YEAR 3 FINAL REPORT

Project Period: September 15, 1998 – September 15, 1999

Project Title: Characterization of phytoplankton communities, primary production and detrital components

Principal Investigators: Maureen D. Keller
Bigelow Laboratory for Ocean Sciences
McKown Point, West Boothbay Harbor, ME 04575
(207) 633-9600; email: mkeller@bigelow.org

and

Andrew C. Thomas
School of Marine Sciences
University of Maine, Orono, ME 04469
(207) 581-4335; email: thomas@maine.maine.edu

Introduction

The Penobscot Bay region has been historically one of the most productive regions of the Gulf of Maine. The area is strongly influenced by the adjacent offshore waters of the Gulf and the products of land and riverine runoff that interact to create temporal and spatial complexity, known to be important in the stimulation of primary productivity which supports all higher trophic levels. At present, there is very little data on the primary productivity, phytoplankton biomass or species diversity in Penobscot Bay. In order to define the carrying capacity of this region, and to identify suitable sites for aquaculture or fisheries restoration, information on the patterns and driving forces of primary productivity are critical. In addition, an apparent enigma exists in Penobscot Bay that sets it apart from other areas of the Maine coast. During the last two decades, most of the Maine coast has been regularly closed to shellfish harvesting due to the presence of the toxin-producing phytoplankter, *Alexandrium tamarense*. However, for unknown reasons, the area of Penobscot Bay is relatively free of the toxins associated with this organism (Shumway et al, 1988). This phenomenon makes the region even more attractive for shellfish culture and the restoration of clamflats and other shellfish habitats.

Remote sensing of ocean color from both aircraft and satellite platforms has the capability to quantitatively measure upper water column phytoplankton biomass if the signals can be quantitatively interpreted. When coupled with appropriate *in situ* measurements, remote sensing data can be used to estimate water column primary productivity. For the purpose of ocean color remote sensing, the nearshore waters of the Gulf of Maine are optically classified as extreme case 2 waters. This means that

water-leaving radiance reaching a remote sensor results from a mixture of optically active substances including phytoplankton chlorophyll**,** detritus, suspended sediment, and colored dissolved organic material. To achieve the goal of estimating water column primary production or quantifying accurately chlorophyll biomass for these regions, actual chlorophyll concentration must be determined with a high degree of accuracy, and absorption due to the competing substances must be determined. Considerable ground-truthing of the upwelling radiance must be conducted to correctly isolate and quantify the signal due to the phytoplankton.

The overall goal of this component of the Penobscot Bay Project is to provide the field measurements necessary for accurate interpretation of oceanographic remote sensing data that is associated with primary production. Here we have collected many of the field data required for effective utilization of ocean color and surface temperature imagery. The data include spatial patterns of chlorophyll and primary productivity, the relative contributions of light absorbing compounds, i.e. chlorophyll, suspended particulates, and DOM, and measurement of concurrent hydrographic conditions. These data are required to develop appropriate algorithms for case 2 waters that will be used for more accurate retrieval of coastal chlorophyll concentrations.

Project Summary

1) Field program

As in 1998, the 1999 field effort consisted of four cruises that occurred in March, April, June, and August. The cruise dates were March 28 and 29, April 19 and 20, June 27 and 28, and August 17 and 18. On each cruise, 30 stations were sampled for continuous vertical hydrographic (CTD) data, and nutrient and chlorophyll concentrations at three depths, to provide broad spatial coverage of the Bay. At a subset of eight stations, in-depth characterizations were compiled of the phytoplankton community and optical properties of the surface waters. These additional data included *in situ* light attenuation, photosynthesis vs. irradiance relationships, phytoplankton community structure, both in terms of size and species identification, suspended particulate matter concentration and absorption, and dissolved organic matter absorption.

2) Coordination with other projects

The field work was coordinated with N. Pettigrew (U. Maine), occupying stations sampled by him at previous times, and the same stations as our 1998 study. Cruise times were planned to provide better temporal coverage of the area. Two scientists from John Cullen's group at Dalhousie University participated in each cruise, collecting multispectral *in situ* light data using a tethered light profiling system. These data will give us coincident measurements of water-leaving radiance to compare with the discrete optical data set. A scientist from the Maine Dept. of Environmental Protection (DEP) also participated in each of the 1999 cruises, gathering dissolved oxygen data.

3) Sample analyses

At this point, all samples have been analyzed, with the exception of some of the phytoplankton identifications (ongoing). The hydrographic, chlorophyll and nutrient data sets are complete and have

been developed into GIS layers and will be submitted under separate cover to Maine Office of GIS (MOGIS) by A. Thomas. The optically-active substances, Suspended Particulates (SPM) and Dissolved Organics (DOM), have been measured and compiled into spread sheets. The photosynthesis vs. irradiance relationships have been determined and compiled into spreadsheet format and graphs. Integrated productivities have been calculated, as well as volume-based production at the surface and to one attenuation-depth (a light-penetration value). These spreadsheets have also been submitted to MOGIS. Phytoplankton cell counts and identifications are continuing and should be completed soon, when they also will be submitted to MOGIS in spreadsheet format.

Methods

Continuous vertical profiles of salinity, temperature, *in situ* chlorophyll fluorescence, and beam attenuation (transmission) were measured at each cruise station using a SeaBird CTD equipped with an *in situ* fluorometer and 25 cm path length transmissometer. Water samples were collected on the up cast from three depths, roughly corresponding to surface, 10% and 1% incident light levels, using a General Oceanics rosette water sampler and 5 L Niskin bottles.

Phytoplankton chlorophyll and phaeopigments were determined fluorometrically (Parsons et al., 1984) on each of the bottle samples. Triplicate subsamples (100 mls each) were filtered onto a GF/F glass fiber filter, placed in cold 90% acetone, and extracted at -20^{o}C in the dark for at least 24 hours before analysis. Chlorophyll was measured fluorometrically with a Turner-Designs 10-005R fluorometer, modified to give a digital output and calibrated against pure chlorophyll *a*. Estimates were corrected for degradation products by acidification (Holm-Hansen 1978).

Nutrient samples were collected at the same depths in 20 ml pre-conditioned plastic vials and frozen at -20^{o}C. Concentrations of dissolved nitrate, nitrite, ammonia, phosphate and silicate were measured using standard autoanalyzer methodology (Whitledge, et al, 1986).

At a subsample of these stations, 4 each day, primary production was measured and phytoplankton dominants were enumerated, sized and identified. Primary productivity samples were collected after determination of a diffuse attenuation coefficient using a submerged scalar quantum irradiance sensor paired with a deck reference. From the vertical profiles, the diffuse PAR (Photosynthetically Active Radiation) attenuation coefficient was calculated. Photosynthesis as a function of irradiance (P vs I; PE) was determined using a photosynthetron and ^{14}C incubation (Lewis and Smith, 1983). The P vs. I curves were generated during peak light intensity hours (1000-1400 h). The number of samples at each station varied depending on the vertical hydrographic structure and fluorescence profile of the water column. In general, a stratified water column was sampled at the surface, the chlorophyll maximum or 10% light level, and at the 0.5-1.0 % light level. Well-mixed water columns were sampled at two depths, as they are described adequately by measurements at the surface and 1% light levels. Two ml (March and April) or one ml (June and August) whole water samples were incubated with $H^{14}CO_3^-$ (200 µCi) at *in situ* temperatures and twenty-four different irradiance levels for a 30 minute period. Incubations were terminated by adding 50 µl of formalin to each sample. Residual inorganic carbon was driven off by acidification with 250 µl of 6N HCl, followed by shaking. Light in the incubator was provided by two General Electric ENH projection lamps and filtered through 2.5 cm of water and a 6mm sheet of blue Plexiglass. Irradiances in the photosynthetron were measured with a

QSL-100 scalar quantum sensor (Biospherical Instruments, San Diego, CA).

The P vs. I equation of Platt et al (1980) was used to model photosynthesis as a function of light, yielding the instantaneous (P^{chl}) and maximum (P_s^{chl}) photosynthetic rates, normalized to chlorophyll *a*:

$$P^{chl} = P_s^{chl} * (1-\exp((-a^{chl}*E)/P_s^{chl}))*\exp((-b^{chl}*E)/P_s^{chl})+P_o^{chl} \quad (1)$$

where P^{chl} is the rate of photosynthesis normalized to chlorophyll a (g C [g Chl]$^{-1}$ h^{-1}) at irradiance E (µmol photons m^{-2} s^{-1}); P_s^{chl} (gC[g Chl]$^{-1}$ h^{-1}) is the maximum rate of photosynthesis in the absence of photoinhibition; a^{chl} (g C[g Chl]$^{-1}$ h^{-1} [µmol m^{-2} s^{-1}]$^{-1}$) is the initial slope of the PE curve and b^{chl} (g Chl [g Chl]$^{-1}$ h^{-1} [µmol m^{-2} s^{-1}]$^{-1}$) is a parameter describing the reduction in photosynthesis at high irradiance. P_o^{chl} (g Chl [g Chl]$^{-1}$ h^{-1}) is an intercept term, subtracted from P^{chl} so that modeled photosynthesis in the dark is always zero. The light-saturated rate of photosynthesis, P_m^{chl} (g Chl [g Chl]$^{-1}$ h^{-1}) was calculated as:

$$P_m^{chl} = P_s^{chl} * (a^{chl}/(a^{chl}+b^{chl}))*(b^{chl}/(a^{chl}+b^{chl}))^{b^{chl}/a^{chl}} \quad (2)$$

With these data, we calculated daily primary production. Total water column production was calculated in a model by integrating photosynthetic rates over depth. Profiles of chlorophyll-specific photosynthesis were calculated from the vertical profile of irradiance and the PE curves:

$$P^{chl}(z) = P_s^{chl} * (1-\exp((-a^{chl} * E(z))/P_s^{chl})) * \exp((-b^{chl} * E(z))/P_s^{chl}) \quad (3)$$

Irradiance at depth z (m) ($E(z)$, µmol m^{-2} s^{-1}) is calculated from incident irradiance (E_0, µmol m^{-2} s^{-1}) and the diffuse attenuation coefficient, k (m^{-1}):

$$E(z) = E_0 * \exp(-k * z) \quad (4)$$

The value of incident irradiance used in Eq. (4) was the mean of that measured during the determination of the diffuse attenuation coefficient at the time of sampling. Three profiles of P^{chl} were constructed for each set of samples, one from the PE parameters of each of the three samples. To account for the vertical variation in photosynthetic responses, a weighted vertical profile of P^{chl} was constructed from the depth-weighted average of upper and lower estimates of P^{chl} in the interval between each pair of samples (cf. Cullen et al., 1992). Vertical profiles of chlorophyll and productivity (the product of chlorophyll and P^{chl}) were constructed by linear interpolation between discrete measurements. The product of the vertical profiles of P^{chl} and Chl was integrated over depth to give areal productivity P (g C m^{-2} h^{-1}), and areal productivity:

$$P = \sum_{z=0}^{z=zm} P(z) * \Delta z \quad (5)$$

was calculated as the integrated productivity over depth (Δz is 0.5 m). The limit with respect to depth ($z = zm$) was the depth of the 1% isolume.

Production values per unit volume (mg C m^{-3} h^{-1}) were estimated from the model described above, and reported for the surface and at one attenuation depth (1/k).

Plankton community structure was assessed at each productivity station. Whole water samples (1000 ml) were taken from each depth and preserved with Lugol's solution. A subsample was concentrated using a settling chamber and counted by inverted phase microscopy. Cells (>10 µm) were enumerated and identified to the lowest possible taxon, with special attention given to the identification of the toxic dinoflagellate *Alexandrium tamarense*. In addition, determination of the pico- and nano-phytoplankton community structure was done using flow cytometry. A Becton Dickinson FACScan flow cytometer equipped with a 15 mW, 488 nm, air-cooled Argon ion laser analyzed all samples that were preserved in 0.5% paraformaldehyde and stored in liquid nitrogen. Size composition and cell abundances of the autotrophic community were quantified by the simultaneous measurements of forward light scatter (FSC; relative size), 90° light scatter (SSC), chlorophyll fluorescence (>650 nm), and phycoerythrin fluorescence (560-590 nm).

Photomultiplier detectors were in log mode, providing 4 decades of log, and signal peak integrals measured. The volume of sample analyzed by the FACScan was determined gravimetrically using an A-160 electronic balance (Denver Instruments Co) whereby each sample was weighed prior to analysis and immediately after the analysis was terminated. The difference in milligrams is proportional to the volume of sample analyzed in microliters. All samples were run at either low (~20 µl/min) or high (~ 56 µl/min) flow rates so as to insure that total particle counts did not exceed 1500 counts per second.

Other optically-active substances (dissolved and particulate organic matter) were assessed at each productivity station. Samples (100 ml) for the measurement of dissolved organic matter were filtered through a 0.2 µm filter and stored in sealed dark bottles until analysis. Total suspended particle matter (SPM) samples were collected by filtering 250-500 ml of seawater through a prewashed, and preweighed GF/F filter, rinsing with 10 ml DIW, and storing the filters, frozen and dark, in a clean, numbered plastic petri dish until analysis. The filters were dried at 50°C for 24 h, reweighed and the concentration computed as (W_2 - W_1)/ volume filtered (Strickland and Parsons, 1972). Spectral absorption (over 350-750 nm) was determined using a Bausch and Lomb Spec 2000 spectrophotometer for both the dissolved fraction (in a cuvette over a 10 cm pathlength) and the particulate fraction, using the SPM filter (before drying) and the filter pad method (Phinney and Yentsch, 1991).

Project results and discussion

Station locations are listed in Table 1. We attempted to sample at slack tide or against the tide to avoid sampling the same water body repeatedly. Stations were chosen from N. Pettigrew's original station grid. To simplify comparisons, these station names were used throughout the cruises. Chlorophyll distributions for each cruise are presented in Tables 2-5 and Figures 1-4. Hydrographic data are not presented in this report, but will be supplied as an additional supplement and have been submitted to MOGIS along with the chlorophyll data. In March, chlorophyll levels were generally low, though a high concentration was observed in the eastern bay, near Deer Isle (NP42 and NP44) at this

time. April chlorophyll levels were appreciably higher, with a similar peak at station NP44 in the eastern bay. Chlorophyll biomass remained at a comparable level in June, though with an increase in the percentage of phaeophytins (pigment degradation products). The greatest concentrations were observed in the southeast part of the bay near Isle au Haut, at the 1% light depth. August chlorophyll levels showed a further increase throughout the bay, with particularly high concentrations found at the surface in the northern part of the bay (NP02).

Data from the phytoplankton/optical properties stations (Figure 5) begin with vertical distributions of chlorophyll, phaeophytins and total suspended solids (TSS) for each cruise (Tables 6-9). March, June and August showed fairly consistent levels of TSS throughout the bay, with an overall increase in April. The highest levels of TSS were observed at NP07 in April, June and August (probably due to riverine influence), and in the east bay in June (NP42 & 44). Particulate absorption measurements (a_p) at selected wavelengths for each cruise are presented in Tables 10-13 and absorption due to dissolved organic matter (DOM) at selected wavelengths are presented in Tables 14-17. Absorption due to DOM (a_y) was again much higher at relevant wavelengths (less than 400 nm) than particulate absorption. Figures 6-9 illustrate the relationship between a_p (400) and TSS plus pigments. $A_p(400)$ is often used in algorithms to distinguish particulate absorption. This relationship was weak in March and April, but was good for June and August, yielding a fair correlation for all the cruises (Figure 10). There was a strong relationship shown between $a_p(670)$ (often used to distinguish chlorophyll absorption) and measured chlorophyll pigments for each month (Figures 11-14). The relationship was less robust when applied to the entire data set (Figure 15).

Phytoplankton population data are presented in Tables 18-19. The concentrations of phytoplankton of different sizes, <3 um, 3-10 um, and >10 um diameter, are shown in Table 18. While numerically insignificant, the biovolume of the larger cells is of major importance to the population. Figures 16-19 show the relative impact of those larger cells compared to the more-numerous cyanobacteria (<3um size). Only in August do the smallest cells form a significant portion of the biomass. Concentrations of cyanobacteria from the 1998 (Table 19) and 1999 cruises may be compared in Figures 20-21. It is interesting to note the numerical dominance of these small cells in June and August of 1999. In 1998, August also showed a large increase in cyanobacteria numbers, while June showed a major decrease.

Vertical distributions of photosynthetic parameters, discrete and integrated water-column primary production are presented in Tables 20-21. Primary production integrated to the first attenuation depth (1/k) is presented in Table 22. Examples of photosynthesis-irradiance relationships and water-column models are presented in Figures 22-27: Figures 22-23 depict a well-mixed environment, Figures 24-25 show a stratified, light-limited water column, while Figures 26-27 illustrate a stratified environment where light is not the limiting factor. Note that the populations from the mid and deep depths are unable to approach the production achieved by the surface sample, regardless of available light (Figure 27). The seasonal range of integrated primary production is considered in Figure 28. On average, the highest production could be found on the west side of Penobscot Bay (NP13, NP11, NP09, NP07), though the eastern bay was higher in the month of April. June showed markedly low production throughout the bay, while August values for the western bay (especially NP07) were notably high. A comparison of chlorophyll biomass and primary production is illustrated in Figure 29. This relationship is poor, demonstrating the difficulty in attempting to predict primary production rates

from chlorophyll concentrations.

Nutrient concentrations for 1999 are presented in Tables 23-26 and Figures 30-33(A-C). Nitrogen (NO_3 +NO_2) (Figures 30-33A) levels showed a steady decrease from March to August. One location of higher nitrogen developed in April in the Southeast portion of the bay near Isle Au Haut and lasted through June. Phosphate (PO_4) (Figures 30-33B) showed a similar decrease over the year. A March high concentration was observed in the far northern reach of the bay, but was not repeated. Silicate (SiO_4) (Figures 30-33C) showed an increase in concentration from March to April, particularly in the western bay and southeast (with the nitrogen peak), and appeared residually in June. Another increase appeared in August, this time in the central and eastern parts of the Bay. Nutrient data from 1998 are presented in Tables 27-30 and Figures 34-37(A-C). A cursory consideration of these data shows distinct differences between the two years, a situation that will be examined fully in the next year.

References

Cullen, J.J., M.R. Lewis, C.O. Davis and R.T. Barber. (1992). Photosynthetic characteristics and estimated growth rates indicate grazing is the proximate control of primary production in the Equatorial Pacific. J. Geophys. Res. 97: 639-654.

Holm-Hansen, O. (1978). Chlorophyll a determination: improvements in methodology. Oikos 30: 438-447.

Lewis, M.R. and J.C. Smith. (1983). A small-volume, short-incubation-time method for measurement of photosynthesis as a function of incident irradiance. Mar. Ecol. Prog. Ser. 13: 99-102.

Murphy, L.S. and E.M. Haugen (1985). The distribution and abundance of phototrophic ultraplankton in the North Atlantic. Limnol. Oceanogr. 30, 47-58.

Parsons, T.R., Y. Maita, and C.M. Lalli. (1984). A manual of chemical and biological methods of seawater analysis. Pergamon Press, 173 p.

Phinney, D.A. and C.S. Yentsch (1991). On the contribution of particles to blue light attenuation in the sea. J. Plank. Res. 13, 143-152.

Platt, T., C.L. Gallegos and W.G. Harrison (1980). Photoinhibition of photosynthesis in natural assemblages of marine phytoplankton. J. Mar. Res. 38: 687-701.

Shumway, S.E., S. Sherman-Caswell, and J.W. Hurst. (1988). Paralytic shellfish poisoning in Maine: Monitoring a monster. J.Shellfish.Res. 7: 643-652.

Strickland, J.D.H. and T.R. Parsons. (1972). A practical handbook of seawater analysis. Fish. Res. Bd. Can. Bull. 167, 310 p.

Whitledge, T.E., D.M. Veidt, S.C. Malloy, C.J. Patton, and C.D. Wirick (1986). Automated Nutrient Analysis in Seawater. Brookhaven National Laboratory Technical Report, Oceanographic Sciences

Div., Dept. of Energy and Environment, Associated Universities, Inc.

Table 1. Station locations for Penobscot Bay cruises. Stations were often occupied in different sequence on cruises, dependent on the tidal cycle, in an effort to avoid sampling the same water parcel repeatedly. As a result, cruise-station numbers could always be used for comparison. Since the original sampling grid was set up using Neal Pettigrew (NP) hydrographic stations, these station numbers were noted for each location for consistent identification.

Station Name (NP#)	Location (Lat. N; Long. W)
1	44 23.85 68 51.78
2	44 24.56 68 53.61
3	44 23.35 68 55.12
4	44 21.40 68 55.80
5	44 19.40 68 56.54
7	44 15.85 68 59.10
9	44 12.10 69 00.30
11	44 08.10 69 00.30
13	44 04.10 69 00.30
14	44 02.10 69 00.30
16	43 58.10 69 00.30
28	43 56.10 68 57.40
30	44 07.40 68 59.00
31	44 09.10 68 57.50
32	44 10.70 68 55.80
33	44 12.20 68 54.20
35	44 16.15 68 52.70
36	44 18.00 68 52.00
38	44 22.00 68 50.85
39	44 16.75 68 49.80
40	44 15.60 68 47.60
42	44 13.10 68 45.60
43	44 12.10 68 45.40
44	44 10.00 68 45.10
45	44 08.00 68 44.80
46	44 06.05 68 44.45
48	44 02.00 68 43.80
50	43 57.90 68 43.40
52	43 56.10 68 46.30
54	43 56.10 68 51.90

Table 2. Vertical distributions of chlorophyll and phaeopigments (chlorophyll degradation products), March 1999, in Penobscot Bay. Chl *a* = chlorophyll; phaeo = phaeophytin

Date & Time	Rockland tide (hrs)	ID	station name	depth(m)	chl a	phaeo
(in ug/liter)						

Table 3. Vertical distributions of chlorophyll and phaeopigments (chlorophyll degradation products), April 1999, in Penobscot Bay.

Date & Time	Rockland tide (hrs)	ID	station name	depth (m)	chl *a* µg 1^{-1}	Phaeo µg 1^{-1}

Table 4. Vertical distributions of chlorophyll and phaeopigments (chlorophyll degradation products), June 1999, in Penobscot Bay.

Rockland tide (hrs)	ID	station name	depth (m)	chl *a* µg 1^{-1}	Phaeo µg 1^{-1}

Table 5. Vertical distributions of chlorophyll and phaeopigments (chlorophyll degradation products), August 1999, in Penobscot Bay.

Date & Time	Rockland tide (hrs)	ID	station name	depth (m)	chl *a* µg 1^{-1}	Phaeo µg 1^{-1}

Table 6. Vertical distributions of chlorophyll, phaeopigments (chlorophyll degradation products), and total suspended solids at phytoplankton/optical properties stations, March 1999, in Penobscot Bay. Chl = chlorophyll in $\mu g\ l^{-1}$; phaeo = phaeophytin in $\mu g\ l^{-1}$; TSS = total suspended solids in $mg\ l^{-1}$.

Date & time	Rockland tide (hrs)	Station name	Depth (m)	Chl $\mu g\ l^{-1}$	Phaeo $\mu g\ l^{-1}$	TSS $mg\ l^{-1}$

Table 7. Vertical distributions of chlorophyll, phaeopigments (chlorophyll degradation products), and total suspended solids at phytoplankton/optical properties stations, April 1999, in Penobscot Bay. Chl = chlorophyll in $\mu g\ l^{-1}$; phaeo = phaeophytin in $\mu g\ l^{-1}$; TSS = total suspended solids in $mg\ l^{-1}$.

Date & time	Rockland tide (hrs)	Station name	Depth (m)	Chl $\mu g\ l^{-1}$	Phaeo $\mu g\ l^{-1}$	TSS $mg\ l^{-1}$

Table 8. Vertical distributions of chlorophyll, phaeopigments (chlorophyll degradation products), and total suspended solids at phytoplankton/optical properties stations, June 1999, in Penobscot Bay. Chl = chlorophyll in $\mu g\ l^{-1}$; phaeo = phaeophytin in $\mu g\ l^{-1}$; TSS = total suspended solids in $mg\ l^{-1}$.

Date & time	Rockland tide (hrs)	Station name	Depth (m)	Chl $\mu g\ l^{-1}$	Phaeo $\mu g\ l^{-1}$	TSS $mg\ l^{-1}$

Table 9. Vertical distributions of chlorophyll, phaeopigments (chlorophyll degradation products), and total suspended solids at phytoplankton/optical properties stations, August 1999, in Penobscot Bay. Chl = chlorophyll in $\mu g\ l^{-1}$; phaeo = phaeophytin in $\mu g\ l^{-1}$; TSS = total suspended solids in $mg\ l^{-1}$.

Date & time	Rockland tide (hrs)	Station name	Depth (m)	Chl $\mu g\ l^{-1}$	Phaeo $\mu g\ l^{-1}$	TSS $mg\ l^{-1}$

Table 10. Vertical distributions of suspended particulate absorption (ap m^{-1}) at selected wavelengths (nm), at phytoplankton/optical properties stations, March 1999, in Penobscot Bay.

Table 11. Vertical distributions of suspended particulate absorption (ap m^{-1}) at selected wavelengths (nm) at phytoplankton/optical properties stations, April 1999, in Penobscot Bay.

Table 12. Vertical distributions of suspended particulate absorption (ap m^{-1}) at selected wavelengths (nm) at phytoplankton/optical properties stations, June 1999, in Penobscot Bay.

Table 13. Vertical distributions of suspended particulate absorption (ap m^{-1}) at selected wavelengths (nm) at phytoplankton/optical properties stations, August 1999, in Penobscot Bay.

Table 14. Vertical distributions of dissolved organic material absorption (ay m^{-1}) at selected wavelengths (nm) at phytoplankton/optical properties stations, March 1999, in Penobscot Bay.

Table 15. Vertical distributions of dissolved organic material absorption (ay m^{-1}) at selected wavelengths (nm) at phytoplankton/optical properties stations, April 1999, in Penobscot Bay.

Table 16. Vertical distributions of dissolved organic material absorption (ay m^{-1}) at selected wavelengths (nm) at phytoplankton/optical properties stations, June 1999, in Penobscot Bay.

Table 17. Vertical distributions of dissolved organic material absorption (ay m^{-1}) at selected wavelengths (nm) at phytoplankton/optical properties stations, August 1999, in Penobscot Bay.

Table 20. Vertical distributions of photosynthetic and irradiance parameters, modeled primary productivity at selected depths, and integrated water column primary productivity at phytoplankton/optical properties stations, March and April 1999, in Penobscot Bay.
Depth (z) is in meters; Ps is in mgC $mgChl^{-1}$ h^{-1}; α and β are in (mgC $mgChl^{-1}$ h^{-1})(μmol $m^{-2}sec^{-1}$)$^{-1}$; Chl is in μg l^{-1}; Io is in 10^{15} quanta $m^{-2}sec^{-1}$; Pz is in mgC $m^{-3}h^{-1}$; Integrated productivity is in mgC $m^{-2}h^{-1}$.

Table 21. Vertical distributions of photosynthetic and irradiance parameters, modeled primary productivity at selected depths, and integrated water column primary productivity at phytoplankton/optical properties stations, June and August 1999, in Penobscot Bay.
Depth (z) is in meters; Ps is in mgC $mgChl^{-1}$ h^{-1}; α and β are in (mgC $mgChl^{-1}$ h^{-1})(μmol $m^{-2}sec^{-1}$)$^{-1}$; Chl is in μg l^{-1}; Io is in 10^{15} quanta $m^{-2}sec^{-1}$; Pz is in mgC $m^{-3}h^{-1}$; Integrated productivity is in mgC $m^{-2}h^{-1}$.

Table 22. Primary production values especially applicable to remote sensing: Surface and average values to one attenuation depth at phytoplankton/optical properties stations, 1999, in Penobscot Bay. P is in mg $C \cdot m^{-3} \cdot hr^{-1}$; 1/k is one attenuation depth.

Table 18. Phytoplankton population density, size structure and biovolume for phytoplankton/optical properties stations in Penobscot Bay, 1999.

Table 19. Phytoplankton cyanobacteria counts for phytoplankton/optical properties stations in Penobscot Bay, 1998.

Table 23. Vertical distributions of nutrients in Penobscot Bay, March 1999. Nitrate plus nitrite (NO3+NO2), phosphate (PO4) and silicate (SiO4) in $\mu g \cdot l^{-1}$.

Table 24. Vertical distributions of nutrients in Penobscot Bay, April 1999. Nitrate plus nitrite (NO3+NO2), phosphate (PO4) and silicate (SiO4) in $\mu g \cdot l^{-1}$.

Table 25. Vertical distributions of nutrients in Penobscot Bay, June 1999. Nitrate plus nitrite (NO3+NO2), phosphate (PO4) and silicate (SiO4) in $\mu g \cdot l^{-1}$.

Table 26. Vertical distributions of nutrients in Penobscot Bay, August 1999. Nitrate plus nitrite (NO3+NO2), phosphate (PO4) and silicate (SiO4) in $\mu g \cdot l^{-1}$.

Table 27. Vertical distributions of nutrients in Penobscot Bay, March 1998. Nitrate plus nitrite (NO3+NO2), phosphate (PO4) and silicate (SiO4) in $\mu g \cdot l^{-1}$.

Table 28. Vertical distributions of nutrients in Penobscot Bay, April 1998. Nitrate plus nitrite (NO3+NO2), phosphate (PO4) and silicate (SiO4) in $\mu g \cdot l^{-1}$.

Table 29. Vertical distributions of nutrients in Penobscot Bay, June 1998. Nitrate plus nitrite (NO3+NO2), phosphate (PO4) and silicate (SiO4) in $\mu g \cdot l^{-1}$.

Table 30. Vertical distributions of nutrients in Penobscot Bay, August 1998. Nitrate plus nitrite (NO3+NO2), phosphate (PO4) and silicate (SiO4) in $\mu g \cdot l^{-1}$.

Figure 1. Distribution of chlorophyll biomass (CHL α , mg $(m^3)^{-1}$) in Penobscot Bay, March 1999. A. Surface (2 m); B. Middle depth (10% light level); C. Bottom (1% light level).

Figure 2. Distribution of chlorophyll biomass (CHL α , mg $(m^3)^{-1}$) in Penobscot Bay, April 1999. A. Surface (2 m); B. Middle depth (10% light level); C. Bottom (1% light level).

Figure 3. Distribution of chlorophyll biomass (CHL α , mg $(m^3)^{-1}$) in Penobscot Bay, June 1999. A. Surface (2 m); B. Middle depth (10% light level); C. Bottom (1% light level).

Figure 4. Distribution of chlorophyll biomass (CHL-α , mg $(m^3)^{-1}$) in Penobscot Bay, August 1999. A. Surface (2 m); B. Middle depth (10% light level); C. Bottom (1% light level).

Figure 5. Location of phytoplankton/optical properties stations in Penobscot Bay.

Figure 24. Example of photosynthesis-irradiance relationships in stratified, light limited environment: photosynthetron curves from three light-depths, station NP42, Penobscot Bay, August 1999.

Figure 25. Example of photosynthesis-irradiance (PE) relationships in a stratified, light limited environment. A. PE relationship; B. light attenuation; C = calculated productivity; D = modeled productivity. Data presented here are from St. NP13, August 1999 in Penobscot Bay. Surf = 2 m; mid = 10% light level; deep = 1% light level. P = chlorophyll specific photosynthetic rate ($gCgChl^{-1}h^{-1}$) vs. irradiance ($\mu mol\ m^{-2}sec^{-1}$) (A and B); productivity P = $mgC\ m^{-3}h^{-1}$; z = depth (m) (C and D).

Figure 26. Example of photosynthesis-irradiance relationships in stratified, non-light limited environment: photosynthetron curves from three light-depths, station NP33, Penobscot Bay, June 1999.

Figure 27. Example of photosynthesis-irradiance (PE) relationships in a stratified, non-light limited environment. A. PE relationship; B. light attenuation; C = calculated productivity; D = modeled productivity. Data presented here are from St. NP33, June 1999 in Penobscot Bay. Surf = 2 m; mid = 10% light level; deep = 1% light level. P = chlorophyll specific photosynthetic rate ($gCgChl^{-1}h^{-1}$) vs. irradiance ($\mu mol\ m^{-2}sec^{-1}$) (A and B); productivity P = $mgC\ m^{-3}h^{-1}$; z = depth (m) (C and D).

Figure 22. Example of photosynthesis-irradiance relationships in well-mixed environment: photosynthetron curves from three light-depths, station NP42, Penobscot Bay, April 1999.

Figure 23. Example of photosynthesis-irradiance (PE) relationships in a well-mixed environment. A. PE relationship; B. light attenuation; C = calculated productivity; D = modeled productivity. Data presented here are from St. NP13, April 1999 in Penobscot Bay. Surf = 2 m; mid = 10% light level; deep = 1% light level. P = chlorophyll specific photosynthetic rate ($gCgChl^{-1}h^{-1}$) vs. irradiance ($\mu mol\ m^{-2}sec^{-1}$) (A and B); productivity P = $mgC\ m^{-3}h^{-1}$; z = depth (m) (C and D).

Figure 6. Comparison of particulate absorption at 400 nm (ap (400)) with cumulative concentrations of total suspended solids (TSS) and chlorophyll pigments (Chl) at phytoplankton/optical properties stations in Penobscot Bay, March 1999

Figure 7. Comparison of particulate absorption at 400 nm (ap (400)) with cumulative concentrations of total suspended solids (TSS) and chlorophyll pigments (Chl) at phytoplankton/optical properties stations in Penobscot Bay, April 1999

Figure 8. Comparison of particulate absorption at 400 nm (ap (400)) with cumulative concentrations of total suspended solids (TSS) and chlorophyll pigments (Chl) at phytoplankton/optical properties stations in Penobscot Bay, June 1999

Figure 9. Comparison of particulate absorption at 400 nm (ap (400)) with cumulative concentrations of total suspended solids (TSS) and chlorophyll pigments (Chl) at phytoplankton/optical properties stations

in Penobscot Bay, August 1999

Figure 10. Comparison of particulate absorption at 400 nm (ap (400)) with cumulative concentrations of total suspended solids (TSS) and chlorophyll pigments (Chl) at phytoplankton/optical properties stations in Penobscot Bay, all cruises 1999.

Figure 11. Comparison of particulate absorption at 670 nm (ap (670)) with concentrations of chlorophyll pigments (Chl) at phytoplankton/optical properties stations in Penobscot Bay, March 1999.

Figure 12. Comparison of particulate absorption at 670 nm (ap (670)) with concentrations of chlorophyll pigments (Chl) at phytoplankton/optical properties stations in Penobscot Bay, April 1999.

Figure 13. Comparison of particulate absorption at 670 nm (ap (670)) with concentrations of chlorophyll pigments (Chl) at phytoplankton/optical properties stations in Penobscot Bay, June 1999.

Figure 14. Comparison of particulate absorption at 670 nm (ap (670)) with concentrations of chlorophyll pigments (Chl) at phytoplankton/optical properties stations in Penobscot Bay, August 1999.

Figure 15. Comparison of particulate absorption at 670 nm (ap (670)) with concentrations of chlorophyll pigments (Chl) at phytoplankton/optical properties stations in Penobscot Bay, all cruises 1999.

Figure 16. Phytoplankton Biovolume comparisons at phytoplankton/optics stations, March 1999, Penobscot Bay. Biovolume is calculated from average volumes for each size class of algae and is expressed as $(\mu m^3 \cdot 10^5) \cdot ml^{-1}$.

Figure 17. Phytoplankton Biovolume comparisons at phytoplankton/optics stations, April 1999, Penobscot Bay. Biovolume is calculated from average volumes for each size class of algae and is expressed as $(\mu m^3 \cdot 10^5) \cdot ml^{-1}$.

Figure 18. Phytoplankton Biovolume comparisons at phytoplankton/optics stations, June 1999, Penobscot Bay. Biovolume is calculated from average volumes for each size class of algae and is expressed as $(\mu m^3 \cdot 10^5) \cdot ml^{-1}$.

Figure 19. Phytoplankton Biovolume comparisons at phytoplankton/optics stations, August 1999, Penobscot Bay. Biovolume is calculated from average volumes for each size class of algae and is expressed as $(\mu m^3 \cdot 10^5) \cdot ml^{-1}$.

Figure 20. Cyanobacteria population comparisons at phytoplankton/optics stations, Penobscot Bay, 1999.

Figure 21. Cyanobacteria populations comparisons at phytoplankton/optics stations, Penobscot Bay, 1998.

Figure 28. Comparison of seasonal integrated water column primary productivity measurements at phytoplankton/optical properties stations in Penobscot Bay, all cruises, 1999. 03ip = March 1999; 04ip = April 1999; 06ip = June 1999; 08ip = August 1999.

Figure 29. Comparison of primary productivity measurements (Pz) (mgC mg $chl^{-1}h^{-1}$) with chlorophyll biomass (Chl) (µg l^{-1}) at phytoplankton/optical properties stations in Penobscot Bay, all cruises, all depths, 1999.

Figure 30. Distribution of Nitrate plus Nitrate concentrations (µM) in Penobscot Bay, March 1999.

Figure 31. Distribution of Nitrate plus Nitrate concentrations (µM) in Penobscot Bay, April 1999.

Figure 32. Distribution of Nitrate plus Nitrate concentrations (µM) in Penobscot Bay, June 1999.

Figure 33. Distribution of Nitrate plus Nitrate concentrations (µM) in Penobscot Bay, August 1999.

Figure 34. Distribution of Phosphate concentrations (µM) in Penobscot Bay, March 1999.

Figure 35. Distribution of Phosphate concentrations (µM) in Penobscot Bay, April 1999.

Figure 36. Distribution of Phosphate concentrations (µM) in Penobscot Bay, June 1999.

Figure 37. Distribution of Phosphate concentrations (µM) in Penobscot Bay, August 1999.

Figure 38. Distribution of Silicate concentrations (µM) in Penobscot Bay, March 1999.

Figure 39. Distribution of Silicate concentrations (µM) in Penobscot Bay, April 1999.

Figure 40. Distribution of Silicate concentrations (µM) in Penobscot Bay, June 1999.

Figure 41. Distribution of Silicate concentrations (µM) in Penobscot Bay, August 1999.

Figure 42. Distribution of Nitrate plus Nitrate concentrations (µM) in Penobscot Bay, March 1998.

Figure 43. Distribution of Nitrate plus Nitrate concentrations (µM) in Penobscot Bay, April 1998.

Figure 44. Distribution of Nitrate plus Nitrate concentrations (µM) in Penobscot Bay, June 1998.

Figure 45. Distribution of Nitrate plus Nitrate concentrations (µM) in Penobscot Bay, August 1998.

Figure 46. Distribution of Phosphate concentrations (µM) in Penobscot Bay, March 1998.

Figure 47. Distribution of Phosphate concentrations (µM) in Penobscot Bay, April 1998.