The Shelf Edge Exchange Processes experiment, SEEP-II: an introduction to hypotheses, results and conclusions

PIERRE E. BISCAYE,* CHARLES N. FLAIGHT† and PAUL G. FALKOWSKI†

(Received 23 March 1994; accepted 15 April 1994)

Abstract—The SEEP (Shelf Edge Exchange Processes)-II experiment was the second of two that took place in the Middle Atlantic Bight (MAB) of the eastern U.S. continental shelf and slope. The experiment included an array of 10 multi-instrumented moorings deployed for 15 months and 10 oceanographic cruises, all designed to address the problem of the fate of continental shelf particulate matter in general, and organic carbon in particular. This paper provides the setting and background for the SEEP Program, the SEEP-II experiment and an introduction to the 18 papers constituting the subject of this special volume. Because those papers lack one of a general nature on the physical oceanographic setting of the experiment, that aspect is treated in somewhat more detail here.

The results of the experiment overwhelmingly show that the working hypothesis on which the SEEP Program was undertaken and sponsored by the Department of Energy is not valid. That is, there is not an export to the adjacent slope and open ocean of a large proportion of the particulate matter introduced to and biologically generated in the waters of the continental shelf; most of the biogenic particulate matter is recycled by consumption (bacterial and otherwise) and oxidation on the shelf, and only a small proportion (of order <<5%) is exported to the adjacent slope. The small amount that is exported appears to be deposited preferentially in the sediments of an area of the slope centered at about 1000 m, and the export and sedimentation to that depocenter appears to increase from the northern to the southern MAB.

1. INTRODUCTION

Relative to the open ocean, continental shelves tend to be areas with large standing stocks of particulate organic carbon and high rates of primary production. This production is fueled by the rapid recycling of nutrients as well as the proximity to both continental and oceanic nutrient sources. Throughout the early 1970s, the fate of primary production on temperate-latitude continental shelves was modeled after the (then) accepted, open-ocean paradigm of a marine food web dominated by macrozooplankton grazers which increased in abundance as the spring phytoplankton bloom progressed. Ultimately, the zooplankton grazing overtook the rate of the net phytoplankton accumulation and led to the summer-time reduction in phytoplankton. This model of marine food webs, developed from early analyses of field data by HARRIS (1980), RILEY (1946), STEELE (1974), WALSH (1976) and others, was used to account for the relatively high fish production on continental shelves (RYTHER, 1969; WALSH, 1988).

* Lamont-Doherty Earth Observatory of Columbia University, Palisades, NY 10964, U.S.A.
† Oceanographic and Atmospheric Sciences Division, Brookhaven National Laboratory, Upton, NY 11973, U.S.A.
By the mid-1970s closer analysis of the field data suggested that a close "coupling" between phytoplankton production and zooplankton grazing was at best an idealization, and more likely invalid (Dagg and Turner, 1982; Judkins et al., 1980). Measurements of macrozooplankton grazing abundance and ingestion rates suggested that only a small fraction of the spring bloom was consumed by the classical pelagic food web. Moreover, measurements of benthic respiratory activity in the shelf sediments were too low to account for the fate of the remaining phytoplankton carbon. To account for this discrepancy, Walsh et al. (1981) suggested that the vast majority of phytoplankton carbon produced during the spring bloom was exported from the continental shelves to the central ocean basins or to the sediments of the upper continental slope. Surveys of organic carbon on shelf and slope sediments appeared to support the notion of a carbon-rich "depocenter" on the continental slope. Simple, "back of the envelope" calculations led to the conclusion that if the shelf export was extrapolated globally, the carbon sequestered in this manner could be relatively significant.

The concept that a significant fraction of primary production could be exported from continental shelves was attractive to a large spectrum of oceanographers. Geochemists and sedimentologists could use the hypothesis to explain both the general absence on the shelf of fine-grained particles, high in organic carbon and 210Pb, and the high accumulation of organic carbon in slope sediments to drive the "manganese pump" (Spencer et al., 1981). Biologists could test hypotheses related to the coupling between primary and secondary production without having to close carbon budgets on the shelf; any leftover carbon could be exported. The major problem was one of physical mechanism. On the northeast coast of the U.S. the continental shelf water column is separated from the slope sea by a temperature–salinity front. Escape of particulate carbon directly through the front was difficult to accept, and attempts were made to support various alternative hypotheses related to sporadic advective events such as entrainment of shelf water by passing Warm-Core Ring eddies, by sinking across the front, or by advection in the benthic boundary layer.

In 1980 the investigators supported by the Department of Energy in the Northeastern U.S., who had previously been working individually on aspects of these problems, proposed an interdisciplinary, interinstitutional program called SEEP—Shelf Edge Exchange Processes to test the shelf-export hypothesis. The experiment would take place in the Mid-Atlantic Bight (MAB) over the course of about a decade at three locations, moving from the northern to the southern end of the MAB. It was anticipated that the net export of particles, including carbon, across the shelf–slope break, would increase with successive, more southerly experiments because of an expected southerly increase in primary productivity, and because of a decrease in the width of the shelf. The processes of exchange across the shelf–slope front—whatever they turned out to be—were regarded collectively as the "diffusive" processes, and those particles not exported by the latter or otherwise consumed on the shelf would be advected offshore at Cape Hatteras where the southwestward-flowing shelf water runs out of shelf and largely joins the slope water and/or the Gulf Stream.

The first experiment, SEEP-I, took place from July 1983 to October 1984 in the waters of the MAB shelf and slope south of Cape Cod and Long Island. Although addressing the same problem, the field program consisted of two, only slightly overlapping experiments run by two different groups. This degree of disintegration of effort was reflected in the diversity of results expressed in the 26 papers constituting the primary output of the
experiment in a special issue of Continental Shelf Research [1988, 8(5-7), 433–946] and summarized in Walsh et al. (1988) in that volume. With respect to the problem of the primary production and fate of carbon, estimates of export ranged from <10% by "diffusive" exchange across the shelf edge, with some indication of its increase towards the southwest (Biscaye et al., 1988), to 10–20%, with most being oxidized on the shelf (Falkowski et al., 1988), to from <10% to almost 40% in model results, with no more than half being consumed by herbivores (Walsh et al., 1988).

The second experiment, SEEP-II, was delayed until February 1988–June 1989, during which time 10 cruises were mounted and 10 moorings were emplaced at 12 locations on the shelf and upper slope south of the Delmarva Peninsula (Fig. 1). Because of a significant likelihood that there would not be a SEEP-III, as originally planned, the moorings were deployed in two transects perpendicular to the mean isobaths and separated by ~90 km. The North Transect comprised the bulk of the instrumentation on six moorings in from 40
to 1000 m of water, and the South Transect only three moorings, but with identical instrumentation and at the same depths as the most seaward three of the North Transect. This second, abbreviated transect was envisioned to achieve at least partial realization of the offshelf export of particles to the slope, separate from that measured at the North Transect. This experiment was more completely integrated than was SEEP-I, with the instrumentation from all participating institutions intercalated throughout all the moorings, and investigators from all institutions represented on all cruises. Other projects separately funded by the National Science Foundation were also integrated into and contributed to the SEEP-II field experiment. The resulting interdisciplinary data represent one of, if not the, most extensive set of moored, synoptic measurements of temperature, salinity, phytoplankton chlorophyll fluorescence, macrozooplankton, oxygen, current conditions and vertical particle flux acquired in an oceanographic program.

This volume is a collection of some of the principle results of SEEP-II, but is more abbreviated than it might otherwise have been, had the SEEP Program not ended before the work was completed and the results been more thoroughly exploited. In this paper we summarize some of the most important results of the papers in this volume in the same order in which they appear. The first section deals with the physics of the water column. This section is somewhat expanded relative to the others because none of the papers in this volume deals with the general hydrography and currents during SEEP-II, and this must be presented as the physical setting for the other measurements. The second section deals with the generation, transport and distribution in space and time of living, biogenic and abiogenic particles. And the third section also deals with particles, but more focused on the production, consumption, transport and budgets of carbon; questions about these facets of the marine carbon cycle were, in part, an initiator of the SEEP program, and have been one of its major foci. Lastly we summarize some of the major conclusions of the SEEP experiment.

2. PHYSICS OF THE WATER COLUMN

2.1. General hydrography of the SEEP-II region

The hydrography of the southern Mid-Atlantic Bight (MAB) has many features that are characteristic of the entire Bight (Beardsley et al., 1976; Beardsley and Boicourt, 1981; Csanady and Hamilton, 1988). There is a permanent thermohaline front between the relatively fresh shelf waters and the more saline waters of the slope sea. The shelf waters undergo large seasonal property and stratification fluctuations from winter to summer. In addition to these standard features, the southern MAB is significantly impacted by the fresh water discharge of the Delaware and Chesapeake Bays and by the proximity of the Gulf Stream and the eddies shed from it. The overall drift of the shelf waters is to the southwest.

The vigorous vertical and horizontal mixing caused by cooling and storms that occur during the late winter–early spring resets the shelf each year to its simplest structure [Fig. 2(a)]. At this time the shelf is vertically well mixed and the mid-shelf horizontal property gradients are at a minimum. The shelf, because of its relatively shallow depths, is colder as well as fresher than the slope waters offshore. The shelf-water/slope-water front is well defined, with an increase in temperature, salinity, and density offshore. Mid shelf temperatures reach their seasonal minima between 5 and 7°C, while mid-shelf salinities are about 33 pss. Offshore of the front, slope water temperatures and salinities for the same
Fig. 2. SEEP-II hydrographic sections showing representative distributions of temperature, salinity and sigma-t. The winter–early spring section in Fig. 2(a) was occupied between 16 and 19 March 1988 while the section characteristic of stratified conditions, Fig. 2(b), was occupied on 12 June 1988.
depth range are typically about 12°C and 35.3 pss, respectively (cf. CSANADY and HAMILTON, 1988). Even though the late winter–early spring precedes the period of maximum freshwater discharge, the effect of the Bay (riverine) waters is evident over the inner half of the shelf [Fig. 2(a)]. The low salinity water flows southward close to shore since the prevailing winds during this period are from the northwest.

In late spring, the decrease in wind forcing, combined with increased solar insolation, causes the near-surface waters to warm, forming a 10–15 m thick seasonal thermocline at a depth of about 20 m [Fig. 2(b)]. Below the thermocline, remnant winter water is isolated from the seasonal warming. This substantial body of cold water is referred to as the "cold pool" and is regularly found all along the outer half of the shelf (HOUGHTON et al., 1982). The water within the cold pool flows southward and is replenished from further north, causing the annual minimum bottom temperatures on the outer shelf to occur in summer.

The salinity of the surface waters is also lower in the summer, partly as a result of increased fresh water discharge from the Bays and the Hudson River. Contributing to the lower surface salinities are the prevailing summertime winds from the south. These upwelling-favorable winds tend to retard the southward, nearshore flow of the fresh water and drive the surface water offshore. After prolonged periods of southwesterly winds, i.e. northeasterly, salinities at the shelf edge can be less than 31 pss. During SEEP-II marsh grass was found floating at the surface in low salinity waters well over 100 km from either Delaware or Chesapeake Bay. The seasonal thermocline dominates the density structure of the upper water column, diffusing the intensity of the shelf–slope front at the surface. Even though the shelf surface temperatures reach 20–25°C, surface temperatures tend to increase offshore due to the impact of the warm Gulf Stream waters on the slope sea. Below the seasonal thermocline the hydrographic structure remains similar to that found in winter, although there is a gradual increase in shelf water temperatures. The cold pool waters along the shelf warm gradually through heat flux from above (WALLACE, 1994) as well as through the shelf–slope front (HOUGHTON et al., 1994). A distinctive feature of the near-bottom cross-frontal onshore heat (and salt) flux is that minimum temperatures in the cold pool are usually found well above the bottom [Fig. 2(b)], while salinities increase all the way to the bottom.

An important aspect of the shelf hydrography of the southern MAB is the proximity of the Gulf Stream. Several articles have been written illustrating the interaction between the shelf and the Gulf Stream and eddies spawned along its northern wall (cf. GAWARKIEWICZ et al., 1990; CHURCHILL and CORNILLON, 1991; GAWARKIEWICZ, 1991; CHURCHILL et al., 1993). Satellite AVHRR photos (Fig. 3) from the SEEP-II period illustrate some of the interactions with the Gulf Stream. The Gulf Stream is a highly variable as well as energetic feature and can move north and south by hundreds of kilometers in a matter of weeks. A review of AVHRR photos for the SEEP-II period showed that the Gulf Stream can remain reasonably stable for a month or more after a large north–south displacement. In Fig. 3(a), (b) and (c) the north wall of the Stream is near its historical mean (TRACY and WATTS, 1986), while in Fig. 3(d) the Stream turns east more than 150 km north of its mean position. Although Fig. 3(d) indicates how close the stream can come to the shelf, it is by no means an extreme example. CHURCHILL and CORNILLON (1991) show much more intense interactions in which Gulf Stream water is found inshore of the 100-m isobath. Figure 3(a)–(c) shows different types of shelf–slope frontal deformations, some of which are caused by small, and sometimes ephemeral, eddies shed from the Gulf Stream and others that seem to be associated with frontal instabilities. The photo in Fig. 3(a) was taken at the
Fig. 3. False-color NOAA AVHRR satellite sea-surface temperature plots which characterize the interaction between the shelf and the slope sea and between the shelf and the Gulf Stream (see text). (AVHRR photos for the SEEP-II program were provided by Jim Churchill.)
same time as the transect in Fig. 2(a), and together they show how a slab of shelf water 40–50 m deep can extend 50–100 km offshore of the shelf break. This situation is common in the AVHRR photos and suggests that a significant proportion of the shelf water leaves the shelf well north of Cape Hatteras to be absorbed by the slope sea. Figure 3(a), (b) and (d) also shows how narrow filaments can be drawn off the shelf to form “Ford” water filaments (Ford et al., 1952) along the Gulf Stream’s north wall. Lastly, Fig. 3(c) shows frontal waves that started out as barely discernable perturbations and quickly developed into southward-propagating, finite-amplitude waves whose shoreward crests are about to catch up with the previous wave and entrain a parcel of shelf water. The wavelength of these frontal waves is about 60 km with a phase speed of about 25 cm s\(^{-1}\) and a period of about 66 h.

2.2. Mean currents in the southern Mid-Atlantic Bight

Currents were measured on 10 moorings at 12 locations during the SEEP-II program. The northern array was the principal focus of the program and consisted of seven moorings, six of which were arranged across the shelf from 40 to 1000 m isobaths while the seventh mooring, #4, was 20 km to the southwest (Fig. 1). The three-mooring, southern array was 90 km to the southwest of the main array spanning the 130–1000 m isobaths. Currents were measured with EG\&G VMCMs, Aanderaa RCM-4s and RCM-5s, and RD Instruments 75 kHz, 300 kHz, and 1200 kHz acoustic Doppler current profilers (ADCPs). There were three mooring deployments during SEEP-II for a total of approximately 400 days. The overall success rate for the current meter array was about 75%, with most of the missing records attributed to lost and damaged equipment from trawling activities. Aspects of the variability of the currents and their association with other measured parameters are discussed elsewhere in this volume. Here we will discuss the means and standard deviations of the observed currents.

Most of the current statistics were calculated from hour-averaged data. The current records from the North Carolina State University instruments, except for those from the ADCPs, had been filtered with a 3-h low-pass filter. All the ADCP data were hour averages of 2.5–5 min ensembles. The coordinate systems for the current components were rotated to approximately the along- and across-isobath directions. For the northern array the alongshore component was defined as positive toward 30° while the offshore component was positive toward 120°. For the southern array the alongshore and offshore components were positive toward 6° and 96°, respectively. Summary current statistics were formed by combining the data from all the successful deployments from each mooring and instrumented depth. The results are given in Table 1.

Regardless of uncertainties about the orientation of the local isobaths and the resolution of some of the current-meter compasses, some conclusions about the offshore mean currents are possible. Firstly, the magnitudes of the mean offshore currents were small, generally less than 2 cm s\(^{-1}\). Only in those cases when the offshore mean was a substantial fraction of the alongshore mean are the signs of the offshore flow likely to be meaningful. Thus, near shore at mooring #1 the bottom flow appeared to be onshore while the deep-bottom currents at moorings #6, #9 and #10 were offshore. At moorings with ADCPs, the velocity profiles were dependent upon a single compass, making possible reliable estimates of the vertical cross-isobath current shear. In all the ADCP records there was a negative offshore current shear, so that the flow was more offshore at the bottom than near the surface. The maximum onshore component occurred at mid-depth, especially at
Table 1. Record mean currents and standard deviations from the SEEP-II current meter array. The current components are approximately across and parallel to the local isobaths for the north and south arrays. Thus, the offshore velocity on the north array (moorings 1–7) is positive toward 120° and the alongshore velocity is positive toward 30°. For the southern array (moorings 8, 9 and 10) the offshore and alongshore components are positive toward 60° and 96°, respectively. Only a few selected depths from the ADCP profiles are shown for moorings 2, 3, 4 and 5.

<table>
<thead>
<tr>
<th>Mooring</th>
<th>Position</th>
<th>Water depth</th>
<th>Deployment dates</th>
<th>Measurement depth (m)</th>
<th>Offshore mean (cm s⁻¹)</th>
<th>Offshore std. dev. (cm s⁻¹)</th>
<th>Alongshore mean (cm s⁻¹)</th>
<th>Alongshore std. dev. (cm s⁻¹)</th>
<th>Record length (days)</th>
<th>Instrument type and institution</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>37°52.60'N</td>
<td>7 Feb 88-19 Oct 88</td>
<td>12</td>
<td>-2.20</td>
<td>12.57</td>
<td>3.01</td>
<td>14.99</td>
<td>114</td>
<td>VMCM/LDGO RCM-5/NCSU</td>
<td></td>
</tr>
<tr>
<td></td>
<td>74°43.90'W</td>
<td></td>
<td>33</td>
<td>-0.35</td>
<td>7.47</td>
<td>-3.46</td>
<td>11.68</td>
<td>239</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>42 m</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1H</td>
<td>37°47.62'N</td>
<td>11 Nov 88-6 May 89</td>
<td>12</td>
<td>0.33</td>
<td>9.30</td>
<td>-0.56</td>
<td>13.04</td>
<td>27</td>
<td>VMCM/LDGO RCM-4/NCSU</td>
<td></td>
</tr>
<tr>
<td></td>
<td>74°44.60'W</td>
<td></td>
<td>32</td>
<td>-1.69</td>
<td>9.33</td>
<td>-0.10</td>
<td>15.54</td>
<td>96</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>38 m</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>37°46.11'N</td>
<td>7 Feb 88-12 Jun 88</td>
<td>12</td>
<td>-1.70</td>
<td>10.31</td>
<td>-7.54</td>
<td>17.60</td>
<td>65</td>
<td>VMCM/LDGO ADCP/NCSU</td>
<td></td>
</tr>
<tr>
<td></td>
<td>74°29.50'W</td>
<td></td>
<td>58/40</td>
<td>-0.89</td>
<td>12.29</td>
<td>-4.20</td>
<td>17.74</td>
<td>116</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>60 m</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2H</td>
<td>37°34.69'N</td>
<td>16 Nov 88-3 May 89</td>
<td>11</td>
<td>1.51</td>
<td>10.77</td>
<td>-2.82</td>
<td>18.45</td>
<td>169</td>
<td>VMCM/LDGO ADCP/NCSU</td>
<td></td>
</tr>
<tr>
<td></td>
<td>74°36.13'W</td>
<td></td>
<td>58/11</td>
<td>1.36</td>
<td>9.32</td>
<td>-2.45</td>
<td>20.25</td>
<td>166</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>61 m</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>37°41.99'N</td>
<td>8 Feb 88-8 May 89</td>
<td>12</td>
<td>-1.14</td>
<td>12.41</td>
<td>-8.86</td>
<td>16.98</td>
<td>392</td>
<td>VMCM/LDGO ADCP/BNL</td>
<td></td>
</tr>
<tr>
<td></td>
<td>74°20.35'W</td>
<td></td>
<td>88/12</td>
<td>0.95</td>
<td>10.48</td>
<td>-7.72</td>
<td>16.17</td>
<td>399</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>90 m</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lat/Long</td>
<td>First Observation</td>
<td>Last Observation</td>
<td>Number of Days</td>
<td>Depth (m)</td>
<td>Temp (°C)</td>
<td>Salinity (psu)</td>
<td>V/S Ratio (m/s)</td>
<td>ADCP/NCSU</td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>--------</td>
<td>------------------</td>
<td>------------------</td>
<td>----------------</td>
<td>----------</td>
<td>-----------</td>
<td>----------------</td>
<td>----------------</td>
<td>-----------</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>37°32.46'N 74°26.72'W</td>
<td>8 Feb 88-17 Oct 88</td>
<td>90 m</td>
<td>37°32.46'N 74°26.72'W</td>
<td>88/18</td>
<td>-0.73</td>
<td>10.24</td>
<td>-7.95</td>
<td>15.94</td>
<td>219</td>
</tr>
<tr>
<td></td>
<td>37°38.80'N 74°15.85'W</td>
<td>11 Feb 88-2 May 89</td>
<td>130 m</td>
<td>37°38.80'N 74°15.85'W</td>
<td>130/27</td>
<td>-2.66</td>
<td>9.18</td>
<td>-10.66</td>
<td>15.97</td>
<td>279</td>
</tr>
<tr>
<td></td>
<td>37°37.91'N 74°12.86'W</td>
<td>12 Feb 88-6 May 89</td>
<td>407 m</td>
<td>37°37.91'N 74°12.86'W</td>
<td>116/402</td>
<td>0.47</td>
<td>12.49</td>
<td>-11.07</td>
<td>18.18</td>
<td>121</td>
</tr>
<tr>
<td></td>
<td>37°37.18'N 74°09.86'W</td>
<td>8 Feb 88-7 May 89</td>
<td>998 m</td>
<td>37°37.18'N 74°09.86'W</td>
<td>994</td>
<td>-0.016</td>
<td>3.29</td>
<td>-0.38</td>
<td>2.52</td>
<td>322</td>
</tr>
<tr>
<td>8</td>
<td>36°52.63'N 74°39.04'W</td>
<td>23 Jun 88-5 May 89</td>
<td>132 m</td>
<td>36°52.63'N 74°39.04'W</td>
<td>128</td>
<td>-0.27</td>
<td>8.74</td>
<td>-7.60</td>
<td>10.83</td>
<td>233</td>
</tr>
<tr>
<td>9</td>
<td>36°52.07'N 74°37.73'W</td>
<td>14 Feb 88-5 May 89</td>
<td>418 m</td>
<td>36°52.07'N 74°37.73'W</td>
<td>135</td>
<td>-0.78</td>
<td>4.60</td>
<td>-2.73</td>
<td>14.10</td>
<td>403</td>
</tr>
<tr>
<td>10</td>
<td>36°52.15'N 74°34.50'W</td>
<td>9 Feb 88-5 May 89</td>
<td>1001 m</td>
<td>36°52.15'N 74°34.50'W</td>
<td>984</td>
<td>1.13</td>
<td>3.77</td>
<td>-0.82</td>
<td>4.24</td>
<td>402</td>
</tr>
</tbody>
</table>
moorings #3 and #5. At moorings #3, #4 and #5 the near-bottom mean flow was marginally offshore while it was onshore for one of the deployments at mooring #2. It thus appears that there was a line of divergence in the offshore flow somewhere between moorings #1 and #2, that is between the 40 and 60 m isobaths. This is consistent with the old bottom drifter data of Bumpus (1973) south of New England from which he inferred a mid-shelf bottom divergence from the lack of drifter returns from offshore. The approximately 1 cm s\(^{-1}\) offshore near-bottom flow on the slope is also consistent with the results from similar depths south of Nantucket Shoals reported by Butman (1988).

The alongshore currents are generally larger than the offshore currents and therefore less affected by uncertainties in the appropriate alongshore direction. Except for a near-surface deployment at mooring #1H and a near-bottom record from mooring #9, all the alongshore means were toward the southwest. The magnitude of the mean alongshore currents increased from about 1 cm s\(^{-1}\) in 40 m of water at mooring #1 to about 10 cm s\(^{-1}\) at mooring #5 in 130 m of water. The distance between moorings #1 and #5 was about 50 km. In general, the alongshore currents were a maximum at mid-depth, decreasing both toward the surface and bottom. The mid-depth maximum was particularly noticeable and the maximum currents were greatest during the stratified summer months within the region affected by the shelf–slope front. This baroclinic velocity structure indicates that the seasonal thermocline–pycnocline must have been deeper and the upper layer thicker over the shelf edge and slope than further onto the shelf. The required slope of the pycnocline would be about 1–2 m over 10 km, which is certainly plausible from some of the hydrographic sections from the area [see Fig. 2(b)]. Offshore of the shelf break the evidence about the currents is scant but suggests that mean currents decreased offshore beginning somewhere between moorings #5 and #6. Alongshore, the mean alongshelf currents near the bottom at moorings #5 and #8 were almost exactly the same, while those further offshore at mid-depth were smaller to the south (mooring #6 at 116 m vs mooring #9 at 128 m). Near the bottom at mooring #9 the mean current was northeastward while at the same depth at mooring #6 the current was southwestward. It would appear therefore that the shelf currents continue southwestward more or less undiminished while currents over the slope, especially near bottom, undergo some changes perhaps related to the proximity of Cape Hatteras, the end of the Mid-Atlantic Bight, and interaction with water masses from within and under the Gulf Stream.

The standard deviations of the alongshore and offshore current components followed a predictable pattern as a result of the cross-shelf dependence of tidal and sub-tidal currents. The standard deviations decreased toward shore from the shelf break region and also toward the bottom. On the shelf the alongshore current standard deviations were always larger than those in the offshore direction by 50–100%. In deeper water, especially near the bottom, the standard deviations of the current components were more nearly equal. The alongshore polarization of the shelf current variations is due to the sub-tidal responses of the shelf to wind forcing. The diurnal and semi-diurnal tides tend to be polarized across the isobaths, except near shore, and were responsible for 75–90% of the variance in the cross-isobath direction but only about 20% of the variance in the alongshore direction. Near the bottom in deep water the tides were responsible for as much as 95% of the variance, because these depths are out of the range of atmospheric forcing and the sub-tidal fluctuations were vastly reduced.

The mean currents from the cross-shelf northern array make it possible to estimate the alongshelf mass flux and compare the result to other estimates from south of New
England. To calculate the alongshelf flux, first the depth-weighted, vertical-average, alongshelf currents were calculated for moorings #1, #2 and #5, and then the integrated flux between pairs of moorings was calculated assuming that both the depth and the depth-weighted currents varied linearly between moorings. Mooring #1 was 40 km from shore, where the depth was assumed to be zero, and the depth mean current at mooring #1 was applied over the entire distance. The alongshore transport between the shore and mooring #1 averaged $-6100 \text{ m}^3\text{s}^{-1}$, between moorings #1 and #2 the transport was $-26500 \text{ m}^3\text{s}^{-1}$, between moorings #2 and #3 $-69500 \text{ m}^3\text{s}^{-1}$ and between moorings #3 and #5 $-89200 \text{ m}^3\text{s}^{-1}$, for a total alongshore mean transport between the shore and the 130 m isobath of $-191300 \text{ m}^3\text{s}^{-1}$, or about 0.19 Sv to the southwest. Because of increased depth and larger mean currents, the 9 km segment between moorings #3 and #5 transports almost as much water as the 80 km segment inshore of mooring #3.

This estimate of the alongshore transport is one-half to one-third the 0.4 Sv estimated for a section south of New England by Beardsley and Boicourt (1981) for the water inside the 100 m isobath, or the 0.6 Sv estimated by Flagg (1977) for the water shoreward of the shelf–slope front. Neither of the earlier estimates was based upon as long-term nor as coherent a data set as the one obtained during SEEP-II. Nevertheless, if these data sets are assumed to be comparable despite disparities in duration, detail and synchronicity, it would appear that on the order of half of the alongshore flow of shelf water leaves the shelf over the approximately 400 km distance between the two regions. This contrasts with the assumption of a near-constant alongshore transport throughout the Mid-Atlantic Bight made by Beardsley et al. (1976) but is consistent with the shelf transport estimate of Falkowski et al. (1988) which assumed that water velocities were uniform along isobaths and that the transport was roughly proportional to the shelf’s cross-sectional area. Assuming that the water leaves the shelf uniformly, this corresponds to an average offshore current through a vertical height of 100 m of about 0.5 cm s$^{-1}$, a value too small to measure directly with our present technology. In addition to this direct volume loss, the water that flows westward from Georges Bank has been diluted approximately 50% by slope water by the time it reaches the Delaware Bay–Chesapeake Bay area based upon the $^{18}$O isotope balances reported by Fairbanks (1982). Thus, about three quarters of the shelf water that flows westward into the MAB from Georges Bank is lost to the slope, about one-quarter of the original shelf water remains on the shelf in the SEEP-II area, while the equivalent of another quarter, but composed of slope water, has moved onto the shelf.

2.3. Structure, dynamics and tracers of the water

In an effort to understand the role of the shelf–slope front in the flux of properties and momentum between shelf and slope, attention was focused on phenomena with a range of periods from interannual to seconds and on spatial scales from hundreds of kilometers horizontally to a few meters vertically. The first group of papers in this volume deals with the flux of physical parameters: momentum, heat, salt and gases and their causes.

Shaw et al. (1994) examine the low-frequency behavior of the shelf and frontal currents during the unstratified period. In the sub-synoptic band with periods between 12 and 24 days there was an offshore and upward phase propagation with maximum energies at the shelf edge, evidence of trapped topographic waves. The source of these motions is unclear, but it is suggested that non-linear processes associated with the cross-isobath movement of the shelf–slope front would provide an upper slope generation mechanism. Within the
lower synoptic band with periods between 5 and 8 days, there was no cross-shelf phase propagation, and hence no cross-shelf momentum flux while the upward phase propagation remained. Within this band shelf currents were coherent with the wind whereas in the frontal zone there was significant coherence between the currents and temperature, but not with the wind. At periods less than 4 days, the response of the shelf to the wind was characterized by coastally trapped, shelf-wave behavior with little coherence between shelf and slope.

Using moored temperature and current data, HOUGHTON et al. (1994) examined the structure of the front, how it was maintained in the face of diffusive processes, and the character of synoptic scale fluctuations. Eddy heat flux is onshore throughout the year but changes its vertical distribution and spectral characteristics between summer and winter. The horizontal eddy viscosity inferred from the heat flux, about $10^2$ m$^3$ s$^{-1}$, is similar to that deduced from the $^{18}$O data of FAIRBANKS (1982). In the summer, the $u', T'$ correlation is concentrated within the 5–11 day band, perhaps as a result of frontal instabilities theoretically described by GAWARKIEWICZ (1991). It was also shown that there was a possible balance toward maintaining the front, at least near bottom, between the diffusive effects and the mean Eulerian offshore flow.

Chlorofluorocarbons (CFCs or “Freons”) are an independent and non-biologically mediated tracer whose solubility characteristics make it useful for studying vertical- and horizontal exchange and mixing processes. Using CFC-II as a tracer, WALLACE (1994) used a one-and-a-half-dimensional model for the flux of freon and heat between the cold pool and the surface layer in an effort to determine the vertical eddy diffusivity within the thermocline. The results suggested a vertical eddy diffusivity of $10^{-5}$ m$^2$ s$^{-1}$, a value that is consistent with previous estimates. This estimate represents an upper bound because no provision was made in the model for the effect of horizontal diffusion of low CFC water from offshore. That the horizontal diffusion from offshore may be important is demonstrated by HOUGHTON et al. (1994), which suggests that most of the cold pool heating could be accounted for by horizontal exchange. Thus, the vertical eddy diffusivity could actually be much less than $10^{-5}$ m$^2$ s$^{-1}$. A more extensive experiment which can distinguish between vertical and horizontal diffusion will be needed to refine this number further.

The shoreward intrusion of high-salinity water within the seasonal thermocline has been noted in hydrographic sections for many years, but the frequency and intensity with which these events occur has not been known. The high resolution current and temperature data from the summer SEEP-II deployment provided an opportunity for FLAEGG et al. (1994a) to study the “S-Max” intrusions more closely. The principal result is that active intrusions can be extremely vigorous with on- and offshore velocities of order 20 cm s$^{-1}$. Estimates of gradient Richardson number indicate mixing with waters above and below the intrusion. Upwelling-favorable winds, as has been noted before, appeared to be a necessary, but clearly not sufficient condition for active intrusions. It also appeared that there had to be preconditioning of the hydrographic structure offshore for the intrusions to appear.

CHURCHILL et al. (1994) investigated the areal and seasonal distribution of bottom shear stress as it pertains to, and is reflected in, resuspension events. They show that there is a predictable offshore decrease in the relative importance of high-frequency wind waves and a concomitant increase in the effect of internal waves for the production of sufficient bottom stress for resuspension. In the region of the shelf break, low frequency currents are also required for resuspension events. The threshold bottom stress required for resuspension appeared to vary by a factor of three over space and time (from 2.4 to 0.8 Pascals) with
lower thresholds evident in water deeper than 100 m and after a series of storms in shallower water.

On longer time scales than previously discussed, Pietrafesa et al. (1994) examined the exchange of water between the Mid- and South-Atlantic Bights around Cape Hatteras. Nearshore water from the MAB that has been substantially freshened by outflow from the Chesapeake and Delaware Bays is found south of Cape Hatteras about 50% of the time. The southward movement of the low salinity water is fostered by southerly winds and usually follows the wind event by about 4 days. The water that makes it south of the Cape does not stay there but rather exits the shelf along the Gulf Stream's north wall. Long-term records of temperature and salinity from the region indicate that there are significant interannual changes in these properties, although the causes are not yet apparent.

3. PARTICLES AND THEIR TRACERS

The SEEP-II experiment was well under way before the start of the recent debate over the relative importance of the dissolved vs particulate organic carbon (DOS vs POC) pools. Neither SEEP-I nor -II had a DOC program, and POC was regarded as the significant organic carbon reservoir as far as potential export vs recycling was concerned. A major strategy throughout was, that, if we studied the processes creating, transporting and removing all particles—fine-grained biogenic and abiotic particles—given their intimate relation in the shelf-slope environment, we would also learn about the fate of primary production carbon. More recent developments in the DOC/POC argument suggest that our strategy was probably a good one. The second group of papers in this volume focus on aspects of particles of all kinds—living biota, biogenic and abiotic—and some of the tracers associated with them. Although papers dealing primarily with the carbon cycle and its budgets are in the third section of this volume, some of the papers in this section also bear on those questions.

Wirick (1994) analyzed the exchange of phytoplankton across the shelf-slope front using current meter and moored chlorophyll fluorescence time series measurements at the 90-m isobath. His analysis, which was primarily confined to periods before the onset of stratification, revealed a net onshore transport of phytoplankton, i.e. import. Consequently, Wirick concluded that the spring phytoplankton bloom from the inner shelf is not exported across the front, although shelf water above the front and seaward of the 100-m isobath could still be exported. This conclusion assumes that the fate of the spring bloom is fixed within the spring period, and does not address the fate of the direct or secondary detritus derived from the bloom.

The acquisition and analysis by Flagg et al. (1994b) of a 15-month set of continuous data from fluorometers and an acoustic Doppler current profiler (ADCP) was the first long-term study of the seasonal and interannual relationships between phytoplankton and zooplankton biomass and external physical forcing at a single location. The ADCP, continuously yielding the water column velocity field, was calibrated to detect biological particles in terms of biomass. The instrument, moored on the bottom at 90 m water depth, recorded differences of a factor of two in the maximum zooplankton standing stocks in two successive spring blooms, while chlorophyll data from the associated fluorometers showed no such difference. Further departures from concepts of closely coupled food web dynamics were also seen in the lack of coherences between the two biological signals in higher frequency domains. And, with the exception of storm-forced events, the highly
variable spatial gradients in the biological signals also resulted in low coherences between
the latter and variations in the physical field, despite a sampling frequency sufficient to
detect changes on physically- and biologically realistic time scales. The insights from this
unique record at a single location, however, open the door to significant understanding of
the highly complex interactions of the physical and biological fields when this technology
can be deployed in a three-dimensional array.

Zooplankton fecal pellets are special biogenic particles that have received much
attention in the story of carbon cycling, because generally high sinking velocities make
them ideal enhancers—for some workers, the major cause—of the vertical flux of carbon
from surface to deeper waters and to the bottom. LANE et al. (1994) report a study of this
phenomenon at a single location for a brief period during the spring of 1988 in which fecal
pellet production rates, sinking rates, fluxes and zooplankton species abundances were
compared. The principal result was that the fecal pellet flux could vary widely as a function
of zooplankton species assemblage, but that the contribution of fecal pellet flux to vertical
carbon flux was small at that time and place.

Fluxes of particles and their biogenic, abiogenic and tracer constituents, and more
importantly, gradients in those fluxes, from a 15-month deployment of an array of
sediment traps is reported by BISCAYE and ANDERSON (1994). As in the SEEP-I experiment
(BISCAYE et al., 1988) the spatial gradients in those fluxes preclude simple, two-
dimensional modelling and require along- as well as downslope transport of particles from
the shelf-slope break and out into the slope water column. The SEEP-II data continue to
support the idea of a depocenter on the slope centered at about 1000 m in which the
maximum in near-bottom vertical flux coincides with a minimum in current speed
expressed as average total kinetic energy density. The observed increase by up to a factor
of four in particulate export to the slope from the SEEP-I to the SEEP-II area, observed as
the near-bottom flux of all components at the depocenter, is probably a maximum when
near-bottom placement of the traps is considered. The export flux of particles from the
shelf to the slope is very seasonally dependent on storm-driven events. This temporal
variability, however, is markedly damped in both the fluxes and composition of the
particles deposited at the depocenter, suggesting intermediate storage and homogeniza-
tion of off-shelf particle fluxes, possibly in continental slope canyons.

BACON et al. (1994) make use of the half-life, the known source function to the shelf, and
the particle-reactive nature of 210Pb to exploit it as a time-dependent tracer of particles in
the shelf water column and sediments. Despite a small base of shelf-sediment data, they
suggest that the atmospheric input and the shelf-sediment inventories of 210Pb are in
balance, implying that the export of particles from the shelf is small. Because of the POC to
210Pb relationship, they use these observations to derive an upper limit to the export of
POC from the shelf: \(<60 \text{ g m}^{-2} \text{ y}^{-1}\), or \(<25\% \text{ (probably } <<25\%)\) of primary production.
Retention of 210Pb in shelf sediments also implies a mean lifetime of fine-grained particles
sequestered in shelf sediments, and the authors propose a model to quantify a cycle of
carbon introduction and residence. They conclude that the order of decades is required to
export a 210Pb-tagged particle from the shelf. A corollary of that residence time and the
210Pb/POC relationship is that refractory organic matter constitutes the bulk of what little
organic carbon is exported from the shelf—a similar conclusion to that drawn by
ANDERSON et al. (1994b) based on C analyses.

The use of radioactive tracers with reasonably well known source functions is extended
from 210Pb to \(^{10}\text{Be}, \; ^{231}\text{Pa}, \; \text{and } ^{230}\text{Th}\) by ANDERSON et al. (1994a) to study the role of slope
SEDiments in sequestering particle-reactive species from the open ocean ("boundary scavenging") as well as from the shelf. One of the goals of the originally proposed SEEP program had been to quantify the relationship of shelf-carbon export to the slope depocenter and the scavenging of $^{210}\text{Pb}$ via the "manganese pump" mechanism of SPENCER et al. (1981). When $^{210}\text{Pb}$ was shown in the SEEP-I area not to behave as had been found elsewhere (ANDERSON et al., 1988; BACON et al., 1988), ANDERSON et al. (1994a) measured the other isotopes in SEEP-I and -II trap and sediment samples and found that their scavenging behavior is also anomalous with respect to each other, compared to studies elsewhere; the slope sediments of the MAB are definitely anomalous from this viewpoint. These authors tentatively propose a different manganese-related mechanism to explain the observations, in which differential adsorption of these nuclides takes place onto fine-grained manganese oxide particles being exported from the shelf.

4. ORGANIC CARBON, CYCLING AND BUDGETS

In view of the potential importance of microbial processes to the budgets of carbon and oxygen, the paucity of bacterial data available to the SEEP-I budgets, and the emphasis on carbon budgets and cycling in SEEP-II, the experiment included a specific program to measure microbial activity in the water column and sediments, and the results are reported in KEMP (1994). He found that bacterially mediated carbon remineralization in both water column and sediments was 90–180 mg C m$^{-2}$ day$^{-1}$ on the shelf (where most bacterial activity was in the sediments), and 270–540 mg C m$^{-2}$ day$^{-1}$ on the slope (where most bacterial activity was in the deep water column). The flux of carbon to the slope system implied by the latter value is greater than that supplied by overlying slope surface waters from trap data (BISCAYE and ANDERSON, 1994), implying a lateral, downslope flux of carbon from the shelf, which KEMP estimates as from 7.5 to 15% of primary production on the shelf. This is consistent in both conceptual process and magnitude to other reports from SEEP-I (BISCAYE et al., 1988) and SEEP-II (BISCAYE and ANDERSON, 1994). KEMP (1994) also reports similar bacterial specific growth rates in sediments over both shelf and slope down to 2000 m, and draws conclusions about limitations on growth rates by nutrient availability in the sediments vs availability in the water column.

In an attempt to resolve the role of phytoplankton and phytoplankton carbon in the export of particulate matter from the shelf, FALKOWSKI et al. (1994) analyzed the spatial and temporal distributions of the species of intact phytoplankton cells, total opaline silica and particulate organic carbon in the sediment traps from the SEEP-I area. These distributions are consistent with those of other biogenic particles in the SEEP-I traps and confirm the export from the shelf of organic carbon and its transport downslope and into the slope water column as described by BISCAYE et al. (1988), but suggest that intact phytoplankton contribute <1% of the export fluxes of carbon and nitrogen. Taken together with the analyses of SEEP-II trap data (BISCAYE and ANDERSON, 1994) they found that the flux of particulate organic carbon in the traps located 500 m below the surface decayed rapidly with distance from the coast. Integration of the area under the curve as function of distance from the coast yields a flux of 5.3 mg C m$^{-2}$ day$^{-1}$. Extrapolation of that flux to the entire north coastline of North America suggests that the contribution of carbon from the shelf to the North Atlantic Ocean is $4.8 \times 10^{12}$ g C y$^{-1}$, which represents about 1% of the new production in that ocean basin.
Walsh (1994) used a barotropic model to calculate fluxes of particles from the shelf from the viewpoint of the sources and sinks of carbon in the Gulf Stream system. His analysis concludes that the flux of carbon from the shelf is only 11% of the annual shelf production, compared with 50% proposed by Walsh (1981). Walsh proposes that the "advective" export at Cape Hatteras constitutes 62–82% of the source of carbon within the Gulf Stream, and consequently is a significant source of carbon to the "sedimentation flux" of the North Atlantic Ocean.

Using time-series measurements of dissolved oxygen from two depths in the center of the shelf at the 40 m isobath, Kemp et al. (1994) developed a closed-carbon budget for the stratified spring and summer condition. They constrained vertical eddy diffusivity of oxygen by analyzing the seasonal changes in the concentration of chlorofluorocarbons as well as heat, and constructed a conservative, one-dimensional, time-dependent model. Biological sources (photosynthesis) and sinks (respiration) of oxygen were taken from shipboard measurements in the SEEP-II area. These authors conclude that, during the stratified period, the shelf is in approximate balance, and no more than 4% of the phytoplankton carbon is available to be exported. These results are similar to those obtained by Falkowski et al. (1983, 1988).

Rowe et al. (1994) use sediment oxygen demand as a measure of organic carbon flux to the sediments, and report measurements made in situ with a benthic lander and via incubations of recovered sediment cores. Shelf sediment values of oxygen demand, and therefore carbon flux, are high on the shelf and decrease exponentially out to abyssal-plain depths with the exception of high values in the region of the depocenter, around 1000 m depth. The depocenter is, in fact, a locus of enhanced organic carbon flux. Comparison of these values to those in the literature for the eastern Pacific indicate that, with the exception of the east-coast depocenter, the flux of organic carbon is higher off the west than the east coast of the USA.

The last organic carbon budget to be constructed and reported in this volume is by Anderson et al. (1994b). It is from the viewpoint of the slope depocenter, and utilizes, in part, new measurements of $^{14}$C. These measurements, along with organic carbon measurements in trap and sediment samples, show that half of the organic carbon exported from the shelf laterally to the slope depocenter is old and refractory, and the half that is young and labile constitutes <1% of the primary productivity of the shelf. They show that the labile carbon fluxed to depocenter sediments is quickly remineralized at the surface (mean life ~1 year), primarily by bacteria. The organic-carbon-rich (1–2%) depocenter on the slope thus turns out to be rich in old, refractory carbon that does not further remineralize, and which has been added over the years, a little bit (compared to shelf productivity) at a time. The depocenter is, in fact, a site of preferential deposition of new, labile carbon as well, but this quickly disappears and contributes nothing to the organic-rich nature of the depocenter sediments. It thus appears that the preservation of organic carbon in slope sediments in the MAB—and probably on carbon-rich slopes elsewhere in the oceans—is due to the refractory nature of the preserved carbon rather than to sediment accumulation rates or other factors controlling rates of organic carbon remineralization.

5. CONCLUSIONS

The results of the SEEP-II study overwhelmingly show that the hypothesis of export of a large proportion of the MAB shelf primary productivity is untenable. All the observatio-
nal data suggest that although a small fraction of carbon is exported across the shelf–slope break and through the front to the slope depocenter, the principal fate of shelf carbon is, in fact, oxidation on the shelf. That small portion that does escape the shelf to the slope water and depocenter appears to increase from the northern to the southern MAB. A number of key questions remain unresolved.

First, the sources of nitrogen for the shelf to support the measured production are unclear. It is difficult to reconcile the flux of nitrate onto the shelf without imposing an export flux of water (and particles). While there is clear evidence of export of shelf water to the slope, the particulate and nutrient composition of that water is uncertain. To sustain a steady-state production from year-to-year there must be an import of nutrient to balance any export loss. One hypothesis is that the regeneration of nutrients on the shelf is much faster than we imagine. Historically, nitrification has been and remains a difficult process to measure in the field; the results of the SEEP studies suggest that it is a key to understanding how shelf production is fueled.

Second, the high frequency moored data reveal that the rate of the oxidation of phytoplankton carbon and its fate do not appear to be that proposed for the metazoic metabolism by Riley and his contemporaries. The high-frequency synoptic measurements of phytoplankton chlorophyll fluoresecence, acoustic backscatter and current vectors reveal that shelves can be extremely dynamic. The notion of a monotonic increase in phytoplankton which is phase-lagged by a monotonic increase of zooplankton was born in an era when monthly cruises were the major means of sampling. In situ observational data reveal that the shelves are much more complex and dynamic, and require both dynamical models which, at present, are elusive, and three-dimensional, continuous (moored) observations, which are expensive.

Third, while the concepts of the microbial food webs emerged in open-ocean biology in an attempt to reconcile the apparent high specific growth rates of phytoplankton with the extremely low concentrations of dissolved nutrients, these concepts came late into shelf (especially temperate shelf) oceanography. The data presented here suggest that while metazoic processes may be greater than heretofore calculated, the microbial oxidation of carbon is much more significant than previously acknowledged. There remains a major problem in developing tools and techniques to address the fluxes through microbial communities with the same frequency and precision as that for phytoplankton, zooplankton and the physical field. While this volume contains an overwhelming amount of information on a shelf ecosystem, we still do not understand food web dynamics in this complex region.

If the caveats about comparison of non-synchronous data sets are accepted, an important result of the SEEP-II mooring program is that most of the shelf water leaves the shelf before it reaches the southern terminus of the Mid-Atlantic Bight, Cape Hatteras, and with it, undoubtedly, a proportion of the suspended and dissolved carbon. Second, because of the slope water that becomes incorporated into the shelf water, the shelf actually discharges into the slope at least 125%, and perhaps as much as 150% of the initial alongshelf transport of shelf water when the remainder of the shelf south of the SEEP-II array is considered. The question remains, however, how much carbon in its various forms is carried along with this water, because we do not know at this time from what depth strata nor from what location along the shelf the water is exported. Thus, an important issue that has yet to be quantitatively resolved is exactly where, how much, and by what mechanisms water leaves or comes onto the shelf, although there are several promising candidates such
as: warm-core ring/frontal interactions, frontal instabilities and eddies, subsurface boluses, bottom-layer mixing, surface layer advection, and near-bottom advection.

Lastly, SEEP-II also showed what is necessary for combined physical and biological studies of the shelf. The SEEP-II data set contain physical and biological measurements on complementary time and space scales and demonstrates that technology is making it possible to address the biophysical interactions on scales more appropriate to the actual biological processes. However, to unravel the convolution of the highly structured physical and biological fields, it will be necessary to pay particular attention to the measurement of horizontal as well as vertical gradients so that larger-scale advective effects can be separated from local processes. The physical and biological structure functions probably will not be dominated by the same scales, necessitating a nested grid of different measurements. If this can be done, then there is some real hope that we can progress beyond the integral measurements customarily used and actually get down to a level commensurate with the biological details incorporated in some of the more complete biological models.

Acknowledgements—This research was supported by the U.S. Department of Energy, Office of Health and Environmental Research under Contracts No. DE-FG02-87ER-60555 (to P. E. Biscaye) and No. DE-AC02-76CH0016 (to C. N. Flagg and P. G. Falkowski). We thank R. F. Anderson and R. W. Houghton for comments. This is LDEO Contribution No. 5230.

REFERENCES


