

Temporal variability of chlorophyll in Narragansett Bay, 1973–1990

Yaqin Li and Theodore J. Smayda



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Weekly measurements of Chl *a* were carried out between 1973 and 1990 in Narragansett Bay, Rhode Island, a temperate estuary along the north-eastern US coast. There was only a threefold variation in mean annual chlorophyll values but a considerably greater variation in the period when the annual maximum was reached. The inter-annual variation in annual means was relatively modest compared with monthly means. For a given month, the inter-annual variability in monthly mean chlorophyll varied from 3- to 30-fold; it was least during the summer months and maximal during the winter–spring bloom period. The long-term variability patterns characterizing individual months differed in their trends, cycles, and irregular fluctuations. Major blooms occurred during most of the year, and were not restricted to the annual winter–spring bloom. However, the frequency and magnitude of blooms were higher during winter–spring months than during summer months. A significant finding is that the annual mean chlorophyll decreased by more than $1 \text{ mg m}^{-2} \text{ year}^{-1}$ over the 18 year time series. This decrease apparently was under multifactorial control, with zooplankton grazing, sea surface temperature and windspeed being the most important factors.

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Introduction

Chlorophyll is traditionally the measure of phytoplankton biomass used as an index of seasonal and regional variations in abundance and bloom dynamics. Its absorption and fluorescence properties make it relatively easy to measure bio-optically. Towed fluorimeter and satellite techniques are also available which allow measurement of chlorophyll on both fine and large scales (e.g. Brown *et al.*, 1985; Ondercin *et al.*, 1995). Collectively, such measurements clearly indicate that chlorophyll-based biomass is characterized by considerable variation at all temporal, regional, and spatial scales. Given growing concerns over anthropogenic modification of coastal waters and related planetary changes affecting phytoplankton growth in such waters, the long-term patterns and trends in chlorophyll variability in response to such habitat modifications have become of major interest. It is thus important to characterize long-term variability of chlorophyll in different regions, not only as a feature of natural variation, but as an essential step in detecting any anthropogenic

effects on phytoplankton dynamics in coastal waters (Smayda, 1984). In this article, we describe the monthly and inter-annual variability of chlorophyll based on an 18-year time series of weekly measurements in Narragansett Bay, a temperate estuary. Some of the factors regulating this variability are also considered.

Materials and methods

Narragansett Bay, located along the north-east coast of the U.S. and well-mixed throughout the year, has a mean depth of 9 m, an area of 450 km^2 and extends inland 50 km from its connection with Block Island Sound. Weekly samples were collected from three depths (top, mid, bottom) at a fixed station (Station II) located in the unpolluted waters of the lower bay ($41^{\circ}30'N$ $71^{\circ}20'W$), where the mean depth is 8 m. Weekly measurements routinely made include temperature, salinity, Secchi disk depth, nutrients (NH_4 , NO_3 , SiO_4 , PO_4), chlorophyll, phytoplankton species composition and abundance, and zooplankton dry weight. Space

availability limits consideration of this data bank to that of chlorophyll *a*, presented as mg m^{-2} , measured fluorimetrically (Yentsch and Menzel, 1963) during the period from 1973 to 1990.

Incident light intensity data measured using an Eppley[®] pyranometer were obtained from the Eppley Laboratory, located 9 km from the study site. The mean daily *in situ* irradiance (*I* bar), as W m^{-2} , received by phytoplankton in the 8 m deep water column at station II was calculated following the equation of Hitchcock and Smayda (1977a):

$$I \text{ bar} = I_0/kz (1 - e^{-kz})$$

where I_0 is the daily incident irradiance, *k* is the extinction coefficient (calculated from Secchi disk depth *D*: $k = 1.44/D$; Holmes, 1970), and *z* is the mixed-layer depth, equivalent to the depth (8 m) of the annually well-mixed Station II. Long-term trends (25 years) in Secchi disk depth and water clarity at Station II are presented by Borkman and Smayda (1998).

The river flow data used in the analyses are taken from the U.S. Geological Survey's database and represent ca. 39% of the total river run-off into Narragansett Bay (Ries, 1990; Pilson, 1985). Precipitation and wind-speed data were measured by National Oceanic and Atmospheric Administration at the Providence Airport located 18 km north-west of the study site.

Statistical analyses were carried out using the computer software Matlab (The Math Works Inc.). A multiple linear regression model was developed to determine the relative importance of selected factors regulating chlorophyll, specifically zooplankton biomass, sea surface temperature, and windspeed. To ensure that each independent variable was equally important in the model, the raw data were linearly transformed to a 1 to 100 scale before being subjected to analysis.

Results

Chl *a* in Narragansett Bay is highly variable on a weekly, monthly, and annual basis. Figure 1A shows the trend in the annual means over the 18-year time series. A significant, twofold, decrease in annual means occurred during this period, from ca. 60 mg m^{-2} in 1973 to ca. 30 mg m^{-2} in 1990, with 1987 being anomalous to this trend. Excluding the 1987 datum, the linear model ($\text{Chl} = -1.44 \cdot \text{year} + 2890$; $r^2 = 0.62$; $p = 0.0002$) predicted a decrease at a rate greater than $1 \text{ mg m}^{-2} \text{ year}^{-1}$. The exceptional mean value in 1987 was 25 mg m^{-2} higher than that predicted by the linear model. [With the 1987 datum, $\text{chl} = -1.09 \cdot \text{year} + 2201$, $r^2 = 0.32$, $p = 0.01$]. The variation in the annual mean chlorophyll (about threefold) was relatively modest compared with the variation in the monthly means, which reached 30-fold (see below).

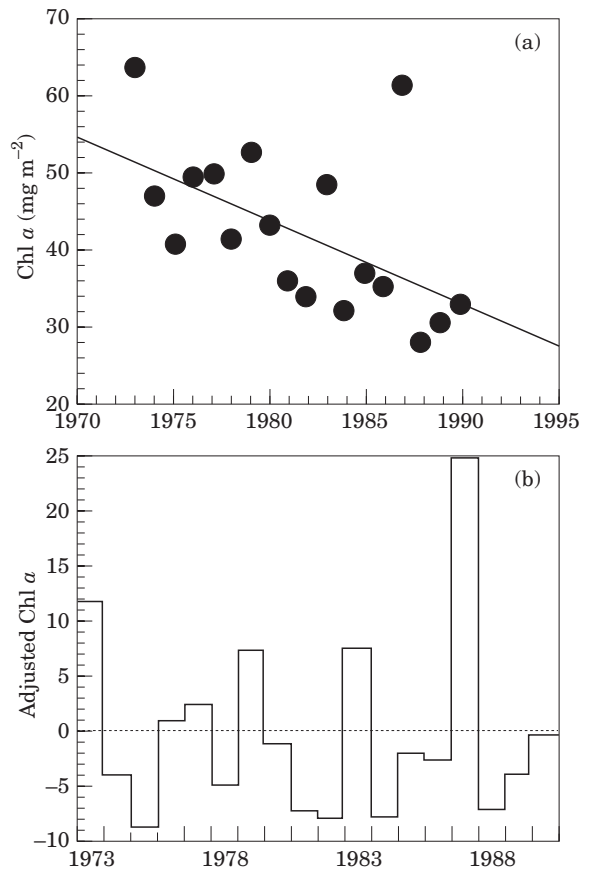


Figure 1. Time series of annual chlorophyll levels in Narragansett Bay, 1973–1990. (a) Annual means. Line represents the linear regression. (b) Adjusted annual mean levels after removal of the long-term trend (see text for details).

The long-term downward trend in mean annual chlorophyll is clearly a feature of the data set. We sought other features characterizing the observed variability embedded within the linear downward trend by statistically removing the latter pattern. The adjusted (measured minus predicted values of the linear model) values revealed (Fig. 1B) a cycle in which chlorophyll peaked every 4–5 years from 1979 to 1990. Variability from 1973 to 1978 tended to occur as irregular fluctuations.

Inter-annual variability of monthly means was greater than that of the annual means: for a given month, it varied from 3- to 30-fold (Fig. 2), and was higher during the period November to March than in summer (June to September). Cycles, trends, and irregular fluctuations characterized the inter-annual variability in monthly means. In February, for example, high chlorophyll levels ($\geq 60 \text{ mg m}^{-2}$) sustained for a second, consecutive year, followed by a precipitous 4-fold decrease (ca. 15 mg m^{-2}) attained in 1 year were usual. In January and April, chlorophyll tended to exhibit strong pulses at

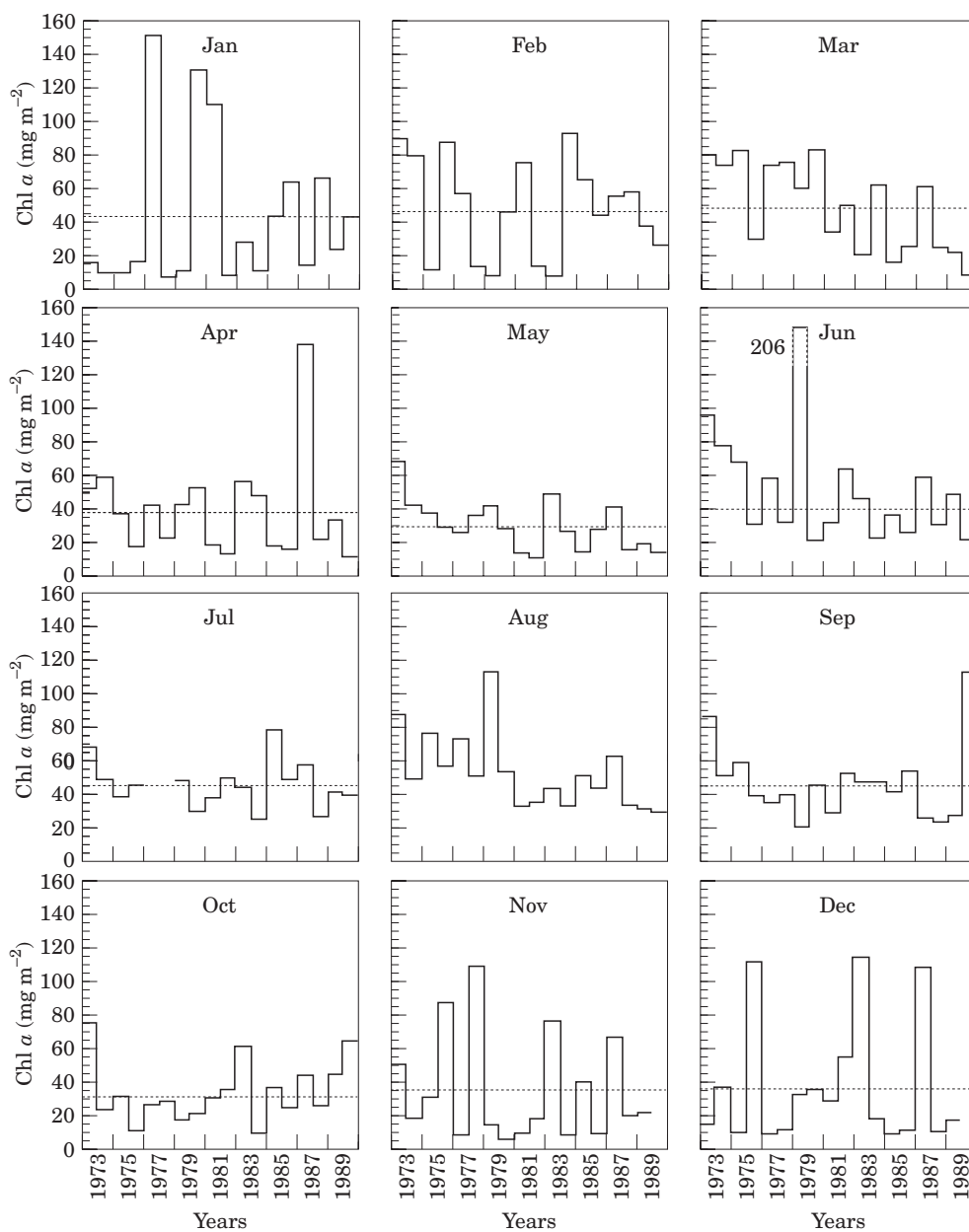


Figure 2. Time series of monthly mean chlorophyll in Narragansett Bay, 1973–1990. Dashed lines represent 18-year mean for a given month.

1-year intervals. A conspicuous downward trend occurred during March interrupted by strong, periodic annual bursts. For other months, the variations in chlorophyll are best characterized as being irregular. Relative to the mean chlorophyll level of 42.1 mg m^{-2} for 1973–90, major phytoplankton blooms occurred during January, February, March, April, June, August, September, November, and December. That is, the mean monthly chlorophyll for a given year then

exceeded the 18-year mean by \geq twofold (Fig. 2). In June 1979, for example, the concentration was ca. four-fold greater than the 18-year mean. In general, the frequency and magnitude of the blooms were higher in the late autumn–spring period (October to April) than during summer. For example, chlorophyll exceeded 150 mg m^{-2} in January, while in July the highest level was only 80 mg m^{-2} . The only time in which a major bloom occurred in April was in 1987. Inspection of

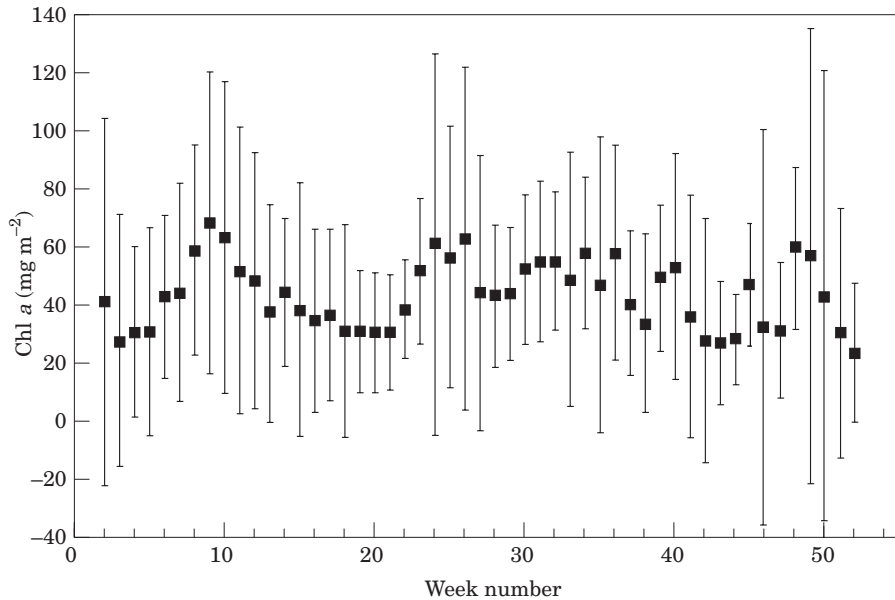


Figure 3. Weekly mean chlorophyll in Narragansett Bay, 1973–1990. Vertical bars represent the standard deviation of the mean for the 18-year time series.

Figure 2 reveals considerable inter-annual variability during a given month, indicative of considerable year-to-year variability in growth-supporting capacity. The ratio of the maximum to minimum chlorophyll level for a given month was as high as ca. 20:1 (in January).

The week-to-week variability characterizing the seasonal cycle in chlorophyll is shown in Figure 3. Given the relatively large deviations, the weekly means of 22 to 62 mg m^{-2} might be considered to be relatively constant throughout the year (i.e. there was little seasonality). However, there is some evidence for an annual rhythmicity of three to four peaks, followed by troughs, notwithstanding the relatively large deviations. Major blooms tended to occur more frequently during the winter–spring months.

The concurrent long-term, annual means of some climatological parameters and zooplankton dry weight (Fig. 4) also show great variability, with some variables exhibiting long-term trends. Zooplankton dry weight almost doubled in 8 years. Sea surface temperature increased 0.5°C over the 18 year period ($r^2=0.17$, $p=0.09$), with windspeed showing an even greater increase. Precipitation, river flow, surface PO_4 and NO_3 concentrations (not shown) did not reveal long-term trends, whereas Si decreased from 1983 to 1990. *In situ* light was fairly constant up to 1986 (Fig. 4), reflecting the increase in water clarity indicated by Secchi disk depth measurements (Borkman and Smayda, 1998).

A significant negative correlation exists between annual mean chlorophyll and zooplankton dry weight

($r^2=0.38$, $p=0.10$; Table 1) and marginal negative correlations characterized the relationship with windspeed and surface temperature. No correlations were found with the other factors. The multiple linear regression model describing the relative effect of transformed values of zooplankton dry weight (X_1), surface temperature (X_2), and windspeed (X_3) on chlorophyll (Y in mg m^{-2}) reads:

$$Y = 50.7 - 0.18 * X_1 - 0.023 * X_2 - 0.0010 * X_3 \quad (r^2 = 0.41, p = 0.06)$$

This model predicts a negative influence of zooplankton dry weight, surface temperature, and windspeed on chlorophyll. Of these three factors, zooplankton dry weight had the highest correlation coefficient. However, since the model explains only 41% of the variations in chlorophyll, other unknown factors are implicated in affecting chlorophyll levels. This suggests that the changes in chlorophyll in response to the modelled factors may not be linear.

Discussion

The main feature of the annual phytoplankton cycle in Narragansett Bay is the occurrence of winter–spring diatom blooms which usually begin in December and end in late March (Smayda, 1957, 1973, 1998; Pratt, 1959, 1965; Durbin *et al.*, 1975; Hitchcock and Smayda, 1977a, b). While the 18-year time series generally agrees with previous reports, it also shows that blooms, based

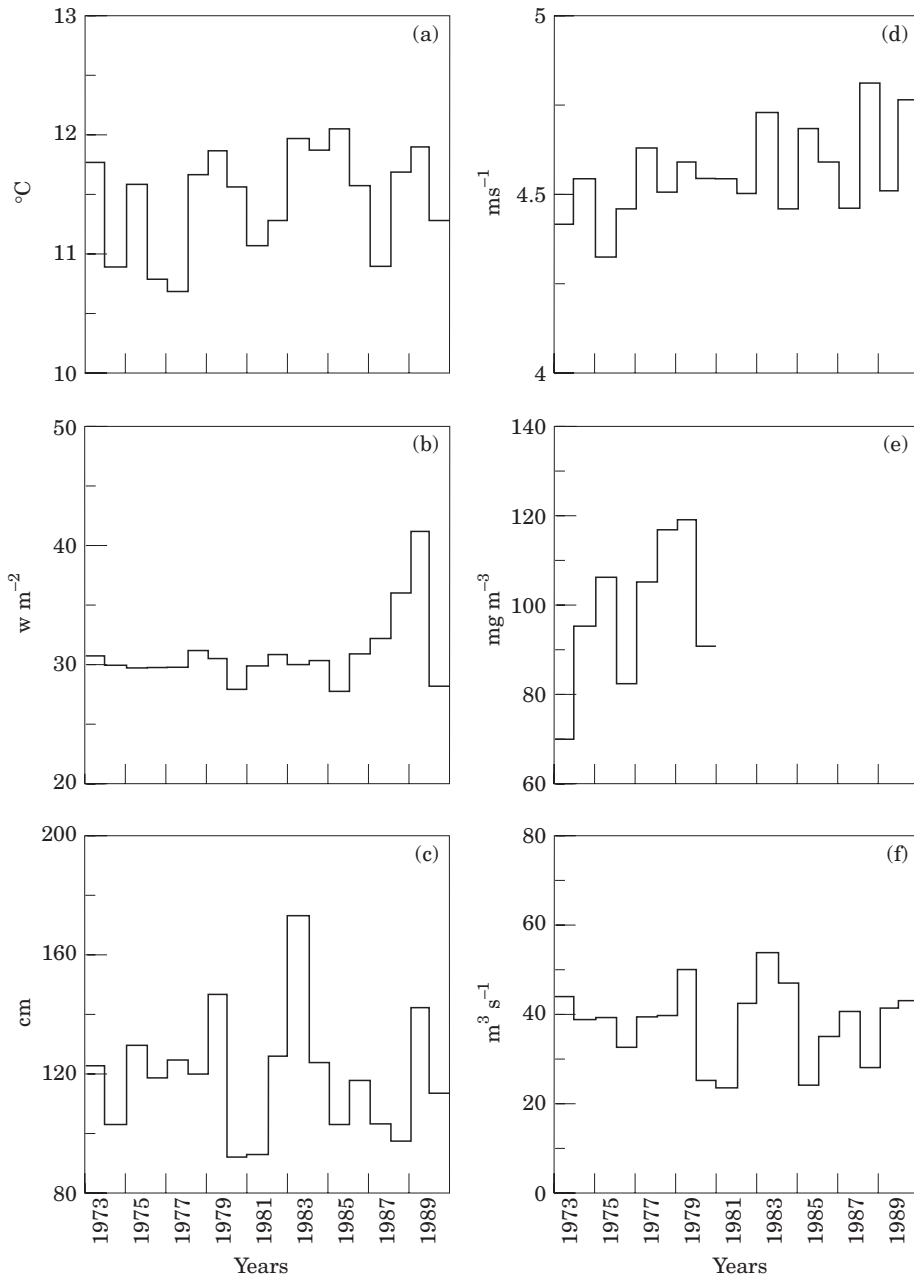


Figure 4. Annual means of environmental parameters, 1973–1990. (a) Surface temperature. (b) *In situ* irradiance. (c) Total precipitation. (d) Windspeed. (e) Zooplankton biomass (dry weight). (f) River flow.

on chlorophyll, may occur in any month, although less frequently so during the summer months.

The most striking finding is the steady decrease in chlorophyll that has occurred in Narragansett Bay between 1973 and 1990. Examination of the nutrient trends reveals that this decrease is apparently not due to decreased nutrient concentrations, such as one would expect from the classical nutrient dose–biomass yield

relationship. Rather, the correlation and multiple linear regression analysis reveal this decrease to be correlated to the observed increase in total zooplankton biomass. This suggests that the chlorophyll decrease is apparently at least partially the result of increased grazing. Top-down control of phytoplankton in Narragansett Bay has previously been documented. Phytoplankton abundance tends to be low when

Table 1. Correlations between annual mean Chl *a* (mg m^{-2}) at Station II and biological, chemical, and climatological parameters, 1973–1990.

Parameters	r^2
Zooplankton dry weight (mg m^{-2})**	0.38
Water temperature ($^{\circ}\text{C}$)	0.10
Mean <i>in situ</i> light (W m^{-2})	0.13
Nitrate ($\mu\text{g atom l}^{-1}$)	0.04
Ammonia ($\mu\text{g atom l}^{-1}$)	0.02
Total inorganic nitrogen ($\mu\text{g atom l}^{-1}$)	0.01
Silica ($\mu\text{g atom l}^{-1}$)	0.00
Phosphate ($\mu\text{g atom l}^{-1}$)	0.00
Si/P	0.00
N/P	0.00
Si/N	0.01
Total annual precipitation (cm year^{-1})	0.02
Mean windspeed (m s^{-1})	0.11
Total river flow rate ($\text{m}^3 \text{s}^{-1}$)	0.01

**Data from 1973 to 1980.

zooplankton abundance is high, and grazing has been shown to be directly responsible for the decline of winter–spring blooms in some years (Martin, 1965). Time-series data reveal that the termination of winter–spring blooms often coincides with increased zooplankton biomass, and summer diatom blooms are initiated when zooplankton abundance has declined as a result of ctenophore predation (Deason and Smayda, 1982a, b).

The suggestion of our model that temperature had a modest negative effect on chlorophyll may reflect an indirect effect via an impact on grazing, rather than a direct effect. For example, a warmer year, particularly a warmer winter and spring, can stimulate the growth of zooplankton and enhance grazing on phytoplankton. Records show (data not presented here) that the difference in temperature between a ‘cold’ and a ‘warm’ winter–spring month may reach 5°C . Such a difference is high enough to affect both zooplankton growth and grazing rates. Włodarczyk *et al.* (1992) documented that the gut evacuation rate of the copepod *Acartia hudsonica* Pinhey, at 8°C when fed the diatom *Thalassiosira constricta* Gaarder, was more than twofold that at 4°C , and increased with temperature up to 16°C ($Q_{10}=1.88$).

Narragansett Bay is a tightly coupled benthic–pelagic ecosystem, with huge population densities of the filter feeding clam, *Mercenaria mercenaria* L., dominating the benthic community (Pratt and Campbell, 1956). The winter–spring diatom bloom is a major event contributing to the rapid vernal increases in the abundance of macrofauna and meiofauna in Narragansett Bay (Rudnick *et al.*, 1985). About 40% of the winter–spring phytoplankton biomass sinks to the bottom, where it is processed by benthic communities (Rudnick and Oviatt, 1986). Thus, benthic grazing, as part of top-down con-

trol, is assumed to be an important regulator of long-term trends in phytoplankton biomass. Unfortunately, a time series of benthic abundance at the study site is not available to allow a quantitative assessment of the potential role of the benthic community in relation to the observed long-term trend of decreasing phytoplankton biomass. We note, however, that the progressive decrease in chlorophyll has been accompanied by opposite trends of increased water clarity (Borkman and Smayda, 1998). Also, there is anecdotal evidence for considerably increased stocks of the oyster, *Crassostrea virginica* Gmelin, in Narragansett Bay over similar time spans. We suggest that the observed chlorophyll trend has somehow been influenced by increased phytoplankton filtration by the changing benthic community. Future efforts will be directed towards evaluation of this prospect. Control of phytoplankton biomass through benthic grazing has been reported in other estuaries (Officer *et al.*, 1982). A long-term decline of chlorophyll in San Francisco Bay since 1987 has followed the invasion and population explosion of the filter-feeding clam *Potamocorbula amurensis* Schrenck (Cloern, 1996). Our results are, thus, not inconsistent with a mechanism of top-down control of the observed long-term decline in annual chlorophyll levels in Narragansett Bay.

There is as yet no evidence that the long-term decrease in chlorophyll involves significant shifts in major phytoplankton groups. This contrasts with reports that long-term changes in chlorophyll, usually due to eutrophication, in other estuaries, coastal waters, and lakes have been accompanied by a shift in species composition (Marasovic and Pucher-Petkovic, 1991; Cadée, 1992; Alvarez Cobelas *et al.*, 1994; Dokulil and Padisak, 1994). For example, the continuous increase in non-diatom phytoplankton since the 1970s observed at the entrance to the Dutch Wadden Sea has been accompanied by anthropogenic increases in phosphate and nitrogen (Cadée, 1992). A similar trend is observed in Kastela Bay, Croatia, where the diatom-dominated phytoplankton community has been gradually transformed into one dominated by dinoflagellates, also in close relation to eutrophication (Marasovic and Pucher-Petkovic, 1991).

Of the other factors evaluated, the model suggests that the slight increase in average windspeed over the period may have adversely affected phytoplankton biomass. However, growth rates of the turbulence-tolerant diatom species dominating the phytoplankton community in Narragansett Bay (Schöne, 1970) are not expected to be susceptible to associated slight increases in turbulence. Another, potential effect of increased windspeed is an increase in the flushing rate from Narragansett Bay into the contiguous Block Island Sound (Pilson, 1985). The rates at which chlorophyll may have been flushed from the bay do not support the notion that a progressive increase in flushing is the cause of the long-term

decrease in mean annual chlorophyll. With regard to light, our analyses do not show that variations in light availability contributed significantly to the observed trends and variations in phytoplankton biomass.

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