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# Satellite detection of phytoplankton export from the mid-Atlantic Bight during the 1979 spring bloom

by

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# ABSTRACT

Analysis of CZCS imagery confirms shipboard and in situ moored fluorometer observations of resuspension of near-bottom chlorophyll within surface waters (1-10 m) by northwesterly wind events in the mid-Atlantic Bight. As much as 8-16 µg chl $\ell^{-1}$ are found during these wind events from March to May, with a seasonal increase of algal biomass until onset of stratification of the water column. Rapid sinking or downwelling apparently occurs after subsequent wind events, however, such that the predominant surface chlorophyll pattern is ~0.5-1.5 µg $\ell^{-1}$ over the continental shelf during most of the spring bloom. Perhaps half of the chlorophyll increase observed by satellite during a wind resuspension event represents in situ production during that 4-5 day interval, with the remainder attributed to accumulation of algal biomass previously produced and temporarily stored within near-bottom water. Our present calculations suggest that about 10% of the primary production of the spring bloom may be exported as ungrazed phytoplankton carbon from mid-Atlantic shelf waters to those of the continental slope.

# INTRODUCTION

Although Francis Richards is mainly remembered for his work on dissolved nutrients and gasses in the sea, his scientific "debut" concerned the characterization of phytoplankton populations by analysis of their pigments (RICHARDS, 1952; RICHARDS and THOMPSON, 1952). In a volume dedicated to his memory 35 years later, it is appropriate to consider the dynamics of a 1979 spring bloom from similar measurements of algal pigments, but from a radiometer on a satellite rather than from a spectrophotometer in the laboratory.

At traditional sampling periods of 25-30 days for a research vessel to steam over the mid-Atlantic Bight from Cape Hatteras to Georges Bank, algal pigment or biomass data relevant to the time scale (hours to days) of phytoplankton processes are hopelessly aliased. Wind events lead to a redistribution of phytoplankton biomass (WALSH et al., 1978) every 3-5 days. This situation confounds attempts to couple the long-term estimates of standing stocks with daily shipboard rate estimates (photosynthesis, nutrient uptake, grazing, or sinking) to compute fluxes of elements through the marine food web. With the launch of the Coastal Zone Color Scanner (CZCS) aboard the NIMBUS-7 satellite during October 1978, however, subsequent algorithm development and data reduction have generated CZCS time series of algal biomass at much faster sampling rates. We can now begin to address questions about the amount, transport, and fate of the residues of coastal primary production, detected by the CZCS within shelf (SMITH et al., 1982; SHANNON et al., 1984; ABBOTT and ZION, 1985) and adjacent slope waters (HOLLIGAN et al., 1983; BROWN et al., 1985).

With a sun-synchronous, polar orbit at an altitude of 955 km, the CZCS scans the ocean surface at 485 swaths minute$^{-1}$ in 6 spectral bands (5 visible and 1 infrared), passing over the mid-Atlantic Bight, for example, in less than 2 minutes with a spatial resolution of 800 m for each pixel of data. Clouds preclude a daily sampling rate, such that 45 "usable" CZCS images are available from January to June 1979. These data matrices constitute a non-stationary time series of the near surface color of the mid-Atlantic Bight during the 1979 spring bloom, when numerous shipboard and moored current meter observations were collected by us and other workers.

The physical theory of remote sensing of ocean color, the algorithms used to remove the effects of Rayleigh and aerosol scattering of solar irradiance in the atmosphere, and the methods of estimating phytoplankton pigment from the reflected irradiance in the blue and green regions of the spectrum have been discussed recently by GORDON and MOREL (1983). In terms of the relative amount of penetration of surface solar irradiance, the first attenuation depth, sensed by the CZCS, varies from ~1 to 10 m as a function of algal biomass and other suspended matter. It represents the 37% light depth in the water column, while the bottom of the euphotic zone (1% light depth) is 4.61 attenuation depths, regardless of corrections for albedo, photosynthetically active irradiance, and spectral filtering of blue-green light with depth. At 50 stations during unstratified water column conditions of the mid-Atlantic spring bloom during April 1982, the near-surface chlorophyll concentrations, integrated to the first attenuation depth, had an $r^2$ of 0.86 with the chlorophyll

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integral of the whole euphotic zone (BROWN et al., 1985). A 1979 time series of algal pigments, compiled with CZCS imagery in the mid-Atlantic Bight, may thus reflect temporal and areal changes of phytoplankton biomass over most of the water column rather than just vertical micro-structure within the first attenuation depth.

A previous study of other regions in the central north Pacific, Sargasso Sea, Gulf of Mexico, Gulf of California, and Californian coastal waters yielded a similar $r^2$ of 0.91 for variation of chlorophyll biomass between the 100%-37% light levels and the entire euphotic zone (SMITH and BAKER, 1978). Within the Benguela Current, an $r^2$ of 0.98 was obtained for surface chlorophyll and the mean value of the euphotic zone (SHANNON et al., 1984). Additional analysis of 850 vertical chlorophyll profiles from diverse Peruvian and Canadian waters (PLATT and HERMAN, 1983) suggests that both the chlorophyll and associated primary production, potentially sensed by the CZCS, are "surprisingly constant proportions of the total chlorophyll and production integrals," respectively 2.9-5.2% and 6.1-10.7%. To provide a seasonal and spatial context for the shelf export of phytoplankton carbon from the mid-Atlantic Bight (WALSH et al., 1981; WALSH et al., 1985), we present four time series of CZCS images obtained during March, April, May, and June of 1979.

## METHODS

Present CZCS algorithms do not distinguish between chlorophyll a and phaeophytin a in derivation of the estimated phytoplankton pigment from ocean color (GORDON and MOREL, 1983). The average

phaeophytin concentration within 100 samples from a March 1979 cruise to the mid-Atlantic Bight, however, was only 11% of the sum of phaeophytin and chlorophyll content as determined by acetone extraction in the fluorometric method (YENTSCH and MENZEL, 1963). Within the inherent error of the satellite estimate of pigment (GORDON et al., 1983), such an overestimate of chlorophyll a would be small, and we thus compare the satellite-derived estimate of "chlorophyll-like" and chlorophyll pigments with the shipboard estimates of chlorophyll a.

The pigment estimate at each CZCS pixel was navigated and averaged over a 5 nm grid (SASC, 1984), such that each data point in our analysis represents the mean of about 100 color measurements. Extracted chlorophyll a data were obtained from cruises of the R/V Albatross IV, Edgerton, Eastward, Oceanus, Kelez, Athena II, Delaware II, Advance II, Julius Nelson, Onrust, Kyma, Pathfinder, Shang Wheeler, Sub Sig II, Short Snort, and Lady Donna during March-July 1979. Additional $^{14}$C, light penetration, C/chl, moored fluorometer, and hydrographic data were obtained on these and other cruises between 1973 and 1984 (WALSH et al., 1978; HAZELWORTH AND BERBERIAN, 1979; THOMAS, 1981; MARRA et al., 1982; MALONE et al., 1983; O'REILLY and BUSCH, 1984; WALSH et al., 1986a).

Our reduced pigment data sets from the CZCS images still consisted of more than 4,500 grid points for each scene. Only 14 concurrent moored time series of the water motion (Fig. 1) were available, however. We thus explored the temporal change of simulated currents at about 6,000 grid points on the mid-Atlantic shelf
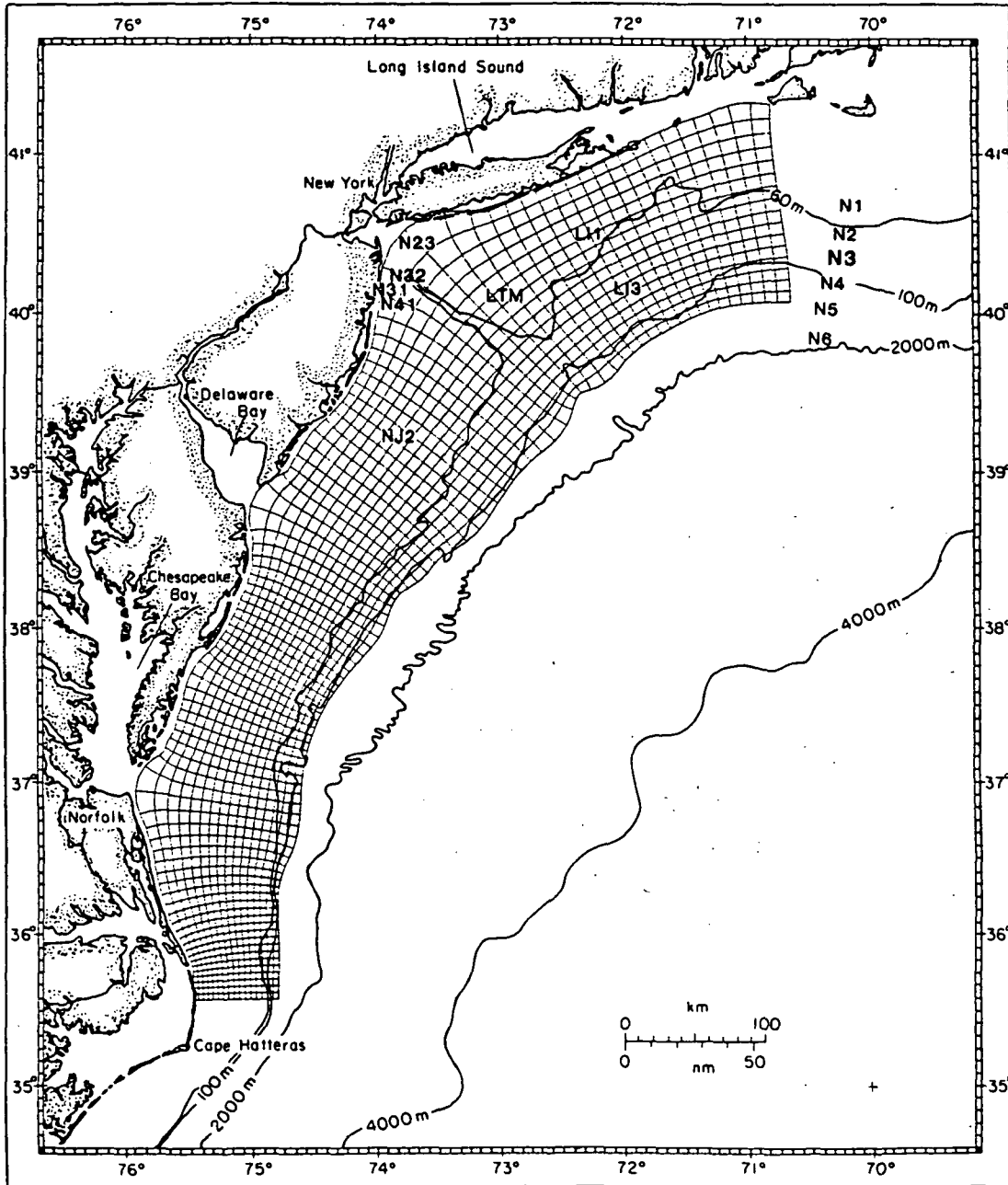
Figure 1.  The spatial grid of a numerical model for comparison of
simulated currents with both WHOI/NMFS current meter
observations (N1 - N6) at the upstream boundary and AOML
observations (LI1, LI3, LTM, N23, N31, N32, N41, NJ2) in
the New York Bight.

(Fig. 1).  A previous model (HOPKINS and DIETERLE, 1983) of the

steady, depth-integrated flow from a vorticity balance of the linear,

barotropic equations of motion was applied to April 1979 wind and

current fields, observed respectively at John F. Kennedy airport and

across the shelf, south of Marthas Vineyard (BEARDSLEY et al., 1983).

The sea elevation at the upstream boundary of the grid (Fig. 1)

was computed from the observed currents; at the offshore boundary it

was set to a constant 5 cm, i.e., mass exchange was confined to

surface and bottom Ekman layers at the shelf-break; and at the

downstream boundary, the long-shore gradient of sea elevation was set

to zero (HSUEH, 1980).  For each steady-state solution, the mean wind

forcing was entered in the model as the alongshore component of the

wind stress at the land boundary, where only long-shore transport of

water occurred.  The simulated currents at various depths were

compared with AOML current meter observations (MAYER et al., 1982)

near 8 interior grid points of the model (Fig. 1) by analytical

solution (HOPKINS and SLATEST, 1985) of the depth-dependent Ekman

equations.

## RESULTS

a)  <u>March 1979</u>

The surface chlorophyll observations taken concurrently along

cruise tracks of the R/V <u>Albatross IV</u>, <u>Edgerton</u>, and <u>Eastward</u> during

16-26 March 1979 (Fig. 2a) suggest separate areas of high chlorophyll,

and presumably high primary production, within slope waters, at the

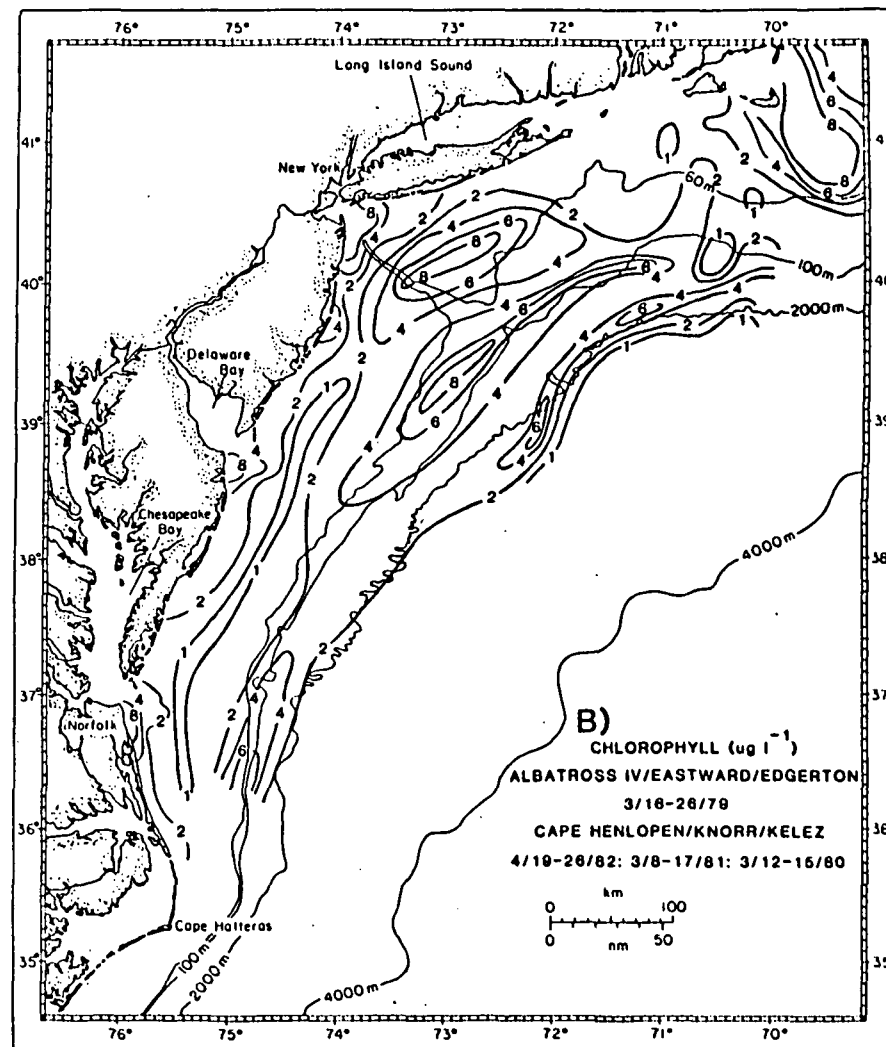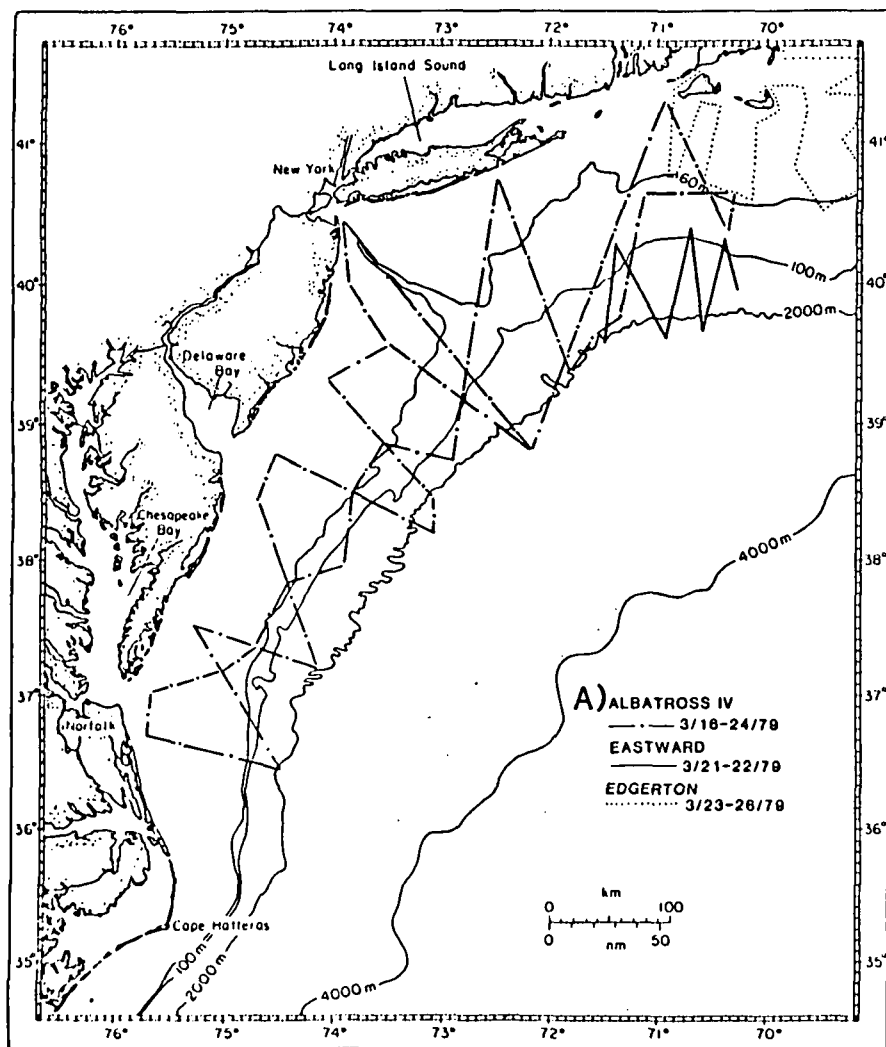shelf-break, and at mid-shelf (Fig. 2b).  The >8 µg chl $\ell^{-1}$ surface

Figure 2.    Cruise tracks A) of R/V Albatross IV, Eastward, and
Edgerton during 16-26 March 1979, and B) the chlorophyll
($\mu$g $\ell^{-1}$) composite of the distribution of phytoplankton
biomass during 16-26 March 1979 as well as during
12-15 March 1980 (Kelez), 8-17 March 1981 (Knorr), and
19-26 April 1982 (Cape Henlopen).

observations (Fig. 2b) near the mouths of the Hudson, Delaware, and Chesapeake estuaries were obtained on other cruises of the Cape Henlopen, Knorr and Kelez during 1980-82. These latter data are presented for comparison with the CZCS observations at the mouth of the estuaries. They suggest that values of $>8$ µg chl $\ell^{-1}$ are correct in each March image (Figs. 3a-3d) and that turbid waters do not affect the accuracy of the CZCS algorithm (VIOLLIER and STURM, 1984) within the mid-Atlantic Bight.

Based on previous shipboard data from the spring blooms of 1975-77 (WALSH et al., 1978), we thought such high chlorophyll concentrations at mid-shelf in 1979 (Fig. 2b) were a quasi-permanent feature of the spring bloom within this shelf ecosystem. Except for the estuarine plumes, the CZCS images for 18 March 1979 (Fig. 3a) and 23 March 1979 (Fig. 3d) instead indicate ubiquitous chlorophyll concentrations of 0.5-1.0 µg $\ell^{-1}$ within shelf and slope waters. Such values are an order of magnitude less than shipboard data collected in March 1975, 1977, and 1979; sampling at the shelf-break nine times between 27 March - 9 April 1975, for example, we did not find such low chlorophyll concentrations (WALSH et al., 1978). During 20 March 1979 (Fig. 3b) and 21 March 1979 (Fig. 3c), however, the CZCS images displayed the "expected" chlorophyll values of 8-10 µg chl $\ell^{-1}$ at mid-shelf.

Analysis of ship positions (Fig. 2a) during the four CZCS overflights suggests that the CZCS estimates of chlorophyll variability are correct in their depiction of an order of magnitude increase of chlorophyll over one day (20-21 March 1979), and a similar
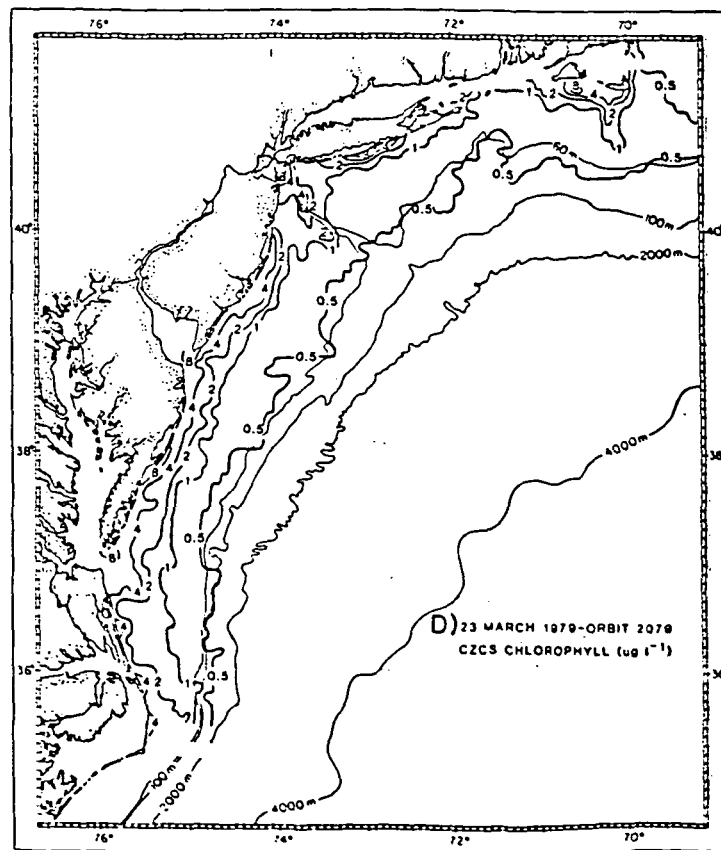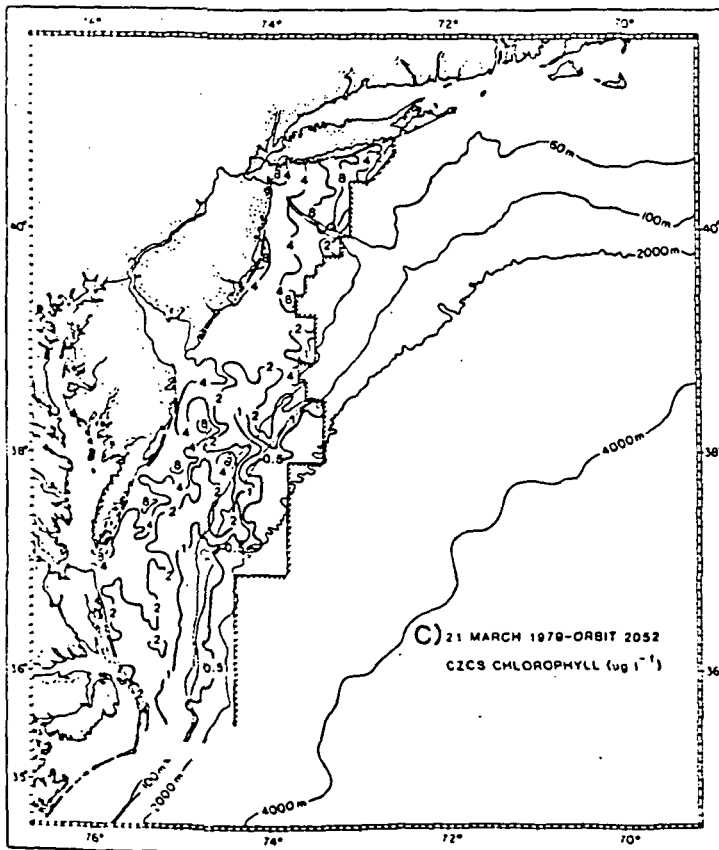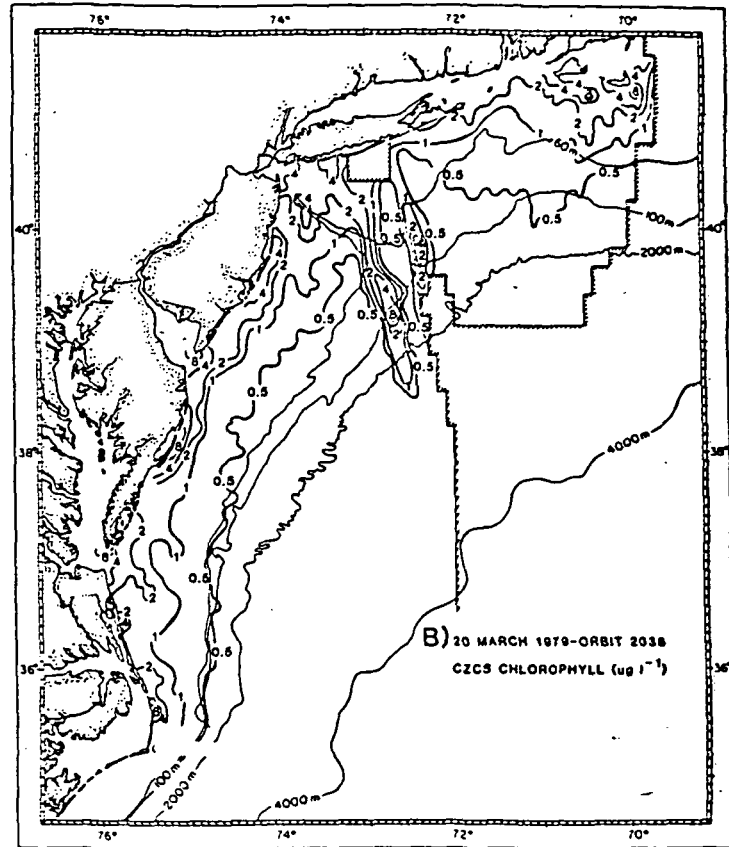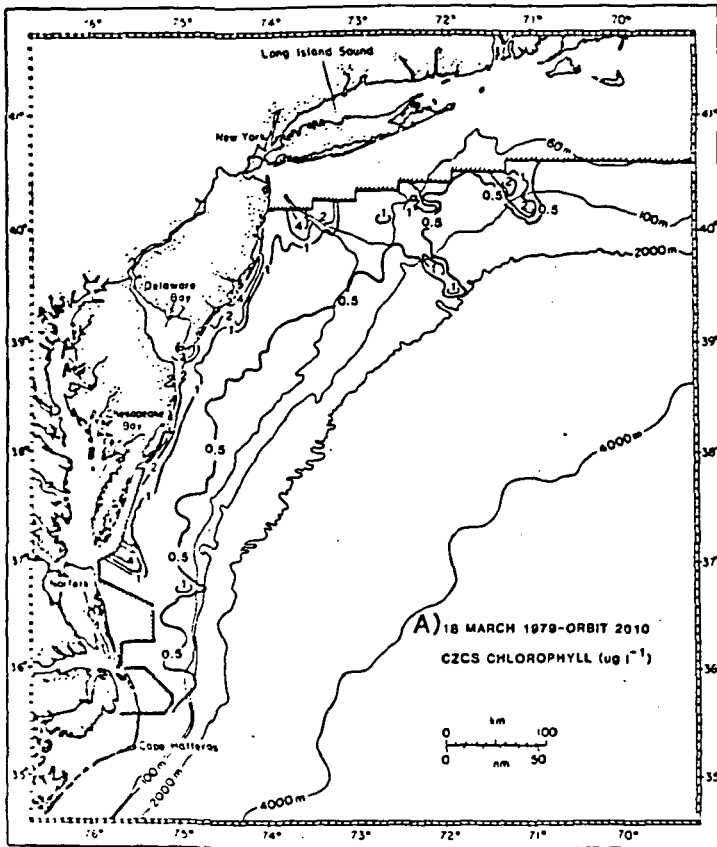
Figure 3. The CZCS estimate of chlorophyll distribution during
A) 18 March 1979, B) 20 March 1979, C) 21 March 1979, and
D) 23 March 1979.

decline over two days (21-23 March 1979). Edgerton remained in the
Nantucket Shoals area (Fig. 2a), where the satellite chlorophyll
gradients did not change significantly on 20 and 23 March (Figs. 3b
and 3d), while Eastward was obscured by clouds on 21 March, and
satellite data are not available for 22 March. Fortunately,
Albatross IV departed Woods Hole and ran a grid of stations southward,
such that the ship was near the New Jersey coast on 18 March, near the
Virginia coast on 20 March, at the shelf-break south of Maryland on
21 March, and at the shelf-break south of Long Island on 23 March
(Fig. 2a). These shipboard data coincided each day with the CZCS
estimates of chlorophyll (Fig. 3) at the appropriate grid location and
time, indicating that longshore continuous bands of high chlorophyll,
as contoured from the ship data (Fig. 2b), were not always present on
the outer shelf. The shipboard data appear to be badly aliased, even
on a sampling time scale of eight days.

At a daily growth rate of 0.4 day$^{-1}$ in March 1979 (Table 1),
i.e., a population doubling time of ~2 days, the phytoplankton
increase of biomass from 0.5 to 8.0 µg chl $\ell^{-1}$ at mid-shelf between 20
and 21 March (Figs. 3b-3c) cannot be due to just in situ primary
production. Such an increment of pigment would have taken at least a
week, with no consumption of the algal populations by herbivores or
bacterioplankton. Resuspension of a chlorophyll concentration of
~11 µg $\ell^{-1}$ within the bottom 10 m of the water column (e.g.,
Figures 4a and 4c) at the 30 m isobath, and mixing of it with 0.5 µg
chl $\ell^{-1}$ within the upper 20 m, would yield a mean concentration of
4 µg chl $\ell^{-1}$, after vertical homogenization by a wind event. A

Table 1. Seasonal variation of phytoplankton growth rate within the mid-Atlantic Bight during 10 "Wind Event" cruises

| Date | Sample Size (n) | Bottom Depth (m) | Euphotic Zone (m) | Chlorophyll Biomass ($\mu g \ \ell^{-1}$) | Primary Production ($g \ C \ m^{-2} \ day^{-1}$) | Growth Rate ($day^{-1}$) |
|---|---|---|---|---|---|---|
| 8-17 March 1981 | 7 | 22.5 | 10.0 | 5.6 | 0.78 | 0.31 |
| 17-24 March 1979 | 7 | 73.5 | 23.3 | 3.7 | 1.38 | 0.36 |
| 23-25 March 1976 | 3 | 58.0 | 21.0 | 5.0 | 2.70 | 0.57 |
| 27 March-7 April 1975 | 6 | 98.4 | 23.0 | 6.3 | 2.96 | 0.45 |
| 31 March 5 April 1978 | 5 | 69.4 | 31.4 | 3.3 | 1.83 | 0.40 |
| 4-8 April 1978 | 4 | 61.0 | 29.0 | 2.2 | 1.12 | 0.39 |
| 1-6 May 1979 | 5 | 44.2 | 27.6 | 0.5 | 0.19 | 0.31 |
| 5-22 August 1977 | 6 | 48.5 | 28.7 | 1.4 | 0.94 | 0.53 |
| 23 Aug.-10 Sept. 1980 | 6 | 93.5 | 43.7 | 0.6 | 0.29 | 0.25 |
| 12-16 October 1978 | 4 | 58.3 | 25.8 | 1.0 | 0.59 | 0.51 |
| Total = | 53 | | Average = | 2.96 | 1.28 | 0.41* |

* With C/chl a ratio of 45/1

CHLOROPHYLL (µg l⁻¹)

TEMPERATURE (°C)

0041 (3/23/79)

0927 (3/24/79)

0.6 µg l⁻¹

17.2 µg l⁻¹

A) PHYTOPLANKTON -50m

3/24

3/23

B) HABITAT -50m

CHLOROPHYLL (µg l⁻¹)

TEMPERATURE (°C)

0444 (3/24/79)

0243 (3/23/79)

4.1 µg l⁻¹

10.9 µg l⁻¹

C) PHYTOPLANKTON -60m
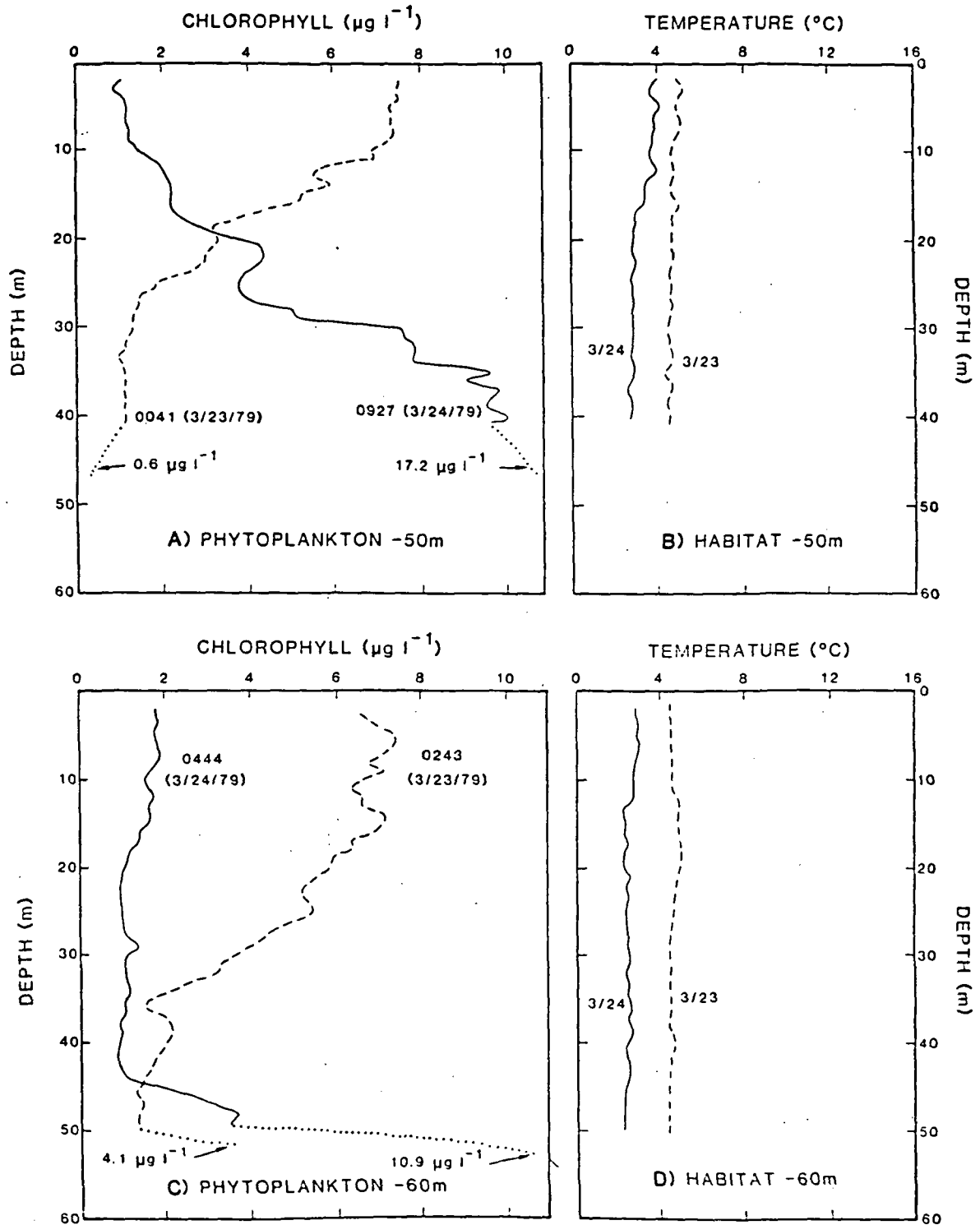
3/24

3/23

D) HABITAT -60m

Figure 4.   The continuous, vertical distribution of A) chlorophyll and
B) temperature at the 50 m isobath off the coast of Long
Island (23 March 1979) and Nantucket Island (24 March
1979), and of C) chlorophyll and D) temperature at the 60 m
isobath off the coast of Long Island (23 March 1979) and
Marthas Vineyard (24 March 1979).

doubling of this phytoplankton abundance over two days would then yield a euphotic zone biomass of ~8 µg chl $\ell^{-1}$, similar to the maximum surface values detected by both the March CZCS images (Fig. 3) and the vertical profiles (Fig. 4) taken on the _Albatross IV_ cruise.

Zooplankton grazing rates in March are ~10% of the daily primary production in the mid-Atlantic Bight (WALSH et al., 1978; DAGG and TURNER, 1982; S. SMITH, personal communication), such that the tenfold decline of pigment between 21 and 23 March (Figs. 3c, 3d) cannot be attributed to consumption by herbivores. A comparison of vertical profiles of chlorophyll at the 50 m (Fig. 4a) and 60 m (Fig. 4c) isobaths on 23 and 24 March 1979 corroborate the surface decline of algal biomass measured by the CZCS between 21 March (Fig. 3c) and 23 March (Fig. 3d). The water column was isothermal on both 23 and 24 March (Figs. 4b and 4c), while surface maxima of chlorophyll may have become near-bottom maxima the following day, implying rapid sinking of diatoms and/or entrainment of the micro-algae within downwelling water at a rate of at least 20 m day$^{-1}$.

Using a one-dimensional model (NIILER, 1975) of a wind-induced mixed layer, WROBLEWSKI and RICHMAN (1986) computed a vertical eddy coefficient, $k_z$, of 68 m$^2$ hr$^{-1}$ over a 44 m deep mixed layer of weak vertical stratification (0.35 $\sigma_t$ 50 m$^{-1}$), after 8.5 hr of a 10 m sec$^{-1}$ wind forcing. During February-May 1979-82, a wind event $\geq$ 10 m sec$^{-1}$ occurred about every 8 days in the mid-Atlantic Bight, i.e., once per week, with 80% of these events originating from the northwest quadrant, 10% from the northeast, and the remainder from the south quadrants. At 27 shelf stations during 16-24 March 1979, the vertical
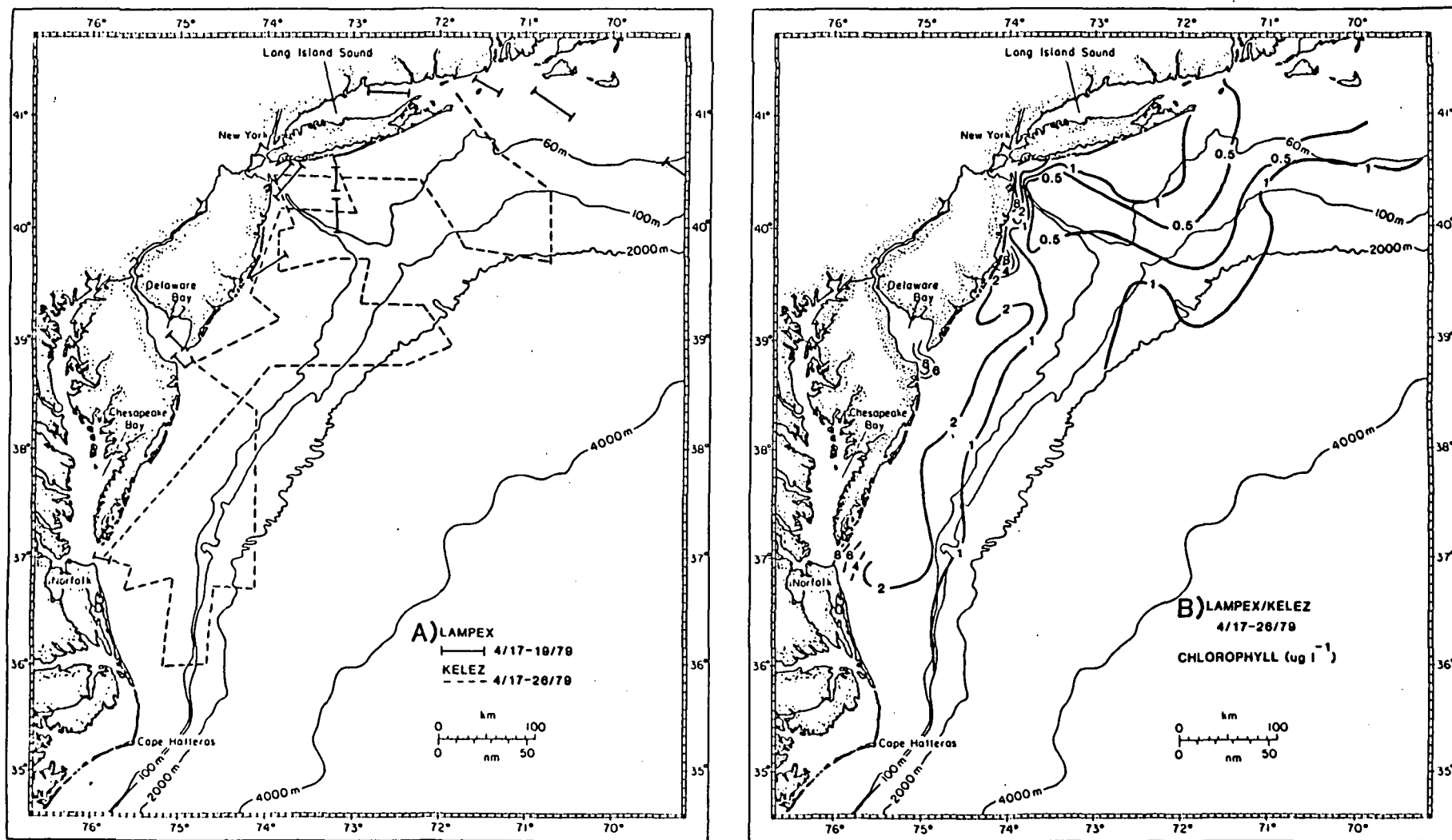
Figure 5. Cruise tracks A) of the R/V Kelez, Advance II, Julius Nelson, Onrust, Kyma, Pathfinder, Shang Wheeler, Sub Sig II, Short Snort, and Lady Donna and B) the chlorophyll ($\mu g\ \ell^{-1}$) composite of the distribution of phytoplankton biomass during 17-26 April 1979.

density gradient was a mean 0.33 $\sigma_t$ 52 m$^{-1}$ and the surface mixed layer

appeared to extend at least 40-50 m down into the water column

(Fig. 4). Over a 44 m surface mixed layer and an appropriate gradient

of algal biomass, the equivalent vertical displacement rate, from such

a $k_z$ of 68 m$^2$ hr$^{-1}$, is 37.1 m day$^{-1}$, i.e., the inferred downward

transfer of chlorophyll in Fig. 4 is a feasible scenario.

The 24 March 1979 station at the 60 m isobath was occupied about

140 km to the east of that on the previous day, i.e., southwest of

Marthas Vineyard, however, while the second station at the 50 m

isobath was taken about 210 km to the east, or southwest of Nantucket

Island (Fig. 1). Although there was no longshore gradient in surface

chlorophyll on 23 March 1979 (Fig. 3d) at the 50-60 m isobaths, it is

possible that a longshore gradient in near-bottom chlorophyll extended

from Nantucket Shoals to the southwest. Nevertheless, a longshore

transect at the 60-70 m isobaths in March 1978 between Georges Bank

and the Hudson Canyon (WALSH et al., 1986b) showed as much near-bottom

chlorophyll off New Jersey as off Marthas Vineyard. Furthermore,

23 µg chl $\ell^{-1}$ were found near-bottom off New Jersey at the 22 m

isobath during 18 March 1979, i.e., just before the apparent

resuspension event (Fig. 3). Since AOML current meter data were not

available for March 1979, we defer discussion of the physical movement

of pigment to the April 1979 time series.


b)  April 1979

Rapid resuspension, offshore transport, and sinking/downwelling

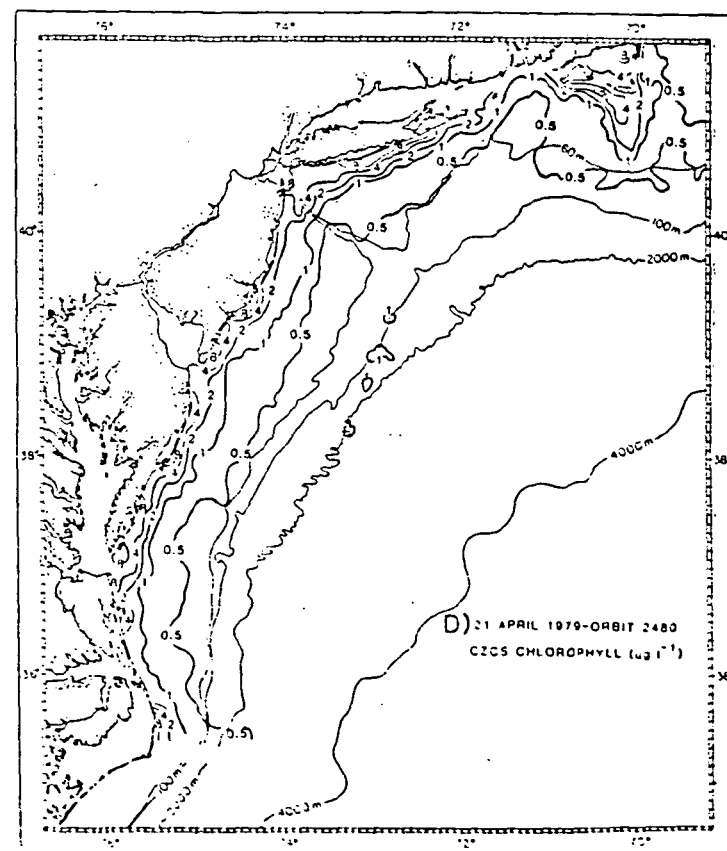events of phytoplankton can also be inferred from the CZCS time series
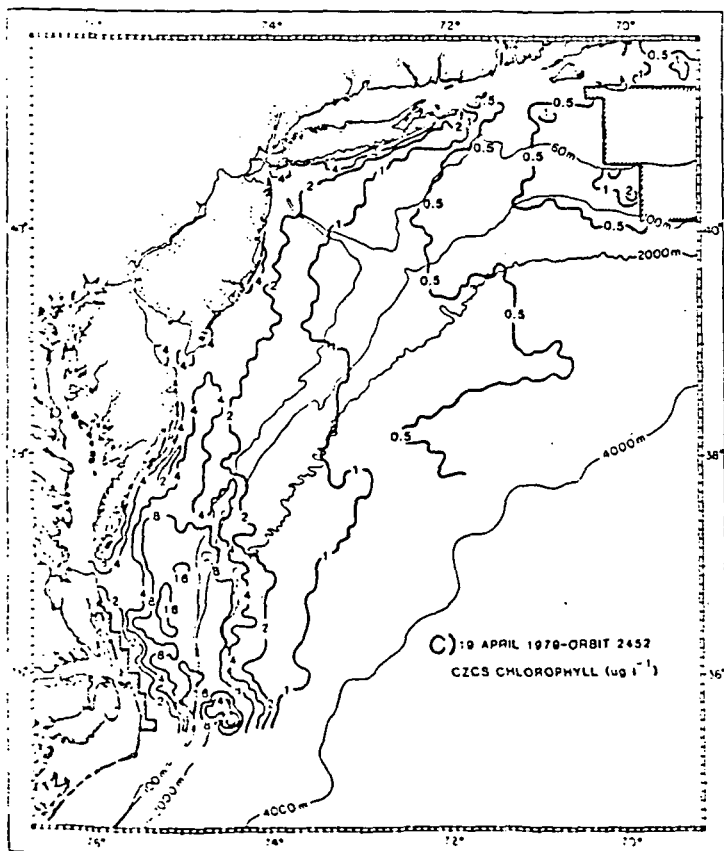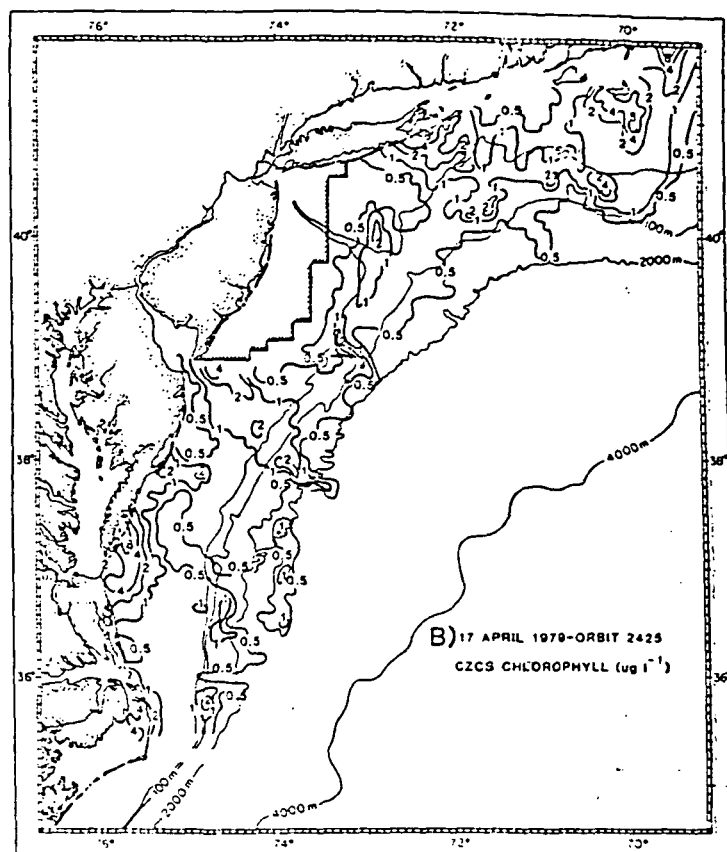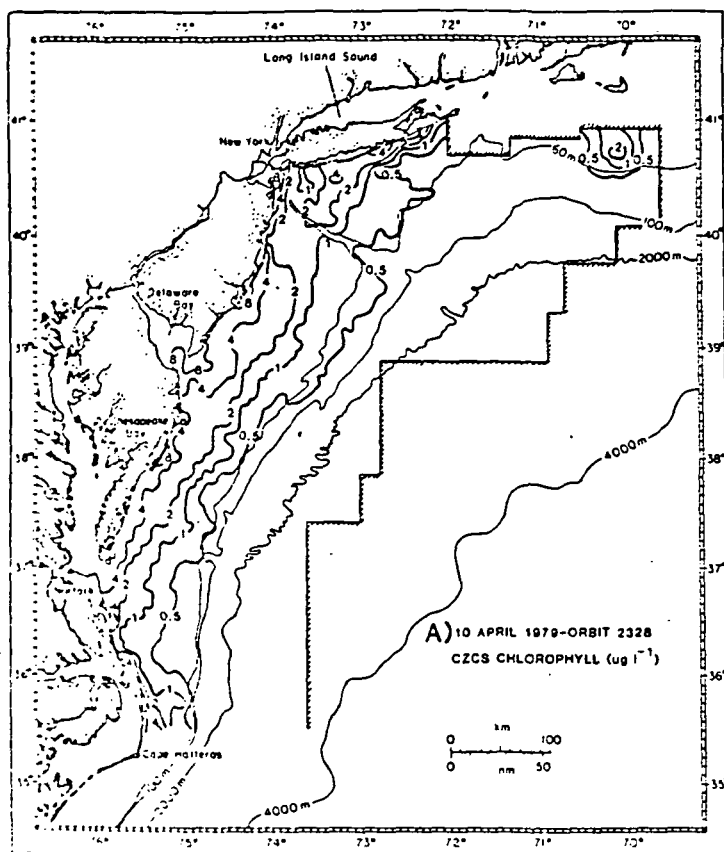
Figure 6.    The CZCS estimate of chlorophyll distribution during
             A) 10 April 1979, B) 17 April 1979, C) 19 April 1979, and
             D) 21 April 1979.

in April 1979. During 17-19 April 1979, ten ships provided ground-truth chlorophyll measurements in the mid-Atlantic Bight (Fig. 5) as part of the LAMPEX experiment for calibration of aircraft and satellite overflights (THOMAS, 1981). The R/V Kelez occupied stations in the apex of the New York Bight during 17-19 April 1979, and most of the chlorophyll observations on these days were taken within 25 km of the coast, south of Hudson Canyon. The rest of the Kelez cruise track (Fig. 5a) was performed after 19 April 1979. Consequently, the shipboard chlorophyll composite (Fig. 5b) is for near-shore waters during the 17 April (Fig. 6b) and 19 April (Fig. 6c) CZCS overflights, but for offshore waters during the 21 April overflight (Fig. 6d).

The high chlorophyll concentrations of the coastal zone (<20 m depth) and the low chlorophyll at the 60-100 m isobaths, southeast of Nantucket Island, measured aboard ships on 17-19 April (Fig. 5b) match quite well these parts of the two CZCS images on the same days (Figs. 6b and 6c). However, the major mid-shelf resuspension of near-bottom chlorophyll, south of Delaware Bay, on 19 April (Fig. 6c) and subsequent disappearance by 21 April (Fig. 6d) remained undetected (Fig. 5b) by the conventional shipboard surveys, since the research vessels were not present during this event.

Figures 6a-d represent various chlorophyll patterns within an upwelling circulation induced by northwesterly and southerly winds. The 10 April 1979 CZCS image of chlorophyll (Fig. 6a) exhibits, for example, a decline of algal biomass with distance offshore during mean northwest wind forcing (296° T) of 1.07 dynes $cm^{-2}$ over 5-12 April 1979 (Fig. 7a). The depth averaged currents of the circulation model
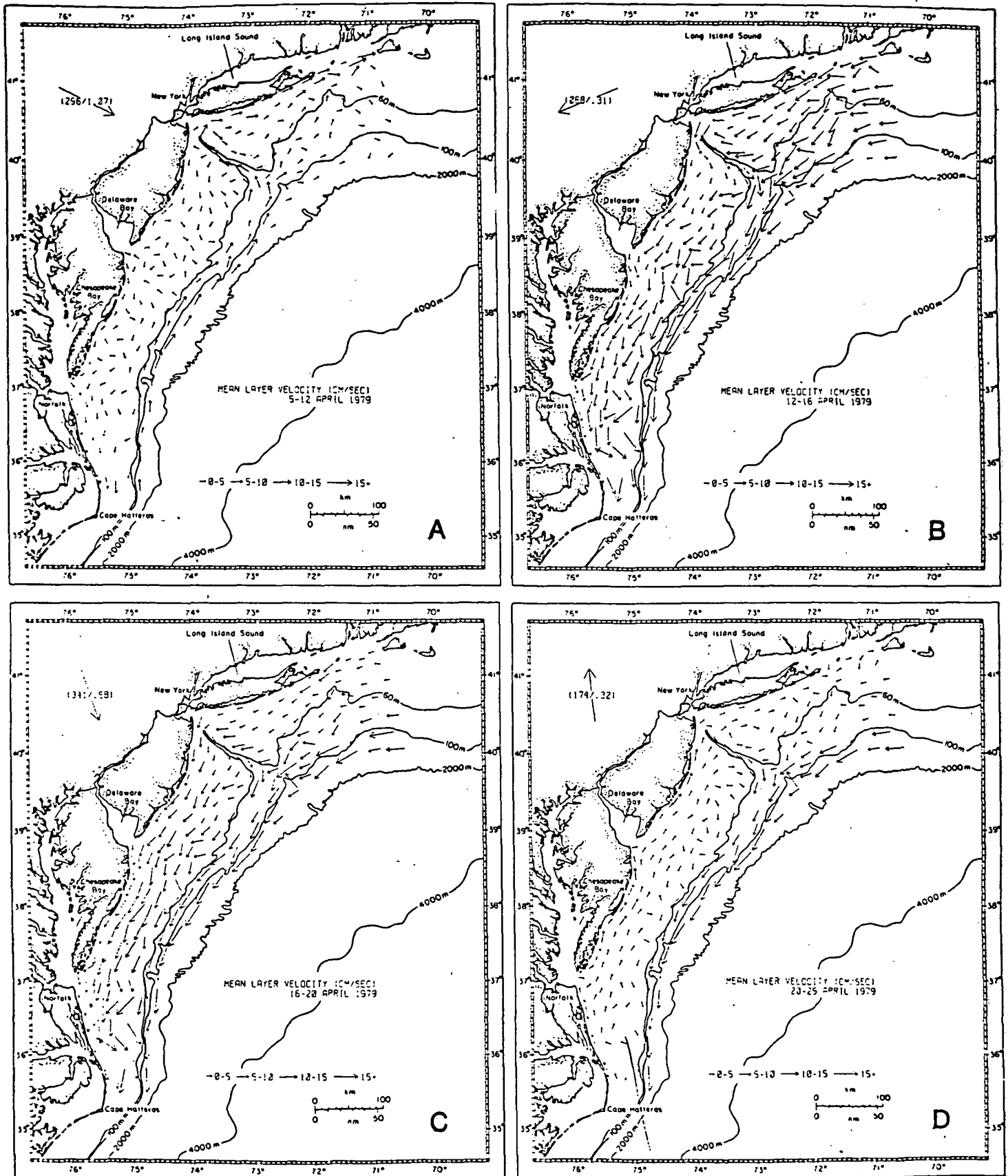
Figure 7.    The depth averaged currents of the circulation model during
A) 5-12 April 1979, B) 12-16 April 1979, C) 16-20 April
1979, and D) 20-25 April 1979.

for this case (Fig. 7a) are $\leq$ 5 cm sec$^{-1}$, with offshore flow between

the 20-40 m isobaths and southwesterly flow between the 40-60 m

isobaths at mid-shelf, south of the Hudson Canyon and north of

Norfolk. In response to such northwest wind events, surface waters

are pushed offshore, and the predominantly westward alongshore flow is

slowed down (BEARDSLEY and BUTMAN, 1974).

Within the surface Ekman layer of the model, >10 cm sec$^{-1}$

offshore flow occurs between the coast and the shelf-break. An

upwelling circulation pattern is created, e.g., as much as 7 m day$^{-1}$

at a depth of 10 m within this model at the coast, in which surface

phytoplankton can be advected offshore and dissolved nutrients can be

returned within subsurface waters to the shelf, providing the source

for the next algal growth cycle (WALSH et al., 1978). At 20 m depth

within the model, the flow is onshore at ~5 cm sec$^{-1}$, such that

particles sinking to this level would be advected shoreward.

During a northeast wind event, the normal westward flow is

intensified (Fig. 7b) and weak onshore flow usually occurs at the

surface, with offshore flow of subsurface water (BEARDSLEY et al.,

1983). Under a wind forcing of only 0.31 dynes cm$^{-2}$ from the

northeast (068° T), the depth-averaged flow of the model's water

column during the case for 12-16 April 1979 was >10 cm sec$^{-1}$ to the

southwest over most of the shelf, except for offshore flows south of

Long Island, near the Hudson Canyon, off Delaware Bay, and south of

Norfolk (Fig. 7b). Consistent with a downwelling circulation pattern,

the offshore flow at 20 m depth was twice that of the surface flow,

south of Norfolk (Fig. 8). In contrast to the surface offshore flow
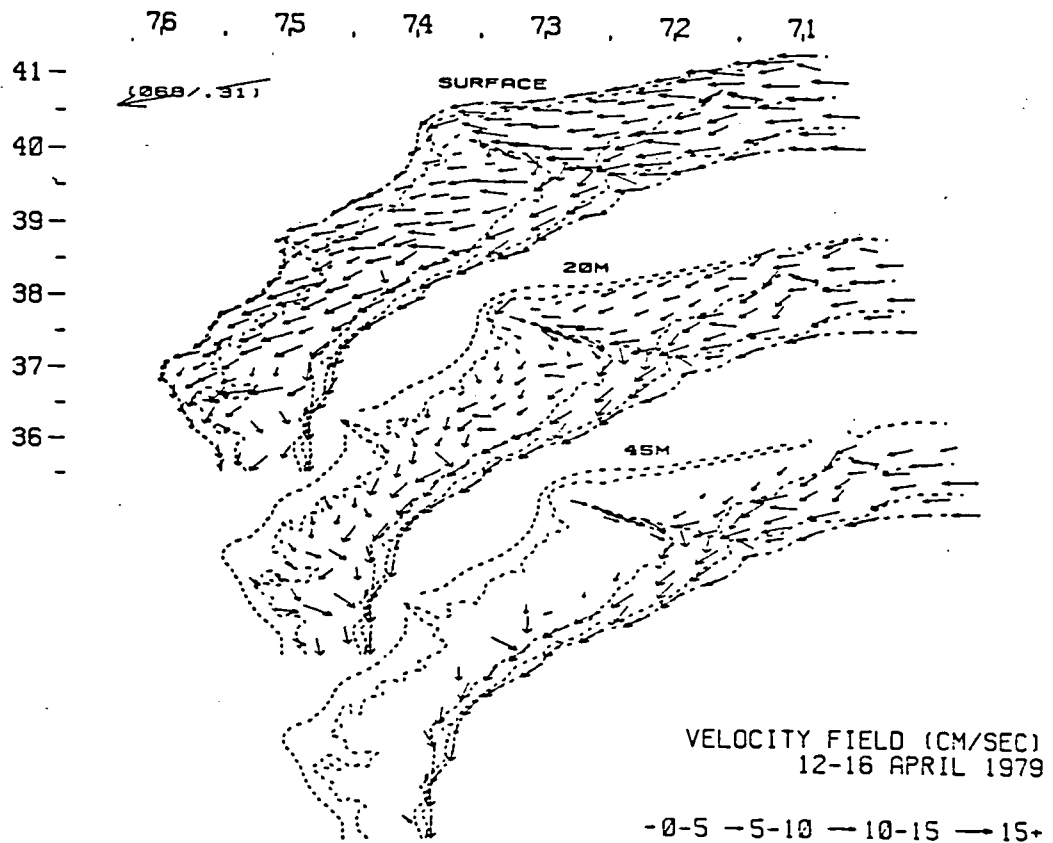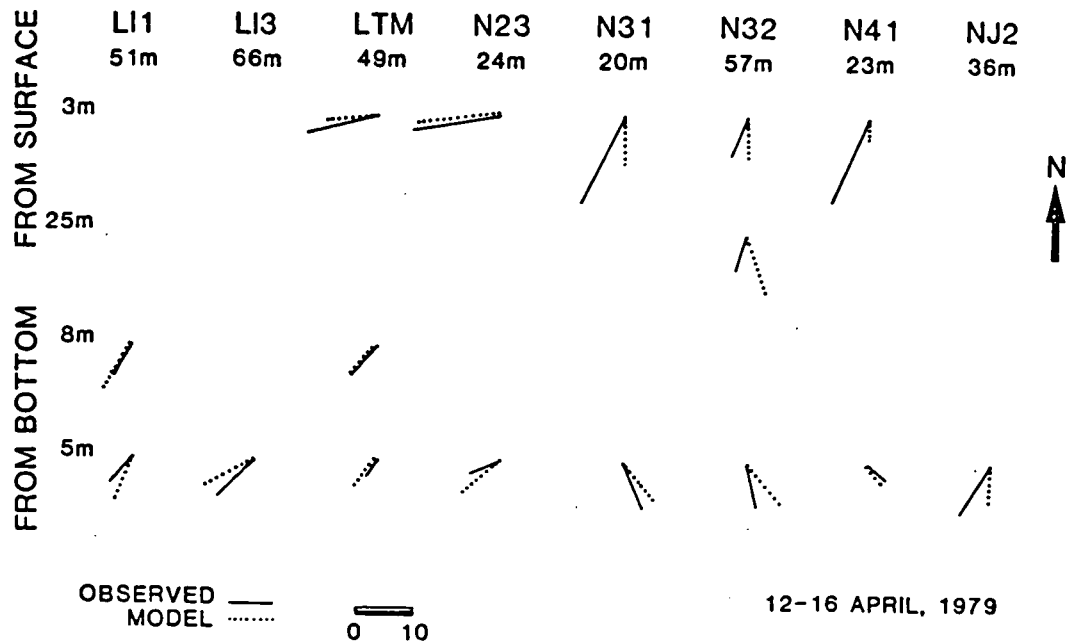
Figure 8.  A comparison of the observed and simulated currents at 4
          depth levels in the New York Bight and of the simulated
          currents at 3 depth levels over the mid-Atlantic Bight
          during 12-16 April 1979.

under northwest wind forcing, it appears that northeast wind forcing could also move algal cells from the coastal zone to slope waters, but within subsurface offshore flow events.

Vertical decomposition of the model's flow field during this northeast wind forcing provides insight for both the veracity (Fig. 8a) and complexity of the simulated currents (Fig. 8b). Except for the nearshore current meter moorings, N31 and N41, where a hydrographic survey (HAZELWORTH and BERBERIAN, 1979) indicated a freshwater plume downstream of the Hudson/Raritan estuaries (Fig. 1), the direction and speed of the model's flow field match the observed currents fairly well. Onshore,flow occurs within the surface Ekman layer of the model, while offshore flow of 5-10 cm $sec^{-1}$ occurs at 20 m and 45 m, particularly south of Delaware Bay, during these events. This is an important circulation mode, because averaging over all of the wind events during April 1979 and February-April 1980, gives a mean subsurface flow (>30 m) of ~2.0 cm $sec^{-1}$ offshore past moorings at the 66-88 m isobaths (Fig. 1) south of Marthas Vineyard (BEARDSLEY et al., 1983), i.e., despite the predominance of average wind forcing (~80% frequency) from the northwest.

Following this northeast wind event, another wind forcing from the northwest (341° T) occurred during the third case for 16-20 April 1979 (Fig. 7c), but with half the intensity (0.58 dynes $cm^{-2}$) of the first case (Fig. 7a). In response to this shift in wind forcing, the depth-averaged alongshore flow was weaker north of the Hudson Canyon and stronger south of Delaware Bay during 16-20 April, compared to the 12-16 April time period (Fig. 7b). In the model, there was little or

no depth-averaged offshore flow south of Long Island and New Jersey, but continued offshore movement of water was simulated off Delaware Bay and Norfolk (Fig. 7c). Even the flow within the surface Ekman layer was directed alongshore rather than offshore in this case, except for waters south of Virginia.

During 17 April 1979, tongues or streamers of 1-2 µg chl $\ell^{-1}$ extended within the CZCS image (Fig. 6b) from the shelf to slope waters in the same areas of the shelf, south of Long Island, south of New Jersey, off Delaware Bay, and off Norfolk, as observed in the March CZCS time series, e.g., Figure 3b. In contrast to these observations of ~1 µg chl $\ell^{-1}$ at mid-shelf off Virginia (Fig. 6b), two days later as much as 16 µg chl $\ell^{-1}$ was apparently detected by the CZCS on 19 April 1979. The region of high chlorophyll ($\geq 8$ µg chl $\ell^{-1}$) extended from off Norfolk to Cape Hatteras, 150 km south along the 40-60 m isobaths (Fig. 6c). At a population growth rate of one doubling every two days (Table 1), such an increase of algal biomass cannot be attributed solely to in situ growth of phytoplankton. Resuspension of near-bottom phytoplankton is the most likely source.

Few near-bottom chlorophyll data are available for April 1979 over the mid-Atlantic Bight. During April 1984, however, near-bottom chlorophyll concentrations of >25 µg chl $\ell^{-1}$ were found at the 60 m isobath (WALSH et al., 1986a). These recent data are similar to our previous observations of 9-17 µg chl $\ell^{-1}$ above the 21-63 m isobaths in April 1978, 10-12 µg chl $\ell^{-1}$ above the 15-35 m isobaths in April 1980, 8-14 µg chl $\ell^{-1}$ above the 21-49 m isobaths in April 1981, 10-29 µg chl $\ell^{-1}$ above the 17-39 m isobaths in April 1982, and 9-15 µg chl $\ell^{-1}$

above the 13-43 m isobaths in April 1983. An accumulated, near-bottom chlorophyll concentration of 15-30 µg chl $\ell^{-1}$ within the lower 10 m of the water column at the 40 m isobath, and 0.5 µg chl $\ell^{-1}$ within the upper 30 m before a resuspension event, would yield 4.13-7.88 µg chl $\ell^{-1}$ after vertical homogenization in response to such a sequence of wind events (Figs. 7a and 7c). A doubling of such phytoplankton populations after two days would then yield the extensive CZCS chlorophyll concentrations of 8-16 µg chl $\ell^{-1}$ seen on 19 April 1979 (Fig. 6c).

Twice as much near-surface chlorophyll was found during the 19 April 1979 resuspension event (Fig. 6c) above the 40-60 m isobaths, compared to the previous 21 March 1979 event above the 20-40 m isobaths (Fig. 3c). One possible explanation for this temporal sequence is a seasonal buildup of chlorophyll within the aphotic zone and a gradual transfer of uneaten phyto-detritus seaward. A 30-40 km offshore migration of the algal resuspension area, from the 20-40 m isobaths to the 40-60 m isobaths, within ~30 days from 21 March to 19 April 1979, suggests a mean net seaward movement of algal particles of 1.0-1.3 km day$^{-1}$ (~1.0-1.3 cm sec$^{-1}$). Since much of the wind forcing is from the north in the mid-Atlantic Bight during February-April, with more frequent northwest storms from off the North American continent, the average net flow of the upper 30 m of the water column past the four current meter arrays, between the 45-105 m isobaths off Marthas Vineyard (Fig. 1), was 7.73 cm sec$^{-1}$ to the west and 1.43 cm sec$^{-1}$ offshore during February-April 1980 and April 1979 (BEARDSLEY et al., 1983), in agreement with the CZCS estimate of seaward transport of particles.

With southerly wind forcing, however, surface flow is at times offshore and to the east, reversing the predominantly westward currents, if a storm is of sufficient intensity. During the fourth case for 20-25 April 1979, a mean wind forcing of 0.32 dynes $cm^{-2}$ from the south (174° T) was sufficient to drive weak depth-averaged currents (<5 cm $sec^{-1}$) to the northeast within the 10-40 m isobaths (Fig. 7d), in contrast to the three previous flow fields of the model (Figs. 7a-7c). This simulated circulation pattern led to an upwelling of ~5 m $day^{-1}$ at 5 m depth on the inner shelf south of Delaware, similar to that observed north of New Jersey during the case of 5-12 April 1979 (Fig. 7a). Within the surface Ekman layer, offshore flow of 5-10 cm $sec^{-1}$ occurred only on the outer shelf, however, south of Delaware Bay during 20-25 April 1979.

Within this region, the chlorophyll concentrations declined by an order of magnitude within two days, i.e., by 21 April 1979 (Fig. 6d). Another 10 m $sec^{-1}$ wind event from the south on 20 April 1979 would have imparted kinetic energy to a surface mixed layer as from the northeast event on 18 April 1979, but the vertical chlorophyll gradient had been reversed by then. With more chlorophyll biomass in surface offshore waters on 20 April 1979, a downward flux of algal biomass may have occurred, as inferred for 23 March 1979. The vertical gradient of density had increased to a mean of 1.02 $\sigma_t$ 56.3 $m^{-1}$ at 41 shelf stations by 1-6 May 1979, however, such that $k_z$ might have been only 23 $m^2$ $hr^{-1}$ over a mixed layer depth of 18 m on 20 April 1979. Nevertheless, an equivalent downward displacement rate of 12 m $day^{-1}$, at mid-shelf where simulated upwelling did not occur,
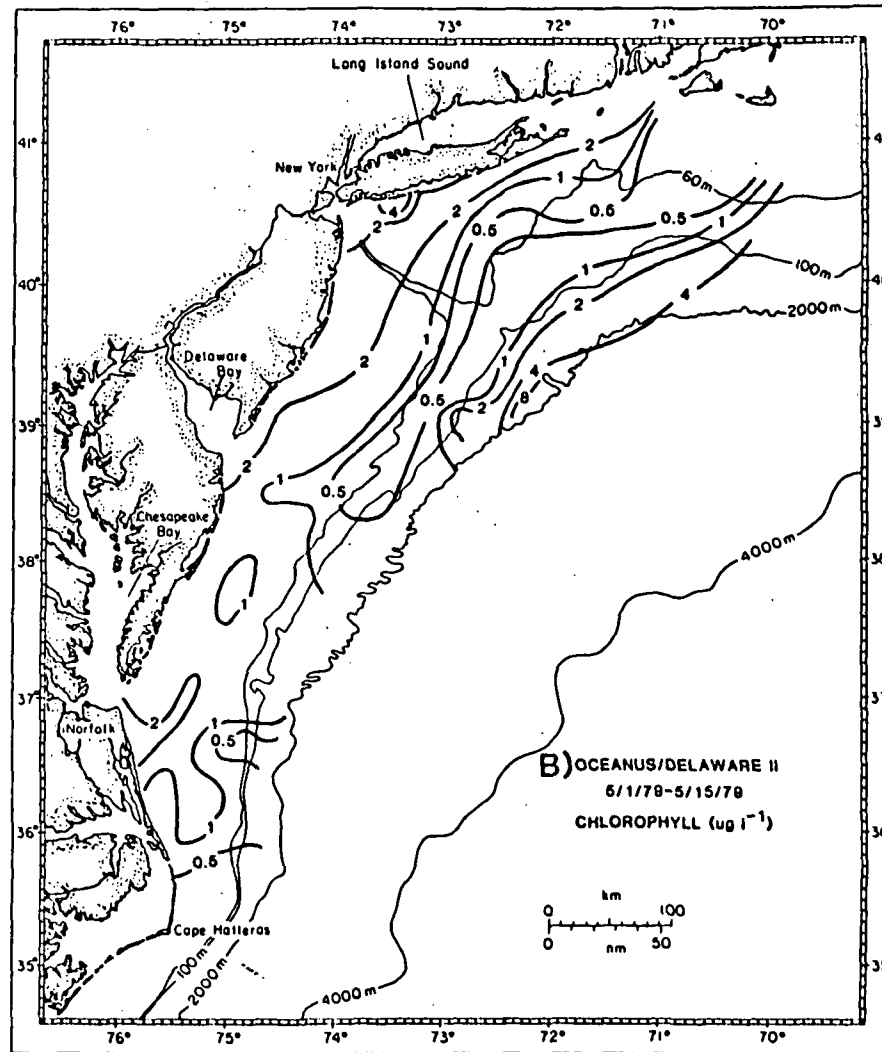
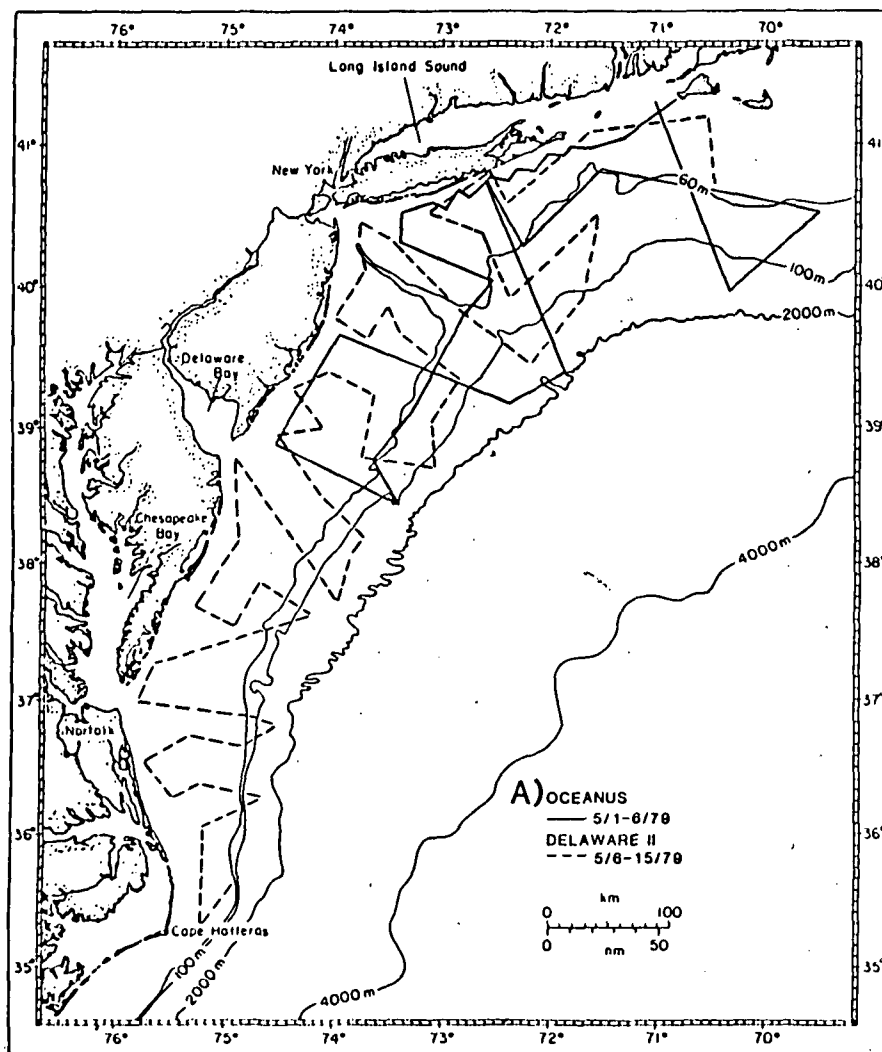Figure 9.   Cruise tracks A) of the R/V <u>Oceanus</u> and <u>Delaware II</u> and
            B) the chlorophyll ($\mu$g $\ell^{-1}$) composite of the distribution
            of phytoplankton biomass during 1-15 May 1979.

would have been sufficient to remove algal biomass below the detection depth (<10 m) of the CZCS sensor in one day.

Dilution of chlorophyll concentrations of the euphotic zone has been observed after wind events in other coastal ecosystems as well. During an upwelling event off California, CZCS imagery similarly detected a tenfold decline in algal biomass over two days, within 20 km of this coast (ABBOTT and ZION, 1985). After an upwelling event off southwest Africa, a CZCS time series suggested at least a threefold decline in algal biomass within four days as well (SHANNON et al., 1984). After March-April wind transport events off Peru, the integrated chlorophyll biomass over the upper 40 m of the water column also decreased by 10-25% in 1976 and 50-75% in 1977 (WALSH et al., 1980). Since diatoms are non-motile, the natural sinking rate of these organisms would add to their downward flux of biomass in these situations of dilution events, where more chlorophyll is initially found at the surface than near-bottom.

Although laboratory sinking rates of diatoms range from only ~1 to 10 m day$^{-1}$ (SMAYDA, 1970), repeated daily field observations of the 1975 diatom spring bloom at the 80 m isobath in the Baltic Sea indicated apparent sinking rates of 30 to 50 m day$^{-1}$ (BODUNGEN et al., 1981). Time series of stations taken ~2 days apart during the 1978-81 spring blooms in the southeastern Bering Sea suggested net in situ sinking rates at the 75 m isobath of only ~3-4 m day$^{-1}$ (WALSH, 1983), but winds were favorable for upwelling about 50% of the time. Vertical chlorophyll profiles taken every 3 hours at the 70 m isobath off Long Island after a 15-20 m sec$^{-1}$ wind event on 3-6 April 1975
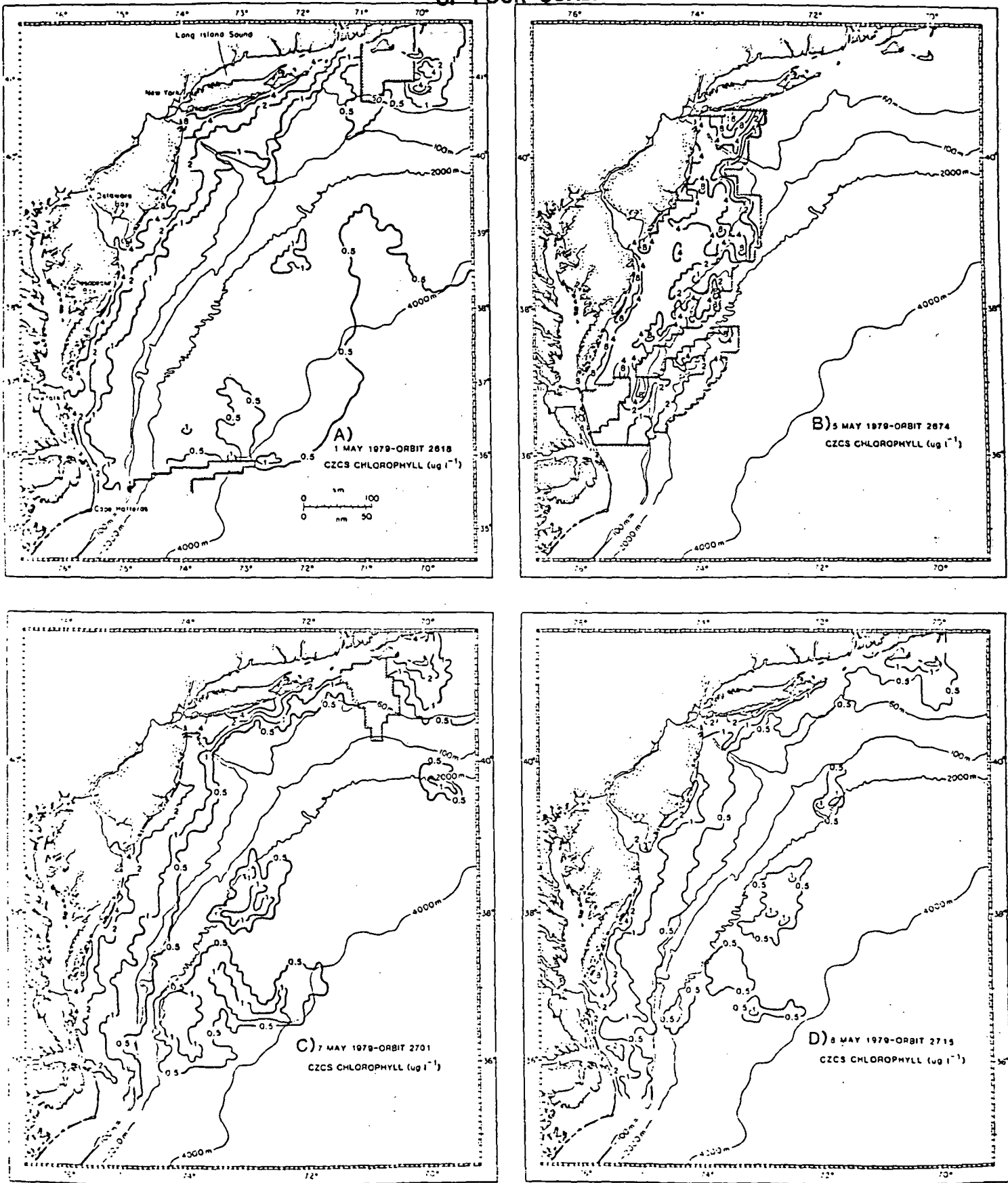
17

Figure 10.  The CZCS estimate of chlorophyll distribution during
A) 1 May 1979, B) 5 May 1979, C) 7 May 1979, and D) 8 May
1979.

(WALSH, 1983) implied a range in sinking and/or downwelling velocities of 12-50 m day$^{-1}$ as well.

Without wind mixing or tidal resuspension of the larger diatoms, they will sink out of the shelf water column despite their high growth rates. In this situation, the diatoms are usually replaced by either motile or very small phytoplankton, as exemplified by the usual flora of the open ocean. A regular seasonal succession of the March diatom net-plankton by May nannoplankton flagellates of slower growth rates (Table 2) occurs each year in the mid-Atlantic Bight (MALONE et al., 1983). We attribute this species replacement to the lack of resuspension of both the diatoms and their required nutrients as seasonal stratification of the water column begins by May-June. With fall overturn of the water column, the diatoms resume their dominance of the shelf phytoplankton community.

c) May 1979

We did not apply the model to the May and June cases, because the same seasonal stratification, that induces species succession of phytoplankton, invalidates our assumption of a barotropic shelf sea. The now familiar sequence of tongues of ~1 μg chl $\ell^{-1}$, extending towards the slope off Long Island, Delaware Bay and Norfolk, can be seen, however, from the CZCS image on 1 May 1979 (Fig. 10a). This pattern was in response to another northwest wind forcing of ~5 m sec$^{-1}$ on 29-30 April 1979. The sampling grids of the Oceanus and Delaware cruises (Fig. 9a) were too coarse to resolve these surface plumes of chlorophyll. The next resuspension event detected by the

DISTANCE OFFSHORE (km)

A)

CHLOROPHYLL (µg l$^{-1}$)

3-4 MAY 1979

SHINNECOCK TRANSECT

STATIONS

DISTANCE OFFSHORE (km)

B)

CHLOROPHYLL (µg l$^{-1}$)

5 MAY 1979
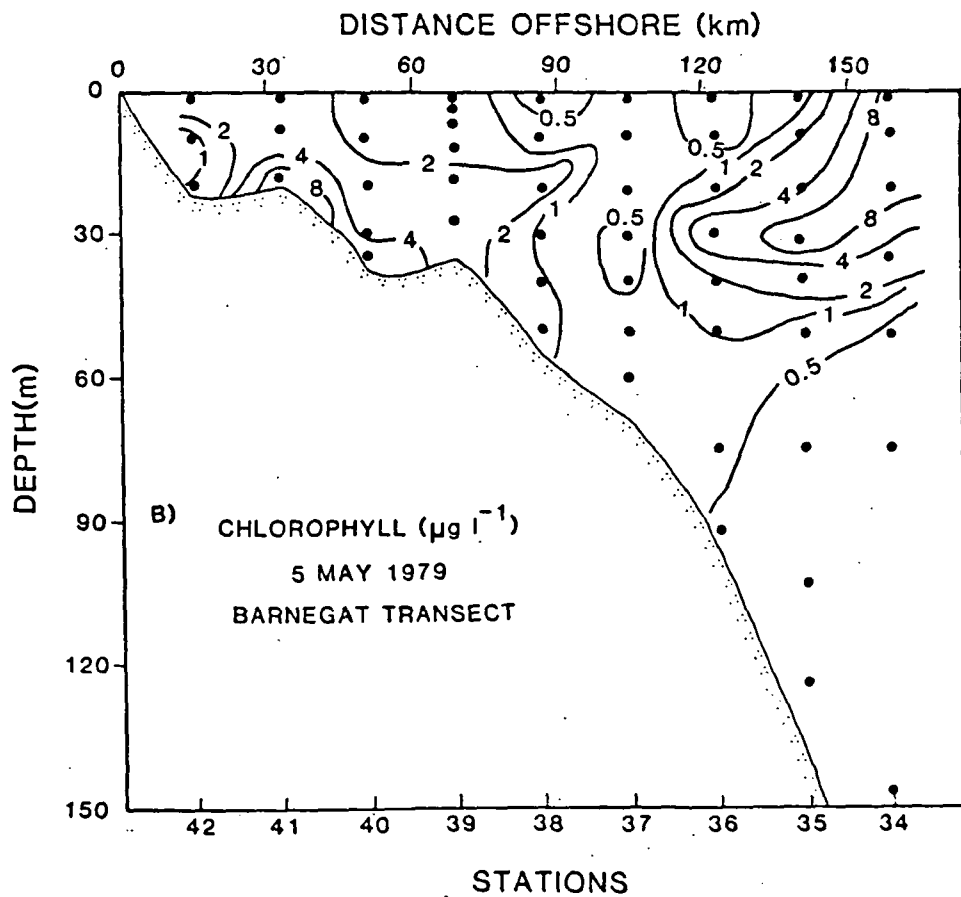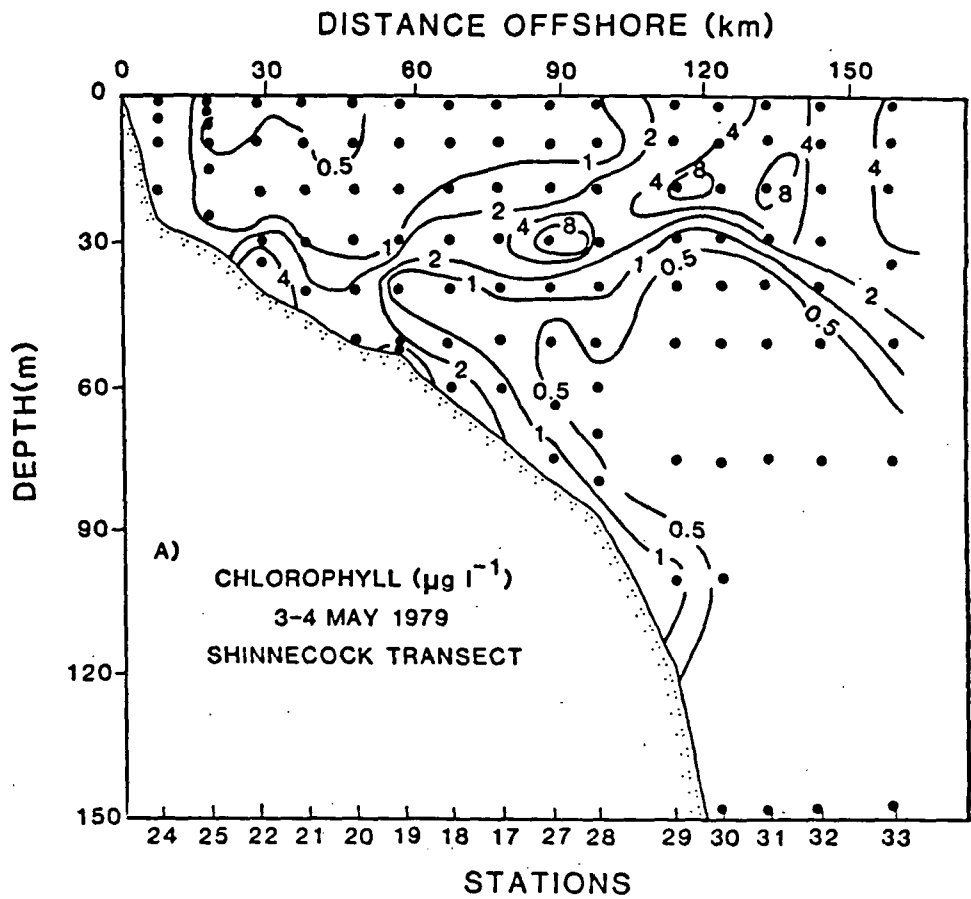
BARNEGAT TRANSECT

STATIONS

Figure 11. The vertical distribution of chlorophyll off the coast of
Long Island (A) and New Jersey (B) during 3-5 May 1979.

CZCS on 5 May (Fig. 10b), was captured, however, when <u>Oceanus</u> was in slope waters off New York (Fig. 9b). In response to a stronger northwest wind forcing of ~10 m sec$^{-1}$ on 4-5 May 1979, ~8 µg chl $\ell^{-1}$ was evidently resuspended above the 60-100 m isobaths and advected seaward over the slope. Similar to the March and April time series, an order of magnitude less algal biomass was then found two days later on 7 May (Fig. 10c) as well as on 8 May (Fig. 10d), after a southerly wind reversal on 6 May 1979.

The resuspended chlorophyll detected by the CZCS south of Delaware Bay may have come from the bottom layer, derived from previous diatom production. The source of chlorophyll detected north of Delaware Bay by <u>Oceanus</u>, was not near-bottom, however, but from the 20-30 m depths of a subsurface chlorophyll maximum of 8-10 µg chl $\ell^{-1}$ (Fig. 11). Higher values have been observed; after seasonal algal species succession at the end of the 1977 spring bloom, for example, 10-20 µg chl $\ell^{-1}$ of motile flagellates were found above the nutricline during May 1977. A subsurface maximum of 20 µg chl $\ell^{-1}$ at 25-30 m and 0.5 µg chl $\ell^{-1}$ over the upper 25 m of the euphotic zone would lead to 3.75 µg chl $\ell^{-1}$ after homogenization by a wind event; a maximum population growth rate of ~0.5 day$^{-1}$ could then yield 7.50 µg chl $\ell^{-1}$ within 2 days to be detected by the CZCS. Conversely, another time series, taken off Long Island during 23-25 May 1977 after southerly wind forcing, suggested a possible downward displacement of the sub-surface maximum of chlorophyll by as much as 10 m day$^{-1}$, analogous to the 21-23 March 1979, 19-21 April 1979, and 5-7 May 1979 removal events.
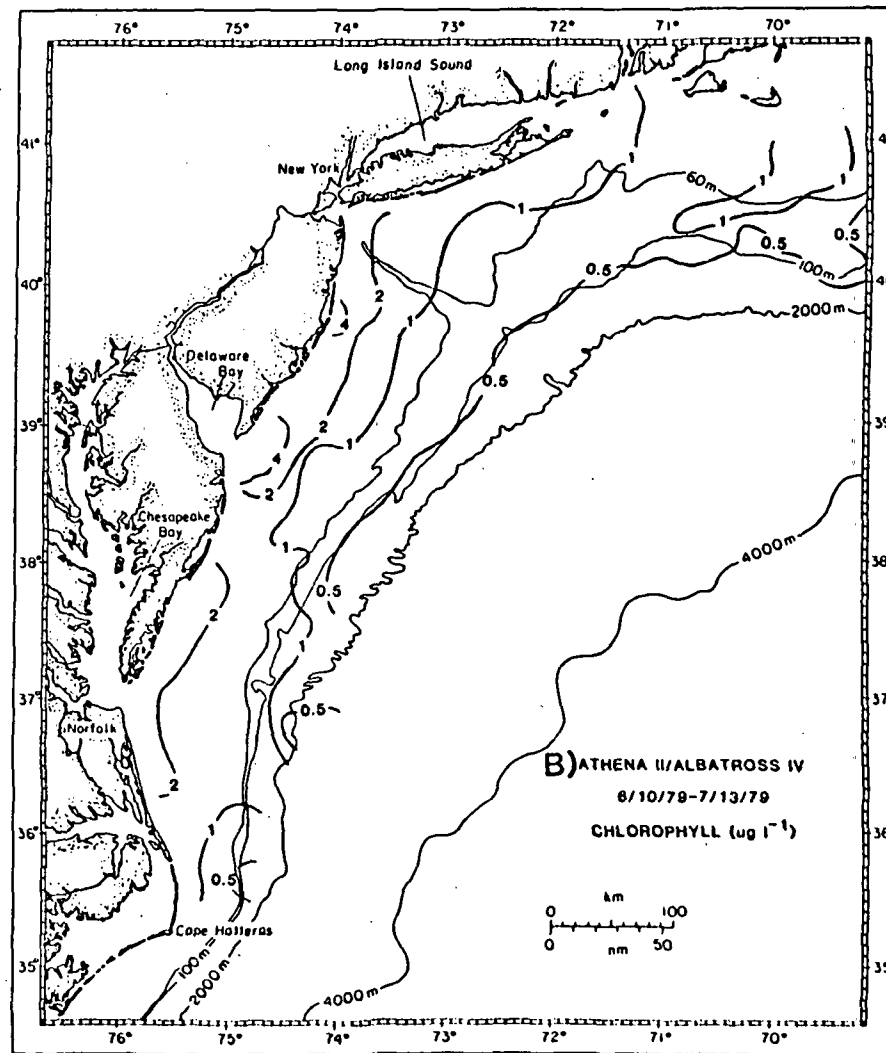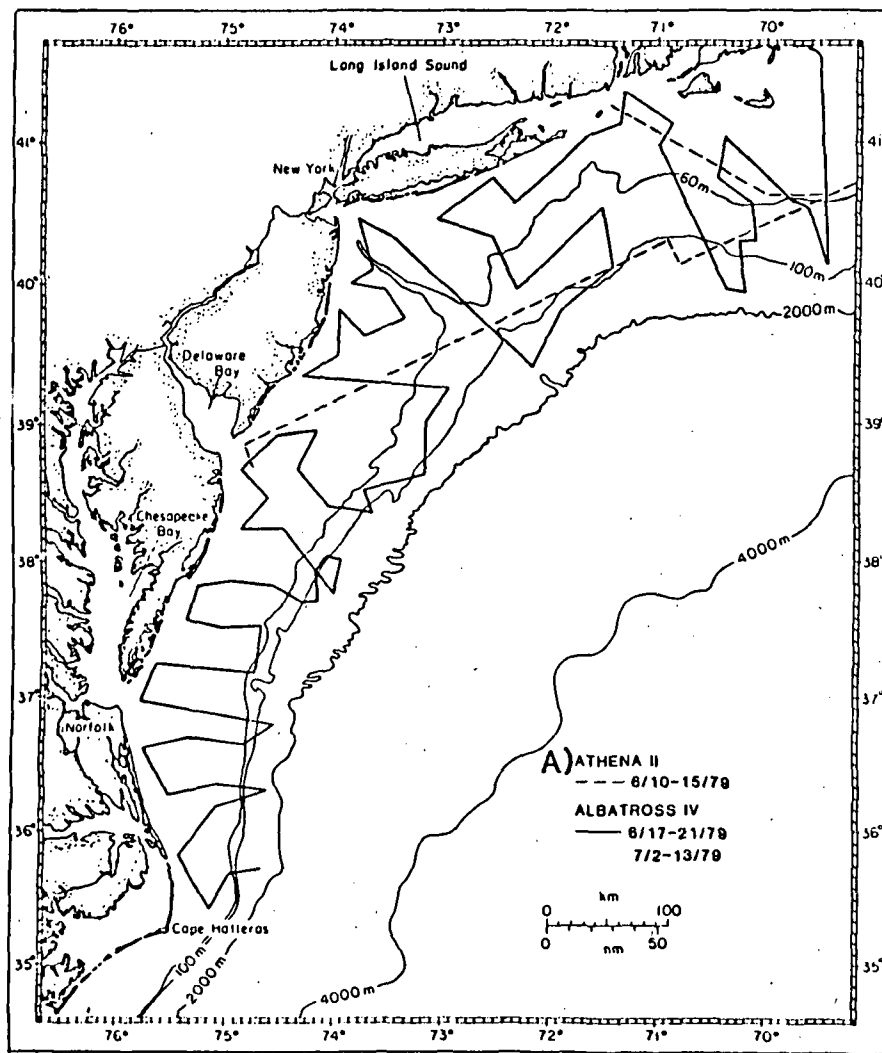
Figure 12. Cruise tracks A) of the R/V _Athena II_ and _Albatross IV_ and
B) the chlorophyll ($\mu g\ \ell^{-1}$) composite of the distribution
of phytoplankton biomass during 10-21 June and 2-13 July
1979.

d)   <u>June 1979</u>

During the 10-15 June 1979 orbits of the NIMBUS-7, very few ground-truth data were available from the cruise track of the <u>Athena</u> <u>II</u> (Fig. 12a).  We have therefore added chlorophyll data from the 17-21 June 1979 and 2-13 July 1979 cruises of the <u>Albatross</u> <u>IV</u> to present a composite of surface chlorophyll (Fig. 12b) measured aboard ship during this period of increased stratification.  With seasonal shift of wind forcing from northwesterly to southerly in early summer, the CZCS images on 10 June 1979 (Fig. 13a) and on 15 June 1979 (Fig. 13d) typify the pigment spatial patterns under these wind conditions; recall the 23 March (Fig. 3d), 21 April (Fig. 6d), and 7 May (Fig. 10c) images.  These two June CZCS images are also similar to the composite chlorophyll pattern obtained by ships over one month (Fig. 12b).

Strong northwest wind forcing of ~10 m sec$^{-1}$ on 12-13 June 1979 evidently generated offshore flow, since tongues of >1 µg chl $\ell^{-1}$ were once more found off Delaware Bay, Norfolk, and south of Marthas Vineyard on 12 June 1979 (Fig. 13b).  Two days later on 14 June 1979 (Fig. 13c), a large plume of 1-2 µg chl $\ell^{-1}$ was found in slope waters, south of Norfolk, and >8 µg chl $\ell^{-1}$ either had been resuspended in shallow shelf waters, or the Chesapeake Bay tongue of high chlorophyll had moved seaward.  Continuous vertical profiles of chlorophyll, taken south of Long Island at the same time of year on 5 June 1980, 6 June 1981, and 3 June 1982, however, indicate sub-surface chlorophyll maxima of only 2-4 µg chl $\ell^{-1}$ at 25-30 m depths of the mid-shelf water column, rather than the 10-20 µg chl $\ell^{-1}$ found at these same depths in
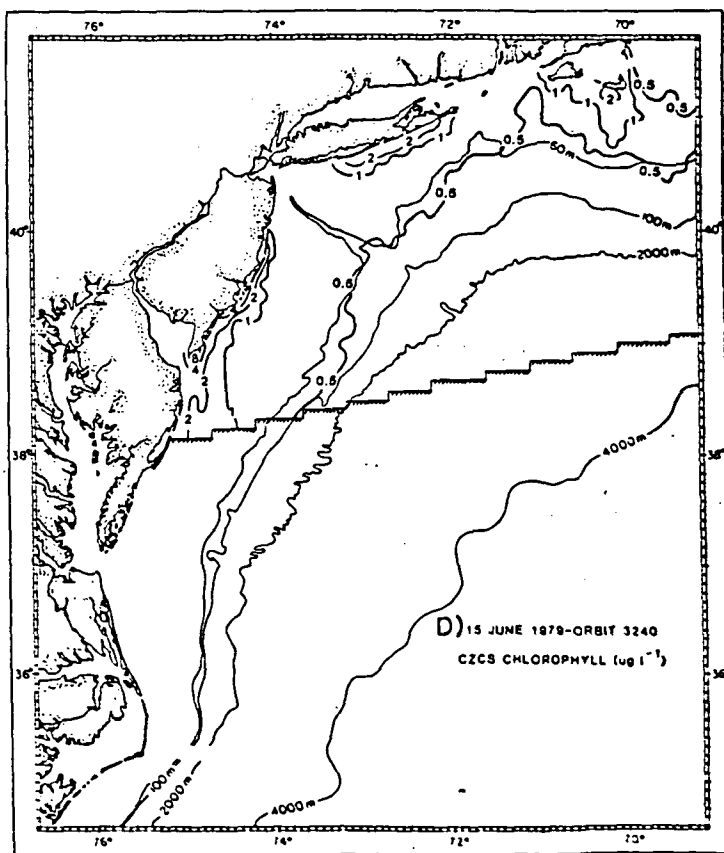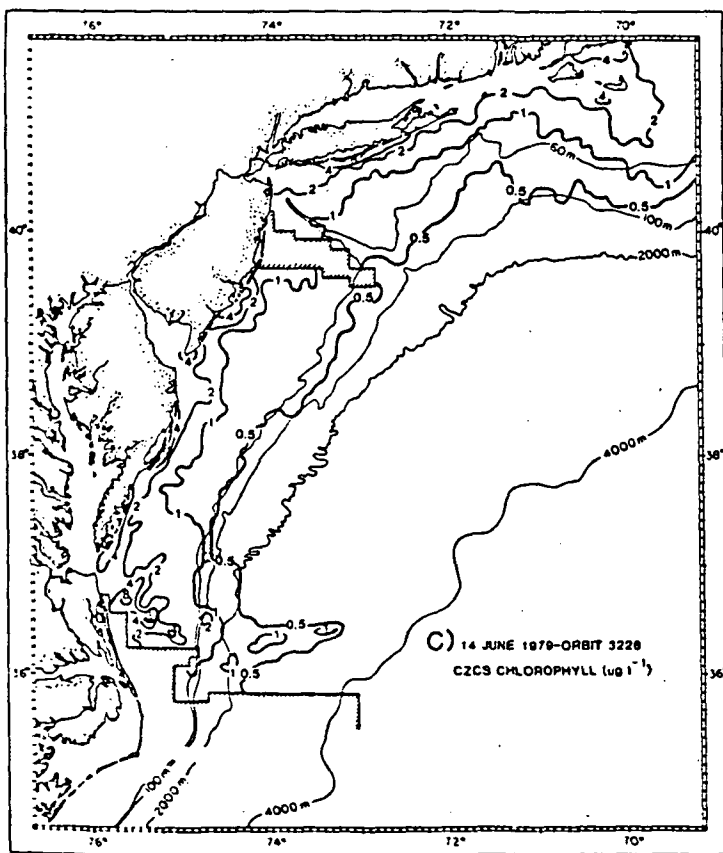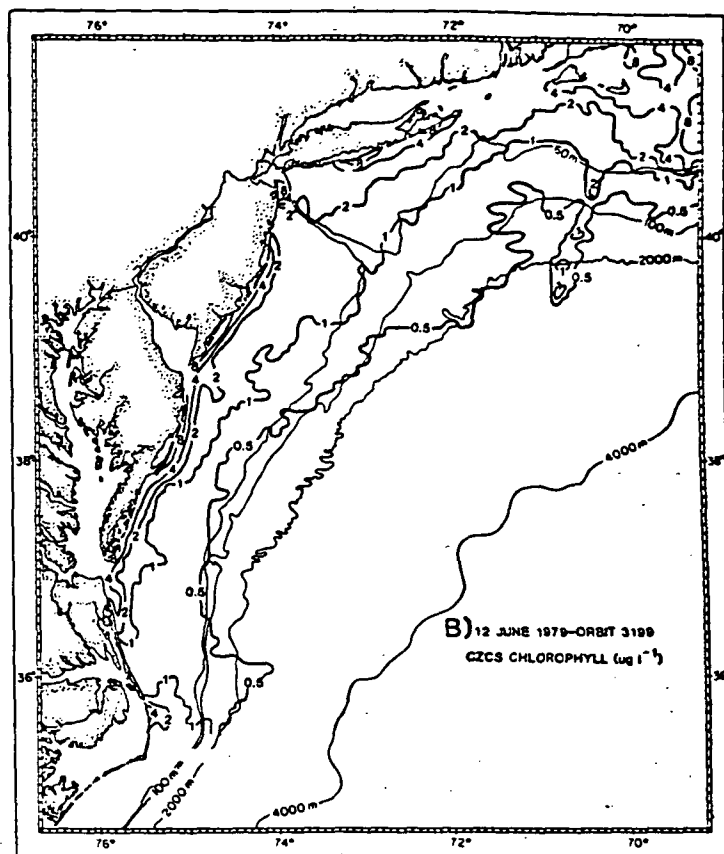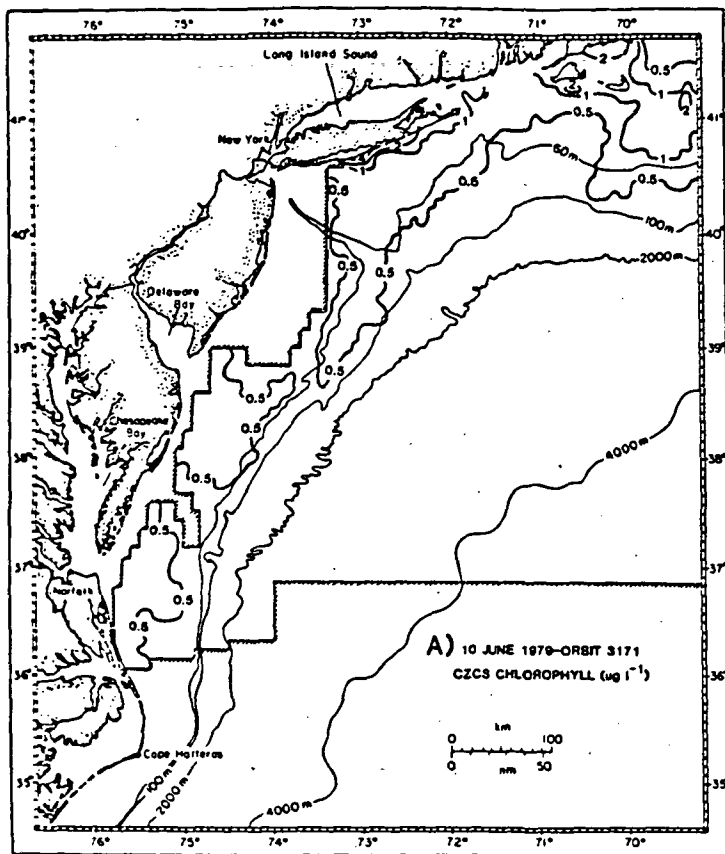
Figure 13.   The CZCS estimate of chlorophyll distribution during
A) 10 June 1979, B) 12 June 1979, C) 14 June 1979, and
D) 15 June 1979.

May 1977 and 1979. A subsurface maxima of 3 µg chl $\ell^{-1}$ at depths of 25-30 m and 0.5 µg chl $\ell^{-1}$ within the overlying water column could yield a mean of 0.92 µg chl $\ell^{-1}$ after homogenization of the 30 m euphotic zone. Two days later, after algal population growth, 1.84 µg chl $\ell^{-1}$ might be detected by the CZCS on the outer shelf in June as part of a seasonal decline of shelf export.

## DISCUSSION

Our satellite description of the spatial redistribution of algal biomass within the mid-Atlantic Bight in response to changes of physical forcing at the wind event and seasonal time scales is consistent with shipboard chlorophyll data taken from over 50 cruises between 1973 and 1984 in this region. Such changes of phytoplankton biomass imply both growth of the population after resuspension of algal cells into the euphotic zone and net seaward transport of the winter-spring diatom bloom over a period of 2-4 months (February-May). Neritic genera of diatoms, e.g., <u>Biddulphia</u>, have been found as deep as 1000 m in the slope water column during spring (P. FALKOWSKI, personal communication), while the biogenic silica content of the underlying slope sediments is tenfold that of shelf sediments (WALSH <u>et al</u>., 1985). To evaluate the possible export of phytoplankton carbon to the adjacent continental slope during this time of the year, we must be able to determine a "representative" chlorophyll value, which reflects both the daily increment from <u>in situ</u> growth and the physical resuspension of uneaten algal residues, for computation of the associated flux of phytoplankton en route to the slope.

The ten cruises of Table 1 were designed to study the biological response to changes in wind forcing within the mid-Atlantic Bight (WALSH et al., 1978), focusing on times and areas in which primary production would be maximal. Such a stratified sampling scheme would emphasize the wind resuspension events depicted by the CZCS time series, but not the background chlorophyll conditions of 0.5-1.0 µg $\ell^{-1}$, frequently found over much of the shelf between March and June 1979. A second set of 23 cruises (Table 2), taken over a wider spatial area and consequently longer time duration, (O'REILLY and BUSCH, 1984) provides a more representative description of the "mean" state of the spring bloom in the mid-Atlantic Bight. We have not included Georges Bank or estuarine data in this second analysis (Table 2), and have reduced their reported values of total primary production (dissolved + particulate) by 15% to subtract their estimate of phytoplankton excretory products, i.e., to compare just the $^{14}C$ estimates of particulate production.

From the 23 "survey" cruises, the mean estimate of daily $^{14}C$ particulate production (0.73 g C m$^{-2}$ day$^{-1}$) is lower than the 10 "wind event" cruises (1.28 g C m$^{-2}$ day$^{-1}$), with little cross-shelf or temporal variation (Table 2). We used the average phytoplankton growth rate of 0.41 day$^{-1}$ (Table 1) and the seasonal changes in the depth of the euphotic zone (Table 2) to estimate the carbon biomass of micro-algae required to account for the observed "survey" primary production. By assuming a constant C/chl ratio and a homogeneous distribution of chlorophyll within the euphotic zone, we can calculate the "effective" chlorophyll (Table 2), that would yield the reflectance sensed by the CZCS (GORDON and CLARK, 1980).

Table 2. Seasonal variation of effective chlorophyll, homogeneously distributed over the euphotic zone, within the mid-Atlantic Bight during 23 "Survey" cruises.

| Date (25-30 Day Surveys) | Sample Size (n) | Bottom Depth (m) | Mean Euphotic Zone (m) | Mean Growth Rate $(day^{-1})$ | Observed Primary Production $(g\ C\ m^{-2}\ day^{-1})$ | Effective Chlorophyll Biomass $(\mu g\ \ell^{-1})$ |
|---|---|---|---|---|---|---|
| March 1977 - 80 | 17 | 0-20 | | | 0.59 | |
| | 13 | 20-60 | 22.3 | 0.41 | 0.66 | 1.46 |
| | 7 | 60-200 | | | 0.55 | |
| April 1977 - 80 | 11 | 0-20 | | | 0.39 | |
| | 10 | 20-60 | 27.8 | 0.41 | 0.41 | 1.04 |
| | 8 | 60-200 | | | 0.80 | |
| May 1977 - 80 | 9 | 0-20 | | | 0.62 | |
| | 6 | 20-60 | 27.6 | 0.41 | 0.70 | 1.45 |
| | 6 | 60-200 | | | 0.89 | |
| August 1977 - 80 | 9 | 0-20 | | | 1.01 | |
| | 10 | 20-60 | 32.2 | 0.41 | 0.83 | 1.32 |
| | 14 | 60-200 | | | 0.81 | |
| September 1977 - 80 | 11 | 0-20 | | | 0.88 | |
| | 7 | 20-60 | 27.6 | 0.41 | 0.64 | 1.47 |
| | 7 | 60-200 | | | 0.72 | |
| October 1977 - 80 | 15 | 0-20 | | | 0.98 | |
| | 14 | 20-60 | 25.8 | 0.41 | 0.98 | 1.90 |
| | 13 | 60-200 | | | 0.76 | |
| Total | 187 | | | Average = 0.73 | | 1.44* |

*Excluding data from the mouths of the Hudson-Chesapeake-Delaware estuaries, and using a C/chl a ratio of 45/1.

A mean chlorophyll value of 1.44 µg $\ell^{-1}$ (Table 2) is more than that depicted on the outer shelf by CZCS images before and after wind events, but half of the mean shipboard biomass value (2.96 µg chl $\ell^{-1}$) observed during the "wind event" cruises (Table 1). Within the resuspension areas during March (Fig. 3c), April (Fig. 6c), and May (Fig. 10b), the CZCS estimates of chlorophyll are more than tenfold higher than this estimate of 1.44 µg $\ell^{-1}$. These high CZCS estimates were observed only within near-surface waters for 2-3 days, so the "effective" value of 1.44 µg chl $\ell^{-1}$ may be a good lower bound of the phytoplankton biomass available for export to the slope. The wind event mean of 2.96 µg chl $\ell^{-1}$ (Table 1) may be an upper bound, at least for the waters away from the mouths of the estuaries (Table 2).

During October-May 1979-80, the mean diabathic component of the surface flow (0-30 m) between the 45-105 m isobaths, south of Marthas Vineyard, was 1.77 cm $sec^{-1}$ offshore (BEARDSLEY et al., 1983); weak onshore flow of 0.05-0.20 cm $sec^{-1}$ occurred during June-August. An offshore flow of ~1.5 cm $sec^{-1}$ during spring and a CZCS estimate of 1.44 µg chl $\ell^{-1}$ within the first attenuation depth, on the landward side of the shelf-break between Cape Hatteras and Marthas Vineyard, imply a net seaward transport of 2.1 ng chl $cm^{-2}$ $sec^{-1}$ from the mid-Atlantic Bight. Assuming a mean C/chl ratio of 45/1 (MALONE et al., 1983), a carbon export from the spring bloom of 0.8 x $10^2$ g C $m^{-2}$ $day^{-1}$ might occur across the shelf break. The tacit assumption in this calculation is that a phytoplankton cell exits the continental shelf only at the surface of the water column.

With an alongshore flow of 8.0 cm sec$^{-1}$ and an offshore flow of 1.5 cm sec$^{-1}$, an ungrazed algal cell would take 66 days to cross the 100 km wide shelf in a 528 km longshore trajectory, i.e., half the length of the mid-Atlantic shelf; during these two months a diatom frustule would certainly experience a number of downwelling or sinking events. In fact, a time series of current meter and fluorometer observations, moored 3-5 m above the bottom at the 80 m isobath off Long Island (near L13 of Fig. 1) during 23 February - 4 April 1984 (WALSH et al., 1986a), yielded a net seaward chlorophyll flux, $\overline{u}\overline{P}$, of 3.0 ng chl cm$^{-2}$ sec$^{-1}$ (Fig. 14c), or 2.67 g chl m$^{-2}$ day$^{-1}$. In terms of carbon, this flux amounts to $1.2 \times 10^2$ g C m$^{-2}$ day$^{-1}$ with a C/chl ratio of 45. Note that the cumulative 1984 downstream flux, $\overline{v}\overline{P}$, was ~12.5 ng chl cm$^{-2}$ sec$^{-1}$ (Fig. 14), similar to the above difference in offshore and longshore flow during 1979-80.

A daily export at the shelf-break of $0.8-1.2 \times 10^2$ g C m$^{-2}$ day$^{-1}$ throughout the spring water column reflects, of course, the previous accumulation of carbon within a water parcel during the trajectory from the coast to the slope. The seasonal buildup of chlorophyll ($P_M$) within the aphotic zone at the shelf-break is clearly depicted, for example, within the first moored fluorometer time series (Fig. 14b), ranging from ~0.3 µg chl $\ell^{-1}$ in February 1984 to ~3.0 µg chl $\ell^{-1}$ in April 1984. During May 1979, 1-2 µg chl $\ell^{-1}$ were found near the bottom of the shelf-break as well (Fig. 11a). Assuming no other losses of this fixed algal carbon, an export of $0.8-1.2 \times 10^2$ g C m$^{-2}$ day$^{-1}$ and a March-April primary production of 1.18 g C m$^{-2}$ day$^{-1}$ (Tables 1 and 2) imply a summation of 68-102 days of time averaged
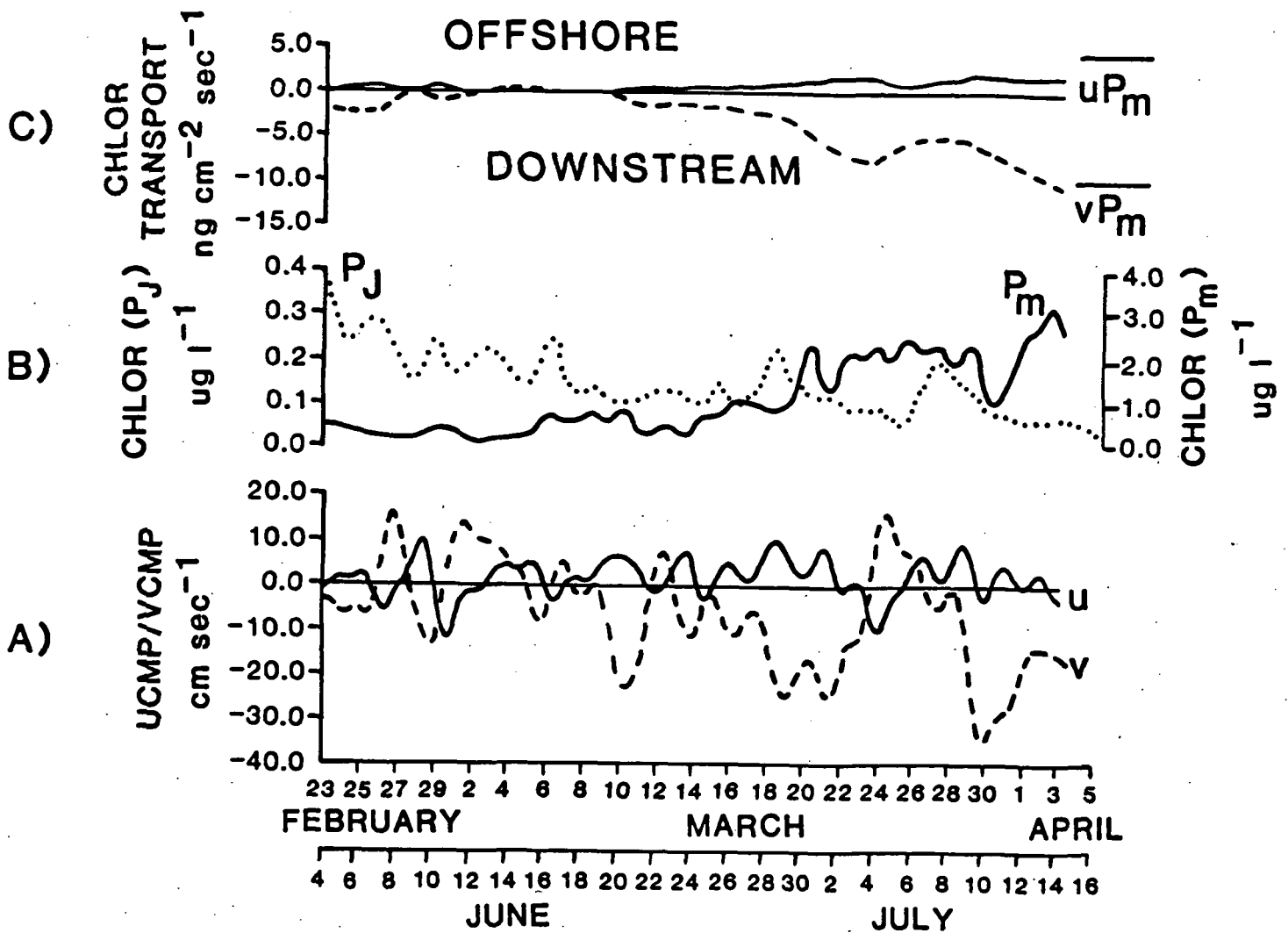
Figure 14. The 40-hr low passed time series of A) currents, B) chlorophyll ($P_M$), and C) phytoplankton transport past both a mooring 3-5 m above the 80 m isobath, south of Long Island, during 23 February - 4 April 1984, and B) of chlorophyll ($P_J$) past another mooring 3 m above the 110 m isobath, south of Marthas Vineyard, during 4 June - 16 July 1983.

photosynthetic input during the trajectory of a water parcel towards Cape Hatteras, i.e., the period from the winter bloom to onset of stratification, when the diatoms are the dominant flora.

Such a similar shelf export of $0.8-1.2 \times 10^2$ g C m$^{-2}$ day$^{-1}$, inferred from high frequency sampling in space and time by the CZCS and moored fluorometer, lacks vertical resolution from either of these data sets. A simple model of the seasonal dynamics of plankton at 3 depth layers, over 58 days from 1 March 1979 to 27 April 1979, was subsequently coupled (Walsh et al., 1986c) to the physical model of this study. The details of the time-dependent light and nutrient regulation, vertical mixing, and grazing stress at 1800 grid points, in conjunction with the changing wind forcing over this 1979 spring bloom, are discussed in the second model. The salient feature of our additional numerical results, however, is that we can reproduce the seasonal cycle of near-bottom chlorophyll ($P_M$) at the 80 m isobath in March-April 1984 (Fig. 14b), with the 1979 plankton model at an adjacent grid point (Fig. 15).

The seaward flux of simulated chlorophyll within the upper third of the 1979 water column at the shelf-break, between Marthas Vineyard and Cape Hatteras (Fig. 1), ranged from a mean of 0.05 to 0.09 g chl m$^{-2}$ day$^{-1}$. Within the bottom third of the water column, however, the mean flux was both much larger, 1.06-3.14 g chl m$^{-2}$ day$^{-1}$, and similar to that of the above moored fluorometer and current meter observations. Over the 46.2 m of the lower third of the model's water column along the $6.6 \times 10^5$ m shelf-break (Fig. 1), the daily carbon flux into slope waters was an export of $1.5-4.3 \times 10^9$ g C day$^{-1}$, with a C/chl ratio of 45.
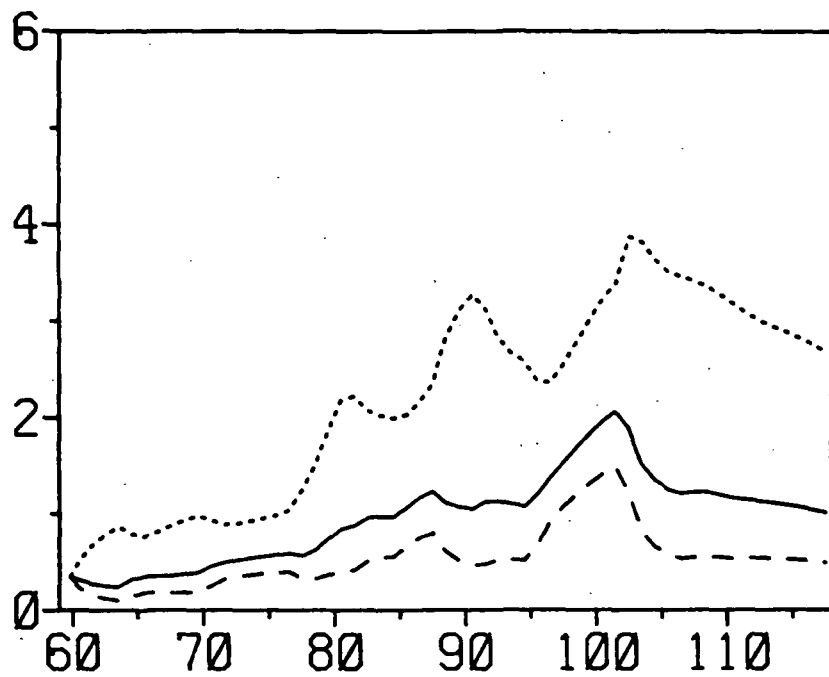
Figure 15.  The simulated chlorophyll content ($\mu g\ \ell^{-1}$) at noon of each
Julian day from 1 March to 27 April 1979 within the upper
(····), middle (——), and lower (‑‑‑) layers of the 80 m water
column at a grid point, adjacent to the 1984 fluorometer
mooring.

Dispersed over the 2.2 x $10^{10}$ m$^2$ surface area of the continental

slope, such a 1979 carbon import would be 0.07-0.20 g C m$^{-2}$ day$^{-1}$;

moored sediment traps at 50 m above the bottom on the upper (500 m

depth) and lower (1250 m) slope caught about 0.08-0.26 g C m$^{-2}$ day$^{-1}$

during April 1984 (BISCAYE and ANDERSON, 1986). Averaging over wind

events for comparison with the model and moored fluorometer results,

the mean March-April primary production of 0.56 g C m$^{-2}$ day$^{-1}$

(Table 2) would yield an estimate of 3.7 x $10^{10}$ g C day$^{-1}$ over the

surface area of the continental shelf (6.6 x $10^{10}$ m$^2$). If we assume

that the depth resolution of the model is accurate, the above shelf

export of the 1979 spring bloom was 4-12% of the average daily primary

production; we would expect the annual export to be less, since as

much as 100% of the algal production can be grazed during summer (DAGG

and TURNER, 1982).

During 4 June - 16 July 1983, another fluorometer mooring at 3 m

above the 110 m isobath, south of Marthas Vineyard (near N4 of

Fig. 1), yielded a mirror image of the 1984 spring time series. The

chlorophyll ($P_J$) declined from 0.40 µg $\ell^{-1}$ in June 1983 to 0.04 µg $\ell^{-1}$

in July 1983 within the aphotic zone (Fig. 14b). Note the scale

change between these two time series of spring ($P_M$) and summer ($P_J$)

chlorophyll observations, taken at 8-minute intervals. Similar to the

seaward flow past the February-April 1984 mooring at the 80 m isobath

(Fig. 14), the annual mean offshore flow was 1.1 cm sec$^{-1}$ past the

near-bottom current meter arrays at the 46-105 m isobaths, south of

Marthas Vineyard, during 1979-1980 (BEARDSLEY et al., 1985).

With an aphotic phytoplankton biomass of ~2.50 µg chl $\ell^{-1}$ for March-May, ~0.25 µg chl $\ell^{-1}$ for June-February, and a mean flow of 1.0 cm $sec^{-1}$, the seaward chlorophyll flux might be 2.50 ng chl $cm^{-2}$ $sec^{-1}$ within the spring bloom and only 0.25 ng chl $cm^{-2}$ $sec^{-1}$ during the rest of the year. A C/chl ratio of 45 suggests a carbon flux of 9.7 g C $m^{-2}$ $day^{-1}$ might thus occur at the edge of the shelf in July, or a summation of only 13.3 days of mean primary production (0.73 g C $m^{-2}$ $day^{-1}$), assuming no losses of the fixed algal carbon to herbivores. Since at least 90% of the summer primary production is removed by herbivores in the mid-Atlantic Bight (WALSH et al., 1978), however, a cumulative carbon flux of 9.7 g C $m^{-2}$ $day^{-1}$ at the shelf-break may actually reflect 132 days of primary production, i.e., the period from the end of the spring bloom to the beginning of the fall bloom over which the flagellates are the dominant flora.

If a near-bottom shelf export of 100 g C $m^{-2}$ $day^{-1}$ in April and 10 g C $m^{-2}$ $day^{-1}$ in July each represent the seasonal extremes over respectively 3 month and 9 month integrals of unconsumed production on the shelf, the annual export of phyto-detrital carbon might be 1.2 x $10^4$ g C $m^{-2}$ $yr^{-1}$. Over the same lower third of the water column along the shelf-break of the mid-Atlantic Bight, at least 3.7 x $10^{11}$ g C $yr^{-1}$ might be exported to the continental slope. At an annual primary production rate of 276 g C $m^{-2}$ $yr^{-1}$ (Table 2) over the non-estuarine shelf area, at least 1.8 x $10^{13}$ g C $yr^{-1}$ could be fixed on the mid-Atlantic shelf; i.e., the annual estimate of shelf export might be as little as 2% of the yearly photosynthetic input of carbon. Over the adjacent slope area, this annual import would be an input of

16.8 g C m$^{-2}$ yr$^{-1}$ to the sediments, assuming no further degradation of the carbon in the slope water column. Recent estimates of $^{210}$Pb and $^{14}$C rates of sediment mixing on the mid-Atlantic slope, of vertical carbon gradients within the upper 10 cm of this sediment, and of anthropogenic nitrogen loading to the coastal zone suggest, in fact, an accumulation rate of 10-17 g C m$^{-2}$ yr$^{-1}$ on this continental slope (WALSH et al., 1985).

The actual amount of phytoplankton export is undoubtedly larger than our present estimate, since the moored fluorometers were deployed south of Long Island and Marthas Vineyard, while the four CZCS time series and simulation models suggested more of the offshore transport of algal biomass may actually occur south of Virginia. Similar longshore inhomogeneity of algal export was observed with CZCS imagery off the California coast (ABBOTT and ZION, 1985). As additional analyses of spatially synoptic satellite data provide more time series on algal biomass changes in both shelf and slope waters, we will be able to specify the areal, interannual, and possible decadal changes of shelf export from the mid-Atlantic Bight.

## ACKNOWLEDGEMENTS

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ABSTRACT

Moorings of current meters, thermistors, transmissometers, and fluorometers on the mid-Atlantic shelf, south of Long Island, suggest a cumulative seaward export of perhaps 0.35 g C m⁻² day⁻¹ [gm/day] between the 80 and 120 m isobaths during February-April 1984. Such a horizontal loss of algal carbon over the lower third of the water column would be 23-78% of the March-April 1984 primary production. This physical carbon loss is similar to daily grazing losses from zooplankton of 32-40% of the algal fixation of carbon. Metabolic demands of the benthos could be met by just the estimated fecal pellet flux, without direct consumption of algal carbon, while bacterioplankton needs could be served by excretory release of dissolved organic matter during photosynthesis. Sediment traps tethered 10 m off the bottom at the 120 m isobath and 50 m above the 500 m isobath caught as much as 0.16-0.26 g C m⁻² day⁻¹ [gm/day] during March-April 1984, in reasonable agreement with the flux estimated from the other moored instruments. If annual estimates of carbon accumulation within sediments of the mid-Atlantic slope were to actually occur during 100 days of the winter-spring bloom, as much as 31% of the above export might be temporarily stored in slope depocenters.