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Thermohaline circulation of shallow tidal seas

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[1] The mechanisms controlling the temperature and salinity structure of shallow continental shelf seas have been understood for over thirty years, yet knowledge of what drives their large-scale circulation has remained relatively unknown. Here we describe a decade long programme of measurements, using satellite-tracked drifting buoys on the northwest European shelf, to draw attention to a striking picture of highly organised thermohaline circulation consisting of narrow, near surface, fast flowing jets. These are ubiquitous above sharp horizontal gradients in bottom temperatures and/or salinities. The circulation phenomena we describe are likely to be prevalent on all similar, wide, tidally energetic continental shelves including those off north-eastern China, Argentina and parts of the Arctic. The robust, repeatable observation of the key role of jets above bottom fronts results in a fundamental reassessment of how we view the dynamics of shelf seas. **Citation:** Hill, A. E., J. Brown, L. Fernand, J. Holt, K. J. Horsburgh, R. Proctor, R. Raine, and W. R. Turrell (2008), Thermohaline circulation of shallow tidal seas, *Geophys. Res. Lett.*, *35*, L11605, doi:10.1029/2008GL033459.

[2] It has been known for over thirty years [*Simpson and Hunter*, 1974; *Simpson*, 1981] that on wide, tidally energetic continental shelves spatial variations in the level of tidal mixing leads in summer to a well defined patchwork of stratified (two layer) and vertically homogeneous waters separated by sharp horizontal boundaries. The discovery of these tidal mixing fronts led to speculation that there should be strong frontal jets parallel to the surface temperature front, but early attempts to find these failed. Instead, our picture of long-term circulation on the European shelf has been based on the presumption that it is driven by episodic storms and is generally weak [*Simpson*, 1981] when averaged over a month or more. Indeed, in the absence of any systematic observations simple schematic circulation cartoons have had considerable currency.

[3] Between 1994 and 2005 we conducted a series of measurements in most parts of the northwest European shelf (see Table 1). Our observations, combined with those of others, now include descriptions of the western English Channel [e.g., *Vanhoutte-Brunier et al.*, 2008], Celtic Sea [e.g., *Brown et al.*, 2003], Irish Sea [e.g., *Hill et al.*, 1996; *Horsburgh et al.*, 2000], western Irish shelf [e.g., *Fernand et al.*, 2006], western [*Hill et al.*, 1997] and northern Scottish shelf, the northern [e.g., *Turrell*, 1992] and central North Sea [e.g., *Brown et al.*, 2001] and the Skagerak. We undertook (a) deployments of satellite tracked drifting buoys (mostly drogued at 20–30 m below the sea surface); (b) extensive high horizontal spatial resolution (<1 km) ship surveys of water column density structure using towed, undulating conductivity-temperature-depth (CTD) systems and; (c) measurements of the vertical and horizontal structure of currents using ship-borne acoustic Doppler current profilers (ADCP).

[4] Each year, from about May to October, large areas of the European shelf seas stratify as surface waters are warmed (Figure 1). A sharp seasonal pycnocline (density interface) is maintained by wind and tide generated turbulence, from the surface downwards and the sea bed upwards respectively. Below the seasonal pycnocline, extensive pools of cold, dense bottom water left over from the previous winter are trapped. The temperature of this bottom water is established, prior to isolation, by surface heat exchange during winter and early spring and thereafter warms only very slowly (e.g., 2°C over 200 days) after the onset of stratification. In addition, in areas of the shelf closest to the open ocean, the ‘cold pool’ waters below the seasonal pycnocline are also more saline (>35.3) owing to the penetration of salty oceanic waters onto the shelf.

[5] Inshore from the dense pools trapped below the seasonal pycnocline, in areas of the shelf where the water depth (h) is relatively shallow, and/or where depth-averaged tidal currents (U) are large, the water column remains vertically mixed by tidal stirring [*Simpson and Hunter*, 1974; *Simpson*, 1981] throughout the year. Characteristically on the European Shelf this occurs where $\log_{10} h/U^3 > 2.7$. Further inshore where freshwater influence is more prevalent, stratification is intermittent depending on levels of freshwater discharge. These regions (shown schematically to the right of the dotted line in Figure 1) are not considered in this paper.

[6] The offshore dense pools are typically bounded by sharp horizontal temperature and/or salinity gradients (bottom fronts) with a horizontal scale of approximately twenty kilometres. At tidal mixing fronts there is usually both a surface front and a bottom front, the latter usually being the more pronounced in terms of density gradient. However, elsewhere bottom fronts can exist without a surface front being present. Whilst surface fronts have received much attention in shelf seas (e.g., they are visible in satellite images), it is the hidden bottom fronts that are the most significant in dynamical terms. On account of the largely static nature of the cold/salt pools the bottom density gradient is expected, by thermal wind balance, to drive a

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Table 1. Summary of Drifter Deployments[a]

Region	Dates	Number of Drifters	Total Drifter-Days	Min. Frontal Jet Speed (cm s^{-1})	Drifter-Days Within Frontal Jet	Avg. Frontal Jet Speed (cm s^{-1})
Western English Channel	03/07–31/10/03	11	513	10	75	12.7
Celtic Sea	13/07–31/10/98	18	719	15	36	20.5
Irish Sea	22/06–17/08/95	12	289	15	24	18.7
West Irish shelf	09/07–02/09/99	7	246	10	47	14.9
	27/07–23/08/01	5	90	10	32	14.5
Western Scottish Shelf	19/04–24/06/95	4	104	20	27	29.5
Northern Scottish shelf (SES)	06/05–31/10/95	7	1079	20	61	26.4
Northern North Sea	23/05–31/10/97	8	341	10	15	12.3
Central North Sea	23/05–08/09/97	20	714	10	26	12.2
	16/06–03/08/99	21	721	10	35	12.8
	04/07–28/08/00	15	725	10	79	14.5
	28/06–26/08/01	13	504	10	71	18.7
	30/06–01/09/02	12	526	10	23	12.7
Skagerak	29/06–25/08/02	1	57	30	9	50.9
Totals		154	6628		560	

[a]Minimum and average frontal jet speed is as defined for each region in the auxiliary material. See text and auxiliary material for specific references for each area.

near surface geostrophic jet located above the region of maximum horizontal density gradients and with a flow direction that is cyclonic (i.e., with the dense bottom water to the left of the direction of flow in the northern hemisphere). With horizontal density gradients of 0.4 kg m^{-3} per 10 km, a characteristic jet velocity 50 m above the bed would be 0.2 m s^{-1}. Apart from limitations in observing technology at the time, we now understand that it was the focus on surface fronts rather than the bottom fronts that explains why the search for frontal jets in the 1970s was fruitless. It is only now that we can assemble the full picture of both the thermohaline structure and circulation of the shelf seas.

[7] A representative summer near-bed temperature field has been derived from a high-resolution (1.8 km) simulation [*Holt and Proctor*, 2008] of the European continental shelf using the POLCOMS three-dimensional model with 34 s-coordinate vertical levels. This model has been shown to reproduce the seasonal variability of northwest European shelf sea tidal mixing fronts in good agreement with oceanographic observations [*Holt and Umlauf*, 2008]. An earlier validation run of the model [*Holt et al.*, 2001], which excluded the effects of a time-varying oceanic density field, generated density-driven flows in reasonable agreement with the drifter observations described here. The surface boundary conditions were provided by the ERA40 meteorological reanalysis data from the European Centre for Medium Range Weather Forecasting. The simulation was for 2001 with oceanic lateral boundary conditions provided by a multi-year run of a wide domain version of the same

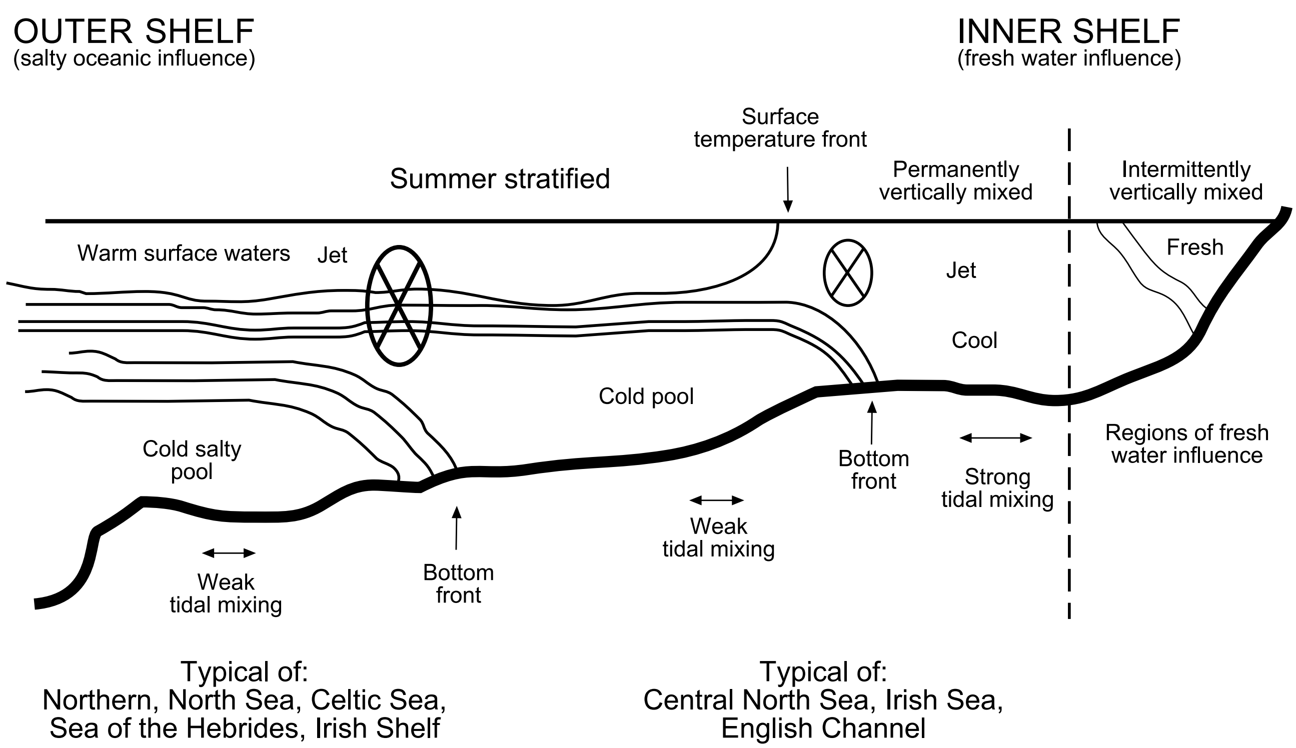

Figure 1. Schematic section across a wide tidally energetic continental shelf in summer. The crossed ellipses showing the jet locations indicate flow into the page.

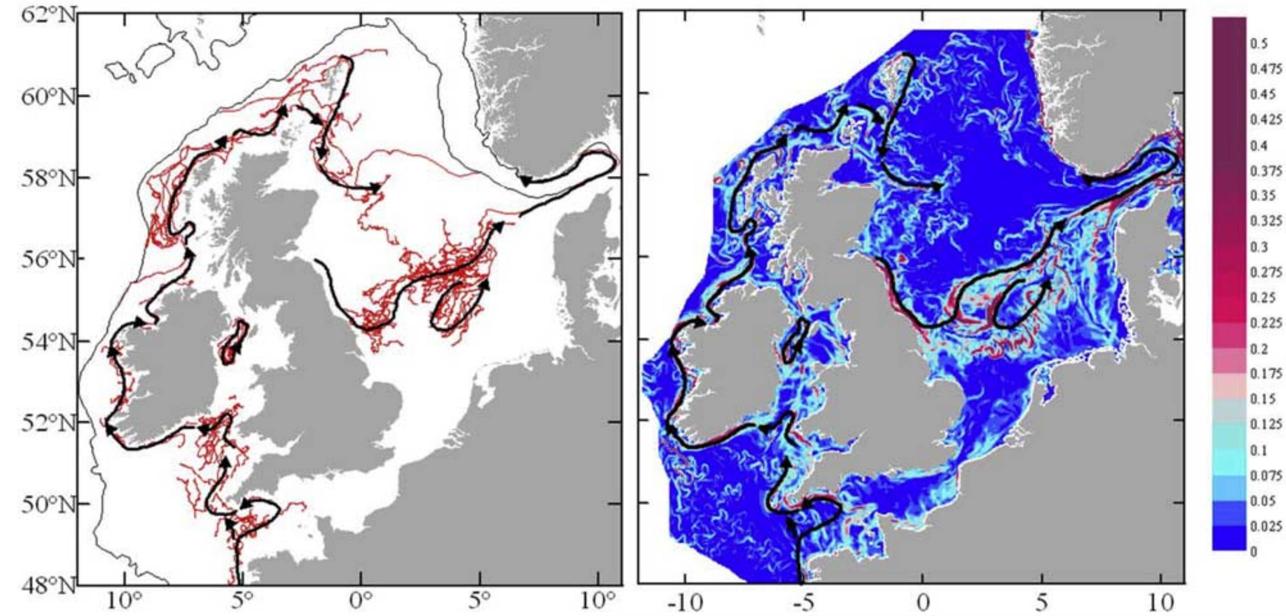

Figure 2. Overview of the shallow thermohaline circulation on the northwest European continental shelf. (left) Trajectories (red) of 154 satellite tracked drifters (see Table 1 for details). Frontal jets are indicated by black arrows. (right) Frontal jets superimposed on contours of the gradient of bottom horizontal temperature (15 August 2001) derived from a three-dimensional hydrodynamic model (Units - °C km^{-1}).

model at 12 km resolution. Figure 2 shows the daily mean horizontal temperature gradient at the lowest model level for 15 August 2001. Superimposed are the trajectories of the 154 drifters released between 1995 and 2003. The drifters show jet speeds of up to 0.3 m s^{-1} at depths of typically 30 m below the sea surface. Direct measurements of the density field, combined with measurements of flow from shipborne ADCP, and geostrophic (thermal wind) velocities confirms that the density field associated with the bottom fronts accounts for the observed drifter velocities [e.g., *Brown et al.*, 2003; *Horsburgh et al.*, 2000; *Fernand et al.*, 2006; *Hill et al.*, 1997].

[8] Further confirmation of the significance of density driven circulation on the European shelf, as a fraction of the total long term flow, comes from manipulation of three numerical model runs with (a) full forcing, (b) wind and

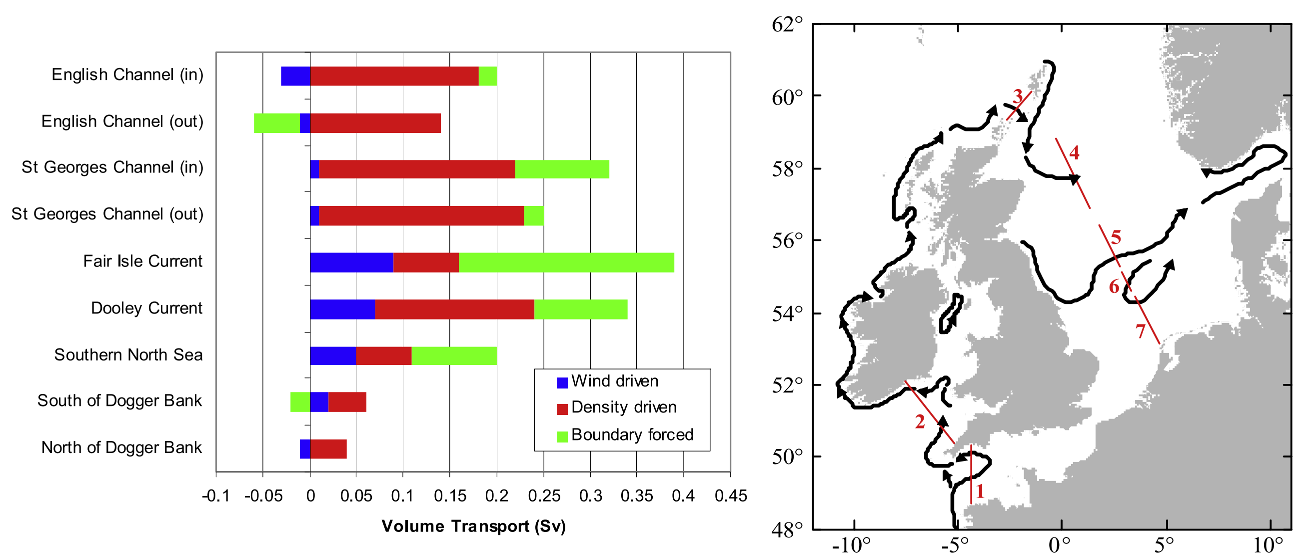

Figure 3. (left) Partitioning of summer (July–September) mean non-tidal transport across selected sections on the European continental shelf, estimated from three runs of a numerical model (see text for details). Note - 1 Sv = 10^{6} m^{3} s^{-1}. (right) Location of those sections through which transport partitioning is estimated. Numbered sections and directions of estimated transports are; 1, English Channel (in, eastwards; out, westwards); 2, St Georges Channel (in, northwards; out, southwards); 3, Fair Isle Current (eastwards); 4, Dooley Current (eastwards); 5, North of Dogger Bank (eastwards); 6, South of Dogger Bank (westwards); and 7, Southern North Sea (eastwards).

open boundary forcing, and (c) open boundary conditions only. By subtraction, it is possible to partition the circulation into that due to the local evolution of the density field (the red bars in Figure 3), the surface wind stress (blue bars), and the effect of the oceanic lateral boundary conditions (green bars). The volume transports depicted in Figure 3 are summer averages (July–September) calculated over sections normal to the density gradients at the stated locations. It is clear that the density driven component is prevalent in all of those areas where we have identified jets associated with bottom fronts.

[9] A first order estimate of the total volume transport (Q) of water associated with jets above bottom fronts can be obtained from a two-layer analytical model (Figure 1) that assumes a horizontal pycnocline at depth h_0 separates light surface waters of density ρ-$\Delta\rho$ from a bottom dense pool of density ρ. With gravitational acceleration (g), total depth H, and Coriolis parameter f (accounting for earth rotation) the total transport is

$$Q = \frac{g\Delta\rho}{2\rho f}\left(H^2 - h_0^2\right)$$

[10] Typical values for shallow, mid-latitude continental shelves are: $\Delta\rho$ = 0.4 kg m^{-3}, H = 80 m, h_0 = 30 m, f = 10^{-4} s^{-1}, giving Q = 0.1 × 10^6 m^{3}s^{-1}, easily the most dominant contributor to persistent transports from late spring to autumn.

[11] The horizontal transport above a bottom front, and the area of retention within the dense pool, influence the spatial heterogeneity of ecosystems and habitats within shallow seas. For instance, on the European shelf, species such as *Nephrops* exploit the area of retention in order to keep larvae above a suitable substrate for post-larval settlement [*Hill et al.*, 1996], while species such as herring exploit the jets in order to transport larvae from spawning grounds to nursery areas [*Turrell*, 1992]. The fronts form natural boundaries between eco-regions, as the area of retention is often characterised by deposition of soft organic sediment, while the frontal region is associated with higher productivity. These features are important when considering the division of shallow seas into biologically relevant management units, as required by the developing ecosystem approach to the sustainable use of marine resources.

[12] The density-driven currents we have found are connected on a shelf-wide scale and provide a continuous transport route from the French coastal region via the Celtic shelf and west of Ireland to the Scottish shelf (Figure 4). This pathway is potentially a conveyor belt for contaminants and plankton. For example, we note that blooms of several harmful algal species (e.g., *Karenia mikimotoi* and *Alexandrium tamarense*) consistently occur along these features, impacting aquaculture whenever local events force them onto the coast [e.g., *Vanhoutte-Brunier et al.*, 2008; *Brown et al.*, 2001]. It is likely that the shelf-wide circulation regime has existed since deglaciation (8000 years ago) and has thus influenced both the evolution of shelf sea ecosystems and the deposited geological record.

[13] Just as the oceanic thermohaline circulation is now receiving more attention than the wind-driven flow, we have shown that the thermohaline circulation of shelf seas is equally important. The recognition that density-driven

Figure 4. Schematic map of principal summer thermohaline transport pathways on the north western European shelf and the cold and salt pools that drive them. Orange shaded areas, regions where seasonally formed bottom dense pools are influenced by both cool winter temperatures and salty oceanic water which has penetrated the outer shelf. Light blue shaded areas, regions where only temperature is responsible for the density of dense water trapped below the seasonal thermocline. Green arrow, European slope current. Red arrows, frontal jets associated with bottom fronts at boundaries of dense cold and salt pools.

frontal jets are the most significant contributor to seasonal shelf transport allows a better assessment of the impact of climate change on this dominant circulation mode. For example, changes which result in weaker gradients across bottom fronts (e.g., warmer winters, and/or cooler summers) will weaken the circulation, while changes which result in stronger gradients will increase it. Even on inter-annual time scales we can observe significant changes. In the northern North Sea, between 1975 and 2005, the average (±s.d.) annual summer density difference across the bottom-front was 0.69 (±0.26) kg m^{-3}, which implies an average density-driven transport in this region of 0.24 (±0.09) × 10^6 m^{3}s^{-1}, representing a variability of approximately ±40% (see auxiliary material).[1]

[14] Another possible outcome of climate change is warming of the tidally energetic Arctic shelves [*Intergovernmental Panel on Climate Change*, 2007], which would then become more like the temperate shallow seas of the European continental shelf. In this case bottom frontal features would become more evident in Arctic seas, and hence their circulation more vigorous. Since such a large proportion of marine biomass production occurs within shelf seas, coupled ecosystem-hydrodynamic models should now focus on the scales and processes discussed here in order to clarify the ecological impact of any climate change.

[1] Auxiliary materials are available in the HTML. doi:10.1029/2008GL033459.

[15] Seasonal bottom density fronts and their associated circulation represent a previously unrecognised mechanism influencing the health and sustainability of marine ecosystems on continental shelves. Effective long-term observation systems in our shallow seas must account for this phenomenon. We recommend that continuous measurement of near-bed density at key locations, combined with data assimilation into a suitable numerical model, would provide an appropriate monitoring capability for shelf sea transport and its variability. We know that many spatially extensive continental shelves (e.g., off north-eastern China [*Hu et al.*, 1991], Argentina [*Glorioso*, 1987] and parts of the Arctic [*Golenko et al.*, 2003]) have the same thermohaline structures as reported here, but that the circulation patterns have not been measured. We predict that jet circulations will be ubiquitous on temperate shelves, and recommend that their presence is investigated and their effects examined.

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