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Down-welling circulation of the northwest European continental shelf: A driving mechanism for the continental shelf carbon pump

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[1] Annually integrated measurements of pCO_2 have demonstrated that seasonally stratified regions of temperate shelf seas can be an important sink of atmospheric CO_2. A key process to support this sink is the transport of carbon from shelf seas to below the permanent pycnocline of the deep ocean. Using a hydrodynamic model simulation of the northwest European Continental shelf, we find that both the large scale circulation and frictional processes support the off-shelf transport of carbon sufficiently quickly to remove ~40% of the carbon sequestered by one growing season before the onset of the next. This transport is highly heterogeneous, with some regions being only weakly flushed. Only 52% of this exported carbon is transported below the permanent pycnocline, hence the shelf sea and open ocean carbon cycles are intrinsically coupled.

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1. Introduction and Model Description

[2] There is now substantial evidence that mid-latitude shelf-seas can make a significant contribution to the oceanic up-take of carbon [e.g., *Thomas et al.*, 2004], through their exceptionally high primary production [e.g., *Cadee and Hegeman*, 2002]. In this paper we investigate how the circulation of the northwest European continental shelf (a broad tidally active shelf-sea, Figure 1) facilitates this carbon up-take. In the hypothesis of the shelf-sea pump [*Tsunogai et al.*, 1999; *Yool and Fasham*, 2001] carbon sequestered by phytoplankton growth during the spring/summer sinks below the seasonal thermocline, and this results in a net-drawdown of atmospheric CO_2. Below the seasonal thermocline heterotrophic processes generally remineralise the particulate organic carbon (POC) to dissolved inorganic carbon (DIC), since in tidally active seas only a small fraction of the carbon is buried in the sediment for long periods [*Eisma and Kalf*, 1987; *Thomas et al.*, 2004; *Wollast and Chou*, 2001]. Across much of the shelf, this high DIC water is initially isolated from atmospheric exchange by the seasonal thermocline [e.g., *Rippeth*, 2005]. However, for this process to be an efficient method for carbon draw-down over an annual cycle, this high DIC water must be exported to the deep-ocean, below the permanent pycnocline, before the onset of the next growing season. Otherwise it will inhibit the CO_2 draw-down in the next season. In fact observations of air-sea pCO_2 gradient over an annual cycle demonstrate that there is indeed a net draw-down of CO_2 in the seasonally stratified regions of the North Sea [*Thomas et al.*, 2004] and Celtic Sea/Biscay [*Frankignoulle and Borges*, 2001]. Hence there is necessarily effective off-shelf carbon transport, leading to a local sink of carbon. The questions remains, however, what is the nature of this transport and does it remove carbon from the atmosphere to the deep-ocean and hence for centennial time scales?

[3] The 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 region; in this area the Malin-Hebrides shelf (LOIS/SES 1995–96 [e.g., *Souza et al.*, 2001]), Goban Spur (OMEX I [e.g., *Wollast and Chou*, 2001]) and the Iberian Margin (OMEX II [e.g., *Huthnance et al.*, 2002]). In previous modelling [*Iversen et al.*, 2002; *Winther and Johannessen*, 2006] and budgeting [*Thomas et al.*, 2005] studies of the North Sea there has been a tendency to consider fluxes through the Fair Isle Channel and the sea between Shetland and Norway, considering inward flow to be a transport of 'Atlantic' water. However, this does not directly address the ocean-shelf exchange and in fact reflects transport of water from the Malin-Hebrides shelf travelling north in the shelf edge current from as far south as the Celtic Sea [*Pingree et al.*, 1999]. Therefore for this work we concentrate on fluxes across the shelf-break (~200m isobath), which provides the natural boundary between oceanic and shelf-sea waters.

[4] The major transport pathway out of the North Sea is the Norwegian Coastal Current (NCC; Figure 1). There have been only limited observations of the vertical current structure of the NCC [e.g., *Johannessen et al.*, 1989], but these concur with modelling studies [*Holt and Proctor*, 2008] that the NCC has both a depth mean component and a strong surface intensification associated with fresher water outflow from the Baltic. Hence, carbon sequestered in North Sea but transported in the surface layer of the NCC might be out-gassed as this current carries water around the coast of Norway. Whereas water transported in the lower layer remains isolated from the atmosphere. In addition to this large scale current, other, generally frictional, processes can transport water off-shelf [*Huthnance*, 1995], particularly Ekman draining and coastal down-welling (discussed below).

[5] To investigate these transport processes we use a simulation of the Atlantic Margin Model (AMM) [*Wakelin et al.*, 2009] application of the Proudman Oceanographic Laboratory Coastal-Ocean Modelling System (POLCOMS) [*Holt and James*, 2001]. Horizontal resolution is ~12 km with 42 s-coordinate levels in the vertical. The simulation period is 1960–2004 after a single year (1960) spin-up. Surface forcing is from ERA-40 and lateral boundary

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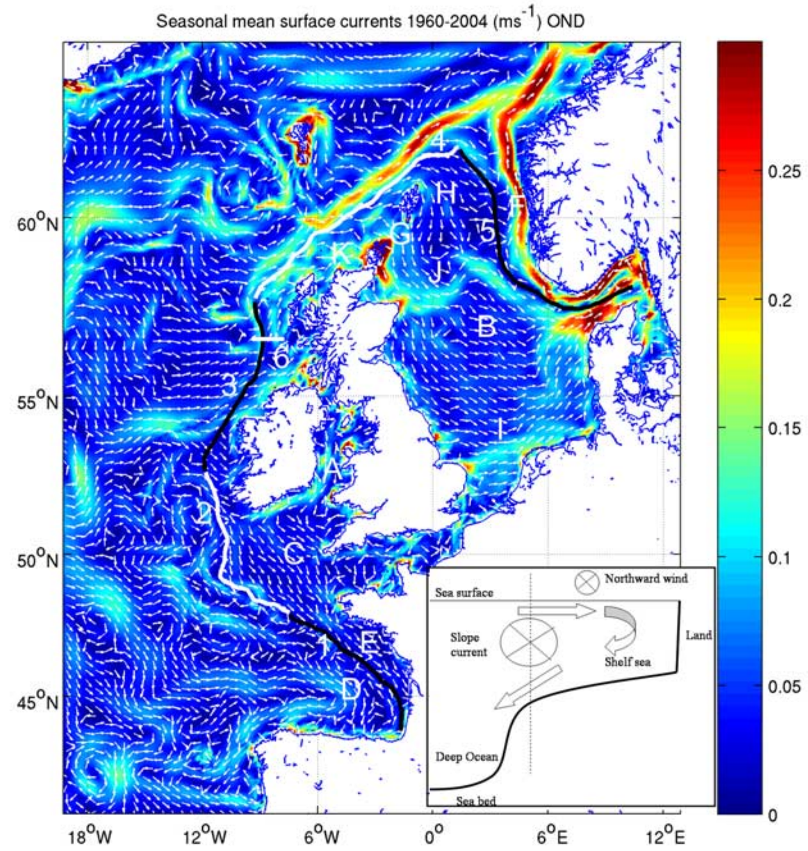

Figure 1. Mean surface currents for autumn and the numbered sections following the 200m isobath used for flux calculations (black and white heavy lines). Insert shows a schematic of the slope current and the Ekman circulation. Geographical areas are: A, Irish Sea; B, North Sea; C, Celtic Sea; D, Biscay; E, Armorican Shelf; F, Norwegian Trench/Coastal Current; G, Fair Isle Channel/current; H, Shetland to Norway; I, Dogger Bank; J, Dooley Current; K, Malin-Hebrides shelf.

conditions from a contemporary run of a ~1° global ocean model. Freshwater discharge is provided by flow data from 290 rivers. While this model configuration is also run coupled to the European Regional Seas Ecosystem Model (ERSEM), here we limit the analysis to the hydrodynamic model and infer the consequences for biogeochemical cycles. The conclusions we reach here are largely independent of the details of the ecosystem.

[6] Model validation is provided by the ~90000 CTD casts in the ICES database for this period (www.ices.dk). The RMS errors are 1.1°C for temperature and 0.75 for salinity. Uncertainties in the velocities are estimated as by *Holt and Proctor* [2008] using the 42 drifters deployed in the UK Shelf Edge Study (SES) project [*Burrows et al.*, 1999]. The RMS error in current speed averaged over each drifter is 0.07ms^{-1} (~37%) in the shelf-slope region (depths less than 1000m), with generally a negative (model too slow) bias. The fractional uncertainty in the corresponding Ekman transport is 74%.

2. Slope Current and the Ekman Layers

[7] A dominant feature of the mean circulation on this shelf (Figure 1) is the slope current centred at the ~500m isobath [*Souza et al.*, 2001]. It is approximately barotropic and thought to be driven by a combination of the poleward density change and sloping topography [*Huthnance*, 1984]. Drifter observations demonstrate its continuity [*Pingree et al.*, 1999] and its dispersion [*Burrows et al.*, 1999] onto the shelf. The occurrence of an off-shelf Ekman drain below a poleward slope current has been considered in theory [e.g., *Huthnance*, 1995] and observation [*Souza et al.*, 2001] based investigations of shelf-edge exchange. The transport in the Ekman layer is given by:

$$Q_B = \frac{\tau_B}{\rho f}, \tag{1}$$

where $\tau_B = \rho C_d u_B^2$ is the bottom stress arising from the near bed, along slope current (u_B), ρ is the water density, f the Coriolis parameter, and C_d is the drag coefficient. The relation for the Ekman transport is remarkably robust since it is independent of the details of the internal variations of stress.

[8] At the surface, the poleward along-slope component of wind tends to drive an on-shelf current (with a similar transport expression to equation (1)). In the classic picture of coastal down-welling (Figure 1) the presence of the coast forces this water downwards. However, the lack of an adjacent coast (here arising from the broad North Sea, Celtic Sea and Irish Sea continental shelves), allows more

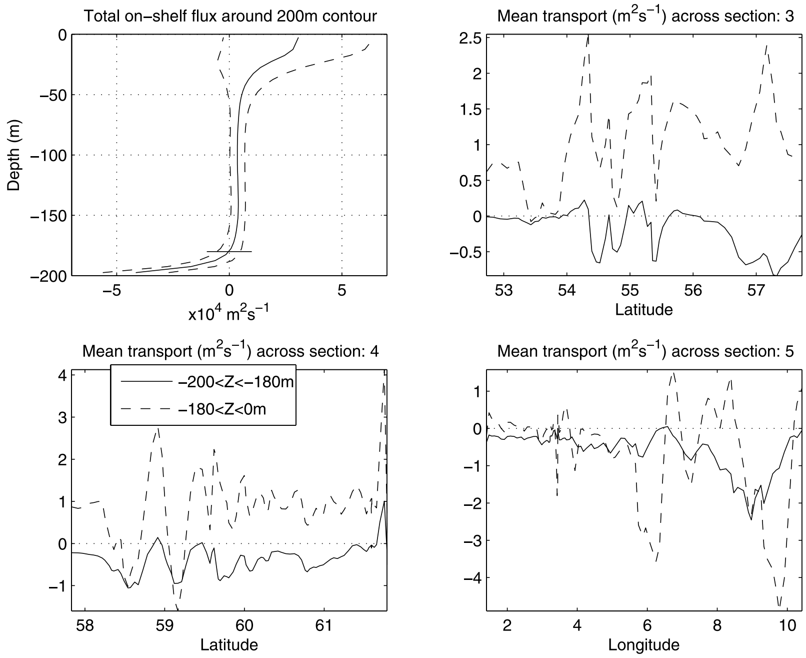

Figure 2. Volume transport (mean from 1960–2004 per length of shelf) across 3 sections shown on Figure 1 in two layers below and above 180m. Positive values indicate an on-shelf flux. Also shown (top left) is the total flux across the 200m isobath (sections 2–5). The dotted lines show 1 standard deviation of the monthly mean flux for the 45-year period.

extensive net on-shelf flow, with scope for return flow off-shelf elsewhere (notably in the NCC).

[9] The transport integrated around the 200m isobath (Figure 2) demonstrates that the shelf edge exchange north of 52.7°N is generally consistent with a surface wind driven transport on-shelf and an off-shelf transport in a thin near-bed Ekman layer. The across shelf edge transport in the Armorican Shelf and Celtic Sea (sections 1, 2, not shown) is weaker and generally on-shelf, whereas there is a strong off-shelf transport from the North Sea to the Norwegian Trench (section 5). Near 6°E and 10°E there are also two, approximately barotropic, intense off-shelf currents. These arise where the large scale circulation crosses the 200m isobath.

[10] The standard deviation of the monthly mean fluxes integrated around the 200m isobath (Figure 2) demonstrates that the benthic Ekman layer shows very little variability. On these time scales, the currents are strongly steered, geostrophically and topographically, and are essentially uni-directional. The wind-driven surface flux is more variable. The total transports are summarized in Table 1, where the transport has been divided between layers above and below 180m. Together these results clearly demonstrate the down-welling nature of the circulation of this shelf: water tends to enter the shelf at the surface and leave at depth.

[11] The characterisation of the off-shelf transport as an Ekman drain is apparent from the strong positive correlation ($r^2 \sim 0.5$) between the along-slope flux (section 6) and the lower layer flux across section 3. A simple Ekman calculation based on the near-bed velocities around the 200m isobath gives a mean off-shelf transport of similar order (Table 1), and where the along slope current is weaker (sections 1 and 2), then so is the near-bed off-shelf transport. However, the temporal variability of this calculated Ekman transport is not so well correlated with the off-shelf transport. That this simple approach does not give accurate quantitative agreement locally is not surprising since the flow conditions here are far from horizontally uniform. In contrast estimates of the surface Ekman transport (Table 1) correlate well with the surface currents, but do not agree so well in magnitude.

3. Ocean-Shelf Transport

[12] The large-scale role of ocean-shelf exchange can be investigated using model tracer transport experiments. At the start of each June during the 45-year simulation, a passive tracer field is re-initialized with a concentration of $1/\delta z$ m^{-3} in the lowest model s-level (thickness δz), but only on-shelf in total water depths less than 200m. This crudely represents the POC generated during the spring phytoplankton bloom that has subsequently settled below the thermocline. Settling and re-suspension processes are not considered further, on the assumption that either the near-bed mixing is strong or the material has been re-mineralised to DIC. The efficiency of the shelf sea pump can be characterised by the amount of material that has been exported from the shelf by December. By this time seasonal stratification has largely broken down, and its role in isolating bottom waters from atmospheric exchange stops. The fate of material in waters that can now be mixed to the surface (on time scales of hours) depends on the details of the carbonate chemistry and air-sea exchange processes. However, for typical oceanic conditions the re-equilibration time is usually slow (~8 months [*Zeebe and Wolf-Gladrow*, 2001]) and similar to the transport time. Hence, the larger scale consequences of the shelf-sea pump can be inferred from the fraction of material that resides below the permanent pycnocline in March, i.e., has been removed from

Table 1. Summary of Mean Transport Across Sections Shown on Figure 1[a]

	Model Fluxes			Calculated Fluxes			
	Upper Layer (Sv)	Lower Layer (Sv)	Total (Sv)	Surface Ek. (Sv)	Surface Corr.	Benthic Ek. (Sv)	Benthic Corr.
Section 1	−0.14	−0.02	−0.17	−0.004	0.33	−0.03	0.06
Section 2	0.26	0.07	0.33	0.10	−0.22	−0.04	0.20
Section 3	0.62	−0.13	0.49	0.38	0.60	−0.20	0.20
Section 4	0.67	−0.28	0.38	0.35	0.88	−0.16	0.24
Section 5	−0.46	−0.42	−0.88	0.004	0.45	−0.33	0.11
Total (2–5)	1.08	−0.77	0.31	0.72	-	−0.77	-
Section 6							
Slope current	-	-	1.6	-	-	-	-

[a] Also shown is the mean Ekman transport based on daily-mean near bed currents and the correlation between the modelled monthly mean modelled fluxes and the corresponding Ekman flux.

contact with the atmosphere for long timescales before the on-set of the next growing season.

[13] Figure 3 clearly shows that by March all the shelf-edge regions have become depleted of material and that this has been transported and dispersed into the deep ocean. This is particularly the case for the shelf adjoining sections 3 and 4, where the transport processes illustrated in Figure 2 are very effective. The shelf from Biscay to Ireland also shows some off-shelf tracer transport despite the flux estimates across sections 1 and 2 being small (Table 1). This indicates a role for "diffusive" horizontal transport here (e.g., tidal shear dispersion and fluctuating wind-forced flow).

[14] The region of the Fair Isle current and Dooley current, and the Dogger Bank are highly depleted, but generally the North Sea is reduced to 50–75% of its original value. This material is transported off-shelf both in the Ekman drain and in the large scale circulation. Both lead to the NCC and hence an accumulation of material in the Norwegian Trench. This is supported by the presence of sediment deposition here [*Eisma and Kalf*, 1987]. In contrast to the shelf-edge regions and the North Sea, the Celtic Sea and Irish Sea show only weak depletion. This is supported by the weak residual currents observed in the Celtic Sea [*Pingree and Cann*, 1989] and the slow flushing of the Irish Sea [*Wakelin et al.*, 2009].

[15] By December, 28% of the material initialized the previous June has left the shelf (inter-annual range: 20% to 33%) and by the following March this increases to 40% (30% to 47%). The fraction transported off-shelf below the pycocline by March is 19%. This is divided between 13% (8 to 17%) below the pycnocline in the Norwegian Trench and 6% (3 to 8%) below the pycnocline in the Northeast Atlantic. The difference arises primarily from differences in pycnocline depth; this is much deeper in the North East Atlantic (200–1000m) than in the Norwegian Trench (∼40m). It is interesting to note that the fraction exported to below the pycnocline in the North East Atlantic in March increases from 1981 to 2004 at a (linear) rate of 0.076 ± 0.025% yr^{-1}. This reflects the shoaling pycnocline over this period (by 1 ± 0.25% yr^{-1}).

4. Discussion and Conclusions

[16] This model simulation demonstrates that water tends to come onto the northwest European shelf near the surface and leave at depth. This down-welling circulation is a product of the slope current and the prevailing wind direction. The slope current generates a local Ekman drain, whereas the surface wind-driven on-shelf transport drives a shelf-scale circulation (both are shown to be reasonably consistent with simple Ekman theory). The on-shelf flow eventually forms a substantially deeper current in the Skagerrak and Norwegian Trench, and hence is still a down-welling circulation albeit on a much larger scale. Here we find the down-welling circulation to be 0.9 ± 0.6 Sv (after subtracting the barotropic component). The uncertainty is based on a comparison with the SES drifters on the Malin-Hebrides shelf, and its size is not surprising given the coarse resolution of this model compared with narrow slope.

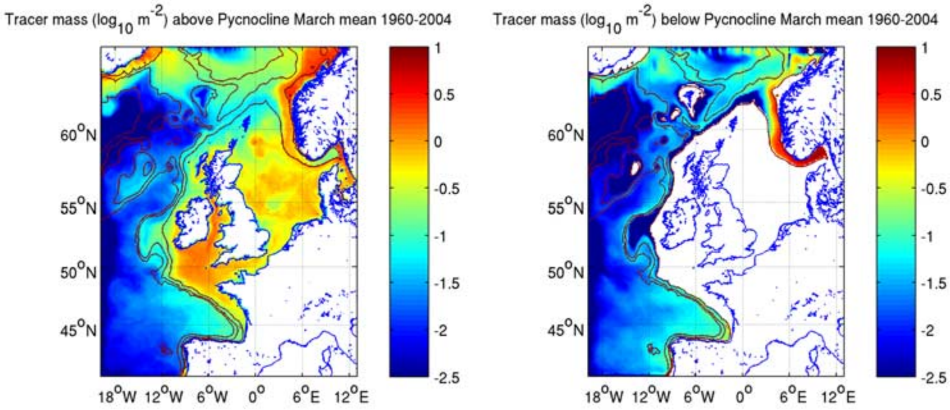

Figure 3. Tracer distribution (left) above and (right) below the mean pycnocline in March (defined as the level where the density has increased by 0.1 kgm^{-3} from the surface value). See text for details of tracer initialization.

[17] In the past, such down-welling circulation has received scant attention. But here we demonstrate that down-welling has an important role in biogeochemical cycles since it allows transport of dissolved material from regions of high production to the deep ocean. Critical for this role is the ability to transport water in a near-bottom layer off the shelf, below the permanent pycnocline on time scales of less than 1 year; any longer and the increased DIC levels from the last growing season will inhibit the CO_2 drawdown of the next growing season.

[18] In a mixed environment, the total down-welling circulation (of ~0.9 Sv) would evacuate the bottom quarter of the shelf (total volume $\sim 7.3 \times 10^{13}$) in ~8 months. However, a tracer transport experiment demonstrates the high degree of heterogeneity in this transport: The shelf near the ocean margin (from south of Ireland to the Norwegian Trench) and areas of the North Sea being most strongly flushed, the Celtic and Irish Seas being least. However, while the Ekman drain delivers material efficiently into the northeast Atlantic, only 39% of the material transported into this region by March is transported below the winter mixed layer. Hence the fate of this material (as a proxy for DIC) is uncertain and depends on the combined efficiency of the vertical mixing and the air-sea exchange processes in the time before the seasonal thermocline is established. Also the down-welling circulation at the shelf edge may well transport carbon (POC and DIC) on-shelf, where it can be down-welled and exported at depth. This is a potentially important mechanism for exporting oceanic carbon that would not otherwise efficiently sink-out (e.g., from picoplankton growth). Hence, the significance of shelf-sea circulation and carbon export on basin-wide scales cannot readily be decoupled from the deep-ocean processes. In the Norwegian Trench, in contrast, there is shallow stratification throughout the year and 61% of the material that enters this region is transport below this stratification in the lower part of the NCC, and hence isolated from atmospheric exchange. Across the whole domain 52% of the material transported off-shelf by March resides below the permanent pycnocline.

[19] While we have focused here on the northwest European continental shelf, the general principle that wind-driven and slope current-driven down-welling supports the export of carbon sequestered on the shelf to the deep ocean is applicable to many shelf seas around the globe. The details vary from region to region, but we can identify this process as being potentially important in subpolar seas, poleward of western boundary currents. Examples include the northeast coast of North America and the western Australian shelf, where the Leeuwin current provides a down-welling slope current.

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