A seminal paper on shelf-sea fronts

Insights that led to a new branch of physical oceanography

Tom Rippeth

In August 1974 John Simpson and John Hunter of the (then) Department of Physical Oceanography at Bangor University published a paper which arguably set the agenda for the development of a new branch of oceanography: the physical oceanography of the shallow continental shelf seas which separate the continents from the oceans. The paper also provided the first quantitative link between dissipation of tidal energy and ocean mixing. Here we investigate the background to the paper and look at its impact in the development of our understanding of the continental shelf seas.

The focus of this research was the Irish Sea and was, at least in part, facilitated by the proximity of the Irish Sea to Bangor and Liverpool universities (Figure 1), and the fact that it was in range of the Bangor University research vessel, the *Prince Madog*. A consequence is that today the Irish Sea has become the 'model' shelf sea for oceanography students globally, despite only accounting for 0.009% of the surface of the Earth!

Early oceanographic measurements in the Irish Sea

The Simpson and Hunter paper built on previous research going back to the early years of the 20th century. Unusually extensive systematic (for the time) hydrographic surveys of the Irish Sea had been carried out between 1907 and 1912 by Donald Matthews of the Department of Agriculture and Technical Instruction for Ireland. The surveys consisted of quarterly visits to 68 stations across the western Irish Sea and Celtic Sea and were undertaken in February, May, August and November of each year. These early measurements were taken from the Dublin-based purpose-built research and fishery protection vessel, the *Helga*.

Water samples were taken at several depths using Ekman reversing water bottles, each of which carried two reversing thermometers. In consequence, only a few samples were collected over the entire water column, so the vertical resolution of the measurements was very low. The water samples were recovered and then preserved in 6 oz milk bottles with porcelain stoppers, rubber washers and spring catches, before titration against International Standard Seawater to calculate the salinity.

The surveys revealed that there were two areas in which temperature stratification was observed, but only during the August surveys. Matthews noted that these areas were places 'where the [tidal] stream is almost imperceptible and where the power of the tide to cause vertical mixing of the water is almost nil'. These areas were the western Irish Sea and the Celtic Sea.

The mean salinity measurements showed that the salinity values of the water in the North Channel, at 34 g kg^{-1}, were lower than those observed in St George's Channel, at the southern entrance of the Irish Sea, where mean salinity was ~ 34.9 g kg^{-1} (Figure 1(a)). By assuming that this drop in salinity was due to diilution by river water, Ken Bowden of Liverpool University used a salt budget to deduce a northward residual (i.e. net) flow through the Irish Sea of a couple of cm s^{-1}. Whilst his calculation revealed a weak net flow through the Irish Sea it did not explain the flow and so it was not possible to use this information to make predictions as to how it might change over long time scales.

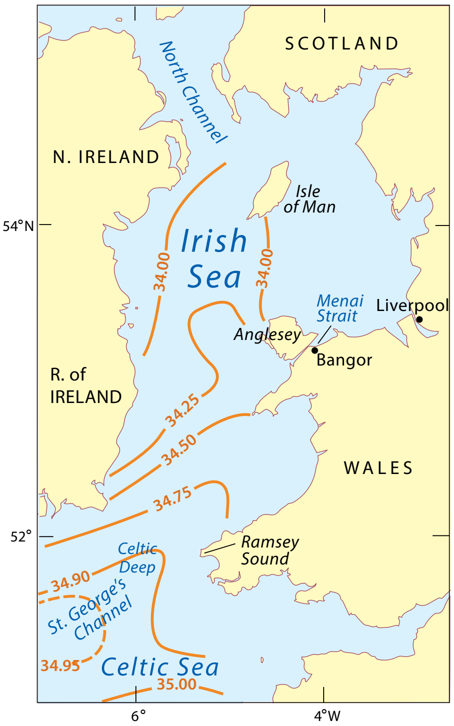

Figure 1 *Annual mean sea-surface salinity in the Irish Sea derived from water bottle samples taken quarterly between 1907 and 1912; contours are from Matthews (1913). Locations mentioned in the article are also shown.*

In a 1920 paper, G.I. Taylor used tidal information collected around the Irish Sea to consider the fate of energy dissipated by the ocean tide. In doing so he expressed the local rate of dissipation of tidal energy as the sum of the direct rate of working by the tide-generating force across the Irish Sea and the net flux of tidal energy into the Irish Sea. The latter was estimated from the difference between high water times, and the timing of the maximum tidal flow through St George's Channel. He then equated the net rate of input of energy by the tide with the tidal dissipation through bottom friction, which is proportional to the cube of the maximum current speed, u^3.

Through this calculation Taylor was able to show that whilst the direct impact of the tide-generating force on the Irish Sea tides is minimal the Irish Sea is a significant sink for tidal energy. The astronomer and geophysicist Harold Jeffreys extended this calculation globally and compared his

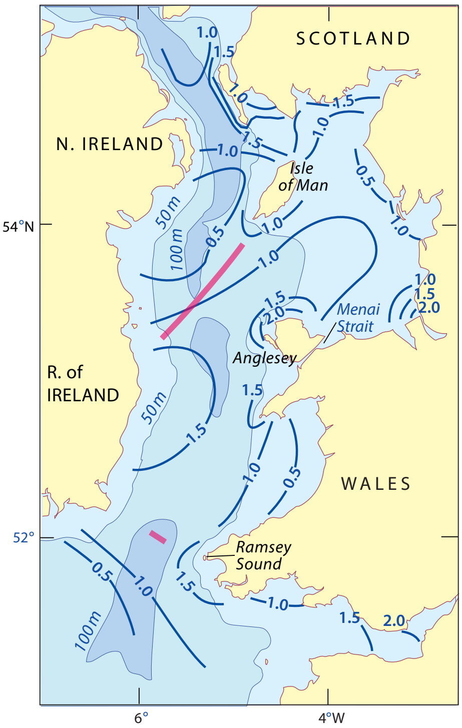

Figure 2 *Contours of tidal current speed (m s*$^{-1}$*) in the Irish Sea at mean spring tides, superimposed on the bathymetry. The positions of the shelf-sea fronts according to Simpson and Hunter are shown in red. (Current speeds are taken from Bowden (1955))*

result to estimates of global tidal dissipation based on the rate at which the Moon was recessing from the Earth. He estimated that, despite their small area (7% of the global ocean total), the shelf seas accounted for over half of total global tidal energy dissipation.

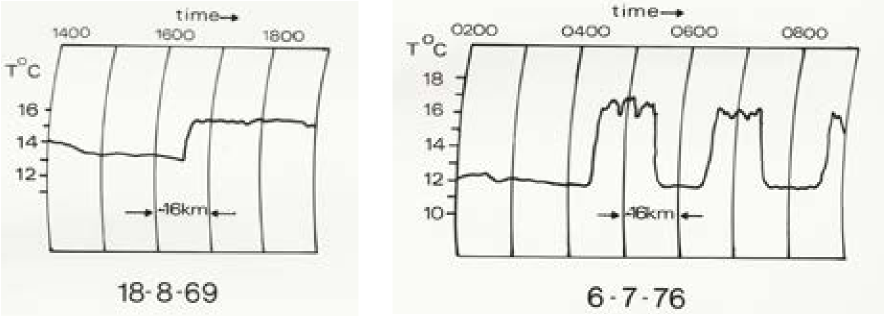

Figure 3 *Thermograph records of sea-surface temperature crossing the Irish Sea front.* ***(a)*** *is for a single crossing from east to west in August 1969 and* ***(b)*** *is for multiple crossings in July 1976.*

There is a large variation in tidal current speed across the Irish Sea, with tidal flows exceeding 4 m s^{-1} in coastal areas such as Ramsey Sound off Pembrokeshore and the Menai Strait (Figure 2), whilst in other areas, such as the western Irish Sea and the Celtic Deep, tidal currents peak at around 10–20 cm s^{-1}.

By the 1950s a number of oceanographers, including Walter Munk at the Scripps Oceanographic Institution and Günter Dietrich of the German Hydrographic Institute, Hamburg, were speculating on the role of the turbulence generated by the dissipation of tidal energy in driving water column mixing.

Advances in the 1960s and 1970s

In 1968 Bangor University took delivery of a new purpose-built research ship, the RV *Prince Madog.* The new vessel, fitted out with state-of-the-art Bathysonde (an early CTD), provided easy access to observations in the Irish Sea from its base in Menai Bridge on the Isle of Anglesey. Surveys in 1968 and 1969 had confirmed the presence of seasonally stratified water in the western Irish Sea, with a region of strong surface gradients (a front) separating the well mixed waters of the eastern Irish Sea from the seasonally stratified water of the western Irish Sea. Thermograph measurements from the ship as it crossed the front revealed a sharp gradient in sea-surface temperature, with higher temperatures on the western side of the front (Figure 3). In June 1973 an airborne Infrared survey was undertaken, coincidently following several weeks of calm weather. The survey revealed the geographic extent of the front with the aircrew noting that 'the line of the front was clearly visible because of an accumulation of surface material in the vicinity of the maximum temperature gradient'.

Informed by these new measurements Simpson and Hunter developed a one-dimensional model of 'buoyancy input' by surface heating (lowering the density of surface water) versus tidal stirring in controlling water column stratification. To quantify the degree of stratification, and how much kinetic energy input would be required to overcome the stratification, they used a quantity called the potential energy anomaly ϕ. In doing so they derived the Simpson–Hunter parameter (h/u^3), where h is the water depth and u the maximum tidal current speed:

$$\frac{h}{u^3} = \frac{8c\rho k\varepsilon}{3\pi\alpha gQ}$$

with k a constant relating to friction, c the specific heat capacity of seawater, α its thermal expansion coefficient, Q the rate of heat input at the surface, ρ seawater density and g acceleration due to gravity. Assuming Q and the mixing efficiency ε are constants, the position of the shelf-sea front will be determined by a critical value of h/u^3. Figure 2 shows positions of fronts in the Irish Sea estimated using the h/u^3 relationship. The model was then applied to all available data for a large section of the European shelf to provide confirmation.

By this stage the first infrared satellite images (from NOAA 4) were becoming available and were able to resolve temperature sufficiently to show the 2–3°C difference across the shelf-sea fronts (Figure 4). Although the first images came from NASA, more soon followed from the newly established Dundee Satellite receiving station courtesy of Peter Bayliss and John Brush.

Independent confirmation of the significance of h/u^3 came from Robin Pingree and David Griffiths at the Plymouth Marine Laboratory who used a two-dimensional depth-averaged numerical model of the tides to derive the Simpson–Hunter parameter for the shelf seas surrounding the British Isles, with the estimated frontal locations matching those observed. Globally other researchers showed that the parameter accurately predicted the location of shelf-sea fronts in, for example, the Gulf of Maine, the Bering Sea and the Patagonian Shelf. Accordingly, the model provided the first quantitative evidence for the role of dissipation of tidal energy in driving ocean mixing.

Figure 4 *The first satellite image to show the presence of shelf-sea fronts in the north-west European shelf seas. The image is an infrared satellite image and the shading corresponds to sea-surface temperature – the darker the shade the higher the sea-surface temperature. The image, for 20 August 1976, was provided by Wayne Esaias at NOAA. It was so heavily rasterised that at the time John Simpson thought it had been created by some students as a joke!*

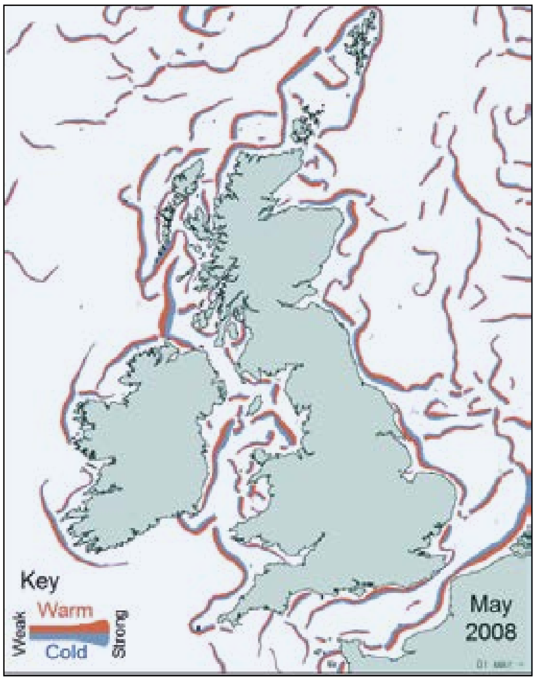

Figure 5 Location of shelf-sea fronts in May 2008, illustrating typical summer locations of persistent fronts around the UK, which influence feeding areas for basking sharks, cetaceans and other marine life. (Red/blue indicate the warm/cold side of each front, and the width indicates the strength of the front.)

(Simplified front map derived by Peter Miller at PML from Miller, Xu and Carruthers (2015); see Further Reading)

Biological and biogeochemical significance of shelf-sea fronts

On the original 1973 flight the aircrew noted changes in colour either side of the front, put down to changes in the standing crop of phytoplankton. The front separates two very different ecological regimes. The well mixed water is nutrient-rich as phytoplankton growth is light-limited, whilst following the spring bloom, on the seasonally stratified side of the front the surface mixed layer is nutrient-limited, and so any primary productivity is limited to the subsurface chlorophyll maximum. Recent DNA analysis has revealed that the community structure and diversity of bacterioplankton communities on either side of the shelf-sea front are very different. A consequence is that the front separates two very different biogeochemical regimes, with the seasonally stratified region acting as an important CO_2 sink and the area that remains well mixed tending to be a net source.

The frontal region benefits from both the high-light regime of the stratified side and the good supply of nutrients of the mixed side, and so supports a rich and diverse ecosystem. On the basis of this knowledge, maps of shelf-sea frontal positions derived from satellite images, compiled by Peter Miller and his team at the Plymouth Marine Laboratory (PML), were used by Defra as a proxy for the abundance and diversity of mobile species in the planning of Marine Protected Areas around the UK (Figure 4).

The accumulation of floating material along the front as noted by aircrew on the original 1973 overflight provides evidence of circulation patterns associated with the front. The front results in a significant lateral density gradient which supports an along-front residual flow (a frontal jet) and a convergence. A decade-long programme of satellite-tracked drifting buoy measurements integrated with numerical modelling, led by Ed Hill (at Bangor, then the National Oceanography Centre), revealed a highly organised 'thermohaline' circulation consisting of narrow, fast-flowing frontal jets. These jets provide a highway through the Irish Sea carrying and dispersing a wide range of marine organisms. At the time, they also provided a mechanistic explanation of Bowden's original residual flow estimate.

Shelf-sea fronts and changing climate

The predictability of the position of shelf-sea fronts has provided insights into the evolution of the shelf seas since the last glacial maximum. Analysis of sea-bed sediment cores, including identifying microfossils from which to infer plankton community structure at different points in the past, allows an estimation of the timing of the movement of shelf-sea fronts over the sediment core location as sea level rose following the last glacial period. As the shelf seas expanded, both the magnitude and geographical distribution of tidal dissipation changed, which could have had global implications, for example in impacting the rate of tidal mixing which supports the Atlantic Meridional Overturning Circulation and the uptake of CO_2 by the ocean (see the Wider Implications section of the Further Reading).

As sea levels continue to rise into the future, and new shelf seas form as ice sheets disappear around Antarctica, shelf-sea fronts will move in response to changes in the global distribution of tidal dissipation. Despite the key role of the shelf seas in the global carbon cycle, and as a major sink for tidal energy, plus their changing geography as sea level has varied over glacial cycles, shelf-sea processes are poorly represented in global climate models. Nevertheless the predictability of the positions of tidal mixing fronts coupled with our ability to time the transgression of those fronts at particular points as sea level changes, provide useful tools in the validation of shelf-sea parameterisations in global climate models.

The significance of the partitioning of shelf seas by seasonal shelf-sea fronts was evident during the Category 4 heat wave which hit the UK shelf seas in June 2023. A sea-surface temperature anomaly map (Figure 6) clearly shows that over the continental shelf, seasonally stratified regions (e.g. the northern half of the North Sea and the western Irish Sea) have sea-surface temperatures up to 5 °C above normal, while in the well mixed regions the anomalies are generally < 1°C. The predictability of the positions of shelf-sea fronts implies that water column structure in shelf-sea regions is controlled to the first order by vertical exchange processes. The distribu-

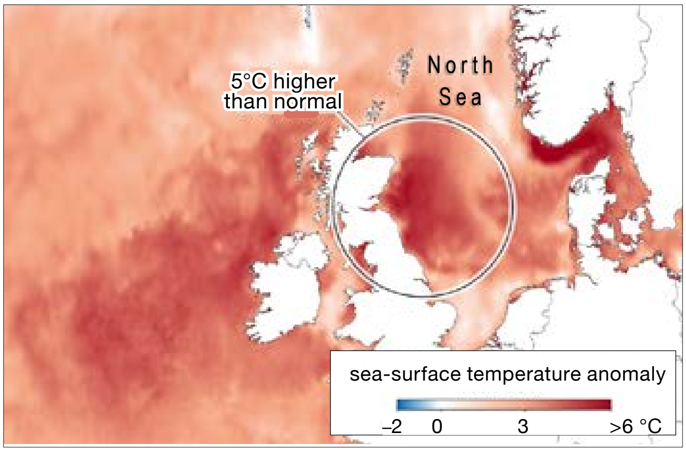

Figure 6 Sea-surface temperature anomaly during the severe marine heat wave off the UK in June 2023.

(Taken from ESA for 18 June 2023; https://www.esa.int/ESA_Multimedia/Images/2023/06/UK_suffers_marine_heatwave)

tion of sea-surface temperature during the heat wave can therefore be explained as resulting largely from changes in stratification in the seasonally stratified regions, and in particular, unusually shallow surface mixed layers concentrating the seasonal heat input.

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Tom Rippeth is the Professor of Physical Oceanography at Bangor University School of Ocean Sciences. T.P.Rippeth@bangor.ac.uk

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Developments in offshore renewable energy

At Cop28 at least 117 governments have agreed to triple the world's renewable energy capacity by 2030. At the time of writing, the draft Cop28 agreement refers to 'reducing both consumption and production of fossil fuels ... so as to achieve net zero by, before, or around 2050 in keeping with the science'.

As part of its plan to reduce carbon emissions by 68% (from 1990 levels) by 2030, the UK goverment aims to have 25 GW of offshore wind generation operational by 2031. However, despite the growth in UK offshore wind in recent years (see p.16), in September 2022, Round 5 of the government's 'sustainable energy auction' saw no new applications for offshore wind farms.

This was the result of a 30–40% increase in supply chain costs, higher interest rates and competition for international capital, and the fact that the maximum price companies could charge the goverment for the energy was set at too low a rate of £44 per MWh – bidders compete in a reverse auction to offer electricity at the lowest cost. The 15-year contracts guarantee top-ups from bill payers if the wholesale electricity price falls below a certain level.

However, Round 5 was not all bad news for offshore energy production, because as a result of there being no bids for floating wind projects – which the industry refers to as FLOW – the allocation was available for tidal stream projects, and bids were accepted for 11 projects in Scottish and Welsh waters, adding to four accepted in Round 4.

After urgent talks with windfarm developers Ministers agreed that for Round 6, in 2024, the starting price in the offshore wind auction would be raised to £73 per MWh to help more offshore projects to move ahead. The starting price for floating offshore wind projects was raised from £116 per MWh to £176 per MWh. FLOW will also have ring-fenced funding in recognition of the large number of projects ready to participate. Developers welcomed this news but time has nevertheless been lost in the UK's struggle towards net zero.

Happily, the general public should be benefitting from the Round 4 auction. For the 2022–23 financial year, the Crown Estate reported a record net revenue profit of £442.6 million thanks to receipt of option fees from developers of offshore wind farms. Some of the profits from the option fees will be directed into the public pot as King Charles III has asked that the share of the offshore wind earnings to which the Royal Family is entitled 'be directed for wider public good'. Option fees are payable for 3–10 years, depending on when a project will be ready for signing a lease.

Ed.