OBSERVATIONS OF THE SEASONAL JET-LIKE CIRCULATION IN THE CELTIC SEA & ST. GEORGE'S CHANNEL

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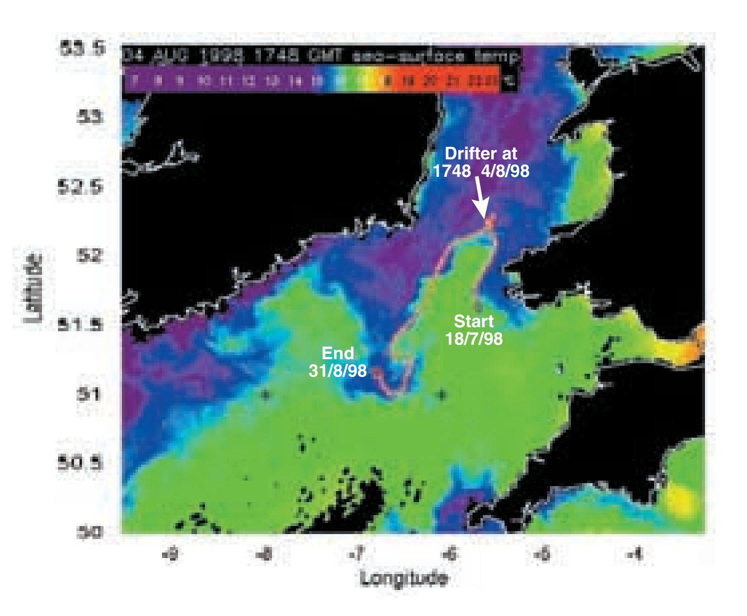
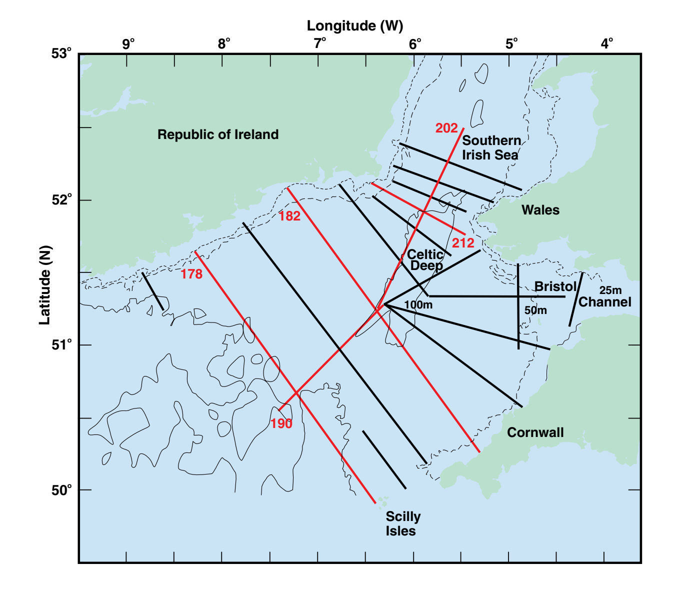
During winter (November to April) the Celtic Sea is vertically mixed and residual circulation is largely controlled by wind forcing. In contrast, the summer regime is dominated by thermal stratification, occurring where tidally-generated turbulent energy is insufficient to mix the increased surface heat input (buoyancy) from solar heating throughout the water column. Situated in St. George's Channel a distinct surface front (below right), visible in infra-red satellite imagery, delineates the boundary with cooler (blue) tidally mixed waters. Generally, there is a southward extension of cold water, frequently attributed to baroclinic instability in the surface front.

Recent publications (see *references*) have described measurements of baroclinic jets associated with cold (or salty), dense pools of bottom water which remain trapped in deep basins on the north-west European continental shelf during the summer months. A key insight of this work is that it is the **bottom density front** that is dynamically significant. This is important because in many tidal mixing systems surface and bottom fronts do not coincide and there may be a bottom front without an attendant surface front. Moreover, bottom fronts appear more stable than surface fronts, are persistent and remain geographically fixed. In this respect, infra-red satellite imagery is not a reliable means of identifying these flows.



Surveys - Summer 1998

From 26 August - 5 September a series of Scanfish (a towed undulating CTD (Brown *et al.*, 1996; Fernand, 1999)) sections were undertaken. Within the raw temperature and salinity data the horizontal distance between successive 'V' shaped profiles is between 150 and 800 m, depending on water depth.



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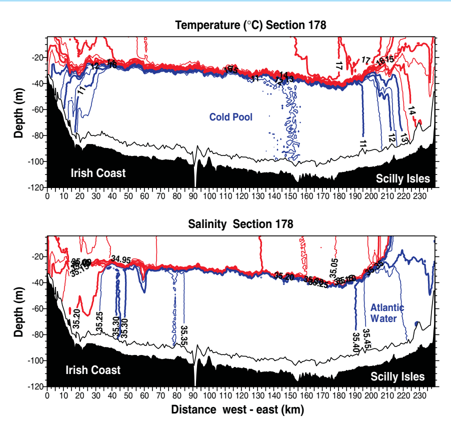
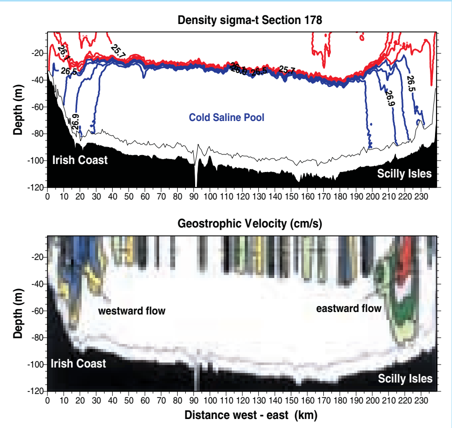
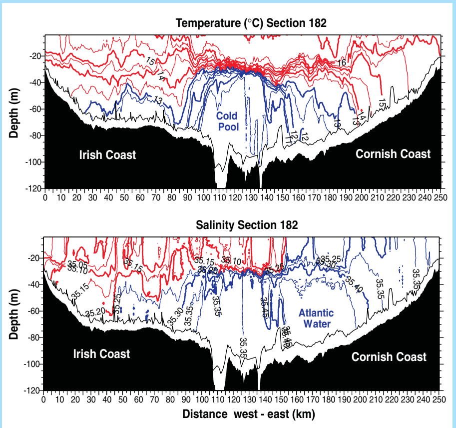
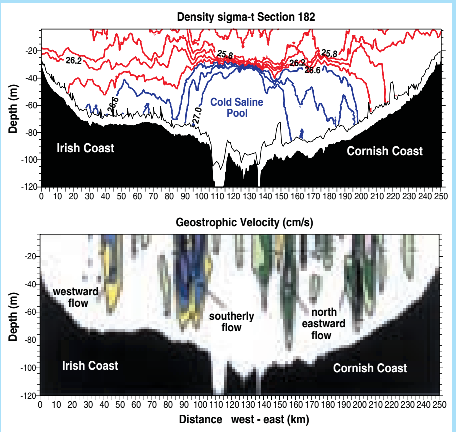
Density and Velocity Structure

In the west (section 178; below) a pool of cold water (< 11 °C) was located below an intense seasonal thermocline and bounded by strong bottom fronts. Salinity exhibited a similar picture, with a deep pool of saline (> 35.3) Atlantic water below fresher (by ~ 0.35) surface waters. To the southeast, a core of high salinity (>35.45) water was situated beneath a distinct surface temperature and salinity front. Overall, the density field reflects the dominance of temperature in determining water column structure. Computed geostrophic velocities normal to the transect and calculated relative to an assumed level of no motion at the sea bed show distinct jets of flow associated with the bottom fronts. The near surface features in the north are related to comparatively small scale perturbations on the pycnocline, probably resulting from high frequency processes such as internal waves and are unlikely to be dynamically significant at low frequency (sub-tidal and sub-inertial) timescales (i.e. days).

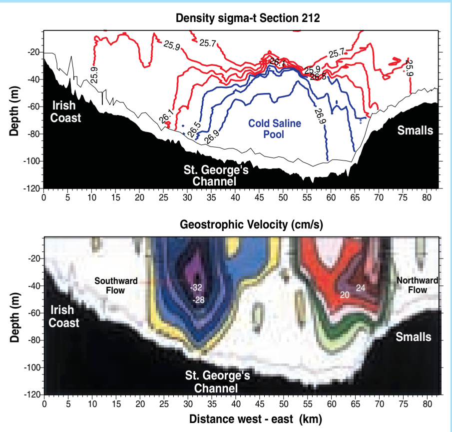




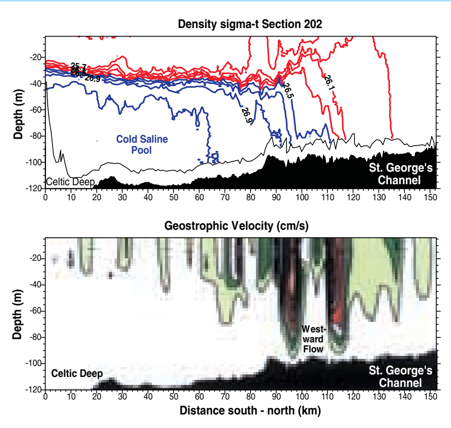


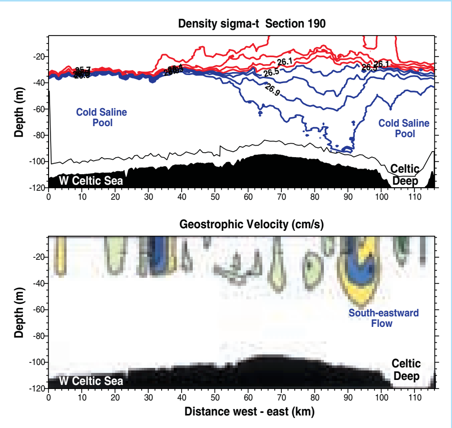


North eastwards, the structure was more complicated (section 182; below left). Centred over the Celtic Deep was a dome of cold (<11°C) bottom water, bounded to the south by a series of bottom fronts. To the north was a secondary dome. In the centre and to the south the thermocline was comparatively strong, but to the north it was diffuse and generally surface frontal features were weak. There was a high salinity (>35.45) core to the south of the deep central channel. To the north and near-surface in the centre the fresher water indicates a coastal origin. Geostrophic estimates indicate two cores (> 0.1 m s^{-1}) of north eastward flow associated with the southern flank of the dense central pool. Centred at approximately 155 and 205 km, these correspond closely to the boundaries of the most saline Atlantic water. On the northern flank of the cold saline pool was a strong south westerly flow and associated with the northern flank of the secondary pool is evidence of a second core of weaker south westerly flow.



Cold (< 12 °C) and saline (> 35.4) bottom water intrudes into St. George's Channel (section 212; left), bounded by strong bottom fronts co-located with comparatively weak surface fronts marking the transition from deep to shallow and strongly tidally mixed waters. Freshest water lies on the Irish side of the Channel. Geostrophic estimates show intense cores of southward and northward flow with velocities > 0.25 m s^{-1}.

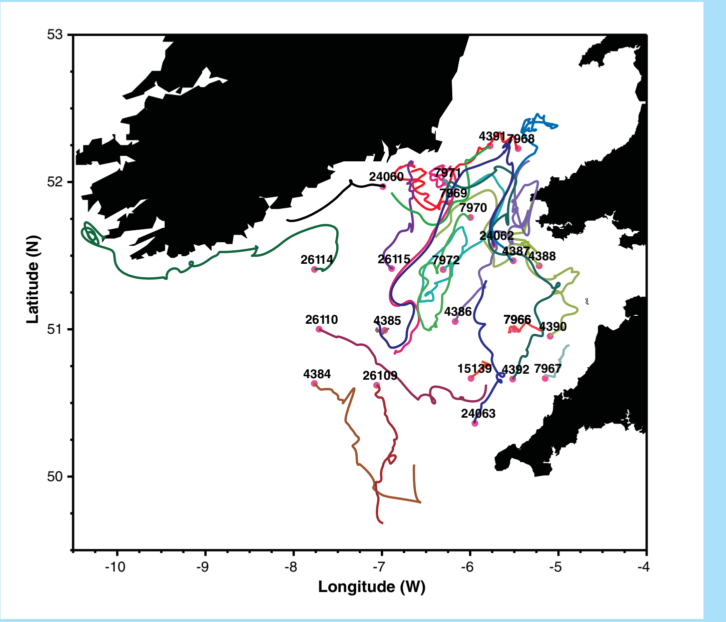




Two sections (190 & 202; below) illustrate the structure along the deep axis of St. George's Channel and the Celtic Deep. Bottom fronts (202) mark the transition from the cold (< 11 °C) saline (> 35.4) bottom water to the well mixed fresher (< 34.7) water of the southern Irish Sea. The comparatively weak Celtic Sea front, observed in satellite imagery, marked the surface boundary. In the centre of the Celtic Sea (190) the density structure was characteristic of an anti-cyclonic (clockwise) eddy of approximate diameter 40 km. A weak bottom front fringes the cold saline pool of the Celtic Deep, with comparatively weak geostrophic flow relative to the sea bed.

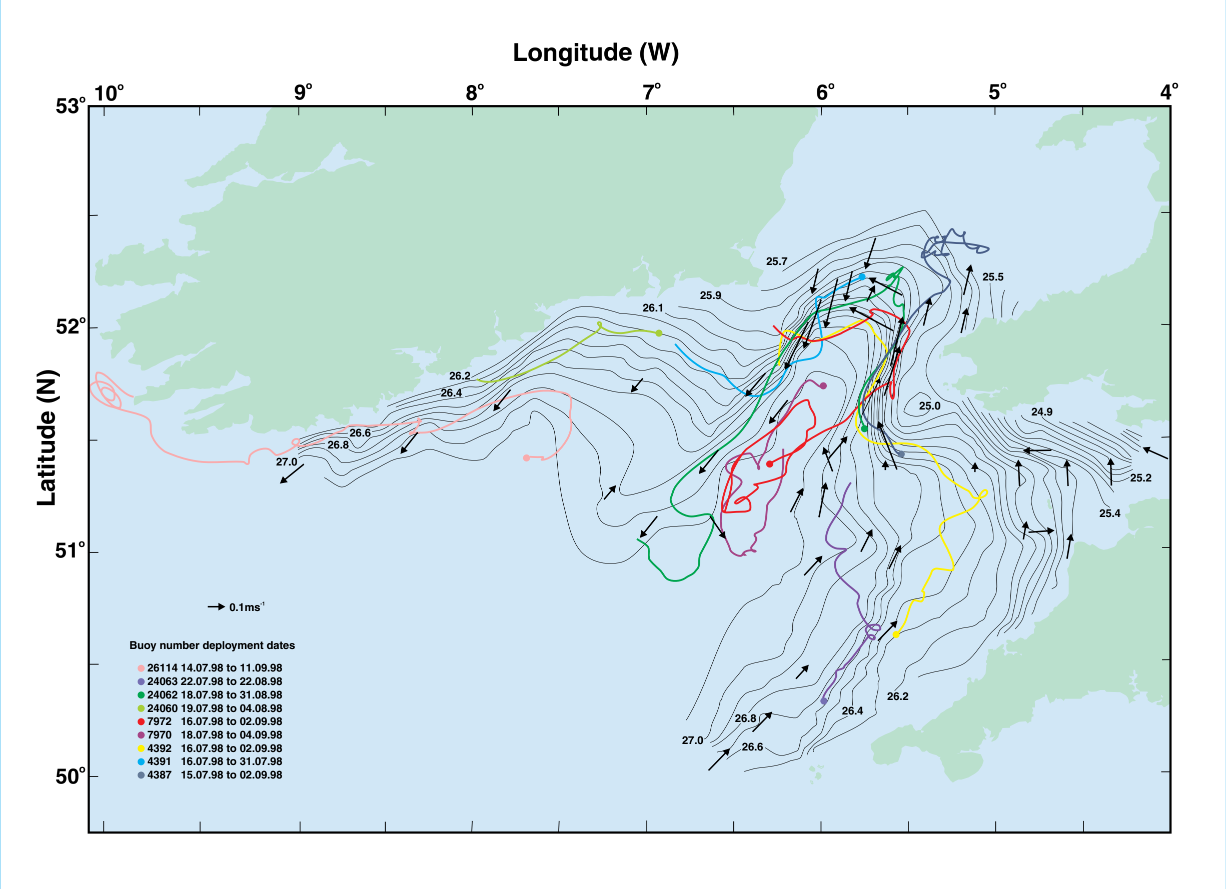
Regional Circulation

During 14 July to 11 September 23 satellite tracked drifters (below), with holey sock drogues 5.5 m long and 1.5 m diameter and centred at 30 m, described an essentially anti-clockwise (cyclonic) circulation pattern. Deployment locations are denoted by ● and durations varied from 5 days to typically 35 days, with the longest being 59 days. The residual (non-tidal) mean speed for all drifters was 6.5 cm s^{-1}, with speeds > 30.0 cm s^{-1} in St George's Channel. Direct wind influence was discounted as a forcing mechanism by performing correlations between the mean daily fluctuations in drifter and wind velocity components, as in previous work (e.g. Horsburgh *et al.*, 1998). Statistically significant correlations of both velocity components were not obtained. Wind forcing was also ruled out by the basic differences in the shape of drifter trajectories over a horizontal distance where the wind field would not be expected to vary.



Trajectories (filtered) of a sub-set of drifters (below) are superimposed on contours of bottom density (σ_t (kg m^{-3})) derived from the Scanfish survey, illustrating the strong correspondence between the drifter tracks and density gradient/bottom fronts. Included is a synthesis of flow (➔ m s^{-1}) derived from geostrophic estimates representing the velocity at the cores of flow. Only velocity components normal to the sections can be computed, so the maximum possible geostrophic flow is underestimated if sections cross density gradients obliquely. Density gradients and flows are strongest in St. George's Channel where bathymetry changes are sharpest and variability in tidal velocity greatest.

A broad comparatively slow northward flow passes along the Cornish coast. In St. George's Channel the flow narrows and intensifies, crossing the channel and returning south. Only one drifter crossed the front, implying comparatively weak exchange with the Irish Sea. Instruments either describe a flow along the Irish coast or 'squirt' into the centre of the Celtic Sea (see satellite image with drifter track), where they describe an anti-cyclonic eddy seen in section 190. Those centred over the Celtic Deep move slowest, retained in an essentially stagnant region of flow.



Summary

The summer circulation of the Celtic Sea is dominated by intense and predictable cyclonic (anti-clockwise) baroclinic jet-like flows associated with bottom fronts bounding a cold saline pool. The regime limits exchange between the Irish and Celtic Sea and is likely to advect water from the Bristol Channel into the Celtic Sea, with a component passing westwards around Ireland. The apparent instability seen in infra-red imagery of the Celtic Sea front can be attributed to a bottom front induced southward 'squirt' of cooler fresher water, resulting in a baroclinic clockwise near-surface eddy. This new understanding of circulation has important implications for our understanding of the advection and dispersion of contaminants, nutrient dynamics and the recruitment variability of several species of fish and shellfish (e.g. herring, plaice, sole and *Nephrops norvegicus*).

These results highlight that for management of the shelf seas it is crucial to consider the appropriate time scales and physical processes. If models are to become reliable and believable management tools for biological and contaminant issues they must accurately represent temperature, salinity and flow fields. This can only be achieved by rigorous comparison with appropriate data such as discussed here and with the inclusion of the best possible forcing for models.

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