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Deep ocean exchange with west-European shelf seas

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Abstract

We review mechanisms and studies of exchange between the north-east Atlantic and the adjacent shelf sea. Mechanisms include: well-developed summer upwelling and associated filaments off Portugal and north-west Spain giving exchange O(3 m^2/s per unit length of shelf); prevailing westerly winds further north driving exchange O(1 m^2/s); poleward flow along most of the upper slope with associated secondary circulation O(1 m^2/s); meanders and eddies in this poleward flow; eddies shed from slope waters into the Bay of Biscay; local exchanges at shelf spurs and depressions or canyons (e.g. dense-water cascading of order 1 m^2/s). Tidal transports are larger; their reversal every six hours makes exchange largely ineffective except where internal tides are large and non-linear, as in the Celtic Sea where solitons carry water with exchange O(1 m^2/s). These various physical exchanges amount to an estimated 2–3 m^2/s per unit length of shelf, between ocean and shelf; a numerical model estimate is comparable: 2.5×10^6 m^3/s onto and off the shelf from Brittany to Norway. Mixing controls the seasonal thermocline, affecting primary production and hence fluxes and fate of organic matter. Specifically, CO_2 take-up by primary production, settling below the thermocline before respiration, and then off-shelf transport, make an effective shelf-sea "pump" (for CO_2 from the atmosphere to the deep ocean). However, knowledge of biogeochemical fluxes is generally sparse; there is scope for more measurements, model validation and estimates from models.

1 Introduction

Ocean-shelf exchange has important consequences for shelf-sea currents, flushing and the supply of nutrients. Conversely, shelf processes impact on the open ocean: they appear to exert some control of circulation around major ocean basins (Hughes and Meredith, 2006); mixing over slopes is suggested to contribute to the main oceanic density structure (Munk and Wunsch, 1998). Topography constrains large-

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scale (geostrophic) flow from crossing the slope, creating interest in special processes enabling exchange (Huthnance, 1995).

Transports of nutrients and carbon between shelf seas and the open ocean are critical parts of nutrient and carbon cycles, e.g. Wollast (1993), Liu et al. (2000), Muller-Karger et al. (2005). Although budgeting this part of their cycles is generally inadequate, there is evidence that the north-west European shelf can make a significant contribution to the oceanic up-take of carbon (Frankignoulle and Borges, 2001; Thomas et al., 2004). This "draw-down" is most efficient over an annual cycle if carbon taken up by plankton growth in spring and summer sinks below the seasonal thermocline before respiration and is exported to the deep ocean below the permanent thermocline.

Observational studies of ocean-shelf exchange have been carried out in several locations including the Middle Atlantic Bight (e.g. Biscaye et al., 1994), the US western shelf (e.g. Jahnke et al., 2008; Kudela et al., 2008; Hickey and Banas, 2008) and the Gulf of Lions (north-west Mediterranean; Monaco et al., 1990). Specific west-European margin studies (including multi-institutional experiments: MORENA, OMEX, SES) form the substance of review in Sect. 3.

Modelling of physical variables on kilometre scales is now possible in 3-D with fair realism for wind- and buoyancy-driven flow over realistic shelf and slope topography, albeit effects of smaller-scale internal waves and turbulence are parameterised (Samelson et al., 2008). Coupling with ecosystem models has progressed, especially for primary production; with higher trophic levels, there are increasing issues of parameter estimation and trade-offs (between number of variables, coverage, resolution and run duration). Modelling is also reviewed in Sect. 3.

These cited studies emphasise that net fluxes are hard to measure in unsteady conditions with along-shelf variations. An empirical approach to balancing a budget needs (in principle) sufficient spatial and temporal resolution covering all faces of a control volume. Typically this is not practical even for water; it is even harder to estimate net fluxes resulting from correlations of constituent concentrations with flow. Hence there is a need for theory and for models to give practical effect to theory. Models hold the prospect of 3-D representation of complex domains and processes, and inherent budgeting (if properly formulated). However, (expensive) measurements are necessary at least to test hypotheses and models. Such testing was the purpose of many of the studies cited. Then there may be more confidence in using (tested) models to estimate exchanges where measurements are not dense enough. Confidence may be strengthened if models are shown to represent well the key processes contributing to ocean-shelf exchange in a region of interest.

The aim here, in the context of the "Deep Ocean Exchange with the Shelf" overview, is to review studies of exchange between the north-east Atlantic ocean and west-European shelf seas. In accord with the above discussion and issues, the emphasis is on a description of exchange processes occurring in this region, on their contributions to exchange in relation to overall estimates of exchange and on process representation in models which may give confidence to model estimates elsewhere.

We outline the west-European context (Sect. 2), review observational and modelling studies in this region (Sect. 3), summarise knowledge of exchange processes here (Sect. 4), give some overall estimates of exchange (Sect. 5), summarise by sector of shelf (Sect. 6) and discuss progress and needs for future work (Sect. 7).

2 Context – west-European margin

In global terms, these shelf seas are quite broad and irregular (Fig. 1), especially compared with other eastern ocean margins. The shelf width varies; 10–60 km off Portugal and northern Spain, 50 km increasing to 100–150 km in eastern Biscay, approximately 500 km in the Celtic Sea, 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 200 km at 65°–68° N before narrowing again to about 50 km around 70° N.

Typical shelf depths are 100–150 m from Biscay to Scotland, increasing to more than 400 m in the Norwegian Trench. The North Sea shoals southwards, to 20–30 m

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depth between south-east England and the near continent. Depths on the Norwegian shelf are variable, extensively 200–300 m or more. The continental slope is steep from Portugal to north-west Scotland, and is indented with a few large canyons off Portugal and in southern Biscay; there are 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 2000 m deep intrusion; Porcupine Bank (depth shoaling to <200 m) is a hydrographically semi-detached extension from the western Irish shelf. Around Scotland the upper slope is relatively smooth, and smaller (~0.02 or less) north-east of the Wyville-Thomson Ridge. Off Norway the shelf edge is less regular.

Rivers' inputs of freshwater, sediments and sediment-bound nutrients and carbon to west-European shelf seas are small in global terms; salinity in most areas is within 1 or 2 of open-ocean values (the Norwegian Trench is an important exception). Nevertheless, excepting west and north Scottish shelves with small-area river catchments, run-off adds more freshwater than precipitation-evaporation. In the adjacent upper ocean, warm North Atlantic water flows poleward past Ireland, Scotland and Norway; water formed by deep convection in northern Biscay flows slowly southwards to Iberia (van Aken, 2001); in 500–1500 m against the slope, northward flow (as far as the entrance to Rockall Trough) includes a Mediterranean Water fraction which increases the salinity.

Riverine input of phosphorus is much less than exchanges with the open ocean or transfers between shelf sectors. 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.

Primary production in the north-east Atlantic is described by (e.g. 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. (The timing varies: inter-annually; also locally, for example if fresh-water inputs give a shallower surface layer, advancing the bloom, or sediment suspension limits light and delays growth). The bloom becomes nutrient-limited when the initial near-surface charge is exhausted. Then 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; fronts between summer-stratified and mixed waters particularly favour phytoplankton growth (Pingree et al., 1978). Mixed waters 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. Typical west-European shelf-sea production is O(100–250 $\mathrm{g\,C\,m^{-2}\,a^{-1}}$), somewhat greater than in the adjacent north-east Atlantic. Ultimately, except in riverine-influenced coastal regions, production is fuelled mostly by nutrients from the open ocean.

3 Review of previous work

Off-shelf transport processes have yet to be explicitly investigated in the context of multi-annual and shelf wide-scales. Observational campaigns are necessarily limited to a few seasons and a particular area; in this region study areas have included the following: *Malin-Hebrides* shelf west of Scotland, regarding internal tides (Sherwin, 1988) and ocean-shelf interaction (LOIS/SES 1995–96, e.g. Souza et al., 2001); *Goban Spur* (OMEX I, 1993–1996; e.g. Wollast and Chou, 2001); *Celtic Sea* for internal tides (e.g. Pingree and New, 1989; New and Pingree, 1990), slope current (Pingree et al., 1999) and residual circulation (Pingree and Le Cann, 1989, 1990); the *Iberian Margin* where there have been several studies of upwelling as well as larger-scale studies of the current structure and biogeochemical exchanges: MORENA, e.g. Fiuza et al. (1998); OMEX II; e.g. Huthnance et al. (2002); Joint and Wassmann (2001); van Weering and McCave (2002). There have been *North Sea* studies of the seasonal cycle (Simpson, 1993) and subsequently more modelling (Lenhart et al., 1995; Radach and Lenhart, 1995; Iversen et al., 2002; Smith et al., 1996; Winther and Johannessen, 2006; Moll and Radach, 2003) and budgeting (Thomas et al., 2005) studies, albeit not directly addressing ocean-shelf exchange. Water, nutrient and carbon cycling along the sub-polar north-east Atlantic margin (Biscay to Norway) has been reviewed in the context of the JGOFS-LOICZ Continental Margin Task Team (Huthnance, 2009).

Holt et al. (2009) have used a 3-D physics-only model with ∼12 km resolution to simulate 45 years exchange between the north-west European shelf and adjacent Atlantic (see Sect. 5). Proctor et al. (2003) modelled a year (1995) of nutrient and phytoplankton fluxes across the shelf edge west of Scotland in 2-D with resolution ∼1.2 km in the horizontal and 60 layers in the vertical; the microbiological model represented nitrate, ammonium, oxygen, microplankton and detritus; there was fair agreement with 1995 measurements but indication of a need to improve bottom boundary-layer processes in the model. In general along-shelf variability influences ocean-shelf exchange (e.g. Kudela et al., 2008; Hickey and Banas, 2008) and calls for a 3-D model.

The 3-D POLCOMS Atlantic Margin Model as used in Holt et al. (2009) has been coupled with the European Regional Seas Ecosystem Model ERSEM (Allen et al., 2001). The 18 years 1988–2005 have been run for carbon cycling with ∼12 km resolution, 42 s-levels, ERA40 and operational ECMWF surface forcing, about 300 river-flow inputs, time-varying (spatially-uniform) atmospheric pCO_2; a mean annual cycle was used at ocean boundaries and for optical attenuation and riverine concentrations of nutrient and dissolved organic carbon (DIC). Inputs to the model budget (largest first) are from rivers and the atmosphere (inorganic C) and advection of organic C. These simulations are presented in detail by Holt et al. (in preparation). A preliminary analysis shows that net burial 0.02×10^{12} mol C yr^{-1} is the small difference between net settling of organic carbon and benthic respiration as inorganic carbon. Horizontal advection is the dominant loss; the net loss of (inorganic) carbon is 0.9×10^{12} mol C yr^{-1}. The advective loss is an effective sink of carbon if it leaves the shelf to deep water below layers where it may re-equilibrate with the atmosphere.

4 Exchange processes

Warm, saline North Atlantic Water (NAW) forms a *poleward current* along the continental slope. The current is approximately barotropic, centred at ∼500 m on the slope; it occurs off Portugal (e.g. Frouin et al., 1990) and again from Biscay past Britain to Norway (e.g. Pingree et al., 1999; Souza et al., 2001, documenting findings in the SES; McClimans, 1999; Skagseth et al., 2004). Drifter observations demonstrate its continuity (Pingree et al., 1999) and its dispersion (Burrows et al., 1999) onto the shelf. It is thought to be forced by the dynamic height of warmer sub-tropical waters (Huthnance, 1984; Hill et al., 1998). On the Celtic Sea shelf, mean flows are weak (Pingree and leCann, 1989) but supply ∼0.1 Sv eastwards through the English Channel (Prandle et al., 1996; 1 Sv=10^6 m^3/s) and ∼0.1 Sv northwards through the Irish Sea (Knight and Howarth, 1999). Atlantic inflow to the northern North Sea, cyclonic North Sea circulation and fresher water from the Baltic all feed the northward-flowing Norwegian Coastal Current. Beneath the poleward slope current is a bottom *Ekman layer* (Fig. 2), modified by the slope and stratification (e.g. Trowbridge et al., 1998), where friction reduces the current to zero. This Ekman layer is expected (with some evidence from observations) to have off-shelf transport $\tau/\rho f$ of order 1 m^2/s or 1 Sv/(1000 km) (Huthnance, 1995; Souza et al., 2001). Here τ is the bottom stress arising from the current, ρ is the water density, f the Coriolis parameter. This Ekman transport is robust, being independent of the detailed form of stress, and forms the basis of an "Ekman drain" concept for off-shelf flux. Model results for the north-west European shelf (Holt et al., 2009) show a strong correlation (r∼0.7) between the along-slope flux (across 56.5° N) and the lower layer flux across the 200 m contour in 52.5° N to 57.5° N, substantiating the "Ekman drain" concept.

The region is subject to strong *wind* forcing, at its most intense around 60° N. Here the winds are variable, usually associated with the passage of cyclones (depressions) driving storm surges (in the form of coastal Kelvin and continental shelf waves) rather than up- or down-welling. However, the relative orientation of the Irish-Norwegian shelves and prevailing westerlies tends to drive on-shelf surface flow and hence downwelling at the coast. Lack of an adjacent coast where the shelf is broad (North Sea, Celtic Sea, Irish Sea) allows more extensive net on-shelf flow, with scope for off-shelf return flow elsewhere (notably in the Norwegian Coastal Current). The surface flow can be estimated as an Ekman transport

$$\rho_a c_D (W^2 \cos\theta + w'^2)/(\rho_w f) \tag{1}$$

where ρ_a, ρ_w are the densities of air and water, c_D is a 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.

Summer upwelling is forced by north-easterly trade winds over the north-south extent of the Iberian shelf and especially around Finisterre (e.g. Joint and Wassmann, 2001); less off the Algarve with different coast orientation. Well-developed upwelling can form filaments with associated off- and on-shelf fluxes, typically O(0.6 Sv) per filament (Barton et al., 2001) which exceeds the Ekman transport over the (semi-regular) spacing between filaments.

Table 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). (In Table 1, W Iberia is given seasonally from Huthnance et al. (2002); the North Sea flux is not at the shelf edge but based on estimates of flow between Scotland and Norway; Huthnance, 1997; see also Sect. 5).

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. However, internal tides with comparable peak currents are generated over steep slopes in many locations: off Portugal (Jeans and Sherwin, 2001a, b); particularly strongly at the Celtic Sea shelf edge (e.g. Pingree and New, 1989); on the Malin Shelf (Sherwin, 1988) and over the

Wyville-Thomson Ridge (Sherwin, 1991). Large-amplitude (non-linear) internal tides can transport water in their wave-forms on the summer thermocline, exceptionally as much as 1 m^2/s at the Celtic Sea shelf edge. 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) is the tidal current amplitude (Prandle, 1984). This approach suggests that shelf-edge exchange from tidal shear dispersion is relatively small unless $U > 0.5$ m/s, as west of Brittany but rarely elsewhere.

Buoyancy inputs are the other main source of forcing. Although direct lateral inputs of freshwater from land and rivers are small in global terms, they drive anti-cyclonic flows around Ireland and Scotland. The largest flux of fresher water is the Norwegian Coastal Current (originally from rivers into the Baltic Sea). Surface fresh-water buoyancy input from precipitation minus evaporation is within ±200 mm a^{-1} over much of the region. However, summer heating and winter cooling force a 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, in sequence from very shallow water out to the open shelf, there are: a nearshore region mixed by waves, a region of freshwater influence that may be stratified, shallow coastal water mixed by strong tidal currents and winds, and deeper shelf water which is thermally stratified in summer. The summer thermocline is at O(50 m) or less. On the north-west European shelf, the "tidal mixing" front between the mixed and summer-stratified areas is inshore of the shelf edge (Simpson, 1998a, b); the outer shelf is stratified in summer.

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 favourable 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, being more than 500 m in Biscay and as deep as 750–900 m around 50°–60° N west of Ireland and Scotland. Water and its contents from below the seasonal thermocline are thus mixed to the surface during autumn and winter. Winter cooling in the Nordic seas occurs as deep convection, in small cells but probably extensively, forming a cold dense bottom layer, which spills southwards over the sills between Greenland and Scotland. 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 $m^2 s^{-1}$; significant when and where they occur. There is evidence that cascading has occurred at the Celtic Sea shelf edge (Cooper and Vaux, 1949) and at the north end of Porcupine Bank (Hill et al., 1998).

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), e.g. at Goban Spur (Pingree et al., 1999). Large slope-current meanders and eddies are observed in the Faroe-Shetland Channel (Sherwin et al., 1999, 2006) and eddies are formed from the slope current off northern Spain (Pingree and LeCann, 1992)

5 Overall estimates of exchange

Empirical estimates of total exchange across some sectors of shelf edge have been made on the basis of (I) changing properties of water flowing along the slope, (II) variance in cross-slope flow, (III) cross-slope dispersion of drifters. Thus along the Iberian slope, northward-flowing Mediterranean water has lateral diffusivity ~500 m^2/s (Daniault et al., 1994; basis I). Off western Galicia, cross-slope current variance $(19\,mm/s)^2$ (basis II) implies cross-slope exchange ~3.8 m^2/s in 200 m, or equivalent lateral diffusivity also ~500 m^2/s taking the offshore scale as the distance from the coast to the 200 m depth contour (26 km; Huthnance et al., 2002). Also off western Galicia, drifters deployed in August 1998 and winter 1998/99 dispersed with effective across-slope diffusivity 870 m^2/s and 190 m^2/s respectively, i.e. an average 560 m^2/s (basis III). West of Scotland, cross-slope current variance ~$(33\,mm/s)^2$ at the 200 m contour (Harikrishnan, 1998; basis II) is equivalent to 6.6 m^2/s exchange. North of Scotland and off Norway, cross-slope current variances are of order $(0.1\,m/s)^2$ and there are estimates of lateral diffusivity from drogued-bouy dispersion (basis III): ~700 m^2/s (Booth, 1988); ~360 m^2/s (Burrows and Thorpe, 1999). Analysis by process contributions is discussed in Sect. 6, initially for west Iberia, and presented in Table 1.

The period 1960–2004 was simulated for the west European shelf and nearby Atlantic by Holt et al. (2009) using surface forcing from ERA-40, COARE3 bulk formulae (Fairall et al., 2003), lateral boundary conditions from a ~1° global model for 1958–2004.(NEMO; Smith and Haines, submitted) and river inputs [Young and Holt, 2007; grdc.bafg.de/]. The overall pattern of across-shelf-edge transport is a net downwelling circulation of about 1.2 Sv. This is the net result of surface transport on to the shelf (variable, driven by prevailing winds) and an off-shelf transport in a thin near-bed Ekman layer under the slope current (little variability on monthly time scales). Total on-/off-shelf exchange (from Brittany to Norway) is larger, about 2.5 Sv, if all on-shelf flows are added and all off-shelf flows are added separately (Fig. 3). Across-shelf-edge transport in the Amorican shelf and Celtic Sea is relatively weak and generally on-shelf, whereas there is strong off-shelf transport from the North Sea to the Norwegian Trench. These features are illustrated by tracer distributions in Fig. 4.

The fate of organic carbon settling to the bottom fraction of the water column was estimated by introducing tracer, each June, into the lowest model layer within the 200 m depth contour, with uniform concentration / area. By the next March, typically 40% of tracer had left the shelf. Particularly for Irish and Scottish shelves, transport processes are very effective at removing material from the bottom layer on the shelf (Holt et al., 2009). This scenario forms the basis for extending the North Sea CO_2 "pump" concept

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(Sect. 6 and Thomas et al., 2004) to the wider west-European shelf.

6 Summary by sector

This section summarises exchanges and some particular aspects of nutrients and carbon cycling for the west-European margin sectors in turn from south to north. Estimated process contribution to ocean-shelf exchange of water are summarised in Table 1.

6.1 West Iberia

This sector has moderate shelf width, significant inputs of fresh water and very strong seasonality: in winter, (north-) westerly prevailing winds give mixing and downwelling overall; in spring, a shallow thermocline typically develops, overlying thicker remnants of the mixed layer from the previous winter (e.g. May 1993; Fiuza et al., 1998); in summer, long-periods of north-easterly winds give upwelling of cooler water rich in nutrients and filaments develop taking surface water off-shelf. Poleward along-slope flow comprises relatively warm and saline Eastern North Atlantic Central Water; it is manifested at the surface in winter, but is present as an undercurrent for much of the year, typically a few tens of kilometres offshore from the shelf break and reaching down to depths of some hundreds of metres. Deeper again, warm saline Mediterranean Water, often with two "cores" centred at levels above and below 1000 m, flows generally northwards with progressive "dilution" by adjacent Atlantic Water (Fiuza et al., 1998).

Overall estimated exchange across the 200 m depth contour is 3.1 m^2/s on the basis of cross-slope current variance $(15.5\,mm/s)^2$ (Huthnance et al., 2002) but differs between summer and winter. Contributions (Table 1; Huthnance et al., 2002) come from up-/down-welling, secondary flow associated with the slope current ($O(1\,m^2/s)$ including the Ekman "drain"), non-linear internal tides on the summer thermocline $O(1\,m^2/s)$, detaching eddies and cross-frontal flow $O(0.6\,m^2/s)$. The overall estimate 5.6 m^2/s for

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summer exceeds that for winter (2.2 m^2/s), owing to non-linear internal tides and to filaments O(3 m^2/s) when upwelling is well-developed. The summer-and-winter average is in fair agreement with the overall 3.1 m^2/s, and the summer enhancement is in fair agreement with the summer-enhanced drifter dispersion (870 m^2/s compared with 190 m^2/s in winter).

6.2 Southern Biscay

This north Spanish shelf is relatively narrow. Estimated ocean-shelf exchange ~1.6 m^2/s is dominated by wind-forced flow. Winds drive summer upwelling around Cape Ortegal and enhance production on the Cantabrian shelf (OSPAR, 2000). Slope water eddies are shed into the ocean, especially around Cape Ortegal Pingree and (LeCann, 1992; Huthnance et al., 2002) 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. 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; it depends on oceanic inputs.

6.3 Eastern Biscay

In this sector, an estimated excess of evaporation over precipitation only slightly offsets freshwater input from rivers, notably the Garonne, Dordogne and Loire. Salinity on the shelf is close to open-ocean values, indicating effective (mostly wind-forced) ocean-shelf exchange, larger than in- and out-flows along the shelf. Again, production greatly exceeds what can be supported by riverine and atmospheric inputs and is inferred to depend on oceanic inputs to the shelf.

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6.4 Celtic Sea

This is a very broad shelf sector between Brittany and south-west Ireland. The Ocean Margin Exchange (OMEX I) project studied biogeochemical fluxes in detail near Goban Spur during 1993–1997.

Low-frequency circulation here is generally weak (Pingree and le Cann, 1989) except along the upper slope and where channelled or accelerated around promontories. Tidal currents exceed 0.5 m/s at the shelf edge west of Brittany, where tidally-rectified flow is 0.1 m/s or more and large internal tides carry on-offshore exchange up to 1.3 m^2/s (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 O(3 m^2/s), greatly exceeding in-/out-flows. Most nutrients come from the ocean but much is exported to the west of Ireland. Production at the shelf edge (Joint et al., 2001) is enhanced by mixing across the summer thermocline by internal waves. OMEX I estimated nutrient and organic carbon fluxes in a Goban Spur section (Wollast and Chou, 2001). Turbid down-slope Ekman flow on the slope (McCave et al., 2001) suggests a route for sediment transport off the shelf.

6.5 Western Ireland shelf

Ocean-shelf exchange is predominantly wind-forced. Turbid down-slope Ekman flow (under the slope current) on the outer slope of Porcupine Bank (Dickson and McCave, 1986) again suggests a route for sediment transport off the shelf. River input of freshwater exceeds precipitation-evaporation, but large ocean-shelf exchange implies only a small salinity reduction, except in the coastal current. The nutrient budget is dominated

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by exchanges with the Celtic Sea and open ocean.

6.6 West Scotland (to Cape Wrath/Wyville-Thomson Ridge)

Tidal currents include a notable internal component on the outer shelf. 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 below the slope current; again 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.

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. 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 have been estimated using a numerical ecological model of the cross-slope section (Proctor et al., 2003); CO_2 uptake from the atmosphere is important therein. Results are validated by flux measurements in SES (Souza et al., 2001).

6.7 North Scotland

This sector 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 North Atlantic Water into the central part of the Channel (2 Sv or more; Sherwin et al., 1999, 2006). Process-based estimates of ocean-shelf exchange accordingly show dominant wind-forced and eddy contributions to a large total 3 m^2/s. (Drifter-based estimates of

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dispersion as large as 700 m^2/s (Sect. 4) give estimated exchange 7 m^2/s across the 500 m contour; Huthnance, 1995).

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

6.8 North Sea

Exchanges are dominated by "Atlantic Water" inflows to the northern North Sea and a similar flow along the continental slope into the Norwegian Trench (Huthnance, 1997). The northern inflow (by various routes around Scotland, notably the Fair Isle Current between Orkney and Shetland, and around Shetland) totals about 1.7 Sv; it greatly exceeds the Dover Strait inflow ~0.1 Sv (Prandle et al., 1996) and combined river inputs (including those via the Baltic). The "Atlantic Water" may have been significantly modified by its long transit across the shelf for the Dover Strait inflow; some of the inflow around Scotland may also have come from the Celtic Sea shelf edge (Pingree et al., 1999). The main transport out of the North Sea is northwards in the Norwegian Coastal current (NCC). River inputs in the southern and eastern North Sea add significantly to nutrient supply locally, although for the North Sea as a whole most nutrient input is via the "Atlantic Water". In the southern North Sea, strong tidal currents in shallow water prevent summer stratification and induce turbidity sufficient to delay the spring bloom in places. However, the frontal regions and southern and eastern areas (off Belgium to Denmark) show large primary production (e.g. Howarth et al., 1993). The North Sea net carbon budget is dominated by carbon inputs from rivers, the Baltic Sea and the atmosphere; the North Sea acts as a sink for organic carbon with final export to the Atlantic Ocean accounting for more than 90% of the CO_2 taken up from the atmosphere (Thomas et al., 2005). The uptake and sink is aided by large $p$$CO_2$ draw-down;

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stratification separates production (upper layer) and respiration causing a carbon dioxide increase in the subsurface layer that is ultimately exported; this more than offsets emission of respired CO_2 in the vertically-mixed southern North Sea (Thomas et al., 2004).

6.9 Norway

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 – current variance is 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 totalling approximately 3 m^2/s show dominant wind-forced and eddy contributions.

Nutrient input from the North Sea greatly exceeds 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. Data and models suggest annual primary production of about 120–160 g C m^{-2} (Slagstad et al., 1999). Integrated along the shelf, average organic carbon production is small relative to import from the North Sea.

7 Discussion and future work

The following characterise the west-European margin: poleward along-slope flow (not uniform, and may not be continuous; it may also lie under different surface flow, especially during upwelling); strong wind forcing with downwelling prevalent north of Biscay and summer upwelling off Iberia – when well developed, filaments increase ocean-shelf exchange; strong tidal currents and mixing on wide shelves; relatively small exchange in eddies; moderate freshwater and stratification except for the Norwegian Coastal Current; local rectified tides, solitons and cascading; overall exchange 2–3 m^2/s.

The combination of estimated exchange-process contributions in Sect. 6 (for W Iberia; Table 1) is encouraging in relation to independent estimates of overall exchange and the summer enhancement. However, exchanges from different processes are not necessarily additive. For example, poleward flow along the slope may occur (as an undercurrent) with summer upwelling, but their effects on cross-slope flow will tend to cancel, or "at best" co-exist with upwelling above the undercurrent and hence correspondingly reduced vertical extent and transport. Or, poleward flow may be in part a response to wind forcing in a downwelling sense so that simple addition has an element of double-accounting.

The encouragement from combining exchange-process estimates nevertheless reinforces the use of models, when tested for their representation of processes. In most locations, measurements are insufficient to determine exchanges; some basis is needed to extrapolate from measured contexts. Numerical models are potentially a rational basis for extrapolation, giving practical effect to theory, especially for 3-D representation of complex domains and processes, with inherent budgeting (if properly formulated).

The model estimate 2.5 Sv (Sect. 5) for overall exchange from Brittany to Norway (about 2000 km of shelf edge) is about half of the amount suggested by the Table 1 values (1.7 to 4 m^2/s per unit length of shelf) over this distance. This is consistent with averaging in the model estimate; entries in Table 1 but averaged out in the model estimate include temporal reversals in wind-driven transports, internal tide contributions on spatial scales unresolved in the model, and seasonal processes.

The overall circulation with downwelling O(1 Sv) north of Biscay has an important role in biogeochemical cycles and specifically the carbon pump. The along-slope current acts to replenish on-shelf nutrients aiding summer draw-down of CO_2 in producing organic carbon. These tidally active shelf seas lack 'export production' or burial; hence (to conserve carbon) large air-sea CO_2 flux implies divergent DIC transport; the overall downwelling allows transport of dissolved material from regions of high production to the deep ocean. In particular, near-bottom transport of DIC off the shelf, below the permanent thermocline on time scales less than a year, facilitates CO_2 drawdown again in the next growing season. (The off-shelf flow of near-bottom water is equivalent to evacuating the bottom quarter of the whole shelf in less than one year; the whole shelf volume in ~3 years). This off-shelf flow is not uniform; the margin from Ireland to the Norwegian Trench and areas of the North Sea are most effective.

There is no simple relation between productivity and air-sea CO_2 flux. Modelling this flux in shelf seas requires accurate representation of the circulation, mixing, chemistry and biology; these are all factors in the carbon "pump" concept. The near-coastal region is particularly important: it can act as either a CO_2 sink or a source; however, it is also the most challenging in the need for model improvements to represent complex optics, fine horizontal resolution and uncertain land-sea fluxes.

The outcome is that the west-European shelf is a net sink of atmospheric CO_2. Within this, shelf edge regions tend to be strong sinks, open stratified regions are neutral or weaker sinks, coastal regions are either sources or sinks.

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Table 1. Estimated process contributions to ocean-shelf water exchange (m^2/s) by sector. Exchange time=shelf volume / total exchange rate.

Sector	Wind	Internal tide	Slope current	Eddies	Filament	~ Total	Exchange time (yr)
Norway	1.22		0.5	1		3	0.21
North Sea	2		2			4	1
N Scotland	1.45		0.5	1		3	0.08
W Scotland	1.17	0.25	0.5			2	0.20
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
W Iberia summer		1	1	0.6	3	5.6	0.02
W Iberia winter	0.6		1	0.6		2.2	0.05

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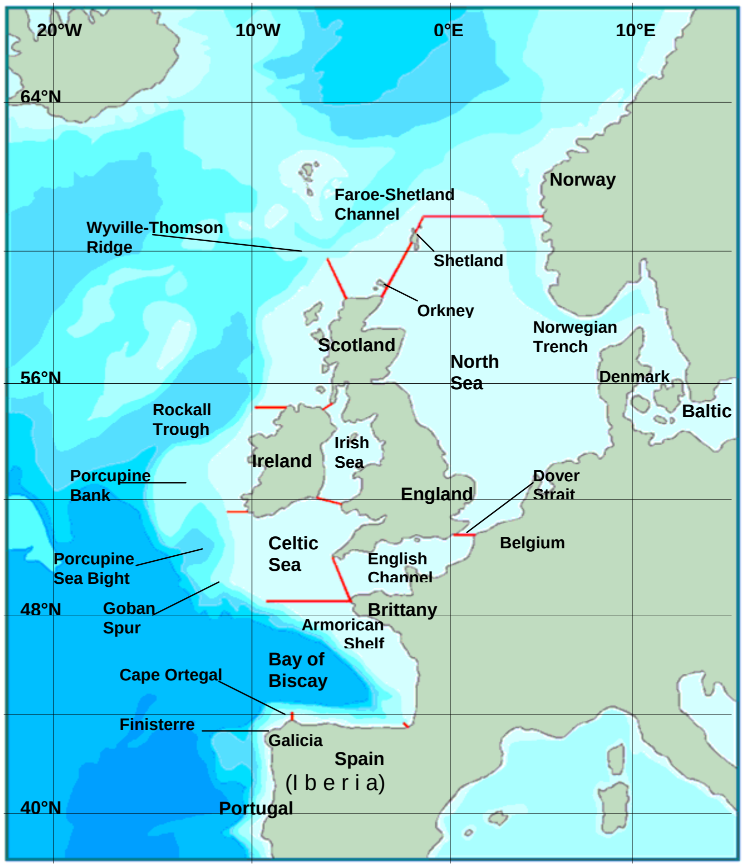

Fig. 1. Outline map of west-European shelf region, with 200 m depth contour, 1000 m contours thereafter and divisions (red) between shelf sectors (Sect. 6).

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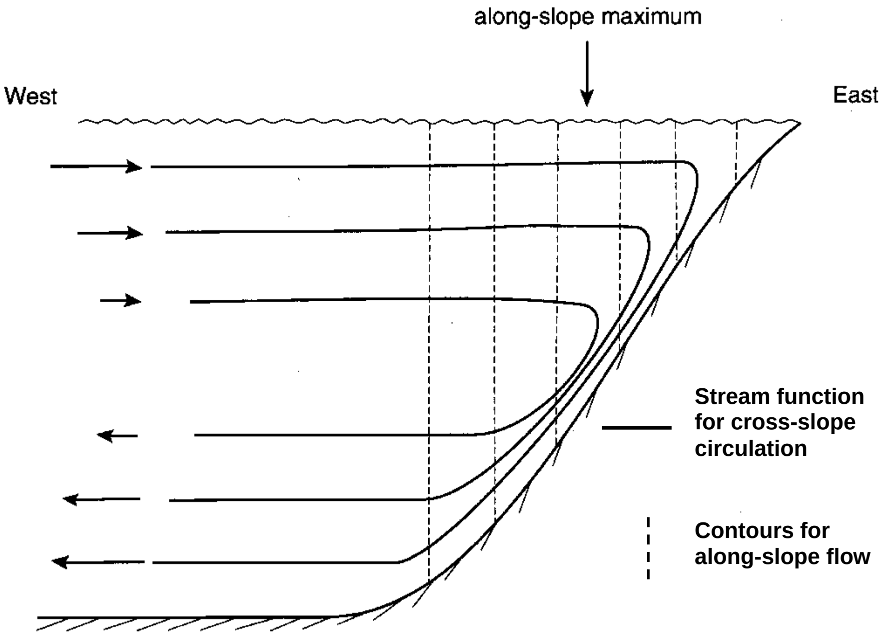

Fig. 2. Schematic of cross-slope circulation associated with poleward along-slope flow.

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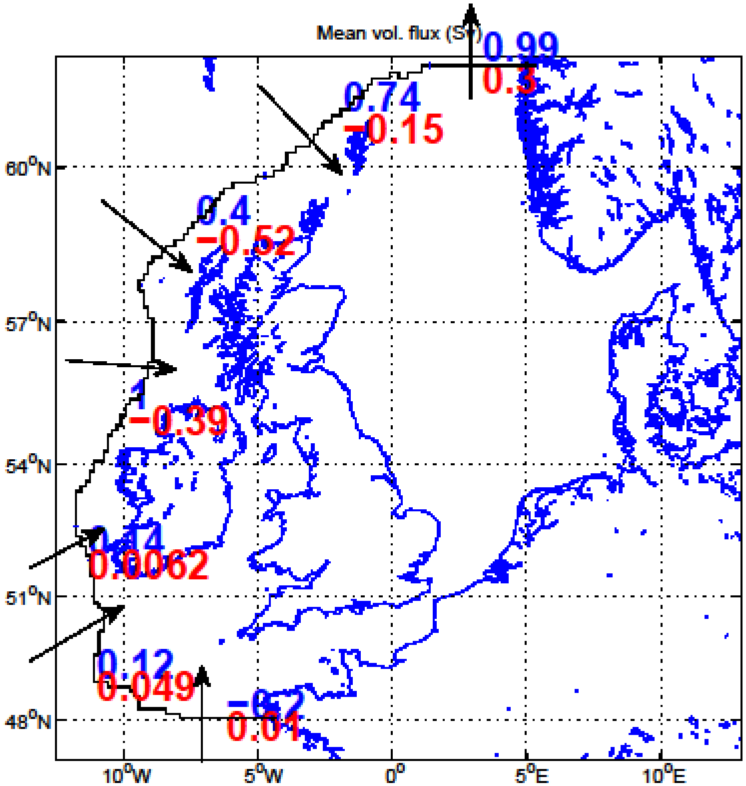

Fig. 3. Fluxes (Sv) above 150 m (blue) and below 150 m depth (red). All fluxes are across the 200 m contour shown; positive is onto the shelf except next to Norway (positive to north).

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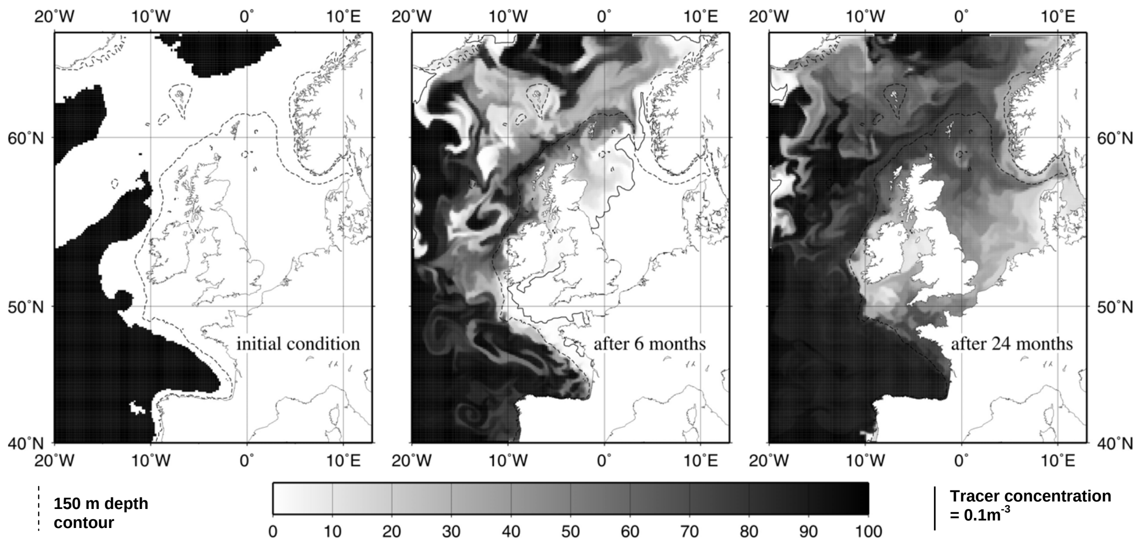

Fig. 4. Evolution of modelled surface concentration of tracer during 2002–2003. Initial concentration (beginning of 2002) was 100 m^{-3} everywhere where total depth >2000 m, zero elsewhere. (Within and somewhat beyond the 150 m isobath, concentrations homogenize through the water column each winter).

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