5.2 The Northeast Atlantic Margins.

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5.2.1. Region and Topography.

This subsection treats sectors of the North Atlantic ocean margin from Cape Ortegal in NW Spain around Biscay and the British Isles to the Norwegian shelf as far as 70°N (Fig. 5.2.1). The Faroes, Iceland and East Greenland shelves are also included. The North Sea is excluded, being treated elsewhere as a marginal sea (Chapter 7.3). Another subsection treats the sub-polar Northwestern Atlantic which continues to Labrador and the American margin as far as Cape Hatteras (Chapter 5.3).

Table 5.2.1 gives some overall shelf areas and volumes. In global terms, North Atlantic sub-polar shelves are quite broad and irregular, especially compared with other eastern ocean margins. The shelf width is variable in the region, ranging from 10-40 km off northern Spain, 50 km increasing to 100-150 km in eastern Biscay, and approximately 500 km in the Celtic Sea. Widths are 50-150 km around Ireland and 100-200 km around Scotland with a very irregular coastal boundary and many islands. The Norwegian shelf broadens from about 20 km at 61°N to 50-100 km at 62°-63°N and 200 km breadth by 65°-68°N, before narrowing again to about 50 km around 70°N. Vestfjorden is a notable feature extending north-east between the Lofoten Islands and the mainland near 68°N.

Typical shelf depths are 100-150 m around Biscay and in the Celtic Sea, continuing at about 150 m around Ireland and Scotland, 130-140 m at 61°N on the N. Scotland shelf and increasing to 400 m in the Norwegian Trench. Depths on the Norwegian shelf are quite large and variable, extensively 200-300 m or more except over banks and close to the coast. The continental slope is steep in the south, and is indented with a few large canyons in southern Biscay and many smaller canyons north of Cape Ferret Canyon (44.7°N) as far as Goban Spur (49°N, 11°W). The Porcupine Sea Bight is a deep (2000 m) intrusion between Goban Spur (depth ~ 1000 m) and Porcupine Bank (depth shoaling to < 200 m but hydrographically semi-detached from the western Irish shelf). Around Scotland the upper slope is relatively smooth and steep south of the Wyville-Thomson Ridge, but relatively gentle (a slope of generally 0.02 or less) to the north east. Off Norway the shelf edge becomes less regular.

The main Atlantic basin and Nordic seas are separated by the Greenland-Scotland ridge, including Iceland and the Faroes. The ridge is typically at 200-400m depth, with maximum depth ~ 640 m in Denmark Strait between Greenland and Iceland, ~ 500 m between Iceland and the Faroes, ~ 850m in Faroe Bank Channel between the Faroes and Scotland. The Faroes shelf has typical diameter 200 km and depth 100-200 m; slopes are relatively gentle except in Faroe Bank Channel to the south-west. The Iceland shelf is part of the Mid-Atlantic Ridge, extending to the southwest (Reykjanes Ridge) and the north (Kolbeinsey Ridge). Although only about 15 km wide off the south coast, the sloping Iceland shelf is generally much broader, reaching 150-200 km to the west. It is indented with "deeps", generally related to fjords and river systems; however, the south coast has no fjords. The east Greenland shelf is typically 100 km wide; the majority is 200-500 m deep. However, it has fjordic indentations so closely spaced that overall dimensions are very approximate and of limited meaning. The coasts of Scotland, Norway, the Faroes, western and northern Iceland and Greenland all have many fjords.

5.2.2 Hydrography and Physical Processes.

Warm, saline North Atlantic Water (NAW) forms a poleward current along the continental slope around Biscay and on past Britain and Norway (e.g. Pingree *et al.*, 1999; Souza et al., 2001; Skagseth *et al.*, 2004). It is thought to be forced by the dynamic height of warmer sub-tropical waters (Huthnance, 1984; Hill et al., 1998). Other branches of NAW flow anticyclonically around the Faroes and Iceland and then mostly eastwards to enter the Nordic seas. On the Celtic Sea shelf, mean flows are weak but supply ~0.1 Sv eastwards through the English Channel and ~0.1 Sv northwards through the Irish Sea. Baltic outflow feeds the northward-flowing Norwegian Coastal Current. Arctic waters form the southward East Greenland Current. A sharp meandering front separates NAW from the East Greenland Current in Denmark Strait. On the SE Icelandic shelf, a sharp front separating NAW from the East Icelandic Current moves seasonally (Stefánsson 1972; Hansen & Østerhus, 2000). Below shelf depths, the Greenland-Scotland Ridge divides warm, relatively saline NAW in the south-west from Arctic waters in the north-east; nutrient concentrations in these deep regions also differ. Winter cooling in the Nordic seas forms a cold dense bottom layer, which spills southwards over the sills between Greenland and Scotland. Water formed by deep convection in northern Biscay flows slowly southwards to Iberia (van Aken, 2001).

The region is subject to strong *wind* forcing, at its most intense around 60°N. The winds are variable, usually associated with the passage of cyclones (depressions), and not particularly associated with up- or down-welling. However, the relative orientation of the Irish-Norwegian shelves and prevailing westerlies favours downwelling. Over the typically broad and relatively weakly-stratified shelf, wind-forced motion is often manifested as storm surges in the form of (coastal) Kelvin and continental shelf waves. Friction and short-term variability enable wind-driven cross-slope exchange. Here we have estimated this as an Ekman transport,

$$T_E = \rho_a c_D \left(W^2 \cos\theta + w'^2 \right) \big/ \left(\rho_w f \right) \qquad (5.2.1)$$

where ρ_a = 1.25 and ρ_w = 1027 are the densities of air and water in kg m^{-3}, c_D = 0.0012 is the drag coefficient, W is the monthly mean wind speed at an angle θ to the along-slope direction, w' is the wind's standard deviation (taken as isotropic) in the along-slope direction, and f is the Coriolis parameter. Table 5.2.1 gives annual averages of this cross-shelf edge Ekman flux, using wind speeds from Josey et al. (1998; 2002), and wind directions and standard deviations from Isemer and Hasse (1985).

Semi-diurnal *tides* are large in the north Atlantic generally. Tidal currents exceed 0.1 m/s across the wide shelves of most of the north-east Atlantic margin, creating significant turbulence and mixing. Locally in straits and around headlands, tidal currents often exceed 0.5 m/s. These currents are primarily barotropic, but internal tides with comparable peak currents are generated over steep slopes. Large-amplitude (non-linear) internal tides can transport water in their wave-forms on the summer thermocline. Locally, strong tidal currents may be rectified to along- and cross-slope flow, usually near small-scale features (e.g. headlands) and the upper slope. Although generally small, such rectified flows may contribute significantly to long-term displacements (Holt and Proctor, 2008).

Shear dispersion, K, results from variations of tidal current with depth. Observed spreading of caesium-137 on the north-west European shelf can be modelled by a horizontal dispersion coefficient $K = t_D U^2$, where $t_D \sim 10^3$s , and U (m s^{-1}) is the tidal current amplitude (Prandle, 1984). This approach suggests that shelf-edge exchange from this cause is relatively small unless U > 0.5 m/s.

Buoyancy inputs are the other main source of forcing. Direct lateral inputs of freshwater from land and rivers are moderate in global terms, but drive anti-cyclonic flows around Ireland, Scotland, the Faroes and Iceland. The largest sources of fresher water are the Norwegian Coastal Current (originally from rivers into the Baltic Sea), the Arctic feeding the East Greenland Current, and melting and calving from the Greenland ice cap. Surface fresh-water buoyancy input from precipitation minus evaporation is within ±200 mm a^{-1} over much of the region. Summer heating and winter cooling force a strong seasonal cycle of stratification in most areas.

Stratification is favoured by the buoyancy inputs but eroded by mixing due to tidal currents, winds and waves (surface and internal). Typically, shelf seas are partitioned in a sequence moving from very shallow water out to the open shelf, e.g. mixed by waves in the nearshore, a Region of Freshwater Influence (ROFI) that may be stratified, shallow coastal water mixed by strong tidal currents and winds, and deeper shelf water thermally stratified in summer. On the northwest European shelf, the “tidal mixing” front between the latter two is inshore of the shelf edge (Simpson, 1998a,b), with the outer shelf being stratified in summer. ROFI stratification depends on riverine freshwater discharge as well as winds and tidal mixing. Intermittency of ROFI stratification arises from variability in all these factors. Additionally, winds can spread the outflow plume or confine it against the coast, according to wind direction. Generally, friction tends to give “estuarine” cross-frontal or cross-shelf circulation: upper offshore flow of fresher water, onshore flow beneath as different waters seek their own density level. Coriolis effects turn the flow anti-cyclonically along fronts.

Inertial-internal waves are particularly active at the shelf edge (a source of these waves). They are distinctive in causing mixing within the thermocline (via shear and large-wave breaking), and at the bottom for a favorable combination of slope, stratification and wave frequency. *Surface waves* are important for surface mixing and for air-sea exchange in this region of strong winds and rough seas.

The depth of winter mixing exceeds shelf depths in the whole region. It reaches only 200-300 m depth in the Iceland Sea, about 300m in the central N Atlantic, >500 m in Biscay, and as deep as 750-900 m around 50°-60°N west of Ireland, Scotland and Iceland (in the Irminger Sea). Deep convection occurs in small cells but probably extensively in the Nordic seas. Water and its contents from below the seasonal thermocline are thus mixed to the surface during autumn and winter. In spring, the developing seasonal thermocline is much shallower than the winter-mixed depth and vertical exchange within, or at the base of, the surface waters becomes limited to a thinning layer.

Dense water formed by winter cooling of shallow shelf seas may cascade down the slope under gravity, eventually leaving the sloping bottom at its density level. Typical values of such cascading fluxes are estimated in Shapiro et al. (2003) as 0.5 – 1.6 m^2s^{-1}; significant when and where they occur. Beneath the poleward slope current is a bottom *Ekman layer,* modified by the slope and stratification (e.g. Trowbridge et al., 1998), where friction reduces the current to zero. Down-slope exchange transport in this Ekman layer is O(1 m^2/s) (Huthnance, 1995). Instabilities in the slope current can also cause exchange.

Our region is north of the area of developed upwelling and regular filaments. However, the irregular shelf , with capes, canyons and varied shelf width, may cause locally-enhanced up-/down-welling and cross-slope flow (Trowbridge et al., 1998). Discrete exchanges may be comparable with the slope current transport, O(1 Sv), equivalent to 1 m^2/s if occurring at 1000 km intervals along the shelf.

Some estimates of overall cross-slope exchange are given in respective sector discussions and Table 5.2.2.

5.2.3 Primary Production.

The sub-polar North-East Atlantic includes the following provinces of Longhurst (1995, 1998): parts of the *Atlantic Subarctic* (SARC) and the *Atlantic Arctic* (ARCT) with irradiance-mediated peak production, the *North Atlantic Drift* (NADR) influenced by westerlies and with a nutrient-limited spring peak, and the *Northeast Atlantic Shelves* (NECS) at mid-latitudes with spring and autumn blooms. Only for the NECS does accumulated organic matter correspond with integrated production on short time scales.

Primary production is described by Pingree et al. (1976) and Longhurst (1998). A spring bloom begins when the light-determined critical depth for net algal growth descends to the mixed-layer depth, which shoals as heating increases and wind stress decreases. From year to year the timing of this bloom event may vary by several weeks. Overall, shoaling of the seasonal thermocline and the bloom progress northwards. However, the timing can be affected locally, for instance shallow ROFI stratification may advance the bloom, or sediment suspension can limit the available light and delay growth in spring so that production peaks with light in summer. The initial spring bloom is normally dominated by diatoms, with flagellates following when silicate is depleted. At the shelf edge around 45°-60°N (Holligan et al., 1983) satellite images sometimes show blooms of the coccolithophore *Emiliania huxleyi*, a source of calcite. Open-sea patches suggest that perhaps eddy dynamics affect spring production, with vertical motion and sloping isopycnals enhancing local and overall production. The bloom becomes nutrient-limited when the initial near-surface charge is exhausted.

Summer growth depends on biologically regenerated nitrogen (as NH_3), NO_3 entrained through the thermocline by turbulence from winds, waves and internal waves, and Ekman suction from wind stress curl. Additionally on the shelf, tidal mixing can supply nutrients to the euphotic zone, with fronts between summer-stratified and mixed waters particularly favoring phytoplankton growth (Pingree et al., 1978). ROFIs with intermittent stratification increase the scope for nutrient supply from depth to a shallow surface layer. Shear dispersion can enhance nutrient supply, and mixed waters also provide nutrients directly from benthic regeneration. An autumn bloom, usually weaker than the spring bloom, may be fuelled by nutrients entrained in the deepening mixed layer, as wind stress increases and solar heating declines.

Production in the open ocean is of the order 60 g C m^{-2} a^{-1} (Wollast, 1998). The shelf/ocean distinction is reduced at sub-polar latitudes (the reason for this separate chapter), with typical shelf-sea production of order 100-250 g C m^{-2} a^{-1} (Table 5.2.3). Estimates in particular areas are given by Russell et al. (1971), Cushing and Walsh (1976), Walsh (1988), Howarth et al. (1993); see also the discussion for individual sectors.

5.2.4 Flux Estimates.

a) Water Fluxes.

Budgeting for a sector of continental shelf and slope with "south" (S) and "north" (N) ends, Huthnance et al. (2002a) found:

$$\left(C_S - C_N\right)\left(q_S + q_N\right)/2 = q_R\hat{C} + \sum_i q_i'C_i' \qquad (5.2.2)$$

Here q_S is the southern inflow, q_N is the northern outflow, and q_R is the river inflow plus precipitation minus evaporation. C_N and C_S are the northern and southern concentrations (i.e. salinities), so that the mean concentration in the box is $\hat{C} = \left(C_S + C_N\right)/2$. The eddy exchange rate across side *i* is q_i' with inflow concentration C_i; $C_i' = \hat{C} - C_i$. The approach described by equation 5.2.2 is analogous to LOICZ methodology with explicit river input. LOICZ methodology uses C_i' to infer q_i' from the other "known" quantities (with typically only the oceanic side *i* being involved). However, for a large sector of shelf this approach may not be valid. The flows q_S and q_N may be larger than q_i' and $\left(C_S - C_N\right)$ uncertain; then the budget is difficult to balance (Huthnance et al., 2002a). The inferred q_i' is thus sensitive to uncertain $\left(C_S - C_N\right)$ and to off-shelf salinity differences C_i', which are relatively small and variable in much of our region (e.g. Lee and Ramster, 1981; values used in Table 5.2.3)). However, process-based estimates of Iberian ocean-shelf exchange and three independent empirical estimates have given fair agreement (Huthnance et al., 2002a). Hence in our Table 5.2.3 estimates of q_i' are based on these process estimates, listed in Table 5.2.2 (using local studies and some extrapolation between sectors), rather than the LOICZ approach.

For *precipitation (Pr)* and *precipitation-evaporation (Pr-Ev),* three alternative estimates are given in the rows of Table 5.2.3. Josey and Marsh (2005) find that Pr and Pr-Ev have increased by O(100-200 mm/yr) during 1960-2000. Hence errors are probably of order 200 mm/yr; more in some sectors judging by comparison between the alternative Pr values. The conversion of Pr and of Pr-Ev to m^3/s in Table 5.2.3 is for the average of the three values in each case.

Mean In-/out-flows in Table 5.2.3 are based on local studies but connect sectors of shelf. Values exclude slope currents. Frouin et al. (1990) suggest a poleward current O(0.2 m/s) into the S Biscay sector above 200 m depth in winter, though continuation to E Biscay is probably relatively small. Figure 15 in Pingree and LeCann (1989) suggests a small Biscay-Celtic Sea shelf transport. Transport estimates from the Celtic Sea to the west Irish shelf and from there to the west Scottish shelf lack a firm basis but adjacent values suggest O(0.1 Sv) in each case. The Irish Sea mean through-flow estimate of 0.077 Sv is from Knight and Howarth (1999); west-to-northern Scotland is from Bradley et al. (1991) and citations therein. Values from/to the North Sea come from Lenhart et al. (1995), Huthnance (1997) and citations therein, and the Norwegian Coastal Current off northern Norway is estimated as 0.7Sv (Gascard et al., 2004).

Inputs of riverine freshwater (Table 5.2.4) are estimated from information accessed via LOICZ (http://www.nioz.nl/loicz), Unesco (1969, 1971), OSPAR (2000) and the UK National River Flow Archive (UK Centre for Ecology and Hydrology: http://www.nerc-wallingford.ac.uk/ih/nrfa/index.htm). Groundwater has been neglected hitherto. While it is probably insignificant as a contribution to water fluxes (since the riverine input is quite small), groundwater constituent concentrations might be large enough to impact on budgets. We have little basis for any estimates.

b) Sediments.

Sediment fluxes for some rivers have been scaled up for three shelf sectors (Table 5.2.5). The calculations use mean annual cycles of flow and suspended particulate concentrations from the UK Department of Environment (now Defra) Harmonised Monitoring Programme. Relative to a global fluvial sediment flux of about 15×10^9 T/yr, which averages to 50 kT/yr per kilometre of shelf edge, these inputs to west-European shelf seas are small. Only a fraction is organic, so sediment inputs in our shelf sectors are also small relative to some other fluxes, e.g. CO_2 from the atmosphere.

Strong currents and turbulence can erode sediments and retain particulates in the water. Especially, waves reaching the bottom suspend sediment effectively. Near-bed turbulence, stress and sediment mobility, studied at several locations around the north-west European margin, show effects of surface waves even at depths of 200m in winter. In all upper slope locations measured, Huthnance et al. (2002b) conclude that bed stresses are often sufficient to move the local sediment. Therefore any sediment reaching the shelf edge is liable to export from the shelf, especially in the down-slope Ekman layer under the slope current. However, much sediment tends to be retained nearshore on the shelf. The reduction in energy offshore may allow deposition, with estuarine-type circulation favouring onshore near-bed transport and even trapping in estuaries. Accordingly, the deposition of organic matter on continental slopes is reduced and burial is estimated to be very small, e.g. O(0.1%) of production over Goban Spur.

(c) Nutrients: phosphorus (P), nitrogen (N), carbon (C)

Considering first riverine fluxes of nutrients, available estimates are summarized in Table 5.2.3. Howarth et al. (1996) estimated total phosphorus and nitrogen inputs to the sea, per km^2 area of catchment, with Seitzinger and Kroeze (1998) estimating a similar value of about 1 tonne N per km^2 for the NE Atlantic margin. For several rivers flowing into the Channel, Celtic and Irish Seas, average phosphorus is about 0.26 mgP l^{-1} (Table 5.2.3; UK Harmonised Monitoring Programme). Cauwet and Martin (1982), Seifert (1982) and Lugo (1983) estimate organic carbon (OC) transport in French rivers, and in Spanish rivers as export to the north Spanish shelf (Table 5.2.3). Nixon et al. (1996) have estimated fluxes of total phosphorus and nitrogen from rivers onto the continental shelf on broader scales (Table 5.2.6). They allowed for P and N retention in estuaries (about 70% retention if their north-west Europe value is to be consistent with the other estimates), and from a wide range of published data they found

$$\text{Retention } \% = 19.2 + 31.83 \log_{10} RT \quad \text{(phosphorus)} \qquad (5.2.3a)$$

$$= 35.2 + 27 \log_{10} RT \quad \text{(nitrogen)} \qquad (5.2.3b)$$

where RT is the residence time in months. Some riverine organic matter may also be retained in the estuary.

Information is also available on atmospheric deposition of nitrogen. Prospero et al. (1996) cite an observed nitrate + ammonia deposition of 9.6 mmol-N m^{-2} yr^{-1} at Maes Head. Models agree well with this value, giving confidence in total model deposition values in our region (Prospero et al., 1996) interpolated for Table 5.2.3. Duce et al. (1991) give values for specific locations, also interpolated for Table 5.2.3. A figure in OSPAR (2000) enables estimation of the oxidised nitrogen component for west-British seas. Prospero et al. (1996) also quote DON wet deposition fluxes 4 and 8 mmol-N $m^{-2}yr^{-1}$ in the North Sea and north-east Atlantic respectively. However, note that Spokes et al. (2000) caution that deposition, e.g. at Maes Head, can be very variable according to wind direction. They found a total 11 mmol-N m^{-2}, including organic nitrogen, in May 1997 alone, largely resulting from south-easterly winds.

The NE Atlantic region is thought to be a net sink for atmospheric CO_2, though estuaries and shallow seas can emit CO_2 (e.g. the Gironde and southern North Sea (Frankignoulle et al., 1998; Thomas et al., 2004)). WOCE sections between Goban Spur, S. Greenland and Iceland show total CO_2 concentrations 2120-2130 μmol kg^{-1} at 200 m depth and surface concentrations 2050-2095 μmol kg^{-1}, with S. Greenland at the top end of this range. The data used in Takahashi et al. (2002 and personal communication) give fluxes of about 17 gC m^{-2} yr^{-1} off east Greenland (limited by ice cover) to > 50 gC m^{-2} yr^{-1} around Scotland and the Faroes where winds are strongest. These values are consistent with other estimates: 1-5 mol m^{-2} yr^{-1} in 44°-50°N (Lefèvre and Moore, 2000), 4.8-7.9 mmol m^{-2} d^{-1} for the Gulf of Biscay and adjacent seas (Frankignoulle and Borges, 2001; the range covers various gas exchange coefficients), and 1.7 mol m^{-2} yr^{-1} in the northern North Sea (Thomas et al., 2004). The sink may be decreasing as pCO_2 in the North Atlantic increases faster than in the atmosphere, perhaps through reduced productivity (Lefèvre et al., 2004). Nevertheless, we use the Takahashi et al. (2002) data for Table 5.2.3.

DIN and DIP concentrations are strongly seasonal as primary production takes up nutrients, but spatial differences are needed for estimates of fluxes between shelf sectors and the ocean. Values in Table 5.2.3 come from many sources as annotated there, and typically are seasonally averaged. USJGOFS covers all sectors (http://usjgofs.whoi.edu/las/servlets/dataset?catitem=1018).

Dissolved organic concentrations in the Atlantic are typically 3-5 µmol-*N* l^{-1}, 0.2 µmol-*P* l^{-1} (Michaels et al., 1996). *DOC* concentration in the NE Atlantic is typically 60 µmol l^{-1} in upper waters and about 45 µmol l^{-1} at depth (Hansell and Carlson, 2001). Other DOC, POC and total particulate N (TPN) concentrations in Table 5.2.3 are estimated from data held by the British Oceanographic Data Centre.

Estimates of advective fluxes exist for many of the lateral in-/out-flows (Table 5.2.3). Phosphate and nitrate fluxes for N Scotland and Norwegian sectors to/from the northern North Sea were estimated by Laane and Kramer (1997) and Radach and Lenhart (1995). However, fluxes in Table 5.2.3 use values in Thomas et al. (2005). Modelled 1995 N and P fluxes between various north-west European shelf sectors based on Proctor et al. (2003a) are also given in Table 5.2.3. Thomas et al. (2005) and Proctor et al. (2003a) use the ecosystem model ERSEM applied for 1 to 3 years (only) on a hydrodynamic model space-time grid with lateral resolution 60-120 km, 12 km respectively. ERSEM includes representations of transport tied to the hydrodynamics, growth, physiology and mortality for phytoplankton, bacteria and zooplankton subdivided according to size classes or feeding method; detritus; sinking and remineralisation; nitrate- and ammonium-nitrogen, phosphorus, silicate and oxygen. Note that standard deviations based on week-to-week variability are typically 1-4 MtN yr^{-1}, 0.1-0.5 MtP yr^{-1}.

Denitrification was estimated by Seitzinger and Giblin (1996) as a fraction of primary production, and is included in Table 5.2.3 insofar as resolvable. Nitrous oxide emissions in Table 5.2.3 use Seitzinger and Kroeze's (1998) estimate of 50 kgN km^{-2} yr^{-1} for shelf seas in our region.

Nitrogen balances for western Europe have been estimated by Nixon et al. (1996) (Table 5.2.6). They used river inputs as described above, estimated atmospheric inputs from Prospero et al. (1996) and denitrification from Seitzinger and Giblin (1996). The balances show that overall (including the North Sea) burial is comparatively small but denitrification exceeds the combined riverine and atmospheric nitrogen input. Hence oceanic supply is inferred. By regression on a wide range of published data, Nixon et al (1996) also find

$$\log_{10} \mathrm{PP} = 0.442 \log_{10} \mathrm{DIN} + 2.332 \qquad (5.2.4)$$

where PP is primary production, gC m^{-2} yr^{-1}, and DIN is the dissolved inorganic nitrogen supply, mol m^{-2} yr^{-1}. Thus a DIN supply 7 to 14 gN m^{-2} yr^{-1} would correspond to a PP of 158 to 215 gC m^{-2} yr^{-1}.

Phosphorus balances are different overall, as there is no counterpart of denitrification to offset river inputs. With little burial, Nixon et al. (1996) infer net export to the ocean of organic and dissolved inorganic phosphorus DIP. The DIP export may be a relatively small imbalance in large ocean-shelf exchange.

5.2.5 Discussion by sector, with previous budget attempts

Southern Biscay

This is the relatively narrow north Spanish shelf from Cape Ortegal at 8°W to the Spanish-French border near 2°W. The estimated ocean-shelf exchange of approximately 1.6 m^2 s^{-1} is dominated by wind-forced flow (Table 5.2.2). Winds drive summer upwelling around Cape Ortegal and on the Cantabrian shelf, enhancing production (OSPAR, 2000). However, the associated exchange is believed to be less than further west (Finisterre) and south where upwelling filaments develop (Huthnance et al., 2002a). Slope water eddies are shed into the ocean, especially around Cape Ortegal (Pingree and LeCann, 1992); Huthnance et al. (2002a) estimated about five eddies per year in this sector, for a relatively small exchange 0.16 m^2 s^{-1}.

Riverine freshwater input greatly exceeds net precipitation-evaporation over this small shelf area (Table 5.2.3). Estimated ocean-shelf exchange is larger than in- and out-flows along the shelf. Production greatly exceeds what can be fuelled by riverine and atmospheric inputs, and so depends on oceanic inputs to the shelf (assuming reasonable adherence to equation 5.2.4). Estimated organic carbon burial is negligible.

Eastern Biscay

This sector extends from the Spanish-French border near 43.4°N to Ouessant (48.5°N). An estimated excess of evaporation over precipitation only slightly offsets freshwater input from rivers, notably the Garonne, Dordogne and Loire. Nevertheless, salinity on the shelf is close to open-ocean values (Table 5.2.3). This is an indicator of effective (mostly wind-forced) ocean-shelf exchange, larger than in- and out-flows along the shelf. Assuming reasonable adherence to equation (5.2.4), production greatly exceeds what can be supported by riverine and atmospheric inputs, particularly as these are exceeded by northward outflow of N, P. Hence production is inferred to depend on oceanic inputs to the shelf. Again, estimated organic carbon burial is tiny.

Detailed studies have been carried out on the Bassin d'Arcachon and Gironde. The former, covering an area of 155 km^2 of which only 40 km^2 is sub-tidal, receives an average of about 30 m^3s^{-1} freshwater inflow giving strong salinity gradients (Castel, Caumette and Herbert, 1996). The majority of the production occurs as sea grass *Zostera noltii,* reflecting the largely intertidal context (the green alga *Monostroma obscurum* is increasing). However, estimated denitrification is low at < 2 gN m^{-2} yr^{-1}. From the Gironde, large suspended sediment discharge is partly transported northwards along the coast in the surface plume, partly deposited on a nearby offshore mud patch, and partly carried to Cap Ferret Canyon (2-3%, a significant proportion compared with small suspended sediment fractions generally reaching the shelf edge; Ruch et al., 1993).

Channel

The English Channel, or La Manche, is taken east of a line from Ouessant to Land's End (50.05°N, 5.7°W) as far as the narrowest section across Dover Strait (North Sea boundary). Transport of about 10^5 m^3 s^{-1} from the Celtic Sea to the North Sea represents a transit time of many months in southern areas of the Channel, longer in the north. River input of freshwater exceeds precipitation-evaporation but has a small effect on overall salinity. Advective fluxes and riverine and atmospheric inputs of N, P appear to be comparable despite varied estimates. However, the N, P budgets of Proctor et al. (2003a; Table 5.2.7a) show a predominance of benthic and recycled contributions to phytoplankton uptake. Russell et al. (1971) estimated primary production in the Channel for 1965-1970 (Table 5.2.3 shows the mean but there appeared to be a rising trend; indeed their value is less than the carbon equivalent of Table 5.2.7a for 1995).

A detailed budget for the Solent exists (Smith, 1996a). With an area of about 200 km^2 and a mean depth of 9 m, this estuary comprises just 0.04% of the total Channel volume. However, it receives ~ 30 m^3 s^{-1}, or 3%, of the run-off with strong nutrient concentrations. The residence time is estimated as 19 days. Production and respiration estimates are ~ 150 gC m^{-2} yr^{-1} (similar to the Channel as a whole) and 100 gC m^{-2} yr^{-1}. Denitrification is large, exceeding fixation by 14 gN m^{-2} yr^{-1}. Thus the Solent is an atypical 0.2% of the Channel area.

Celtic Sea

We take this as the area north of 48.5°N, west of the Channel, and south of the Irish Sea and Ireland as far as Dursey Head (51.6°N). The Ocean Margin Exchange (OMEX I) project studied biogeochemical fluxes in detail near Goban Spur during 1993-1997.

Low-frequency circulation in the Celtic Sea is generally weak (Pingree and le Cann, 1989) except along the upper slope and where channeled or accelerated around promontories. Tidal currents are strong, exceeding 0.5m s^{-1} at the shelf edge west of Brittany, where tidally-rectified flow is 0.1 m s^{-1} or more and large internal tides carry on-offshore exchange up to 1.3 m^2 s^{-1} (Huthnance et al. 2001). At the shelf edge, strong internal tides mix and diffuse the seasonal thermocline, and cooler water brought nearer to the surface is exposed by wind mixing as a cool surface band. There is evidence of dense winter-cooled water cascading. Pingree et al. (1999) show a satellite image suggesting slope-current "overshoot" into the ocean at Goban Spur. This localised exchange could be comparable with the slope current transport, O(1 Sv), when it occurs. These processes along with wind-forcing suggest a large ocean-shelf exchange of approximately 3 m^2 s^{-1} (Table 5.2.2), greatly exceeding in-/out-flows.

River input of freshwater exceeds precipitation-evaporation (despite the broad shelf) but has a small effect on salinity. Most nutrients come from the ocean but much is exported to the west of Ireland (Table 5.2.3). Production at the shelf edge (162 gC m^{-2} yr^{-1}; Joint et al., 2001) is enhanced by mixing across the summer thermocline by internal waves. Estimated nutrient and organic carbon fluxes in a Goban Spur section are shown in Tables 5.2.7b,c (OMEX I; see figures 14, 16 in Wollast and Chou, 2001). Down-slope Ekman flow has been observed as turbid on the slope (McCave et al., 2001) suggesting a route for sediment transport off the shelf. In Table 5.2.7b, the lateral transport decreases offshore as the shelf export spreads across 150 km of slope. Nitrogen fluxes were derived from the carbon cycle (Table 5.2.7c; Wollast and Chou, 2001). Some organic carbon is preserved on the deeper slope but not on the shelf (Joint et al., 2001); organic matter burial is O(0.1%) of production in Table 5.2.7b.

Smith (1996b) has provided a budget for Lough Hyne near 9.4°W, 51.5°N. This fjord is just 0.52 km^2 in area with a mean depth of 18 m, receiving only 0.04 m^3 s^{-1} run-off. Estimates are an exchange time of 40 days (primarily with the open sea), primary production-respiration of 15 gC m^{-2} yr^{-1}, and denitrification exceeding fixation by 1.5 gN m^{-2} yr^{-1}. In context these latter net values are small, as is Lough Hyne (0.6 x 10^{-6} of Celtic Sea volume).

Irish Sea

This is defined to extend between a line from St. David's Head (51.9°N, 5.3°W) to Carnsore Point (52.15°N, 6.4°W) and the shortest line from Mull of Kintyre (55.3°N, 5.8°W) to Northern Ireland (55.2°N, 6°W). This is an extended definition that includes the North Channel and Clyde Sea. In the east of the region Liverpool Bay has ROFI-type stratification, while in the western Irish Sea winter-cooled water remains underneath summer-heated surface waters. Local circulation in the west has a nearly closed, cyclonic gyre in the upper layer during summer (Hill, 1998). A mean through-flow of 7.7 x 10^4 m^3 s^{-1} (Knight and Howarth, 1999) would flush the whole Irish Sea in about a year, but affects primarily the eastern side.

Rivers dominate freshwater inputs and reduce the salinity noticeably, aided by the long flushing time. Riverine inputs of N, P exceed those from the atmosphere and significantly add to inputs from the Celtic Sea. Resulting nutrient distributions are complex. Winter values in Table 5.2.3 come from Gillooly et al. (1992). Foster et al (1977; 1978a, b) give a seasonal cycle for Liverpool Bay where river inputs increase concentrations. Values are also given by Beardall et al. (1982), Gowen et al. (2002) and Hydes et al. (2004; winter). ISSG (1990) provides more estimates of inputs (Table 5.2.3).

A LOICZ budget (Table 5.2.7d; Dupra, http://data.ecology.su.se/MNODE/Europe/Irish%20Sea/Irishbud.htm) used a river inflow of 41 km^3 yr^{-1}, inflow through St. Georges Channel of 1775 km^3 yr^{-1} with salinity 34.9, a North Channel outflow of 1816 $km^3 yr^{-1}$ with salinity 34.1, and found production to be in approximate balance with respiration. Simpson and Rippeth's (1998) budget has similar values, but they ascribe a DIN imbalance to denitrification at about 0.3 mol N m^{-2} yr^{-1}.

Western Ireland shelf

This is taken from Dursey Head (51.6°N) to Bloody Foreland (55.2°N). The dimensions in Table 5.2.1 omit Porcupine Bank (51°-54°N, 13°-15°W). Ocean-shelf exchange is predominantly wind-forced. Turbid down-slope Ekman flow (under the slope current) has been observed on the outer slope of Porcupine Bank (Dickson and McCave, 1986) suggesting a route for sediment transport off the shelf. Intermittent nepheloid layers may form when unusually strong currents (perhaps internal waves) erode slope sediment.

River input of freshwater exceeds precipitation-evaporation, but ocean-shelf exchange implies only a small salinity reduction, except in the coastal current. The nutrient budget is dominated by exchanges with the Celtic Sea and open ocean.

West Scotland

This comprises the Malin and Hebridean shelves from Bloody Foreland (55.2°N) to a line between Cape Wrath (58.7°N, 5°W) and the Wyville-Thomson Ridge (59.8°N, 6.3°W). Tidal currents include a notable internal component on the outer shelf. Rectified tidal currents were modelled by Xing and

Davies (2001). Irish Sea outflow forms the northward-flowing Scottish Coastal Current (SCC) with branches on both sides of the Outer Hebrides island chain. There is evidence of dense winter-cooled water cascading. Harikrishnan (1998) estimated a downslope Ekman transport of 0.46 $m^2 s^{-1}$ below the slope current, while turbid down-slope flow near 56.5°N (McCandliss et al., 2000) suggests a route for sediment transport off the shelf. Wind forcing is the dominant cause of ocean-shelf exchange, which greatly exceeds in-/out-flows from/to adjacent shelf sectors. Harikrishnan (1998) found root-mean-square cross-slope currents of about 33 mm s^{-1} at the 200 m contour, equivalent to 6.6 $m^2 s^{-1}$ exchange. His estimates of cross-slope diffusivity, only 40-45 m^2s^{-1}, were based on salinity loss from the along-slope current and "eddy" heat flux across the slope, using cross-slope scales 10 km, 12 km respectively.

As well as the Irish Sea outflow, river input and precipitation-evaporation are comparable in adding freshwater, but the effect on salinity is small except in the SCC. Although CO_2 uptake from the atmosphere is important, riverine and atmospheric sources of nutrients are negligible compared with dominant oceanic supply. Nutrients from the Irish Sea also help to supply production and a large export to the north Scottish shelf. Balanced carbon fluxes (Table 5.2.7e) have been estimated using a numerical ecological model of the cross-slope section (Proctor et al. 2003b). The model was forced by tides and 1995 meteorological time series, to evolve turbulence (for vertical mixing), microplankton state variables (organic carbon, nitrogen, chlorophyll), detritus (organic carbon, nitrogen), ammonium, nitrate and oxygen. Results are validated by flux measurements in the UK LOIS Shelf Edge Study (Souza et al., 2001).

North Scotland

This shelf sector from Cape Wrath to the Norwegian Trench is taken as bounded to the east and south by a line from (58.7°N, 3°W) through Orkney and Shetland to 61°N and along 61°N to the Trench. It lies near the latitude of maximum wind forcing. The Wyville-Thomson Ridge is a source of internal tidal currents and waves. Prominent meso-scale activity in the Faroe-Shetland Channel is probably generated locally from slope-current instability or from the Iceland-Faroe Front; sometimes eddies deflect much of the slope current NAW into the central part of the Channel (2 Sv or more; Sherwin et al., 1999). Process-based estimates of ocean-shelf exchange (Table 5.2.2) accordingly show dominant wind-forced and eddy contributions to a large total 3 $m^2 s^{-1}$. Drifters have shown large dispersion at approximately 360 or 700 $m^2 s^{-1}$ (Burrows and Thorpe, 1999; Booth, 1988) and current variance of 0.01 $m^2 s^{-2}$. A dispersion of 700 $m^2 s^{-1}$ gives an estimated exchange of 7 $m^2 s^{-1}$ across the 500 m contour (Huthnance, 1995).

Dominant inflow from the ocean is required to supply the estimated outflow to the North Sea. There is relatively little river inflow, with precipitation-evaporation providing most of the freshwater input. The overall effect on salinity is small. Nutrient budgets are dominated by supply from the ocean (supplemented from the West Scottish shelf), inferred uptake by production and outflow to the North Sea.

Norway

We consider this shelf from 61°N to 70°N. Tidal currents are strong with a significant diurnal component off Northern Norway. The Norwegian Coastal Current (NCC) transports 1-2 Sv northwards from inflow across 61°N, with its variability also 1-2 Sv (or a current variance of about 0.01-0.02 $m^2 s^{-2}$ (Poulain et al., 1996)). NCC salinity (reduced by Baltic outflow) is less than 33 at 61°N. Despite much riverine freshwater (greatly exceeding precipitation-evaporation), the salinity increases to about 34 off northern Norway as Atlantic water is entrained. The NCC is unstable, forming large eddies, but there is no clear estimate of an eddy separation-rate to the ocean interior. The NCC also spreads under north/easterly winds, while south/westerlies confine it against the coast. Process-based estimates of ocean-shelf exchange totaling approximately 3 $m^2 s^{-1}$ show dominant wind-forced and eddy contributions (Table 5.2.2). Between sections NW from (68°N, 15°E) and along 20°E, on-offshore exchange of 1$m^2 s^{-1}$ has been inferred from iodine-129 concentrations and transfers from the NCC to North Atlantic Water (Gascard et al. 2004).

Nutrient input from the North Sea greatly exceeds the riverine or atmospheric sources. By analogy with North Scotland, oceanic input is probably comparable but we lack an estimate. Estimated production would only use a small fraction of the nutrient supply, with the balance probably exported to the Arctic. Particulate organic carbon (POC) from the North Sea is estimated as 15% of the 11.4 Mt yr^{-1} suspended matter, i.e. 1.7Mt/y (De Haas et al., 1997, 2002). Of this POC, 10^5 t yr^{-1} is refractory. This POC is only 2-3% of net North Sea primary production, a small fraction of total organic carbon export that includes DOC, and tiny compared with DIC flux; Table 5.2.3.

Fluxes were estimated in the region 69°20′N - 70°30′N, including Malangendypet Trench and Nordvestbanken, during the main productive period of March-October in 1994. Modelled on-offshore flux in the Trench was typically 0.2 Sv (Moseidjord et al., 1999). Cumulative nitrate consumption, down to the 40m stratification depth, was a maximum in June (inner shelf), August (mid-shelf), and July (outer shelf), with respective values of 72, 52, 55 gC m^{-2} equivalent. These are lower bounds for new production (Wassmann et al., 1999). Previous data suggest annual production is approximately 126 gC m^{-2} on the shelf. Modelled annual values with nitrogen or silicon limitation are about 120 gC m^{-2} (ocean), up to 160 gC m^{-2} (shelf break), and 130 gCm^{-2} (inner-mid shelf). About 70% of this is new production (Slagstad et al., 1999). Evidence suggests strong grazing of phytoplankton. POC vertical fluxes, typically 0.1gC m^{-2} d^{-1} (a daily loss rate of 1% or less) peaked at about 0.3 gC m^{-2} d^{-1} in May and July (a daily loss rate of 1.7%). PON fluxes were about 12% of POC fluxes, but the ratio varied (Andreassen et al., 1999). Modelled carbon flow via mesozooplankton was 60 gC m^{-2} annually. Average modelled daily export (across the shelf break, including advection) during the productive period was 12.5 kg C m^{-1}, with 350 kgC m^{-1} offshore on the north side of the Trench offsetting 200 kgC m^{-1} onshore on the north side of the bank (Slagstad et al., 1999). Integrated along the shelf, average OC production is small relative to import from the North Sea.

Faroes

Tidal currents are strong with a significant diurnal component on this shelf. Hansen (1992) argued that tidal rectification drives an anticyclonic circulation, which is correlated with tidal current strength and follows depth contours. Direct run-off reduces salinity by 0.05-0.2 with a front near the 100m depth contour, although precipitation-evaporation provides more freshwater to the shelf as a whole. There is little independent basis for budgeting, but by comparison with other sectors we can infer dominant exchanges with the ocean as a result of wind forcing.

Iceland

This shelf is distinctive for the strong influence of various impinging oceanic waters. The north Icelandic Irminger Current carries relatively warm, saline and nutrient-rich NAW from the south-west (Fig. 5.2.2, using Stefánsson and Olafsson, 1991) past the north-west peninsula and eastwards on the northern shelf. This flow, 0.2 to 1 Sv with a mean of 0.6 Sv (Stefánsson 1962), varies inter-annually and on shorter time scales with regional winds (Ólafsson 1999), but not with North Atlantic Oscillation variability. NAW influences northern-shelf spring salinity, temperature and nutrient distributions (Stefánsson and Olafsson 1991). It mixes in variable proportions with Polar Water from the East Greenland Current and Arctic Intermediate and Surface Waters. NAW influence is generally minimal off the east coast where the East Icelandic Current prevails. Surface currents flow off-shelf in the south-east, and south of the north-west peninsula. River input greatly exceeds precipitation-evaporation and freshens coastal waters, which can be spread or confined against the coast according to wind direction (Stefánsson and Guðmundsson 1978; Ólafsson et al. 2002). Winter ice cover comes closest to Iceland in April-May. In 1965-1971, when the Irminger Current was weak, sea ice reached the northern and eastern Iceland shelf and even became land-fast (Sigtryggsson 1972), reducing primary production (Thordardottir 1974).

Production requirements for nutrients (equation 5.2.4) must be met by oceanic sources as riverine and atmospheric sources are negligible (Table 5.2.3). The spring bloom can be as early as March north and east of Iceland, owing to a shallow fresher surface layer, and is often dominated by *Phaeocystis pouchetii*. The south coast ROFI is thought to be important for the onset of primary production (Thordardottir 1986; Ólafsson 1985; Begg and Marteinsdottir 2002). Mixing and hence nutrient supply and production (Figure 5.2.3) are large off NW and SE Iceland near mixing fronts, and in the NAW region south and west of Iceland (in south-west bays, tidal amplitudes of several metres suggest strong tidal mixing; Thordardottir, 1994). In the north, primary production decreases from west to east with the advected nutrients.

East Greenland

We consider the shelf from Cape Farewell to 80°N. The East Greenland Current flows southwards, is 150-200 km wide, cold (< 0°C) and has upper waters freshened (S < 34.5) by run-off and melting ice, which greatly exceed precipitation-evaporation. Its seaward boundary entrains warmer saltier Atlantic water at the East Greenland Polar Front. Eddies and a wind-driven jet occur along the ice edge

(Gawarkiewicz et al., 1998). Pack ice is carried south to about 70°N, while winter ice cover extends south to Cape Farewell. There is little independent basis for budgeting. However, nutrients required for production are probably supplied by the ocean as atmospheric inputs are negligible (Table 5.2.3) and nutrient inputs from run-off and melting ice are also probably small.

5.2.6 Outline conclusions

In all sectors with an open-ocean boundary, wind forcing is an important contributor to ocean-shelf exchange. Additional factors are important in particular sectors, notably (Table 5.2.2) internal tides (eastern Celtic Sea), slope current separation (Goban Spur) and associated Ekman transport (Biscay to Norway), and eddies (N Scotland, Norway).

Exchange times are typically a few months (Table 5.2.2). Exceptions are the narrow South Biscay shelf (2-3 weeks) and North Scotland (about one month) which have large exchange across a relatively narrow shelf sector. The Irish Sea and Channel (exchange times of a year or more) lack exchange with the open ocean and exchange depends on through-flow. Through-flows are also important off North Scotland (from the Atlantic to the North Sea), Norway (Norwegian Coastal Current) and Greenland (East Greenland Current), in each case comparable with ocean-shelf exchange transports. In the other cases ocean-shelf exchange exceeds in- and out-flows along the shelf.

Rivers' inputs of freshwater and sediments are small in global terms. On West- and North-Scotland and Faroese shelves, precipitation-evaporation contributes more freshwater than rivers having only small-area catchments. Elsewhere run-off contributes more freshwater than precipitation-evaporation. The small freshwater inputs generally imply small salinity deficits relative to the open ocean. Salinity deficits are largest in the Norwegian Coastal Current (from the Baltic outflow) and the Irish Sea (retaining river inputs for about 1 year). The East Greenland Current (from the Arctic) has lower salinity than the adjacent ocean. There is ice in the East Greenland Current and sometimes off northern Iceland. The few estimates of terrestrial sediment input via rivers imply small fluxes of nutrients and carbon from this source, relative to other fluxes in their budgets.

Phosphorus input from rivers is much less than exchanges with the open ocean or transfers between 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 influxes 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(5km or finer) and ecosystem representation.

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Figure captions.

Fig. 5.2.1. Outline map of NE Atlantic region, with 200m and 500m contours and shelf sector divisions.

Fig. 5.2.2. Schematic map of circulation. NAW – (warm, salty) North Atlantic Water ➡ ; shelf-sea and coastal currents →, NCC – Norwegian Coastal Current, SCC – Scottish Coastal Current; (cold, fresher) Polar and Arctic waters ⇨ , EGC – East Greenland Current; deep Nordic Sea outflows ⇢ ; fronts – – – – – – – .

Fig. 5.2.3. Mean annual primary production around Iceland for the period 1958-1982 (Thordardottir, 1994).

Table 5.2.1. Some properties of shelf sectors and estimated wind-forced cross-slope exchange. Depths and volumes south of 65°N were obtained from the 1/6°×1/9° bathymetric grid used in POLCOMS (numerical model; Holt and James, 2001).

Sector	Area Km^2	Volume Km^3	Direction ºE of N	Mean $W^2\cos\theta$ m^2s^{-2}	Mean w'^2 m^2s^{-2}	Transport m^2s^{-1}
E Greenland	200000	50000	40 & 10	61	19	0.85
Iceland	107272	12400	all	52	43	0.95
Faroes	26779	3892	all	59	42	1.01
Norway	150000	26000	30	69	42	1.22
Cape Wrath to Norway	50780	5820	50	84	41	1.45
W Scottish shelf	87100	7626	10	55	43	1.17
W Irish shelf	53229	4974	10	51	45	1.19
Irish Sea	54000[Ir]	2430+400	-	-	-	-
Celtic Sea	162340	17444	-50	36	34	0.91
Channel	90450	4404	-	-	-	-
E Biscay	107437	10404	-40	46	24	0.97
S Biscay	14073	1311	90	44	24	0.99

[Ir]Irish sea area about 47000 km^2 (Bowden, 1955) + 7000 km^2 for North Channel and Clyde Sea.

Table 5.2.2. Estimated process contributions to ocean-shelf water exchange (m^2s^{-1}; omitting Channel, Irish Sea) and exchange time = shelf volume / total exchange rate.

Sector	Wind (Table 5.2.1)	Internal tide	Slope current	Eddies	Filament	~ Total (in Table 5.2.3)	Exchange time (yr)	lateral diffusion, exchange flux (m^2 s^{-1}) from sectoral discussions
E Greenland	0.85		0			1	0.63	
Iceland	0.95		0			1	0.30	
Faroes	1.01		0			1	0.14	
Norway	1.22		0.5	1		3	0.21	– , 1
N Scotland	1.45		0.5	1		3	0.08	360, 3.6
W Scotland	1.17	0.25	0.5			2	0.20	45, 6.6
W Ireland	1.19		0.5			1.7	0.23	
Celtic Sea	0.91	1	0.5		1	3	0.28	
E Biscay	0.97		0.2			1.2	0.34	
S Biscay	0.99		0.5	0.16		1.6	0.05	

Table 5.2.3. Summary of budgetary elements including fluxes for North-East Atlantic shelf sectors. Gaps imply no known estimate and do not imply zero. "?" indicate uncertainty.

	S Biscay	E Biscay	Channel	Celtic	Irish Sea	W Ireland	ScotlandW	ScotlandN	Norway	Faroes	Iceland	Greenland
Catchment, km^2	23050	225330	137000	51400	54000	40000	26500	4500	200000	1399	103125	1087800
River input, m^3/s	580	2555	877	983	1344	856	1056	137	9000	44	5300	10000
Shelf area, km^2	14073	107437	90450	162340	54000	53229	87100	50780	150000	26779	107272	200000
Volume, km^3	1311	10404	4404	17444	2830	4974	7626	5820	26000	3892	12400	50000
Length adjacent to ocean, km	480	800	150 (west) 30 (east)	650	70 (south) 20 (north)	400	600	800	1300	900	1300	2500
Precipitation, mm/yr												
LOICZ, MNODE	1385, 830	856, 860	938, 1100	1161, 1100	1137, 1000	1605, 1200	1782, 1300	1355, 1200	1192, 900	1854, 10^3	1556, 800	821, 300
ERA-40	730	689	747	832	815	1088	1117	932	1120	961	1119	912
Equivalent m^3/s	438	2729	2661	5304	1684	2189	3863	1870	5089	1079	3938	4295
Pr-Ev, mm/yr												
MNODE, NSEP	0, 100,	-100, 0	100, -200	100, 0	0, 0	400, 200	500, 200	400, 100	0, 300	500^{GH},100	0, 100	180, 500
ERA-40	43	-170	18	22	196	201	246	139	397	185	550	782
Equivalent m^3/s	14	-392	17	166	140	450	916	329	1184	229	850	3194
Inflow, $10^5 m^3/s$ from	3 W Iberia	~ 0 S Biscay	1 Celtic	2 E Biscay	0.77 Celtic	1? Celtic	0.77Irish Sea 1? W Ireland	1.5 ScotlandW	18 North Sea			
Outflow, $10^5 m^3/s$ to	~ 0 E Biscay	2 Celtic	1 North S.	0.77Irish S. 1 Channel 1? W Ireland	0.77 ScotlandW	1? ScotlandW	1.5 ScotlandN	17 North Sea	7 Barents Sea			
q'ocean, m^2s^{-1}	1.6	1.2	-	3	-	1.7	2	3	3	1	1	0.9
× length, $10^5 m^3/s$	7.68	9.6	-	19.5	-	6.8	12	24	39	9	13	22.5
Shelf salinity		35.4	35.0	35.2	34.1	35.2	35.1	35.1	33.3^{LH}	35.1	-	-
Ocean salinity	35.8	35.6	35.2 Celtic	35.6	34.9 Celtic	35.4	35.4	35.3	35.2	35.25	34.9	-
RiversTP												
Catchment $kg/km^2/yr$	101	101	117	82	117	82	82	82	82	82	-	-
Total kt/yr	2.3	23	16	4.2	6.3	3.3	2.2	0.4	16	0.1	-	-

kt/yr (other reports) kT/yr with average P= 0.26 mg/l	-	28[OS]	10[OS], 1[Pa] 7.2	6.5[OS] 8.1	8.5[OS], 25[IS], 27[D] 11.0	1.4[OS]	0.9[OS]	-	-	-	2.9[IH]	-
River TN Catchment kg/km^2/yr Total kt/yr kt yr^{-1} (other reports)	 367 8.4 -	 367 83 347[OS]	 1450 199 109[OS], 15[Pa]	 1300 67 95.7[OS]	 1450 78 75[OS], 94[IS], 136[D]	 1300 52 31.7[OS]	 1300 34 10.5[OS]	 1300 5.8 -	 1300 260 -	 1300 1.8 -	 - - 4.4[IH]	 - - -
River OC mg/l, kt/yr	1.7, 35	6, 483	-	-	-	-	-	-	-	-	-	-
Atmos. Inorganic N, mmol/m^2/yr Equivalent, kt/yr Oxidized, kt-N/yr [OS] total, kt/yr	23[P], 10[Dc] 4.7, 2.1 - -	28[P], 15[Dc] 42, 23 - -	55[P], 30[Dc] 70, 38 - -	35[P], 20[Dc] 80, 45 5 -	55[P], 30[Dc] 39, 21 14 N: 43[OS, IS] P: 2[IS]	9.6[P], 22[Dc] 7.2, 16 4.8 -	25[P], 25[Dc] 30, 30 2.6 -	15[P], 20[Dc] 11, 14 - -	15[P], 16[Dc] 32, 34 - -	11[P], 31[Dc] 4.1, 12 - -	6.6[P] 9.9 - -	6.6[P] 18 - -
Atmos. kt C yr^{-1} (absorbed by sea)	410[Tak]	3100[Tak]	2700[Tak], 0[BF]	5000[Tak]	1800[Tak]	2000[Tak]	4500[Tak]	2700[Tak]	6000[Tak]	1500[Tak]	3900[Tak]	3400[Tak], 8700[Sa]
DIP, µmol/l USJGOFS phosphate surface/200m	- 0.32/0.44	- 0.36/0.47	0.52[CRL] 0.41/0.57	0.45-1.4[H] winter 0.5[H] summer 0.39/0.50	0.7-2[G++] winter 0.5-0.9[H] winter 0.44/0.59	- 0.43/0.54	0.4[OS] 0.5[H] winter 0.49/0.63	0.57[RG] 0.50/0.66	- 0.46/0.65	- 0.52/0.67	1.01, 0.9, 0.83[IR] 0.57/0.72	- 0.58/0.74
DIP ocean, µmol/l (cf. open ocean 0.8-0.9[RG])							0.7[H] surface 0.7[OS] deep	0.73[RG]				
DIN, µmol/l USJGOFS nitrate surface/200m	2.3/5.4	2.5/5.5	5.1[CRL] 2.7/6.0	5-12[H] winter ~10 summer 2.7/5.9	7-28[G++]winter 6-8[H] winter 2.8/5.7	3.2/5.8	4.6[OSPAR] 8[H] winter 3.0/4.8	6.5[RG] 3.0/4.5	5.5/7.2	3.4/5.0	15.3, 13.2, 12.9[IR] 6.0/8.3	9.2/11.6

DIN ocean, µmol/l (cf. open ocean 10-12[RG])	7.6 top						11[H] surface 15[OS] deep	8.6[RG]			13 upper 14 deep	
TPN, µmol/l [BODC]	~15 ocean	~0.5 ocean	-	~5 ~0.5 ocean	~20 May	~1 ocean	~3 summer ~0.3 winter	-	-	-	-	-
POC, µmol/l [BODC]	~100 ocean	~10 ocean	-	~20 ~8 ocean	~40 May	~10 ocean	~10 summer ~3 winter	-	8-38 summer	-	-	-
DOC (cf. 60 µmol/l for NE Atlantic) [BODC]	91 upper ocean	~150 ocean	-	~160 ocean	-	~120 ocean	~80	-	-	-	-	-
Prim.Prod, g C $m^{-2}yr^{-1}$ Equivalent kt C/yr	428 [OS] 6023		171[RU] 15467	115[J] 18669			158[PC], 125[W] 13762, 10888		140[SL] 21000		218[S], 151[O] 23171	27[SG] 5400
De-Nitrification g N $m^{-2}yr^{-1}$ Equivalent kt N/yr N_2O emission [SK] kt N/yr	7.8[SG] 110 0.7	5.4	4.5	8.1	4.2[SR] 227 2.7	2.7	4.4	2.5	3.1[SG] 465 7.5	1.3	1.7[SG] 182 5.4	0.6[SG] 120 10
kt P/yr inflows from			0.3[Pa] Celtic	3.1[Pa] Irish 53[Pa] Biscay 269[Pa] ocean	22[D] Celtic	305[Pa] Celtic 24[Pa] ScotlandW	39[D], *47*[Pa] Irish 164[Pa] ocean	268[Pa] ScotlandW *747*[Pa] ocean	1054[T], 336[Pa] North Sea			
kt N/yr inflows from			7[Pa] Celtic	9.2[Pa] Irish 340[Pa] Biscay 1874[Pa] ocean	199[D] Celtic	2120[Pa] Celtic 204[Pa] ScotlandW	160[D], *297*[Pa] Irish 1134[Pa] ocean	1865[Pa] ScotlandW 5206[Pa] ocean	8060[T], 2344[Pa] North Sea			
kt P/yr outflows to		53[Pa] Celtic	~100[GK], 39[T], 17[Pa] North Sea	0.3[Pa] Channel 305[Pa] WIreland	39[D], 47[Pa] ScotlandW 3.1[Pa] Celtic	358[Pa] ocean	24[Pa] WIreland 268[Pa] ScotlandN	940[T], 546[Pa] North Sea				
kt N/yr outflows to		340[Pa] Celtic	260[T], 66[Pa] North Sea	7[Pa] Channel 2120[Pa] WIreland	160[D], *297*[Pa] ScotlandW 9.2[Pa] Celtic	2536[Pa] ocean	204[Pa] WIreland 1865[Pa]	6510[T], 3788[Pa] North Sea				

							ScotlandN					
DIC kt/yr from (+) or OC to (-) North Sea	-	-	-123000[T] -3500[T]	-	-	-	-	-1290000[T] -47000[T]	+1450000[T] +44500[T]	-	-	-
OC to bed, kt/yr assuming 0.2 g C m^{-2} yr^{-1} [WC]	3	21	18	0 (de Haas et al. 2002)	11	11	17	10	30	5	21	40

[BF]denotes Borges & Frankignoulle (2002).

[BODC] is the British Oceanographic Data Centre

[CRL] denotes Cooper (1956), Russell et al. (1971), Radach & Lenhart (1995).

[D]denotes Dupra (http://data.ecology.su.se/MNODE/Europe/Irish%20Sea/Irishbud.htm) *and* Simpson & Rippeth (1998).

[Dc] denotes Duce et al. (1991).

De-N.: denitrification.

[GH]Gaard & Hansen (2000) assumed values in the range 500-1500 mm/y for P-E over the Faroes shelf.

[GK] Gieskes & Kraay (1977)

[G++] See the sectorial description for the Irish Sea.

[H]Hydes et al. (2004); surface values in winter.

[IH]Icelandic riverine nutrient inputs from Iceland National Energy Authority, Hydrological Service using nutrient concentrations based on Stefánsson & Olafsson (1991), Gislason et al. (1996), Gíslason et al. (1997), Ólafsdóttir & Ólafsson (1999), Gíslason et al. (2001).

[IR] phosphate (as DIP) and nitrate (as DIN) for three Iceland regimes: Atlantic 600m, Arctic 600m, Arctic 200-300m (Stefánsson & Olafsson, 1991; Ólafsson, 2003).

[P] denotes Prospero et al. (1996).

[Pa]denotes Proctor et al. (2003a). Only the values in italics exceed the standard deviation based on week-to-week variability.

[PC]denotes Perez-Castillo (1999), [W]denotes Wilson (2000).

[RG] denotes Radach & Gekeler (1997) and Radach & Lenhart (1995). These seasonal means obscure small upper-layer values in summer, especially for nitrogen

[RU] denotes Russell et al. (1971).

[Sa] from Soegaard et al. (2004) value for Greenland Sea scaled by shelf area here.

[SG] denotes denitrification values from Seitzinger & Giblin (1996) estimated as a fraction of primary production.

[SK] denotes Seitzinger & Kroeze (1998).

[SL] denotes Slagstad et al. (1999).

[SR]denotes Simpson & Rippeth (1998).

[T] denotes Thomas et al. (2005).

[Tak] denotes Takahashi et al. (2002).

[Th] denotes Thordardottir (1994)

[WC] Wollast & Chou (2001) for Goban Spur, see text at end of *Sediments*.

In the upper row of the precipitation values, the first value is from the LOICZ Typology Web site http://hercules.kgs.ukans.edu/hexacoral/envirodata/partialbudgetdb (after Willmott et al.); the second value is derived from

[IS]: ISSG (1990) for the Irish Sea includes direct inputs (domestic, industry, sludge) in addition to riverine inputs of Nitrogen and Phosphorus. [J] denotes Joint et al. (2001). [LH] denotes Lundberg & Haugan (1996). [OS] denotes OSPAR	http://data.ecology.su.se/MNODE, Schmitt et al. (1989), Da Silva et al. (1994) and Josey et al. (1998; 2002). This latter source also provided the first Precipitation-Evaporation (Ev) value, with the second (upper-row) Pr-Ev value calculated using 1960-2000 NSEP data. The Pr and Pr-Ev values in the ERA-40 row are direct from 1° gridded time-averaged ERA-40 data for the respective shelf sectors. "Equivalent" precipitation and Pr-Ev are based on the mean of the 3 reported values for each.

Table 5.2.4. Estimates of freshwater input to NE Atlantic margin sectors.

Sector	Catchment area km^2	Gauged flow m^3 s^{-1}	Gauged area km^2	Scaled-up flow m^3 s^{-1}
E Greenland	0.5 × 2175600	P-E 180mm/y		6209 16000 OSPAR 10000[a]
Iceland[b]	103125			5300
Faroes	1399	P-E[c] 1000mm/y		44
Norway 61°N - 70°N	200000	310.2	7000	9000 OSPAR
Cape Wrath to Norway	3100[e], Orkney/Shetland 1000	n/a[e]	1094.4, 0	86.7+25
Bloody Foreland to Cape Wrath	Scotland11000[e],N.Ireland ?[e] Hebrides 6500	n/a[e]	3899.5, – 0	1670.4 +800
Dursey Head to Bloody Foreland	44060	556.5	28640	856
Irish Sea	Eire 11100 UK 34500[e]	123.5 n/a[e]	9650 22550.7	143 +1201[d]
Celtic Sea	Ireland 19000 Wales & SW England 29700[e]	320.2 n/a[e]	16000 21246.7	381 +602
Channel	England 16400[e] France 117000	n/a[e] 380	9020 75000	284.6 +592.8
E Biscay	France 259330	2218	225120	2555
S Biscay	Spain 23050			580

a. This value is estimated from precipitation in Bromwich et al. (1999; figure 1a therein). Evaporation should be subtracted and net ice melt added. Bacon et al. (2002) infer nearly 20000 m^3 s^{-1} from E. Greenland coastal current hydrography.

b. Catchment area and drainage information from the Iceland National Energy Authority, Hydrological Service

c. Gaard and Hansen (2000) assumed values in the range 500-1500 mm/y.

d. Bowden (1955) estimated 990 for the smaller area south of Mull of Galloway so that Scottish inputs north thereof were not included.
e. UK mainland and Northern Ireland inputs from UK Natural Environment Research Council, Centre for Ecology and Hydrology (1960-2001 mean) are already scaled up for sub-sector hydrological areas. The land area given is run-off weighted and indicates the overall factor of scaling up; it is not strictly a catchment area.

Table 5.2.5. Estimates of suspended particulate fluxes in rivers to NE Atlantic margin sectors.

Sector	Gauged flow with measured SPM $m^3\ s^{-1}$	Scaled-up flow (Table 5.2.4) $m^3\ s^{-1}$	SPM flux $kg\ s^{-1}$	Scaled-up SPM flux $kt\ yr^{-1}$
Irish Sea	225.2 (Dee, Mersey, Lune, Clyde)	1344	3.54	670
Celtic Sea	121.2 (Neath, Severn)	983	4.21	1080
Channel	74.2 (Exe, Tamar)	877.4	1.96	730

Table 5.2.6. Riverine inputs and Nitrogen balances (Gmoles yr^{-1}) estimated by Nixon et al. (1996). "NW Europe" corresponds approximately with E Biscay to Norway but also includes the North Sea. "SW Europe" includes Biscay S but also western Iberia.

	Riverine P	Riverine N = Flux from land	Atmospheric deposition	Denitrification loss	Net loss
NW Europe	1.8-3.7	49-90	38-54	165-258	37-155
SW Europe	0.8-1.6	5-10	1.1-1.8	19-29	7.9-22

Table 5.2.7a. Channel phosphorus and nitrogen budgets (fluxes in kt yr^{-1}), Proctor et al. (2003a).

	Phosphorus	Nitrogen
Net advective out	2	31
Benthic in	84	553
Rivers in	1	15
Recycled	154	1066
Phytoplankton uptake	215	1473

Table 5.2.7b. Goban Spur organic carbon fluxes, $gC\ m^{-2}\ yr^{-1}$, from Wollast and Chou (2001, figure 14).

		Abyssal Plain	Off-shelf Lateral transport	Slope	Off-shelf Lateral transport	Shelf break
Euphotic	Primary Prod.	140		160		200
	Respiration	110		106		100
	Export/settling (downwards)	30		54		100
Mid/deep	Respiration	28	1?	57	10 30	50
	Deposition	3		6		20
Sediment	Respiration	3		6		20
	Burial	0.1		0.1		0.2

Table 5.2.7c. Goban Spur shelf break nitrogen fluxes, gN m^{-2} yr^{-1}.

Euphotic	Nitrate supply from below (+ nitrification?)	18
	Ammonia supply from detrital remineralisation	18
	Phytoplankton to detritus	36
	Detrital export/settling (downwards)	18
Aphotic	Nitrate import from ocean	5.5
	Nitrate from ammonia	12.5
	Export from detritus	5.5
	Detritus to ammonia: remineralisation in water column	9
	Via benthic remineralisation	3.5

Table 5.2.7d. LOICZ Irish Sea budget (excluding the North Channel and Clyde Sea).

	River input, Gmol yr^{-1}	St Georges Channel Input, Gmol yr^{-1}	North Channel Output, Gmol yr^{-1}	Uptake, mol m^{-2} yr^{-1}
Dissolved inorganic phosphorus	0.87	0.71	1.27	0.01
Dissolved inorganic nitrogen	9.75	14.19	11.44	0.3

Table 5.2.7e. Carbon fluxes (mol yr^{-1} per along-shelf metre) west of Scotland (Proctor et al. 2003b).

Location (depth, m)	Ocean (1500)	Upper slope (300)	Shelf edge (140)	Shelf (140)
POC net production, mol m^{-2} yr^{-1}	6			6
Upper layer shelf-ward flux, mol m^{-1} yr^{-1}			12	
Midwater settling, mol m^{-2} yr^{-1}	0.35			
Down-slope POC flux, mol m^{-1} yr^{-1}		41	23	
Arrival on bed, mol m^{-2} yr^{-1}	1.1; 0.68			0.33

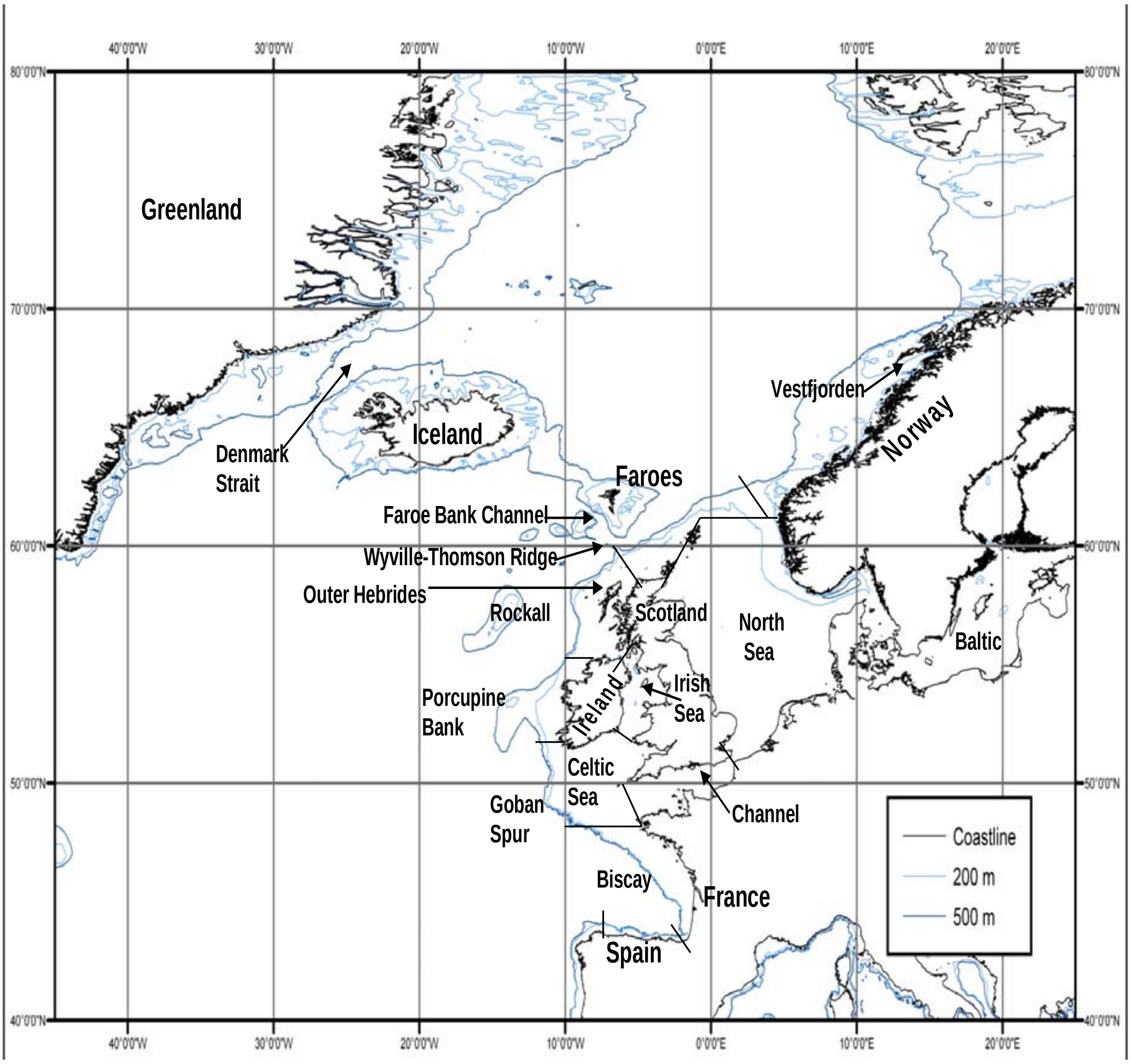

Fig. 5.2.1. Outline map of NE Atlantic region, with 200m and 500m contours and shelf sector divisions.

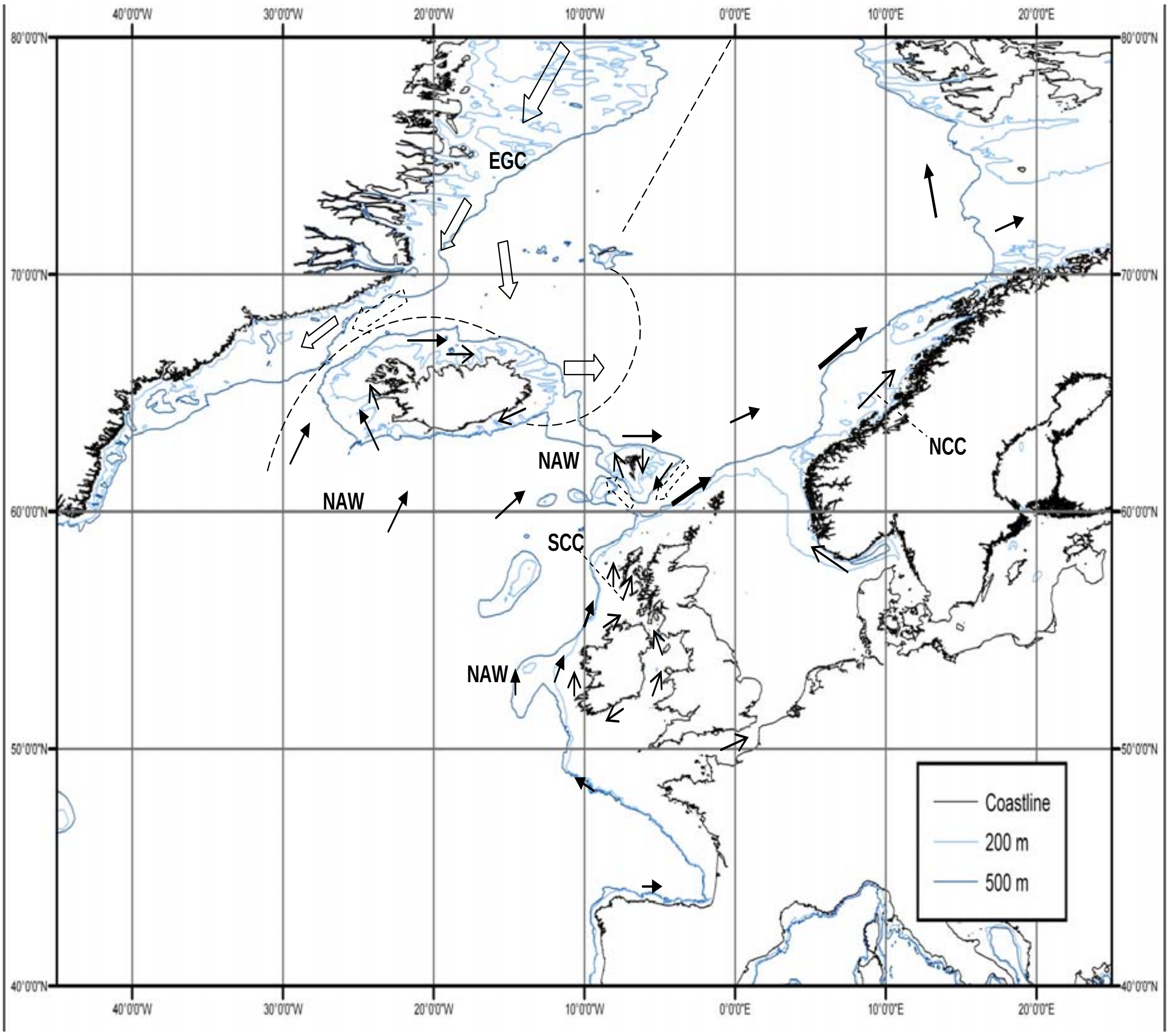

Fig. 5.2.2. Schematic map of circulation. NAW – (warm, salty) North Atlantic Water ➡ ; shelf-sea and coastal currents →, NCC – Norwegian Coastal Current, SCC – Scottish Coastal Current; (cold, fresher) Polar and Arctic waters ⇨ , EGC – East Greenland Current; deep Nordic Sea outflows ⇢ ; fronts – – – – – – – .

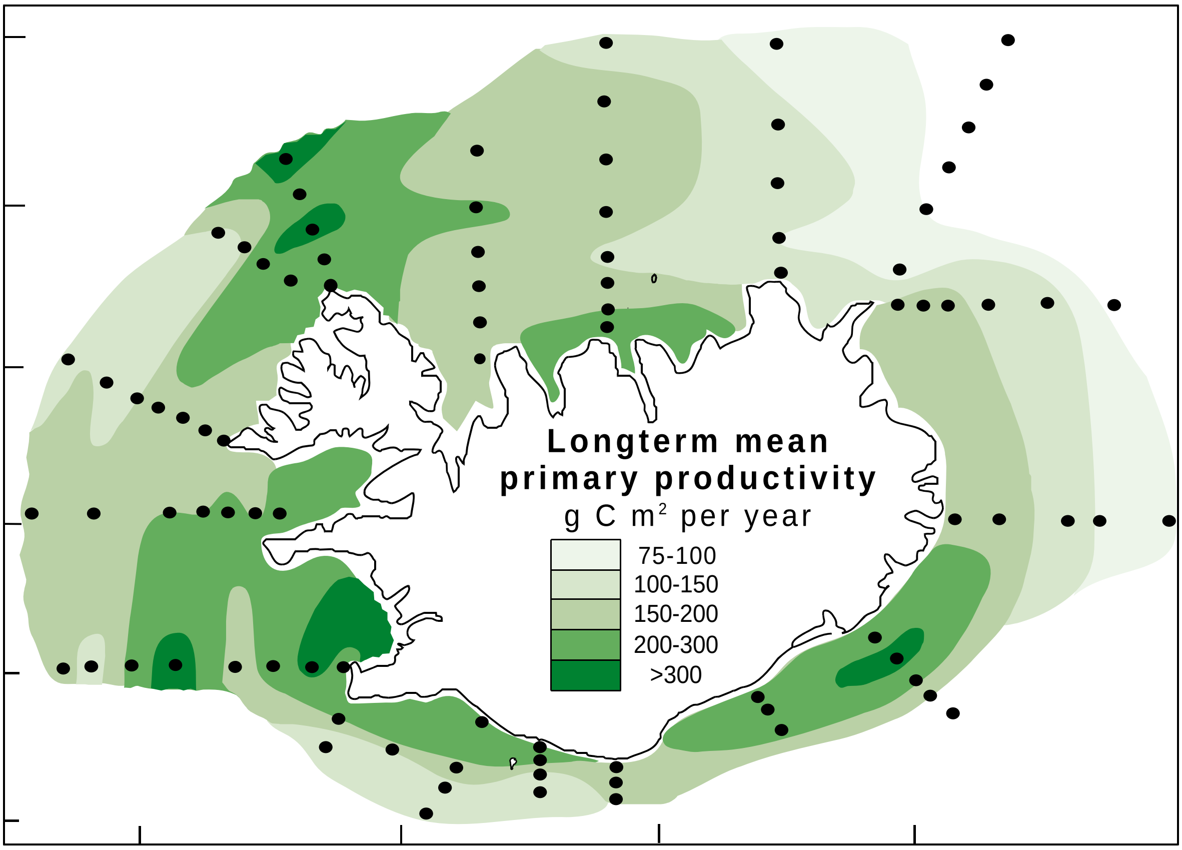

Fig. 5.2.3. Mean annual primary production around Iceland for the period 1958-1982 (Thordardottir, 1994).