The Ocean Margins Program: an interdisciplinary study of carbon sources, transformations, and sinks in a temperate continental margin system

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Abstract

The cycling of carbon on the US east coast shelf and upper slope has been studied for 20 years in a variety of interdisciplinary programs focused on the Mid and South Atlantic Bights. The culmination of this research was a comprehensive field study conducted in 1996 to ascertain whether the Cape Hatteras shelf was a net source or sink for atmospheric CO2, and the associated transformations and pathways of inorganic and organic carbon. The rationale, objectives, design, and overview of the Ocean Margins Program are given here as a framework to interpret the results of the papers presented in this special issue. © 2002 Elsevier Science Ltd. All rights reserved.

1. Introduction

Since the beginning of the Industrial Revolution, anthropogenic activities have dramatically altered the global carbon cycle, and consequently this cycle is not in a steady-state. To reduce major uncertainties in predicting future global environmental quality, it is essential to understand the sources and sinks of atmospheric CO2, the role of human activities in disrupting the natural carbon cycle, and effects of and feedbacks between these activities and the natural carbon cycle. Within the oceans, the carbon cycle of its margins will likely be impacted to a greater extent than its interior for a variety of reasons. Due to increased loading of nutrients to the margins, which is related to the rate of human population growth and high population densities in coastal areas (Malone, 1998), biological carbon fixation has been stimulated. Depending on the fate of the fixed carbon, this stimulation has the potential to mitigate anthropogenically derived CO2 increases (OMP, 1994). Determining the factors that control the magnitude of carbon exchanges between the ocean margins, the adjacent continents, and the atmosphere, and the subsequent fate of this carbon, is crucial to predicting the strength and capacity of the oceans to absorb excess anthropogenic CO2 (Walsh et al., 1985; Sabine and MacKenzie, 1991; Walsh, 1991).
Earlier programs designed to assess the inventories and fluxes of carbon in ocean margins, especially the Mid Atlantic Bight (Walsh et al., 1988a, b; Biscaye et al., 1994), concluded that shelf environments exported a relatively small fraction of the carbon fixed on them. Falkowski et al. (1988) and Anderson et al. (1994) estimated that less than ~20% of the spring bloom and <1% of annual primary productivity in MAB shelf waters was exported off-shelf in the form of particulate organic matter to the slope and North Atlantic Ocean. Less than ~1% of the export flux was found to consist of “intact” phytoplankton, i.e., recently derived primary production (Biscaye et al., 1988; Falkowski et al., 1994), thus suggesting that the balance of the flux must be comprised of older, more refractory particulate organic material. Further extrapolation of the trap-based estimates to the northeastern North American continental margin yielded an estimated export flux of approximately $5 \times 10^{12} \text{ g C yr}^{-1}$ from this system—or <1% of the new production for the North Atlantic Ocean (Biscaye et al., 1994). In contrast to these trap-based estimates, Walsh (1994), using a barotropic transport model, calculated the annual export flux of particulate organic carbon (POC) from the shelf to be about 11% of shelf primary production—a downward revision of earlier (Walsh, 1991) estimates of ~50%. Walsh (1991) also estimated that the advective flux of POC offshore at Cape Hatteras specifically could account for as much as ~60–80% of the POC in Gulf Stream waters, and hence be more significant than flux estimates derived from more northern parts of the MAB.

At least two major considerations arise from these important early studies. First, have all the relevant carbon inventories and fluxes been adequately assessed in this particular system, as well as in other ocean margin systems? Second, can we gain additional insight into the sources and fates of the various carbon pools and the overall carbon budget of an ocean margin system by more fully characterizing them chemically and biogeochemically? It is important to note that earlier studies of carbon fluxes within, and export from, ocean margins assumed that these fluxes are dominated by particulate organic carbon (POC, typically measured as organic carbon collected by filtration of seawater on ~0.7 μm glass-fiber filters). These fluxes were estimated most often by measuring the larger sinking fraction of POC that was collected in sediment traps. The flux estimates derived from the earlier studies excluded contributions from dissolved organic carbon (DOC, or the organic carbon that passes through glass filters), dissolved CO$_2$ gas, and suspended POC, all of which may be quantitatively significant and provide independent assessments and constraints on carbon cycling in margins. Unlike river and estuarine systems, where contributions from DOC and suspended POC fluxes can be comparable (Spitzy and Ittekot, 1991; Fisher et al., 1998), concentrations of DOC are typically one to three orders of magnitude greater than POC concentrations in most marine systems (Druffel et al., 1992; Bauer et al., 2001). Therefore, if the appropriate advective and eddy diffusive transports are of sufficient magnitudes, fluxes of DOC and suspended POC, particularly in the horizontal dimension (Jenkins, 1977; Hung et al., 1999), could be comparable to, if not greater than, sinking POC fluxes (Bauer and Druffel, 1998; Bianchi et al., 1998; Sherrell et al., 1998), by factors similar to the differences in horizontal vs. vertical eddy diffusivity (Ledwell et al., 1993).

The southern portion of the MAB has been the sight of numerous investigations because of its many singular characteristics. The area forms the terminus of not only the southwestward flow along the Bight itself, but also of the much larger scale equatorward coastal current system that originates along the Greenland, Labrador, and New Found-land shelves (Chapman and Beardsley, 1989). Although exchange between shelf and open ocean waters occurs all along the Bight to varying degrees, it is in the area south of Chesapeake Bay and north of Cape Hatteras where a significant portion of shelf waters meet their ultimate fate as they are advected offshore to the south and east. This area is also characterized by a complicated water mass structure as half of the fresh water introduced to the Bight from the coast flows out of Chesapeake Bay (Beardsley and Boicourt, 1981), and warmer and more saline waters from both the South Atlantic Bight (SAB)
and Gulf Stream periodically enters the area from the south. The limited areal extent of the southern bight reduces the time necessary for mixing of these water masses.

The US Department of Energy designed and implemented a field study called the Ocean Margins Program (OMP) to examine carbon cycling in the continental margin of the western North Atlantic Ocean. While a primary focus was on the southern portion of the MAB between Cape Hatteras and Chesapeake Bay, where a large flux of freshwater and organic carbon flows to the North Atlantic Ocean (Churchill et al., 1993; Blair et al., 1994), it also included a significant regional effort covering the entire MAB shelf and upper slope between Cape Cod and Cape Hatteras. The OMP effort was directed on these two levels after earlier studies found that only a small fraction of the new production was exported across the shelf-slope front on the central MAB (Walsh et al., 1988a, b; Biscaye et al., 1994).

The central objectives of the OMP were (1) to quantify the processes and mechanisms that affect the cycling, flux, and storage of carbon in its various organic and inorganic forms and other biogenic elements at the land/ocean interface; (2) to define ocean-margin sources and sinks of carbon in global biogeochemical cycles; and (3) to determine whether ocean margins, including continental shelves, are quantitatively significant in removing carbon dioxide from the atmosphere and isolating it via burial in sediments or by export to the interior ocean, or elsewhere. To achieve these objectives, an integrated multidisciplinary field program was conducted during 1993–1996 to quantify the physics and biogeochemical processes affecting carbon fluxes, nutrient cycles, and ecological dynamics in shelf and slope waters of the entire MAB and at Cape Hatteras, where conditions for carbon burial in sediments and carbon export to the interior ocean were expected to be optimal (Blair et al., 1994; Jahnke and Verity, 1994). In this context, the Ocean Margins Program was an ambitious attempt to decipher not only the physical interactions that occur in the area but also the biogeochemical clues to the processes responsible for the cycling of carbon and other biogenic elements prior to their advection into the North Atlantic.

2. Field study design

In order to determine the magnitude and fate of both allochthonous and autochthonous organic matter in the MAB, an experimental approach was needed that encompassed a broad range of spatial and temporal scales. The overall experimental design may be viewed as a hierarchy of sampling modes over different temporal and spatial scales. Short-term studies of transformation processes were embedded within longer-term, continuous sampling of chemical, biological and physical parameters by moored instruments. Both moorings and process cruises in turn were nested within larger-scale surveys of the northeast US shelf and slope as a whole, and the larger-scale surveys were nested within regional data acquired by remote sensing. Integrating parameters created links and relations across all spatial and temporal scales of the OMP. The heart of the program was a heavily instrumented moored array between the Chesapeake outflow and Cape Hatteras. The complete array is shown on a SeaWIFS color image of chlorophyll $a$ (chl $a$) on the cover of this issue, and also in Fig. 1, to illustrate the mooring locations relative to the structure of the eastern seaboard and Gulf Stream. Instrument arrays were deployed between February and November 1996, and an unprecedented suite of high-frequency three-dimensional physical, chemical, and biological measurements were made. Simultaneous with the mooring deployment, process cruises were conducted in the same area to measure rates and distributions of key biological and chemical tracers in the water column and at the sediment/water interface. Finally, three major survey cruises were made between Cape Cod and Cape Hatteras to measure many of the same features across the entire MAB. In the following sections, each of these efforts is summarized.

2.1. The mooring array

The OMP moored array (Fig. 1) was designed so that a comprehensive suite of biological,
chemical, meteorological, and physical oceanographic processes could be quantified on the shelf and upper slope between the Chesapeake Bay and Cape Hatteras. A total of 26 moorings were deployed during the first deployment, between 5 February and 16 May 1996, while 23 moorings were deployed during the second deployment from 23 June to 14 October 1996. The goal was to create an array with high resolution in both cross and along-shelf directions to evaluate the coherency and temporal scales over which oceanographic processes occurred during the spring transition when biological productivity is generally the highest, and also during the stratified summer period when productivity is less, with high nutrient gradients below the surface layer. The intent was to determine processes, both horizontally and vertically, from the smallest (~10 km) to the largest (~135 km) scales that were feasible within the study region. For this purpose, a sub-array was included along the northern mooring transect to provide locally higher spatial resolution. On a larger scale, the northern and southern cross-shelf transects and the picket fence of moorings along the 75 m isobath, monitored the flow in and out of the area. The northern transect would be primarily influenced by the physical processes of the MAB, while the southern-most transect was intended to monitor the nearshore flows and exchanges that are known to occur (Churchill et al., 1993; Pietrafesa et al., 1994). The data set from the most southeastern mooring (1000 m isobath) extended over 2 years, allowing for seasonal to interannual variability assessment. The set of complementary moored instruments from 7 to 8 m below the surface to 2 m above the bottom provided velocity and water property measurements throughout the water column. During the first deployment four moorings in the central area increased the overall spatial resolution. Due to
instrument attrition, these central moorings were not included during the second deployment.

The sub-array placed at the northern mooring line focused on quantifying fluxes of $O_2$ and $CO_2$ within a hydrographically well-defined volume. The location of the array was chosen to be hydrographically the simplest, minimizing complications from the Chesapeake Bay outflow on one hand, and Gulf Stream or Southern Atlantic Bight intrusions on the other. The sub-array strategy evolved from a 1994 pilot study (DeGrandpre et al., 1997) that demonstrated that mooring-based measurements of biogenic gases could be used to estimate daily net community production. Such estimates were obtained by partitioning the local rate of change in dissolved oxygen ($O_2$) or total inorganic carbon (TCO$_2$) into biological and physical components. Mooring-based estimates of TCO$_2$, or total dissolved inorganic carbon (DIC), were obtained by using the mooring $pCO_2$ and salinity-derived alkalinity in combination with equilibrium calculations. Sensors for chlorophyll fluorescence, nitrate, and light (PAR) also were placed at various depths and locations in the mooring control volume to provide independent estimates of primary and new production based on photosynthesis, irradiance, and nutrient relationships. Additional $O_2$ sensors were placed on moorings outside the sub-array with the intent of extrapolating relationships determined in the control volume to the entire array.

2.2. The hydrographical, biological, and chemical surveys

The hydrographic component of the program consisted of eight hydrographic surveys (Fig. 2) during which an extensive array of physical, biological, and chemical parameters were measured. The cruises to the MAB shelf and OMP area actually started 3 years before the main observational period with a series of four spring and summer pre-OMP surveys to elucidate conditions to be expected and to help with the overall program design. Three of the early cruises concentrated on the area between Chesapeake Bay and Cape Hatteras, carrying out a series of cross-isobath transects and TOYO sections to define the relative disposition of the various water masses and their relation to the topography. Partly because the OMP study area lies at the terminus of the MAB's southwestward flowing current system, a fourth pre-OMP cruise occupied a series of across-shelf sections from Cape Cod to Cape Hatteras to define any systematic along-shelf biochemical gradients. Generally, these early sampling plans worked very well and were continued during the remainder of the program. Thus, the last four cruises consisted of winter and summer along-shelf extended surveys, together with more focused surveys of the OMP study region.

2.3. Water column process studies

There were two process cruises during 1996: one took place near the time of the surface water temperature minimum (March), and the other took place during the strongly stratified summer period (July). The intent of the process cruises was to provide a link between the highly detailed and complete set of measurements possible from a ship to the less encompassing data set provided by the moored array. Additionally, the ship-based measurements provided a means to calibrate and quantify those data obtained from the moored instruments. Together, the plan was to obtain a temporal and spatial picture of the flow of the various water masses passing through the area and biological transformations that occurred within those waters. The first segment of the cruises was a regional-scale survey consisting of cross-isobath transects. The second segment of the cruises concentrated on the control volume sub-array, located over the outer shelf just south of the northern transect. The objective behind this portion of the cruises was to understand the similarities and differences between the seasonal biological processes that are inherently Lagrangian in nature, and the Eulerian measurements that the moorings would provide. Pairs of Lagrangian drifters were followed as they passed through the sub-array while periodically making Eulerian type measurements at the fixed location of the central mooring.
Fig. 2. Station locations for the eight OMP cruises conducted in 1993, 1994, and 1996. See text for details.
An important component of the OMP study region surveys was time-series sampling following water parcels marked by pairs of Davis-type Lagrangian drifters as two-dimensional tracers of water parcels for the chemical and biological sampling program. During the winter cruise in unstratified conditions, holey-sock drogues were deployed between 10 and 16 m from the surface. During the stratified summer conditions, one pair of drifters was drogued between 4 and 10 m to mark the surface layer while a second pair was drogued between 18 and 24 m in the lower thermocline. During both the winter and summer deployments, the drifters passed southwestward through the densely deployed moorings in the northeast of the array, describing corkscrew patterns as the drifters were advected by mean, tidal, and inertial currents. The major difference between the winter and summer deployments was that there was very little horizontal or vertical shear in the winter, while there was extremely high cross-thermocline shear during the summer. In the winter the semi-diurnal tidal currents were between 0.1 and 0.2 m s\(^{-1}\), with a southwestward residual of, initially, \(\sim 0.1\) m s\(^{-1}\), which gradually slowed nearly to a stop. In summer, extremely vigorous, slightly sub-inertial oscillations produced currents of \(\sim 0.2\) m s\(^{-1}\) in the near surface layer, and \(\sim 0.1\) m s\(^{-1}\) in the lower thermocline, with a very strong shear between the layers that reached \(\sim 0.3\) m s\(^{-1}\) over the 16 m separating the drogues. These conditions existed throughout the summer drifter deployment against a background current of \(\sim 0.1\) m s\(^{-1}\) to the southwest. In both drifter deployments, study of the hydrographic characteristics following the drogues indicated that they were able to follow their assigned water masses rather well.

The biological and physical measurements made on both cruises included the standard hydrographic parameters of temperature, salinity, dissolved oxygen, transmission, and fluorescence from the surface to within 1 m of the bottom. On the summer cruise an FRR fluorometer also was mounted on the Rosette providing profiles of a set of photosynthetic parameters. Bottle samples were analyzed for a wide range of parameters including: nutrients, dissolved oxygen, DOC, TCO\(_2\), alkalinity, chlorophyll, phaeophytin, photosynthetic parameters via an FRR fluorometer, POC/PON, bacterial activity, biomass of all major photo- and heterotrophic plankton groups, and HPLC phytoplankton pigments. In addition, depth-resolved mesozooplankton tows were obtained at most sites. Productivity, photoautotrophic C biomass, and C-specific growth rate measurements derived from either simulated in situ on deck incubations or from photosynthesis–irradiance photosynthetic studies also were made each day at selected stations. Underway measurements included temperature and salinity, chlorophyll, \(p\)CO\(_2\), and currents from an ADCP. Growth of phytoplankton and grazing by nano/microzooplankton, and bacterial production and grazing by nano/microzooplankton were determined daily. Shipboard incubations to determine predation on microzooplankton by mesozooplankton were conducted at regular intervals. Molecular studies also were conducted aboard ship to determine mechanisms of regulation of ribulose biphosphate carboxylase (RubisCo) in natural phytoplankton communities.

In addition to the process cruises, three earlier process cruises provided background information for this complex region that were used to define the optimal locations for the moorings and process measurement components. They also yielded valuable insights into water-column biology and its relation to carbon fluxes (Paffenhofer et al., 1995; Verity et al., 1996; Flagg et al., 1998), as well as the opportunity to test methodology developed in the first 3-year phase of OMP (e.g., Verity and Paffenhofer (1996). A ship-based OMP time-series component also operated from 1994 to 1996. The time series consisted of monthly to bi-monthly transects off the New Jersey coast (Boehme et al., 1998). Inorganic carbon parameters (TCO\(_2\), alkalinity, \(p\)CO\(_2\)), and nutrients were determined at stations extending from the shore to the 30 m isobath. The resulting biogeochemical time-series provides valuable insight into interannual variability on the MAB.

### 2.4. Benthic process studies

The seafloor has a central role in the cycling of carbon and other reactive biogenic material in
continental shelf/slope regions. Bottom deposits act both as sites of dynamic processing of organic debris and rapid interchange with overlying water, as well as relatively permanent repositories and integrative records of past or present elemental cycling patterns. Significant percentages of total water column primary production are typically remineralized on the bottom at continental shelf depths (~20–30%), and, over sandy regions, a substantial proportion of total primary production may be benthic in origin (~50%) (Cahoon et al., 1994; Alongi, 1997; Jahnke et al., 2000). In the case of the east coast, the existence of a carbon-rich (1–2% C) band of sediment stretching along slope between ~1 and 2 km water depth implies possible extensive export of shelf-derived biogenic material and storage in slope depocenters (e.g., Walsh et al., 1985). Understanding processes that might originate and maintain such a sedimentary feature was a major impetus for examining shelf-slope interactions at Cape Hatteras.

In order to test the hypothesis that significant off-shelf export of reactive organic carbon occurs in this region, the benthic processes program sought to: (1) determine the magnitude, source, and patterns of reactive carbon deposition and remineralization rates at the seafloor; (2) quantify permanent burial rates of carbon and associated biogenic material; and (3) evaluate and model the major factors controlling observed remineralization rates and patterns of carbon storage.

Individual benthic processes that are important in controlling the fate of organic material include particle deposition, metabolism and remineralization pathways, organic matter associations, bioturbation and physical reworking, secondary production, net lateral transport of particles, and permanent burial. The individual components of the benthic group were designed to constrain each of these factors in selected regions and depth zones. A variety of techniques were used to directly measure or infer DIC and DOC remineralization rates, sedimentary processes, and net burial of carbon. Measurements included natural and anthropogenic radiochemical tracer distributions, stable isotopic studies of particulate and dissolved organic and inorganic carbon pools, direct measures of benthic remineralization and net fluxes of solutes both in situ and shipboard, benthic community species composition, biomass, and faunal isotopic composition, molecular biomarker distributions, bioturbation and irrigation rate measurements to >1 m, and in situ manipulative experiments to directly examine the fate of pulsed carbon inputs. Submersibles also were used for conditional sampling in areas of complex topography and to carry-out in situ experiments.

Nine cruises were made in the study region, including some done for closely related studies funded by NSF and NOAA/NURP. Although samples were recovered throughout the OMP study region, including the continental shelf and Chesapeake Bay, the majority of the sampling was focused on the adjacent slope, which serves as a potential depocenter for material transported off the shelf. Remineralization and diagenetic process studies were centered on, but not exclusively limited to, 3–4 cross-margin transects. These efforts combined multiple station spatial-pattern sampling, detailed local process studies, and oriented conditional topographic sampling. Sampling included kasten and box coring, free-vehicle flux chambers, submersible-deployed flux chambers, and submersible-deployed remineralization and tracer incubation probes (13-C, 35-S).

2.5. Shelfwide surveys

Three whole-shelf cruises were conducted in 1996 to survey the entire MAB, two in late winter/spring 1994 and 1996, and one in summer 1996. This field program surveyed the shelf under two very different biogeochemical regimes. In the late winter/spring, river discharge and primary productivity were maximal. The water column was well mixed, relatively fresh, and had high standing stocks of nutrients and biomass. In summer, both primary production and river discharge decreased. A strong pycnocline developed that restricted the freshwater inputs to a very shallow surface layer, and isolated surface water from colder deep water (cold pool). The objective was to inventory and characterize DOC and POC (and to the extent possible, organic N and P as well) in order to establish spatial gradients and seasonal patterns of
elemental distribution and fluxes on a much wider area of the shelf and upper slope than accounted for by the moored array. A combination of geochemical tracers that integrate over longer spatial and temporal scales, underway and rosette-based FRR, and microbiological incubation experiments were used to complement C-cycling studies conducted by the benthic, water-column processes, and moored-array teams.

3. Overview

3.1. Physical oceanographic studies

To date, four separate analyses focusing on the physical processes have been completed; two already have been published, while two more form part of this special issue. Together, they attempt to examine and quantify water mass transformations, their movement on and export from the shelf, and the forcing that lead to these processes. Flagg et al. (1998) examined a heretofore unknown process by which shelf water is able to escape into the slope sea gyre. During a pre-OMP cruise on the R.V. Gyre to the southern MAB, cold-pool water was observed in AVHRR SST photos to have surfaced offshore of the shelf break over an extended portion of the southern MAB. Investigation of this escaping shelf-water plume showed that the water carried T, S, and nutrients characteristic of cold-pool waters. The cold water appeared to have spun-up into a series of anticyclonic eddies with diameters 3–4 times the Rossby radius, ∼35–45 km, which proceeded southward along the offshore edge of the shelf/slope front at a speed of ∼0.2 m/s. Shipboard ADCP data show that these cold eddies penetrated to a depth of ∼250 m, much deeper than the shelfbreak. The dynamics that caused the cold-pool water to migrate up along isopycnals and to form deep eddies is unclear although coincident intrusions onto the shelf of Gulf Stream water from the south, may have played a role by producing an alongshore baroclinic pressure gradient sufficient to drive the cold-pool waters offshore. The high nutrient content of the upwelled cold-pool water caused a localized phytoplankton bloom within the eddies.

Together with local production, this export method can result in a significant export of biogenic carbon to the deep ocean.

Kim et al. (2001) made use of the current and salinity observations for the two moored array deployments to investigate the transports of water and salts along and across the shelf. Mean transports through the region were southward at rates of 0.13–0.17 Sverdrups, which were comparable to the transports from the SEEP-II line off Delaware/Maryland of approximately 0.19 S (Biscaye et al., 1994). About 65% of the alongshore flow occurred within the shelf break region due to a combination of both larger mean currents and deeper waters. The estimated mean fluxes through the boundaries of the OMP region for the winter/spring and summer deployments nearly balanced, and the differences were not significant based upon the transport error estimates. According to the transport estimates, ∼45% of the alongshore flow from the north exited the region by way of the southeast corner of the array, ∼35% exited through a broad flow toward the east, with ∼20% exiting to the south in the vicinity of Cape Hatteras. This southward flow agrees with the estimate of Pietrafesa et al. (1994) for the needed input from the north into the SAB. However, the southern OMP line is north of Diamond Shoals, and the southward transport appeared to occur uniformly along the western portion of the south line into an area dominated by northeastward flowing SAB and Gulf Stream waters. Consequently, it is not clear what portion of this water actually makes it into the SAB. The temporal variability of the alongshore flow showed that there was high coherence between the transports through the northern and southern lines, and the alongshore wind stress and sea level fluctuations. In addition, there was a clear relation between the north–south transport gradient and the eastward off-shelf transport. The salt flux was dominated by the behavior of the transports times the cross-sectional mean salinities, while the turbulent salt fluxes produced insignificant contributions.

Flagg et al. (2002) used data from the eight cruises to the OMP region together with temperature and salinity data from the moored array to document the establishment of the regional
seasonal stratification. The observations show a complex interplay between the numerous water masses endemic to the area, moderated by wind stress, air–sea interaction, solar insolation, and Gulf Stream intrusions to produce highly variable hydrographic conditions during the seasonal transition. The set of detailed hydrographic cruise observations made possible a refinement of the complex water mass descriptions for the area as compared to the fairly broad definitions in the past. The dense array of moored temperature and salinity observations from the first OMP mooring deployment (Fig. 1) showed that the hydrographic scales were greater than 150 km (100 km) in the along-shelf direction for temperature (salinity), greater than 80 km (40 km) in the cross-shelf direction, and greater than 60 m in the vertical for both parameters. The vertical scale represents the mostly unstratified winter conditions of the spring mooring deployment. This made possible for the first time an objective interpolation of the hydrographic conditions over the shelf and the formation of a three-dimensional time series of the seasonal transition. During the spring of 1996, the gradual warming of the surface waters typical of most broad continental shelves was not evident in the OMP area, as the prevailing downwelling favorable southward winds provided a continuous flow of cold, unstratified MAB water from the north, while keeping the low salinity Chesapeake Bay plume close to the coast. While some gradual warming of near-shore waters was observed, the water column over most of the area remained relatively unstratified until two things happened. First the prevailing southward winds turned toward the north. This reversed in some areas, and slowed in others, the southward flow of cold MAB waters and caused the Chesapeake Bay plume to spread offshore. Shortly thereafter, a major intrusion of saline waters from the SAB and Gulf Stream penetrated onto the shelf, accelerating the offshore spread of plume waters, resulting in the abrupt establishment of stratified conditions over the entire area. The decrease of the alongshore flow permitted the surface heat flux to strengthen the stratification. Prior to the spring transition, the densest surface waters in the area were the MAB waters flowing into the area from the north. After the transition, the north–south surface-density distribution reversed completely and the lightest near-surface waters were those warmed waters formed from the offshore and northward spreading Chesapeake Bay plume waters that mixed with the more saline MAB waters.

Pietrafesa et al. (2002) present a discussion of the winds, tides, and low frequency currents observed during the first of the two OMP mooring deployments. Among the points highlighted during this winter/spring transition period was the southward increase in wind energy due to southerly pathways of synoptic scale atmospheric events, and the fact that the period was characterized by two wind regimes. The winter regime of predominantly southward winds lasted into April, when a reversal of the winds started a second regime that helped to initiate a wide-spread change in water-mass characteristics (see Flagg et al., 2002). Tidal current exhibited a mid-shelf maximum due to frictional effects in shallow water, on one hand, and deeper water at the edge of the shelf on the other. It also was noted that despite the hydrographic complexities of the area, the synoptic scale currents were conventionally responsive to alongshore wind forcing but with an extra factor that came into play in the southern half of the area. Because of partial blockage by Diamond Shoals, sea level tended to rise to the south due to either southward-flowing MAB water or north-eastward flowing SAB water. The inability of coastal Kelvin waves to propagate northward caused the resulting south to north pressure gradient to persist, causing a geostrophically balanced off-shelf interior flow to the east. The prevalence of the north–south pressure gradient may be partially responsible for the strong mean offshore flow through the southeast corner of the OMP area and a general blockage of the south-westward flow of the MAB at this, its southern terminus.

3.2. Water column process studies in the southern MAB

Continental shelf and adjacent slope waters represent 10–20% of the surface area of the global
oceans, but contribute 25–50% of total oceanic primary production (Walsh, 1988). Determining the factors, which influence the magnitude of carbon exchanges between the ocean margins and atmosphere, and the fate of that carbon, is essential to understanding and predicting the ocean’s capacity to store anthropogenic CO₂.

Five papers in this issue deal principally with the impacts of planktonic organisms on rates of organic carbon formation, degradation, and transformation. These papers present data on primary production and standing stocks of phytoplankton (Lohrenz et al., 2002; Redalje et al., 2002); bacterial stocks, bacterivory, and detrital carbon (Sherr et al., 2002); phytoplankton growth and microzooplankton grazing rates (Verity et al., 2002); and abundances and distribution patterns of metazooplankton (Paffenhöfer and Flagg, 2002). The major conclusions as they relate to the production and fate of carbon on the Hatteras shelf are summarized below.

Redalje et al. (2002) measured primary production as part of Lagrangian studies in March and July 1996, which attempted to use drogues to follow shelf water masses as they were advected by local winds and also under the influence of tidal forces (Flagg et al., 2002). In both cases, following the path of the drogues permitted interpretation of daily patterns of primary production as probably representing real variability in natural phenomena rather than just spatial heterogeneity in water masses and the phytoplankton contained therein. In March, production ranged from 0.50 to 0.65 g C m⁻² d⁻¹ with one half to two thirds of the production attributed to the <8 μm size fraction. About 50% of the total chl a was found in the <8 μm size fraction. In July, production was more variable at 0.38–2.09 g C m⁻² d⁻¹ with 41% to 83% of production attributed to the <8 μm size fraction. Most of the chl a was found in the <8 μm size fraction. Correlation analyses indicated that primary production was positively correlated with light and temperature.

The shelf edge is a region where the physical setting can either impede or facilitate exchanges of water and materials, and also cause injections of deep-water nutrients onto the shelf. This physical variability likely accounts for the broad range of estimates of annual primary production for the MAB from 142 to 310 g C m⁻² yr⁻¹ (O’Reilly and Busch, 1984; O’Reilly et al., 1987; Kemp et al., 1994; Walsh, 1994). Lohrenz et al. (2002) estimated primary production for the Hatteras shelf during the OMP using a wavelength-resolved photosynthesis–irradiance mode. Average shelf-wide productivities were 1.3 g C m⁻² d⁻¹ in March and 2.1 m⁻² d⁻¹ in July. March resembled the classical early winter/spring conditions typical of the MAB with enhanced phytoplankton biomass near the shelf-slope front. A different picture was observed in July, when Gulf Stream intrusions injected nutrients onto the shelf. These processes stimulate phytoplankton production and increase the pool of organic matter available for export from the shelf. Estimates of annual shelf production derived from the model were approximately two-fold higher than those from prior studies, further suggesting the importance of shelf-edge processes. Similar to Redalje et al. (2002), Lohrenz et al. (2002) emphasize that small (<8 μm) cells were surprisingly important to productivity, especially at higher temperatures.

It is well recognized that bacteria play a key role in the transformation of organic matter in aquatic ecosystems, however, little is known about the activity and viability of the cells participating in these transformations. The question of whether or not bacteria are growing, dividing, or even viable is crucial for our understanding of their potential role in these ecosystems. Sherr et al. (2002) investigated bacterial community abundance, biomass, activity levels, and losses to grazers during the four spring and summer cruises. Data were grouped according to inner, mid, and outer shelf sample sites, and compared to independent estimates of the volume of particulate organic detritus. Concentrations of bacteria, their grazers, and detritus were generally higher in spring compared to summer communities. Bacteria activity levels typically decreased inshore to offshore and were highest among particle-associated cells. Bacteriovores generally removed 2–9% of bacteria stocks daily but if they selectively grazed active cells (as has been shown elsewhere), bacterivory could remove most of the daily bacterial production.
Three processes determine the fate of primary production occurring on ocean margins: portions can be oxidized within the water column, portions can sediment to shelf/slope depots, and portions can be exported to the interior ocean. Zooplankton mediate all three of these processes and thus can alter the pathway and residence time of particulate organic carbon. The magnitude of each fate for newly formed POC depends, to a large extent, on the size structure and composition of the zooplankton and phytoplankton communities. Traditionally, relatively large centric diatoms have been considered to be the most abundant phytoplankton in shelf waters in this region (Marshall, 1971). More recent studies using fluorescence microscopy have shown that nanophytoplankton contribute substantially to algal biomass (Paffenhofer et al., 1995; Verity et al., 1996). When larger animals such as copepods and gelatinous zooplankton are important grazers, the high sinking rates of their fecal material should increase retention of particulate organic matter on the shelf. When protozoans dominate the zooplankton community, grazing rates and gross growth efficiencies will be high but fecal carbon will remain in suspension. Thus an active microbial and small plankton community functions to retain nutrients and carbon in the euphotic zone, enhancing regenerated production and minimizing vertical export of POC.

Verity et al. (2002) determined grazing of phytoplankton production by microzooplankton, in order to better constrain the potential routes for carbon fluxes on the MAB and SAB shelves. Grazing and growth rates were measured via dilution incubation experiments using chl $a$ as a proxy for phytoplankton biomass. Nano- and microzooplankton grazed 65% of $<200 \mu m$ chl $a$ production, and 81% of $<8 \mu m$ chl $a$ production. These relationships were temperature-dependent: losses of chl $a$ production in both size fractions to microzooplankton herbivory increased with increasing temperature. According to the Lohrenz et al. (2002) biooptical model, microzooplankton ingested 42% and 61% of primary production in March and July, respectively, with an overall mean of 52%. These data imply that significant fractions of primary production were consumed while suspended in Hatteras and SAB waters. Since the particulate egesta of microzooplankton are very small particles, which remain suspended (Stoecker, 1984), this portion of shelf primary production either became colloidal or dissolved DOC, was oxidized to CO$_2$ by bacteria, or was exported with entrained waters departing the shelf, where its ultimate fate was most likely oxidation. This general scenario is supported by observations of an active bacterial community and considerable suspended detritus (Sherr et al., 2002). Thus a significant fraction of the original primary production may not have been exported to surficial or repository sediments on the shelf or beyond.

Only that fraction of particulate primary production not eaten by microzooplankton, lysed by viruses, or ingested by larger metazooplankton may sediment from the euphotic zone. Metazooplankton can be seasonally abundant or intermittently high year-round depending upon physical forcing (e.g., Paffenholz et al., 1987). Direct information on the extent of grazing of primary production by metazooplankton on the Hatteras shelf is currently unknown. Paffenholz and Flagg (2002) show that the magnitude of zooplankton biomass in spring approaches the highest values reported from any shelf environments, which implies a significant impact on their prey. Also, gelatinous zooplankton occur in bloom concentrations and can then decimate their prey (Paffenholz et al., 1995). Copepods in contiguous waters are selective feeders and can remove specific phytoplankton and microzooplankton prey based upon criteria more complicated than just prey size (Verity and Paffenholz, 1996). Repackaging of microzooplankton into larger fecal pellets with high sinking speeds via predation by larger zooplankton may add to vertical export, although this must necessarily be a small fraction of the original primary production.

In summary, the Hatteras shelf is a biologically productive environment. Gradients in organic matter and productivity extend seaward from the inner shelf, but the dynamic nature of the Gulf Stream has a profound effect upon the physics and biology of the outer shelf. There is evidence of high rates of CO$_2$ incorporation into new organic matter in size fractions, which support both
remineralizing microbial food webs but also traditional large zooplankton food chains. It appears that much of the particulate production is consumed on the shelf, except perhaps for shelf-edge blooms, which may cascade onto slope sediments as observed in the South Atlantic Bight (Yoder and Ishimaru, 1989).

3.3. Benthic process studies in the southern MAB

3.3.1. The nature of sediment reaching the seafloor

The OMP studied benthic processes providing insight into many aspects concerning the nature and amount of material reaching the seafloor, the transformations occurring within the seabed, and the chemical characteristics and flux of the material buried in the sediment column. By summing the inorganic carbon fluxes out of the seabed (diffusive and bioirrigation) with the organic carbon burial rate, Thomas et al. (2002) estimated that the rain rate of organic carbon to the upper slope seabed off Cape Hatteras ranges from 5 to 13 moles C m\(^{-2}\) yr\(^{-1}\). In comparison, Anderson et al. (1994) estimated the depositional organic carbon flux at the SEEP-II site was on the order of 2 moles C m\(^{-2}\) yr\(^{-1}\), whereas DeMaster et al. (1994) reported depositional fluxes off Cape Hatteras, Cape Lookout, and Cape Fear (water depth of \~850 m) to be 14, 3, and 1 moles-C m\(^{-2}\) yr\(^{-1}\), respectively. The high deposition rate reported by DeMaster et al. (1994) is believed to be accurate for a subset of the OMP study area, but not regionally representative of slope sedimentation off Cape Hatteras.

Santschi et al. (1999) published particle trap data short-term, near-bottom deployments indicating that the \(\Delta^{14}C\) content of the material reaching the seafloor in the OMP study area varied from +4 to \(-107\) per mil. The lack of a dominant bomb \(^{14}C\) signal in this trap material suggests that rarely does material reaching the seabed come directly and/or predominantly from pelagic sources (which over the past few decades would have a \(\Delta^{14}C\) content of +80 to +110 per mil). These findings are consistent with the results of Anderson et al. (1994), who reported long-term, near-bottom particle trap measurements from the SEEP-II slope site further north in the Mid-Atlantic Bight (organic carbon \(\Delta^{14}C\) values of \(-60\) to \(-120\) per mil). Based on \(\Delta^{14}C\) measurements of surface sediments from the continental slope off Cape Hatteras and estimates of turnover times for various organic carbon sources, DeMaster et al. (2002) suggest that at least 3 sources of organic matter contribute substantially to the sediments reaching the seafloor and they are: (1) organic matter recently transported directly from the surface ocean (\(\Delta^{14}C\) content of approximately +80 per mil and a turnover time of less than a year); (2) relatively young organic matter processed by zooplankton, benthic fauna, and/or microbes that moves down the slope from the shelf on a time scale of at least decades (\(\Delta^{14}C\) content of approximately \(-10\) per mil and a turnover time of 100 years); and (3) old refractory marine organic matter reworked from the shelf during storms (\(\Delta^{14}C\) content of \(-150\) or greater and a turnover time of the order of 1000 years). If these end member characterizations accurately represent the organic sources reaching the seabed, mass balance calculations suggest that plankton make up from 0 to 30% of the organic C reaching the seafloor. The young processed organic carbon source is estimated to provide 60–90% of the organic carbon flux to the seafloor, whereas the refractory source contributes 10–15%. Based on surface area, organic carbon, and EHAA (enzymatically hydrolizable amino acids) measurements, Mayer et al. (2002) suggest that organo-mineral aggregates may be winnowed from shelf sediments and serve as an important source of organic carbon to the deeper slope deposits.

The flux of organic carbon reaching the seafloor commonly is compared to benthic faunal abundance to examine the chemical/biological coupling occurring in the upper sediment column (e.g., DeMaster et al., 1994, for three North Carolina slope stations). As a result of the relatively small variation in POC rain rate within the OMP study area, the correlation between macrofaunal abundance and POC rain rate is not significant (Aller et al., 2002). However, including the OMP data with the data collected further south on the North Carolina slope (DeMaster et al., 1994) yields a significant correlation \((r^2 = 0.66; p = 0.002)\) between these parameters.
3.3.2. The nature of sediments in the upper 3 m of the seabed

The organic carbon content of the surface sediments on the upper continental slope off Cape Hatteras ranges from 1.0% to 3.5% (Thomas et al., 2002; Mayer et al., 2002). Based on the $^{13}$C content of the bulk organic matter in the seabed (~$-21$ per mil; Thomas et al., 2002), marine carbon is believed to be the dominant source of the sedimentary organic matter. These fine-grained sediments have a surface area ranging from 3 to 25 m$^2$ g$^{-1}$ (Mayer et al., 2002). Sedimentary organic carbon contents increase as grain size decreases (with water depth a secondary control). Mayer et al. (2002) describe the organic loadings (organic carbon content/sediment surface area) for these slope sediments (1.5–4.5 mg organic carbon m$^{-2}$) as the highest measured in continental margin sediments under an oxygenated water column. Despite very high organic loadings, the mineral surfaces are essentially bare of organic coatings. High levels of dissolved organic carbon (DOC) in OMP study area pore waters appear to have little effect on the organic loading of the slope sediments (Alperin et al., 1999).

There are several lines of evidence indicating that relatively fresh marine planktonic material reaches the sediment-water interface and comprises a small, but finite, fraction of the surface sedimentary material. The most convincing evidence is that marine infaunal tissues (primarily polychaetes) have $^{14}$C contents ranging from +20 to +80 per mil (DeMaster et al., 2002). These issues typically are 100 per mil or more enriched in $^{14}$C relative to the surface sediment bulk organic $^{14}$C values (~$-41$ to $-215$ per mil). The tissue enrichment probably results from particle selection during ingestion as well as preferential digestion of labile organic material. Based on $^{14}$C mass balance equations, estimates of turnover times for the various organic carbon sources, as well as constraints resulting from the $^{14}$C content of near-bottom particle trap material, the amount of fresh planktonic material occurring in the upper 5–8 cm of the seabed is believed to be on the order of a few tenths of a percent or less (DeMaster et al., 2002). Therefore, in spite of very small abundances in the seabed, the planktonic material is efficiently sequestered into the benthic food web, where it serves as the predominant carbon/energy source. Other evidence of young reactive carbon being deposited on the seafloor comes from the abundance of chl $a$ in these surface sediments (typically 10–20 mg chl $a$ m$^{-2}$; Green et al., 2002) as well as the fact that viable diatoms have been reported in slope sediments down to a water depth of 2000 m (Cahoon et al., 1994). In addition, EHAA levels are high in upper slope sediments between 400 and 1500 m water depth (0.5–1.5 mg g$^{-1}$). In response to this supply of reactive organic matter, these continental slope deposits support an unusually high abundance of macrofauna (typically 50,000–80,000 individuals m$^{-2}$) and substantial populations of meiofauna and bacteria (Aller et al., 2002; Schaff et al., 1992). In terms of biomass (typically 20–25 g organic C m$^{-2}$ for the study area), macrofauna (> 0.3 mm) make up the greatest fraction of the organic matter (80–90%), followed by meiofauna (~ 10%), and then bacteria (3–10%). Estimates of organic carbon production by benthic fauna (Aller et al., 2002) suggest that bacterial carbon fixation and macrofaunal carbon fixation occur at comparable rates for water depths greater than 500 m. However, at depths less than 500 m where there are higher abundances of bacteria, microbial fixation rates may exceed the macrofaunal rates by a factor of threefold or more.

3.3.3. Bioturbation and bioirrigation

Several types of measurements made during the Oceans Margin Program suggest that the seabed on the upper continental slope off Cape Hatteras is extensively bioturbated and bioirrigated. $^{234}$Th data (24 day-life) and chl $a$ data indicate that the upper 2–5 cm of the sediment column are characterized by particle mixing coefficients ($D_b$) ranging from 1 to 200 cm$^2$ yr$^{-1}$, with non-local penetration of these tracers as deep as 8 cm (Green et al., 2002). On a time scale of 50–100 years, Pu and $^{210}$Pb distributions suggest that the upper 10–27 cm of the sediment column are mixed more slowly, with $D_b$ values ranging from 0.3 to 5.2 cm$^2$ yr$^{-1}$ (Alperin et al., 2002). In addition to particle mixing, bioirrigation is a very important process for transporting materials of biogeochemical relevance. The distributions of pore water
dissolved inorganic carbon (DIC) and dissolved sulfate have been modeled in the OMP study area sediments (Thomas et al., 2002), and the results suggest that bioirrigation can occur to depths as great as 200 cm (commonly 60–100 cm) and that the bioirrigation fluxes out of the seabed (DIC fluxes range from 2.9 to 7.8 moles C m$^{-2}$ yr$^{-1}$) typically are 3–4 times greater than the diffusive fluxes (DIC fluxes varying from 0.6 to 3.3 moles C m$^{-2}$ yr$^{-1}$). For comparison, Jahnke and Jahnke (2000) used benthic flux chamber data from many of these same slope stations and determined that the DIC flux across the sediment-water interface from remineralized organic matter varied from 1 to 4 moles C m$^{-2}$ yr$^{-1}$. Bioirrigation has expanded to a significant extent the vertical range over which sulfate reduction occurs in the sediment column (Albert et al., 2001). This process also may contribute to the high amount of remineralized nitrogen ($\sim$68%) that ultimately becomes denitrified (Jahnke and Jahnke, 2000). Bromide incubation experiments on board ship corroborate the rapid transport of overlying water down into the sediment column (Green et al., 2002). The penetration depths for bromide were as great as 7 cm over a period of 24 h, with the mean bromide penetration rates suggesting transport more than an order of magnitude greater than molecular diffusion. In addition to measuring DIC fluxes from the seabed, studies also determined the transport of dissolved organic carbon from the seabed, which generally accounted for less than 2% of the remineralized organic carbon in the sediment column (Alperin et al., 1999).

3.3.4. The nature of sediment buried in the seabed

Based on $^{210}$Pb and Pu chronologies from the upper slope of the OMP study area, Alperin et al. (2002) estimate that accumulation rates on a 100-year time scale range from 10 to 425 cm kyr$^{-1}$. The corresponding rates of organic carbon burial vary from 0.1 to 4.7 moles C m$^{-2}$ yr$^{-1}$, with the highest values generally occurring between 500 and 800 m water depth. On a 1000-year time scale, organic carbon $^{14}$C data indicate that sediment accumulation rates range from 3 to 150 cm kyr$^{-1}$ with organic carbon accumulation rates ranging from 0.02 to 1.7 moles m$^{-2}$ yr$^{-1}$ (mean value of 0.7 moles C m$^{-2}$ yr$^{-1}$; Thomas et al., 2002; DeMaster et al., 2002). On the upper slope (300–500 m water depth) the $^{210}$Pb chronologies suggest that accumulation rates may be greater on 100-year time than on 1000-year time scales, but the reverse is true at water depths $\geq$1000 m. Averaging over the entire OMP study area, there is no obvious difference in accumulation rate for these different time scales (Alperin et al., 2002). To compare the organic carbon accumulation rates in the OMP study area with those from nearby studies (Anderson et al., 1994, SEEP-II; DeMaster et al., 1994, NC slope), the $^{14}$C data should be used to maintain a consistent time scale. Anderson et al. (1994) reported an organic carbon burial rate at SEEP-II (off southern Virginia) of 0.7 moles C m$^{-2}$ yr$^{-1}$ (similar to the mean value in the OMP study area), whereas the DeMaster et al. (1994) values ranged from 12 to –0.05 moles C m$^{-2}$ yr$^{-1}$. The rate of organic carbon accumulation at the SEEP-I site off New England varied from 0.1 to 0.2 moles C m$^{-2}$ yr$^{-1}$ (see Thomas et al., 2002, for regional comparisons).

The seabed preservation efficiency for organic carbon can be calculated by dividing the organic carbon burial rate by the organic carbon rain rate reaching the seafloor. The range in values for the various OMP slope stations was from 3% to 40% (mean $\sim$15%; Thomas et al., 2002) with little systematic down-slope variation. In comparison, the preservation efficiency at the SEEP-II site was 38% (Anderson et al., 1994) and the values from further south on the North Carolina slope ranged from 6% to 88% (DeMaster et al., 1994). Down-core EHAA measurements indicate that hydrolyzable amino acids persist well beyond the base of the mixed layer down to the bottom of the kasten cores (Mayer et al., 2002). Therefore, some fraction of EHAA must be sufficiently refractory (or protected in some manner) to avoid microbial decomposition over a period of several thousand years. Based on pore water $^{14}$C data, Thomas et al. (2002) estimate that the $^{14}$C content of the decomposing organic matter deep in the kasten core sediments is on the order of –550 per mil. Consequently, organic matter that is $\sim$4000 years old appears to be microbially regenerated after the
younger, and more labile material, is consumed near the sediment surface.

One of the dominant reasons for examining organic carbon burial in the OMP study area was to assess the burial rate of organic carbon relative to primary production rates on the shelf and slope to determine if there was any indication of increased organic carbon burial in slope deposits as a result of anthropogenic additions of nutrients to coastal waters during the past several decades (Walsh et al., 1985). A summary of the benthic organic carbon fluxes for the OMP study area is provided in Fig. 3 along with characteristic $^{14}$C signatures of the various source materials. Also provided in this figure is the fraction of continental slope primary production represented by each of the organic carbon fluxes depicted in the figure. The calculations are based on the assumptions that: (1) primary production rates in shelf and slope waters are $\sim 15$ moles C m$^{-2}$yr$^{-1}$, (2) no organic carbon is buried permanently on the continental shelf, and (3) the ratio of the continental margin area (shelf and slope) to the continental slope area is $\sim 8.6$ (see DeMaster et al., 2002, for discussion of assumptions). Fig. 3 illustrates that organic carbon deposition on the seafloor of the continental slope represents approximately 7% of the total primary production occurring on the continental margin. The burial of organic carbon on the slope represents only 0.6–1.5% of the margin primary production, which is a small fraction. Therefore, despite the fact that the OMP site was selected to maximize the offshore transport and deposition of organic carbon, burial of organic matter in North Carolina slope sediments is not a major sink for primary production occurring in this continental margin system (Alperin et al., 2002; DeMaster et al., 2002).

3.3.5. Down-slope variations in sediment characteristics

The distribution of sedimentary characteristics down slope is useful to evaluate because it can provide insight into the processes responsible for the chemical and physical variations associated with increasing water depth. Between 300 and 1500 m water depth, the organic carbon content of the sediments varies from 1.0 to 3.5 wt%, with the highest values occurring near 700 m water depth (Mayer et al., 2002; Thomas et al., 2002). In contrast, the peak in sediment surface areas occurs at $\sim 1300$ m water depth and the peak in the organic C/surface area ratio is evident at a water depth of 300 m (Mayer et al., 2002). Thus the downslope increase in organic matter concentrations is largely driven by grain size variations rather than organic matter delivery rates, although the latter influence can be detected. There is very little down-slope variation in the abundances of macrofauna (>0.5 mm) and meiofauna in the OMP study sites (water depth 200–1500 m). However, bacterial abundances appear to be $\sim 2$-fold greater for sediments from water depths <500 m as compared to sediments collected from water depths >500 m. Benthic biomass appears to show little down-slope variation. Alperin et al. (2002) suggest that organic carbon burial rates may be
somewhat higher between water depths of 500 and 800 m, but measurements from more stations on several cross-slope transects are needed to corroborate fully the initial trend in the data set. Bioirrigation rates were estimated at only 5 stations in the OMP slope study area. As a result of bioirrigation making up such a large fraction of the regenerated DIC flux back into the water column, accurate preservation efficiencies could only be established at 5 stations (Thomas et al., 2002). There was no obvious trend in these 5 values with water depth.

3.3.6. Variations in sediment characteristics as a result of topography

In some of the OMP data sets (e.g., organic-carbon burial rates), the distribution of chemical flux is integrated spatially over the entire study area. Inherent in this process is the assumption that small-scale variations in a particular parameter (scale length of 1 km or less) are small relative to the regional trends occurring over spatial scales of 10–100s of kilometers. Clearly, small-scale variations in many of these sedimentary characteristics do occur because of the ridge and swale topography covering much of the OMP slope area (see Alperin et al., 2002, for an along-slope bathymetric profile). Benninger and Suayah (2001) have shown through the use of submersible-collected cores and $^{234}$Th (24-day half life) and $^{210}$Pb (22-year half life) inventories that sedimentological properties can vary substantially over km-scale distances when comparing ridge, valley, and valley wall environments. Since the exact topographic setting of samples collected from surface research vessels is not known (e.g., box core or kasten core locations), the presumption is made that small-scale variations average out when the large-scale gradients are examined. Certainly, the substantial variations in bottom topography observed in the OMP study area will have contributed to the scatter in the collected data, potentially obscuring regional trends and functional relationships among sedimentary parameters. However, the fact that all of the organic carbon $^{14}$C profiles showed a systematic increase in age with depth suggests that much of the short-term variations observed in $^{234}$Th and $^{210}$Pb sedimentary inventories may be averaged out on time scales of hundreds to thousands of years.

3.4. Whole shelf studies

In addition to autochthonous shelf primary production, these coastal regions are also important zones for the discharge of terrestrial and riverine organic matter and nutrients (Mantoura and Woodward, 1983; Mulholland and Watts, 1982; Moran et al., 1991; Hedges et al., 1997; Kiel et al., 1997; Jickells, 1998). Primary production in margins (estimated at $\gtrsim 8 \times 10^{15}$ g C yr$^{-1}$ globally; Valiela, 1995), coupled with significant regional inputs of terrestrial organic matter by rivers ($\sim 0.40 \times 10^{15}$ g C yr$^{-1}$ for the sum of DOC and POC globally; Hedges et al., 1997), make continental shelf and slope systems important and dynamic regions of carbon fixation, flux, and transformation (Wollast, 1998). The dominance of low-salinity, buoyant plume waters on the MAB shelf (Boicourt, 1981; Malone and Ducklow, 1990; Churchill and Berger, 1998; Bates and Hansell, 1999) also suggests that there may be a significant contribution, and subsequent cycling, of organic matter derived from terrestrial, river and estuarine systems that is transported to shelf and slope waters.

Although they represent a relatively small portion of the total world ocean, margins have been hypothesized to serve as quantitatively important regions through which the respiration of the ocean's interior may be subsidized (Smith and MacKenzie, 1987; Bauer and Druffel, 1998; del Giorgio et al., 1997). The net autotrophic character of ocean margins (Smith and Hollibaugh, 1993; del Giorgio et al., 1997; Duarte et al., 1999) also indicates that they should exhibit a slight excess of CO$_2$ fixation vs. heterotrophic organic matter respiration. Until recently, these estimates of net autotrophy in shelf systems have been established primarily through a combination of incubation studies of phytoplankton and bacterioplankton productivity, and mass balance models. New direct measurements of CO$_2$ gas exchange in several continental shelf systems (see Frankignoulle and Borges, 2001; DeGrandpre et al., 2002) indicate that of those studied so far,
all appear to mediate net annual drawdown of atmospheric CO₂. Margins therefore may function as net carbon sinks in two major yet very different ways, by: (1) net annual uptake of atmospheric CO₂ by a combined biological/abiotic pump, and (2) importing recalcitrant riverine organic matter (both dissolved and particulate) and dissolved inorganic carbon (as CO₂ and bicarbonate). These two potential mechanisms taken together also necessitate that there be a net burial (in the case of sinking POC) and/or export to the contiguous open ocean (in the case of DOC and suspended plus sinking POC) of organic carbon. It also has been speculated that some fraction of this surplus organic matter may be transported from the continental shelf and slope into the deep, interior ocean (Walsh, 1988, 1991; Smith and Hollibaugh, 1993; Bauer and Druffel, 1998), thereby subsidizing its hypothesized net heterotrophic nature (Smith and MacKenzie, 1987; del Giorgio et al., 1997).

Several papers in this special issue have explicitly examined the sources and fluxes of organic and inorganic carbon as part of the OMP. pCO₂ measurements were made in the MAB from 1994–2000 by employing both shipboard (using an underway pCO₂ NDIR-equilibrator system) and mooring-based (using an autonomous, in situ pCO₂ system; DeGrandpre et al., 1995) sampling techniques. Flux calculations of pCO₂ indicate that the MAB is a modest net annual sink for atmospheric CO₂, with the inner, mid, and outer-shelf regions taking up ~0.1, 0.7, and 0.2 Mt C yr⁻¹, respectively, for a net shelf-wide uptake of ~1 ± 0.6 Mt C yr⁻¹. The majority of the net uptake appears to result not from biological pumping, but from the annual cycle of heating and cooling combined with high winds during the period of undersaturation (winter). Thus one intriguing possibility is that the MAB may sequester atmospheric CO₂ without net production of organic carbon. Recent results from other ocean margin regions have observed significantly larger pCO₂ fluxes than the MAB, including the European North Atlantic (90–170 Mt C yr⁻¹; Frankignoule and Borges, 2001) and the East China Sea (Tsunogai et al., 1999). The increase in pCO₂ that occurs in MAB waters due to summer heating appears to be counterbalanced in the other margin systems by new production, and the pCO₂ never rises significantly above atmospheric saturation in these areas. The relatively sparse global dataset on pCO₂ measurements and fluxes in ocean margins nonetheless strongly suggests that these systems are significant components of the total oceanic uptake of CO₂. In fact, the European shelf alone has been estimated to sequester up to an additional 45% more CO₂ relative to that estimated annually for the open North Atlantic (Frankignoule and Borges, 2001; Takahashi et al., 1995; Sarmiento and Sundquist, 1992). That the world’s continental shelves and margins are clearly in need of continued, and even expanded, study is indicated by (a) the high degree of regional variability in the strength of the shelf CO₂ sink, and (b) the fact that even the small number of them studied to date suggest that the sink may rival or even exceed (when integrated globally) that of the much larger open ocean.

Dissolved organic carbon is by far the largest standing pool of organic matter in all oceanic systems, including the MAB (Druffel et al., 1992; Bauer and Druffel, 1998; Bauer et al., 2002). Vlahos et al. (2002) present the highest spatial (both regional and with depth) resolution dataset so far assembled for DOC distributions in an ocean margin system. During April 1994, March 1996, and August 1996 cruises, concentrations of DOC were greater in inner vs. outer shelf waters and increased southward along the shelf toward Cape Hatteras. Strong concentration gradients in DOM occurred between shelf and oceanic waters and between surface and deeper waters of both the shelf and slope. Coupled with appropriate vertical and horizontal advective and eddy diffusive transports, DOM export from the MAB and other shelf systems may be a significant component of ocean C dynamics. Total DOC inventories on the shelf during the March and April cruises were nearly identical at ~5.9 × 10¹² g C, and these increased by 0.4 × 10¹² g C (7%) in August. A mass balance of the DOC in the MAB resulted in total export of between 18.7 and 19.6 × 10¹² g C yr⁻¹. As much as 67% of this DOC appeared to be recycled oceanic material that is believed to be refractory with respect to MAB
residence times. Approximately 4% of shelf DOC is estimated to be imported from a combination of rivers, estuaries, atmospheric deposition, and sediment porewater flux, and at least 29% of the exported shelf DOC \((4.1-7.4 \times 10^{12} \text{ g C yr}^{-1})\) is produced on the shelf. Net ecosystem production of DOC in the MAB is estimated at between 10% and 18% of MAB primary productivity estimates. These data support the hypothesis that the MAB is, in fact, net autotrophic for the periods of study and that DOC is an important component of ocean margin carbon budgets.

Aluwihare et al. (2002) investigated the chemical composition of the high molecular weight (HMW) fraction of dissolved organic matter (DOM), which accounts for 30% of the total DOC. Using ultrafiltration, Aluwihare et al. (2002) sampled HMW-DOM from surface and deep waters throughout the Bight. Even though concentrations of DOC vary by 3-fold across the MAB, there was little change in the composition of HMW-DOC. In all samples, polysaccharides were the dominant component of HMW-DOM. Molecular level analyses of HMW-DOM polysaccharides yield seven major neutral sugars in a remarkably fixed distribution. Nuclear magnetic resonance (NMR) spectra of HMW-DOM also show a fixed ratio of carbohydrate to acetate, to lipid. Aluwihare et al. (2002) suggest these components are biologically derived and represent a component of algal organic matter that is resistant to degradation by bacteria, thereby accumulating in seawater. NMR spectra of HMW-DOM from samples collected close to shore, and particularly near major rivers, show an enhanced contribution from humic substances. Based on Aluwihare et al. (2002) and Bauer et al. (2002) analyses, the new carbon added to the MAB and measured by Vlahos et al. (2002) has both marine and terrestrial components.

The distribution and sources of DOC were also investigated by Chen et al. (2002) using continuous underway and CTD mounted fluorometer measurements. Terrestrially derived DOC is highly fluorescent, and the distribution of fluorescent dissolved organic matter (FDOM) in low salinity surface waters can be used to trace terrestrially derived DOM on the shelf. Using this technique, Chen et al. (2002) were able to observe the movement of terrestrially derived FDOM from Chesapeake Bay and other major rivers through the Bight. Terrestrial organic matter is not the only significant source of FDOM however. Chen et al. (2002) show that most fluorescence on the shelf is derived from upwelled deep water, and that there are significant sources from in situ production as well.

The relative amounts of bioavailable and refractory dissolved organic C, N (DON) and P (DOP) in the MAB were evaluated using long-term incubations of surface and deep shelf and slope water in March and August 1996 (Hopkinson et al., 2002). On average the C:N:P ratio of shelf DOM (431:36:1) was substantially higher than the Redfield ratio, but not nearly as high as that of deep slope water (2700:215:1). No significant changes were observed in concentrations of DOC, DON or DOP during incubations of deep slope water, confirming the old refractory nature of this material. In contrast, major differences in the relative amounts of “very labile”, “labile” and “recalcitrant” fractions of shelf water DOC, DON and DOP occurred as a result of preferential remineralization of P over N, and of N over C. Averaged over stations, the decomposable portion of the bulk DOC, DON and DOP pools increased from 30% to 40% to 81% for C, N and P. Average half-lives calculated from decay coefficients were 4, 12 and 8 days for the very labile DOC, DON and DOP pools and 54, 113 and 90 days for the labile DOC, DON and DOP pools. On the basis of pool turnover times relative to shelf water residence time (~100 days), shelf phytoplankton production is hypothesized to be the source of the very labile DOM pools. These results for the MAB indicate that while substantial amounts of DOM are remineralized in the same time frame as shelf water residence time, there is also substantial DOM available for export that is depleted in N and P relative to C.

4. Conclusions

The data presented primarily in this issue indicate that the Cape Hatteras shelf is a physically dynamic environment with several water masses
which transport particulate and dissolved matter, and which directly affect the production of organic matter. Rates of primary production are relatively high due to terrestrial nutrient sources but also shelf-edge exchange processes. Activities of heterotrophs imply that much of this production is consumed within the water column of this ocean margin, as concluded in the SEEP programs to the north (Walsh et al., 1988a, b; Biscaye et al., 1994), and also recently in a northeast Atlantic ocean margin (Joint et al., 2001; Wollast and Chou, 2001). The rate of organic carbon burial on the upper continental slope of the OMP area corresponds to very small fraction (<2%) of the primary production on the margin. Most of the organic matter reaching the continental slope seafloor off Cape Hatteras is of marine origin and at least decades old (reworked from shallower environments). Fresh plankton make up less than 30% of the organic matter raining down on the seabed and less than 1% of the organic matter in the upper 5–8 cm of the seabed.

The analysis of the extensive data set produced during the OMP has been extremely abbreviated due to funding constraints caused by unexpected programmatic changes. This applies to all of the data but perhaps especially to the physical data. Much more can be done with this dataset, such as using the observations to sea-truth physical/biochemical models. The density and completeness of the observations would provide major constraints on these models and thus produce improved realistic simulations of any shelf model to date. Such models could be used to gain a better understanding of the time and space scales of biochemical processes on the shelf and thus lead to a better understanding of the importance of shelves in the global ocean carbon cycle.

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References


