Chapter 8. CIRCULATION, MIXING AND THE DISTRIBUTION OF REMINERALIZED NUTRIENTS

LARRY P. ATKINSON

Old Dominion University

JOHN HUTHNANCE

Proudman Oceanographic Laboratory

JOSE L. BLANCO

Old Dominion University

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1. Introduction

The circulation and mixing processes that affect the distribution of re-mineralized nutrients (referred to as 'nutrients' from now on) in the global coastal ocean are the topic of this chapter. The coastal ocean is at the dynamic edge between ocean and land. Thus we are concerned with the two fundamental sources of nutrients: the deep ocean and runoff from land. Processes that control the flow of nutrients from the deep ocean include instabilities in western boundary currents, coastal upwelling, and deep mixing. The inflow of nutrients from land occurs through rivers and estuaries. During this journey nutrients may be chemically altered, deposited and recycled.

The discussion expands on the chapter by R. Wollast (1998) in Volume 10 of The Sea. In that chapter, Wollast clearly established that about 80% of the new nutrients involved in primary production in coastal waters are from the deep-ocean: the other 20% coming from rivers. This chapter will focus on both process but emphasize the circulation and mixing processes that affect nutrient flux and place these introduced nutrients in the euphotic zone of coastal waters. We will follow the scheme in Huthnance (1995). His methodology was to examine a variety of processes in regard to circulation, exchange and water mass formation. As he noted, these processes equate on a time-length scale consideration to advection, stirring and mixing. Other authors (e.g. Walsh 1988) have also focused on processes such as eastern boundary current upwelling. Since most oceanographic studies are related to specific processes such as western boundary currents or coastal upwelling, we have partitioned this paper in that manner, while using Huthnance's (1995) terminology and scaling.

We must note that we barely understand the processes involved in temperature and salinity exchange, circulation and mixing at the shelf edge; their quantification is especially problematic. Thus, our understanding of how physical processes affect nutrients is even more difficult. Nevertheless, research is progressing and we hope this review will help the cause.

In general terms, the distribution of any constituent nutrient "N" is controlled by a transport equation

$$\partial N/\partial t + \mathbf{u}.\text{grad } N = K_H \left(\partial_x^2 + \partial_y^2\right) N + K_V \partial_z^2 N + \text{sources} - \text{sinks} \qquad (1)$$

Thus temporal plus advective change is caused by often unresolved dispersive and mixing processes, sources and sinks. Advection is resolved by flow or circulation, in principle reversible, that is associated with various processes discussed in sections 3 to 5. Dispersion and mixing are irreversible and caused by small-scale processes; vertical mixing is discussed in section 6. For the coastal ocean, important sources of nutrients are the open ocean, remineralization in the water column (from detritus) and in the sea bed, rivers locally, and the atmosphere over extensive shelf seas or estuaries. There may be urban and industrial inputs; groundwater is a general possibility but rarely quantified or even identified. Primary production is an important sink as may be sedimentation and denitrification.

After providing a historical perspective, we give an overview (section 3) of the riverine and open-ocean sources of nutrients in coastal seas. Transport processes in the coastal ocean are discussed in sections 4–6, with examples of their effects on nutrient distributions: along-shelf flows and their adjuncts with an emphasis on western oceanic boundaries in section 4; cross-shelf transports and their adjuncts with an emphasis on eastern oceanic boundaries in section 5; mixing in section 6. Further discussion of successive regions offshore is given in section 7 followed in section 8 by a few coastal ocean "system" cases that illustrate the degree of process understanding and applicability.

2. Historical Perspective

The focus on the circulation, mixing and distribution of re-mineralized nutrients results from their critical role in primary productivity. This topic attracted oceanographers nearly a century ago. Redfield (1936) noted:

> "The view has been increasingly accepted, since first put forth by Nathansohn (1906), that the fertility of the sea depends upon the restoration to the surface of plant nutrients such as phosphates and nitrates liberated by the decomposition of organic matter within its depths. In shallow coastal waters the turbulence due to wind and tide, aided in high latitudes by the instability resulting from cooling in winter, suffice to maintain this part of the nutritional cycle. In the deep sea, organic matter generated in the surface as the result of photosynthesis processes appears in large part to sink to great depths before being finally oxidized to its ultimate inorganic products."

Redfield (1936) went on to note the processes that accomplish this in the deep ocean:

> " … four processes by which these materials are brought again to the surface in the Atlantic Ocean and thus made available for the organic cycle … [Include] … (1) upwelling resulting from offshore trade winds off the African coast; (2) upwelling of deep Atlantic water in the Antarctic; (3) upwelling in the boundary between currents as in the Arctic polar front; and (4) winter convection in high latitudes."

The landmark paper by Riley (1967) on nutrients in coastal waters stated clearly stated the importance of the deep-water source of nutrients to coastal waters:

> "Coastal waters generally are more productive than the open sea. Two factors are believed to be responsible, in varying degrees according to local circumstances. The first is shoreward transport, from the edge of the continental shelf, of deep and nutrient rich water, which then becomes available to surface phytoplankton populations in the inshore waters as a result of tidal vertical mixing. The other in enrichment by freshwater drainage."

He further noted that:

> "General conclusions are that the usual pattern of exchange between inshore and offshore waters tends to enrich the coastal zone irrespective of enrichment by freshwater drainage…"

Since these key papers we have learned about the processes, such as eastern and western boundary currents, that cause the enrichment of coastal waters. Additionally we now better understand the mixing processes that bring those nutrients upward into the photic zone of the coastal ocean.

3. Recent work and process overview

The last decade has seen an increase in review papers and books on the coastal ocean. The following are recommended for the topic of this paper: (Walsh, 1988; Blanton, 1991; Jickells, 1991; Huthnance, 1995; Brink, 1998; Robinson and Brink,

1998; Wollast, 1998). Recent papers that discuss the global coastal ocean in relation to global carbon and climate issues underscore the importance of understanding these process (Tsunogai et al., 1999; Liu et al., 2000). In addition, several papers are in preparation as part of the IGBP, JGOFS and LOICZ programs.

Of the principal external sources of nutrients in coastal seas, both riverine and oceanic inputs are subject to considerable buffering or constraint.

Riverine inputs

Anthropogenic inputs often enhance riverine concentrations of nitrogen and phosphorus species. However these inputs are relatively lacking in silicon, which composes a large fraction of river-borne sediments. These inputs are typically buffered by estuarine processes and often have little effect on the wider coastal ocean.

Algal production may severely deplete silica, phosphate and nitrate, as happens in the eutrophic Loire River due to the long residence time O(1 week) (Meybeck et al., 1988). Biomass degradation will generally release dissolved silica, phosphate, and ammonium. This may result in a nutrient maxima if particulate matter is concentrated around a turbidity maximum. Water column nitrification may augment nitrite at very low salinity (e.g. in the Tamar; Knox et al., 1986). For example nitrification in the upper Forth estuary is aided by ample particulate organic nitrogen (PON) in the turbidity maximum (Balls et al., 1996). This process increases downstream nitrite+nitrate concentrations, especially during low river flows when upper-estuary residence times are longer. In the Humber River, NE England, nitrate, nitrite and silicate have mid-estuarine maxima (>500 •M for nitrate) influenced by physical transport, which is strongly correlated with inflows to the estuary and with the freshwater-saltwater interface location or (for nitrate in summer/autumn) the turbidity maximum (Uncles et al., 1998a; Tappin et al., 2001; a UK contribution to LOICZ). However, the Humber nitrite peak was somewhat upstream of the nitrate, silicate, owing to possible sources from ammonia and bacterial remineralization of organic matter; it decreased through the turbidity maximum and further downstream, possibly through oxidation to nitrate. Around the Humber mouth (Uncles et al., 1998b) bacterial processing of ammonia may be the source of the observed nitrite.

Sediments host denitrification and regeneration of ammonia and nitrite. In Humber sediments, denitrification has been correlated with sediment organic carbon content, macrofauna abundance and nitrate concentrations in the overlying water (Barnes and Owens, 1998). Denitrification rates were significant throughout the estuary with rates up to 10 mmol N $m^{-2}d^{-1}$ in the inner estuary, as low as 1 mmol N $m^{-2}d^{-1}$ elsewhere in the estuary and at most 0.19 mmol N $m^{-2}d^{-1}$ below the plume outside the estuary. Note that 1 mmol N $m^{-2}d^{-1}$ • 0.1 •mol d^{-1} in 10 m water depth. Upper Forth ammonia and nitrite distributions are consistent with PON breakdown processes (e.g. denitrification) in reducing sediments. Rates of their benthic source are 19–44 and 0.39–0.81 mmol $m^{-2}d^{-1}$ respectively with higher concentrations in summer when there is less oxygen in the water and sediments (Balls, 1992). In the Tamar, nitrite and ammonium have maxima indicating sediment production at rates 1–2 mmol $m^{-2}d^{-1}$ (Knox et al., 1986). The intertidal zones of estuaries behave similarly. The Humber overall is a sink for nitrate, a strong source of ammonia, and a small source of nitrite (Mortimer et al., 1998). Large nitrate concentrations

favor denitrification and hence this nutrient sink. Some zones were sources of nitrate such as where lower temperatures suppressed denitrification or oxygen levels. Local sinks and sources also prevail on tidal flats in the German Bight, where high ammonium concentration occur (Brockmann et al., 1994).

Transformations of phosphorus in estuaries may be complex, typically beginning with phosphate removal to suspended particulate matter (SPM) in low-salinity reaches. Examples are the Forth and Tay (especially in summer at a large turbidity maximum in the Forth) and the Ouse where colloids may also be a factor (Rendell et al., 1997). In the Chesapeake Bay, biological processes strongly affect phosphorus cycling. Particulate phosphorus is dominant, highest in the upper estuary and suffering most changes of composition in low salinity parts of the estuary. Dissolved organic phosphorus often exceeded dissolved inorganic phosphorus and both had highest concentrations in bottom water during summer anoxia (Conley et al., 1995). Further down-estuary, desorption from SPM often occurs, e.g. around the Humber mouth (Uncles et al., 1998b). In the Forth and Tay, there are mid-estuary inputs from desorption and sediment pore-waters; the summer flux from sediments greatly exceeds the upstream river input (Balls, 1992). In the Delaware River a half or more of total phosphorus was retained, mainly via geochemical processes (Lebo and Sharp, 1992). Downstream in Delaware Bay, dissolved inorganic phosphorus (DIP) was taken up in phytoplankton and the particulate fraction of flux increased from 35% to 62%. The Bay retained total phosphorus during the winter-spring bloom and acted as a source during fall. Overall, a majority of regeneration occurred in the water column and 84% of the freshwater input of total phosphorus was eventually exported to coastal waters.

Outer-estuary nutrients are typically more conservative. Examples include the outer Loire estuary (Meybeck et al., 1988), the Humber mouth to the North Sea, even though nitrate ranged from 1.4 to 106 •mol (Uncles et al., 1998b), and nine large Chinese estuaries, despite upper-estuary desorption and variable riverine sources (Zhang, 1996).

The overall effect of estuarine processes can be assessed by comparing their rates, e.g.

$$\text{Depletion rate} =$$
$$\text{(uptake or dissolved-particulate exchange rate) / concentration} \qquad (2)$$

with a flushing rate. If concentrations are moderate and flushing is slow, then even slow uptake may cause a notable reduction in downstream nutrient fluxes, as in the Tweed (Shaw et al., 1998). Fluxes in larger slowly-flushed Scottish estuaries are also affected (Balls, 1994). In the Ouse (Rendell et al., 1997) variations in flow, and hence flushing time (1 to 14 days), control the degree of nutrient conservation or depletion by production. Overall transport numbers for the Humber are shown in Table 1.

Silica and nitrate inputs from the Loire to the ocean are barely modified, but phosphate and ammonium inputs are increased; some large-flow events markedly change the pattern (Meybeck et al., 1988).

TABLE 1

Transport of nitrate and ammonium from the Humber to the North Sea
(Tappin et al., 2001). Values in kmol/day.

	Inputs	To (from) bed	To North Sea	denitrification
NO_3^-	9700	1000	9900, 10600	260 (spring), 600 (summer)
NH_4^+	1500	(430)	200	

The various processes just mentioned show how the ratios of nutrients eventually entering the coastal sea from the estuary may differ considerably from ratios in their riverine sources. The ratios may also differ between estuaries and with the adjacent coastal sea. The differing ratios of nutrients entering the coastal ocean will cause different limitations to plankton growth and plankton type. For example phosphorus limitation is found in the Gironde plume (Biscay; Herbland et al., 1998), relative depletion of silicate from the Ouse affecting coastal-sea production species (Rendell et al., 1997), and limitation by nitrogen or phosphorus according to discharge concentrations and location in the Mississippi plume (Lohrenz et al., 1999). Nutrient-salinity plots often help the interpretation of distributions where the estuarine outflow pattern is complex (e.g. the German Bight; Körner and Weichart, 1991).

The flow of nutrients from land to the coastal ocean can vary. The nutrients may flow through a long estuary spending days or weeks such as in the Chesapeake or they may not encounter coastal waters at all but be directly placed in the open ocean as occurs off the Amazon or Mississippi on occasion. The pathway to the coastal ocean will affect the biogeochemical processes the nutrients undergo and, in the end, affect the ratios of the various nutrients when they finally enter the coastal waters. The ratios of the nutrients and their absolute concentration are, of course, critical to plankton growth. The open ocean on the other hand represents a large source of nitrate, phosphate and silicate in rather constant ratios compared to the riverine/estuarine source.

Oceanic inputs

The major source of nutrients to coastal waters is from the deeper oceanic waters offshore over the slope. Currents transporting nutrients tend to flow along isobaths not across them thus other processes than normal along-isobath geostrophic flow must occur. These processes are as follows (Huthnance, 1995):

1. Processes specific to or enhanced at the shelf edge.
2. Relaxation of the geostrophic constraint near the equator (Coriolis term goes to zero).
3. Friction as occurs in Ekman layers.
4. Non-conservative processes. The net flux <uC> may be non-negative along some boundary as C may vary due to phytoplankton uptake of nitrogen for example.
5. Small scale (time O(1 day), length O(2–10 km), speed O(0.2–1 m/s)) local, non-linear and time dependent flows tend towards ageostrophic.

The following summary gives a flavor for the diversity of processes of circulation (advection), exchange (stirring), and water mass formation (mixing) that may enrich or deplete coastal ocean nutrient concentrations. Tables 2 and 3 show the scaling parameters and typical speeds of shelf-edge circulation processes and shelf-edge exchange processes respectively.

Of the various circulation processes (Table 2) those related to coastal currents, western boundary currents and their associated eddies, warm core rings and jets, and tides appear to be the most important for moving large amounts of water, and thus nutrients. Of course the importance depends on the nutrient concentrations.

TABLE 2

Scales and estimated values of process contributions to shelf-edge circulation. From Huthnance (1995) and see that paper for details.

Process	Scale	e.g. m/s
Coastal current	?	0.1–1
Slope current forced by		
JEBAR	$h_o^2 \lvert \rho^{-1} \, grad \, \rho \rvert g/8k$	0.1
Steady wind	$\tau/\rho \, k$	0.1
Unsteady wind	$t \, \tau / \bullet h$	0.1
Biased form drag	$\tau/(2\pi \rho) \, min(1/k, \, t/h)$	0.01
Wave rectification	$u^2 f / L_T \sigma^2$	0.01
Eddy momentum	$u \, v \, h/L_T k$	0.1
Western boundary current	$(L_x/L_y) \, \sigma/\rho \, k_1$	1
Eddies, warm-core rings, jets	?	0.5
Tides	$\zeta \, max\{(g/h)^{1/2}, \, \sigma \, W_s/ \, h\}$	0.3
In strait to marginal sea	$\sigma \, \zeta \, A / h \, b$	>1

Shelf-edge exchange processes are the most important as they directly affect flow from the deep-ocean to the coastal ocean. The following table (Table 3) shows relative magnitudes of volume flow of the different processes. Note that the flux of nutrients depends on the concentrations of the nutrients times the volume flux. Most of the processes will be discussed in the following text.

Many of the processes shown in the two previous tables bring nutrients into coastal ocean waters but they are often in a bottom layer. Mixing and stirring are required to bring nutrient-rich waters to the upper layers to complete the ascent of nutrients from the deep ocean to the near-surface in the coastal ocean. Table 4 shows the relative importance of different processes that create or destroy stratification. Wind generated surface waves, tidal friction (for strong tidal currents) and especially intensified internal waves can create significant mixing.

TABLE 3

Scales and estimated values of process contributions to shelf-edge exchange.
From Huthnance (1995) and see that paper for details.
(See also table 4 below for topographic effects).

Process	Scale	e.g. m^2/s
Slope current	kv/f	1
e.g. Atlantic inflow Malin-Lewis		0.2Sv/300km
Total Scottish slope		1
Topographic irregularities	$V \Delta h_t$	1
Eddy	$© h_o (h_o/\Delta h)/f$	(1 Sv × 12 d)
Warm-core ring streamer	?	(1 Sv)
Aggregate (Middle Atlantic Bight)		0.3
Impulsive wind	$\tau/\rho f$	1
Upwelling–wind	$\tau/\rho f$	1
– div. W boundary current	$2h_o^2 V_w \partial_x (h_o V_w/\partial_x h_o)\ div/f$	20
Jets (narrow-shelf upwelling areas)	?	(2 Sv)
Aggregate		2
Cascading (Shapiro et al., 2003)	$0.36\ g\ (\rho^{-1}\Delta\rho)\ h_z/f\ (•/f)^{1/2}$	1
Front	$\alpha'h\ [g(\rho^{-1}\Delta\rho)\ h']^{1/2}$	0.3
e.g. along isopycnals, Middle Atlantic Bight		0.2
Tides	$\sigma\zeta W_s$	10
Strait to marginal sea	$\sigma\zeta A$	(> 1 Sv)
Shear dispersion (hu = $\sigma\zeta W_s$)	$t_D uh\ |\boldsymbol{u}|/L_T$	0.1
Internal tide solitons	$<\zeta>\lambda/tide$	1
Waves' Stokes drift	$0.01w^2$	1

. TABLE 4

Scales and estimated values of process contributions to energy potentially available for mixing. Mixing energy values (mW/m^2) are based on typical values for the quantities in the 'Scale' column given in Huthnance (1955, page 355). From Huthnance (1995); see that paper for details.

Process	Scale	Typical Mixing Energy, mW/m^2
Buoyancy flux (heat, cooling, rain)	$\alpha\ g\ h\ H/2c_p,\ gh\ \Delta\rho(rain\ rate)/2$	1
Surface waves	$1.5 \times 10^{-5}\ \rho\ g\ \sigma_w\ a^2$	150
	or $5 \times 10^{-7}\ \rho\ w^3$	500
Wind	τv	10
Internal tides	$\rho g(\rho^{-1}\Delta\rho)<\zeta^2>\lambda/L_T\ per\ tide$	50
Internal waves	$0.1 \times 1\ kW/m/L_T$	10
Bottom-reflected internal waves	$Fn\ (h_x, f/N) \times 30\ mW\ m^{-2}\ flux\ •$	1
Bottom friction	$\rho\ C_D\ v^3$	3
Tidal (currents 0.3 or 0.7 m/s)		100 or 1000
Canyon-intensified internal waves	$<\rho\ C_D\ u^3>$	150

Most of the processes mentioned here are shown schematically in Figure 8.1.
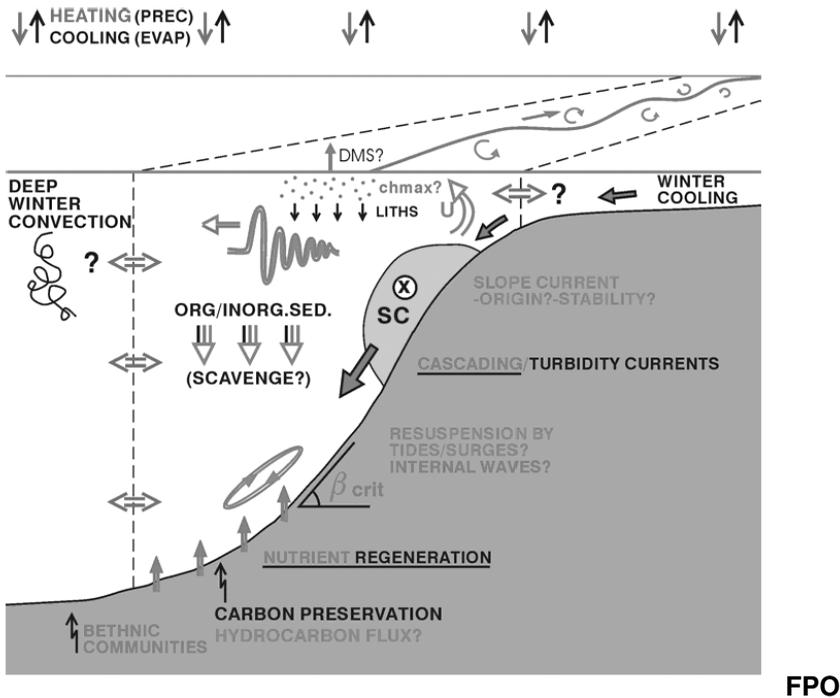
Figure 8.1   Schematic depiction of coastal ocean processes. From an original by John Simpson.

Sources, transport and sinks within shelf seas

The oceanic source of nutrients is present to a greater or lesser extent at all shelf break regions. Typically the deep ocean is the largest source of nutrients however there are exceptions near the outflows of very large rivers. For example ~ 60% of nitrogen input to the northern shelf of the Gulf of Mexico is from the Mississippi River (Ortner and Dagg, 1995). Whether concentrations are comparable with oceanic values depends on the exact location of river outflow to the coastal ocean and on the balance, as in estuaries, between a depletion rates and flushing rates. Broad shelves tend to be flushed slowly by oceanic waters, so that the balance determining nutrient concentrations may appear to be relatively local (even though salinity may be near oceanic values and the ocean dominates primary nutrient supply). Riverine sources (via estuaries) are initially localized at estuary mouths. Their domain of influence depends on a balance between the depletion rate and the transport rate. In the Celtic Sea, for example, separate nitrate/salinity mixing lines above and below salinity 35 suggest a long (seasonal) time scale for riverine influence to reach the majority of this shelf with salinity > 35 (Hydes et al., 2001). Rivers flowing into the southern North Sea are a locally important nutrient source limited to the sides of the English Channel (Laane et al., 1993), in the German Bight and west of Denmark (despite relatively small water volume transport). However, the typical transit time to the Skagerrak is O(6 months) allowing time for dissolved inorganic nitrogen (principally) to be taken up by production; these

riverine inputs reach the Skagerrak mostly by down-gradient dispersion and after exceptionally large winter discharges of fresh water (Rydberg et al., 1996).

Total atmospheric nitrogen input per unit area, 50 mMol m^{-2}y^{-1} or less (Duce et al, 1991; Cornell et al., 1995), is typically modest compared with water column cycling rates. For example, atmospheric nitrogen input to the North Sea is about 4% of the total, but 38% of that is from river runoff (Chester et al., 1993).

As already implied, production in the water column is a sink for inorganic nutrients. Organic nutrients (not emphasized here) may increase and in turn be taken up by some phytoplankton species (e.g. in the English Channel; Butler et al., 1979). Organic particles are subject to water-column remineralization (a direct source of inorganic nutrients), denitrification (a sink) and transport; particulate matter also sinks, at a rate that depends on particle size and hence turbulence (large particles tend to form in stratification with reduced turbulence and break up in strong turbulence). Organic material in the sediment bed is subject to erosion (resuspension), denitrification and remineralization (generally more slowly than in the water column). Resuspension of several centimeters of sediment is needed before there is significant total nitrogen input to the overlying water (of order 1 •M through 1m depth; Blackburn, 1997).

Nitrate exchanges with the bottom depend on sediment C/N ratios. The exchange is into the water column from low C/N sediments with fastest net regeneration and into high C/N (nitrogen-poor) sediments due to denitrification in deposition areas (Skagerrak; Hall et al., 1996). This is consistent with the Humber estuary findings previously mentioned (Barnes and Owens, 1998) except that in the Skagerrak the association is with C/N, not organic carbon content. Ammonium fluxes to the sediment were correlated with nitrate effluxes; take-up by nitrifying bacteria was suggested. Nitrite influxes to the sediments accompanied both high nitrate influxes and high nitrate effluxes. Phosphate fluxes in the Skagerrak appeared to be correlated with clay in the sediments. Nitrogen flux estimates for the Washington shelf (Christensen et al., 1987) are: 28.6 nmol N m^{-2}s^{-1} total regeneration on the basis of carbon oxidized; nitrate influx 8.1 nmol N m^{-2}s^{-1} and ammonium efflux 5.3 nmol N m^{-2}s^{-1} on the basis of pore-water profiles; the "missing" regenerated nitrogen could be accounted for by coupled nitrification and denitrification (11.6 nmol N m^{-2}s^{-1}) and higher C:N ratio in the organic matter oxidized. Overall, the annual ammonium efflux was about half of the organic burial rate plus the nitrate influx suggesting a net sink for nitrogen. In 100m water depth, these rates were O(10 nmol N m^{-2}s^{-1}) or about O(3 •mol yr^{-1}).

In general, strong currents and turbulence favor water-column recycling while more quiescent water flow favors deposition and sea-bed recycling. The character of recycling in either the water column or the sediment medium—regeneration, (de-) nitrification, nutrient fluxes in/out of sediments—depends on redox chemistry. Models exist that represent our present understanding of nutrient behavior in the water column and in the sediment. A benthic module in the European Regional Seas Ecosystem Model (ERSEM) includes N, P, Si nutrient cycles with vertical transport, oxic and anoxic mineralization, silicate dissolution, adsorption, nitrification and denitrification. The model describes the seasonal variation of nutrient fluxes including sediment-water exchanges and (in the North Sea) the influence of organic matter deposition on benthic nitrification and denitrification

via changes in oxygen availability to the nitrifiers (Ruardij and van Raaphorst, 1995).

In successive regions from the coast offshore, the relative importance of the different sources, transport processes and sinks varies. In turn there may be:

a) near-shore regions: surface-wave currents at the sea bed increase turbulence and mixing;
b) ROFIs: regions of freshwater influence with river/estuary buoyancy and nutrient input, strong offshore salinity and temperature gradients and possible rapidly-varying stratification;
c) regions well-mixed throughout the year by tidal and wind-driven currents;
d) tidal-mixing fronts between (c) and (e);
e) regions that are thermally stratified in summer;
f) the shelf edge adjacent to the open ocean and with particular processes including internal waves that can be an interior source of turbulence and mixing.

Regions a) and f) always exist; the others may be well-expressed on a wide shelf but merge over a narrow shelf. A more specific discussion is given in section 7.

We now discuss the processes that appear important for understanding nutrient distributions.

4. Along-slope Currents

High currents in the vicinity of the shelf break is a common feature of most continental shelves. The forcing mechanisms are many (Huthnance 1992) but an important common aspect is that cross-isobath flow does occur (in particular, in any bottom Ekman layer) as do vertical motions. Thus, along-slope currents are of importance to the distribution of nutrients along and across the coastal ocean. In this section, we discuss the following from Table 9–02: freshwater buoyancy forced flows; western boundary currents; eddies, warm core rings and jets.

Buoyancy Forced Coastal Currents

Freshwater buoyancy fluxes into the coastal ocean cause baroclinic coastal currents. In such regions of freshwater influence (ROFIs), the buoyancy input and strong offshore salinity and temperature gradients may cause rapidly-varying stratification. The baroclinic coastal currents are usually narrow compared with shelf width; thus the influence on nutrient distributions may be localised. On narrow shelves, such as off southeast Alaska or Norway, the coastal current may be over the slope or shelf break. Associated cross-isobath flows are O(0.1 m s^{-1}). Classic coastal currents occur off southern Chile, British Columbia and southeast Alaska, the northeast coast of North America, Norway, China, and other locations receiving freshwater input. They are obviously important if the river influx carries a significant nutrient load. In fact many ROFIs carry high concentrations of riverine nutrients that may support primary production. Some ROFIs carry particulate matter which may block light, inhibiting production. The strong stratification imparted by

the buoyancy flux can inhibit vertical mixing and thus affect biogeochemical proc-
esses.

In the Adriatic, fresher water from the Po River outflow extends southwards
along the Italian coast with strong offshore decreases of nutrient (and phytoplank-
ton) concentrations; phosphorus appears to be the element limiting production
(Zoppini et al., 1995). Fresh-water sources of nutrients are illustrated by similar
salinity and nutrient contours in the Rhine outflow northwards along the Dutch coast
(Simpson et al., 1993).

In the Mississippi plume, closely-linear decreases of nitrate, silicate and phos-
phate with increasing salinity (Hitchcock et al., 1997) illustrate their riverine
source (riverine nitrate and silicate commonly exceed 100•mol; Ortner and Dagg,
1995). Figure 8.2 shows surface nitrate concentrations in April during high Missis-
sippi River flow and subsequent high nitrate transport and in October when nitrate
transport is low. The high concentrations in April are advected westward in the
buoyancy- and wind-forced coastal current.
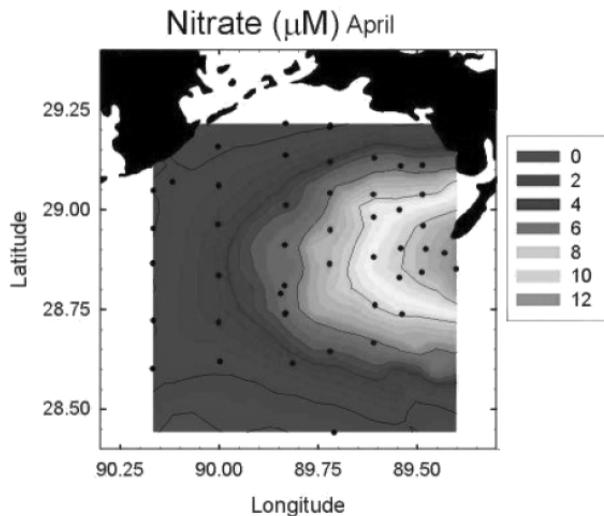
FPO

Figure 8.2   Surface nitrate concentrations off the Mississippi River (From Rabalais et al., 2002).

Biological uptake depletes the nutrients in the Mississippi plume, but only by a
small fraction in its core; farther from the Mississippi River mouth regenerated
nutrients become more significant. Similar maxima of primary production (at
salinities 15–30) and biomass (at the convergent plume front) are light-limited in
turbid low-salinity water and nutrient-limited outside the plume (Hitchcock et al.,
1997; Lohrenz et al., 1999). SPM at these primary production maxima is less than
in the river, allowing light penetration; nutrients are still present after near-
conservative mixing. Because time scales are short (1–2 days in the plume the
water reaching the plume front has experienced maximal time for phytoplankton
growth. Walsh et al. (1989) estimate that less than 25% of the nitrogen effluent
from the Mississippi may remain in the sediments, most of the input being remate-

rialized after several cycles of production and remineralization. To the west on the Louisiana-Texas shelf, the Mississippi River nutrient source, combined with cross-frontal flows at the plume boundary and production in illuminated upper waters, gives a "dome" of concentrated nutrients near the bottom of the plume front (Chen et al., 1997).

Studies of other large river plumes show similar processes. SPM limitation of light and production in the plume *versus* nutrient limitation outside the plume gives highest primary production bordering the high-nutrient Changjiang plume (Tian et al., 1993) and Amazon plume (DeMaster et al., 1996). These processes tend to sharpen the nutrient front. Around Chinese river plumes, regeneration from organic matter decomposition and nitrification may sustain concentrated nutrients near the bottom (Zhang, 1996), however, phosphate is limiting near the coast. Strong currents in the Amazon outflow inhibit burial of biogenic material, implying that regeneration would occur, there would be little trapping of nutrients, and phytoplankton production would continue by repeated utilization of reminer-alized nutrients. Sub-surface oceanic water also supplies nutrients in onshore near-bed flows converge (DeMaster and Pope, 1996).

Distributions of reactive phosphorus near the Otago peninsula, New Zealand, provide a contrast. There riverine nutrient concentrations hardly exceed those on the shelf and advection from offshore along the outer shelf dominates the supply. The outcome is nutrient depletion on the shelf relative to further offshore, espe-cially in spring and summer (Hawke and Hunter, 1992). More gradual depletion in one spring was attributed to lower river flow and hence less stable stratification.

Variable stratification also affects nutrient supplies. Stratification in the Rhine River plume may be destroyed by spring tides or wind-mixing. An April example of strong wind-mixing making nutrients available near the illuminated surface (and fuelling a bloom) is described by Joordens et al. (2001). In the Gulf of Gdańsk, where tides are small, winds have a strong effect on movements of its waters and riverine nutrients. High ammonia concentrations in July may have come from regeneration by abundant zooplankton and silicate concentrations in November may have been depleted by a diatom bloom (Pastuszak, 1995).

At higher latitude locations, such as the Gulf of Gdańsk, wind stress is high and variable. Downwelling-favourable winds tend to confine an outflow plume near the coast and mix it strongly downward. Upwelling winds tend to spread it in a surface layer away from the coast. Such varied mixing and vertical motions during repeated upwelling and downwelling events complicate the nutrient distribution regime.

Western Boundary Currents

Western boundary currents affect the distribution of nutrients in three general ways. The first process is the shelf-parallel transport of nutrients in the overall flow of the western boundary current. This has been called the 'nutrient stream'. The second process is inherent in the dynamics of the large-scale boundary current; it combines cross-slope flow along isopycnals (flow along constant density surfaces) and diapycnal mixing (across constant density surfaces). The third, smaller-scale, group of processes is related to instabilities in the western boundary current front, interactions with adjacent bathymetric features, Ekman related upwelling and cross-isobath flow.

For context, we look at the distribution of nutrients across a western boundary current such as the Gulf Stream. A typical section shows the uplifting of colder, nutrient-rich water over hundreds of meters in the front (Figure 8.3). The nutrient content of the ascending waters depends on the characteristics of the water masses in the front: the T/S/nutrient relationships. Nutrient-temperature correlations in the Gulf Stream show a strong correlation below the surface layer. Gulf Stream water colder than about 18°C invariably has elevated nutrient concentrations. Similar relationships hold in other western boundary currents.
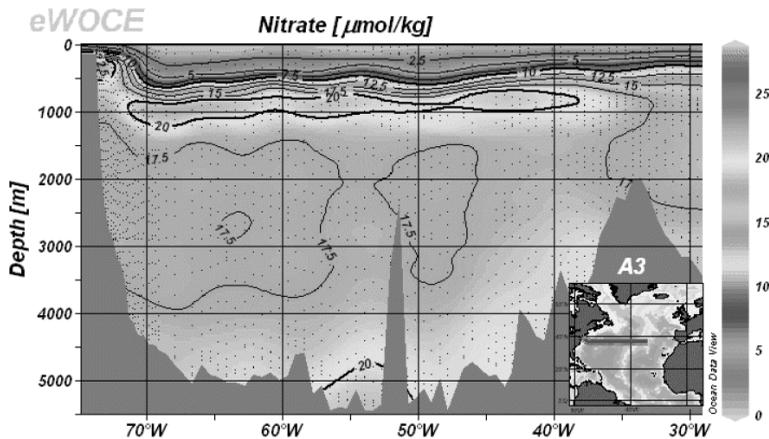
Figure 8.3   Nitrate section across Gulf Stream. Data from WOCE Section A03.

The Nutrient Stream   The 'nutrient stream' refers to the nutrient transport inherent in the flow of western boundary currents. It is simply the integrated sum of the nutrient concentrations and along-stream velocities (Figure 8.4). Pelegri and Csanady (1991) made several calculations between 24°N and 35°W in the Gulf Stream. Typical results for the 36°N section were: nitrate 863 kmol s^{-1}; phosphate 55 kmol s^{-1}; silicate 508 kmol s^{-1}. This transport northward into the North Atlantic gyre represents the main source of nutrients to that region (Brewer et al., 1989).
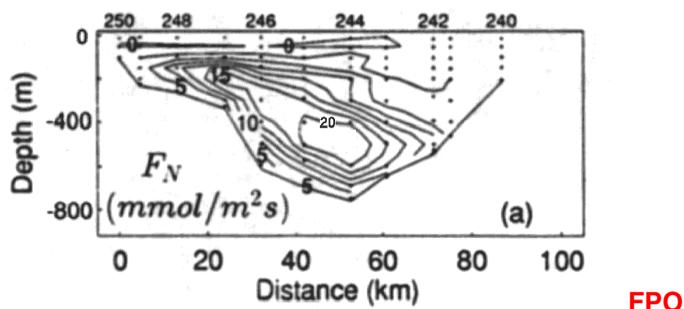
Figure 8.4   Nitrate flux density distribution for section in 24°N across Gulf Stream (From Pelegri and Csanady, 1991).

The shelf-parallel 'nutrient stream' might seem to be unimportant to the distribution of nutrients in the global coastal ocean. However, this process brings nutrient-laden water poleward from the tropics to areas where other processes (to be described next) bring the water laterally into the coastal ocean and upwards into the surface layer.

Isopycnal Flow and Diapycnal Mixing   Cross-stream advection along isopycnal layers in the Gulf Stream (Rossby, 1936) effectively transports nutrient-rich deep ocean water (Redfield, 1936) to upper layers and adjacent slope and shelf waters. As noted so succinctly by Yentsch (1974):

> "The combined effects of the earth's rotation and pressure gradients which are associated with ocean current flow produce the effect of drawing water in along the right side of a current … and discharging into a counter current to the left of the main flow. … This transfer of waters is along lines of equal density which slope dramatically upward toward the coast. The higher density waters are nutrient rich and stimulate production along the left side of the current. … This means the biochemical factors of slope and coastal waters are generated from nutrient characteristics of deep open ocean waters."

Studies of the isopycnal flow and diapycnal mixing processes from the thermocline layer to the surface layer show the upward entrainment rate into the surface waters is typically 1.6 m^3s^{-1} per meter along the axis of the Gulf Stream (Pelegri and Csanady, 1991). Over the approximate 80 km width of the Gulf Stream, this amounts to a diapycnal upwelling velocity of $2x10^{-5}$ m s^{-1}. Interestingly the equivalent upwelling velocity including exchange was similar to equatorial upwelling that is about 3.2 m^2s^{-1}. The diapycnal velocity causes the advection of high nutrients into the surface waters of the coastal ocean from the deeper waters of the boundary current.

Typical fluxes by this process can be calculated assuming that half the entrained water(0.8 m^2s^{-1}) feeds into an onshore flux, rather than directly into production in Gulf-Stream surface waters and a nitrate concentration 20 µmol/l (Pelegri and Csanady, 1991). This would amount to an onshore flux of 16 mmol s^{-1} per meter along the axis of the Gulf Stream. Over a 1000 km long segment of the Gulf Stream this amounts to a nitrate flux 16,000 or 7 Mtons N per year. This nutrient rich water feeds directly into the productive surface waters of the Gulf Stream front and adjacent coastal waters.

Recent studies of advection of nutrients along isopycnals (Schollaert et al., 2003) show that the supply of nutrients into the Slope Sea north of Cape Hatteras is constant regardless of the position of the Gulf Stream (onshore or offshore). However, the concentration of nutrients in the Slope Sea (between the Gulf Stream and the shelf break) varies as the volume of Slope Sea varies: there are higher concentrations when the Gulf Stream is onshore and the volume of the Slope Sea is less; vice-versa for an offshore position of the current.

The magnitude of the flow and exchange in the main part of the western boundary current depends on many factors. The strength of the current causes the slope of the isopycnals to vary. The nutrient content may vary on a given density surface depending on the source of the water (Richards and Redfield, 1955). Surface proc-

esses such as heat flux and wind-mixing alter the mixing between the surface layer and the thermocline.

Meanders   Large meanders, such as the Charleston Bump off Charleston, South Carolina (Fig. 8–005) or the large gyre off Japan, result in localized upwelling and onshore flow. Upwelling is due to the conservation of potential vorticity; surface waters are carried onshore on the downstream side of the meander (Brooks and Bane 1978). North of Cape Canaveral, onshore flow brings nutrient rich water from depths of several hundred meters in the Gulf Stream into waters 20 m deep on the adjacent shelf (Arthur, 1965; Blanton et al., 1981). As the Gulf Stream passes the Charleston Bump a gyre forms with upwelling in its center (Brooks and Bane, 1978; McClain and Atkinson, 1985). The gyre has elevated nutrient concentrations because of the internal upwelling; the adjacent shelf waters receive these nutrient-rich upwelled waters through advection around the gyre. The shelf waters also receive warm buoyant waters that induce stratification in winter, when these shelf waters are otherwise usually unstratified (Atkinson et al., 1989).
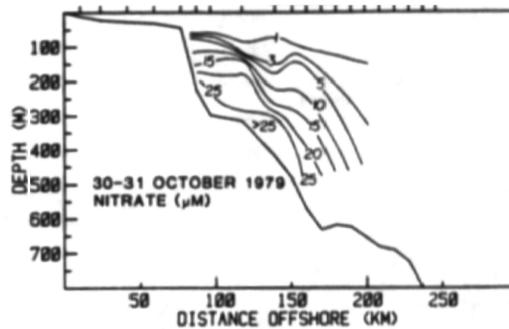
FPO

Figure 8.5   Nitrate section across the Charleston Bump off Charleston, South Carolina (from Singer et al., 1983).

Instability Processes   Instabilities along the western boundary current front create frontal eddies which migrate poleward in the front. These features have an upwelling core. Upwelled, nutrient rich water can move from the eddy core onto the shelf under special circumstances (Fig. 8–006). Upwelling winds along the shelf break can induce an onshore Ekman flow at depth that brings the nutrient rich water from the eddy core to the shelf.

Overall nutrient fluxes   Extensive measurements of nutrient fluxes related to the passage of frontal eddies were summarized by Lee et al. (1991). These observations present the net effect of many processes related to the interaction of western boundary currents with the shelf and slope. Figure 8.7 shows the resultant cross-shore flux.
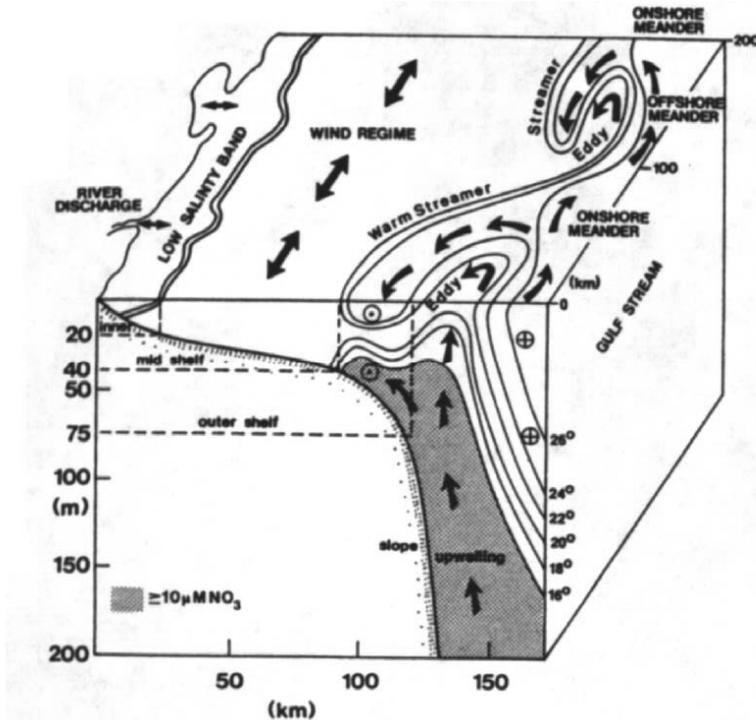
Figure 8.6   Schematic of Gulf Stream frontal eddies and meanders together with shelf flow regimes on the South Atlantic Bight (SAB) (From Lee et al., 1991).

Eastern boundary currents

The ubiquitous combination of oceanic meridional density and pressure gradients with shelf-slope topography provides forcing for poleward along-slope flow. Such flows are most obvious on eastern oceanic boundaries. Poleward currents originate equatorward of upwelling areas and typically reach high latitudes (exchanging water laterally as they go but retaining characteristics of water at lower latitudes). The Peru-Chile Undercurrent reaches at least 48°S (Silva and Neshyba, 1979). Off the west coast of North America, the poleward undercurrent reaches at least 51•N (Pierce et al., 2000). Off western Europe, poleward along-slope flow extends from Portugal to Scotland. Typically the currents are confined over the upper slope, flowing at depths ranging from 200 to 500 m or more (Blanco et al., 2001; Kosro, 2002). Outside upwelling latitudes such poleward currents may reach the surface during certain seasons.
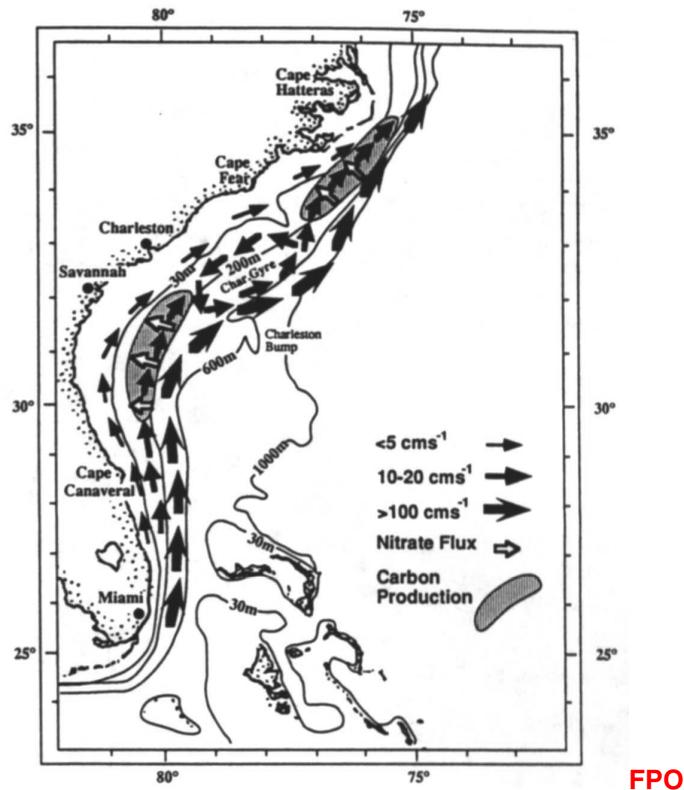
Figure 8.7 Characterization of mean circulation, onshore nitrate flux and sites of potential Gulf Stream-induced new carbon production in the SAB during winter and spring conditions (From Lee et al., 1991).

Broader-scale eastern boundary currents typically form part of an ocean gyre (with offshore extent set by the decay distance of baroclinic Rossby waves). In contrast with western boundary currents, eastern boundary currents are typically slow, and the adjacent shelf is often very narrow. The four major eastern boundary current (EBC) systems are the California, Canary, Peru-Chile and Benguela currents.

5. Cross-shelf transports

In this section cross-shelf transport processes affecting nutrient distributions are described. A discussion of processes dominant in upwelling systems are followed by discussion of the effects of canyons and capes, embayments, coastal trapped waves, and tidal processes.

Upwelling

All eastern boundary current systems have a strong seasonal upwelling cycle associated with the relative strength of atmospheric pressure systems. The strength and duration of upwelling varies seasonally, latitudinally and interannually. In general,

at lowest latitudes the upwelling variability is linked to the ITCZ, where equator-ward wind stress predominates all year. In these lower latitudes, rainfall often creates significant freshwater buoyancy flux. At mid-latitudes, upwelling winds vary seasonally and precipitation is scarce (Bakun and Nelson, 1991). It is here that coastal upwelling brings cold and high-nutrient subsurface water into the euphotic zone, causing phytoplankton growth. With increasing latitude, atmospheric pressure fields produce greater seasonality. Fresh-water buoyancy and downwelling often dominate in winter. In higher latitudes, upwelling winds are less frequent and downwelling becomes dominant. Because of the heavy rainfall and runoff, buoyancy-forced coastal flows become more important at higher latitudes (Hill, 1998). On the Washington shelf, for example, summer upwelling causes higher nutrient concentrations in bottom waters, even inshore of the surface Columbia River plume (and supporting high primary productivity); in winter, without upwelling, nutrient concentrations may be higher in the surface river water (Carpenter, 1987); the Columbia River may often be a relatively large source of dissolved silicon, but upwelling contributes most of the nitrate and phosphorus. The Columbia River plume combined with the coastal upwelling presents an interesting and complex nutrient supply situation.

In eastern boundary current systems, the transport of nutrients into the coastal ocean relies on two basic elements: onshore Ekman transport and a deep offshore source of nutrients, often a poleward-flowing undercurrent. The movement onshore and offshore is complicated by bathymetric features, such as capes and canyons, and by cross-shore flowing jets, streamers and intrusions. The following subsections describe these elements of nutrient transport.

Poleward flowing undercurrent   In almost all upwelling systems, the source of upwelled water is the nutrient-rich water of the subsurface poleward current (Neshyba et al., 1989; Morales et al., 1996; Blanco at al., 2002). Figure 8.8 shows nutrient and oxygen profiles off central Chile. Note the very low oxygen and high nutrient concentration in the core of the poleward flowing Peru-Chile Undercurrent. Also note the intrusion into the coastal waters as part of the onshore Ekman flow. In near-coastal waters, this transport of new nutrient results in chlorophyll concentration exceeding 3 mg m^{-3} (Thomas et al., 1994) and in annual production rates > 200 g C m^{-2} (Berger et al., 1987). The water also has high salinity, low pH and high CO_2. These properties result from the equatorial origin and the cumulative effects of planktonic community respiration as the water moves poleward. High oxidation rates of sinking POM contribute to the nutrient maximum and oxygen minimum. Denitrification may also be an important respiratory mode in these oxygen-deficient waters (Codispoti and Christensen, 1985); organic matter degradation and denitrification were the suggested cause of near-zero nitrate in equatorial water at 50–90 m depth off the Peru shelf (~ 15°S westward of up-tilted isotherms; accompanied by low oxygen and more ammonia; Copin-Montégut and Raimbault, 1994).
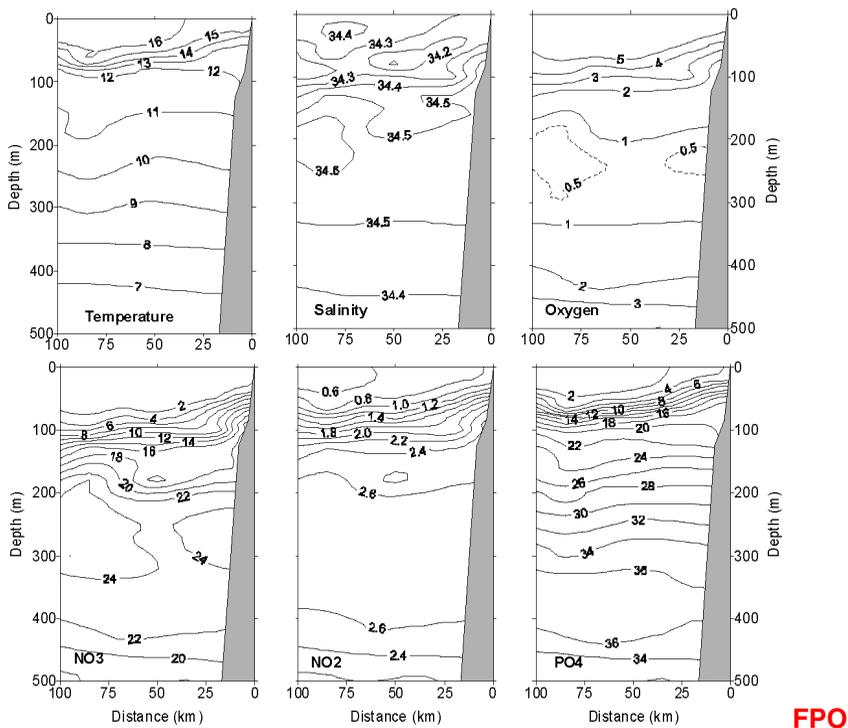
Figure 8.8 Vertical/cross-shelf distribution of temperature (°C), salinity (psu), oxygen (ml/l), nitrate, nitrite and phosphate off Coquimbo (30°S), Chile, May 1992. SCORPIO cruise database.

Ekman Process The generally alongshore flows of nutrient-laden water over the slope would be inefficient nutrient sources for coastal seas were it not for Ekman transports. Near-surface offshore Ekman transport τ/f (proportional to alongshore wind stress and inversely proportional to the Coriolis parameter) is compensated by onshore flow at depth. Figure 8.9 shows the deeper compensation flow of water from the undercurrent moving onshore and into shallower waters. The quantity of the nutrient transport depends on the mass flux that is set by the alongshore wind speed and the nutrient content of the undercurrent source waters.
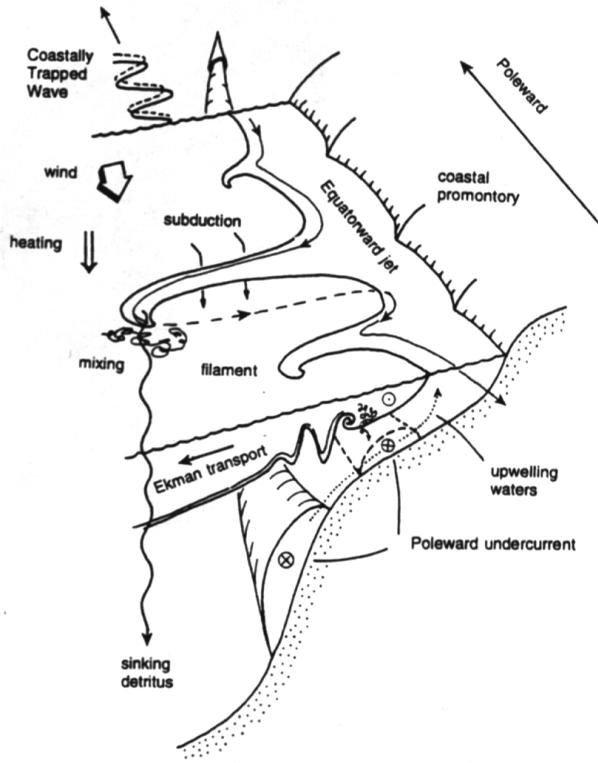
Figure 8.9   Schematic upwelling system for the northern hemisphere (From Hill et al., 1998).

During upwelling, cold nutrient-rich water moves onshore and shoals, eventually breaking the surface. This is the typical upwelling signature: cold, high-nutrient, high-salinity, and low-oxygen. With further upwelling, the band of upwelled water moves offshore. The front between the upwelled water and the displaced warmer surface water is in approximate geostrophic balance. Flow at the front is geostrophic and in the same direction as the along-shore wind; it may be unstable to on-offshore disturbance. The flow interacts with any capes or canyons and can lead to important cross-isobath flow: jets, squirts and offshore eddies (Fig. 8–010). These cross-isobath transports often exceed the Ekman transport. Off California, the jets may be regarded as meanders in the along-shore geostrophic flow. As a result, e.g. off Point Arena, California, some of the upwelling nutrient may be nitrite resulting from upstream production and regeneration (Kadko, 1993).
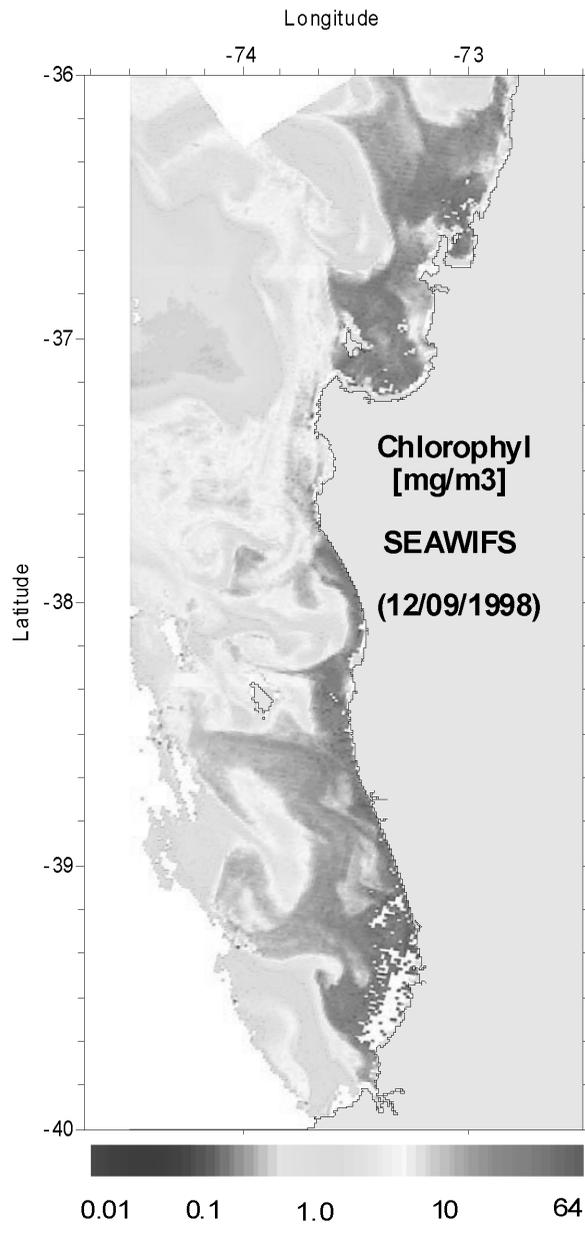
Figure 8.10 Surface chlorophyll SeaWiFS image over the Chilean coast, for 9 December 1998 (From Atkinson et al., 2002).

Filaments

The interaction between the subsurface upwelling water and the more oceanic surface water has been the object of intensive studies in upwelling areas, especially

through the Coastal Transition Zone Program off California (Brink and Cowles, 1991) and the Ocean Margin Exchange (OMEX) project in the Iberian peninsula (Joint and Wassmann, 2001).

According to Strub et al. (1991), several conceptual models of velocity structures can be associated with cold filaments that have been observed through satellite images in the California Current System and in other eastern boundary currents. The first model corresponds to squirt-like jets, which transport coastal upwelling waters to the open ocean, becoming a pair of vortices that probably rotate in opposite directions. A second conceptual model incorporates a series of mesoscale whirls embedded in a slow equatorward current (Mooers and Robinson, 1984; Rienecker et al., 1987). A third conceptual model consists of a steady equatorward jet, which meanders toward and away from the coast. However, in this model of a meandering jet, the jet is the primary structure and source of energy; this structure also implies that the nutrients (and biomass) of the coastal ocean tend to remain on the inshore side of the jet (Strub et al., 1991).

Filaments are typically cold, less than 100 km wide but several hundreds of kilometers long, extending from the coast towards the open ocean (e.g. off California; Brink and Cowles, 1991; Sobarzo and Figueroa, 2001). These cold filaments are associated with the upwelling season (spring and summer) rather than wintertime; they are mainly associated with capes or promontories. In these areas, meandering currents separate coastal and oceanic waters that differ physically and biologically (Lutjeharms and Stockton, 1987).

Exchange flows in filaments after upwelling are variable, but appear to produce more cross-margin exchange than the Ekman transport forced upwelling. Filaments transport water offshore and may also bring water from large distances onto the shelf. Off northwest Iberia, the estimated filament flux is about $1.5 \text{ m}^2 \text{ s}^{-1}$ or half of the overall ocean-shelf exchange, which in turn would replace the volume of water on this fairly narrow shelf in about 12 days (Huthnance et al., 2002). Upwelling and, to some extent mixing, is estimated to supply the shelf with the nutrients from the upper 200m of water annually. A patch of upwelled water, followed along the shelf break in early August 1998, showed reduction of near-surface nitrate and nitrite by primary production; depletion deepened to 30 m in 5 days; just below, nitrite then had a marked maximum (Joint et al., 2001a,b). A filament tracked in mid-August had extremely low upper-layer nitrate, nitrite and ammonium but a small nitrite maximum at ~ 50 m depth. In both cases, silicate and phosphate were closely related to nitrate, but some silicate and phosphate remained even where nitrate was exhausted.

Coastal Trapped Waves

Rather than making an independent contribution, coastal trapped waves (CTW) underlie and modify most processes in ocean-margin circulation, exchange and mixing, especially regarding their space-time distribution along the margin (Huthnance, 1995).

Strong, intraseasonal variability (of sea level, coastal currents and sea surface temperature with periods of about 40 to 70 days) has been observed along the eastern boundary (Enfield, 1987; Shaffer et al., 1997; Hormazabal et al., 2001). Much of this variability has been attributed to the presence of free CTW, which

are generated when oceanic equatorial Kelvin waves impinge on the eastern boundary and are then deflected to propagate poleward along the coast (Enfield, 1987; Shaffer et al., 1997). Effects of CTW on the circulation, exchange and mixing patterns are more important during summer and particularly during El Niño events (Blanco et al., 2002, Hormazabal et al., 2002).

Embayments

Equatorward facing embayments, such as the Gulf of Arauco and Monterey Bay, cause enhanced cross-shore flux of nutrients and retention within the embayment. In both cases, submarine canyons further complicate the situation. Especially in the Gulf of Arauco (Valle-Levinson et al., 2003), the nutrient transport is apparently very high and other conditions, such as stratification and mixing, facilitate very high production at primary and higher trophic levels.

Canyons and Capes

Capes and submarine canyons have long been recognized as areas of enhanced biological production. This implies that some combination of advection and vertical mixing brings nutrients into the euphotic zone. This process is enabled by small bathymetric scale features such as capes or canyons that may cause along-shore flow to become ageostrophic. Stratification may decouple the flow from the bathymetry (at scales O (10km)), inertia may become important (at scales O(1 km)) or a small cyclonic bend may cause an offshore movement of the current. Locally, small-scale topography can induce tidal rectification and e.g. ridge-associated up- and down-welling (Tee et al., 1993); off Nova Scotia, after mixing to the surface, anomalously high nutrients (and low temperatures) from depth are found in summer.

The cross isobath flow associated with these processes is summarized in the following table:

TABLE 5.
Cross isobath flow processes (from Huthnance 1995).

Process	Scale	e.g. m^2/s
Western boundary current and bend	$(h/h_o)^2 (L_x/L_y)\, \tau/\rho\, \beta$	(0.5 Sv)
Slope current and bend •	$v\, \theta\, k\, L_T/f$	(0.01 • Sv)
Cape eddy	$h\, v\, L_T$	(0.1 Sv)
Canyon return flow	$h\, \tau/\rho\, k$	10
Ridge-associated upwelling	$(2\Delta h/h_o)\, \tau/\rho\, f$	1

A schematic of flow in a canyon is shown in Figure 8.11.
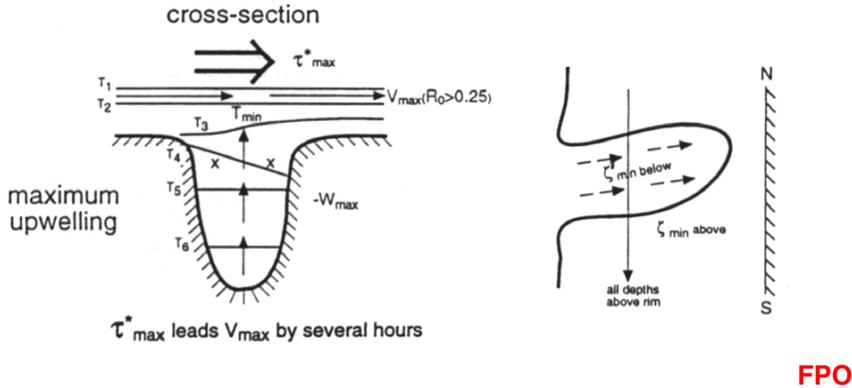
Figure 8.11 Schematic of flow in submarine canyon illustrating data derived characteristic timescales and spatial patterns of alongshelf wind stress, velocity, temperature and vorticity of a maximum upwelling event (From Hickey, 1997).

As with the other processes, the impact on the distribution of nutrients depends on the nutrient content of the water being exchanged.

Tides, internal tides and shear dispersion

Tidal currents have along-shore and across-shore components that vary greatly with location. A scaling for the across-shore transport, hu, is provided by the water required to raise the surface from low to high tide: $hu \sim \sigma W_s \zeta$ where σ, ζ are the tidal frequency and amplitude (in elevation) and W_s is the shelf width (Huthnance, 1995). This may be very large, e.g. 14 m^2s^{-1} for semi-diurnal σ, W_s = 100 km, ζ = 1 m. However, most of this transport returns six hours later (for semi-diurnal tides) and gives little time for any nutrient content to be changed. Hence shear dispersion may be the main process of lateral exchange: nutrients with different depth histories in vertically-sheared tidal currents suffer different net lateral displacements. Comparing modeled to observed tidal-average dispersion over the northwest European shelf, Prandle (1984) found an effective dispersion coefficient $t_D u|u|$ with $t_D = 10^3$s, u being the tidal current above bottom boundary shear, e.g. 20 m^2s^{-1} for the above example and (shelf-edge) depth h = 100 m. This is relatively small: a reduction factor h/L_T gives the equivalent exchange rate, L_T being the topographically related distance for substantial changes in nutrient concentrations.

Internal tides, which are typically induced by tidal flow across the steep continental slope, vertically displace isopycnals, and associated pressure fields and depth-varying currents. Sufficiently large vertical displacements form (non-linear) solitons that transport water and nutrients "bodily" within the wave form. Fluxes per tide are $<\zeta>\lambda$ and may be O(1 m^2s^{-1}) for soliton amplitude $\lambda \sim 50$ m and aggregate soliton length $\lambda \sim 1$–2 km. This means of nutrient transport may be significant for production on the Scotian shelf (Sandstrom and Elliott, 1984).

Rectified tidal flow scales as $u^2/(\sigma L)$ and is small except where tidal currents u are strong and vary on a short length scale L. This may be the result of topography

(cf. the example in *Canyons and Capes* above) or internal tide structure (notably close to the shelf break).

6. Mixing Processes

While it is common for exchange processes to bring water from depth into the coastal ocean, those processes often do not bring nutrient-laden water into the euphotic zone itself. To bring the nutrients to the surface layers where phytoplankton can grow, mixing is critical. Processes that are potentially available for mixing are summarized in Table 4. In particular, buoyancy flux can provide the energy to stratify or de-stratify a water column. Heat loss can equal the mixing of winds and waves. Conversely heat gain and rain or freshwater influx enhances stratification inhibiting mixing. Typically, several processes are greater than the wind-mixing rate.

Since this book is meant for a broad audience, it is worthwhile to review the processes that create and destroy stratification. A stratified water column of a given depth has denser water at the bottom than at the top. When the water column is mixed such that the density is increased at the top and decreased at the bottom, the center of gravity of the water column is raised. This potential energy increase requires energy, which comes from buoyancy forcing (heat, freshwater, evaporation) and mixing forces in as shown in Table 4.

Since many parts of the coastal ocean are stratified, it is apparent that during much of the year heating and freshwater influxes overcome the mixing forces of wind, waves and tide. Only in the cooler seasons, with heat loss, stronger winds, and (in some areas) decreased freshwater influx, does the water column mix. Relatively easy calculations can determine what strength and duration of winds or tidal currents will mix a water column. Lund-Hansen et al. (1996) provide equations and examples of the procedure. The following is taken from their paper.

Stratification in coastal waters can be quantified as follows (Simpson and Hunter 1974):

$$\varphi = \frac{1}{h} \int_{-h}^{0} (\overline{\rho} - \rho)\, g z\, dz$$

where $\overline{\rho}$ is the vertically averaged density, g is the gravitational acceleration (9.8 m s^{-2}), ρ is the water density (kg m^{-3}), and z is the sample depth(m). Changes in stratification can be represented by using the following formulation (used generally for coastal waters):

$$\frac{\partial \varphi}{\partial t}_{w,h,e,c} = -\delta K_s \rho_a \left(\frac{W^3}{h} \right) + \frac{\alpha g Q}{2 c_p} + \frac{1}{320} \frac{g^2 h^4}{N_z \rho} \left(\frac{\partial \rho}{\partial x} \right)^2 - \varepsilon K \rho_w \left(\frac{\overline{u}^3}{h} \right)$$

| Time change of φ | Wave Mixing | heating cooling | Estuarine Circulation | Tidal Mixing |

where the first term on the right is the energy derived from the wind (W), the second is the buoyancy gain(loss) from heating(cooling), the third term is the change related to estuarine circulation, and the fourth is the change related to

bottom tidal currents. Of the four terms, the wind is usually an order of magnitude more important than the others. Advection of buoyancy is occasionally very important (Atkinson et al., 1989).

Estimating variations in stratification is relatively straightforward given the energy inputs (heating, cooling, freshwater influx) and advective effects related to estuarine circulation, shelf edge Ekman processes, etc. Such analysis often yields useful insights that assist the understanding of nutrient dynamics in coastal waters.

However, it is also known that primary production and nutrient uptake are very sensitive to the details of mixing through the water column. Apparently similar stratification resulting from slightly different models of vertical mixing (Chen and Annan, 2000) may be accompanied by significant differences in (i) spring-bloom timing (this may vary by weeks, and can occur before seasonal stratification is obvious), (ii) the continuing chlorophyll maximum near the base of the seasonal thermocline, and (iii) total primary production (50% differences). The sensitivity arises because light near the surface is critical (how much of the time plankton are illuminated enough to grow) and nutrient supply is limited by mixing through the thermocline from below. A model has shown that variations in surface wind stresses episodically weaken the thermocline inhibition to allow nutrient input to the photic zone from below (important to forming a mid-water chlorophyll maximum; Sharples and Tett, 1994). Observational support is given by (e.g.) Eppley and Renger (1988): winds of 5–9 ms^{-1} for about 40 hours off Los Angeles caused mixed layer deepening by about 4 m, entraining about 0.5 mmol m^{-2} nitrate from the nitracline (increasing concentrations in the top ~ 20 m from 20 nmol to up to 100 nmol). Ongoing nutrient supply (to the mid-water chlorophyll maximum) is enabled by turbulence from tidal shears (lagging tidal currents) below and in the thermocline. Sharples et al. (2001) estimated an average nitrate flux 2 ± 1.2 mmol m^{-2}d^{-1} in the strongly stratified western English Channel; here nitrate decreased from 5.7 mmol m^{-3} below to zero just 2 m above; vertical diffusivity K_z was estimated from turbulent dissipation as averaging 0.8×10^{-5} m^{2}s^{-1} (only), but varied by a factor of 100 overall and is the main source of uncertainty in the estimate.

7. Successive regions offshore

Near-shore

In the near-shore region turbulence, mixing, sediment suspension and light attenuation are increased by surface-wave currents resuspending material at the sea bed. Shallow water emphasizes the role of (current-affected) benthic regeneration and fluxes; nutrients from groundwater can be significant.

Vertical mixing forced by wind and waves is exemplified by coastal waters off Perth, Australia, and in the Humber plume, where tidal currents add to the mixing. Off Perth, lateral variability suggests turnover faster than lateral mixing. Nutrient concentrations are low (little runoff and low concentrations in the adjacent ocean), but a productive benthic community can partly account for lateral variability by reducing nitrate more in shallower water (Johannes et al., 1994).

Light limitation by SPM is the main constraint on primary production in the Humber plume. The Humber River plume is a ROFI in one sense—see next section—but the freshwater influence is through SPM content rather than typical ROFI dynamics. Nitrate and silicate are nearly conservative in winter; primary

production and exchanges with the bed affect distributions at other times (Morris et al., 1995). Primary production (hence nutrient depletion) begins when the euphotic-layer depth exceeds 15% of the water-column depth (the diatom bloom is eventually silicate-limited; autotrophic flagellates are eventually limited by grazing because SPM limits nutrient uptake; Allen et al., 1998).

Dissolved inorganic nutrient fluxes from sediments appear to be the major nutrient source (e.g. of order 0.1•mol d^{-1} nitrogen through the water column) in depths < 5m near-shore in the Great Barrier Reef lagoon. For typical adsorbed and pore-water concentrations, resuspension of 0.1 m sediment would add 0.12–0.2 •mol total nitrogen in 10 m water (Ullman and Sandstrom, 1987).

Groundwater input of nitrate in the absence of typical freshwater input is inferred for the Colorado River (an "inverse estuary" with evaporative enhancement of salinity but large tides causing resuspension, turbidity and a near-shore character; Hernández-Ayón et al., 1993). High nitrite, phosphate and silica values are attributed to resuspension of sediments and mixing of pore water into the water column, plus, for nitrite, ammonia oxidation. Leaching of fertilizer has been estimated to exceed natural nutrient flux in groundwater to near-shore waters in several Hawaii locations. Its fate by plankton uptake depends on mixing through the water column (Dollar and Atkinson, 1992).

Regions of freshwater influence (ROFIs)

Buoyancy input from rivers/estuaries, and strong offshore salinity and temperature gradients often create rapidly-varying stratification. ROFIs typically carry high concentrations of riverine nutrients that fuel production and also may carry particulate matter which may block light and inhibit production. Strong offshore gradients combine with strong mixing and rapid exchange out of the Bay of Brest to prevent eutrophication (Le Pape and Menesguen, 1997). Alternatively, upwelling conditions can rapidly advect low-salinity plume waters offshore taking their contents as far as 60 km from the coast of Chesapeake Bay (Reiss and McConaugha, 1999).

Freshwater sources of nutrients are illustrated by several examples: very similar salinity and (nitrate + nitrite) contours in Baie de Seine (France), April-June 1994 (Videau et al., 1998); fluvial and sewage inputs increase winter DIN and DIP in Liverpool Bay (Irish Sea; Gowen et al., 2000); near-surface phosphate and silicate (and chlorophyll-a) decrease rapidly off Georgia as salinity approaches oceanic values (Yoder et al., 1993); near linear decreases of silicate with increasing salinity in the Fly River plume, and a nitrate/phosphate-limited decrease in production further offshore where salinity > 25 (Ayukai and Wolanski, 1997).

The nutrient sources may enhance production, e.g. in spring and summer in Liverpool Bay relative to a location near the Irish coast. However, SPM shading may inhibit production, e.g. in Baie de Seine the spring bloom progresses inshore between April and June, inhibited by Seine-plume turbidity which is most intense near the coast; the Fly River plume has high SPM close inshore in salinity < 10 (Robertson et al., 1998). In this area (Gulf of Papua) rapid detrital decomposition releases benthic nutrients thus satisfying substantial proportions of the phytoplankton requirements for N and P. Inorganic nitrogen is low off Georgia with inputs from riverine and other sources being consumed by primary production near the coast throughout the year but there are high rates of nitrogen recycling

(Yoder et al., 1993). Denitrification is inferred from some offshore reduction in Liverpool Bay nitrogen concentrations (Gowen et al., 2002).

The Gulf of Finland has a near-permanent halocline. Estuarine-type exchange with the Baltic Sea supplies phosphorus to the Gulf and takes nitrogen from the Gulf. Nutrient concentrations are dominated by this exchange, discharges (mostly from rivers) and some atmospheric input. A near-balanced budget appears to hold (Perttilä et al., 1995) in which nitrate and phosphate removal play a role and are mediated by oxygen transfer down through the halocline. In the Polish section of the Baltic Sea, nutrient distributions are affected by sources and depleted by primary production in spring-summer; the ratio of nitrogen and phosphorus seasonal cycles is up to 9 in the open sea and 16 in bays; at depth an oxygen deficiency leads to increasing phosphates and silicates but decreasing nitrates and mineralization (Trzosińska, 1990).

The fjord like Clyde Sea receives nutrient-rich water from the river Clyde. Spatial and temporal variations in near-surface production give corresponding variations in nutrient depletion, and from May into the summer, strong vertical gradients develop (Rippeth and Jones, 1997). Nitrate in the deepest basins increased to ~ 14 •M with more marked increases in phosphate and silicate associated with remineralization of organic matter. These mechanisms and exchanges with the external shelf sea result in the Clyde Sea importing nitrate in summer and exporting in the winter and spring.

Well-mixed regions

Regions of the coastal ocean lacking seasonal stratification occur where tidal and wind-driven currents are strong and buoyancy fluxes are weak. River inflow and atmosphere deposition may be important sources of nitrogen (up to 50% of the winter increase in the German Bight). If these shallow areas are suitably located, upwelling can contribute additional nutrients: e.g. by along-shore advection off southern California (Barnett and Jahn, 1987); strong tidal currents and an eastward jet give "centrifugal upwelling" on the northeast flank of Georges Bank (Pastuszak et al., 1982). Shallow depth and mixing will emphasize the role of benthic processes.

Typically, nutrient concentrations increase in winter and continue until there is enough light for production to begin. This occurs, for example, from October to February in the extensive mixed areas of the southern North Sea outside ROFIs (Howarth et al., 1993), and on Georges Bank, with similar distributions in space and time of nitrate, phosphate and silicate. There is a decrease to near zero in summer (Pastuszak et al., 1982). Higher concentrations of nutrients (and chlorophyll), occur in depths < 30 m than further offshore of southern California. The cause is apparently the increased eddy diffusion, including tidal stirring, and from nutrient recycling (Barnett and Jahn, 1987).

For the southern North Sea, a budget suggests that regeneration from the sediment can explain the silicon increase in winter, but that organic detritus in the water column is an important source for the nitrate increase rather than external sources (Hydes et al., 1999). More remineralization in the water column than in sediments is also found by the model of Tett and Walne (1995). The degree of recycling is spatially variable, and largest at fronts (see next section). N:P ratios 2:1

to 6:1 (< Redfield ratio 16:1 and lower than in any of the source waters; Hydes et al., 1999) suggest that nitrogen is the limiting nutrient element, along with silicate (generally < 60% of nitrate concentrations; Tett and Walne, 1995). Hydes et al. (1999) ascribe the nitrogen deficit to denitrification (equivalent loss rate ~ 0.7 mmol N m^{-2}d^{-1}).

Benthic efflux of silicon supports the summer diatom production at a station near the Irish coast (Gowen et al., 2000). In the Barents Sea coastal zone, nutrients, except nitrate, are input from the bottom all year except spring, when the benthic community also uses nutrients; in 20 m depth or less, the daily fluxes are comparable with the water-column inventory (of which a majority is organic, especially in summer; Kuznetsov and Volkovskaya, 1994).

Tidal-mixing fronts

Tidal-mixing fronts occur at the boundary between well-mixed regions (previous section) and summer-stratified regions (next section). There is a tendency for water from the mixed side to intrude between the upper and lower layers on the stratified side. With mixing across all interfaces, there is increased chance for some lower-layer nutrients to reach the base of the upper layer and then "ride up" over the intruding mixed layer. Evidence that this process caused enhanced plankton growth was found at central North Sea fronts and in the German Bight (where stratification patterns are complex) by Brockmann et al. (1990) and Howarth et al. (1993). Frontal sites in the North Sea optimally combine light and nutrient supply to be locations of maximum nutrient recycling (Tett and Walne, 1995).

Regions that are thermally stratified in summer

Summer thermal stratification occurs in the deeper more offshore portions of the coastal ocean. Here riverine inputs are reduced and oceanic sources are more important. The lower layer tends to moderate benthic effects. Typically, after winter replenishment, upper-mixed-layer nutrients are depleted by a spring bloom near the time of initial thermal stratification (by increased solar heating of the upper waters). Thereafter production is limited by the amount of continuing nutrient supply to illuminated upper waters.

Replenishment of nutrients to the upper layer may occur because of many process: cross-shelf dispersion from the ocean starting with the bottom layer of the middle and outer shelf; vertical diffusion and mixing by storms; benthic release and possibly nitrification (see Whitledge et al. (1986) for examples from the Bering Sea); and, current-topography interaction (see Macdonald and Wong (1987) for examples from Mackenzie shelf).

Spring blooms and ongoing summer production deplete upper-layer nutrients and are sensitive to physical conditions controlling the supply of nutrients to the euphotic zone. There are many examples. In the southeast Bering Sea (Whitledge et al., 1986) production is variably enhanced by wind-mixing prolonging nitrate uptake and by weather systems driving nutrient-rich water from outer- to mid-shelf (Sambrotto et al., 1986). The Argentinean shelf has spatially variable thermocline timing and advection of lower-salinity coastal waters (Carreto et al., 1995). The southwest Gulf of Maine has relatively later in the season depletion by spring

primary production where the (upper) mixed layer is deeper; other variations are introduced by a strong pycnocline in a low-salinity plume—low nutrients with maxima of ammonia and chlorophyll-a below—and mixing over shoals, thus enhancing nutrient and phytoplankton concentrations (Durbin et al., 1995). Remaining (interannually variable) ice cover reduces summer production and nutrient depletion (down to ~ 50 m) on the Mackenzie Shelf (Macdonald and Wong, 1987).

Some regeneration and ammonium are produced in the bottom layer after the spring bloom in the southeast Bering Sea (Whitledge et al., 1986) as well as in the Gulf of Maine. Limited advection in the Gulf of Maine implies that a substantial fraction of the rich-nutrient "reservoir" below ~ 120 m is a result of water-column regeneration. Then higher near-surface concentrations (with cooler temperature) occur repeatedly at a couple of locations near Georges Bank, (Pastuszak et al., 1982). Such regeneration is more widely typical see (section 8).

Shelf edge

The proximity of the shelf edge to the deep ocean lends importance to oceanic sources and the exchange processes discussed in previous sections. Internal waves can cause interior turbulence and mixing.

Off South Carolina, USA, winter wind-driven transports (aside from effects of Gulf Stream eddies, section 4) bring nutrients onto the shelf from the nutrient-rich Gulf Stream (aided by occasional strong wind-mixing throughout the shelf-water depth; Atkinson et al., 1996). Tidal, wind- and wave-forced currents drive cross-slope exchanges $O(1 \text{ m}^2\text{s}^{-1})$ southwest of Britain, and west of Scotland, in a "down-welling" sense on average. Modeled annual nitrate fluxes west of Scotland are on-shelf near the surface: 65 kmol N $\text{m}^{-1}\text{y}^{-1}$ at the top of the slope (140m depth), 126k mol N $\text{m}^{-1}\text{y}^{-1}$ over the slope (300m depth). Near the bed, fluxes are 59 and 194 kmol N $\text{m}^{-1}\text{y}^{-1}$ respectively down the slope (Proctor et al., 2003a; this model lacked several benthic processes). Distributed over the shelf cross-section of $O(20 \text{ km}^2)$, these represent large in/outputs $O(5\bullet\text{M y}^{-1})$. Input of sub-thermocline waters and nitrate in the Yucatan Current onto Campeche Bank is attributed to lateral movement along isopycnals that are geostrophically-tilted raising the nutricline above the shelf break (Furnas and Smayda, 1987; this is analogous to advection across the Gulf Stream to the eastern US slope and shelf waters, section 4).

Upwelling is a source of nutrients at more than just eastern boundaries (discussed in section 5). Along the Siberian coast, it appears to be a source of high concentrations of nutrients in the Anadyr Stream (Nihoul et al., 1993). In the Gulf of Maine, upwelling from the Jordan Basin contributes much of the high nutrient concentrations in flow along the Maine coast (Townsend et al., 1987). Upwelling with increased nitrate occurs around the northern Gulf of Mexico in association with the Loop Current (Walsh et al., 1989), and over the Texas-Louisiana shelf edge (in an Ekman layer below north-eastward flow along the outer shelf; Sahl et al., 1993); here, water with high silicate, phosphate and nitrate concentrations (but low nitrite if coming from below the nitrite maximum) reaches the base of the upper mixed layer. Off the Brazil coast at 23°S, upwelling has been observed with nutrient transfer to the shelf. (Regeneration at the bed, perhaps offset by some denitrification, continued to increase nutrients and deplete dissolved oxygen as the water went further onto the shelf; Braga and Müller, 1998). Upwelling from depth

in the central Skagerrak (e.g. total nitrogen 7.46 ± 1.43 •mol) is a basis for high production over the whole Skagerrak (Fonselius, 1996).

In many cases, the main influences on nutrient distributions are probably upper-layer production, vertical mixing and entrainment to supply the upper layer from below (showing as an inverse nitrate/surface-temperature correlation). On Campeche bank, sporadic mixing into the surface water creates elevated nitrate concentrations (and phytoplankton patches; Furnas and Smayda, 1987). Southwest of Britain, the top 50 m is depleted by summer production (when nutrients in 100–300 m are greater than in winter; Hydes et al., 2001). Autumn deepening entrains more nutrients to (late-season production in) the surface layer, which is replenished by winter mixing. For mixing and entrainment, Huthnance et al. (2001) estimated O(100m) equivalent entrained water depth near Goban Spur; possibly hundreds of meters depth further east where large internal tides diffuse the thermocline. Wollast and Chou (2001) estimate 18 g N m^{-2} annually entering the euphotic zone from below annually in order to balance the nitrogen budget; in terms of nitrate at (typically) 8 •mol this is a comparable 160 m equivalent entrained depth. Wollast and Chou also show most water column detritus remineralizing to ammonium, much of which nitrifies to nitrate (especially below the euphotic zone).

Benthic fluxes in slope and shelf waters off Washington, USA, were equivalent to 0.4 to 1.7 mol N m^{-2}y^{-1} nitrogen gas to the water column, and exceeded the nitrate flux to the sediments; the difference could be accounted for by oxidation of ammonium to nitrate and subsequent denitrification to N$_2$ (Devol and Christensen, 1993). These rates (aided by macrobenthic irrigation) correspond to ~ 10•M through 100m water depth (per year), and so can be significant in nitrogen budgets.

8. System studies

North Sea

Non-seasonal components of North Sea nutrient distributions indicate specific riverine and broader oceanic sources. Full-depth winter mixing gives similar surface and bottom values (e.g. Brockmann et al., 1990; Howarth et al., 1993). Nutrient minima in the shallower Dogger Bank region of the North Sea indicate some winter production. In spring, concentrations generally decrease, especially in the surface layer above seasonal stratification; production nearly exhausts limiting nutrients there (Tett and Walne, 1995). However, ammonia in the bottom layer can increase as settling biomass decomposes (Brockmann et al., 1990). A seasonal cycle accounts for most of the variance in nutrients and shows summer depletion of nitrate and silicate consistent with their role as limiting nutrients (Prandle et al., 1997). Annual cycles of some nutrients have been modeled quite well (Radach and Lenhart, 1995), but ammonium and nitrate were not depleted enough by the model's primary production in spring (possibly also an effect of excess nutrient dispersion in the model's coarse horizontal scale). As well as production, remineralization is critical to nutrient concentrations and especially to nutrient availability for further production (with recycling several times per year). Nedwell et al. (1993) estimated benthic fluxes of nutrients out of the sediments as fractions of the corresponding element assimilated in net primary production: N, 4–10%; P, 10–26%; Si, 14–38%; for N, this is an excess of nitrate and ammonium out of the sediments over nitrite into the sediments. The North Sea is a large shelf sea;

over nitrite into the sediments. The North Sea is a large shelf sea; advection plays only a minor role during the season of production; vertical exchanges are all-important. On longer time-scales, however, the North Sea is a net sink for nitrogen (with substantial denitrification, see section 7, **Well-mixed Regions**) requiring an average oceanic inflow of 0.6 Sv with 7.5 •M nitrate for balance (Hydes et al., 1999).

The ability of models to describe North Sea ecology has been reviewed by Moll and Radach (2003). Models can reasonably represent nutrient sources from land and ocean, mixed and stratified regimes, light attenuation, for at least one nutrient. However, model capabilities should be extended to include multiple nutrient s, algal partitioning and succession, and improved simulation of turbulence and nutrient supply across the thermocline. Present sediment chemistry parameterization is insufficient for modeling long-term trends.

Budgeting is implicit in any correctly functioning model. Thus Proctor et al. (2003b) modeled advective, cross-thermocline, plankton uptake, benthic, riverine and recycling components for 1995 in sub-areas of the northwest European shelf, and fluxes across selected sections. Overall import from the ocean to offset denitrification is confirmed. The large-scale fluxes are similar to each other, tending to follow large-scale circulation, except that nitrate and phosphate (not silicate) exit the Irish Sea from the south as well as the north to give a net export. In the northern and central North Sea, near-surface depletion causes the majority of nitrogen and phosphate uptake by plankton to be in or below the thermocline. While, below the thermocline and in the mixed southern North Sea, most nitrogen and phosphate supply is benthic or from recycling. Finally, for silicate, the balance is largely between benthic flux and plankton uptake.

Irish Sea

The Proctor et al. (2003b) Irish Sea fluxes contradict the following table (in Gmol/yr) from Simpson and Rippeth (1998), which uses the LOICZ budgeting approach.

TABLE 6
Irish Sea Fluxes (Proctor et al, 2003b). Units Gmol/yr.

	River input	St Georges Channel input	North Channel output	mol $m^{-2}yr^{-1}$
DIP	0.87	0.71	1.27	0.007 uptake
DIN	9.71	10.6–14.1	11.4	0.3 denitrification

The LOICZ approach could only export P and N to the south if in- and out-flow concentrations were known to differ, given the net inflow of water. (Sensitivity to P and N inputs and boundary values or gradients render the phosphorus uptake below the level of significance).

Northern Adriatic

Northern Adriatic nutrients have been budgeted by Degobbis and Gilmartin (1990). They found that contributions to N, P and Si exceeded losses by 20–50%. The Po river input (see ROFIs) is important with at least 50% of the input. Denitrification in sediments is about 40% of the nitrogen output; for phosphorus and silicon, burial in the sediments is a significant loss. Biological recycling exceeds the inputs and makes the water column the principal location of N and P regeneration; most orthosilicate regeneration is in the sediments.

9. Summary

The simple transport of nutrients into and out of the global coastal ocean critically determines a large percentage of primary and higher-level production in the ocean as a whole. Globally, the atmosphere and rivers are minor sources of coastal-ocean nutrients, but riverine inputs are important locally. The deep-ocean source of remineralized nutrients is effectively limitless but supply to the coastal ocean is severely restricted by dynamic processes. Small variations in the relevant forces cause large variations in the nutrient influx. The processes that affect the movement depend on interactions of currents with topography, winds and vertical mixing, all of which can vary. Recycling in the water column and through the seabed is important to nutrient and plankton composition in shallower coastal seas.

Many of the important processes such as upwelling winds, mixing events or boundary current eddies are episodic. Some may occur only a few times during a season or vary strongly with latitude. This variability will no doubt change as climate changes; it behooves us to learn more about these processes. With that knowledge, we may better predict the effect on fisheries and carbon sequestration.

Acknowledgements

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