The 1983–1984 Shelf Edge Exchange Processes (SEEP)—I experiment: hypotheses and highlights

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Abstract—A multidisciplinary SEEP—I study of particle formation, transformation, transport, sedimentation, and storage was conducted across the shelf-break south of Martha’s Vineyard and Long Island during July 1983–October 1984. Moored arrays of current meters, thermistors, transmissometers, fluorometers, and sediment traps provided time-series data on the distributions of currents, temperature, light transmission, fluorescence, organic carbon, carbonate, and particulate $^{210}$Pb within shelf and slope waters of the Mid-Atlantic Bight. Shipboard and aircraft measurements focused on the birth and death processes of plankton during the spring bloom, when seasonal fluxes of carbon, carbonate, and $^{210}$Pb to slope waters and sediments were maximal.

Simulation models of nitrogen, carbon, and oxygen transfers during the 1979 and 1984 spring blooms suggested that 50–60% of the daily primary production was consumed by the rest of the shelf food web. Surviving shelf particles enter a near-bottom physical regime on the continental slope which favors their downslope transport and deposition. On an annual basis, $^{210}$Pb budgets of the slope sediments suggest that only 20–60% of organic debris from the adjacent shelf ecosystem may exit the shelf-break in the SEEP—I region, with the remainder entrained downstream towards Cape Hatteras.

After spring export, continued oxidation of organic matter within slope sediments of the SEEP—I region allows carbon accumulation rates here of <1% of the annual primary production on the shelf. The SEEP—I study area represents a region of minimal export of particles from the Mid-Atlantic Bight, however. For example, 250 km farther south on the 1000-m isobath, the annual fluxes of organic carbon and $^{210}$Pb at 25 m above bottom in 1985–1986 were two- to three-fold greater than those at equivalent depths in the SEEP—I experiment.

INTRODUCTION

LIKE the tribes of tri-partite Gaul, the SEEP project evolved from an equal mixture of physical, geochemical, and biological oceanographers studying diverse processes within the Mid-Atlantic Bight. During the 1970s the Department of Energy, at that time the Atomic Energy Commission and then the Energy Research and Development Administration, had funded oceanographic research at several institutions in the northeastern United States, with the broad objective of understanding the fate of “energy-related pollutants” that might be introduced into the coastal marine environment. During this initial period there was some degree of collaboration and cooperation among the DOE-funded researchers at Brookhaven National Laboratory, Lamont-Doherty Geological Observatory, Woods Hole Oceanographic Institution, and Yale University, but certainly not to any degree approaching an integrated research effort.
In 1980 these investigators met to see what aspects of their research could be better pursued under closer collaboration. There was broad agreement that, not only were there significant areas of complementary or even overlapping interests, but that there were experimental approaches that could be collectively considered. The resulting SEEP—I experiment was one which we could never have undertaken separately within the traditional disciplines of physical, geochemical, and biological oceanography.

Two areas of common interest were broadly centered on the fate of particles in the continental shelf water column, and on the dynamics of the slope water column as these might affect the sedimentation of particles onto the slope. Both of these relate to DOE’s mandate to understand what happens to “energy-related pollutants” that may be introduced to the continental shelf environment, since most pollutants are quite particle-reactive and become quickly associated with particulate matter in seawater. A study of the fate of continental shelf particles, therefore, is crucial to an understanding of the fate of many “energy-related pollutants” and the nature of their eventual pathway to man.

One of the roots of the 1983-1984 Shelf Edge Exchange Processes (SEEP)—I experiment (Fig. 1) was thus the recognition that fine-grained organic particles are the primary carriers of heavy metals and other xenobiotic compounds in the sea. These compounds are a by-product of human activity, notably of energy generation in the coastal zone, for example, copper from condenser tubes of a power station, removed by the corrosive action of seawater, or accidental discharges of reactor radionuclides. In the process of consuming the estuarine input of nutrients, nearshore phytoplankton can assimilate these heavy metals, accumulate them as much as forty-thousand-fold for copper and lead (LOWMAN et al., 1971), and pass this material up the food chain. Coastal discharges of mercury have induced Minimata disease and of cadmium led to Itai itai disease in Japan, for example, while an abalone kill off California was attributed to copper pollution from the condensers of a coastal power plant. As a result of the affinity of heavy metals and other harmful substances for particles, the dissemination of waste constituents in the sea is strongly influenced by the transport of particles (MOREL and SCHIFF, 1983).

Within the decade preceding the 1983-1984 DOE SEEP—I experiment in the Mid-Atlantic Bight, over 5000 bottle casts had been made by previous DOE-, NOAA-, and NSF-funded investigators to estimate the temporal and spatial properties of algal biomass left behind in the water column, i.e. a major constituent of organic particles. Numerous seasonal measurements of primary production, zooplankton grazing, bacterioplankton growth, and benthic metabolism had been used, in conjunction with the data on algal standing stocks, to construct budgets of carbon and nitrogen flow in the Mid-Atlantic Bight (WALSH, 1983). They suggested that as much as 50% of the annual carbon fixation and 90% of the production of spring bloom might not be immediately consumed (WALSH et al., 1981; MALONE et al., 1983a). Conventional shipboard surveys of 1- to 3-weeks duration, however, 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-driven resuspension (0.2 day⁻¹) events, thereby severely aliasing estimates of primary production and its consumption (WALSH et al., 1987a).

Nevertheless, the salient observation on the shelf had been that, despite an abundance of both biogenic and abiogenic particles produced in and transported to the continental shelf water column, the sediments of the Mid-Atlantic shelf are characterized by huge expanses of clean, coarse relict sands (EMERY and UCHUPI, 1972). Only local, small
Fig. 1. The location of the 1983–1984 SEEP—I experiment (DOE) in relation both to concurrent MASAR (MMS) and NASACS (USGS) studies and to the 1988–1989 SEEP—I experiment in the Mid-Atlantic Bight.
pockets of fine-grained sediments of >0.5% dry wt carbon content occur (Fig. 2). The same "missing" reservoir question was applicable to tracers which tend to be associated with fine-grained particulates.

Lead-210, for example, is introduced into continental shelf waters from the atmosphere at known rates, but budgets of production and decay of $^{210}\text{Pb}$ within shelf sediments cannot account locally for the fate of this natural radioisotope (SPENCER et al.,

![Fig. 2. The distribution of organic carbon (% dry wt) within surficial sediments of the Mid-Atlantic Bight (after WALSH et al., 1985).](image-url)
Conversely, the sediments of the continental slope are characterized by a very fine-grained composition (Biscaye and Olsen, 1976), with higher carbon content (>1.0% dry wt; Fig. 2). In addition, there were some suggestions from previous current meter data and from distributions of another natural radioisotope, radon-222, in near-bottom waters of the slope (Carson, 1987) that at least certain portions of the continental slope might be an environment conducive to deposition (and non-resuspension) of particles.

**Hypotheses**

The SEEP—I experiment was thus focused on the fate of fine-grained lithogenic and organic particles, either those released near the coast into the ocean and already carrying waste constituents, or others which acquired such xenobiotic substances in the waters of the continental shelf. A primary working hypothesis of SEEP—I was that some of these particles are transported southward along the Mid-Atlantic shelf for long distances by the prevailing circulation, to be eventually entrained into a western boundary current at Cape Hatteras; others, however, quickly cross the shelf edge in random motions as part of the shelf-edge mass exchange process.

In the Mid-Atlantic Bight, alongshelf transport (advection) is predominantly south-westward, with potential for resuspension of near-bottom particles by a number of wind events during a year-long, 1000-km trajectory of individual water parcels (Chapman et al., 1986). This alongshore advective process finally terminates with the entrainment of shelf waters at 35–36°N by the Gulf Stream. In contrast, particles crossing the shelf edge via “dispersion” (in an extended sense, including random motions of tens of kilometers in scale) need only move out a short distance to waters overlying the continental slope. Here it is possible for particles to settle out, thereby quickly escaping consumption by biota of the shelf and slope water columns.

Geochemical investigations prior to SEEP—I had suggested that fine organic particles must settle in substantial numbers over a midslope belt (Fig. 2), within the depth range of 1–2 km (Biscaye and Olsen, 1976). This was then adopted as one of the central, organizing hypotheses of SEEP—I: the midslope region was presumed to be a “sink” for both biogenic and abiotic particles. It was further hypothesized that the slope “sink” might also be of sufficient magnitude to alter geochemical processes, for example, the cycle of manganese within surficial sediments (Bacon et al., 1976). A suite of measurements from the water column, from sediment cores, and from moored sediment traps along 71°W (Fig. 1), taken between July 1983 and October 1984, constituted part of the SEEP—I data base to test these ideas.

The adjunct physical hypothesis was that particle deposition on the slope was made possible by a quiescent bottom current environment. Tentatively, the quiescence was ascribed to the “insulating” effect of the continental slope, arising from dynamical constraints on a rotating planet (Csányi and Shaw, 1983). This idea was subject to confirmation by the DOE current meters within the two lines at 71° and 72°W of the SEEP—I experiment, as well as by the upstream U.S. Geological Survey (USGS) moorings of the North Atlantic Slope and Canyon Study (NASACS) experiment at 70°W, and by the downstream Marine Minerals Service (MMS) moorings of the Mid-Atlantic Slope and Rise (MASAR) experiment at 73° and 74°W (Fig. 1). Especially, the
limitations of the physical hypothesis were of interest: under what conditions are bottom currents over a steep incline, in waters of 1 km or more depth, not sluggish, but vigorous?

The biological part of the SEEP—II hypotheses had its origin in previous annual carbon budgets (WALSH, 1983). A continental shelf ecosystem is composed of interdependent, interacting biological components that can be defined in terms of a common currency, such as mass of carbon and nitrogen, or potential energy. Biogenic particles in such a system are produced primarily by photosynthesis of the phytoplankton. This organic matter is then either consumed by herbivorous zooplankton and bacterioplankton food webs, or sinks out to the bottom where it is consumed by the benthos. The recalcitrant organic carbon, escaping oxidation, is finally incorporated within the sediments (Fig. 2).

In a steady state of such an ecosystem, it is assumed that primary production equals consumption and burial. SEEP—II was designed to test the hypothesis, based on earlier work, that such a local, time-invariant balance on the shelf did not exist, i.e. one must consider the adjacent continental slope ecosystem as well.

In fact, over continental shelves during the spring bloom as much as 90% of the primary production could not be traced either to burial on the seabed or to immediate respiration by the food chain, prior to SEEP—II (WALSH, 1983). It was therefore hypothesized that, while the daily summer primary production could all be consumed (ROWE et al., 1986), most of the spring production might be instead exported to the continental slope (MALONE et al., 1983a). The purpose of the biological components of SEEP—II was thus to examine this “excess” production hypothesis with shipboard rate measurements and moored arrays of fluorometers and transmissometers. Limited at that time by the power demands of the fluorosensor, these instruments were deployed within the two SEEP—II transects from February to April 1984 (Fig. 1).

If seasonal components of the annual production were in excess within the Mid-Atlantic shelf ecosystem, a companion step was then to determine their fate. Even if sluggishness of the Mid-Atlantic slope currents could be established, for example, it would not necessarily mean that fine organic particles in large numbers would settle there. These must be supplied either by local production within the overlying slope water column or from the shelf, and in the latter case must traverse the shelf edge in quantity.

The SEEP—II experiment was therefore also aimed at understanding the mechanisms of shelf-edge fluid and particle exchange. Preliminary estimates suggested that total particle exchange across the shelf edge by “dispersive” processes might be as important in the particle mass balance of the continental shelf as their southwestward “advection”.

It was envisioned that the local “dispersive” flux of particles and pollutants across the shelf/slope break would also increase towards the south from New England to Cape Hatteras, since the organic carbon content of slope sediments is greater to the south (Fig. 2), the Mid-Atlantic shelf narrows to the south, and the influx of anthropogenic pollutants increases to the south. The SEEP—II experiment was thus designed to first measure this “dispersive” exchange of particles from shelf to slope waters at a location in the Mid-Atlantic Bight, where it might be a minimum, i.e. off New England. In contrast, the upcoming SEEP—II experiment was designed to measure the cross-shelf “dispersive” flux of particles, where it may be a maximum (Fig. 1).

**HIGHLIGHTS**

1. **Food web dynamics**

Within the first four contributions to this special issue, the biological synthesis of SEEP—II results contains as many different carbon budgets as the individual papers,
reflecting divergent viewpoints of the senior authors. A general consensus appears to be that all of the primary production of the 1984 spring bloom was neither quickly exported, nor immediately consumed on the shelf. For example, an oxygen budget was constructed for the water column over 40 days between the east and west SEEP—I lines, south, respectively, of Martha’s Vineyard and Long Island (Fig. 1). It suggests that a maximal consumption of 50% of the daily photosynthetic evolution of oxygen occurred from all pelagic and benthic respiration by 4 April 1984 (FALKOWSKI et al., 1988). The concomitant average 1984 particulate production of carbon by phytoplankton on the shelf was estimated to be 0.6 g C m⁻² day⁻¹ during March and 1.3 g C m⁻² day⁻¹ during April (FALKOWSKI et al., 1988).

Although more computed respiration and a stronger vertical gradient of dissolved oxygen were found on the west SEEP—I line than on the east one in the above oxygen budget, the ecosystem processes of the former may be more typical of the Mid-Atlantic Bight. For example, the SEEP—I current meter data for the spring period (WALSH et al., 1988b) and continuity considerations (FALKOWSKI et al., 1988) suggest that surface water moved onshore along the east line, compared to offshore flow along the west line and farther to the south. Phytoplankton species composition was different from that of the rest of the shelf on the east line (FALKOWSKI et al., 1988), only slight seasonal increases of zooplankton biomass occurred during March-April in this region (SMITH and LANE, 1988), and sediment organic carbon was 10-fold higher within this part of the shelf (ROWE et al., 1988).

The following summary is thus based on the results from the SEEP—I west line. A daily 1984 ingestion rate by all copepods of 0.10 g C m⁻² day⁻¹ during March and 0.50 g C m⁻² day⁻¹ during April within shelf waters south of Long Island (SMITH and LANE, 1988) would consume 17-38% of the daily fixation of particulate algal carbon. Such a grazing stress in terms of carbon is greater than the equivalent respiratory sink for oxygen evolution, since losses of the assimilated algal carbon to zooplankton reproduction must also be budgeted.

In this same shelf region, estimates of benthic secondary production and all respiration requirements suggest a daily total carbon demand of only 0.15 g C m⁻² day⁻¹ (ROWE et al., 1988), or, respectively, 12–25% of the March–April primary production. This carbon equivalent again represents an upper bound on the benthic consumption of the oxygen input from photosynthesis and resupply across the air–sea interface. At a measured fecal pellet flux of 0.12 g C m⁻² day⁻¹ (SMITH and LANE, 1988), however, little or no photosynthetic input of phytoplankton needs to be directly consumed by the benthic food web. Estimates of the seasonal input of sinking pellets might be 0.02 g C m⁻² day⁻¹ in March and 0.11 g C m⁻² day⁻¹ in April, with an assimilation efficiency of 70% assumed for the zooplankton herbivores (SMITH and LANE, 1988). Such estimates suggest that the direct ingestion by the benthos might be, respectively, 22 and 3% of the daily primary production over these 2 months.

Without respiration measurements in 1984, the spring oxygen budget (FALKOWSKI et al., 1988) may not be an accurate assessment of the metabolic demands of the bacterioplankton within slowly warming shelf waters of 3–9°C. Assuming a 50% consumption of daily photosynthesis by the rest of the food web, however, these microorganisms would, by difference, require carbon inputs of at least 11% of the particulate algal production in March and 9% in April. If the daily March–April oxygen demands over the water column are partitioned as 10% to phytoplankton, 30% to zooplankton,
and 30% to benthos, one can assign the remaining 30% of the aerobic metabolism to bacterioplankton, i.e. about 15% of the gross photosynthesis.

With a bacterial secondary production of only ~2% of the rate of photosynthesis at this time of year (Ducklow et al., 1982), one then arrives at a total (production and respiration) carbon demand for the bacterioplankton of about 17% of the daily particulate carbon fixation by phytoplankton. This is an upper bound on microbial metabolism, since the 14C technique presumably approximates net photosynthesis of shelf waters. Such food requirements of the bacterioplankton may perhaps be equally met from algal release of dissolved organic carbon (DOC) rather than from bacterial colonization of particles. The mean DOC release rate is ~16% of the daily particulate fixation of carbon by phytoplankton in the Mid-Atlantic Bight, for example (Walsh et al., 1987b).

From such various estimates, one can sketch the following conservative scenario (Fig. 3) for the fate of a mean particulate primary production of 1.00 g C m^{-2} day^{-1} on the west line over 60 days in March-April 1984. An input of 0.16 g C m^{-2} day^{-1} from DOC exudates leads to a total net carbon fixation of 1.16 g C m^{-2} day^{-1} by phytoplankton (Fig. 3) for transfer of organic matter to the rest of the food web. About half may be
removed directly within the water column, i.e. 0.30 g C m\(^{-2}\) day\(^{-1}\) by the zooplankton and perhaps 0.17 g C m\(^{-2}\) day\(^{-1}\) by particle-related bacteria, if they attach to living phytoplankton. The other free-floating forms of the bacterioplankton might derive an additional 0.16 g C m\(^{-2}\) day\(^{-1}\) from phytoplankton exudates of DOC, for a total microbial sink of 0.33 g C m\(^{-2}\) day\(^{-1}\).

Since little algal biomass accumulates in surface waters, the other half of the spring bloom particulate production evidently sinks to the bottom (WALSH et al., 1987a). Here perhaps 0.06 g C m\(^{-2}\) day\(^{-1}\) of the primary production is directly taken up by the benthic communities, which ingest a fecal pellet flux of 0.09 g C m\(^{-2}\) day\(^{-1}\) for a total benthic consumption of 0.15 g C m\(^{-2}\) day\(^{-1}\) (Rowe et al., 1988). The unconsumed algal production of \(~0.47\) g C m\(^{-3}\) day\(^{-1}\) presumably moves downstream, in time and space, to be either utilized by the summer shelf food web (Rowe et al., 1986), or exported to the slope (WALSH et al., 1981).

Size fractionation of phytoplankton as well as untraditional herbivores, i.e. protozoans and gelatinous zooplankton, have yet to be considered in this scenario (Fig. 3), however. Assessment by the near-bottom arrays of fluorometers and current meters on the west line of how many particles were left behind in the spring water column suggested a smaller seaward flux of 0.30 g C m\(^{-2}\) day\(^{-1}\) over 40 days (WALSH et al., 1988b). We first summarize the evidence for such a particle transport process from the physical and geochemical results of SEEP—I, measured over a longer period of 12 months, and then return to additional considerations of the food web within the slope water column.

2. Circulation

Like the analysis of interacting biological life cycles, ranging from hours of bacteria to months of zooplankton, the physical synthesis of SEEP—I data involves processes at many time scales, from the days of topographic waves to the minutes of internal waves. Such complexities of the shelf/slope physical habitats are introduced with a description of the general circulation of slope water (CSANADY and HAMILTON, 1988). Inflow of surface Coastal Labrador Sea Water (CLSW) around the Grand Banks occurs at about 4 Sv from the north. From the Gulf Stream thermocline, another 6 Sv of subsurface Antarctic Intermediate Water (AIW) is injected from the east. Geostrophic adjustment leads to southwest drift, with eventual entrainment of part of these shelf and slope waters at Cape Hatteras, i.e. draining seaward along the north wall of the Gulf Stream. Some of the CLSW retroreflects eastward at \(~42^\circ\)N, 50\(^{\circ}\)W, however, since only 3 Sv of slope water moves south along the New Jersey coast, while only 0.4 Sv of shelf water exits at Cape Hatteras (CHAPMAN et al., 1986; CSANADY and HAMILTON, 1988).

Similarly, of the 1 Sv apparently upwelled to the surface by the wind curl within the slope sea to the west of the Gulf Stream at a weak rate of \(~0.3\) m day\(^{-1}\), only 20% enters the shelf (Fig. 4). The shoreward advection of subsurface AIW along isopycnal surfaces, originating in the thermocline of the Gulf Stream, upwells salty, nutrient-rich, and oxygen-poor waters into the shelf euphotic zone at an estimated transport of 0.2 m\(^{-2}\) s\(^{-1}\) per unit length of shelf-break. Over a 1000 km long shelf-break, such an influx of slope water would amount to half of the shelf transport exiting at Cape Hatteras, if shelf water were not locally exchanged with slope water. However, shelf water at Cape Hatteras is only slightly saltier than that off New England (CHAPMAN et al., 1986), suggesting export of some of the upwelled water.

Over a 20- to 40-m euphotic zone, the compensatory offshore Ekman transport
A schematic depiction of cross-slope water exchange ($m^2 \cdot s^{-1}$) per meter of shelf length within the Mid-Atlantic Bight (after Csanyd and Hamilton, 1988).

(Csanyd and Hamilton, 1988) of the upwelled slope water at the shelf-break (Fig. 4) would lead to cross-isobath surface flows of 0.5–1.0 cm s$^{-1}$. A separate continuity analysis of the narrowing of the Mid-Atlantic shelf width from Long Island (155 km) to Cape Hatteras (125 km) requires depth-averaged divergent outflows of Labrador-derived shelf water at the 100-m isobath of another 0.3 cm s$^{-1}$ off New York and 0.9 cm s$^{-1}$ off Virginia (Falkowski et al., 1988). This amounts to an additional outflow of $\sim$1.0 cm s$^{-1}$ within a bottom Ekman layer of perhaps 33-m thickness at the shelf-break within the SEEP-I region.

Observed cross-isobath currents during SEEP-I were indeed offshore at means of 0.6–1.2 cm s$^{-1}$, measured within both the surface (10 m below) and bottom (5 m above) Ekman layers, on the 80-, 125-, and 150-m isobaths of the outer shelf during each of the autumn–winter (9 September 1983–15 January 1984) and spring–summer (19 April 1984–17 October 1984) deployments (Aikman et al., 1988). Onshore flow of slope water at the shelf-break over the two 6-month periods, to replace the shelf export of water in the surface Ekman layer (Fig. 4), presumably occurred at mid-depth, where no meters were deployed on the east line. At least during 40 days in March–April 1984, however, the mean flow at 84 m on the 120-m isobath was onshore at about 1 cm s$^{-1}$ on the west line (Walsh et al., 1988b).

Within slope waters, there were also offshore mean flows of 0.3–3.3 cm s$^{-1}$ within the surface (20-m) layer, supporting the hypothesis of cross-slope Ekman transport depicted in Fig. 4. Within bottom layers (+50 to +100 m) on both the upper slope (200–1150 m) at the NASACS moorings (Butman, 1988) and on the lower slope (2300–2700 m) at the SEEP-I moorings (Aikman et al., 1988), similar downslope flows were found. Finally, on the upper slope at mid-depths of 120–1150 m, above the 500- and 1250-m isobaths, onshore mean currents of 0.2–1.1 cm s$^{-1}$ were observed (Aikman et al., 1988).

Within such a relatively weak, diabathic flow regime, i.e. the parabolic currents in the surface Ekman layer were instead a mean towards the west of 8.7 cm s$^{-1}$ on the shelf and 3.4 cm s$^{-1}$ over the slope (Aikman et al., 1988), only neutrally buoyant particles would transit the $\sim$140-km wide shelf, without intersecting the bottom a number of times. Tides, wind, and topographic waves represent external forcings of different frequencies, which are all capable of resuspending biogenic and lithogenic particles. Spatially
coherent, wind-driven motion did not extend seaward of the shelf-break, however, past which the spectral gap at this synoptic scale of variance leads to a minimum of total kinetic energy at mid-slope. Here, spectral analysis of the current meter records suggest a quiescent zone, with a mean westerly parabolic flow of only 2.2 cm s\(^{-1}\) near the bottom (AiKMAN et al., 1988; CsANADY et al., 1988).

Flows within the bottom Ekman layer on the shelf were frequently greater than a velocity of 20 cm s\(^{-1}\), which is probably sufficient to resuspend and transport sediment. However, such current speeds were observed <1% of the time above the slope sediments, where depositional velocities of 5 cm s\(^{-1}\) instead prevailed during the SEEP—I, NASACS, and MASAR experiments (CsANADY et al., 1988). On the lower slope, the low-frequency part of the current variance increased as a result of both less dissipation here of the topographic Rossby waves and greater proximity to their source, i.e. Gulf Stream meanders (CsANADY, 1988).

3. Frontal exchange

Based on freshwater discharge, salt budgets, \(^{18}\)O ratios (FAIRBANKS, 1982), and nutrient fluxes required to sustain the shelf primary productivity (Riley, 1975), the long-term, two-way exchange rate of shelf and slope waters at the shelf-break is estimated to be 0.2–0.4 m\(^{2}\) s\(^{-1}\) (CsANADY and HAMILTON, 1988). Warm-core rings, baroclinic instabilities, and wind events are all causative factors in the mixing process, parameterized by this exchange coefficient. Within the shelf-break front, moreover, greater diabathic fluxes of dissolved substances, for example, temperature, salt and perhaps nutrients, may occur in the summer when isopycnal surfaces extend continuously across the frontal zone (HOUGHTON et al., 1988).

Summer boluses of shelf water were found offshore, for example, while slope water intrusions were instead detected on the shelf during autumn. Convective overturn of the upper 200 m of the slope water column during winter may lead to downwelling velocities of 1.0 m day\(^{-1}\) (CsANADY and HAMILTON, 1988), compared to the estimated upward motion of 0.3 m day\(^{-1}\) from wind curl-driven upwelling. Such a net downward motion would effectively curtail further resupply of nutrients to the shelf, after the first few autumn destratification events within the nutrient-impoverished euphotic zone.

During winter–spring, large cross-isobath excursions of the shelf-break front over distances of 10–20 km are correlated with the alongshore wind stress in an Ekman sense (HOUGHTON et al., 1988), when diabathic flows of 10–20 cm s\(^{-1}\) are observed (WALSH et al., 1988b). Figure 5 presents a scenario for seaward transport of shelf particles during events of wind forcing from the northwest (upwelling circulation) and northeast (downwelling circulation). During an upwelling-favorable wind event, particles situated near the bottom on the landward side of the inclined shelf-break front could be resuspended off the bottom and be advected seaward in a surface Ekman layer. After this wind event, the biogenic and lithogenic particles could then fall through the inclined front to bottom waters of the outer shelf (Fig. 5). Once seaward of and beneath the front, however, near-bottom particles could no longer be mixed up again to the surface. They must depend instead on seaward transport within a bottom Ekman layer for further export to the slope during a downwelling-favorable wind event.

Resuspension by both tides and internal waves (OU et al., 1988; FLAGG, 1988) of particles, trapped beneath the shelf-break front, would actually be enhanced during periods of downwelling. In these events, the bottom of the front is steepened and
Fig. 5. A schematic depiction of particle transport within a surface Ekman layer of the inner shelf and a bottom Ekman layer of the outer shelf during the spring bloom in the Mid-Atlantic Bight.

Baroclinic tides are amplified (Ou and Maas, 1988). On the outer shelf, the semidiurnal tide generates mean near-bottom velocities of ~4 cm s\(^{-1}\) amplitude for the cross-shelf component (Ou and Maas, 1988). However, at this and even higher frequencies of internal waves, originating within slope waters and dissipating on the outer shelf bottom, transitory near-bottom oscillations of 10–30 cm s\(^{-1}\) amplitude have been observed.

These flows constitute a bottom stress of as much as 6 dyne cm\(^{-2}\) on the outer shelf, i.e. equivalent to the storm-induced friction velocities on the inner shelf (Flagg, 1988). To place these forces in perspective, a bottom stress of ~1 dyne cm\(^{-2}\) would be required for resuspension of particles of 37 μm diameter (Churchill et al., 1988), i.e. larger
diatoms and silt-sized sediments. High-frequency fluctuations of water motion on the upper slope may similarly lead to resuspension and preferential downslope transport of near-bottom particles (Butman, 1988), once they penetrate the shelf-break front.

Having summarized the SEEP—I physical habitat, the next section deals with three reports on transport of biogenic and lithogenic particles across the shelf (Walshe et al., 1988a) and thence from the shelf-break seaward to the upper slope (Churchill et al., 1988; Butman, 1988). Since the first paper deals with transport at lower frequencies of wind forcing, compared to mostly higher frequencies of oceanic forcing in the latter two, we deal first with the implications of the simulation analysis.

4. Particle transport

Utilizing shipboard and satellite data on the 1979 spring bloom in the Mid-Atlantic Bight, growth, consumption, sinking, and seaward translation of phytoplankton populations were studied at ~18,000 grid points over a 58-day sequence of upwelling and downwelling circulation patterns, induced by wind-forced, time-dependent Ekman transport (Walshe et al., 1988a). Similar to the previous oxygen budget, 57% of the mean daily carbon fixation of the three-layered model was removed by organisms, when an exponential increment of losses of the phytoplankton was invoked from February to April 1979. With the same consumption process and a settling velocity of 20 m day⁻¹, another 14% of the primary production was exported seaward at the shelf-break and 7% downstream at Cape Hatteras. Extending the calculations of the model for another 22 days led to a total mean export from the model's boundaries of 27% of the average daily production of the phytoplankton over the whole shelf.

With such a sinking rate and a mean seaward flow of 1.1 cm s⁻¹ in the lower third of the water column, most of the model's export at the shelf-break, i.e. 60% of the total, actually occurred within the bottom Ekman layer. Furthermore, the export of chlorophyll at the shelf-break trebled southward, from 1.3 g Chl m⁻² day⁻¹ off New York to 3.6 g Chl m⁻² day⁻¹ off Virginia, as a result of shorter residence time and less susceptibility to predation. Finally, the simulated time history of the 1979 spring bloom, at a grid point adjacent to the 80-m fluorometer mooring during 1984 (Walshe et al., 1988b), realistically approximated the algal biomass left behind in the March–April 1984 water column, providing insight into the sources of suspended matter at the shelf-break.

Time-series of near-bottom light transmission and fluorescence were obtained from instruments moored 3–5 m above bottom at the 60- and 80-m isobaths south of Long Island. They indicated that, during the onset of the spring bloom in February–April 1984, major offshore movements of suspended matter between the two isobaths could be related to a seasonal buildup of algal biomass and to northeast wind forcing, i.e. a downwelling circulation pattern (Walshe et al., 1988b). Similarly, at 10 m above bottom on the 125-m isobath, south of Martha's Vineyard, another transmissometer record during the onset of the autumn bloom in September–December 1983 displayed a seasonal increase in beam attenuation during resuspension events. During the events on the outer shelf, near-bottom velocities exceeded 20 cm s⁻¹ at time scales of the semidiurnal tide (Churchill et al., 1988).

In water depths >70 m, the bottom stress contributed by surface waves is a minor factor in resuspension of particles (Churchill et al., 1988). Similarly, resuspension events at the shelf-break were poorly correlated with direct changes in wind stress, but were related instead to low salinities, i.e. seaward movement of the foot of the shelf-
break front, where the kinetic energy of semidiurnal tides and internal waves is focused (Ou and Mass, 1988; Flagg, 1988). Resuspension by high-frequency forcing of tides and internal waves on the outer shelf, as well as by surface waves on the inner shelf, coupled with offshore advection within surface and bottom Ekman layers in response to low-frequency wind events, is a feasible net export mechanism, if the particles settle out of the water column before the next onshore movement of the shelf-break front.

An offshore displacement of the shelf-break front of 15–20 km at speeds of 5–20 cm s⁻¹ (5–20 km day⁻¹), measured at the 125-m isobath (Churchill et al., 1988), suggests a particle may have a seaward journey of 0.8–4.0 days during a downwelling event. It must sink out of the bottom Ekman layer onto the outer shelf during such a seaward excursion, before return of the shelf-break front towards the coast. With no further resuspension, a sinking velocity of 10–20 m day⁻¹ over a 10- to 30-m nepheloid layer would strip particles from the bottom water column within 0.5–3.0 days. Assuming no motility of algae or detritus, this is a likely scenario for particles, whose diameter exceeds 48–68 μm in order to approach such Stokes settling velocities (Csanydy, 1986).

Such a range in diameter of a sinking particle is somewhat larger than the 37 μm size, which can be resuspended by a minimum bottom stress of 1 dyne cm⁻² (Churchill et al., 1988). However, they are the typical diameters of solitary diatom species, for example, Coscinodiscus and Biddulphia, found in slope sediments during SEEP—I (Falkowski et al., 1988). When colonial diatoms of individual diameters of 10–20 μm form chains, for example, Chaetoceros, Thalassiosira, andSkeletonema as in March–April 1984 (Smith and Lane, 1988), the resultant diameters of the colony can also be in the range of 48–68 μm, or larger. It would appear that both diatoms and other fine-grained (<63 μm) particles could sink out of the shelf-break water column, during surface or bottom excursions of the front, to be incorporated within a near-bottom nepheloid layer of the upper slope.

In another study of sediment transport, the net diabathic current was seaward at 7 m above bottom on the upper slope (200–1150 m), between 67° and 70°W from October 1983 to November 1984 during the NASACS experiment (Butman, 1988). Over a Mid-Atlantic continental slope of 10% inclination, a downslope flow of 1 cm s⁻¹ is equivalent to a depth change of about 100 m day⁻¹ (Butman, 1988). This apparent vertical displacement rate is similar to that estimated from time-lapse bottom photography for the arrival of phytodetritus on the Irish slope after the spring bloom (Billet et al., 1983; Lampitt, 1985).

Similar floes of near-bottom organic debris have been detected visually at mid-slope (989–1750 m) during a camera sled traverse along the SEEP—I east transect during 4–5 May 1986 (B. Hecker, personal communication). The thickness of this slope bottom boundary layer was >7 m and <50 m, with an average downslope current of 3.8 cm s⁻¹ at the 200-m isobath, 1.4 cm s⁻¹ at the 500-m isobath and 1.8 cm s⁻¹ at the 1150-m isobath (Butman, 1988). A vertical displacement of 140–380 m day⁻¹ would ensure rapid delivery of particles to the lower slope, after their resuspension by high-frequency, asymmetric oscillating currents, with downslope flows which were 2–3 time greater than the upslope flow.

At the same depth in the water column as the transmissometer at 115 m, but above the upper slope on the 500-m isobath, where we would expect small biogenic particles to constitute most of the mid-water signal of light transmission (Walsh et al., 1988b), another transmissometer record was obtained 30 km farther seaward. It was not
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significantly related to the shelf-break transmissometer record, however, either statistically or on an event-by-event basis (CHURCHILL et al., 1988). Particles left behind in the surface layer of the slope water column may not have a shelf origin, but may result instead from the overlying euphotic zone (Fig. 3).

At low beam attenuation values of 0.35–0.55 m\(^{-1}\) from 15 September 1983 to 15 March 1984 at this upper slope transmissometer (CHURCHILL et al., 1988), most of the light attenuation could be attributed to dissolved substances of coastal water, i.e. 0.46 m\(^{-1}\) (WALSH et al., 1988b). In this case, little autumn or spring export of phytodetritus and fine-grained particles from either shelf or slope waters may have been detected by this instrument at 115 m depth, but ~385 m above the bottom. If shelf particles sank within 30 km of the shelf-break (Fig. 6), one would expect radioactive and chemical tracers to provide insights about the source of particles within the deeper water column and sediments of the slope.

5. Sedimentation

Similar to the numerous carbon budgets in this issue, separate \(^{210}\)Pb budgets were constructed for the dissolved and particulate phases of this radionuclide within the water column (BACON et al., 1988), within sediment traps (BISCAYE et al., 1988), and within surficial sediments (ANDERSON et al., 1988). A daughter product, \(^{210}\)Po, of much shorter half-life (0.4 y) than the parent \(^{210}\)Pb (22.3 y) may also produce additional information on the fate of short-lived particles. The daughter may trace processes involving living plankton, compared to long-lived particles, i.e. detritus of marine and terrestrial origin tagged mainly by the \(^{210}\)Pb (BACON et al., 1988).

Fig. 6. A schematic depiction of particle transport from the shelf into the interior waters of the slope (after BISCAYE et al., 1988).
During July–August 1983, for example, removal of dissolved $^{210}$Po from shelf and slope surface waters was associated with its incorporation on particles and a sinking flux out of the euphotic zone (Bacon et al., 1988). After decomposition of these sinking particles, excess dissolved $^{210}$Po was returned to the water column and was found above the bottom on the shelf; recall the oxygen budget (Falkowski et al., 1988). Similarly, an increase of dissolved $^{210}$Po was found at depths of 50–100 m on the upper slope; recall the above discussion of transmissometer records at 115 m on the 125- and 500-m isobaths (Churchill et al., 1988). Within the deeper water column on the upper slope, $^{210}$Po was again removed from the water column, presumably scavenged by falling particles.

The dissolved $^{210}$Pb was more strongly depleted in surface waters on the shelf (2–4 dpm 100 kg$^{-1}$), compared to surface abundances in slope water (6–10 dpm 100 kg$^{-1}$) and in the Sargasso Sea (15 dpm 100 kg$^{-1}$), reflecting the more efficient removal of $^{210}$Pb by detritus within the shelf ecosystem (Bacon et al., 1988). A shelf budget of $^{210}$Pb suggests that all of the atmospheric deposition of $^{210}$Pb (1.0 dpm cm$^{-2}$ y$^{-1}$), dissolved within shelf waters, must be removed by export of particulate $^{210}$Pb, either seaward to the slope sediments or downstream for entrainment by the Gulf Stream at Cape Hatteras. Shelf sediments are a negligible sink of $^{210}$Pb, ~10% of atmospheric input, while in situ production of $^{210}$Pb from $^{226}$Ra within shelf waters is similar to its loss from radioactive decay (Bacon et al., 1988).

Within another $^{210}$Pb budget of continental slope waters, overlying just the 200- to 2000-m isobaths in the SEEP—I area, the sediment storage of particulate $^{210}$Pb was assumed to be 2.2 dpm cm$^{-2}$ y$^{-1}$ (Bacon et al., 1988). Such an accumulation rate is similar to previous estimates over the whole Mid-Atlantic Bight, suggesting a $^{210}$Pb input to slope sediments, which is two- to three-fold that of the atmospheric deposition rate (Buesseler et al., 1985). Ignoring for a moment the seasonality of particle fluxes, the annual mean of particulate $^{210}$Pb flux out of the slope water column at 150 m on the 500- and 1250-m isobaths was only 0.65 dpm cm$^{-2}$ y$^{-1}$ (Biscaye et al., 1988), i.e. 65% of the rate of local atmospheric deposition and only 30% of the rate of sediment accumulation of $^{210}$Pb. Production of $^{210}$Pb from $^{226}$Ra is estimated to be 0.25 dpm cm$^{-2}$ y$^{-1}$ within the slope water column, while its loss by further radioactive decay is 0.16 dpm cm$^{-2}$ y$^{-1}$. Using the observed gradient in dissolved $^{210}$Pb across the summer shelf-break and the exchange coefficient of 0.2 m$^{-1}$ s$^{-1}$ between surface shelf and slope waters, 0.8 dpm cm$^{-2}$ y$^{-1}$ of soluble $^{210}$Pb per meter alongshore may be transported shoreward (Bacon et al., 1988).

The mean $^{210}$Pb particulate flux increased to 1.35 dpm cm$^{-2}$ y$^{-1}$ in the sediment traps at 450 m on the 500- and 1250-m isobaths, implying that the shelf was a local source for particulate $^{210}$Pb of at least 0.70 dpm cm$^{-2}$ y$^{-1}$, i.e. the difference between fluxes within the sediment traps at depths of 150 and 450 m (Biscaye et al., 1988). The cross-frontal gradient of suspended particulate $^{210}$Pb in July–August suggested that particle export to the slope might be negligible at that season, however (Bacon et al., 1988). At this time, the particulate $^{210}$Pb flux in the traps at 150 m on the upper slope was also a seasonal minimum, ranging from <0.3 dpm cm$^{-2}$ y$^{-1}$ in August to >3.0 dpm cm$^{-2}$ y$^{-1}$ in May (Biscaye et al., 1988).

One constraint on the magnitude of export of organic matter from the shelf is the amount of $^{210}$Pb which might accumulate in the slope sediments on an equal area basis, over longer time scales than the spring bloom. Based on sediment inventories of $^{210}$Pb from all six SEEP—I cores taken between the 500-m and 2000-m isobaths, the mean
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210Pb accumulation rate in surface sediments of the slope might only be 1.4 dpm cm$^{-2}$ y$^{-1}$, the same as that caught with sediment traps moored 50 m off the bottom at the 500- and 1250-m isobaths (Biscaye et al., 1988). From the three SEEP—I cores on the 500-, 870- and 1130-m isobaths of the upper slope, however, the mean 210Pb accumulation was instead 1.9 dpm cm$^{-2}$ y$^{-1}$, similar to the estimate in the above budget (Bacon et al., 1988). Since the downslope transport of particles apparently occurs in a bottom boundary layer of <50-m thickness (Butman et al., 1988), the near-bottom sediment traps in SEEP—I may not have caught all of the lateral export of particulate 210Pb and organic carbon from the shelf (Fig. 6).

Assume that the shelf width is twice that of the slope (~50 km), with an atmospheric input of 210Pb over the entire region of 1.0 dpm cm$^{-2}$ y$^{-1}$. If all of the atmospheric 210Pb fallout over the shelf were exported to the slope, with none buried within shelf sediments, then the total input of 210Pb focused in the slope sediments would be 3.0 dpm cm$^{-2}$ y$^{-1}$. A measured 210Pb accumulation rate of 1.4–2.2 cm$^{-2}$ y$^{-1}$ in slope sediments would then account for 100% of its atmospheric input to slope waters (1.0 dpm cm$^{-2}$ y$^{-1}$). Another 20–60% of the atmospheric input of 210Pb to shelf waters (2.0 dpm cm$^{-2}$ y$^{-1}$) would also be stored in slope sediments. Presumably, the remaining 40–80% of the shelf 210Pb is absorbed on detritus which exists at Cape Hatteras, where 50% of the shelf water (Falkowski et al., 1988) and 33% of the unconsumed phytoplankton (Walsh et al., 1988a) may be exported as well. The above dissolved and particulate 210Po data suggest dissolution of plankton within surface slope waters, however. One must thus ask on what type of detritus does the longer-lived particulate 210Pb enter local slope and eventually Gulf Stream waters?

6. Size fractionation

The March–April 1984 particulate production of phytoplankton was 1.19 g C m$^{-2}$ day$^{-1}$ within slope waters (Falkowski et al., 1988), suggesting a DOC production of perhaps 0.19 g C m$^{-2}$ day$^{-1}$. The same bacterial demand of 0.33 g C m$^{-2}$ day$^{-1}$ and a mean copepod grazing stress of 0.16 g C m$^{-2}$ day$^{-1}$ (Smith and Lane, 1988) allows a possible sinking flux of 0.94 g C m$^{-2}$ day$^{-1}$ from the slope water column (Fig. 3). About 95% of this potential spring input to the slope aphotic zone would be phytodetritus with unknown sinking rates, rather than fecal pellets, i.e. offshore picoplankton might sink at only 6 m y$^{-1}$.

Low C/N ratios of <7 were measured for organic matter within the near-bottom sediment traps at 1000–2500 m (Biscaye et al., 1988). A seasonal peak of the calcium carbonate flux was also found in April at 500 m on the upper slope (Biscaye et al., 1988). Finally, observations of shelf diatom species were made within the bottom layer at 400–1000 m on the slope (Falkowski et al., 1988). These SEEP—I data all suggest that fast sinking (~100 m day$^{-1}$) macro-aggregates of diatoms and coccolithophores, in contrast to thecate dinoflagellates and picoplankton, were the bulk of the carbon caught in the upper slope traps (Fig. 3).

High C/N ratios (>10) of particulate matter were instead found within the slope euphotic zone during SEEP—I (Falkowski et al., 1988). These element ratios of particles left behind in the water column suggest preferential recycling of reduced nitrogen compounds during the grazing and remineralization processes of the slope food web. The impact of heterotrophic activity within the slope water column was clearly underestimated during SEEP—I, since only 6% of the hypothetical combined March—
April input of 1.41 g C m\(^{-2}\) day\(^{-1}\) of shelf and slope detritus was caught as a particle flux of 0.09 g C m\(^{-2}\) day\(^{-1}\) at 50 m above the 500-m isobath (Fig. 3).

Picoplankton were not enumerated during SEEP—I, but earlier size fractionation studies in March 1981 suggested that >80% of the algal community might be <22-\(\mu\)m diameter within slope waters, compared to only 20% on the shelf (MALONE et al., 1983b). Furthermore, of the March–April 1984 netplankton community, only 25% were motile dinoflagellates on the shelf, in contrast to 50% within slope waters (FALKOWSKI et al., 1988). Dinosterol, a biomarker of dinoflagellate origin, was actually more abundant within shelf sediments, however, with seven-fold less concentrations of this sterol found in slope sediments at 2300 m (VENKATESAN et al., 1988).

Assume that 20% of both the particulate phytoplankton production (0.24 g C m\(^{-2}\) day\(^{-1}\)) and of bacterial remineralization attached to detritus (0.03 g C m\(^{-2}\) day\(^{-1}\)) within slope waters involves netplankton. Some of the estimated release of DOC may actually represent particulate production of organic carbon by picoplankton, not trapped on filters, but their input of carbon would still be budgeted in Fig. 3. The daily consumption of the netplankton particles by copepods would then leave a sinking flux of only 0.05 g C m\(^{-2}\) day\(^{-1}\) for microalgae >22 \(\mu\)m, as indicated by the flux in parentheses of the slope budget in Fig. 3.

The smaller phytoplankton have lower Stokes settling velocities (Csanady, 1986). An algal cell of 20-\(\mu\)m diameter, for example, might sink at 1.7 m day\(^{-1}\), while picoplankton of 2-\(\mu\)m diameter might sink at 6.2 m y\(^{-1}\). Based on the vertical gradient of particle fluxes within the SEEP—I arrays of sediment traps (BISCAYE et al., 1988), these slow-sinking flagellate and picoplankton components of the slope phytoplankton community must be consumed by the protozoa and gelatinous zooplankton herbivores within the upper 150 m of the slope water column.

Vertical transfer of some diatom and coccolithophore carbon from surface to deeper waters of the slope may occur, in conjunction with lateral injection of particles at the shelf-break (Fig. 6). Assuming that 80% of the shelf community is netplankton with high sinking rates (10–100 m day\(^{-1}\)), the lateral input within slope waters would then be 0.30 g C m\(^{-2}\) day\(^{-1}\), depicted by the flux in parentheses of the shelf budget in Fig. 3. This is undoubtedly a fortuitous convergence to the same shelf export of carbon estimated from the SEEP—I instruments moored at the shelf-break (Walsh et al., 1988b).

7. Sediment storage

Survival of ~25% of a combined shelf/slope detrital input of 0.40 g C m\(^{-2}\) day\(^{-1}\), during its March–April descent from 100 to 450 m in the upper slope water column may occur (Fig. 3), rather than the 6% previously estimated in Section 6. This would be more consistent with the near-bottom sediment trap observations of low C/N ratios at 1000–2500 m, i.e. suggesting lateral downslope input of unconsumed particulate matter with presumably high fall velocities. Radionuclide and organic tracers provide an estimate of the further survival rate of organic matter within slope sediments.

Within near-surface sediment traps at 150- to 450-m depths where particulate matter first enters the slope water column, the daily organic carbon flux can be roughly related to the annual 210Pb flux by 25 mg C m\(^{-2}\) day\(^{-1}\) = 1 dpm 210Pb cm\(^{-2}\) y\(^{-1}\) (BISCAYE et al., 1988). Within subsurface sediment traps, less organic carbon flux was found for the same input of 210Pb, i.e. implying more oxidation of the organic matter took place during the longer residence time in the deeper water column. Without decomposition of the detrital
carbon, a $^{210}$Pb accumulation rate of 1.4–2.2 cm$^{-2}$ y$^{-1}$ within slope sediments and the above relationship imply an organic carbon input of 12.8–20.1 g C m$^{-2}$ y$^{-1}$. This is 6–9% of a mean annual primary production of just 220 g C m$^{-2}$ y$^{-1}$. A previous estimate of sediment accumulation of carbon over the whole Mid-Atlantic Bight was similar, 9.9 g C m$^{-2}$ y$^{-1}$ (Walsh et al., 1985).

In the SEEP—I region, where a priori we thought carbon export would be minimal, revised estimates of carbon burial on the slope are instead 1.0–2.5 g C m$^{-2}$ y$^{-1}$ (Anderson et al., 1988). The source of this refractory organic matter in slope sediments can be traced with biomarkers, e.g. lignin phenols or sterols from the higher vascular plants (Venkatesan et al., 1988). The abundance of vanillin and $\beta$-sitosterol, in comparison with total organic carbon content of the SEEP—I surficial sediments, suggests that 47–49% of the organic carbon in slope sediments was imported from the shelf and coastal regions. The absence of most lignin phenols from the sediment trap moored 50 m above bottom on the 1250-m isobath implies that near-bottom, downslope sediment movement, rather than atmospheric deposition and zooplankton scavenging within slope waters, is the transport mode of shelf export of organic carbon (Venkatesan et al., 1988).

Our present estimate of annual sedimentary storage of organic carbon (Anderson et al., 1988) is a daily average of only 0.01 g C m$^{-2}$ day$^{-1}$ within surficial slope sediments of the SEEP—I region (Fig. 3). Assuming the near-bottom traps caught all the slope import, an April input of 0.09 g C m$^{-2}$ day$^{-1}$ was instead measured at 50 m above the bottom of the upper slope (Fig. 3). Such a difference implies continued oxidation and/or downslope transport of particles (Fig. 6) to the rise. Comparison of CaCO$_3$ fluxes and inventories in the sediments suggests that, indeed, half of the input of calcareous matter may be dissolved during biogenic production of CO$_2$ within the bottom layer (BisCaye et al., 1988).

**IMPLICATIONS**

Particle-reactive, xenobiotic compounds may be left behind in slope sediments after oxidation and dissolution of the carrier organic matter, Biogenic CO$_2$, evolved during such a remineralization process, would also be below the main thermocline. Here, isopycnal transport might allow horizontal dispersion of biogenic CO$_2$ towards the deep sea, to be possibly sequestered within the inorganic bicarbonate cycle as a possible coastal sink for emissions of fossil fuel.

The spring pulse of particles caught in the SEEP—I sediment traps on the outer shelf and slope of the continental margin was 10-fold that of the adjacent rise (BisCaye et al., 1988). On a daily basis, the seasonal peak of sinking carbon within other sediment traps during an annual study at 3200 m near Sta. S in the Sargasso Sea was 3–4 mg C m$^{-2}$ day$^{-1}$ (Deuser, 1986). This offshore flux at Sta. S is somewhat less than that found throughout the water column at the SEEP—I mooring on the 2750-m isobath of the continental rise. Since the surface area of the continental shelves and slopes is ~20% that of the open ocean, the total carbon export from the continental margins which eventually arrives at 2000 m may be equivalent to that from the open ocean. From the SEEP—I and Sta. S results, it would appear that the horizontal export of organic matter from the shallow boundaries of the ocean to its subthermocline interior (Fig. 6) may be the same as vertical losses from surface waters of the deep sea.

Furthermore, recall the increased carbon content of slope sediments to the south (Fig. 2), the narrowing of the shelf, and the suggestion of increased export off Virginia
from our simulation models (Walsh et al., 1988a). We expect the SEEP—II experiment to yield greater estimates of biogenic export of particulate matter and xenobiotic compounds from the Mid-Atlantic Bight, and perhaps from continental margins in general. Some hint of this anticipated increase in export was provided by another year-long, near-bottom sediment trap mooring at 1000 m on the northern MMS line near 73°W (Fig. 1). The fluxes of \(^{210}\text{Pb}\) and organic carbon were measured at 25 m above the bottom from April 1985 to March 1986 as well. The annual mean inputs of these radioactive and biogenic constituents were two- to three-fold those measured, about 250 km upstream (Fig. 1) near 71°W, at comparable depth during the 1983–1984 SEEP—I experiment (Biscaye et al., 1988).

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