGillicuddy et al., 2011). Thus far, however, these forecasts have used vague and undefined terms such as “significant” or “moderately large” to describe the extent and possible impact of forecasted blooms and toxicity on shellfish harvesting.

These recent advances in forecasting HABs raise an important question—how can we categorize and describe the extent of the bloom that is being forecast? In 2008, the first seasonal forecast for PSP in the Gulf of Maine was issued, stating that conditions were ripe for a “significant bloom” that year, perhaps similar to the historic one of 2005 (Anderson et al., 2005a). This prediction was borne out as the region experienced a widespread bloom that year, with areas closed to shellfish harvesting along much of the eastern and western Gulf of Maine (EGOM, WGOM) as far south as the Cape Cod Canal in Massachusetts (Fig. 1). The closures were sufficiently extensive and severe that federal disaster assistance was provided to Maine, New Hampshire, and Massachusetts.

Seasonal forecasts in the years since 2008 were categorized as follows: 2009—“moderately large”; 2010—“significant”, and 2011—“moderate”. The categories were not defined in terms of specific bloom impacts such as projected extent of shellfish bed closures, and thus were somewhat confusing to the public and press. These examples illustrate the need to categorize and describe blooms in such a way that these descriptors can be consistently applied to seasonal forecasts. In order to be useful, bloom descriptors need to be easily understood and informative to managers and the public—similar to those used for forecasting major weather events such as hurricanes and typhoons.

There are five categories on the Saffir/Simpson Hurricane Wind Scale, each providing a description of expected wind severity, property damage, loss of life, and power outages. For example, a Category 2 hurricane (sustained winds of 154–177 km/h) is described as “*extremely dangerous winds* [*that*] *will cause extensive damage. Well-constructed frame homes could sustain major roof and siding damage. … Near total power loss is expected with outages that could last from several days to weeks*.” For a Category 5 hurricane (sustained winds of 252 km/h or higher) “*catastrophic damage will occur. …Most of the area will be uninhabitable for weeks or months*.”

The Fujita intensity scale for typhoons has six levels, also providing descriptions of expected damage to property and wind strength. In addition to the numbers, the typhoon scale has names to accompany the categories, such as light damage, severe damage, etc. For example, the second level, F1, with wind speeds of 116–180 km/h is classified as “*moderate damage*:… *surfaces peeled off roads*, *autos pushed off the road*…” and the second highest level, F5, is described “*devastating damage*: …*cars thrown and large missiles generated*”.

Here we present a scheme to characterize blooms of *A. fundyense* in the Gulf of Maine using a well-defined metric based on the geographic extent of shellfish bed closures along the coast. To our knowledge, this is the first attempt to develop a formal categorization for the prediction of the severity of HABs in a region. The duration of harvesting closures was also considered, using data derived during the Anderson et al. (this issue-a) study of interannual variability of PSP toxicity in the GOM[1].

2. Methods

2.1. Historical data on closures

Data on shellfish bed closures due to presence of PSP toxins in *M. edulis* were collected from shellfish resource managers in the three New England states (Maine, New Hampshire, and Massachusetts) for the period 1978–2011. As described below, the availability of data varied among the three states. These records were used to create maps to depict the extent of closures for each year (Fig. 1). In preparing these maps, only closure data using *M. edulis* toxicity were used as these organisms are considered “indicator” species, taking up and depurating the PSP toxins more quickly than other organisms such as surf or hard clams (Bricelj and Shumway, 1998). In particular, hard clams such as the surf clam and ocean quahog can retain toxin for years and thus, closure

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[1] In this study, we have focused on the harmful algal species *Alexandrium tamarense* Group I, which we refer to as *A. fundyense*, the renaming proposed by Lilly et al. (2007).

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