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A Chlorophyll Time Series for Narragansett Bay: Assessment of the Potential Effect of Tidal Phase on Measurement

Y. Li and T. J. Smayda*

Graduate School of Oceanography, University of Rhode Island, Narragansett, Rhode Island 02882

ABSTRACT: An 18-yr chlorophyll time series for Narragansett Bay based on weekly samples collected without regard to tidal phase revealed a long-term decrease in mean annual levels. The potential influence of neglecting tidal phase in the sampling strategy on measured chlorophyll and its apparent long-term decrease is evaluated. A two year data set (1995–1996) is used as a proxy for the 1973–1990 time series together with an observed relationship between continuous measurements of in situ chlorophyll fluorescence and accompanying tidal phase. The deviations in chlorophyll from long-term means relative to deviations from mean low water at the time of sample collection are also analyzed, as is the potential influence of tidally-induced advective increases or dilution on measured chlorophyll levels. The analyses, which compare the magnitude and trends in tidally adjusted and directly measured chlorophyll, indicate that semi-diurnal intratidal variations in chlorophyll had little apparent effect on the long-term and seasonal patterns and trends deduced from the chlorophyll measurements. Neither tidal advection of the chlorophyll gradient, nor bloom magnitude appear to compromise application of the model. The 18-yr decline in annual mean chlorophyll observed between 1973–1990 in Narragansett Bay is considered to be a bonafide portrayal of actual events, and not an artifact of failure to consider tidal phase in the weekly sampling strategy. The results also suggest that intratidal variability in chlorophyll does not seriously confound its meaningful measurement and usefulness as a representative index of phytoplankton abundance at the permanent monitoring station established for Narragansett Bay. Nonetheless, there is need to refine and to incorporate temporal sampling strategies more closely attuned to the tempo of growth, grazing, and nutrient recycling which accompany estuarine phytoplankton dynamics.

Introduction

Estuaries are dynamic environments where freshwater and saline oceanic water move and mix constantly, often under the influence of semi-diurnal tidal cycles. Numerous studies have revealed that intratidal variations in phytoplankton biomass (usually measured as chlorophyll) can accompany such dynamics, as in the St. Lawrence estuary (Therriault and LaCroix 1976; Demers et al. 1979; Legendre et al. 1985), New York Bight (Duedall et al. 1977), Penzé estuary in Northern Brittany (Riaux and Douvillé 1980; Riaux 1981), Bedford Basin (Lewis and Platt 1982; Mitchell 1991), Bahia San Quintin (Lara-Lara et al. 1980; Millan-Nuñez et al. 1982), South San Francisco Bay (Cloern et al. 1989), Newport River estuary (Litaker et al. 1987), and Narragansett Bay (Swanson 1997). In the typical, tidally-induced diurnal pattern in biomass variability, higher biomass occurs during low (ebbing) tidal phases and lower biomass during high (flooding) tidal phases. In Narragansett Bay, a semi-diurnal signal (12.2 h) in chlorophyll fluorescence corresponded with phase of the tidal cycle: peak fluorescence accompanied low tidal periods, while daily fluorescence troughs accompanied flooding tidal phases (Swanson 1997; Magnuson 1997). Despite the evidence that estuarine chlorophyll levels vary intratidally, routine sampling strategies, as in Narragansett Bay (Pilson 1985; Li and Smayda 1998), San Francisco Bay (Cloern 1991), and Chesapeake Bay (Fisher et al. 1988), have usually not been phased with the semi-diurnal tidal cycles. This neglect in sampling strategies potentially affects the resultant chlorophyll measurements, and accurate characterization and interpretation of seasonal cycles and interannual trends.

Our specific interest in this matter stems from our finding that the mean annual chlorophyll abundance in Narragansett Bay (Figs. 1 and 2) decreased by 2-fold between the years 1973–1990. Mean water column chlorophyll levels decreased from about 60 to 30 mg m^{-2}, corresponding to an annual rate of decrease of 1.4 mg m^{-2} yr^{-1} (Li and Smayda 1998). This 18-yr trend appears to be real, since it was accompanied by a long-term increase in mean annual Secchi disc depth, from about 2.5 to 3.5 m (Fig. 3 in Borkman and Smayda 1998). The habitat conditions triggering and sustaining this interlinked long-term decrease in phytoplankton biomass and increased transparency remain to be resolved. Given the evidence that estuarine intratidal dynamics influence parameter measure-

* Corresponding author; tele: 401/874-6171; fax: 401/874-6682; e-mail: tsmayda@gsosun1.gso.uri.edu.

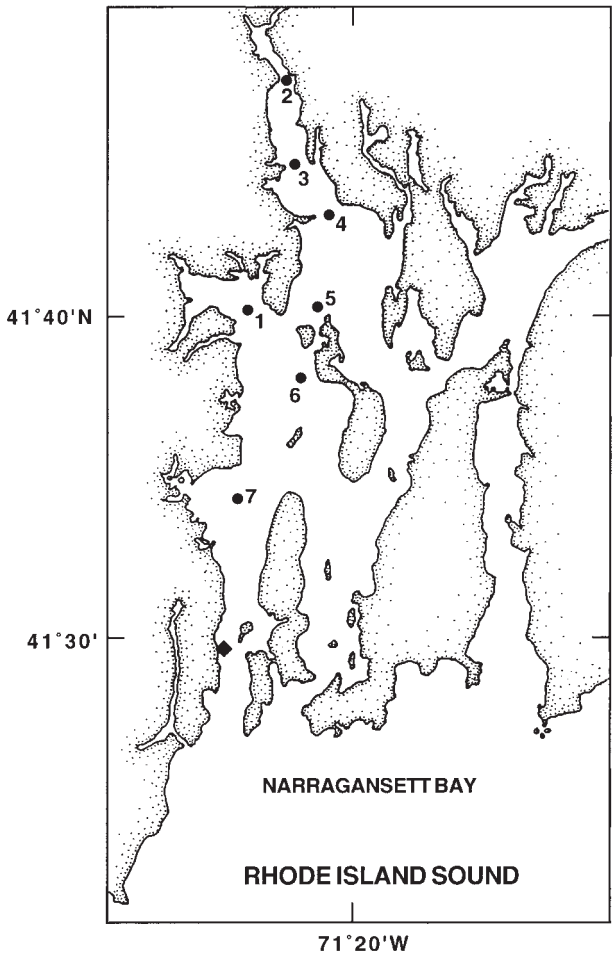

Fig. 1. Sampling stations in Narragansett Bay; the permanent, long-term monitoring site is Station 7. The diamond symbol (◆) designates location of the University of Rhode Island Graduate School of Oceanography dock, where in situ fluorescence measurements were carried out.

ments, it is first necessary to determine whether the apparent long-term decrease in mean annual chlorophyll biomass is an artifact of the field sampling program. Samples were collected without regard to tidal phase and its potential influence on the chlorophyll (and other) measurements. We evaluate the potential effect of time of sampling, e.g., the neglect of tidal stage effects, on averaging the observed chlorophyll measurements to generate the time series shown in Fig. 2.

Materials and Methods

Weekly measurements of chlorophyll and other biological, chemical, and physical parameters have been made since 1959 at a permanent station located in unpolluted, lower Narragansett Bay and designated as Station 7 in Fig. 1 (Pratt 1965; Karentz and Smayda 1984, 1998; Smayda 1984, 1998;

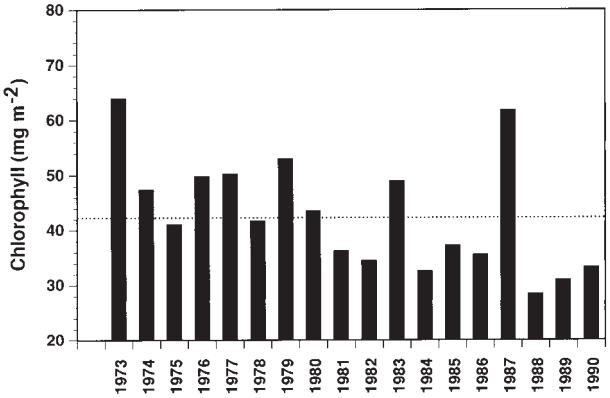

Fig. 2. Mean annual chlorophyll concentrations at Station 7 in Narragansett Bay from 1973–1990 (modified from Li and Smayda 1998).

Borkman and Smayda 1998; Li and Smayda 1998). Samples were always collected during daylight, usually between 0800 and 1000, without regard to tidal phase. The interannual variability in mean weekly chlorophyll concentration embedded within this time series and identified by week number (n = 52) is shown in Fig. 3. Chlorophyll concentrations during week numbers 22, 28, 37, and 44 were consistently less variable from year-to-year over the 18-yr period than weekly bloom events in the period from January through May.

The following criteria were applied in developing the procedures used to evaluate the effect of time of sampling (i.e., tidal phase) on the 18-yr chlorophyll trend and derivative conclusions (see Li and Smayda 1998). We wanted to reduce the number of requisite weekly calculations from n = 936 (= 18-yr time series) to a more manageable number; to select a sampling period outside of that used to generate the 18-yr time series; and to utilize Swanson's (1997) observations on a chloro-

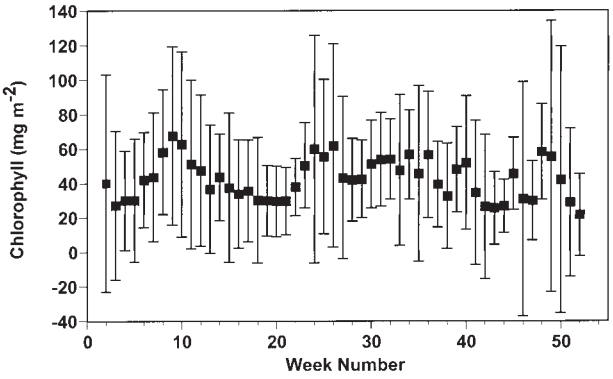

Fig. 3. Weekly mean chlorophyll concentrations at Station 7 in Narragansett Bay, 1973–1990; vertical bars represent one standard deviation (from Li and Smayda 1998).

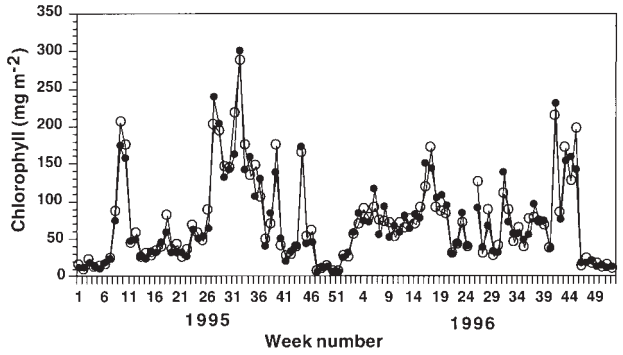

Fig. 4. Weekly chlorophyll levels during 1995 and 1996 at Station 7 in Narragansett Bay (●) compared to recalculated, tidally adjusted levels (○). See text for further details.

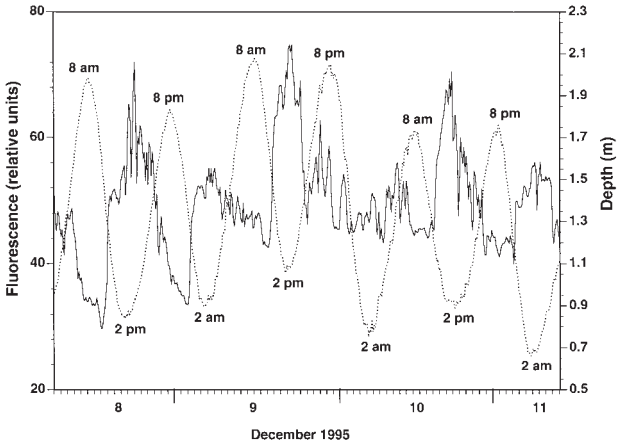

Fig. 5. In situ fluorescence pattern measured at the University of Rhode Island Graduate School of Oceanography dock in Narragansett Bay during December 8–11, 1995 and accompanying tidal pattern. (Based on data presented in Swanson 1997).

phyll fluorescence-tidal phase relationship in Narragansett Bay in developing procedures for tidal adjustment of chlorophyll. The specific objective was to compare the fidelity between the tidally adjusted and directly measured chlorophyll levels. Any significant divergence of the patterns and trends in the tidally adjusted levels from observed levels would suggest that failure to consider tidal phase in the sampling program introduced a serious artifact biasing the putative cycles and trends (Fig. 2) and their interpretation. The chlorophyll data set from 1995–1996 based on weekly measurement at Station 7 (Fig. 1) was selected as a proxy for the 18-yr time series, and the years when Swanson carried out her study. Weekly mean chlorophyll levels and their seasonal and interannual variability during 1995–1996 (Fig. 4) exhibited patterns not too dissimilar from those characterizing the weekly and annual behavior of the 18-yr time series (Fig. 3).

To approximate potential effects of tidal phase on the chlorophyll measurements, each direct measurement was adjusted to the level expected, should that sample have been collected during mid-high tide or mid-low tide on that sampling date. Local tide charts for Newport, Rhode Island provided the daily tidal times for the sampling dates. A 30-d segment of Swanson's (1997) 1995–1996 time series expressing the relationship between phytoplankton fluorescence versus tidal phase for Narragansett Bay was modeled to derive the relationships needed to tidally adjust measured chlorophyll levels. In Swanson's study, chlorophyll fluorescence was continuously measured in samples aspirated into a flow-through system positioned at a fixed depth of about 2.0 m above the bottom sediments. The collection site was at the dock of the Graduate School of Oceanography located approximately 9 km down-bay from Station 7 (Fig. 1). Fluorescence was measured once per minute and averaged over 10-min intervals. A pressure-sensor depth recorder attached to the intake of the deployed flow-through system recorded depth of the overlying water column at 10-min intervals (Magnuson 1997). The fluorescence-tidal phase relationships during the periods from December 8–22, 1995 (Figs. 5 and 6) and October 29 through November 12, 1995 (similar and therefore not shown) were used in our analysis. The crisp diel changes in chlorophyll fluorescence and day-to-day variability in magnitude and in apparent synchrony with diel tidal rhythms are evident. To assess the magnitude of intratidal variability in chlorophyll level, the ratio of peak to trough fluorescence during the tidal cycle in the 30-d time series segment was calculated (Fig. 7). The ratio is based on the mean of five measurements made at 10-min intervals during low tide (peak) and high tide

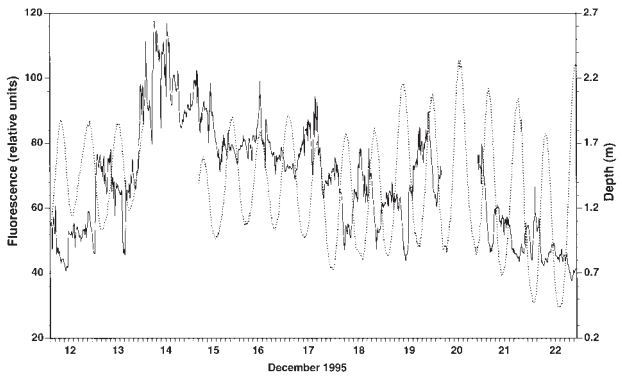

Fig. 6. In situ fluorescence pattern measured at the University of Rhode Island Graduate School of Oceanography dock in Narragansett Bay during December 12–22, 1995 and accompanying tidal pattern. (Based on data presented in Swanson 1997).

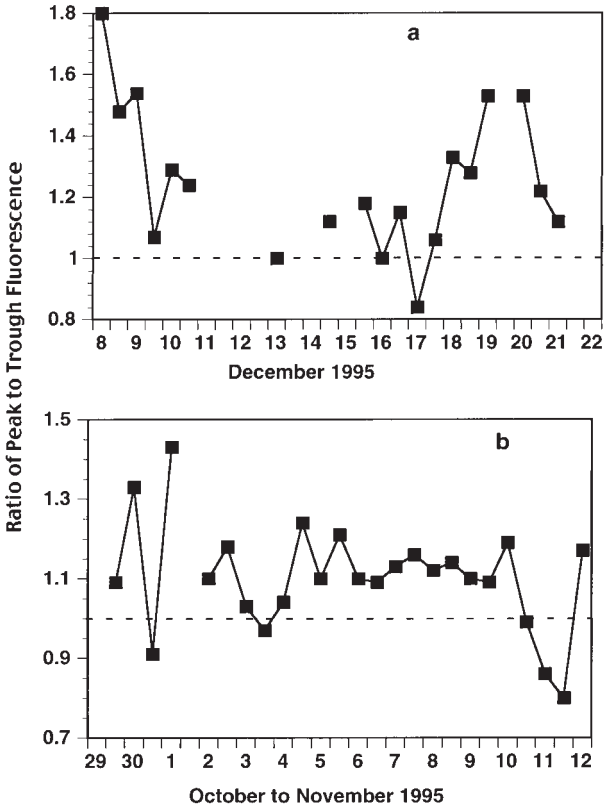

Fig. 7. Ratio of peak to trough fluorescence during tidal cycles: a) from December 8–22, 1995; b) from October 29 to November 12, 1995. (Calculated from data in Swanson 1997).

(trough). From this time series, a 76-h segment of the fluorescence pattern determined for the period from 0317 on December 8 to 0719 on December 11, 1995 was selected for use as the standard (model) of intratidal variability of chlorophyll in Narragansett Bay (Fig. 8). This time segment was selected because the strength of fluorescence peak and trough signals was relatively constant from day to day (Fig. 5). This, and all time segments of the series, exhibited a coherent sequence of fluorescence peaks and valleys in synchrony with the tidal phases. Six peaks and six troughs in fluorescence occurred, and in each case the semi-diurnal peak in fluorescence coincided with a low tide, and each diurnal trough in fluorescence occurred during a high tide. The tidal variations in height during this period ranged from 0.7 to 2.0 m, i.e., the depth of water overlying the flow-through intake. The annual winter-spring diatom bloom (c. 350 cells ml^{-1}) was then just beginning at nearby Station 7, dominated by *Skeletonema costatum* and *Thalassiosira* spp. An abundant (200 cells ml^{-1}) cryptomonad population was also present. A noteworthy feature of the fluorescence pattern is that day peaks in fluorescence were much higher than the night

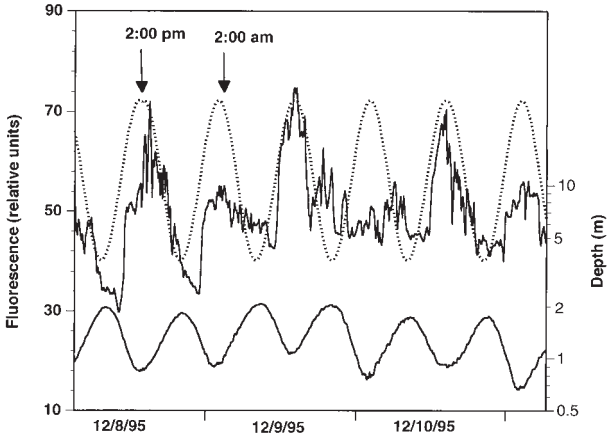

Fig. 8. Comparison of observed fluorescence profile (solid line) measured during December 8–11, 1995 with the modeled profile (dotted line), and the accompanying tidal pattern. See text for further details.

peaks. This is consistent with the well known, in situ diel cycles and changes which occur in cellular chlorophyll levels and zooplankton grazing. We also selected this 76-h segment of the time series because the peak to trough ratio was particularly high relative to other time segments (Fig. 7). The mean ratio during this time segment was 1.5 (maximum = 1.8) versus < 1.2 for most of the 30-d sequence. This selection avoided biasing of the analyses towards an underestimation of tidal effects that would accompany selection of a low peak to trough ratio.

A sine model modified from Legendre et al. (1985) was used to fit the fluorescence-tidal phase data (Fig. 8). Night-peaks in fluorescence, which were lower than day peaks, were not considered in generating the model, since our samples were day-collections:

$$Y = 56.25 + 16.03 \sin(2\pi/12.2 \times X + \pi/2) \quad (1)$$

where Y is the fluorescence (relative units), and X is the number of hours since the last low tide. The resultant model (Fig. 8) has a peak fluorescence of 72.28 (relative units), with a peak occurring at a frequency of once every 12.2 h. The modeled and measured fluorescence data are significantly correlated ($r^2 = 0.71$, $p < 0.001$). The 1400 and 0200 entries in Fig. 8 record the times of peak fluorescence on December 8 and 9, respectively, and match up with the times of low tides recorded at Newport, Rhode Island on those dates: 1402 and 1355, respectively. This confirms our assumption that there is a synchronous, inverse relationship between the local, diurnal fluorescence maxima and minima and tidal phase which can be exploited to estimate tidally adjusted chlorophyll levels. This insight and the assumption that the diurnal

pattern in intratidal variability of chlorophyll at Station 7 follows that exhibited by the dockside fluorescence measurements are applied along with the above model (Eq. 1) to calculate tidally adjusted chlorophyll levels, after first estimating the mean fluorescence at mid-high tide or mid-low tide, Fm:

$$\text{Fm} = 56.25 + 16.03 \sin(2\pi/12.2 \times 6.1 + \pi/2) = 56.25 \quad (2)$$

In Eq. 2, the mid tidal time (X) is fixed at 6.1 h, given that peak (or trough) fluorescence occurred at semi-diurnal intervals of 12.2 h (Fig. 8). Fm has a constant value of 56.25 relative units. The projected percent difference, P, expected between the fluorescence level in a chlorophyll sample collected at a given stage in the tidal cycle, Fs, and that occurring at the previous mid-high or mid-low tide, Fm, is derived from:

$$P = (Fs - Fm)/Fm \quad (3)$$

To illustrate the calculation procedure up to this point: the 1995, week 1 sample for measurement of chlorophyll was collected at 0830, which was 6.75 h after the previous low tide on that date. Using Eq. 1, Fs for this sample is calculated to be:

$$\text{Fs} = 56.25 + 16.03 \sin(2\pi/12.2 \times 6.75 + \pi/2) \quad (4)$$

which yields Fs = 41.11 relative units. Now, from Eq. 3, the percent difference in fluorescence between Fs and the expected fluorescence (relative units) at that mid low tide is: P = 41.11–56.25/56.25 = −0.2695 or −26.95%.

Assuming that this difference, P, in fluorescence values also applies to the directly measured chlorophyll levels comprising the time series, tidally adjusted chlorophyll levels (i.e., that at mid-high or mid-low tide) can be estimated from the known values of P and Chl_m:

$$P = (Chl_m - Chl_a)/Chl_m \quad (5)$$

where Chl_m is the observed chlorophyll level and Chl_a is the tidally adjusted chlorophyll level. Continuing with our example, the 1995 week 1 Chl_m was 14.67 m^{-2} which yields a tidally adjusted chlorophyll level of 10.72 m^{-2} based on the value of 0.262 derived for P for that sampling date.

The potential effect of tidal transport of a spatial chlorophyll gradient causing significant variations in the magnitude of intratidal variability in chlorophyll not detected by the 30-d high frequency model used, and biasing the results was examined. Spatial surface chlorophyll distribution patterns at the seven stations (Fig. 1) during 62 transects carried out between July 25, 1985 and June 29, 1987 (Fig. 9, Smayda unpublished data) were subgrouped into two regions and the monthly slopes statistically analyzed for differences in chlorophyll spatial and temporal patterns. Stations 2 through 5 were grouped as upper bay stations, and Stations 1, 6, 7 as lower bay stations. Down-bay distances from Station 2 to Stations 1 and 7 were about 12 and 25 km, respectively.

Results and Discussion

The tidally adjusted weekly chlorophyll levels calculated for 1995–1996 are compared in Fig. 4 to the chlorophyll cycles based on direct measurements. The relationship between observed and adjusted chlorophyll levels is shown in Fig. 10. A statistically significant correlation occurred between observed and adjusted chlorophyll levels (r^2 = 0.92, $p \leq 0.001$). The annual mean estimations for the directly measured and tidally adjusted levels are similar (Table 1). For directly measured chlorophyll, the annual means are 68.72 and 71.82 mg m^{-2} for 1995 and 1996, respectively; the corresponding tidally adjusted annual means were 74.23 and 71.41 mg m^{-2}. These differences in annual means are only 7.4% and 0.6% for 1995 and 1996, respectively, and are not statistically significant using the paired student *t*-test (n = 103, t = −1.26, p = 0.21).

Two potential error sources accompany development of the periodic model to calculate tidal-scale fluctuations in chlorophyll based only on the 76-h fluorescence-tidal stage time series (Fig. 5). Application to other time periods assumes that the relevant features of the intratidal variability in chlorophyll and spatial chlorophyll gradients and concentrations then extant do not bias general application of the model. These assumptions are not contradicted where nullification tests could be applied. Peak to trough ratios (mean = 1.5) during the 76-h time series were the highest among those calculated for the 30-d segment perused (Fig. 7). Only 5 of the 44 ratios calculated for the 30-d time series exceeded this ratio; 66% of all ratios were < 1.2. Selection of a high ratio in our model therefore maximized potential tidal effects, i.e., favors overestimation of tidally-induced diurnal changes in chlorophyll levels. This bias would favor a finding that tidal artifacts (if they occurred) were indeed an important determinant of the observed long-term decline in chlorophyll observed in Narragansett Bay (Fig. 2). The issue of whether the model would differ if constructed from high frequency measurements during an intense bloom was examined. Chlorophyll levels were relatively low at nearby Station 7 during the 76-h time series used to construct the model (Fig. 2): generally < 10 mg m^{-2}, with a mean peak: trough ratio of 1.5.

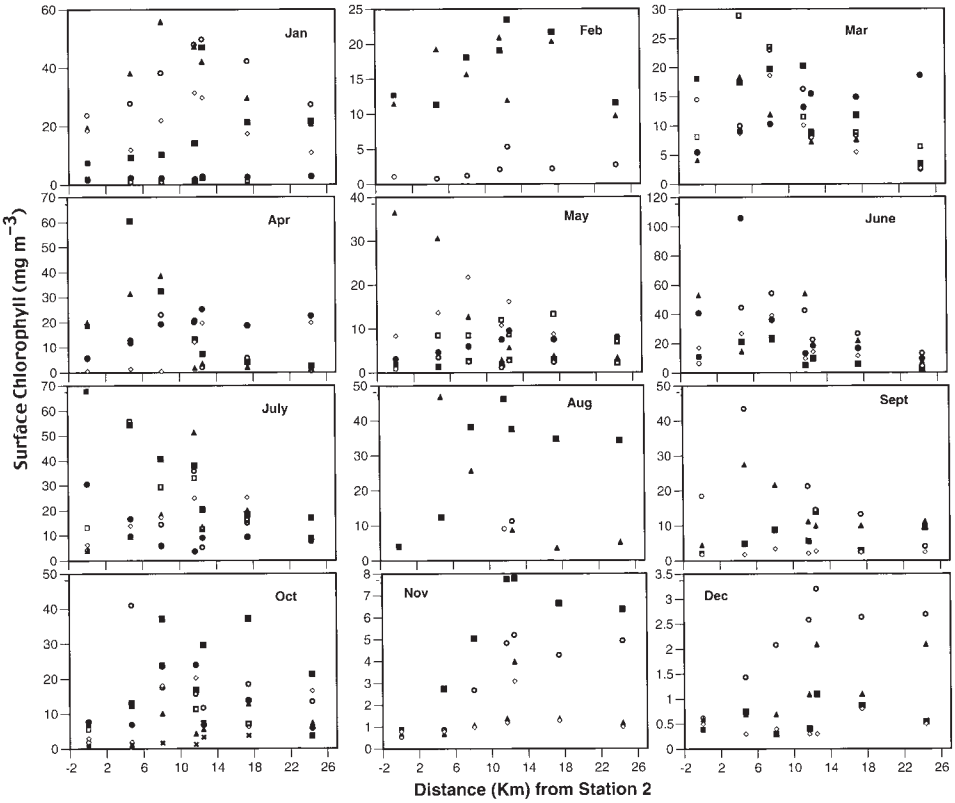

Fig. 9. Surface chlorophyll gradients in Narragansett Bay between Stations 1–7 (see Fig. 1) during 1985–1987. Similar symbols in each monthly panel along gradient indicate same transect date. Stations 1 and 7 located circa 12 and 25 km, respectively, downbay from Station 2.

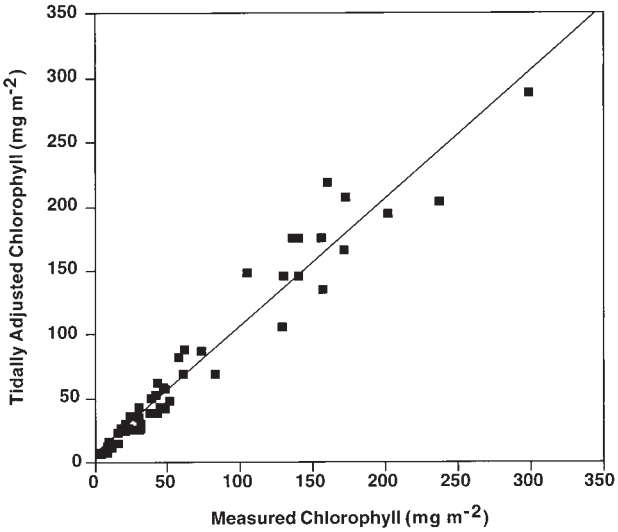

Fig. 10. Relationship between the tidally corrected and directly measured chlorophyll levels during 1995 and 1996 shown in Fig. 4. The linear regression is expressed as $Y = 0.98 \times X + 3.46$, and has an $r^2 = 0.92$, with $p < 0.001$.

An intense bloom (172 mg m^{-2}) in progress on October 30 (Fig. 4) was accompanied by a peak: trough ratio of about 1.3 (Fig. 7); lower than the modeled ratio. We conclude that our model accommodates higher bloom events.

Admixture and tidal advection of watermasses differing in phytoplankton biomass levels, tidal and wind-driven resuspension of sedimented cells, diel growth, vertical migration, and grazing patterns can influence variations in chlorophyll levels on diel and intratidal time scales (Riaux and Douvillé 1980; Litaker et al. 1987; Cloern 1991; Cloern et al. 1989). Diel cycling in grazing by migratory zooplankton (Fofonoff and Smayda in review) is considered to have relatively minor effects on daylight variability in measured chlorophyll levels, given that our samples were day-collections. This contrasts with the potential influence of the intratidally variable horizontal advection of water masses characterized by different concentrations and assemblages of phytoplankton. Figure 9 presents the surface chlorophyll levels at 7 stations in Narragansett Bay based on 62 transects carried out during 1985–1987. A distinct spatial gradient in chlorophyll level is evident: time series Station 7 is the

TABLE 1. Statistics of mean annual chlorophyll in Narragansett Bay during 1995 and 1996 and modeled chlorophyll fluorescence (in relative units, RU) during the tidal cycles indicated in Fig. 8.

Data	Mean	Standard Deviation	Coefficient of Variance	Range
1995 Chlorophyll	68.72 mg m^{-2}	67.84	0.99	4.58–300 mg m^{-2}
1996 Chlorophyll	71.82 mg m^{-2}	45.43	0.63	10.64–230 mg m^{-2}
Fluorescence	56.25 RU	11.38	0.20	40.22–72.28 RU

down-bay end member along a 13 km gradient (from Station 1) over which chlorophyll levels decrease by about two-fold (see also Farmer et al. 1982). We statistically analyzed the monthly chlorophyll spatial gradients to test whether a seasonal signal or annual cycle in pattern occurred restricting application of the model to periods of low spatial gradients and/or when chlorophyll levels were low. Grouping of upper Narragansett Bay Stations 2–5 showed that the slopes of the linear regressions used to quantify spatial chlorophyll patterns in the upper bay region were extremely significant. In lower Narragansett Bay (Stations 1, 6, and 7), e.g., the 13 km segment in which tidal transport of chlorophyll can be expected to particularly influence diurnal changes, the linear regression slopes of the month-to-month spatial gradients in chlorophyll were not statistically different. This suggests that application of our model to other seasons and bloom periods in this region, and specifically to the long-term monitoring station at Station 7 (Fig. 1), is valid.

The coefficients of variance calculated for the directly measured chlorophyll levels and the fluorescence proxy used as the reference standard confirm this conclusion. The variability coefficients of directly measured chlorophyll in 1995 and 1996 are much greater than that for fluorescence used as the reference standard to estimate intratidal chlorophyll variability (Table 1). The variance coefficients for mean 1995 and 1996 chlorophyll levels are 0.99 and 0.63, respectively; that for fluorescence only 0.20. We then arbitrarily selected ten years of surface chlorophyll measurements ($n = 488$) from our data bank and regressed the standard deviation of each measurement from the long-term annual chlorophyll mean against tidal height expressed as the deviation from mean low water depth. There was no statistical correlation, for the data set taken as a whole, or when subgrouped by month or quarterly.

From these analyses, we conclude that the diverse times of the weekly sample collection at the long-term, time series Station 7 in Narragansett Bay relative to tidal phase has little effect on adequately portraying the basic trends and cycles of the depicted chlorophyll data, and that failure to collect samples at the same tidal phase seemingly does not introduce a significant artifact when calculating annual mean chlorophyll levels, or their interannual variations, cycle, and trends. Extrapolating from the proxy 1995–1996 results, we accept the 18-yr downward trend in annual mean chlorophyll observed in Narragansett Bay between 1973–1990 (Fig. 2) as a bonafide portrayal of actual events, and not an artifact of failure to consider tidal phase in the weekly sampling strategy followed. The strength of the weekly, seasonal, and interannual variations of chlorophyll, whatever their causes, appears to exceed intratidal modifications. The long-term patterns in variability of chlorophyll (week-to-week, month-to-month, year-to-year) appear to mask diurnal, tidally-induced advective modification of chlorophyll levels. To the extent that significant, intratidal swings in diel and advective chlorophyll levels occur, these effects seem to have been balanced out by the tidally indifferent strategy of sampling duration and frequency used. This effect and difference in signal strength revealed the general features of the embedded cycles and trends characterizing the 18-yr time series (Fig. 2). This further suggests that intratidal variations in chlorophyll levels can be more or less ignored in characterizing chlorophyll seasonality, cycles, and trends for Narragansett Bay, and in deriving mass balance calculations from chlorophyll biomass. This is not to deny the occurrence of diel and intratidal effects at phytoplankton cellular and population levels. Internal or endogenous cyclical rhythms induced by repetitive environmental stimuli, such as tidal cycles (Brady 1979; Laval-Martin et al. 1979; Owen et al. 1980), occur. Other cellular mechanisms potentially contributing to diurnal variability in biomass include the diel changes in chlorophyll content and photosynthetic activities exhibited by both natural and laboratory populations of phytoplankton (Sournia 1974; Prézelin et al. 1977; Harding et al. 1981). Legendre et al. (1985) found that experimentally manipulated natural phytoplankton populations exhibited semi-diurnal cycles in cellular chlorophyll levels and photosynthetic efficiency phased in response to tidal fluctuations.

The conclusion that intratidal variability of chlorophyll in Narragansett Bay is relatively low compared to longer-term variability may not apply to

other estuaries. In South San Francisco Bay, the coefficient for variance for the intratidal variability of chlorophyll ranged from 0.28 to 0.47 (Cloern et al. 1989) compared to 0.20 in Narragansett Bay. In St. Lawrence estuary, intratidal variability was even higher: near-surface chlorophyll concentrations over a tidal cycle could vary by a factor of two to five (Therriault and LaCrox 1977). Irrespective of the conclusion with regard to Narragansett Bay, sampling strategies focus much more on accommodating the spatial patchiness in distribution and abundance of phytoplankton than the infradiem variability in these community attributes resulting from semi-diurnal tidal effects, diel metabolism, grazing, or other entrained diel biological and physical parameters. There is a growing need to refine and adopt temporal sampling strategies more closely attuned to the tempo of growth, grazing, and nutrient recycling which accompany phytoplankton dynamics.

Acknowledgments

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