Centre: **Plymouth Marine Laboratory (PML)**

Title of case study: Satellite-derived ocean front maps inform the designation of national and international areas for marine protection

1. Summary of the impact

Our oceans face multiple stressors due to climate change, overexploitation and pollution. Area-based conservation approaches are used throughout the world but do not always protect highly mobile marine fauna, such as basking sharks and turtles. PML has provided a means to address this challenge by using satellite data to create maps that identify hotspots of marine life. These maps were the only datasets selected by the UK government to represent mobile species in the planning of marine conservation areas. This resulted in PML's research informing the designation of 1,884,700ha of Marine Protected Areas around the UK. The research has also been used on a global scale to help to define the boundaries of 60,133,500ha of Ecologically or Biologically Significant Marine Areas that contribute to the protection and sustainable use of marine biodiversity.

2. Underpinning research

The UK government is required by law to create an ecologically-coherent network of Marine Protected Areas (MPAs) to protect the diversity of species that live in the ocean. This is a considerable challenge for the pelagic (water column) ecosystem that is constantly changing in time and space and the highly mobile species that live within it. Management approaches that rely on defining fixed areas of the ocean need to take into account the key areas that mobile species frequently use as feeding grounds. Using satellite data, PML have developed a technique to identify the areas of greatest value to mobile species to inform the development of this network. PML's solution provides a cost-effective, readily available and reliable source of information that can address this policy need.

Starting in 1997, the Remote Sensing Group at PML developed the capability to automatically process large quantities of satellite data into ocean temperature and colour products. These can be used for monitoring coastal and oceanic processes across the globe. Dr Peter Miller (PML since 1997) led a team that used this capability to develop novel techniques for visualising ocean fronts - dynamic structures where two water masses of different temperature, density or other property meet. These areas benefit from increased nutrient supply and hence greater biological productivity. Dr Miller first combined the location, strength and persistence of all fronts observed over several days into a single composite front map in 2004 using 1km resolution data [3.1]. Uniquely, Dr Miller's methodology allowed the visualisation of both dynamic and stable fronts, generating metrics to indicate their temperature gradients, persistence and spatial variability over time [3.2].

Soon after the technique was developed, the University of Aberdeen was studying satellite tracking of basking shark movements off Scotland. Dr Miller analysed satellite data to compare composite front maps with the tracking data to provide further evidence of the link between fronts and key feeding sites for marine megafauna. The research confirmed that the shark was swimming parallel to a front, and believed to be feeding along the line of the front [3.3]; this research emphasised the importance of fronts for supporting marine life. The enhanced nutrient supply found at fronts supports increased abundance of plankton, which in turn supports higher trophic levels, demonstrating that fronts can be used as a proxy for biodiversity [3.4].

In 2010 PML contributed to a Department for Environment, Food and Rural Affairs (Defra) project to collate data for the planning of a network of MPAs. Dr Miller's team produced one of the final project reports and a key data layer on ocean fronts, used as a surrogate for hotspots of pelagic diversity for the UK continental shelf [3.5]. The report described the methodology used to develop the data layer and provided direction on interpreting and applying front maps to inform the designation of MPAs. This was the first time that ocean front maps had been compiled to guide the process of defining protected areas.

Ten years of satellite data, incorporating more than 30,000 images, were processed to encompass interannual variability. Ocean fronts were detected on every scene and combined to generate monthly front maps displaying the location, gradient, persistence and proximity of all fronts over a given time-period. The maps were then combined into a seasonal ocean front data layer providing a robust indication of where pelagic diversity hotspots occur throughout the year (Figure 1).

Further advancement to this technique came in 2012 when Dr Miller and Dr Xu, in collaboration with Scottish Natural Heritage, successfully applied front detection and aggregation techniques to higher-resolution (300m) satellite data in Scottish coastal waters. This allowed smaller frontal zones or those in close proximity to the coast to be detected for the first time as this had not been possible using medium resolution data. Seasonal frequency front maps, derived from both chlorophyll and sea surface temperature data, revealed a number of key frontal zones. Some of which were identifiable due to new insights into the sediment and plankton dynamics provided by the higher-resolution data [3.6].

Since his formative paper in 2004, Dr Miller has authored 30 papers on ocean fronts which have been cited widely. His method has been used in a wide range of applications from cetacean habitat modelling, seabird behaviour, conservation of marine megafauna, to the effects of renewable energy installations on biodiversity. This work has been supported by PML colleagues including Dr Saux-Picart, S. (2008-2013), Christodoulou, S (2009-2011) and Xu, W (2012-2014).

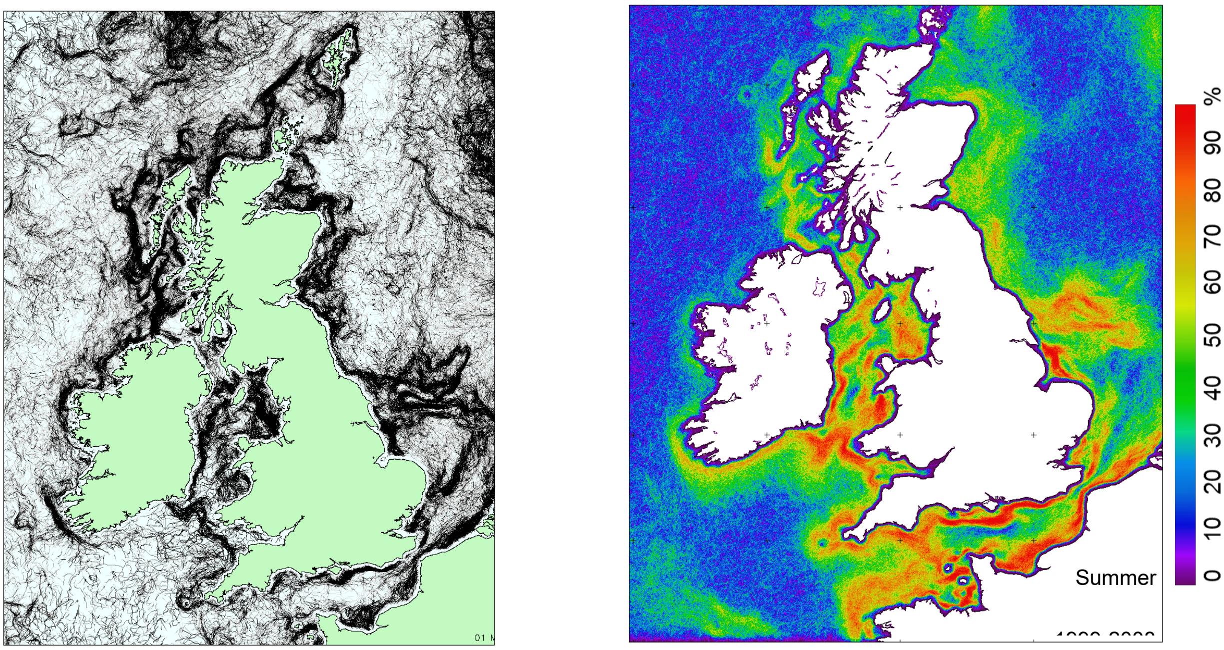

Figure 1. Example monthly front map (left) used to generate a 10-year front frequency map (right)

3. References to the underpinning work

PML authors are highlighted in bold type, citations numbers from Web of Science 7 January 2020

3.1. **Miller, P.** 2004. Multi-spectral front maps for automatic detection of ocean colour features from SeaWiFS. *International Journal of Remote Sensing*, 25(7-8), 1437-1442. doi:10.1080/01431160310001592409. [32 citations].

3.2. **Miller, P.** 2009. Composite front maps for improved visibility of dynamic sea-surface features on cloudy SeaWiFS and AVHRR data. *Journal of Marine Systems*, 78(3), 327-336. doi:10.1016/j.jmarsys.2008.11.019. [59 citations].

3.3. Priede, I.G., **Miller, P.I.** 2009. A basking shark (*Cetorhinus maximus*) tracked by satellite together with simultaneous remote sensing II: New analysis reveals orientation to a thermal front. *Fisheries Research*, 95(2-3), 370-372. doi:10.1016/j.fishres.2008.09.038. [11 citations].

3.4. **Miller, P.I.**, Christodoulou, S. 2014. Frequent locations of oceanic fronts as an indicator of pelagic diversity: Application to marine protected areas and renewables. *Marine Policy*, 45, 318-329. doi:10.1016/j.marpol.2013.09.009. [26 citations].

3.5. **Miller, P.I.**, **Christodoulou, S.**, **Saux-Picart, S.** 2010. *Oceanic thermal fronts from Earth observation data – a potential surrogate for pelagic diversity*. Report to the Department of Environment, Food and Rural Affairs. Defra Contract No. MB102, Plymouth Marine Laboratory, subcontracted by ABPmer. 28pp. http://sciencesearch.defra.gov.uk/Document.aspx?Document=MB0102_9104_TRP.pdf

3.6. **Miller, P.I.**, **Xu, W.**, Carruthers, M. 2015. Seasonal shelf-sea front mapping using satellite ocean colour and temperature to support development of a marine protected area network. *Deep-Sea Research Part Ii-Topical Studies in Oceanography*, 119, 3-19. doi:10.1016/j.dsr2.2014.05.013. [8 citations].

4. **Details of the impact**

Producing key evidence for the designation of national Marine Protected Areas

Ocean front maps, compiled by Dr Miller, were the only datasets selected by Defra to represent mobile species in the planning of MPAs in the UK [3.4]. The UK and Scottish governments have a duty to develop a network of MPAs, under the EC Marine Strategy Framework Directive, UN Convention on Biological Diversity (CBD) and UN Sustainable Development Goal 14.5 (to conserve at least 10% of coastal and marine areas by 2020). PML's maps informed the designation of 1,884,700ha of protected ocean, contributing to an ecologically coherent network of MPAs around the UK [5.1].

In 2010 the UK government established four regional projects in England and Wales to work with local stakeholders to develop proposals for new MPAs. Each of these groups was provided with a range of data including the ocean front maps to ensure that they had the best available information to identify the most suitable areas to put forward. *"The ocean front maps were used by all of the regional Steering Groups as part of discussions to determine the key areas to put forward for protection. They provided a strong indication of the importance of sites for mobile species and pelagic biodiversity and as such were tremendously important."* Project Manager, Finding Sanctuary [5.2].

PML's ocean front maps influenced decision making in all of the regional MPA projects with 16 of the 46 proposed MPAs in the first round of designations specifically mentioning ocean fronts in their assessments [5.1]. To date the ocean front maps have informed the designation of 7 MPAs, ensuring the protection of an area of more than 397,000ha [5.1]. By providing evidence of the spatial variability of fronts over time, PML helped to inform the government of the appropriate size and boundaries of the designated areas.

The Scottish government used ocean front maps to inform the MPA designation process [5.3], in particular the high-resolution maps compiled in 2012. *"Oceanic fronts were one of just five large-scale features selected for protection as part of the Scottish MPA network. Dr Miller's reports contributed towards their selection – they provided the evidence that fronts are persistent features over time and space and were used to inform the definition of fronts for the process. The data products from these reports were used to underpin the inclusion of fronts in the Clyde Sea Sill MPA (designated 2014), Southern Trench proposed MPA and the Sea of the Hebrides proposed MPA (consulted on in 2019)."* Scottish Natural Heritage [5.4].

The MPAs in Scottish waters informed by Dr Miller's maps will cover a combined area of 1,328,700ha. In all three cases fronts have been recognised for their importance as features that contribute to the overall health and biodiversity of the marine environment [5.1]. The MPAs ensure protection for key species such as black guillemots (Clyde Sea Sill), minke whales (Southern Trench and Sea of the Hebrides) and basking sharks (Sea of the Hebrides). Fisheries management measures have been implemented for the Clyde Sea Sill MPA, similar management measures will follow for the other MPAs once designated (decision due in Spring 2020). The management measures are used to limit the use of fishing gear that would adversely impact the habitat or mobile animals.

The overall benefits of the Scottish network of MPAs was estimated to be at least GBP6,300,000,000 over 20 years [5.5]. Assessed in a report for Scottish Environment LINK, the calculation was based on the types of habitat in each MPA and the expected change in value of the goods and services under the proposed management scenarios. The methodology and valuations were underpinned by PML research published by Dr Beaumont (PML since 2002) who was the first researcher to define and value the benefits provided by the marine environment [5.6].

Informing the protection of international marine sites

Ocean front maps were used on a global scale as evidence in 4 workshops in 2013. Led by the UN Convention on Biological Diversity (CBD) the workshops identified Ecologically or Biologically Significant marine Areas (EBSAs). Covering national, transboundary, or areas beyond national jurisdiction, EBSAs contribute to the protection and sustainable use of marine biodiversity by describing areas of particular significance. The scientific criteria for identifying EBSAs include biological productivity and diversity; both of which reference fronts as example indicators [5.7].

PML's maps directly influenced the selection of EBSAs in the Eastern Tropical and Temperate Pacific Regional Workshop and North Pacific Regional Workshop. "*The maps were used, along with sea turtle inter-nesting data, to extend the initial offshore proposal for the Costa Rica Dome to meet the coast along the Gulf of Papagayo"* University of Duke [5.8], and *"to help identify a boundary for the Carnegie Ridge and Equatorial front EBSA description"* University of Duke [5.8]. These two areas equate to 60,133,500ha of protected marine habitats. The EBSAs have been approved by the UN and used to inform national planning processes and to secure international funding [5.9]. For example, The Global Ocean Biodiversity Initiative has been awarded a grant of EUR5,200,000 (05-2016) to support the EBSA process. Part of this funding has been used to conduct oceanographic surveys and create an Atlas of the Costa Rica Dome, part of the Upwelling System of Papagayo EBSA. An analysis of possible governance schemes for the area is under review which will form the basis for negotiations with regional authorities to define an appropriate governance regime for the region [5.10].

In the most recent round of designations, front maps featured prominently in the description of the North Atlantic Current and frontal system at the mid-Atlantic EBSA. This is an area of high productivity, with a high density of foraging activity, home to 21 species of seabird including the endangered Zino's Petrel and Bermuda Petrel. The EBSA description was approved at the NE Atlantic workshop and will now go forward for approval by the CBD Conference of Parties in 2020.

"PML's front maps underpinned the description of the Mid-North Atlantic frontal system EBSA. This site corresponds to an important foraging area for 21 seabird species, including 6 globally threatened species as defined by International Union for Conservation of Nature and Natural Resources Red List. The maps were crucial for defining the area including identifying persistent and ephemeral hydrographic features" BirdLife International [5.11].

The benefits of Marine Protected Areas

MPAs are primarily policy tools for conservation, used to protect and enhance marine biodiversity. However, it has been shown that they can also deliver tangible economic benefits as well as other societal benefits through ecosystem services and climate change mitigation. In 2017 a European Commission study, co-led by PML's Dr Caroline Hattam (PML since 2008), reviewed the economic benefits of MPAs, illustrated by case studies from across Europe for a range of sectors [5.12].

Fisheries were shown to benefit through improved fish stocks, both for fisheries still permitted inside the MPA as well as outside due to a spill-over effect. In Italy, MPAs were demonstrated to have supported stock improvements with increases in catch rates of 100% for some species, and catch per unit effort inside the MPA double that of the rate outside. The spill-over effect was shown to improve the yield of spiny lobsters by 10% annually in a Spanish MPA. In some areas, such as Lyme Bay in the UK, the MPA has even resulted in a higher market value of products to boost income for local fishermen.

MPAs can facilitate increases in tourism and changes in visitor behaviour that result in higher revenues, increased jobs and additional livelihood opportunities. For example, income generated through tourism inside the Lyme Bay MPA increased by GBP1,500,000 within 3 years of its designation. Acknowledging the study, the European Commission said that MPAs generate "*tangible economic growth"* [5.13].

5. Sources to corroborate the impact (indicative maximum of ten references)

5.1. PML (ed). 2019. *Satellite derived ocean front maps inform the designation of national and international areas for marine protection*. A compilation of site selection documents, or other appropriate evidence, as corroboration of the impact of PML research in the MPA planning process, 313pp. https://www.pml.ac.uk/People/Science_Staff/Dr_Peter_Miller/MPA_selection.pdf

5.2. 5 November 2015. PML ocean front data [email]. *Project Manager, Finding Sanctuary, SW Regional Group*.

5.3. Scottish Natural Heritage. 2018. *Marine protected areas and large-scale features*. Position paper. 34pp. https://www.nature.scot/sites/default/files/2018-08/Scottish%20MPA%20Project%20-%20Large%20Scale%20Features%20position%20paper.pdf

5.4. 15 July 2019. PML ocean front maps application [email]. *Marine Policy & Advice Manager – MPAs, Scottish Natural Heritage*.

5.5. Álvarez-García, M.Á., González-Álvarez, J., García de la Fuente, L., Colina-Vuelta, A. 2012. *Valuing the benefits of designating a network of Scottish MPAs in territorial and offshore waters.* . A report to Scottish Environment LINK: Perth, UK, 90pp. http://www.scotlink.org/files/publication/LINKReports/Valuing_the_benefits_MPA_Network_Scotland_Report_%28final%29.pdf

5.6. **Beaumont, N.**, **Townsend, M.**, **Mangi, S.**, **Austen, M.C.** 2006. *Marine biodiversity: an economic valuation. Building the evidence base for the Marine Bill*. Department for Environment, Food and Rural Affairs (Defra), 64pp. http://randd.defra.gov.uk/Document.aspx?Document=WC04029_4013_FRP.pdf

5.7. Convention on Biological Diversity. 2009. *Azores scientific criteria and guidance for identifying ecologically or biologically significant marine areas and designing representative networks of marine protected areas in open ocean waters and deep sea habitats*. CBD Secretariat, Québec, Canada. 12pp. https://www.cbd.int/marine/doc/azores-brochure-en.pdf

5.8. 9-10 October 2015. Lenfest Pelagic Conservation Grant Conference Call - PML [email thread]. *University of Duke. Commissioned by CBD Secretariat to support them in scientific and technical preparation of data to inform the description of EBSAs*.

5.9. Bax, N.J., Cleary, J., Donnelly, B., Dunn, D.C., Dunstan, P.K., Fuller, M. *et al.* 2015. Results of efforts by the Convention on Biological Diversity to describe ecologically or biologically significant marine areas. *Conservation Biology*, 30(3), 571-581. doi:10.1111/cobi.12649.

5.10. Global Ocean Biodiversity Initiative (GOBI). 2020. The Costa Rica thermal dome. [online] [Cited 9 January 2020]. http://gobi.org/projects/iki_wp3_crtd/

5.11. 8 January 2020. PML ocean front maps [letter]. *Marine Science Officer, BirdLife International*.

5.12. **Hattam, C.**, Haines, R., Pantzar, M., Russi, D. 2018. *Study on the environmental benefits of MPAs*. European Commission: Brussels doi:10.2826/449575

5.13. Hodgson, R. 5 November 2018. EU executive sees MPAs as driver of economic growth. In: *ENDS Europe* [online] [Cited 9 January 2020]. https://www.endseurope.com/article/1648628/eu-executive-sees-mpas-driver-economic-growth