



## THE NERC MARINE CENTRES' STRATEGIC RESEARCH PROGRAMME 2007-2012

### Theme 6: Science for Sustainable Marine Resources

To achieve an 'ecosystems approach' for marine resource management, we need to disentangle human impacts from natural variability, over a range of temporal and spatial scales. This Theme combines physical modelling and trophic dynamics to re-assess past changes in marine ecosystems and predict their future development. It includes consideration of the ecological impacts of renewable energy schemes, and factors affecting the introduction and spread of non-native species.

Theme 6 comprises three Research Units and eight Work Packages:

#### **Climatological trends in the physical environment (Proudman Oceanographic Laboratory)**

*POL Theme Leader: Judith Wolf [jaw@pol.ac.uk](mailto:jaw@pol.ac.uk)*

WP 6.1 Decadal variability of the northwest European shelf seas

#### **Understanding how environmental changes translate to ecological responses and economic impacts (Plymouth Marine Laboratory).** *PML Theme Leader: Jerry Blackford*

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WP 6.2 Re-analysis of existing long-term data sets to determine patterns and potential causal links

WP 6.3 Model hindcasts to determine the basis of observed variability and ensemble forecasting of human effects

WP 6.4 Using ecosystem knowledge to predict bioresources and services, and provide policy advice

#### **Integrating individual to population processes in a changing marine environment (Marine Biological Association).** *MBA Theme Leader: David Sims [dws@mba.ac.uk](mailto:dws@mba.ac.uk)*

WP 6.9 Examining regional differences in fish movements, behaviour and population structure

WP 6.10 Disentangling climate change responses and fishing impacts on marine fish and benthos

WP 6.11 Identifying colonisation processes and impacts of non-native species

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## Theme 6: Science for Sustainable Marine Resources

### Strategic setting

Marine ecosystems supply critical goods (e.g. food, renewable energy, transport) and crucial but less tangible services (e.g. climate regulation, waste assimilation) to society. Each use we make of the sea has important consequences for the ecosystem, ranging from the direct and indirect effects of fishing on habitats and populations (Jennings & Kaiser, 1998), to the spreading of non-indigenous species by ballast waters, and to noise pollution from both civilian and military sources.

Human exploitation of the seas, together with environmental change, is affecting marine ecosystems at a pace that is challenging our ability to provide innovative, effective and adaptive scientific solutions (Jackson *et al* 2001). As a result, the sustainability of the marine ecosystem is in question (Pauly *et al* 2002). Thus, there is a pressing need for knowledge to underpin sustainable management of marine ecosystems for stewardship of our seas (Defra, 2002; 2004; 2005).

Progressive ecosystem modifications resulting from human-induced environmental change are becoming evident across all scales from global (e.g. climate, pH, introduced species) through regional (e.g. fishing, eutrophication) to local scales (e.g. habitat loss, point-source pollution). There is already extensive evidence for climate change impacts on marine biogeography, biodiversity and assemblage structure (Beaugrand *et al* 2002; Genner *et al* 2004; Perry *et al* 2005); phenology (Sims *et al* 2001; Edwards & Richardson, 2004); food web dynamics (McGowan *et al* 2003); and productivity (Bopp *et al* 2001). Although the oceans have slowed the rate of atmospheric CO<sub>2</sub> increase, the resulting changes in pH, together with changes in temperature and circulation will undoubtedly be potent drivers of ecosystem change in the future. Climate change and other environmental stresses are at play in the increasing prevalence of non-indigenous species, spread through human agency (Ruiz *et al* 1999; Stachowicz *et al* 2002; Occhipinti-Ambrogi & Salvini, 2003).

The above pressures have resulted in large-scale and ongoing alterations in the structure of biological populations and communities, habitat complexity and persistence, and ecosystem attributes. With increasing demands on the use of marine resources, there is an urgent need for a step-change in our understanding of how the functioning of marine ecosystems responds to such pressures. How do these responses cascade through the trophic structure? and how might the supply of goods and services alter as a result? The development of advisory, management and governance tools are essential for sustainable exploitation of marine bioresources and habitats. A recent scoping study (Barange, 2005), commissioned by NERC, Defra and SEERAD, identified the national need for a strategic and holistic ecosystem-orientated research programme, integrating natural and social-economic approaches, to underpin sustainable management and exploitation.

The development of a sustainable strategy to manage the marine ecosystem will be largely dependent on knowledge of how bioresources and the environments in which they live respond to natural variability and human-induced changes. Despite there being substantial global evidence that both fishing (Jackson *et al* 2001; Pauly *et al* 2002; Myers & Worm, 2003) and climate change have impacted marine bioresources (Walther *et al* 2002; Parmesan & Yohe, 2003; Genner *et al* 2004; Devine *et al* 2006), how these interact has attracted relatively little attention. Commercial fishing has dramatically altered the structure of many target and non-target populations with many formerly abundant species within coastal ecosystems now functionally or entirely extinct (Brander, 1981; Casey & Myers, 1998; Frank *et al* 2005; Scheffer *et al* 2005). Climatically-induced regime shifts have also been implicated as major causes of fluctuation in species abundance acting through reproduction, phenology, recruitment, growth, and hence distribution (Walther *et al* 2002). Climate variability can exert a dramatic influence on population and assemblage dynamics (Stenseth *et al* 2002) potentially obscuring the effects of fishing pressure (O'Brien *et al*, 2000; Walther *et al* 2002). However, the extent to which climate forcing and fisheries exploitation co-vary to enhance or obscure changes in marine fish populations and communities is not understood.

Deciphering how population and food web dynamics relate to ecosystem processes, including biogeochemical cycles, and how they are in turn influenced by human activities is a major intellectual challenge. Ecosystem models need to incorporate bottom-up processes (e.g. nutrient loading) as well as changes in top-down controls, e.g. due to fishing. They also need to factor in newly-identified concerns such as pH change that will influence processes at all trophic levels (nutrient uptake, eutrophication, calcareous bodied consumers; Raven, 2005). They must also account for pelagic-benthic fluxes. Linked to this is the effect of habitat loss and degradation, either by persistent chemical pollution and eutrophication, or by physical damage (e.g. due to coastal and off-shore development, or by towed fishing gear) In addition, there is interference with behaviour of top predators due to noise and introduced electromagnetic fields.

The increasing prevalence of non-indigenous species, initially spread through human agency, is transforming some ecosystems. Invasions may be exacerbated by other aspects of local or global environmental stress, including climate change (Ruiz *et al.* 1999; Stachowicz *et al.* 2002; Occhipinti-Ambrogi & Salvini, 2003). Improved risk analysis for potential or existing introductions requires better understanding of the invasion process, while improved detection and rapid monitoring of alien species on appropriately broad scales is necessary for effective management.

Sourcing renewable energy from the sea is currently a subject of active development, especially relating to wave and tidal power, with the prospect of significant contributions to the UK and European energy portfolio. In order to support this endeavour, research is required on predicting changes in wave and wind regimes under future climate change scenarios, and quantifying and mitigating impacts on natural habitats and their commercially important and protected species. Progress is currently impeded by a lack of knowledge of these ecosystem interactions, which may occur during development, operation and decommissioning.

Over the past 30 years, global aquaculture production has increased rapidly, both in absolute and relative terms, compared with that from capture fisheries; it is likely that parity will be reached before 2030. UK production of cultured fish and shellfish is currently over 200,000 tonnes pa and farmed fish are Scotland's most valuable food export. This dramatic expansion of aquaculture has raised concerns relating to sustainable marine resource usage, transport of invasive species, eutrophication, chemical contamination, habitat degradation, community changes and detrimental interactions with wild populations (Black, 2001; Black *et al.* 2002). Yet aquaculture has the potential to make a sustainable and significant contribution to human health, and to the economies of remote, rural areas. To do so it must be appropriately located, supplied from sustainable resources and equipped for efficient recycling of energy and nutrients. Aquaculture must be integrated with other users and on a scale appropriate to ecosystem capacity. We currently lack the necessary knowledge of trophic linkages, efficiencies and feedbacks to optimise this process.

Our ability to manage marine resources in a way that reflects ecological processes and sustainability is currently constrained by the lack of quantifiable information on what drives variability across a broad range of scales and on how this variability affects ecosystem services (Perry & Ommer, 2003). Better predictive modelling of key physical and biological processes, across trophic levels and from the individual to the ecosystem, is urgently needed to underpin an integrated ecosystem approach. Such an approach requires effective synergies between the NERC research community in Centres and universities, government marine laboratories, management agencies and the Economic and Social Research Council to develop science-based ecosystem assessment methodologies capable of placing resource sustainability and ecosystem conservation needs in the context of the future multi-objective European Marine Strategy.

The science proposed here is fully consistent with NERC's current strategic priorities (NERC, 2002) and those under development for 2007-12 ([www.nerc.ac.uk/consult/strategy07/](http://www.nerc.ac.uk/consult/strategy07/)). It also directly addresses key gaps in developing the ecosystem approach, as identified by the UK government (PMSU, 2004; Defra, 2002, 2005) and a wide range of other national (RCEP, 2004; RSE, 2004), European (e.g. CFP, 2003) and international bodies (e.g. CBD, 2002; FAO, 2001, 2003).

### **Theme-wide science aims**

The over-arching goal of Theme 6 is to determine and disentangle the effects of anthropogenic impacts (global, regional, local) from natural variability on the provision of marine renewable resources, biological and non-biological. Working closely with Theme 3 (with its emphasis on the hydrodynamics and biogeochemistry of shelf seas), Theme 4 (relating biodiversity to ecosystem functioning), Theme 9 (predictive ecosystem modelling) and Theme 10 (long-term data sets), the knowledge gained will be shared with research users via innovative and adaptive policy advice, to assist sustainable development and stewardship of marine resources. The main science aims are as follows, grouped under five headings – although closely linked, as a continuum:

#### ***Physical drivers***

- To identify the processes that structure macro-scale components of ecological systems, e.g. sensitivity to temperature, salinity and physical disturbance due to currents, waves and bed stress, using physical modelling of the marine environment [POL, PML]
- To characterise and quantify the functional basis of the North East Atlantic ecosystem and North West European shelf seas during different states (regimes) experienced over the last 50 years [PML, POL, MBA].

#### ***Ecosystem dynamics***

- To identify the historical changes occurring in marine communities (pelagic to benthic), disentangling the effects of climate change and fishing by analyses of long-term data sets spanning plankton to benthos and fish [MBA, PML]
- To determine the spatial ecology of marine fish and shellfish populations in different geographic regions in relation to environmental heterogeneity, and hence identify biologically relevant management units and scales of response [MBA].

#### ***Dispersal of exploited and non-native species***

- To identify the role of dispersal in early life history of fish and shellfish and the mechanistic processes by which alien species successfully invade new marine habitats [MBA]
- To elucidate the source, frequency and scale of primary arrivals, mode of subsequent spread, and the prevalence of continuing immigration for representative marine introductions [MBA].

#### ***Renewable energy***

- To investigate the potential changes in wind, wave and tidal power distribution due to climate change and the impacts of renewable energy schemes on the physical environment, including implications for coastal processes e.g. morphodynamics, coastal defences [POL]
- To determine the influence of offshore renewable energy devices and aquaculture on natural populations, and on the integrity and persistence of marine habitats [POL, MBA].

#### ***Marine resource management***

- To predict ecosystem responses to future environmental perturbations in terms of the sustainability of marine bioresources [PML, POL, MBA]
- To provide policy relevant advice and decision-support tools for environmental managers to help maintain, and ultimately improve, the sustainability of marine ecosystems [PML, MBA, POL]
- To address the fragmentation of marine data by performing coupled analysis of several key observational data sets and identify the key gaps in long-term time series making recommendations for existing and future monitoring strategies [PML, POL, MBA].

### **Centre contributions**

The POL contribution considers the fundamental physical drivers of ecosystem change and this is closely meshed with the PML contribution, which focuses on lower trophic ecosystem function. Together, they consider how the physical and environmental drivers act to structure planktonic communities and how they in turn interact with higher trophic levels. The MBA Research Unit focuses on higher trophic levels, considering the environmental processes that contribute to the spatial dynamics and abundance changes of marine animal populations (native and non-native)

across a wide range of scales. During the course of this work, information and ideas will be shared between all Centres, promoting interdisciplinary approaches and allowing efficient response to new environmental issues and policy scenarios as they emerge.

## **Climatological trends in the physical environment**

*Contribution to Theme 6 by the Proudman Oceanographic Laboratory*

### **Background**

POL's capability in integrated systems modelling makes it ideally placed for investigating effects of changes in the natural environment. The coupled hydrodynamics-ecosystem model POLCOMS-ERSEM (Allen *et al* 2001; Holt *et al* 2005) has been developed in a close collaboration between POL and PML over the last seven years through core funding, numerous NERC and EU projects, and Met Office commissioned research; it has been cited as the most advanced model of its kind (Raddach & Moll, 2000). Recent developments to include surface waves (WAM: Wolf, 2004) and improved turbulence parameterizations (GOTM; Umlauf & Burchard, 2005) substantially enhance its capability. New opportunities exist for validation against the increasing number of long term data sets; e.g. arising from the Marine Environmental Change Network (MECN), and the Helgoland Marine Biological Station. Computing power is now sufficient to perform these long-term (multi-decadal) runs of coupled models, and recent atmospheric model re-analyses provide surface forcing over time scales of 50 years. POL has been involved in defining eco-hydrodynamic units for the JNCC Irish Sea pilot project on habitat mapping and the follow-on UK waters SeaMap project. It is therefore exceptionally well-placed to deliver the resource and marine environmental mapping required for management of the UK coastal seas.

### **Aims and rationale**

Shelf seas have low volume, and low thermal and mechanical inertia (cf the deep ocean), so their physics is strongly constrained by external forcing from the atmosphere, oceans and rivers. Hence any attempt to assess the response of shelf seas to climate change needs to start with knowledge of the sensitivity to these forcing factors in a deterministic (rather than statistical) fashion.

The focus of this Research Unit is to quantify the natural and anthropogenic contributions to changes in physical processes e.g. temperature, salinity, location of fronts, wave climate and transports, occurring in northwest European shelf seas over the last 50 years and assess the likely changes in the next 50 years. POL will work in close collaboration with PML, MBA and SAMS on understanding the effects of these variables on biological responses. Specific emphasis will be on the strategic needs, such as exploitation of biological and energy resources. Multi-decadal runs of coupled physical-ecosystem models will be analysed to enhance our understanding of the processes affecting biological resources, map renewable energy sources and investigate impacts of climate change and exploitation of resources on coastal defences and habitats.

This work will help to determine the physical causes of inter-decadal change in ecosystems, together with the likely environmental responses to various management policies e.g. marine reserves, exploitation of renewable energy, fishing, and aggregate dredging. It will also consider the likely impacts of projected climate change on the distribution of marine resources.

## **WP 6.1 (POL) Decadal variability of the northwest European shelf seas**

### **Specific objectives**

- i) Quantify the relative importance of atmospheric, oceanic and riverine forcing on shelf sea hydrodynamics and identify how these signals propagate through the ecosystem to higher trophic levels.
- ii) Identify mechanisms by which climate change affects these interconnections and quantify the expected levels of natural versus anthropogenic variability on decadal time-scales.

- iii) Investigate the potential changes in wind, wave and tidal power distribution due to climate change and the impacts of renewable energy schemes on the physical environment, including implications for coastal processes e.g. morphodynamics, coastal defences and habitats.
- iv) Implement models to aid marine spatial planning and management in order to minimize damage to marine habitats caused by exploitation of marine resources

### Approach and methods

This part of Theme 6 is closely linked to Theme 9, with the latter developing modelling tools and providing the base-line multi-decadal ( $\pm 50$  yr) runs. These will include future climate change scenarios, which will be validated (also in Theme 9) against existing and projected datasets, e.g. long time series such as collected in the EU-MAST NORWESP project (Radach & Gekeler, 1996), coastal observatory data, EO and other *in situ* measurements (e.g. from Theme 10). These simulations will use a range of forcing data sets to investigate the sensitivity of the shelf sea hydrodynamics to large scale oceanic and atmospheric variability and explore different physics and numerics, complemented by process model studies in Theme 3.

In Theme 6, POL will focus on the analysis of model predictions of physical variables, their sensitivities to forcing and consequent variability in biophysical interactions (with PML WP 6.3). We will address pressing science questions related to the management and exploitation of marine resources, examining the 'best' long (50 yr) simulations of the coupled POLCOMS-ERSEM-GOTM-WAM system to quantify the climatology and trends of key variables. Through additional high resolution model simulations we will assess the impacts of using biotic and abiotic marine resources (e.g. fishing, dredging or wind farms) on the physical environment and the health of the ecosystem, and identify an appropriate modelling framework for management of shelf seas. Specifically we will:

- Identify the sensitivity of the model to the forcing terms (oceanic, atmospheric, riverine) and examine how these sensitivities propagate from physics to ecosystem
- Examine the modes of variability of the temperature, salinity and transports of the NW European continental shelf over a 50 year time scale, including future climate scenarios
- Use the model results in collaboration with other institutes to test hypotheses on sustainable exploitation of shelf seas

### Summary of research plan and main deliverables (WP 6.1)

2007 - 09	Analysis of multi-decadal runs of coupled wave-current models, producing climatological maps of tide and wave energy
2008 - 10	Analysis of multi-decadal runs of coupled physical-ecosystem model producing better quantified maps of benthic habitats by including the relevant physical variables such as temperature, salinity and bed stress
2009 - 11	Analysis of model sensitivity studies (carried out in Theme 9) to improve understanding of the sensitivity of key variables to changes in meteorological, ocean and river forcing
2010 - 12	Analysis of the trends in the multi-decadal model runs to improve our understanding of the changes in shelf seas due to natural and anthropogenic effects.

## Understanding how environmental changes translate to ecological responses and economic impacts

*Contribution to Theme 6 by Plymouth Marine Laboratory*

### Background

The need for an ecosystem approach to understand marine resources and their vulnerability is highlighted in many recent policy and strategic recommendations (CBD, 2000; FAO, 2001; CFP, 2003; Defra, 2002–2005; RCEP 2004), reviewed by Barange (2003, 2005). The overall need is for a management regime that maintains the health of the ecosystem alongside appropriate, multiple human-uses of the marine environment, for the benefit of current and future generations. Such concepts are driving the development of the UK Marine Bill, the European Marine Strategy and

other legislation., and the practicalities of their implementation are a concern of Defra, EN/NE, SNH, CCW, EA and regional coastal zone managers.

Goods and services from the marine environment include food provision, raw materials, nutrient cycling, gas and climate regulation, and resilience. Each of these map onto a different set of ecological processes (de Groot *et al* 2002), the relative importance of which varies across temporal and biogeographic scales. The marine environment is dynamic, and currently in a state of flux – experiencing local, direct perturbations and indirect global effects, each provoking a range of ecosystem transformations (Turner *et al* 1998). To ensure our resource utilisation is sustainable, efficient and equitable, there is urgent need for knowledge and multi-disciplinary assessment methods capable of evaluating how these transformations affect the provision of goods and services.

Barange (2005) identified the need for a strategic and holistic ecosystem orientated research programme, integrating natural and social-economic approaches to underpin sustainable management and exploitation. The work proposed in this Research Unit is fully aligned to that approach, its objectives and initial research plan (long-term variability and change, comparative regional functioning, dynamics of bioresources and policy relevance). The challenge is to understand how human uses and environmental changes translate to ecological responses and economic impacts, to enable UK marine waters to be managed using an ecosystem approach.

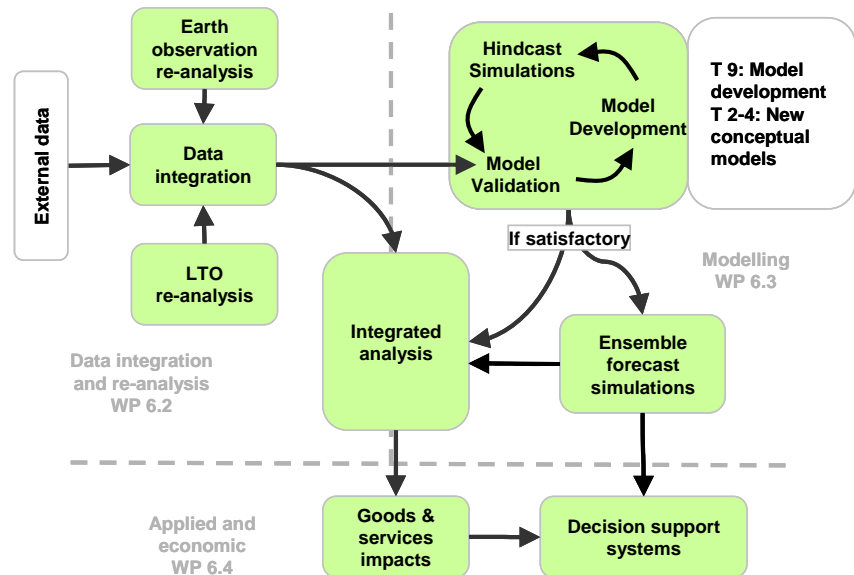
A number of significant and long-lasting shifts in marine populations have been observed over the last 50 yr, including increases in primary production, phenological changes in planktonic organisms, and substantial species shifts at several trophic levels (e.g. Reid *et al* 1998; Beaugrand *et al* 2002). These changes happen against a background of extensive ecosystem exploitation and substantial inter-annual variability that is only partially understood. While the available observations tell us about the state of the oceans and provide some insights to mechanisms (e.g. Irigoien & Harris, 2003; Edwards *et al* 2002; Beaugrand & Reid, 2003; Clark & Frid, 2001), they are fragmented and do not measure the underlying ecological processes creating these dynamics nor identify their causes or consequences. Without such ecosystem understanding we are unable to predict how our oceans and regional seas will react to continuing (and accelerating) environmental perturbation, modification and resource exploitation. It is evident that the changes in marine ecosystems depend on the integration of several uncoupled, and often spatially and temporally inconsistent process responses (e.g. the mis-match hypothesis, Cushing, 1990; Beaugrand *et al* 2003). By improving the understanding of the structure, function and vulnerability of regional ecosystems we aim to inform the necessary development of spatially-based, sustainable management strategies for goods and services in line with the responsibilities of Defra, SEERAD, DARDNI and their executive agencies.

The overall aims of this Research Unit are to:

- Identify and quantify the functional basis of ecosystem variability and regime shifts over the last 50 years in the NE Atlantic and NW European Shelf seas
- Use that knowledge base to predict the ecosystem response to future environmental change in terms of the sustainability of marine bioresources and the provision of goods and services, and hence
- Provide policy relevant advice and decision-support tools for environmental managers and policy makers with the aim of ensuring the maintenance and ultimately improving the provision of sustainable ecosystems.

This Research Unit consists of three strongly linked Work Packages: ecosystem data re-analysis (WP 6.2), hindcast and forecast modelling (WP 6.3) and integrated ecological and social-economic interpretation (WP 6.4); see Figure 1. [*Also WP 6.12, originally part of Theme 7*].

**Fig 1.** Linkages between PML Work Packages 6.2 -6.4



Rather than propose an expensive experimentally led approach, our aim is to derive significant added value from existing and ongoing data collections. These will be augmented by model simulations to provide comprehensive descriptions of UK regional seas and their extended margins. We then propose a predictive phase, using our refined 3D modelling skills to determine the probability of

ecosystem outcomes given the expected range of future local and global environmental perturbations. By applying sophisticated and sometimes novel analytical techniques consistently to both observational and model data we will identify key dynamics, the controlling processes and indicators. Throughout we will analyse our target domain in terms of ecosystem robustness, bioresource sustainability, and the provision of other goods and services, creating policy-relevant decision support tools (Hardman-Mountford, 2005). Our study domain is the continental shelf waters surrounding the UK and their extended Atlantic margins.

## WP 6.2 (PML) Re-analysis and integration of existing long-term data sets to determine patterns and potential causal links

### Specific objectives

- i) To address, at least partially, the fragmentation of marine data by performing coupled analysis of several key observational data sets
- ii) To identify and dissociate the vectors responsible for variability from those responsible for long term changes in biological populations
- iii) To identify the key gaps in long-term time series and make recommendations for existing and future monitoring strategies.

### Approach and methodology

Marine data are fragmented and typically not collected on the scales at which policy is applied (Perry & Ommer, 2003). Hence existing and new marine data need to be integrated, not only to address data fragmentation, but also to enable policy scale interpretation. In WP 6.2 we will initially focus on the re-analysis of three major long-term data sets orchestrated by the PML community: the Atlantic Meridional Transect (AMT, [www.amt-uk.org](http://www.amt-uk.org); SO 1) which will provide ~10 years of detailed spatially resolved information; the Western Channel Observatory (SO 10) centred on station L4 which provide very long-term and temporarily-detailed information (Southward *et al* 2005); and relevant spatially and temporally-explicit Earth Observation data sets ([www.npm.ac.uk/rsg/](http://www.npm.ac.uk/rsg/)). Subsequently we will integrate and analyse these with other key data sets, including the CPR (SO 15) and, in conjunction with available environmental data, aim to elucidate both causal links and differences between domains and years.

*Earth Observation data.* SeaWiFS data have enabled quantitative changes to be observed in phytoplankton abundance, globally (Gregg *et al* 2005) and regionally (e.g. Groom *et al* 2005), while the longer, more limited, AVHRR archive has been used to detect major changes in coccolithophore abundance (e.g. Smyth *et al* 2004). New data sets (e.g. Gregg *et al* 2003) combining past (CZCS 1978-86) current and future (NPOESS to beyond 2020) ocean colour sensors will provide long

time-series enabling investigation of global or regional scale changes in timing (e.g. Edwards & Richardson, 2004), intensity or functional type of phytoplankton, while the global visible AVHRR re-analysis (a joint NOAA-PML project) will enable Earth-scale observations of changes in coccolithophore abundance. Focusing on our domain we will elucidate changes in the distribution, seasonality, variability and community structure of phytoplankton. We will use phenological statistics together with clustering techniques to identify common areas and how these have changed over 30 years. By analysing SST and surface roughness we will determine if the surface physical structure of the ocean has altered, inferring changes in the coverage and persistence of stratification and frontal mixing and correlating this with ecosystem dynamics (Miller, 2004). Spectral classifiers for key species and functional types will be developed and applied to the SeaWiFS-MODIS-MERIS era archive (from 1997) (Miller *et al* 2006).

*Oceans 2025 Sustained Observations.* We will differentiate the AMT domain in terms of trophic status and interdependence in relation to nutrient supply (Serret *et al* 2002, 2006). We will assess if ‘function’ descriptors can be predicted from less labour intensive measurements e.g. respiration from plankton biomass and/or temperature or P:R from  $^{14}\text{C}$  (Robinson & Williams, 2005, Serret *et al* 2001). We will develop phenological analyses of planktonic events at L4 (SO 10) and assess if these provide a good indicator of the speed and direction of change (Irigoiien *et al* 2000b; Irigoien & Harris, 2003). We will evaluate connections with large-scale signals (building on Irigoien *et al* 2000a) and coastal environmental drivers, and also examine over-wintering influences on the succeeding year’s dynamics.

*Integrated data sets.* Natural spatio-temporal variability and ecosystem dynamics, trends and anomalies and potential causal relationships will be determined using established expertise in multivariate analysis, neural networks, empirical orthogonal functions, and phenological analyses (Clarke, 1993; Richardson *et al* 2003; Hardman-Mountford *et al* 2003; Hewitson & Crane, 2002; Hardman-Mountford & McGlade, 2002; Edwards & Richardson, 2004; Richardson *et al* 2006). We will develop integrated, quantifiable indicators of ecosystem processes and shifts that can be used to quantify changes in relation to climate variability, fishing pressures and nutrient status. The integrated observational data products will provide a validation base for the proposed hindcast simulation models, prior to incorporating model results into the analysis framework.

## WP 6.3 (PML) Model hindcasts to determine the basis of observed variability and ensemble forecasting of human effects

### Specific objectives

- i) To recreate, with a complex regional coupled ecosystem-hydrodynamic model the observed ecosystem patterns of the last ~50 years.
- ii) To identify, on the basis of ecosystem function, the mechanisms that connect environmental drivers of variability and change with ecosystem response in the region and its sub-domains.
- iii) To produce an ensemble of predictive model scenarios and a probabilistic assessment of system vulnerability.

### Approach and methodology

Our initial aim is to recreate, with dynamic process models, the ecosystem patterns of the last 50 years. We will subsequently combine the long-term data re-analysis (WP 6.2) and outputs from this hindcast modelling using sophisticated analysis techniques to characterise, as far as possible, the ecological or functional basis of variability and change in our regional seas. This combined model/data approach has already proved a powerful tool in identifying some potential causal relations (e.g. Reid *et al* 2003; Taylor *et al* 2002; Richardson & Schoeman, 2004; Heyen *et al* 1999) as it enables us to connect the observations with the prevailing physical drivers, ecosystem process rates and trophic flows. Our goal is to perform predictive model scenarios, assessing probabilistically the risks associated with future ecosystem change. Environmental modellers have often been criticised for attempting single deterministic simulations when there are large uncertainties in

forcing functions and system parameters. Here, by using many scenario simulations, we will test the uncertainties of model parameterisation and a range of environmental predictions relating to North Atlantic-wide forcing of ecosystems at the scale of UK regional seas. For example: what are the impacts of the melting of Arctic sea-ice? or increased storminess? what will be the impact of ocean acidification, both from the atmosphere and from sequestration leakage (building on Blackford *et al*, 2006)? and how will CO<sub>2</sub> mediated impacts interact to affect carbon cycling and resources?

*Hindcasting the last 50 years.* We will reproduce observations of variability and change in a ~50 year 3D simulation model hindcast (ERSEM-POLCOMS and developments (Allen *et al* 2001; Holt *et al* 2005) forced by the ECMWF-ERA (climate) re-analysis. This model system is the result of a long-term and ongoing collaboration between POL (hydrodynamics) and PML (ecosystems). These complex, multivariable model systems have demonstrated skill in replicating spatial and temporal dynamics and inter-annual variability (Blackford *et al* 2004; Taylor *et al* 2002; Allen *et al* in press [a]). We will further develop the model complexity to capture the newly synthesised historical observations as necessary, building on PML's proposed refinement of process understanding (Themes 2 and 4) and development of optimal model complexity (building on Theme 9 and existing programmes e.g. QUEST). Hindcast acceptability will be judged using rigorous, quantitative and independent validation techniques (Allen *et al* in press [b]). A key test is the geographically resolved replication of observed non-linear ecosystem responses or regime shifts.

*Ecosystem analysis.* When satisfactory validation is demonstrated, the analytical techniques described in WP 6.1 will be used to interpret the model results. We will quantify the differences between regional seas production pathways and identify the environmental drivers causing these differences. We will assess if the changes in the various climate vectors (wind, temperature, cloud) and their differential effect on the controlling mechanisms specific to each ecosystem component are responsible for the observed non-linearity and breakdowns in ecosystem dynamics (with WP 6.1). We will aim to differentiate between drivers of natural variability and drivers of human change. We will analyse the model domain in conjunction with the observations of *Calanus finmarchicus* and *C. helgolandicus* species shifts (Reid *et al* 2003) to try and understand the underlying causes for this ecologically significant event. Can we determine, for example, the functional basis of this change, and whether it tells us anything in a generic sense about regime shifts? We propose to develop new and apposite metrics of ecosystem state, (e.g. trophic balance / robustness) for assessment purposes and identify the key indicators or observations required.

*Ensemble forecast modelling.* We will create a set of 50-100 year model forecasts, integrating high CO<sub>2</sub> and other predicted anthropogenic changes, into a probabilistic ensemble of scenarios. We will utilise a range of 1D model systems and 3D sub-domains as well as full domain simulations, taking due regard of the limitations of each. We will analyse the simulations to determine the range of ecosystem states and likely productivity distribution, variability and stability, the potential for ecosystem decline (or recovery), given predicted environmental changes and evaluate the likelihood of encountering tipping points by assessing the phase trajectories of key system indicators.

## WP 6.4 (PML) Using ecosystem knowledge to predict bioresources and services, and provide policy advice

### Specific objectives

- i) To identify appropriate ecosystem indicators to provide objective and quantifiable indices for the major goods and services derived from the marine system.
- ii) To analyse the sensitivity of goods and services to anthropogenic impacts at different spatio-temporal scales.
- iii) To develop conceptual decision support tools to guide environmental management practice.

### Approach and methodology

Effective ecosystem-based environmental management solutions require that ecosystem knowledge should be used synergistically with social and economic considerations. To facilitate knowledge

transfer to environmental policy makers and managers, the ecosystem insights from WP 6.2 and 6.3 will be translated into socio-economic terminology (e.g. goods and services). Working with socio-economists (with additional SOFI opportunities), we will identify and develop appropriate assessment methodologies – to lead to the identification of objective and quantifiable ecosystem indicators, and to provide a supportive basis for management and policy decisions. We will develop innovative models linking ecological, social and economic systems to improve our quantitative understanding of how specific changes in ecosystem functioning affect the provision of particular marine goods and services. These bioeconomic models will provide the basis of decision support tools to underpin the ecosystem approach for sustainable management of the marine environment.

*Impacts of global environmental change on goods and services.* Building on the analysis of environmental and ecological coupling described in WP 6.2 and 6.3, we will analyse the integrated databases to determine the resource implication of various types of anthropogenic disturbance over a range of spatio-temporal scales. We will use established eco-informatic techniques of meta-analyses, including multivariate and standard correlation approaches, to determine the interactions and cumulative impacts of multiple uses of the marine environment on ecosystem functioning and diversity, and hence on the provision of goods and services (e.g. Kaiser *et al* 2006; Gurevitch & Hedges, 1999). This research will also use data arising from Themes 2, 3 and 4, and published data.

*Tools and models to underpin the ecosystem approach.* The bioeconomic models linking ecosystem and resource will be applied to estimate historical, recent and future trends in the value of marine ecosystem goods and services, and to determine the likely causes of these trends. Where possible standard valuation methodology will be used; for example, replacement costs, contingent valuation and benefit transfer (Bateman & Langford 1997, Polome *et al* 2005, Soderquist *et al* 2005). Where this is not possible, non-monetary techniques will be developed for the marine sector (e.g. [www.cost-impact.org](http://www.cost-impact.org)). We will develop a scenario testing approach utilising the model forecasts (WP 6.3) as a spatial planning and management tool for different current and future human uses of the marine environment. These decision support tools will be applied to identify plausible management scenarios over the short, medium and long term, and to specific case studies including implementation of Marine Protected Areas (SOFI opportunity).

### Summary of research plan and main deliverables (WP 6.2- 6.4)

2007 - 09	<ul style="list-style-type: none"> <li>• Re-analysis of AMT, WEC/L4 and Earth Observation data sets.</li> <li>• 50 year model hindcast, archived and validated.</li> <li>• Meta-analysis of anthropogenic impacts on ecosystem function and diversity</li> </ul>
2008 - 10	<ul style="list-style-type: none"> <li>• Production of a model 50 year hindcast validation data set.</li> <li>• Ecosystem functional analysis of causal links to observations and regional comparison.</li> <li>• Identification of ecosystem indicators that provide quantifiable indices for bioresources</li> </ul>
2009 - 11	<ul style="list-style-type: none"> <li>• Integrated data analysis for WP 6.2</li> <li>• Bioeconomic model to estimate value trends of marine ecosystem goods and services</li> </ul>
2010 - 12	<ul style="list-style-type: none"> <li>• Multi year scenario forecasts with probability statistics with assessments of robustness.</li> <li>• Recommendations for improved monitoring and observation strategies</li> <li>• Conceptual models for spatial planning and decision support tools</li> </ul>

## Integrating individual to population processes in a changing marine environment

*Contribution to Theme 6 by the Marine Biological Association*

### Background

Both climate-induced responses and introductions of non-native species are leading to global changes in marine biodiversity. Sea surface temperatures are forecast to increase by up to 4°C over

the next century, whilst the temperature changes that have already occurred have been linked to changes in distribution and abundance (Walther *et al* 2002; Parmesan & Yohe 2003; Genner *et al* 2004; Perry *et al* 2005), the timing of migrations (Sims *et al* 2001, 2004), and recruitment declines through trophic mismatch (Beaugrand *et al* 2003). Increased pressure from fishing also threatens marine populations worldwide, with the potential for trophic cascades by removal of top predators (Jackson *et al* 2001; Springer *et al* 2003). However, the ways in which climate and fishing may interact to stabilise or further reduce populations remains unknown.

Climate change has also been linked to an increased spread of non-native species, with profound implications for ecosystem functioning (Stachowicz *et al* 2002). Since the spatio-temporal dynamics of dispersal and connectivity among marine populations are poorly understood (Hunter *et al* 2004; Block *et al* 2005), it is unclear whether effects observed in one region can be extrapolated across greater scales. This knowledge gap limits our understanding of how environmental change, such as climate-linked temperature fluctuations and fishing impacts, influence population occupancy, structuring and dynamics. There are clear implications for the definition of management units both in terms of populations and for marine spatial planning. Determining how species respond to environmental changes over a wide range of scales, from individual behaviour to population abundances through time, will identify key mechanisms.

This Research Unit will contribute directly to the strategic needs identified by Barange (2005; Modules 1 and 3) by investigating: climate change and fishing impacts on marine ecosystem components and their interactions; differential behavioural traits among fish populations; and the genetic structuring of populations. Such information is essential for the development of spatial management tools, such as the size, location and networking of Marine Protected Areas (MPAs).

The colonisation of marine habitats by non-native species may also have a profound effect on marine resources. The accelerating rate of such introductions has been linked to climate change (Stachowicz *et al* 2002), and threatens global homogenisation of some biota. These effects need to be understood in relation to environmental factors and spatio-temporal dynamics (as noted above in a fisheries context) so that appropriate management measures can be developed.

The MBA is uniquely placed to conduct these studies because of its longterm datasets centred on the Western English Channel (to be continued under Theme 10, SO 10). This region is important both for fisheries and climate change as it is a key biogeographic boundary between southern and northern species in the North East Atlantic. The region is also important as a likely major route for the introduction of invasive species through intensive international trade, military and yachting uses. There are many first records of non-native species in the well-catalogued marine fauna of the Western Channel (Arenas *et al* in press). In Theme 6, the MBA will use novel data analysis methods in spatial ecology, not currently used for such purposes elsewhere in the UK, supplemented by the MBA's capability in molecular ecology.

### **Aims and rationale**

The overall aims of this Research Unit are to:

- Identify the role of fish movements, behaviour and population structure in relation to environment using a combination of electronic tagging and molecular genetic approaches to test the 'stock' concept in fisheries at the regional scale.
- Determine the relative signals of climate change and fishing in marine fish and benthos abundance trends using high-temporal-resolution long-term datasets to define reference states and predict future responses
- Characterise the events leading to an introduced species becoming established, and identify the factors governing their subsequent spread and impact on native assemblages.

All these aims directly relate to the need for management solutions to the problems of climate change and human impacts, such as fishing and introduced species. For example, if populations of

the same fish species have different migration and movement patterns in different geographic regions, management solutions based on spatial criteria (i.e. fishery closed areas) may vary in effectiveness. This research will therefore help to: define ecologically-relevant units for bioresource management; understand the mechanisms and spatial extent of species invasions; and elucidate the complex effects of global environmental change on populations. The outcome will be improved understanding of how behaviour, reproductive biology, population abundance and distributions respond to environmental change, be it seasonal or climatic, natural or anthropogenic, and how these processes may be mediated by life-history traits.

The approach to the science questions detailed below will be through individual-based and population-level investigations. Electronic tagging for resolving behaviour and movements of commercially important fish (Sims *et al* 2006a) will be used together with novel behavioural analyses (e.g. multi-scale spatial modelling, signal processing techniques) to identify consistent patterns in behaviour in relation to habitat types (WP 6.9) (Sims *et al* 2006b). Some of the telemetric tracking initiatives have been implemented jointly with CEFAS; however, our new analytical approaches present a novel capability that we will transfer to CEFAS and FRS laboratories through collaborations. Telemetric tracking will enable behaviour datasets from different geographic regions to be compared quantitatively to examine key differences and make the link from individuals to populations. Genetic markers for identification of population extent and sub-structure will be used to examine spatial patterning in commercial fish and to probe colonisation processes of invasive species (WP 6.9, 6.11). Multivariate statistical analysis of long-term data sets of demersal and pelagic fish from different regions will determine the relative influences of climate and fishing on population abundances (WP 6.10).

The high frequency of historical (weekly, fortnightly) and re-started (fortnightly) sampling provides greater temporal resolution than most other data sets, and can be coupled with studies of larval fish in the plankton. The re-start and continuation of MBA high-temporal-resolution long-term data sets have been developed jointly with SO 10 and CEFAS. This combination of complementary approaches provides an overview encompassing scales spanning days to multiple generations.

## WP 6.9 (MBA) Examining regional differences in fish movements, behaviour and population structure

### Specific objectives

- i) To determine movement patterns of marine fish in relation to environment (natural habitats and human-made submerged structures), and adaptive responses across increasing space-time scales.
- ii) To identify whether changes in behavioural complexity are linked to specific environmental conditions associated with the biogeographic boundary in the English Channel.
- iii) To characterise the genetic component of fish stock differentiation in the Western English Channel and Celtic Sea compared with adjacent stocks
- iv) To examine regional differences in fish movement and behaviour patterns with respect to population-level genetic differentiation, to identify stock structure and biological limits of dispersal, thereby defining management units.

### Approach and methodology

Many marine fish stocks are managed by controlling rates of human exploitation in a specific political-economic area that is thought to encompass the stock in question. The spatial limits of real-world 'stocks' are generally poorly known, because movement patterns and behaviour have not been determined. Populations of fish have complex spatial and temporal dynamics characterised by migrations, distinct habitat preferences, and age and sexual segregation. These complex patterns may be integrally linked to oceanographic regime, particularly via temperature, that produces wider scale patterns of population abundance and distribution that are equally complex. The processes structuring natural fish populations are not well known, even though a responsive management

framework requires defined management units that represent the scales over which actual populations operate.

The sustainable management of fish populations requires detailed knowledge of how they distribute themselves and how abundance changes are affected by external drivers. At present only very coarse and simplistic data on fish movements and behaviour are available for identifying stock management units and for parameterising spatially-structured fish population models; most use random movements (e.g. Guenette *et al* 2000). However, changing habitat selection associated with daily movements and seasonal migrations are likely to be much more complex behaviourally, so patterns and underlying processes need to be determined (e.g. for better parameterisation of models) if responsive management tools for managing fish spatially (regionally) are to be developed. To address this, our aim is to characterise region-specific fish movements, behaviour and population structure in relation to environment in the Western Channel and Celtic Sea that will contribute to testing the ‘stock’ concept in marine fisheries and scales of designation of Marine Protected Areas.

*Natural habitats:* The behavioural study will identify patterns of space use and behaviour in relation to habitat, including thermal regime, in selected species of electronically-tagged fish using a range of powerful modelling and analytical techniques (e.g. signal processing) (Sims *et al* 2006b). MBA has extensive expertise in this area, and has also worked closely with CEFAS, Lowestoft. In WP 6.9, new approaches unique to MBA will be used, and then transferred to fisheries laboratories through further collaboration. Commercially important species such as Atlantic cod *Gadus morhua* and thornback ray *Raja clavata* will be investigated. Movement data are largely absent for these species in the Western English Channel and the Celtic Sea, which are valued fishing areas not only for the UK but also Ireland, France, Belgium, Spain and Denmark.

SW Britain is an important faunal boundary between southern (Lusitanian) species and northern, boreal species. At such range extremes, individuals’ behaviour may differ from those nearer to centres of their distributions. The tracking studies therefore have additional management relevance: tools developed for use in some areas may be inappropriate for others if re-distribution patterns of fish differ significantly between areas. Because stocks in the Western Channel and Celtic Sea are managed separately from other adjacent areas, it is important to know the spatial extent of movements, potential interchange with other ‘stocks’, and whether behaviour patterns are defined by oceanographic (thermal) regime. We will complement individual-based spatial studies on cod with molecular genetic analysis of population differentiation (using micro-satellite markers), concentrating on whether apparent ‘stocks’ off SW Britain are well separated from other putative stocks and represent true biological units.

*Human-made structures.* Another related aspect of spatial ecology in marine fish is how human-made devices may modify space use compared to adjacent areas. There is increasing interest in generating electricity from renewable energy resources such as offshore wind, wave and tidal power (Gill, 2005). Offshore renewable energy devices (OREDs) are likely to have direct and indirect impacts on shelf and coastal ecology over a wide range of scales. Environmental effects may include: habitat change; increased water turbidity and contaminant remobilisation during construction and decommissioning; and increased habitat heterogeneity, noise, vibration and electromagnetic fields during operation. We will investigate the effects of ORED-derived electromagnetic fields on fish space use and sensory responses using the same movement analyses as above. This work is expected to benefit from, but not depend on, collaboration with CEFAS Lowestoft, and also offers opportunities for SOFI involvement.

Overall, WP 6.9 will help identify whether apparent regional differences in species abundance trends (Genner *et al* 2004; Perry *et al* 2005) are linked to environmentally-driven behavioural complexities, re-distribution patterns and stock identity of adult fish associated with region-specific niche characteristics, and overall thermal regime. The research will contribute to defining biologically-meaningful management units by determining structure through an understanding of population movements in relation to environment.

## WP 6.10 (MBA) Disentangling climate change responses and fishing impacts on marine fish and benthos

### Specific objectives

- i) To identify climate and fishing signatures in abundance trends of commercial and non-commercially important species from different biogeographic guilds (Lusitanian, boreal).
- ii) To determine whether southern and northern species off SW Britain have responded over the past 100 years as predicted by the ‘climate envelope’ hypothesis
- iii) To assess how re-structuring of the size spectra of fish (through exploitation) coupled with changes in benthos (due to climate and fishing-related disturbance) influence foodweb interactions
- iv) To examine the basis for using fishing and climate-driven signals in species abundances for predicting future responses.

### Approach and methodology

The ‘climate envelope’ hypothesis predicts that as climate warms the geographic range of southerly distributed organisms in the Northern Hemisphere should expand northwards. Similarly, northern species should retreat northwards under this scenario (e.g. Perry *et al* 2005). However, factors such as preferred habitat availability and species interactions can confound this simple picture of species’ responses to climate (Davis *et al* 1998; Warren *et al* 2001). WP 6.10 will help unravel climate and fishing effects on the compositional responses of populations and assemblages (e.g. marine fish and benthos) within an ecosystem context. The Atlantic cod, for instance, is a boreal species at its extreme southern limit of distribution around SW England; it might therefore be expected to be retreating north with the persistent sea-temperature warming conditions since 1990 (Genner *et al* 2004). However, the SW England cod stock is not declining, in contrast to the documented decreases in the North Sea and elsewhere around the UK (ICES data; Sims *et al* unpublished).

We will examine the combined effects of climate change and fishing exploitation on populations and assemblages by comparing the relative impact of stressors on different biogeographic guilds of species. We will use multivariate statistical techniques (Genner *et al* 2004) to identify characteristic ‘signatures’ to climate and fishing among the 90 species monitored in MBA long-term datasets since 1913 (see SO 10). We will analyse the changes in relative abundance of southern, central and northern species in the Western English Channel. This work will be extended to compare responses of populations between regions to identify the relative influences of natural and anthropogenic factors to identify how an apparently single population may be affected differently by climate change in different geographic regions within its range (e.g. Genner *et al* 2004). Historical data sets on fish and benthos will be used to investigate the effects of size-spectra re-structuring and to reconstruct past reference states (e.g. Araujo *et al* 2006) that will inform targets for recovery and restoration plans, taking into account the moving baseline generated by climate change. There will be opportunities for SOFI-funded research to deploy modelling expertise in this specific area (e.g. ECOPATH routines).

## WP 6.11 (MBA) Identifying colonisation processes and impacts of non-native species

### Specific objectives

- i) To elucidate the spatio-temporal pattern of immigration leading to successful introductions of non-native species, including interactions with climate change
- ii) To investigate the mechanisms of secondary spread and the consequences for native assemblage re-structuring.

### Approach and methodology

Invasive species, carried far beyond their native range by human vectors, are major agents of global ecological change, with the potential to reduce native biodiversity, modify habitats and alter ecosystem structure and dynamics. They may also damage economic interests: aquaculture has been the repeated victim, as well as the common agent, of biological invasions. Appropriate management action depends on improved understanding of the invasion process. Conventional ecological monitoring is a vital part of any surveillance and control programme, and protocols are being developed at the MBA for rapid assessment of sites by trained personnel. However, conventional monitoring has limited ability to identify native-range source populations and the number of introductions, or to infer *a posteriori* the pattern of secondary spread. In contrast, DNA-based techniques of genetic analysis can permit elucidation of the contemporary and historical structure of both native and introduced populations. WP 6.11 will exploit these possibilities, tracing the origin and development of historical and recent introductions, while taking into account the considerable reproductive and life-history diversity demonstrated by the species concerned. The aim is to investigate population-genetic case studies of established invasions (retrospective studies), and of early-stage invasions from more recent introductions (monitoring and periodic genetic sampling) to identify the processes of invasion and its consequences.

We will use genetic markers to investigate invasive species at the population level. The MBA has considerable expertise in using such techniques to investigate dispersal, reproductive biology and population differentiation in marine animals (Bishop *et al* 1996; Heipel *et al* 1998; Pannacciulli *et al* 2005). Furthermore, the MBA is situated in a key geographical region for the study of marine invasions: the English Channel has several major ports, significant aquaculture activities, busy local traffic of ferries and pleasure craft, and is used by a large proportion of global shipping. As a result, the Channel coasts of England and France have hosted a large number of documented introductions (Eno *et al* 1997; Nishikawa *et al* 2000; Arenas *et al* in press). Sampling of invasive species for tissue analysis will be carried out by surveys in harbours, marinas and natural habitats. Settlement panels deployed in marinas will be used to measure rates of arrival; test the influence of non-native species on the structure and dynamics of assemblages; and, ultimately, determine their contribution to ecosystem functioning.

### Summary of research plan and main deliverables (WP 6.9- 6.11)

2007 - 09	<ul style="list-style-type: none"> <li>• Electronic tag deployments completed, first data available for analysis; samples for molecular analysis collected and marker development in progress (WP 6.9)</li> <li>• Analysis of long-term data to identify climate and fishing signals in fish abundance trends (WP 6.10)</li> <li>• Molecular marker development and sampling for suite of non-native species (WP 6.11)</li> </ul>
2008 - 10	<ul style="list-style-type: none"> <li>• ORED space-use experiments and field observations completed (WP 6.9)</li> <li>• Comparative analysis with other regional datasets complete (WP 6.10)</li> <li>• Analyses of genetic datasets for non-indigenous species completed. (WP 6.11)</li> </ul>
2010 - 12	<ul style="list-style-type: none"> <li>• Completed integrated analysis and interpretation of behavioural and genetic datasets (WP 6.9)</li> <li>• Completed analysis for predictions of abundance trends under different warming scenarios (WP 6.10)</li> </ul>

## Theme 6 Synthesis and Concluding Material

### Oceans 2025 synergies and wider links

The Theme 6 collaborations between POL, PML and MBA bring together scientists with complementary expertise in modelling, field and laboratory studies, with access to unique datasets (via Theme 10). Specific interactions include joint work on renewable energy (WPs 6.1, 6.8 and 6.9); climate change and bioresources (WPs 6.1 - 6.4 and 6.10); and spatio-temporal structure of resources (WPs 6.1 - 6.4 and 6.9). Together, the three Centres will address how populations,

communities and ecosystems respond to global changes across different space and time-scales, and the implications for the sustainable use of biotic and abiotic renewable marine resources.

Major links between Theme 6 and other parts of Oceans 2025 are outlined in Table 1, and the main relevant linkages outside Oceans 2025 are given in Table 2. There are also opportunities for new linkages to e-Science (NERC data grid), and an obvious three-way interaction between Theme 6, BODC (NF 1) and the new Defra-funded Data Archive for Seabed Species and Habitats, at MBA.

PML and POL have previously worked together to create a state-of-the-art modelling expertise, successfully developing coupled hydrodynamic-ecosystem models of the UK continental shelf (Allen *et al* 2001; Proctor *et al* 2003) and jointly contributing to many programmes (e.g. QUEST, NCOF, MERSEA, e-Science and MarProd). The work proposed in WPs 6.1 and 6.3 builds on this collaboration to produce 50 year model hindcasts and forecasts; PML developing the ecosystem components and POL the hydrodynamics. Data will be sourced from Theme 10, in particular from the Western Channel Observatory (SO 10) and CPR information from SAHFOS (SO 15).

Joint work between MBA and SAHFOS (Theme 10) includes analyses linking foraging behaviour of top predators with zooplankton prey (e.g. Sims *et al* 2006).

**Table 1** Main links between Theme 6 and other parts of Oceans 2025

Theme 3	Topographic controls on transport pathways considered in terms of propagule dispersion (WPs 3.1, 3.7 & 3.9) Climate change and ecosystem function (WPs 3.11 & 3.12) Long-term trends in coastal morphology and extreme events (WPs 3.5 & 3.6)
Theme 4	Biological invasions in relation to the stability and resilience of food webs (WP4.6 – linking to WP 6.11)
Theme 8	Support in developing acoustic measuring technologies and algorithms for WP 6.8
Theme 9	Long (50 yr) oceanographic model runs will be carried out in conjunction with Theme 9 building on the long-standing collaboration between POL and PML (POLCOMS-ERSEM). Ecosystem model development at PML (Theme 9) will be grounded in the biological realism generated in Themes 2-4 providing the appropriate model complexity to address the 'big' questions identified here.
Theme 10	Theme 6 will use datasets collected by Sustained Observations (SOs) to identify human impacts on marine populations, communities and habitats. Specifically, SO 10 data on demersal fish in the western English Channel will help disentangle fishing and climatic influences on bioresource units and top-down processes in ecosystem models. WEC (SO 10), AMT (SO 1), CPR (SO 15) and EO data amongst others will underpin the lower trophic re-analysis proposed by PML.
BODC (NF 1)	Management of field, experimental and model data from Theme 6; supply of data from Theme 10 and other parts of Oceans 2025

**Table 2** Main existing science collaborations between Theme 6 and other research Groups (UK and International) not part of Oceans 2025

#### UK Institutes

Ardtoe	Environmental effects on larval development
CEFAS	Behavioural ecology of commercially important fish
Met Office	Environmental drivers of marine systems, coupled atmosphere-hydrodynamic-ecosystem models
Univ of Aberdeen	Molecular ecology to investigate the spatial structuring of marine fish populations
Univ College London	Policy interactions with ecosystem change
Univ Cranfield	Behaviour of sharks and rays, including responses to electromagnetic fields
Univ East Anglia	Social-economic evaluation of ecosystem changes
Univ of Hull	Molecular ecology to investigate the spatial structuring of marine fish populations. Policy interactions with ecosystem change.
Univ of Leicester	Climate and fishing effects on marine food webs and reconstruction of past ecosystems using modelling approaches
Univ of Liverpool	Impacts of coastal engineering and marine renewable energy
Univ of Plymouth	Social-economic evaluation of ecosystem changes; invasive species ecology
Univ Wales Swansea	Spatial ecology of marine vertebrates; animal movement analysis

#### National Programmes

NCOF	Key interest in operational (short-term) forecasting. Long term hindcast/forecasts are potentially a key NCOF deliverable
MECN	Archiving and analysis of marine datasets to understand responses to environmental change
QUEST	Optimal complexity for global carbon cycle models
e-Science	Methodologies for simulating the global coastal ocean

#### International

GLOBEC	Effects of global change on the abundance, diversity and productivity of marine populations
EU Projects	ECASA (Ecosystem Approach for Sustainable Aquaculture); ETHOFISH (effect of turbidity and hypoxia on the behaviour of coastal marine fishes); EurOceans (network of excellence for Ocean Ecosystems Analysis); KEYZONES (Sustainable biological carrying capacities of key European coastal zones); MarBEF (Marine biodiversity network of excellence); Marine Genomics network of excellence; SAMI (Synthesis of Aquaculture and Marine Ecosystem Interactions); SPICOSA (Science & Policy Integration for Coastal System Assessment ; in evaluation);
IMBER	Sensitivity of marine biogeochemical cycles and ecosystems to global change
Station Biol Roscoff	Non-indigenous species
Univ de Lille	Climate-linked plankton effects on cod recruitment
Univ New Brunswick	MoU on Integrated Aquaculture research with SAMS

#### Theme-wide stakeholder relevance and Knowledge Transfer

Stakeholder relevance and Knowledge Transfer are built-in to the Oceans 2025 programme: all the marine Centres involved have obtained, and will continue to obtain, both private sector and governmental funding for applied research that meets specific research-user needs. Such commissioned research is not presented here; nevertheless, it is the direct consequence of previous NERC strategic funding, and Oceans 2025 will provide the underpinning capabilities, expertise and facilities to continue to make that possible in future, whilst also itself delivering data, information and understanding directed at ‘real time’ national needs. In the preparation of the proposal, major stakeholders were consulted, and many of the components have involved additional discussions with research users. To take that process forward, a Stakeholders Consultation Group will be established for Theme 6 (and other Themes) early in 2007, to meet at 6-9 monthly intervals throughout the duration of the programme. This will ensure effective communication between scientists and research users; it will also allow for any re-direction that may be necessary, to reflect significant changes in research user needs.

Theme 6 will contribute to marine spatial planning (including the siting of Marine Protected Areas) by integrating scientific information on a range of marine renewable resources, their interactions and their sensitivity to exploitation and climate change. Such issues are crucial for the successful implementation of the UK Marine Bill, currently in preparation.

Attention will be given to improving prediction and assessment procedures for non-native species, in support of the Convention on Biological Diversity, the EC Habitats Directive and the forthcoming EU Marine Strategy Directive. Research on non-native species will focus on developing management tools (risk analysis procedures, prediction of invasiveness, codes of conduct, and domestic legislation to enforce international agreements) for use by government agencies, coupled to a public education and awareness campaign (initial funding from the Esmée Fairbairn Foundation to SAMS, and via the Marine Life Information Network, MarLIN, at MBA; [www.marlin.ac.uk/marine\\_alien](http://www.marlin.ac.uk/marine_alien)).

By focusing on commercially-important and non-native species, this Theme is directly relevant to several important policy drivers (Table 3). At the European level, the reformed Common Fisheries Policy (CFP, 2003) identifies the need to implement the ecosystems approach, regionalise fisheries management through regional advisory councils, and improve environmental protection. These aims are also central to the EU Habitats Directive (2004), the recently announced EC Marine Strategy Directive, and the developing UK Marine Bill, to be put before Parliament in autumn 2006. The science to underpin these new policies is, as yet, not well developed; nationally, it requires targeted

and well-coordinated work, such as that proposed here, ideally within the wider framework of a UK marine bioresources initiative, such as the Marine Ecosystem Research Partnership proposed by Barange (2005).

**Table 3.** Examples of policy/application issues and stakeholders in relation to Theme 6 science

Policy/application issues	Key stakeholders with interests	Relevant Theme 6 science
Ecosystem approach to fisheries	Defra/CEFAS, SEERAD/FRS, , DARDNI, EU, fishing industry	Coupled physics-ecosystem models, ecosystem variability, larval transport
Renewable energy prospecting	DTI, SE, Industry	Modelling wave/tide energy distributions and future predictions
Renewable energy – ecosystem interactions	DTI, SEERAD, EN/NE, SNH, Industry	Determining ecosystem interactions including modelling acoustic disturbance
Marine spatial planning	DTI, Defra, SEERAD, DARDNI, EA, SEPA, LAs, EN, SNH, industry	Determining spatial ecology, larval dispersal, predicting effects of MPAs, capacity for aquaculture
Sustainable aquaculture	SEERAD/FRS, Defra/CEFAS, SEPA, EA, LAs, industry	Determining trophic linkages on integration, socio-economic benefits and mitigation of impacts
Climate change and associated effects (ocean acidification)	SEERAD/FRS, Defra/CEFAS, Industry	Hind-casting ecosystem variability, determining spatial ecology and biologically relevant management units, predicting effects of pH changes,
Invasive species	SEERAD, Defra	Elucidating mechanisms of introduction, spread and prevalence of immigration, developing rapid assessment protocols for surveillance
Acoustic pollution	DTI, MoD, FRS, SMRU	Modelling a realistic acoustic arena

### Strategic Ocean Funding Initiative (SOFI)

Significant funding for additional strategic research complementary to Oceans 2025 will be made available to UK universities and other academic institutions eligible to receive NERC support. SOFI awards will be made in defined topic areas through a series of funding calls (first call to be announced in 2007). For Theme 6, the following SOFI opportunities have been identified:

- related work on marine spatial planning, Marine Protected Areas, fisheries modelling (e.g. Ecopath) and socio-economics.
- partnership studies on the impact of coastal and offshore engineering structures, including renewable energy devices.
- enhancement of decision-support work by incorporation of detailed analyses of current and predicted policy drivers and context
- linkage with health impact assessment methodologies, to include effects on public health of different management scenarios for the marine environment (jointly with Theme 7).
- research on marine genetics, particularly in identifying the genetic components of fish ‘stock’ differentiation.

### Summary of main outcomes

Theme 6 will underpin the application of the ecosystem approach to marine resources in the UK, placing the demands for specific resource exploitation in the broader context of the multiple uses, demands and conservation needs of the marine ecosystem. Theme 6 will directly inform stakeholders by quantifying these conflicting demands and needs alongside the distribution and robustness of marine bioresources in a probabilistic framework. We will translate functional ecosystem science for economists, policy makers, marine environmental and resource managers, NGOs, health authorities and the public. We will provide data on the interactive effects of global environmental change on ecosystem function and diversity, and conceptualize models of human activities in the marine environment for spatial planning at local, regional and global level. We will work across disciplines to develop marine ecosystem assessment methodologies capable of addressing the multiple uses of the marine ecosystem and its services.

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## Acronyms

AMT Atlantic Meridional Transect  
 AVHRR Advanced Very High Resolution Radiometer  
 BGS British Geological Survey  
 BODC British Oceanographic Data Centre  
 CASIX Centre for observation of air-sea interactions & fluxes  
 CBD Convention on Biodiversity  
 CCW Countryside Council for Wales  
 Cefas Centre for Environment, Fisheries & Aquaculture Science  
 CEH Centre for Ecology and Hydrology  
 CPR Continuous Plankton Recorder  
 CSERGE Centre for Social and Economic Research on the Global Environment  
 CZCS Coastal Zone Colour Scanner  
 DARDNI Dept of Agriculture and Rural Development NI  
 DEFRA Department of the Environment, Food & Rural Affairs  
 DNA Deoxyribonucleic acid  
 DTI Department of Trade & Industry  
 ECMWF European Centre for Medium-Range Weather Forecasts  
 EN/NE English Nature (to change to Natural England)  
 EO Earth Observation  
 EU European Union  
 ERSEM European Regional Seas Ecosystem Model  
 FRS Fisheries Research Service  
 GIS Geographic Information System  
 GLOBEC Global Ocean Ecosystem Dynamics project  
 GOTM General Ocean Turbulence Model  
 IBM Individual Based Models  
 ICES International Council for Exploration of the Seas  
 IPCC International Panel on Climate Change  
 IMBER Integrated Marine Biogeochemistry and Ecosystem Research

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LA Local Authority  
 MarBEF Marine Biodiversity and Ecosystem Functioning  
 MarProd Marine Productivity programme  
 MECN Marine Environmental Change Network  
 MERIS Medium Resolution Imaging Spectrometer  
 Mersea Marine Environment & Security for the European Area  
 MoD Ministry of Defence  
 MODIS Moderate Resolution Imaging Spectroradiometer  
 MPA Marine Protected Area  
 NCOF National Centre for Ocean Forecasting  
 NOAA National Oceanic & Atmospheric Administration (US)  
 NGO Non Governmental Organisation  
 NPOESS National Polar-orbiting Operational Environmental Satellite System  
 ORED Offshore renewable energy devices  
 P:R Primary production to respiration ratio  
 POLCOMS Proudman Oceanographic Laboratory Coastal Ocean Modelling System  
 QUEST Quantifying and understanding the Earth system  
 RCEP Royal Commission on Environmental Pollution  
 RSDAS Remote Sensing Data Analysis Service  
 SAHFOS Sir Alister Hardy Foundation for Ocean Science  
 SE Scottish Executive  
 SeaWiFS Sea-viewing Wide Field of view Sensor  
 SEERAD Scottish Executive Environment & Rural Affairs Department  
 SEPA Scottish Environmental Protection Agency  
 SMRU Sea Mammal Research Unit  
 SNH Scottish Natural Heritage  
 SO Sustained Observation (in Oceans 2025)  
 SST Sea Surface Temperature  
 WAM WAve Model