Introduction

With a strong track record in excellent marine science over four decades, we are committed to addressing the challenges facing our ocean today for the benefit of us all.

As a truly interdisciplinary marine science centre, Plymouth Marine Laboratory (PML) is increasing understanding of how marine ecosystems function, how the ocean contributes to a thriving society and how this vital resource can be protected for future generations. Specifically its research focuses on the interactions between the marine environment and society in estuarine, coastal and shelf waters, as well as the upper layers of the global ocean.

PML science remains globally significant, as evidenced by the quality of its publication performance, often in high impact journals. 2013 saw a record number of 149 peer-reviewed papers published in the scientific literature.

For more information about PML please visit www.pml.ac.uk or follow us on Twitter @PlymouthMarine, Facebook, LinkedIn and YouTube (PMLAdministrator)
Welcome to PML

Welcome to our Annual Review 2013, which encapsulates our activities for the past year, a year that has seen PML continue to grow and enhance its position as a world-leading marine science centre.

Pivotal to PML’s success has been our pursuit of collaborations with partners across the globe and this approach has continued in 2013. Our fruitful, existing relationships with the University of Exeter and, further afield, with the Korea Institute of Science & Technology (KIOST) gain in strength. Working with the UK Met Office we launched a new databuoy at one of our long-term monitoring stations in the western English Channel. We were also invited to participate with the UK Met Office on the Joint Weather & Climate Research Programme (JWCRP) Strategic Programme Board, along with the Natural Environment Research Council (NERC).

Our excellent relationship with NERC continues through delivery of National Capability and a range of other research studies. These include the start of new projects under the Shelf Seas Biogeochemistry Programme, as well as our latest success with the NERC/Defra funded Marine Ecosystems Research Programme, demonstrating the strength of our research in both biogeochemistry and biodiversity.
PML’s excellent science is attracting even more attention globally, and the past year has seen an increase in approaches from institutes in countries with strong or growing economies, seeking partnerships and advice. We are especially pleased to have forged one such strategic alliance with Pontifícia Universidade Católica (PUC) do Rio de Janeiro, Brazil. We are also looking forward to strengthening ties with other South American countries.

Leadership is central to the way we work and PML is often the project leader, or partner of choice within UK and European marine research programmes. We are delighted at our ongoing collaboration with the European Space Agency and have started a number of new projects in the area of Earth observation, one of PML’s key areas of expertise.

PML’s capability in environmental modelling is recognised globally; the widely acclaimed MEECE Atlas, its relevance and its value to policy makers and other stakeholders is a tangible product which has further enhanced our international standing. PML’s reputation in modelling goes from strength to strength with many new projects coming on stream.

Earth observation and modelling underpin much of the science within PML and it is this ability to draw upon multidisciplinary teams to address scientific questions, to inform societal issues, that remains a key feature of how we operate. The year has seen many successes in bringing together the diverse strands of our expertise to bear on some of the challenges resulting from the interaction between humans and the ocean.

Sharing the results of our research is a major output for PML. Our publication output remains enviable with 149 peer-reviewed articles – a record year in our history and a testament to the breadth and quality of the PML team.

Beyond the academic community, our engagement with stakeholders continues to be strong; during the year an exhibition at the House of Lords attracted much attention and positive response. Targeted materials, including the Food and Agriculture Organization (FAO) sponsored Ocean Challenge Badge, Digital Explorer educational resources, as well as a series of short films about our science, have been produced to engage students, schools and the wider public in our science.

This has been another successful and exciting year but PML never rests on its laurels. Investment in our future is important – having the right tools for the job is essential. A complete refurbishment of PML’s server room is underway. This will double its footprint and provide the essential infrastructure upgrades necessary to house the planned installation of a new next generation, High Performance Computer. Investment in a second new databuoy has also been approved by our Board.

All of these exciting developments and more about PML’s world-class science can be found on our brand new website www.pml.ac.uk.

Also essential to our world-class science output is a whole raft of other expertise, including communications, finance, human resources, IT, marketing, technical services and project management. Investing in a strong team, including six new post-doctoral research fellowships, and providing the appropriate infrastructure and facilities, are crucial to our ability to understand the marine environment and help us to Listen to the Ocean®.

Prof. Terence Lewis FRCS
Chair of the PML Board of Trustees

Prof. Stephen de Mora
PML Chief Executive
PML uses the best available science, but also develops new techniques and approaches to provide novel scientific solutions to address those challenges facing the marine environment that are of interest to society.

By bringing together our own interdisciplinary teams to follow a multidisciplinary approach and working collaboratively with partners internationally, nationally and locally, we can address the ‘big’ questions. Tangible outputs from our research feed into outcomes that are relevant for decision makers, scientific strategists, education providers and industrial and commercial needs. PML aims to further scientific endeavour whilst producing potential solutions of benefit to society.

Key facts

- 166 members of staff - 67% scientists, 33% operations
- 50 hosted students from around the globe
- 26 visiting researchers each month
- 350 partners in 45 countries worldwide
- 149 scientific documents published in 2013
- 27% increase in the average impact factor per paper
The research we undertake is set within the context of challenges facing society. Through our own interdisciplinary teams and wider collaborations, our multidisciplinary research produces high quality outputs, leading to specific outcomes and increasing our understanding of the marine environment. This subsequently benefits society by providing information and scientific interpretation relevant to areas such as policy, industry and resource management, whilst also helping to identify topics of future research.
In partnership with the ocean

As the human population accelerates towards the nine billion mark, the demands we make on the ocean are increasing in parallel. Once thought to be inexhaustible and resilient we now understand that ocean resources are finite and the ocean itself fragile.

Yet still the ocean has much to offer, if only we can manage our expectations and its ability to provide in a sustainable way. At PML we recognise that the ocean is the great provider of food, fuel, energy, medicines and minerals. We also recognise that these can be harvested for the good of humankind while not being detrimental to the ocean.

Elements of PML science investigate potential new resources from the ocean while at the same time ensuring that the seas remain healthy and ecologically sound. PML’s interdisciplinary approach, and ability to muster multidisciplinary teams, aims to seek new marine products and services, while ensuring the ocean remains healthy. As never before humanity and the ocean are an essential partnership for the future.
Social impacts review

PML’s socio-economic group led the compilation of the report, ‘Social impacts of fisheries, aquaculture, tourism, recreation and marine protected areas in marine plan areas in England’, for the Marine Management Organisation (MMO). Understanding social impacts and value of marine activities is legally required to support the implementation of a holistic marine planning system for UK waters. However, evaluating social impacts and values is extremely complex as they vary so much over timescales and what might be positive for some may be negative for others.

The PML-led interdisciplinary team concluded, among other things, that social impacts and benefits to individuals and communities might well outweigh any short-term economic gain and valuing what the marine environment means to people is necessary when analysing and conducting trade-off scenarios.
Impacts assessed

Human demands on marine ecosystems are increasing, and Marine Protected Areas (MPAs) are acknowledged as being one method of maintaining ecological diversity in the face of multiple pressures. However, the establishment of MPAs is not simply an ecological desirability, there are social dimensions that have to be taken into account.

MPAs are the result of social processes or transactions, involving dynamic interactions between individuals and groups. They also have political and societal aspects including views on the desirable state of the marine environment. PML’s group of socio-economists and others looked at the social impacts of a fisheries’ closure in Lyme Bay in Dorset, UK.

The study, through face-to-face interviews, meetings and focus groups, engaged with as many stakeholder groups as possible ranging from commercial fishermen through anglers to birdwatchers, divers and service providers. The social impacts or ‘costs’ to stakeholder groups varied with their interests but are mostly borne by those who lost rights as a result of the closure. The study has provided valuable information, not just for the Lyme Bay closure but for any potential closures in the future.

Climate change, fish and fisheries

Fish and fisheries provide protein to billions of people worldwide, so any changes that may impact the productivity of fisheries are of great concern to the global human population. The marine science community now regularly uses climate change projections, generated by the world science community through the Intergovernmental Panel on Climate Change, to make its own qualitative and quantitative projections of marine ecosystem responses to a warming world.

This has resulted in a broad and large literature covering many aspects of climate change and the marine environment. Working within an international group of specialists PML has contributed to a thorough literature review of the published science to gain an insight into the likely impacts on fish and fisheries.

The review reached a number of conclusions and highlighted the need for continued interdisciplinary research across a number of topics.
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**Foothold for crabs**

A review of existing literature carried out at PML shows that offshore windfarms may benefit certain types of fisheries. Edible crabs and lobsters should be able to take advantage of the hard substrates of the turbine foundations in otherwise softer sediment areas, but there is little information about how these crustaceans react to noise, vibration and electromagnetic fields that are likely to occur around the installations.
Biofouling, barnacles and bacteria

Biofouling costs the shipping industry approximately US$60 billion each year; additional drag of up to 60% slows ships by as much as 10%, increases fuel consumption and thus costs by around 40% and adds to the CO₂ being emitted to the atmosphere from ships by anything from 40% to 70%, which exacerbates climate change and its impacts. Clearly, preventing biofouling before it begins is a major imperative for the shipping industry, as well as other industries, that deploy equipment on or below the sea: power stations, offshore renewable energy devices, sub-sea sensors, for example.

PML in conjunction with Göteborg University has been taking a close interest in the initial mechanism that attracts a biofouling organism to its substrate, the idea being that once the mechanism of attraction is known, steps can be taken to deter the initial colonisation.

Communities of microorganisms form thin coats over solid surfaces and it is known that components of the biofilms produce cues that draw invertebrate larvae and algal spores towards these surfaces, where they can establish themselves and continue to develop. It is the detail of the cues that intrigues PML scientists and has been the focus of research. Working on an existing hypothesis that the cyprid larvae of the barnacle Balanus improvisus ‘eavesdrop’ on the bacterial signal molecules N-acylhomoserine lactones (AHLs), single species biofilms of AHL producing bacteria were prepared.

Batches of cyprids were released into the wells containing the biofilm culture plates and monitored daily for settled larvae, exploring larvae and dead larvae. Single species biofilms of some bacteria were shown to attract larvae which then settled. In further experiments it was also shown that when AHL production was inactivated the ability of the biofilms to attract cyprid larvae of the barnacle ceased. Other biofilm producing bacteria that expressed the relevant genes for AHL were actively explored by the larvae but interestingly E.coli, that did not have this capacity, was not explored. Finally, synthetic AHLs at similar concentrations to those found in natural biofilms also resulted in increased larval settlement. The next step is to test this hypothesis further in more natural conditions.

Understanding how the AHLs attract barnacle, and other invertebrate larvae is a step in finding natural compounds that might inhibit their production – this is of great interest to those industries that carry the cost of biofouling.
Ballast test

The vast majority of international trade is carried via commercial vessels plying the world’s seas; combined with military shipping the global fleet reaches even the most far flung corners of the ocean. Each vessel has the capacity to carry hitchhiking organisms, encrusted to the outside of the ship or hidden away in the ballast water within.

Many such organisms may not survive when introduced to different environmental conditions but some do and, if they thrive, can cause significant damage to ecosystems and become a threat to human health. PML, through its commercial arm, PML Applications Ltd, has been investigating how to prevent or remove fouling organisms and how to screen ballast water to ensure it is clear of potential alien species before it is discharged.

PML Applications Ltd has been working in partnership with the cruise line, Carnival UK, and the wastewater treatment company, Alfa Laval, to conduct an independent shipboard test of the Alfa Laval Pureballast 2.0 fitted to a Carnival UK vessel. Both parties wanted to be sure that the retro-fitted system was able to meet the International Maritime Organization (IMO) D-2 discharge standard for ballast water under normal operating conditions. PML Applications Ltd. sampled the ballast water and analysed for the three IMO D-2 discharge standard categories. All were well within the IMO D-2 regulation standards.

There is a drive for surfactants to be derived from microorganisms, such as bacteria, to replace those traditionally obtained from petrochemical origins.

Bacterial biosurfactant

Some of the seemingly endless array of microorganisms to be found in the ocean are seen as problematic; others represent an enormous source of potential products that can be utilized commercially, these range from therapeutics to biofuels.

One area that is attracting more and more attention is that of surfactants, chemicals that lower the surface tension between two liquids or a liquid and a solid, and are used in many industrial and food production processes as detergents, wetting agents, foaming agents and dispersants. There is a drive for surfactants to be derived from microorganisms, such as bacteria, to replace those traditionally obtained from petrochemical origins.

The search for these biosurfactants is a novel area of study for PML and PML Applications Ltd, its commercial offshoot. Investigation of a novel strain of the bacterium Rhodoccus sp (strain PML026), revealed by screening PML’s in-house bacterial collections, showed useful properties and was singled out for further study. The bacterium was found to produce a biosurfactant which showed high surfactant properties under a range of conditions and could be a potential candidate for bioremediation in, for example, oil recovery or oil spillages.
In it for the long term

The world around us is experiencing global changes including rising temperatures and alterations to ocean chemistry. Coupled together, or working in tandem with a wider range of stressors, these are thought likely to lead to climatic and environmental changes at a level which will have serious impacts on biodiversity and, ultimately, our own well-being.

Predicting future change and contextualising effects and consequences depends upon a reliable historical record, providing baselines for comparison and statistical data that enable us to measure the rate and extent of such changes. Running in parallel with a wide range of projects at PML are long-term programmes aimed at gathering near continuous observations and measurements.

The Western Channel Observatory (WCO) and the Atlantic Meridional Transect (AMT), both part of UK National Capability, are two such initiatives which have been gathering data from our coastal sea and along a route into the South Atlantic, respectively. These have been supplemented by ongoing satellite Earth observations for a more global view. Collected data has an immediate use but also fuels longer term studies, populating environmental models which become predictive tools to use past and present data to inform us about possible future scenarios.
The new databuoy withstood 14 metre waves during the winter and now a second databuoy is planned for the L4 monitoring site.

WCO upgrade

In collaboration with the UK Met Office, PML has been able to replace and upgrade the autonomous databuoy at the Western Channel Observatory (WCO) monitoring station E1, some 25 nautical miles off Plymouth.

The UK Met Office is responsible for the meteorological parameters such as air temperature, humidity, atmospheric pressure, wind speed, wind direction, wave height and wave direction on the buoy. PML has brought expertise to this project in the measurement of oceanographic parameters and is reporting hourly the sea temperature, salinity, dissolved oxygen, chlorophyll fluorescence, turbidity, Coloured Dissolved Organic Material (CDOM), nitrate and Photosynthetic Available Radiation (PAR). The data is already being received by both organizations and PML is currently working to present this data hourly on the WCO website (www.westernchannelobservatory.org.uk).

Deployment took place in June thanks to the expertise of the crew of the Trinity House vessel THV Patricia and despite severe storms and 14 metre waves over the winter the E1 buoy remained on station and continued to transmit data back to land. This project is an excellent example of PML working co-operatively with other organizations. It is hoped that the E1 buoy is the start of many more future collaborations between PML and the UK Met Office in marine and environmental monitoring. A second replacement databuoy, at the L4 monitoring station, is planned for 2014.
The floats are at the cutting edge of ocean observation and will continue to monitor the water column as they drift with ocean currents for the next three to five years. Putting the data from the floats together with ship-borne observations and satellite remote sensed data will revolutionize our understanding of marine biogeochemistry.

**E.hux impacts CO₂ exchange**

Understanding the pathways, sources, sinks and impacts of CO₂ on the Earth’s climate system is essential for monitoring climate and predicting future scenarios. The global ocean is considered to be the only true net sink of anthropogenic CO₂, annually absorbing around 30% of emissions, much of it taking place in the North Atlantic, but it is not clear whether the global oceanic sink parallels increasing atmospheric levels.

*Emiliania huxleyi* (E.hux), a cosmopolitan cocolithophore species, is a major calcifier which can contribute to outgassing of CO₂ to the atmosphere and, when blooms decline, acts as a long-term carbon sink. Its mean annual surface coverage in the North Atlantic is around half a million square kilometres. By using 10 years of Earth observation data from the Sea-viewing Wide Field of view Sensor (SeaWiFS) PML remote sensing scientists have shown that it fluctuates massively under the influence of the El Niño/southern Oscillation index, there is a resulting average reduction in the monthly CO₂ sink of 1.2%, with a maximum of 32%. This suggests that variability, frequency and aerial extent of blooms can impact upon, and so should be included when modelling, the variability of the air-to-sea CO₂ flux.

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**Long term aids short term**

Underpinning the requirement for ecosystem-based management decisions is the need for objective, measurable ecological indicators. One of these is the timing and magnitude of the seasonal plankton cycle, especially the dominant event of the spring bloom. Inter-annual fluctuation in the plankton cycle is important for the marine ecosystem; has wide applications for fisheries’ management; affects our understanding of the carbon cycle and has effects on the upper ocean heat budget. Such fluctuations can be detected by ocean-colour radiometry, although the time series recovered this way is still relatively short, but can be complemented by continuous plankton recorder (CPR) data, which stretches back to 1931.

PML scientists, working with colleagues in Canada and using data from the Sir Alister Hardy Foundation for Ocean Science, demonstrated that the onset of the bloom in the North Atlantic, as derived from the CPR is similar to that from ocean colour, and correlate well with sea surface temperature (SST) and the North Atlantic Oscillation (NAO). The blooms appear to have been initiated later in the season in the 1980s than in the 1990s. Furthermore, the ratio of diatom and dinoflagellate abundances to total phytoplankton abundance showed close correlation with the NAO and SST.

By extrapolating the time series of SST and NAO over the period 1985-2009 to represent community structure, a decadel shift from diatoms towards dinoflagellates was shown.

**Adding a new dimension**

Research cruises continue to be a mainstay of ocean research; increasingly, satellites complement direct and local observation with global scale data at high temporal and spatial resolution. However, the former is expensive and the latter is largely restricted to cloud-free conditions and can only detect a limited set of ocean parameters. So we are only gaining a limited picture, mostly in surface waters, of what is happening in the three-dimensional ocean. Over the last few years a third observational opportunity has been introduced into the arsenal of technology available to the marine scientist – the Argo float.

*Argo floats are autonomous robotic platforms carrying sensors to measure physical characteristics of the ocean, such as temperature and salinity. There are about 3,500 argo floats across the world ocean; they spend most of their time parked at 1,000m depth but are about 3,500 argo floats across the world ocean; they spend most of their time parked at 1,000m depth but every ten days or so they drop to 2km, switch on their instruments and take measurements as they rise to the surface where they transmit data back to land via a satellite link; they then return to parking depth for another recording cycle. Now PML, working in collaboration with a French team, has added refinements to the floats together with ship-borne observations and satellite remote sensed data will revolutionize our understanding of marine biogeochemistry.*

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**Predicting toxic booms**

The diatom *Pseudo-nitzschia* is thought to be cosmopolitan and in many coastal regions, abundant. Globally 37 species are recognised, of which 14 are known to produce a potent neurotoxin - domoic acid (DA). DA is known to produce both acute and chronic effects on the health of many marine organisms including mammals, birds and humans through shellfish vectors which, if eaten, can lead to amnesic shellfish poisoning.

So its impacts are both ecological and socio-economic in scope and knowing what triggers *Pseudo-nitzschia* blooms and toxin production is of immense importance. Weekly samples collected at the Western Channel Observatory L4 site over an extended period of a year detected three species, which overlapped in time but differed in relative abundance, with the seasons.

Studying the seasonal variation in tandem with several environmental parameters, as well as water analysis showed the presence of DA peaking when the three species were present between June and July. Each of the three species was influenced by differing combinations of environmental factors, but the scientists concluded that there is potential for toxic events at this site, especially when the temperature of surface waters increased. The results from this detailed high-resolution sampling will aid the development of toxic bloom predictions.
Validating phytoplankton

Knowledge of phytoplankton cell abundance is important for the understanding of oceanic primary production, and thus valuable in comprehending a range of issues from carbon cycling to fisheries’ management. It is now recognised that different phytoplankton groups perform an array of diverse functions in the marine environment and, in recent years, the development of phytoplankton functional types (PFTs) has been defined to represent specific biogeochemical functions.

There is growing concern that the relative global distributions of PFTs are being modified by climate and other human driven changes. Detecting these PFTs from space via satellite sensors has increasingly been the subject of ocean-colour research and a variety of indicators has been devised which rely on interpretation of phytoplankton size or type from pigment data. However, independent valuation has been difficult due to a lack of appropriate in situ cell size data. A total of 1100 samples from Atlantic Meridional Transect data, collected between 1996 and 2009, and from other North Atlantic research cruises, were analysed by a PML-led team of scientists and used to test a conceptual model designed to calculate the fractional contributions of pico-, nano-, and microplankton to the total phytoplankton biomass.

The results obtained indicate that the estimation of cell abundances from remotely-sensed chlorophyll a seems to be a promising avenue and that long-time series of remote sensing derived information on size structure offer the possibility to detect shifts in phytoplankton communities.

Viruses from the depths

Broad-scale imagery from satellites has captured the vast milky-white colouration of the sea as Emiliania huxleyi blooms then dies and its calcium carbonate plates are released; it is one of the important bloom-forming algae in global biogeochemical cycling. Now PML scientists are applying molecular techniques to investigate coccolithoviruses, which cause bloom termination.

The PML team investigated both the biogeographic and temporal distribution of coccolithoviruses and their diversity using techniques to identify certain genetic markers establishing diversity and function during infection. Seawater samples taken during the Atlantic Meridional Transect-20 research cruise and from the L4 station of the Western Channel Observatory (WCO) over the years 2001-2007, as well as samples held in the PML DNA Archive, collected from a 1999 RRS Discovery research cruise through a bloom in the North Sea, were analysed. Only the North Sea samples showed evidence of coccolithophores with their viruses at the time of collection; mostly they remain ‘invisible’ for most of their life cycles. Nine new coccolithovirus genotypes were found from the AMT and L4 sites during the investigation; the majority at the deep chlorophyll maximum (DCM) layer, where phytoplankton exists away from the sea surface, and a further four genes (encoded during infection) were identified from the North Sea and L4 sites.

It may be that the depths are harbouring reservoirs of genetic potential, species of virus ready to infect the algal blooms that will form later near the sea surface. Indeed most of the AMT samples from the DCM had a higher diversity of coccolithoviruses. So the study confirms that coccolithovirus diversity exists, that it can be measured in the natural environment and it translates into environmentally relevant forms which contribute to and impact upon global ecosystem function, and that is important for the wider marine environment.
A question of time

Studies of the common shore-dwelling gastropod Littorina littorea carried out in PML’s mesocosm have thrown into doubt the reliability of short–term experiments when it comes to predicting the impacts of environmental changes. The structure and function of coastal marine ecosystems reflect the interaction of natural and, increasingly, anthropogenic drivers and, whilst it is widely recognised that individual changes can drive the biology of particular species, little is known about the impacts of multiple stressors which, however small, might drive significant physiological and ecological responses.

Ninety-one microcosms, small transparent plastic boxes with lids, were housed in PML’s mesocosm facility for a period of five weeks at various combinations of temperature and CO₂. Each of these microcosms held two of the gastropods; one had been kept under the relevant experimental conditions for five months, the second was exposed to laboratory conditions for two weeks prior to commencement of the experiment.

To summarise the results, grazing rates in animals pre-exposed to experimental treatments for five months prior to the experiment were greater, and they were more sensitive to changes in temperature and CO₂ than grazing rates in two-week animals; in effect the two-week animals showed a depressed metabolism. Metabolic rate was also measured and found to increase with temperature in the five-month group, which resulted in them requiring more food than two-week grazers.

This might mean that, for future studies, there is a need to estimate energy budgets to identify whether the depressed consumption in the two-week animals can be maintained in the longer term, or whether the animals are consuming metabolic reserves. This would seem to point to the need for a longer acclimation period before such experiments begin. The results also indicate that in the absence of long-term acclimation periods ecosystems might become trophically restructured.

Certainly long-term experiments to complement shorter laboratory studies are needed if predictions of impacts of climate change are to be of value.

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The ocean, vast, varied and in constant motion, has evolved through time and continues to change at a steady, natural rate. Now some changes are accelerating at a rate far beyond what could be described as natural – the common driver is human activities. The concept of climate change is well established in the consciousness of scientists, politicians and the general public; less well known, however, are its impacts on the marine environment. More recently recognised is ocean acidification which has the potential to impact a wide range of ocean life.

Plastic pollution is more obvious along our beaches, but beyond our sight are the microplastics that are impacting the very foundations of ocean food chains. PML is ideally suited to address these threats to the ocean’s sustainability by investigating impacts, contributing to the search for avoidance or mitigation measures and developing its science to face these modern threats to the life-giving sea. Having the ability to gather teams with cross-cutting interests and expertise enables PML researchers to work at a range of scales to gain the detailed information that builds into a wider and more readily understandable view. Intricate measurements of sea surface chemistry help explain global chemical cycles.

Understanding the effects of change on individuals, species, communities and ecosystems provides a glimpse of what may be around the corner for the world ocean, satellite imaging provides the wider view, modelling ties the threads together, and working in international collaborative partnerships brings a global perspective.
Microplastic, big problem

Plastic debris in the form of bottles, ropes, crates and a wide range of other discarded litter is a familiar sight on most of the world’s beaches. The impacts of plastics are well documented with many examples of mortality of wildlife: albatrosses, turtles and whales, for example, but scant attention has been paid to the so-called microplastics – tiny, often microscopic fragments that enter the sea directly or are the products of larger items when they break down - and how they affect zooplankton. It has been, until recently, a question of out of sight out of mind.

However, by using sophisticated bioimaging techniques thirteen zooplankton taxa were shown to have the capacity to ingest the minute plastic spheres that are used in some personal hygiene and cosmetic products and are commonly found as marine debris. Under laboratory conditions the plankton were exposed to seawater containing these tiny beads and then observed to monitor uptake. Sure enough the beads could be seen within the plankton’s digestive tracts. Further, the zooplankton were provided with algae to determine whether ingested plastics affected feeding – which they did.

Observations also showed that the plastic beads could lodge amongst the animals’ appendages, so potentially hindering movement, food capture and mating.

Microplastics are an issue of great importance, not simply for the zooplankton, but also for those animals further up the food chain and have the potential to accumulate plastic particles and the cocktail of chemicals they contain.

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Under-ice measurements showed persistent high CO$_2$ and low pH through late winter, providing an opportunity to study its effects on calanoid copepods and compare them with manipulated ocean acidification conditions.

**Migrate to survive**

The phenomenon of ocean acidification is only relatively recently recognised and, as such, there is only a short body of research to look back upon. However, it is known that the Arctic Ocean already experiences high CO$_2$ and low pH and there is the expectation that it will be the most rapidly affected by these changes. Within the Arctic zooplankton copepods are the dominant group and thus any impacts they may suffer could have important implications for the wider ecosystem. Gaining any knowledge of what happens under the Arctic ice is especially challenging, but now a team of scientists from PML and the Universities of Exeter and Manchester with colleagues from Canada, working together as part of the Catlin Arctic Survey, have obtained unique under-ice measurements that showed persistent high CO$_2$ and low pH through late winter, providing an opportunity to study their effects on calanoid copepods and compare them with manipulated ocean acidification conditions.

Amongst the copepods some migrated vertically each day and passed through different pH ranges; when exposed to manipulated high CO$_2$ conditions they showed only minor responses, probably because they already 'experience' quite large changes on a daily basis. Others, such as Oithona similis which remain in surface waters, exhibited reduced adult and larval survival. This highlights that globally important non-migrating species may be more sensitive to future ocean acidification conditions than migrant species.

One conclusion from this study may be that migratory species might not need to adapt to future scenarios, whereas the non-migrants may well face local extinctions as ocean acidification progresses. As many marine organisms time larval release to coincide with food availability, even small changes can upset this balance and have far-reaching consequences in the wider Arctic ecosystem.
Climate change, CCS and copepods

It has been established that some plankton groups are negatively affected by ocean acidification, while others are likely to be less sensitive. A group, including PML scientists, looked at the effect of predicted CO₂ levels (range 480–750ppm), as well as a very high (9830ppm) CO₂ treatment that mimicked a potential carbon dioxide capture and storage (CCS) leak, on the reproductive success of two copepod species Centropages typicus and Temora longicornis.

In this experiment there was no significant effect on egg production and hatching success under the climate change predicted CO₂ levels. However, under the CCS level treatment, egg production and hatching rate of C. typicus were reduced, but T. longicornis was unaffected. So while both species appear to be unaffected by exposure to CO₂ levels predicted for the year 2100, C. typicus does seem more sensitive to acute elevated seawater CO₂ than T. longicornis.

To generalise, effects are probably species specific but some might, depending on duration and season, be reproductively affected. As copepods are significant dietary components of larger animals this line of research deserves more attention.

Arctic microbes

An increasing body of work is showing that some organisms and ecosystems are prone to be affected by the chemical changes associated with ocean acidification, but little attention has been paid to the response of microbes and microbial-driven biogeochemical cycling. Nitrogen limits the biological productivity in most marine systems and so, of all the cycles that might be affected, it is the marine nitrogen cycle that should be of most concern and is likely to be more impacted than any other of the essential nutrient biogeochemical cycles.

Using mesocosms PML scientists designed an experiment to investigate how ocean acidification might affect the microbial process of ammonia oxidation to nitrate and nitrite, the pathway that makes nitrogen available to algae, so a key part of coastal productivity. Undisturbed Arctic sediment cores from Svalbard were incubated using seawater adjusted to five different CO₂ concentrations for a period of 14 days. DNA and RNA were extracted from the surface sediment in each of the treatments and the abundance of bacterial and archaeal ammonia oxidising genes and transcripts quantified.

Results suggest that microbes in marine sediments have different optimum pH requirements and the impact of ocean acidification on the microbial community is likely to be dependent upon the relative abundance of archaea and bacteria, but the bacteria appear to be more vulnerable.

Is enhanced alkalinity the answer?

With the seemingly inexorable rise of anthropogenic CO₂ into the atmosphere and then absorbed into the ocean, resulting in ocean acidification, various geoengineering solutions have been suggested as mitigating measures. One of these is chemical sequestration using a technique called ‘enhanced alkalinity’ to counteract the effects of lowering pH and increasing acidity.

PML and Plymouth University in a novel study used the robust shore crab Carcinus maenas as a test species to assess the impacts on marine life of adding ‘alkali’ to seawater. Crabs were exposed to the same levels of calcium hydroxide that would be required to reverse pH to pre-industrial levels and, despite the robust nature of the species, their acid-base balance and their respiration were affected, with females showing the strongest response.

The next step is to use much lower concentrations of calcium hydroxide levels that, while not reversing pH to the same extent, would counteract carbonate decline, the process that reduces shell and skeleton growth in a wide range of marine organisms.
It’s only words
ECO2 is a multinational, multidisciplinary project investigating the possible environmental impacts of a potential leakage of CO₂ from sub-seabed storage facilities. ECO2 draws expertise from many European countries and across a wide range of scientific and other disciplines including lawyers and economists. Within such a diverse partnership there is much room for misinterpretation of even the simplest terminology.

PML led a project with colleagues at the Universities of Edinburgh and Sapienza, Rome to bring together the lexicon of technical terms and jargon that have grown up around the burgeoning technology of CCS. This has been produced as a booklet – ‘The language of CCS – definitions and explanations’.

Modified model
The existing hydrodynamic Finite Coastal Ocean Model (FVCOM) was modified as part of the Quantification and Monitoring Potential Ecosystem Impacts of Geological Carbon Storage (QICS) project to gain increased resolution. It will take real data from QICS measurements and use it to populate the fine-scale model, thus providing a more accurate prediction of how plumes might behave in a complex coastal environment.

So far the modified model system shows great promise for addressing impact assessment and monitoring strategies. What has become obvious is that a leak will be complex and monitoring might need to be adaptable to take this into account.

Leakage impacts function
Sea urchins are especially susceptible to seawater acidification: not only do they possess a calcareous test, or shell, they also have no impermeable barrier between seawater and their internal body cavity, and they have no active transport mechanisms which can buffer changes in the acid-base balance of their body fluids.

Sea urchins move sediment which increases the supply of nutrients into overlying waters; clearly they support marine biodiversity. Two burrowing heart urchin species were the subject of investigations into the relationships between presence and body size, and the rates of sediment nutrient flux; also studied was the impact of seawater acidification on these relationships. In the experiment Echinocardium cordatum and Brissopsis lyrifera were held in captivity in their favoured substrates: sandy and muddy sediments respectively.

The study showed that they indeed play an important role in microbial cycling of nutrients and that elevated levels of CO₂ can disrupt this role. A conclusion from this is that leakage from sub-seabed carbon dioxide storage has not only the potential for mortality, but also the likely disruption of wider ecosystem function.

PML’s mesocosm can be manipulated to mimic temperatures and pH changes predicted for future seas.

In the experiment Echinocardium cordatum and Brissopsis lyrifera were held in captivity in their favoured substrates: sandy and muddy sediments respectively.
Shallow behaviour

In a collaborative study PML and the University of Aberdeen investigated the effects of a severe short-term exposure to acidified seawater on the ecosystem processes mediated by animals living within seabed sediments.

Brittlestars, Amphiura filiformis, the focus of the study, were observed to emerge from the sediment following acidification similar to a potential CCS leakage.

The brittlestars moved to shallower sediments, reducing considerably the depths available for occupancy. So, while a rapid and severe acidification event might not kill the animals, it may result in behavioural changes that could have longer-term implications for species survival, ecosystem structure and functioning.

A rapid and severe acidification event might not kill the animals but it may result in behavioural changes.
Biodiversity

The global ocean covers almost three-quarters of our planet’s surface, contains more than 95% of its living space and estimates suggest it harbours nine out of ten organisms on Earth. Yet this vast environment remains little studied and largely unknown. The shallower coastal waters are the most productive in the ocean and so have attracted the majority of attention over the last few centuries, but even here our knowledge remains piecemeal and there is still much to learn about even the most familiar waters around our own coasts.

Understanding biodiversity, how much there is, where the hotspots are, what it does and how we are affecting it are key questions being asked by PML scientists. Such questions are gaining in imperative as we humans continue to change the world in which we live. Biodiversity in the marine environment is complex and requires a multidisciplinary approach and interdisciplinary working methods – both strengths of PML.

Long-and short-term field observations, laboratory-based observation and manipulation, real-time field manipulation and the interrogation and combining of large datasets are brought together to help unravel relationships and functions within the marine environment from sediment to sea surface.

World-leading strengths of PML are its modelling and remote sensing capacities. Understanding biodiversity informs what we see in satellite images and populates models; both feedback into increasing our knowledge of biodiversity function and behaviour.
Surprise, surprise!

Plymouth Sound and the adjoining Western Channel are amongst the most studied stretches of sea on Earth and PML continues to build upon historic records through regular collections and sampling at a number of locations in the area as part of the Western Channel Observatory activities.

Occasionally ‘exotics’, animals or plants that are not expected and have come in from outside of the area, turn up and always raise a whole series of interesting questions. Earlier in the year, however, something really different was found in seabed cores that had been carefully lifted to minimise disturbance so they could be used in bioturbation observations in PML’s mesocosm - tissue-paper-delicate creatures emerged from the sediment.

A few centimetres across and radiating thread-like pseudopodia, nothing like these had been seen before from local seas and so they were an exciting find. They were soon identified as giant naked foraminiferans, very different from the usual microscopic, shelled forams normally observed.

Detailed identification awaits genetic analysis, but it is likely that it is the same or similar to a species that has only been found at two other locations in UK waters, off the coast of Scotland a few years ago – *Toxisarcon alba*. Its presence raises many questions: is this just a one-off occurrence; is it new to the area; has it always been here but overlooked; if it occurs off Devon and Scotland does it exist in between; and how does it fit into the benthic ecosystem? Even off our own shores, the most studied seas still hold surprises, but if we want to manage our seas sustainably we have to know what species live there and what part they play in marine ecology.

Biodiversity in the marine environment is complex and requires a multidisciplinary approach and interdisciplinary working methods – both strengths of PML.
Scaling down

Ecological models rely on accurate data for them to work effectively, the more detail, the higher the likelihood of greater precision in the model’s ‘predictions’. The complexity of ocean systems is magnified by its variability across time and space, so challenges the skill of models. In the deep sea it seems that structural and functional characteristics of benthic communities are regulated by a multitude of biotic and environmental processes acting in concert at different spatial scales. However, when compared to terrestrial ecosystems our understanding of spatial distributions of species and communities and the processes that regulate them is poor, even knowing at what scale to work has been elusive.

The nature of marine ecological research is that studies, especially in the deep sea, focus on limited scale ranges so only a partial picture of the processes driving the structural and functional diversity of communities is gained. By using an integrated dataset of free-living nematodes obtained from deep-sea sediments PML and collaborating institutes have managed to disentangle the different spatial scales and to understand the relative importance of some benthic communities.

The researchers analysed different community descriptors, including: structure, functional and structural diversity and standing stock at different scales covering two margins in the North-east Atlantic, several submarine canyons, channel and slope areas. Over a depth range of 700-4300 metres, several locations at each station were sampled and vertical sediment profiles obtained. Results indicate that it was the smallest spatial scale that was the most important for structural and functional diversity and standing stock. In fact, it seems that differences between sediment depth layers at a scale of centimetres are highly variable and much more important than larger scales when it comes to regulating benthic life and its functions.

NEODAAS images throw light on bloom formation

Near real-time images from the NERC Earth Observation Data Acquisition and Analysis Service (NEODAAS) and supplied by PML stimulated a serendipitous study which has shown, for the first time, the simultaneous existence of a deep chlorophyll maximum at 70-100 metre depths and a surface chlorophyll signature in the Madagascar bloom. NEODAAS provided images to the RRS Discovery during the 2005 MadEx research cruise. The images showed clearly that there was a plankton bloom to the East of Madagascar, so the opportunity was taken to investigate it using SeaSoar an advanced open ocean, towed undulating vehicle to acquire in situ data. SeaSoar carried a range of sensors for temperature, salinity, chlorophyll fluorescence and an optical plankton counter.

The Madagascar bloom shows significant interannual variability and at its largest extent can cover around 1% of the world ocean surface area. In the past it has been studied by ocean colour observation, but the lack of in situ data has left many questions unanswered. The coincidence of an available research vessel fortuitously able to detour to take ‘at sea’ samples and NEODAAS imagery of the bloom, from the SeaWiFS satellite observation platform, provided an ideal opportunity to fill in some of the knowledge gaps and to investigate how eddies modulated the bloom. The project team, led by colleagues at the National Oceanography Centre, Southampton, conjecture that the bloom may be fertilized by iron carried eastward from the upwelling region to the south of Madagascar; the spread of this iron limits the spread of the bloom and its consumption also determines the duration of the bloom.
PML analysed different community descriptors, including: structure, functional and structural diversity and standing stock at different scales covering two margins in the North-east Atlantic.

Enhancing microscopy skill

Plankton dominates the pelagic fauna both in abundance and biomass and so plays a crucial role in biogeochemical cycling, and as a key link in ocean food chains, including as food for commercially important fish species. Knowing which species are present, how they are distributed and how their numbers vary through the seasons is crucial to understanding marine ecosystem functioning, especially under the influence of global environmental change. While microscopical analysis by highly trained 'experts' remains the cornerstone of plankton research, species identification is complicated, challenging and time consuming.

Now researchers at PML have applied modern techniques to enhance the identification process. Plankton net hauls collected at the Western Channel Observatory L4 station were analysed by microscopy and by metagenetic analysis using the 454 pyrosequencing platform for Next Generation Sequencing (NGS). Over 400,000 sequences were obtained from all the samples collected in September 2010 and January 2011 representing 205 operational taxonomic units (OTUs) including 135 species, 11 genera and 1 order – a skilled microscopist was able to routinely enumerate only 58 taxonomic groups.

So the metagenetic approach was able to reveal a taxonomic richness that had previously been hidden and regionally rare species, such as Calanus finmarchicus, overlooked by microscopy, were picked up by NGS, as were parasites that were not identified in morphological analysis. So, the researchers conclude, advances in NGS technology, make them ideal for large-scale biodiversity analysis, especially being able to identify previously unseen diversity in samples. But, they caution the techniques do not replace the skill of the expert taxonomic microscopist.
Hidden complexity

The idea that the more complex a habitat is, the greater the biodiversity it can support is a cornerstone of current ecological theory. Hence those organisms that form complex structures, so increasing habitat diversity by providing niche and shelter opportunities are likely to harbour more species than bare substrate.

Such species are known as ‘ecological engineers’ altering or enhancing their environment, so being regarded as keystone species. The kelp Laminaria hypoborea is one such species, anchored to the substrate by holdfasts, with intricate internal structures and numerous entangling root-like haptera. It is host to the largest number of species in the kelp habitat and so provides an ideal opportunity to test the suggestion that habitat complexity leads to a greater number of species.

PML and Plymouth University investigated the theory with the help of the South Devon Healthcare NHS Foundation Trust at Torbay Hospital, who made a medical high resolution scanner (Discovery CT750HD, GE Healthcare) available for the study. Each of twenty holdfasts was imaged using the CT-scanner to gain a detailed picture of internal architecture. After scanning the holdfasts were opened and the organisms that inhabit them identified and counted. The CT-scans revealed that the number of haptera per cm² and the volume of each holdfast explained the variance in the communities within holdfasts in general and between individual holdfasts, rather than just size or surface area as was previously thought.

Laminaria hypoborea is host to the largest number of species in the kelp habitat and so provides an ideal opportunity to test the suggestion that habitat complexity leads to a greater number of species.
Diatom diversity

Collaborating with partners in Portugal and France PML has been investigating the structure and diversity of intertidal benthic diatom assemblages within the Tagus Estuary, Portugal. A total of 183 diatom taxa were identified. Sandy sediments showed greater diversity than muddy sediments, which generally were less disturbed; the muds harboured medium-sized species that showed seasonal blooming activity while the sands were home to smaller species that did not demonstrate any temporal patterns.

So intertidal diatom assemblages were largely defined by the interplay between the mudflat and sandflat sediment types, supporting the idea that they are not uniformly distributed across a tidal shore.

Just visible but overlooked

Meiofauna (0.1mm-1mm) is ubiquitous, living on and within sediments, where it can occur in vast numbers and high density, nematode worms are often the dominant metazoans present and hence of great significance in the ecology and processes at depth. PML, collaborating with Ghent University and others, has been investigating nematode communities, in the dynamic environment of deep-sea canyons which can also be subject to intense disturbance, so affecting the biogeochemical processes and benthic life beyond the continental shelf.

Concentrating on the Blanes submarine canyon slope system in the NW Mediterranean sediment samples and environmental data were collected over an annual cycle; nematodes communities were also sampled in November 2003 and April 2004 from 8 stations. The November samples showed an expected decrease in standing stocks with depth, whilst the May samples did not follow the normal decline in numbers with depth. However, the size of individual nematodes decreased over the same period, with a very high 70%-90% of juveniles.

This suggests to the scientists that ‘food pulses’ in the varied and dynamic environment of submarine canyons override normal (albeit food rich) conditions to enable opportunistic species to exploit added food richness and increase the population with new, smaller and faster maturing generations of nematodes. The research is part of an interdisciplinary project aimed at investigating the ecology of the Red Shrimp (Aristeus antennatus).
Governance and performance

Governance and performance are intrinsically linked, with the governing body of PML – its Board of Trustees – having ultimate responsibility for monitoring the organization’s performance and ensuring delivery of its outcomes.

Governance structure

There are ten Trustees who together bring a wide range of skills to the organization, including business, communication, financial, human resources and scientific expertise. During the year the Board evaluated its own performance, and the resulting actions are being implemented, in particular to further increase the amount of engagement with staff.

Complementing the main Board are a number of sub-committees, including the Audit and Finance Committee, the Remuneration Committee and the Science Advisory Council (SAC). In July 2013 a panel of the SAC undertook a review of PML’s research programmes in ocean biogeochemistry and biodiversity, as well as associated facilities and concluded that the quality of the science and facilities was outstanding.

SAC Review Panel Members 2013

Prof. John Field, University of Cape Town
Prof. James Barry, Monterey Bay Aquarium Research Institute
Dr Veronique Garçon, LEGOS Observatoire de Midi-Pyrénées
Prof. Tim Jickells, University of East Anglia
Prof. Alan O’Neill, University of Reading
Prof. Dave Raffaelli, University of York
Prof. Ulrich Sommer, GEOMAR, Kiel
Governance and performance

View online at www.pml-ar2013.org

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STOP PRESS: PML was highly successful in the NERC 2013 Big Data capital call. Funding for new Bio-Argo floats attracted the largest award with large-scale data services and visualisation facilities for Earth observation and model data also gaining significant investment.

In 2013 PML scientists produced a record 149 peer-reviewed publications, an increase of 17% on the previous year. The average impact factor per paper also increased by 27%.

During the year PML has sought new, or strengthened existing, strategic alliances with partners whose research is aligned with its own. In the summer of 2013 PML and the Pontifícia Universidade Católica do Rio de Janeiro, Brazil, signed a Memorandum of Understanding to work together to investigate fundamental questions relating to sustainable management of the ocean.

In July PML cemented its relationship with the University of Exeter with the signing of a second Memorandum of Understanding (MoU) in the last four years. The latest agreement formalises joint projects, enhancing several existing co-operative research themes, and creating new opportunities for collaboration to address some of the key questions facing the sustainable future of the ocean.

PML and the University of Exeter also became partners in Gw4+, one of a number of NERC funded Doctoral Training Partnerships (DTPs) announced in November 2013, which specialise in training environmental science PhD students. Gw4+ includes the Universities of Bristol, Bath and Cardiff, as well as other research organizations. PML is also part of two other DTPs, led by the University of East Anglia and the University of Southampton.

In addition to providing a learning environment for students, PML hosts a significant number of visiting researchers, on average 25 per month from all over the world, who choose to come to PML to advance their understanding in marine science.

Supporting science

Whilst excellent science is the lifeblood of PML, supporting the science by way of high calibre operational staff, facilities and systems is also of paramount importance. Investment has been made during the year in upgrading a number of PML’s facilities, not least of which is the work underway on transforming and improving our server room to accommodate a new high performance computer in 2014.

Other initiatives include:

- development of a new PML website – www.pml.ac.uk
- a new, open access archive for publications (with our local partners)
- building refurbishment

Performance

A key aspect of performance is financial wellbeing. PML’s current financial year ends on 31 March 2014 and indications are that PML’s turnover for the year will be of the order of £10m. PML scientists have been successful in securing some major new commissioned research contracts during the year notably with the Natural Environment Research Council (NERC) and the European Space Agency.

Competitively won National Capability funding from NERC supports long-term and underpinning science at PML in the following areas: the Atlantic Meridional Transect (AMT), the Western Channel Observatory (wCO), Ecosystem (Analysis) Modelling and the NERC Earth Observation Data Acquisition and Analysis Service (NEODAAS).

Investment in the future is of critical importance and during the year the Board gave its approval to fund six post-doctoral research fellows, who will take up their positions during 2014.

Sharing science

The previous sections of this Annual Review detail the research undertaken by PML during the year. One of the key outputs from PML’s research, which acts as a measure of performance, is scientific publications.
PML’s A to Z

Often taking on the role of project lead, PML scientists are currently involved in a wide range of marine science programmes in the UK, across Europe and further, with international partners. It is a strength of PML that it can bring together interdisciplinary teams to address the ‘big’ marine environmental questions through multidisciplinary science.

From air-sea gas exchange to zooplankton research PML’s A-Z of research presents a wide-ranging and impressive coverage of many of the challenges facing today’s ocean. Some of these projects, capabilities and services are highlighted here; for further information and details of other projects visit the new PML website www.pml.ac.uk/Research/Projects
→ AMT
The Atlantic Meridional Transect - biological, chemical and physical oceanographic research

→ ARSF
Airborne Research & Survey Facility

→ Biodiesel
an integrated approach to cost effective production of biodiesel from marine microbes

→ CANDYFLOSS
Carbon/Nutrient Dynamics and Fluxes of the Shelf System

→ DECIPHER
Decadal change in phytoplankton community ecology through remote sensing

→ DEVOTES
DEVelopment Of innovative Tools for understanding marine biodiversity and assessing Good Environmental Status

→ EarthServer
Solutions for 'big data'

→ ESA CCI
European Space Agency Climate Change Initiative

→ ESPA
Ecosystem Services for Poverty Alleviation

→ ECO2
Sub-seaCO2 Storage: Impact on Marine Ecosystems

→ ERSEM
The European Regional Seas Ecosystem Model

→ FastNet
Nutrient and carbon exchange between shelf and oceanic waters

→ FLOWBEC
Impact of tidal and wave energy devices on marine environment

→ GloboLakes
How lakes respond to climate change and other environmental influences

→ GreenSeas
Plankton and environmental change

→ Human health
Benefits from the marine environment

→ INDO-MARECLIM
Co-operation between Europe and India to understand environmental change on societies

→ i-MarNet
Developing ocean biogeochemical models

→ JWCRP
Joint Weather and Climate Research programme

→ Knowledge exchange
PML co-ordinates knowledge exchange for a number of significant projects including UKOA, VECTORS and OPEC

→ Learning
PhD, Doctoral Training programmes and other opportunities at PML

→ MEDINA
Improving Mediterranean policies, conventions and protocols

→ MedSeA
Ocean acidification in the Mediterranean

→ MyOcean2
Accessing satellite remote sensing data for European marine waters

→ NCEO
Predicting changes in carbon fluxes at the Earth’s surface

→ NEODAAS
Supporting UK science with remote sensing data

→ OPEC
Predicting the health of European marine ecosystems

→ PERSEUS
Supporting better management of the Mediterranean and Black Seas

→ Publications
2013 was a record year for PML with 149 scientific publications

→ QICS
Impact potential and monitoring strategies for CCS installations

→ RAGNARoCC
Exchange speed of natural and man-made gases at the ocean-atmosphere interface

→ RECIF
Artificial reefs from shellfish waste

→ RISCS
Potential environmental impacts of geological storage of CO2

→ Sustainability
The underlying driver for most PML projects

→ TwAP
Transboundary Water Assessment Programme

→ UKERC II
Impact of energy and greenhouse gas mitigation technologies in marine the environment

→ UKOA
Response of marine organisms, biodiversity and ecosystems to ocean acidification

→ VALMER
Valuing Marine Ecosystem Services in Europe

→ VECTORS
Impact of environmental and man-made factors on marine ecosystems

→ Vortex bioreactors
development and integration of vortex bioreactors into toilet systems

→ Western Channel Observatory
Long-term monitoring, observation and marine biodiversity reference site

→ XPRIZE
Supporting the search for new ocean acidification sensors

→ YouTube
Just one way that PML shares its science with a wider audience

→ Zooplankton research
Focuses on environmental change