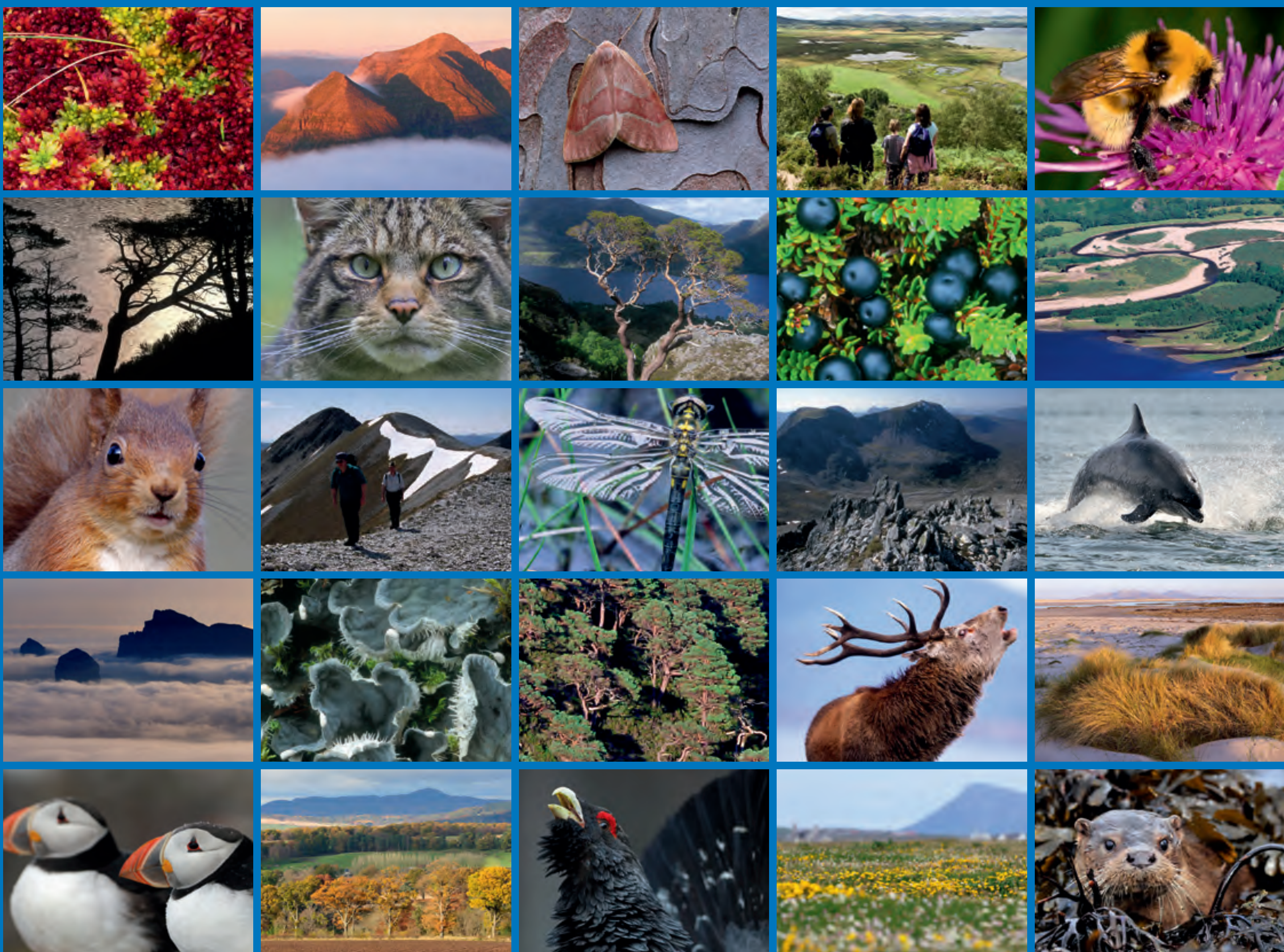
Scottish Natural Heritage
Commissioned Report No. 538

Seasonal shelf-sea front mapping using satellite ocean colour to support development of the Scottish MPA network



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COMMISSIONED REPORT

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Seasonal shelf-sea front mapping using satellite ocean colour to support development of the Scottish MPA network

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COMMISSIONED REPORT

Summary

Seasonal shelf-sea front mapping using satellite ocean colour to support development of the Scottish MPA network

Commissioned Report No.: 538
Project no: 13056
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Keywords

Fronts; satellite data; ocean colour; sea surface temperature; Marine Protected Areas; Scottish waters.

Background

The Marine (Scotland) Act (2010) and the UK Marine and Coastal Access Act (2009) include new powers and duties to designate Nature Conservation Marine Protected Areas (MPAs) to protect biodiversity and geodiversity considered to be of importance in Scotland's seas. The principles for the identification of a MPA network in Scotland's seas are set out in the MPA Selection Guidelines, which establish that MPA search features will be used to guide the design of the network.

Fronts are one of five large-scale features included on the list of MPA search features. Large-scale features were included on the list in order to help build ecosystem function into the development of the MPA network, for example through helping to identify areas of wider functional significance within Scotland's seas. Persistent hydrographic features, such as fronts, are widely recognised as supporting enhanced biological activity. Mixing at the boundary between two water bodies can lead to elevated primary and secondary production and therefore may result in aggregations of species at higher trophic levels.

This contract seeks to utilise recently available high resolution ocean colour imagery in order to create mapping and interpretive products that can be used to support application of the MPA Selection Guidelines and inform advice on MPAs in Scotland's seas.

Main findings

- Front detection and aggregation techniques have been successfully applied to high-resolution (300 m) satellite ocean colour data for the first time, to describe frequently occurring fronts near to the Scottish coast.
- Seasonal frequent front maps derived from both chlorophyll and sea surface temperature data, revealed key frontal zones, which may assist the identification of Scottish MPAs.
- Many researchers have determined that the abundance and diversity of pelagic species is related to fronts, and hence such areas may be considered of ecological importance.

Earth observation data also have high spatio-temporal coverage and fine spatial resolution, which is lacking for many other diversity, abundance and habitat datasets.

- Four key frontal zones were analysed to describe their spatial and temporal extent and variability, and possible mechanisms of formation.
- The high-resolution colour front maps revealed new insights into the sediment and plankton dynamics close to the Scottish coast.
- An additional dataset of medium-resolution (1 km) ocean colour data was also analysed for fronts, in order to increase the data coverage of the Scottish region. In total over 6,000 satellite ocean colour scenes were processed from 2009 to 2011.

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1. INTRODUCTION

The Marine (Scotland) Act (2010) and the UK Marine and Coastal Access Act (2009) include new powers and duties to designate Nature Conservation Marine Protected Areas (MPAs) to protect biodiversity and geodiversity considered to be of importance in Scotland's seas. The principles for the identification of a MPA network in Scotland's seas are set out in the MPA Selection Guidelines, which establish that MPA search features will be used to guide the design of the network.

Fronts are one of five large-scale features included on the list of MPA search features. Large-scale features were included on the list in order to help build ecosystem function into the development of the MPA network, for example through helping to identify areas of wider functional significance within Scotland's seas. Persistent hydrographic features, such as fronts, are widely recognised as supporting enhanced biological activity. Mixing at the boundary between two water bodies can lead to elevated primary and secondary production and therefore may result in aggregations of species at higher trophic levels.

This contract seeks to utilise recently available high resolution ocean colour imagery to provide a description and interpretation of shelf-sea fronts that can be used to support application of the MPA Selection Guidelines and inform advice on MPAs in Scotland's seas.

Frequent front maps for UK seas have previously been produced under the DEFRA led contract MB0102 (Task 2F) (Miler *et al.,* 2010).The maps produced for MB0102 were based on ocean thermal imagery at 1 - 4 km resolution and indicate on a continuous scale the percentage of time over each season that strong fronts are observed at each location. These maps provide a useful indication of surface thermal fronts in Scotland's seas, however, only fronts with surface thermal signatures were detected. Furthermore the mapping was not of sufficient resolution to capture smaller frontal zones or those in close proximity to the coast. Scotland has a particularly convoluted coastline which means that a significant proportion of frontal zones were beyond reach of these existing thermal front maps.

Higher resolution (300 m) ocean colour data are now available through Medium Resolution Imaging Spectrometer (MERIS). The aim of this project was to apply front detection to the 300 m ocean colour data, allowing observations of fronts much closer to the coast and within estuaries. Ocean colour products such as chlorophyll-*a* offer a number of benefits for observing fronts. 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. In addition visible light is reflected back from several metres into the water column, so it is possible to observe fronts that would be obscured in sea surface temperature data by wind mixing, stratification or surface heating. Mapping fronts based on the chlorophyll signal, rather than temperature alone, may also provide a more direct indication of the enhanced primary production that can be associated with frontal areas.

2. METHODOLOGY

2.1 Geographical area

The study region was selected to cover most of Scottish waters, extending beyond the shelf break, but not the large westerly extension in offshore waters. This is because processing the full resolution data is computationally intensive and more important for coastal and shelf regions. The UK Continental Shelf (UKCS) region was intersected with the bounding box: 54.1 to 64.2°N, 13.8°W to 3.8°E.

2.2 Satellite data

2.2.1 MERIS Full-resolution 300 m ocean colour

The primary dataset for this study was the Medium Resolution Imaging Spectrometer (MERIS) sensor on board the European Space Agency (ESA) Envisat satellite, launched in March 2002. MERIS acquires 15 spectral bands in the 390-1040 nm range of visible to near-infrared reflectance. A global archive of 300 m MERIS full-resolution (FR) data were acquired from the ESA near-real time rolling archive, as Level 2 (ESA N1 format) files containing calibrated reflectances, geophysical parameters and georeferencing data.

Queries were implemented using ESA's Earth Observation Link (EOLi) system to identify all the MERIS data granules that overlapped the study region. The matching data were located in the Plymouth Marine Laboratory (PML) data archive and processed and mapped using PML's Generic Earth Observation Processing System (GEOPS). The data were mapped to Mercator projection, giving image dimensions of 3316x3743 pixels.

The MERIS FR data are able to detect features closer to the coast than reduced resolution (RR) data at 1.2 km, which are commonly used for ocean colour studies because they are more readily available. Nevertheless, there are a couple of limitations associated with use of MERIS FR data. The narrow swath width (1150km) of MERIS compared to other colour sensors means that a region in mid-latitudes will be covered only every 1-2 days, rather than several times per day. Therefore the quantity of data available for processing was less. In addition the MERIS FR data are not recorded globally, but only made available for shelf-sea regions; this limited the northern extent of the data processed for this project.

Initially data from 2010-2011 were processed, but due to the limited coverage and considerable cloud cover in this dataset, the processing was extended to include 2009. There were over 2,600 files of MERIS FR mapped scenes processed over the three years.

The product considered in this study was the ESA standard chlorophyll-a (*Chl-a*) product, called Algal-1, a semi-empirical algorithm based on the ratios of four reflectance bands. This algorithm is designed for open ocean (Case 1) waters, but has been found to be applicable to coastal regions also, and has less noise and artefacts than the Algal-2 neural network algorithm designed for coastal (Case 2) waters. The colour properties of Case 1 waters are determined by the concentration of phytoplankton and its associated chlorophyll, while in Case 2 waters the colour properties are determined by other constituents such as sediment or coloured dissolved organic matter.

Although Algal-1 is designed to estimate the *Chl-a* concentration only, due to the inherent complexity of marine optics it will also indicate some suspended sediment features. This is an advantage for the current study, as the *Chl-a* fronts will delineate both phytoplankton blooms and sediment plumes.

2.2.2 *MODIS 1 km ocean colour*

Due to the limited coverage of the MERIS FR dataset, *Chl-a* fronts were also processed using the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor on the National Aeronautics and Space Administration (NASA) Aqua satellite, launched in May 2002. This sensor covers a wider swath at 1 km resolution, providing 1 or 2 views of the region every day. Over 3,400 Aqua-MODIS mapped scenes were processed for 2009-2011, using the PML GEOPS processing system.

The product considered was the NASA standard *Chl-a* algorithm, called OC3M, which is a semi-empirical algorithm based on the maximum of three reflectance band ratios. Similarly to the MERIS Algal-1, it is calibrated using Case 1 data but has been found to be generally applicable to Case 2 waters as well.

2.3 Detection of ocean colour fronts

2.3.1 *Composite front map*

The next stage of processing was to detect ocean fronts on every individual *Chl-a* scene, and combine these to generate 8-day composite front maps (e.g. Figure 1). The composite front map technique combines the location, gradient, persistence and proximity of all fronts observed over a given period into a single map (Miller, 2009). 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. It is important to emphasise that: (a) front detection is based on local window statistics specific to frontal structures (homogenous regions of distinctly different temperature), and not simply on horizontal gradients; and (b) fronts are not detected on *Chl-a* composites, but rather on individual *Chl-a* scenes that reveal the detailed structure without averaging artefacts.

This front detection approach based on detecting 'edges' has been previously applied successfully to *Chl-a* data (e.g. Miller, 2004), but it is recognised that there are other approaches, for instance to target peaks of enhanced *Chl-a* along a front (Belkin and O'Reilly, 2009).

2.3.2 *Extensions for high-resolution MERIS data*

The composite front map technique includes a 'proximity' term to correctly weight persistent features that may be displaced during the 8 day compositing time period due to advection, tides, or residual geocorrection errors. To highlight such features it is necessary to consider the spatial proximity of front contours in one scene to those in other scenes. The Gaussian smoothing filter used to define the proximity was increased in width by 4 times to 8 pixels (~2.4 km), to account for the unusually high resolution of the FR *Chl-a* data.

2.4 Frequent ocean colour front maps

2.4.1 *Frequent front maps*

As in the previous study of thermal front distribution (Miller *et al.*, 2010), it was important to capture some of the spatio-temporal variability of the shelf-sea, and so front maps have been presented seasonally. Results, validation and the application of thermal frequent front maps to the identification of MPAs are described in Miller and Christodoulou, in press).

Therefore the next stage of analysis was to aggregate the 8-day composite 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, which estimates the percentage of time a strong front is observed within each grid location. Each grid cell and 8-day period 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.

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 seasons were defined using whole months:

- winter: December to February;
- spring: March to May;
- summer: June to August; and
- autumn: September to November

This resulted in 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. The final maps were visualised using a colour palette, contrast stretched to highlight the majority of the range of data values.

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, areas with persistent strong fronts 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.

A data quantity metric was constructed to convey 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.

2.4.2 Application to high-resolution MERIS data

The threshold used to indicate a 'strong' front was $F_{comp} \geq 0.007$, where F_{comp} is a measure of the combined front gradient and persistence (Miller, 2009). These quantities were then used to generate seasonal maps of frequent fronts and data quantity. Statistics were calculated using a 4 x 4 grid of the 300 m pixels, resulting in a final resolution of 1.2 km x 1.2 km. This is necessary as small offsets of the same feature over the time-series will be accumulated; however, the final map still retains the unique information obtained from the 300 m resolution.

2.4.3 *Application to standard resolution MODIS data*

For the standard resolution MODIS *Chl-a* analysis, the threshold used to indicate a 'strong' front was $F_{comp} \geq 0.010$. This threshold is slightly higher than for MERIS FR data, as the increased data quantity improves the differentiation of stronger fronts. Statistics were calculated using the source resolution of 1 km x 1 km.

2.4.4 *Data products*

For each of the seasonal and combined frequent front maps (MERIS 300 m *Chl-a* and MODIS 1 km *Chl-a*), a GeoTIFF raster layer was generated for usage in ArcGIS.

3. RESULTS

3.1 Ocean colour composite front maps

3.1.1 *Selected 8-day high-resolution chlorophyll front maps*

Selected 8-day high-resolution chlorophyll front maps (Figures 1- 3) provide examples of the initial stages of the front processing (section 2.3), and also demonstrate that the detection of ocean colour fronts at 300 m resolution is revealing novel features of physical structures in coastal and shelf seas that are beyond the capability of 1.2 km resolution thermal front maps.

Figure 1 shows selected 8-day MERIS 300 m chlorophyll front maps, focusing on coastal fronts. In particular notice how close to the coast features are delineated along the North Sea coast, Galloway peninsula and the outer coast of the Hebrides.

Figure 2 presents a second selection of 8-day MERIS 300 m chlorophyll front maps, highlighting offshore and shelf-break fronts. The fine resolution reveals turbulent sub-mesoscale eddies and other structures within the phytoplankton blooms.

Figure 3 reveals fine-scale features within the Faroe-Shetland current and around the Shetland coast using a MERIS 300 m chlorophyll front map for an unusually cloud-free period in August 2011.

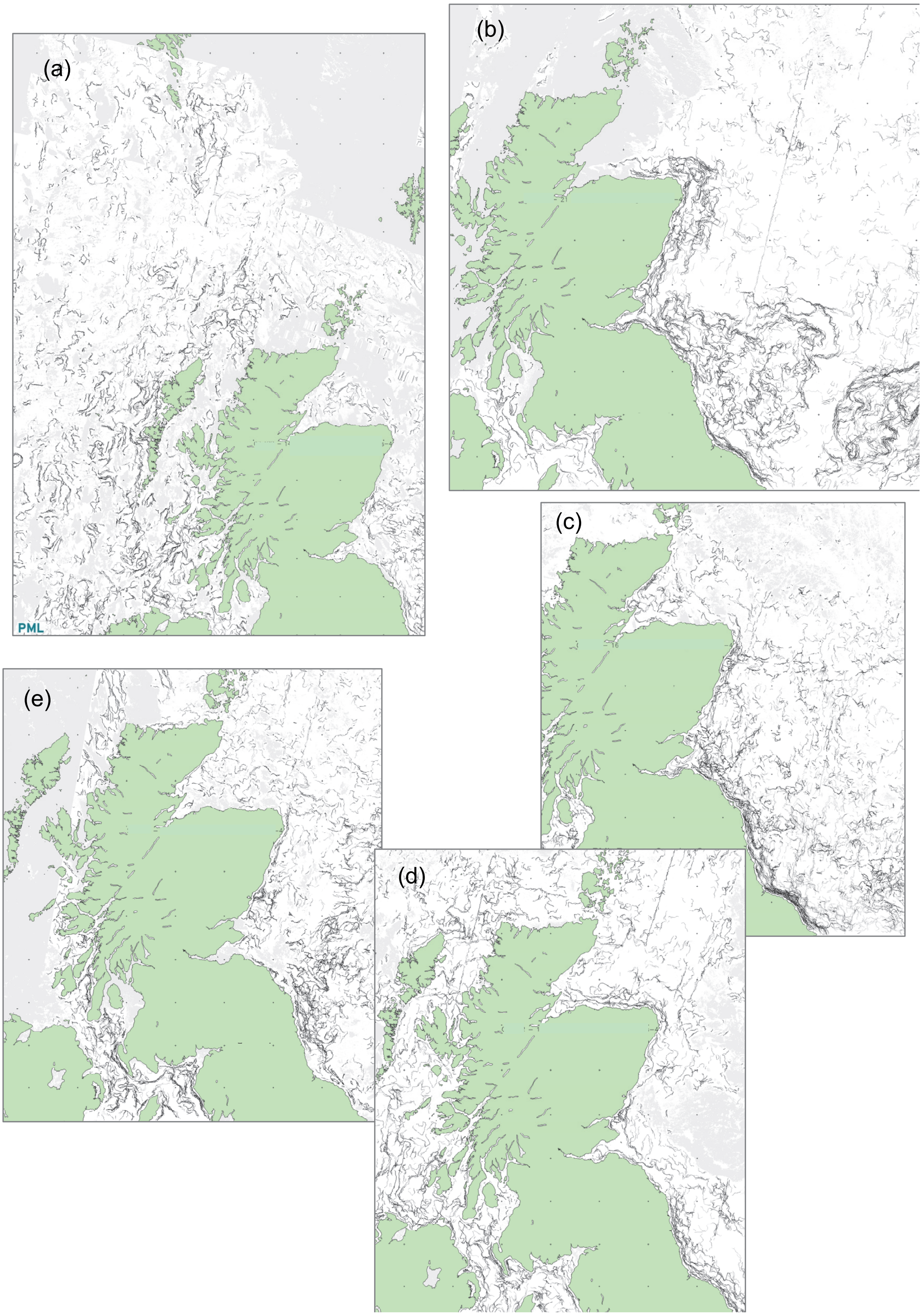

Figure 1. *Selected 8-day MERIS 300 m chlorophyll front maps, indicating coastal fronts. Clockwise from top left, 8 days ending on: (a) 14 Apr. 2011; (b) 21 Mar. 2011; (c) 16 Nov. 2010; (d) 13 Mar. 2011; (e) 29 Sep. 2010.*

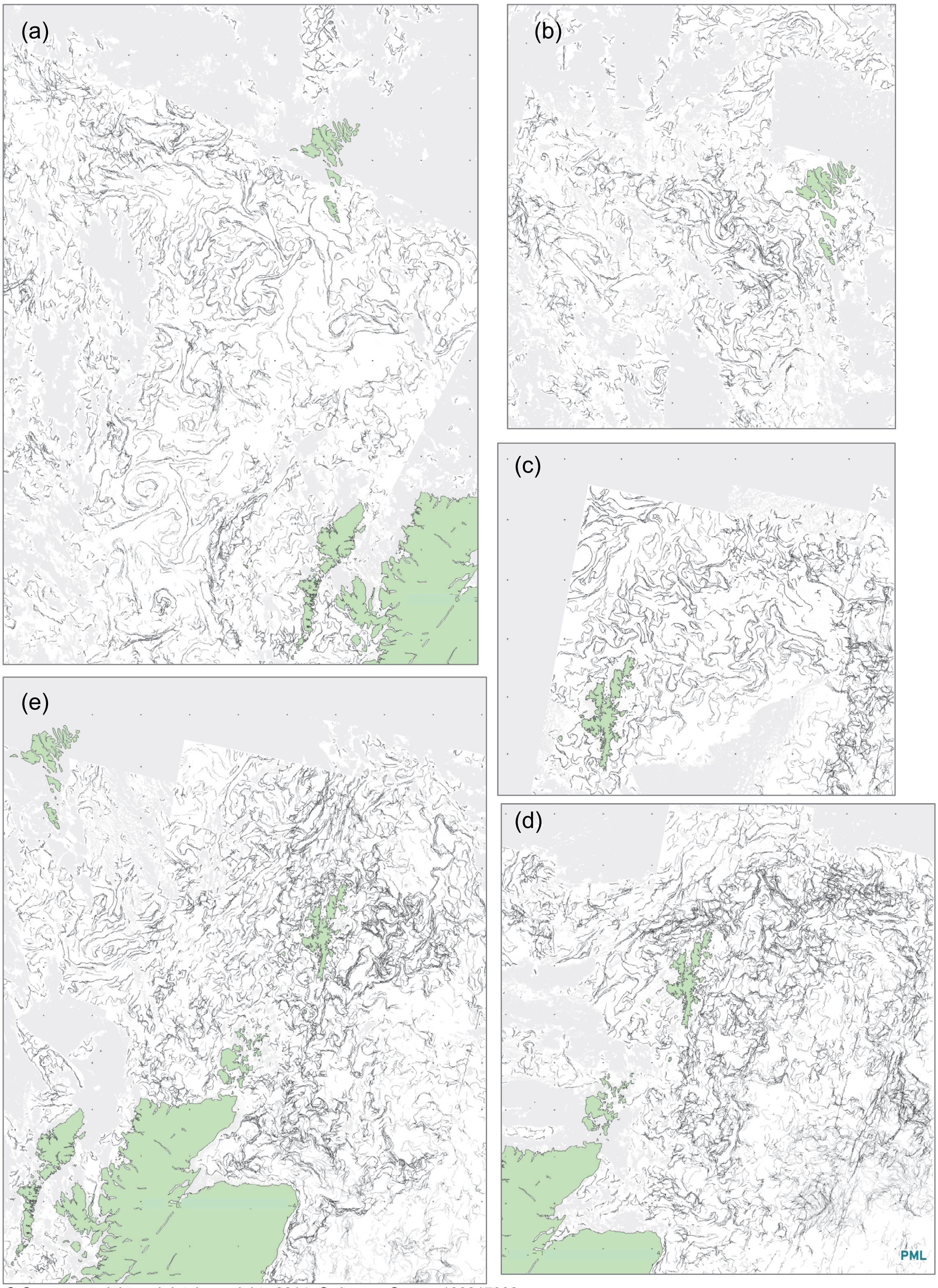

Figure 2. *Selected 8-day MERIS 300 m chlorophyll front maps, depicting offshore and shelf-break fronts. Clockwise from top left, 8 days ending on: (a) 04 Aug. 2011; (b) 27 Jul. 2011; (c) 08 May 2011; (d) 19 Jul. 2010; (e) 03 Jul. 2011.*

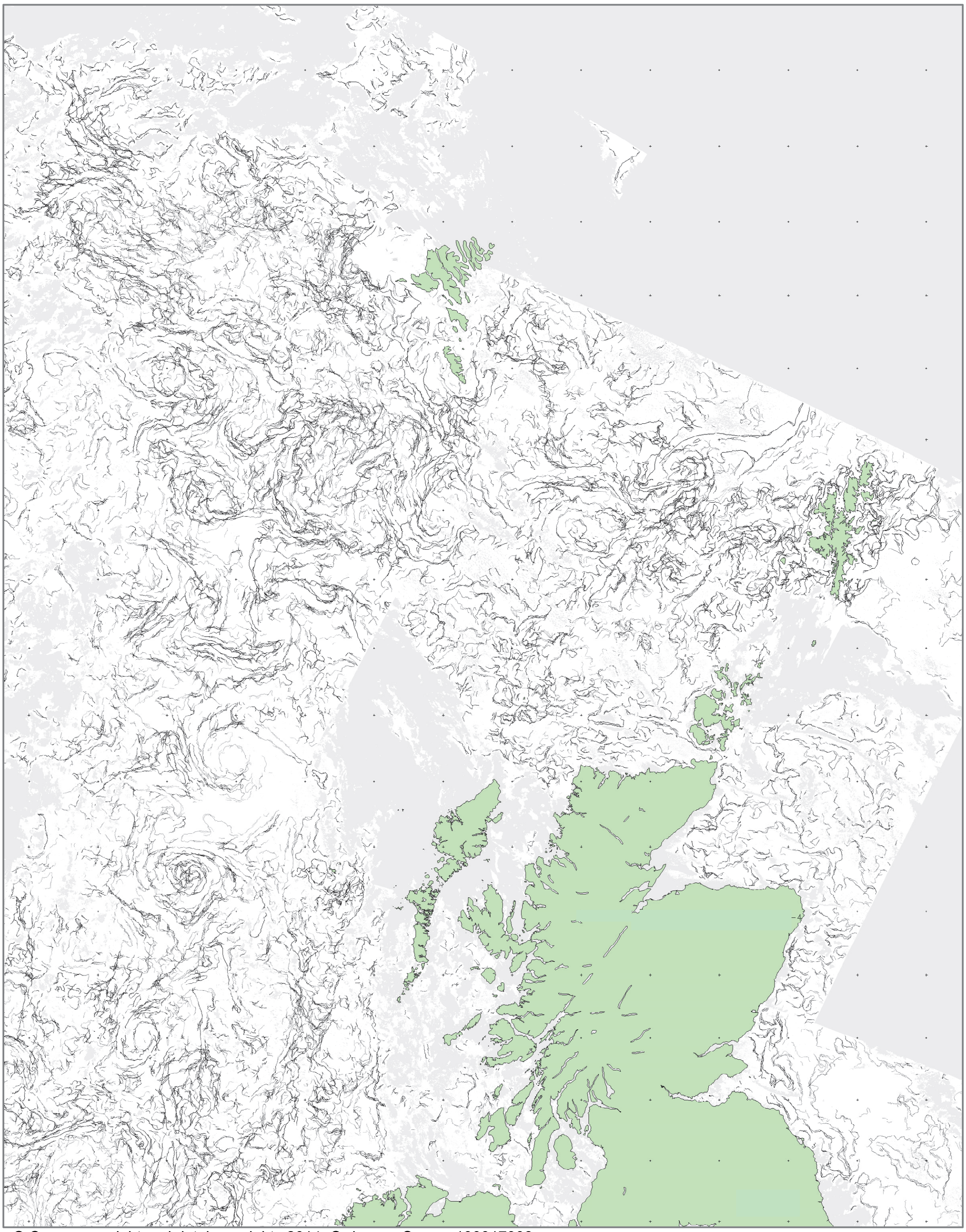

Figure 3. Selected 8-day MERIS 300 m chlorophyll front maps: an unusually cloud-free period 13-20 Aug. 2011

3.2 Ocean colour frequent front maps

3.2.1 MERIS high-resolution chlorophyll front metrics

3.2.1.1 Seasonal high-resolution chlorophyll front frequency

Figure 4 presents the ocean colour front frequency for each season, derived from all MERIS 300 m chlorophyll data 2009-2011. The colour scale indicates the average front occurrence for each location during that season, from 0% (purple) to 40% (red) of the time when not cloud-covered. The clusters and bands of green/yellow/red lines can be interpreted as zones with a higher likelihood of colour fronts at the surface, and thus potentially of greater ecological importance to certain marine animals.

Some seasonality can be inferred, mainly due to the presence of stratified / tidal-mixing fronts (e.g. south and south-west of Shetland) during spring and summer. The higher frequency of near-coastal fronts along the North Sea coast in autumn is also noteworthy, and is explored later in this report (section 4.1.2).

3.2.1.2 Seasonal high-resolution chlorophyll data quantity

The ill-defined patches of higher front frequency and large areas with no data (purple) in Figure 4 also indicate the limitations of the MERIS FR dataset (section 3.2.2), which are depicted more clearly using seasonal data quantity maps (Figure 5). The narrow swath width reduces the repeat coverage rate; and the bias towards shelf-seas acquisition has limited the northern extent of the data. There would also be less northern coverage in autumn and winter due to the low sun angle reducing the validity of chlorophyll estimations. The spring and summer maps show greater data availability for the North Sea than the Atlantic shelf.

3.2.1.3 Combined seasons high-resolution chlorophyll front frequency

In order to consider the significant features of all seasons in a single map, the colour front frequencies for the four seasons were averaged (Figure 6).

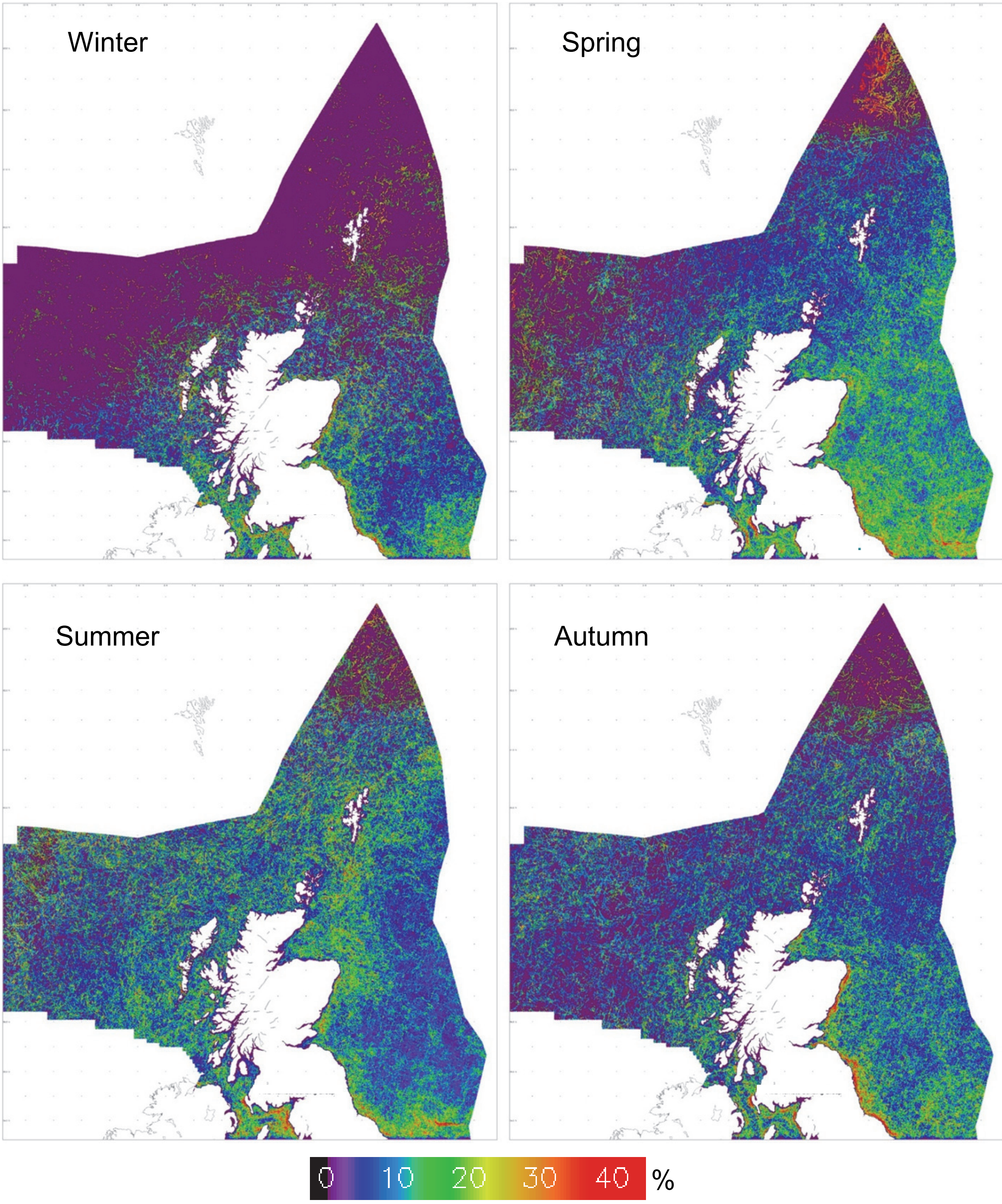

Figure 4. *Comparison of ocean colour front frequency for all seasons, derived from MERIS 300 m chlorophyll data 2009-2011. Colour scale has been stretched to enhance frequencies in the range 0 to 40%. The clusters and bands of green/yellow/red lines can be interpreted as zones with a higher likelihood of colour fronts at the surface.*

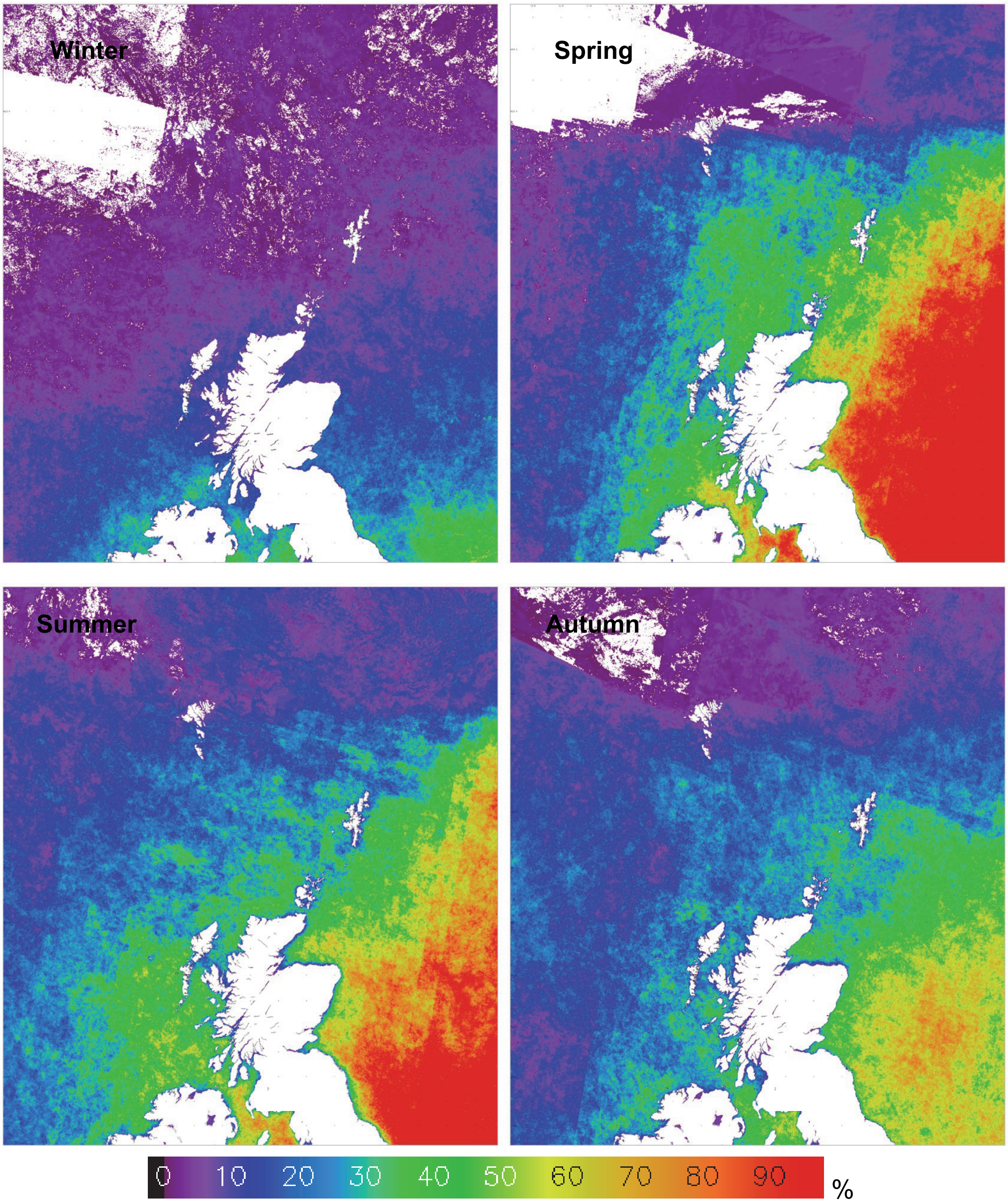

Figure 5. *Seasonal data quantity for MERIS 300 m ocean colour data. There is a lack of data (purple- blue) in the far north and west areas of the study region and relatively more data (red-yellow) available for areas of the North Sea, especially during spring and summer.*

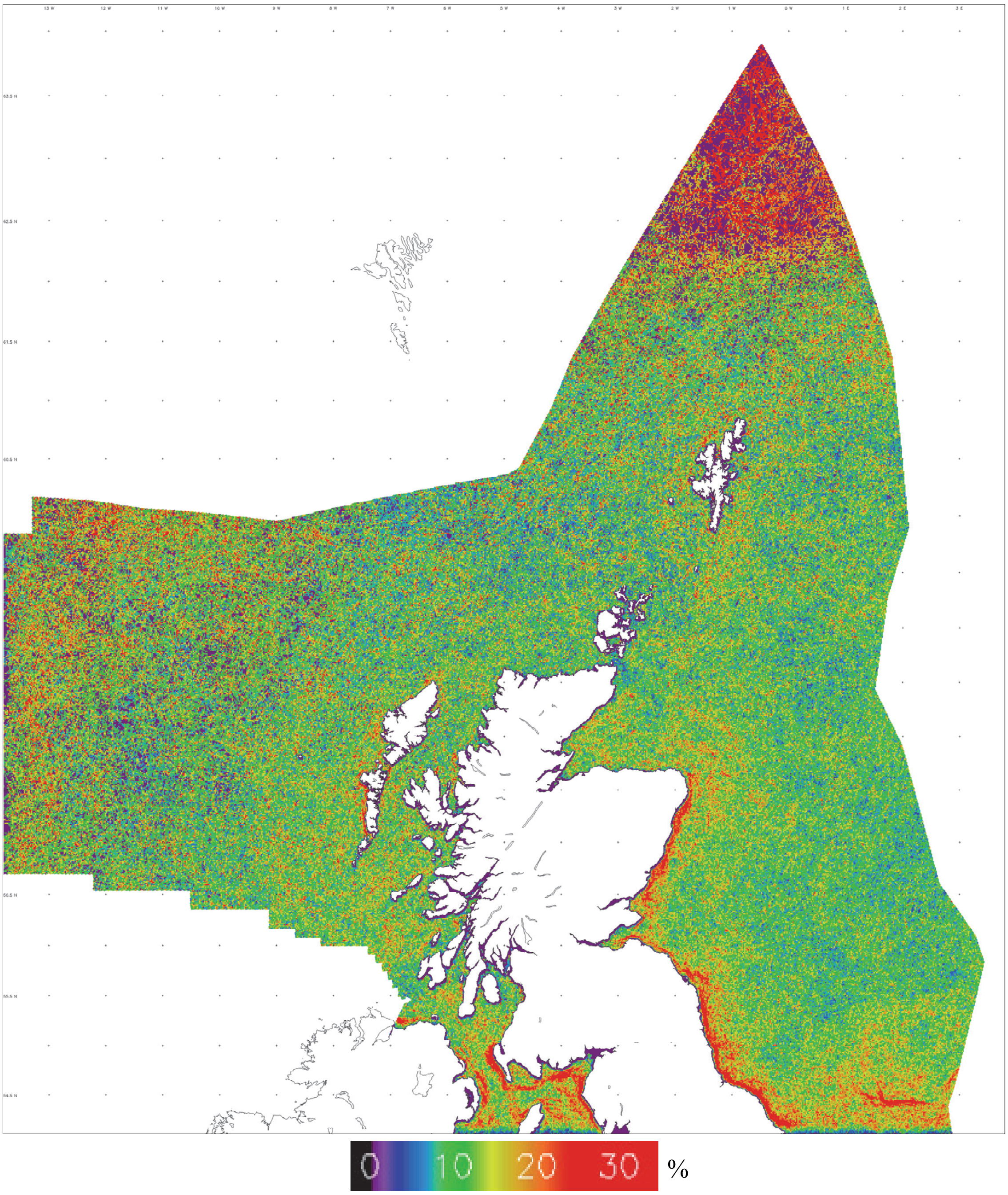

Figure 6. *Mean colour front frequency across four seasons, derived from MERIS 300 m Chl-a data 2009-2011. Colour fronts occur with relatively higher mean frequency in areas including the Aberdeenshire coast, Luce Bay and the Mull of Galloway and to the west of the Uists. Colour scale enhances range 0 to 25%.*

3.2.2 Limitations of MERIS 300 m data

MERIS FR data are only acquired within a certain distance from major coastlines, as these data were originally envisaged only for coastal applications, and acquisition is limited to approximately 40% of each orbit.

It can be seen on Figure 5 that there is a lack of data in the northern part of the study region in all seasons, and also low data quantity in the west, over the deeper water off the shelf. Hence the noisy red lines in these regions shown in Figures 4 and 6 should be considered with low confidence. Front frequency was masked for regions in which there was less than 2% temporal coverage during that season.

3.2.3 Aqua-MODIS 1 km chlorophyll front metrics

3.2.3.1 Seasonal medium-resolution chlorophyll front frequency

In order to extend the coverage of ocean colour fronts to the off-shelf parts of the study region, chlorophyll fronts were derived additionally from medium-resolution (1 km) Aqua-MODIS *Chl-a* data from 2009 to 2011. Figure 7 shows a comparison of ocean colour front frequency for all seasons, which improves the identification of colour front hotspots and analysis of their seasonal variations as a result of greater coverage. In particular it can be seen that colour fronts are pervasive in the east of the region during spring and summer, though there are consistent features with higher frequency that may be associated with tidal mixing fronts, islands, seamounts and banks (e.g. Firth of Forth banks and Dogger Bank), or riverine influence. Note that these maps are lacking the fine scale and near-coast fronts only visible in the MERIS FR analysis, such as the North Sea, Shetland and Hebrides coastal fronts.

3.2.3.2 Combined seasons medium-resolution chlorophyll front frequency

Figure 8 shows the mean colour front frequency across four seasons, derived from MODIS 1 km chlorophyll data, in order to show the significant surface features in a single map.

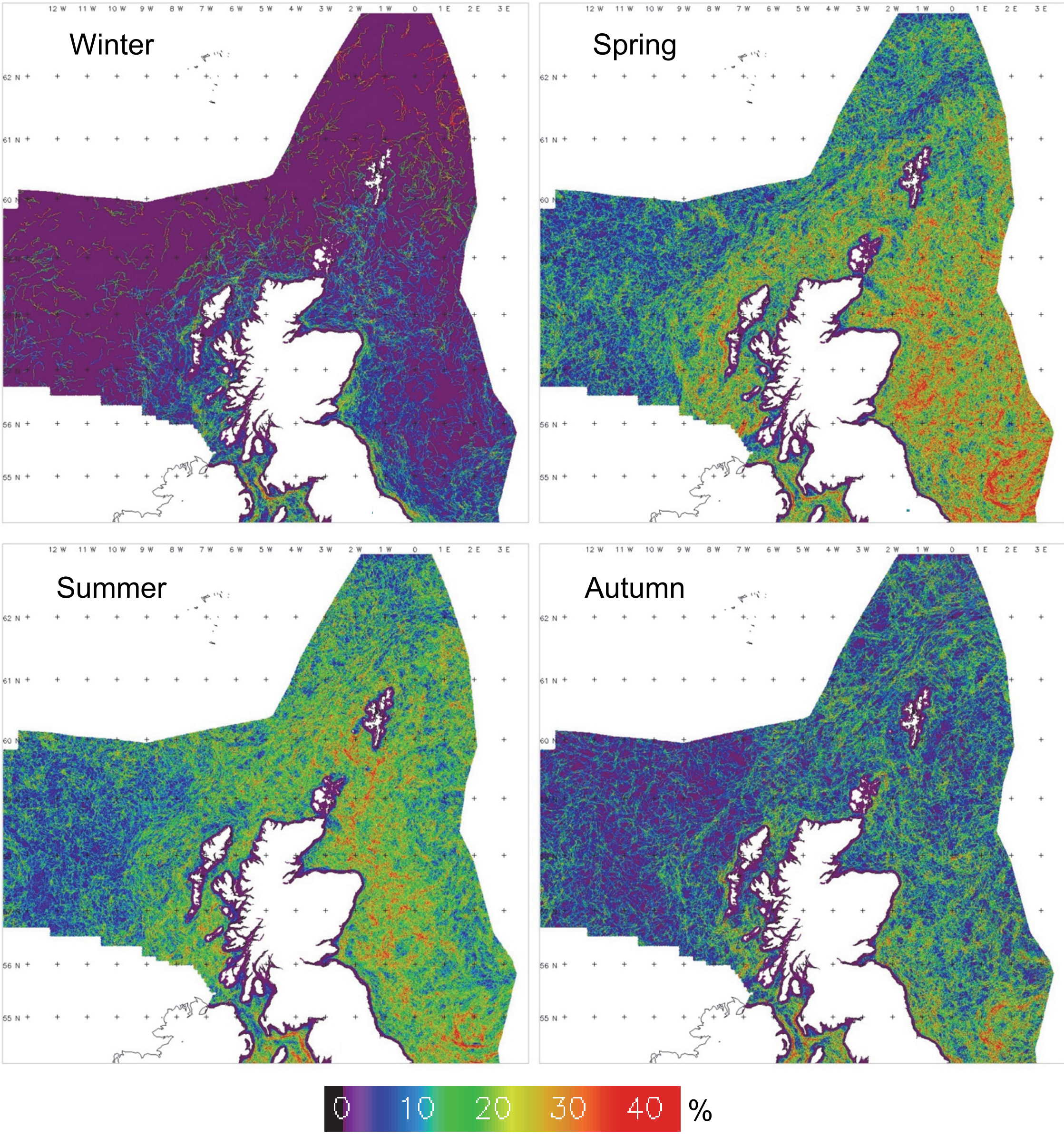

Figure 7. *Comparison of ocean colour front frequency for all seasons, derived from MODIS 1 km chlorophyll data 2009-2011. Frequent colour fronts are present in the North Sea during spring and summer. Near coastal colour fronts are less evident at this resolution. Colour scale enhances range 0 to 40%.*

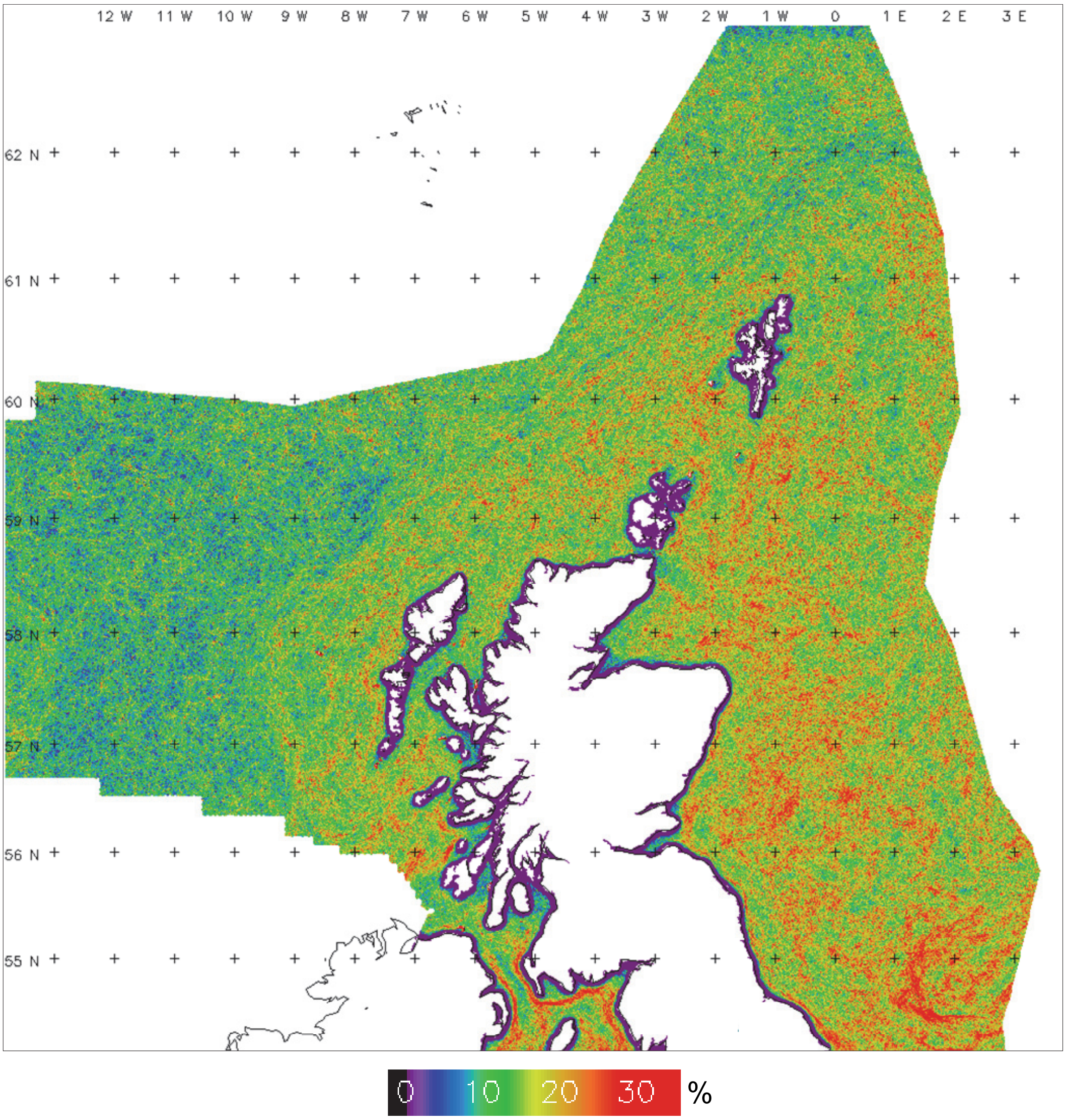

Figure 8. *Mean colour front frequency across four seasons, derived from MODIS 1 km chlorophyll data 2009-2011.Colour scale enhances range from 0 to 30%.*

3.2.4 AVHRR 1.2 km thermal front metrics

3.2.4.1 Seasonal medium resolution thermal front frequency

To facilitate comparison with the thermal front distributions generated for Defra project MB0102 using Advanced Very High Resolution Radiometer (AVHRR) 1.2 km sea surface temperature (SST) data between November 1998 – December 2008 (Miller *et al.*, 2010), the Scottish part of the UK seasonal maps are reproduced in Figure 9. Greater clarity in delineating the frontal hotspots is achieved through thermal front maps due to the more frequent coverage from multiple satellites, and no high latitude limitation in winter.

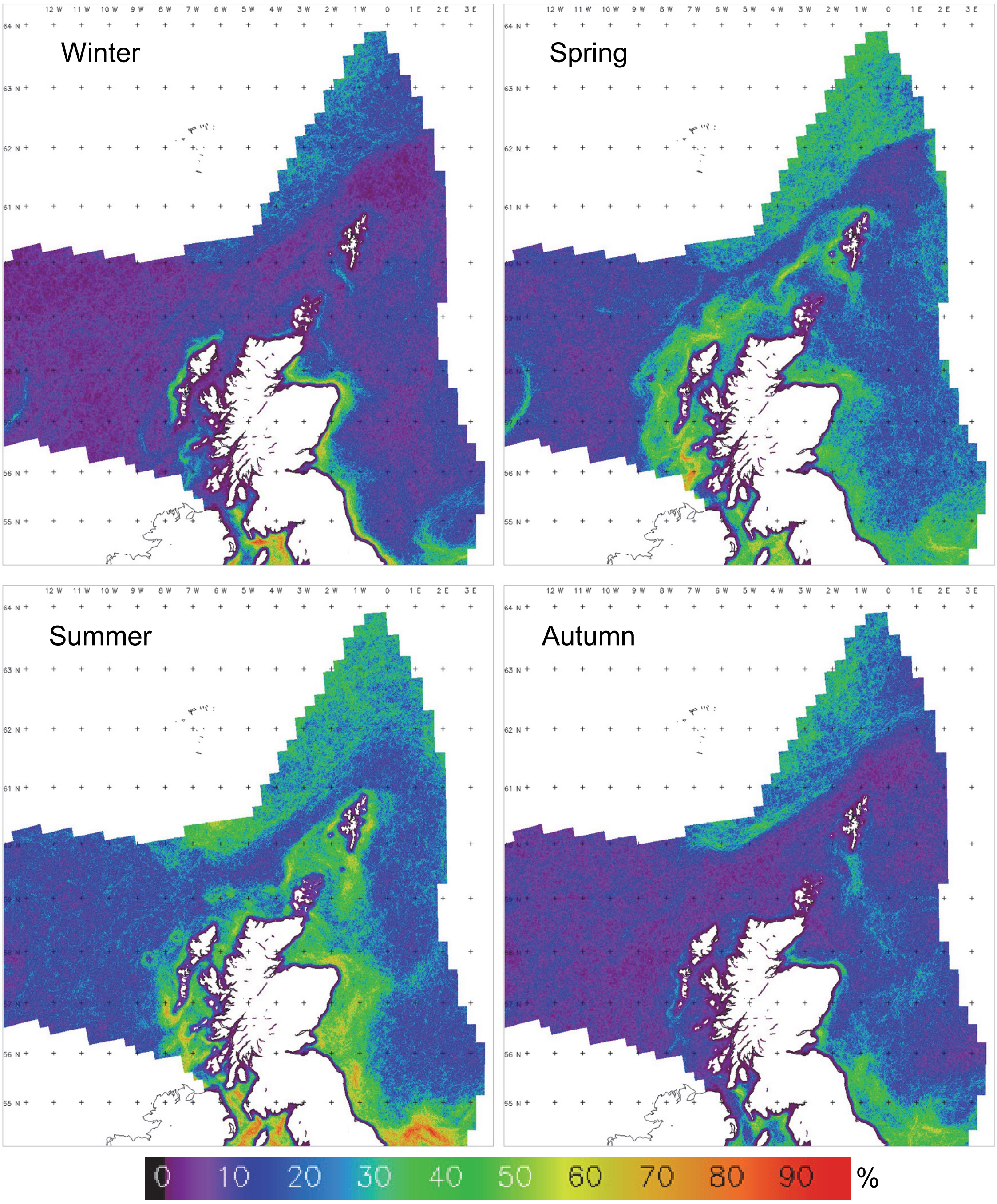

Figure 9. Comparison of ocean thermal front frequency for all seasons, derived from AVHRR 1.2 km SST data Nov 1998 - Dec 2008.

3.2.4.2 Combined seasons medium-resolution front frequency

Figure 10 shows the mean thermal front frequency across four seasons, for direct comparison with the equivalent ocean colour analyses using MERIS 300 m and Aqua-MODIS 1 km data. The following section considers the interpretation and integration of these datasets.

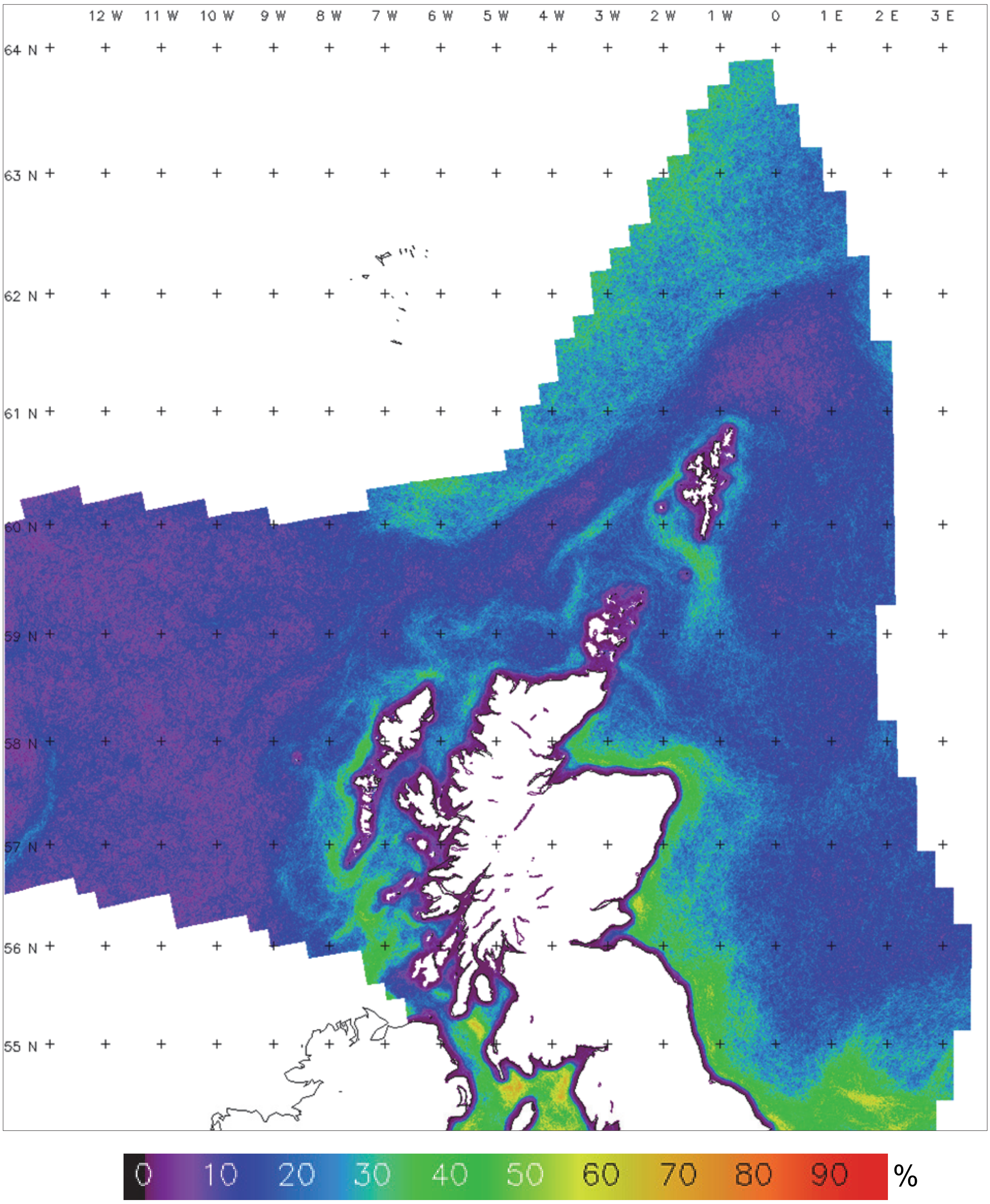

Figure 10. Mean thermal front frequency across four seasons, derived from AVHRR 1.2 km SST data Nov 1998 - Dec 2008.

4. INTERPRETATION OF SHELF-SEA FRONT DISTRIBUTIONS

4.1 Identification of potential frontal hotspots

4.1.1 Visual identification of chlorophyll front hotspots

Figure 11 shows the mean all-season high-resolution chlorophyll front distribution, overlaid with blue ellipses indicating four key frontal zones described in this report; yellow ellipses indicate additional near-coastal frontal zones. These zones were selected through discussion between SNH and the report authors. Selection was based on visual analysis of the seasonal and combined colour front maps generated for this contract, thermal fronts generated for Defra contract MB0102 (Miller *et al.*, 2010), and discussions during a 2012 workshop on fronts for the Scottish MPA project, which included consideration of overlap with existing MPA search locations. This figure does not attempt to define the precise boundaries of these zones; each zone is analysed and described in the following sections:

- Frontal zone 1: Aberdeenshire to Firth of Forth
- Frontal zone 2: Fair Isle
- Frontal zone 3: Galloway peninsula and Clyde sill
- Frontal zone 4: South-west of Tiree
- Additional near-coastal frontal zones: Uist and North-west Shetland.

The following descriptions are based only on satellite data of the sea surface, and do not attempt to explain the detailed physical or biological oceanography of Scottish waters.

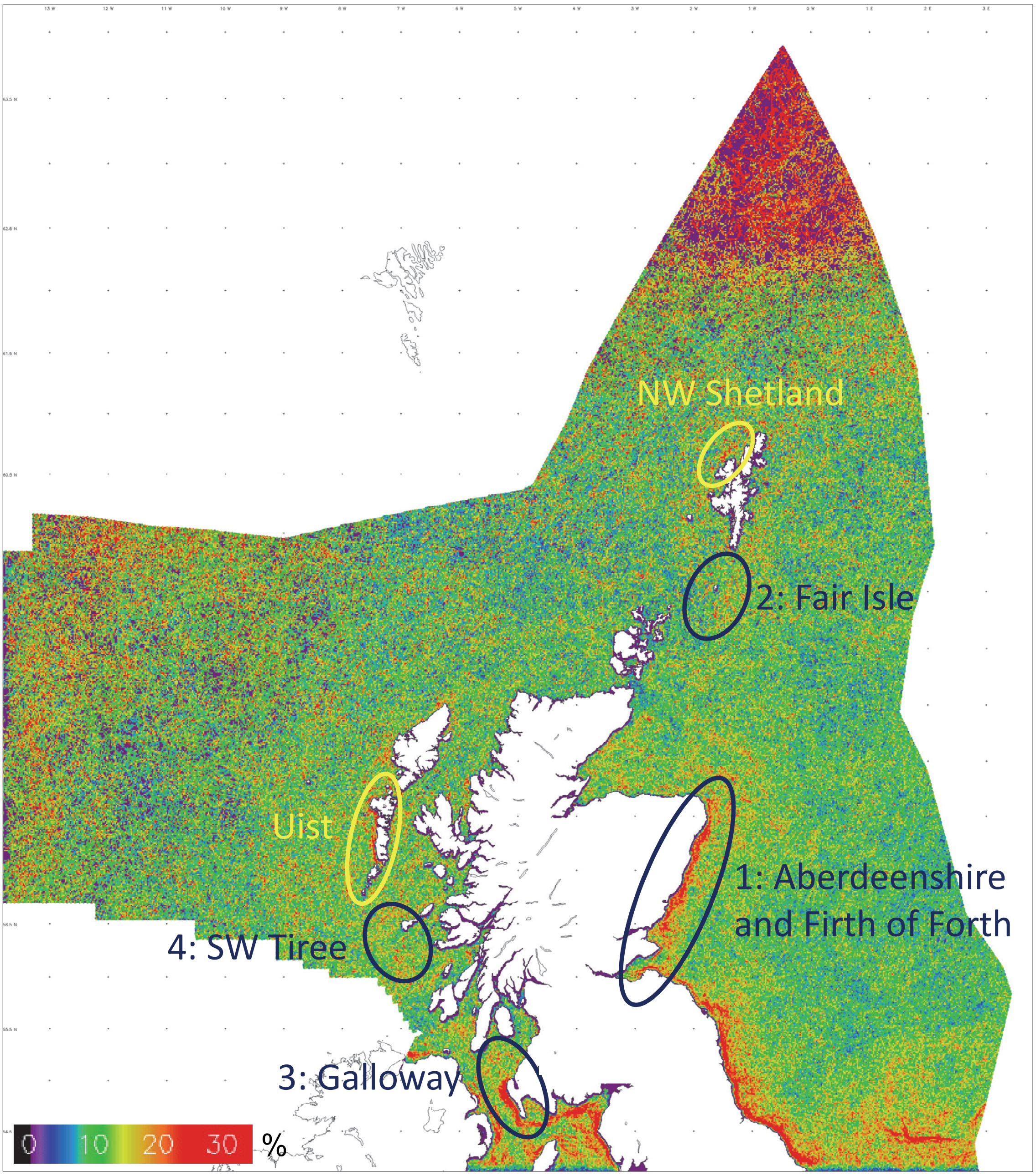

Figure 11. *Mean all-season high-resolution chlorophyll front distribution, with blue ellipses indicating key frontal zones described in this report, yellow ellipses for additional near-coastal frontal zones.*

4.1.2 Frontal zone 1: Aberdeenshire to Firth of Forth

Figure 12 summarises the spatial distribution of thermal and colour fronts in this region. This frontal zone can be defined as extending from the coast out to the limit of the green region (>35%) on the thermal front frequency map (Figure 12a). These thermal fronts appear to correspond to a narrow shallower inner shelf on detailed bathymetry charts (e.g. SeaZone website), and so may be associated with enhanced tidal mixing. The MERIS 300 m combined frequency map (Figure 12b) allows hotspots to be identified within this zone, such as east Aberdeenshire and the southern coast of the Firth of Forth.

There is considerable seasonal variation of these fronts: in autumn and winter the thermal fronts are focused near to the coast, whereas in spring and summer the stratification generates additional surface fronts that extend much further offshore (Figure 9). Colour fronts are mainly present in spring and summer (Figure 7), though near-coastal fronts are particularly obvious in autumn (Figure 4).

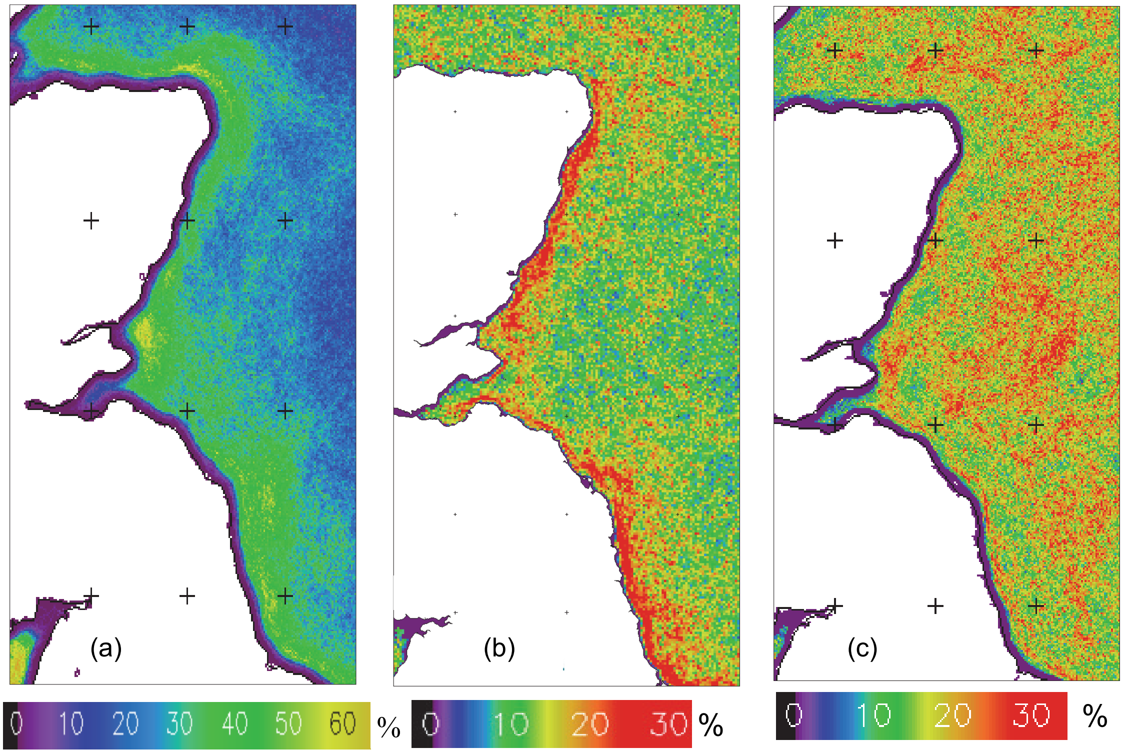

Figure 12. Mean all-seasons front frequency for Aberdeenshire-Firth of Forth: (a) thermal fronts; (b) 300 m Chl-a fronts; (c) 1 km Chl-a fronts.

Figure 13 provides example MERIS FR data to explain the mechanisms for front occurrence in this region during spring, using the same 8-day period as for Figure 1b. The *Chl-a* composite (Figure 13a) depicts a significant phytoplankton bloom extending into the North Sea that appears to be intensified along the coast. However, the enhanced colour version (Figure 13b), which stretches the blue-green part of the visible spectrum to fill the blue-red range, discriminates between the bloom offshore (green/brown colour) and suspended sediment along the coast (yellow/orange colour). As explained at 2.2.1, the *Chl-a* algorithm will often overestimate the concentration when there is also sediment in the water; though this actually assists the analysis as both *Chl-a* and sediment fronts are of interest. There appears to be a coastal process that is retaining the sediment from east coast rivers in a narrow band; this may relate to the thermal front seen there (Figure 10). It is likely that a boundary of turbid water would have a structuring effect on a fish community due to the impact of turbidity on prey and predator visibility (Utne-Palm, 2002).

The simplified *Chl-a* front map (Figure 13c) delineates the main colour fronts present during the 8-day period and indicates the high and low (red-blue) sides of the front. Off Rattray Head there are two distinct fronts, the inner front more related to sediment and the outer front resulting from a bloom. Both of these colour features correspond to peaks of thermal front frequency. Further examples of the coastal sediment fronts in this region have been studied, including in autumn/winter when there is less plankton, such as the 16 November 2010 example (Figure 1c).

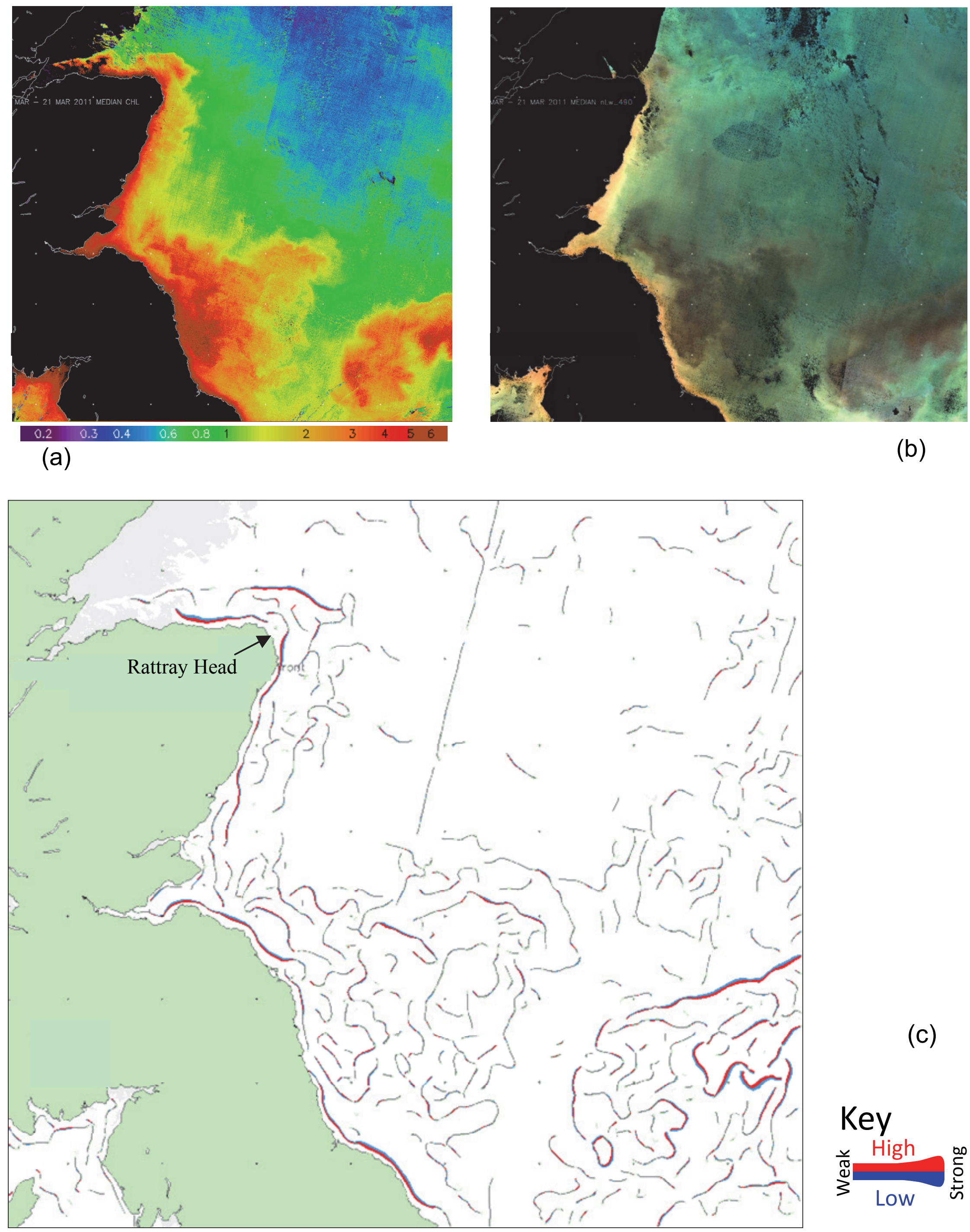

Figure 13. *Analysis of colour fronts in Aberdeenshire/Firth of Forth region using 14-21 March 2011 MERIS FR composites: (a) chlorophyll-a; (b) enhanced colour; (c) simplified Chl-a front map using red-blue to indicate the high-low side of each front. Chlorophyll-a and enhanced colour composites are created using different combinations of ocean colour channels, with the latter version giving a 'true' colour view. Different channels have different missing values, therefore areas with 'no data' are inconsistent between the two versions.*

4.1.3 Frontal zone 2: Fair Isle

Figure 14 shows enlarged sections of the summer thermal and colour front frequency for the Orkney and Shetland region. The strong tidal currents through this region generate well defined fronts separating mixed and stratified water. It can be seen that several of these thermal fronts correspond to predictable *Chl-a* fronts, in particular the band that extends north-to-south a short distance east of Fair Isle.

The seasonal variability of these fronts corresponds to the strength of stratification, so the fronts are most prominent in spring and summer, though still present for part of autumn and winter (Figure 9).

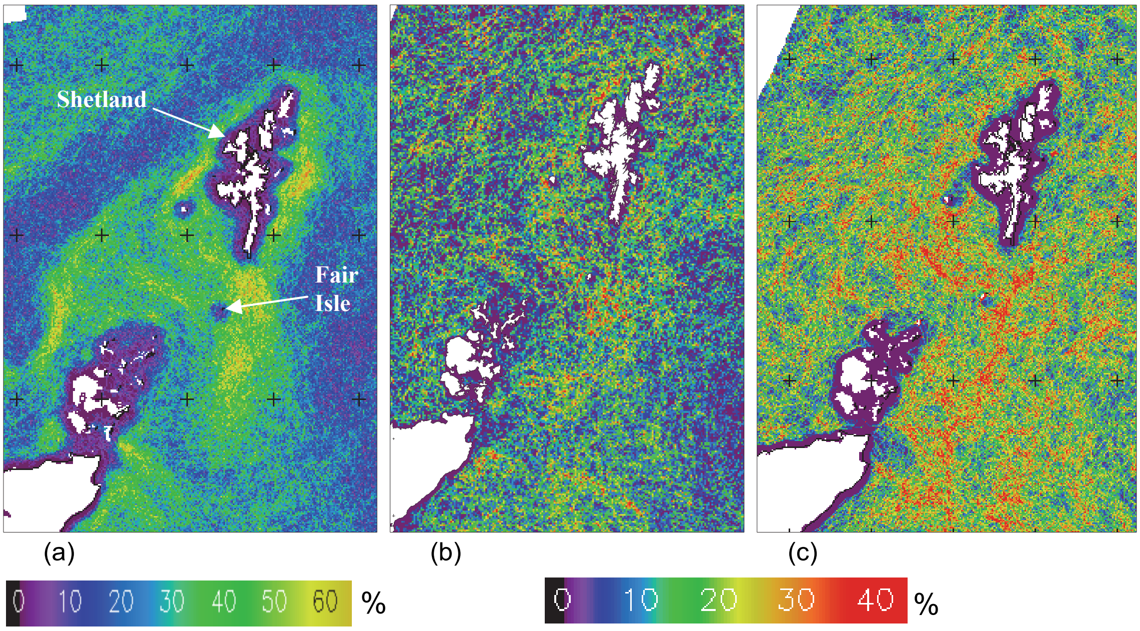

Figure 14. Summer front frequency for Fair Isle region: (a) thermal fronts; (b) 300 m Chl-a fronts; (c) 1 km Chl-a fronts

Figure 15 explores the *Chl-a* features around Fair Isle using 8-day MERIS FR composites from two summers. In the first example there is a plankton bloom south and east of Shetland which is restricted to remain to the east of the tidal mixing front near Fair Isle; this is indicated by the presence of colour fronts with the low side toward Fair Isle (Figure 15a & b). This contrasts with the second example in which the island is contained within a bloom that extends south past Orkney, and so the fronts show the opposite polarity with the island on the high side (Figure 15c & d). These two snapshots are not representative of the overall biological variability or patchiness, but do at least indicate that the plankton distribution is much more variable than the physical structures.

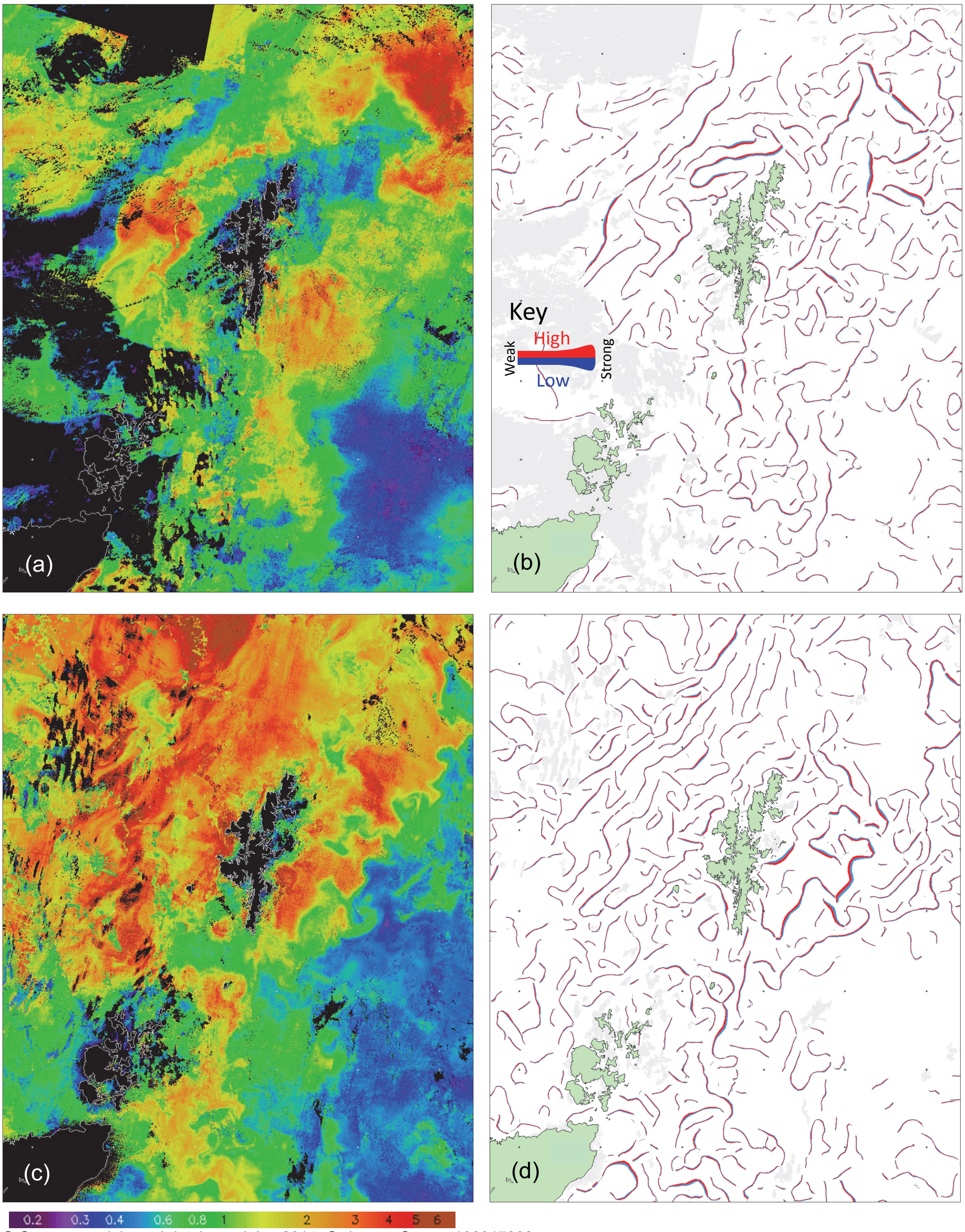

Figure 15. *Analysis of colour fronts around Fair Isle using MERIS FR composites: (a) 12-19 Jul. 2010 chlorophyll-a; (b) simplified Chl-a front map; (c) 26 Jun.-03 Jul 2011 chlorophyll-a; (d) simplified Chl-a front map.*

4.1.4 Frontal zone 3: Galloway peninsula and Clyde sill

The third proposed frontal zone of interest encompasses the Galloway peninsula and north to the Clyde sill (Figure 16). The high-resolution *Chl-a* fronts were of particular value in this zone, revealing a highly persistent colour feature close to the west coast and extending south towards Isle of Man and east around the south of the peninsula further offshore. At the Clyde sill the frequent thermal front corresponds to a less frequent colour front.

The thermal and colour fronts are present throughout the year (Figure 5, Figure 7, Figure 9), which points to an estuarine front caused by salinity differences between the Clyde and Solway Firths and the Irish Sea.

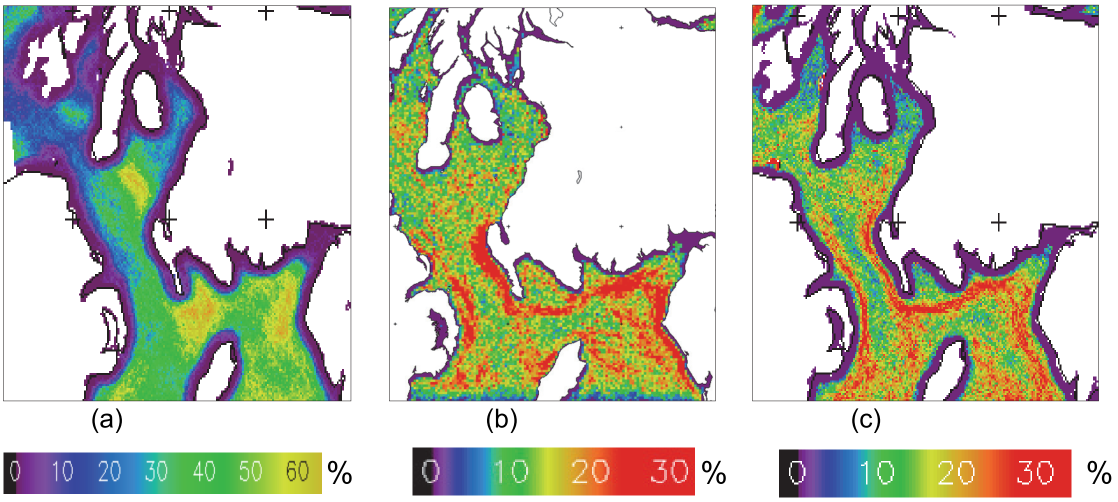

Figure 16. Mean all-seasons front frequency for Galloway peninsula: (a) thermal fronts; (b) 300 m Chl-a fronts; (c) 1 km Chl-a fronts

An example 8-day period in autumn is explored in Figure 17: the enhanced colour image (Figure 17b) shows high suspended sediment concentrations throughout Solway Firth, and perhaps advecting north along the west Galloway coast. There is a slight increase in phytoplankton along the Clyde sill. Hence in this region the thermal fronts indicate more biological activity in terms of primary production, and the colour fronts are more associated with sediment processes.

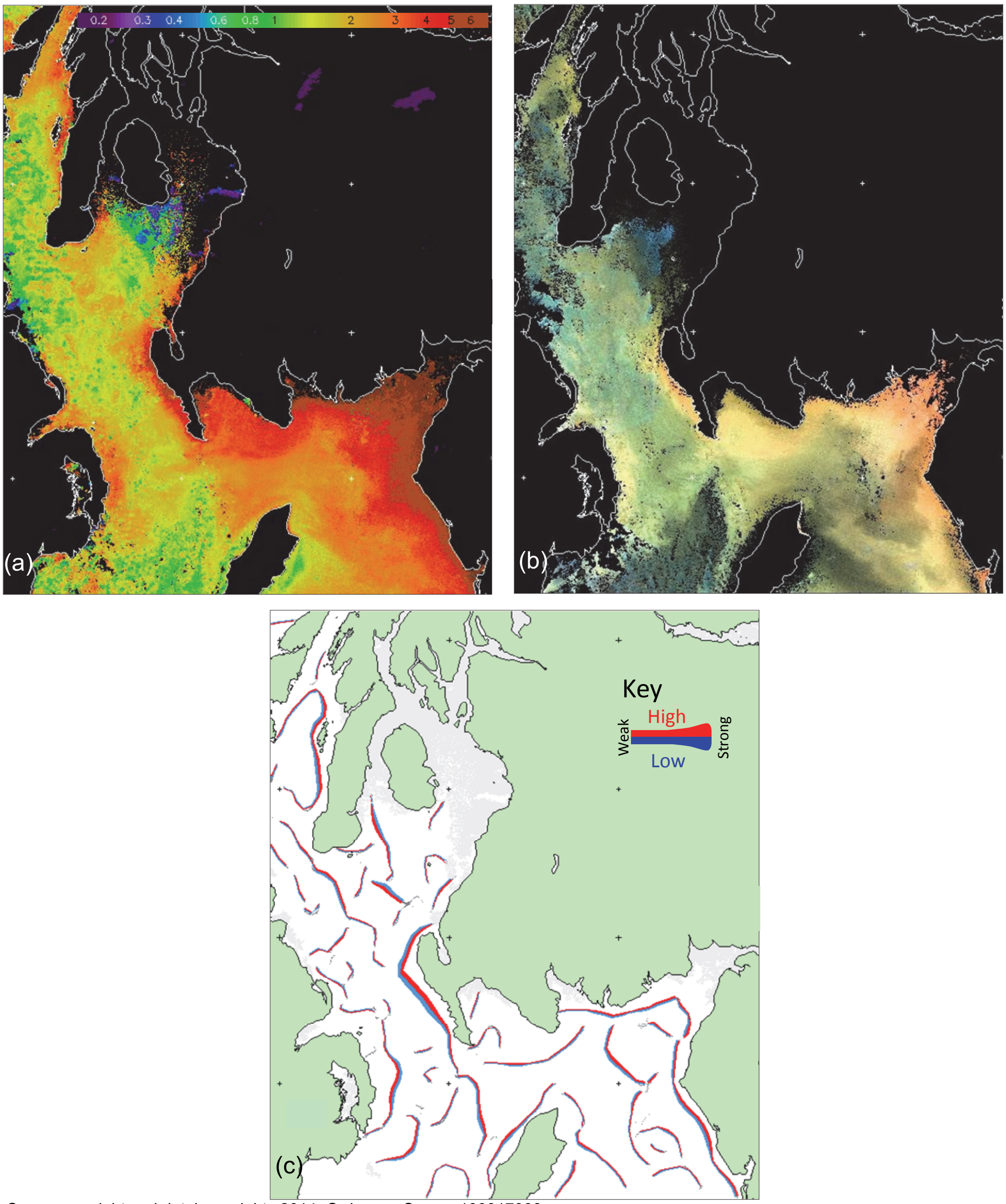

Figure 17. Analysis of colour fronts around Galloway peninsula and Clyde using 22-29 Sep. 2010 MERIS FR composites: (a) chlorophyll-a; (b) enhanced colour; (c) simplified Chl-a front map.

4.1.5 Frontal zone 4: South-west of Tiree

Figure 18 shows that the fronts observed south-west of Tiree are primarily thermal: though there is a slightly increased frequency in the Aqua-MODIS 1 km *Chl-a* fronts. This could be explained by the position of *chl-a* fronts being more variable than the physical features, or a low surface *chl-a* concentration; in some areas the deep *chl-a* maximum will be more significant for marine animals, and such features cannot be detected using Earth observation data. The distance of this front from Tiree is related to the shallow inner shelf that extends south-west from the island and causes tidal mixing. It is also possible that upwelling could occur off such a submerged promontory. The thermal front is usually present during spring and summer (Figure 9).

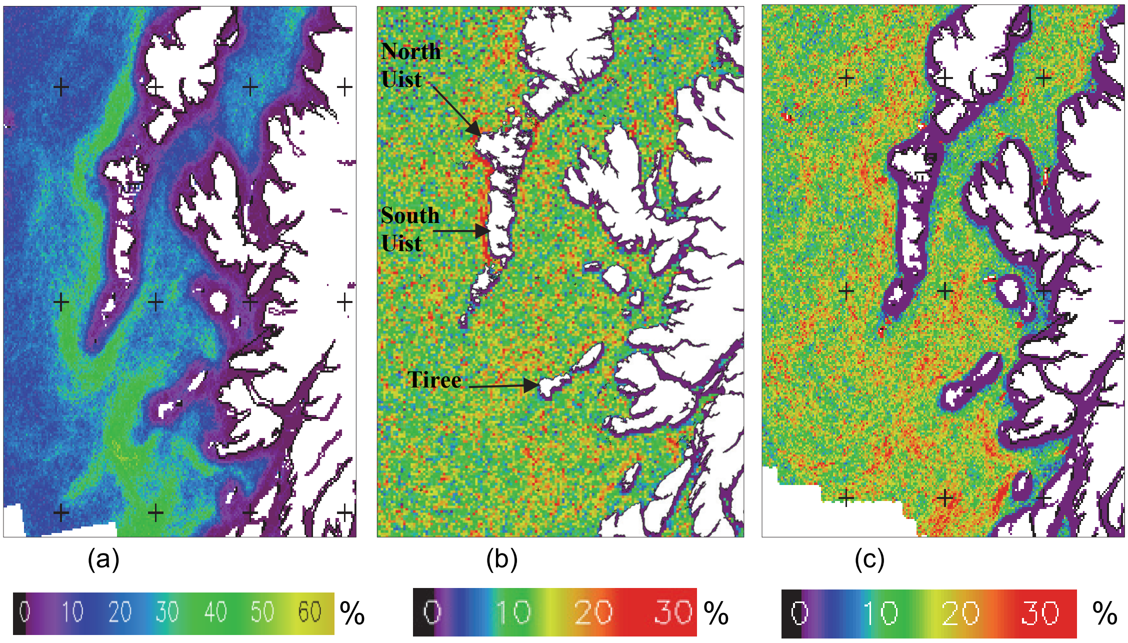

Figure 18. *Mean all-seasons front frequency for Tiree and the Hebrides: (a) thermal fronts; (b) 300 m Chl-a fronts; (c) 1 km Chl-a fronts*

A rare example of a corresponding ocean colour front was observed during April 2011 (Figure 19), where there is a sharp contrast between the nutrient-rich shelf water and clearer oceanic water during the spring bloom.

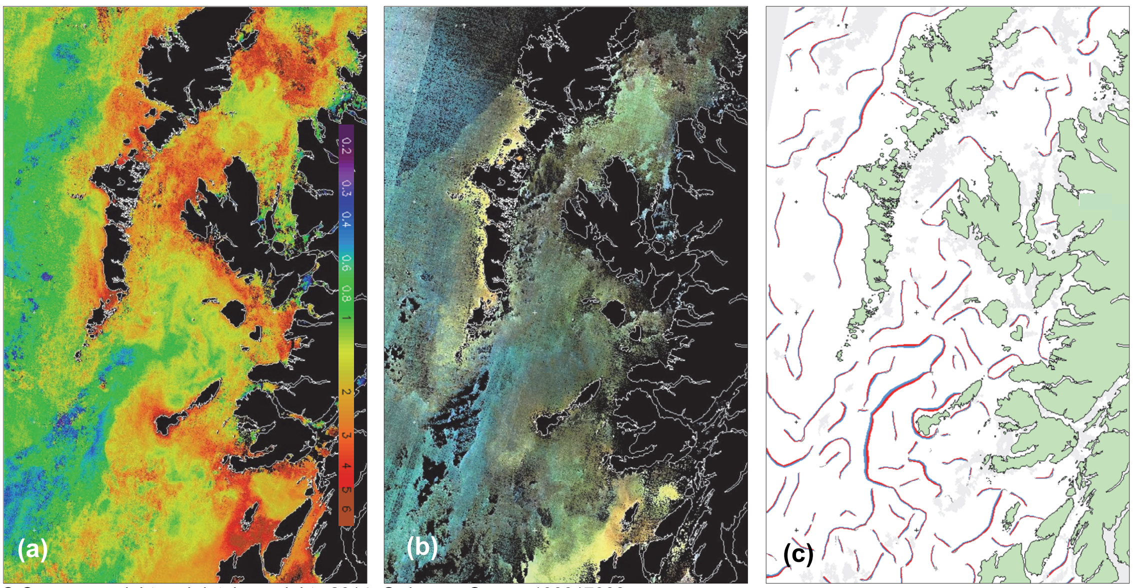

Figure 19. *Analysis of colour fronts around Tiree and the Hebrides using 23-30 Apr. 2011 MERIS FR composites: (a) Chl-a; (b) enhanced colour; (c) simplified Chl-a front map.*

4.1.6 Additional near-coastal frontal zones

In addition to the four key frontal zones described, the high-resolution *Chl-a* frontal analysis revealed other smaller regions close to the coast that had not been observed previously using coarser Earth observation data.

4.1.6.1 North and South Uist, Outer Hebrides

The 300 m *Chl-a* fronts showed higher frequency along the outer coast of the Uists in the Outer Hebrides (Figure 18b). This may be as a result of coastal sediments (Figure 19b), rather than enhanced concentration of phytoplankton.

4.1.6.2 North-west Shetland

A small zone of frequent *Chl-a* fronts is observed close to the north-west of Shetland during summer (Figure 14b), and appears to correspond to fine scale features seen in individual weeks (e.g. Figure 15c). This suggests that small fronts are arising quite regularly in this location during summer.

5. DISCUSSION

The key frontal zones were selected through detailed analysis of the seasonal chlorophyll and thermal front distributions. However, the limitations of Earth observation data prevent this from being viewed as a complete and objective list of important frontal zones. Such limitations include cloud cover, and the omission of deep *Chl-a* maxima, and are detailed below. There is a possibility that deep *Chl-a* maxima may occasionally be visible to Earth observation, for example where topographic features cause internal waves that force the thermocline up towards the surface. However, such events will be transient, so are unlikely to be indicated on the seasonal maps.

It should be appreciated that the *Chl-a* front maps delineate a mixture of both chlorophyll and sediment boundary features (for example Figure 16b, c). This is because both properties may be influenced by the same physical process, and also that the chlorophyll algorithm may not entirely distinguish between these coloured constituents. It would be possible to perform a similar frontal analysis on a time-series of Earth observation-derived suspended sediment concentration, as this may confirm which are truly sediment features, and those can be discounted from the *Chl-a* fronts. It was not possible to undertake this analysis within the time-scale of this project.

Each of the key frontal zones was illustrated using example 8-day maps of ocean colour, *Chl-a*, or *Chl-a* fronts, in order to depict certain short-term processes which contribute to the seasonal front distribution. However, these snapshots should not be taken as representative of the whole season, due to the dynamic variability of shelf-sea processes, and also that their selection was necessarily biased towards periods of lower cloud cover. Only the seasonal front frequency maps (Figures 4, 7 and 9) should be viewed as representative of the frontal distribution for the whole season.

5.1 Limitations of satellite front maps

All Earth observation data are limited by cloud cover, though the composite front map 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; however, this report is based on sufficient data to minimise such biases.

Currently the resolution of most global monitoring thermal and colour sensors is limited to 1 km, so there is a lack of useable SST and *Chl-a* data within a few kilometres of the coast. The MERIS 300 m *Chl-a* data have addressed this issue, though suffer from their own limited repeat rate and variable coverage.

Satellites only observe surface fronts, though strong and persistent surface fronts usually indicate a depth profile through the whole surface layer. Ocean colour is retrieved from only the top few metres of the sea, and so deep *Chl-a* maxima (e.g. at the thermocline depth of perhaps 20-50m) will not be visualised. It should be remembered that these subsurface features are known to be of importance to fish and diving animals such as seals (Scott *et al.,* 2010).

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 many published studies associating marine animals with fronts, for example fish (e.g. Bakun, 2006), seabirds (e.g. Bost *et al.*, 2009) and basking sharks (Sims and Quayle, 1998). The techniques presented here 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. 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 shift according to changing climate, winds or currents.

6. CONCLUSIONS

Front detection and aggregation techniques were successfully applied to high-resolution (300 m) satellite ocean colour data for the first time, to describe frequently occurring fronts near to the Scottish coast. Seasonal frequent front maps, derived from both chlorophyll and SST data, revealed key frontal zones, four of which are described in this report. Two further frontal zones were identified based on new insights into the sediment and plankton dynamics provided by the high-resolution *Chl-a* data. The methodology for identifying potential front zones involved detailed analysis and comparison of patches where *Chl-a* or thermal fronts occurred more frequently in the seasonal and combined maps.

Many researchers have determined that fronts are related to the abundance and diversity of pelagic species (reviewed by Jackson *et al.*, 2009), and hence may be considered a proxy for pelagic diversity. Earth observation data also have high spatio-temporal coverage and fine spatial resolution, which is lacking for many other diversity, abundance and habitat datasets. Hence the identified frontal zones are potentially of ecological importance and may assist in the identification of Scottish MPAs.

Each key frontal zone was analysed to describe its spatial and temporal extent and variability, and possible mechanisms. This involved searching through the dataset for examples of ocean colour 'snapshots' that helped to explain the phytoplankton and sediment processes that generated the front.

The MERIS 300 m data were limited in terms of the repeat rate and spatial coverage, and so an additional dataset of medium-resolution (1 km) ocean colour data was also analysed for fronts, in order to increase the data coverage of the Scottish study region. In total over 6,000 satellite ocean colour scenes were processed from 2009 to 2011.

The outputs from the current contract complement and improve upon the thermal front distribution maps produced for MB0102 (Miller *et al.*, 2010) in order to provide more comprehensive products to inform the Scottish MPA project. These are being used to assess the significance of fronts in Scottish waters, and to help support application of the Scottish MPA Selection Guidelines.

Several studies are underway on the distribution of different marine megafauna taxa in relation to fronts, in order to increase the evidence for these relationships (e.g. Oppel *et al.,* 2012). Frequent front data are currently being used to help model cetacean and basking shark distributions in Scottish territorial waters (Paxton *et al.*, in press). It is hoped that these tools can provide guidance in many aspects of marine spatial planning and conservation.

6.1 Recommendations for future work

The narrow swath width for the MERIS data restricted the amount of cloud-free data that could be acquired for the three years studied, and this limited the statistical descriptions of frontal hotspots for the near-coastal regions. The same methodology could be applied to the whole archive of MERIS FR data, from 2002 to present.

It would be of considerable value to relate these new findings on Scottish fronts to datasets of animal tracks gained from tagging, for example seabirds, seals and basking sharks. Geostatistical approaches are being developed to explore the relationships between marine animals and ocean fronts; these techniques could be focused on the key frontal zones identified in this project in order to further our understanding of their potential wider functional importance in Scotland's seas.

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