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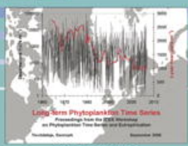

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Long-term Phytoplankton Time Series

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Long term phytoplankton monitoring, including harmful algal blooms, in the Bay of Fundy, eastern Canada

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A B S T R A C T

A monitoring program was initiated in May 1987 to study phytoplankton populations in the Bay of Fundy, southwest New Brunswick, eastern Canada. Samples are collected for phytoplankton distribution and abundance at five locations in the Bay of Fundy. Other parameters measured include plant nutrients (ammonia, nitrite, nitrate, phosphate and silicate), Secchi depth, and depth profiles for fluorescence, oxygen, temperature and salinity.

Alexandrium fundyense abundance from the 5 sites and between years is compared to physical and chemical properties of seawater using principle component analyses (PCA) to identify factors showing the greatest amount of variance in temporal and spatial distribution patterns. Analysis of *A. fundyense* abundance over the 19-year period 1987–2005 indicates that cell abundance from one year does not reflect the following year's phytoplankton concentration, and nitrate values and cell densities appear to have a negative relationship. A further comparison between the 2 years 2004 and 2005 (years with very different intensities of *A. fundyense* maximum cell concentrations) further supported these findings.

Preliminary analyses indicate that many species abundances and intensities appear to be more climate or weather related than nutrient flux related. Examination of relationships between harmful algal bloom (HAB) cell density, nutrients and environmental variables indicates that there is no evidence that HABs are linked to eutrophication processes at the temporal and spatial scales of the study.

1. Introduction

A phytoplankton monitoring programme was initiated in 1987 in the southwest New Brunswick portion of the Bay of Fundy. The purposes of the programme were: a) to establish baseline data on phytoplankton populations, since little detailed work had been published since studies by Gran and Braarud (1935) in the early 1930s; b) to identify harmful algal species that could potentially cause harm to the salmonid aquaculture industry; c) to provide an early warning to the salmon aquaculture industry by sorting and identifying samples soon after collection; and d) to determine patterns and trends in phytoplankton populations. Another purpose of the study was to determine whether there were changing trends in phytoplankton populations or nutrient loads as a result of the expanding salmon industry. In addition, the monitoring programme could provide an early warning to regulatory agencies such as the Canadian Food Inspection Agency (CFIA) for the occurrences of harmful algal bloom (HAB) species that produce toxins resulting in shellfish toxicities and closures of shellfish beds to harvesting.

Phytoplankton blooms are notoriously difficult to predict, and scientists in various parts of the world have been working on prediction for decades with little success to date. Two decades of monitoring phytoplankton within the southwestern New Brunswick area of the Bay of Fundy have indicated that the general seasonal timing of the blooms of some species is somewhat consistent and hence predictable. Although total phytoplankton community has been identified through the study, more detailed analyses have been conducted on species that have been known to cause problems or harm either in the Bay of Fundy or elsewhere in the world. These species include *Eucampia zodiacus*, *Ditylum brightwellii*, *Mesodinium rubrum*, *Chaetoceros socialis*, *C. concavicornis*, *C. convolutus*, *Corethron criophilum*, *Leptocylindrus minimus*, *Alexandrium fundyense* and *Pseudo-nitzschia* spp. (Chang et al., 2007; Martin et al., 2001a,b, 2006a, 2007a,b, 2008; Page et al., 2004, 2005, 2006). Results from the HAB species in the Bay of Fundy *A. fundyense* (PSP), *Pseudo-nitzschia* spp. (domoic acid) and *M. rubrum* (fish kills) populations are presented in this paper.

2. Methods

Sampling was initiated in 1987 in Lime Kiln Bay (where a number of salmon aquaculture sites are located) and at the following three stations in 1988: Brandy Cove (a brackish site influenced by the St. Croix River estuary), Deadmans Harbour (an open bay with offshore influence), and the Wolves Islands (an offshore indicator site) (Fig. 1).

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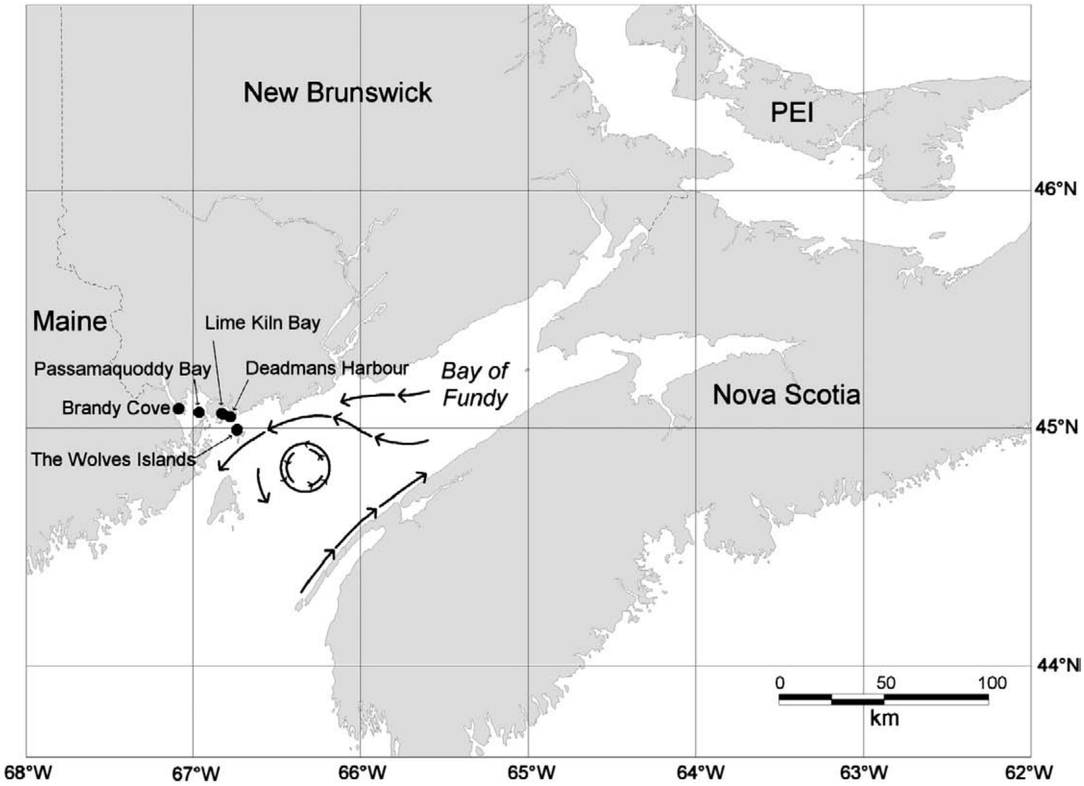

Fig. 1. Map with sampling locations (Brandy Cove (#17), Passamaquoddy Bay (#25), Lime Kiln (#3), Deadmans Harbour (#15) and Wolves Islands (#16)) and circulation patterns in the Bay of Fundy, eastern Canada.

An extra sampling site was added in mid-Passamaquoddy Bay in 1999 following the observation that Brandy Cove was not a good indicator site for cell densities of algal blooms within Passamaquoddy Bay.

Sampling was conducted aboard the research vessel, CCGC *PANDALUS III*. Weekly samples were collected from early May to the end of September or October, depending on the timing of the decline of phytoplankton blooms in a given year. Biweekly sampling was conducted in the shoulder bloom months such as April and October (when phytoplankton cell densities had begun to increase or decrease) and sampling was conducted monthly during colder months (November–March).

Nutrient and phytoplankton samples were collected at the surface by bucket from all five stations and at depths of 10, 25, and 50 m with a Niskin bottle at Station 16. In addition, samples were collected subsurface (by bucket) and 1 m above bottom (Niskin bottle). Water samples (250 mL) were immediately preserved with 5 mL formaldehyde:acetic acid. (There may be a slight bias toward armoured/thecate dinoflagellates and diatoms as a result of using this preservative.) Later, 50-mL subsamples were settled in counting chambers for 16 h. Phytoplankton greater than 5 µm were identified and enumerated (as cells L^{-1}) with the Utermöhl technique using a Nikon inverted microscope (Sournia, 1978). Some of the *Pseudo-nitzschia* species were sorted into two groups because of difficulty in differentiating with the light microscope. The *P. delicatissima* group refers to the two species *P. pseudodelicatissima* and *P. delicatissima* that are separated because of their small size (1.5–2.0 µm width). The *P. seriata* group includes *P. seriata*, *P. multiseries*, *P. fraudulenta*, *P. subpacifica* and *P. pungens* (>2.0 µm width). Further identification was done using either a JEOL JSM-5600 scanning electron microscope (SEM) or a Hitachi S-2400 SEM. Samples for nitrate + nitrite (subsequently referred to as nitrate), nitrite, ammonia, phosphate and silicate were frozen immediately and later measured using a Technicon Autoanalyzer II as described by Strain and Clement (1996). CTD depth profiles were also done for measurement of dissolved oxygen, fluorescence, temperature, sigma-*t* and salinity. Data from phytoplankton analyses of the total community for 1987–2000 have been published previously (Wildish et al., 1988, 1990; Martin et al., 1995, 1999, 2001b, 2006b); the data from 2001–06 is not as yet published (J.L. Martin, pers. commun.).

Phytoplankton abundance and distribution data were entered into a Microsoft Access database. The dataset was used to generate a time-series of the near surface abundance of various species of phytoplankton for each of the five primary sampling stations. SigmaPlot was used for plotting time-series of abundance and bubble plots for each

Table 1
Number of sampling days per station for each year from 1987–2004

Year	Station 3	Station 15	Station 16	Station 17	Station 25
1987	20	n/a	n/a	n/a	n/a
1988	28	23	25	25	n/a
1989	31	30	25	31	n/a
1990	31	28	25	29	n/a
1991	32	32	22	32	n/a
1992	29	29	24	29	n/a
1993	29	29	26	29	n/a
1994	27	27	19	27	n/a
1995	27	27	27	27	n/a
1996	25	24	22	24	n/a
1997	25	26	23	24	n/a
1998	29	28	27	29	n/a
1999	29	28	28	29	26
2000	29	30	31	31	31
2001	30	30	30	31	31
2002	28	25	24	27	26
2003	33	33	30	33	32
2004	31	31	31	31	31
2005	30	30	30	30	30
Total	543	510	469	518	207

"n/a" means samples were not collected.

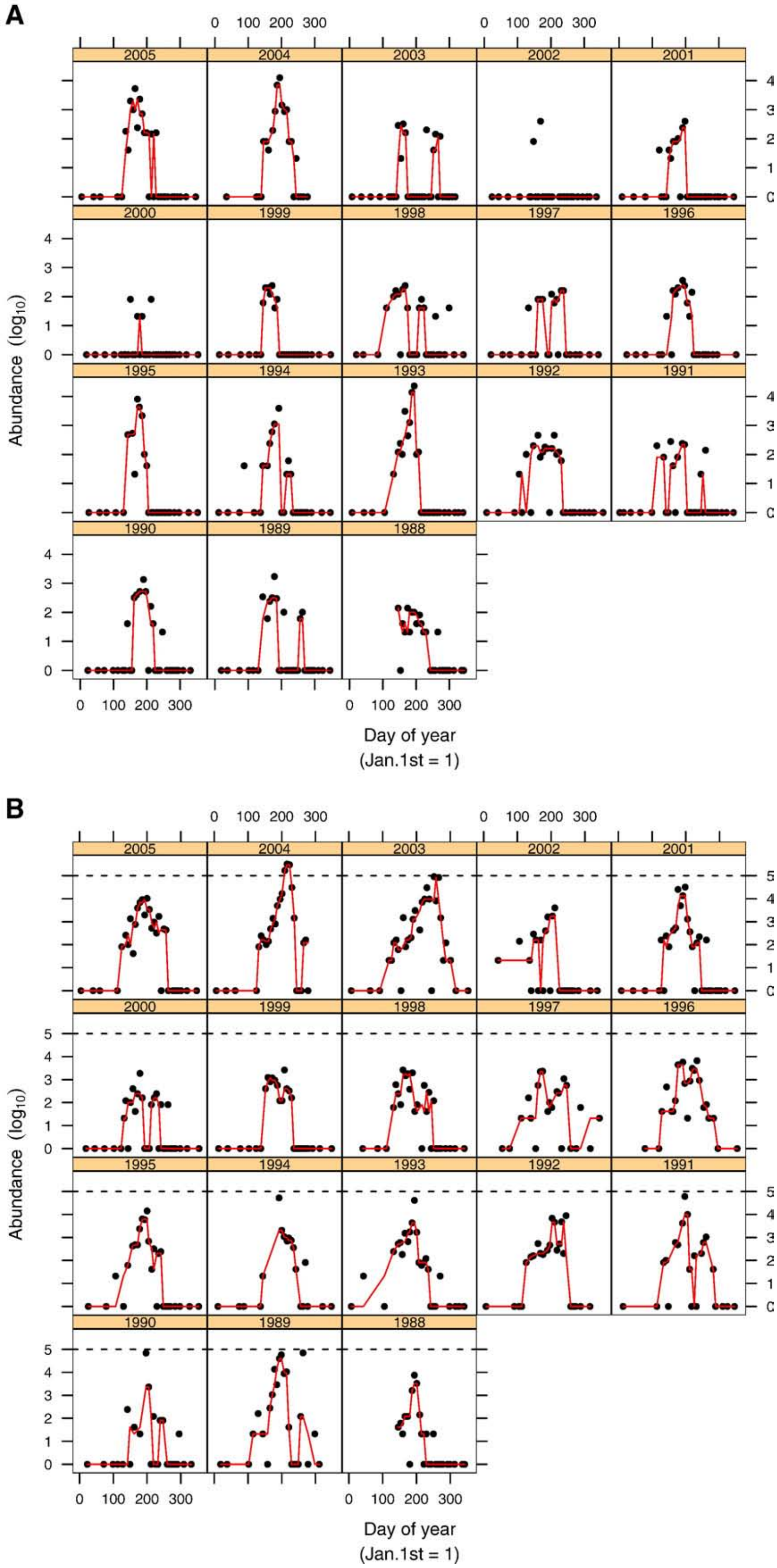

Fig. 2. *A. fundyense* concentration (in cells L^{-1}) at Brandy Cove (A) and Wolves Islands (B) from 1988–2005 on a log transformed scale. Brandy Cove results are on a different scale from results from the Wolves Islands.

station. Bubble plots were produced for the time-series of each year where concentration (cells L^{-1}) defined the area of the circle (bubble). In order to detect patterns of variation in species data that can be associated with quantified environmental variables, correspondence analyses (CA) were performed on the data set (Jongman et al., 1995) using Canoco v. 4.5 (ter Braak and Smilauer, 2002).

3. Results

Table 1 shows the number of sample days for each station during each year from 1987–2005. Numbers of sample days varied depending on when sampling was initiated at a particular station, access to a particular site and was also dependent on weather or sea conditions required for deployment of sampling gear. During this particular time period, >93 000 records were logged into the database.

Water temperatures ranged from −1.5 to 16 °C; phosphate from 0.073–1.663 µM; silicate from 0.02–19.66 µM; and nitrate from 0.01–13.81 µM. Nutrient values did not vary significantly between the inshore and offshore or between salmon aquaculture and non-aquaculture locations.

During the study period there were 162 diatom species (including 58 genera), 65 dinoflagellates (17 genera) and 26 smaller zooplankton, silicoflagellates and ciliates observed. Algal composition and concentration were found to be variable through the area, between seasons and between years. Phytoplankton populations within Passamaquoddy Bay tended to behave differently from those in other more exposed areas and those influenced by the central Bay of Fundy currents and gyre (Fig. 1).

Additionally a number of new species to the area were observed during more than one year or annually since the time of first observation and include the following: (dinoflagellates) *Alexandrium pseudogonyaulax*, *Amphidinium carterae*, *Amphidinium sphenoides*, *Ceratium macroceros*, *Polykrikos schwartzi*, *Preperidinium meunieri*, *Protoperidinium crassipes*, and *Pyrocystis lunata*, and (diatoms) *Attheya septentrionalis*, *Attheya longicornis*, *Chaetoceros radicans*, *Cylindrotheca gracilis*, *Grammatophora serpentina*, *Lithodesmium undulatum*, *Mediopyxis helysia*, *Membraneis challengeri*, *Neodenticula seminae*, *Odontella sinensis*, *Proboscia eumorpha*, *Pseudo-nitzschia subpacifica*, *Pseudo-nitzschia fraudulenta* and *Thalassiosira punctigera* (Martin and LeGresley, 2008). Most of these species are cold temperate species that tend to exist in many regions of the world with similar ecosystems to the Bay of Fundy.

3.1. *A. fundyense*

Studies of *A. fundyense* in the Bay of Fundy have shown that both the over-wintering cysts and vegetative cells tend to concentrate in the central Bay of Fundy in the area influenced by the central gyre (Fig. 1) (White and Lewis, 1982; Martin and White, 1988) suggesting that the major bloom initiation for the Bay of Fundy occurs in this region. Cells disperse from this area through the Bay via tides and currents.

A. fundyense is observed annually in the Bay of Fundy (Fig. 2). Bloom intensity varies annually and blooms occur between May and October, with July being the most common month when cell densities are higher. Concentration and bloom characteristics vary spatially with the greatest differences observed between Passamaquoddy Bay (Brandy Cove and mid-Passamaquoddy Bay sites), which tends to have significantly lower cell densities, and those sites located in the more exposed Bay of Fundy (Lime Kiln, Deadmans Harbour and the Wolves). The date at which *A. fundyense* first appears in water samples varies from April 15 to June 28 depending on sampling location (Page et al., 2006). Bloom initiation inside Passamaquoddy Bay tends to occur at a later date than outside in the Bay of Fundy. The overall mean date of the first appearance is May 16. The date when the maximum cell concentrations are observed varies by about 30 days between stations and years. Additionally, maximum cell concentrations occur earliest at the inshore estuarine station, Brandy Cove (day 172–175) and latest offshore at the Wolves Islands station (day 197–203). The annual

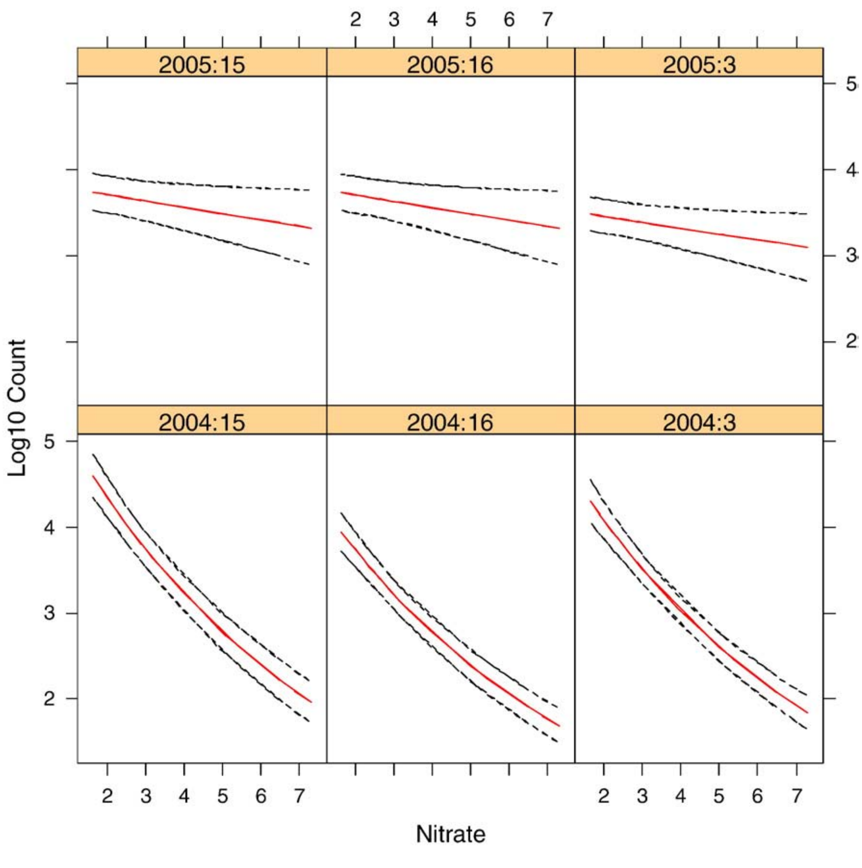

Fig. 3. Nitrate (µM) and *A. fundyense* concentrations in cells L^{-1} at Lime Kiln (3), Deadmans Harbour (15) and Wolves Islands (16) in 2004 (bottom graphs) and 2005 (upper graphs).

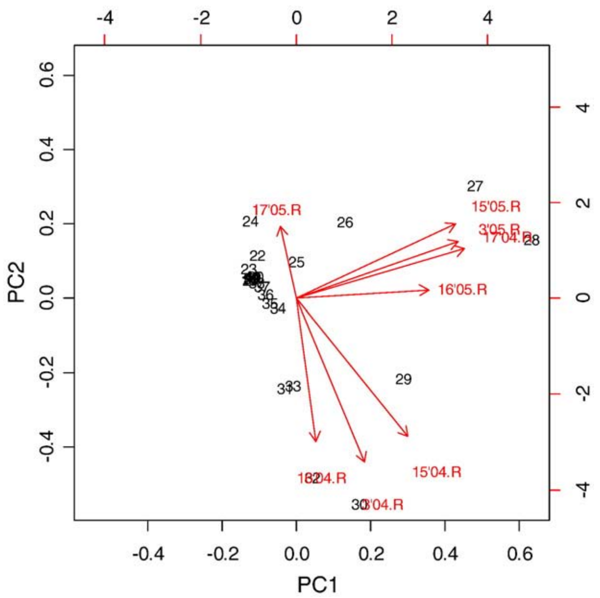

Fig. 4. PCA analyses from the 4 stations Brandy Cove (17), Lime Kiln (3), Deadmans Harbour (15) and Wolves (16) in 2004 and 2005. The "R" following station number and year at the end of each arrow depicts *Alexandrium*.

maximum concentration of *A. fundyense* varies by about three orders of magnitude and the range is about one order of magnitude in station mean concentrations. Bloom duration ranges from 42 to 205 days. Mean (median) bloom duration is 114 (112) days. The temporal character of the *A. fundyense* bloom also varies inter-annually with some consisting of 1 to 3 pulses per year. Cell abundance from one year does not reflect the following year.

The years 1989, 1993, 2002, 2003 and 2004, when concentrations exceeded 9.0×10^4 cells L^{-1}, were considered to be higher than normal for *A. fundyense* concentrations. For these years, a relationship was found between low nitrate and high *A. fundyense* concentration (Fig. 3). This relationship was consistent across the sites as shown in the comparison between a high density year (2004) with a low density year (2005). Principle component analyses (PCA) conducted on *A. fundyense* cell abundance data from the 4 sites (Lime Kiln, Wolves Islands, Deadmans Harbour and Brandy Cove) in 2004 and 2005 plotted by sampling week and nutrients show that the 2004 Lime Kiln, Wolves and Deadmans Harbour sites cluster together whereas the 2004 Brandy Cove site, where cell densities were an order of magnitude lower, clustered with the lower cell density 2005 sites (Fig. 4).

Phosphate levels showed seasonal variations with higher concentrations observed during winter months, but there was not a strong signal between *A. fundyense* and phosphate.

It appears that the magnitude and timing of *A. fundyense* blooms may be linked more to other factors such as water temperature occurring as much as several months prior to a bloom. The coldest temperatures in April seem to correspond to the highest *A. fundyense* cell densities (A.R. Hanke, pers. comm.). Additionally *A. fundyense* bloom intensity seems to be climate related and influenced by extended periods of fog and associated low winds.

Results from shellfish toxicity records collected since 1944 (Martin and Richard, 1996, Canadian Food Inspection Agency, unpublished) show that there are cyclical periods for shellfish toxicity, with higher values detected in the mid 1940s, the early 1960s, late 1970s and again in 2003–04. *A. fundyense* cell densities tend to follow similar patterns when cells are transported to inshore shellfish beds.

3.2. *Pseudo-nitzschia* spp.

Although 8 species of *P. pseudo-nitzschia* (including *P. americana*, *delicatissima*, *fraudulenta*, *multiseries*, *pseudodelicatissima*, *pungens*, *seriata* and *subpacifica*) have been observed in the Bay of Fundy (Kaczmarska et al., 2005), all species were not present every year. Additionally, *P. Americana*, *P. subpacifica* and *P. seriata* were not present in 1931 and 1932 (Gran and Braarud, 1935). *P. pseudodelicatissima*, the major producer of domoic acid (Martin et al., 1990), has only been observed at concentrations greater than one million cells L^{-1} (that resulted in domoic acid in shellfish above regulatory levels) during the 2 years 1988 and 1995 (Fig. 5).

Pseudo-nitzschia spp. are observed throughout most of the year with higher concentrations observed between May and October. Cells tend to be dispersed throughout both the inshore and offshore so there is no clear evidence as to whether its growth is in situ or seeded from offshore.

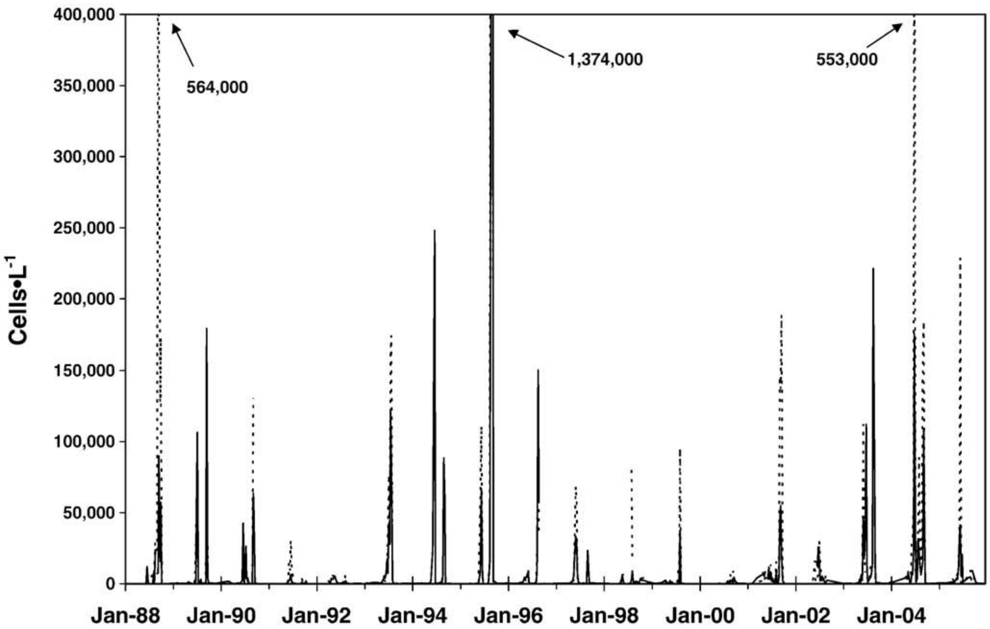

Fig. 5. *Pseudo-nitzschia pseudodelicatissima* concentrations at the Wolves Islands (—) and Lime Kiln (---).

Canonical correspondence analyses (CCA) were performed on 2003 results from *Pseudo-nitzschia* spp. abundance and included variables such as Secchi depth, silicates, phosphates, nitrite + nitrate, sigma-*t*, tides, depth, fluorescence and oxygen (Kaczmarska et al., 2007). Results showed that each *Pseudo-nitzschia* species is unique in behaviour and abundance for species and groups of species correlated with differing parameters. For example, *P. pseudodelicatissima* and *P. delicatissima* abundance correlated positively with nitrates and

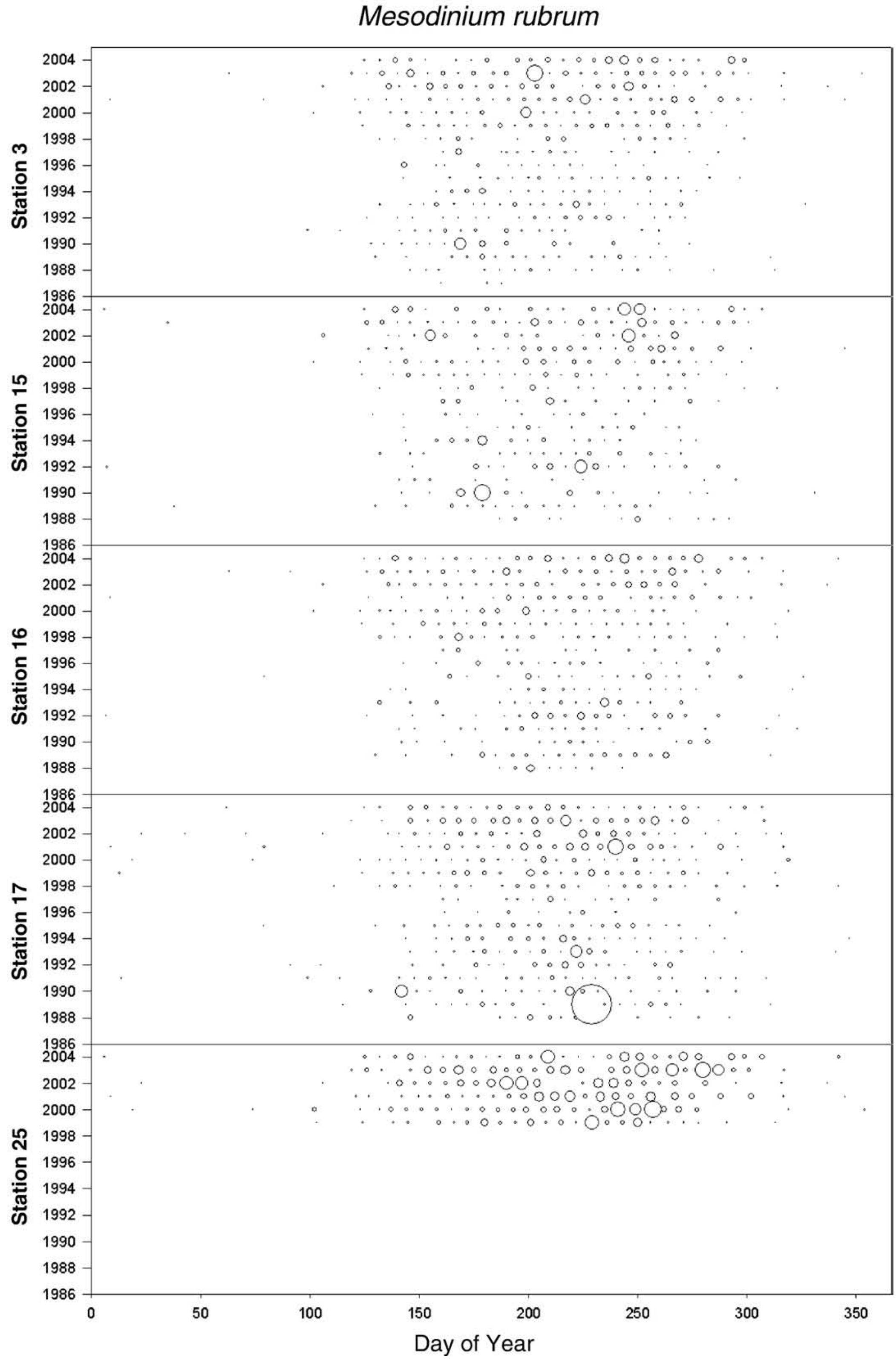

Fig. 6. Bubble plots showing *M. rubrum* presence from 1987–2004 at Brandy Cove (#17), Passamaquoddy Bay (#25), Lime Kiln (#3), Deadmans Harbour (#15) and Wolves Islands (#16). The concentration of *M. rubrum* is proportional to the area of the circle – the larger the bubble, the larger the bloom concentration. The largest bubble circle corresponded to the cell concentration of 5.61 × 10 cells L^{-1} at Brandy Cove (Station 17). Station 25 was not sampled prior to 1999.

P. americana correlated with water depth. *P. pungens* was more abundant in samples with higher phosphates and lower nitrates. *P. seriata* abundance was negatively associated with fluorescence.

3.3. *M. rubrum*

M. rubrum was present at all stations in an average of 94% of the sampling dates from 1987 to 2004. The date for the first appearance of *M. rubrum* in a given year was varied inter-annually and ranged from January to April. Maximum concentrations occurred anywhere between May and October and tended to be earliest at Lime Kiln Bay and the Wolves and latest in the more inshore Passamaquoddy Bay stations and Deadmans Harbour. Brandy Cove, the most inshore station in Passamaquoddy Bay, had the highest concentrations, suggesting that this region was more conducive to the higher cell densities and blooms of *M. rubrum*, as shown on the bubble plots on Fig. 6. Cell concentrations in 1989 were clearly more than 5-fold greater than any other concentration observed during the study period. Unfortunately the mid-Passamaquoddy Bay station was not sampled at that time so we are unable to say whether numbers from that station might have been greater. The annual maximum concentration varied among stations and between years by up to 5.7 orders of magnitude. The median maximum value (cells L^{-1}) was 13740 (Lime Kiln), 12600 (Deadmans Harbour), 16400 (Wolves Islands), 19460 (Brandy Cove) and 70296 (mid-Passamaquoddy Bay). The annual duration of the presence of *M. rubrum* ranged throughout the year and had a mean of 244 days, whereas the duration of the presence containing the annual maximum concentration varied from 7–365 days. The characteristics of the annual *M. rubrum* blooms varied between years and stations with the number of blooms or high abundance periods varying from one to two per year.

M. rubrum was first documented to form brick-red patches in our study area in 1931 (Powers, 1932) and has a long history of sightings (McAlice, 1968; White et al., 1977). Since sampling was initiated, red water discolouration as a result of *M. rubrum* have been observed in Passamaquoddy Bay in 1989, 1993, 1998, 1999, 2000, 2002, 2003, 2005, 2006 and 2007.

4. Discussion

The Bay of Fundy is a very dynamic system as a result of its large tides (5–16 m from the U.S. border to the inner bay) and tidal currents. It does not appear to be nutrient limited. The circulation and currents play an important role in retaining the cells within the system. Where flushing time for the Bay of Fundy has been estimated by Ketchum and Keen (1953) to be about 76 days, there is the potential (provided conditions for growth and division are optimal) for algal blooms to be retained within the Bay of Fundy for extended periods. When extended periods of low winds, calm waters, fog and warmer waters occur in the summer, conditions are conducive for phytoplankton such as *A. fundyense* to grow to proportions such that water discolouration and red tides form.

In most cases during our study, the harmful phytoplankton species being studied were not the major components of the phytoplankton community and it is therefore difficult to relate physical and chemical parameters to particular species. Each species is also unique, and parameters important to growth and sustainability of one organism do not apply to another. Additionally some species tend to concentrate in thin layers at depth and may not be captured in sampling devices.

The inshore area in Passamaquoddy Bay has more fresh water influence, little mixing and lower flushing than other parts of southwest New Brunswick. These conditions can be more suitable for growth of some species, such as *M. rubrum*, and water discolouration has occurred in many years in this bay.

Results indicate that species concentration and diversity can vary between locations and years, especially between the Bay of Fundy and Passamaquoddy Bay. Some species such as *A. fundyense* exhibit cyclical behaviour in which there can be periods of higher cell concentrations (18–20 years) followed by periods of lower cell densities. One must exercise caution in data interpretation as one might perceive that a long-term change has occurred when the phenomenon may only be for a few years and not permanently. This further emphasises the need for long term datasets.

The dominant species tended to vary from year to year through the sampling period, and the longer the dataset, the more anomalies observed. Generally the seasonal succession has been for diatoms to be dominant in the spring, followed by dinoflagellates and diatoms again in the late summer and fall. However, this did not occur every year as during 1991, 1992, 1996 and 1998, there were no fall diatom blooms and during the years 1998–2004 the spring diatom blooms persisted through the summer and co-existed with the dinoflagellate blooms. For example, in 2003, when *A. fundyense* cell densities were greater than 8.0×10^5 cells L^{-1}, there were more than 5.0×10^5 *D. brightwellii* cells L^{-1}. It appears that a 20-year dataset is not sufficient to realize trends in phytoplankton behaviour from the Bay of Fundy as often what may look like a change or shift in regime will return to an earlier observed trend.

There is no strong evidence that nutrients are changing or increasing in the Bay of Fundy, which suggests that eutrophication has not occurred. Nor is there evidence to date from the Bay of Fundy dataset to show that HABs are increasing over time as there is a long history of *A. fundyense* blooms and resulting shellfish toxicity including cyclic periods of higher toxicities that extends more than one hundred years to North American Indian anecdotal records. The blooms tend to be initiated in the offshore region that is not so strongly affected by inshore industrial development. Additionally, *Pseudo-nitzschia pseudodelicatissima* has only been observed in concentrations exceeding one million cells L during 2 years and does not appear to be increasing in intensity nor influenced by eutrophication.

Although synthesis has begun on the dataset to provide information on patterns and trends of phytoplankton in the Bay of Fundy, it is in an initial phase of analysis and documentation of trends for the region. A continuation of sampling and data collection with further analyses in association with related physical, chemical and environmental data will improve the search for relationships among variables influencing blooms.

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