CAMPUS

Combining Autonomous observational models
for Predicting and Understanding Shelf Seas

SCIENCE IN ACTION

www.campus-marine.org

START

How to navigate this document

The seven case studies can be accessed by using the numbered boxes on the right.

It is also possible to return to the start by clicking on the 'home' button in the bottom right corner.

Introduction

Glossary

1.
2.
3.
4.
5.
6.
7.

Funders

WWF

Department for Environment Food & Rural Affairs

UKRI Natural Environment Research Council

Partners

Cefas

PML Plymouth Marine Laboratory

SAMS Scottish Association for Marine Science

National Oceanography Centre

Met Office

Newcastle University

University of Exeter

INTRODUCTION

The CAMPUS project developed an integrated approach to combine autonomous observing networks and marine ecosystem models. This enabled better understanding of fine-scale marine processes and system variability, thereby demonstrating the utility of a combined observation-modelling system for ecosystem-based management.

Marine ecosystems are vulnerable to climatic and non-climatic stressors that result in changes to their physical, chemical, and biological state. These changes impact on marine ecosystem services and resources, such as climate regulation, biodiversity and sustainable fisheries. In response to these changes, marine legislation is becoming more sophisticated to the extent that marine ecosystem-based management is now specified within some national and regional legislative frameworks.

To enact these frameworks effectively requires an evidence base of detailed environmental data, backed up by a thorough understanding of marine processes.

Understanding, predicting, and ultimately managing, the relationship between multiple stressors and ecosystem services requires a close symbiosis between marine observing networks and marine ecosystem models. CAMPUS has advanced and integrated operational ecosystem models with autonomous data products to address the knowledge gaps associated with fine temporal and spatial scales with respect to plankton growth and associated biogeochemical cycles.

The autonomous data products were provided to CAMPUS by the twin AlterEco project, which provided a continuous measurement campaign in the North Sea between November 2017 and January 2019.

As part of CAMPUS, we performed a ground-breaking field campaign where an autonomous underwater glider was deployed and driven by model forecasts for three months in the western English Channel.

The aim of the mission was twofold. Firstly, to challenge the navigational methodology, and to develop the concept of truly autonomous piloting driven by operational ecosystem model forecasts. Secondly, to use the glider's sensors to capture the variability in the spring bloom of phytoplankton in unprecedented detail.

The glider took a virtual snapshot of the environmental conditions every 20 minutes, resulting in a total of 5,533 profiles. This allowed CAMPUS to capture finescale variability in the bloom dynamics that would have been missed by traditional sampling methods.

CAMPUS and AlterEco jointly delivered the NERC Marine Integrated Autonomous Observing Systems (MIAOS) Programme, co-funded by the Department for Environment, Food and Rural Affairs (Defra) and the WWF-UK, and supported by in-kind contributions from Cefas, the Defence Science and Technology Laboratory (Dstl) and the Met Office.

Next steps

This document demonstrates through specific case studies how the cutting-edge science delivered by CAMPUS can be utilised and applied.

Specifically, CAMPUS

- demonstrated the applicability of merged model-data products to Good Environmental Status (GES) assessment,
- demonstrated short term forecast systems addressing phytoplankton blooms, Harmful Algal Blooms (HABS) and oxygen depletion events,
- undertook a cost benefit analysis of potential observing system strategies for the UK,
- improved our understanding of the distribution of marine litter in UK waters, and
- assessed the applicability of CAMPUS outputs to industrial and ODA requirements.

CAMPUS has set the pathway for 'smart' autonomy to tackle pressing environmental challenges, by uniting the most advanced observing systems with state-of-the-art computer modelling.

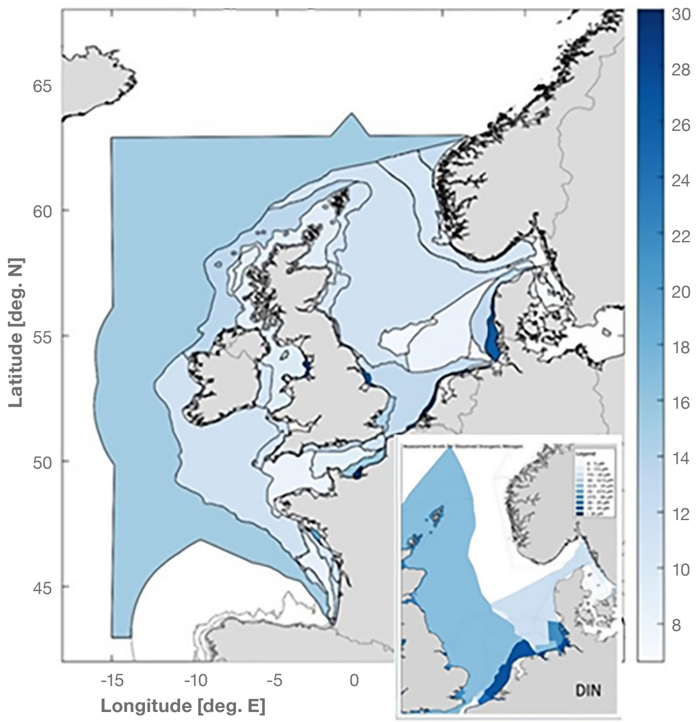


Figure 1. Thresholds of Dissolved Inorganic Nitrogen (DIN) generated from ensemble modelling simulating a 1900 historic scenario. Inset, previous assessment levels derived from salinity and expert judgement. Note the smoother, more realistic gradients in the modelling approach.

1. GETTING MARINE ECOSYSTEM MODELS USED AND ACCEPTED AS EVIDENCE AT AN INTERNATIONAL LEVEL

Author: Liam Fernand (CEFAS)

One of the key goals of CAMPUS is to deliver improved information for marine management. There is also increasing pressure on managers and policy-makers to make decisions based on such information including using predictions of ocean change, key to this is confidence that the information can be relied upon.

Marine ecosystem models have not previously been used in UK policy and the uptake of models is also poor in international fora. CAMPUS has contributed to the OSPAR Commission multi-model ensemble application that has simulated historic scenarios of a pre-eutrophication state (c.1900s), and thereby defined "high status" for European regional seas. The associated derived thresholds (Fig.1) will be used in the next OSPAR Eutrophication Assessment reporting round. This is the first time that marine models have been used as evidence, in this policy context.

Furthermore, the above ensemble application supported by CAMPUS has opened the door to models being used as evidence in future marine environment state assessments. International agreements require multi-country alignment on methods and outcomes.

New understanding and new capabilities

CAMPUS has contributed to acceptance at international level of modelling as an evidence base, key to this is confidence in the outcome. Specifically, a methodology has been implemented to combine the outputs from the ensemble modelling to enhance confidence. The method of incorporating models together does not treat all model outcomes as equal but weights them by region according to how well they compare to observational data sets. The advantages of this approach are multiple:

1. It enables better models to get the weighting they deserve and encourages model improvement;
2. Typically, models tend to be tuned to perform best in national areas of interest, therefore this approach, has the advantage of enabling acceptance by national delegates meeting at the international level;
3. An incentive for national organizations to improve their models, if they perform poorly in areas of concern.

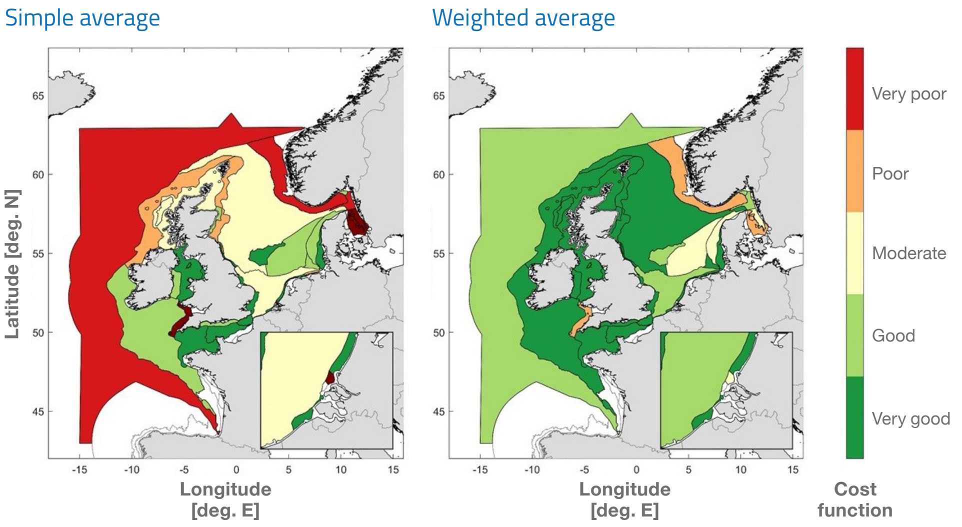


Figure 2. Outcome of comparison of model results for dissolved organic nitrogen with observations for each OSPAR region. Left: simple average of each model member. Right: outcome of weighted average, each model is weighted by comparison to observations.

Improved the state of the art

CAMPUS has moved one step closer to models being used as evidence in assessment. In situ observations sample the marine environment poorly: e.g. moorings give high temporal resolution but poor spatial resolution.

CAMPUS has also moved closer to the acceptance of the concept of combining models and observations. Observations are vital to ensuring confidence in the models, and are needed to demonstrate that models are able to replicate the spatial and temporal behaviour.

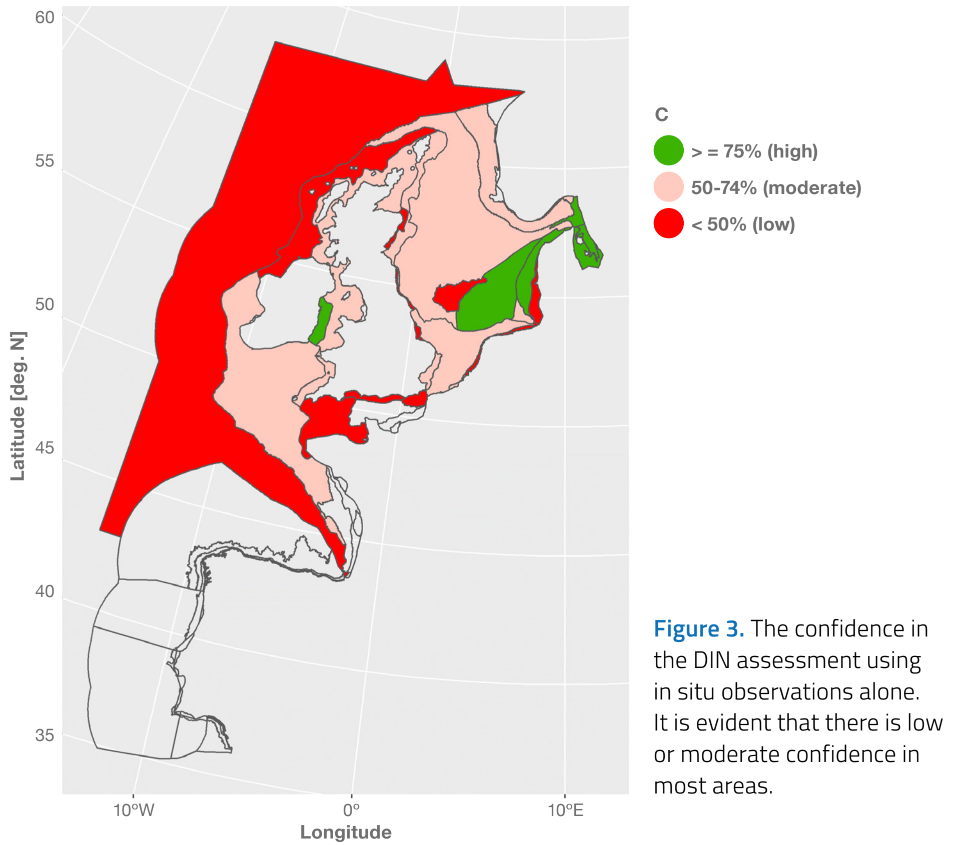


Figure 3. The confidence in the DIN assessment using in situ observations alone. It is evident that there is low or moderate confidence in most areas.

“The work has progressed our understanding of historical scenarios, and also the value of using in situ and modelled values to understand our current state. We accept the method that has been used to derive the values and think that the use of model weighting has been a valuable addition to this method.“

Vanessa Fairbank
UK OSPAR Delegate, Defra

Opportunities for exploitation

The opportunity is for models to be used directly in future OSPAR assessments. Specifically, for parameters which are poorly observed (e.g. dissolved inorganic nitrogen and phosphorus, and oxygen), models offer the possibility to identify regions of concern, which observations can not resolve. This in turn allows national authorities to direct targeted field campaigns at areas of concern. The use of the weighted ensemble method has wider application to other geographic areas or applications, ensemble modelling in the marine environment is rare and usually consists of much fewer models than in atmospheric science. Our weighting ensemble method is useful when the numbers of model members is low and confidence in results is variable.

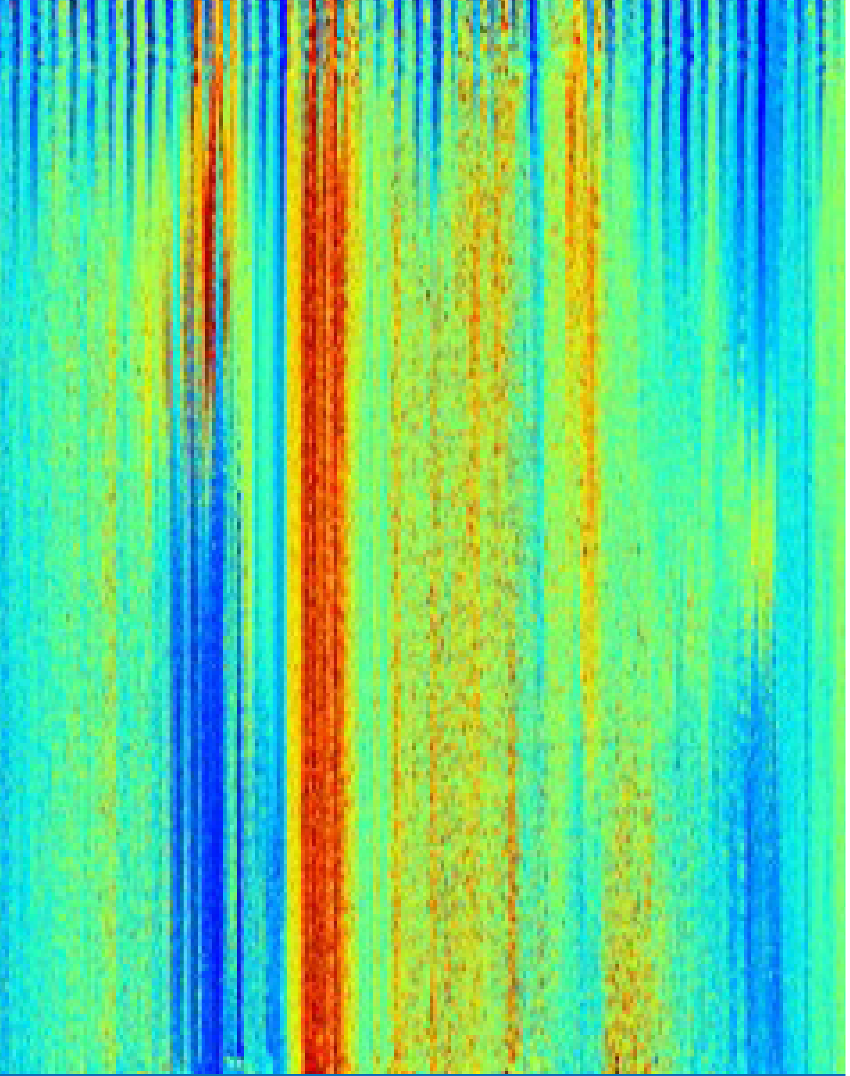
Roadmap for operalization

The next stage is two pronged:

1. The model enhancements developed within CAMPUS to be used operationally and made available via Copernicus. These can then be picked up by OSPAR and other groups.
2. At the international level, through ensemble comparisons, build trust and confidence and demonstrate utility of model outputs for ecosystem assessment.

Further contact
liam.fernand@cefas.co.uk

References
Lenhart, H., A. Blauw, X. Desmit, L. Fernand, R. Friedland, B. Heyden, et al. 2021. ICG-EMO report on model comparison for historical scenarios as basis to derive new threshold values. OSPAR Convention for the Protection of the Marine Environment of the North-East Atlantic Intersessional Correspondence Group for Eutrophication Modelling (ICG-EMO). September 2021.



> “CAMPUS delivered a step-change in our ability to forecast and observe phytoplankton blooms.“

2. ESTABLISHING PREDICTIVE SKILL OF THE SPRING BLOOM

Authors: Jozef Skakala (PML, NCEO), Shenan Grossberg (UoE), David Ford (Met Office), Gianmario Rinaldi (UoE), Tim Smyth (PML), Stefano Ciavatta (PML, NCEO).

Phytoplankton are tiny photosynthetic organisms that are the foundation of the food web for most of marine life. Phytoplankton blooms are a key driver of the ecosystem state, influencing nutrient and oxygen levels, and the distribution of fish and other higher trophic level groups. Blooms that contain toxic algae can be harmful killing fish stocks and damaging aquaculture farms. CAMPUS delivered a step-change in our ability to forecast and observe phytoplankton blooms. In a break-through three-month long field campaign, CAMPUS deployed an autonomous underwater vehicle which was “smart” in searching for blooms. The glider data were assimilated in an operational model that directed the pilot in setting the path of the vehicle. The smart system was successfully tested in the English Channel and is expected to lead to major advances in the management of fisheries or aquaculture.

New understanding and new capabilities

CAMPUS established an innovative smart autonomous biogeochemical observing system based on glider technology. This advances our present capability to predict and observe phytoplankton blooms by providing:

1. observations of phytoplankton blooms, at high spatio-temporal resolution in the water column, which are beyond the scope of the currently used ocean-colour remote sensing technology (for the importance of resolution see Fig.1, left hand panel),
2. high quality observations in coastal areas where satellite technology is challenged by riverine discharges of coloured organic matter and sediment re-suspension,
3. good horizontal and vertical spatial coverage, which cannot be delivered by observing stations at fixed locations,
4. capacity to use artificial intelligence (AI) rather than human pilots to navigate the glider trajectory, optimizing the observing system efficiency,
5. capability to observe variables (such as oxygen) that cannot be observed from space.

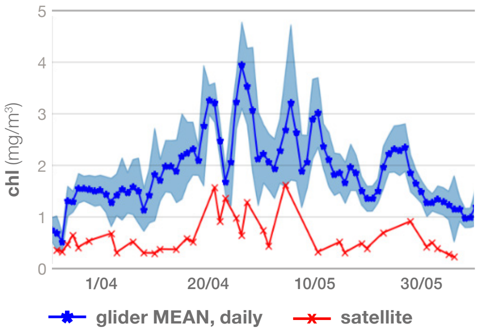


Figure 1a. The plot shows the daily surface chlorophyll measured by the glider with chlorophyll sub-daily variability marked by the light blue colour. This variability cannot be captured by the satellite due to its coarse resolution. The satellite is compared to the glider in the same plot, showing that in the coastal regions the satellite measurements can have substantial biases.

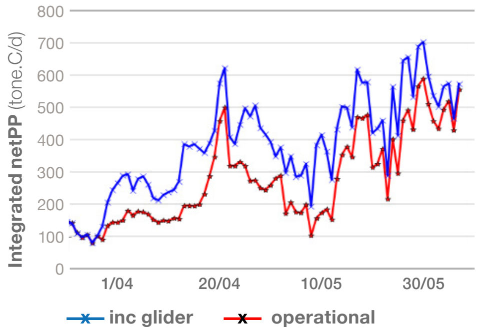


Figure 1b. The plot shows that assimilating glider chlorophyll into the model corrects the model bias in the net primary production. The primary production is shown as total integrated (carbon) biomass produced in time through photosynthesis in the whole water column throughout the glider region (with size of ~ 40 x 40 km).

Improved the state of the art

The system developed in CAMPUS assimilates the glider data into an operational model. This provides forecasts that are downscaled by a stochastic model and used to direct the glider towards the predicted blooms. This hugely improves the efficiency of the observing system, optimizing the observing strategy in real time, while reducing the need for human input.

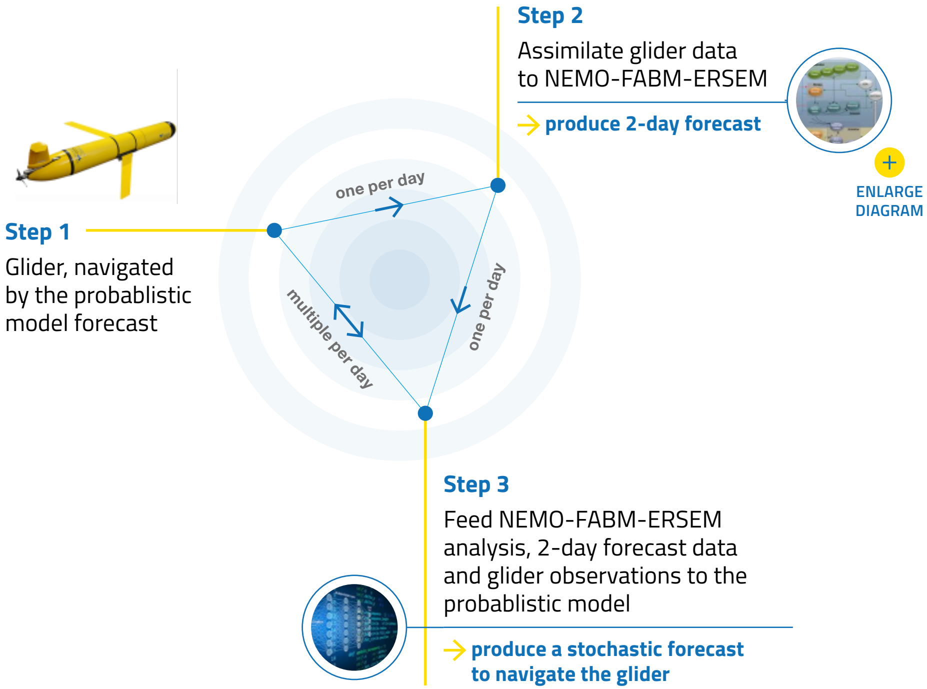


Figure 2. The schematic diagram showing the design of the smart autonomous system exchanging data between the glider, operational system and the high-resolution stochastic model navigating the glider.

Improved the state of the art
continued

The system's capability was demonstrated with a successful mission designed to track the onset of the phytoplankton spring bloom in the SmartSound region in the English Channel (Fig.3). The mission supplied essential data for key biogeochemical tracers of interest (see Fig.4), which was assimilated to improve the operational ocean forecasts (see Fig.1, right hand panel).

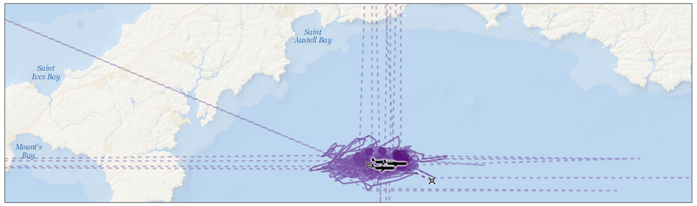


Figure 3. The area in the English Channel covered by the glider Frazil mission that took place between March and June 2021, and focused on phytoplankton bloom detection and observation.

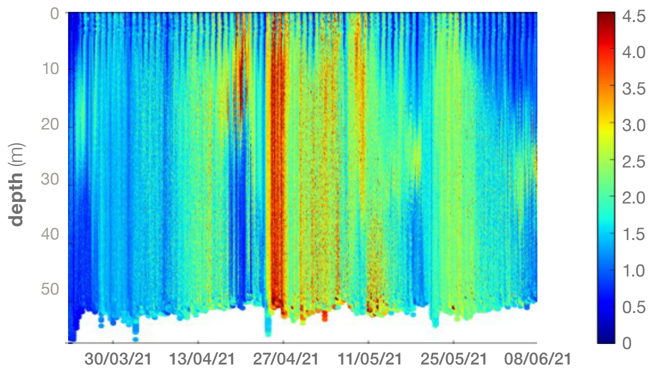


Figure 4. The observed chlorophyll (in mg/m^3) distributed both in time and throughout the whole water column, as provided by the Frazil glider mission.

Opportunities for exploitation

The system provided phytoplankton bloom observations (e.g. temperature, salinity, chlorophyll, oxygen, CDOM) that are publicly available from the BODC portal. The glider mission and the relevant plots for the measured variables were also monitored at a public (MARS, NOC) website. There is a great opportunity to use the glider technology to optimize observing systems and enhance our understanding of bloom dynamics on the North West European Shelf. Similar technologies could be adopted on a global scale, e.g. to control other key platforms such as Biogeochemical-Argo floats.

Roadmap for operalization

A complete integrated and autonomous monitoring network would require an increased number of autonomous vehicles and an agreed framework for their operation. Required data feeds need to be implemented, along with a reliable online quality control system for the glider observations. Operational forecasts are already run for the Copernicus Marine Service (CMEMS), and this framework could implement glider assimilation.

PML Plymouth Marine Laboratory

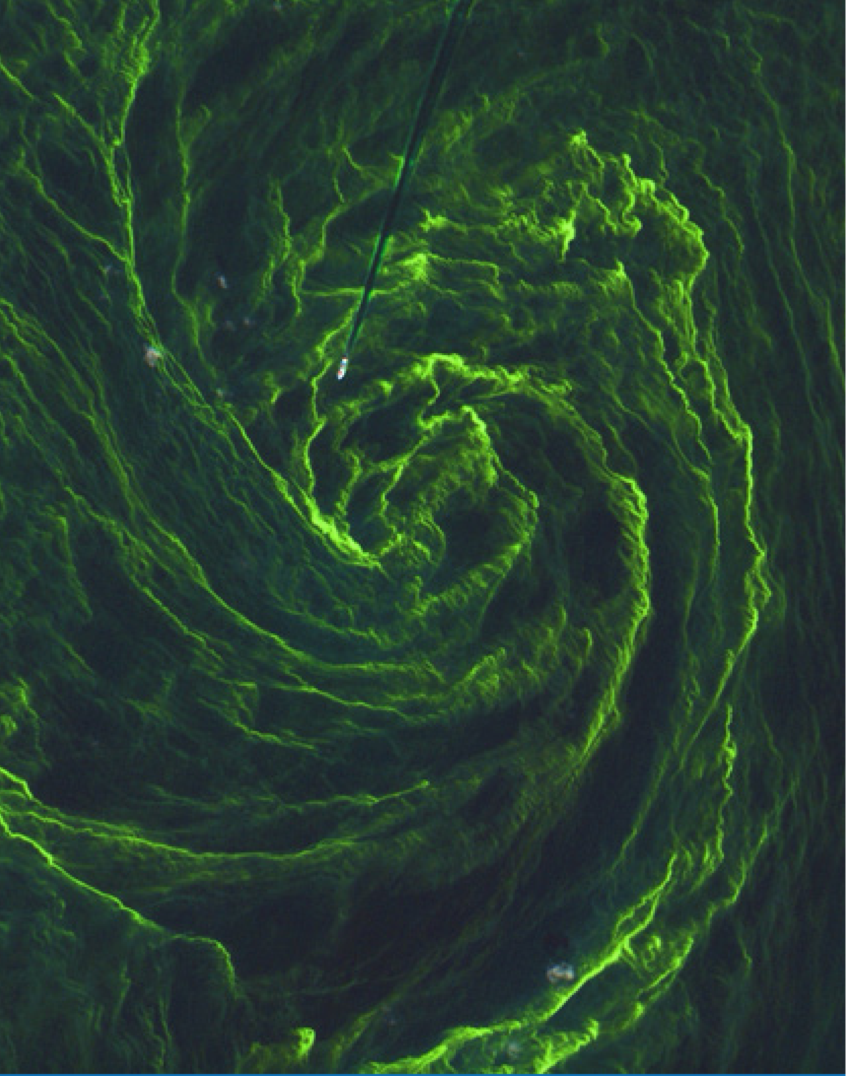
Further contact
jos@pml.ac.uk

References

Skákala, J., D. Ford, J. Bruggeman, T. Hull, J. Kaiser, R.R. King, B. et al. 2021. Towards a multi platform assimilative system for North Sea biogeochemistry. Journal of Geophysical Research: Oceans, 126(4) e2020JC016649. doi: 10.1029/2020JC016649

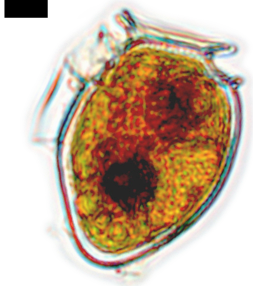
Rue, H, S. Martino and N. Chopin. 2009. Approximate Bayesian inference for latent Gaussian models using integrated nested Laplace approximations. Journal of the Royal Statistical Society, Series B, 71(2):319-392. doi: 10.1111/j.1467-9868.2008.00700.x

Smith, R.N., Y. Chao, P.P. Li, .D.A. Caron, B.H. Jones and G.S. Sukhatme. 2010 Planning and implementing trajectories for autonomous underwater vehicles to track evolving ocean processes based on predictions from a regional ocean model. The International Journal of Robotics Research, 29(12): 1475-1497. doi: 10.1177/0278364910377243



The eye of an algal storm in Baltic Sea photographed from space. Credit: European Space Agency, CC BY-SA 3.0 IGO.

3.
A MODEL BASED EARLY WARNING TOOL FOR ADVECTIVE HARMFUL ALGAL BLOOMS IN SCOTLAND



Authors: Dmitry Aleynik, Keith Davidson (SAMS)

The Scottish aquaculture sector has a value of ~£900 million annually and aims to double in size within a decade. Production is impacted by naturally occurring harmful algal blooms (HABs), which therefore need to be predicted reliably to allow sufficient time for mitigation measures on aquaculture sites. The CAMPUS project upgraded an existent HABs prediction system, enabling seamless internal and external data flows and Lagrangian virtual particles advection and tracers dispersion simulations. Finally, CAMPUS has helped to establish the user-friendly web-portal www.HABreports.org to facilitate the exploitation of HABs prediction by aquaculture stakeholders.

Better understanding and new capabilities

The prototype HAB warning system was funded by the EU FP7 Asimuth project (2013) and has been operational at SAMS since 2015. The CAMPUS project advanced this system by enabling a novel combination of advective models and initiation triggers, including: i) algorithms to identify the offshore location of HABs through satellite remote sensing and ii) microscope counts of algal cells to identify harmful biotoxin producing species at aquaculture sites through the Scottish regulatory shellfish monitoring programme. If either method provides counts exceeding predefined thresholds, virtual particles are "seeded" for advection into the flow fields. These fields are derived from an ensemble of hydrodynamic forecasting models.

Improved the state of the art

The CAMPUS project also has enabled the transition to higher resolution models, such as the new Met-Office Atlantic-Margin AMM15 (1.5km) model that includes hourly current predictions which, since autumn 2020, have been accessible via Copernicus CMEMS data-portal. With help from CAMPUS, SAMS' operational forecasting modelling system WeStCOMS has been expanded (Aleynik et al., 2016 to Davidson et al., 2021). Implementation of WeStCOMS allows prediction of the anticipated size and spreading trajectory of the detected HABs at aquaculture sites.

Roadmap for operationalization

CAMPUS also funded the enhancement of the dissemination and visualization component of the www.HABreports.org portal that was initiated with support from the Scottish government. It enables stakeholders and the general public to view HAB advection predictions in real time. A 'traffic-light' indexing system allows quick visual risk assessment of locations with elevated HAB/biotoxin levels with fading colours and diminishing particle size used within HAB spreading animations (Fig. 1). Numerical models output also become accessible via thredds.sams.ac.uk. To speed up frequent data assimilation SAMS deployed an autonomous ImagingFlowCytobot in Shetland.

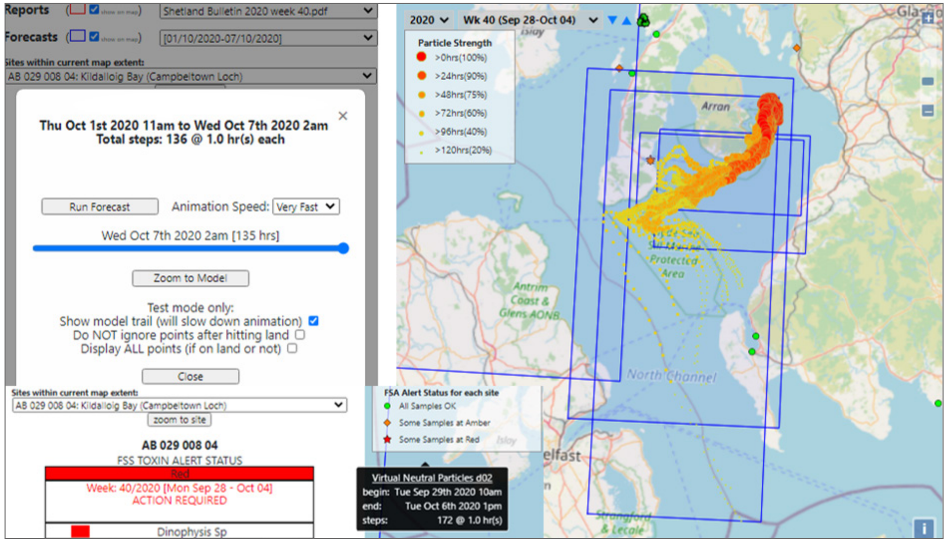


Figure 1. HAB development in the Firth of Clyde, Scotland on 28 September 2020 was notified with the VRS.L3 satellite-based algorithms and soon confirmed with cell counts of samples, collected from Campbelltown Loch. The shown excessive abundance of *Ceratium lineatum* and *Noctiluca scintillans* exceeded regulatory threshold concentrations of shellfish biotoxin producing by Dinophysis spp. Coloured particles show the modelled HAB spreading pattern prediction from our WeStCOMS-FVCOM model up to 4 October 2020.

“Mortality of farmed fish as a result of harmful algal blooms is an increasing threat to the aquaculture industry in Scotland. Scottish Sea Farms requires early warning of these events to implement appropriate mitigation. We are very pleased that the CAMPUS funding of the model based Scottish HAB early warning system has allowed it to progress to a point that we can now seek to use it operationally in our management practices.“

Ralph Bickerdike
Head of Fish Health and Welfare,
Scottish Sea Farms

Opportunities for exploitation

Since spring 2021 we have been rolling out model-based alerts for two of the largest salmon producers in Scotland (Scottish Sea Farms and MOWI), under a collaborative project supported by SAIC (Sustainable Aquaculture Innovation Centre) and entitled ‘Real time modelling and prediction of harmful algal blooms to minimize their impact on finfish aquaculture’. Once validated, this service will be offered more widely to the Scottish aquaculture industry.

Key stakeholders

Marine Scotland Science, Scottish Environment Protection Agency, Food Standards Scotland, finish aquaculture and shellfish industries and their insurers.

SAMS
Scottish Association for Marine Science

Further contact
Dmitry.Aleynik@sams.ac.uk,
Keith.Davidson@sams.ac.uk

References

Aleynik, D., A.C. Dale, M. Porter and K. Davidson. 2016. A high resolution hydrodynamic model system suitable for novel harmful algal bloom modelling in areas of complex coastline and topography. Harmful Algae, 53: 102-117. doi: 10.1016/j.hal.2015.11.012

Davidson, K., C. Whyte, D. Aleynik, A. Dale, S. Gontarek, A.A. Kurekin et al. 2021. HABreports: online early warning of harmful algal and biotoxin risk for the Scottish shellfish and finfish aquaculture industries. Frontiers in Marine Science, 8: 631732. doi: 10.3389/fmars.2021.631732

Kurekin, A., P. Miller and H. Woerd. 2014. Satellite discrimination of Karenia mikimotoi and Phaeocystis harmful algal blooms in European coastal waters: Merged classification of ocean colour data. Harmful Algae, 31: 163–176. doi: 10.1016/j.hal.2013.11.003

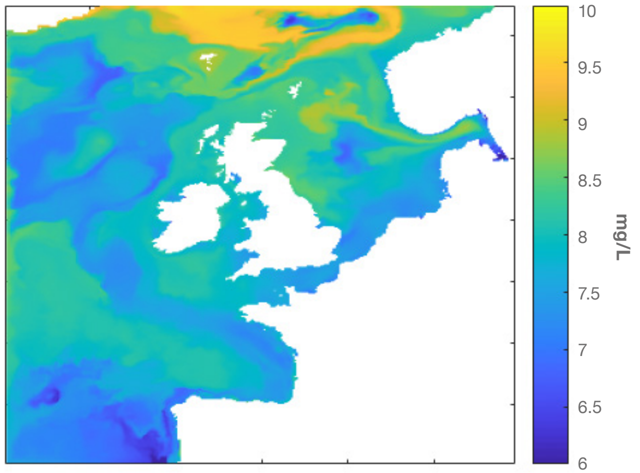


Figure 1. The map shows the near-bottom oxygen computed by using the CAMPUS assimilative outputs and the OSPAR assessment methodology. The oxygen indicator of the eutrophication criterion remained above the oxygen deficiency threshold (6 mg/L) in most of the North West European Shelf-seas (NWES), with the only exception of the Kattegat region east of Denmark. Relatively low oxygen values were simulated in the Central North Sea, where CAMPUS assimilated AlterECO glider oxygen data significantly reducing errors of the previous operational model.

4. OXYGEN DEPLETION IN THE NORTH WEST EUROPEAN SHELF SEAS

Authors: Stefano Ciavatta, Jozef Skakala (PML, NCEO)

Oxygen deficiency is a key eutrophication indicator, which is important for both determining Good Environmental Status in UK waters and for the operational management of fisheries. Work within CAMPUS assimilated oxygen data measured by AlterECO gliders into models, to significantly improve the predictive capability for oxygen deficiency in North West European Shelf-sea (NWES) waters. Identifying areas where oxygen depletion could endanger marine benthic life is important for the fisheries sector and UK marine status reporting (Fig.1).

Stakeholders are exploiting the CAMPUS oxygen datasets to investigate the increased mortality of commercial fishes in the NWES and the data is being input into the Cefas Marine Assessment Tool to address marine policy questions.

New understanding and new capabilities

CAMPUS demonstrated that enhancing the plankton component of the current operational model improves the oxygen predictions in the Central North Sea. The assimilation of the glider chlorophyll improved the oxygen predictions by up to 15% due to non-linear feedback on the phytoplankton, zooplankton and bacteria components linked to oxygen (yellow arrows in Fig.2).

Assimilating glider temperature data improved oxygen by 7%. AlterECO showed that oxygen concentrations are strongly impacted by stratification and transport. CAMPUS demonstrated that such impact is and these are well simulated by the operational physical model in the North Sea.

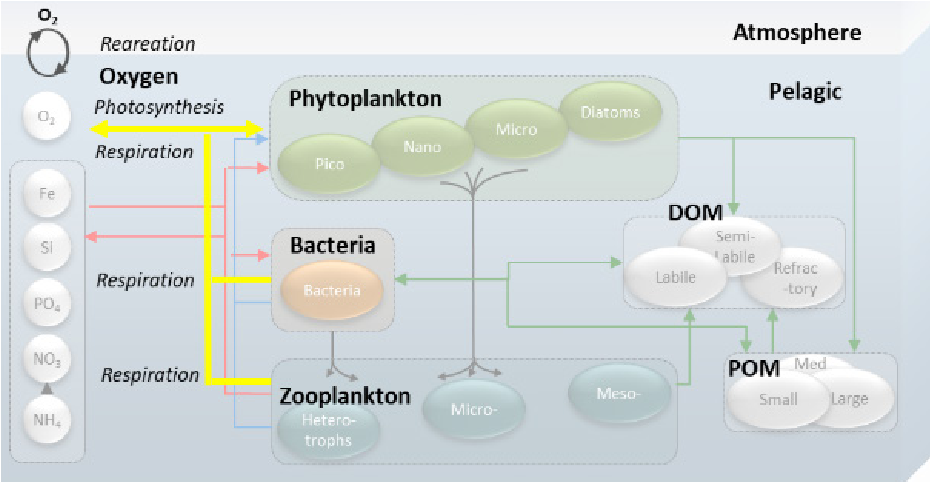


Figure 2. The European Regional Seas Ecosystem Model (ERSEM): Schematic of the processes and variables linked to the prediction of oxygen (yellow arrows) in the NWES with the ERSEM operational model. DOM and POM represent dissolved and particulate organic matter, respectively.

Improved the state of the art

CAMPUS has improved the accuracy of oxygen simulation by up to 95% in the Central North Sea. The previous model simulation (red line in Fig.3) overestimated the oxygen data of an AlterECO glider (violet line, measured along the gold area in the map – Fig.3). The assimilation of the data into the biogeochemical model led the CAMPUS simulation closer to the observed oxygen (blue line). The results are comparable to the one of the "multi-platform" assimilation of both physical and biogeochemical data, from both glider and satellite (green line). Crucially, data assimilation impacted the previous simulation in a large area of the North Sea (red area surrounding the gold glider trajectory).

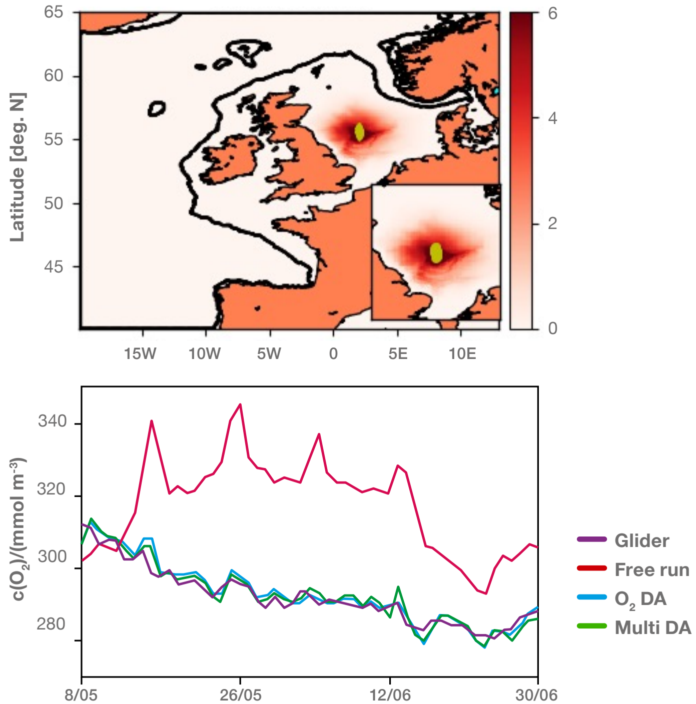


Figure 3. Simulation of dissolved oxygen in May-June 2018 with and without the assimilation of oxygen and physical data observed by the glider in the Central North Sea. In the map, the gold points represent the glider trajectory, while the red colour represents the area and intensity of the impact (%) of oxygen data assimilation.

1.
2.
3.
4.
5.
6.
7.

> "The CAMPUS project might be used to provide extremely valuable inputs for helping us start a more ecosystems-based approach to salmon management, examine the proximate drivers of increasing salmon mortality at sea, and ultimately determine if there are ways we can possibly mitigate or improve management to prevent stock collapses."

Dr Colin Bull
Principal investigator of The Missing Salmon Alliance

Roadmap for operationalization

The full operationalization of the CAMPUS method for ocean prediction requires an enlarged fleet of gliders. This would provide more data for assimilation in the most critical fall season and for bottom shelf areas in the Central North Sea. Automatic procedures for oxygen data quality control need to be developed for assimilating reliable data in near real-time into the operational model of the NWES marine ecosystems.

Opportunities for exploitation: Understanding operational use in marine policy, fisheries, and aquaculture

CAMPUS oxygen prediction and methods were communicated and disseminated via an innovative data portal, open webinar and a questionnaire, engaging DEFRA and the aquaculture community of the Aquaculture Research Collaborative Hub – UK (ARCH-UK) supported by UKRI.

CAMPUS oxygen predictions have highlighted potential causes of the decline of commercial fish stocks and demonstrated improvements in the assessment of eutrophication in the UK.

PML | Plymouth Marine Laboratory

Further contact
s.ciavatta@pml.ac.uk

References

Skákala, J., D.A. Ford, J. Bruggeman, T. Hull, J. Kaiser, R.R. King et al. 2020. Towards a multi-platform assimilative system for North Sea biogeochemistry. Journal of Geophysical Research – Oceans, 126(4): e2020JC016649. doi: 10.1002/essoar.10503848.2

5. INTEGRATED NETWORK DESIGN, COST EFFECTIVE ANALYSIS AND COST BENEFIT

Author: Liam Fernand (CEFAS), Jason Holt (NOC)

CAMPUS explored how to enhance the use of autonomous instruments, using understanding from the AlterECO project, combined with hydrodynamic / ecosystem models to provide a cost-effective marine monitoring system for the UK.

CAMPUS:

i. developed realistic scenarios for a future UK network, integrating a variety of autonomous vehicles and instrumentation with in situ observations,

ii. costed each scenario, and then

iii. demonstrated their effectiveness at accurately assessing the status of the UK seas relating to the OSPAR Eutrophication Assessment. The existence of the network can provide data in real time to be assimilated into models, which can then forecast water quality status.

New understanding and new capabilities

Cost effective network

OSPAR requires that the health of each ocean region is classified for various water quality parameters as high, good, moderate, poor, and bad, with the intention to return each water region to Good Environmental Status (GES). However the confidence of the each estimate is quite limited as the number of in situ data points is limited.

CAMPUS derived four scenarios of observational networks: Minimum fuss, (part time moorings and limited observation); Present system (combination of moorings, glider and ship-borne); Present plus (enhanced glider transects and ferry routes) and Enhanced autonomy (replacing moorings with autnomous surface vehicles). These were based on a combination of existing time series of water quality, data gaps and the natural length scale (Fig.1) at which observations are needed to resolve the environment.

New tools, which incorporate different data sources (Fig.2) have been used to assess the confidence of these scenarios in measuring the health status of the North West European Shelf Seas as defined by OSPAR.

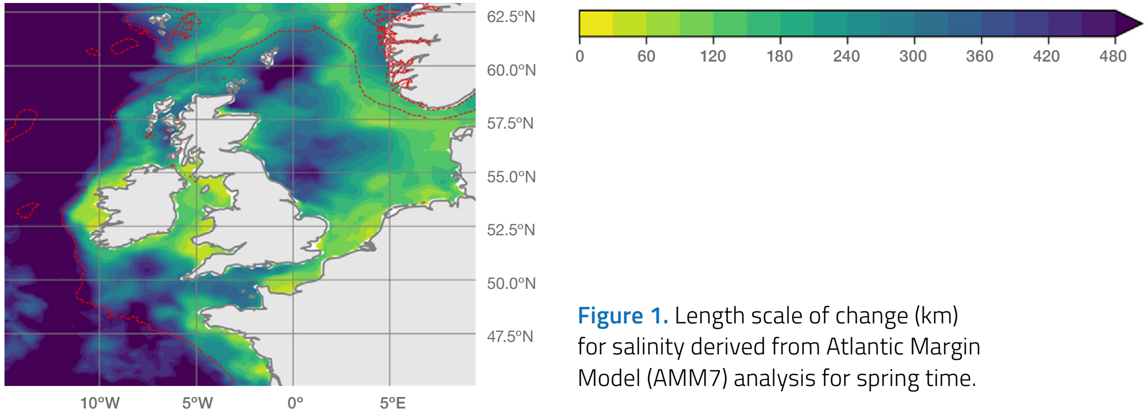


Figure 1. Length scale of change (km) for salinity derived from Atlantic Margin Model (AMM7) analysis for spring time.

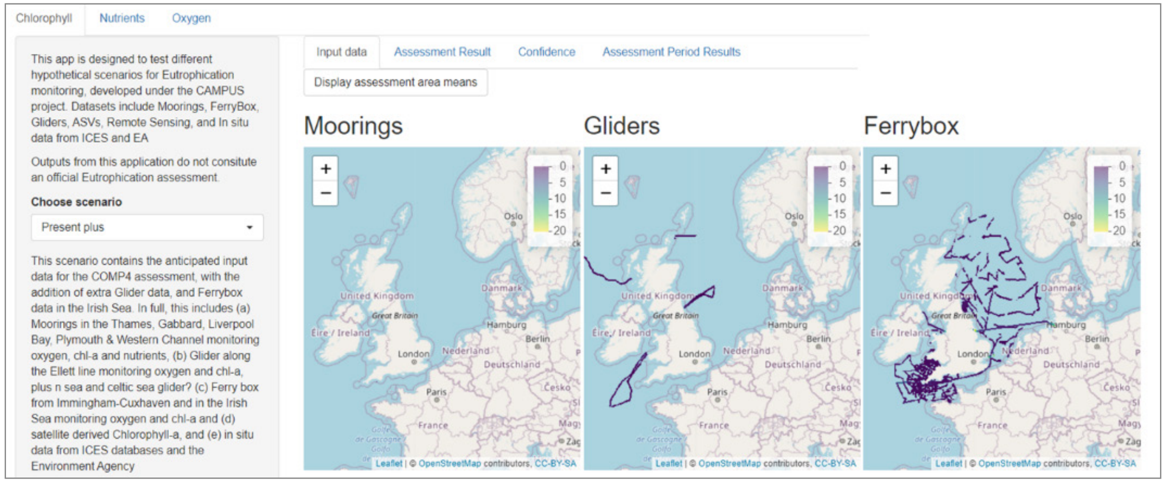


Figure 2. R – Shiny app to enable, moorings, gliders, ferrybox, spot samples, satellite, and model information to be assimilated.

1.
2.
3.
4.
5.
6.
7.

New understanding and new capabilities

Cost effective network
continued

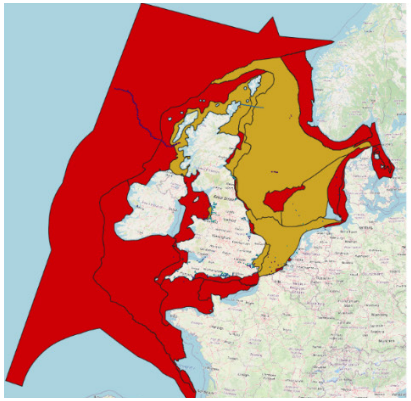
The outcome of the scenarios on the confidence of the assessment for each area is shown on the right (Fig.3).

Cost effectiveness of scenarios

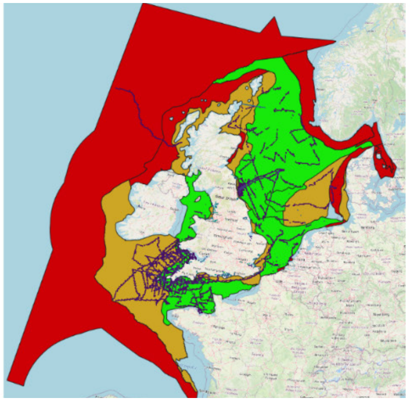
The outcome of the scenarios on the confidence of the assessment for each area is shown in Figure 3. The table within the figure shows the cost effectiveness of the four different monitoring scenarios and gives an indication of annual costs and the number of in situ data points. The number of regions with low, medium or high confidence metrics are given for the UK assessment areas only. The enhanced autonomy scenario has the highest number of regions with a high confidence outcome.

Figure 3. Outcome on change in confidence for each scenario with observations for the scenario overlain

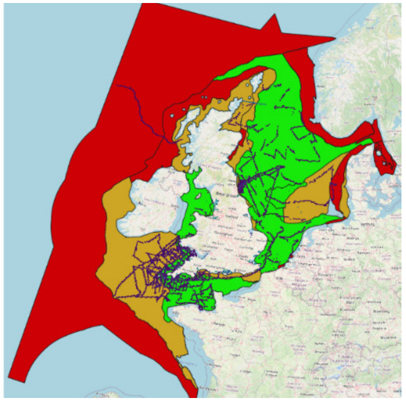
Confidence outcome
Low Medium High



Present
- Moorings
- One glider track
- Ship-borne measurements

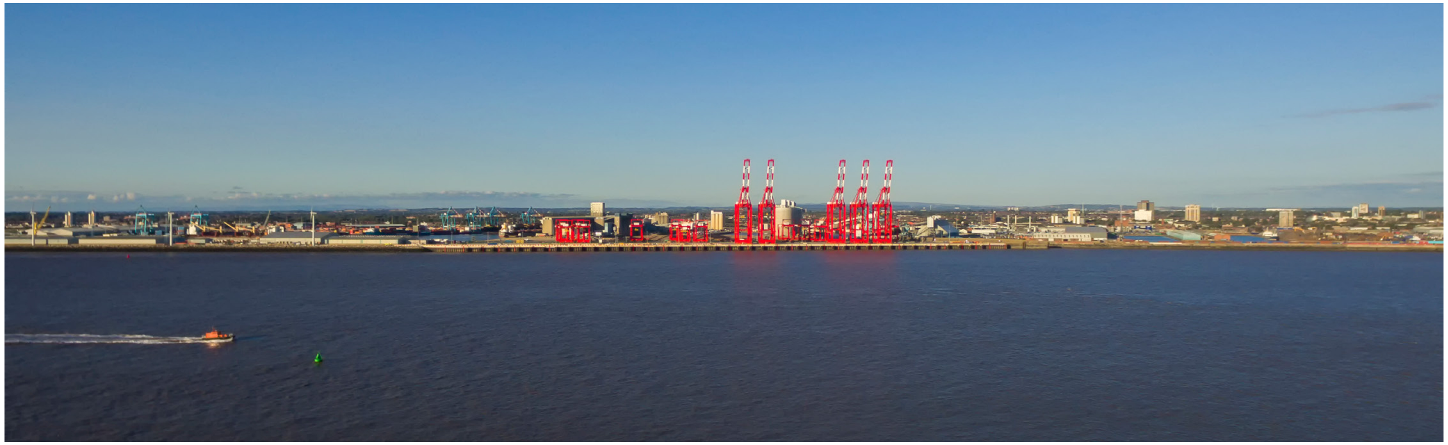


Present plus
- Moorings
- Three glider lines
- Continuous ship-borne measurements



Enhanced autonomy
- Autonomous surface vessels
- Three glider lines
- Continuous ship-borne measurements

		Minimum fuss	Present	Present plus	Enhanced autonomy
Annual cost		£371,000	£792,000	£977,000	£1,267,000
Number of in situ data points		434	812	10,169	25,405
Number of regions at overall confidence outcome	Low	25	22	11	11
	Medium	4	7	11	9
	High			7	9



Costs avoided benefits: Liverpool Bay case study

There are many benefits of having good environmental status, however, making the case for good monitoring needs more specific analysis, i.e. the cost of getting an assessment wrong. For example, in Liverpool Bay, considering dissolved inorganic nitrogen, the difference between each assessment criteria is approximately 8,500 tonnes per assessment classification. Abatement costs for removal of nitrogen vary depending on method from £5-£1,100 per kg. If poor monitoring assesses Liverpool Bay as MODERATE when the true state is actually GOOD, then, using the lowest estimate of abatement cost (£5/kg), this gives a minimum cost of £42,500,000. Alternatively if poor monitoring assesses the state as GOOD when the true state is MODERATE, then the loss of environmental services is estimated at £139,000,000.

Roadmap for implementation

The adoption of the enhanced autonomy network is recommended to Defra and UKRI funding organisations.

The network has been designed building on the existing UK National monitoring and modelling capabilities of UKRI and government agencies. The delivery mechanisms for data already exist but protocols need to be enhanced so that Quality Assured /Controlled data is distributed in a timely manner to international data centres. The integrations of the in situ data with satellite observational and marine models will greatly increase confidence in the quality of ecosystem assessments. Furthermore, such an integrated system would greatly increase the reliability and confidence for stakeholders in the outputs and forecasts of ecosystem models.

Cefas

Further contact
liam.fernand@cefas.co.uk

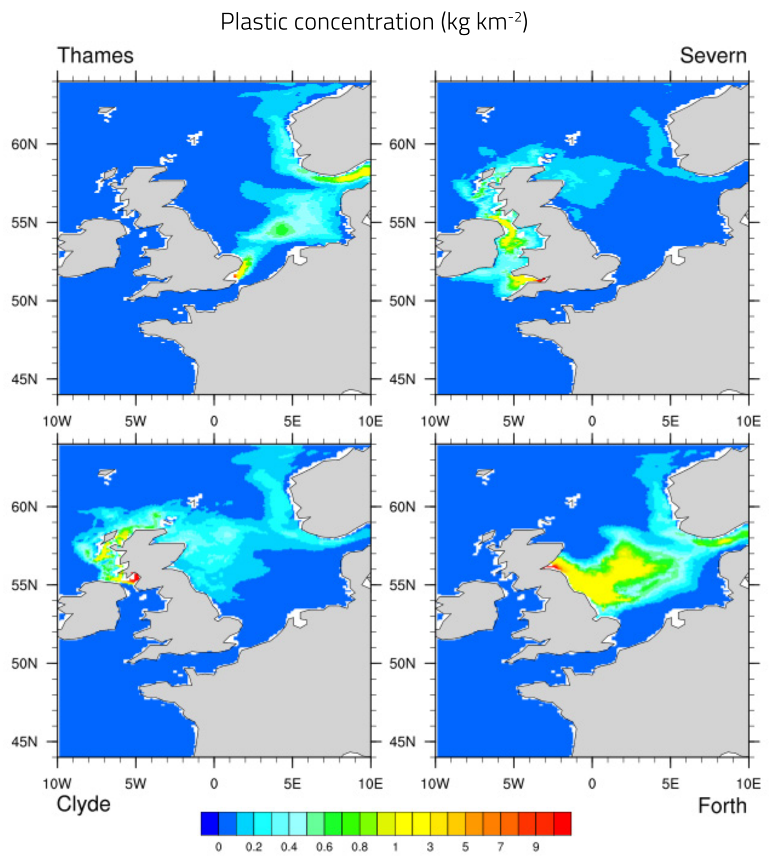


Figure 1. Distribution of plastics through the entire water column (in kg m-2 after 5 years of integration. Four sources of equal magnitude (~50 t year-1) are located at the mouths of the Thames, Severn, Clyde and Forth rivers. Dispersion of these plastics reaches nearly every corner of the European North West Shelf Seas.

6. DISTRIBUTION AND DISPERSION OF MARINE PLASTIC LITTER IN THE NORTH WEST EUROPEAN SHELF SEAS

Author: Miguel Ángel Morales Maqueda (Newcastle University)

Concerns about the impact of plastic litter on marine fauna and ecosystems, human health and tourism have grown dramatically in the last few years. Northern Europe is not a significant marine plastic polluter, but certain parts of the North and Irish seas are potential areas of accumulation of marine plastics. A model of marine microplastic dispersion in the North West European Shelf Seas has been developed within CAMPUS. With the model, we are currently investigating the fate of plastics released into the ocean from selected UK rivers (Fig. 1). Model simulations can be used to inform monitoring and cleaning operations, assist in predicting pollution risks to MPAs and, in general, be used for UK marine status reporting.

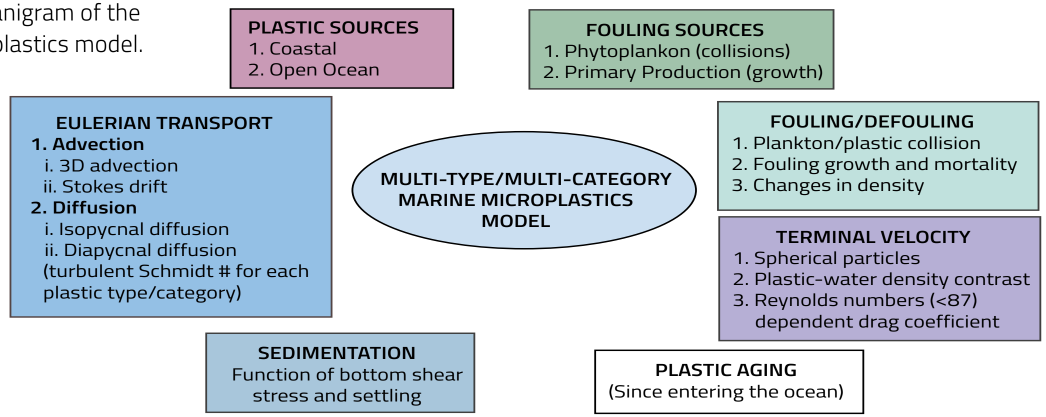
New understanding and new capabilities

CAMPUS has allowed us to create a model of marine plastic dispersion which is one of the most complete models currently available (Figuree 2). It includes buoyant and non-buoyant plastics and simulates the transport of plastics due to waves, currents and turbulent motions, the effects of biofouling and the settling and accumulation of plastics at the seafloor. Estimates of the amounts of plastics entering the ocean at coastlines (for example, through river discharge) or in the open ocean (for example, because of fishing activities) are too uncertain, if they exist at all, to warrant the use of any model to forecast actual plastic concentrations. Nevertheless, the model can be effectively applied to the determination of pathways of plastic litter dispersion and identify potential accumulation hotspots in the water column or in the sediments.

Improved the state of the art

The CAMPUS microplastic model is not only state of the art but is also already fully coupled to the NEMO ocean modelling system, which is used by the Met Office North-West European Shelf ocean forecasting systems. The model is, therefore, ideally tailored to investigate and forecast the distribution of marine plastic litter and its impacts in this part of the ocean. It can also be run offline requiring as only inputs the three-dimensional fields of temperature, salinity, phytoplankton concentrations and primary production, together with surface waves, surface currents from the Atlantic Margin Models at either 7 km or 1.5 km resolutions.

Figure 2. Organigram of the marine microplastics model.



Opportunities for exploitation

The model can be used by environmental agencies, such as Defra and Marine Scotland, to support baseline data collection and, eventually, monitoring microplastic dispersion and accumulation in the water column and the seafloor. Simulations carried out for CAMPUS have highlighted the potential for plastic litter to spread rapidly across the North and Irish Seas on timescales of just a few years, with ramifications for economic sectors that cause significant plastic pollution, such as fishing, and for the health of our seas, especially as regards the preservation of MPAs.

Roadmap for operalization

It is not clear what would be the interest of using this model in an operational way. The most promising applications of the model are rather those of a diagnostic character. For example, to establish the possible sources of plastic litter detected and a particular region or, conversely, to predict the likely fate of microplastics released from a coastal or open ocean source.

Newcastle University

Further contact
Miguel.Morales-Maqueda@newcastle.ac.uk

References

Kreczak, H., A.J. Willmott and A.W. Baggaley. 2021. Subsurface dynamics of buoyant microplastics subject to algal biofouling. Limnology and Oceanography, 66(9): 3287-3299. doi: 10.1002/lno.11879

Mountford, A.S. and M.A. Morales Maqueda. 2021. Modeling the accumulation and transport of microplastics by sea ice. Journal of Geophysical Research – Oceans, 126(2): ee2020JC016826. doi: 10.1029/2020JC016826

Mountford, A.S. and M.A. Morales Maqueda. 2019. Eulerian modelling of the three-dimensional distribution of seven popular microplastic types in the global ocean. Journal of Geophysical Research: Oceans, 124(12): 8558-8573. doi: 10.1029/2019JC015050

7. EXTRAPOLATION OF CAMPUS RESEARCH TO ODA COUNTRIES

Author: Susan Kay (PML)

Tools and methods developed in CAMPUS offer a way to implement marine monitoring in low and middle-income countries at lower cost than traditional ship sampling. Based on the experience of CAMPUS partners and a small informal survey of contacts in ODA countries, we find that:

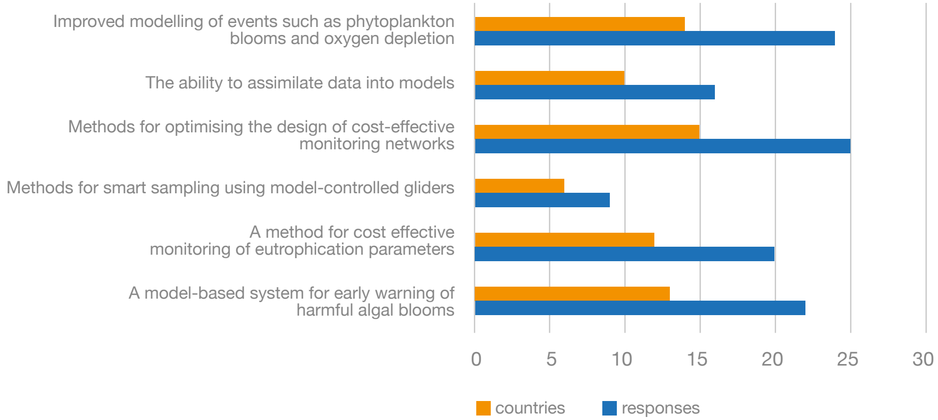
- CAMPUS tools would be of interest and value in ODA settings.
- Successful deployment will need investment in infrastructure as well as the direct CAMPUS technology.
- Listening to ODA partners and focusing on outcomes is fundamental to success.

> "Marine monitoring is Vanuatu's priority highlighted by the Vanuatu Oceans Policy and Fisheries Policy, but we need technical support and assistance in this area."
>
> **Sunny Kamuta Seuseu**
> *Project Manager Van-KIRAP Project,*
> *Secretariat of the Pacific Regional Environment Programme*

New understanding

The technologies and methods developed in CAMPUS would be of value in ODA countries. A small survey of PML contacts (30 responses from 17 countries) suggests that there could be interest in techniques for network design, improved modelling of phytoplankton blooms and oxygen depletion and methods for monitoring harmful algal blooms and eutrophication parameters.

Which of these CAMPUS methods could be useful in your seas?



Lack of infrastructure may be a barrier to roll-out. NOC, deploying autonomous marine vehicles in Tanzania for the first time, found that there were no suitable local ships. Cefas's work on water quality monitoring in the South Pacific was hindered by lack of laboratories. Responses to the PML survey indicate that models and data assimilation are used in less than half the countries represented. A successful project must be ready to provide the infrastructure that is needed in the short-term or, better, invest in long-term infrastructure development.

NOC's work in the Western Indian Ocean region also shows the importance of developing, sharing and retaining skills in the partner country. This is particularly true for data processing and analysis skills, which are essential for independent, informed use of autonomous vehicles and model outputs.

The Potential Fishing Zone service in India shows how marine monitoring can support local needs, given the right investment. The service provides information for small-scale fishers, based on integrated information from biogeochemical models, satellite observations and Biogeochemical-Argo floats.

Opportunities for exploitation

Small island developing states (SIDS), where marine resources can be particularly important for the economy and well-being, are likely to be interested in better observation and monitoring of the marine environment. Successful work will be founded on long-term partnerships and will focus on the use of the work to aid resource management and decision-making.

Short-term projects can have some success as demonstrators, developing experience and building local experience of what is possible and useful - NOC's work in Tanzania provides an excellent example (Palmer et al., 2021). But long-term impact will require a funding framework that allows for confidence in future funding opportunities to sustain development, retain skills and maintain equipment.

> "Palau and the successful conservation of the Palau National Marine Sanctuary would greatly benefit from the development of effective monitoring systems and being able to use monitoring data in simulations and predictive models."

Louw Claassens
Science officer and Researcher for the Palau National Marine Sanctuary

Photo: Michelle Devlin, Cefas

Roadmap for operalization

Based on the experience of NOC and Cefas, we suggest the following principles for implementing the CAMPUS work in ODA settings. These steps will help to maximise the likelihood of the work having long-term take-up and benefit:

- Work closely with local partners at all stages of planning and implementation. Start with the desired outcomes and identify which CAMPUS technologies are most relevant.
- Invest some time to look for previous work and existing data, which may be hidden.
- Assess local infrastructure (ships, labs, computing resource) and plan how any gaps will be filled. Plan for long-term investment in both infrastructure and skills.
- Communicate with local stakeholders and communities to explain the aims and get their support. Plan how the monitoring data will be made available and accessible.
- Expect logistics to be difficult and time-consuming.

There is potential for high-impact development spending, if given the necessary long-term infrastructure investment. The work would offer benefits for the management of marine resources and development of technical expertise in the partner country.

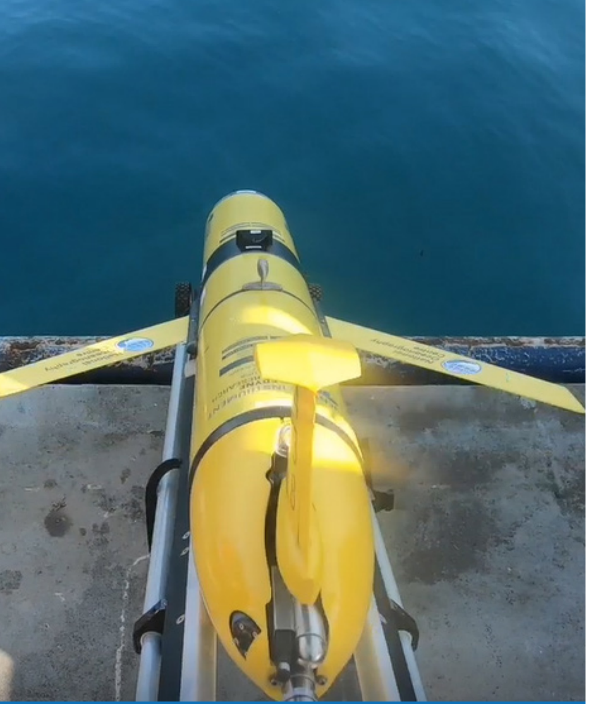
PML | Plymouth Marine Laboratory

Further contact
suka@pml.ac.uk

References

Palmer, M.R., Y.W. Shagude, M.J. Roberts, E. Popova, J.U. Wihsgott, S. Aswani et al. 2021. Marine robots for coastal ocean research in the Western Indian Ocean. Ocean & Coastal Management, 212: 105805. doi: 10.1016/j.ocecoaman.2021.105805

ESSO - Indian National Centre for Ocean Information Services. 2021. Potential fishing zone advisory. https://incois.gov.in/MarineFisheries/PfzAdvisory (Accessed 13 December 2021).



GLOSSARY

AlterECO
Alternative Framework to Assess Marine Ecosystem Functioning in Shelf Seas

AMM
Atlantic Margin Models

ARCH-UK
Aquaculture Research Collaborative Hub

BODC
British Oceanographic Data Centre

CDOM
Coloured dissolved organic matter

DIN
Dissolved Inorganic Nitrogen

ERSEM
European Regional Seas Ecosystem Model

EU FP7
European Seventh Framework Programme

FABM
Framework for Aquatic Biogeochemical Models

FVOM
Finite Volume Community Ocean Model

HABs
Harmful Algal Blooms

MARS
Marine Autonomous and Robotic Systems

MPA
Marine Protected Area

NEMO
Nucleus for European Modelling of the Ocean

NWES
North West European Shelf-sea

ODA
Official Development Assistance

OSPAR
Oslo/Paris convention (for the Protection of the Marine Environment of the North-East Atlantic)

QA/QC
Quality Assurance/
Quality Control

SIDS
Small island developing states

UKRI
UK Research and Innovation

WeStCOMS
West Scotland Coastal Ocean Modelling System

CAMPUS

SCIENCE IN ACTION

CONCLUSION

CAMPUS, AlterEco and the NERC MIAOS programme as a whole delivered a blueprint of a smart, fully integrated, and cost-effective predictive system for ocean biogeochemistry to meet the needs of policy and Blue Growth stakeholders.

Supported by this outcome, we envision the future implementation of a world-leading, fully operative modelling-monitoring network in the UK shelf-seas. This network would integrate high-resolution physical-biogeochemical models and machine learning algorithms with satellite data and water column observations of biogeochemistry, optics and acoustic. Short-term forecasts would lead the cruising of gliders towards predicted ecosystem "hot-spots": e.g., phytoplankton blooms, hypoxia phenomena. Implementation of such a network would require investment to sustain the continuous operation of smart gliders and a system for near-real-time control of data quality. Such a system would become a cornerstone of a Digital Twin of the Ocean for UK and overseas marine ecosystems. This system would also contribute to delivering a major outcome of the UN Decade of Ocean Science for Sustainable Development (2021-2030): "A predicted ocean, where society understands and can respond to changing ocean conditions".

For further information about the CAMPUS project please contact Stefano Ciavatta,
s.ciavatta@pml.ac.uk

To cite this document
CAMPUS Science in Action. Ciavatta S; Fernand L; Aleynik D; Davidson K; Skakala J; Morales Maqueda M A; Kay S; Grossberg S; Ford D; Rinaldi G; Smyth T; Holt J; Heard J. Report from the UKRI CAMPUS project.
doi: https://zenodo.org/10.5281/zenodo.6448596

The full community of CAMPUS researchers contributed to the work summarised in these case studies:

Plymouth Marine Laboratory
Jerry Blackford
Jorn Bruggeman
Stefano Ciavatta
James Fishwick
Susan Kay
Helen Powley
Jozef Skakala
Tim Smyth

National Oceanographic Centre
David Byrne
Jason Holt
Joanne Hopkins
Matthew Palmer
Jeff Polton
Sarah Wakelin
Charlotte Williams
Sarah Zedler

Met Office
David Ford
Rob King
Matthew Martin

Scottish Association for Marine Science
Dymitry Aleynik
Keith Davidson
Mark Inall
Matthew Toberman

University of Exeter
Peter Challenor
Shenan Grossberg
P.M. Prathyush
Gianmario Rinaldi

Cefas
Kate Collingridge
Stephen Dye
Liam Fernand
Kieran Hyder
Ellen McHarg
Joseph Ribeiro

Newcastle University
Miguel Morales-Maqueda
Andrew Willmott

Howell Marine
Dickon Howell
Tarquin Dorrington