sectors: Celtic – W Ireland – W Scotland – N Scotland – (North Sea) – Norway. However, phosphorus from rivers is significant in Channel and Irish Sea budgets. As losses are small, overall net export to the ocean is inferred. Nitrogen input from rivers and atmosphere is less than de-nitrification, and much less than exchanges with the open ocean or transfers between sectors. However, nitrogen from rivers is significant in Channel and Irish Sea budgets.

Rivers' and atmospheric input of nitrogen are broadly comparable with each other (Tables 5.2.3 and 5.2.6). However, their combination is less than denitrification and much less than the primary production requirement, even allowing for typical recycling factors. Exceptions are the Irish Sea and the Channel. The modelled Channel budget shows a large recycled element in phytoplankton uptake. In-flux from the Celtic Sea is important off W Ireland and in-flux from W Scotland is important off N Scotland. Off Norway, production appears to be small compared with what nutrient in-fluxes could support. Elsewhere, production is fuelled primarily by nutrients from the open ocean and distinguishes different oceanic waters off Iceland.

There is a general ranking of (organic carbon flux to the sea bed) << (atmospheric input) << (primary production (except off East Greenland)) << (dissolved organic (and inorganic) carbon flows between sectors). The lack of significant sequestration in sediments implies a net export of organic carbon.

5.2.7 *Gaps and Prospects*

Several limitations need to be overcome in order to close shelf-sector budgets in general. Open-sea flux measurements have tended to estimate vertical rather than lateral exchanges. Direct measurement of net fluxes is impractical; flows are two-way and complex, and differences of nutrient or carbon species concentrations are small. Even vertical exchanges involve fluxes to and from the bed with varied character (steady deposition, erosion events), and net benthic fluxes are also difficult to measure directly. Processes also vary in space, e.g. desorption of phosphate from patchy SPM, and denitrification correlated with sediment organic carbon. River inputs are strongly modified by processes in estuaries, so that riverine fluxes are not reliable in application to the shelf sea. Groundwater contributions have been ignored for lack of data.

The previous budgets vary in character, with most not corresponding to the LOICZ marginal-sea scheme. While Table 5.2.3 follows the elements of the scheme, we have not followed the methodology because inference of ocean–shelf exchange from salinity is uncertain; fresh-water inputs are relatively small and shelf areas are too large for homogeneity; emphasis is thrown on other ways of estimating ocean–shelf exchanges. Many gaps in the data needed for budgeting appear in Table 5.2.3, highlighting a need for more systematic measurement of constituents.

Flux quantification, integrating over the complex processes and domains, needs numerical models. These exist and show promise but have yet to be widely applied. Several of the budgets herein use POLCOMS applied to the NW European shelf and adjacent Atlantic (Proctor et al., 2003a). Model runs were also used by Thomas et al. (2005) in discussing their budget for the North Sea (which interacts with three of our sectors). Closed budgets are guaranteed if models are correctly formulated. However, when run for a finite period (just 1–3 years here), the final stock of any constituent may differ from the initial stock. Such a change may indeed be correct and challenges the implicit concept of a steady state in some budgets. Increases in computing power allow models covering a typical shelf sector here to be run for decades with useful resolution O(5 km or finer) and ecosystem representation.

5.3 Northwest Atlantic Continental Shelf[3]

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[3] We gratefully acknowledge Maura A. Thomas at the University of Maine for locating references, reducing data and preparing most of the graphics used in this review. We also thank two anonymous reviewers for their excellent suggestions for improving an earlier draft. Finally, we acknowledge that much of the content of this paper has called our recollections of numerous conversations with many of our colleagues over the years; we apologize if we have in any way misrepresented their work or insights they have shared with us.

5.3.1 Introduction

The region covered by this discussion includes primarily the continental shelf waters of the North Atlantic Ocean between the Nova Scotia and the New York Bight, with limited discussion of waters to the north, including the Labrador Sea and the Grand Banks of Newfoundland (Fig. 5.3.1). We have placed a disproportionate emphasis on the Gulf of Maine and Georges Bank region, which reflects differences in availability of published information, and we focus on nitrogen dynamics in relation to primary productivity, much of which is taken from Townsend (1997, 1998) and Townsend et al. (2006).

The continental shelves of the Northwest Atlantic Ocean are broad and extend more than 200 km offshore in some locations (Fig. 5.3.1). They connect with the open ocean by several deep channels, including the Gully (east of Sable Island on the Nova Scotian Shelf), the Laurentian Channel (connecting the Gulf of St. Lawrence), the Northeast Channel (connecting the Gulf of Maine) and the Hudson Channel (connecting the Hudson River to the Hudson Canyon on the slope). Each of these channels provides for exchanges between deep and bottom shelf waters with continental slope waters. Several major rivers, especially the St. Lawrence River and the Hudson River, and many smaller rivers and streams collectively contribute significant volumes of freshwater and nutrients to shelf waters, but much of the fresh water input to these shelves comes from ice melt farther north which is advected to the south as part of a large-scale coastal current system (Beardsley et al., 1976; Chapman and Beardsley, 1989).

Generally speaking, coastal and shelf waters throughout the region exhibit relatively high biological productivity, much of which results from cross-isobath fluxes of nutrient-rich deep waters, which occurs year round, as well as winter convective mixing; anthropogenic nutrient sources to shelf waters become significant south of the New England shelf region, coming primarily from rivers flowing through urban areas. On the shelves, winter mixing annually replenishes surface nutrient concentrations, setting the stage for important winter–spring plankton blooms that often begin at cold water temperatures ($<1.0°$C), which facilitate efficient benthic–pelagic coupling. The spring bloom period is followed by strong vertical stratification that persists throughout the summer and early fall, established by both freshwater additions and vernal

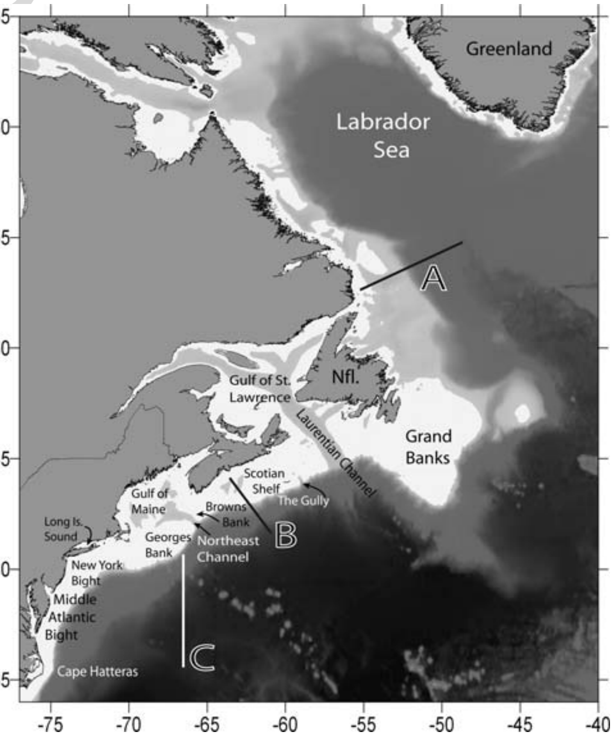

Fig. 5.3.1 Map of the Northwest Atlantic continental shelf region showing the major features referred to in the text. Transects A, B and C are labelled (A coloured version of this figure is available on-line. See Appendix C.)

warming. Patterns of vertical stratification are punctuated throughout much of the region by areas of vertical mixing by tides, which are amplified by local resonant effects and which further stimulate nutrient fluxes that promote high levels of plankton production. In addition, estuarine systems such as the St. Lawrence and Hudson River estuaries, and the Delaware, Narragansett and Chesapeake Bays are highly productive.

Interannual variability in nutrient fluxes to these shelves, and the potential primary productivity that results, is modulated by many processes, but the principal ones are the following: (1) the type of deep-water masses (slope water) that intrude onto the shelves and (2) the degree of winter convective mixing. Each can be shown to have an important potential effect on primary productivity in the Gulf of Maine, for example. Carbon and nitrogen budgets for the region are also controlled in part by local water-column nitrification. We discuss here the relationships among new and recycled primary production, export production and internal nitrification, in the context of the larger-scale and regional oceanography.

5.3.2 Oceanographic Setting

5.3.2.1 Circulation and Water Masses

Much of the following overview of the physical oceanography of the region is taken from the review by Townsend et al. (2006); we have limited this discussion to major features as they affect waters southwest of Cabot Straight (between Newfoundland and Nova Scotia).

Water properties on the Northwest Atlantic continental shelf are influenced both by the Gulf Stream and processes occurring farther to the north (Loder et al., 1998). The major current systems (Fig. 5.3.2) include the Labrador Current, the Gulf Stream, and their Shelf and Slope Water current counterparts, which have been described by Csanady and Hamilton (1988) and Chapman and Beardsley (1989). A coastal current system extends throughout the region, flowing equatorward from Newfoundland to the Middle Atlantic Bight (Beardsley et al., 1976). The Labrador Current itself extends from Baffin Island in

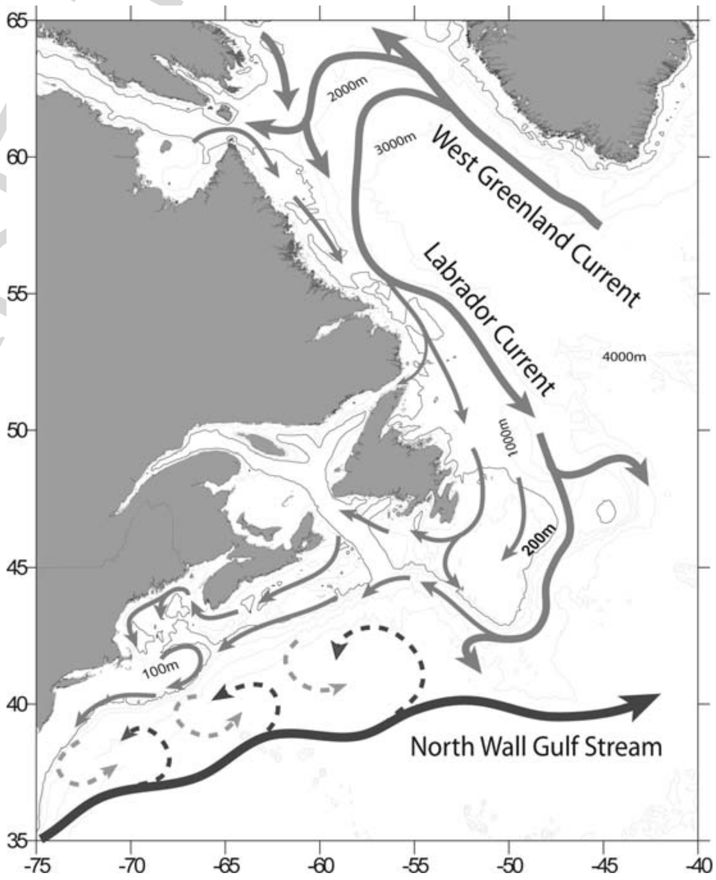

Fig. 5.3.2 Major current systems in the region. *Dashed arrows* indicate area of mixing between shelf–slope waters and Gulf Stream waters. Bathymetric contours 100, 200, 1000, 2000, 3000 and 4000 m are given, with the 200 m isobath indicated by the *heavier line* (A coloured version of this figure is available on-line. See Appendix C.)

the Canadian Arctic south to the area of the Grand Banks where it meets and mixes with the Gulf Stream and North Atlantic Current. The Labrador Current is a cold, relatively fresh, buoyancy-driven coastal current that begins on the west coast of Greenland, with much of its freshwater deriving from Greenland glacial melt (Chapman and Beardsley, 1989). Winter cooling and additional freshening by Arctic rivers and ice melt contribute to the Labrador Current's water properties. This cold and fresh mixture of shelf and slope waters continues to the Nova Scotian Shelf, some of which spreads across the shelf as deep-water flows, and, passing through the Laurentian Channel, mixes with waters of the Gulf of St. Lawrence. Some also continues to the mouth of the Northeast Channel and enters the Gulf of Maine, although the extent of this penetration so far south is highly variable from year to year. An additional freshwater flux, from the St. Lawrence River, is added to shelf waters west of Cabot Strait. The general flow of shelf waters continues south as Middle Atlantic Bight water to Cape Hatteras where the shelf width becomes constricted, and mixing with the slope waters and the Gulf Stream become important (Churchill and Berger, 1998).

Each spring along the shelf edges off Nova Scotia, Georges Bank and the Middle Atlantic Bight, a seasonal pycnocline develops that isolates below it a relatively cold water mass, known as "the cold pool" (Bigelow, 1933; Houghton et al., 1982; Flagg et al., 1998; Bignami and Hopkins, 2003). Cold pool waters flow along the shelf to the southwest, which results in some of the coolest bottom temperatures in the southern Middle Atlantic Bight occurring in the summer rather than in winter; those waters also bring additional nutrients to the southern Middle Atlantic Bight from the northern Middle Atlantic Bight. Cold pool waters subsequently experience a narrowing of the shelf as they flow towards Cape Hatteras, where anticyclonic eddies form and result in the loss of those waters beyond the shelf break. Flagg (1998) point out that if cold pool waters accumulate the products of biological production on the shelf (e.g. Falkowski et al., 1988), those losses of shelf waters could represent export of organic carbon from the shelf. Similarly, a cold intermediate water mass forms on the Nova Scotian Shelf and in the Gulf of Maine (Hopkins and Garfield, 1979).

The Gulf Stream, which is the most dominant physical feature in the northwestern Atlantic Ocean, impacts the dynamics of the adjacent continental shelf and slope waters. Its offshore position ranges from as close as 30 km from the coast of Cape Hatteras to much greater distances offshore as it flows north and east. Interactions between the Gulf Stream and shelf/slope waters take the form of Gulf Stream eddies which can entrain shelf waters bringing them and their biogenic materials off the shelf (e.g. Ryan et al., 2001).

5.3.3 Shelf Subregions

5.3.3.1 The Grand Banks

The shallow waters of the Grand Banks of Newfoundland are affected by the relatively fresh, cold water currents from the north. Despite relatively weak tidal mixing on the Banks as compared with shelves to the west (e.g. the Gulf of Maine and Georges Bank), the Grand Banks are nonetheless considered to be highly biologically productive and have supported a rich fishery for centuries. There is a relatively scant body of literature on plankton production dynamics, and available information indicates that primary production is actually lower than one might expect. For example, Prasad and Haedrich (1993) reported rates of primary production on the Grand Banks based on satellite ocean colour measurements during the spring bloom period (April and May) to be on the order of $1{,}000\,\mathrm{mgC\,m^{-2}\,d^{-1}}$, and about $300\,\mathrm{mgC\,m^{-2}\,d^{-1}}$ the rest of the year, giving an annual primary production rate of about $200\,\mathrm{gC\,m^{-2}\,yr^{-1}}$. Anderson and Gardner (1986) presented hydrographic sections across the southern portion of the Banks during the month of May, which indicated that nutrients were depleted from top to bottom over the shallow (50 m) Bank, and that the Bank is vertically well stratified this time of year (pyncnocline at ca. 20 m). We assume, therefore, that cross-shelf fluxes of deep-water nutrients to the Grand Banks, of unknown magnitude, likely set the upper limit to new primary production.

5.3.3.2 The Nova Scotian Shelf

The relatively broad Nova Scotian Shelf is more tidally energetic than the Grand Banks. Tidal ranges increase from east to west across the Scotian Shelf (some of the highest tides in the world are found in the Gulf of Maine at the upper reaches of the Bay of Fundy).

Maximum tidal current speeds on the southwest Nova Scotian Shelf and over Browns Bank are on the order of 100 cm s^{-1} and produce significant vertical mixing of the water column (Garrett et al., 1978), and as a consequence, the surface shelf waters off southwest Nova Scotia are noticeably colder than surrounding areas during the warmer months. Vertical mixing by tides in combination with the flow of cold Scotian Shelf water from the east, plus localized upwelling, maintain cold temperatures here year round (Lauzier, 1967; Garrett and Loucks, 1976; Smith, 1983) and drive significant nutrient fluxes onto the shelf (Fournier et al., 1984). Water properties on the Scotian Shelf reflect a mixture of waters from the Gulf of St. Lawrence and the Labrador Current, as well as deeper continental slope waters from beyond the shelf edge (Loder et al., 1998). During the warmer months, the shelf waters exhibit three distinct layers: a cold intermediate water layer is trapped beneath the seasonal thermocline and above warmer, but saltier bottom waters that intrude from beyond the shelf edge. This cold intermediate-depth water layer constitutes the origin of the "cold pool" (discussed earlier) that extends along the shelf edge to the Middle Atlantic Bight.

The Scotian Shelf proper, between the Laurentian Channel and the Northeast Channel, has long been known to be biologically productive with respect to fisheries (Brown et al., 1975). Fournier et al. (1977) reported that phytoplankton biomass and primary production on the shelf varied with position offshore along a transect off Halifax, N.S., being highest about 90 km offshore, in association with the shelf break front. They estimated annually averaged primary production rates on the shelf to be 96 gC m^{-2} yr^{-1}. Fournier et al. (1977) also showed that about 80% of the nitrogen requirements of the shelf phytoplankton could be accounted for by heterotrophic recycling, and that the remaining nitrogen is likely delivered to the shelf by fluxes of slope waters from beyond the shelf break. Thus, the *f-ratio* was equal to 0.2[4]. They also showed that the deep basins on the Scotian Shelf are not directly dependent on a cross-frontal flux of nutrient-rich slope waters, since the deeper shelf waters are supplied with slope water that flows in through deep channels and which is subsequently mixed upwards by internal waves and tidal mixing. Fournier et al. (1979) showed that elevated primary production in winter can result episodically when there is a decrease in the steepness of the isopycnals at the shelf break front, which reduces the mixed layer depth, thus increasing the light environment in already nutrient-rich winter waters; such events can increase annual primary production by about 25%. Fournier and his co-workers went on to show that a similar frontal phenomenon is responsible for enhanced primary production on the southwest Scotian Shelf, in this case as a result of a tidal mixing front (Fournier et al., 1984).

5.3.3.3 The Gulf of Maine

The Gulf of Maine covers a broad area between Cape Cod, Massachusetts and southwestern Nova Scotia. It is effectively isolated from the open Northwest Atlantic Ocean by Georges and Browns Banks, making it a semi-enclosed continental shelf sea. The exchange of waters between the Gulf and the North Atlantic below depths of about 100 m is confined to the Northeast Channel, a >200-m deep channel that separates Georges Bank from Browns Bank and the Nova Scotian Shelf. The Northeast Channel connects with three major deep basins in the Gulf: Georges, Jordan and Wilkinson, all isolated one from another below a depth of 200 m. These characteristics of deep basins and limited deep-water exchanges with the open Atlantic, in concert with other important features and processes, control the general oceanography of the Gulf, including nutrient fluxes and biological productivity. The more important of these features and processes are vertical mixing by tides (Garrett et al., 1978); the seasonal cycle of heating and cooling, which leads to winter convection and vertical stratification in summer; pressure gradients from density contrasts set up by deep-water inflows and lower salinity waters (Brooks, 1985); and influxes of the cold, but fresher waters associated with Scotian Shelf Water (Smith, 1983; Mountain, 2004).

Tides in the Gulf of Maine decrease from northeast to southwest, creating a gradient in tidal mixing (e.g.

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[4] The *f-ratio* is defined as a ratio of nitrate uptake by phytoplankton to total nitrogenous uptake; e.g. $[NO_3^-]/([NO_3^-] + [NH_4^+]$. N*ew primary production* is defined as that resulting from the uptake of NO_3^- and *recycled primary production* is defined as that resulting from the uptake of NH_4^+. The parameter R is also sometimes used to differentiate new and recycled primary production, where R = (potential new primary production)/(total measured primary production).

Loder and Greenberg, 1986) which influences the spatial pattern of hydrographic structure in the Gulf, nutrient delivery to the euphotic zone, benthic–pelagic coupling (Townsend et al., 1992a), and, ultimately, total biological productivity. Satellite images of sea surface temperatures in the interior Gulf of Maine during the warmer months of the year routinely exhibit distinct thermal fronts separating the cold, tidally mixed surface waters of the eastern Gulf from the warmer, vertically stratified waters of the west (Townsend et al., 1987). Tidal mixing, winter convection, influxes of fresher waters from rivers and Scotian Shelf Water and influxes of dense Slope Waters at depth through the Northeast Channel, combine to create three distinct water masses (Hopkins and Garfield, 1979) similar to Scotian Shelf Waters and the cold pool just discussed.

The mean circulation in the Gulf of Maine–Georges Bank region is generally cyclonic, forced by density contrasts between dense slope waters in the offshore basins, and less dense coastal waters freshened by discharges from the major river systems: The St. John, Penobscot, Kennebec/Androscoggin and Merrimac Rivers (Brooks, 1985; Xue et al., 2000). River discharges account for about one half the freshwater budget for the Gulf of Maine; the remainder enters as low salinity Scotian Shelf Waters (Smith, 1983). Beardsley et al. (1997) and Lynch et al. (1997) described the surface circulation in the Gulf as a buoyancy-driven coastal current system flowing counterclockwise around the edges. Pettigrew et al. (1998) describe the Maine coastal current system as beginning with the Eastern Maine Coastal Current (EMCC; Townsend et al., 1987; Brooks and Townsend, 1989), a cold band of tidally mixed water that originates on the southwest Nova Scotian shelf, crosses the mouth of the Bay of Fundy and continues along the coast of eastern Maine to Penobscot Bay on the Maine coast. Before the EMCC reaches Penobscot Bay, it is often directed away from the coastline and out over the central Gulf of Maine as a plume-like feature of colder water clearly visible in satellite images of sea surface temperature. The exact trajectory of the EMCC is variable (Brooks and Townsend, 1989; Bisagni et al., 1996; Lynch et al., 1997; Pettigrew et al., 1998).

The coastal current system in the Gulf of Maine is important to the overall nutrient budget and biological oceanography of the Gulf (Townsend et al., 1987; Brooks and Townsend, 1989; Townsend, 1998). Vertical nutrient fluxes driven by vigorous tidal mixing at the upstream end of the EMCC in the northeastern Gulf create summertime surface nitrate concentrations in excess of 7 μM NO_3^- (Townsend et al., 1987). The EMCC and its offshore plume feature of nutrient-rich water are important to the species composition and abundance of plankton in the offshore waters of the Gulf; the magnitude of this EMCC-plume feature is significant: approximately 44% of the inorganic nutrient flux (to surface waters) required to meet estimated levels of new primary production for the entire Gulf of Maine can be attributed to the EMCC-plume system (Townsend et al., 1987).

The Gulf of Maine's offshore waters, which are least productive, average about $270\,\mathrm{gC\,m^{-2}\,yr^{-l}}$ (O'Reilly and Busch, 1984; O'Reilly et al., 1987). The major source of nutrients to the Gulf is the influx of deep Slope Water through the Northeast Channel (Ramp et al., 1985; Schlitz and Cohen, 1984; Townsend, 1991; Townsend, 1998). Those high-nutrient waters make their way to the surface by way of vertical mixing by tides and upwelling in the eastern Gulf and on the southwest Nova Scotian Shelf; fluxes via the EMCC-plume system discussed above; vertical fluxes across the seasonal pycnocline; and, winter convection, which supplies the standing stock of nutrients that fuels the spring phytoplankton bloom (Townsend, 1991). Additional vertical nutrient fluxes throughout much of the year in offshore waters are driven by processes associated with internal waves (Brickley, 2000).

The extent of winter convection in the Gulf of Maine depends on winter weather conditions and interannual variations in surface water salinity, but convective mixing is generally limited to a depth corresponding to the top of the dense bottom water, of Slope Water origin (Brown and Beardsley, 1978; discussed further below). Seasonal heating of the surface layers then traps a cold intermediate water layer beneath the seasonal thermocline and above the warmer, but saltier (and hence denser) bottom waters, thus creating three distinct water types, termed Maine Surface Water, Maine Intermediate Water and Maine Bottom Water (Hopkins and Garfield, 1979). These three layers are most obvious over the deeper offshore Gulf waters, away from tidally mixed coastal waters; they become eroded by tides throughout the summer and fall, disappearing first from the eastern Gulf of Maine.

Origins of Gulf of Maine water masses are, first, the buoyant, relatively fresh and cold Scotian Shelf Water that enters in the surface layer around Cape Sable, Nova Scotia (Smith, 1983), and, second, higher salinity, warmer Slope Water that enters along the bottom through the Northeast Channel (Ramp et al., 1985). It is the deep inflow of Slope Water that is the primary source of inorganic nutrients to the Gulf, as just discussed, but the surface inflow of buoyant Scotian Shelf Water is important in winter convective mixing, which is the dominant mechanism in the Gulf that brings those nutrients to the surface (Townsend, 1998). Each of these inflows is highly variable among years, as is winter weather and the degree of winter convective mixing (Mountain, 2004). For example, in the late 1970s the mean Scotian Shelf Water inflow was half that of the 1990s (Smith et al., 2001). Thus, surface salinity in the Gulf varies accordingly and affects the degree of winter convection; e.g. bottom water temperatures in Wilkinson Basin from January through March in the 1980s were cooler than during the 1990s (Mountain, 2004). An example of winter convective mixing is given in Fig. 5.3.3 for the winter of 2005. Note in that figure how mixing is confined to the western Gulf of Maine, away from the freshest surface waters, influenced by Scotian Shelf Water in the eastern Gulf and closest to the North American continent. In this case, vertical mixing extended to about 135 m.

The deep Slope Water residing on the Nova Scotian Shelf and in the Gulf of Maine also varies in its properties and reflects variations in the relative contributions of two Slope Water masses in the Northwest Atlantic region: Warm Slope Water, which is influenced by the Gulf Stream, and Labrador Slope Water, which is influenced by water from the Labrador Sea (Gatien, 1976). The Labrador Slope Water is colder, fresher and generally has lower (∼50%) concentrations of dissolved inorganic nitrogen than the Warm Slope Water (Townsend et al., 2006). During low North Atlantic Oscillation (NAO) conditions, Labrador Slope Water tends to extend farther southwestwards along the edge of the North America continental shelf and thus can enter the Gulf of Maine through the Northeast Channel. This phenomenon of NAO lows and influxes of Labrador Slope Water into the Gulf occurred persistently during the 1960s, resulting in colder bottom water conditions in the Gulf (Petrie and Drinkwater, 1993). It occurred again in response to the sharp drop in the NAO in 1996 (Pershing et al., 2001)

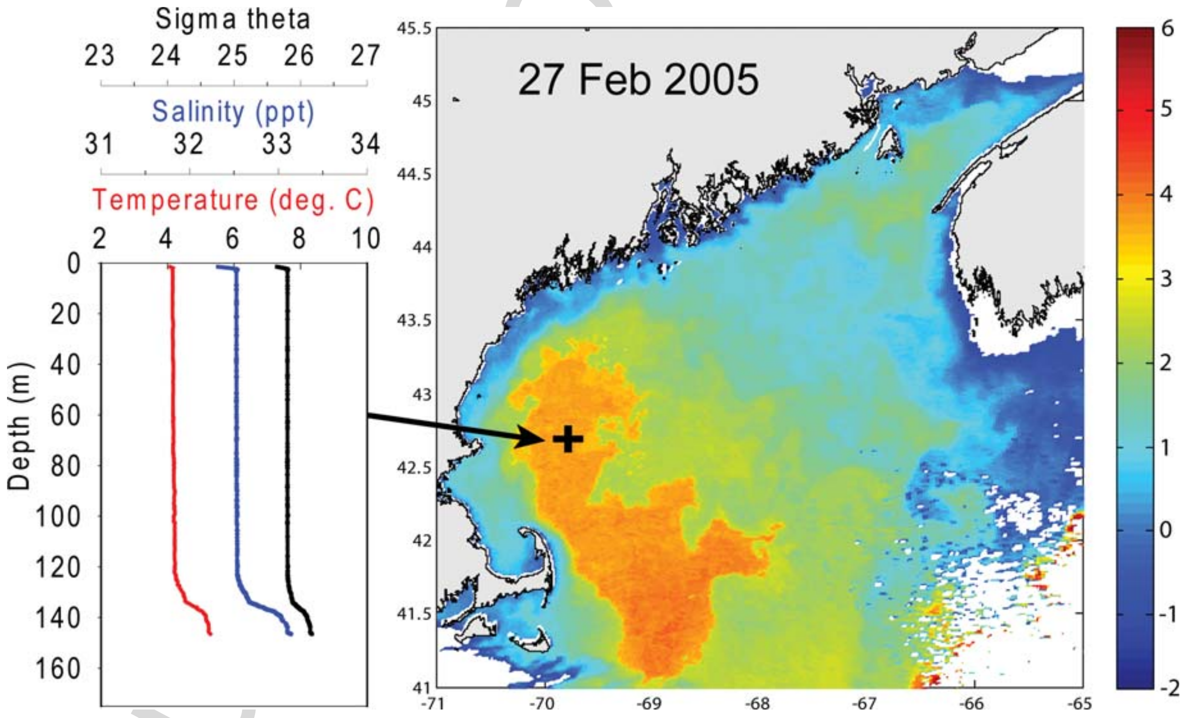

Fig. 5.3.3 Vertical profiles of T, S and sigma–theta on 5 March 2005 at station indicted on satellite image of sea surface temperature on 27 February 2005 (with colour bar in °C)

with Labrador Slope Water entering the Gulf during 1998 after an approximately 2-year transit from the Labrador Sea; those deep waters were significantly lower in dissolved inorganic nitrogen than Warm Slope Water that enters in other years (Thomas et al., 2003; Fig. 5.3.4).

Differences in the nutrient loads of these different types of slope water can be seen in Fig. 5.3.5, which presents vertical cross sections at three locations: off southern Newfoundland and into the Labrador Sea; across the Scotian Shelf; and across the continental slope and into the Gulf Stream south of Georges Bank (see Fig. 5.3.1). Those data show relatively low nitrate (<18 μM) and silicate (<11 μM) in the Labrador Sea, intermediate concentrations of nitrate and silicate in slope waters off Nova Scotia and relatively high concentrations of each in slope waters off Georges Bank (nitrate >25 μM; silicate >15 μM). These nutrient loads apparently reflect the relative ages of the deeper water masses, with recently formed Labrador Sea slope waters reflecting low nutrient concentrations of the surface waters from which they originated, while older slope waters associated with the Gulf Stream having accumulated over time regenerated nutrients from sinking organic matter (e.g. Broecker, 1974).

Source water nutrient inputs to the surface ultimately control the absolute amount of new primary production that can be supported in the Gulf of Maine (Thomas et al., 2003). While nitrate concentrations are highest in Warm Slope Water, silicate concentrations in both water masses, are not as variable, and in general, nitrate concentrations are greater than silicate. Thus silicate, not nitrate, would limit the spring bloom in the Gulf of Maine, which is dominated by diatoms (diatoms take up silicate and nitrate in approximately equal molar proportions). On the other hand, nearer the coast and the influence of riverine sources of silicate (Schoudel (1996) reported >200 μM silicate in Maine rivers), the bloom would be limited first by nitrate (Townsend et al., 2005).

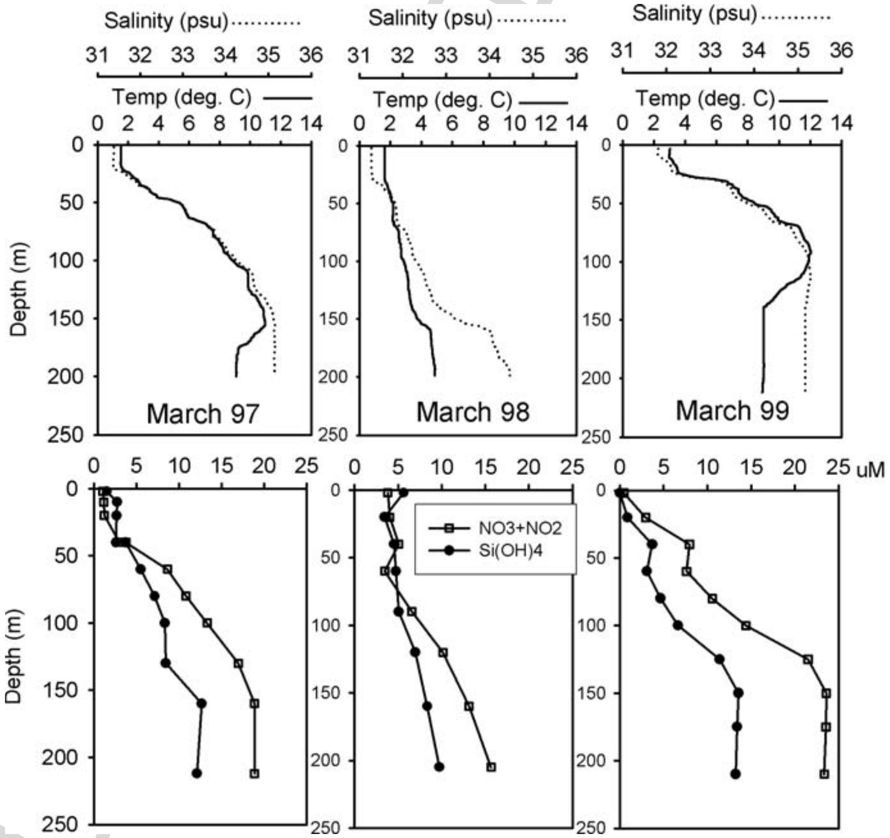

Fig. 5.3.4 Vertical profiles of T, S, nitrate+nitrite and silicate in March of 1997, 1998 and 1999 at a single station in the mouth of the Northeast Channel

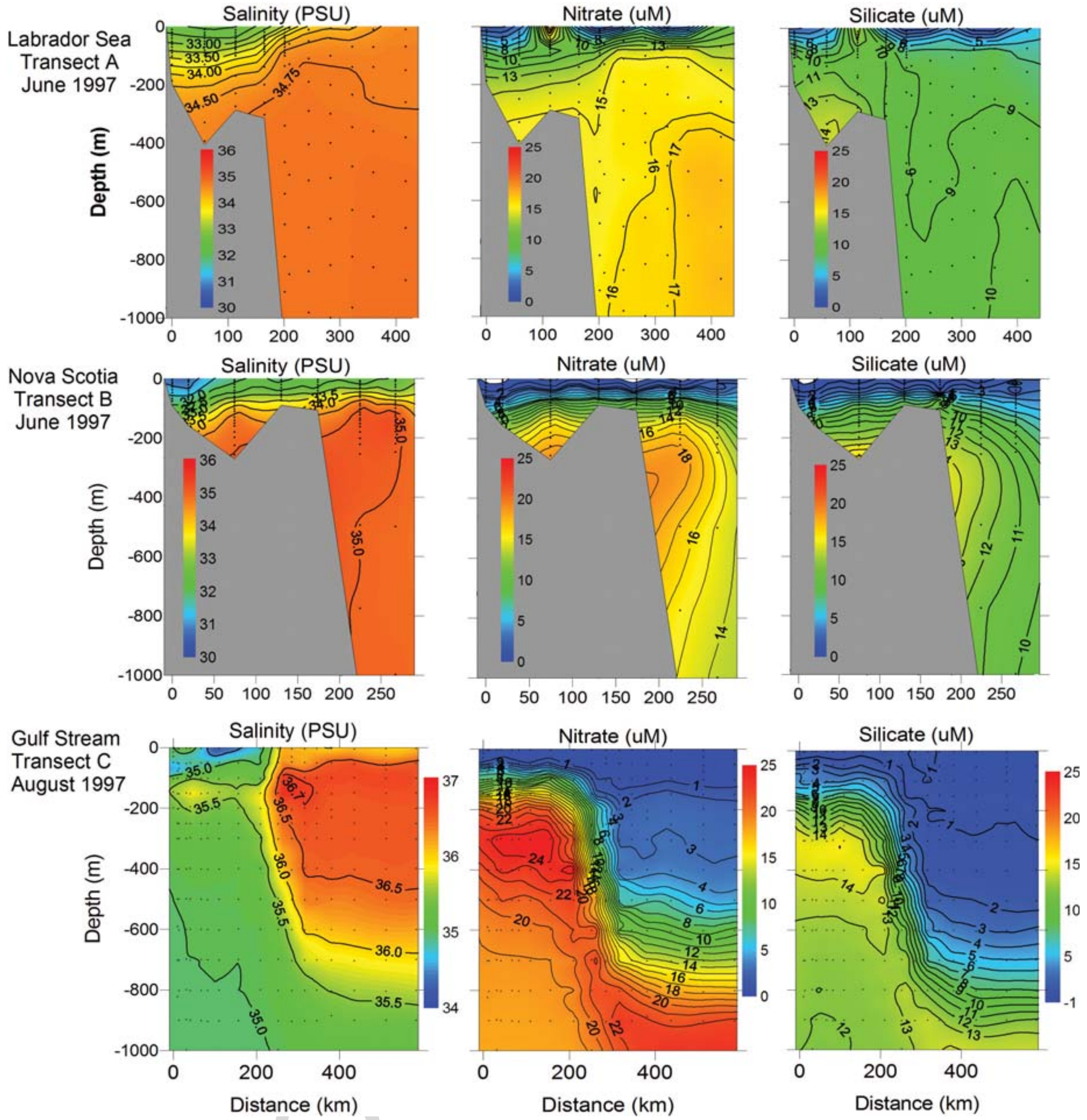

Fig. 5.3.5 Vertical sections of salinity, nitrate and silicate in the top 1000 m along Transects A, B and C in Fig. 5.3.1. Transect A is in the Labrador Sea; B is across the Scotian Shelf; C is off Georges Bank to the Gulf Stream (see Fig. 5.3.1). Data source: World Ocean Circulation Experiment ("eWOCE – Electronic Atlas of WOCE Data", at http://www.ewoce.org/)

5.3.3.4 Georges Bank

Georges Bank is a shallow submarine bank sitting at the mouth of the Gulf of Maine. It is smaller than the Grand Banks, and generally considered to be biologically productive (reviewed in Backus, 1987). It is dominated by tidal mixing throughout much of its area, which is most pronounced in the central shallow region on the top of the Bank, inside the 60 m isobath, where the water column is kept vertically well mixed throughout the year. Surface currents are anticyclonic, and flow clockwise around the Bank (see Loder, 1980; Butman et al., 1982; Butman and Beardsley, 1987; Limeburner and Beardsley, 1996; Lynch and

Namie, 1993; Namie, 1996; Chen et al., 2001 and others; see especially recent results of the U.S. GLOBEC program [Global Ecosystem Dynamics], much of which is presented in Wiebe and Beardsley, 1996, and Wiebe et al., 2001).

Primary productivity of Georges Bank is high, with rates reported to exceed 400 $\mathrm{gC\,m^{-2}\,yr^{-1}}$ in the central portion of the Bank (O'Reilly et al., 1987). The production cycle is highly seasonal, marked by a pronounced late winter–early spring phytoplankton bloom (Riley, 1941; Walsh et al., 1987; Cura, 1987; Townsend and Pettigrew, 1997; Townsend and Thomas, 2001, 2002), which can begin as early as January (Townsend and Thomas, 2001, 2002) over the central shallow (<60 m) regions, where bathymetry determines the base of the upper mixed layer (Townsend et al., 1994). The bloom is triggered once the critical depth exceeds the water depth, which can occur over the shallow portions of the Bank even during winter under conditions of reduced cloud cover (Riley, 1941). The winter–spring bloom on Georges Bank is dominated by diatoms (Cura, 1987; Kemper, 2000; Townsend and Thomas, 2001, 2002) and depleted silicate limits primary production as early as February. It is only after silicate has already become depleted that dissolved inorganic nitrogen concentrations are reduced to levels that would limit phytoplankton production, which usually occurs in April (Townsend and Thomas, 2001, 2002). For the remainder of the year, primary production is thought to be fuelled largely by recycled nitrogen (Horne et al., 1989).

Cross-isobath mixing and nutrient injections onto Georges Bank appear to be most important along the Northern Flank of the Bank (Pastuszak et al., 1982; Townsend and Pettigrew, 1997; Houghton and Ho, 2001) where nutrient-rich slope water resides nearby, having entered Georges Basin via the Northeast Channel. This pattern often leads to greater phytoplankton biomass accumulations on the Northeast Peak (Cura, 1987). Cross-isobath nutrient fluxes around the remainder of the Bank, especially gently sloping southern flank where nutrient gradients are weaker, have farther to go to reach the shallower waters of the central Bank and much of that nutrient flux is utilized by phytoplankton in a subsurface chlorophyll maximum layer (Townsend and Pettigrew, 1997).

Loder et al. (1992) reported higher rates of new primary production along the northern edges of Georges Bank, in the vicinity of tidal mixing fronts and upwelling (e.g. Houghton and Ho, 2001), measured using ^{15}N tracer techniques to arrive at *f-ratios* along a transect from deep waters north of the Bank to the tidally well-mixed waters on the Northeast Peak. Loder et al. (1992) reported *f-ratios* of 0.7 in frontal regions, where nitrate is mixed upwards and onto the Bank, whereas *f-ratios* on the top of the Bank were on the order of 0.1–0.2. Thus, during the warmer (stratified) months, cross-isobath nitrate fluxes appear to support nitrogen requirements of about 70% of primary production along the Bank's edges, while recycled ammonium supports 80–90% of primary production on the Bank itself. We return to this discussion in Sect. 5.3.8.

5.3.3.5 Southern New England and the New York/Middle Atlantic Bights

The continental shelf region west of Georges Bank forms a comma-shaped system that tapers in width and curves from an east–west orientation off southern New England to north–south orientation at Cape Hatteras. This region includes Nantucket Shoals, Long Island Sound, the New York Bight and the Delaware, Narragansett and Chesapeake Bays.

Both Nantucket Shoals and Long Island Sound exhibit high biological productivity, but for different reasons. The shallow Nantucket Shoals (<50 m) is tidally well mixed, and apparently supplied with new nutrients that upwell in the apex of the Great South Channel of the Gulf of Maine, between Cape Cod, Massachusetts and Georges Bank. Satellite images of summer sea surface temperature show that this region is consistently colder than surrounding waters, which is strongly suggestive of upwelling of cold, subsurface Gulf of Maine waters. Durbin et al. (1995) showed that during June, deep Gulf of Maine waters upwell onto the Shoals, producing relatively high concentrations of inorganic nutrients ($\mathrm{NO_3}^- > 5\ \mu\mathrm{M}$). Few of their stations extended onto the Shoals, however, and we are unaware of any published accounts of more detailed nutrient measurements in this area; however, satellite ocean colour imagery shows consistently high phytoplankton chlorophyll on the Shoals throughout the warmer months (Thomas et al., 2003).

Long Island Sound is a shallow (average depth 20 m) temperate estuary with salinity ranging between 23 and 31 psu (Capriulo et al., 2002; Bogden and

O'Donnell, 1998). Capriulo et al. (2002) provided a general overview of the plankton of the Sound as an update of the pioneering work of Gordon Riley and his co-workers (e.g. Riley et al., 1956) who presented the first comprehensive study of the Sound's waters and benthos. The primary productivity of Long Island Sound is very high, approaching 470 gC m^{-2} yr^{-1} (Riley et al., 1956), much of which is driven by anthropogenic nutrient additions from the surrounding populated area.

South of Long Island, the shelf waters of the New York Bight, in the northern portion of the Middle Atlantic Bight, are more biologically productive than the Gulf of Maine, but less productive than Georges Bank (O'Reilly et al., 1987). The system is characterized by a combination of estuarine-like physical processes (from the Hudson River discharge), as well as cross-shelf interactions that promote nutrient fluxes and high rates of biological production (Falkowski et al., 1980).

Two large estuarine systems dominate the near shore coastal environment of the Middle Atlantic Bight: the Delaware and Chesapeake Bays. Biological productivity in each is high, and each has experienced new and emerging problems related to anthropogenic nutrient enrichment (see reviews in Sharp et al. (1982) and Magnien et al. (1992)).

The biological productivity of the New York Bight and Middle Atlantic Bight is relatively high and is comparable to waters of the Gulf of Maine and Georges Bank (O'Reilly et al., 1987); that productivity is driven primarily by cross-frontal mixing events and nutrient fluxes between slope and shelf waters (Walsh et al., 1978; Marra et al., 1990). Walsh et al. (1978) showed that wind-driven upwelling from storm events can provide one-third of the nitrate necessary to meet the primary production demand over an annual cycle. They also reported that rates of primary production in summer were an order of magnitude greater than 60–70 km offshore in the vicinity of the shelf–slope front, which is similar to that reported on the Scotian Shelf, and are consistent with the map of primary productivity produced by J. O'Reilly and his co-workers (O'Reilly and Busch, 1984; O'Reilly et al., 1987; O'Reilly and Zetlin, 1998). The general oceanography of the Middle Atlantic Bight shelf waters was reviewed in Gross (1976) and was the focus of major research programmes: SEEP I and SEEP II (Shelf Edge Exchange Programs), which were concerned with the exchanges of carbon and other biogenic materials between the continental shelves and the deep ocean (Walsh et al., 1988; Biscaye et al., 1994). Still more continues to be learned about the oceanography of the shelf waters of the Middle Atlantic Bight as a result of recent interdisciplinary research initiatives, especially the Ocean Margins Program (e.g. see Bauer et al., 2002).

5.3.4 New Production and Export Production

In this review we distinguish between new and recycled primary production (sensu Dugdale and Goering, 1967, and Eppley and Peterson, 1979). In the case of Georges Bank, it was shown that despite the high rates of total primary production over the majority of the Bank (O'Reilly et al., 1987), the particulate nitrogen formed by the phytoplankton is principally the result of recycled primary production. Thus, fluxes of new nitrogen (principally nitrate) delivered to the Bank from deeper waters around its edges are low as compared with the relatively high rates of total primary production averaged over the entire Bank (Loder and Platt, 1985; O'Reilly et al., 1987; Walsh et al., 1987). This prompted Townsend and Pettigrew (1997) to argue that secondary production is likely to be nitrogen limited. Lateral mixing across the Bank apparently limits new production to a "donut"-like region around the Bank's periphery (Townsend et al., 2006). Consequently, the centre of Georges Bank is an area of predominantly recycled primary production and an area where secondary production would be nitrogen limited. This trophodynamic context of new primary production is not quite the same as export primary production – each depends on whether one follows nitrogen or carbon.

Field measurements of new and recycled primary production in shelf waters, performed by the "traditional" method of following the uptake of ^{15}N-labeled NO_3^- and NH_4^+ into phytoplankton, arrive at a measure of new primary production based on the uptake of NO_3^- as a percentage of the total uptake (of both NO_3^- and NH_4^+). But some of the presumed "new" NO_3^- may not be truly new to the system; it could be "recycled" NO_3^- produced by water-column nitrification. This would mean that nitrogen budgets of shelf systems like the Gulf of Maine should perhaps consider only fluxes of new nitrogen that come from beyond the shelf's edges, rather than assuming that all NO_3^- in the system is so delivered. In addition, viewing new primary production in terms of nitrogen, we would need to take account of internal water-column nitrification in order to model the potential production of higher trophic-level biomass (which can be considered to be exported from the system). Viewing new primary production in terms of carbon is similarly complicated in that even recycled primary production could result in the export of carbon, both into higher trophic levels (as energy stores) and by the sinking of organic matter with greatly enriched C:N ratios. New and export primary production on the Northwest Atlantic shelf should also consider the role of silicate as a limiting nutrient, in that much of the organic material that settles to the benthos and deep waters is diatoms from the spring bloom. The bloom in the Gulf of Maine and Georges Bank, at least, and probably throughout the Northwest Atlantic Shelf region, is limited by silicate and not nitrogen. We know that the ratios NO_3^- and $Si(OH)_4$ vary with type of slope source waters, which in turn can influence the species composition of phytoplankton production (e.g. Townsend and Thomas, 2002).

5.3.5 The Spring Phytoplankton Bloom

The spring phytoplankton bloom is perhaps the single most important biological oceanographic phenomenon throughout the Northwest Atlantic continental shelf system in terms of particulate organic matter flux out of the surface waters. For example, Smetacek et al. (1978) showed that as much as half of the total annual input of organic matter to the benthos in shelf waters (in European shelf waters) may be the result of the spring bloom. Townsend and Cammen (1988) took that argument further and argued that delivery of fresh (unrespired) organic matter to the benthos in the Gulf of Maine would be significantly enhanced in years when the bloom begins at especially cold water temperatures, when rates of heterotrophic consumption and respiration would be reduced.

The stage becomes set for the spring phytoplankton bloom in the Gulf of Maine following the winter period of intense vertical mixing that recharges surface nitrate levels to concentrations on the order of 7–10 μM NO_3^-(Townsend et al., 1987). Conditions for the initiation and evolution of the spring phytoplankton bloom in the Gulf may conform to one of two scenarios: (1) it may be set up according to the classical Sverdrup (1953) model, whereby a thermocline develops in spring creating a shoaling upper mixed layer, which, in conjunction with deepening light penetration in spring, reaches a critical light intensity in the upper layer and net planktonic production commences. Riley (1957, 1967) suggested that the value of the critical light intensity that triggers the bloom is reached when the depth averaged, vertically integrated solar irradiance within the mixed layer increases to ca. 20.9 $W\,m^{-2}$; this has been corroborated by a number of subsequent reports (Gieskes and Kraay, 1975; Pingree et al., 1976; Hitchcock and Smayda, 1977; and others). (2) The spring bloom may develop in the absence of any vertical water-column stability at all (Townsend et al., 1992b, 1994), provided that wind speeds (for vertical mixing) are below a certain threshold, which in the Gulf of Maine is about 20 kts (Townsend et al., 1994). In such cases, phytoplankton bloom production may not exhaust the supply of nutrients prior to the development of the seasonal thermocline. Instead, there may be several spring bloom pulses, each interrupted by light limitation. Eventually the seasonal thermocline develops and nutrient exhaustion curtails bloom production. The possibility of a succession of episodic bloom means that the spring bloom may be significantly more productive, results in more export production and be more important to the carbon and nitrogen cycles, than has been previously assumed (Townsend et al., 2006).

5.3.6 Bottom Sediments

The bottom sediments play important roles in the functioning of Northwest Atlantic continental shelf ecosystems insofar as they are the repository for biogenic material settled from the water column. Thus, they serve as storage and processing sites for materials contained in the settling detritus, and they are sites of denitrification, as well as temporary or long-term storage of organic matter produced in the water column.

Shelf sediments in both the Gulf of Maine and along the Mid-Atlantic Bight areas are thought to be an important sink for oceanic nitrogen (Seitzinger and

Giblin, 1996). Christensen et al. (1987, 1996) showed that denitrification in the Gulf of Maine removes about one-fourth of the combined nitrogen delivered into the Gulf. Hopkinson et al. (2001) found that most denitrification in muddy sediments at 30–75m depth in the Gulf of Maine was supported by mineralization of detritus, and that it accounted for 60% of the total nitrogen remineralized. Laursen and Seitzinger (2002) obtained similar results at the 15 m deep, sandy, LEO-15 site off New Jersey, finding virtually all of the denitrification to result from coupled nitrification–denitrification of remineralized organic detritus. These shelf sediment denitrification rates are estimated to exceed that which could be accounted for from riverine and atmospheric inputs of nitrogen, which led Seitzinger and Giblin (1996) to suggest that about half of the nitrogen is derived from the ocean upwelling onto the shelves.

Two programmes, the Shelf Edge Exchange Program (SEEP) and Ocean Margin Program (OMP), reviewed by Walsh et al., 1988; Biscaye et al., 1994 and Verity et al., 2002, were based on observations by Walsh (1991) that organic matter did not appear to accumulate in the shelf sediments, and that it was more likely to be deposited in adjacent sediments on the continental slope. It was concluded from subsequent measurements and modelling efforts that while some fraction of shelf primary production was exported to the continental slope, it was only a very minor fraction of the total continental shelf primary production on the shelf (Biscaye et al., 1994; Verity et al., 2002; Charette et al., 2001). Export of organic carbon from the continental shelf is most likely driven by wave resuspension, which is capable of resuspending sediments as deep as 130 m (Churchill et al., 1994), but that organic carbon, mostly from sinking diatoms (Falkowski et al., 1994), resides in shelf sediments on the order several years prior to being resuspended and transported off the shelf (Bacon et al., 1994).

5.3.7 A Nitrogen Budget for the Gulf of Maine

Because of the greater availability of data for the Gulf of Maine, it can be instructive to examine how nitrogen is cycled in the Gulf of Maine and where data may be lacking or incomplete to do a similar calculation for the wider Northwest Atlantic shelf region. The first nitrogen budget for the Gulf of Maine was published by Schlitz and Cohen (1984), which emphasized the importance of Slope Water fluxes into the Gulf through the Northeast Channel. Based on Schlitz and Cohen's work, Townsend (1991) assessed the major oceanographic processes that affect nitrogen fluxes in the Gulf, and later, Christensen et al. (1996) examined the nitrogen cycle in the Gulf with particular attention to the importance of sediment denitrification. Based on these earlier works and additional measurements, Townsend (1998) constructed a budget using a box model approach, linking the major sources and processes operating in the Gulf.

Accounting for inputs of dissolved inorganic nitrogen to the Gulf at the surface (by atmospheric deposition, rivers and advection) and at depth via Slope Water, and outputs via advective fluxes in the surface layers and intermediate-depth layers, gave a gross horizontal nitrogen flux into the productive surface waters of the Gulf of 41.6×10^9 g at N yr^{-1}. The estimated vertical nitrogen flux was 34.4×10^9 g at N yr^{-1}; together these fluxes totaled 76×10^9 g at N yr^{-1}, which, when averaged over the area of the Gulf of Maine, equaled a flux of 0.69 g at N m^{-2} yr^{-1}. Using a C:N Redfield Ratio of 5.68 by weight, this flux explained 55 gC m^{-2} yr^{-1} of potential *new* primary production. Divided by the estimated total primary production of 290 gC m^2 yr^{-1} measured by O'Reilly and co-workers gave an *f-ratio* of ca. 0.2, which is a value more in keeping with an oligotrophic sea than a productive continental shelf. Townsend argued that for the *f-ratio* to be closer to 0.5 (e.g. based on Eppley and Peterson, 1979) there would need to be a significantly greater flux of new nitrogen into the Gulf than was accounted for. Of course, any number of uncertainties in the nitrogen budget could lead to an error in estimated *f-ratio*, but Townsend (1998) offered, as a possibility, water-column nitrification.

New primary production assumes "new" fluxes of nitrogen into the Gulf of Maine by way of the several fluxes listed in Table 5.3.1. However, there is evidence that "new" nitrogen may be created within the Gulf itself, and that therefore not all nitrates that are delivered to surface waters are from external sources. Townsend (1998) showed vertical profiles of ammonium in the Gulf of Maine that exhibited a slight maximum at pycnocline depths, likely the result of heterotrophic grazer activity at that depth producing recycled nitrogen from shallow water-produced organic matter, as indicated in the intermediate waters in Fig. 5.3.6. The profiles also exhibited

Table 5.3.1 Advective fluxes of nitrogen into and out of the Gulf of Maine (from Townsend, 1998)

Flux	Volume (10^{12} m^3 yr^{-1})	[N] (μg at N l^{-1})	N Flux yr^{-1} (10^9 g at N yr^{-1})
Inflows			
Atmosphere (wet and dry)[A]			9.3
Rivers[B]	0.08	10	0.8
Scotian Shelf Water[B]	6.31	5.0	31.5
Slope Water (NE Channel)[B]	8.7	17	147.9
Total			***189.5***
Outflows			
Surface water[C]	5.04	3.5	17.6
Intermediate water[C]	10.06	8.0	80.5
Total			***98.1***
Other Losses			
Denitrfication[D]		33.1	
Burial[E]		4.4	
Net Flux			**+53.1**

[A] From Talbot and Mosher (unpublished).
[B] Modified from Christensen et al. (1995) and McAdie (1994).
[C] From Townsend and Christensen (1986) and Townsend et al. (1987).
[D] From Christensen et al. (1995).
[E] From Christensen (1989).

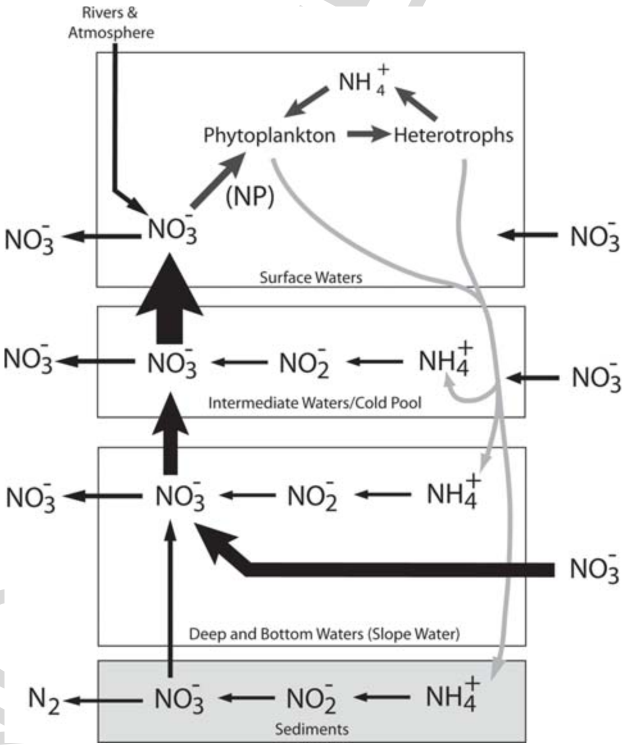

Fig. 5.3.6 Schematic diagram illustrating the major nitrogen cycle pathways in continental shelf waters of the Northwest Atlantic Ocean. Four boxes represent (**a**) surface waters (shallower than the seasonal pycnocline), (**b**) intermediate and cold pool waters (remnants of previous winter convection), (**c**) deep and bottom waters of Slope Water origin and (**d**) bottom sediments. Advective fluxes are indicated by *horizontal arrows*. New primary production, using (primarily) nitrate fluxes from beneath the surface layer, is indicated (NP). Recycled primary production and loop through heterotrophs is given by the loop in the top box. The internal recycling of nitrogen back to nitrate by internal water-column nitrification, especially in intermediate and cold pool waters, has not been quantified, but may be significant, as indicated by the *large arrow*

a subsurface maximum in nitrite (NO_2^-) beneath the ammonium maximum, as was reported by Holligan et al. (1984). This deep nitrite maximum layer had been described much earlier by Rakestraw (1936) who showed that the nitrite maximum is present throughout the Gulf of Maine for much of the year. Townsend (1998) thus hypothesized that the *f-ratio* in the Gulf of Maine was nearer to 0.5 than 0.2, with the additional nitrogen flux being attributed to internal nitrification. A later study of organic carbon export in the Gulf of Maine by Benitez-Nelson et al. (2000), based on naturally occurring radionuclides, supported this hypothesis.

We emphasize here that the contribution of internal nitrification to new primary production in the sense of organic carbon export should be viewed differently from secondary biological production. In the case of secondary biological production, the nitrogen content of the particulate organic material being passed on to higher trophic levels is important because it potentially leaves the system (surface layer). In the other scenario, some of the nitrogen might be returned to the system and lead to recycled primary production. In the case of internal nitrification, the nitrogen and carbon are returned to the system via upwelling/winter convection.

5.3.8 *Final Considerations*

In the Northwest Atlantic Shelf system, the cycling of nitrogen is complex and depends on numerous processes including advection, vertical mixing, new primary production, secondary primary production, internal nitrification, secondary production and export, as diagrammed in Fig. 5.3.6. Townsend (1998) was able to determine actual values for many of these processes in order to arrive at an understanding of the significance of internal nitrification for a relatively small geographic region such as the Gulf of Maine. However, it is not possible to expand this type of calculation of nutrient and carbon fluxes for the wider Northwest Atlantic Shelf system owing to a lack of measurements.

Slope Waters dominate the flux of nitrogen into these shelf systems, but even slight errors in either the magnitude of the flows, or the loads of nutrients, or both, can have very large effects on the estimated net nutrient flux. For example, Ramp et al. (1985) reported a standard error for the flow of Slope Water through the Northeast Channel into the Gulf of Maine is 69% of the mean. We also have shown that there is a significant difference in the nutrient loads carried by Warm Slope Water and Labrador Slope Water, and that one or the other of those water masses will dominate depending on such phenomena as the North Atlantic Oscillation.

There is a clear need to evaluate and understand much better the significance of nitrification in intermediate shelf waters. The rates reported by Townsend (1998), arrived at by subtraction, and Benitez-Nelson et al. (2000), who performed measurements based on natural isotopes, are both higher than actual measurements reported by Kaplan (1983) in his review of other coastal regions. Thus, the upward vertical nitrate fluxes, indicated by the heavy arrows in Fig. 5.3.6, are scaled to represent the flux supplied by each process, which places an emphasis on the deep-water source and the degree of nitrification occurring in intermediate waters, and which is subsequently brought to the surface. Townsend (1998) has suggested that the role of internal nitrification is significant in the Gulf of Maine region. We would take that argument further and suggest that the importance of internal nitrification extends beyond the Gulf of Maine to intermediate and cold pool waters throughout the Northwest Atlantic shelf.

5.4 The Continental Shelf of the South-Western Atlantic Ocean[4]

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