Temporal and Spatial Characteristics of the Diatom *Leptocylindrus minimus* in the Western Isles Region of the Bay of Fundy

J.L. Martin, C.D. Hastey, M.M. LeGresley and F.H. Page

Science Branch, Maritimes Region
Fisheries and Oceans Canada
Biological Station
531 Brandy Cove Road, St. Andrews, NB
E5B 2L9

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J. L. Martin, C. D. Hastey, M. M. LeGresley and F. H. Page

Fisheries and Oceans Canada, Maritimes Region, St. Andrews Biological Station,
531 Brandy Cove Road, St. Andrews, New Brunswick, Canada E5B 2L9

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ABSTRACT

Martin, J. L., Hastey, C. D., LeGresley, M. M., and Page, F. H. 2010. Temporal and spatial characteristics of the diatom *Leptocylindrus minimus* in the Western Isles region of the Bay of Fundy. Can. Tech. Rep. Fish. Aquat. Sci. 2903: iii+25 p.

The abundance of the diatom *Leptocylindrus minimus* has been monitored at five locations in the Bay of Fundy, eastern Canada, at weekly to monthly intervals since 1987. *L. minimus* was observed each year. The date for the first appearance of *L. minimus* in a given year was inter-annually variable and ranged from January to July. Maximum concentrations occurred anywhere between May and October and there was no pattern as to whether *L. minimus* occurred earliest in the offshore or in the more inshore sheltered Passamaquoddy Bay stations. The more inshore stations in Passamaquoddy Bay had the highest concentrations, suggesting that this region was more conducive to the higher cell densities and blooms of *L. minimus*. The annual maximum concentration varied among stations and between years by up to 300 orders of magnitude. The median maximum value (in chains of cells•L^{-1}) was 3220 (Station 3), 2240 (Station 15), 2800 (Station 16), 11 700 (Station 17) and 12 360 (Station 25). The annual duration of the presence of *L. minimus* ranged from January to November and had a mean of 25 d, whereas the duration of the bloom containing the annual maximum concentration varied from 14-34.5 d. The characteristics of the annual *L. minimus* blooms varied between years and stations with the number of blooms or high abundance periods varying from one to two per year.

RÉSUMÉ

Martin, J. L., Hastey, C. D., LeGresley, M. M., and Page, F.H. 2010. Temporal and spatial characteristics of the diatom *Leptocylindrus minimus* in the Western Isles region of the Bay of Fundy. Can. Tech. Rep. Fish. Aquat. Sci. 2903: iii + 25 p.

Depuis 1987, l'abondance de la diatomée *Leptocylindrus minimus* a été suivie à 5 sites situés dans la baie de Fundy, dans l'est du Canada soit de façon hebdomadaire ou mensuel. *L. minimus* était présent à chaque année. La date de la première observation de l'année du *L. minimus* était variable entre années et s'étalait de janvier à juillet. Les concentrations maximales ont lieu entre mai et octobre et les analyses de modèle ne suggèrent aucune tendance qu'elle commence plus tôt dans les régions plus côtières. Cependant, les stations plus côtières de la baie Passamaquoddy jouissaient des concentrations les plus élevées suggérant que cette région est plus propice aux proliférations de *L. minimus.* La concentration maximale annuelle variait entre stations et aussi entre années par 300 ordres de grandeur. La valeur médiane maximale (en chaînes de cellules •L^{-1}) était 3220 (Station 3), 2240 (Station 15), 2800 (Station 16), 11 700 (Station 17) et 12 360 (Station 25). La durée annuelle de la présence de *L. minimus* était de 25 jours tandis que la durée de l'efflorescence ayant la plus grande concentration variait de 14-34.5 jours. Les caractéristiques des efflorescences annuelles du *L. minimus* diffèrent entre années et entre stations et varient d'une à deux proliférations par année.

INTRODUCTION

Although the majority of phytoplankton species occur in the environment without causing adverse effects, there are a few that are known to cause harm. When these harmful algal blooms (HABs) occur in areas where Atlantic salmon (*Salmo salar*) farming is conducted, the health of the caged salmon can be compromised. Farmed fish are particularly vulnerable to harmful phytoplankton blooms because they do not have the luxury of being able to swim away to avoid blooms, and heavy mortality can occur within hours. The salmonid mariculture industry in southwest New Brunswick consists of more than 90 active farms which could potentially be impacted by HABs.

Impacts to fisheries from HABs have been observed in various regions of the world (White 1980; Anderson et al. 2001; Landsberg 2002; Kim et al. 2004; Doucette et al. 2006). Particularly, cultured salmon in aquaculture operations have been affected in regions such as: Atlantic Canada - Bay of Fundy: *Alexandrium fundyense,* and *Mesodinium rubrum* (Martin et al. 2001a, 2006a, 2008a); Nova Scotia - *Alexandrium tamarense* (Cembella et al. 2002); Faroe Islands – *Alexandrium* (formerly *Gonyaulax*) *excavata* (Mortensen 1985); Northwest Pacific - *Chaetoceros convolutus*, *Chaetoceros concavicornis* and *Corethron* sp. (Gaines and Taylor 1986; Rensel et al. 1989; Speare and Ferguson 1989; Horner et al. 1990, 1997; Albright et. al. 1993; Rensel 1993); Europe - *Gyrodinium aureolum* (Dahl and Tangen 1990, 1993; Romdhane et al. 1998); and Chile - *Leptocylindrus minimus* (Clément 1994; Clément and Lembeye 1993).

HABs have been known to affect fish through either of the following methods: neurotoxins, gill irritation/damage (mechanically or through the production of haemolytic substances) or asphyxiation (oxygen depletion). The result for farmed salmon may be mortality or stress in both smolts and market-size salmon and loss of growth during a severe bloom event. These effects have caused millions of dollars of lost revenue to the affected salmon farmers and insurance companies are interested in knowing what farmers are doing to mitigate potential phytoplankton related losses. In cases where there is an anticipation of a problem, market size fish could be harvested, feeding could be reduced or the introduction of fall smolts into cages may need to be delayed due to sensitivity to phytoplankton blooms.

Salmon operations in the southwestern New Brunswick region of the Bay of Fundy have been impacted by HABs several times within the past decade. Those farms located within the Passamaquoddy and Bocabec Bay areas have been impacted more so than those elsewhere. HABs occur less frequently at farms outside Passamaquoddy Bay. Blooms occurred in the Grand Manan area only in 2003 and caused severe economic losses at several farms in eastern Grand Manan. In 2004, blooms occurred in the region between Letang and Seeleys Cove, affecting salmon farms in that area as well (Fig. 1).

A phytoplankton monitoring program was initiated in the Western Isles region of the Bay of Fundy in 1987 due to growing concerns that the incidents involving HABs seemed to be increasing in intensity, frequency and geographic distribution throughout the world (Anderson 1989; Smayda 1990; Hallegraeff 1993, 1995). The purposes of the phytoplankton study when it was initiated were: to establish baseline data on phytoplankton populations in the lower Bay of Fundy, since little detailed work had been published since studies by Gran and Braarud (1935);

to identify harmful algal species that could potentially cause harm to the aquaculture industry; to provide an early warning to the aquaculture industries by sorting and identifying samples soon after collection; and to determine patterns and trends in phytoplankton populations. Another purpose of the study was to determine whether there were environmental changes, such as changing trends in phytoplankton populations as a result of the salmon industry. Incidences of fish mortalities, especially those held captive in net pens, had also been increasing in other regions of the world. Some of these increases can be attributed to increased awareness, both in the scientific and public communities, as well as the increased use of inshore coastal waters for aquaculture, tourism and other activities.

It is well known that phytoplankton blooms are notoriously difficult to predict. Scientists in various parts of the world have been working on this 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 quite consistent and hence predictable to this extent. Some initial statistical analyses have indicated that sophisticated time series analysis techniques have potential for forecasting of phytoplankton abundance.

A research program (Chang et al. 2005; 2006, 2007; Martin et al. 2006b) was funded under the Department of Fisheries and Oceans (DFO) Aquaculture Collaborative Research Development Program (ACRDP) to study data analysis strategies to provide information concerning:

1) the temporal and spatial scales of variability in the concentration of potentially harmful phytoplankton species;
2) the effectiveness of sampling and data analysis approaches for detecting the presence of potentially harmful phytoplankton species; and
3) the effectiveness of the sampling and data analysis approaches for detecting and projecting a temporal trend in the abundance of a harmful algal species.

This manuscript is part of a series dealing with: determining temporal and spatial characteristics of particular blooms of harmful algae in the southwestern New Brunswick area from existing phytoplankton monitoring data since 1987; evaluating the statistical potential of these time series to give an early indication of a pending HAB; and determining the similarity between time series of phytoplankton collected at individual locations. Although a number of species of phytoplankton were selected from the dataset for analyses, this particular paper focuses on the diatom *Leptocylindrus minimus*. A total of 10 species have been suggested to have caused problems with salmon in either the Bay of Fundy or species observed in the Bay of Fundy that have been implicated in fish problems elsewhere in the world, such as *Eucampia zodiacus, Ditylum brightwellii, M. rubrum, Chaetoceros socialis, C. concavicornis, C. convolutus, Corethron criophilum, L. minimus, A. fundyense* and *Pseudo-nitzschia* spp. Results for *A. fundyense* have been published previously (Page et al. 2004, 2005, 2006). As part of this series, reports on *D. brightwellii*, *E. zodiacus* and *M. rubrum* have been completed (Martin et al. 2007a, 2007b, 2008b).

L. minimus Gran (Fig. 2) is a diatom that appears to be cosmopolitan, and mostly in coastal areas (Horner 2002). Cells are 10 times longer than they are wide and 1.5-4.5 µm in diameter. It is a chain forming diatom with two chloroplasts per cell (occasionally one when the valve diameter is smallest) and described as being cylindrical and joined in long straight chains (Lebour 1930). Its distribution on the Atlantic coast has been reported to extend on both sides of the Atlantic and on the west side from Nova Scotia to North Carolina (Hargraves 1990). Although it has not been documented to have caused problems with fisheries in the Bay of Fundy, it has been implicated in deaths of sea trout *Salmo trutta* morpha *trutta* morpha *trutta* and Atlantic salmon reared in aquaculture operations in Chile (Clément 1994; Clément and Lembeye 1993). Although the mode of action was not determined, their results found that salmon swam to the salmon cage corners and the trout swam at the surface with their dorsal fins out of the water. Salmon gills were observed to be pale with some mucus secretion.

MATERIALS AND METHODS

Sampling was initiated in 1987 at Lime Kiln Bay (#3 – Letang estuary where a number of aquaculture sites are located) and at the following three stations in 1988: Brandy Cove (#17 – a brackish site influenced by the Saint Croix River estuary), Deadmans Harbour (#15 – an open bay with offshore influence), and the Wolves Islands (#16 – an offshore indicator site). An extra sampling site (#25) 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 (Fig. 1).

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 decline of the fall phytoplankton blooms. 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 monthly during all other colder months.

Phytoplankton samples were collected at the surface by bucket from all five stations, and at depths of 10 m, 25 m, and 50 m with a Niskin bottle at station #16. Water samples (250 mL) were immediately preserved with 5 mL formaldehyde:acetic acid. Later, 50-mL subsamples were settled in counting chambers for 16 h. All phytoplankton greater than 5 µm were identified and enumerated (as cells or chains of cells•L^{-1}) with the Utermöhl technique using a Nikon inverted microscope (Sournia 1978). Counts for cells were recorded as cells•L^{-1}. As *L. minimus* (Fig. 2) forms chains, a chain of cells actually refers to chains of individual cells.

Following analyses for phytoplankton abundance and distribution, the results were entered into a Microsoft Access database with the following fields: survey type, sampling station, date, organism (species name), code (“1” – dinoflagellate, “2” – diatom and “3” other which included ciliates and smaller zooplankton), and depth (only surface samples were used for this report although samples were collected at depths of surface, 5, 10, 25 and 50 m at the Wolves Islands site). The dataset was used to generate a time-series of the near surface abundance of *L. minimus* for each of the five primary sampling stations. Data was retrieved from Access using queries for the first occurrence, maximum occurrence, etc., and copied into an Excel spreadsheet for sorting and data manipulation. Three point running medians and logarithms were calculated using

Excel. Data were then imported into SigmaPlot (2001) for plotting. SigmaPlot was used for plotting time series versus abundance, three point running medians and bubble plots for each station. Lattice plots showing annual first appearance versus year, date of maximum occurrence versus year, length of maximum bloom versus year and maximum concentration versus year were created using "R" (v. 2.4.0): A Program Environment for Data Analysis and Graphics.

Data from phytoplankton analyses of the total community for 1987- 2000 have been previously published (Wildish et al. 1990; Martin et al. 1995, 1999, 2001b, 2006c); the data from 2001-04 is not as yet published (J.L. Martin, Biological Station, 531 Brandy Cove Road, St. Andrews, NB E5B 2L9, pers. commun.).

RESULTS

Table 1 shows the number of sample days for each station for each year from 1987- 2004. Sample days varied between the stations from 177 days at Station #25 to 513 days at Station #3.

Table 1. Number of sampling days/station for each year from 1987-2004. n/a means that samples were not collected.

Year	Station 3 Lime Kiln Bay	Station 15 Deadmans Harbour	Station 16 The Wolves Islands	Station 17 Brandy Cove	Station 25 Passamaquoddy Bay
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
Total	513	480	439	488	177

Variables, such as the fact that sampling occurred only at Station #3 in 1987 and the first part of 1988, resulted in the higher number of sample days at that particular location. Station #17 was sampled on a regular basis once sampling was initiated due to its easy access and close proximity to the Biological Station. Very occasionally it was not possible to sample Station #15

due to weather or the fact that the harbour was shut off for the herring fishery. Sampling at Station #16 was occasionally affected by weather or sea conditions either unsafe or not conducive for working the gear. Sampling at Station #25 was initiated in 1999.

Figures 3, 4, 5, 6 and 7 show cell densities of *L. minimus* from 1987 to 2004 on both log and linear scales from Lime Kiln (#3), Deadmans Harbour (#15), the Wolves Islands (#16), Brandy Cove (#17) and mid-Passamaquoddy Bay (#25), respectively. *L. minimus* was detected during all years at all stations. There was significant interannual and spatial variability. Concentrations were higher annually at Passamaquoddy Bay and Brandy Cove than those sites outside Passamaquoddy Bay with the exception of 1995 when the highest count was 1120 and occurred at all stations. The only year that cell concentrations exceeded 100 000 cells•L^{-1} at Lime Kiln, Deadmans Harbour and the Wolves Islands sites was 1990 whereas concentrations exceeded 100 000 cells•L^{-1} at Brandy Cove in 1989, 1990, 1997 and 2004. Unfortunately the mid Passamaquoddy Bay site was not monitored prior to 1999, so there is no data for that period. However, concentrations exceeded 100,000 cells•L^{-1} in mid Passamaquoddy Bay in 2002 and 2004.

Table 2 and Fig. 9 show the *L. minimus* maximum cell densities observed during each year at each of the 5 stations. During 1990, concentrations were the highest at all stations with concentrations of 3.56 x 10^5 cells•L^{-1} at Brandy Cove on July 31, the highest concentration observed during the study period. The highest counts generally occurred at Brandy Cove and mid-Passamaquoddy Bay earlier than at stations outside Passamaquoddy Bay. During 2002, the mid-Passamaquoddy Bay site had concentrations >2.31 x 10^5 cells•L^{-1}. Station 16 had a high concentration of 1.27 x 10^5 cells•L^{-1} on July 24, 1990. This was almost seven times larger than any occurrence at the Wolves over the seventeen year study. The high of 2.06 x 10^5 cells•L^{-1} at Deadmans Harbour was almost nine times larger than any other occurrence detected over the study period.

Table 2. Maximum *L. minimus* cell densities (in cells•L^{-1}) from 1987-2004 at stations 3, 15, 16, 17 and 25. Shaded numbers indicate maximum cell density for a particular station over the time series. n/a means that samples were not collected.

Year	Station 3 Lime Kiln Bay	Station 15 Deadmans Harbour	Station 16 The Wolves Islands	Station 17 Brandy Cove	Station25 Passamaquoddy Bay
1987	860	n/a	n/a	n/a	n/a
1988	1 040	480	5 380	11 700	n/a
1989	5 200	2 200	1 800	195 840	n/a
1990	55 480	205 640	127 300	355 780	n/a
1991	14 560	4 960	14 400	84 860	n/a
1992	460	640	1 960	2 560	n/a
1993	3 040	2 240	3 240	10 440	n/a
1994	8 380	10 680	19 040	50 592	n/a
1995	1 120	600	320	960	n/a
1996	1 640	1 280	360	2 420	n/a
1997	3 840	600	840	168 670	n/a
1998	3 400	2 200	2 600	11 320	n/a

1999	1 120	2 080	1 760	7 840	2 600
2000	2 240	4 480	2 800	10 080	1 760
2001	1 520	10 800	1 734	10 880	22 080
2002	17 440	13 600	10 080	32 960	231 713
2003	7 520	5 280	6 358	14 880	2 640
2004	36 080	23 409	13 583	190 038	196 520

A bloom event for *L. minimus* is characterized as an event where *L. minimus* cells are detected in the water, or an unbroken sequence of two or more consecutive samples with *L. minimus* present. Fig. 8 shows bubble plots indicating the presence of *L. minimus* at the four stations (Brandy Cove, Lime Kiln, Deadmans Harbour and the Wolves Islands) since 1987 and mid-Passamaquoddy Bay since 1999. The size of the circle reflects the number of cells observed – the larger the circle, the larger the bloom or concentration of cells. It shows that cells were observed at low concentrations prior to day 140 (mid May) but can often persist at least until day 300 (late October) or occasionally to day 320 (mid November). There can be one or more bloom events or unbroken sequences in a given year, but generally the bloom with the highest cell density occurs between June and September (Table 3, Fig. 10). Highest concentrations for the five stations during the sampling period were observed during the month of July.

Table 3. Month of the year where the maximum cell concentration of *L. minimus* occurred at the five stations: 3, 15, 16, 17 and 25. Shaded months indicate years of maximum cell density during the sampling period for a particular station.

Year	Station 3	Station 15	Station 16	Station 17	Station 25
1987	June				
1988	July	June	June	June	
1989	July	July	July	July	
1990	July	July	July	July	
1991	June	June	June	June	
1992	June	June	July	June	
1993	July	July	August	July	
1994	July	July	July	June	
1995	September	September	September	September	
1996	August	August	June	August	
1997	June	September	September	June	
1998	May	June	May	August	
1999	August	August	August	September	June
2000	August	August	August	July	July
2001	October	October	September	June	June
2002	July	August	July	July	July
2003	September	September	September	July	July
2004	August	September	August	July	July

The duration for the bloom events that had the maximum cell densities for *L. minimus* for each year varied from 1-132 d (Table 4, Fig. 11). The bloom with the longest duration (132 d) of the

time series occurred in 2004 at stations 15 and 16. The bloom with the next longest length (90 d) occurred at station 17 in 1990. Interestingly, Station 17 was the only location where the maximum bloom length occurred in the same year as the maximum bloom density.

Table 4. Length (in days) of the maximum bloom for each station in each year. Shaded numbers indicate the longest bloom period for a given station during the study period. n/a means that samples were not collected. If the maximum cell density for a particular year was <500 cells•L^{-1} the bloom was counted as 1 day in duration.

Year	Station 3	Station 15	Station 16	Station 17	Station 25
1987	1				
1988	1	1	7	7	
1989	28	56	35	14	
1990	43	50	43	90	
1991	35	35	7	21	
1992	1	1	7	84	
1993	40	35	47	62	
1994	13	13	1	28	
1995	21	1	1	7	
1996	20	1	1	43	
1997	7	1	1	21	
1998	21	28	14	21	
1999	21	1	1	8	1
2000	77	27	29	20	1
2001	40	35	32	20	20
2002	61	35	49	28	56
2003	74	68	21	76	78
2004	90	132	132	49	49

The date of first occurrence for *L. minimus* varied considerably between years and stations (Table 5, Fig. 12) and ranged from Day 7 (January 7) to Day 192 (July 11). At Station #3, the earliest observations of the presence of *L. minimus* was January 7, 1993 and January 13, 1999. Although the earliest presence was generally in the winter months at Station #3, it did occur as late as mid-May in 1990, 1991 and 2004. These first occurrences were at very low numbers – none greater than 200 cells•L^{-1}. At Station #15, the earliest occurrences were observed on January 3, 2003 and January 19, 2001 with the latest first occurrences in mid-May of 1995, 2000, and 2004. At Station #16, the earliest observation was on January 7 in 1992 and 2003 and the latest first occurrence was in mid-May of 1995, 2000, and 2004. The first observation for Station #17 was January 7, 2003 and the latest was June, 1994. For this site it was common (>50% of the time) for the first observation to be in May or June. Station #25 had earliest observations on January 7, 2003 and January 9, 2001. Although earliest observations at Station #25 were usually in the winter months, the latest was in May, 2000.

The mean day of the first occurrence for all stations ranged from 49-102 (February 18 – April 12) and the median day ranged from 23-132 (January 23-May 12).

Table 5. Range of days for first occurrences of *L. minimus*, including mean and median days of occurrences for the five stations.

Values expressed in days	Station 3	Station 15	Station 16	Station 17	Station 25
Range for 1st occurrence	7 - 141	7 - 137	7 - 192	7 - 158	7 - 144
Mean	55	84	93	102	49
Median	38	104	108	132	23

Further information on the description of the blooms of *L. minimus* indicates that the median day of the maximum cell abundance ranged from day 196 – day 222 or from July 15–August 10 (Table 6). Median duration of the blooms ranged from 14 -34 days; and the median maximum cell abundance ranged from 2 240-12 360 cells•L^{-1}.

Table 6. Summary of descriptive analyses from data on *L. minimus* including: median day of first occurrence, median day of maximum cell abundance, median duration in days of the bloom with the greatest cell abundance and median of the maximum cell abundance for all years.

Variable (units)	Station 3	Station 15	Station 16	Station 17	Station 25
Median day of first appearance (Day of Year)	38 Feb 7	104 Apr 14	108 Apr 18	132 May 12	23 Jan 23
Median day of maximum cell abundance (Day of Year)	196.5 Jul 15 or 16	222 Aug 10	210 Jul 29	207 Jul 26	196.5 Jul 15 or 16
Median maximum bloom (presence) duration (days)	24.5	28	14	21	34.5
Median maximum cell abundance (cells·L-1)	3 220	2 240	2 800	11 700	12 360

DISCUSSION

The phytoplankton monitoring program was initiated in 1987 following concerns that the local salmon industry might experience problems that were happening elsewhere in the world where the industry has been established for a longer period. Although more than 65 species of dinoflagellates, 162 species of diatoms and 26 other species (including smaller zooplankton and ciliates), have been observed from the region, the majority do not cause harm. Results from monitoring of phytoplankton cell densities from 1987-2004 show that occurrences of phytoplankton species have seasonal, inter-annual and decadal variations in abundances, and all species in the Bay of Fundy behave differently. Earlier analyses of *A. fundyense* populations further emphasize this variation, but on a different scale and magnitude (Page et al. 2004, 2005, 2006).

L. minimus was observed in the Bay of Fundy in the early 1930s and is therefore not a new species to the area (Gran and Braarud 1935). Their records indicated that during 1931 and 1932 the maximum cell density (8 000 chains of cells•L^{-1}) was observed in June along the coast of Maine and in Passamaquoddy Bay in July. This study revealed that *L. minimus* was observed annually at all of our sampling sites. As the appearances and abundances of *L. minimus* appear to vary greatly between years, and the study in the early 1930's was only for a 2-yr period, we do not know whether there have been periods of higher cell density in the interim. It was interesting to see that in 1990, cell concentrations were significantly higher than other years for stations 3, 15 and 16 (5.5×10^4 - 3.5×10^5 cells•L^{-1}). These numbers were less than those observed during harmful events in Chile which occurred at 2.6-3.4 x 10^4 cells•mL^{-1} (Clement and Lembeye 1993).

The more inshore stations, Brandy Cove and mid-Passamaquoddy Bay, had the highest concentrations (3.55×10^5 cells•L^{-1} and 2.32×10^5 cells•L^{-1}) in 1990 and 2002, by an order of magnitude. Analyses from the study period suggest that the Passamaquoddy Bay region was more conducive to the higher cell densities and blooms of *L. minimus*. The inshore area has more freshwater influence, shallower water, and enhanced mixing and flushing. Additionally, conditions in 1990 must have been conducive to blooms of *L. minimus*. The high cell densities in that year were the highest recorded in the 18 yr of the phytoplankton monitoring program. These observations suggest that if concentrations reach levels that were detected in 1990, there might be problems with salmon in adjacent net pens. Further exposure of Atlantic salmon to *L. minimus* under laboratory conditions would also need to be conducted.

This synthesis provides information on the patterns and trends of populations of *L. minimus* from 1987-2004 in the southwestern New Brunswick region of the Bay of Fundy area. It is an initial phase of analysis of the data and the first documentation of the trends for this particular species from the Fundy region. This phytoplankton monitoring program is ongoing, with additional data being collected each year. Continued studies with this valuable long time series and analyses of the phytoplankton data in association with related physical, chemical and environmental data will aid and further improve our predictive/hindcasting capabilities and the search for relationships between the linkages and variables influencing the blooms.

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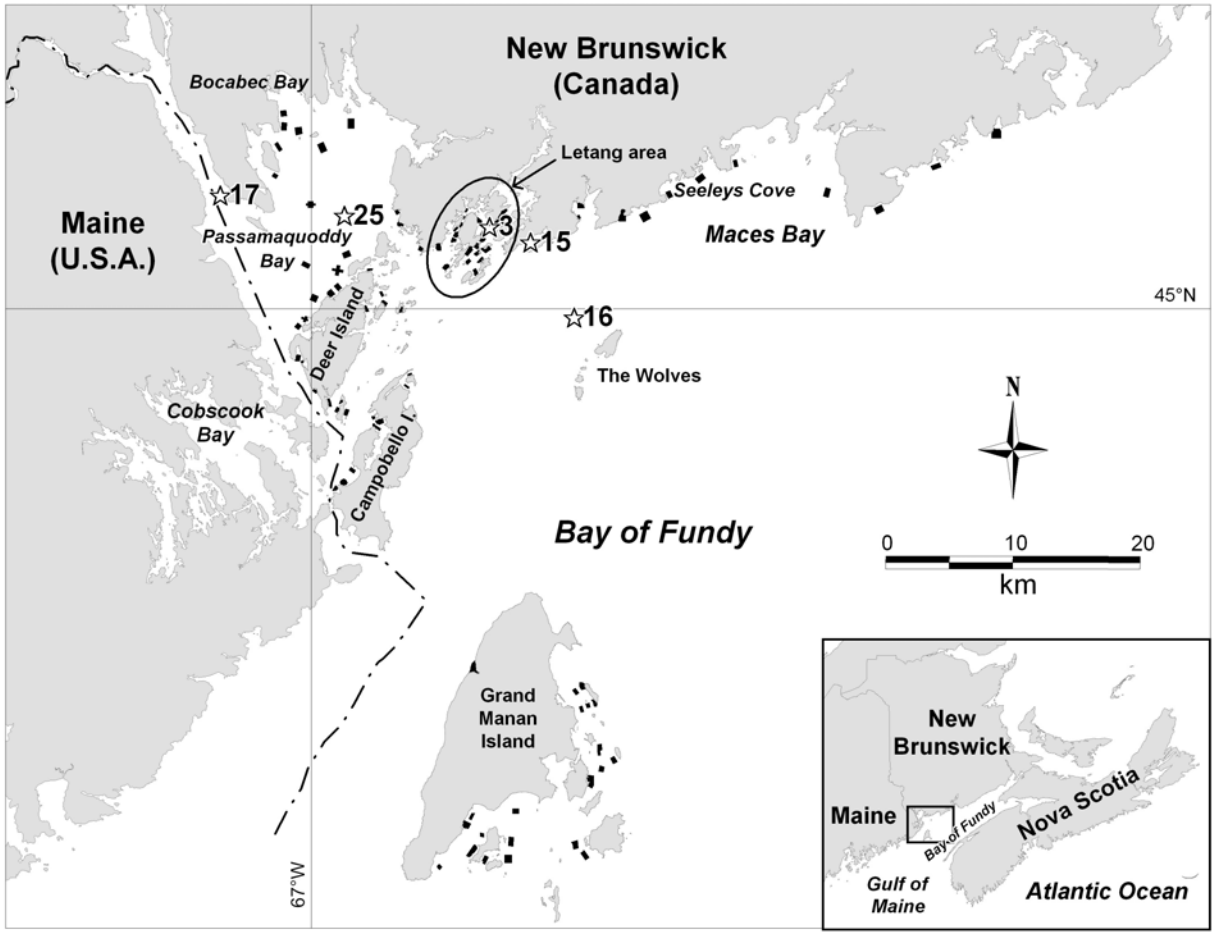

Fig. 1. Map showing Bay of Fundy with sampling stations marked with stars (✯)- Brandy Cove (#17), Lime Kiln Bay (#3), Deadmans Harbour (#15), the Wolves Islands (#16) and mid-Passamaquoddy Bay (#25). Solid shapes indicate locations of salmon aquaculture operations.

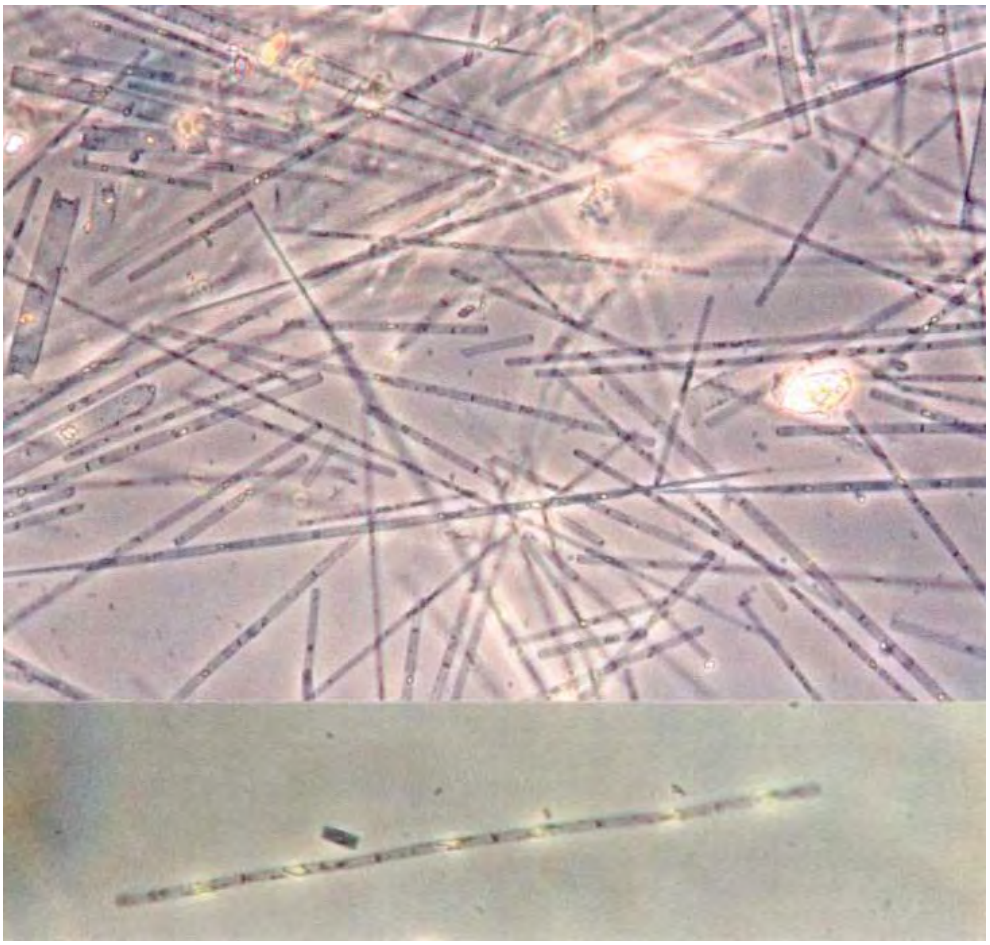

Fig. 2. *Leptocylindrus minimus* (photo courtesy of R. Horner, U. Washington)

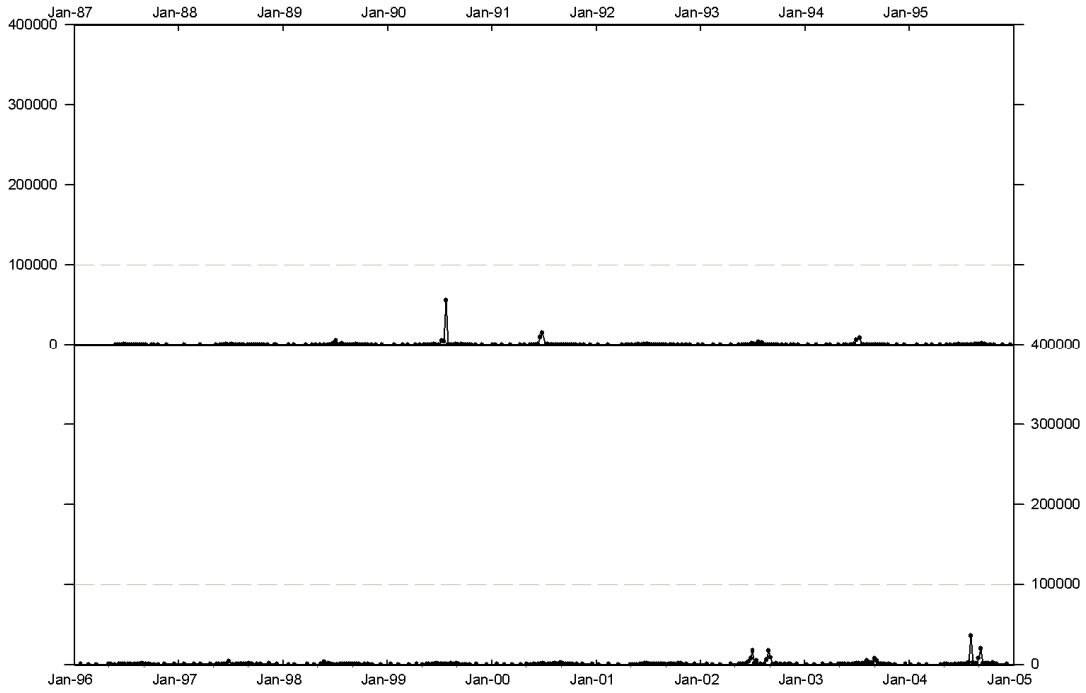

Fig. 3A. Concentrations (cells·L^{-1}) of *L. minimus* from Lime Kiln Bay (#3) from 1987-2004 on a linear scale. Upper portions of figures are 1987-95 and the lower portions are 1996-2004. Dotted line indicates the 100 000 cells•L^{-1} concentration.

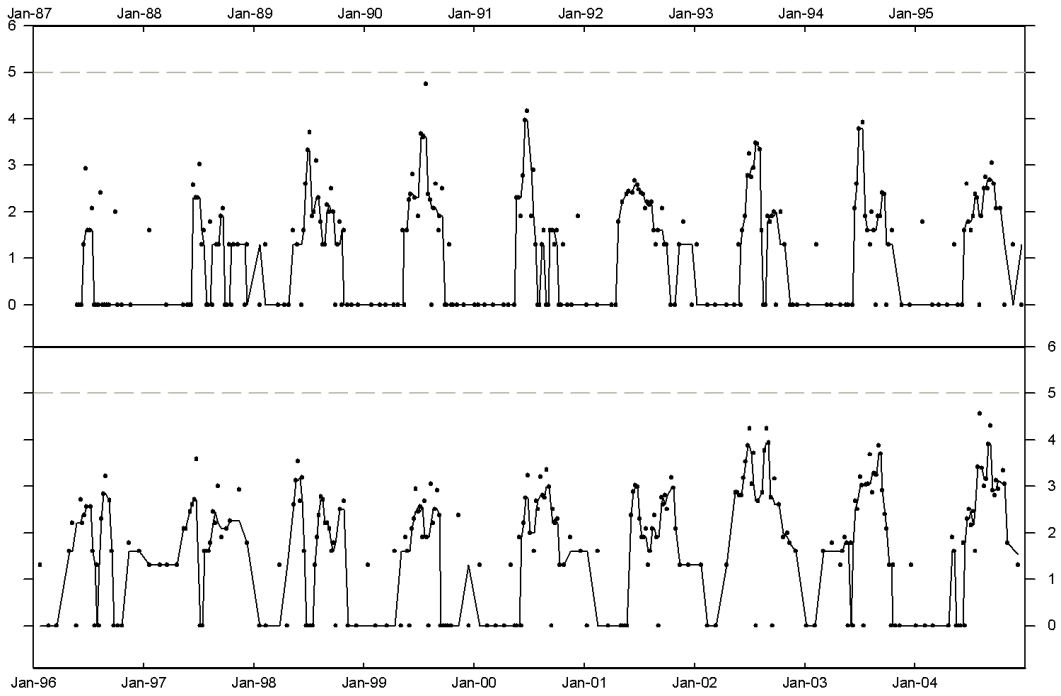

Fig. 3B. Concentrations (cells·L^{-1}) of *L. minimus* from Lime Kiln Bay (#3) from 1987-2004 on a log-transformed scale. Upper portions of figures are 1987-95 and the lower portions are 1996-2004. Dotted line indicates the 100 000 cells•L^{-1} concentration.

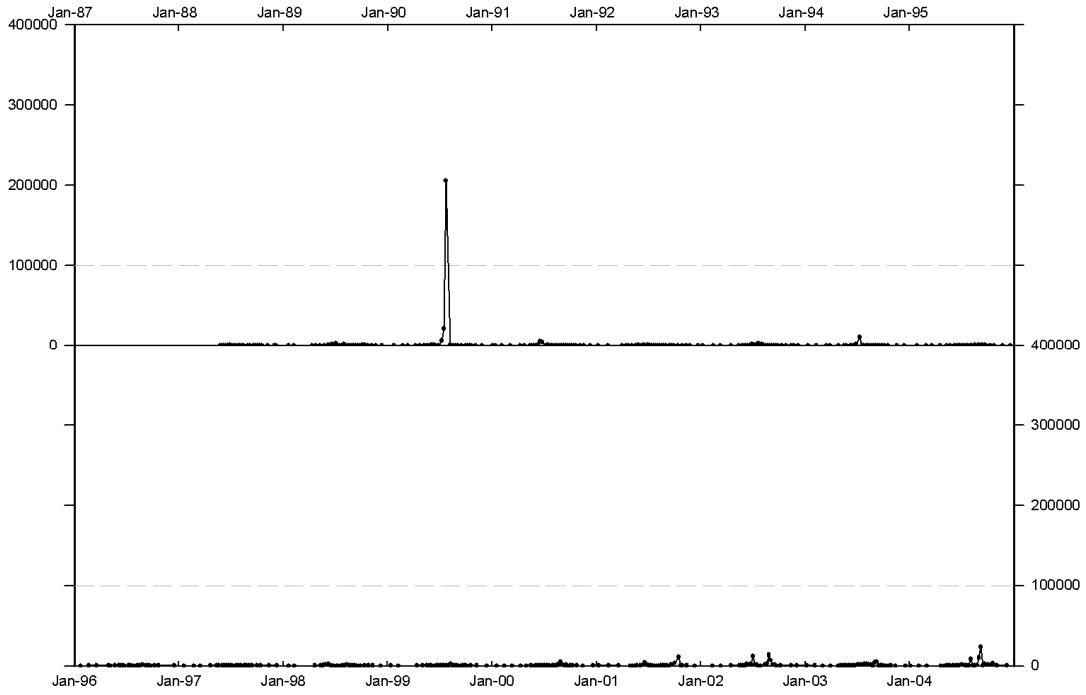

Fig. 4A. Concentrations (cells•L^{-1}) of *L. minimus* from Deadmans Harbour (#15) from 1988-2004 on a linear scale. Upper portions of figures are 1988-95 and the lower portions are 1996-2004. Dotted line indicates the 100 000 cells•L^{-1} concentration.

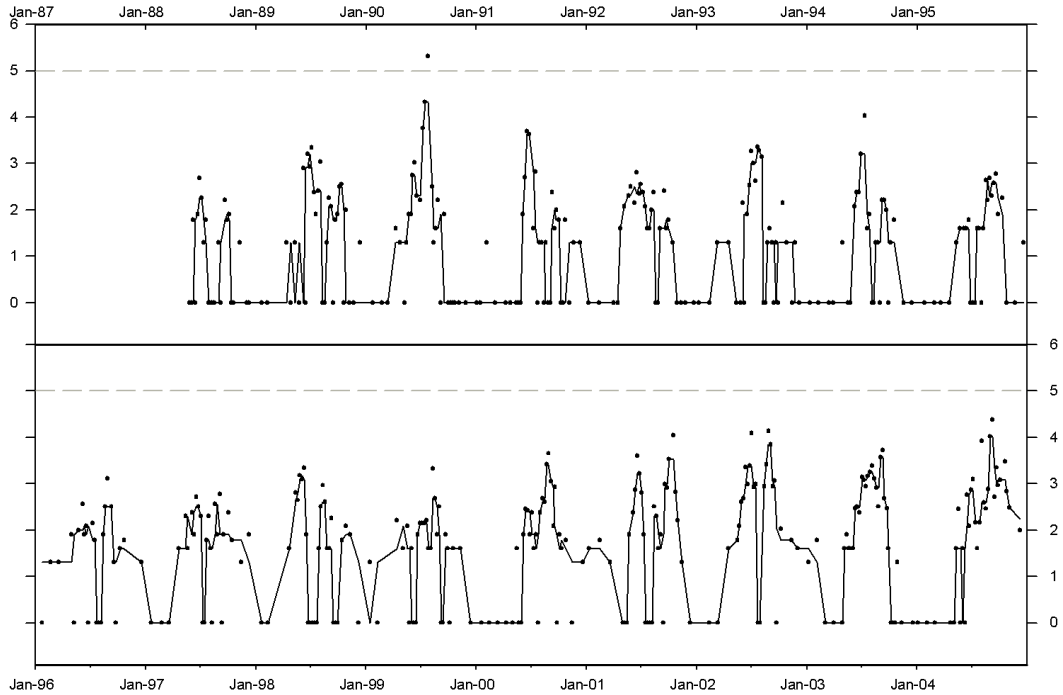

Fig. 4B. Concentrations (cells•L^{-1}) of *L. minimus* from Deadmans Harbour (#15) from 1988-2004 on a log-transformed scale. Upper portions of figures are 1988-95 and the lower portions are 1996-2004. Dotted line indicates the 100 000 cells•L^{-1} concentration.

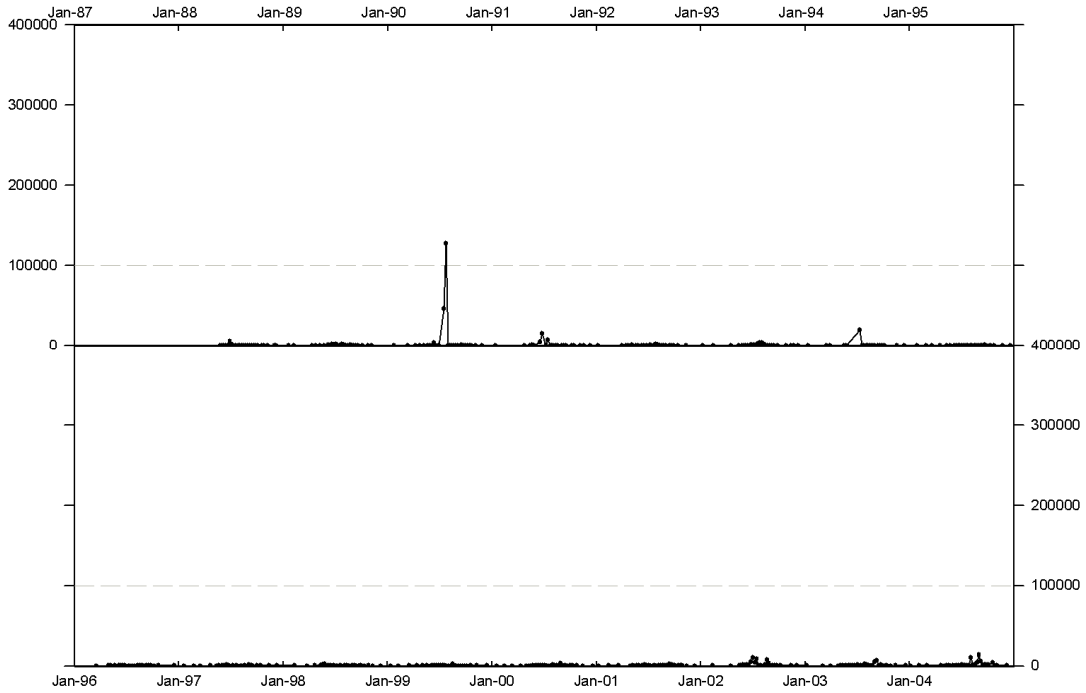

Fig. 5A. Concentrations (cells•L^{-1}) of *L. minimus* from the Wolves Islands (#16) from 1988-2004 on a linear scale. Upper portions of figures are 1988-95 and the lower portions are 1996-2004. Dotted line indicates the 100 000 cells•L^{-1} concentration.

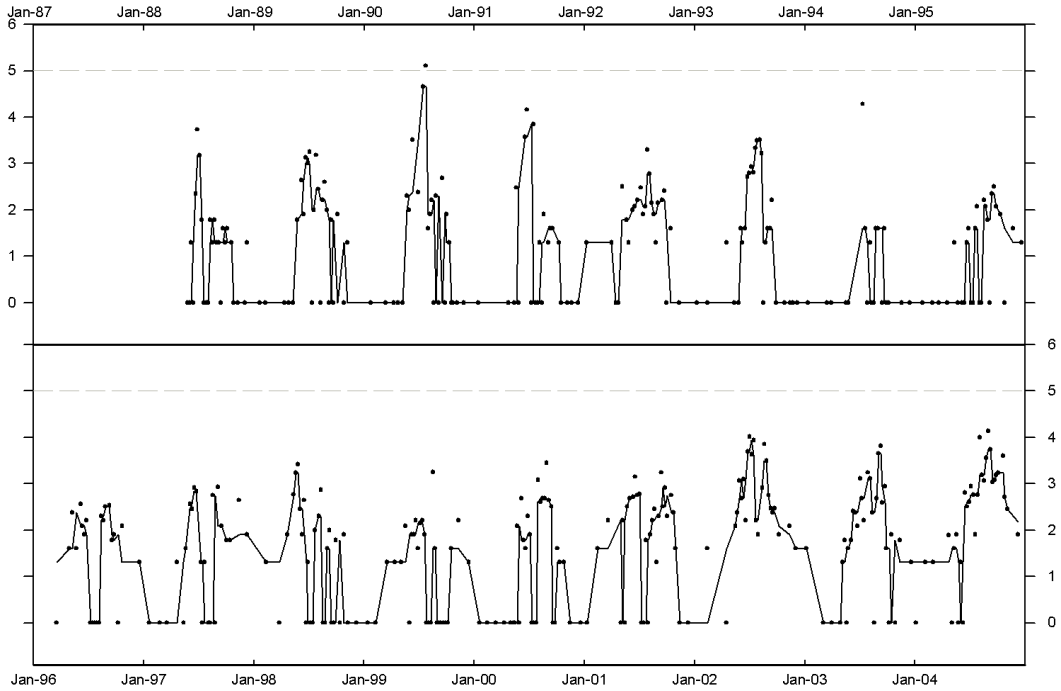

Fig. 5B. Concentrations (cells•L^{-1}) of *L. minimus* from the Wolves Islands (#16) from 1988-2004 on a log-transformed scale. Upper portions of figures are 1988-95 and the lower portions are 1996-2004. Dotted line indicates the 100 000 cells•L^{-1} concentration.

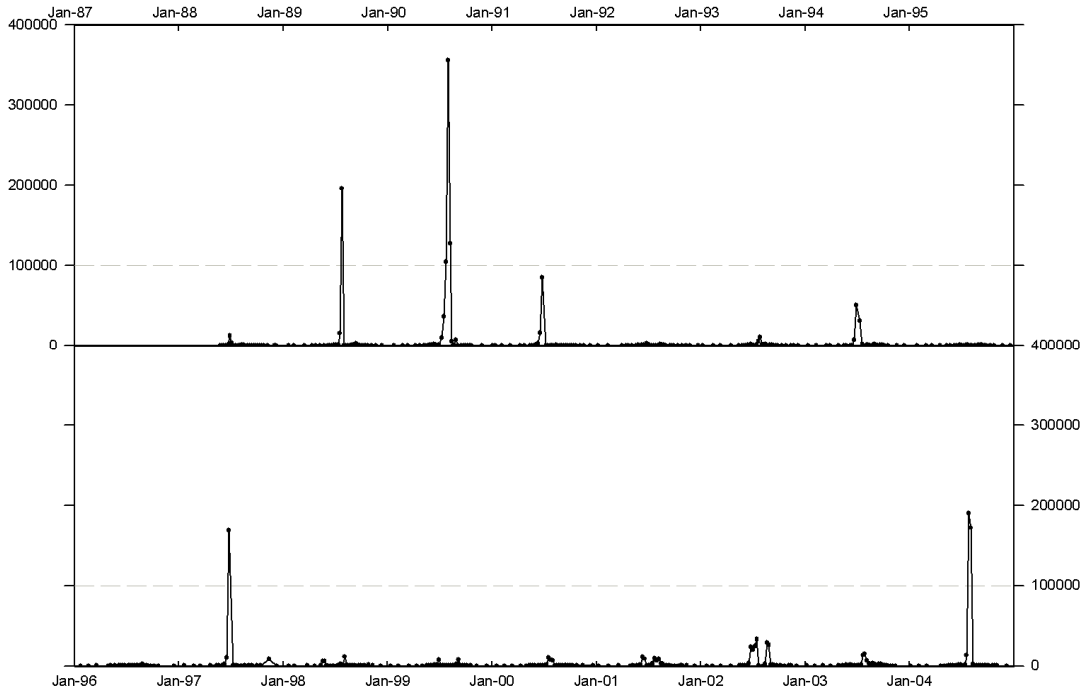

Fig. 6A. Concentrations (cells•L^{-1}) of *L. minimus* from the Brandy Cove (#17) from 1988-2004 on a linear scale. Upper portions of figures are 1988-95 and the lower portions are 1996-2004. Dotted line indicates the 100 000 cells•L^{-1} concentration

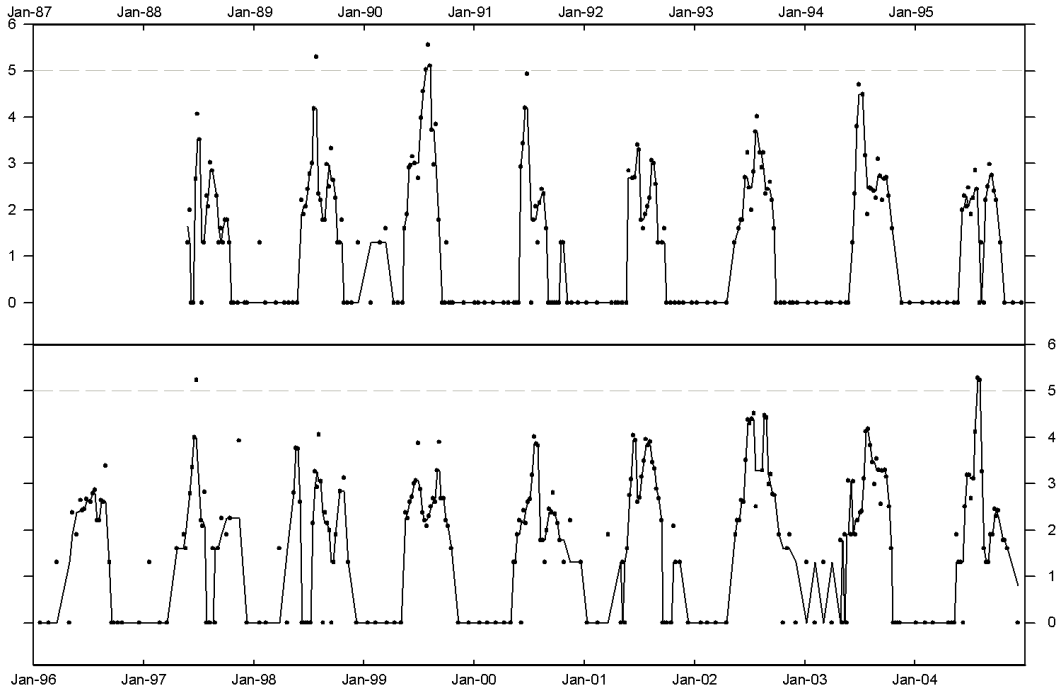

Fig. 6B. Concentrations (cells•L^{-1}) of *L. minimus* from Brandy Cove (#17) from 1988-2004 on a log-transformed scale. Upper portions of figures are 1988-95 and the lower portions are 1996-2004. Dotted line indicates the 100 000 cells•L^{-1} concentration.

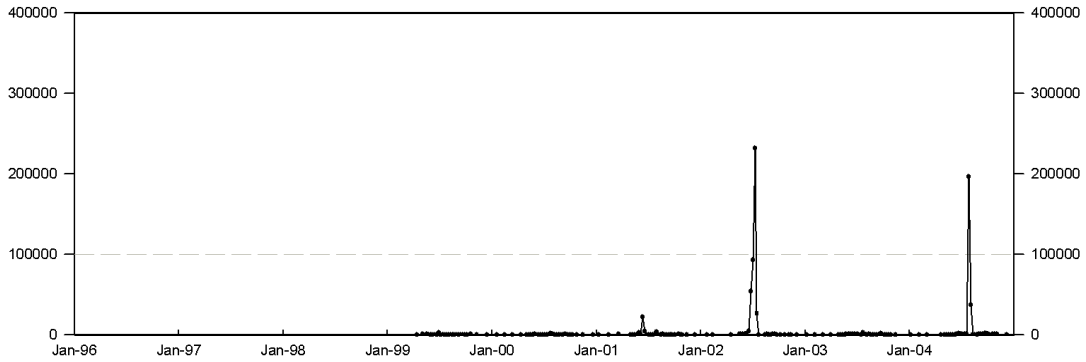

Fig. 7A. Concentrations (cells•L^{-1}) of *L. minimus* from mid-Passamaquoddy Bay (#25) on a linear scale (1999-2004). Dotted line indicates the 100 000 cells•L^{-1} concentration.

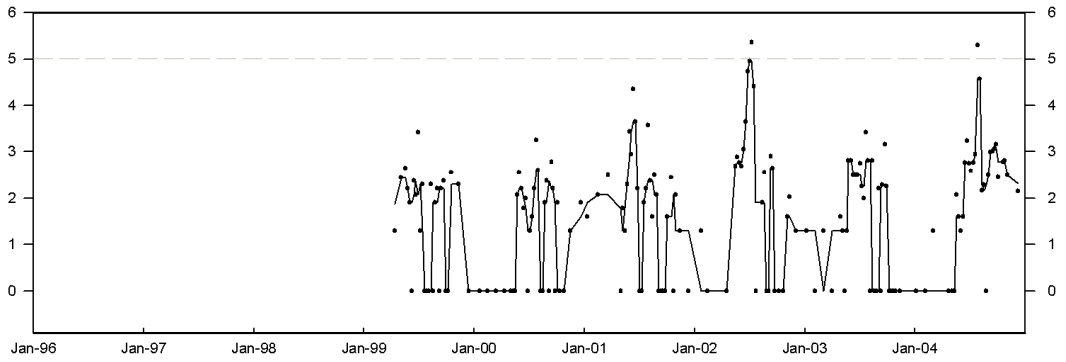

Fig. 7B. Concentrations (cells•L^{-1}) of *L. minimus* from mid-Passamaquoddy Bay (#25) on a log-transformed scale (1999-2004). Dotted line indicates the 100 000 cells•L^{-1} concentration.

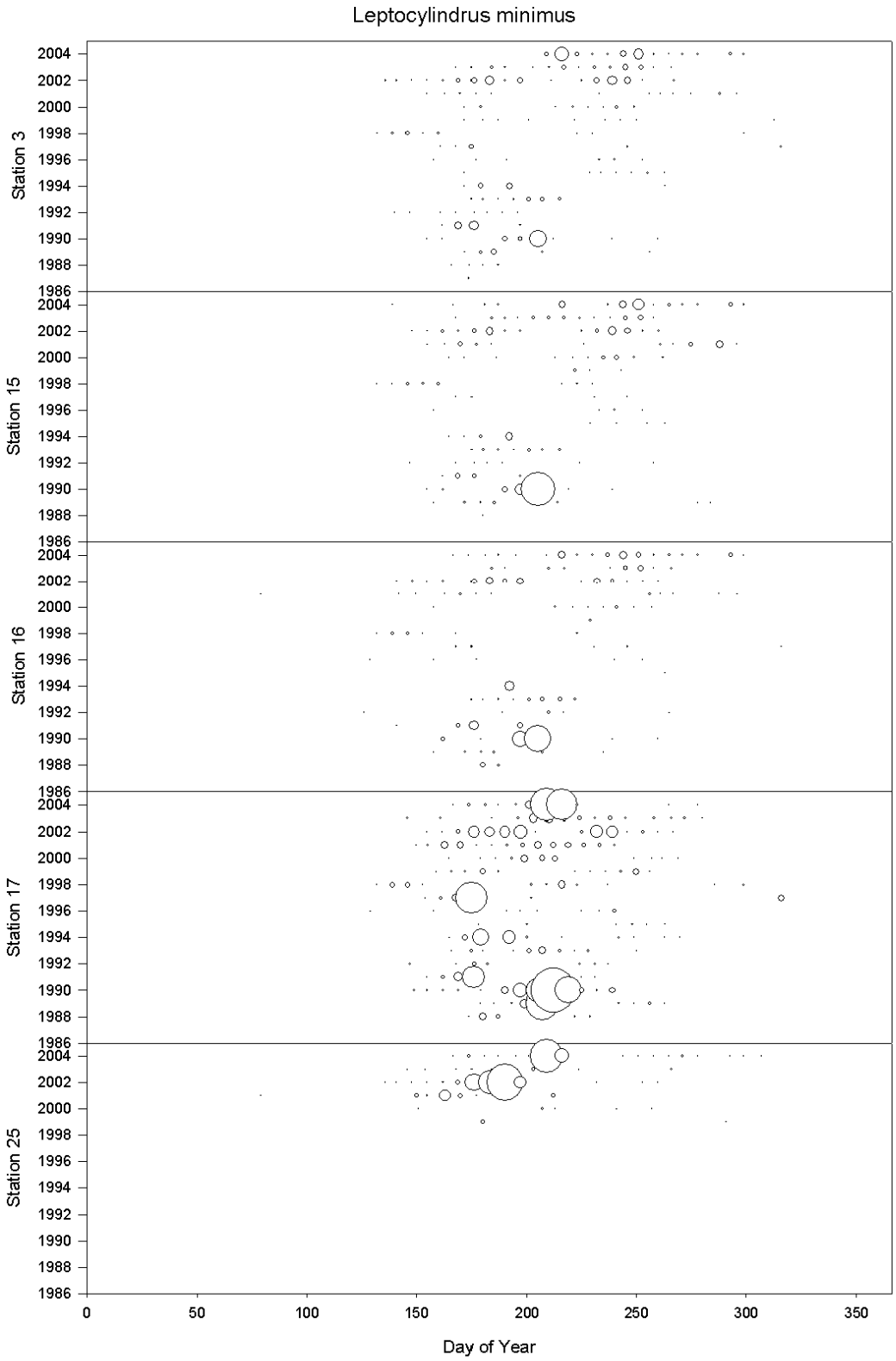

Fig. 8. Bubble graphs showing the *L. minimus* bloom durations from 1987-2004. Size of the circles indicates the cell concentrations (cells•L^{-1}). Station #25 was not sampled prior to 1999.

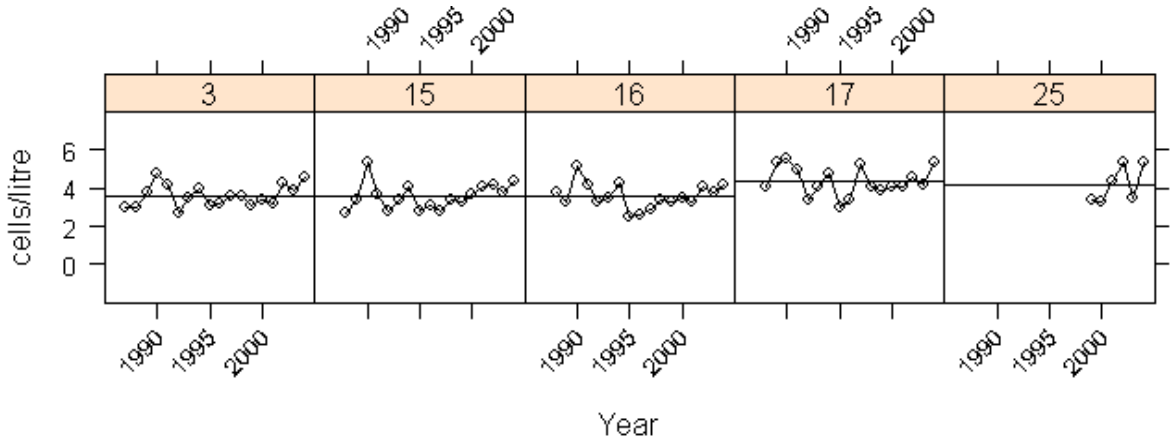

Fig. 9. Maximum density (cells•L^{-1}) of *L. minimus* at Stations 3, 15, 16, 17, and 25 on a log-transformed scale. Solid line indicates the mean of the log cell concentrations.

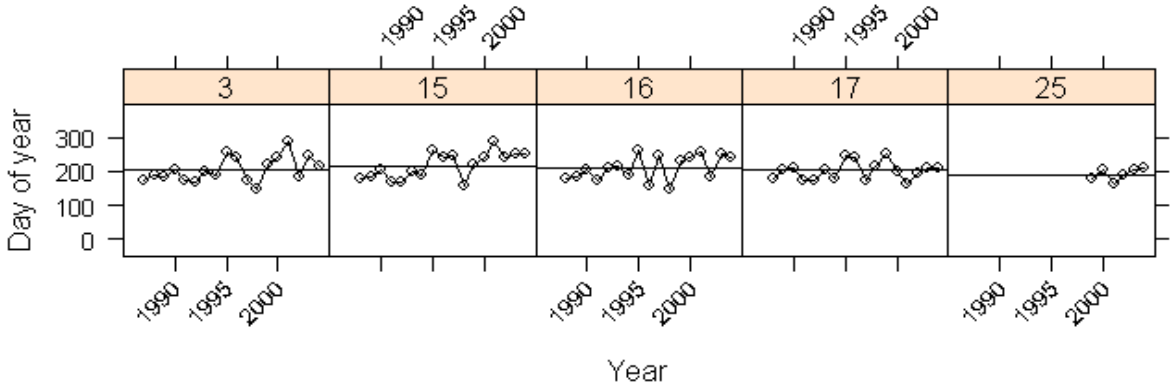

Fig 10. Day of the year that the maximum cell density was observed. Solid line indicates the mean.

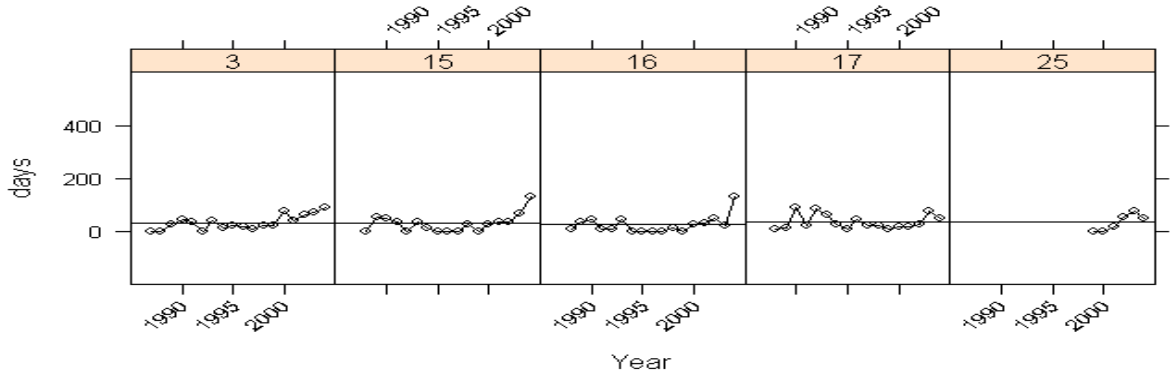

Fig. 11. Length of the bloom containing the maximum cell density for each year 1987-2004.

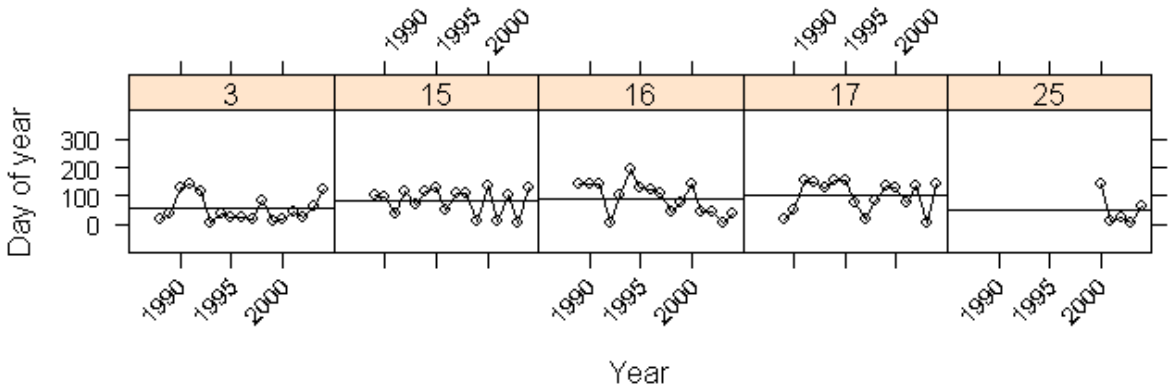

Fig. 12. Date of the first appearance of *L. minimus* cells in a given year.