Deep-Sea Research II 103 (2014) 277–287

Contents lists available at ScienceDirect

Deep-Sea Research II

journal homepage: www.elsevier.com/locate/dsr2

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

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ARTICLE INFO

Available online 16 March 2013

Keywords:
Alexandrium fundyense
Harmful algal blooms
HABs
PSP
Forecasts

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., 2014a; 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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0967-0645/$ - see front matter
http://dx.doi.org/10.1016/j.dsr2.2013.03.027

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., 2014a; 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., 2014b). 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. (2014a) 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

[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).

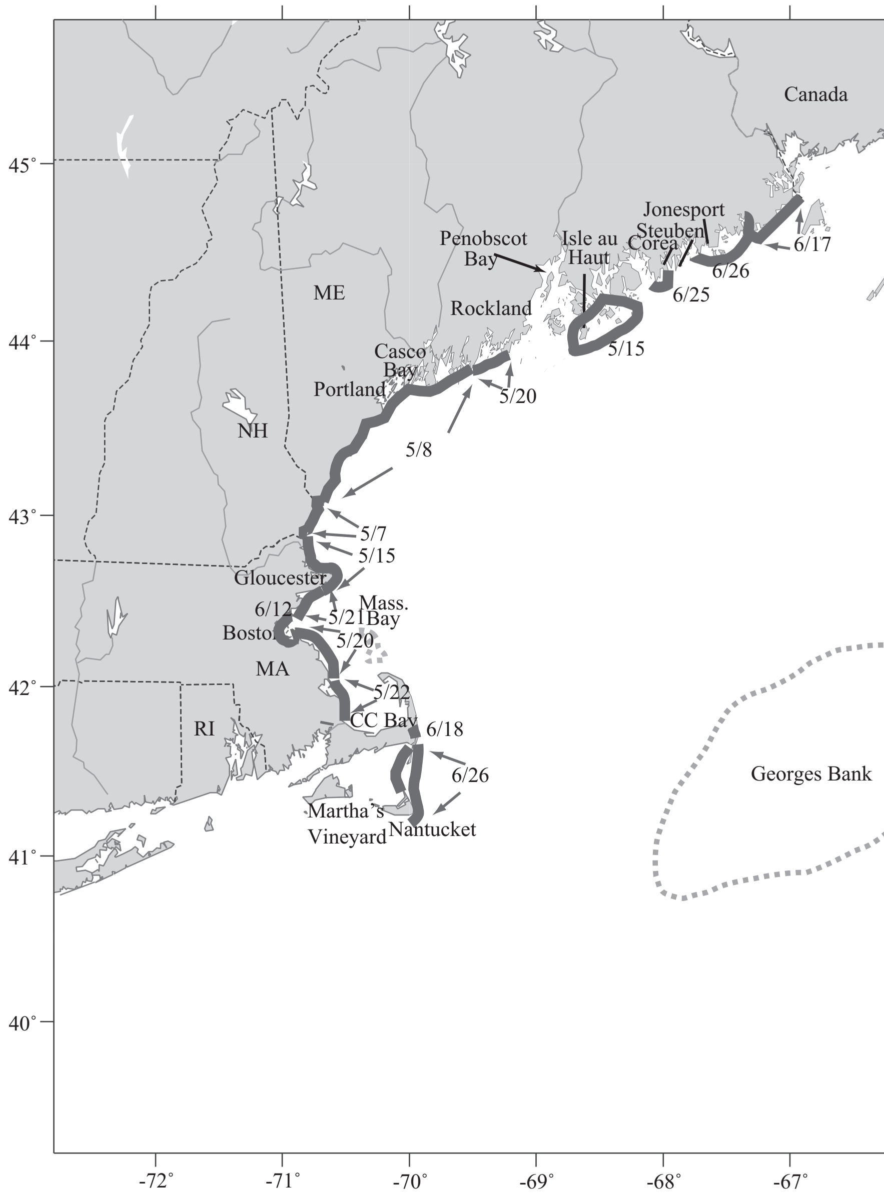

Fig. 1. Shellfish closures along the coast of Maine, New Hampshire, and Massachusetts due to detection of PSP toxins during the 2008 *A. fundyense* bloom. Issuance dates of initial closures are also indicated (Compiled from information provided by the Massachusetts Division of Marine Fisheries, the New Hampshire Department of Environmental Services, and the Maine Department of Marine Resources).

information on those species would not necessarily relate to a particular year's bloom.

The study region is defined as the area from the border between Maine and Canada and the border between Massachusetts and Rhode Island. Historically, the range of widespread, regional GOM *A. fundyense* blooms has not extended beyond Massachusetts (Anderson, 1997). This region is further broken down into two subregions—the WGOM and the EGOM. Penobscot Bay has often been used as a logical delineator between the EGOM and WGOM subregions, each system having unique hydrographic features (Anderson, 1997; Anderson et al., 2005b; Anderson et al., 2014b; McGillicuddy et al., 2005b; Thomas et al., 2010; Townsend et al., 2001).

2.1.1. *Maine*

The Maine Department of Marine Resources posts official notices regarding shellfish harvesting closures due to PSP toxins on their website—http://www.state.me.us/dmr/rm/public_health/closures/pspclosures.htm. These notices provide details on the affected shellfish and areas closed, as well as a map depicting the closure area(s) and any exceptions. As areas are re-opened or closures expanded, or different shellfish impacted, new notices are posted, replacing the earlier version. Notices for the period 1978–2011 were reviewed, and areas of closure for each year noted (e.g., New Hampshire/ Maine border to Cape Elizabeth, Maine). Information was then translated onto a map of the entire study area for each of the 34 years of the study.

2.1.2. *New Hampshire*

From 2005 onward, the author has been keeping records of actual closures in this state. The New Hampshire Department of Environmental Services (NH DES) provided closure records for the period 2000–2004. Historical closure notices before 2000 were not available, however, PSP toxicity results were obtained from NH DES dating back to 1991. Using these data, assumptions regarding closures for the years 1991–1999 were made. Based on the quarantine level of 80 μg saxitoxin equivalents (STX eq) per 100 g of shellfish meat, the data were reviewed to determine in which years the quarantine level was approached or exceeded. These results were reviewed with NH DES personnel to corroborate the assumptions. For the period 1978–1990, assumptions were again made, using data from the neighboring states. If areas in Maine were closed adjacent to the New Hampshire border, and the north shore of Massachusetts was also closed, it was assumed that the intervening New Hampshire coastline was also closed. If western Maine was closed, but the north shore of Massachusetts was open, it was assumed that half of the New Hampshire coastline was closed. This approach was used solely for the purpose of making the best assumption possible for those years where data were not available.

2.1.3. *Massachusetts*

The Massachusetts Division of Marine Fisheries (MA DMF) provided maps for this study depicting closed areas for the period 1990–2004. As described above, the author has been keeping records of closures from 2005 to the present. For the period prior to 1990, closure data were not available, so historical PSP toxicity records for *M. edulis* were reviewed and sorted according to toxin scores. In those years and locations where the quarantine level was reached, assumptions were made based on closures and toxin data available for the later time periods. In making these determinations, data from the years where closure maps were available (1990–2004) were compared with those prior to 1990 so that consistency in closure determination was maintained. For example, if there was toxicity at or above 80 μg STX eq per 100 g shellfish meat in the area between Gloucester, Massachusetts and that state's border with New Hampshire, typically the entire segment, including Cape Ann, is closed. These assumptions were also reviewed with the MA DMF to ensure that they were consistent with their policies.

2.2. *Quantifying the geographic extent of closures*

To quantify the geographic extent of closures for each year, the length of coastline closed needs to be calculated. This is a fractal problem in that the result depends on the length and type of line that is drawn to depict the coastline. That is, curved lines attempting to trace the coastline give a higher number than straight line segments drawn from one point to the other (Mandelbrot, 1983; Fig. 2A and B).

2.2.1. *ImageJ and straight line segments*

ImageJ is public domain open source imaging system software developed by the National Institutes of Health (Rasband, 1997–2012: http://rsbweb.nih.gov/ij/). The software allows use of various image formats to derive distance. Using the jpeg images for the closure maps already created, ImageJ software was used to trace straight-line segments of coastline closures and convert these results to distance in km. Care was taken to use the same resolution on each jpeg version of the maps as the ImageJ measurements are based on pixels. Straight-line segments were drawn for each major section of coastline, using the same approach each year (Fig. 2B). Results were tabulated to derive a total closure distance for each year for the WGOM and EGOM subregions and for the total area (Table 1 and Fig. 3).

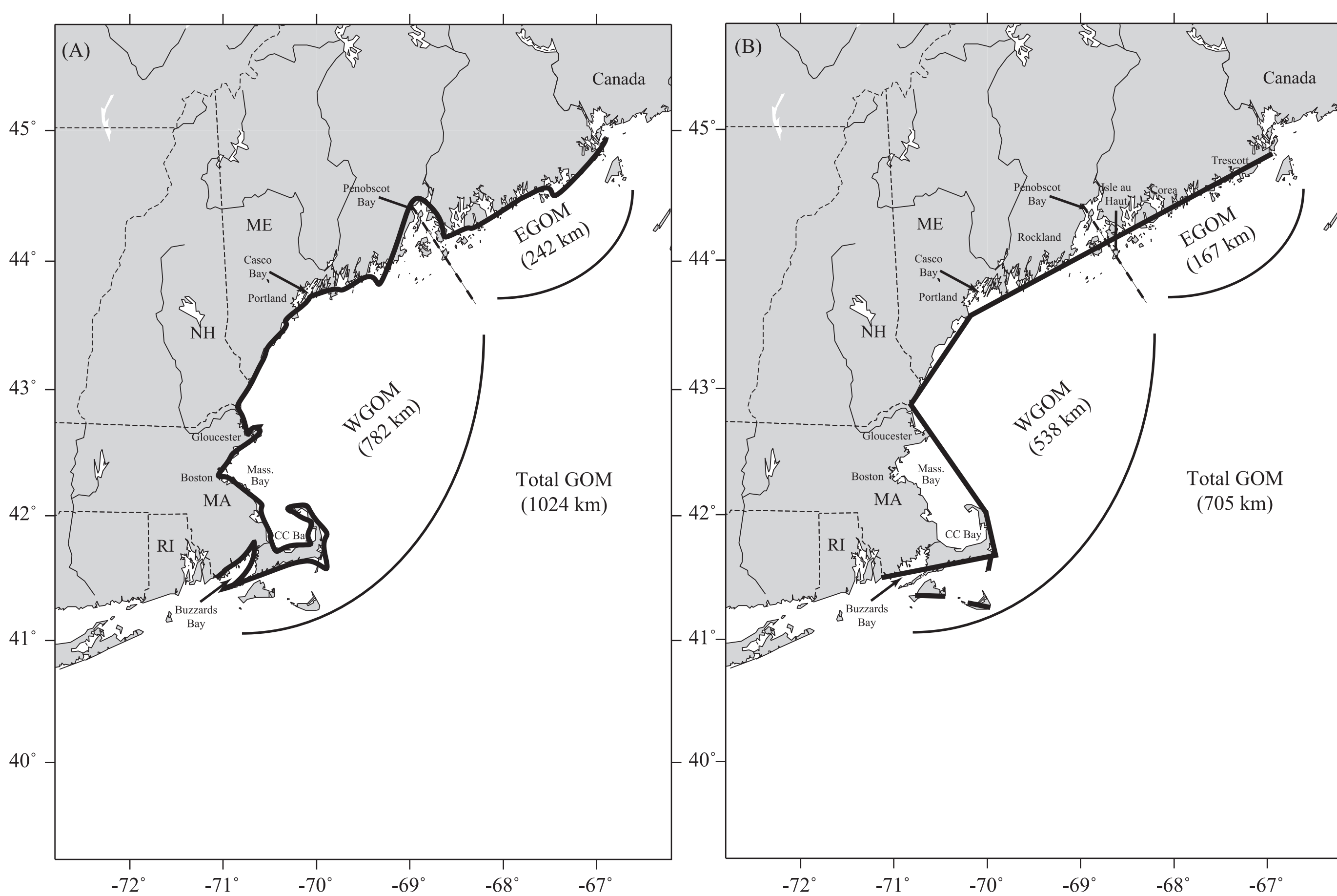

Fig. 2. Calculation of coastline lengths using a curved line approach, tracing the coastline (A) and a straight-line approach (B). Both calculations were done using ImageJ software.

Table 1
Closures due to presence of PSP toxins in the Gulf of Maine —1978–2011.

Year	Extent of closure WGOM (km)	Extent of closure EGOM (km)	Total closure GOM[a] (km)	Southernmost closure (Latitude)	Duration of closure WGOM (days)	Duration of closure EGOM (days)	Duration of closure GOM (days
1978	317	149	466	42.06	206	94	206
1979	152	20	172	42.61	162	97	162
1980	255	167	422	42.61	206	262	288
1981	255	70	325	42.61	143	198	198
1982	255	84	339	42.61	149	135	149
1983	157	106	263	42.61	126	140	147
1984	243	14	257	41.75	106	114	131
1985	208	66	274	42.06	112	127	114
1986	272	29	301	42.06	134	195	196
1987	145	14	159	43.0	177	150	177
1988	214	60	274	42.125	96	114	114
1989	219	106	325	42.61	130	136	137
1990	258	14	272	42.0	106	134	167
1991	190	151	341	42.61	92	65	119
1992	28	29	57	42.7	70	134	151
1993	212	29	241	41.75	72	134	147
1994	107	14	121	43.0	37	58	71
1995	85	31	116	43.0	59	93	105
1996	0	14	14	44.75	63	79	131
1997	112	14	126	42.87	24	22	48
1998	131	32	163	42.87	51	50	63
1999	70	14	84	43.1	24	58	84
2000	194	14	208	42.6	52	56	91
2001	0	74	74	44.25	72	84	89
2002	14	14	28	43.7	87	92	111
2003	265	113	378	42.3	164	123	179
2004	202	145	347	42.87	148	156	176
2005	391	146	537	41.25	114	119	120
2006	286	131	417	42.0	96	103	124
2007	222	96	318	42.6	107	104	134
2008	335	123	458	41.25	77	142	152
2009	298	167	465	42.25	140	141	197
2010	110	167	277	42.87	92	171	205
2011	295	66	361	42.0	77	134	152

[a] *Note*: This total includes EGOM and WGOM, but not BOF.

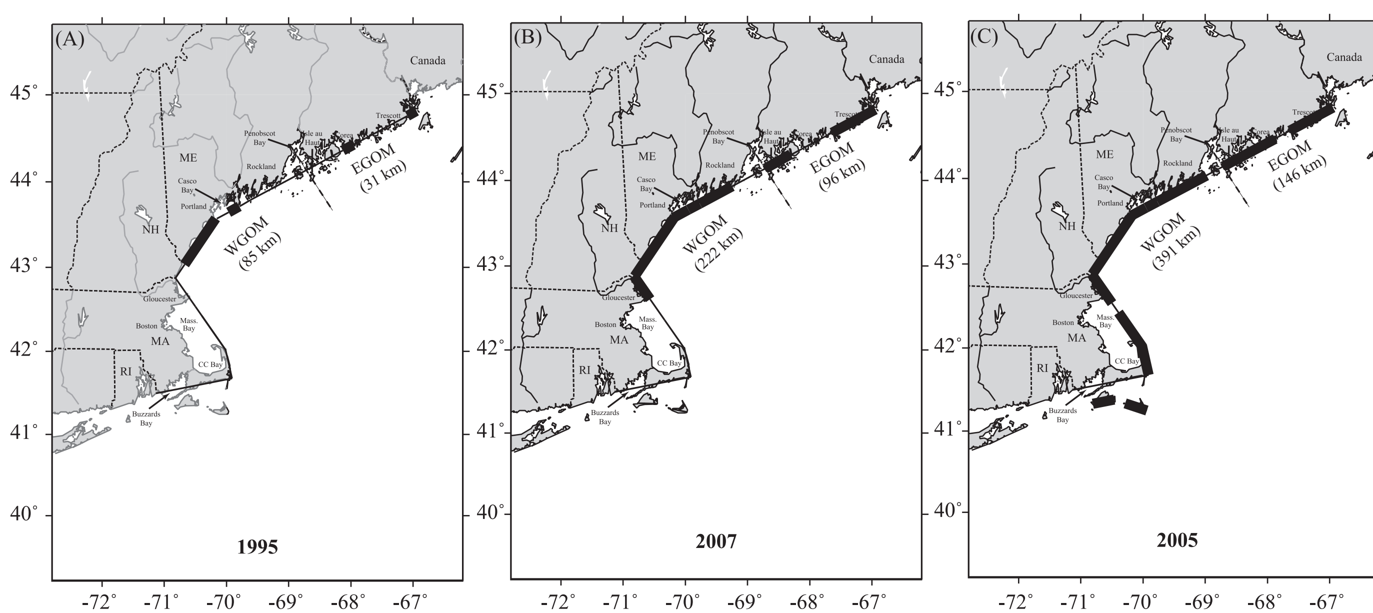

Fig. 3. Representative shellfish closure maps for the coasts of Maine, New Hampshire, and Massachusetts—(A) 1995; (B) 2007; and (C) 2005. These are illustrated in order of bloom severity (i.e., "Limited", "Moderate", and "Extensive").

2.2.2. Southernmost closure

The latitude of southernmost closure each year was also noted as indicated in Table 1. Though not an actual measure of total coastline closed, southernmost closure could be used as a metric to categorize the extent of closures over the GOM region. McGillicuddy et al. (2011) examined the relationship between the most southerly latitude of closure and cyst abundance, as well as closures and cyst abundance, during the period 2005–2009, determining that fall cyst abundance is a first order predictor of bloom severity (as defined by closures) in the following year. (Anderson et al., 2014b) carried this analysis further to include 2010–2012 and found that the cyst abundance corresponded with the geographic scale of the bloom (e.g., southernmost closure or total km of coastline closed) and not other metrics of bloom severity such as cumulative toxicity, duration of toxicity and termination date. To explore this relationship over a longer period of time, the correlation between southernmost closure and geographic extent of closure was examined for the 34 years of this study.

2.3. Duration of closures

To adequately describe the impact of a closure, one would like to consider duration as well as geographic extent. Calculating duration of closures is complicated in that areas in the Gulf of Maine do not open and close in synchrony. One area may close for a certain period of time and then part of that closed area may reopen while other areas are experiencing closures and partial reopenings at different dates throughout the bloom season. This is true for the entire coast, making it a difficult variable to assess over large scales. Nonetheless, given its importance as a measure of impact, we considered the problem of duration in our study, and obtained “date of toxicity onset” and “date of toxicity termination” for the EGOM and WGOM from data compiled from the Maine Department of Marine Resources (Table 1; Anderson et al., 2014a). Toxicity duration (days) was calculated for each year for the entire region based on the difference between the earliest onset and the latest termination of detectable toxicity anywhere in the study area (Table 1). The limit of detection for the mouse bioassay is ~40 μg STX eq per 100 g shellfish meat. A total duration of toxicity was thus determined for each year for the entire Gulf of Maine.

Duration information is only available for the state of Maine, since Massachusetts and New Hampshire do not have records as far back as Maine, nor do they have historical records of duration. However, analysis of duration information for the years in which that information is available for all states in the region indicate that alongshore toxicity (closures) always initiate first and terminate last in Maine. Thus, information from closures in Maine may be considered representative of the entire region. It should also be noted that the duration information is for the interval of detectable toxicity, not actual closure time, as the latter information is not readily available. Total duration should be a reasonable indicator of actual closure, however, since the length of time between first detection of toxicity and subsequent closure is roughly equivalent to the length of time between termination of toxicity and subsequent reopening (Couture, unpublished data). In other words, total duration for each year should be close to the actual closure time for that year even though the onset and termination dates are based on a different toxicity threshold than closure or re-opening decisions.

3. Results

3.1. Calculating length of coastline

The U.S. Coast and Geodetic Survey (which is now incorporated into the NOAA National Ocean Services (NOS)) conducted a survey in 1939–1940 in which the coastline of each U.S. state was measured “*with a unit of measure of 30 min of latitude on charts as near the scale of* 1:1,200,000 *as possible. Coastline of sounds and bays is included to a point where they narrow to a width of unit measure*, *and the distance across at such point is included*.” (NOAA/PA 71046). Study results using ImageJ to calculate the length of straight segments of coastline compared favorably with the NOAA NOS results (Table 2).

Table 2
Comparison of ImageJ/straight-line method for calculating coastline with NOS official record, 1939-40.

State	NOAA/NOS	ImageJ/Straight-line segments
Maine	367 km	374 km
New Hampshire	21 km	23 km
Massachusetts	309 km	309 km

Historical maps were redrawn using this straight-line approach, and the length of coastline closed determined for each year and each subregion using ImageJ software (Table 1). Fig. 2B illustrates the straight-line segments that were chosen to measure the GOM coastline. These segments were chosen by closely following the coastline where possible (e.g., most of Maine) and intersecting the major bays and islands. Along the coast of Massachusetts, a straight line was drawn to cover the south shore, rather than curving inwards to follow the features of Massachusetts and Cape Cod Bays. In converting the historical maps, perpendicular lines were drawn from the terminal points of closures to maintain consistency. Representative toxicity closure maps for selected years are presented in Fig. 3. The complete set (1978–2011) is presented in Supplementary materials online.

3.2. Geographic extent of closures

Fig. 4A provides a histogram of the geographic extent of closures for each year from 1978 to 2011, organized in order of severity. The results range from a low of 14 km (1996) to a high of 537 km (2005). Fig. 4B provides the same information organized by year, illustrating the interannual variability in closures in this region. Anderson et al. (2014a) explore the mechanisms behind this variability and decadal trends in their study.

A variety of approaches were considered for binning these data. One was to divide the number of years by the number of bins (i.e., 34 divided by the number of bins (3, 4, 5, …)) to give categories with approximately equal number of years. This approach was rejected because it was arbitrary and did not capture some of the pattern that is evident in Fig. 4A. In that regard, there are four inflection points in the data (1979, 2003, 2010, and 1978). If each of these were used to define the breakpoint for a category, there would be four levels; however, state managers felt that three was an appropriate number of categories. Accordingly, the years were divided into three bins using two of the inflection points (1979, 2003), which conveniently divided the coastline closed into 200 km increments. The levels thus consisted of 11 years in the interval from 0 to 200 km of coastline closed, 17 years in the interval from 201 to 400 km closed, and 6 years in the interval from 401 to 600 km closed.

3.3. Location of closures

Fig. 5A and B illustrate the location of coastline closures in the Gulf of Maine for the 34 years of the study for each of the three levels of closures. Partial or entire segment closures are expressed as a percentage for each segment of coastline in the top half of the Fig. 5(A); entire segment closures are shown in the bottom half (5B). Examining each of these in more detail, we find:

Level 1: In the 11 years represented in the “Limited” category, a small segment from South Trescott, Maine to the Canadian border was closed every year (100%). Other closures in the EGOM occurred in only four of the years examined (36%) and were limited to the area between Isle au Haut and Schoodic Peninsula, with the length of closure ranging from 15 to 60 km of coastline. In

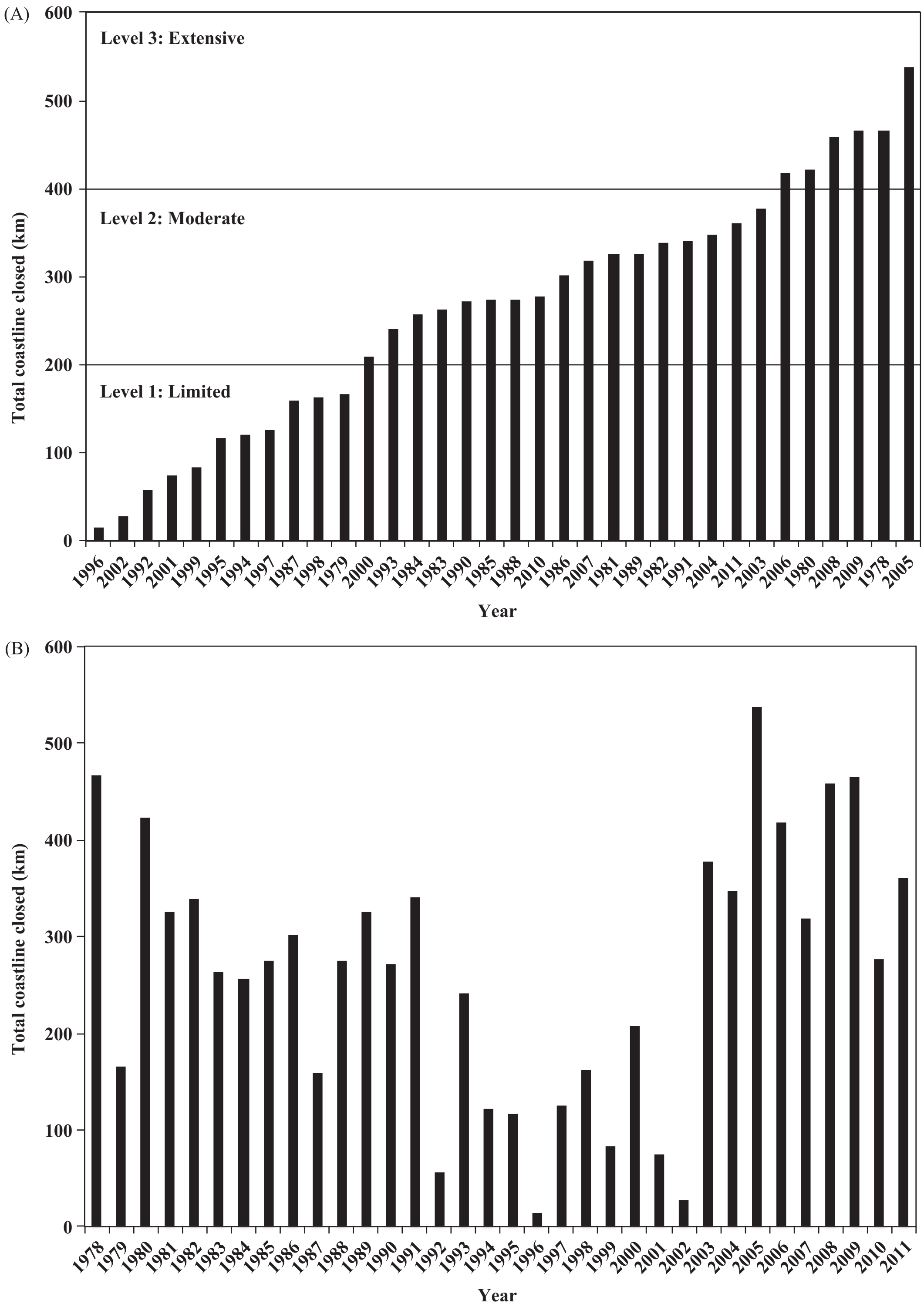

Fig. 4. Total km of coastline closed in the Gulf of Maine, 1978–2011 (A) binned by total closure; and (B) binned by year. The rationale for "Level 1: Limited", "Level 2: Moderate" and "Level 3: Extensive" are explained in the text.

the WGOM, the area between Portland, Maine and the WGOM/EGOM border experienced some closures in 73% of the years, ranging from 14 to 63 km of coastline in the area between Casco Bay and Rockland, Maine. From Portland, Maine south to the Massachusetts/New Hampshire border, closures occurred in 64% of the years, typically including the entire segment (98 km). Portions of the Massachusetts coastline between Gloucester and the New Hampshire border were closed in 18% of the years, while in 9% of the years that entire segment was closed.

Level 2: During the 17 years represented in the "Moderate" category, a small segment from South Trescott, Maine to the Canadian border was closed every year (100%). The entire EGOM coastline was closed only one of those years (6% of the time), however, sections of the EGOM coastline were closed in 82% of the years, ranging from 15 to 139 km. In the WGOM, portions of the area between Portland, Maine and the WGOM/EGOM border experienced closures every year (100%), but the entire segment (133 km) was closed for only two of those years (12%). In other

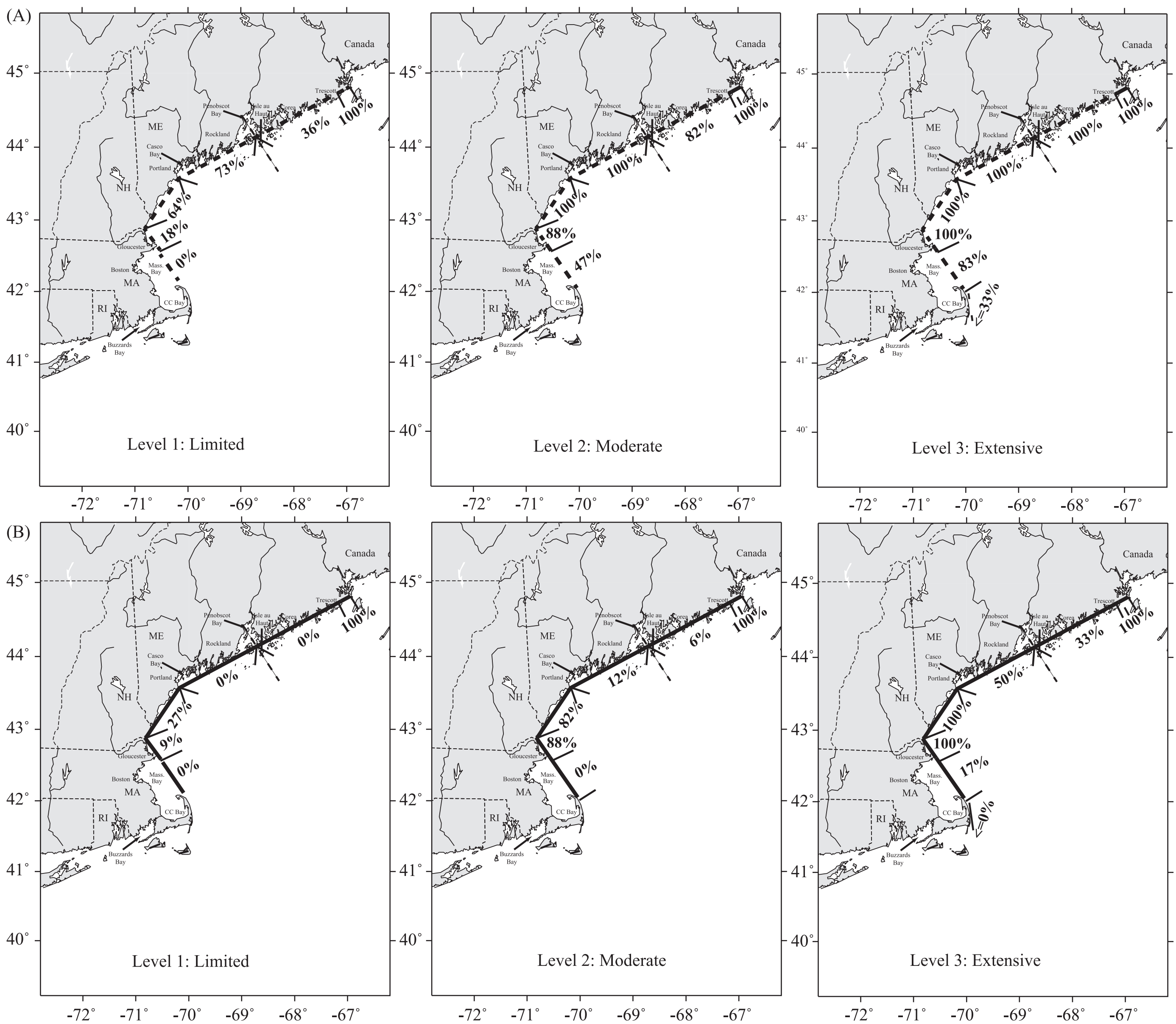

Fig. 5. Geographical location of closures during the period 1978–2011, expressed as percentage of time during the years studied. (A) Partial or complete closure of coastal shoreline segments; and (B) complete closure of coastal shoreline segments.

words, some areas within this section of coastline remained open during each of the other 15 "moderate" years of the study—typically east of Casco Bay. From Portland, Maine south to the Massachusetts/New Hampshire border, closures occurred in 100% of the years—during 14 of the years in this category (82% of the years) the entire area was closed, while during the remaining 3 years most of that segment was closed with only the New Hampshire coastline remaining open. The area between Gloucester, Massachusetts and the New Hampshire border experienced closures in 88% of the years. Closures extended into portions of Massachusetts Bay in 47% of the years, typically to the Duxbury area, but areas from Plymouth, MA southward remained open.

Level 3: During the 6 years represented by the "Extensive" category, a small segment from South Trescott, Maine to the Canadian border was closed every year (100%). The entire EGOM coastline was closed during two of the 6 years (33%), however, major sections of that coastline were closed for all 6 years, with only a small area from Corea to Jonesport, Maine remaining open 50% of the years (three of six). In the WGOM, portions of the area between Portland, Maine and the WGOM/EGOM border experienced closures every year (100%), with the entire segment closed for three of those years (50%). Openings were limited to the 50 km area between Rockland and the WGOM/EGOM border (50% of the years). The entire segment from Portland, Maine south to the Massachusetts/New Hampshire border was closed 100% of the years. Likewise, the entire segment between Gloucester, Massachusetts and the New Hampshire border was closed 100% of the 6 years. Massachusetts Bay experienced some closures during all but one of the years represented (83%), with the entire area closed 17% for one of the six years. Cape Cod experienced closures during two of the years studied (33%).

3.4. Duration of closures

Fig. 6 shows a weak relationship between the geographic extent (total length) of closures and duration of closures. Over the 34 years studied, there was considerable variation in duration, ranging from a low of 48 days (1997) to a high of 288 days (1980), averaging 142 days with a high standard deviation (+48.6).

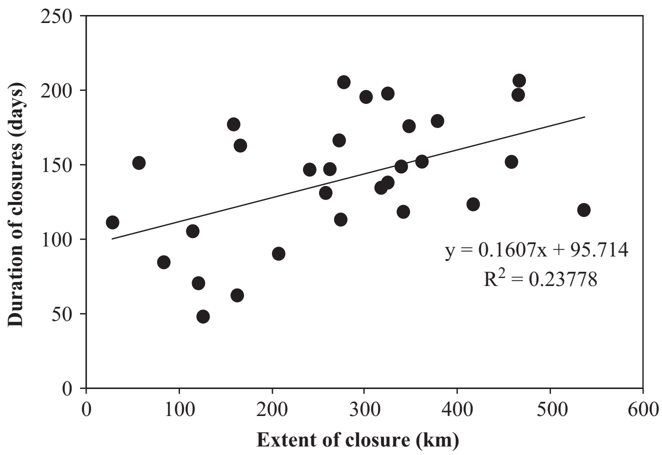

Fig. 6. Relationship of duration (days) of closure to geographical extent (km) of closure.

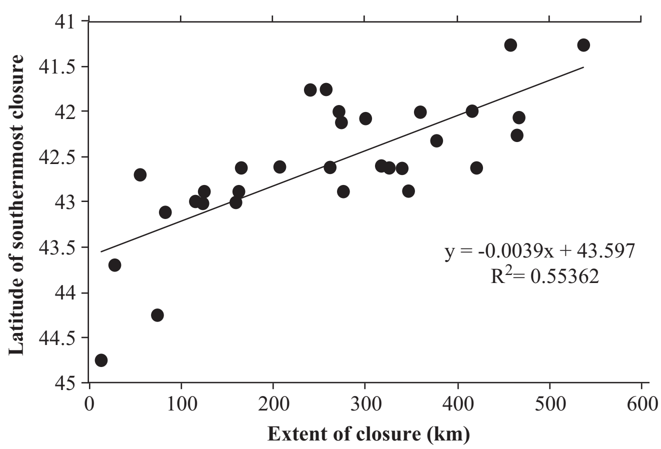

Fig. 7. Relationship of latitude of southernmost closure (axis reversed) to geographical extent of closure ($p < 0.0001$).

4. Discussion

This study addresses a fundamental HAB management issue associated with high levels of interannual variability in bloom extent and duration within a region. We describe a method to characterize bloom severity on the basis of the extent of coastline closed in a given year due to PSP toxicity, and offer three specific levels and descriptors that can be used in bloom forecasts, as well as retrospective analyses. The tool that has been developed will be of value to managers, scientists, journalists, and the general public in their response to HAB events. The approach can readily be adapted to other regions and HAB impacts, as long as sufficient time-series data are available.

4.1. Defining the geographic extent of closures

Several methods were considered for categorizing the extent of closures in the GOM due to PSP toxins in shellfish. Using the straight-line segment approach consistently each year and the ImageJ software for calculating the length of coastline gave us similar results to the comprehensive U.S. Coast and Geodetic Survey study conducted in 1939–1940 (Table 2). Therefore, this method was chosen.

There is good correlation between the geographic extent of blooms and the southernmost latitude of closure (Fig. 7). This is not surprising since blooms originate in Maine waters and, due to alongshore transport in the Maine Coastal Current (Brooks, 1985), may travel southwest into New Hampshire and Massachusetts waters. However, for management purposes, the latitude of southernmost closure is not necessarily the most useful factor to distinguish between levels of severity, as it does not provide an indication of the extent of closures in Maine and New Hampshire. The goal of this study was to define levels of severity of PSP outbreaks for the entire Gulf of Maine region and for that reason geographic extent was used to define the categories.

4.2. Definition of levels

Based on our review of severity scales for typhoons and hurricanes and our discussions with resource managers in the Gulf of Maine region and elsewhere, we are recommending that three levels be used to distinguish and define the severity of PSP outbreaks in the Gulf of Maine (Table 3 and Fig. 4A). These levels are differentiated by defined lengths of coastline closed (0–200 km; 201–400 km; and 401–600 km). The associated names recommended for those three categories are “Level 1: Limited”, “Level 2: Moderate” and “Level 3: Extensive”. These terms were chosen as they have a geographic or spatial connotation. These levels are meant to be descriptive of the geographic range of coastline closed. Furthermore, we recommend that forecasts focus on this metric for the Gulf of Maine – rather than breaking this down by state or subregions (WGOM and EGOM), as we believe that one level for the entire region will be more useful and less confusing to managers and the public. Information on the historical geographic extent, latitude of southernmost closure, and duration of detectable toxicity are also included for each subregion, however (Table 1), for use in future studies.

In addition to indicating the possible geographic extent of closures (km closed) for the Gulf of Maine region, the following location descriptions could be added, based on a review of the historical closures. These are brief summaries, with more specific geographic details given in Fig. 5A,B and Section 3.3.

Level 1: Limited (1–200 km closed) – Historically this has included closures in far eastern Maine, and varied areas throughout the rest of the region, typically with portions of the coastline closed between the Massachusetts/New Hampshire border and the WGOM/ EGOM border. Closures have never occurred south of the north shore of Massachusetts.

Level 2: Moderate (201–400 km closed) – Historically this has included closures in far eastern Maine with varied closures in the remainder of the EGOM. In the WGOM, closures have often occurred from the north shore of Massachusetts to Portland, Maine with portions of the coastline closed between Portland, Maine and the WGOM/EGOM border 100% of the years that are within this category or level. Closures have occurred in portions of Massachusetts Bay in 47% of the years.

Level 3: Extensive (> 400 km closed) – Historically, “extensive” years have included closures through most of eastern Maine (Isle au Haut to the Canadian border), the Massachusetts/New Hampshire border northward to Rockland, Maine, the north shore of Massachusetts, and portions of Massachusetts Bay. Very rarely, this toxicity extends to the outer (eastern) side of Cape Cod, and the nearby islands of Martha’s Vineyard and Nantucket.

Table 3
Recommended levels and descriptions of PSP outbreaks in the Gulf of Maine region.

Level	Extent of closure	Description	Range of duration	Average duration
1	0–200 km	Limited in extent	48–177 days	108 (+42.4)
2	201–400 km	Moderate in extent	91–205 days	150 (+32.7)
3	> 400 km	Extensive	124–288 days	181 (+63.5)

The detailed information given in Fig. 5A,B and Section 3.3 has practical value since shellfishermen can anticipate that although portions of the coast may be closed to harvesting, other areas will likely be open.

4.3. Duration of closures

We hypothesize that in some years when there is anomalously strong alongshore transport resulting in closures through much of the region (e.g., 2005; Anderson et al., 2005a; He and McGillicuddy, 2008; He et al., 2008), cells may reach portions of western Maine more quickly than in other years when they might be retained in the mid-coast and eastern regions, causing toxicity levels to be higher and duration to be longer. Since the two metrics do not correlate well (Fig. 6), we cannot use them both to designate our categories of bloom severity. We have, therefore, chosen the geographic extent of toxicity closures as the primary indicator of impact.

Nevertheless, we can make some general observations about duration (Table 3). In Level 1: Limited bloom years, duration ranged from 48 to 177 days, in Level 2: Moderate bloom years, duration ranged from 91 to 205 days, and in Level 3: Extensive bloom years, the range was from 124 to 288 days. The average number of days for those same categories would be 108, 150 and 181, respectively, but the standard deviation for each is high (42.4, 32.7, and 63.5). Given the analysis conducted here and the nature of the individual metrics, it seems unlikely that duration will be included as a parameter in the category descriptions for future forecasts.

5. Conclusions

Three levels representing the geographic extent of shellfish harvesting closures due to PSP toxins for the Gulf of Maine region were defined based on lengths of coastline closed. These can now be used in future forecasts instead of vague descriptors. In addition to giving the HAB forecasters a convenient tool for communicating their results, we believe this will provide much-needed information to the shellfish industry, the public and to resource managers. Possible benefits to these groups include, among many others, assistance with staffing decisions for state resource managers, development of contingency plans by shellfishermen, distributors, restaurants, tourists, and other elements of the seafood and recreation industries, and enhanced confidence in the management and scientific communities during outbreaks. Revisiting the HAB severity forecasts for 2008, 2009, 2010 and 2011 for this region, these would be termed Level 3: Extensive, Level 3: Extensive, Level 2: Moderate, and Level 2: Moderate, respectively. Future forecasts will utilize these terms, explaining the expected range of closure. Consideration should be given to adding information about typical closure areas such as described in Section 3.3 and using the maps in Fig. 5A and B. Duration of toxicity has not yet proven to be a useful categorization.

Efforts are underway to devise a strategy that can convert seasonal forecast model output (which currently gives only cell abundance estimates; e.g., McGillicuddy et al., 2011) into an estimated length of coastline to be closed, which can then be used to derive a bloom level characterization. This will rely on a toxicity submodel currently under development; (D. McGillicuddy, unpublished data) which will take cell abundance and distribution from the *A. fundyense* population dynamics model and transform these into estimates of shellfish toxicity along the coast. This will in turn be used to estimate both length of coastline closure and duration of toxicity for the next bloom season.

Another value of this study is that it illustrates the critical importance of long time series for assessing interannual variability. Other regions might consider a similar mapping strategy and binning of closure data to determine patterns and ranges of severity of other types of HABs.

Acknowledgments

We thank the staff in the Maine Department of Marine Resources, the New Hampshire Department of Environmental Services, and the Massachusetts Division of Marine Fisheries for their provision of historical toxicity data. Thanks also to the helpful comments from two anonymous reviewers. Research support provided through the Woods Hole Center for Oceans and Human Health, National Science Foundation (NSF) Grants OCE-0430724, and OCE-0911031; and National Institute of Environmental Health Sciences (NIEHS) Grant 1-P50-ES012742-01, the ECOHAB Grant program through NOAA Grant NA06NOS4780245, and the PCM HAB Grant program through NOAA Grant NA11NOS4780023. This is ECOHAB contribution #740; PCM HAB contribution #2.

Appendix A. Supplementary Information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.envdev.2013.02.005.

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