Frequent locations of oceanic fronts as an indicator of pelagic diversity: application to marine protected areas and renewables

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Abstract

Frequent locations of thermal fronts in UK shelf seas were identified using an archive of 30,000 satellite images acquired between 1999 and 2008, and applied as a proxy for pelagic diversity in the designation of Marine Protected Areas (MPAs). Networks of MPAs are required for conservation of critical marine habitats within Europe, and there are similar initiatives worldwide. Many pelagic biodiversity hotspots are related to fronts, for example cetaceans and basking sharks around the Isle of Man, Hebrides and Cornwall, and hence remote sensing can address this policy need in regions with insufficient species distribution data. This is the first study of UK Continental Shelf front locations to use a 10-year archive of full-resolution (1.1 km) AVHRR data, revealing new aspects of their spatial and seasonal variability. Frontal locations determined at sea or predicted by ocean models agreed closely with the new frequent front maps, which also identified many additional frontal zones. These front maps were among the most widely used datasets in the recommendation of UK MPAs, and would be applicable to other geographic regions and to other policy drivers such as facilitating the deployment of offshore renewable energy devices with minimal environmental impact.

Keywords: marine protected areas, pelagic biodiversity, fronts, sea-surface temperature, remote sensing, offshore renewable energy.

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Highlights:

- Frequent thermal fronts in UK seas were identified using 10 years of satellite data.
- These were applied as a proxy for abundance and diversity of pelagic marine animals.
- Analysis revealed new aspects of spatial and seasonal variability of ocean fronts.
- Ocean fronts can assist marine spatial planning and to define protected areas.
- Frequent front maps were widely used in the process to recommend UK MPAs.

1 Introduction

This paper presents tools for mapping the seasonal distribution of oceanic and shelf-sea fronts using Earth observation (EO) data, as a proxy for pelagic diversity. A thermal front is the boundary between water masses that differ in temperature, and if it extends to the sea-surface may be observed by a satellite sensor.

The policy context of this research is the need to establish an ecologically coherent network of marine conservation zones (MCZs) by 2012. This was one of the most prominent requirements of the UK Marine and Coastal Access Act 2009, which was itself a national response to the target of Good Environmental Status under the EC Marine Strategy Framework Directive and conservation aims of the EC Habitats and Birds Directives. The UK MCZ project provided Ecological Network Guidance (ENG) to the regional teams on the best practice for designating candidate MCZs to achieve the nature conservation aims of the Act [1]. The UK department of the environment (Defra) funded a large project to gather the data layers needed to decide the designation of the Marine Protected Areas.

The MCZ project is focussed on protecting seabed habitats that are associated with high levels of marine biodiversity or are essential for limited mobility species of conservation importance. The nursery and feeding grounds of highly mobile species such as cetaceans, seabirds and pelagic fish are not considered as they are already protected through other directives or fisheries management. However, the ENG does recommend that the additional ecological importance of regions to mobile species be used to prioritise candidate MCZs that pass the other criteria. Factors can include areas of high pelagic productivity and biodiversity, and areas used for key life cycle stages and behaviours. Many such 'hotspots' are understood to be related to oceanographic features such as fronts, which can concentrate nutrients and plankton and hence attract higher trophic levels to forage [2]. The long-term remote sensing of frontal locations provides a proxy for pelagic biodiversity, and hence may be applied to regions with insufficient species distribution data. This may be particular pertinent to the ongoing efforts to define ecologically or biologically significant marine areas (EBSAs) for high seas (as required by the Convention on Biological Diversity), as some candidates will be unexploited areas that have not been well studied.

A further policy need is in marine planning, where challenging targets for renewable energy result in increasing demand for sites for offshore wind, wave and tidal energy generators. The planning process must ensure that marine animals are not adversely affected, so an environmental impact assessment (EIAs) is made, involving surveys of the usage of that site by key species. This paper proposes that oceanic front distributions would provide a cost-effective initial comparison of candidate sites to estimate their importance to marine life, and expedite the planning process by ensuring that EIAs are only applied to sites most likely to be approved [3]. Such tools may be necessary in order to meet the competing demands of the offshore renewable industry and conservation stakeholders.

Knowledge of the abundance and diversity of pelagic organisms is scarce, though a recent review identified and appraised a series of metrics for mapping aspects of pelagic biodiversity [4]. These included: diversity measures for different system components including phytoplankton, zooplankton and fish; satellite EO surrogate measures (thermal fronts, sea surface temperature (SST) and ocean colour); and indicators such as pelagic megafauna (e.g. basking sharks, cetaceans), seabirds and pelagic fish spawning areas. Only EO oceanic fronts were selected to represent the pelagic diversity data layer in the Defra project, and this paper describes the techniques used to exploit a long time-series of EO data to map frequently occurring thermal fronts within UK waters.

1.1 Fronts in UK waters

Research to understanding the formation and distribution of shelf-sea tidal-mixing was pioneered by Pingree [5]. They used early EO data to verify the locations of UK shelf-sea fronts predicted by the Simpson-Hunter stratification parameter derived from a numerical model. More complex 3D hydrodynamic models have been used to simulate the location of surface and bottom fronts, in comparison with frontal locations estimated from integrating in situ CTD measurements from many cruises [6, 7].

Ocean fronts have been studied using EO data for various studies around the world, e.g. northeast US coast [8]. Indeed, Belkin [9] attempted to locate the major fronts in all the large marine ecosystems around the world. That paper did include several fronts within the North Sea, though the analysis was performed on fairly coarse SST data (9 km resolution), and did not study the seasonal or interannual variability. Techniques have been developed to study the particularly dynamic fronts experienced in shelf seas [10], and this paper presents their application to the UK region.

2 Methodology

2.1 Detection of thermal fronts

The source of data for this frontal analysis was the AVHRR archive acquired by Dundee Satellite Receiving Station, comprising several passes per day over the UK continuously since August 1981

[11]. The maximum spatial resolution is 1.1 km, sufficient for detection of all scales of fronts relevant to pelagic diversity, including mesoscale and shelf-sea fronts. 10 years of data were processed to encompass the interannual variability, from December 1998 to November 2008. In future it would be possible to process the entire archive (currently 30 years) to provide greater confidence in describing interannual variability and long-term trends.

The first stage was to convert the raw (Level 0) infrared AVHRR data into SST maps (Level 2). Plymouth Marine Laboratory (PML) have developed automated processing systems to allow AVHRR infrared data to be calibrated into SST values, navigated, cloud-masked and mapped consistently for the UK region [11]. For the 10 year sequence, over 30,000 AVHRR passes were processed, totalling 2.4 Terabytes of input data. The SST data were mapped onto a UK Continental Shelf (UKCS) region in Mercator projection, with a spatial resolution of approximately 1.2 km/pixel; the UKCS limits were set out under section 1(7) of the Continental Shelf Act 1964 [12].

The second stage was to detect ocean fronts on every individual SST scene and combine them to generate monthly front maps. Algorithms developed by PML enable fronts to be located accurately and objectively. The composite front map technique combines the location, gradient, persistence and proximity of all fronts observed over a given period into a single map [10, 13]: this often achieves a synoptic view from a sequence of partially cloud covered scenes without blurring dynamic fronts, an inherent problem with conventional time-averaging methods (Figure 1). It is important to emphasise that: (a) front detection is based on local window statistics specific to frontal structures, not simply on horizontal SST gradients; and (b) fronts are not detected on monthly SST composites, but rather on individual SST 'snapshots' that reveal the detailed thermal structure without averaging artefacts.

Fig. 1

2.2 Improved detection of near-coastal fronts

The standard composite front map algorithm [10] was designed for open ocean and shelf-seas fronts, and would not detect fronts within approximately 5 km of the coast; hence improvements were required for near-coast front detection.

The front detection algorithm employed a fast median smoothing filter to pre-process the SST map both to reduce noise and to generate more realistic frontal contour curves. This standard median filter included zero values (indicating cloud or land) in calculations, and so the smoothed SST map tailed off in the pixels neighbouring land or cloud, resulting in weaker front detection for those pixels. The median filter was improved to omit missing values, which resulted in an increase in the detection of near-coastal fronts (Figure 2). The change also resulted in greater likelihood of front detection in particularly cloudy regions in which the majority of valid pixels over the month are close to cloud. The new smoothing filter was adopted, even though the improvement was not universal, and in some areas the detection appeared to be degraded, probably due to the reduction in the effective size of smoothing filter close to coast and cloud.

Fig. 2

However, there remains a coastal limit of detection due to the cloud-masking of SST data. There is a genuine increased likelihood of cloud cover at the coastal zone; but also the automated cloud masking algorithms are careful to avoid sub-pixel cloud contamination by extending the masked region by at least one pixel width around the detected cloud. The cloud-masking usually treats cloud and land similarly as 'non-sea' pixels, and so the pixels neighbouring the coast will rarely remain unmasked.

2.3 Front metrics

Unlike most terrestrial and benthic systems, the pelagic ecosystem is not restricted by biotope boundaries (reef edge, change in substrate) and is therefore mobile. The pelagic system is constantly changing and this variability is manifest at a variety of spatio-temporal scales: from species fluctuations driven by short-term changes (including weather); to seasonal cycles, inter-annual and long-term change (such as climate change). It was important that this data layer captured some of this variability, and so it was decided that front maps would be presented seasonally, with indications of both spatial and temporal variability.

Therefore the next stage of analysis was to aggregate the monthly front maps into seasonal front climatologies to identify strong, persistent and frequently occurring features. Such frontal systems could be key factors influencing the distribution of productivity and diversity. An algorithm was developed to perform this aggregation, and estimates the percentage of time a strong front is observed within each grid location.

Each grid cell and month between December 1998 and November 2008 was analysed according to the total number of satellite passes, the number of cloud-free observations (valid if at least 1), and whether a strong front was indicated. The threshold used to indicate a ‘strong’ front was $F_{comp} \geq 0.015$. These quantities were then used to generate seasonal maps of frequent fronts, interannual standard deviation and data quantity, both at the full resolution of 1.2 km/pixel and at reduced resolution of 4.8 km/pixel. Although that reduces fine scale structure, it makes many features more prominent as small offsets of the same feature over the time-series will be accumulated.

The aggregation method is explained in Figure 3, and example metrics for summer are shown in Figure 4. The following calendar seasons were used: winter: December to February; spring: March to May; summer: June to August; and autumn: September to November.

Fig. 3-4

2.3.1 Frequent fronts

Frequent front maps were created by averaging the ratio of strong fronts to valid observations for each pixel for a particular season over all years. The result was the percentage of time in which strong fronts occurred in that pixel in that season. As this was averaged over all years for which data are available, the bias caused by cloud cover was reduced; thus a year with only one valid winter observation for a particular pixel had an equal contribution to the final seasonal winter map as a year with valid observations on each month of the season.

2.3.2 Interannual variability

Interannual variability was indicated using the standard deviation of the seasonal percentage of time for a strong front, over all years. As the calculation was performed on percentages of time, each year’s contribution was equally weighted in the final result. In the examples provided in Figure 4, areas with persistent strong fronts (e.g. near-coastal fronts in the summer) are shown in blue (very low standard deviation). Areas where there is a persistent front but with considerable variability in its location give much higher values of standard deviation and are closer to red on the standard deviation map.

2.3.3 Data quantity

The preceding metrics were based on the monthly front maps, and so do not indicate the actual number of satellite observations. A data quantity metric was constructed to convey that information, as the fraction of satellite observations that were cloud-free, averaged over each season and year. This shows seasonal and regional variation in cloud cover, and can be considered a metric of the representivity of the front statistics for each grid cell, and hence a relative measure of data confidence.

3 Results and discussion

Coloured maps of the final ocean front data layers are presented here: frequent fronts (Figure 5), interannual variability (Figure 6), and data quantity (Figure 7). The selected metrics appear to be effective in revealing pertinent information on the spatial and temporal distribution of ocean fronts.

Fig. 5-7

3.1 Interpretation of Irish Sea fronts

The Irish Sea region has been extracted from all of the seasonal front maps at 4.8 km/pixel resolution (Figure 8), as a case study in the interpretation of these front metrics. Starting with the top row, these are the frequent front maps for each season, and represent the percentage of time a strong front was observed at each location. This metric indicates the varying frequency of front occurrence, so the red zones highlight frontal systems that persist for 90-100% of the season. Spatial variability is indicated by a band of decreasing frequency surrounding the peak location of a front.

Fig. 8

For example, the Celtic Sea front in summer in the south of the region shows a prominent meander in the peak shape, with a band of lower frequencies (40-80%) indicating the range of possible extent of this front. This front delineates the boundary between colder tidally-mixed water in the shallow Irish Sea and the warmer seasonally stratified water in the deeper Celtic Sea. Hence the front will tend to extend southwards in response to the greater tidal mixing according to the lunar cycle. The seasonal variability in this front is apparent: it is always absent in winter as both the Celtic and Irish Seas are well mixed; it is present around 50% of the time during spring, depending on when the Celtic Sea stratifies; it is present 40% of autumn in a wide band.

The middle row of Figure 8 shows the corresponding interannual standard deviation, indicating the temporal variability in front locations. This metric can be used to discriminate front hotspots that occur only in certain years from those that occur every year. For instance, the band of low values at the Celtic Sea front in summer shows there is little annual variability (±10%) in the frequency of fronts there. Indeed, the SD metric will tend to be low when the front frequency is very high or very low. High SD values indicate that frequent fronts are either present only in certain years, or are found in different locations in each year.

The data quantity is estimated using the cloud-free percentage of the available EO SST data. The bottom row of Figure 8 indicates that there is least cloud in spring; and in winter there is most cloud in the south but in summer there is most cloud in the north. Note that there is a band along the coast with low data quantity, due to limitations of the cloud-masking and front detection algorithms, and potentially genuine cloudiness close to the coast. It is possible to relate the data quantity to confidence in the other front metrics. For instance less than 3% data quantity (purple in the data quantity maps) would indicate a region with only 1 cloud-free day each month on average, and hence a poor estimator of the front distribution for that season.

These sample metrics indicate many further frontal systems within the Irish Sea (less studied than the Celtic Sea front). The higher resolution maps (1.2 km/pixels, shown in Figure 4a and Figure 9) resolve smaller features and provide greater detail, though show individual front contours rather than a distribution. The lower resolution maps (4.8 km/pixel) aggregate contours to give a better statistical distribution, and a good trade off with detail: they appear to show the boundaries of each feature more clearly.

3.2 Other selected fronts

Over the Dogger Bank in the North Sea there is striking seasonal variability, with highly frequent fronts observed in the summer (when the sea can stratify), and relatively low frequency at all other times. The most persistent fronts (observed in all seasons) in the UK Continental Shelf are located close to the coast in the central and eastern English Channel; these are likely to be influenced by the rivers in south England. Extending southwest of Shetlands (near 60°N 3°W) there is a narrow front observed in spring but rarely at other times.

There is a surface front far out into the Atlantic that follows the western edge of the Rockall Bank (57°N 13°W), and is most often observed in spring. This may be the first identification of this front according to an initial literature survey [e.g. 14, 15, 16]. It is assumed that currents across the Rockall Bank are causing the generation of internal waves, leading to enhanced mixing that sometimes reaches the surface. This is analogous to the well-studied band of cooler water observed along the Celtic shelf-break in summer [17]. There is evidence of increased pelagic abundance and diversity at Rockall, for example in gelatinous zooplankton, fisheries and turtles [18, 19], though this is more likely to be associated with the shelf-break currents than this particular surface front.

3.3 Comparison with previous UK front analyses

This is believed to be the first long term frontal analysis of the UK continental shelf using full resolution EO data. In that regard it would be instructive to compare the resulting locations with previous analyses based on ocean models. Firstly, a comparison with the Pingree and Griffiths [5] modelled locations shows that the main tidal mixing fronts (e.g. Flamborough, Ushant and Celtic Sea fronts) agree very well with the observed summer distribution (Figure 9). The frequent front map indicates considerable spatial variability related to the tidal cycle and mesoscale processes, and this corresponds to predicted transitional mixed/stratified zones, which also encompass further fronts

Fig. 9

detected above the Dogger Bank in the North Sea. Of equal interest is identifying where observed fronts were not predicted by this model. The persistent fronts observed along the south England coast and near the Wash and Thames estuaries were not predicted, as they are likely to result from the buoyancy-generated stability of the water column resulting from the fresher river inputs. Upwelling fronts observed around the southwest UK peninsula are dependent upon wind forcing, so were not represented in the tidal model.

Ocean modelling has advanced considerably in terms of the resolution and complexity of processes that can be simulated. The EO frequent front map agrees closely with frontal locations predicted by a recent 7 km resolution continental shelf model [7], and with the mean summer front locations based on the ICES in situ measurement database [7]. In addition, the trajectories of drifters following the shelf-sea thermohaline circulation [6] are aligned with many of the major fronts detected in the frequent front map, in particular the Ushant and Celtic Sea fronts. Further work is underway to develop tools for quantitative comparison of remotely-sensed and modelled front locations.

A previous satellite study of global fronts at a coarser scale [9, Fig. 8] indicates a majority of the same frontal systems in the North Sea; though certain features (e.g. the ‘Central Front’) are not clearly seen in the frequent front map (Figure 9), perhaps due to the selected strong front threshold. In comparison with all previous front analyses and predictions, the higher resolution of the new frequent front map indicates many additional frontal zones, such as those within the Irish Sea and near the Wash. It is likely that these are similarly important in the understanding the distribution and biodiversity of pelagic marine life.

3.4 Data quality implications for policy usage of frequent front maps

Thermal infrared EO data are limited by cloud cover, though the SST processing and composite front maps techniques optimise the visualisation of fronts by combining all observations derived from sequences of partially cloudy scenes. Cloud cover may lead to biases in data analysis, for instance if features such as upwelling or stratification fronts are correlated with clear skies. Currently the resolution of global monitoring thermal sensors is limited to 1 km; and despite the improvements to near-coastal detection of fronts described, there remains a lack of useable SST data within a few kilometres of the coast. Hence these frontal distributions do not yet assist decision-making regarding marine animal use of estuaries and the coastal zone. Satellites only observe surface fronts, though strong and persistent surface fronts usually indicate a depth profile through the whole surface layer [20]. It should be remembered that subsurface features such as tidal mixing and the deep chlorophyll maximum are known to be of importance to fish and diving animals such as seals [21].

There are also methodological implications of the approach, in its assumption that fronts are correlated with increased abundance and biodiversity of pelagic animals. This is a simplification of complex bio-physical interactions, in which each marine taxon reacts to fronts to a varying degree, for different aspects of their life cycle or survival strategy. Nevertheless, there are a multitude of published studies on the influence of fronts on commercial fish, turtles and seabirds [e.g. 22, 23]. The techniques presented in this paper allow for much wider application of fronts to conservation issues, and additional studies of particular species distributions are now underway with the aim of further increasing confidence in this approach. A further issue is whether past front distribution will be representative of future locations, for example if these influenced decisions on the siting of renewable energy devices. The approach is careful to indicate the spatial and temporal variability within the time-series, and most frequent fronts are due to tidal mixing that is tied to bathymetry. However, other fronts could possibly be shifted according to changing climate, winds or currents.

3.5 Usage of frequent front maps within UK MPA project

These frequent front maps were successfully applied to the UK MPA planning process [24], influencing decision-making in all 4 of the regional MCZ projects. Overall the thermal fronts were an important factor in recommending at least 11[1] of the 46 offshore MCZs [25], indicating that this was among the most widely applied datasets. The planning of MCZs was a stakeholder-led process, aiming to fulfil ecological design criteria whilst minimising negative economic impact. During the stakeholder meetings conservation representatives explained why fronts are important, both in the pelagic – higher productivity and biodiversity, and attracting larger fauna and birds; and benthic – benthic-pelagic coupling often results in differences in the benthos beneath frontal zones. Although the ENG was mainly focussed on benthic habitat types, the front maps were important in guiding stakeholders towards regions that would make greater contributions to the additional ecological considerations of the MCZ network.

In most cases the seasonal frequent front maps were combined into a single map, either as an average or by extracting the most persistent zones as linear features. This minimised 'map overload' during stakeholder meetings, and helped to summarise the aims of the conservation sector so that the industry sector could better understand their point of view. Applying a threshold to the map allowed the key fronts to be overlaid onto other data layers, as the frontal data were mostly referred to visually. One exception was the Areas of Additional Pelagic Ecological Importance (AAPEI) [26], which combined the frontal data quantitatively with other pelagic metrics based on seabird foraging radii, marine mammal and basking shark hotspots, and fish spawning and nursery grounds (Figure 10). The AAPEI map appears similar to the front map, presumably because the hotspots indicated by the other pelagic metrics coincide with frequent fronts, and this provides further justification for the use of this technique as a proxy for pelagic diversity.

Fig. 10

The front maps influenced the final MCZ network in several ways: indicating frontal zones as possible conservation targets; prioritising existing recommendations based on their ecological contribution; and refining the boundaries of conservation zones. For example, the northwest corner of the North St George's Channel MCZ was extended to incorporate an area of high pelagic productivity predicted by the frequent front map.

4 Conclusions

A novel approach to the mapping of pelagic diversity has been implemented for the UK continental shelf, using a long time-series of EO SST data to automatically detect thermal ocean fronts, and then aggregating observations into climatological seasonal metrics. Three selected metrics characterised the spatial, seasonal and interannual variability of fronts observed in 30,000 satellite passes over a 10-year period. Many researchers have determined that fronts are related to the abundance and diversity of pelagic species [reviewed by 4], and hence may be considered a surrogate of pelagic diversity. EO data also have high spatio-temporal coverage and fine spatial resolution, which is lacking for many other diversity, abundance and habitat datasets.

The decision to segregate the analysis into seasons was justified by the resulting maps, which showed considerable and consistent seasonal variation in the occurrence, location and frequency of fronts. This result raises the possibility that management measures should vary seasonally to account for seasonal changes in the water column and likely changes to species distributions. The EO front maps agreed closely with in situ and modelled analyses of frontal locations in this region, and also identified many additional frontal zones.

The resulting front maps were successfully applied to the UK MPA project, and influenced the designation of 11 of the recommended MCZs. These results assign some confidence to the use of long-term remote sensing of frontal locations as a proxy for pelagic biodiversity, and hence may be applicable to other regions with a lack of biodiversity observations, such as the high seas. Several studies are underway on the distribution of different marine megafauna taxa in relation to fronts [e.g. 27], in order to increase the evidence for these relationships. For example, frequent front data are currently being used to model cetacean distributions in the Irish Sea for the Countryside Council for

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[1] Recommended MCZs: South-west: Canyons, Mid and East Celtic Deep, Western Channel; Irish Sea: Mid and North St George's Channel, North of Celtic Deep; North Sea: Holderness, Compass Rose; South-east: Goodwin Sands, East Meridian.

Wales. It is hoped that these tools can provide guidance in many aspects of marine spatial planning and conservation, for instance to expedite the planning process for marine renewable energy installations [3].

Future research in this area should consider ocean colour fronts in addition to thermal fronts. EO ocean colour products such as chlorophyll-a offer a number of benefits for observing fronts [28, 29]: the algae or suspended sediment acts as a tracer for physical processes, and hence may indicate fronts that only have a density gradient rather than a thermal gradient; and visible light is reflected back from several metres into the water column, so may observe fronts that would be obscured in SST by wind mixing or surface heating. Fusion of remotely-sensed and model-simulated fronts could be investigated to provide a more complete analysis of pelagic frontal dynamics.

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List of figures

Figure 1. Schematic diagram of composite front map technique. 30 AVHRR SST maps (three shown) of the Irish shelf within a 7-day window are processed to detect front locations, which are then composited to calculate the mean frontal gradient F_{mean}, the probability of detecting a front P_{front}, and the evidence for a feature in proximity F_{prox}. These weighting factors are combined as the composite front map F_{comp} to provide optimal visualisation of all oceanic features observed during the period. Adapted from [10].

Figure 2. Improvement to near-coastal front detection: (a)-(c): Enlarged sections of monthly front maps using standard median smoothing filter, circles indicate fronts detected only using standard filter; (d)-(f) Corresponding sections using improved median smoothing filter, circles indicate improved near-coastal front detection.

Figure 3. Front aggregation method. Each grid location is analysed through the time-series of monthly front maps to calculate the percentage of months in which a strong front was observed.

Figure 4. Front metrics for summer season, UK Continental Shelf using 1999-2008 data: (a) Frequent front map at 1.2 km resolution; (b) same map at 4.8 km resolution; (c) Interannual standard deviation at 4.8 km resolution (d) Data quantity indicated by cloud-free observations as a percentage of total satellite passes.

Figure 5. Seasonal frequent front maps, indicating the percentage of time a strong front was observed at each location (UKCS region, 4.8 km resolution, 1999-2008 data).

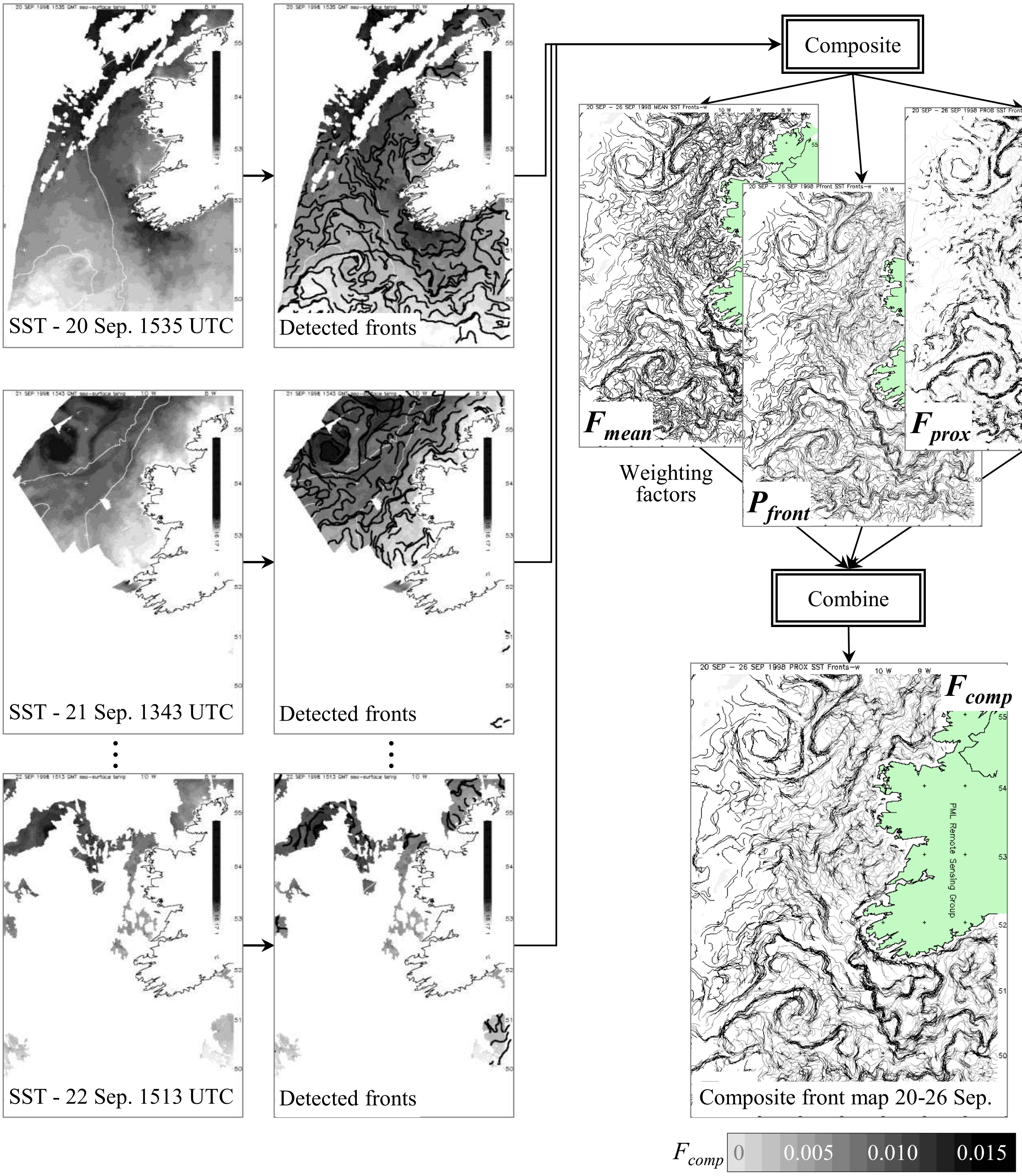
Figure 6. Seasonal interannual variability maps, indicating the temporal variability in frontal occurrence (UKCS region, 4.8 km resolution, 1999-2008 data).

Figure 7. Seasonal data quantity maps, indicating the mean percentage of observations that were cloud-free at each location (UKCS region, 4.8 km resolution, 1999-2008 data).

Figure 8. Ocean front seasonal metrics for sample Irish Sea region: top: frequent fronts; middle: interannual variability; bottom: data quantity (UKCS region, 4.8 km resolution, 1999-2008 data).

Figure 9. Summer frequent front map compared with fronts predicted by a numerical model based on tidal currents and bathymetry (dashed lines where Simpson-Hunter stratification parameter S=1.5, adapted from [5, Fig. 6]). FF=Flamborough front, UF=Ushant front, CF=Celtic Sea front, DB=Dogger Bank, W=Wash, TE=Thames Estuary. (UKCS region, 1.2 km resolution, 1999-2008 data).

Figure 10. Areas of Additional Pelagic Ecological Importance (AAPEI) produced by Natural England. This is a simple combination of data layers on thermal fronts, seabirds, whales, dolphins and fish.



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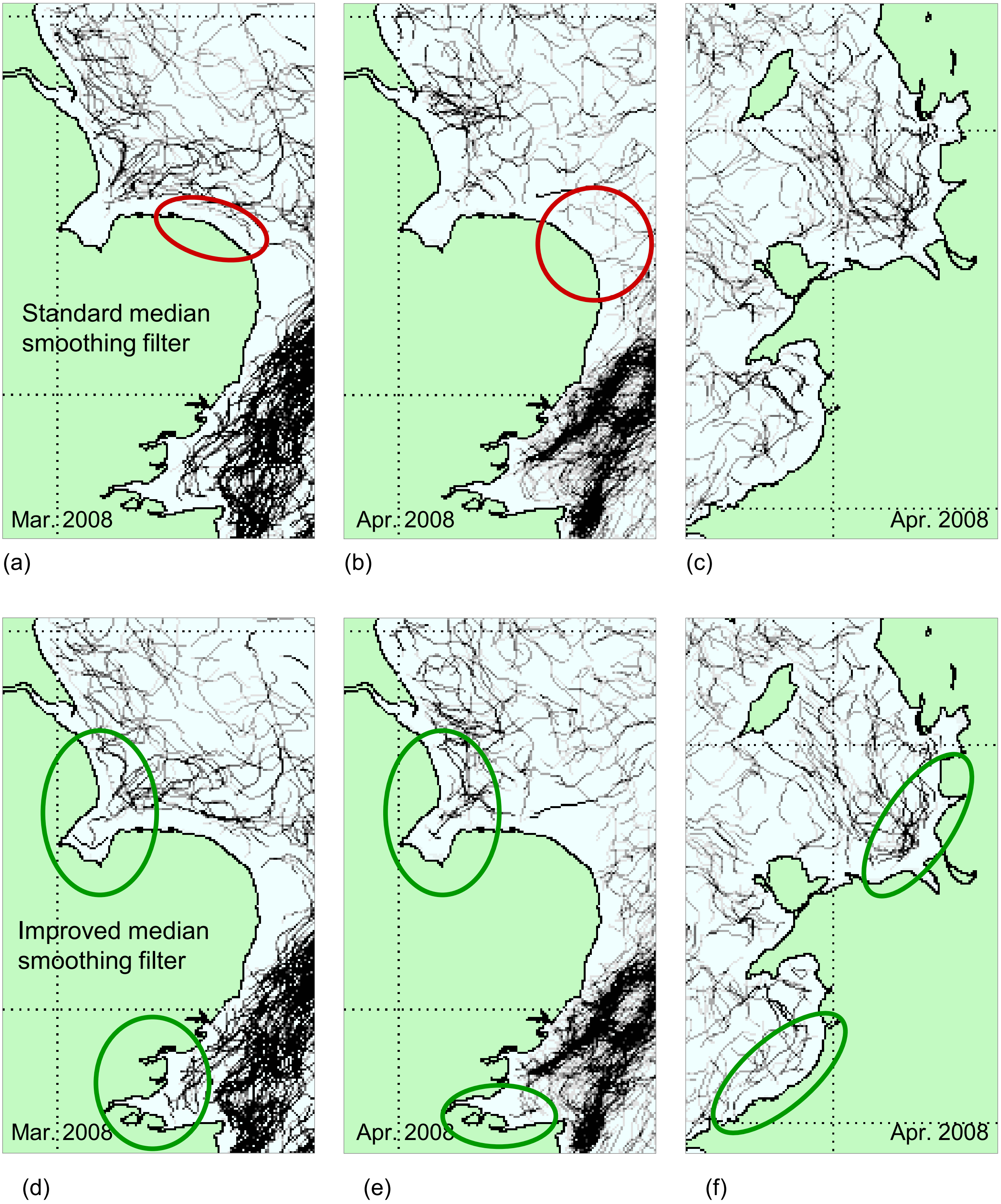

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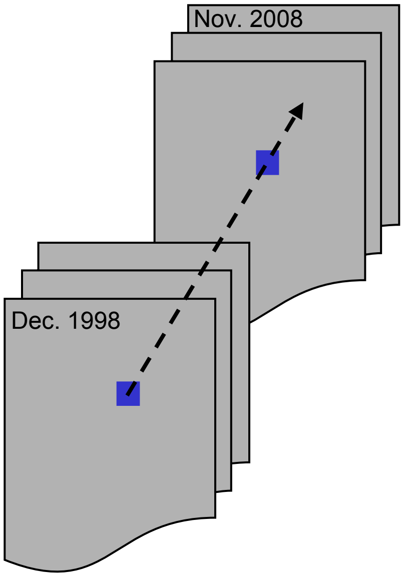
GREYSCALE (use as is)



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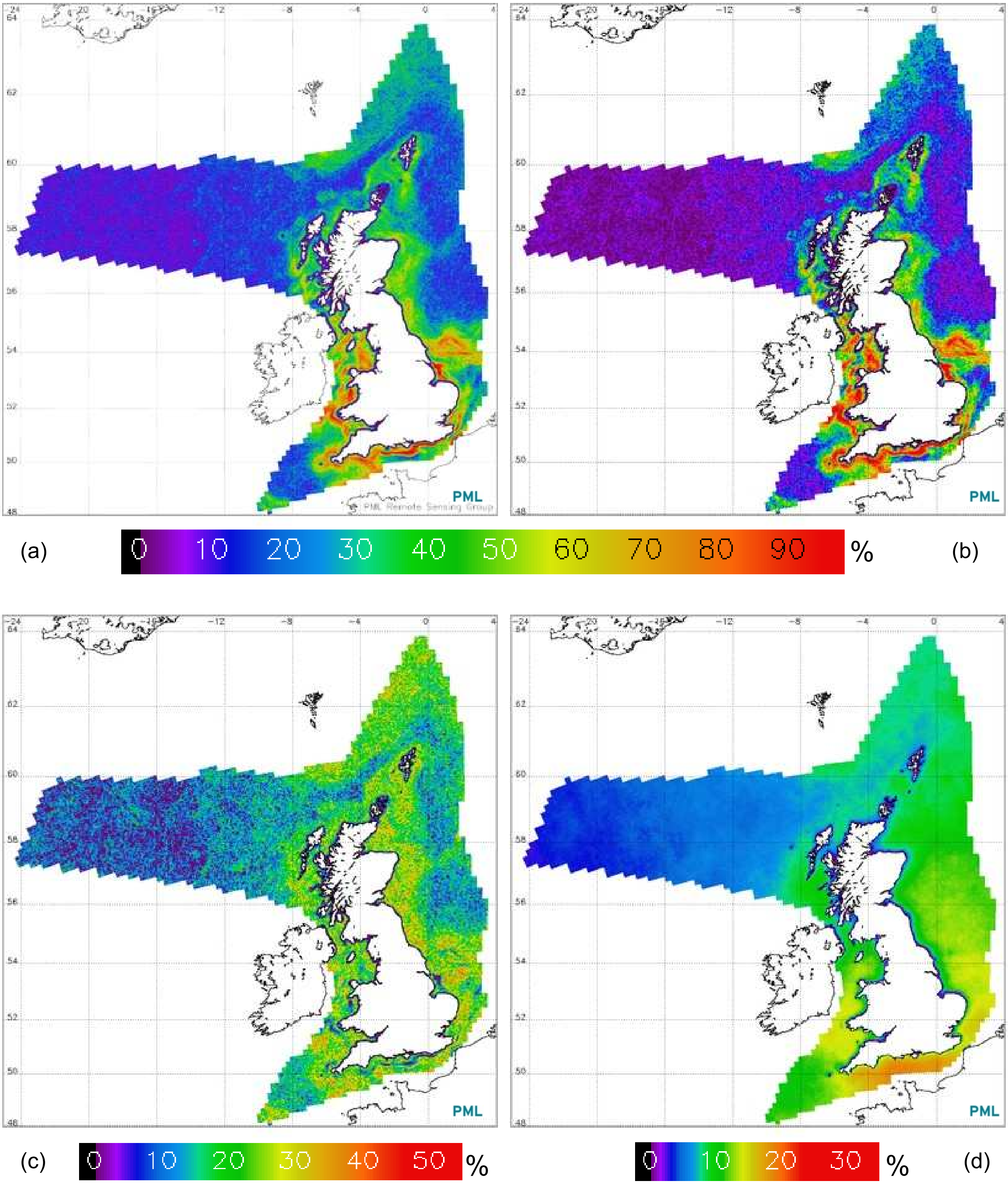

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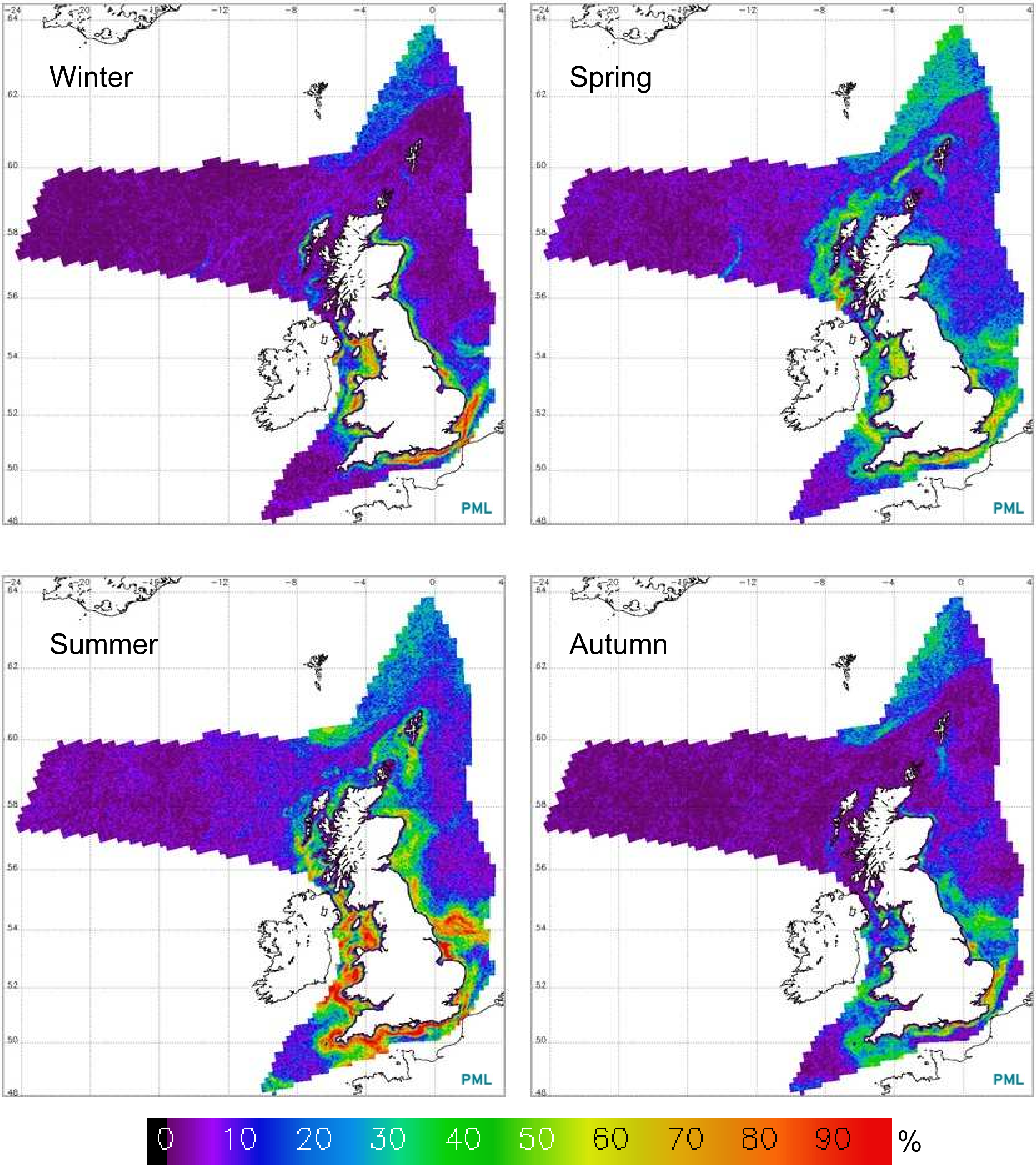
Miller, Fronts as an indicator of pelagic diversity Figure 4

COLOUR



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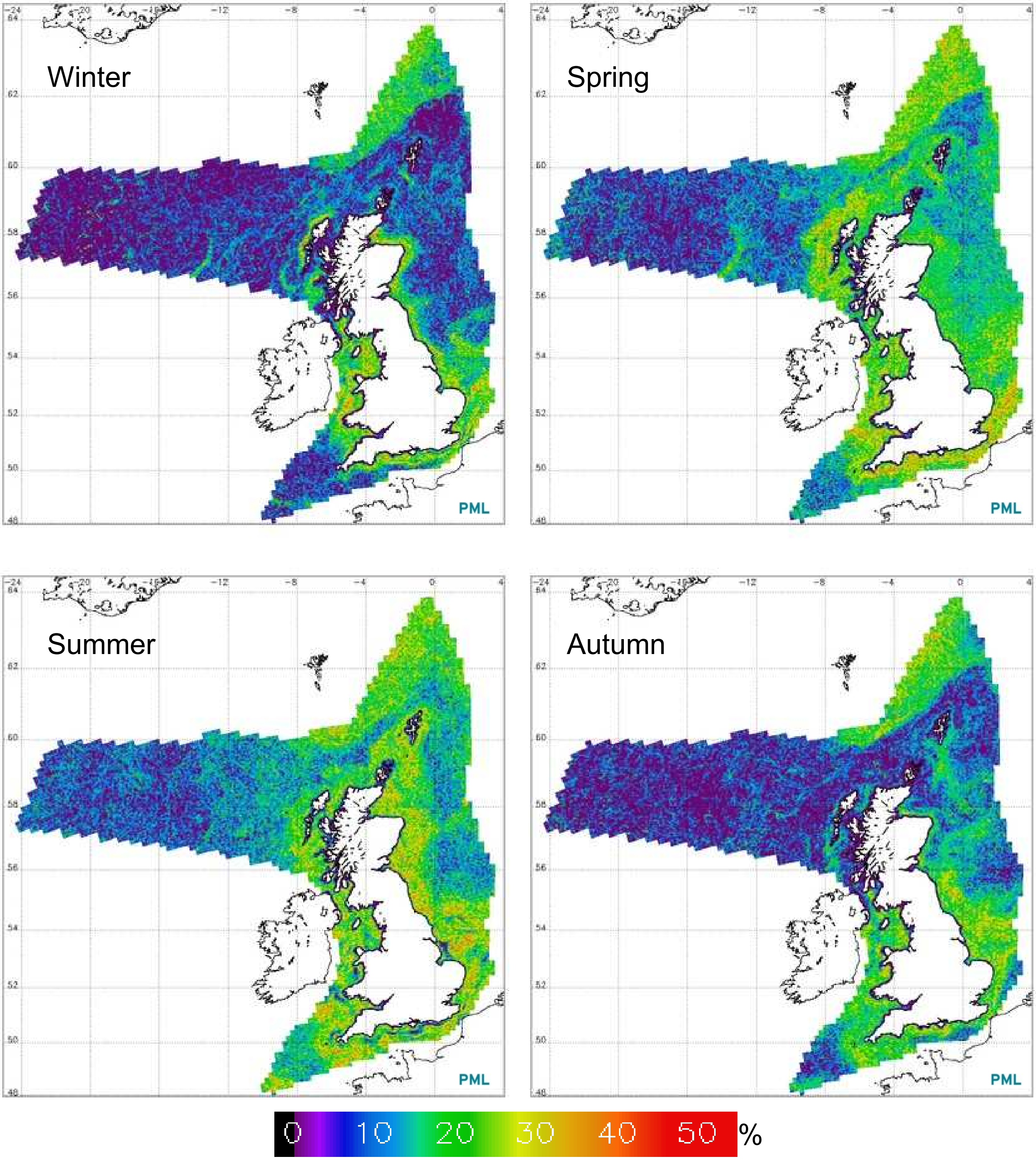

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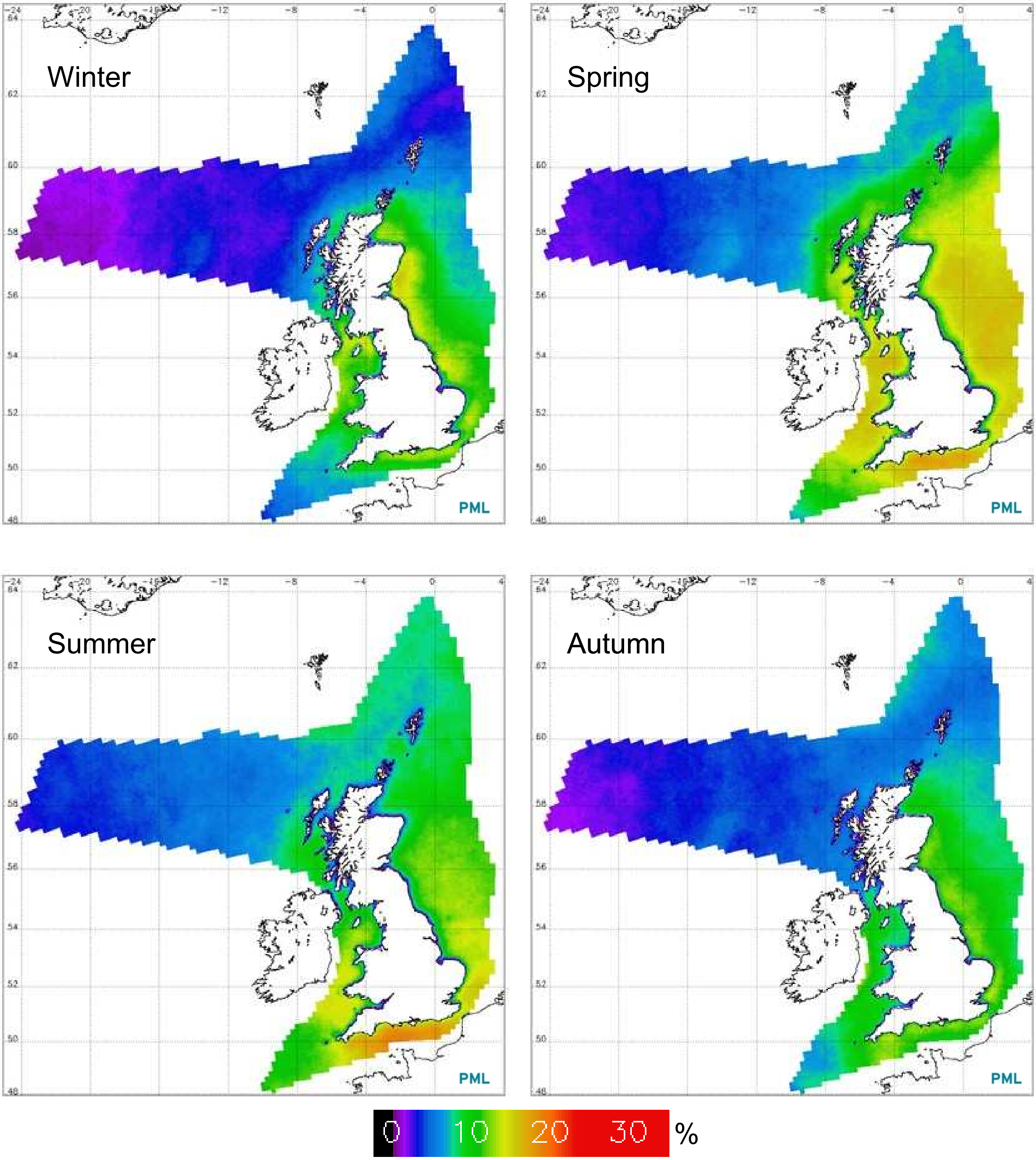

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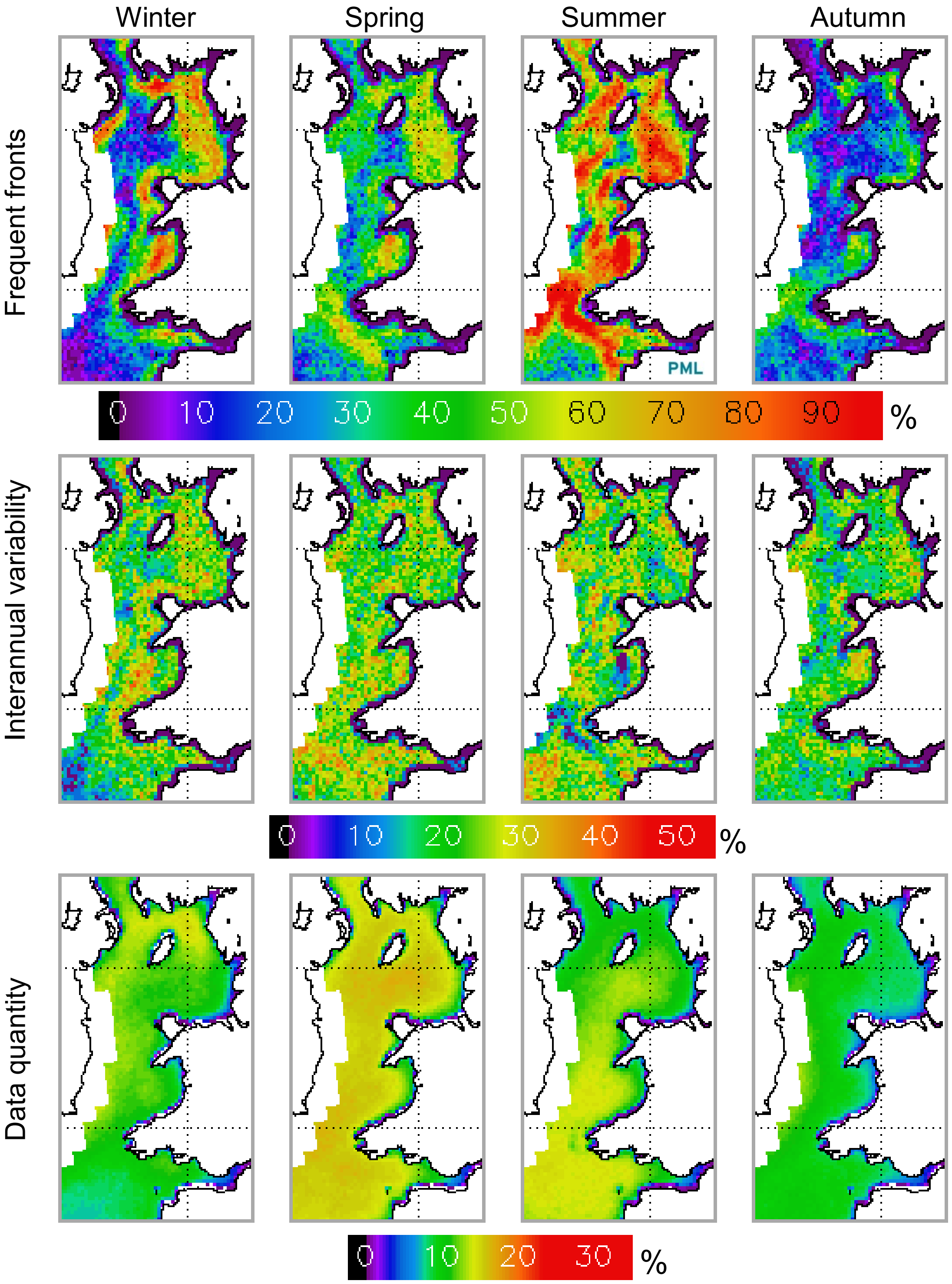

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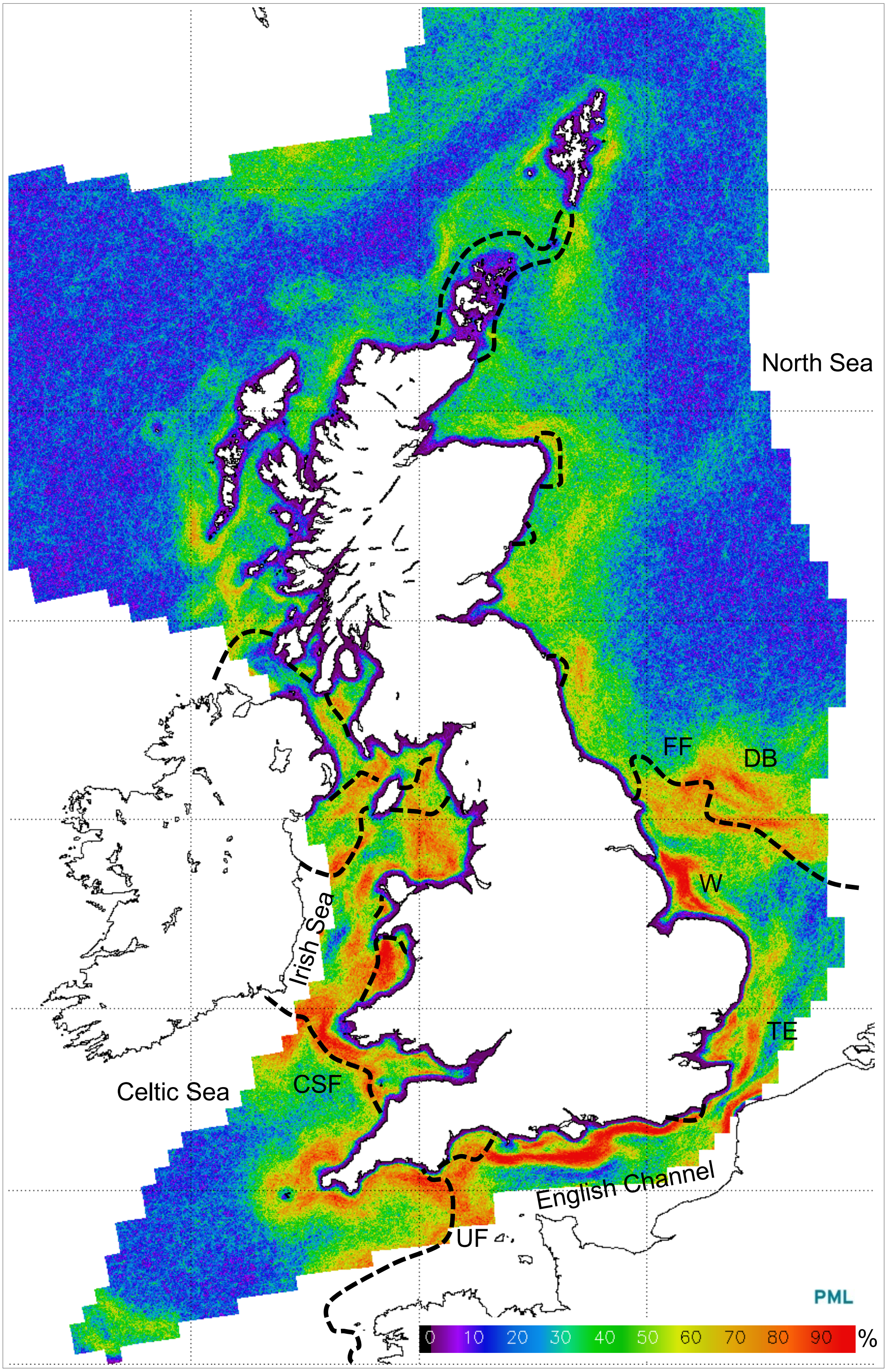
COLOUR



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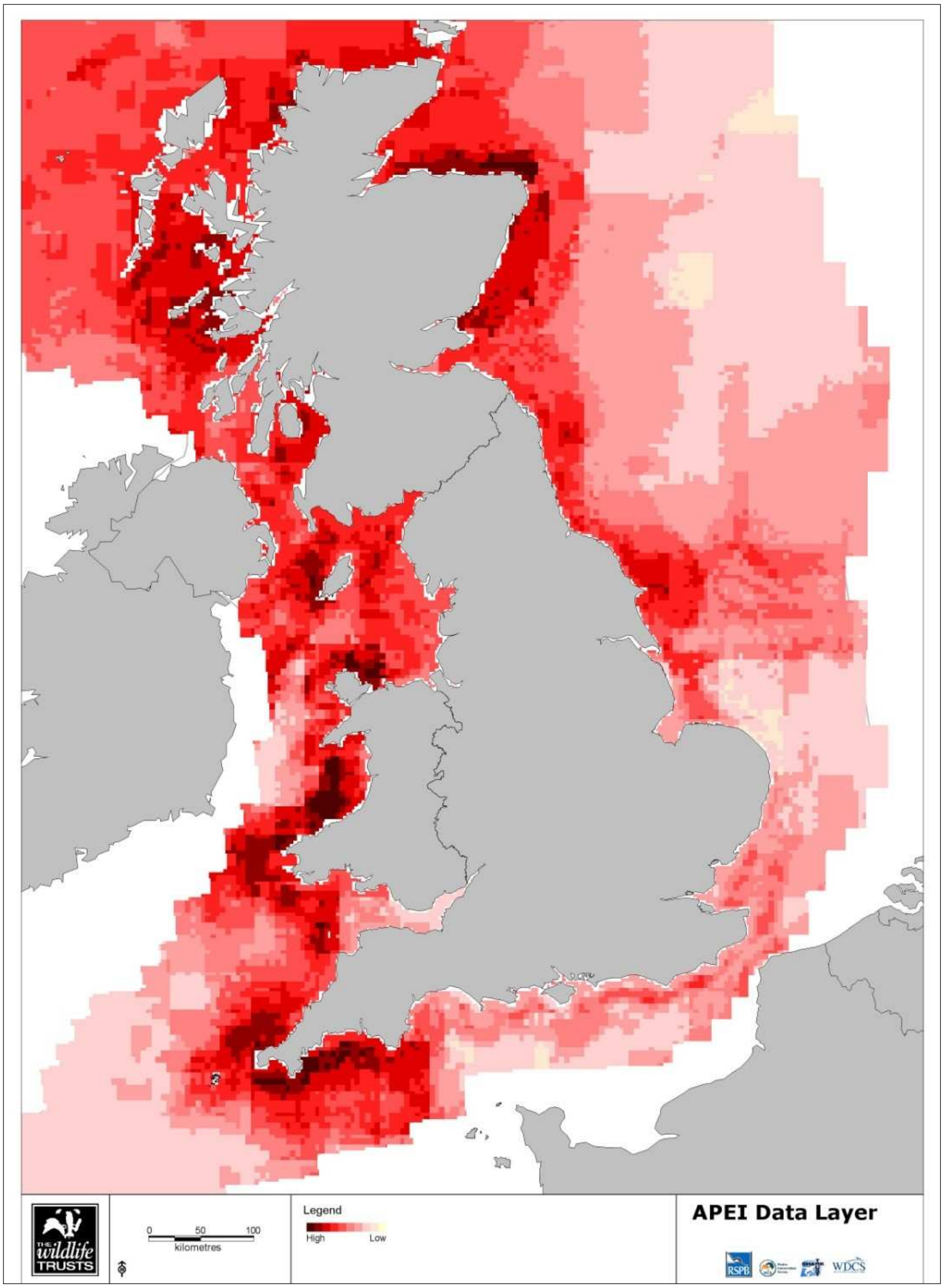
COLOUR



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