High frequency sampling of the 1984 spring bloom

within the mid-Atlantic Bight:

synoptic shipboard, aircraft, and in situ perspectives

of the SEEP-I experiment

by

John J. Walsh[1], Creighton D. Wirick[2], Leonard J. Pietrafesa[3],

Terry E. Whitledge[4], Frank E. Hoge[5] and Robert N. Swift[6]

[1]Department of Marine Science
University of South Florida
St. Petersburg, Florida 33701

[2]Department of Applied Science
Brookhaven National Laboratory
Upton, New York 11973

[3]Department of Marine, Earth, and Atmospheric Sciences
North Carolina State University
Raleigh, North Carolina 27650

[4]Marine Science Institute
University of Texas
Port Aransas, Texas 78373

[5]Goddard Space Flight Center
Wallops Flight Facility
Wallops Island, Virginia 23337

[6]E. G. and G.
Washington Analytical Services Center
Pocomoke City, Maryland 21851

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} 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} 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.

INTRODUCTION

Conventional shipboard surveys of 1-3 week duration, which attempt to study dominant shelf phytoplankton processes, such as the spring bloom, cannot resolve either algal population growth (0.5 day^{-1}) or wind resuspension events (0.2 day^{-1}), thereby severely aliasing estimates of primary production and its consumption (WALSH, DIETERLE and ESAIAS, 1987a). As part of a multidisciplinary effort to determine the fate and transport of biogenic particles from the coastal zone to slope depocenters, a series of moored fluorometers, transmissometers, thermistors, current meters and aircraft overflights were deployed in the DOE SEEP-I (Shelf Edge Exchange Processes) experiment during February-April 1984 within the mid-Atlantic Bight (Fig. 1).

The sampling rates of the 4 moored instruments were sufficient (0.007-0.012 day^{-1}) to resolve major scales of physical and biological variability. Four times, a NASA P-3A aircraft overflew the arrays (Fig. 1) in less then 2 hours, providing synoptic estimates, as well, with an infrared radiometer and a laser fluorosensor of the surface temperature and chlorophyll fields around the moored instruments. We compare these time series data of the Eulerian measurements with concurrent aircraft and shipboard data, to both estimate the export of phytoplankton from the mid-Atlantic shelf during the 1984 spring bloom, and to provide validation data for a simulation model of this ecosystem (WALSH, DIETERLE and MEYERS, 1987b).
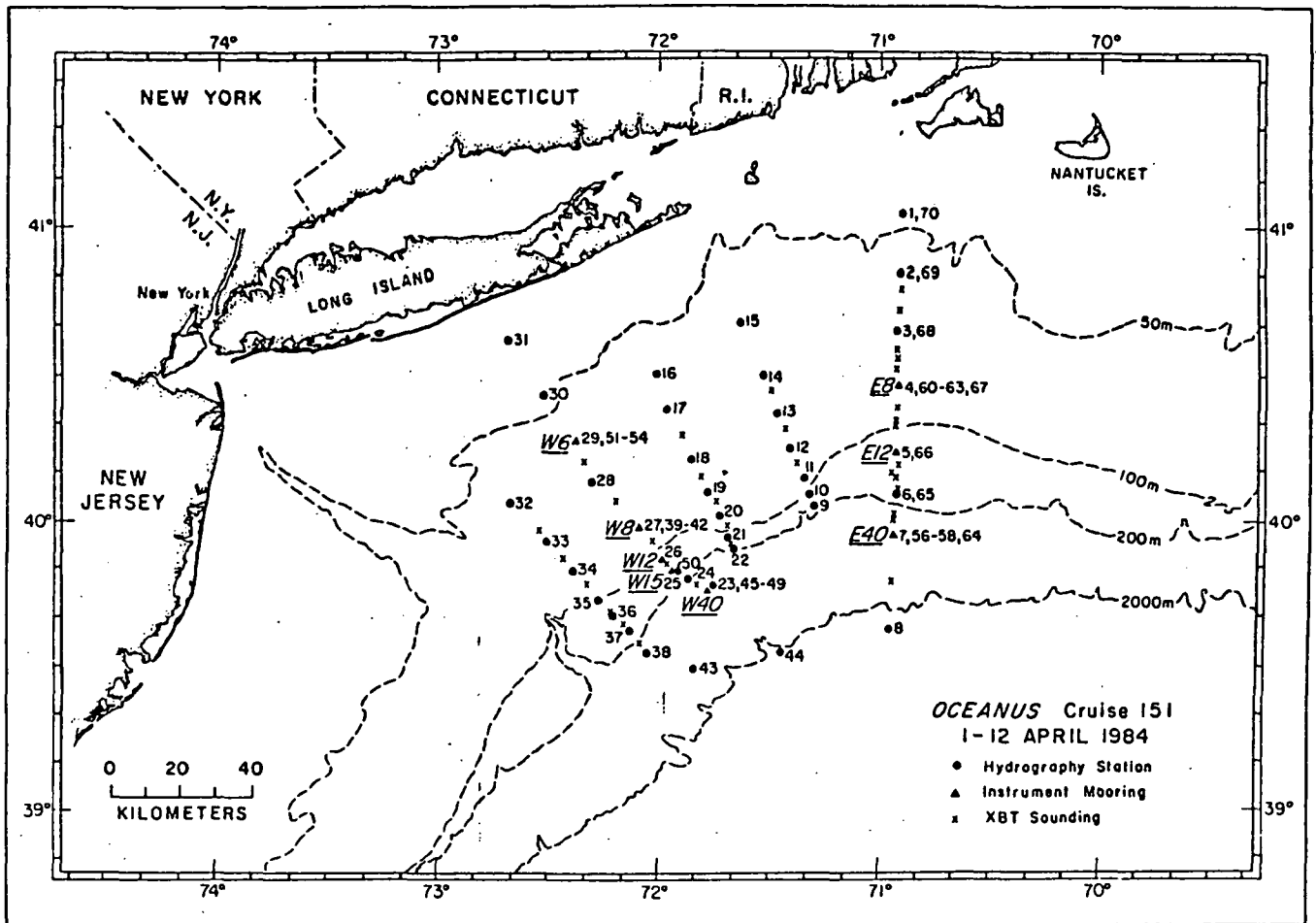
Figure 1.   Location of fluorometer, transmissometer, thermistor, and
current meter moorings (W6-W40, E8-E40) during SEEP-I in
relation to hydrographic stations taken during the recovery
cruise of R/V Oceanus.

Endeco current meters in the euphotic zone and Aanderaa current meters below were moored within the same arrays of fluorometers, Fenwal thermistors and Sea Tech transmissometers (Fig. 2) from 14 February 1984 to 8 April 1984, south of Long Island and Martha's Vineyard. Of the eight moorings, two were lost, with recovery of W6, W8, W12, and W40 at the 60 m, 80 m, 120 m, and 400 m isobaths south of Long Island, and of E8 and E40 at these respective isobaths south of Martha's Vineyard (Fig. 1). In this analysis, the fluorescence, light attenuation, temperature, and current data were subjected to both 2- and 40-hour low pass filters to remove some of the high frequency fluctuations, e.g., diel changes in photosynthesis or tidal motion.

Extracted chlorophyll data from the shipboard observations (WALSH, WHITLEDGE, BARVENIK, WIRICK, HOWE, ESAIAS and SCOTT, 1978) were used to calibrate both measurements of the in situ xenon-flash fluorometers (AIKEN, 1981) and the laser-induced estimates of chlorophyll from the airborne Lidar system (HOGE and SWIFT, 1981; 1985). An r^2 of 0.92 was obtained for the shipboard and aircraft measurements in SEEP-I during 1984, similar to a range in r^2 of 0.77 to 0.95 within mid-Atlantic Bight waters off Virginia in 1980 (HOGE and SWIFT, 1981). The r^2 of shipboard and in situ measurements of chlorophyll is usually >0.60 and, at times, as high as 0.98 (WHITLEDGE and WIRICK, 1983).

The precision of the chlorophyll estimate is ± 0.05 µg ℓ^{-1} from the fluorometers at high sensitivity (WHITLEDGE and WIRICK, 1986), of the current velocity estimate is ± 1.0-1.3 cm sec^{-1} from the Endeco and Aanderaa meters above a threshold velocity of 2.5 cm sec^{-1}, and of the

INSTRUMENT BUOY W12

DEPTH(M)

7.9   ORE FLOAT (SS-288) (318+)

13.0   FLUOROMETER

15.3   ENDECO

21.8   VINEY FLOATS

23.2   FLUOROMETER AND
             TRANSMISSOMETER

25.2   THERMISTER

79.7   VINEY FLOATS

81.3   FLUOROMETER AND
             TRANSMISSOMETER

83.5   AANDERAA

             VINEY FLOATS

116.0   FLUOROMETER AND
             TRANSMISSOMETER

117.7

119.8   AANDERAA

122.3   AMF RELEASE

124.0   ANCHOR

DEPLOYED: 16 FEB 84   1327HR
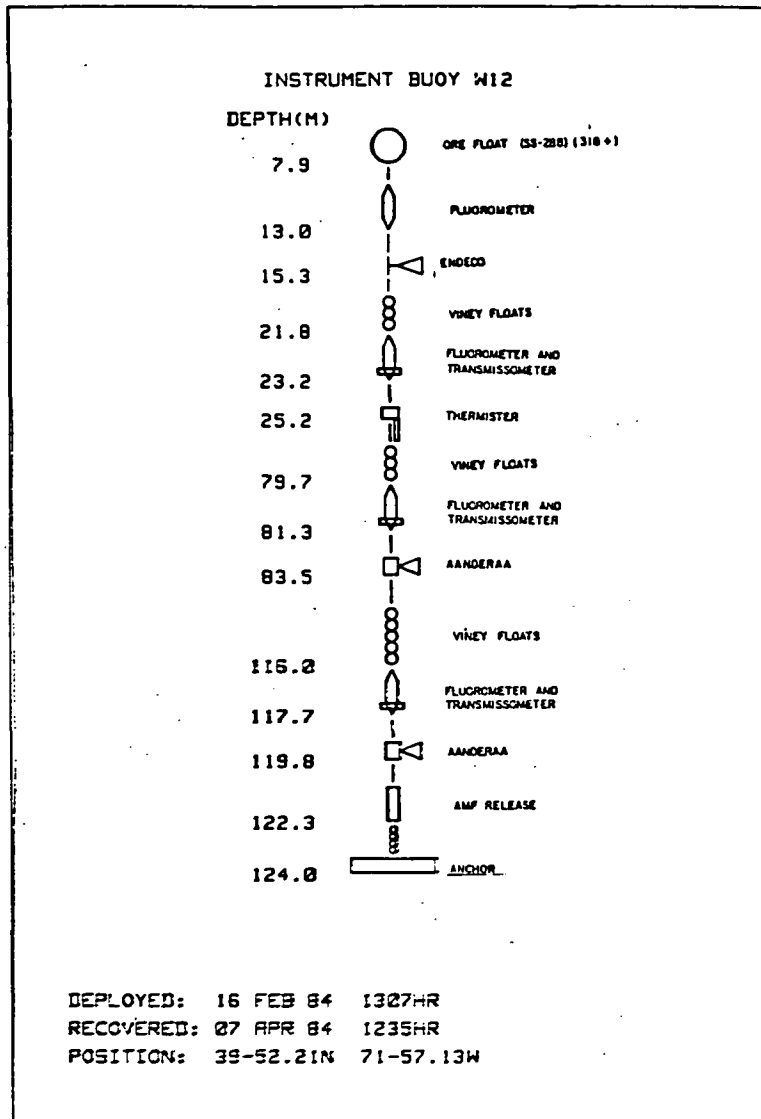RECOVERED: 07 APR 84   1235HR
POSITION: 39-52.21N   71-57.13W

Figure 2.   Instrumentation of the moored array at the 120m isobath,
south of Long Island.

temperature estimate from the thermistors is ±0.02°C. Analysis of the aircraft and shipboard measurements of temperature, with respectively a Precision Radiometric Thermometer (PRT-5) and a Niel Brown CTD, suggests, however, that the aircraft estimates were consistently ~2°C higher. Such a disparity does not preclude analysis of the spatial and temporal patterns of relative temperature; we have thus made this correction in constructing the aircraft maps of surface temperature.

RESULTS

Shipboard Perspective

During several 1984 cruises of R/V Oceanus to deploy, calibrate, and recover our moored instruments, hydrographic stations (e.g., Fig. 1) were occupied with a combined F/CTD, equipped with a rosette of 5.0 ℓ Niskin bottles, to obtain vertical profiles of temperature (Fig. 3), nitrate (Fig. 4), and chlorophyll (Fig. 5). Airborne sensors only provide data in the surface layer of the water column (POOLE and ESAIAS, 1982) while the moored instruments only provide time series at a few points in the sea. The locations of the surviving 12 moored fluorometers, for example, are indicated by Δ in Figure 5 of the cross-shelf chlorophyll transects.

A ~5-fold increase of vertical resolution can be obtained from bottle casts and >100-fold increase from F/CTD casts, compared to the moored arrays. The shipboard data base thus provides successive snapshots in time of the vertical cross-shelf structure of physical, chemical, and biological variables (Figs. 3-5). From these data, at least inferences can be drawn (WALSH et al., 1978) about the
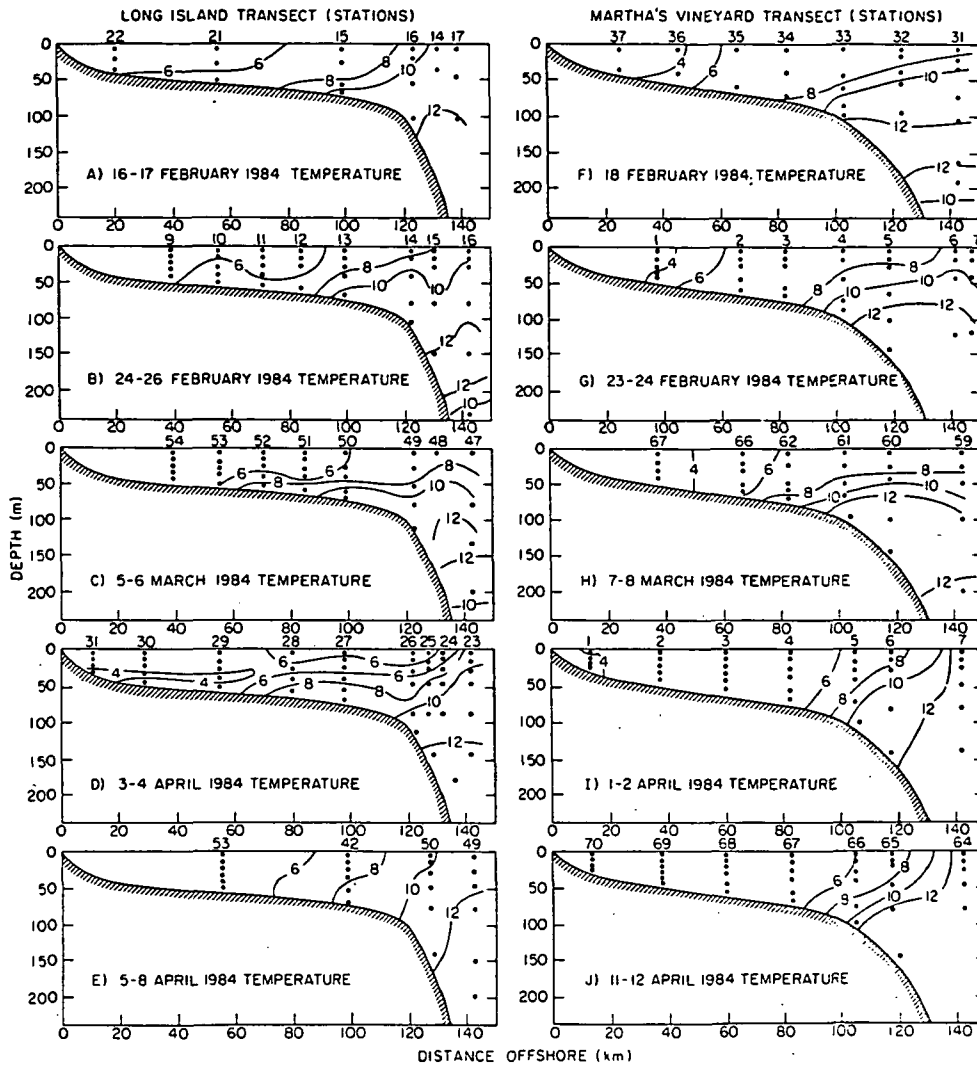
3

Figure 3.   Cross-shelf sections of temperature (°C), taken south of Long Island and Martha's Vineyard, from 16-17 February to 11-12 April 1984.
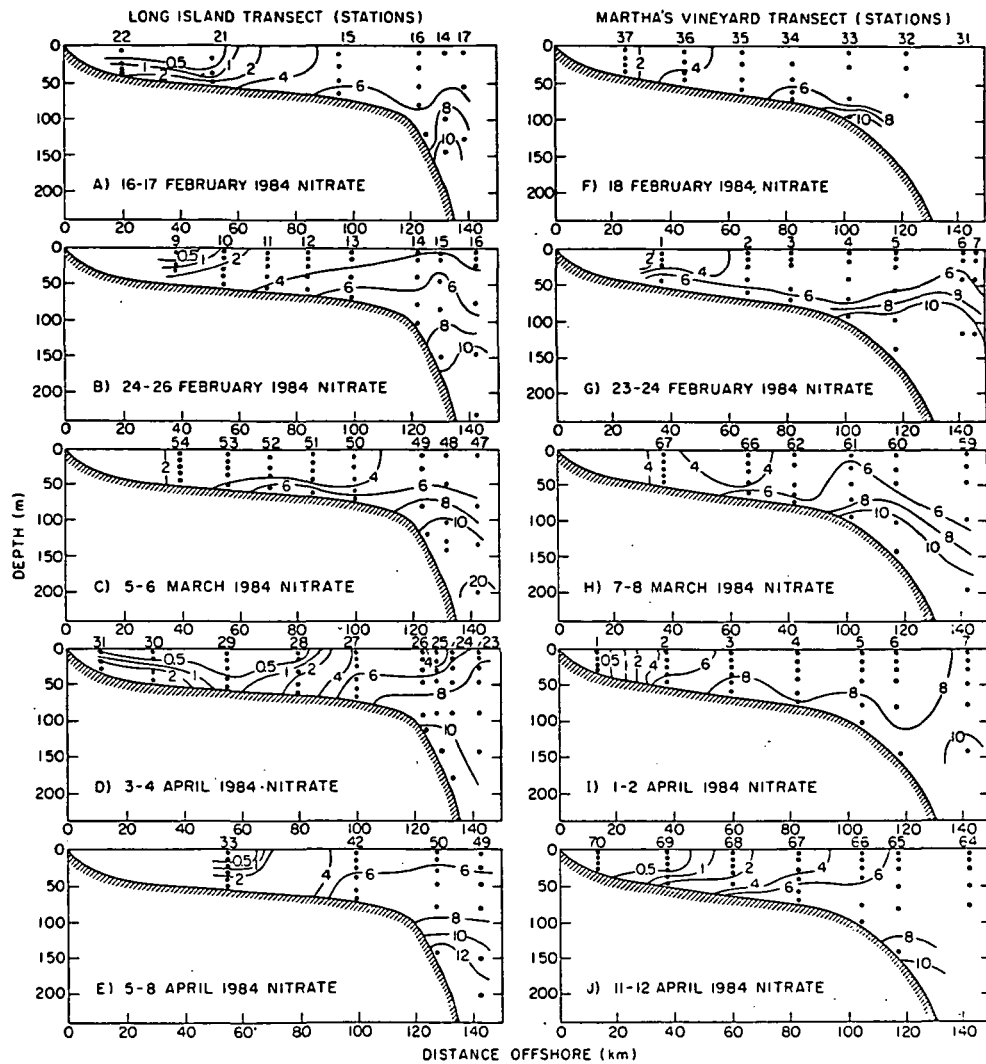
Figure 4. Cross-shelf sections of nitrate (μg-at NO_3 ℓ^{-1}), taken south of Long Island and Martha's Vineyard, from 16-17 February to 11-12 April 1984.

biological responses to changes in physical forcing at the wind event time scale (Fig. 6).

During February-May 1979-82, for example, 60 wind events >9 m sec^{-1} occurred in the mid-Atlantic Bight. Of these, 80% originated from the northwest quadrant, 10% from the northeast quadrant, and the remainder from the south quadrants. Under northwest wind forcing, an upwelling circulation occurs on this continental shelf, with an offshore Ekman layer at the surface and return onshore flow at depth (BEARDSLEY and BOICOURT, 1981; WALSH et al., 1987a). Northeast storms intensify the predominantly westward flow of the mid-Atlantic Bight, however, with a downwelling circulation as the diabathic pattern of shelf water transport. The rarer southeasterly wind events of the winter-spring seasons lead to eastward and onshore flow of surface water as well.

In response to a combination of such wind forcing, the mean flow of the upper 30 m of the water column past 4 moorings between the 46-105 m isobaths, south of Martha's Vineyard during February-April 1980 and April-May 1979 was 7.7 cm sec^{-1} to the west and 1.3 cm sec^{-1} offshore (BEARDSLEY, MILLS, VERMERSCH, BROWN, PETTIGREW, IRISH, RAMP, SCHLITZ and BUTMAN, 1983). On the outer shelf, within the lower part of the water column between the 66-105 m isobaths, the flow was also offshore at 1.4 cm sec^{-1} during these time periods in 1979-1980. We thus expected in 1984 to find an average offshore transport of the spring bloom within both the euphotic and aphotic zones of the mid-Atlantic Bight, as well, in response to a similar combination of northwest and northeast wind events.
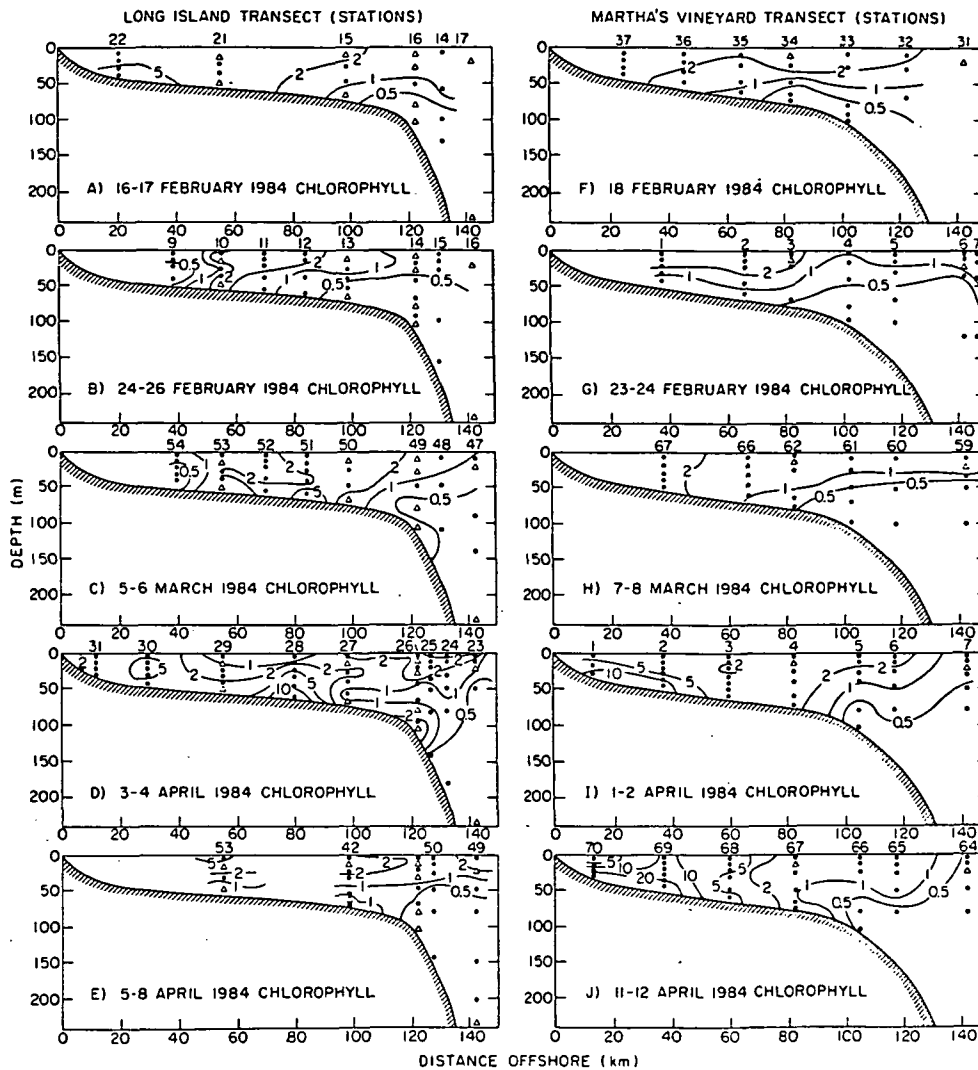
4

Figure 5. Cross-shelf sections of chlorophyll (μg chl ℓ^{-1}), taken south of Long Island and Martha's Vineyard, from 16-17 February to 11-12 April 1984.

Before the 1984 cross-shelf sections of hydrographic stations were taken south of Long Island and Martha's Vineyard, for example, five storms of I.0-1.5 dynes cm^{-2} intensity occurred from the northwest quadrant on 22 February, 3 March, 1 April, 8 April, and 10 April. After the first upwelling-favorable (northwest) wind event on 22 February 1984, an upward doming of the 6°C isotherm was found on the shelf off Long Island (Fig. 3b) and a seaward, surface tilt of the 4° and 6°C isotherms occurred within the colder shelf water south of Martha's Vineyard (Fig. 3g). In response to this first northwest wind event, at least 1-2 µg-at NO_3 ℓ^{-1} had been resupplied to the euphotic zone at mid-shelf off Long Island by 24-26 February (Fig. 4b), compared to <0.5 µg-at NO_3 ℓ^{-1} of surface waters found during the previous transect on 16-17 February (Fig. 4a). At this time, the near-bottom 6 µg-at ℓ^{-1} isopleth of nitrate had also apparently moved onshore ~40 km within 5-6 days between February 18 (Fig. 4f) and 23-24 (Fig. 4g) on the shelf off Martha's Vineyard, similar to other time series of this type (WALSH et al., 1978), implying an onshore flow of at least 6-8 cm sec^{-1}.

Seaward tongues of >2 µg chl ℓ^{-1} were found within the euphotic zone at mid-shelf off both Long Island (Fig. 5b) and Martha's Vineyard (Fig. 5g) after this nutrient injection. No subsurface maxima of chlorophyll were then found near-bottom on the inner shelf, as had been observed previously (Figs. 5a, 5f). The other four northwest wind events on 3 March, 1 April, 8 April, and 10 April 1984 led to similar physical, chemical, and biological patterns. An apparent 30 km onshore movement occurred, for example, of both the 8°C
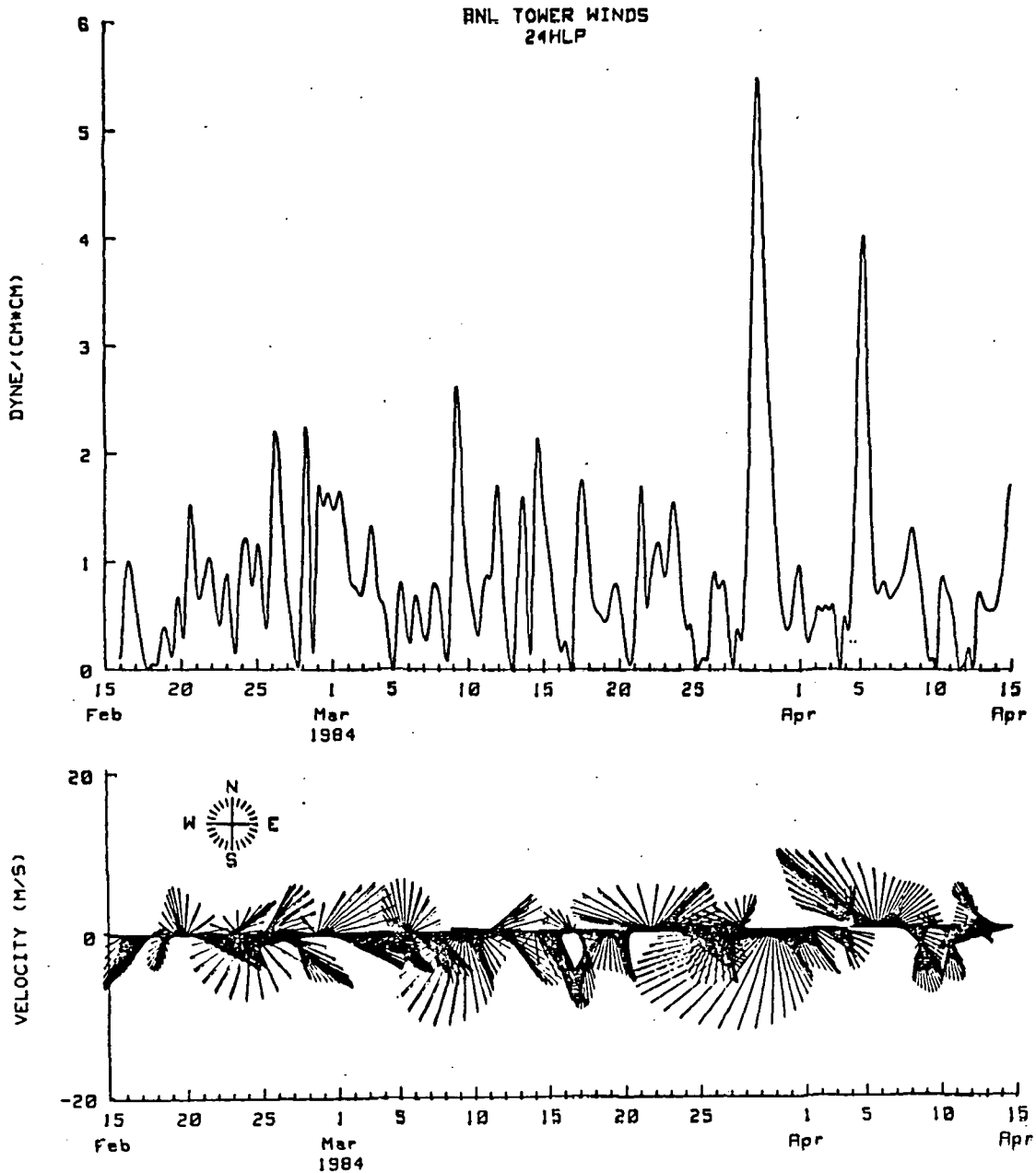
5

Figure 6.   The 24-hr. low-passed wind stress (dynes cm^{-2}), speed ($m\ sec^{-1}$), and direction (°T), measured at 88.4m on the Brookhaven National Laboratory meteorological tower, near Upton, Long Island, during 15 February - 15 April 1984.

isotherm (Figs. 3b, 3c) and the 6 µg-at ℓ^{-1} isopleth of nitrate
(Figs. 4b, 4c) between 24-26 February and 5-6 March. Similarly, at
least a doubling of the algal biomass took place within the euphotic
zone of the inner and middle shelves between 1-2 April and 11-12 April
(Figs. 5i, 5j).

In contrast, a strong "northeaster" of 29 March was followed by
the appearance of a bolus of sub-surface 4°C water on the Long Island
shelf (Fig. 3d), extending seaward near the bottom and presumably
originating from the north on the colder shelf off Martha's Vineyard
(Figs. 3h, 3i). Impoverished nitrate conditions (<0.5 µg-at NO_3 ℓ^{-1})
were then found in the euphotic zone, resulting from both a lack of
physical replenishment and previous biological uptake, while a
suggestion of downwelling of nutrient-poor water was found at
mid-shelf (Fig. 4d). Three regions of chlorophyll maxima were found
near-bottom in the cross-shelf transects taken after imposition of
this northeast wind forcing.

More than 10 µg ℓ^{-1} of chlorophyll were found near the bottom
within 20-40 km of the coast, upstream off Martha's Vineyard
(Fig. 5i). A similar amount of near-bottom algal biomass was found
downstream at mid-shelf off Long Island (Fig. 5d). Finally, a third
pool of >2 µg chl ℓ^{-1} of near-bottom chlorophyll was found at the
shelf-break off Long Island (Fig. 5d). These particular spatial
patterns of chlorophyll within a downwelling circulation, caught by
the relatively instantaneous vertical sampling (2 days) of the
shipboard transects, may reflect snapshots of a gradual seaward
translation of biogenic particles from the coast to the shelf-break,
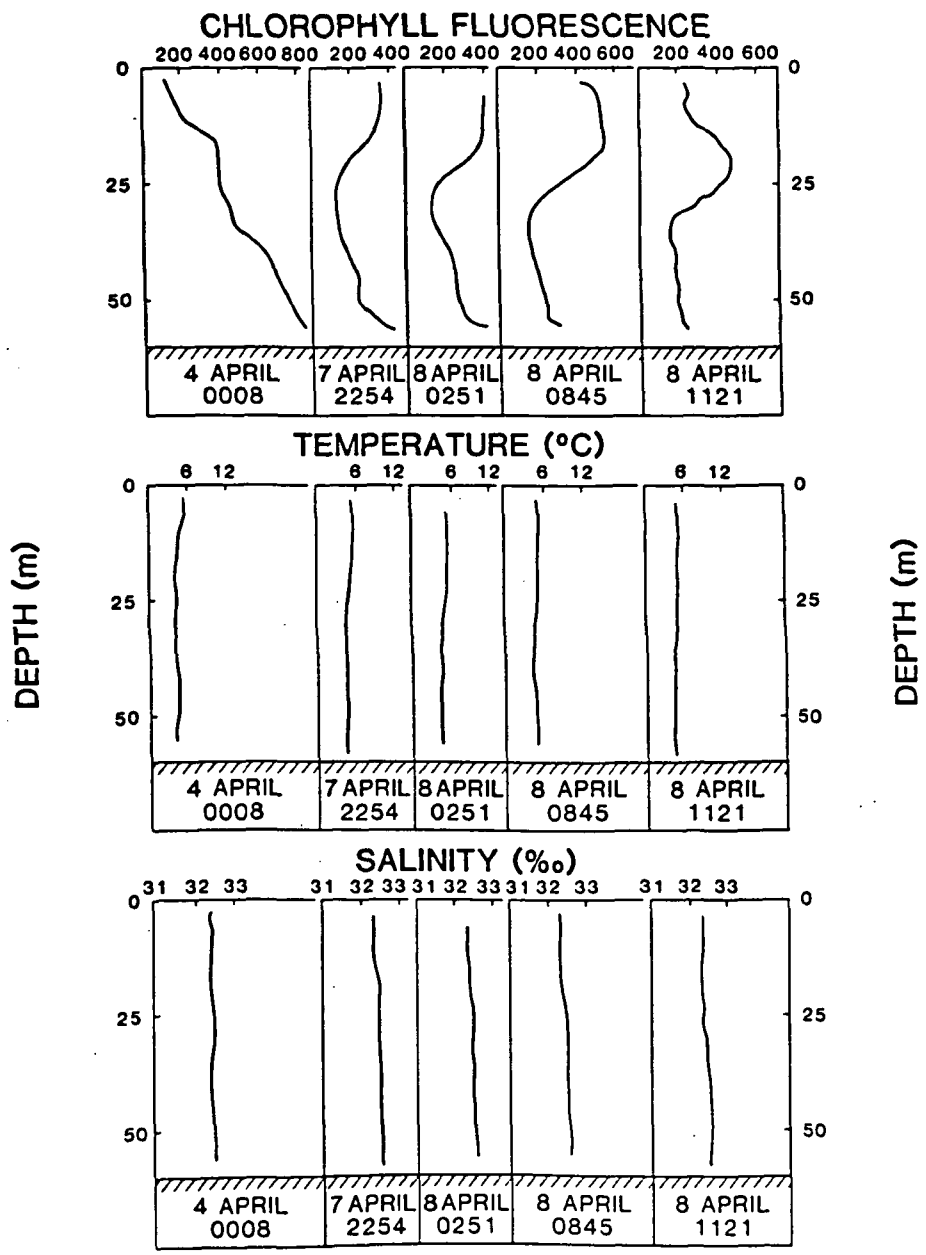over the winter-spring bloom of ~100 days (WALSH et al., 1987a).

CHLOROPHYLL FLUORESCENCE

TEMPERATURE (°C)

SALINITY (‰)

Figure 7.   A time series of continuous vertical chlorophyll fluorescence, temperature (°C), and salinity (%), taken with a F/CTD at the 60 m isobath, south of Long Island, during 4-8 April 1984.

A shorter time series (Fig. 7) of F/CTD vertical profiles at the 60 m isobath, south of Long Island, provides additional insight into the likely trajectory of phytoplankton cells after wind events within the mid-Atlantic Bight. During the weak wind conditions of 2-3 April 1984 (Fig. 6), the phytoplankton had evidently sunk out of the water column, to constitute a near-bottom fluorescence maximum, measured on 4 April 1984 at 0008 with the F/CTD (Fig. 7) and at 0030 with a bottle cast of less vertical resolution (Fig. 8). In response to the 8 April 1984 wind forcing from the northwest (Fig. 6), the algal biomass was evidently resuspended off the bottom, formed a surface maximum to be detected by remote sensing (Fig. 13), and sank within 12 hours to the middle of an unstratified water column (Figs. 7 and 8).

The continuous vertical profiles of the F/CTD time series, as well as the bottle casts, suggest a sinking rate of 20-40 m day^{-1} on 7-8 April 1984, similar to other FTD observations in March 1979 (WALSH et al., 1987a). Furthermore, the four estimates of depth integrated biomass of phytoplankton, in suspension above the 60 m isobath on 7-8 April 1984, were only 54-72% of that sunk out on 4 April 1984, i.e., a loss of biomass had apparently occurred during the 8 April 1984 resuspension event (Fig. 7). Grazing stress removes less than 10-30% of the daily primary production of the mid-Atlantic Bight at this time of year (DAGG and TURNER, 1982; WALSH, 1983; SMITH and LANE, 1987), suggesting that seaward export of phytoplankton biomass may have occurred.

After offshore transport events off Peru, the depth integral of algal biomass over the upper 40 m of the water column similarly
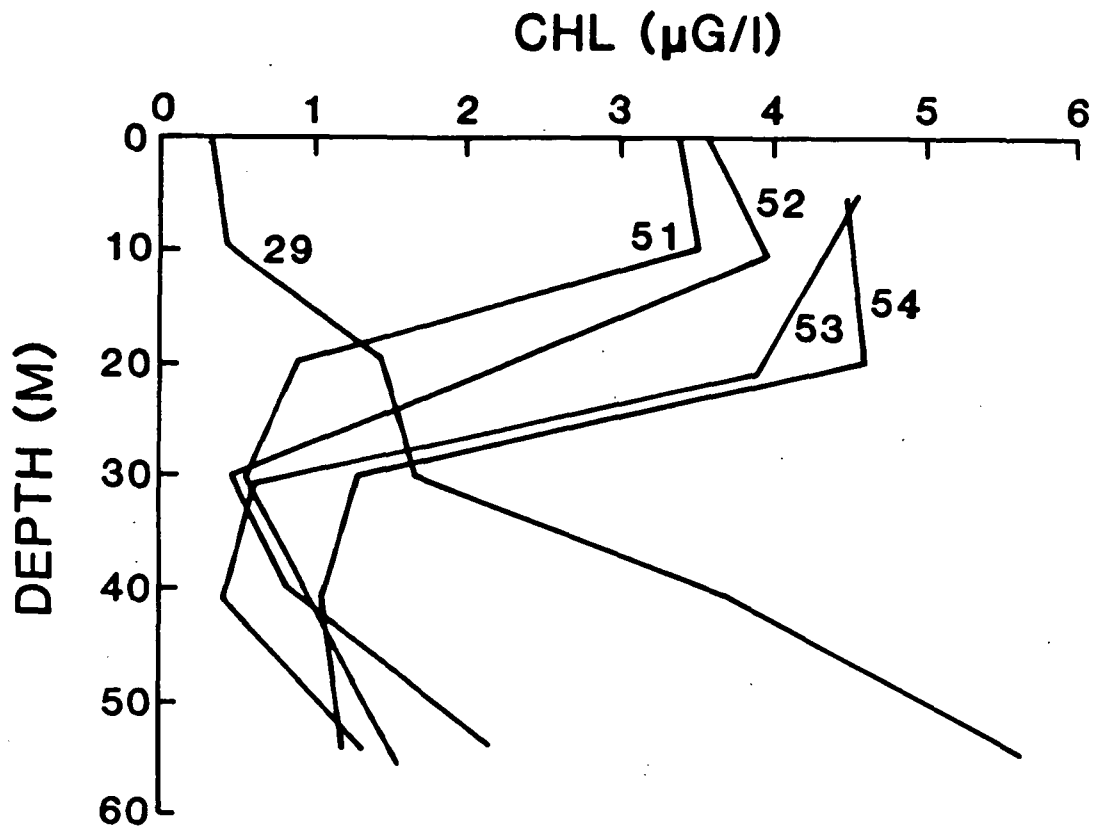
7

Figure 8. A time series of _in vitro_ chlorophyll measurements ($\mu g\ \ell^{-1}$) taken with 5ℓ Niskin bottle casts at the 60 m isobath, south of Long Island, during 0030 on 4 April (#29), and 0430 (#51), 0534 (#52), 0915 (#53), 1205 (#54) on 8 April 1984.

decreased by 10-25% in 1976 and 50-75% in 1977 (WALSH, WHITLEDGE, ESAIAS, SMITH, HUNTSMAN, SANTANDER and DeMENDIOLA, 1980). A sampling rate of 6 cross-shelf sections taken by a ship over ~50 days, of course, cannot capture the biological response to every change of wind forcing, let alone resolve the Nyquist frequency of one wind event (>0.5 day^{-1}), except for the above F/CTD and Niskin bottle time series. Higher sampling rates in both the horizontal and temporal dimensions during SEEP-I did corroborate, however, the inferences drawn from our vertical sampling program.

Aircraft Perspective

An aircraft overflight provides 20-fold more surface temperature or chlorophyll measurements within 2 hours than can be provided by a ship over ~200 hours of routine sampling at hydrographic stations, to be later contoured as surface maps of the thermal (Fig. 9a) and phytoplankton (Fig. 9b) fields. The April 1984 aircraft overflights were taken after the northwest wind events of 1.0-1.5 dynes cm^{-2} intensity on 1 and 8 April (Fig. 6). The areal extent of these overflights, with respect to the simultaneous Oceanus survey, is demarcated by the rectangle in Fig. 9b of the shipboard chlorophyll field.

The aircraft thermal fields from 2 (Fig. 10) and 8 (Fig. 11) April 1984 were similar to the 5-day shipboard temperature composite (Fig. 9a). Cold water of 5°C temperature was found near the mooring at the 60 m isobath south of Long Island (the moorings are denoted by ▲ in Figs. 10-13), while the shelf-break front, represented by the
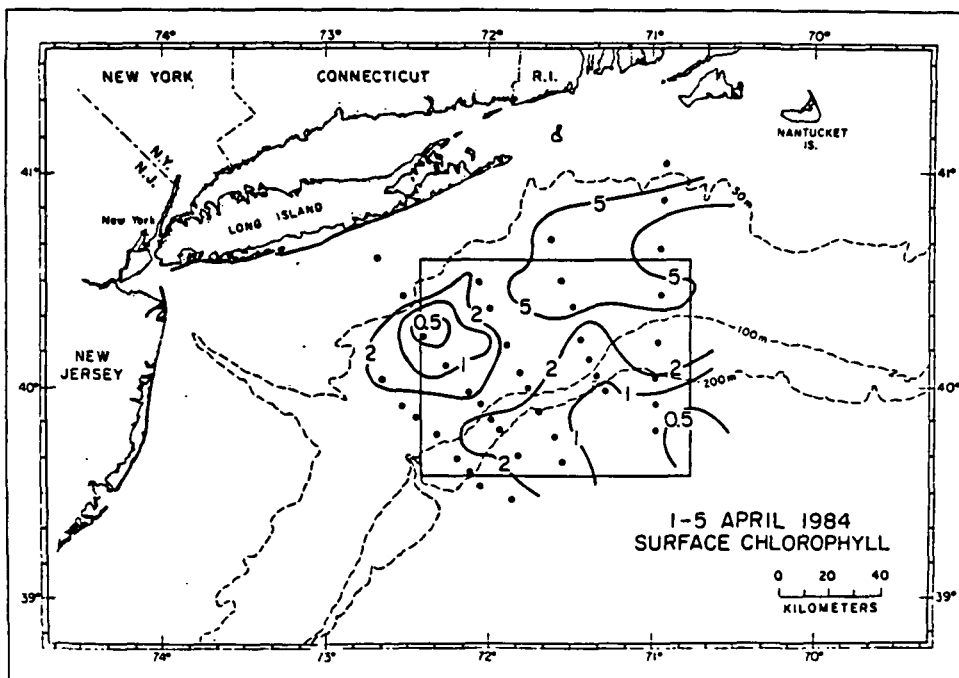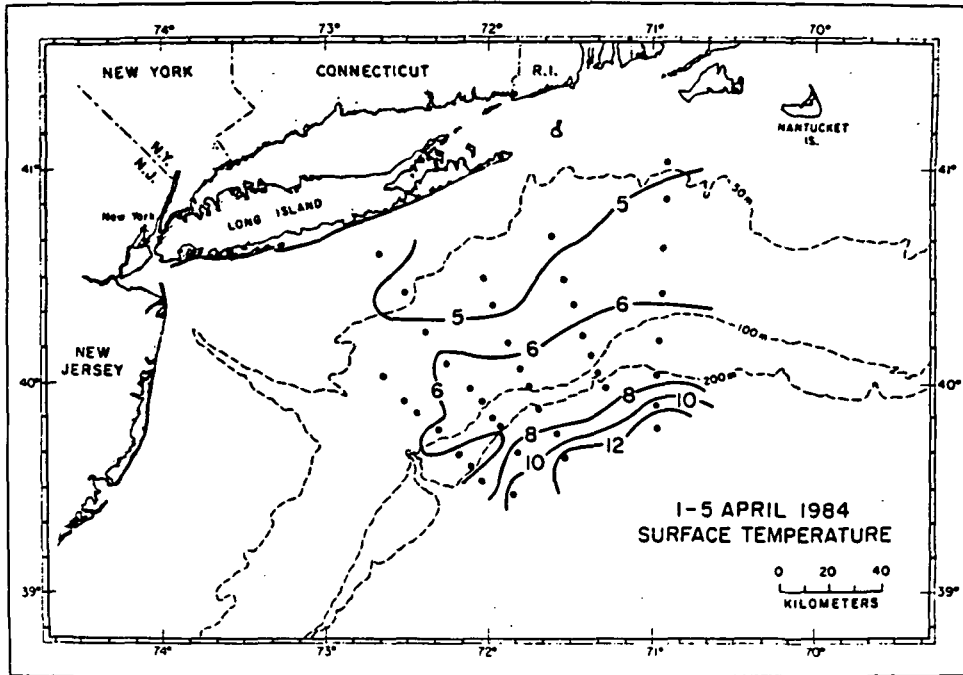
Figure 9. The surface distribution of a) temperature (°C) and of b) chlorophyll (µg ℓ^{-1}), measured aboard R/V <u>Oceanus</u> during 1-5 April 1984.

10°C isotherm, was detected along the moorings at the 400 m isobath. With the exception of the 7°C isotherm, which exhibited wave-like characteristics from one overflight (Fig. 10) to the next (Fig. 11), the relative cross-shelf positions of the isotherms did not change after an increase in the northwest wind forcing, from 1.0 dyne cm^{-2} on 1 April to 1.5 dynes cm^{-2} on 8 April.

The aircraft phytoplankton fields on 2 (Fig. 12) and 8 (Fig. 13) April 1984 were apparently different, however, with shelf plumes of 3-4 µg chl ℓ^{-1} extending out over the slope during the latter overflight, compared to seaward tongues of 1-2 µg chl ℓ^{-1} encountered during the former. Both phytoplankton fields contained algal biomasses of 6-7 µg chl ℓ^{-1} at the landward edge of the overflight pattern (Figs. 12, 13), similar to the right half of the shipboard chlorophyll composite (Fig. 9b).

Note that the seaward tongues of 1-2 µg chl ℓ^{-1} were captured by the coarse sampling grid of the ship during 1-5 April 1984 as well. Since the hydrographic stations were occupied on Oceanus from east to west (Fig. 1), however, and a major southwesterly wind event of 4.5 dynes cm^{-2} occurred on 5 April 1984 (Fig. 6), between the two northwest wind events, the shipboard composite (Fig. 9b) is badly aliased. As a result, the left half of the 1-5 April 1984 chlorophyll map from the Oceanus survey is very different from the aircraft overflight of 2 April 1984 (Fig. 12).

The aircraft sampling of chlorophyll on 8 April 1984 (Fig. 13) occurred during a northwest wind event, while the overflight of 2 April 1984 (Fig. 12) took place 24 hours after a previous northwest

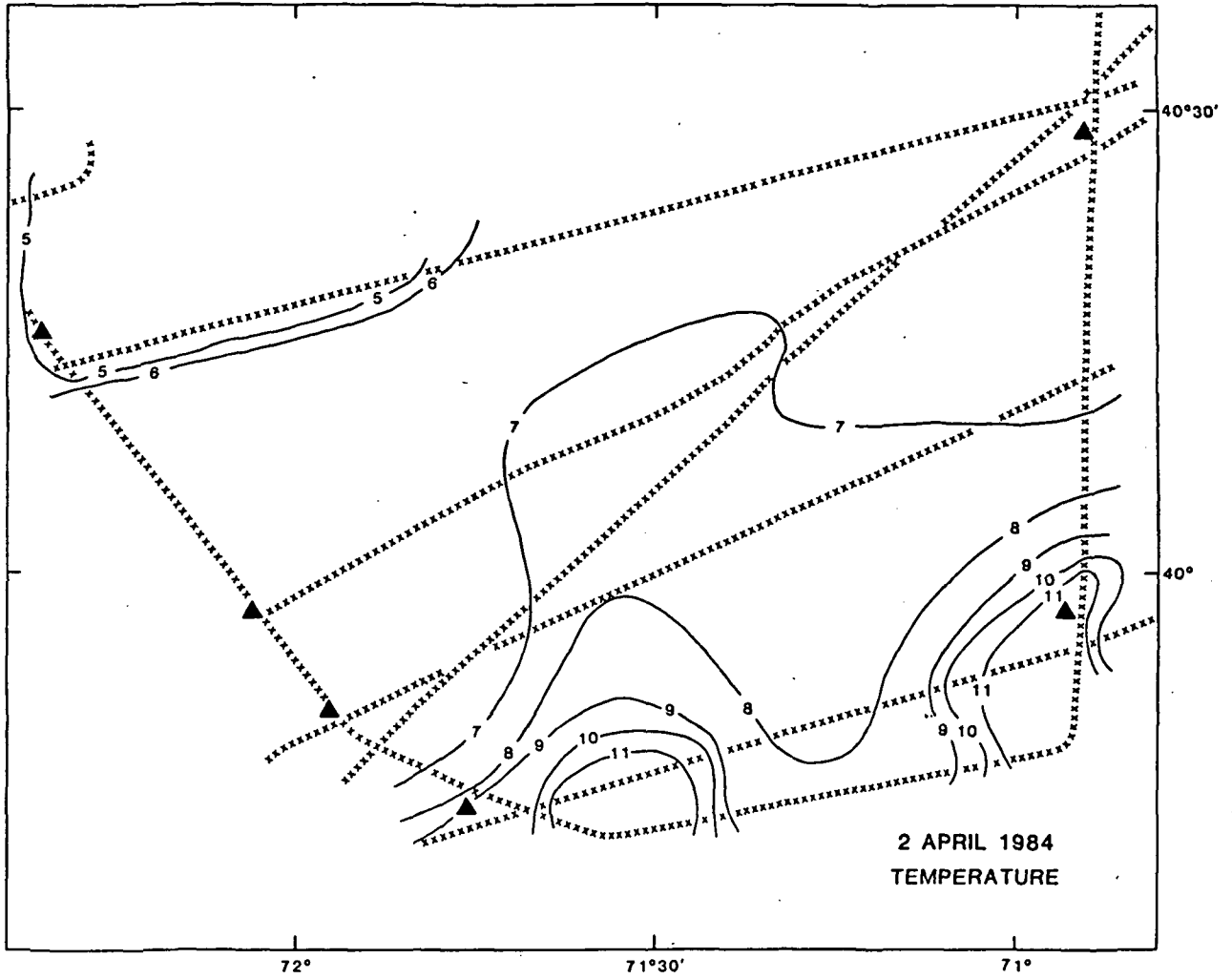Figure 10. The surface distribution of temperature (°C), measured aboard the P-3A aircraft with a PRT-5 during 2 April 1984.
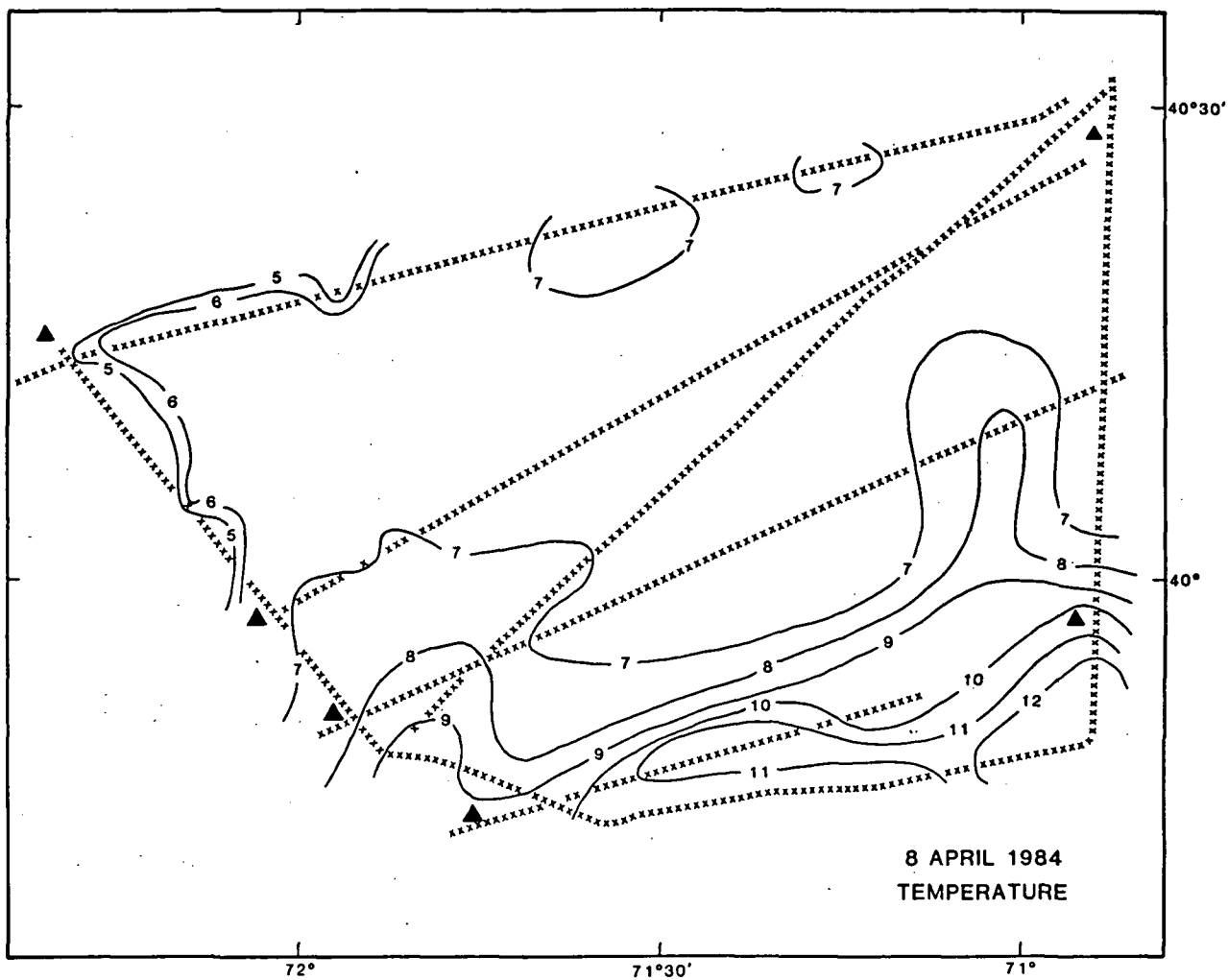
Figure 11. The surface distribution of temperature (°C), measured
aboard the P-3A aircraft with a PRT-5 during 8 April 1984.

event. The higher chlorophyll values encountered over the slope during the second overflight may represent phytoplankton cells which had yet to sink out of the water column. Recall the ~30 m day^{-1} sinking rate inferred from the F/CTD and rosette time series on 8 April 1984 at the 60 m isobath (Figs. 7 and 8), during a time when downwelling of water would have been minimal. After 24 hours of such a sinking rate in a shelf region seaward of the resuspension area, algal biomass would no longer be detected at the surface of the sea by the aircraft's Lidar fluorosensor.

The high chlorophyll biomass, detected by the aircraft at mid-shelf, may reflect a combination of in situ growth and resuspension of phytoplankton, previously sunk and/or downwelled out of the water column (Fig. 14). Such an accumulated, near-bottom algal biomass of 25 mg chl m^{-3} (Fig. 14) within a 10 m bottom layer at the 50 m isobath, together with a minimal amount of 0.5 mg chl m^{-3} within the upper 40 m before a resuspension event (Fig. 5b or 5c), would yield a mean concentration of 5.4 mg chl m^{-3} after vertical homogenization. A growth rate of 0.5 day^{-1} for the spring bloom (WALSH et al., 1987a) would lead to a total chlorophyll concentration of 8.1 mg chl m^{-3} within one day after an upwelling event, i.e., the amount detected at mid-shelf during both aircraft overflights. It appears that rapid vertical exchange processes may be of great biological consequence within the mid-Atlantic Bight (WALSH et al., 1987b), in addition to the horizontal fluxes, mainly measured by the moored arrays.
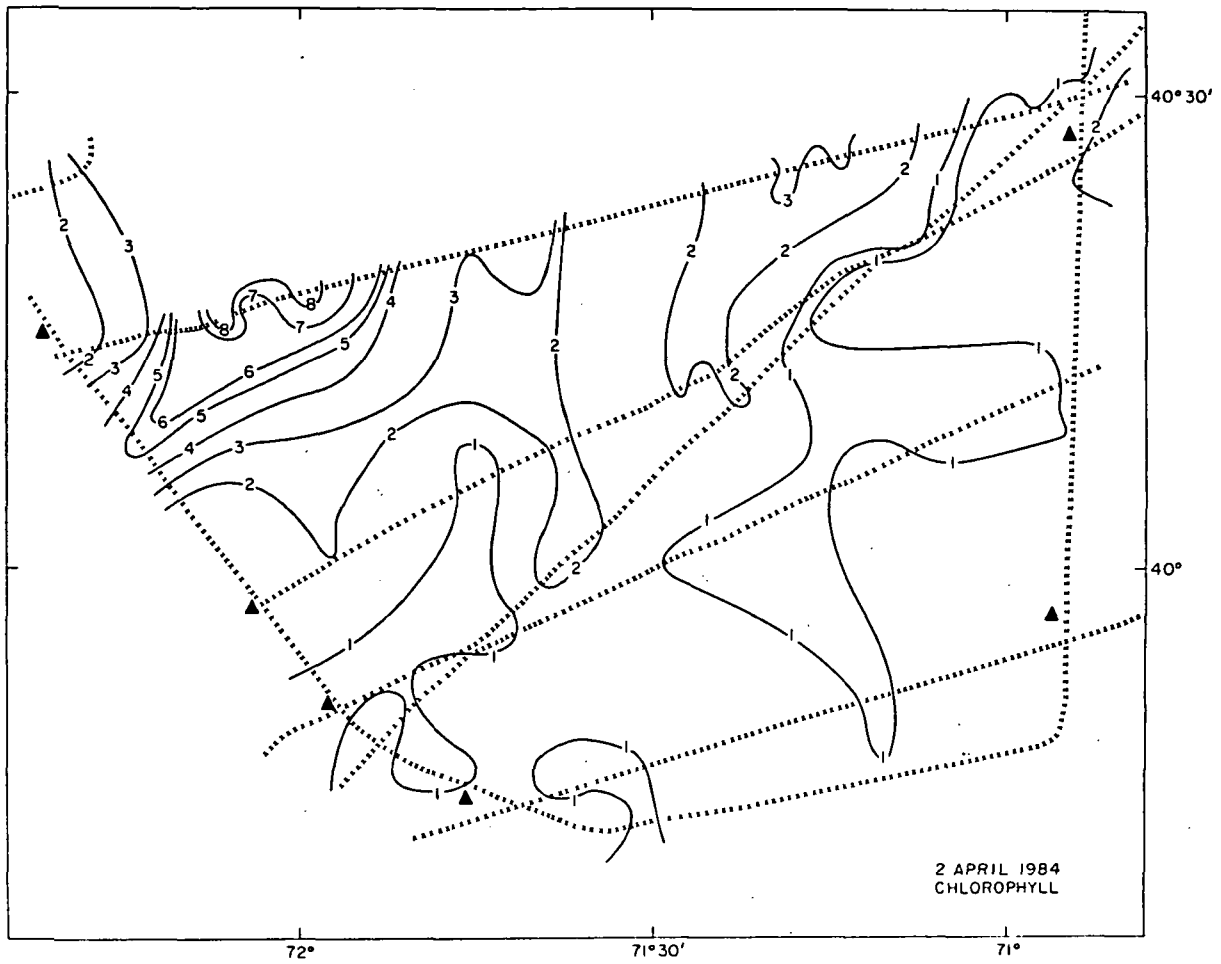
Figure 12. The surface distribution of chlorophyll ($\mu g \ \ell^{-1}$), measured
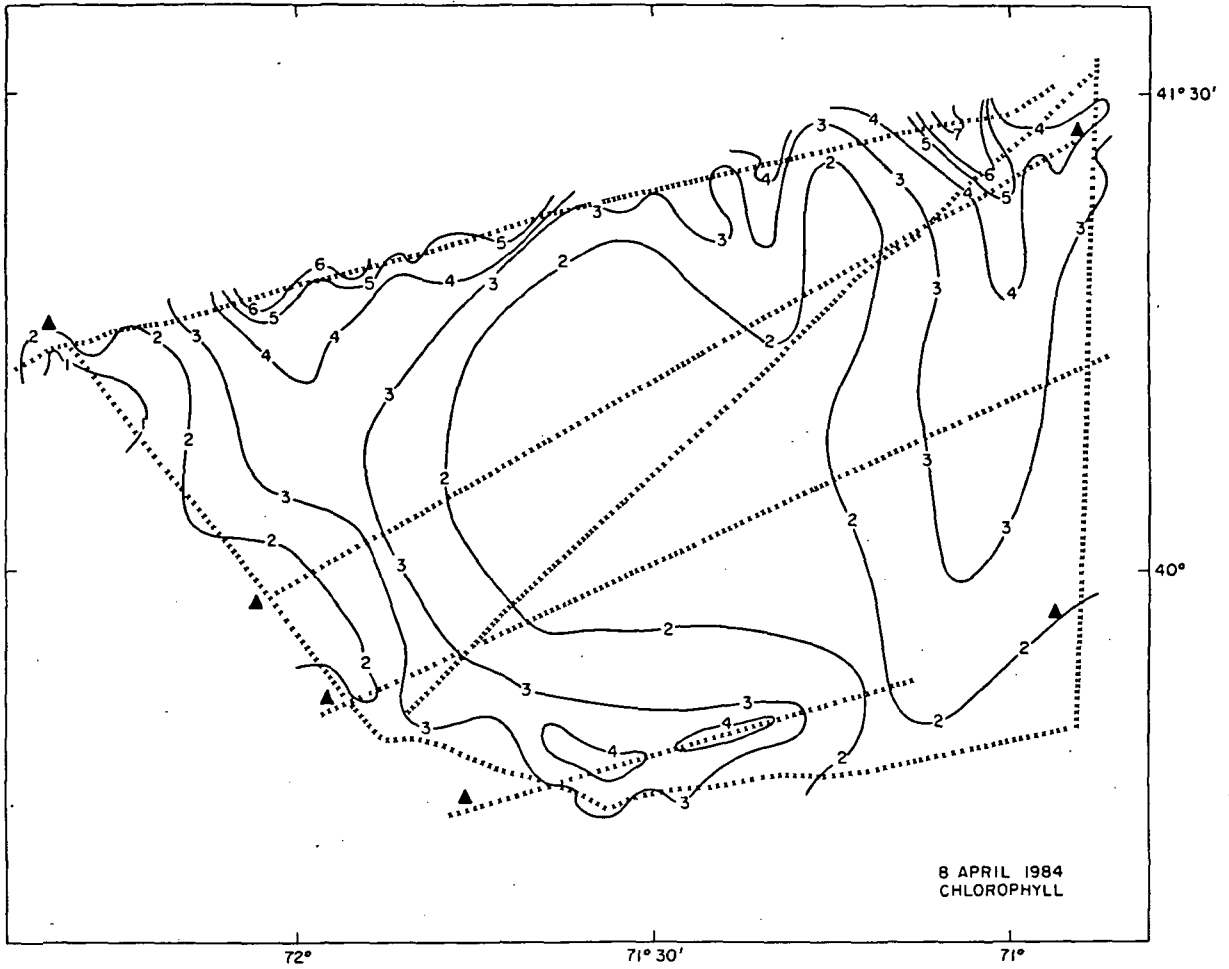aboard the P-3A aircraft with LIDAR during 2 April 1984.

Figure 13. The surface distribution of chlorophyll (μg ℓ^{-1}), measured aboard the P-3A aircraft with LIDAR during 8 April 1984.

In situ perspective

    a) Surface fluxes

    A few geographic locations in the mid-Atlantic Bight during
SEEP-I were sampled 4 times by aircraft, 6 times by ship, and ~5000
times by the moored arrays of current meters, thermistors,
fluorometers, and transmissometers. The cross-shelf response of the
water column at ~13 m depth to each wind event (Fig. 6) can be
inferred from time series of temperature at three of the moorings on
the 60 m, 80 m, and 120 m isobaths south of Long Island (Fig. 15).
Among 17 wind events from the northwest during the 1984 winter-spring
bloom, the offshore movement of cold shelf water, in response to those
storms detected by the ship time series, was traced at the moorings
(Fig. 15) by the seaward displacement of the 7°C isotherm on
22 February, 3 March, and of the 5°C isotherm on 1 April. Similarly,
among the 6 "northeasters" (Fig. 6), the onshore movement of warmer
water was clearly depicted on 9 March, and at just the dates of the
cross-shelf sections, by the landward displacement of the 6°C isotherm
on 29 March (Fig. 15).

    The current meter record of surface flow (~15 m) past the array
at the 80 m isobath south of Martha's Vineyard (Fig. 16) provides
confirmation of the inferences about water circulation drawn from
the temperature data off Long Island (Fig. 15). For example, the
diabathic component of flow here (Fig. 16a) was offshore at 1-10 cm
sec^{-1} during 2-6 March and 1-4 April 1984 after the northwest forcing,
and onshore at 5-15 cm sec^{-1} during 27-30 March in response to the
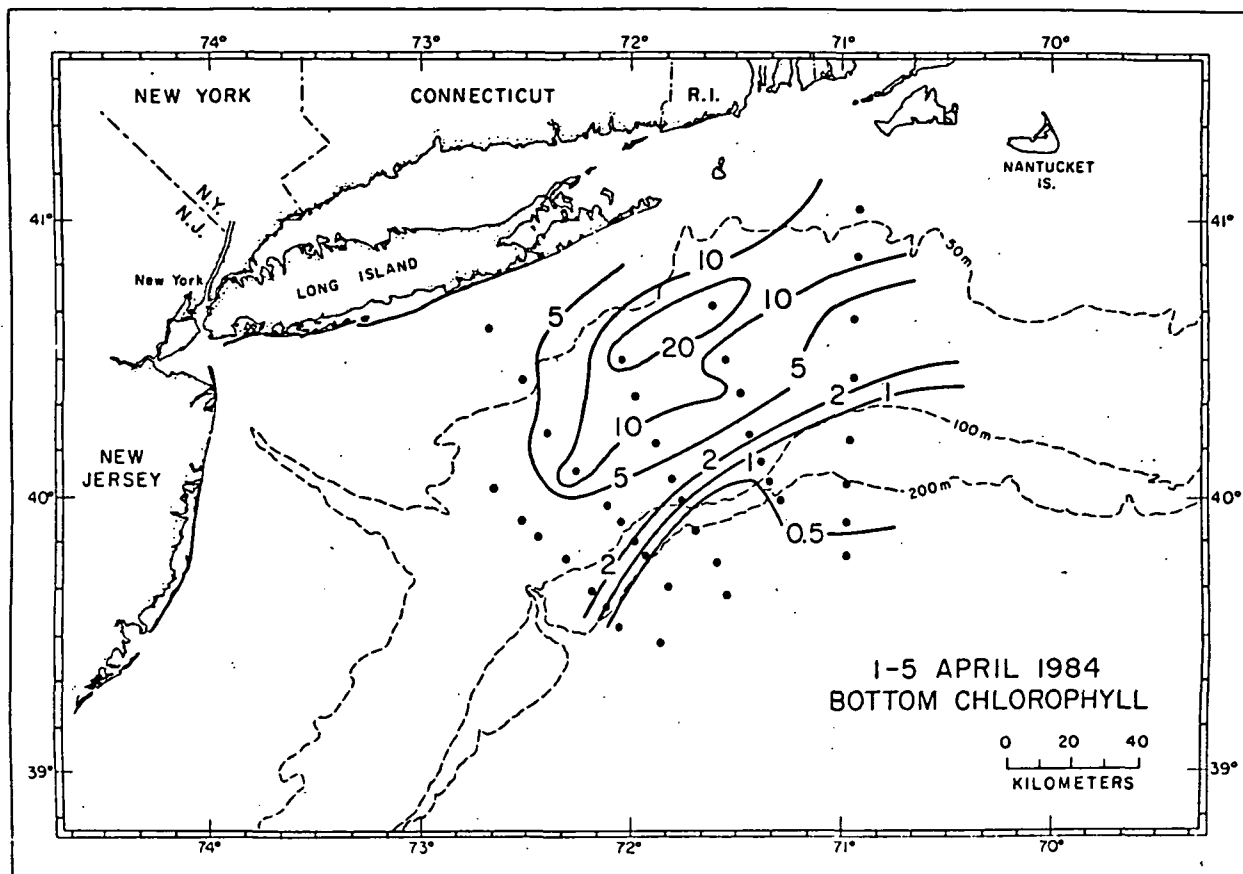strong northeasterly wind event. The temperature (Fig. 16b) and

Figure 14. The bottom distribution of chlorophyll (μg ℓ^{-1}) measured aboard R/V Oceanus with 5ℓ Niskin bottles during 1-5 April 1984.

chlorophyll concentrations (Fig. 16c) both declined here during the offshore surface flow on 2-6 March and 1-4 April 1984, as well, with a contrasting increase of temperature and algal biomass during the onshore flow on 27-30 March. Averaging over all of these wind events during the SEEP-I experiment, the net transport of chlorophyll, $\overline{uP}$, at the 80 m isobath south of Martha's Vineyard, was onshore at ~2.5 ng chl cm^{-2} sec^{-1} (Fig. 16d).

Seaward of the shelf-break at the 400 m isobath, south of Martha's Vineyard, the surface flow was stronger, the temperature gradients were greater, but less variation in algal biomass was observed (Fig. 17). The sense of the wind event response within the time series at the 80 m isobath was retained within those at the 400 m isobath, e.g., the 2-6 March northwest wind event, but other physical forcing was evident as well. The symmetric reversals here of the 25 cm sec^{-1} diabathic current (Fig. 17a), and of the temperature (Fig. 17b), between 26 March and 2 April suggest passage of a warm core ring, for example, with a systematic reduction in the amount of chlorophyll within surface slope waters, i.e., the lowest found in this record (Fig. 17c). The cumulative mean transport, $\overline{uP}$, of algal biomass was also onshore at the 400 m isobath (Fig. 17d) and about the same value, 2.5 ng chl cm^{-2} sec^{-1}, as at the 80 m isobath.

At the shelf-break mooring on the 120 m isobath (Fig. 18), south of Long Island and away from the mid-shelf resuspension area, the chlorophyll concentrations at the 13 m depth were lower than those at the 80 m isobath (Fig. 16). The temperature gradients and the current velocities here were also intermediate between the records obtained at

12

13M TEMPERATURE
40HLP DT-1DAY

W6

MOORING

W8

W12

15   20   25   1   5   10   15   20   25   1   5   10   15
Feb   Mar   Apr   Apr
                     1984
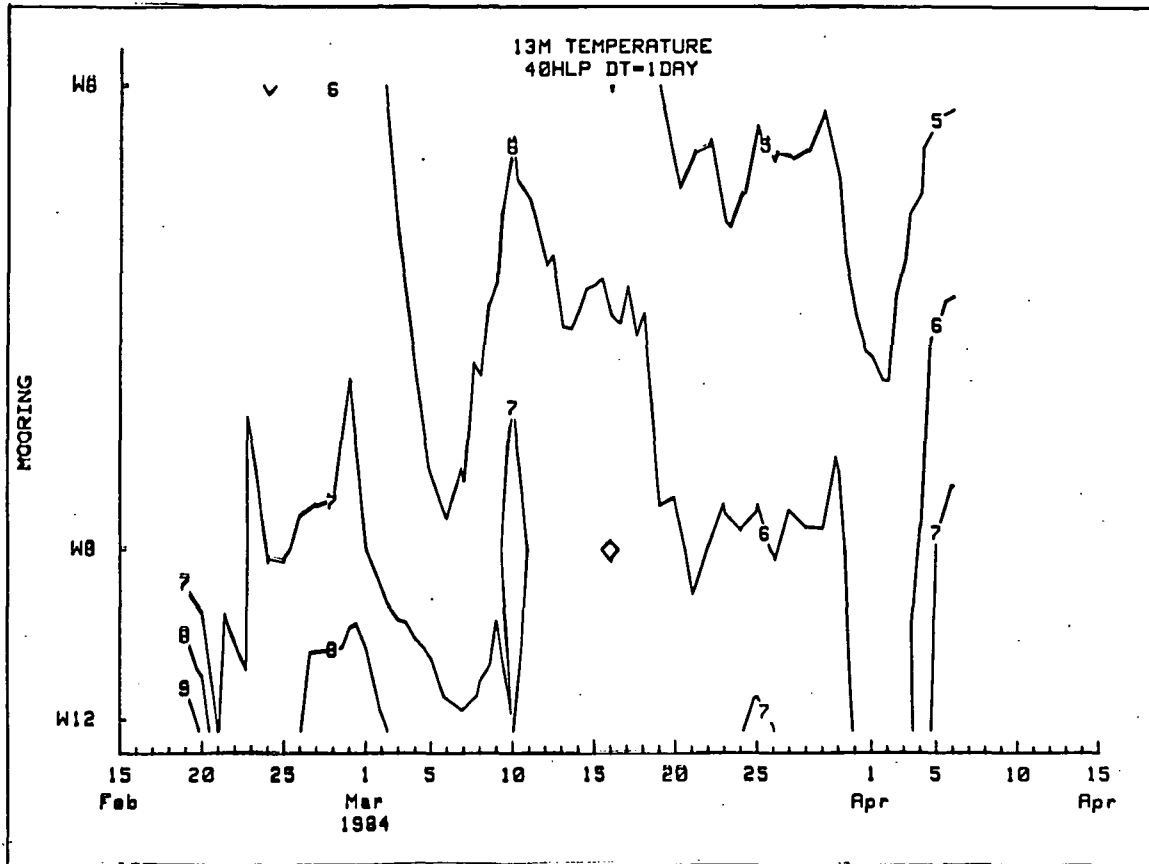
Figure 15. A time series of 40-hr. low-passed surface temperature
(°C), measured at 13m of the moorings on the 60, 80, and
120m isobaths with Fenwal thermistors during 18 February -
6 April 1984.

the 80 m and 400 m isobaths. Offshore surface flow of 5-15 cm sec^{-1} occurred during the 2-6 March and 1-3 April northwest wind forcings, with stronger onshore flow, up to a mean of 30 cm sec^{-1}, observed during the "northeaster" on 27-30 March (Fig. 18a). The temperatures of this record also increased and decreased with onshore and offshore reversals of the cross-shelf flow (Fig. 18b), similar to changes in chlorophyll concentrations (Fig. 18c) during the second half of the record. For most of this time series, the cumulative transport of chlorophyll, $\overline{uP}$, was offshore at the shelf-break, e.g., ~4.5 ng chl cm^{-2} sec^{-1} for 2 weeks, except for the last 8 days of the record, when chlorophyll biomass was lower and the strong onshore transport events dominated this running mean calculation (Fig. 18d).

Considering the apparent rapid sinking rate of diatoms during the 1984 spring bloom and the differences in physical forcing of shelf and slope waters, it is not surprising that chlorophyll fluctuations within the euphotic zone were poorly correlated at these moorings (Fig. 19). The coefficient of determination, r^2, of the 2-hr. low-passed surface (13 m) chlorophyll data at E8 (80 m isobath south of Martha's Vineyard - Fig. 16c) with those downstream at W12 (120 m isobath south of Long Island - Fig. 18c), for example, was only 0.046 at a zero time lag. A 40-hr. low-pass filter of these data at zero time lag removed more of the high frequency fluctuations in these chlorophyll records (Fig. 19), such that the r^2 of the data at E8 and W12 then became 0.125. The r^2 of 40-hr. low-passed chlorophyll records of 13 m at E8 with W8 (0.019), and W8 with W12 (0.002), were even less, despite this reduction in variance (Fig. 19).

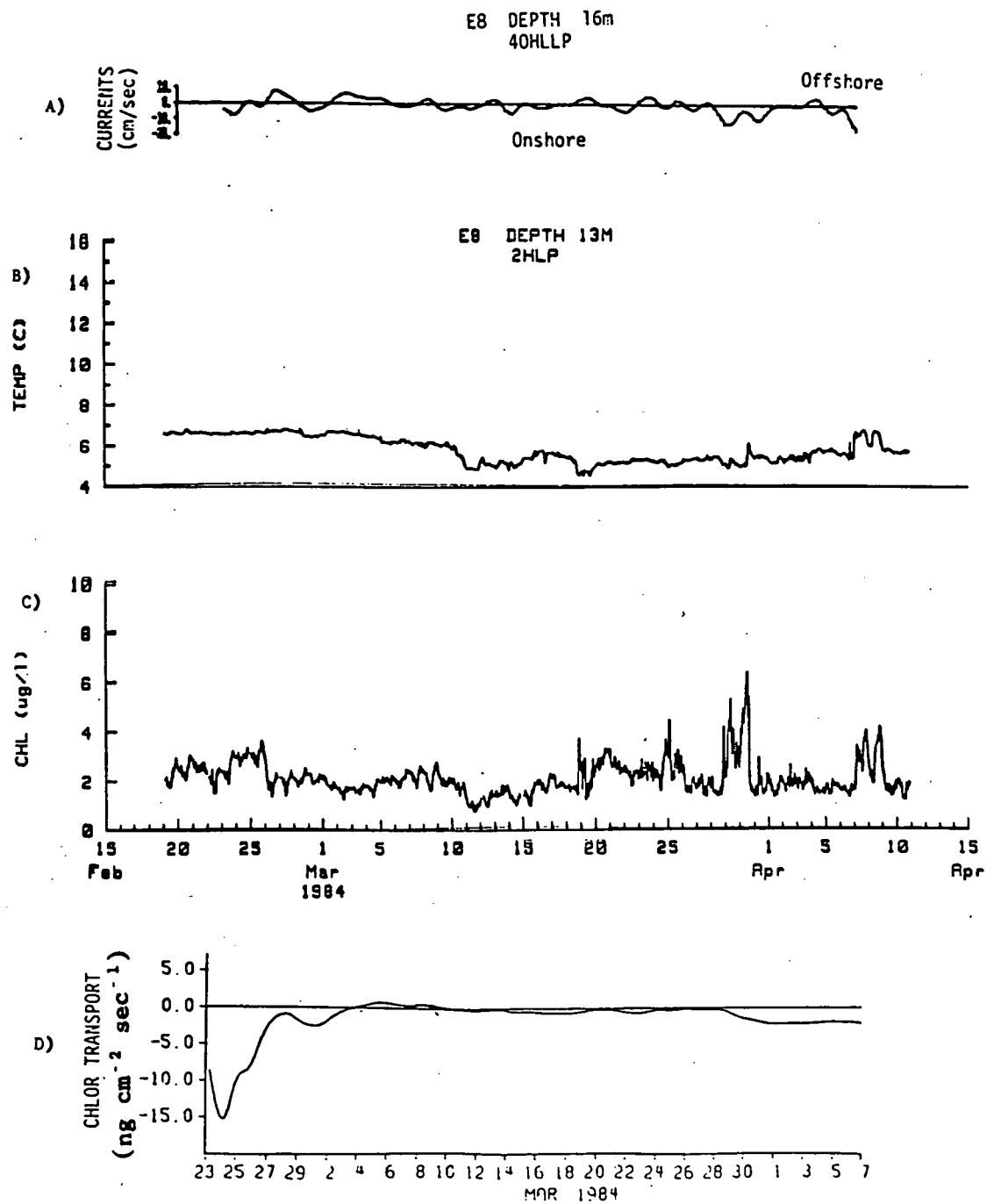**Figure 16.** A time series of a) 40-hr. low-passed currents (cm sec^{-1}),
b) 2-hr. low-passed temperature (°C), c) 2-hr. low-passed
chlorophyll (μg ℓ$^{-1}$), and d) 40-hr. low-passed cumulative
chlorophyll transport (ng cm^{-2} sec^{-1}) at 13-16 m depths on
the 80 m isobath, south of Martha's Vineyard during
19 February - 11 April 1984.

The downstream, or parabathic, component of the surface flow (15 m) at the W12 mooring was, at times, greater than 40 cm sec^{-1} (Fig. 20), while the mean vector flow along a trajectory from E8 to W12 (Fig. 1) during SEEP-I was ~15 cm sec^{-1}. Over a separation distance of 80 km between these two moorings and a flow of 15-20 cm sec^{-1}, a particle would take ~4-6 days to move from E8 to W12, if it were retained within surface waters. The r^2 of the 40-hr. low-passed, surface chlorophyll data between E8 and W12 (Fig. 19) at 4- and 5-day time lags, in fact, became much less, respectively 0.001 and 0.004. The flow near the bottom at W12 was weaker (Fig. 20), with a parabathic mean of only 1.6 cm sec^{-1} and a diabathic mean of 1.0 cm sec^{-1}. Within such a flow regime, a near-bottom particle would exit first at the shelf-break, 20 km south of E8, before arriving 60 km farther downstream at W12, if if were not resuspended higher in the water column.

The poor coherence of these surface (13 m) chlorophyll records over the presumed transit time suggests both that sinking of phytoplankton is rapid in the mid-Atlantic Bight, and that resuspension of near-bottom particles does not occur within the euphotic zone on the outer part of the shelf. The memory of algal population changes is thus not maintained here throughout the whole water column, to be later recorded, downstream of a propagation event, at a near-surface depth of 13 m. This is in contrast to our other Eulerian studies in the South Atlantic Bight and the Bering Sea, where over a similar separation distance, but at bottom depths of only 15-45 m, time-lagged r^2 of near-surface fluorometer records were as

E40 DEPTH 16m
40HLLP

A) CURRENTS (cm/sec)   Offshore
              Onshore

B) TEMP (C)   E48 DEPTH 13M
                               2HLP
    18
    14
    12
    10
     8
     6
     4

c) CHL (ug/l)
    10
     8
     6
     4
     2
     0
    15   20   25   1   5   10   15   20   25   1   5   10   15
    Feb   Mar   Apr   Apr
                     1884

D) CHLOR TRANSPORT (ng cm⁻² sec⁻¹)
    15.0
    10.0
     5.0
     0.0
    -5.0
   -10.0
    23 25 27 29 2 4 6 8 10 12 14 16 18 20 22 24 26 29 30 1 3 5 7
                        MAR 1984
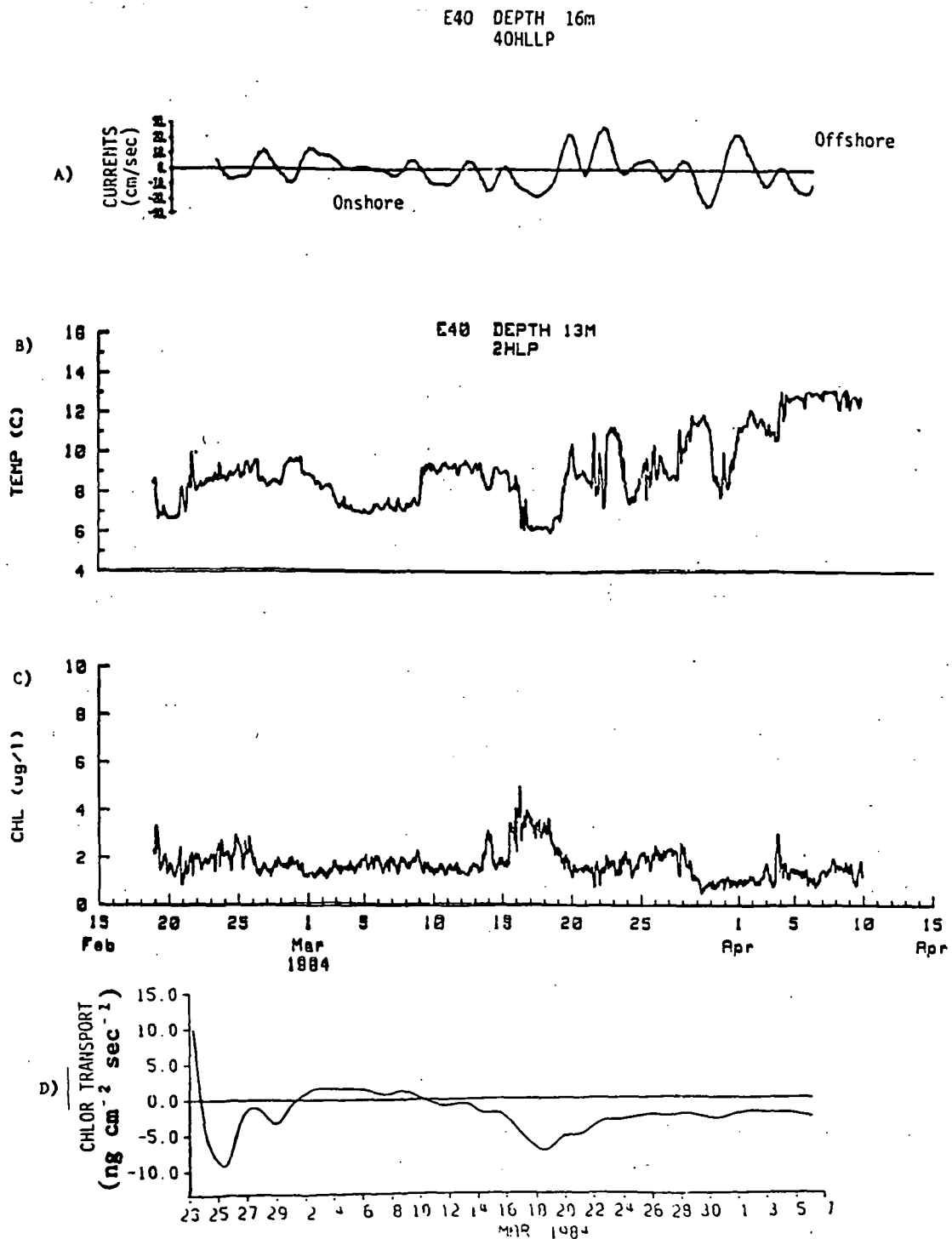
Figure 17. A time series of a) 40-hr. low-passed currents (cm sec⁻¹),
            b) 2-hr. low-passed temperature (°C), c) 2-hr. low-passed
            chlorophyll (µg ℓ⁻¹), and d) 40-hr. low-passed cumulative
            chlorophyll transport (ng cm⁻² sec⁻¹) at 13-16 m depths on
            the 400 m isobath, south of Martha's Vineyard during
            19 February - 11 April 1984.

high as 0.1-0.2, i.e., two orders of magnitude larger than those of

the outer mid-Atlantic Bight.

b) Bottom fluxes

The fluorometer records from instruments overlying each other at

13 m, 23 m, and 81 m depths on the 120 m isobath (Fig. 21), south of

Long Island, showed high correlations, however, compared to the low

spatial coherence of surface algal biomass. For example, the r^2 of

the 40-hr. low-passed records of algal biomass between 13 m and 23 m

at W12 was 0.38, again two orders of magnitude greater than between

the 13 m records at W12 and W8. Over the whole water column, the r^2

of the 13 m and 81 m chlorophyll records at W12 was somewhat less,

0.28, because the near-bottom phytoplankton were entrained within a

different flow regime, moving onshore when the surface water was

advected seaward and moving offshore when the surface flow was onshore

(Fig. 20).

An increase of chlorophyll within the aphotic zone during

"northeasters" (Figs. 5 and 21) implies either downwelling of surface

algal biomass, and/or seaward movement of near-bottom chlorophyll from

shallow sources (Fig. 14), during the intense longshore and offshore

movement of the near-bottom water, e.g., on 9-10 March, 17-18 March,

and 29-30 March (Fig. 20). The temperature records at 3-5 m above the

bottom on the 60 m, 80 m, and 120 m isobaths, south of Long Island,

trace these near-bottom flow events, with seaward displacement of the

7°C isotherm, for example, on 9-10 March, 17-18 March, and 29-30 March
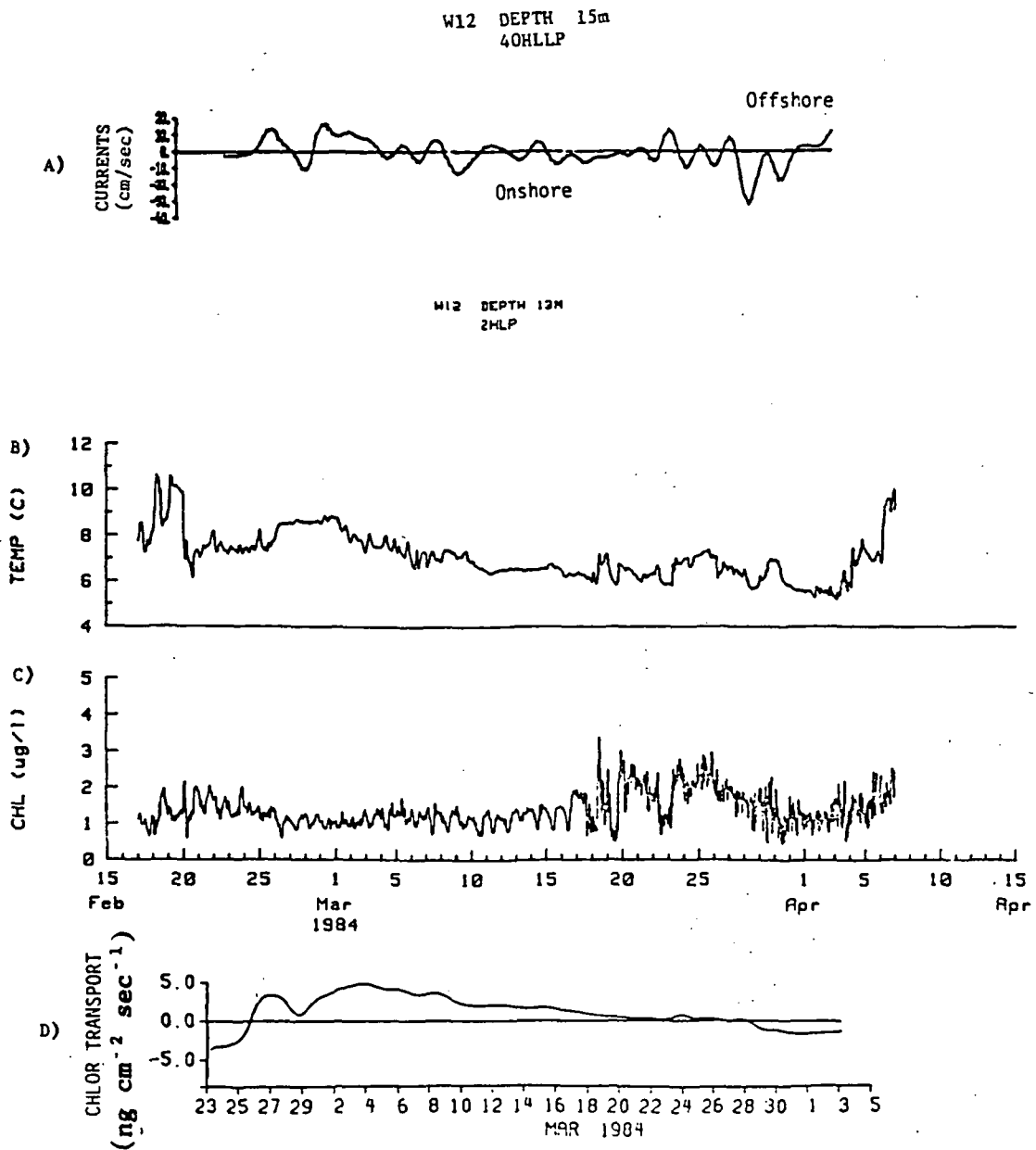

15

W12 DEPTH 15m
40HLLP

Offshore

A) CURRENTS (cm/sec)

Onshore

HI2 DEPTH 13M
2HLP

B) 12
    TEMP (C) 10
              8
              6
              4

c) CHL (ug/l) 5
                4
                3
                2
                1
                0

15   20   25   1   5   10   15   20   25   1   5   10   .15
Feb   Mar   Apr   Apr
                     1984

D) CHLOR TRANSPORT (ng cm⁻² sec⁻¹)   5.0
                                      0.0
                                     -5.0

    23 25 27 29 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 1 3 5
                            MAR 1984

Figure 18. A time series of a) 40-hr. low-passed currents (cm sec⁻¹),
            b) 2-hr. low-passed temperature (°C), c) 2-hr. low-passed
            chlorophyll (µg ℓ⁻¹), and d) 40-hr. low-passed cumulative
            chlorophyll transport (ng cm⁻² sec⁻¹) at 13-15 m depths on
            the 120 m isobath, south of Long Island during
            17 February - 6 April 1984.

(Fig. 22). High chlorophyll was also observed at 5 m above the bottom on the 80 m isobath after the 17-18 March northeaster (Fig. 23).

Evidence for resuspension of both chlorophyll and fine-grain sediments during these offshore flow events of near-bottom water was also provided by the transmissometer records at the 80 m (Fig. 23) and 120 m (Fig. 25) isobaths. In response to each of the bottom offshore transport events (Fig. 23a), the extinction coefficient of the near-bottom water, k, increased, with little difference in maximum value (~1.75 m^{-1}) at the beginning or end of this record at the 80 m isobath (Fig. 23c). In contrast, the chlorophyll record (Fig. 23b) exhibited here an order of magnitude increase in biomass with time, reflecting the seasonal buildup, seaward export, and sinking to the bottom of the spring bloom. The r^2 of zero lag between the 40-hr. low-passed chlorophyll records of 13 m and 75 m depths at W8 was 0.32, similar to the vertical coherence at W12. Some of these near-bottom increments of algal biomass might thus be in response to northwest wind forcing, surface export, and then sinking, e.g., 1-3 April, while other occurred after "northeasters" and near-bottom export, e.g., 29-30 March.

To perhaps distinguish between surface and bottom export events of phytoplankton, we first computed those parts of the light extinction attributed to phytoplankton (0.0852 x chl) and coastal surface water (0.459 m^{-1}), and then subtracted them from the concurrent observations obtained by the moored transmissometers (Fig. 24). At 5 m above bottom on the 80 m isobath (Fig. 24c), for example, the abiotic particles were apparently a major component of
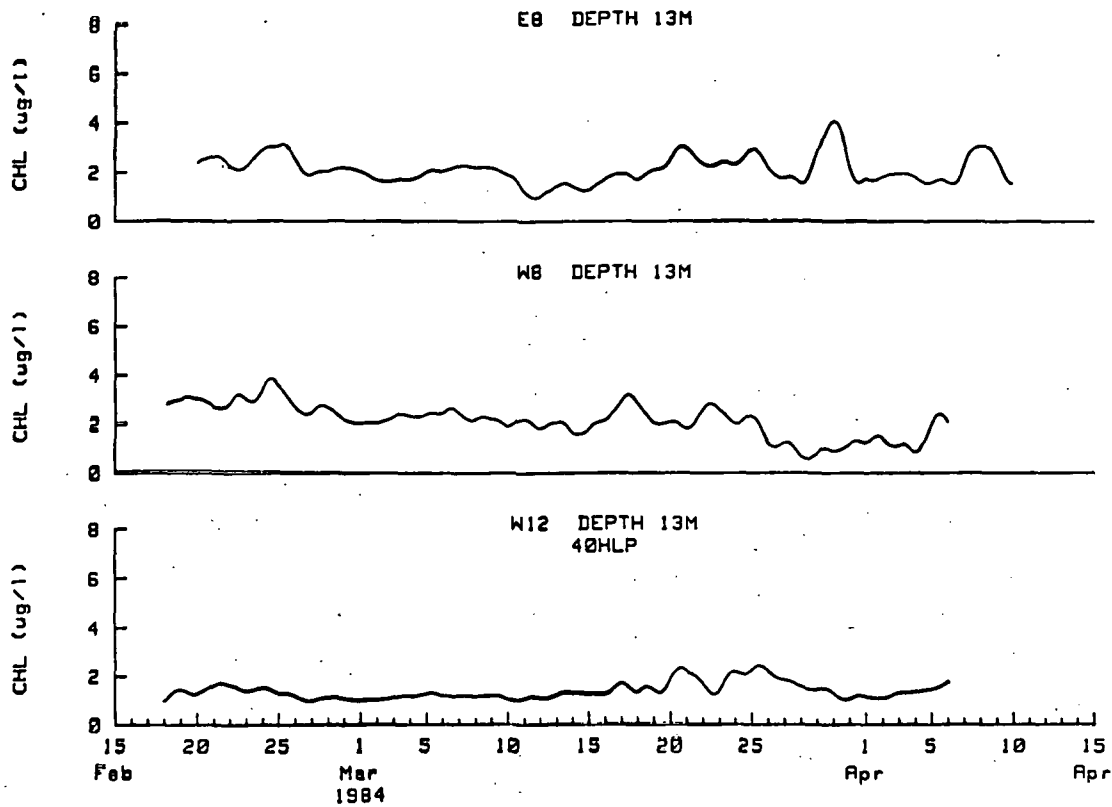
16

Figure 19. A time series of 40-hr. low-passed chlorophyll ($\mu g\ \ell^{-1}$) at 13m depth on the 80m isobath, south of Martha's Vineyard, and on the 80m and 120m isobaths, south of Long Island, during 17 February - 11 April 1984.

light extinction after offshore flow events on 28 February,
9-10 March, 17-18 March, 24 March, 29-30 March, and 5 April, i.e.,
those prominent within the temperature time series as well (Fig. 22).
During northwest wind events on 2-6 March and 1-4 April, however, the
abiotic contribution to light extinction was negligible (Fig. 24c),
similar to the transmissometer observations during most of the time at
23 m below the surface on the 120 m isobath (Fig. 24a).

The same biotic sinking events, after northwest wind forcing,
were also captured by another transmissometer, moored 3 m above the
bottom on the 120 m isobath. The abiotic signal was much weaker 40 m
above the bottom at this isobath (Fig. 24b), however, suggesting that
most of the export of fine-grain particles, and perhaps of
phytoplankton, occurred within the lower third of this water column.
For example, summing over these surface and bottom Ekman transport
events, the cumulative chlorophyll transport, $\overline{uP}$, at 75 m depth on the
80 m isobath was a net seaward export of 3.0 ng chl cm^{-2} sec^{-1} during
all of SEEP-I (Fig. 23d).

DISCUSSION

Using a mean C/chl $\underline{a}$ ratio of 45/1 for live phytoplankton within
the spring bloom of the mid-Atlantic Bight (MALONE, HOPKINS, FALKOWSKI
and WHITLEDGE, 1983), this near-bottom chlorophyll flux of 2.67 g chl
m^{-2} day^{-1} implies a net daily carbon export of 1.2 x 10^2 g C m^{-2} day^{-1}
past the 80 m isobath during February-April 1984. Such an export
reflects, of course, the previous accumulation on the inner shelf of
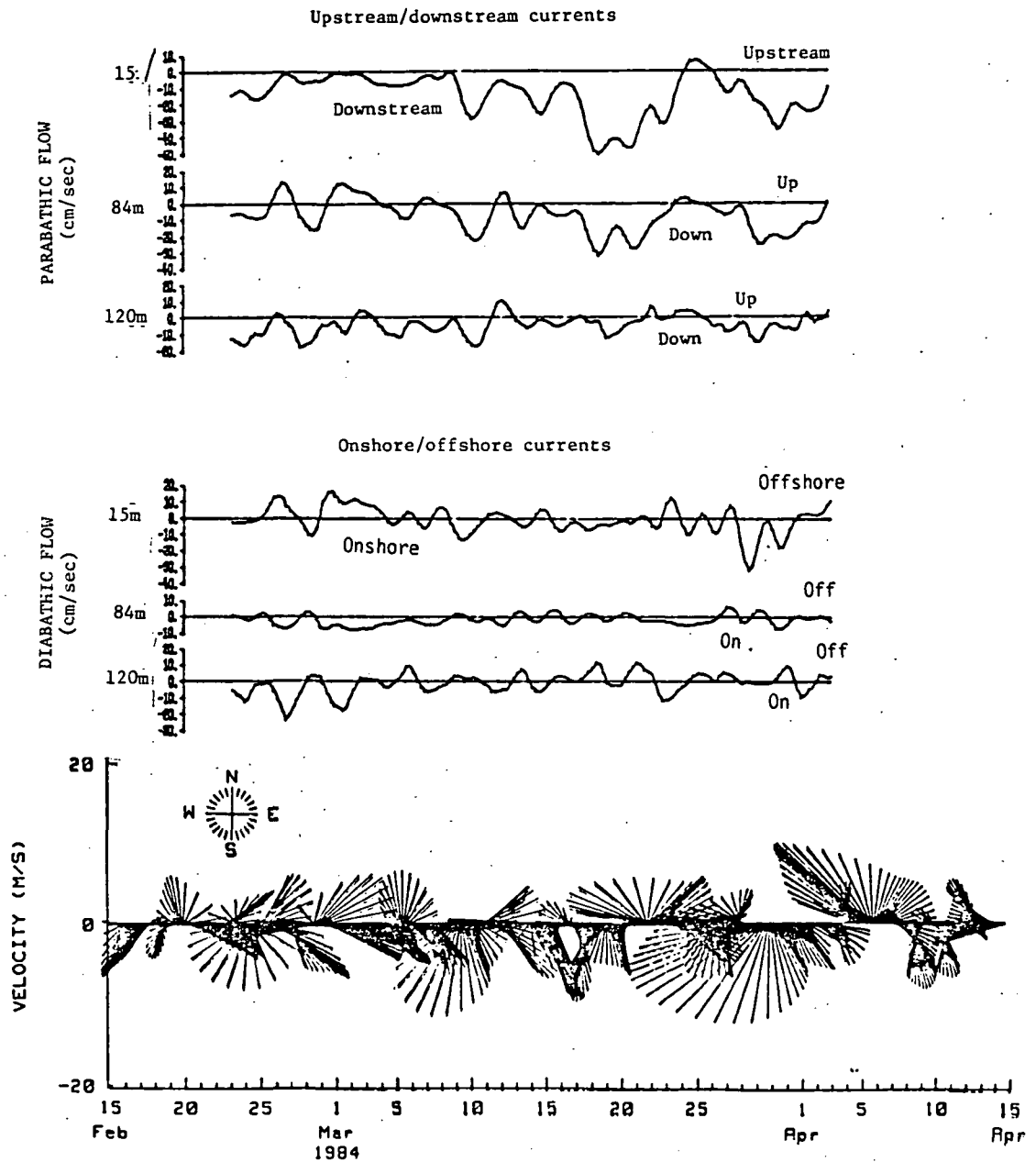phytoplankton carbon within a water parcel, during its trajectory from

Figure 20. A time series of the 40-hr. low-passed parabathic and diabathic components of flow (cm sec^{-1}) at 15, 84, and 117m depths on the 120m isobath, south of Long Island, during 17 February - 6 April 1984 in relation to the wind speed (m sec^{-1}) and direction (°T) as measured at the Brookhaven National Laboratory tower.

the coast to the slope. At this export and a mean primary production

rate of 1 g C m^{-2} day^{-1} during March-April 1984 (P. FALKOWSKI,

personal communication), with no grazing losses, an accumulation

interval, or a residence time, of 120 days on the mid-Atlantic shelf

is derived for the winter-spring bloom of phytoplankton. Within a

mean offshore flow regime of 1 cm sec^{-1} (0.86 km day^{-1}), successive

daughter cells of a diatom population could, in fact, transit the

100-km wide mid-Atlantic shelf after 116 days, departing Georges Bank

in January and arriving at our Long Island moorings in April.

Imposition of a seasonal grazing stress on the primary producers

would both increase the presumed residence time of this algal

population on the shelf, and introduce detrital carbon to the spring

ecosystem. Use of a larger C/chl a ratio, reflecting such

phytodetritus, for conversion of the fluorescence records would

decrease, however, the required residence time, i.e., more carbon

would be exported per unit chlorophyll over the same time period. To

place the daily estimates of grazing and sinking losses of

phytoplankton made during SEEP-I in perspective, we thus computed the

local daily rate of change of chlorophyll, $\frac{\partial(uP)}{\partial x}$, in the aphotic

zone.

We used the cumulative mean transports, $\overline{uP}$, at 75 m on the 80 m

isobath (Fig. 23d) and at 81 m on the 120 m isobath (Fig. 25d) for

this calculation. The 40-hr. low-passed chlorophyll records of zero

lag at these depths (Figs. 23b and 25b) had an r^2 of 0.32, as high as

the vertical coherence between the surface and deepest fluorometers at

these isobaths. Recall that the r^2 was only 0.002 for the W8 and W12

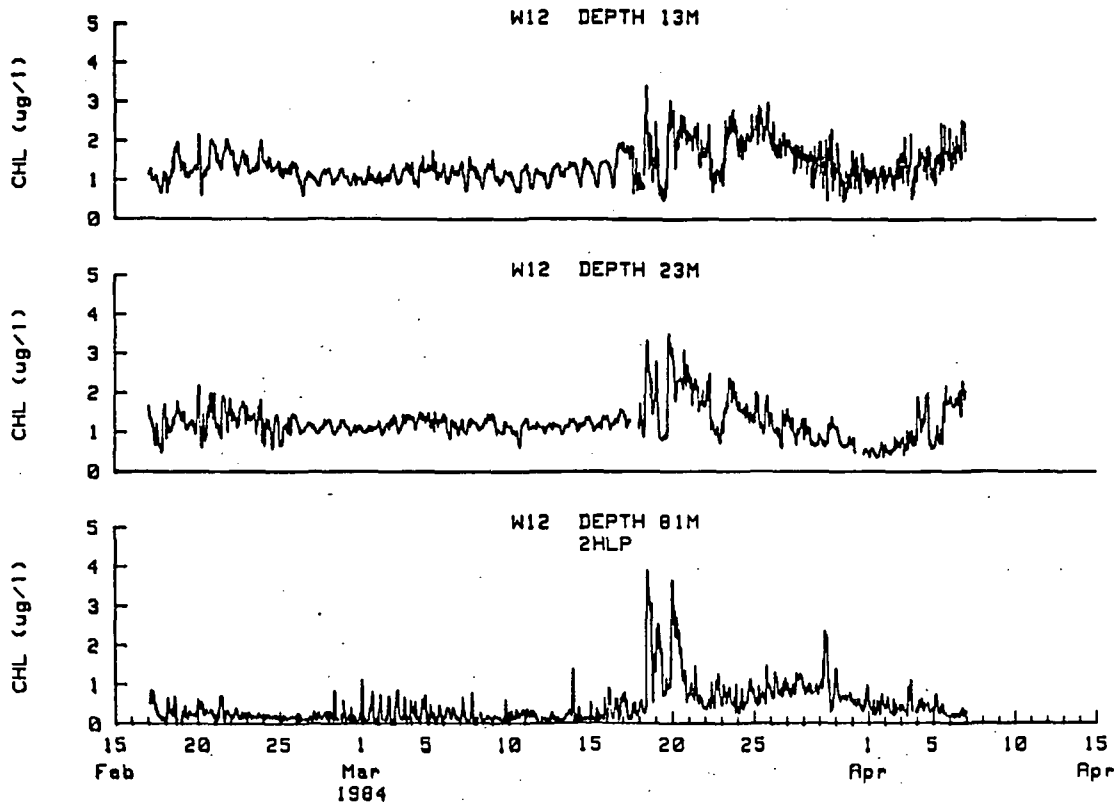chlorophyll records at 13 m (Fig. 19). This hundred-fold difference

Figure 21. A time series of the 2-hr. low-passed chlorophyll ($\mu g \ \ell^{-1}$) at 13, 23, and 81m depths on the 120m isobath, south of Long Island, during 17 February - 6 April 1984.

in horizontal coherence between the surface and near-bottom chlorophyll time series at W8 and W12 underscores the importance of vertical transfer processes on this shelf, i.e., a particle can no longer sink when at the bottom boundary.

The mean diabathic flow past the current meter at 84 m on the 120 m isobath was weakly onshore (Fig. 25a), however, while the flow past the meter at 78 m on the 80 m isobath was offshore (Fig. 23a). These current meter records suggest that a convergence of water at 78-84 m depths might have occurred somewhere over the ~12 km separation distance, between W8 and W12, to satisfy the bottom Ekman layer constraints on the predominantly downstream parabathic flow (Fig. 20). Recall that the mean diabathic, near-bottom (118 m) flow at W12 was also offshore at 1.0 cm sec^{-1} during February-April 1984, similar to an offshore flow of 1.4 cm sec^{-1} near the bottom on the outer shelf during February-May 1979-80. Downwelling of water, in addition to passive sinking of phytoplankton, may thus be involved in particle transport on the mid-Atlantic shelf (WALSH et al., 1987b).

Without additional vertical resolution of the flow field, however, we can only make an estimate of the mean horizontal flux over time at 75-81 m depths in finite difference form, with $\frac{(uP_{W8} - uP_{W12})}{\Delta x}$. We obtain 0.26 µg chl ℓ^{-1} day^{-1} from this expression and Figures 23d and 25d, or 11.9 mg C m^{-3} day^{-1} with the C/chl a ratio of 45/1. Since the primary production, daily grazing losses, and organic matter caught with sediment traps are usually reported as depth integrals, a depth range of possible carbon export must now be specified.
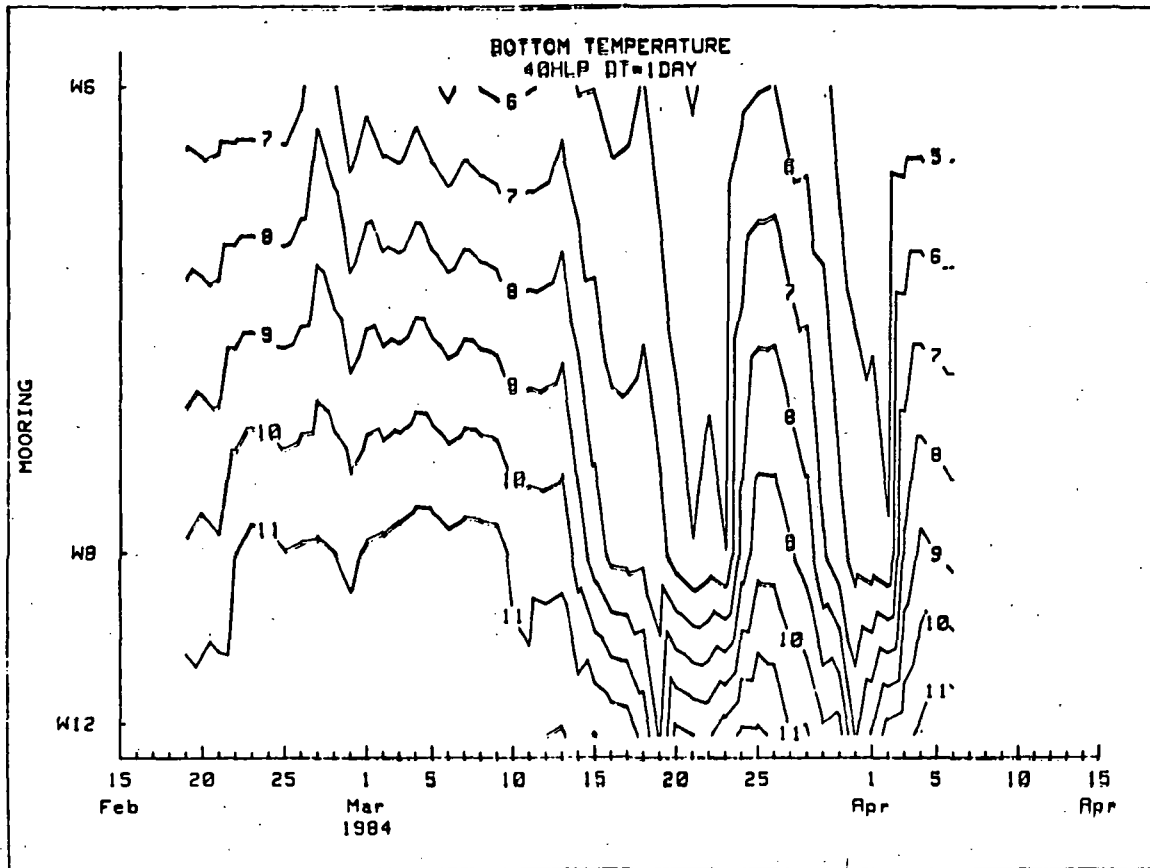
Figure 22. A time series of 40-hr. low-passed bottom temperature (°C),
measured at 3-5m above bottom of the moorings on the 60,
80, and 120m isobaths with Fenwal thermistors during
18 February - 6 April 1984.

A simulation model of the 1979 spring bloom (WALSH et al., 1987b) suggested that as much as 90% of the algal export from the mid-Atlantic Bight might occur within the lower third of the water column. Over a 30-40 m bottom layer at the 120 m isobath, we thus further estimate that the daily horizontal algal export might have been 0.35-0.47 g C m^{-2} day^{-1} from the mid-Atlantic shelf during February-April 1984. It is based on the above moored temperature, current meter, fluorometer, and transmissometer data at the 80 and 120 m isobaths, south of Long Island.

Such possible carbon fluxes of algal export constitute 78-100% of the 1984 March mean primary production, 0.45 g C m^{-2} day^{-1}, and 23-30% of that during April 1984, 1.55 g C m^{-2} day^{-1} (P. G. FALKOWSKI, personal communication). During these same Oceanus cruises, the biomass of the dominant zooplankton herbivore, Calanus finmarchicus, was observed to increase 8-fold over a 33-day period of the 1984 spring bloom, ingesting a daily mean phytoplankton ration of 0.18 g C m^{-2} day^{-1} in March and 0.50 g C m^{-2} day^{-1} in April (SMITH and LANE, 1987). Assuming that the seaward horizontal export of phytoplankton occurred over only the lower 30 m of the water column at the shelf break, i.e., 0.35 g C m^{-2} day^{-1}, the physical and biological losses of algal carbon (export and pelagic grazing) would have consumed 118% of the March primary production and 55% of the April fixation of carbon.

Sediment traps, moored 10 m and 70 m off the bottom on the outer shelf at W12 during March-April 1984 (G. T. ROWE, personal communication), caught respectively 0.16 and 0.10 g C m^{-2} day^{-1}, about half that estimated from the moored instruments within the lower part

W8 DEPTH 78m
40HLLP

Offshore

A) CURRENTS (cm/sec)

Onshore

B) CHL (ug/l)

W8 DEPTH 75M
2HLP

10
8
6
4
2
0

C) K(1/M)

3.0
2.5
2.0
1.5
1.0
0.5
0.0

15   20   25   1   5   10   15   20   25   1   5   10   15
Feb   Mar   Apr   Apr
                    1984

D) CHLOR TRANSPORT (ng cm⁻² sec⁻¹)

5.0
0.0
-5.0

23 25 27 29 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 1 3 5
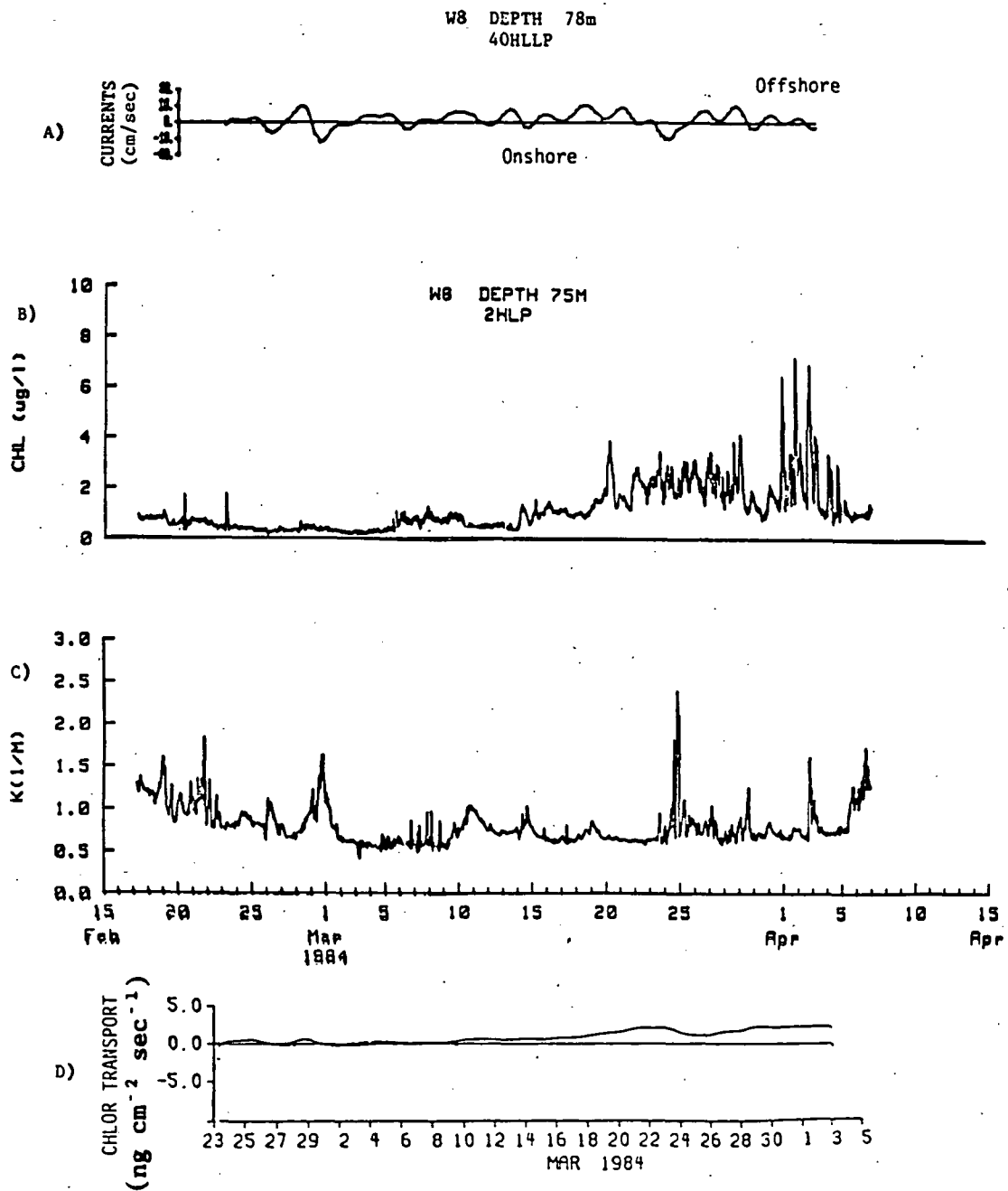   MAR 1984

Figure 23. A time series of a) 40-hr. low-passed currents (cm sec^{-1}),
b) 2-hr. low-passed chlorophyll (μg ℓ^{-1}), c) 2-hr. low-
passed light attenuation (m^{-1}), and d) 40-hr low-passed
cumulative chlorophyll transport (ng cm^{-2} sec^{-1}) at 75-78m
depth on the 80m isobath, south of Long Island during
17 February - 11 April 1984.

of the water column. This sediment trap flux represents presumably a combination of the daily vertical fallout of both fecal pellet carbon and phytodetrital carbon, as well as the particulate matter resuspended off the bottom from previous inputs. At a herbivore assimilation efficiency of 60%, as much as 0.20 g C m^{-2} day^{-1} of the April grazing flux might sink as fecal pellets, at rates of 150 m day^{-1}, to be caught in these near-bottom sediment traps. The slower 1-20 m day^{-1} sinking flux of phytoplankton might instead have been advected past these sediment traps on the shelf.

Earlier estimates of benthic metabolism during August-October on the mid-Atlantic shelf (FLOREK and ROWE, 1983) suggested that, as the bottom of the water column warms from its seasonal minimum in March, the benthos might consume an average of 0.16 g C m^{-2} day^{-1} (WALSH, 1983). This would be 25% of the April 1984 primary production not lost to horizontal export or pelagic grazers, if ingested directly by the benthos. A more recent analysis (ROWE, THEROUX, PHOEL, QUIMBY, WILKE, KOSCHORECK, WHITLEDGE, FALKOWSKI and FRAY, 1987) of benthic metabolism during SEEP-I suggests that a similar amount of 0.15 g C m^{-2} day^{-1} would be required by the benthos, i.e., less than the potential fecal pellet flux and equal to that caught near the bottom at the 120 m isobath.

Finally, bacterioplankton productivity is less than 2% of the spring algal production in the mid-Atlantic Bight (DUCKLOW, KIRCHMAN and ROWE, 1982), decomposing perhaps 20% of the organic carbon caught in sediment traps (DUCKLOW, HILL and GARDNER, 1985). Bacterioplankton may be a carbon sink in coastal food webs (DUCKLOW, PURDIE, WILLIAMS
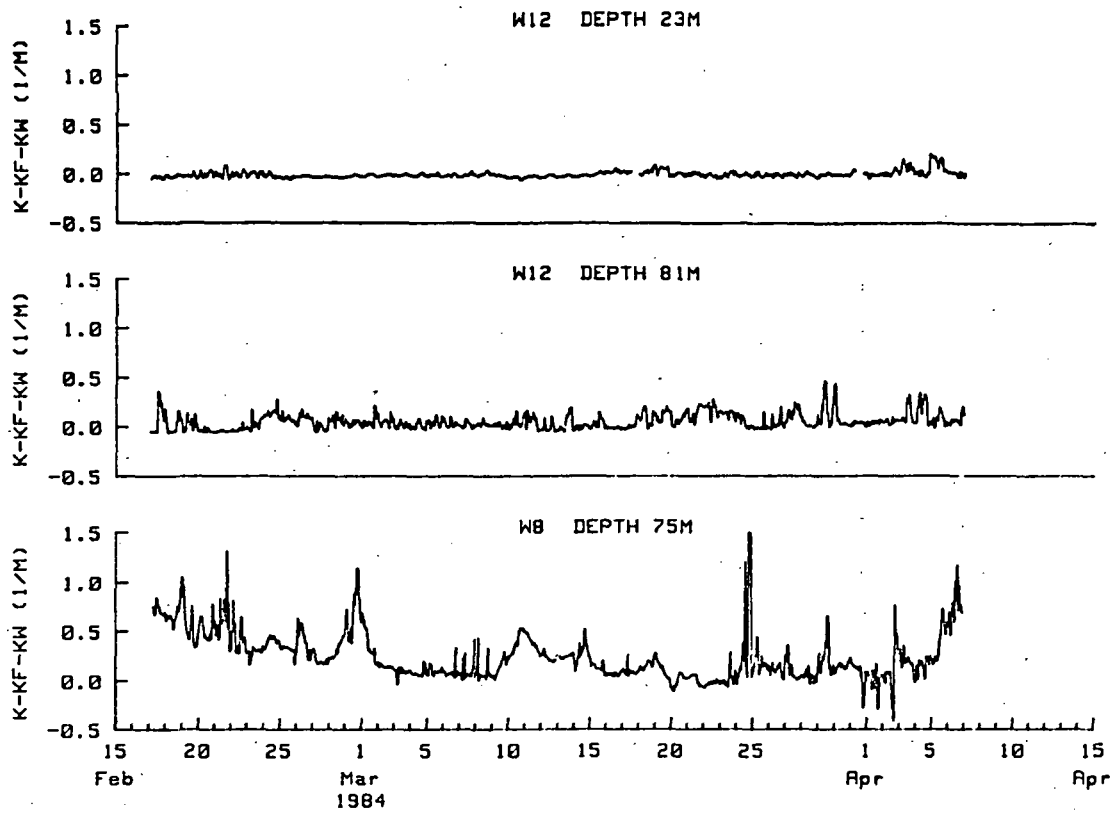
Figure 24. A time series of 2-hr. low-passed light attenuation (m^{-1}), attributed to abiotic particles (measured - computed due to phytoplankton and water), at a) 23m depth of water on the 120m isobath, b) 81m depth of water on the 120m isobath, and c) 75m depth of water on the 80m isobath, all south of Long Island.

and DAVIES, 1986), however, with little carbon or nitrogen passed to other organisms in the form of food for higher trophic levels. A recent nitrogen budget (WALSH, WHITLEDGE, O'REILLY, PHOEL and DRAXLER, 1987c) suggests, furthermore, that the secondary production of bacterioplankton can be maintained from dissolved organic matter excreted each day by phytoplankton in the mid-Atlantic Bight. These heterotrophs may thus be a sink for dissolved not particulate carbon, with little direct remineralization of algal biomass.

We conclude that the immediate fate of shelf algal carbon during SEEP-I may now be known, with ~50% of the March-April 1984 primary production exported to the slope and caught in sediment traps on the 500 and 1250 m isobaths (BISCAYE and ANDERSON, 1987). Annual estimates of ^{210}Pb and ^{14}C mixing rates, combined with vertical carbon gradients in the surface sediments (WALSH, PREMUZIC, GAFFNEY, ROWE, BALSAM, HARBOTTLE, STOENNER, BETZER and MACKO, 1985) suggest that the average daily carbon accumulation rate in slope sediments off the mid-Atlantic Bight might be 0.03 g C m^{-2} day^{-1}, i.e., <10% of our export estimate. Some of the slope import of carbon must be remineralized by the local benthos, although the benthic biomass and metabolism is lower on the slope than on the shelf, i.e., 0.005 g C m^{-2} day^{-1} at 1800 m (ROWE et al., 1987). Marked seasonal fluxes of particulate matter were observed, however, with sediment traps moored on the slope during SEEP-I (BISCAYE and ANDERSON, 1987). During April, for example, 0.08-0.26 g C m^{-2} day^{-1} were found respectively within sediment traps 50 m above the bottom at the 1250 and 500 m isobaths, compared to ten-fold less during August to November.
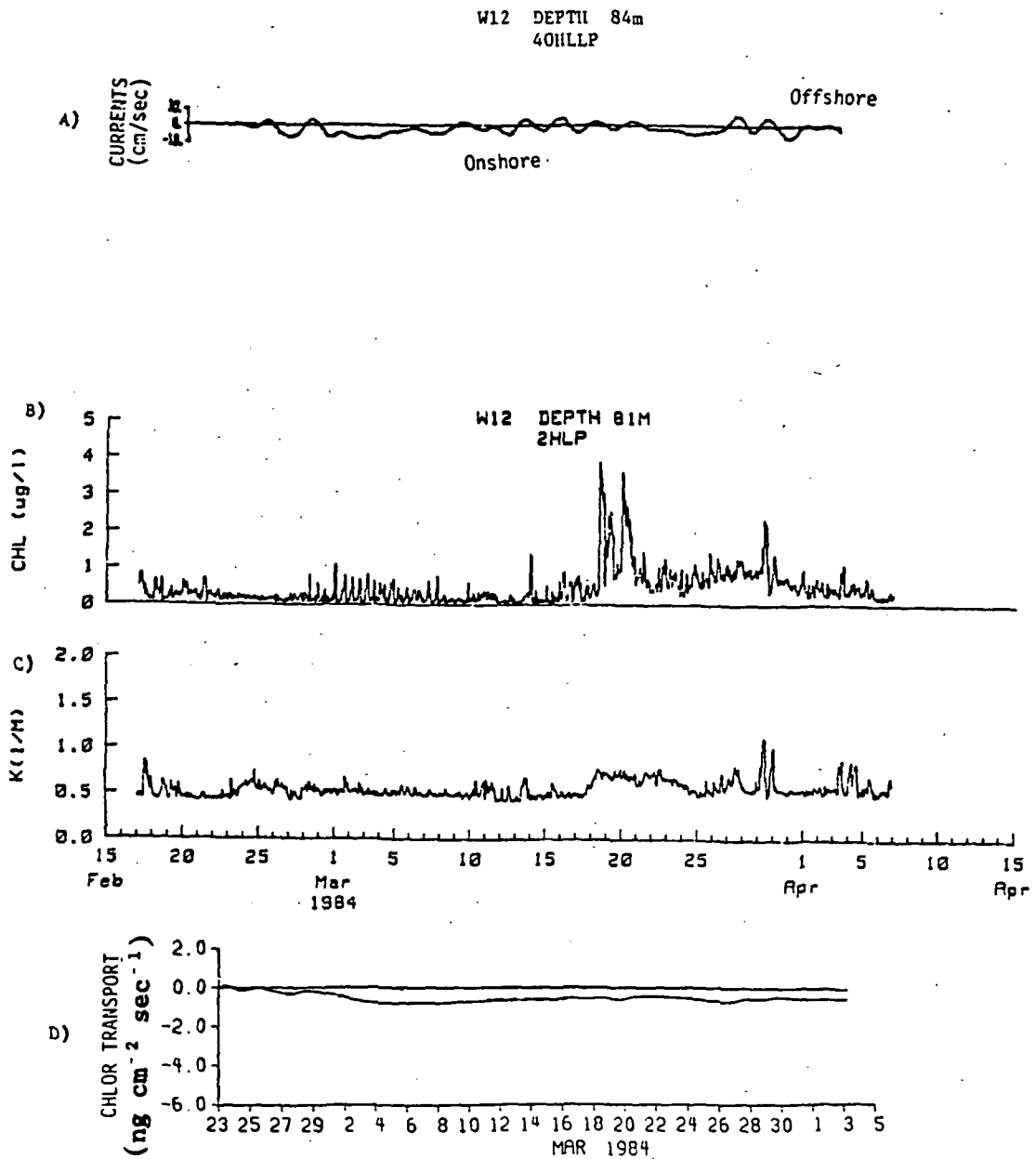
Figure 25. A time series of a) 40-hr. low-passed currents (cm sec^{-1}), b) 2-hr. low-passed chlorophyll (µg ℓ^{-1}), c) 2-hr. low-passed light attenuation (m^{-1}), and d) 40-hr. low-passed cumulative chlorophyll transport (ng cm^{-2} sec^{-1}) at 81-84m depth on the 120m isobath, south of Long Island during 17 February - 11 April 1984.

Little import of phytoplankton carbon may thus occur on the slope during summer and fall, with most of the annual carbon loading as the result of the spring bloom. If the annual accumulation rate of carbon, estimated by ^{14}C and ^{210}Pb mixing rates on the continental slope, were actually to occur over only 100 days, the daily sediment accumulation rate on the slope during the spring bloom would then be 0.11 g C m^{-2} day^{-1}, i.e., 31% of our export estimate and similar to that measured in the April 1984 sediment trap samples on the slope. Future experiments are planned by us to further examine the geographical nature of this shelf export, but we believe that the results of SEEP-I provide the first direct measurements of a flux of algal carbon from a continental shelf.

A set of shipboard and aircraft observations, sparsely sampled in time, and a set of moored data, sparsely sampled in space, provide corroboration of initial hypotheses of shelf export of phytoplankton from the mid-Atlantic Bight (WALSH, ROWE, IVERSON and McROY, 1981; MALONE et al., 1983; WALSH et al., 1985; WALSH et al., 1987a). Within the vertically homogeneous water column of the inner shelf (<60 m isobath), algal biomass which has previously sunk out, is evidently resuspended and transported seaward within a surface Ekman layer in response to northwest wind events. Within the vertically stratified waters of the outer shelf (60-100 m isobaths), where the shelf-break front impedes vertical exchange in the middle of the water column (Fig. 26), near-bottom phytoplankton are evidently resuspended and transported seaward within a bottom Ekman layer in response to northeast wind events. We have sketched this process in Figure 26,
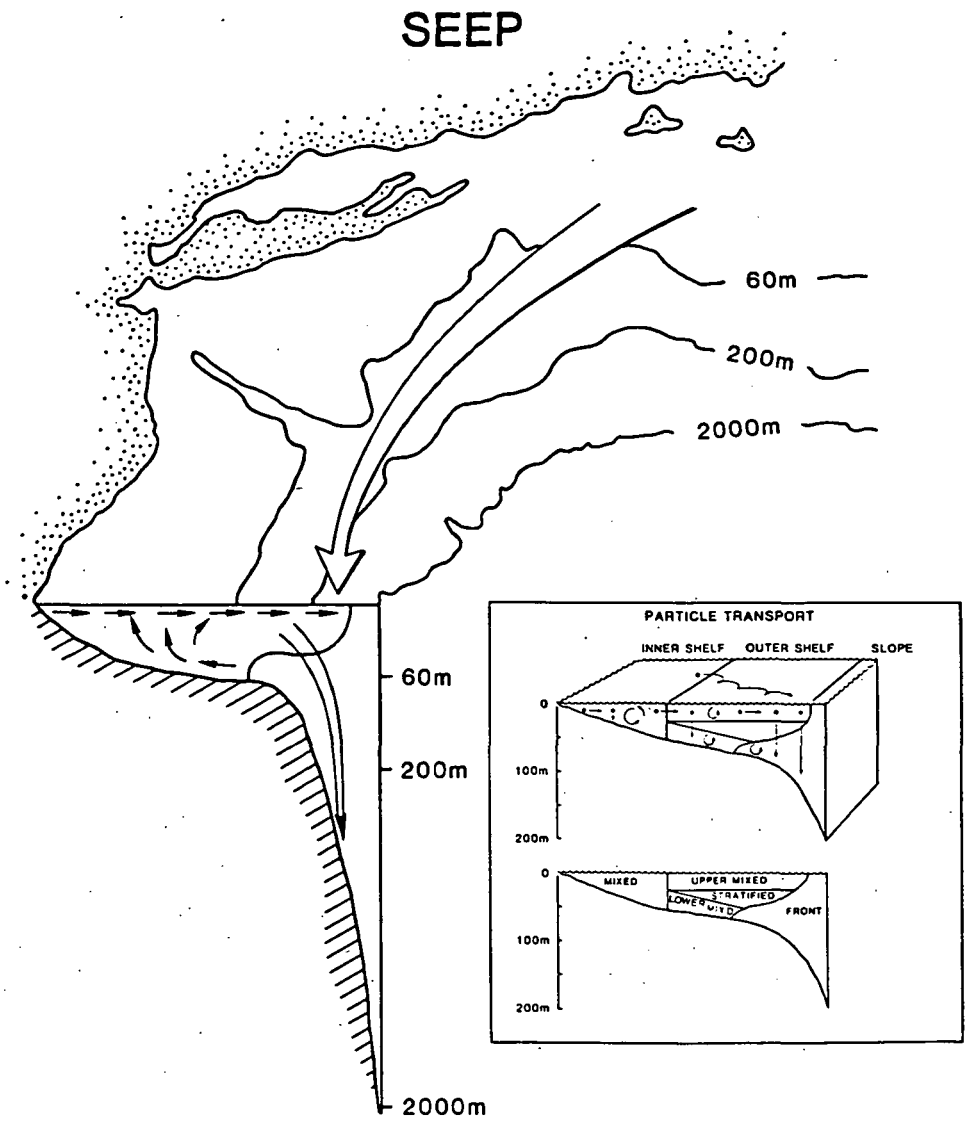
SEEP

Figure 26. A schematic trajectory of surface Ekman transport of a particle within the homogeneous water column of the inner shelf, and bottom Ekman transport within the stratified water column of the outer shelf during the spring bloom in the mid-Atlantic Bight.

where the shelf export of phytoplankton carbon is estimated to be a surface process at mid-shelf (WALSH et al., 1987a) and a sub-surface phenomenon at the shelf-break (WALSH et al., 1987b). A SEEP-II experiment off the Delmarva peninsula will provide confirmation of our present estimates of shelf export from the mid-Atlantic Bight.

LITERATURE CITED

AIKEN J. (1981) A chlorophyll sensor for automatic, remote operation in the marine environment. Marine Ecology Progress Series, 4, 235-239.

BEARDSLEY R. C. and W. C. BOICOURT (1981) On estuarine and continental-shelf circulation in the Middle Atlantic Bight. In: Evolution of Physical Oceanography, B. A. WARREN and C. WUNSCH, editors, MIT press, pp. 198-234.

BEARDSLEY R. C., C. A. MILLS, J. A. VERMERSCH, W. S. BROWN, N. PETTIGREW, J. IRISH, S. RAMP, R. SCHLITZ and B. BUTMAN (1983) Nantucket Shoals Flux Experiment (NSFE 79) Part 2: Moored Array Data Report. WHOI-83-13, pp. 1-140.

BISCAYE P. and R. ANDERSON (1987) Particle fluxes in an array of sediment traps on the U.S. eastern continental slope: SEEP-I. Continental Shelf Research (this volume).

DAGG M. J. and J. T. TURNER (1982) The impact of copepod grazing on the phytoplankton of Georges Bank and the New York Bight. Canadian Journal of Fisheries and Aquatic Science, 39, 979-990.

DUCKLOW H. W., D. L. KIRCHMAN and G. T. ROWE (1982) Production and vertical flux of attached bacteria in the Hudson River plume of the New York Bight as studied with floating sediment traps. Applied Environmental Microbiology, 25, 769-776.

DUCKLOW H. W., S. M. HILL and W. D. GARDNER (1985) Bacterial growth and the decomposition of particulate organic carbon collected in sediment traps. Continental Shelf Research, 4, 445-464.

DUCKLOW H. W., D. A. PURDIE, P. J. WILLIAMS and J. M. DAVIES (1986)
Bacterioplankton: a sink for carbon in a coastal marine
community. Science, 232, 865-867.

FLOREK R. J. and G. T. ROWE (1983) Oxygen consumption and dissolved
inorganic nutrient production in marine coastal and shelf
sediments of the Middle Atlantic Bight. International Revue
gesampte Hydrobiology, 68, 73-112.

HOGE F. E. and R. N. SWIFT (1981) Application of the NASA airborne
oceanographic LIDAR to the mapping of chlorophyll and other
organic pigments. In: Chesapeake Bay Plume Study, NASA
Conference Publication 2188, 349-374.

HOGE F. E. and R. N. SWIFT (1985) Airborne mapping of Laser-induced
fluorescence of chlorophyll a and phycoerythrin in a Gulf Stream
Warm Core Ring. In: Mapping Strategies in Chemical
Oceanography, A. ZIRINO, editor, American Chemical Society,
Washington, D.C., 353-372.

MALONE T. C., T. S. HOPKINS, P. G. FALKOWSKI and T. E. WHITLEDGE
(1983) Production and transport of phytoplankton biomass over the
continental shelf of the New York Bight. Continental Shelf
Research, 1, 305-337.

POOLE L. R. and W. E. ESAIAS (1982) Water Raman normalization of
airborne Laser fluorosensor measurements: a computer study.
Applied Optics, 21, 3756-3761.

ROWE G. T., R. THEROUX, W. PHOEL, H. QUIMBY, R. WILKE, D. KOSCHORECK,
T. WHITLEDGE, P. FALKOWSKI and C. FRAY (1987) Benthic carbon
budgets for the continental shelf south of New England.
Continental Shelf Research (this volume).

SMITH S. L. and P. V. LANE (1987) Grazing of the spring diatom bloom in the New York Bight by the calanoid copepods, Calanus finmarchicus, Metridia lucens and Centropages typicus. Continental Shelf Research (this volume).

WALSH J. J. (1983) Death in the sea: enigmatic phytoplankton losses. Progress in Oceanography, 12, 1-86.

WALSH J. J., T. E. WHITLEDGE, F. W. BARVENIK, C. D. WIRICK, S. O. HOWE, W. E. ESAIAS and J. T. SCOTT (1978) Wind events and food chain dynamics within the New York Bight. Limnology and Oceanography, 23, 659-683.

WALSH J. J., T. E. WHITLEDGE, W. E. ESAIAS, R. L. SMITH, S. A. HUNTSMAN, H. SANTANDER and B. R. DeMENDIOLA (1980) The spawning habitat of the Peruvian anchovy, Engraulis ringens. Deep-Sea Research, 27, 1-27.

WALSH J. J., G. T. ROWE, R. L. IVERSON and C. P. McROY (1981) Biological export of shelf carbon is a neglected sink of the global CO_2 cycle. Nature, 291, 196-201.

WALSH J. J., E. T. PREMUZIC, J. S. GAFFNEY, G. T. ROWE, W. BALSAM, G. HARBOTTLE, R. W. STOENNER, P. R. BETZER and S. A. MACKO (1985) Storage of CO_2 as organic carbon on the continental slopes off the mid-Atlantic Bight, Southeastern Bering Sea, and the Peru coast. Deep-Sea Research, 32, 853-883.

WALSH J. J., D. A. DIETERLE and W. E. ESAIAS (1987a) Satellite detection of phytoplankton export from the mid-Atlantic Bight during the 1979 spring bloom. Deep-Sea Research (in press).

WALSH J. J., D. A. DIETERLE and M. B. MEYERS (1987b) A simulation
    analysis of the fate of phytoplankton within the mid-Atlantic
    Bight. Continental Shelf Research (this volume).

WALSH J. J., T. E. WHITLEDGE, J. E. O'REILLY, W. T. PHOEL and
    A. F. DRAXLER (1987c) Nitrogen cycling within seasonally
    stratified and tidally mixed regions of the mid-Atlantic Bight:
    the New York shelf and Georges Bank. In: Georges Bank and the
    Surrounding Waters, R. H. BACKUS, editor, MIT Press (in press).

WHITLEDGE T. E. and C. D. WIRICK (1983) Observations of chlorophyll
    concentrations off Long Island from a moored in situ fluorometer.
    Deep-Sea Research, 30, 297-309.

WHITLEDGE T. E. and C. D. WIRICK (1986) Development of a moored in
    situ fluorometer for phytoplankton studies. In: Tidal Mixing
    and Plankton Dynamics, M. J. BOWMAN, C. M. YENTSCH and
    W. J. PETERSEN, editors, Springer-Verlag (in press).