Available online at www.sciencedirect.com
SCIENCE DIRECT®
Harmful Algae 3 (2004) 305–320
HARMFUL ALGAE
www.elsevier.com/locate/hal

Assessment of brown tide blooms, caused by *Aureococcus anophagefferens*, and contributing factors in New Jersey coastal bays: 2000–2002

Mary Downes Gastrich [a,*], Richard Lathrop [b], Scott Haag [c], Michael P. Weinstein [d], Michael Danko [d], David A. Caron [e], Rebecca Schaffner [e]

[a] *New Jersey Department of Environmental Protection, Division of Science, Research and Technology, P.O. Box 409, Trenton, NJ 08625, USA*
[b] *Rutgers University Center for Remote Sensing and Spatial Analysis (CRSSA), 14 College Farm Road, Cook College/Rutgers University, New Brunswick, NJ 08901-8551, USA*
[c] *Jacques Cousteau National Estuarine Research Reserve (Mullica River and Great Bay), P.O. Box 231, New Brunswick, NJ 08903-0231, USA*
[d] *New Jersey Marine Sciences Consortium, Building #22, Fort Hancock, NJ 07732, USA*
[e] *Department of Biological Sciences, University of Southern California, 3616 Trousdale Parkway, AHF 301, Los Angeles, CA 90089-0371, USA*

Received 30 June 2003; received in revised form 5 November 2003; accepted 4 June 2004

Abstract

A 3 year study (2000–2002) in Barnegat Bay-Little Egg Harbor (BB/LEH), New Jersey (USA), was conducted by the New Jersey Department of Environmental Protection, Division of Science Research and Technology (DSRT) in cooperation with several partners to assess brown tide blooms in coastal waters in NJ. Water samples were collected by boat and helicopter at coastal stations from 2000 to 2002 along with field measurements. *Aureococcus anophagefferens* were enumerated and associated environmental factors were analyzed. *A. anophagefferens* abundances were classified using the Brown Tide Bloom Index and mapped, along with salinity and temperature parameters, to their geo-referenced location using the ArcView GIS. The highest *A. anophagefferens* abundances ($>10^6$ cells ml^{-1}), including category 3 blooms ($\geq$200,000 cells ml^{-1}) and category 2 blooms ($\geq$35,000 to $\leq$200,000 cells ml^{-1}), recurred during each of the 3 years of sampling and covered significant geographic areas of the estuary, especially in Little Egg Harbor. While category 3 blooms were generally associated with warmer water temperatures (>16 °C) and higher salinity (>25–26 ppt), these factors were not sufficient alone to explain the timing or distribution of *A. anophagefferens* blooms. There was no significant relationship between brown tide abundances and dissolved organic nitrogen measured in 2002 but this was consistent with other studies. Extended drought conditions, with corresponding low freshwater inputs and elevated bay water salinities, occurring during this time were conducive to blooms. *A. anophagefferens* abundances were well above the reported levels that have been reported to cause negative impacts on shellfish. It was shown that over 50% of the submerged aquatic vegetation (SAV) habitat located in Barnegat Bay/Little Egg Harbor was categorized as having a high frequency of category 2 or 3 blooms for all 3 years.

Keywords: *Aureococcus anophagefferens*; Barnegat Bay; Brown tide; Little Egg Harbor; New Jersey

* Corresponding author. Tel.: +1-609-292-1895; fax: +1-609-292-7340.
E-mail address: mary.downes-gastrich@dep.state.nj.us (M.D. Gastrich).

1568-9883/$ – see front matter © 2004 Elsevier B.V. All rights reserved.
doi:10.1016/j.hal.2004.06.003

1. Introduction

Brown tide blooms, caused by the minute alga *Aureococcus anophagefferens*, were suspected to occur in Barnegat Bay, New Jersey in 1985–86, at the same time as the occurrence of massive blooms in coastal bays of Long Island, New York and Narragansett Bay, Rhode Island (Cosper et al., 1989), because of a yellow–brown discoloration of the water (NJDEP, 1985, 1986). However, *A. anophagefferens* abundances in Barnegat Bay (Fig. 1) were first confirmed in 1988–1990, using an immunofluorescence technique (Anderson et al., 1993). *A. anophagefferens* abundances in the New Jersey coastal bay sites were low ($<35{,}000$ cells ml^{-1}) in September 1988 with the exception of Manahawkin Bay, New Jersey (141,000 cells ml^{-1}) (Anderson et al., 1993). In 1995, a dense brown tide bloom occurred in Barnegat Bay, with *A. anophagefferens* abundances of approximately 10^6 cells ml^{-1} that were associated with a reduction in growth of hard clams at a commercial aquaculture facility in Tuckerton, New Jersey (NJDEP, 1995; Nuzzi et al., 1996). In 1999, another brown tide bloom was reported; the highest *A. anophagefferens* abundances ($>10^6$ cells ml^{-1}) were in lower Barnegat Bay, between Surf City and Manahawkin, south to Little Egg Harbor and Great Bay and north to Forked River (NJDEP, 1999a). During the 1999 and subsequent 2000 brown tide blooms, when *A. anophagefferens* abundances peaked $>1.8 \times 10^6$ cells ml^{-1}, intracellu-

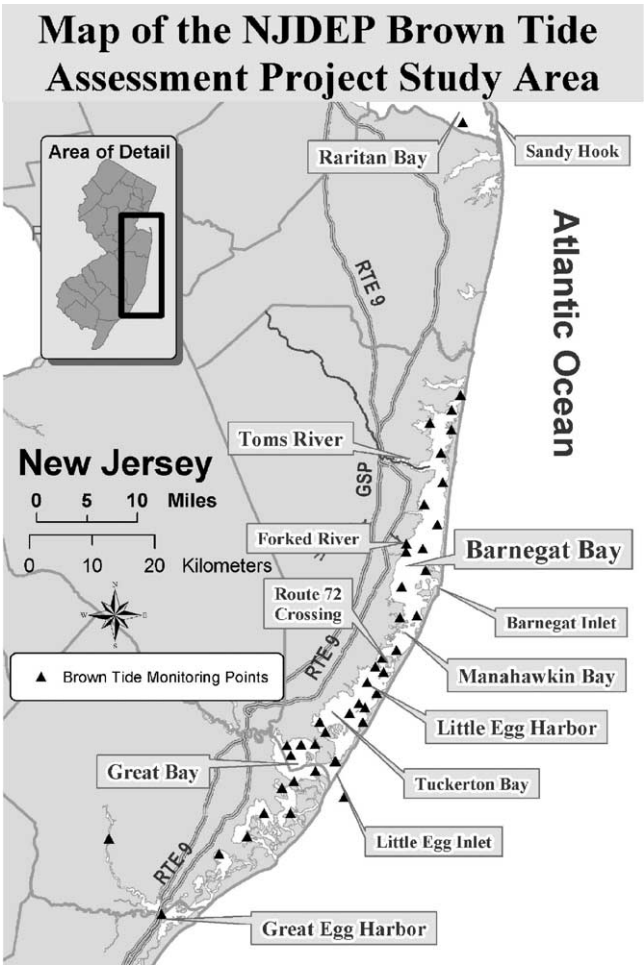

Fig. 1. Map of the Brown Tide Assessment Project study area.

lar viral-like particles (VLPs) were documented for the first time in natural populations of *A. anophagefferens* in Little Egg Harbor (Gastrich et al., 2002).

Brown tide bloom abundances have been categorized according to their potential reported negative impacts to natural resources, mainly shellfish and seagrasses (Gastrich and Wazniak, 2002). *A. anophagefferens* abundances as low as 35,000 cells ml^{-1}, have been reported to cause a sharp reduction in clearance rates of the juvenile hard clam (northern quahog) *M. mercenaria* (Bricelj, 1999; Schaffner, 1999; Bricelj et al., 2001). Water column turbidity is a major factor controlling the productivity and health of seagrasses (Short and Wyllie-Echeverria, 1996). The occurrence of *A. anophagefferens* blooms can result in a high density of small particles (2–3 μm) in the water column which can, in turn, cause light scattering sufficient to reduce Secchi disc depth (Dennison et al., 1989). By severely reducing light transparency, category 3 level *A. anophagefferens* blooms have been documented elsewhere to have significant negative impacts on the health and productivity of seagrass (Cosper et al., 1989; Dennison et al., 1989; Bricelj and Lonsdale, 1997).

To assess the brown tide bloom phenomena in New Jersey's coastal bays, the New Jersey Department of Environmental Protection, Division of Science, Research and Technology (NJDEP/DSRT) established the Brown Tide Assessment Project in 1999 in cooperation with the New Jersey Marine Sciences Consortium/NJ Sea Grant (NJMSC/NJSG), Center for Remote Sensing and Spatial Analysis at Rutgers University, NJDEP Bureau of Marine Water Monitoring, US Environmental Protection Agency Region 2, and the University of Southern California. The objectives were to: (1) assess the spatial and temporal extent of brown tide in several coastal bays; (2) determine the relationship between the *A. anophagefferens* abundances and environmental data; and (3) analyze the risk of brown tide blooms to submerged aquatic vegetation (SAV) communities.

2. Methods

2.1. Field sampling

Water samples were collected at selected stations of the state's water quality monitoring network (NJDEP, 2000) from 2000 to 2002 ($N = 523$) in Raritan Bay (2000), Barnegat Bay/Little Egg Harbor (BB/LEH) (2000–02), Great Bay (2000–2002), Great Egg Harbor (2000–2001) and other coastal stations (Fig. 1). Water samples were collected by boat at 44 stations on a variable schedule in 2000 (April through December) and at eleven stations on the same day in 2001–02 during April (1X), May (1X), June (4X), July (2X), August (1X) and September (1X) (2000, $N = 245$; 2001, $N = 149$; 2002, $N = 129$). Water samples were also collected at six stations by helicopter (bi-weekly) (2000–02) and were pre-fixed in 1% glutaraldehyde in seawater and enumerated for *A. anophagefferens* using a monoclonal antibody technique (Caron et al., 2003). Environmental data were collected and analyzed (e.g. salinity, water temperature, nitrogen species, Secchi disk, photosynthetically active radiation and reference, light transmittance, pH, chlorophyll a and dissolved oxygen) according to the quality assurance plan requirements of the USEPA (1994). The nitrogen species ($N = 51$) in 2002 included total nitrogen (TN), ammonia (NH_3), nitrite (NO_2) and nitrate (NO_3) and dissolved organic nitrogen (DON). DON was calculated from TN in concentrations of parts per billion (μg/L), converted to 'μM' (NJDEP, 1999b). The monthly average daily flow from the Toms River (northern Barnegat Bay), as well as the 74-year mean, freshwater discharge was graphed across the 3-year-period as an indicator of the prevailing precipitation and/or drought conditions.

2.2. Geographic information system (GIS) mapping and data analysis

To visualize the spatial and temporal patterns of the *A. anophagefferens* abundances, the field sampling locations were mapped to their georeferenced location and interpolated to create two-dimensional surface maps for the various sampled parameters (i.e. *A. anophagefferens* abundance, salinity and water temperature). The data collected within a single weekly period were pooled for the spatial interpolation analysis. The data were interpolated to create a grid cell map of 100 m × 100 m size using an inverse distance weighted interpolation routine and ArcView geographic information system (GIS) software. A shoreline boundary file was used as a barrier in the interpolation process. As in any interpolation procedure,

a major concern was how well the resulting outputs "honored the data points" (Davis, 1986). There was a limit on how fine the output grid cell size could be made given the spatial frequency and distribution of the input sampling points. Various output cell sizes, ranging from 100 to 1000 m, were examined. The grid cell size (100 m × 100 m) was chosen to provide a suitably detailed picture of the water turbidity for the seagrass modeling effort without unduly compromising the integrity of the input data. The maximum, median and mean value per year of the interpolated *A. anophagefferens* concentration data were calculated for every grid cell in the interpolated grid cell maps. In addition to the *A. anophagefferens* abundances, salinity and temperature were also mapped for each time period.

The resulting interpolated *A. anophagefferens* abundances maps were classified into the three categories of the Brown Tide Bloom Index (Gastrich and Wazniak, 2002): category 1 blooms (>0 and $<35{,}000$ cells ml^{-1}); category 2 blooms ($\geq 35{,}000$ and $<200{,}000$ cells ml^{-1}); and category 3 blooms ($\geq 200{,}000$ cells ml^{-1}). For display purposes, additional finer gradations (three sub-categories) were delineated within each of the three bloom categories. For each time period, an ArcView map was exported as a ".jpeg" graphic file and then combined to create an animated graphic for each of the 3 years of sampling. The resultant maps displayed the spatial patterns of the blooms and identified "hotspots" of high brown tide bloom activity (e.g. several months of category 2 or 3 blooms). In addition, the time series for the data was displayed and the maps facilitated the visualization of the spatial and temporal patterns of bloom onset, progression and decline. These animated maps are available for display online at http://crssa.rutgers.edu/projects/btide/index.html.

To assess the relationship between *A. anophagefferens* abundances and the sampled environmental data, basic univariate statistics were calculated using the SAS™ Statistical Package UNIVARIATE. The mean and standard deviation of the *A. anophagefferens* concentration data were determined on a yearly and multi-year basis (i.e. for combined 2000, 2001, and 2002 data). Graphical plots and regression analysis were used to examine the relationship between the *A. anophagefferens* abundances and measured environmental data using the SAS™ REG procedure. Analysis of variance (ANOVA) and a Kruskal–Wallis test of Wilcoxon rank sum scores were calculated using the SAS™ NPAR1WAY procedure to test whether there was a significant difference between the three brown tide bloom index categories of *A. anophagefferens* abundances and the measured environmental parameters. One-sided *t*-test was used to test whether the mean salinity and temperature for category 3 blooms were significantly different than the previously observed levels of 25 ppt and 16 °C, respectively.

To examine the potential influence of freshwater inflow from the upland watershed on *A. anophagefferens* occurrence, the discharge (ft s^{-1}) of the Toms River, the largest tributary to the BB/LEH system, was analyzed. The monthly average daily flow from the Toms River, as well as the 74-year mean, freshwater discharge was graphed across the 3-year-period. While these data do not provide a complete water budget of the BB/LEH system, they do provide an indicator of the prevailing precipitation and/or drought conditions.

3. Results

A. anophagefferens abundances were detected at most stations sampled over the 3-year-period (Fig. 1). Elevated *A. anophagefferens* abundances, category 2 and 3 brown tide blooms, occurred at all eleven boat stations and one helicopter station during the 3 year sampling period; all stations sampled in BB/LEH in 2002 had category 3 blooms, with exception of one station (station 1824A/B located in the middle of Little Egg Inlet) (Table 1). Five stations in Little Egg Harbor had category 3 blooms throughout the 3 years (Table 1). The highest *A. anophagefferens* abundances ($>10^6$ cells ml^{-1}) occurred for all 3 years at two stations each year in Stafford TWP (Ship Bottom) (1703C) and Long Beach Township (TWP) (near Beach Haven Terrace) (1820A) with the highest maximum concentration recorded in southwest Little Egg Harbor inTuckerton Bay (1820A) in 2000 (Table 1). In addition, stations as far north in Raritan Bay (4.5×10^4 cells ml^{-1} in August in 2000) and to the south in Great Egg Harbor had category 2 blooms (9.1×10^4 cells ml^{-1} in August 2000 and 1.19×10^5 cells ml^{-1} in August 2001). Fig. 2 shows the pattern and levels of *A. anophagefferens* abundances at one station that consistently experienced

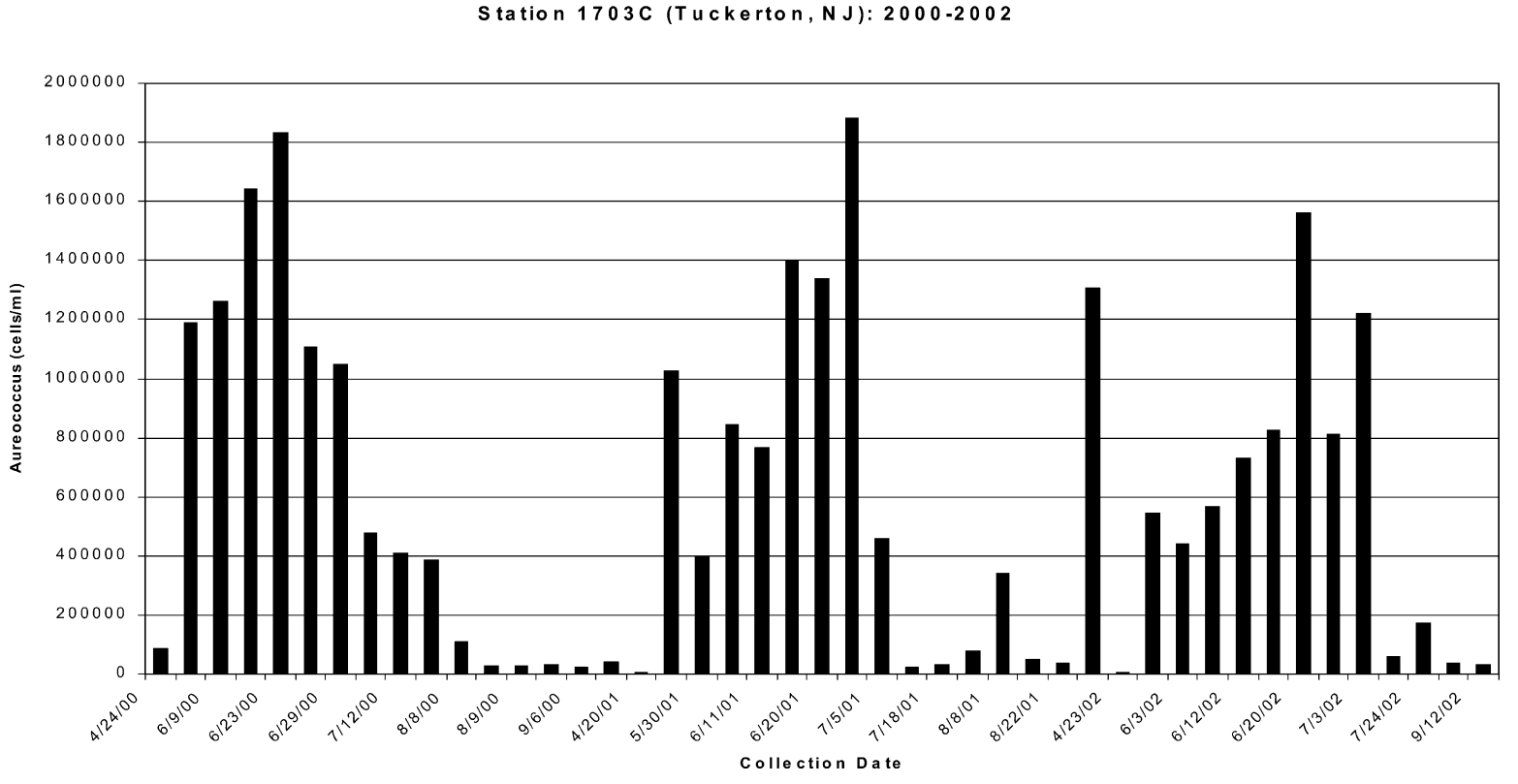

Fig. 2. Three years of *A. anophagefferens* blooms (2000–2002) at a station (1703C) in Little Egg Harbor, NJ (N = 45).

Table 1
Highest category of brown tide bloom levels with maximum *A. anophagefferens* abundances (cells/ml) observed over 3 years in Barnegat Bay/Little Egg Harbor, New Jersey (2000–2002)

Station/year[a]	Bloom category/(*Aureococcus* Abundance (cells ml^{-1}))		
	2000	2001	2002
1635E	2 (82,000)	2 (39,000)	3 (277,000)
1651D	2 (153,000)	2 (35,000)	3 (862,000)
1691E	2 (75,983)	2 (123,000)	3 (498,000)
1670D	3 (933,000)	2 (109,000)	3 (820,000)
1675	2 (154,885)	3 (1,404,000)	3 (851,000)
1703C	3 (1,834,000)	3 (1,883,000)	3 (1,561,000)
1719E	3 (2,144,000)	3 (1,285,000)	3 (1,228,000)
1800B/D	3 (1,902,000)	3 (1,309,000)	3 (866,000)
1818D	3 (2,027,000	3 (903,000)	3 (792,000)
1820A	3 (2,155,000)	3 (907,000)	3 (415,000)
1834A	3 (1,683,000)	3 (1,688,000)	3 (553,000)
1824A/B	3 (536,000)	2 (154,000)	2 (55,000)

[a] All stations were sampled by boat except station 1670D which was sampled by helicopter.

some of the highest *A. anophagefferens* abundances (Station 1703C, near Manahawkin Bay, New Jersey, located within 7 miles of a commercial aquaculture facility in Tuckerton Bay). While category 3 blooms occurred over all 3 years of the study at this station, a significant secondary bloom occurred in September 2001 with *A. anophagefferens* abundances as great as 1.3×10^6 cells ml^{-1}.

Each year, there were especially high *A. anophagefferens* abundances (e.g., category 3 blooms) in the vicinity of Manahawkin Bay (station 1703C, Figs. 2 and 3), which is the connecting section of the BB/LEH system that lies north of Little Egg Harbor and south of Barnegat Bay proper. A consistent pattern emerged from analysis of the animated graphics, across all 3 years of study, showing that category 3 blooms first originated in the vicinity of Manahawkin Bay and persisted longest at that location. Increasing from a category 2 bloom, category 3 blooms recurred most frequently at stations in Little Egg Harbor and Tuckerton Bay. While category 2 or category 3 blooms extended further to the northern- and southern-most regions of the BB/LEH system, in general, the northern half of Barnegat Bay had the lowest *A. anophagefferens* median abundances (Fig. 3) and category 3 blooms there in June 2002 were near the lower limit of this categorization (Fig. 3). Year 2002 had the highest mean and median *A. anophagefferens* abundances of the 3 year study period (Table 2).

The mean salinity was >26 ppt throughout the study period, with the highest mean/median salinity (29.5/30.3 ppt) in 2002 (Table 2). These relatively high values were in agreement with evidence of lower freshwater flows immediately prior to and during 2002 (Fig. 4). Category 3 blooms were more common when salinities were >25 and <31 ppt (Fig. 5A), with mean salinity for category 3 blooms significantly greater than 25 ppt (Z-value = 13.4; $P < 0.0001$). There was no detectable simple linear relationship between brown tide abundance and salinity. Category 2 conditions were observed across the full range of salinities observed during the study. During the summer bloom months, many sample locations had salinities within the 25–31 ppt range but had *A. anophagefferens* abundances in the category 1 or 2 ranges (Fig. 5A). Regression analysis of the pooled data set did not show a significant relationship between *A. anophagefferens* abundances and salinity ($F = 0.59$; $P = 0.4418$, $R^2 = 0.0013$) (Table 3). The analysis of variance test showed that there was no significant difference in salinity between the three bloom categories ($F = 0.5822$; $P = 0.5591$) (Table 4). The Kruskal–Wallis test was also not significant (chi-square = 1.2858 ($P = 0.5258$) (Table 4).

The questions guiding the data analysis of water temperature and *A. anophagefferens* abundances were whether (1) category 3 brown tide blooms were associated with warmer temperatures (>16 °C) and (2) there was a consistent pattern of the association of

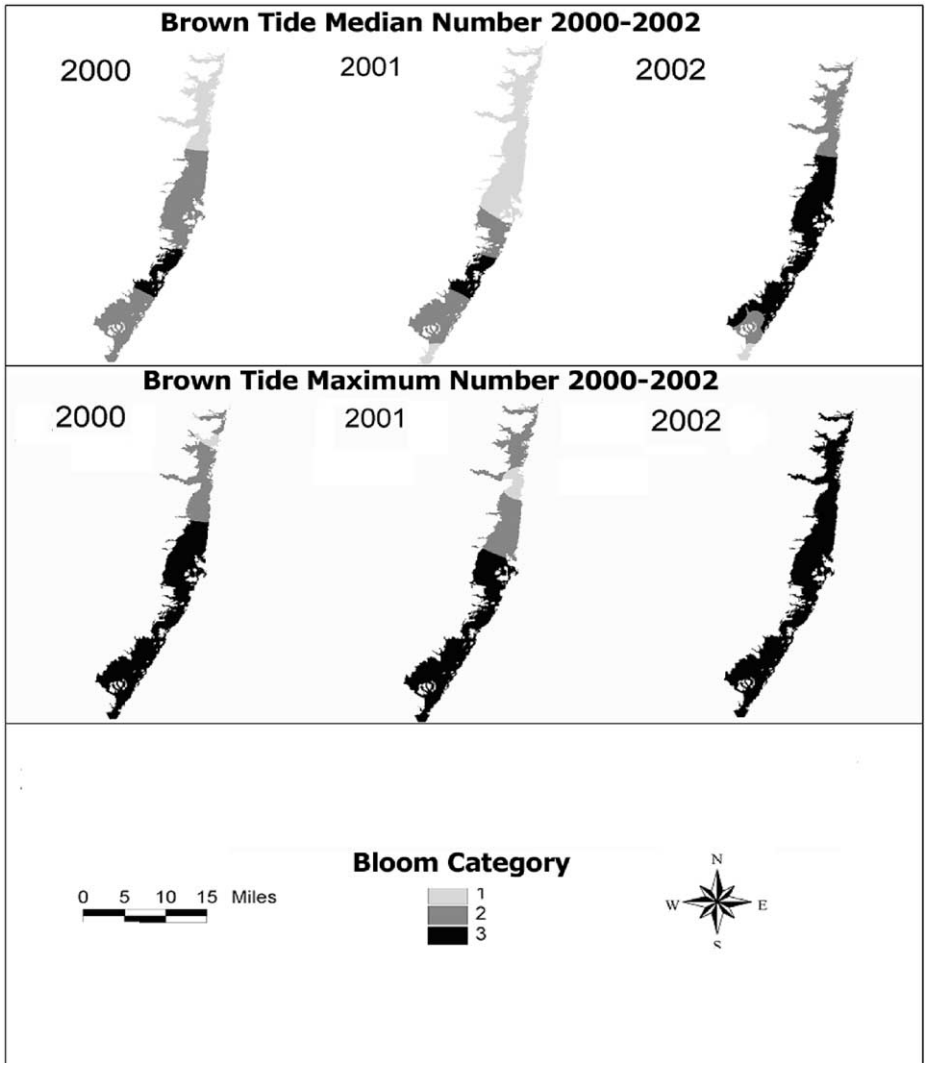

Fig. 3. Maps of median and maximum brown tide (*A. anophagefferens*) abundances (cells ml^{-1}) for the April to September sampling period for years 2000, 2001, and 2002 in Barnegat Bay/Little Egg Harbor, NJ.

category 2 blooms and water temperature. The mean temperatures for the 3 years of the study ranged from 19.7 to 21.6 °C with the highest mean/median temperatures (21.6/23.1 °C) in 2001 (Table 2). The annual pattern in the onset of bloom conditions and warming water temperatures was similar for all 3 years of the study (Fig. 5B). Category 3 blooms were observed when the water temperature increased above 16 °C in 2000, 17 °C in 2001 and 13 °C in 2002. The category 3 blooms were observed up to the highest temperatures observed (i.e. 27–28 °C). There appeared to be a relationship between category 3 blooms and a water temperature of approximately 16 °C with the mean temperature for category 3 blooms significantly greater than 16 °C (Z-value = 16.0, $P < 0.0001$). Category 2 bloom conditions were observed across all water temperatures and seasons of the year (Fig. 5B). While regression analysis of the pooled data set indicated a significant relationship between temperature and *A. anophagefferens* abundance (F = 11.22,

Table 2
Univariate statistics for *A. anophagefferens* concentrations (cells ml^{-1}), temperature (°C), salinity (ppt), nitrogen (μM), Secchi disc depth (m), PAR (μE/s/m^2), Chlorophyll a (μg/l), transmittance (%), pH, and dissolved oxygen (mg/l)

Parameter/year	*N*	Mean	Median	Standard deviation	Maximum
A. anophagefferens					
2000	207	216,000	41,000	456,000	2,155,000
2001	148	253,000	40,000	422,000	1,883,000
2002	128	282,000	125,000	317,000	1,561,000
Temperature					
2000	208	19.7	21.6	5.4	28.3
2001	149	21.6	23.1	4.6	29.2
2002	111	20.9	21.3	4.5	28.2
Salinity					
2000	207	27.1	28.2	3.3	33.8
2001	114	26.9	27.8	3.5	31.6
2002	111	29.5	30.3	3.1	34.1
Nitrogen (2002)					
Total nitrogen	46	24.2	19.9	13.1	62.7
NH_3	46	0.66	0.46	0.59	3.4
NO_2NO_3	46	3.3	0.93	7.86	51.9
DON[a]	46	22.2	17.3	13.15	60.8
Secchi depth					
2001	109	0.9	0.9	0.5	2.8
2002	109	0.7	0.6	0.5	3.0
PAR[b]					
2001	114	0.51	0.56	0.25	0.95
2002	86	0.57	0.58	0.21	0.97
Chlorophyll a					
2002	44	1.64	0.60	2.22	9.76
Transmittance					
2001	116	62.2	65.5	22.0	98.3
2002	109	41.9	39.3	21.0	91.6
pH					
2001	116	7.8	7.7	0.31	8.5
2002	109	7.8	7.8	0.26	8.3
DO[c]					
2001	127	7.2	6.5	2.14	16.8
2002	109	7.2	7.5	1.16	9.7

[a] DON: dissolved organic nitrogen.
[b] PAR: photosynthetically active radiation/reference PAR.
[c] DO: dissolved oxygen.

$P = 0.0009$), the R^2 was quite low ($R^2 = 0.0223$) (Table 3). In other words, temperature explained only about 2% of the variation in the observed *A. anophagefferens* cell abundances.

The purpose of the analysis of nitrogen data was to determine whether there was a positive association of category 3 blooms and higher nitrogen abundances, especially abundances of dissolved organic nitrogen (DON). DON concentrations (μM) varied throughout the season and ranged from 8.9 to 60.8 μM, with a mean yearly concentration of 22.2 μM with the lowest concentration in April and the highest concentrations in August and September. There was no statistically significant relationship (Tables 3 and 4) between *A. anophagefferens* abundance or bloom categories and any measured nitrogen species.

As expected, category 3 blooms resulted in reduced light transmission as shown by the Secchi depth data

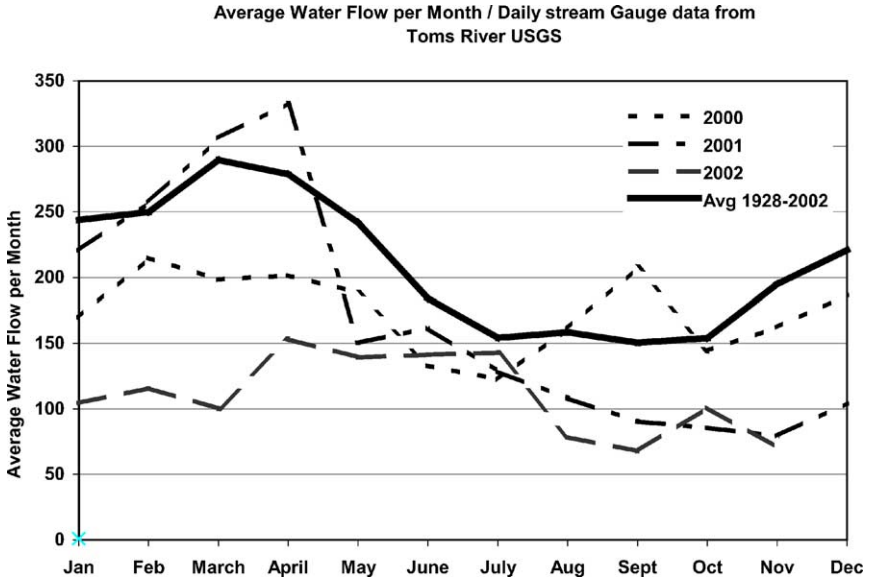

Fig. 4. Graph of monthly average water flow (ft sec^{-1}) for the Toms River for the years 2000, 2001 and 2002 and a 74-year (1928–2002) average.

Table 3
Regression statistics for the analysis of *A. anophagefferens* concentration (dependent variable) vs. the various environmental variables (independent variable)

Parameter	d.f.	*F*-value	*P*-value	R^2
Temperature	491	11.22	**0.0009**	0.0223
Salinity	461	0.59	0.4418	0.0013
Total nitrogen	45	2.44	0.1257	0.0525
NH_3	45	2.74	0.1049	0.0587
NO_3No_2	45	1.11	0.2985	0.0245
DON	45	2.33	0.1345	0.0502
Secchi depth	215	27.77	<**0.0001**	0.1149
PAR	198	3.28	0.0717	0.0164
Chlorophyll a	42	2.17	0.1487	0.0502
Transmittance	223	77.78	<**0.0001**	0.2595
pH	223	2.45	0.1191	0.0109
DO	233	0.77	0.3807	0.0033

Note: bolded values represent statistical significance using a criterion of *P*-value of less than an alpha of 0.05. d.f.: degrees of freedom; DON: dissolved organic nitrogen; PAR: photosynthetically active radiation/reference PAR; and DO: dissolved oxygen.

(Table 2). The mean Secchi depth for a category 3 bloom category was 0.58 m as compared to 1.07 m for a category 1 bloom. There was a significant negative relationship between Secchi depth levels and the three categories of bloom levels (Fig. 6).

The 74-year mean monthly water flow data shows a general pattern of highest flows in the winter and spring months with a peak in March and April, then dipping to the lowest flows in July through October, and then increasing again through the fall into winter (Fig. 4). Year 2000 followed this general pattern but with somewhat suppressed winter/spring flows and a greatly enhanced September discharge (Fig. 4). Year 2001 began with flow similar to long-term means but then entered into an extended drought as evidenced by the lower than normal flows during the summer and autumn months (Fig. 4). This drought period continued into 2002, with lower than average flows during every

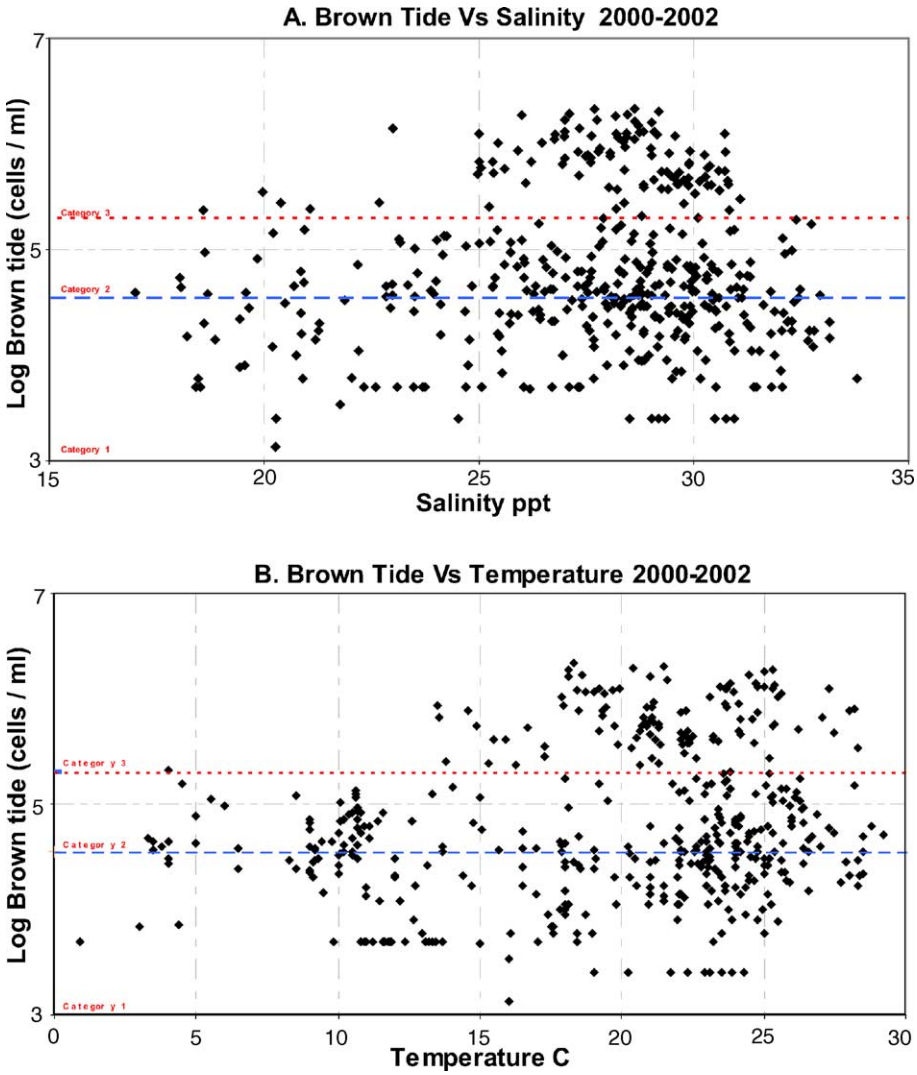

Fig. 5. (A) Comparison of *A. anophagefferens* abundances (BT) (cells ml^{-1}) and salinity (ppt) (2000–2002) and (B) comparison of *A. anophagefferens* abundances (BT) (cells ml^{-1}) and temperature (°C).

month of the year (Fig. 4). Overall, it appeared that the cumulative discharge from the Toms River to the BB/LEH system was lower than normal over the entire study period.

3.1. Analysis of risk of brown tide blooms and submerged aquatic vegetation (SAV)

While *A. anophagefferens* blooms are only one of many potential factors that may negatively impact water transparency (e.g. other phytoplankton blooms, suspended sediment and dissolved organic color) in the BB/LEH estuary (Styles et al., 2001), analysis of the Secchi disc data indicates that the increased turbidity associated with category 3 blooms depressed the Secchi disk depth from a mean of 1.1–0.6 m (Table 2). Similarly, during the 1985–88 brown tide blooms in Long Island coastal bays, the Secchi disc depth dropped from 1.4 m in pre-bloom years to 0.6 m during brown tide blooms years (Dennison

Table 4
ANOVA and Kruskal–Wallis test results for the difference across three brown tide (*A. anophagefferens*) bloom index categories and the associated environmental parameters

Parameter	ANOVA *F*-value	ANOVA *P*-value	Kruskal–Wallis chi square	Kruskal–Wallis *P*-value
Temperature	5.6759	**0.0037**	5.0174	0.0814
Salinity	0.5822	0.5591	1.2858	0.5258
Total nitrogen	2.3820	0.1044	1.2124	0.5454
NH_3	2.2165	0.1213	3.5502	0.1695
NO_3NO_2	1.4473	0.2464	3.9631	0.1379
DON	1.8485	0.1698	0.9142	0.6331
Secchi depth	23.8351	<**0.0001**	46.4391	<**0.0001**
PAR	3.7307	0.0257	6.2805	**0.0433**
Chlorophyll a	0.5911	0.5585	2.7855	0.2484
Transmittance	70.9705	<0.0001	89.1778	<0.0001
pH	2.7449	0.0664	5.0855	0.0787
DO	8.7408	0.0002	17.4437	0.0002

Note: bolded values represent statistical significance using a criterion of *P*-value of less than an alpha of 0.05. DON: dissolved organic nitrogen; PAR: photosynthetically active radiation/reference PAR; and DO: dissolved oxygen.

et al., 1989). Previous work modeling the light requirements of seagrass communities in the BB/LEH estuary (Lathrop et al., 2001) based on the Duarte (1991) model of light compensation depth of *Zostera marina* estimated that a reduction of Secchi depth from 1.0 to 0.6 m would reduce the potential habitat area of seagrass (e.g., area where there is sufficient light environment to the bay bottom) by nearly 40% (Lathrop, unpublished). Based on this modeling work and documented impacts on seagrass in other estuaries (Dennison et al., 1989), we suggest that this reduction in light associated with category 3 blooms poses a potential risk to the productivity and health of seagrass in the BB/LEH system and may be stressing seagrass communities that are already stressed by a number of other factors such as epiphytic algae and wasting disease (McClain and McHale, 1996; Bologna et al., 2000).

To quantify the possible risk of brown tide blooms to seagrass habitat, the GIS was used to determine the spatial coincidence between locations of high *A. anophagefferens* abundances and duration and the mapped location of seagrass habitat. The seagrass map was based on data and field mapping efforts conducted in the mid 1990s and described previously (Lathrop et al., 2001). The two major types of sea-

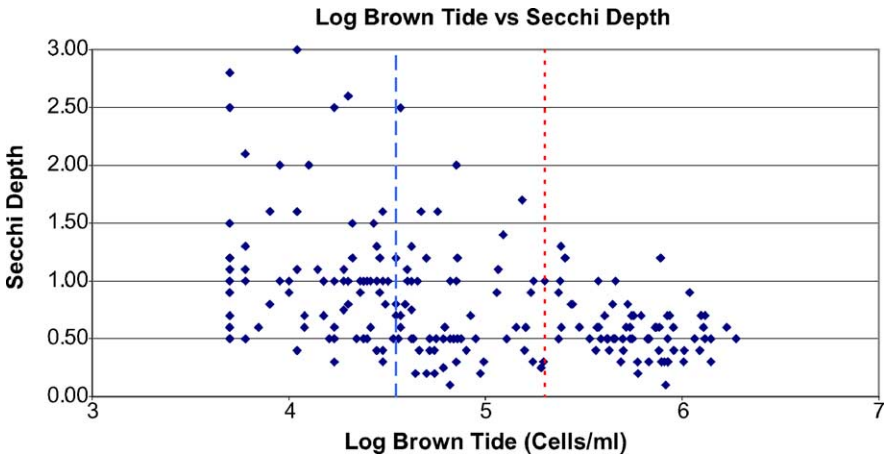

Fig. 6. log of the Brown Tide (*A. anophagefferens*) abundances (cells ml^{-1}) and Secchi depth (m).

grass, eelgrass (*Z. marina*) and widgeongrass (*Ruppia maritima*) were combined for the analysis. The median *A. anophagefferens* abundance for each mapped grid cell for each year was classified into the appropriate Brown Tide Bloom Index category. This allowed both the duration and the severity of *A. anophagefferens* blooms to be compared to seagrass beds in that a median value (for each grid cell) of *A. anophagefferens* falling in category 3 meant that at a minimum over half of the sampling dates (i.e. 6 out of 11 sampling dates) were also category 3 blooms. These brown tide bloom maps were then overlaid and compared with the seagrass map to determine the locations and areal amount of seagrass in relation to bloom conditions. High-risk areas were characterized as seagrass habitat areas that had a high occurrence of category 3 brown tide blooms (i.e. median *A. anophagefferens* abundances in category 3). With roughly bi-weekly sampling, a median value in category 3 means that the brown tide blooms extended beyond the 1 and 1.5–2 months in duration that Dennison et al. (1989) suggested may result in severe shading on growing eelgrass beds. Medium-risk areas were classified as areas that had a high occurrence of category 2 brown tide blooms (i.e. median abundances classified as category 2 blooms) and low-risk (median abundances classified as category 1 blooms) areas for seagrass in relation to *A. anophagefferens* abundances.

The analysis of mapped overlays of brown tide bloom category versus seagrass habitat for each year indicated that more than 50% of the seagrass habitat area in Little Egg Harbor was classified as having a high frequency of category 2 or 3 blooms (Table 5, Fig. 7). Year 2002 was especially severe with over 85% or over 12,800 acres (Table 5) of the mapped seagrass beds falling into a median category 3 bloom. Year 2001 was the lowest risk year with the lowest percentages of both categories 2 and 3 coinciding with areas covered by seagrass. The highest risk areas for seagrass habitat are associated with the *A. anophagefferens* concentration "hotspots" (e.g. category 3 blooms) in the Manahawkin Bay (Fig. 7). The medium risk areas for seagrass habitat (i.e. associated with category 2 blooms) extend variably north into Barnegat Bay and south into Little Egg Harbor. Unfortunately, most of BB/LEH's seagrass beds

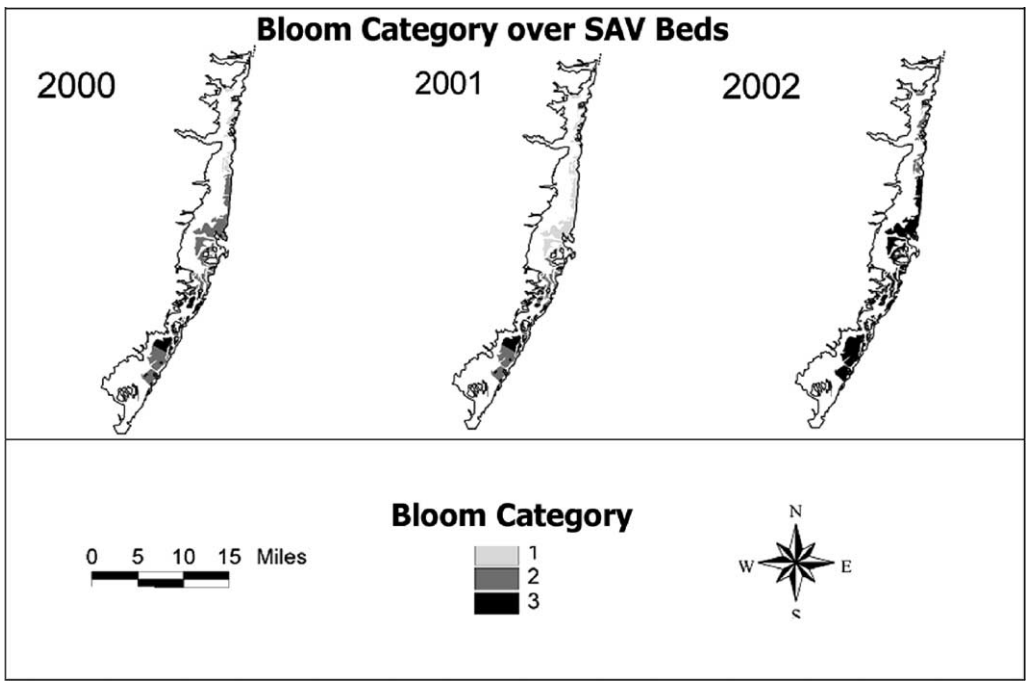

Fig. 7. Map of median brown tide (*A. anophagefferens*) bloom category vs. SAV beds for years 2000, 2001, 2002. *Note*: Only mapped SAV beds are displayed; non-SAV areas are displayed same as white background.

Table 5
Results of the cross-tabulation of the median Brown Tide Bloom Index categories and submerged aquatic vegetation (SAV) maps for years 2000, 2001, and 2002

Bloom category	Year 2000	Year 2001	Year 2002
Acres of SAV			
1	1905.6	7386.5	0.0
2	10373.0	5197.6	2006.4
3	2600.4	2294.9	12872.6
Percent of SAV			
1	12.8	49.7	0.0
2	69.7	34.9	13.5
3	17.5	15.4	86.5

A median index of 3 was considered high-risk, 2 was considered medium-risk and 1 was considered low-risk.

are located in southern Barnegat Bay and Little Egg Harbor, in the medium to high bloom risk areas.

4. Discussion and conclusions

Elevated *A. anophagefferens* abundances, especially category 3 ($\geq$200,000 cells ml^{-1}) blooms, occurred at all eleven stations monitored over the 3-year-period in Barnegat Bay and Little Egg Harbor. In 2002, all stations but one had category 3 blooms and several stations in Little Egg Harbor had abundances $>10^6$ cells ml^{-1} for a 3-year-period. These elevated levels of brown tide abundances have been shown in other studies to cause negative impacts to shellfish (Tracey, 1988; Gallagher et al., 1989; Bricelj, 1999; Schaffner, 1999; Bricelj et al., 2001).

The results obtained during this 3-year study appeared to indicate that salinity and temperature levels were necessary for the occurrence of the highest *A. anophagefferens* concentrations (category 3) blooms but were not, alone or in combination, an explanation of the blooms. Category 3 blooms in Barnegat Bay/Little Egg Harbor generally occurred within the broad salinity range of 25–31 ppt and were associated with warmer temperatures (>16 °C). These results are consistent with findings of previous studies of brown tide blooms in Long Island coastal bays (Cosper et al., 1989; Bricelj and Lonsdale, 1997, Glibert et al., 2001; Lomas et al., 2001). The higher salinities (>26 ppt) at which *A. anophagefferens* bloomed in the BB/LEH system may have resulted from reduced rainfall during 1999–2002. Also, the temperatures during the BB/LEH brown tide blooms were within range of the optimum temperature (20–25 °C) for growth of *A. anophagefferens* in laboratory studies, although growth was possible over a wide temperature range (Cosper et al., 1989). Our results appear consistent with previous studies indicating that low rainfall levels followed by winter and spring drought periods, which may increase salinity, may precede brown tide blooms (Cosper et al., 1989). The 1999 brown tide blooms in coastal bays of Maryland also indicated some relationship to the lack of spring rain (Glibert et al., 2001). The onset of brown tides have also been linked to reduced estuarine flushing rates in some Long Island embayments (Vieira, 1989; Vieira and Chant, 1993).

Based on the salinity data and the calculation of the tidal exchange rate, the Barnegat Bay's flushing time was estimated to be very long at 24 days (46 tidal cycles) in January 1995 and 74 days (142 tidal cycles) in June/July 1995 (Guo and Lordi, 2000). For January 1995, only 25% of the flood tide volume passing through Barnegat Inlet was estimated as new ocean water, which can mix with the Bay water. This means that 75% of the water entering the Bay on the flood tide leaves the Bay on the following ebb tide (Guo and Lordi, 2000). The fraction of new ocean water for June/July 1995 was estimated to be 10% which was even lower than that for January 1995. There are strong tidal currents at both the Barnegat Inlet and the Little Egg Harbor Inlet (up to 2 m/s) (Seabergh et al., 1998) which may influence the salinity in these bays. The high salinity in the areas of Little Egg Harbor, where elevated brown tide blooms occurred may be influenced by the horizontal salinity gradient from both Barnegat Inlet and Little Egg Inlet. The horizontal salinity gradient was measured (Guo et al., 1995) from Barnegat Inlet toward both the north and south which extends into southern Barnegat Bay and Little Egg Harbor.

The results of the analysis of only 1 year of nitrogen species are relatively consistent with previous studies in 1999 in coastal bays in Long Island, New York and Maryland that showed no significant relationship or a clear-cut pattern between *A. anophagefferens* abundances and inorganic or organic nutrients (Lomas et al., 2001). However, the ranges of DON concentration (8.9–60.8 μM,) and the yearly average DON concentration (22.2 μM) in BB/LEH during the 2002 brown tide blooms were comparable to ranges

in DON concentrations in coastal bays in Long Island (17–27 μM) (Lomas et al., 2001) and Maryland (25.0–70.0 μM) (Glibert et al., 2001). However, in the New York and Maryland bays, elevated levels of *A. anophagefferens* were associated with greater than Redfield DOC:DON ratios and approximate Redfield ratios of DON:DOP (Lomas et al., 2001). The results of the comparison of 1997, 1998 and 1999 algal bloom events in Maryland coastal bays indicated that blooms were associated with elevated ratios of DOC:DON (Glibert et al., 2001). While studies have shown that *A. anophagefferens* prefers urea as the organic nitrogen source (Berg et al., 1997; Glibert and Terlizzi, 1999; Glibert et al., 2001; Kana et al., 2002), urea may comprise <10% of the total DON in coastal systems such as Barnegat Bay (Seitzinger et al., 2003). However, total DON may comprise over half of the total nitrogen inputs to estuaries in New Jersey (Seitzinger and Sanders, 1997, 1999; Seitzinger et al., 2002).

Have these elevated levels of brown tide bloom activity in New Jersey had a negative impact on the shellfish resource? A direct link to increased occurrences of *A. anophagefferens* cannot be made, but stocks of these species have declined over the last decade. In 2001, a shellfish stock assessment was conducted by the NJDEP's Bureau of Shellfisheries in Little Egg Harbor (Celestino, 2003). The results indicated that the estimated standing stock of hard clams in Little Egg Harbor Bay was 64.8 million clams, a decline of over 67% from the previous 1986–87 stock estimate (Celestino, 2003). *A. anophagefferens* abundances in this area during the present study (2000–2002) exceeded the level of abundances that have been determined in other studies to have negative impacts on juvenile hard clams (quahogs) (Bricelj et al., 2001; Schaffner, 1999). Therefore, continued monitoring of brown tides in the future in Barnegat Bay/Little Egg Harbor is important for understanding and potentially predicting the impact of brown tide blooms on shellfish populations in these waters. In addition, more frequent shellfish stock assessments may be needed along with studies that distinguish the potential negative impacts of brown tide blooms as opposed to other causes of shellfish declines in these areas.

The results of the present study also indicate that *A. anophagefferens* blooms occurred at elevated abundances and over time periods that might pose a significant risk to BB/LEH's seagrass (i.e. eelgrass *Z. marina* and widgeongrass *R. maritima*) habitat. While our GIS analysis showed that known seagrass habitat areas are located in the high-risk category 3 bloom hotspot areas, no direct causal link has yet been established between brown tide blooms and seagrass decline problems in Barnegat Bay/Little Egg Harbor. However, with over 70% of the state's seagrass beds currently located in the BB/LEH estuarine system (Lathrop et al., 2001), the potential for brown tide-associated impacts on seagrass take on a broader regional importance.

In conclusion, our 3-year study of *A. anophagefferens* abundance and environmental factors in coastal bays of New Jersey indicate a potentially important impact of these harmful brown tide bloom events on shellfish resources and submerged aquatic vegetation. Additional research and continued monitoring of brown tides, including clam surveys, would elucidate the ecological risk of *A. anophagefferens* blooms to natural resources and contribute to the understanding, and potential prediction, of the impact of brown tide blooms on shellfish populations in these waters. Specifically, assessments are needed to provide a greater understanding of the relative importance of maximum brown tide bloom concentration versus bloom duration on seagrass health and productivity. In addition, the impact of chronic lower level category 2 brown tide blooms during the summer growing season on BB/LEH's seagrasss health and productivity needs clarification.

Acknowledgements

We are grateful to the New Jersey Department of Environmental Protection, Division of Science, Research and Technology (NJDEP/DSRT) for providing funding for this study and especially, Dr. Alan Stern, for his support. We would like to thank Helen Grebe and Randy Braun at the US Environmental Protection Agency for collecting helicopter samples and Robert Connell, Robert Schuster, and Michael DiLeo of the NJDEP Bureau of Marine Water Monitoring for analyzing nitrogen data.

References

Anderson, D.M., Keafer, B.A., Kulis, D.M., Waters, R.M., Nuzzi, R., 1993. An immunofluorescent survey of the brown tide

chrysophyte *Aureococcus anophagefferens* along the northeast coast of the United States. J. Plankton Res. 15, 563–580.

Berg, G.M., Glibert, P.M., Lomas, M.W., Burford, M., 1997. Organic nitrogen uptake by the chrysophyte *Aureococcus anophagefferens* during a brown tide bloom event. Mar. Biol. 129, 377–387.

Bologna, P., Able, K., Lathrop, R.G., Bowers, P.B., 2000. Assessment of the health and distribution of submerged aquatic vegetation from Little Egg Harbor, New Jersey. Technical Report #2000-11, Institute of Marine and Coastal Sciences, Rutgers University, New Brunswick, New Jersey.

Bricelj, M., 1999. Perspectives on possible factors influencing the abundance of hard clams. In: Schlenk, C.G. (Ed.), Workshop on Hard Clam Population Dynamics Research Priorities for the South Shore of Long Island. Port Jefferson, New York, NY Sea Grant, Stony Brook, NY.

Bricelj, V.M., Lonsdale, D.J., 1997. *Aureococcus anophagefferen*s: causes and ecological consequences of brown tides in US mid-Atlantic coastal waters. Limnol. Oceanogr. 42, 1023–1038.

Bricelj, V.M., MacQuarrie, S.P., Schaffner, R.A., 2001. Differential effects of *Aureococcus anophagefferens* isolates (brown tide) in unialgal and mixed suspensions on bivalve feeding. Mar. Biol. 139, 605–615.

Caron, D.A., Dennett, M.R., Moran, D.M., Schaffner, R.A., Lonsdale, D.J., Gobler, C.J., Nuzzi, R., McLean, T.I., 2003. Development and application of a monoclonal antibody technique for counting *Aureococcus anophagefferens*, an alga causing recurrent brown tides in the mid-Atlantic United States. Appl. Environ. Microbiol. 69, 5492–5502.

Celestino, M.P., 2003. Shellfish stock assessment of Little Egg Harbor Bay. Final Report by the Bureau of Shellfisheries to the Division of Science, Research and Technology. New Jersey Department of Environmental Protection, Trenton, NJ.

Cosper, E.M., Dennison, W., Milligan, A., Carpenter, E.J., Lee, C., Hozapfel J., Milanese L., 1989. An examination of the environmental factors important to initiating and sustaining "brown tide" blooms. In: Cosper, E.M., Bricelj, V.M., Carpenter, E.J. (Eds.), Novel Phytoplankton Blooms: Causes and Impacts of Recurrent Brown Tides and Other Unusual Blooms. Springer-Verlag, New York, pp. 317–140.

Davis, J.C., 1986. Statistics and Data Analysis in Geology. Wiley, New York.

Dennison, W.C., Marshall, G.J., Wigand, C., 1989. Effect of "brown tide" shading on eelgrass (*Zostera marina* L.) distributions. In: Cosper, E.M., Bricelj, V.M., Carpenter, E.J. (Eds.), Novel Phytoplankton Blooms: Causes and Impacts of Recurrent Brown Tides and Other Unusual Blooms. Springer-Verlag, Berlin, pp. 675–692.

Duarte, C.M., 1991. Seagrass depth limits. Aquat. Bot. 40, 363–377.

Gallagher Jr., L.F., Stoecker, D.K., Bricelj, V.M., 1989. Effects of the brown tide alga on growth, feeding physiology and locomotory behavior of scallop larvae (*Argopecten irradians*). In: Cosper, E.M., Bricelj, V.M., Carpenter, E.J. (Eds.), Novel Phytoplankton Blooms: Causes and Impacts of Recurrent Brown Tides and Other Unusual Blooms. Springer-Verlag, Berlin, pp. 511–541.

Gastrich, M.D., Wazniak, C.E., 2002. A brown tide bloom index based on the potential harmful effects of the brown tide alga, *Aureococcus anophagefferens*. Aquat. Ecosyst. Health Manage. 5, 1–7.

Gastrich, M.D., Anderson, O.R., Cosper, E.M., 2002. Viral-like particles (VLPs) in the alga, *Aureococcus anophagefferens* (Pelagophyceae), during 1999–2000 brown tide blooms in Little Egg Harbor, New Jersey. Estuaries 25, 938–943.

Glibert, P.M., Terlizzi, D.E., 1999. Co-occurrence of elevated urea levels and dinoflagellate blooms in temperate estuarine aquaculture ponds. Appl. Environ. Microbiol. 65, 5594–5596.

Glibert, P.M., Magnien, R., Lomas, M.W., Alexander, J., Fan, C., Haramoto, E., Trice, M., Kana, T.M., 2001. Harmful algal blooms in the Chesapeake and coastal bays of Maryland, USA: comparison of 1997, 1998 and 1999 events. Estuaries 24, 875–883.

Guo, Q., Lordi, G.P., 2000. Method for quantifying freshwater input and flushing time in estuaries. J. Environ. Eng. (ASCE). 126, 675–683.

Guo, Q., Psuty, N.P., Lordi, G.P., Glenn, S., Mund, M.R., 1995. Hydrographic study of Barnegat Bay, Year 1, Final Report, Submitted to New Jersey Department of Environmental Protection, Division of Science and Research, Trenton, New Jersey, September.

Kana, T.M., MacIntyre, H., Cornwell, J., Lomas, M., 2002. Benthic–pelagic coupling and Long Island brown tide. Brown Tide Research Institute. Report #7.

Lathrop, R.G., Styles, R., Seitzinger, S., Bognar, J., 2001. Use of GIS mapping and modeling approaches to examine the spatial distribution of seagrasses in Barnegat Bay, New Jersey. Estuaries 24, 904–916.

Lomas, M.W., Glibert, P.M., Clougherty, D.A., Huber, D.R., Jones, J., Alexander, J., Haramoto, E., 2001. Elevated organic nutrient ratios associated with brown tide algal blooms of *Aureococcus anophagefferens* (Pelagophyceae). J. Plankton Res. 23, 1339–1344.

McClain, P., McHale, M., 1996. Barnegat Bay eelgrass investigation 1995–96. Barnegat Bay Ecosystem Workshop. Toms River, NJ.

New Jersey Department of Environmental Protection, 1985. Annual summary of phytoplankton blooms and related conditions in New Jersey coastal waters summer of 1985. New Jersey Department of Environmental Protection, Bureau of Water Monitoring, Trenton, NJ.

New Jersey Department of Environmental Protection, 1986. Annual summary of phytoplankton blooms and related conditions in New Jersey coastal waters summer of 1986. New Jersey Department of Environmental Protection, Bureau of Water Monitoring, Trenton, NJ.

New Jersey Department of Environmental Protection, 1995. Annual summary of phytoplankton blooms and related conditions in New Jersey coastal waters summer of 1995. New Jersey Department of Environmental Protection, Bureau of Water Monitoring, Trenton, NJ.

New Jersey Department of Environmental Protection, 1999a. Annual summary of phytoplankton blooms and related conditions in New Jersey coastal waters summer of 1999.

New Jersey Department of Environmental Protection, Bureau of Water Monitoring, Trenton, NJ.

New Jersey Department of Environmental Protection, 1999b. Water Monitoring Report. Bureau of Marine Water Monitoring, P.O. Box 405 Stoney Hill Road, Leeds Point, NJ 08220.

New Jersey Department of Environmental Protection, 2000. Water Quality Monitoring Networks 2000. New Jersey Department of Environmental Protection, Bureau of Marine Water Monitoring.

Nuzzi, R., Olsen, P., Mahoney, J.B., Zodl, G., 1996. The first *Aureococcus anophagefferens* brown tide in New Jersey. Harmful Algae News, vol. 15, pp. 8–9.

Schaffner, R.A., 1999. The Role of Suspension Feeding Bivalves in the Initiation and Control of *Aureococcus anophagefferens* Blooms. M.Sc. Thesis. SUNY of New York at Stony Brook.

Seabergh, W.C., Cialone, M.A., McCormick, J.W., 1998. Effects of inlet modifications at Barnegat Inlet, New Jersey. Technical Report, US Army Corps of Engineers, Vicksburg, Mississippi.

Seitzinger, S.P., Sanders, R.W., 1997. Biologically reactive dissolved organic nitrogen inputs from rivers to estuaries. Mar. Ecol. Progr. Set. 159, 1–12.

Seitzinger, S.P., Sanders, R.W., 1999. Atmospheric inputs of dissolved organic nitrogen stimulate coastal bacterial and algae. Limnol. Oceanogr. 44, 721–730.

Seitzinger, S.P., Sanders, R.W., Styles, R.V., 2002. Bioavailability of DON from natural and anthropogenic sources to estuarine phytoplankton. Limnol. Oceanogr. 47, 353–366.

Seitzinger, S.P., Styles, R.M., Lauck, R., Mazurek, M.A., 2003. Atmospheric pressure mass spectrometry: a new analytical chemical characterization method for dissolved organic matter in rainwater. Environ. Sci. Technol. 37, 131–137.

Short, F.T., Wyllie-Echeverria, S., 1996. Natural and human-induced disturbance of seagrasses. Environ. Conserv. 23, 17–27.

Styles, R.M., Seitzinger, S.P. Lathrop, R.G., 2001. Data synthesis report for the Barnegat Bay estuary program: water quality and primary production in the Barnegat Bay-Little Egg Harbor Estuary and Watershed, Appendix 2. In: Kennish, M. (Ed.), Characterization Report for Barnegat Bay-Little Egg Harbor Estuary and Watershed. JCNERR Contribution No. 100-5-10, Institute of Marine and Coastal Science, Rutgers University, New Brunswick, New Jersey, 47 pp.

Tracey, G.A., 1988. Feeding reduction, reproductive failure, and mortality in the mussel, *Mytilus edulis*, during the 1985 “brown tide” in Narragansett Bay, Rhode Island. Mar. Ecol. Progr. Ser. 50, 73–81.

United States Environmental Protection Agency, 1994. EPA Requirements for Quality Assurance Project Plans (QAPP) for Environmental Data Operations. EPA/QA/R-5. August 1994. Office of Water, Washington, DC.

Vieira, M.E.C., 1989. The case of meteorologically driven fluctuations in residence times of Long Island waters subject to algal blooms, In: Cosper, E.M., Bricelj, V.M., Carpenter, E.J. (Eds.), Novel Phytoplankton Blooms: Causes and Impacts of Recurrent Brown Tides and Other Unusual Blooms. Springer-Verlag, Berlin, pp. 295–306.

Vieira, M.E.C., Chant, R., 1993. On the contribution of subtidal volume fluxes to algal blooms in Long Island estuaries. Estuar. Coast. Shelf Sci. 36, 15–29.