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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 seas. Well-developed summer upwelling and associated filaments off Portugal and north-west Spain give exchange O(3 m^2/s per unit length of shelf). Prevailing westerly winds further north drive exchange O(1 m^2/s). Poleward flow along most of the upper slope has associated secondary circulation O(1 m^2/s), meanders and eddies. Eddies are shed from slope waters into the Bay of Biscay, and local exchanges occur at shelf spurs and depressions or canyons (e.g. dense-water cascading of order 1 m^2/s). Tidal transports are larger, but 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, giving 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 ocean basins (Hughes and Meredith, 2006) and mixing over slopes is suggested to contribute to the main oceanic density structure (Munk and Wunsch, 1998). Topography constrains large-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, representation in models is less sure and trade-offs are needed (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

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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 observations and models with overall estimates of exchange in this region (Sect. 3), outline exchange processes (Sect. 4), summarise by shelf sector (Sect. 5) and discuss progress and needs for future work (Sect. 6).

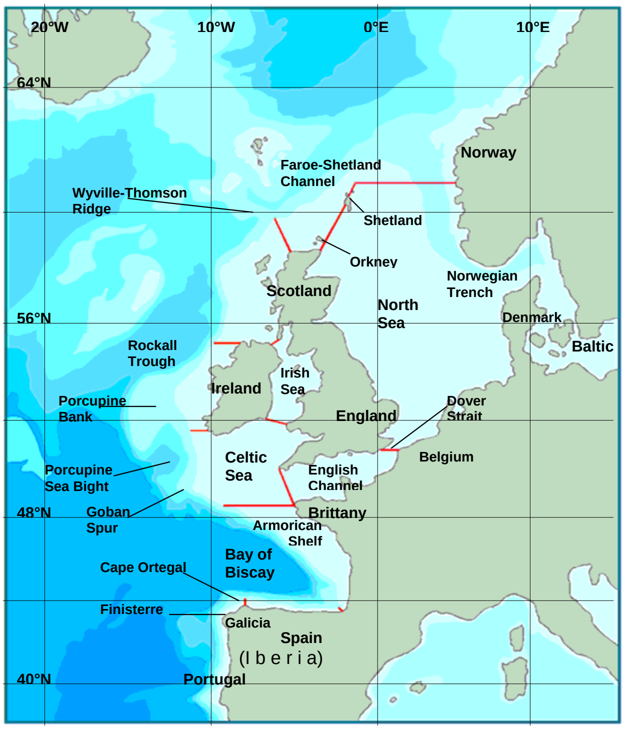

Fig. 1. Outline map of west-European shelf region, with 200 m depth contour, 1000 m contours thereafter and divisions (red) between shelf sectors (Sect. 5).

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 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 $<$200 m) is a hydrographically semi-detached extension from the western Irish shelf. Around Scotland the upper slope is relatively smooth, and less steep ($\sim$0.02 or less) north-east of the Wyville-Thomson Ridge. Off Norway the shelf edge is less regular.

The region is subject to important forcing by (i) the adjacent oceanic density field (driving a "slope current"), (ii) winds, (iii) tides and (iv) other sources of buoyancy, Fig. 2. In the adjacent upper ocean (i), 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. Winds (ii) cause ocean-shelf exchange and are discussed further in Sect. 4. Semi-diurnal tides (iii) are large in the north Atlantic generally. Tidal currents, primarily barotropic, 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. Freshwater inputs are sources of buoyancy (iv). Rivers' inputs of freshwater to west-European shelf seas are small in global terms, and salinity in most areas (except adjacent to Scandinavia) is within 1 or 2 of open-ocean values. Nevertheless, excepting west and north Scottish shelves with small-area river catchments, rivers add more freshwater to this region's seas than rainfall-evaporation, which is within ±200 mm/year over much of the region. Moreover, inputs

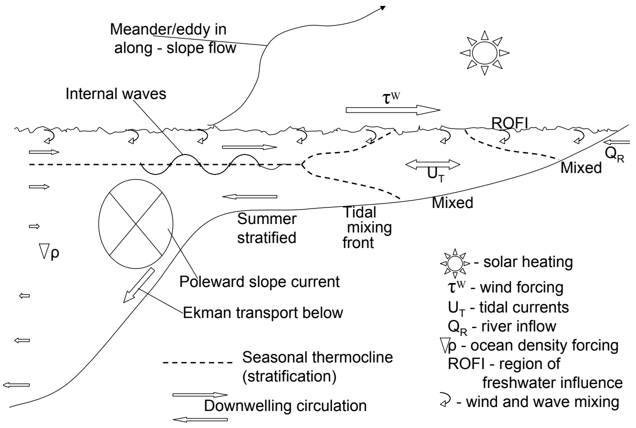

Fig. 2. Schematic of stratification and cross-slope exchange processes.

from land and rivers 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). Summer heating and winter cooling (iv) 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 (Fig. 2): 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 depth is 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 also cause mixing at the bottom (for a favourable combination of slope, stratification and wave frequency) and especially within the thermocline (via shear and large-wave breaking); these waves are particularly active near the shelf edge (an area of their generation). Surface waves cause much surface mixing and 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.

Rivers' inputs of sediments and sediment-bound nutrients and carbon to west-European shelf seas are small in global terms. 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. Spring bloom timing varies, inter-annually and locally, for example if fresh-water inputs give a shallower surface layer, advancing the bloom, or if 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 $\mathrm{g\,C\,m^{-2}\,yr^{-1}}$), 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 and overall estimates of exchange

Off-shelf transport processes have yet to be explicitly investigated in the context of multi-annual and shelf wide-scales. Here we consider previous observations and modelling in turn.

3.1 Observations

Observational campaigns are necessarily limited to a few seasons and a particular area. The *Malin-Hebrides* shelf west of Scotland has been studied for internal tides (Sherwin, 1988) and ocean-shelf interaction (UK LOIS Shelf Edge Study (SES) 1995/96, e.g. Souza et al., 2001). The Ocean Margin EXchange project (OMEX) I, 1993–1996, was over *Goban Spur* (e.g. Wollast and Chou, 2001). *Celtic Sea* studies include internal tides (e.g. Pingree and New, 1989; New and Pingree, 1990), the slope current (Pingree et al., 1999) and residual circulation (Pingree and Le Cann, 1989, 1990). *Iberian Margi*n studies include several of upwelling and larger-scale studies of current structure and biogeochemical

Table 1. Estimated process contributions to ocean-shelf water exchange (m^2/s) by sector. Exchange time=shelf volume/total exchange rate. Under Slope current are estimated bottom Ekman layer transports (Sect. 4) based on the steric slope and stratification depth (Huthnance, 1995) relative to conditions off W Scotland (Sect. 6) where there is a direct estimate (Harikrishnan, 1998). Under Wind are "winter" (November–April) and "summer" (May–Octotber) averages of cross-shelf edge Ekman flux (Sect. 4); these use monthly wind speeds from Josey et al. (1998, 2002) and wind directions and standard deviations from Isemer and Hasse (1985); typical standard deviations of the six monthly values about the given average are ±25%. However, North Sea fluxes (not at the shelf edge) are based on estimates of flow between Scotland and Norway, see Sect. 5.8. For other contributions see respective sections as indicated.

Sector (see Sect. no.)	Slope Current (Ekman layer)	Eddies	Wind summer	Wind winter	Filament	Internal Tide (summer only)	∼Total	Exchange time (yr)
Norway (5.9)	0.5	1	0.90	1.48			3	0.21
North Sea (5.8)	2			2			4	1
N Scotland (5.7)	0.5	1	1.06	1.81			3	0.08
W Scotland (5.6)	0.5		0.80	1.73		0.3	2	0.20
W Ireland (5.5)	0.5		0.67	1.55			1.7	0.23
Celtic Sea (5.4)	0.5		0.78	1.09	1	1	3	0.28
E Biscay (5.3)	0.2		0.77	1.22			1.2	0.34
S Biscay (5.2)	0.5	0.16	0.64	1.26			1.6	0.05
W Iberia summer (5.1)	1	0.6	1.03		3	1	5.6	0.02
W Iberia winter (5.1)	1	0.6		0.99			2.2	0.05

exchanges: MORENA (e.g. Fiuza et al., 1998) and OMEX II (e.g. Huthnance et al., 2002; Joint and Wassmann, 2001; van Weering and McCave, 2002).

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; Huthnance et al., 2002, Table 7). 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. Around Scotland, estimates of lateral diffusivity from drogued-buoy dispersion (basis iii) are: ∼700 m^2/s (Booth, 1988); ∼360 m^2/s for both winter and summer (Burrows and Thorpe, 1999a). North of Scotland and off Norway, cross-slope current variances are of order (0.1 m/s)^2. Analysis by process contributions is discussed in Sect. 5, initially for west Iberia, and presented in Table 1.

Water, nutrient and carbon cycling along the north-east Atlantic margin (Biscay to Norway) has been reviewed for the JGOFS-LOICZ Continental Margin Task Team (Huthnance, 2009).

There have been North Sea studies of the seasonal cycle (Simpson, 1993).

3.2 Modelling

The North Sea has been the subject of 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.

To simulate 1960–2004 exchange between the north-west European shelf and adjacent Atlantic, Holt et al. (2009) have used a 3-D physics-only "POLCOMS Atlantic Margin" model with ∼12-km resolution, 42 s-levels and COARE3 bulk formulae for surface fluxes (Fairall et al., 2003). The simulation used ERA40 forcing, lateral boundary conditions from a ∼1° global model for 1958–2004 (NEMO; Smith and Haines, 2009) 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 (1 Sv=10^6 m^3/s). 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 onto-shelf values in Fig. 3 are added and all off-shelf flows are added separately. Across-shelf-edge transport in the American 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 figure shows some tracer advance or

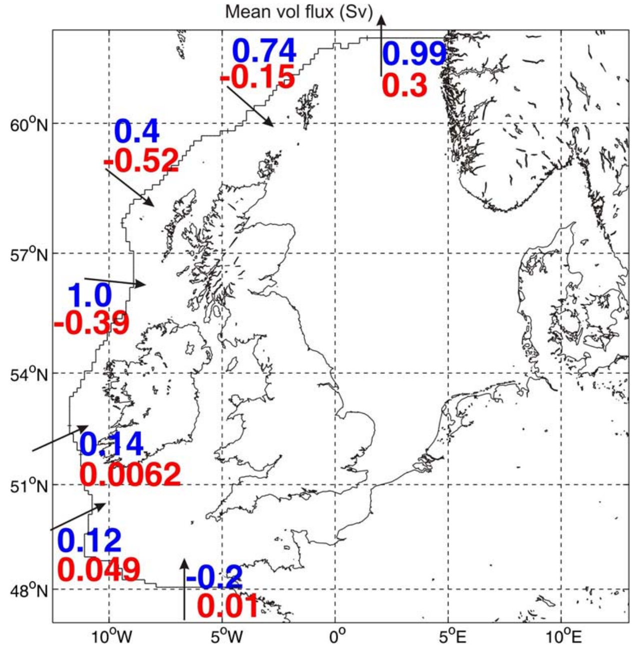

Fig. 3. Fluxes (Sv) above 150 m (blue) and below 150 m depth (red). All fluxes are across the 200 m contour shown; positive is onto the shelf except next to Norway (positive to north).

entry of Atlantic water on to the shelf south-west of the UK and subsequently into the English Channel, on to the shelf west of Scotland and in to the northern North Sea both west and east of Shetland; there is a marked tongue along the west side of the Norwegian Trench. Tracer also advances over Porcupine Bank west of Ireland and along the slope around Scotland (cf. Sect. 4, *slope current*). Strong tracer concentrations at 24 months south-west of the UK confirm the lack of off-shelf transport in this sector. Elsewhere the off-shelf picture is more complex as reduced tracer values can derive from the various banks west and north of Britain. The initial tracer quantity equates to a mean density of 84.3 m^{-3}, if spread over the whole domain. The tracer over the shelf (water depth<200 m, volume 91 000 km^3) has mean density 12.8 m^{-3} after 6 months, 57.4 m^{-3} after 24 months. Allowing for an initial delay for tracer to reach the 200 m contour, this is an approach to 84.3 m^{-3} as $1-\exp(-0.65\,t)$ where t is time in years, i.e. about 1.9 Sv effective exchange rate for the tracer. This estimate is appropriately less than total exchange 2.5 Sv which includes some off-shelf tracer transport.

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 $\mathrm{CO_2}$ "pump" concept (Sect. 6 and Thomas et al., 2004) to the wider west-European shelf.

Proctor et al. (2003) modelled a year (1995) of nutrient and phytoplankton fluxes across the shelf edge west of Scotland in 2-D with horizontal resolution ∼1.2 km and 60 layers in the vertical. The microbiological model represented nitrate, ammonium, oxygen, microplankton and detritus. Results were validated by 1995 flux measurements in SES (Souza et al., 2001), with fair agreement, but indicated 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.

For 3-D carbon cycling, POLCOMS 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 with ERA40 and operational ECMWF surface forcing, about 300 river-flow inputs and time-varying (spatially-uniform) atmospheric $p\mathrm{CO_2}$. A mean annual cycle was used at ocean boundaries, for optical attenuation and for riverine concentrations of nutrient and dissolved organic carbon (DIC). Inputs to the model budget (largest first) are from rivers and the atmosphere (inorganic carbon) and advection of organic carbon (Table 2 and Fig. 5). These simulations are presented in detail by Wakelin et al. (2009). 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, an effective sink of carbon if it leaves the shelf to water too deep to re-equilibrate with the atmosphere. The net effect as a sink of (inorganic) carbon from the atmosphere is 0.9×10^{12} mol C yr^{-1}.

4 Exchange processes

Estimated process contributions to ocean-shelf water exchange are shown by sector in Table 1. Here we outline the contributing processes (deferring sector-specific aspects to Sect. 5) (italicised processes are shown in the table. Others mentioned are relatively small).

Warm, saline North Atlantic Water (NAW) forms a poleward *slope current* along the continental slope, in most sectors from Portugal past Britain to Norway. Its spatial continuity is shown by drifter observations and satellite altimetry (Pingree et al., 1999; Skagseth et al., 2004). The current is approximately barotropic, centred at ∼500 m on the slope (e.g. Huthnance, 1986, and references therein; Pingree and LeCann, 1989, 1990). It is thought to be forced by the dynamic height of warmer sub-tropical waters (Huthnance, 1984; Hill et al., 1998a; Fig. 2). Below the poleward slope current is a bottom *Ekman layer* (Huthnance, 1995, and Fig. 2), modified by the slope and stratification (e.g. Trowbridge et al., 1998), where friction reduces the

Table 2. Model estimates of carbon budget elements, 47°–62° N from Wakelin et al. (2009).

Inorganic Carbon units 10^{12} molC/yr		Organic Carbon units 10^{12} molC/yr		
Respiration – Production	-0.05	Production – Respiration	$+0.05$	
Advection	-4.0	Advection	$+0.65$	
Air to sea	$+0.9$			
Benthic respiration	$+0.8$	Erosion - settling	-0.82	Difference is burial 0.02
Rivers	$+2.4$	Rivers	?	?: model numerics generate some
$\partial C/\partial t$	$+0.05$	$\partial C/\partial$t	$+0.01$	

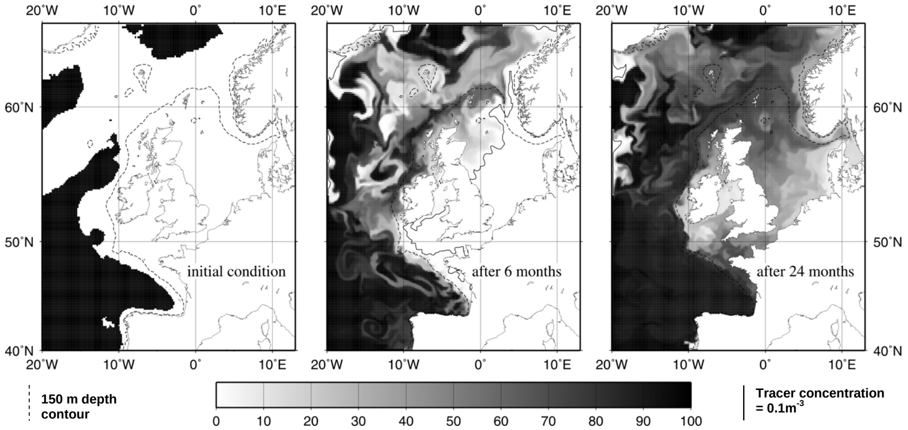

Fig. 4. Evolution of modelled surface concentration of tracer during 2002–2003. Initial concentration (beginning of 2002) was 100 m^{-3} everywhere where total depth >2000 m, zero elsewhere (within and somewhat beyond the 150 m isobath, concentrations homogenize through the water column each winter).

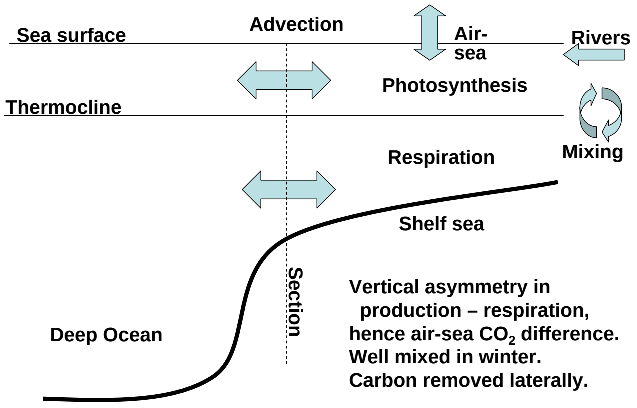

Fig. 5. Elements of shelf-sea carbon budget.

current to zero. This Ekman layer is expected (with some evidence from observations) to have off-shelf transport $\tau/\rho f$ with maximum $gh_O s/8f$ 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, s the slope of dynamic height as a result of poleward density gradient through depth h_O. 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 ($r \sim 0.7$) 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 irregular shelf, with capes, canyons and varied shelf width, may cause cross-slope flow (Trowbridge et al., 1998), slope-current meanders (Fig. 2) and *eddies* (detailed by sector in Sect. 5).

The region is subject to strong *wind* forcing. Except off Iberia in summer, winds are variable, usually associated with the passage of cyclones (depressions) driving storm surges (in the form of coastal Kelvin and continental shelf waves) and intermittent up- or down-welling. The surface flow can be estimated as an Ekman transport

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

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 northerly trade winds over the western Iberian shelf (Fig. 6). Well-developed upwelling can form *filaments* with off- and on-shelf fluxes exceeding the Ekman transport over the corresponding length of shelf. Shelf irregularities (capes, canyons and varied width) may cause locally-enhanced up-/down-welling.

Internal tides are generated in many locations (Sect. 5) by tidal flow over steep slopes and can strongly affect tidal currents. Large-amplitude (non-linear) internal tides transport water in their wave-forms on the summer thermocline (Fig. 2). 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 be significant for 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.

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 $\mathrm{m^2\,s^{-1}}$, significant when and where they occur but highly intermittent.

5 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.

5.1 West Iberia

This sector has moderate shelf width and significant inputs of fresh water. Poleward along-slope flow comprises relatively warm and saline Eastern North Atlantic Central Water (e.g. Frouin et al., 1990). It is manifested at the surface in winter, but 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).

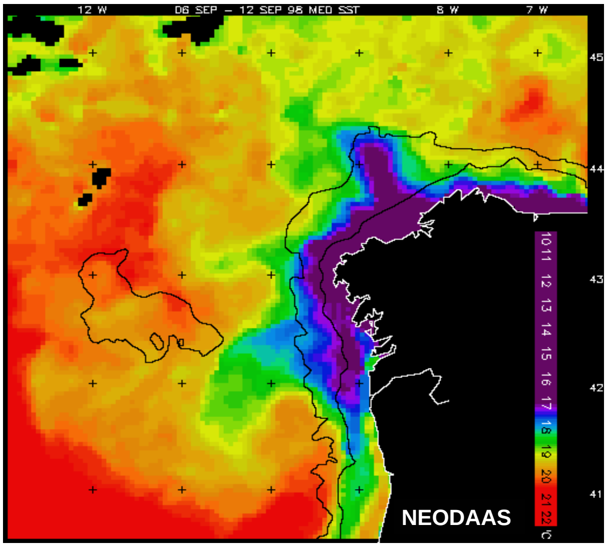

Fig. 6. Sea-surface temperature off Iberia, 6–12 September 1998, showing upwelled water (coldest against coast) and filaments of cooler water extending offshore near (44° N, 9° W), (43° N, 10° W) and (42° N, 10° W). Satellite data were received and processed by the NERC Earth Observation Data Acquisition and Analysis Service (NEODAAS) at Dundee University and Plymouth Marine Laboratory (www.neodaas.ac.uk).

Seasonality is very strong. In winter, winds are variable and upwelling can happen in any month, but (north-) westerlies prevail and give mixing and downwelling on average (NOAA upwelling index values analysed in Huthnance et al., 2002). 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 nutrient-rich water, along the north-south extent of the Iberian shelf and especially around Finisterre (e.g. Joint and Wassmann, 2001) but less off the Algarve with different coastal orientation. Well-developed upwelling can form filaments taking surface water off-shelf, with complementary on-shelf flow (beside and below). Filament fluxes are typically O(0.6 Sv) each (Barton et al., 2001) exceeding the Ekman transport over the (semi-regular) spacing between filaments.

Internal tides having peak currents comparable with barotropic tidal currents are generated in summer over steep slopes off Portugal (Jeans and Sherwin, 2001a, b).

Overall estimated exchange across the 200 m depth contour is 3.1 $\mathrm{m^2/s}$ on the basis of cross-slope current variance $(15.5\,\mathrm{mm/s})^2$ (Huthnance et al., 2002) but differs between summer and winter. Contributions (Huthnance et al., 2002, and Table 1) come from up-/down-welling, secondary flow associated with the slope current (O(1 $\mathrm{m^2/s}$) including the Ekman "drain"), non-linear internal tides on the summer thermocline O(1 $\mathrm{m^2/s}$), detaching eddies and crossfrontal flow O(0.6 m^2/s combined). The overall estimate 5.6 m^2/s for 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 (Huthnance et al., 2002). 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 summer-enhanced drifter dispersion (870 m^2/s cf. 190 m^2/s in winter, Sect. 3).

5.2 Southern Biscay

This north Spanish shelf is relatively narrow. Freshwater input from rivers greatly exceeds net rainfall-evaporation over this small shelf area. Estimated ocean-shelf exchange $\sim$1.6 m^2/s is dominated by wind-forced flow (Table 1). 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, of order 500 km^3 each, for a relatively small exchange 0.16 $\mathrm{m}^2\,\mathrm{s}^{-1}$ in this sector.

The estimated ocean-shelf exchange is larger than along-shelf flows from/to adjacent sectors. Production uses oceanic nutrient inputs greatly exceeding riverine and atmospheric sources.

5.3 Eastern Biscay

In this sector, freshwater input from rivers (notably the Garonne, Dordogne and Loire) is estimated as more than six times (evaporation – rainfall). Salinity on the shelf is close to open-ocean values, indicating effective (mostly wind-forced) ocean-shelf exchange, larger than along-shelf flows from/to adjacent sectors. Again, production greatly exceeds what can be supported by riverine and atmospheric inputs and is inferred to depend on oceanic inputs to the shelf.

5.4 Celtic Sea

This is a very broad shelf sector between Brittany and south-west Ireland.

Low-frequency circulation in the Celtic Sea is generally weak (Pingree and le Cann, 1989) except along the upper slope and where channelled or accelerated around promontories. Pingree et al. (1999) show a satellite image suggesting slope-current "overshoot" into the ocean at Goban Spur. This localised exchange, when it occurs, could be comparable with the slope current transport, O(1 Sv or 1 m^2/s if attributed to the whole sector). The discontinuous coast allows on-shelf wind-forced flow to extend eastwards through the English Channel (about 0.1 Sv; Prandle et al., 1996) and northwards through the Irish Sea (about 0.1 Sv; Knight and Howarth, 1999). Tidal currents exceed 0.5 m/s at the shelf edge west of Brittany, where tidally-rectified flow reaches 0.1 m/s. Internal tides with comparable peak currents are particularly strong at the Celtic Sea shelf edge (e.g. Pingree and New, 1989) and carry on-offshore exchange up to 1.3 m^2/s in their wave-forms on the summer thermocline (Huthnance et al., 2001). At the shelf edge, the 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 (Cooper and Vaux, 1949).

These processes suggest a large ocean-shelf exchange O(3 m^2/s), greatly exceeding flows to/from adjacent shelf sectors. 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.

5.5 Western Ireland shelf

Ocean-shelf exchange is predominantly wind-forced. Prevailing westerlies tend to drive on-shelf surface flow and hence downwelling on average. Under the slope current, turbid down-slope Ekman flow on the outer slope of Porcupine Bank (Dickson and McCave, 1986) again suggests a route for sediment transport off the shelf. There is evidence of cascading at the north end of Porcupine Bank (Hill et al., 1998b). River input of freshwater exceeds rainfall-evaporation, but large 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.

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

Irish Sea outflow forms the northward-flowing Scottish Coastal Current (SCC) with branches on both sides of the Outer Hebrides island chain. As well as the Irish Sea outflow, river input and rainfall-evaporation are comparable in adding freshwater, but the effect on salinity is small except in the SCC. Poleward along-slope flow, and some dispersion onto and away from the shelf around Scotland, were shown by hydrography, moorings (Souza et al., 2001) and drifters (Burrows et al., 1999b) in the SES. Harikrishnan (1998) estimated a downslope Ekman transport 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. There is evidence of dense winter-cooled water cascading. Tidal currents include a notable internal component on the outer shelf (Sherwin, 1988). The flux estimate in Table 1 is based on the mean-square vertical displacement (potential energy density) given therein, and a (very approximate) 10% non-linear element to give water flux. Prevailing westerly winds tend to drive on-shelf surface flow and hence downwelling on average. Drifters moved across the 200 m contour onto the shelf at mean speed 4 mm/s in winter, 2 mm/s in summer (Burrows and Thorpe, 1999a) corresponding to respective transports 0.8, 0.4 m^2/s if extrapolated through the whole depth. Winds are the dominant forcing for ocean-shelf exchange, which greatly exceeds flows from/to adjacent shelf sectors.

Rivers 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. CO_2 uptake from the atmosphere is important in the Proctor et al. (2003, Sect. 3) model for balanced carbon fluxes in the cross-slope section.

5.7 North Scotland

This sector is at the latitudes near 60° N of maximum wind forcing. Aided by the south-west to north-east orientation of the shelf, prevailing westerlies tend to drive on-shelf surface flow. Downwelling is implied on average, insofar as the coast provides a barrier; there is also substantial flow to the North Sea requiring net inflow from the ocean. North Atlantic Water flows polewards as a (West Shetland) slope current. Prominent meso-scale meanders and eddies in the Faroe-Shetland Channel (probably generated locally by slope-current instability or from the Iceland-Faroe front) sometimes deflect much of the slope current into the central part of the Channel (2 Sv or more; Sherwin et al., 1999, 2006). Sherwin et al. (2006) suggest that possibly the variability helps (via mixing) to draw as much as 2 Sv of Modified North Atlantic Water into the Channel from the north. The Table 1 value 1 m^2/s is somewhat less, reflecting the uncertainty. The Wyville-Thomson Ridge is a source of internal tidal currents and waves (Sherwin, 1991). Process-based estimates of ocean-shelf exchange show dominant wind-forced and eddy contributions to a large total 3 m^2/s. Drifter-based estimates of dispersion as large as 700 m^2/s (Sect. 3) give estimated exchange 7 m^2/s across the 500 m contour (Huthnance, 1995). Burrows and Thorpe (1999a) estimated $\sim$360 m^2/s across-slope dispersion around Scotland (west and north together). East of the Wyville-Thomson Ridge, their drifters moved across the 200 m contour onto the shelf at mean speed 10 mm/s in winter, -15 mm/s in summer, or transports 2, -3 m^2/s if extrapolated through the whole depth.

There is relatively little river inflow; rainfall-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.

5.8 North Sea

Exchanges are dominated by "Atlantic Water" inflows to the northern North Sea (by various routes around Scotland, notably around Shetland and the Fair Isle Current between Orkney and Shetland) and a similar transport along the continental slope into the Norwegian Trench (Huthnance, 1997). These northern transports total about 1.7 Sv, greatly exceeding the Dover Strait inflow $\sim$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).

Nutrient supply from rivers is significant locally in the southern and eastern North Sea, but 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 turbidity delays 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. Final export to the Atlantic Ocean accounts for more than 90% of the CO_2 taken up from the atmosphere (Thomas et al., 2005), and the North Sea acts as a sink for organic carbon. The uptake and sink is aided by large $p\mathrm{CO_2}$ draw-down as stratification separates upper-layer production from respiration which increases CO_2 in the subsurface layer that is ultimately exported. The stratified area more than offsets emission of respired CO_2 in the vertically-mixed southern North Sea (Thomas et al., 2004).

5.9 Norway

Northward flow comprises a slope current and the fresher Norwegian Coastal Current (NCC) near the surface and coast (McClimans et al., 1999; Skagseth et al., 2004), fed by Atlantic inflow to the northern North Sea, cyclonic North Sea circulation and fresher water from the Baltic. The NCC transports 1–2 Sv northwards from inflow across 61° N, with 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. There is no clear estimate of an eddy separation-rate to the ocean interior but the value in Huthnance (2009) and Table 1 is on the basis that much of the NCC transport is lost in O(1000 km) along the Norwegian shelf. The NCC also spreads under north/easterly winds, while south/westerlies

Table 3. Model estimates of fluxes (Sv), above (upper) and below 150 m (lower) across the 200 m contour, for the seven shelf sectors counting poleward, as in Fig. 3. Means and standard deviations (StDv) are over the 45 years 1960 to 2004.

Sector	Summer mean	Winter mean	Summer StDv	Winter StDv
7 upper	0.906	1.071	0.089	0.136
7 lower	0.246	0.346	0.086	0.125
6 upper	0.679	0.807	0.086	0.130
6 lower	−0.129	−0.162	0.020	0.027
5 upper	0.317	0.483	0.085	0.136
5 lower	−0.452	−0.588	0.075	0.112
4 upper	0.946	1.134	0.253	0.298
4 lower	−0.358	−0.413	0.163	0.207
3 upper	0.143	0.132	0.039	0.043
3 lower	0.009	0.003	0.010	0.012
2 upper	0.071	0.167	0.156	0.168
2 lower	0.056	0.042	0.083	0.072
1 upper	−0.163	−0.243	0.161	0.170
1 lower	0.009	0.011	0.021	0.021

confine it against the coast. Prevailing winds being westerly tend to drive on-shelf surface flow and hence downwelling on average. Tidal currents are strong with a significant diurnal component off northern Norway. 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.

6 Discussion and future work

6.1 Process contributions

The following characterise the west-European margin. There is poleward along-slope flow, which is not uniform, may not be spatially continuous, e.g. there is less evidence for it around south-east Biscay, and may also lie under different surface flow, especially during upwelling. Strong wind forcing with downwelling prevails north of Biscay and summer upwelling off Iberia. Well developed upwelling may form filaments increasing ocean-shelf exchange. There are strong tidal currents and mixing on wide shelves. Eddy exchange is relatively small except in the north. Freshwater influence is moderate except for the Norwegian Coastal Current. There are local rectified tides, solitons and cascading. Overall exchange is estimated as 2–3 m^2/s.

The combination of estimated exchange-process contributions in Sect. 5 (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. 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. During summer upwelling off western Iberia, the filaments probably take up most of the offshore wind-driven Ekman transport (shown under "Wind" in Table 1 but omitted from the summer "Total"). Otherwise, eddy and filament entries in Table 1 are for discrete localised features and can probably be added to the more extensive slope current and wind-forced exchanges. Internal tides are on a relatively small scale (especially the non-linear solitons giving water transport) and are probably additive on the basis of scale separation. In principle, larger-scale flow might advect internal waves and modulate their contribution, but on-offshore flows are relatively slow except locally in filaments and eddies (1 m^2/s corresponds to 0.01 m/s in 100 m depth).

The encouragement from combining exchange-process estimates 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. Budgeting is inherent in models (if properly formulated).

6.2 Variability

The model estimate 2.5 Sv (Sect. 3) 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.

Seasonality from the 1960–2004 model calculation is shown in Table 3 for the seven sectors illustrated in Fig. 3. In most sectors (either upper or lower level) mean fluxes (and their standard deviations) are rather larger in winter than summer. This accords with Table 1 estimates for winds (the main contributor) from West of Ireland to North of Scotland, albeit the winter-summer differences are less in the model results.

Interannual variability in the model results is quite small. Individual sectors, layers and seasons, from Sects. 4 to 7, and Sect. 3 upper layer, have the same sign of seasonal flux every year (except Sect. 4 lower is just positive in winter 1969). The overall exchange estimate 2.5 has standard deviation less than 0.4 over the 45 years 1960 to 2004.

6.3 Relation to carbon budget

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. Modelled inorganic and organic carbon budgets for this region (47°–62° N) are outlined in Table 2. Production is almost balanced by respiration within the water column (as a whole; production is biased to the upper layer and respiration to the lower layer during summer stratification). These tidally active shelf seas lack "export production" or burial (settling is almost balanced by benthic respiration). Hence (to conserve carbon) large air-sea CO_2 flux implies divergent dissolved inorganic carbon (DIC) transport. Then the overall downwelling allows transport of dissolved material from river input and 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, or the whole shelf volume in $\sim$3 years. The implied inorganic carbon concentration in the modelled 2.5 Sv exchange is about 0.05 molC/m^3 (excess of export to the ocean over import from the ocean)). 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, this region 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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