

Floating and fixed offshore wind intersect contrasting frontal and fishing seascapes in the Celtic Sea

Yang Yang

yang.yang@plymouth.ac.uk

University of Plymouth <https://orcid.org/0000-0002-0928-0219>

Peter Miller

Plymouth Marine Laboratory <https://orcid.org/0000-0002-5292-8789>

Liam Langley

Stephen Votier

Michel Kaiser

Heriot-Watt University <https://orcid.org/0000-0001-8782-3621>

Lilian Lieber

University of Plymouth <https://orcid.org/0000-0002-4833-9594>

Article

Keywords:

Posted Date: September 23rd, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10840981/v1>

License:   This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: There is **NO** Competing Interest.

Abstract

Offshore wind is expanding into deeper, seasonally stratified shelf seas where ecological and fisheries baselines remain incomplete. The Celtic Sea provides a timely test case, with 4.5 GW of planned floating offshore wind (FLOW) alongside fixed-bottom offshore wind (FBOW) closer to shore. We combine weekly satellite-derived thermal fronts (2012–2025), Global Fishing Watch apparent fishing activity and offshore wind planning boundaries to establish a pre-construction exposure baseline. Fronts were strongly seasonal, whereas fishing was more spatially concentrated and weakly associated with front proximity. FLOW areas intersected seasonal frontal habitat, including tidal mixing fronts, with front and fishing hotspots occupying up to 85% and 69% of the FLOW footprint in March and August, respectively. In contrast, front hotspots occupied up to 89% of the FBOW footprint in winter, mainly reflecting persistent coastal and inner-shelf fronts, while fishing hotspot occupancy remained low. These distinct exposure regimes provide an evidence base for anticipating spatial conflict, targeting monitoring and identifying where development, fisheries and future nature-recovery priorities may need to be reconciled.

Introduction

Renewable energy from offshore wind is expanding from a regional industry into a major new use of continental shelf seas. Globally, the offshore wind market grew nearly 30% per year between 2010 and 2018, and is projected to increase fifteen-fold by 2040, attracting around USD 1 trillion of cumulative investment¹. In Europe, offshore wind has become central to energy security and climate policy: EU member states have agreed cumulative regional goals of 86–89 GW of offshore renewable capacity by 2030, rising to 356–366 GW by 2050². This expansion is also changing where offshore wind is built. Development is moving beyond shallow fixed-bottom banks into deeper, seasonally stratified shelf seas as floating offshore wind (FLOW) technology matures. This expansion broadens the challenge facing marine spatial planning, from where turbines can technically and economically be installed, to how increasingly extensive renewable energy footprints can be accommodated within shelf seas that sustain dynamic habitats, marine fauna, and ecosystem processes alongside fisheries, shipping, conservation interests and coastal economies^{3–6}.

The Celtic Sea is a timely test case for this transition. Unlike the North Sea, where the offshore wind evidence base is dominated by a mature, fixed-bottom offshore wind (FBOW) landscape, the Celtic Sea remains largely pre-construction for commercial-scale wind. The UK's Crown Estate Round 5 leasing process has identified three floating offshore wind (FLOW) project development areas (PDAs) in the Celtic Sea, each with a potential capacity of up to 1.5 GW, with additional demonstration-scale (100 MW) projects underway including *Erebus* and *Llŷr*. If fully delivered, the three PDAs would provide power for more than four million homes⁷. Across the Irish portion of the Celtic Sea, planning and industrial strategy point to an equally rapid scale-up, with national targets of 5 GW of offshore wind by 2030 and 37 GW by 2050⁸. To date, planned FBOW and FLOW areas occupy approximately 4,781 km², while the wider FLOW Area of Opportunity (AOO) covers approximately 32,303 km², almost equivalent to the combined area of

Wales and Northern Ireland (Fig. 1). These developments are being introduced into a productive and heavily used shelf sea that supports recurrent ocean fronts, commercial fisheries, a high abundance and diversity of marine predators, shipping routes and cross-border planning interests⁹. This creates an unusual opportunity to establish pre-construction baselines before access arrangements, fishing behaviour and regional ecological conditions are altered by offshore wind development.

A robust baseline for offshore wind development must account for the ocean dynamics that structure marine habitats and productivity. Continental shelf seas are characterised by ocean fronts: strong horizontal transitions between adjacent water masses, commonly expressed in gradients in temperature, salinity and density, and often accompanied by marked changes in nutrient and chlorophyll-a concentrations^{10,11}. In summer, temperate shelf seas are often partitioned into thermally stratified regions, where surface heating causes warmer, less dense water to overlie cooler, denser bottom water, and vertically well-mixed regions, where energetic tidal stirring prevents persistent stratification from developing. The transition between these regimes forms shelf-sea tidal mixing fronts, often marked by strong horizontal temperature gradients of typically $1^{\circ}\text{C km}^{-1}$ ¹². In the Celtic Sea, recurrent tidal mixing fronts include the Celtic Sea Front (south of St George's Channel, between southeast Ireland and southwest Wales) and the Ushant Front (off northwest Brittany), as well as island-associated fronts (e.g. around the Isles of Scilly), and shelf-break fronts along the continental margin¹³. These features arise from different combinations of tidal mixing, seasonal stratification, bathymetry, freshwater influence and shelf-ocean exchange.

Together, these frontal regimes form dynamic habitats that can enhance nutrient supply, primary production, and prey aggregation¹⁴. Additionally, fronts can alter phytoplankton community composition itself, including shifts toward diatom-rich assemblages and distinct fine-scale frontal communities relative to adjacent water masses^{15,16}. These processes can then influence prey availability, predator foraging and fishing activity: for instance, fronts have been associated with up to a five-fold increase in secondary production and a twenty- to forty-fold increase in production for commercially important species such as anchovies, sardines and salmon¹⁷. Where fronts are associated with surface convergence, they can concentrate plankton, other weakly swimming organisms and flotsam, thereby directly increasing prey density or accessibility to higher trophic levels. As such, fronts form part of a wider suite of dynamic physical features – including eddies, filaments and surface slicks – that can directly structure prey fields and provide important foraging habitat for marine predators^{18–25}, as well as supporting fisheries¹⁷. This ecological importance makes fronts particularly valuable for offshore wind planning and, unlike many other habitat features, they can be mapped repeatedly from satellite remote sensing at high temporal and spatial resolution²⁶. In the Celtic Sea, where seasonal stratification, tidal mixing and shelf-edge processes create a dynamic physical seascape, long-term maps of frontal features are therefore not merely descriptive but provide a planning layer for identifying recurrent ecologically important ocean habitat before large FLOW infrastructure is installed.

Offshore wind farms (OWFs) may also modify the physical processes that maintain these frontal habitats, through two distinct mechanisms. The first is atmospheric: wind turbines extract energy from moving air, generating an atmospheric wake in which wind speed can fall by up to 40% and conditions may not fully recover until 70 km downwind, reducing wind-driven surface currents and thereby altering surface mixing, increasing stratification^{27,28}. The second is hydrodynamic and acts downstream of submerged infrastructure: as tidal currents pass submerged monopiles, they generate turbulent wakes that can reduce stratification^{29,30}, a mechanism confirmed by field measurements at the DanTysk wind farm, where turbulence downstream of a single monopile measurably weakened local stratification³¹. At the scale of whole wind farm clusters, North Sea modelling of these wind wake effects projects large-scale changes in annual primary production, with local changes of up to $\pm 10\%$ extending well beyond the wind farm clusters themselves, alongside increased sediment carbon and reduced dissolved oxygen in already low-oxygen bottom waters³². Many floating foundation designs (i.e. semi-submersible, Spar, and tension leg platforms) can extend tens of metres below the surface, deep enough to intersect the stratified layer itself by introducing mixing directly across the thermocline²⁹. These direct physical and associated biogeochemical changes may cascade through food webs by altering nutrient supply, plankton production, prey aggregation and predator habitat, with potential consequences for fish^{33–35}, seabirds^{36,37} and marine mammals^{13,38,39}. These findings cannot be transferred directly to the Celtic Sea, where water depth, hydrography, tidal forcing and the strength and seasonality of stratification differ from those of the North Sea. However, they identify possible mechanisms through which offshore wind infrastructure could alter the Celtic Sea's frontal environment. In marginally stratified waters, including those near the planned FLOW sites (Fig. 1), additional tidal wake mixing could shift the balance between stratification generated by surface heating and turbulent mixing, potentially delaying the seasonal onset of stratification, weakening the thermocline or accelerating its breakdown. Whether these effects will occur, and whether they would be sufficient to alter the timing, strength or position of nearby fronts, remains unresolved. Addressing this uncertainty requires pre-construction baselines that capture the seasonal evolution and variability of dynamic ocean fronts, rather than only accounting for lease boundaries and static seabed characteristics.

Fishing activity forms a second, highly dynamic layer of this baseline. Fishing remains one of the main pressures on ecosystem health across the Celtic Seas ecoregion³⁹, which supports diverse commercial fleets targeting species from hake and Nephrops to demersal and pelagic stocks^{9,39}. Exposure of fisheries to offshore wind development is socially, spatially and economically uneven. Evidence from other regions shows that the distribution of exposure among vessel sizes, fleet sectors and gear types and vessel classes varies considerably between ports and regions, rather than following a consistent pattern⁴¹. North Sea modelling studies show that offshore wind effects on fisheries and marine protected areas depend strongly on wind-farm location, gear-specific access restrictions, and whether displaced fishing activity is redistributed into surrounding areas⁴². Therefore, co-location cannot be treated as a one-size-fits-all solution, its consequences depend on the specific management rules, fleet groups and ecological context of each site. Current management approaches illustrate this variability. In

the Netherlands, Area Passport Guides spatially identify areas within wind farms where co-use may occur, while excluding passages and safety and maintenance zones around turbines, platforms and cables; the revised Borssele plan identifies areas for passive fishing, including pots, handlines and gillnets, subject to permitting and access requirements⁴³. Germany instead regulates access through site-specific safety-zone rules: for example, passive fishing with baskets and traps is permitted outside the developed footprint of Meerwind Süd/Ost and Nordsee Ost subject to prescribed separation distances from turbines, cables and platforms, whereas fishing is prohibited within the safety zones of some other developments, including Gode Wind 01–03^{44,45}. UK policy takes a case-by-case approach, explicitly recognising that activities such as potting may remain possible within operational wind farms where navigational safety and other regulatory requirements are satisfied⁴⁶. These contrasting arrangements reinforce that fisheries–offshore wind coexistence is fundamentally a spatial and management-specific issue, requiring consideration of where fishing occurs, which fleets and gears are involved, and how access may change following development. These examples show that spatial overlap should not be interpreted as a direct measure of displacement, catch loss or economic impact, rather, documenting that overlap represents an essential starting point for evaluating potential consequences^{4,47}.

The unresolved planning challenge is therefore both oceanographic and fisheries related. Planned wind areas are fixed spatial polygons, whereas fronts and fishing activity are dynamic, shifting seasonally, interannually and across the seascape^{26,48,49}. Yet existing planning evidence rarely integrates recurrent frontal habitat, apparent fishing activity and future floating-wind footprints within a common seasonal framework. This gap is particularly important in the Celtic Sea, where commercial-scale floating wind is being planned in the absence of any comparable operational history. A pre-construction baseline can establish whether planned wind development areas intersect recurrent physical ocean habitat, whether fishing hotspots occupy the same parts of the seascape, and whether front-associated fishing is concentrated in particular seasons or wind-development classes. Capturing this pre-construction baseline is essential to provide a robust reference against which subsequent changes can be evaluated, while observations collected post-development will already reflect a system modified by offshore wind construction.

Here we develop this baseline for the Celtic Sea by combining weekly satellite-derived thermal fronts from 2012 to 2025 with concurrent model-derived apparent fishing activity, bathymetry and offshore wind planning boundaries. Our objectives are to determine: (1) where and when recurrent seasonal front hotspots occur; (2) how apparent fishing hotspots vary across space, season and year; (3) whether apparent fishing activity is associated with proximity to fronts after accounting for bathymetry, distance from coast, season, year and residual spatial structure; and (4) the extent to which frontal habitat and fishing hotspots intersect planned or consented offshore wind areas, including both FLOW and FBOW developments. Throughout, we treat spatial overlap as exposure rather than impact. The result is a transparent pre-construction baseline that identifies where offshore wind planning coincides with

recurrent ocean fronts and long-term fishing use, and where future monitoring, consultation and fisheries impact assessment should be prioritised.

Figure 1: Study area and offshore wind planning context in the Celtic Sea. The inset locates the Celtic Sea area within the wider northwest European shelf. The main map shows bathymetric contours, planned and consented offshore wind areas, exclusive economic zone (EEZ) boundaries, and the Celtic Sea boundary. Fixed-bottom offshore wind (FBOW) sites are shown in purple, floating offshore wind (FLOW) sites in green, and the wider FLOW Area of Opportunity (AOO) in yellow. EEZ boundaries are shown as solid green lines, and the Celtic Sea boundary is shown as a red dashed line. The figure provides spatial context for the front, fishing and wind farm exposure analyses.

Results

Planned FLOW areas include Round 5 PDAs in the Celtic Sea, with FBOW developments closer to Ireland and Wales, and with the wider Celtic Sea AOO designated for future FLOW planning (Fig. 1). This spatial configuration creates varying degrees of overlap because offshore wind development type, frontal habitats, and fishing activity are distributed differently across bathymetric zones, distances from shore and national planning areas. The following analyses therefore examine these interactions within the context of the Celtic Sea's historical seascape, including bathymetry, decadal patterns of frontal persistence and fishing activity.

A long-term frontal baseline

The Celtic Sea study area (Fig. 1) spans a dynamically structured shelf sea where strong tidal currents, seasonal stratification, freshwater influence, mixed coastal waters and shelf-edge exchange interact. Together, these gradients generate persistent frontal systems across much of the study area, either within or near current offshore wind planning boundaries. Front persistence shows a clear spatial pattern and seasonal cycle (Fig. 2). Seasonally persistent tidal mixing fronts are visible near the Celtic Sea and Irish Sea transition consistent with the Celtic Sea front, with other frontal features around the Isles of Scilly, along shelf and bank features in the central Celtic Sea region, and in large parts of the shelf-edge region ('shelf-slope fronts'). Winter months contain fewer persistent frontal cells across the offshore domain, whereas spring and summer show expansion and strengthening of recurrent frontal structures. Nearshore and inner-shelf frontal features are more persistent than many offshore cells (apart from shelf slope fronts), consistent with fronts generated or anchored by tidal mixing, bathymetric gradients and coastal hydrography. The strongest recurrent feature in the northern Celtic Sea is the Celtic Sea Front, located near the southern entrance to the Irish Sea. It is most clearly expressed during spring and summer, consistent with the seasonal intensification of a tidal mixing front separating stratified Celtic Sea shelf waters from the more strongly mixed waters of St George's Channel. This pattern indicates that the monthly front field is not a collection of random weekly detections, but a recurrent seasonal seascape shaped by predictable physical controls.

Fig. 3 shows that the F1 score, defined as the summed occurrence of detected fronts across the Celtic Sea for each weekly time step, is strongly seasonal and varied among years. Higher F1 values indicate periods when fronts are more widespread and frequently detected. Frontal activity is lowest during winter, increases through spring with the onset of stratification, and remains elevated from May to late September. The timing and magnitude of the seasonal peak varied among years, with the strongest summer activity concentrated around the middle of the record and a particularly pronounced peak around 2018. Front activity was also lower in several recent years, particularly after 2022, compared with the peak around 2018.

Long-term fishing hotspots

Apparent fishing activity is concentrated in a smaller set of recurring areas than the front field (Fig. 4). High-use cells recurred near established fishing grounds, including the Celtic Deep and central Celtic Sea banks, and along sections of the shelf break characterised by steep bathymetric gradients. Some hotspots are also visible outside the core Celtic Sea analysis boundary, including areas of the Irish Sea, English Channel and Bay of Biscay, but these were excluded from the statistical modelling or exposure summaries. In February and March, some low-activity areas coincide with the conservation or fisheries management zones highlighted (yellow rectangles in Fig. 4), consistent with seasonal management effects alongside fleet behaviour and habitat structure.

The monthly fishing maps do not simply mirror the seasonal expansion and contraction of fronts. This contrast is clearest in shallow nearshore waters, where frontal activity is often persistent, but apparent fishing activity is sparse or absent. Fishing grounds and frontal habitat overlap in some parts of the Celtic Sea, but fishing hotspots are more spatially concentrated and less seasonally variable than frontal features.

The temporal distribution of apparent fishing activity (Fig. 5) shows a more episodic temporal structure than front activity. Fishing activity varies strongly among months and years, with peaks occurring in discrete periods rather than following a smooth seasonal climatology. Several high-activity periods occur in spring and early summer, while elevated activity is also visible in winter during some years. Apparent fishing activity appears lower in more recent years than in the early part of the record, particularly during July and August, when high activity is more evident around 2014-2016 than after 2020. This pattern indicates that apparent fishing activity varies both seasonally and interannually, although the observed trend should be interpreted cautiously because it may reflect changes in fleet composition, gear targeting, AIS behaviour or model-derived effort estimates.

Front-proximate fishing

The GAM indicates that apparent fishing activity is structured mainly by depth, distance to coast, seasonality and interannual variation, while front proximity, measured as distance to the nearest front,

adds a detectable but modest additional signal. The GAM explained 18.5% of deviance in apparent fishing hours. The model estimated low apparent fishing activity in shallow cells and higher activity across deeper waters (Fig. 6a). It also estimated higher activity on flatter seabed and lower activity on steeper seabed, although uncertainty increased at the steepest slopes where observations were sparse (Fig. 6b). Apparent fishing activity declined at intermediate distances from the coast and increased farther offshore, with wider uncertainty at the farthest distances (Fig. 6c). The seasonal smooth showed higher fitted activity in spring and early summer and lower activity from late summer into autumn (Fig. 6d). The year smooth showed higher fitted activity in the mid-2010s and lower activity after 2020, with the lowest fitted values toward the end of the time series (Fig. 6e).

Front proximity contributed a small fitted effect. The front-distance smooth peaked at approximately 5 km from the nearest front and declined towards a distance of 100 km (Fig. 6f). A direct contrast between 5 km and 100 km from the nearest front gave a fitted ratio of 1.055, equivalent to 5.5% higher positive apparent fishing hours near fronts (95% CI: 3.7-7.4%). Front strength and front persistence did not show clear adjusted effects and were not retained in the final model. Gear group shows a clear fitted difference. The model estimated 5.76 h of apparent fishing activity for trawlers (95% CI: 5.40-6.16) and 2.93 h for drifting longlines (95% CI: 2.73-3.14). Spring-neap tide state showed a smaller difference. The model estimated 4.15 h during neap tides (95% CI: 3.88-4.43) and 4.08 h during spring tides (95% CI: 3.81-4.36).

Offshore wind exposure

Spatial overlay of the upper 20% of long-term hotspot layers shows that planned offshore wind areas intersect distinct components of the long-term Celtic Sea seascape (Fig. 7). Front and fishing hotspots are spatially related but not identical. Fishing hotspots form a broad southwest–northeast corridor from the Celtic Deep toward the Isles of Scilly, the English Channel and the Ushant region, with additional concentrations over the central Celtic Sea banks and parts of the shelf break. Front hotspots are more prominent near the northern Celtic Sea and Irish Sea entrance, around the Isles of Scilly, and toward Ushant. Shelf-edge fronts are visible in the monthly persistence maps (Fig. 2) but are less prominent in Fig. 7 because this overlay shows only the strongest 20% of long-term hotspot cells. This suggests that shelf-edge fronts are recurrent but generally ranked below the strongest nearshore, tidal mixing and regional frontal features under the hotspot definition used here. Hotspots outside the Celtic Sea analysis boundary are shown for spatial context but are not included in the exposure metrics reported below. Gear-specific hotspot maps are shown in Supplementary Fig. 1-6.

FLOW footprints show a distinct seasonal profile of exposure to front and fishing hotspots (Fig. 8). Floating wind areas intersect about 2.5% of the total Celtic Sea front hotspot area from January to March, before declining through late spring and summer. Fishing hotspot overlap peaks in August at about 2.0% of the regional fishing hotspot area, with a secondary peak in November. The planned FLOW footprint covers 1,463 km² of the Celtic Sea. In absolute terms, overlap with front hotspots is highest in

late winter and early spring, reaching about 1,247 km² in March, equivalent to approximately 85% of the floating footprint. Front hotspot overlap then declines through spring and summer when strong tidal mixing fronts develop mostly outside of planned FLOW development and falls to less than 10% of the floating footprint in October. By contrast, overlap with fishing hotspots is highest in August, when fishing hotspot intersections approach about 1,013 km², equivalent to roughly 69% of the floating footprint.

Together, the regional percentages shown by the solid lines in Fig. 8 indicate the proportion of the wider Celtic Sea hotspot network that overlaps the FLOW footprint, while the bars show the absolute area of OWF overlapping hotspot cells. Footprint-normalised percentages, calculated as hotspot overlap area divided by total OWF footprint area, are reported in the text to show the proportion of each wind-farm footprint occupied by hotspots.

FBOW footprints show a different exposure profile from FLOW areas (Fig. 9). FBOW footprints intersect approximately 6.8% of the Celtic Sea front hotspot area in January and February and 6.3% in December. Fishing hotspot overlap is lower and more stable, generally remaining below 1.6% of the regional fishing hotspot area. These results indicate that FBOW planning areas are most strongly exposed to recurrent nearshore and inner-shelf thermal front habitat, whereas floating footprints show a stronger seasonal fishing hotspot signal. These exposure estimates are threshold dependent because the main analysis defines hotspots as the upper 20% of monthly front cells by strength and fishing cells by apparent fishing hours. Monthly hotspot maps and threshold sensitivity are reported in Supplementary Fig. 7-10. The FBOW footprint covers 3,318 km² of the Celtic Sea. In absolute terms, intersections with front hotspots are largest in winter, approaching 2,968 km² in January and February, equivalent to about 89% of the FBOW footprint. Front hotspot overlap is also high in December and remains substantial in several summer and late autumn months. By contrast, apparent fishing hotspots occupied less than 20% of the FBOW footprint throughout the year.

Discussion

This study provides a long-term pre-construction baseline of frontal dynamics and apparent fishing activity across a seasonally stratified shelf sea environment entering an unprecedented phase of offshore wind development. Our results show that seasonally persistent frontal habitat, long-term apparent fishing activity and planned wind footprints form distinct but partly overlapping spatial systems, rather than a single shared hotspot pattern. Fronts were spatially recurrent but strongly seasonal, while fishing activity was seasonal, but spatially more concentrated, episodic and consistent with habitual fishing grounds shaped by bathymetry, access and fleet behaviour. FLOW areas showed strong seasonal exposure to front hotspots in late winter and early spring, suggesting comparatively limited overlap with the persistent summer tidal mixing fronts characteristic of the stratified shelf sea environment. Fishing hotspot exposure was greatest in summer, especially around the planned FLOW sites, rather than the wider AOO (Fig. 1). By contrast, FBOW areas were dominated by persistent coastal and inner-shelf frontal exposure with lower fishing-hotspot occupancy. These results provide a baseline

for monitoring access change, displacement and ecological response, and highlight the need for more localised fisheries and front-system evidence.

Frontal regimes and baseline variability

The long-term front baseline reveals persistent patterns of frontal recurrence across the Celtic Sea, rather than isolated or random weekly detections. These structures are unlikely to represent a single front type. Based on their spatial distribution and seasonality, these recurring frontal systems likely comprise seasonal tidal mixing fronts, persistent coastal and inner-shelf fronts, shelf-slope fronts and bathymetrically or topographically generated frontal features associated with banks, headlands, and island wakes^{11,50}. These frontal regimes should not be regarded as ecologically interchangeable. Tidal mixing fronts form near the boundary between tidally mixed and seasonally stratified waters, where tidal stirring interacts with seasonal surface heating to establish strong horizontal density gradients. Such fronts can separate water masses with contrasting physical and biogeochemical properties, enhance lateral transport, nutrient supply near the surface, and promote plankton production, prey aggregation and predator foraging^{50–54}. Consequently, the seasonal offshore frontal habitat intersecting planned FLOW areas represents a particularly important component of the environmental baseline for ecological monitoring and impact assessment. By contrast, nearshore and inner-shelf fronts occurred throughout much of the year, particularly near the Irish southeast coastline and within FBOW footprints (Fig. 7). These fronts may reflect seasonal heating and cooling of shallow coastal waters, under the influence of tidal stirring, freshwater input, headland effects, turbidity gradients or bathymetric control^{55,56}. These fronts may still be ecologically important, but are likely to influence different ecosystem and management processes, more closely associated with coastal habitat structure, sediment transport⁵⁷ and local hydrography⁵⁸, than with the stratified shelf sea processes characteristic of offshore tidal mixing fronts. This distinction suggests that planned floating and FBOW developments are likely to interact with different oceanographic regimes and associated ecological processes, reinforcing the need for monitoring strategies tailored to the dominant frontal environments within each development area.

The interannual variability in the F1 score, the summed occurrence of detected fronts per week, further shows why a long baseline is needed. Frontal activity varies among years, with a prominent peak around 2018, but this study does not attribute that peak to a single driver. Year-to-year variability in shelf-sea fronts can arise from changes in surface heating, wind mixing, storminess, freshwater input and the timing or strength of seasonal stratification⁴⁸. Larger scale climate variability, including the North Atlantic Oscillation (NAO), can influence regional temperature, precipitation and wind forcing, while marine heatwaves can alter shelf sea thermal structure and stratification^{48,59,60}. The 2018 peak should therefore be interpreted cautiously. It indicates that the Celtic Sea frontal seascape is temporally variable and potentially sensitive to interannual variability in climate and weather forcing, rather than demonstrating a specific underlying mechanism. This matters for planning because climate projections for UK shelf seas suggest longer seasonal stratification by the end of the century, with earlier onset and

later breakdown, while increased rainfall and river runoff may strengthen coastal stratification³⁹. These changes could alter frontal timing, persistence and ecological functioning, with consequences for nutrient supply, primary production and knock-on effects to higher trophic levels as well as fisheries. Offshore wind planning should therefore treat front exposure as a dynamic baseline shaped by both climate forcing and infrastructure effects: turbulence from foundations and moorings may enhance nutrient exchange during stratified periods, but may also delay the onset of stratification and modify tidal mixing fronts in marginally stratified seas^{29,32}. Future work should examine the Earth observation time-series for insights into natural and climate-forced variations in the distribution of shelf-sea fronts.

Fishing activity and front proximity

While close associations between ocean fronts and fishing grounds have been observed in other marine systems, including tuna, saury and squid near thermal, chlorophyll, upwelling and eddy fronts^{61–65}, the Celtic Sea pattern suggests that this relationship is shaped by seabed habitat, target resources and established fishing grounds. Apparent fishing hotspots did not simply follow the seasonal expansion of surface thermal fronts. Nearshore and inner-shelf waters often contained frequent front detections but relatively low apparent fishing activity, whereas offshore fishing hotspots were concentrated around the Celtic Deep, the central Celtic Sea banks and parts of the shelf edge (Fig. 4). This spatial structure is consistent with previous VMS-based work in the Celtic Sea, in which shelf-edge fishing activity was reported to be about five times greater than activity within the broader Celtic Sea, while fishing in the Celtic Deep was about 3.3 times greater than in the central Celtic Sea⁴⁰. These regions also have different ecological and operational bases: the Celtic Deep provides muddy habitat for *Nephrops norvegicus*, the central banks include structured bathymetric features such as Jones Bank, Labadie Bank and Northwest Bank, and the shelf edge supports mixed pelagic and demersal targeting linked to slope, shelf-break and migration processes^{9,39,40}. Consistent with this, the GAM estimated only a modest front-proximity effect, with apparent fishing activity 5.5% higher at 5 km than at 100 km from the nearest front after accounting for gear, tidal state, bathymetry, distance to coast, seasonal timing, interannual variation and spatial structure. Fronts therefore appear to contribute to the productive seascape in which Celtic Sea fishing grounds form, but they do not by themselves explain the distribution of apparent fishing hotspots.

The temporal fishing baseline also reflects regional seasonality rather than one uniform Celtic Sea fishing cycle. Previous work found relatively weak seasonality in the Celtic Deep, where fishing activity was low early in the year but then persisted from spring into winter. By contrast, fishing over the central Celtic Sea banks was more concentrated in spring and summer, while shelf-edge activity was low in April to June, increased sharply in July and August, and then declined more gradually⁴⁰. The year-month apparent fishing activity heatmap showed a similar episodic pattern, with spring and early-summer peaks, late-year activity in some years and lower apparent activity after 2020 (Fig. 5). The GAM in this study also detected a small spring-neap tide effect, estimating 4.15 h of positive apparent fishing activity

during neap tides compared with 4.08 h during spring tides. This 1.7% difference is small, but its direction is consistent with previous evidence from the Celtic Deep, where reduced fishing around spring tides has been linked to lower Nephrops availability outside burrows under stronger tidal flows⁴⁰. In contrast, bank and shelf-edge fisheries may respond less directly to the spring-neap cycle because internal-tide mixing, nitrate fluxes, prey aggregation and fish distributions operate across longer ecological timescales^{66–68}. These temporal contrasts show why offshore wind exposure assessments should not treat fishing as a single static layer. AIS- or VMS-derived activity should be combined with logbooks, métier codes, landings, value and port dependence, so that bottom-contact gears, pelagic mobile gears and passive gears can be assessed separately.

Offshore wind exposure and planning implications

Distinguishing offshore tidal mixing fronts from coastal and inner-shelf fronts changes how offshore wind exposure should be interpreted. FBOW footprints overlapped most strongly with persistent coastal and inner-shelf front hotspots, especially in winter, but had relatively low fishing-hotspot occupancy. This exposure mainly indicates potential interaction with recurrent coastal hydrographic environments, where sediment dynamics, turbidity, shallow-water mixing and coastal habitat structure may be most relevant. FLOW footprints showed a more seasonal profile. Their strongest front-hotspot overlap occurred in late winter and early spring, within seasonal offshore frontal habitat associated with the Celtic Sea Front, the Celtic Deep, central Celtic Sea banks and approaches to the Bristol Channel. Fishing-hotspot exposure peaked in summer and partly coincided with these offshore frontal regions. This is important because FLOW development is expanding into deeper, seasonally stratified shelf waters, where turbine wakes, foundation-induced mixing and array-scale hydrodynamic change may interact with stratification, nutrient supply and primary productivity^{29,31,32,69}. The exposure metrics therefore do not imply a common mechanism for FBOW and FLOW. Rather, they identify two distinct monitoring challenges: persistent coastal and inner-shelf frontal exposure around FBOW sites, and seasonal stratified-shelf frontal exposure around planned FLOW areas. Regional assessment should therefore be tailored to the dominant frontal regime within each development area.

The Area of Opportunity should be interpreted differently from project footprints. The floating AOO covers 32,303 km², far larger than the 1,463 km² floating footprint used as the main exposure layer. It is a strategic planning space, not a realised wind farm footprint or access restriction. However, it remains important because future FLOW development could occupy a substantially larger area than the current project development areas. For context, developing even 12% of the AOO would correspond to an approximate footprint of 3,876 km², larger than the current FBOW footprint and roughly three times the current floating footprint. The current baseline is therefore timely as it provides scenario context for future FLOW expansion and supports early consultation before larger development footprints are fixed.

These results also speak to the co-location debate. North Sea evidence reveals that spatial overlap alone does not determine fisheries impact: outcomes depend on gear type restrictions, vessel size, turbine

spacing, cable and mooring layouts, safety zones, insurance, compensation, licensing and governance^{42,70}. In the German EEZ, VMS-logbook analysis suggested that planned offshore wind areas could overlap large fractions of gillnet plaice landings, with potential losses under full exclusion depending strongly on fleet and access assumptions⁷¹. In more recent North Sea analyses, co-location potential was greatest for some passive gears, but remained constrained by safety rules, evidence gaps, insurance and economic viability⁷⁰. These models cannot be transferred directly to the Celtic Sea because commercial-scale FLOW introduces different operational constraints, including moorings, dynamic cables and greater uncertainty around fishing access. This baseline therefore does not determine whether co-location is feasible, but identifies where co-location, exclusion, compensation and monitoring are most urgent before rules become fixed.

Limitations and uncertainty

Several limitations constrain the scope of inference. Satellite-derived sea-surface-temperature fronts capture only one component of the ocean's frontal environment, while salinity fronts, chlorophyll fronts, subsurface density gradients and internal-wave features may also structure productive habitats⁴⁰. Front detection is affected by satellite retrieval uncertainty, cloud processing, front-strength thresholds, gridding and the choice of hotspot definition. GFW apparent fishing activity has a different set of limitations. It is derived from AIS and behavioural classification models, not from logbooks or catch records. AIS coverage varies by vessel size, flag state, region, receiver density and compliance. Vessels may carry no AIS, transmit intermittently, switch devices off, change identifiers, or be misclassified. The model can also confuse gear classes or fishing states, and fishing hours are not equivalent to catch, revenue, seabed contact or fishing pressure^{72,73}. These issues matter most for absolute trends, gear comparisons and economic inference. They do not invalidate the headline result because this study uses GFW conservatively: as apparent fishing activity, ranked hotspots and relative exposure, not as total effort, catch loss or displacement. At present, GFW provides one of the few publicly available fisheries datasets with sufficient spatial and temporal coverage to examine these long-term regional patterns consistently.

Future monitoring

The next step is to refine both sides of the exposure framework. For fronts, future work should classify front regimes explicitly, separating coastal and inner-shelf fronts from offshore tidal mixing and shelf-slope fronts using hydrography, stratification metrics, tidal mixing indices (e.g. Simpson and Hunter parameters), and *in situ* validation. For fisheries, future work should distinguish bottom trawls from pelagic trawls, separate passive gears more precisely, and connect apparent activity to catch, landed value, target species and port dependence. Ecologically, targeted *in situ* sampling of seasonal tidal mixing fronts intersecting with planned FLOW developments is needed to establish how these features influence ecosystem structure and function. This should distinguish direct physical pathways⁷⁴, whereby

density gradients or associated upwelling and downwelling aggregate or redistribute plankton, prey and predators, from indirect and potentially lagged pathways mediated through changes in nutrient supply, primary production and subsequent trophic transfer. Such observations would help determine whether fronts function primarily as immediate physical aggregation and foraging features, as sites of enhanced biogeochemical production, or through a combination of both mechanisms^{14,16}. Resolving these pathways would also provide a basis for assessing how infrastructure-induced mixing may interact with the formation and strength of tidal mixing fronts, and whether such changes alter their associated biogeochemical and ecological functions. Combining such data with hydrodynamic and ecosystem models, acoustic surveys, eDNA, seabird and marine mammal tracking, and before-after-control-impact (BACI) monitoring would allow future work to test whether construction and operation alter front-associated habitat, fishing behaviour or ecological function. The Celtic Sea represents a valuable study system because this evidence can still be assembled prior to large-scale FLOW construction. The present study provides the pre-construction spatial layer for that adaptive planning process.

Materials and methods

Study area

The analysis focused on the Celtic Sea shelf region shown in Fig. 1. The domain includes UK, Irish and French waters where long-term apparent fishing activity, recurrent fronts and current offshore wind planning boundaries overlap. Offshore wind boundaries were compiled from The Crown Estate and 4C Offshore^{75,76}. Polygons were classified by development status and, where available, expected foundation. Floating Round 5 project development areas in the central Celtic Sea were treated separately from planned or consented fixed wind developments closer to shore. Dissolved footprint areas used in the exposure analysis were 1,463 km² for FLOW and 3,318 km² for FBOW. The floating AOO covered 32,303 km² and was used only for supplementary scenario context because it is a strategic search area rather than a committed development footprint.

Thermal front data

Weekly thermal front data for 2012 to 2025 were derived from Earth observation sea surface temperature (SST) imagery using the single image edge detection (SIED) algorithm⁷⁷ and composite front mapping framework²⁶. SST scenes were georeferenced, screened for invalid observations and cloud-masked before weekly compositing was used to reduce data gaps. Detected front fragments were further processed using line clustering to derive contiguous front structures⁷⁸. These simplified lines are composed of waypoints, each with an associated front strength defined as the local SST gradient (°C km⁻¹). Waypoints were assigned to 0.1° analysis grid cells. Where multiple waypoints occurred within the same grid cell and week, the maximum front strength was retained to represent the strongest local

signal. Where no waypoint occurred in a grid cell during a given week, front strength was set to zero for persistence and hotspot calculations.

Monthly front persistence was calculated for each grid cell as the fraction of analysed weeks from 2012 to 2025 in which that cell contained a detected front in a given calendar month. The F1 score was calculated following previous frontal climatology work⁴⁸ and summarised the cumulative occurrence of detected SST fronts across the analysis grid for each weekly time step. For exposure analysis, the monthly front score for each cell was calculated as the summed waypoint strength assigned to that cell for a given calendar month across all years. Monthly front hotspot layers were then defined from ranked cell level front scores within the Celtic Sea analysis domain. The main hotspot definition used the upper 20% of ranked cells, and sensitivity analyses repeated the calculation using alternative hotspot fractions. Because thermal SST fronts can arise from several physical regimes, including coastal, inner shelf, tidal mixing and shelf edge fronts, front exposure was interpreted as exposure to recurrent thermal front conditions rather than to a single front type.

Apparent fishing activity

Weekly apparent fishing activity was obtained from Global Fishing Watch (GFW), via its 4wings API, and aggregated to the same 0.1° grid cells and weekly temporal resolution as the front data⁷⁹. The response variable was model-derived apparent fishing hours by cell, week and gear group. These values were interpreted as apparent fishing activity, not catch, economic value, seabed contact or complete fishing effort. This terminology is important because the GFW product is derived from vessel tracking and machine-learning behaviour classification and can be affected by AIS carriage, reception quality, identity errors, gear classification and behaviour-model uncertainty^{72,73,80}. To reduce nearshore artefacts and avoid grid cells where fishing activity, bathymetry and coastal geometry are poorly represented at the analysis resolution, cells shallower than 10 m or located within 3 km of the shoreline were excluded from the analyses.

Original GFW gear labels were harmonised into analysis groups to reduce sparsity while retaining operationally meaningful distinctions. Trawlers and dredges were retained as separate groups. Set longlines, set gillnets, and pots and traps were grouped as static gear, while purse seine and seine categories were grouped as seiners. Ambiguous labels, including inconclusive, fishing, fixed gear, trollers, and pole and line, were grouped as other and excluded from the main modelling dataset. This classification retained the dominant fishing methods while avoiding overinterpretation of rare or poorly resolved labels. After harmonisation, the gear-classified dataset was dominated by trawlers, which accounted for 62.0% of records. Static gears accounted for 13.7%, drifting longlines for 1.1%, dredges for 2.2%, and seiners for 0.9%. The remaining 20.1% of records were assigned to the other category. Fishing hotspots were defined as the upper 20% of ranked cells by summed apparent fishing hours within the analytical period (monthly or annually) and the Celtic Sea analysis domain. Because the GFW

fishing surface is model-derived, hotspot definitions were based on ranks rather than presence-absence thresholds.

Generalized additive modelling

Generalized additive models (GAMs) were used to test whether apparent fishing activity was associated with front proximity, after accounting for environmental, seasonal, spatial and gear-related structure in the fishery⁸¹. The response variable was apparent fishing activity per grid cell, week and gear group, treated as a relative index rather than complete fishing effort. The response was modelled on the original cell-week scale using a Gamma distribution with a log link. The final model included gear group and spring-neap tide state as fixed effects, and smooth terms for bathymetry, seabed slope, distance to coast, distance to the nearest front, week of year, year, and spatial location. Week of year was fitted as a cyclic smooth to represent seasonality, while the two-dimensional spatial smooth of grid-cell coordinates accounted for persistent fishing grounds and other unmeasured regional structure. Distance to coast and distance to the nearest front were log-transformed to reduce skewness and limit leverage from large-distance observations while preserving resolution near zero, where ecological responses are expected to change most rapidly. Spring-neap tide state was derived from astronomical lunar phases. New and full moons were classified as spring-tide phase events, and first- and last-quarter moons as neap-tide phase events. To account for the age of the tide, each event date was shifted by two days before assigning the weekly tide label. Weekly observations were then assigned the tide type of the corresponding spring or neap event. Temporal autocorrelation within each grid-cell and gear series was accounted for using an AR1 correlation structure.

Candidate response distributions, including Gamma and Tweedie alternatives, were compared using AIC, deviance explained and residual diagnostics^{81,82}. This comparison was used to select the response family and link function, not to perform automated stepwise variable selection. The final covariate set was specified a priori to control for major non-frontal drivers of fishing activity before testing the focal front-proximity term. Distance to the nearest front was retained as the main front covariate because it directly tested whether apparent fishing activity was associated with fronts after adjustment for gear, tide, bathymetry, seasonality, interannual variation and spatial structure. Front strength and persistence were examined as additional frontal covariates, but were not retained as their adjusted effects were small and did not alter the main interpretation. Because the dataset was large, front proximity was interpreted using fitted effect size and uncertainty rather than statistical significance alone.

Exposure metrics and sensitivity analyses

Exposure was quantified as long-term spatial overlap, not as ecological impact or predicted fisheries displacement. For each calendar month, front and apparent fishing hotspot layers were defined within the Celtic Sea domain. Front hotspots were identified as the upper 20% of ranked cells by summed

monthly front strength, calculated at cell-month scale across 2012–2025. Apparent fishing hotspots were identified as the upper 20% of ranked cells by summed monthly apparent fishing hours. All overlap areas were calculated after projection to EPSG:3035 and reported in km².

Two percentage metrics were calculated because they answer different planning questions. The primary exposure metric was the proportion of each Celtic Sea hotspot layer that overlapped an offshore wind footprint, calculated as hotspot area inside offshore wind divided by total hotspot area in the Celtic Sea analysis domain. This regional hotspot percentage describes how much of the wider front or fishing hotspot layer falls inside planned wind areas. A second, footprint-normalised metric was calculated as hotspot area inside offshore wind divided by total offshore wind footprint area. This metric describes how much of a given wind footprint is occupied by hotspot habitat or activity. This study reports the regional hotspot percentage as the primary exposure metric and uses footprint-normalised values to aid planning interpretation. Sensitivity analyses repeated the same calculations using upper 10%, 20% and 30% hotspot thresholds. The main analyses use the upper 20% monthly hotspot definition to keep front, fishing and exposure metrics directly comparable across figures.

Declarations

Data availability

The derived analysis grid, monthly hotspot layers and exposure summaries are prepared for deposition in a public repository before submission or upon acceptance. Global Fishing Watch (GFW) data are subject to the provider's access and licensing conditions.

Analysis code is prepared for archiving in a public repository upon acceptance. The archived version will include the software environment and scripts used to generate the manuscript outputs.

Acknowledgments

The authors acknowledge the NERC Earth Observation Data Acquisition and Analysis Service (NEODAAS) for providing satellite data and access to computing facilities. We also gratefully acknowledge Global Fishing Watch (GFW) for providing the open-access fishing activity data used in this study.

Funding

This work was supported by UK Research and Innovation (UKRI) through the Natural Environment Research Council (NERC), with co-funding from The Crown Estate, under grant NE/Z504373/1 (FRONTLINE: Impacts of FLOW on Celtic Sea Ocean Fronts and Biodiversity).

Author information

Contributions

Y.Y. and L. Lieber conceived the study. Y.Y. processed and analysed the data, produced the figures and wrote the original manuscript draft. P.M. provided and processed satellite front data. L. Langley contributed to the statistical modelling and fisheries interpretation. S.V. contributed to ecological interpretation. M.K. contributed to fisheries and marine spatial planning interpretation. L. Lieber contributed to offshore wind and shelf sea interpretations. P.M., S.V., M.K. and L. Lieber secured funding. All authors contributed critically to the drafts and gave final approval for publication.

Corresponding authors

Correspondence to Yang Yang (yang.yang@plymouth.ac.uk)

Ethics declarations

The authors declare no competing interests.

References

1. IEA. *Offshore Wind Outlook 2019*. (2019).
2. European Commission, Directorate-General for Energy. Member States agree new ambition for expanding offshore renewable energy. https://energy.ec.europa.eu/news/member-states-agree-new-ambition-expanding-offshore-renewable-energy-2024-12-18_en (2024).
3. Galparsoro, I. et al. Assessment tool addresses implementation challenges of ecosystem-based management principles in marine spatial planning processes. *Commun. Earth Environ.* 6, 55 (2025).
4. Trifonova, N. et al. Fishing, offshore wind energy, climate change and marine spatial planning: Is it possible to plan for a best use of space? *Ecol. Solut. Evid.* 6, e70039 (2025).
5. Galparsoro, I. et al. Reviewing the ecological impacts of offshore wind farms. *NPJ Ocean Sustain.* 1, (2022).
6. Chiroasca, A. M. & Rusu, L. Sea state characteristics and the maritime traffic in the European seas. in *International Multidisciplinary Scientific GeoConference, SGEM* 863–870 (2020).
7. The Crown Estate. The Crown Estate announces successful award to develop third floating wind farm in the Celtic Sea. *The Crown Estate press release* <https://www.thecrownestate.co.uk/news/the-crown-estate-announces-successful-award-to-develop-third-floating-wind-farm-in-the-celtic-sea> (2025).
8. Department of Enterprise. *Ireland's Offshore Wind Industrial Strategy*. (2022).

9. Moore, C. *et al.* Defining métier for the Celtic Sea mixed fisheries: A multiannual international study of typology. *Fish. Res.* 219, 105310 (2019).
10. Estrada, M. Primary production in the northwestern Mediterranean. *Sci. Mar.* 60, 55–64 (1996).
11. Simpson, J. H. & Sharples, J. *Introduction to the Physical and Biological Oceanography of Shelf Seas.* Cambridge University Press (2012). doi:10.1017/CBO9781139034098.
12. Simpson, J. H. & Hunter, J. R. Fronts in the Irish Sea. *Nature* 250, 404–406 (1974).
13. Cox, S. L., Embling, C. B., Hosegood, P. J., Votier, S. C. & Ingram, S. N. Oceanographic drivers of marine mammal and seabird habitat-use across shelf-seas: A guide to key features and recommendations for future research and conservation management. *Estuar. Coast. Shelf Sci.* 212, 294–310 (2018).
14. Holligan, P. M. Biological implications of fronts on the northwest European continental shelf. *Phil. Trans. R. Soc* 302, 547–562 (1981).
15. Lévy, M., Haëck, C., Mangolte, I., Cassianides, A. & El Hourany, R. Shift in phytoplankton community composition over fronts. *Commun. Earth Environ.* 6, 591 (2025).
16. Oms, L. *et al.* Fine-scale observations reveal distinct frontal phytoplankton communities. *Commun. Earth Environ.* 7, 468 (2026).
17. Woodson, C. B. *et al.* Ocean fronts drive marine fishery production and biogeochemical cycling. *Proc. Natl. Acad. Sci. USA* 112, 1710–1715 (2015).
18. Kai, E. T. *et al.* Top marine predators track Lagrangian coherent structures. *Proc. Natl. Acad. Sci. U. S. A.* 106, 8245–8250 (2009).
19. Scales, K. L. *et al.* On the front line: Frontal zones as priority at-sea conservation areas for mobile marine vertebrates. *J. Appl. Ecol.* 51, 1575–1583 (2014).
20. Miller, P. I. & Christodoulou, S. Frequent locations of oceanic fronts as an indicator of pelagic diversity: Application to marine protected areas and renewables. *Mar. Policy* 45, 318–329 (2014).
21. Miller, P. I., Xu, W. & Carruthers, M. Seasonal shelf-sea front mapping using satellite ocean colour and temperature to support development of a marine protected area network. *Deep Sea Res. Part II Top. Stud. Oceanogr.* 119, 3–19 (2015).
22. Grecian, W. J., Lane, J. V., Michelot, T., Wade, H. M. & Hamer, K. C. Understanding the ontogeny of foraging behaviour: Insights from combining marine predator bio-logging with satellite-derived oceanography in hidden Markov models. *J. R. Soc. Interface* 15, (2018).
23. Lieber, L. *et al.* Selective foraging behavior of seabirds in small-scale slicks. *Limnol. Oceanogr. Lett.* 8, 286–294 (2023).
24. Abrahms, B. *et al.* Climate mediates the success of migration strategies in a marine predator. *Ecol. Lett.* 21, 63–71 (2018).
25. Lieber, L., Nimmo-Smith, W. A. M., Waggitt, J. J. & Kregting, L. Localised anthropogenic wake generates a predictable foraging hotspot for top predators. *Commun. Biol.* 2, 123 (2019).

26. Miller, P. Composite front maps for improved visibility of dynamic sea-surface features on cloudy SeaWiFS and AVHRR data. *J. Mar. Syst.* 78, 327–336 (2009).
27. Finserås, E., Herrera Anchustegui, I., Cheynet, E., Gebhardt, C. G. & Reuder, J. Gone with the wind? Wind farm-induced wakes and regulatory gaps. *Mar. Policy* 159, 105897 (2024).
28. Li, R., Zhang, J. & Zhao, X. Long-range near-surface wake signatures of offshore wind farm clusters revealed by satellite observations. *Commun. Eng.* 5, 144 (2026).
29. Dorrell, R. M. et al. Anthropogenic mixing in seasonally stratified shelf seas by offshore wind farm infrastructure. *Front. Mar. Sci.* 9, (2022).
30. Lieber, L., Fraser, S., Coles, D. & Nimmo-Smith, W. A. M. Sheared turbulent flows and wake dynamics of an idled floating tidal turbine. *Nat. Commun.* 15, 8244 (2024).
31. Schultze, L. K. P., Merckelbach, L. M., Horstmann, J., Raasch, S. & Carpenter, J. R. Increased Mixing and Turbulence in the Wake of Offshore Wind Farm Foundations. *J. Geophys. Res. Oceans.* 125, e2019JC015858 (2020).
32. Daewel, U., Akhtar, N., Christiansen, N. & Schrum, C. Offshore wind farms are projected to impact primary production and bottom water deoxygenation in the North Sea. *Commun. Earth Environ.* 3, 292 (2022).
33. Werner, K. M., Haslob, H., Reichel, A. F., Gimpel, A. & Stelzenmüller, V. Offshore wind farm foundations as artificial reefs: The devil is in the detail. *Fish. Res.* 272, 106937 (2024).
34. Bergström, L., Sundqvist, F. & Bergström, U. Effects of an offshore wind farm on temporal and spatial patterns in the demersal fish community. *Mar. Ecol. Prog. Ser.* 485, 199–210 (2013).
35. Buyse, J., Hostens, K., Degraer, S. & De Backer, A. Offshore wind farms affect the spatial distribution pattern of plaice *Pleuronectes platessa* at both the turbine and wind farm scale. *ICES J. Mar. Sci.* 79, 1777–1786 (2022).
36. Stienen, E. W. M., Courtens, W., Van De Walle, M., Verstraete, H. & Vanermen, N. Frequent Use of Offshore Wind Farms in the Southern North Sea by Migrating Terns. *Ardea* 112, 331–337 (2024).
37. Bost, C. A. et al. The importance of oceanographic fronts to marine birds and mammals of the southern oceans. *J. Mar. Syst.* 78, 363–376 (2009).
38. Russell, D. J. F. et al. Marine mammals trace anthropogenic structures at sea. *Curr. Biol.* 24, R638–R639 (2014).
39. ICES. Celtic Seas ecoregion – Ecosystem Overview. (2022) doi:10.17895/ICES.ADVICE.21731615.V1.
40. Sharples, J., Ellis, J. R., Nolan, G. & Scott, B. E. Fishing and the oceanography of a stratified shelf sea. *Prog. Oceanogr.* 117, 130–139 (2013).
41. ICES. *EU Request on Economic, Social, and Ecological Impacts of Offshore Wind Farms (OWFs) and Floating Offshore Wind Farms (FLOWs) on Fisheries in the Baltic Sea, Celtic Seas, and Greater North Sea.* (2025) doi:10.17895/ICES.ADVICE.28759328.V1.

42. Püts, M., Kempf, A., Möllmann, C. & Taylor, M. Trade-offs between fisheries, offshore wind farms and marine protected areas in the southern North Sea – Winners, losers and effective spatial management. *Mar. Policy* 152, (2023).
43. Rijkswaterstaat. *Handreiking Gebiedspaspoort Windenergiegebied Borssele 2.0*. (2026).
44. Federal Waterways and Shipping Agency (GDWS). *General Order on Navigation in the Joint Safety Zone around the “Gode Wind 1”, “Gode Wind 2” and “Gode Wind 3” Offshore Wind Farms as Well as the Planned Offshore Wind Farms “NC 1” and “NC 2”*. (2025).
45. Federal Maritime and Hydrographic Agency (BSH). *Nachrichten Für Seefahrer / Notices to Mariners*. vol. 155 (2024).
46. Department for Energy Security and Net Zero. *National Policy Statement for Renewable Energy Infrastructure (EN-3)*. (2025).
47. Roach, M., Revill, A. & Johnson, M. J. Co-existence in practice: a collaborative study of the effects of the Westernmost Rough offshore wind development on the size distribution and catch rates of a commercially important lobster (*Homarus gammarus*) population. *ICES J. Mar. Sci.* 79, 1175–1186 (2022).
48. Belkin, I. M., Cornillon, P. C. & Sherman, K. Fronts in Large Marine Ecosystems. *Prog. Oceanogr.* 81, 223–236 (2009).
49. Scales, K. L. et al. Mesoscale fronts as foraging habitats: Composite front mapping reveals oceanographic drivers of habitat use for a pelagic seabird. *J. R. Soc. Interface* 11, (2014).
50. Bowers, D. G. & Simpson, J. H. Mean position of tidal fronts in European-shelf seas. *Cont. Shelf Res.* 7, 35–44 (1987).
51. Simpson, J. H. & Sharples, J. Tidal mixing fronts: their location, dynamics and biological significance. in *Introduction to the Physical and Biological Oceanography of Shelf Seas* 233–265 (Cambridge University Press, 2012).
52. Sheehan, P. M. F. et al. Shelf sea tidal currents and mixing fronts determined from ocean glider observations. *Ocean Sci.* 14, 225–236 (2018).
53. Suberg, L. A. Investigations of the variability of tidal mixing fronts and their importance for shelf-sea ecosystems across multiple trophic levels. *Doctoral dissertation, University of Southampton* (2015).
54. Pingree, R. D. & Griffiths, D. K. Tidal fronts on the shelf seas around the British Isles. *J. Geophys. Res. Ocean.* 83, 4615–4622 (1978).
55. Tully, O. et al. *Monitoring and Assessment of Scallops off the South East Coast of Ireland. Fisheries Resource Series, Bord Iascaigh Mhara (Irish Sea Fisheries Board)*. vol. 5 (2006).
56. Fernand, L. et al. The Irish coastal current: A seasonal jet-like circulation. *Cont. Shelf Res.* 26, 1775–1793 (2006).
57. Bailey, L. P. et al. Monopile-induced turbulence and sediment redistribution form visible wakes in offshore wind farms. *Front. Earth Sci.* 12, (2024).

58. Hendriks, E. *et al.* The impact of offshore wind turbine foundations on local hydrodynamics and stratification in the Southern North Sea. *Front. Mar. Sci.* 12, 1619577 (2025).
59. Holbrook, N. J. *et al.* A global assessment of marine heatwaves and their drivers. *Nat. Commun.* 10, (2019).
60. Smith, K. E. *et al.* Biological Impacts of Marine Heatwaves. *Ann. Rev. Mar. Sci.* 15, 119–145 (2023).
61. Belkin, I. M. Remote Sensing of Ocean Fronts in Marine Ecology and Fisheries. *Remote Sens.* 13, 883 (2021).
62. Tseng, C. Te *et al.* Sea surface temperature fronts affect distribution of Pacific saury (*Cololabis saira*) in the Northwestern Pacific Ocean. *Deep Sea Res. Part II Top. Stud. Oceanogr.* 107, 15–21 (2014).
63. Oh, Y., Kim, D. W., Jo, Y. H., Hwang, J. D. & Chung, C. Y. Spatial variability of fishing grounds in response to oceanic front changes detected by multiple satellite measurements in the East (Japan) sea. *Int. J. Remote Sens.* 41, 5884–5904 (2020).
64. Chen, X., Tian, S. & Guan, W. Variations of oceanic fronts and their influence on the fishing grounds of *Ommastrephes bartramii* in the Northwest Pacific. *Acta Oceanol. Sin.* 33, 45–54 (2014).
65. Laurs, R. M., Fiedler, P. C. & Montgomery, D. R. Albacore tuna catch distributions relative to environmental features observed from satellites. *Deep Sea Res. Part A. Oceanogr. Res. Pap.* 31, 1085–1099 (1984).
66. Palmer, M. R., Inall, M. E. & Sharples, J. The physical oceanography of Jones Bank: A mixing hotspot in the Celtic Sea. *Prog. Oceanogr.* 117, 9–24 (2013).
67. Martinez, I., Ellis, J. R., Scott, B. & Tidd, A. The fish and fisheries of Jones Bank and the wider Celtic Sea. *Prog. Oceanogr.* 117, 89–105 (2013).
68. Ellis, J. R., Martinez, I., Burt, G. J. & Scott, B. E. Epibenthic assemblages in the Celtic Sea and associated with the Jones Bank. *Prog. Oceanogr.* 117, 76–88 (2013).
69. Zampollo, A., Murray, R. O. H., Gallego, A. & Scott, B. Does the oceanographic response to wind farm wind-wakes affect the spring phytoplankton bloom? *Prog. Oceanogr.* 237, 103512 (2025).
70. Bonsu, P. O. *et al.* Co-location of fisheries and offshore wind farms: current practices and enabling conditions in the North Sea. *Mar. Policy* 159, 105941 (2024).
71. Stelzenmüller, V. *et al.* Co-location of passive gear fisheries in offshore wind farms in the German EEZ of the North Sea: A first socio-economic scoping. *J. Environ. Manage.* 183, 794–805 (2016).
72. Kroodsma, D. A. *et al.* Tracking the global footprint of fisheries. *Science* 359, 904–908 (2018).
73. Kroodsma, D. A. *et al.* Response to Comment on ‘Tracking the global footprint of fisheries’. *Science* 361, eaat7789 (2018).
74. Lieber, L., Nimmo-Smith, W. A. M., Waggitt, J. J. & Kregting, L. Fine-scale hydrodynamic metrics underlying predator occupancy patterns in tidal stream environments. *Ecol. Indic.* 94, 397–408 (2018).
75. TGS. TGS 4C Offshore Wind Intelligence Platform. <https://www.tgs4c.com/> (2026).

76. The Crown Estate. The Crown Estate Open Data Portal. <https://opendata-thecrownestate.opendata.arcgis.com> (2026).
77. Cayula, J. F. & Cornillon, P. Edge detection algorithm for SST images. *J. Atmos. Ocean. Technol.* 9, 67–80 (1992).
78. Miller, P. I., Scales, K. L., Ingram, S. N., Southall, E. J. & Sims, D. W. Basking sharks and oceanographic fronts: Quantifying associations in the north-east Atlantic. *Funct. Ecol.* 29, 1099–1109 (2015).
79. Global Fishing Watch. Global AIS-Based Apparent Fishing Effort Dataset (Version 3.0.0). (2025).
80. Hintzen, N. T. *et al.* Bias in Global Fishing Watch AIS data analyses results in overestimate of Northeast Atlantic pelagic fishing impact. *ICES J. Mar. Sci.* 82, 33 (2025).
81. Wood, S. N., Goude, Y. & Shaw, S. Generalized additive models for large data sets. *J. R. Stat. Soc. Ser. C Appl. Stat.* 64, 139–155 (2015).
82. Pedersen, E. J., Miller, D. L., Simpson, G. L. & Ross, N. Hierarchical generalized additive models in ecology: An introduction with mgcv. *PeerJ* 2019, e6876 (2019).

Figures

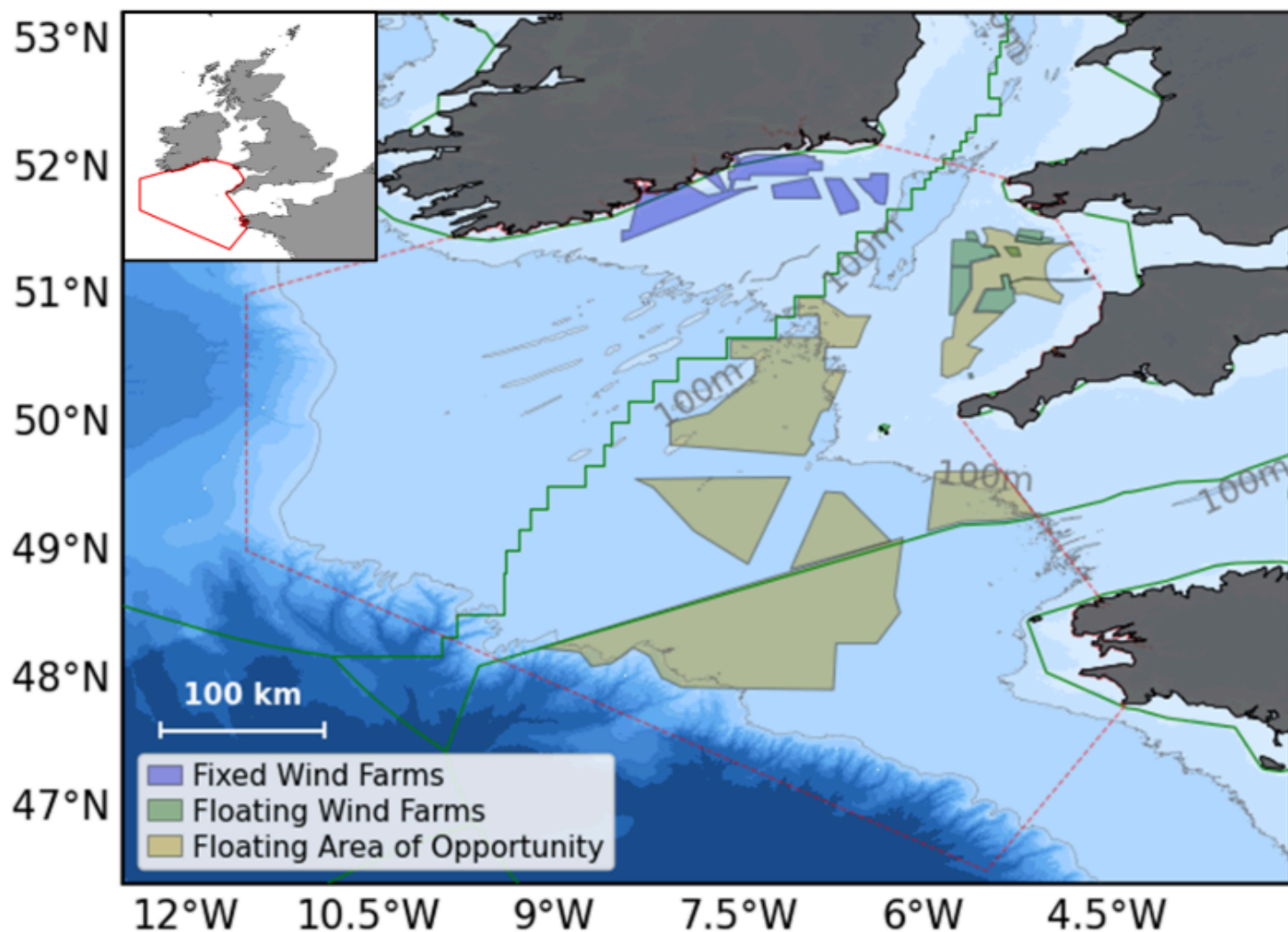


Figure 1

Study area and offshore wind planning context in the Celtic Sea. The inset locates the Celtic Sea area within the wider northwest European shelf. The main map shows bathymetric contours, planned and consented offshore wind areas, exclusive economic zone (EEZ) boundaries, and the Celtic Sea boundary. Fixed-bottom offshore wind (FBOW) sites are shown in purple, floating offshore wind (FLOW) sites in green, and the wider FLOW Area of Opportunity (AOO) in yellow. EEZ boundaries are shown as solid green lines, and the Celtic Sea boundary is shown as a red dashed line. The figure provides spatial context for the front, fishing and wind farm exposure analyses.

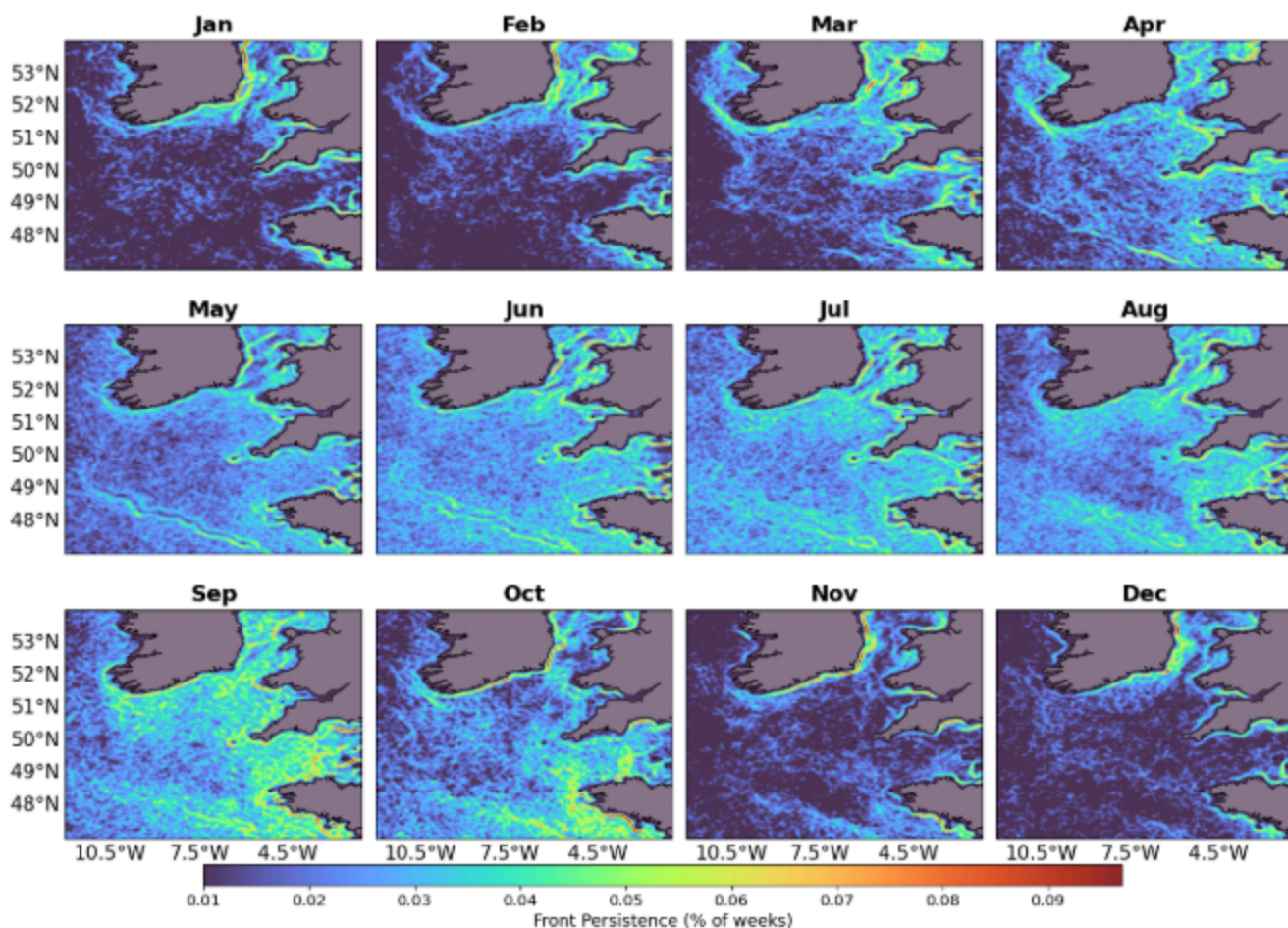


Figure 2

Monthly persistence (% of weeks across data from 2012 to 2025) of front conditions. Panels show, for each calendar month, the fraction of analysed weeks from 2012 to 2025 in which each grid cell was classified as frontal after gridding the weekly front product. The monthly sequence highlights seasonal emergence, expansion and contraction of recurrent frontal habitat.

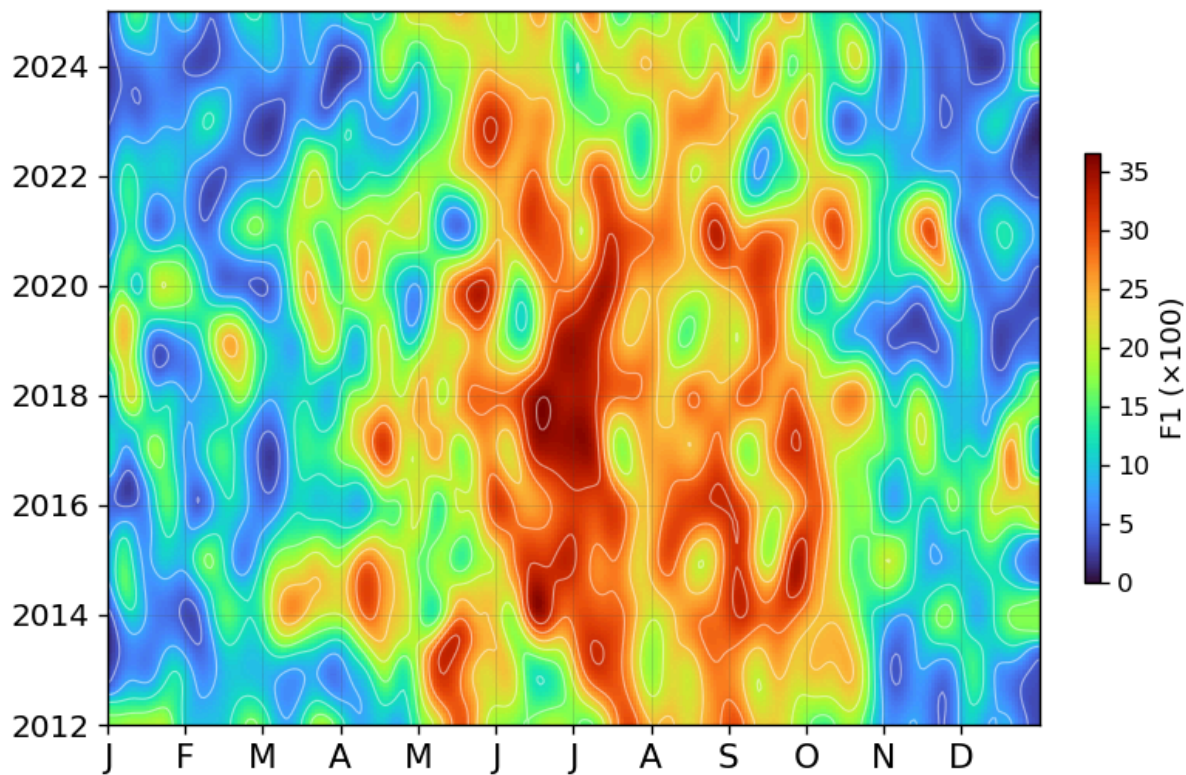


Figure 3

Seasonal and interannual variability in the Celtic Sea F1 score, defined as the summed occurrence of detected fronts across the Celtic Sea for each weekly time step. The heatmap shows the F1 score by month and year across the weekly front record. Higher values indicate weeks when detected SST fronts were more frequent or more spatially extensive within the analysis grid.

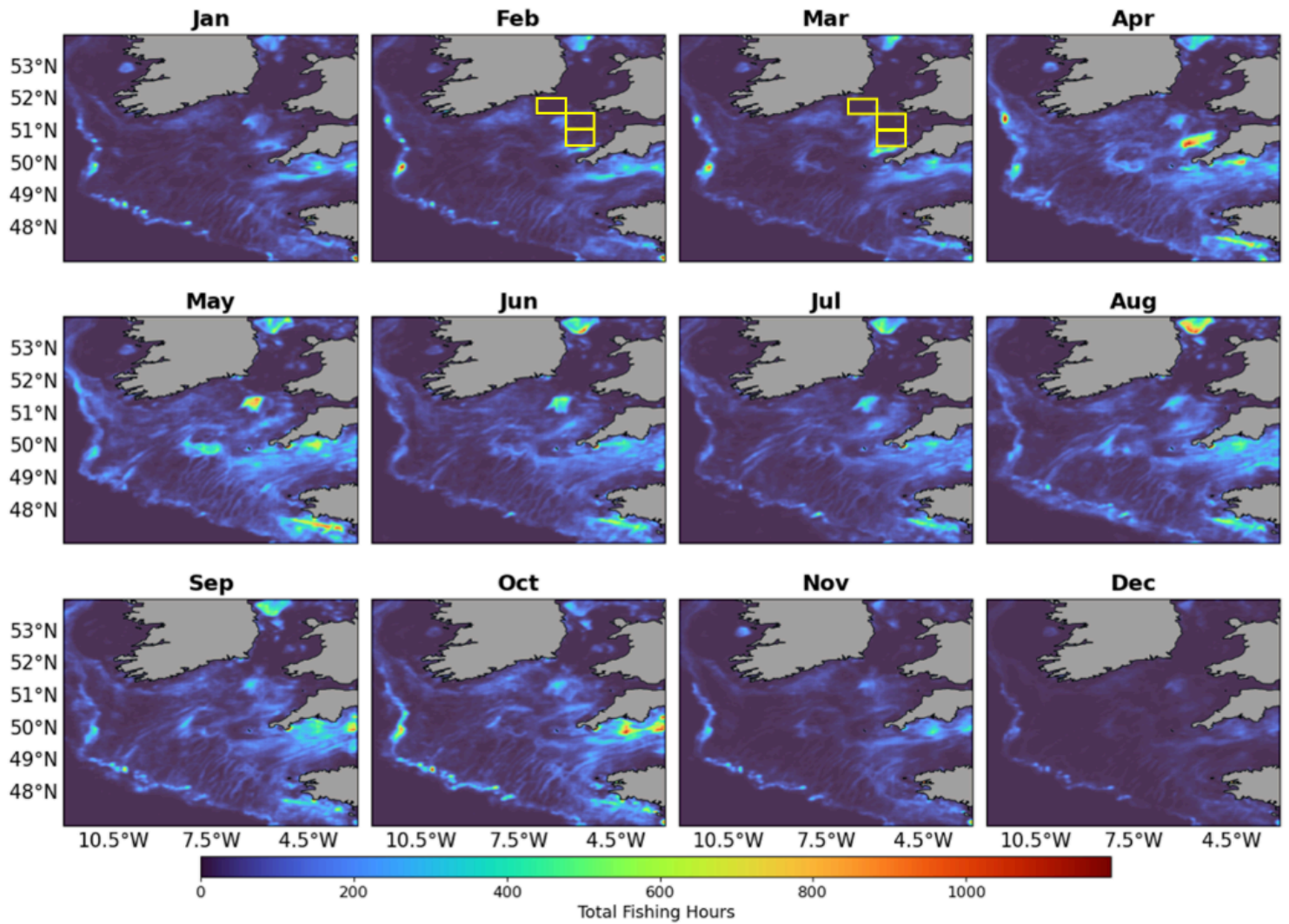


Figure 4

Monthly apparent fishing activity hotspots across 2012–2025. Panels show the spatial distribution of high apparent fishing activity by month after gridding model-derived fishing hours to the same weekly grid used for the front data. Hotspots are based on ranked monthly cell-level apparent fishing activity. Yellow rectangles in February and March highlight conservation or fisheries management zones where low apparent fishing activity is visible within the mapped hotspot layer.

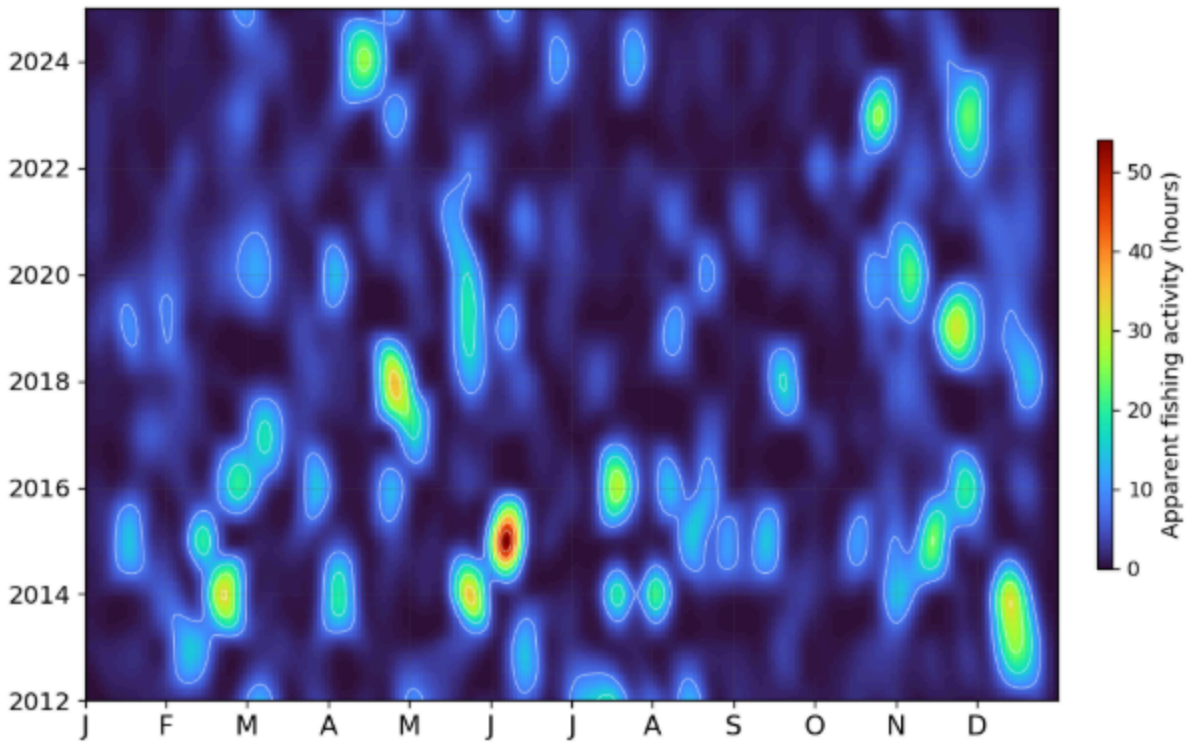


Figure 5

Seasonal and interannual variability in apparent fishing activity across 2012–2025. The heatmap shows domain-scale apparent fishing activity by month and year after gridding the weekly fishing effort on 0.1° grid cells within the Celtic Sea boundary. Peaks indicate periods of elevated apparent fishing activity and demonstrate that fishing-use intensity is temporally uneven across the record.

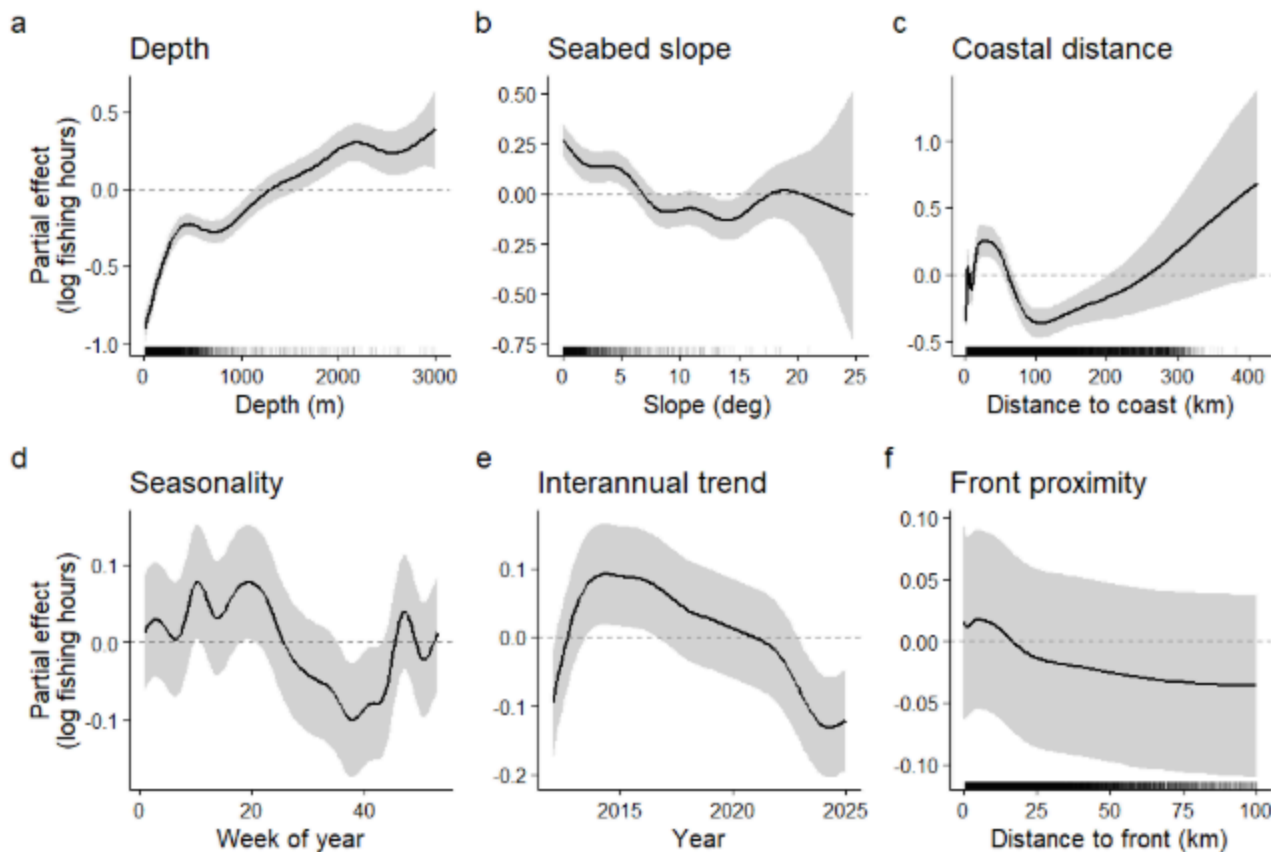


Figure 6

Partial effects from the generalized additive model (GAM) of apparent fishing activity. Smooth terms show the fitted effects of depth, seabed slope, distance to coast, week of year, year and distance to the nearest thermal front. Effects are shown on the log expected-hours scale, with shaded bands indicating approximate 95% confidence intervals. Rug marks show the distribution of observations along each covariate. The distance-to-front smooth represents a weak fitted association with front proximity after adjustment for gear, tide state, bathymetry, seasonality, interannual variation and spatial structure.

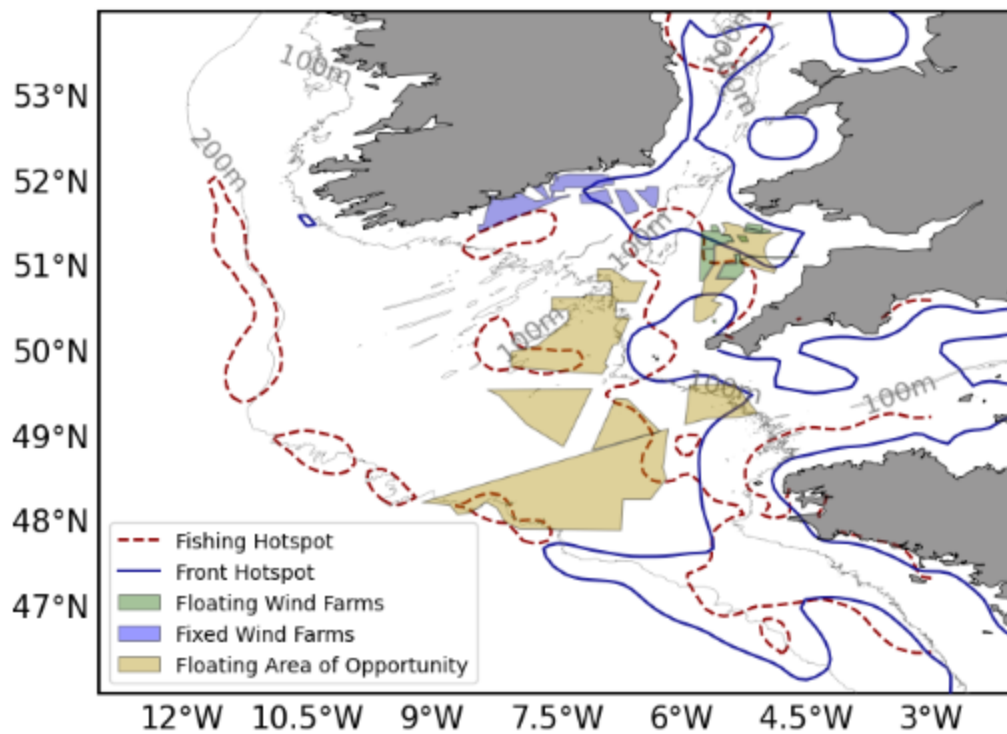


Figure 7

Long-term front and fishing hotspot overlap with planned offshore wind areas. The map shows the spatial distribution of upper 20% thermal front hotspots and upper 20% apparent fishing hotspots across 2012–2025. Purple polygons show planned or consented fixed-bottom offshore wind (FBOW) areas, green polygons show planned floating offshore wind (FLOW) areas, and yellow polygons show the wider floating Area of Opportunity (AOO), where included. Blue solid lines indicate front hotspots, and red dashed lines indicate fishing hotspots. The map provides spatial context for the monthly exposure metrics quantified in Fig. 8 and Fig. 9.

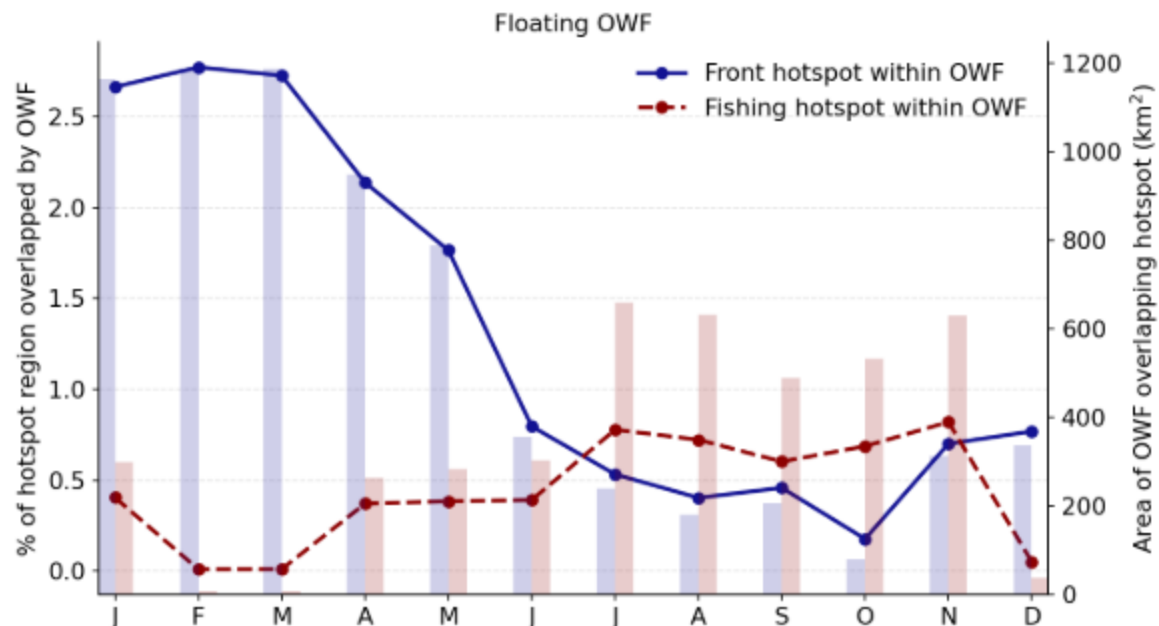


Figure 8

Monthly overlap between planned floating offshore wind (FLOW) footprints and Celtic Sea hotspot areas. Lines show the percentage of hotspot region overlapped by FLOW, using the total monthly hotspot area in the Celtic Sea as the denominator. Shaded bars show the corresponding absolute overlap area in km². Hotspots are the upper 20% of ranked monthly grid cells within the Celtic Sea analysis domain, using summed front strength for frontal habitat and summed apparent fishing hours for fishing.

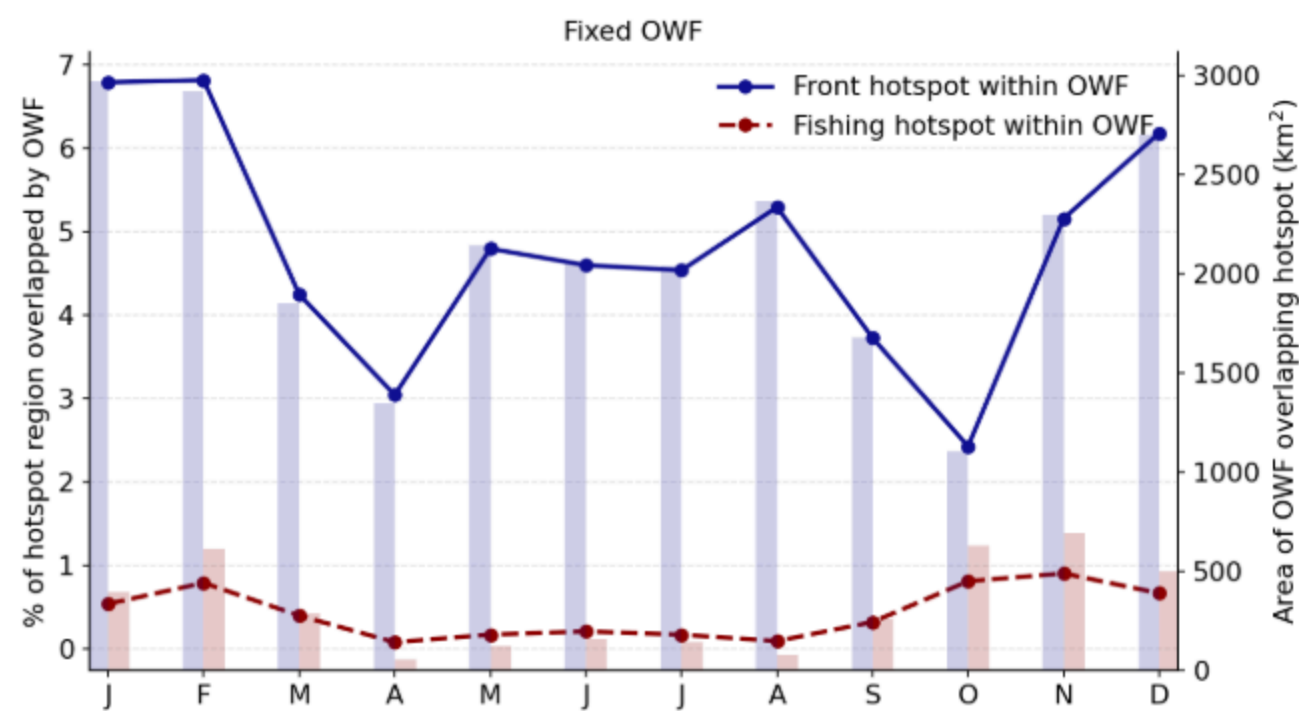


Figure 9

Monthly overlap between planned fixed-bottom offshore wind (FBOW) footprints and Celtic Sea hotspot areas. Lines show the percentage of hotspot region overlapped by FBOW, using the total monthly hotspot area in the Celtic Sea as the denominator. Shaded bars show the corresponding absolute overlap area in km². Footprint-normalized percentages are used only as complementary planning context.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [Supplementary.docx](#)