THE NERC MARINE CENTRES' STRATEGIC RESEARCH PROGRAMME 2007-2012

Theme 3: Shelf and Coastal Processes

UK shelf seas, coasts and estuaries are of high economic importance, contain around half the national biodiversity, and play important roles in larger-scale ocean and climate processes. The sustainable management and protection of these complex and valuable systems require better knowledge of their internal interactions and behaviour – and their likely responses to future human impacts and climate change.

Theme 3 comprises three Research Units and twelve Work Packages:

Coastal and shelf sea processes and interactions (Proudman Oceanographic Laboratory).
POL Theme Leader: Jonathan Sharples js1@pol.ac.uk

- WP 3.1 Global impacts of shelf seas
- WP 3.2 Horizontal patchiness in vertical mixing in stratified shelf seas
- WP 3.3 Bottom boundary processes
- WP 3.4 Suspended particulate material, transport, and water column optics
- WP 3.5 Coastal morphodynamics and bathymetric evolution
- WP 3.6 Causes and impacts of extreme events

Topographic regime control over shelf sea systems (Scottish Association for Marine Science). *SAMS Theme Leader: Mark Inall* mei@sams.ac.uk

- WP 3.7 Role of topography in determining spatial variability in horizontal dispersion
- WP 3.8 Pelagic and benthic biogeochemical processes: response to spatial variability in topographically controlled mixing
- WP 3.9 Topographic controls on sediment transport pathways on the shelf

Consequences of climate change and anthropogenic activity on ecosystem functioning of estuaries, coasts and shelf seas (Plymouth Marine Laboratory). *PML Theme Leader: Stephen Widdicombe* swi@pml.ac.uk

- WP 3.10 Biological processes affecting ecosystem function: key organisms and mechanisms in a physico-chemical context
- WP 3.11 Implications of biotic processes for ecosystem functioning at spatial scales relevant for management
- WP 3.12 Environmental impacts of global change on ecosystem function in estuaries and coastal seas
- WP 3.13 Pollutant pathways

Theme 3: Shelf and Coastal Processes

Strategic setting

The UK economy has a particularly high dependence on the use of coastal and shelf seas: at least £39bn in 1999-2000 (IACMST 2002). The full range of marine-related activities (transport, fisheries, fossil fuel resources, renewable energies, waste disposal, aggregate mining and leisure) contributes 3-4 % of UK GDP and directly employs ~ 423,000 people (Defra, 2002). In addition to their financial importance, shelf seas, coasts and estuaries are thought to contain up to half of the UK's biodiversity; over 44,000 species (Defra, 2002), and they play a role in global climate via transfers of carbon and nutrients across the shelf edge.

Over the next 20 years, these local marine environments are predicted to experience ever-increasing rates of change – including increased temperature and seawater acidity, changing freshwater run-off, changes in sea level, and a likely increase in flooding events – causing great concern for those charged with their management and protection. The future quality, health and sustainability of UK marine waters require improved appreciation of the complex interactions that occur not only within the coastal and shelf environment, but also between the environment and human actions. This knowledge must primarily be provided by whole-system operational numerical models, able to provide reliable predictions of short- and long-term system responses to change. In parallel with observationally-based improvements to our conceptual models, such numerical models not only feedback to refining the conceptual models, but also provide the only practical means of:

- Providing synoptic snapshots of environmental status over the 3-D, spatially-complex, time-varying structure of coastal, shelf, and shelf edge waters, including the two-way connection between the shelf seas and the open ocean.
- Providing short-term forecasts, such as warnings of HABs, flooding, pollutant transport and its effects. These are needed to underpin the capabilities of NCOF, the management/stewardship requirements of the Marine Bill, and to implement the Water Framework Directive.
- Providing long-term predictions of possible environmental responses to changes in forcing (e.g. changes in coastal morphology and the shape of our coastline, ecosystem responses to a changing environment, impacts of changing ocean circulation on transports to shelf seas, responses of the open ocean to shelf sea variability, shelf sea responses to a changing atmosphere).
- Providing an investigative tool with which to hindcast past shelf/coastal systems and so to separate natural and anthropogenic factors in determining the causes of environmental change.
- Predicting the risks presented by plausible, but as yet unobserved, combinations of extreme events (e.g. storm surges and fluvial flooding) in both present and future climates.
- Providing the means to express the state of our knowledge, and investigate specific scientific questions, in a complex system.

However, such tools are only viable if we understand the underlying processes we are attempting to model and can interpret the resulting data. Many fundamental processes in shelf edge, shelf, coastal and estuarine systems, particularly across key interfaces in the environment, are not fully understood. Theme 3 addresses the following broad questions:

- How do biological, physical and chemical processes interact within shelf, coastal and estuarine systems, particularly at key environmental interfaces (e.g. coastline, sediment-water interface, thermocline, fronts and the shelf edge)?
- What are the consequences of these interactions on the functioning of the whole coastal system, including its sensitivity and/or resilience to change?
- Ultimately, what changes should we expect to see in our coastal environment over the next 50 years and beyond and how might these changes be transmitted into the open ocean?

Within Oceans 2025, Theme 3 will develop the necessary understanding of interacting processes to enable the consequences of environmental and anthropogenic change on UK shelf seas, coasts and estuaries to be predicted. Theme 3 will also provide the knowledge that can improve the forecasting capability of models being used for the operational management of human activities in the coastal marine environment. Theme 3 is therefore directly relevant to all three of the NERC's current strategic priorities; Earth's Life-Support Systems, Climate Change, and Sustainable Economies.

Theme-wide science aims

Theme 3 will integrate observational, experimental and modelling studies to:

i) Identify, quantify and understand the interactions between key processes involved in the functioning of UK estuaries, coastal and shelf seas.

ii) Determine the extent to which these processes and interactions vary through space and time.

iii) Use this understanding to better parameterise whole-system numerical models as well as create novel conceptual models of specific processes.

iv) Quantify the impacts of shelf processes on the open ocean, providing new model development to incorporate shelf effects into global models.

v) Predict the consequences of environmental change at scales appropriate for ecosystem management using the outputs of both models and field/laboratory observations.

vi) Provide new tools for the forecasting and prediction of changes to the shape of, and threats to, the UK coastline.

Centre contributions

- Determine the global impacts of shelf seas, including the development of suitable shelf sea parameterisations for global models. [POL]
- Predict the environmental impacts of global change on ecosystem function in estuaries and coastal seas. [PML]
- Predict extreme flooding events around the UK coast in response to climate changes. [POL]
- Improve forecasting of coastal flooding by coupling coastal and fluvial models. [POL]
- Identify and quantify the biological processes affecting ecosystem function, with a focus on key organisms and mechanisms in a physico-chemical context. [PML]
- Identify and quantify pelagic and benthic biochemical processes in topographically contrasting shelf environments. [SAMS].
- Determine the wider implications of biotic processes for the functioning of ecosystems at larger spatial scales relevant for management. [PML]
- Quantify the roles of varying bathymetry and episodic meteorological forcing on the horizontal patchiness of vertical mixing in shelf seas. [POL]
- Clarify and quantify the role of topography in determining the spatial scales of variability in horizontal dispersion on the shelf. [SAMS]
- Improve descriptions of sediment re-suspension and transport and its impacts on water optical properties. [POL]
- Determine topographic controls on sediment transport pathways on the shelf. [SAMS]
- Provide a large-scale, temporally-resolved context for sediment processes by using new techniques for coastal morphology observations. [POL]
- Quantify the causative connections between patchiness in the physics, the pelagic and benthic ecology, and the cycling of nutrients and carbon in shelf and coastal environments. [POL, SAMS, PML]
- Understand the role of "bio-engineers" in (de-)stabilising coastal sediments. [PML, POL]
- Couple sediment re-suspension, transport pathways, and morphological change across whole coastal-shelf seas. [POL, SAMS]

Coastal and Shelf Sea Processes and Interactions

Contribution to Theme 3 by the Proudman Oceanographic Laboratory

Background

Managing, and predicting whole shelf systems and their integrated impacts on the global ocean, both in terms of short-term forecasts and against the background of a changing climate, needs reliable numerical models. However, despite continuing improvements, numerical models of shelf seas and their interaction across the shelf edge are still hampered by poorly-understood or inadequately-parameterised physics. The POL work packages address a range of these problems: the impact of shelf seas on the global ocean, the patchiness of vertical mixing in shelf seas, sediment dynamics and impacts on coastal morphology and water column optics, and coastal flooding and how flooding events might change in response to a changing climate.

At the shelf edge, transports of nutrients and carbon between shelf seas and the open ocean are critical parts of carbon and nutrient cycles (e.g. Liu *et al*., 2000), and it is becoming evident that the shallow margins play previously unrecognised roles in the control of the physical circulation round the major ocean basins (Hughes & Meredith, 2006). These shelf impacts are not presently included in global models. There remains a real modelling challenge in linking the contrasting physics of shelf and deep ocean environments across the steep bathymetry of the shelf slope, and in providing descriptions of shelf processes suitable for global modelling.

Over much of the seasonally-stratified shelf, accurate forecasting of the transport and modification of material in shelf seas depends on realistic descriptions of how vertical turbulent mixing controls the horizontal distribution of thermocline depth, thickness, and strength. However, thermoclines predicted by shelf models are often too shallow and too diffuse. This has important consequences for the light and nutrients supplied to the modelled ecosystem. With at least half of the annual pelagic primary production of a stratified shelf sea taking place in the seasonal thermocline (Richardson *et al*., 2000), this can lead to substantial errors in calculating the distribution and magnitude of shelf sea production. Such inaccurate predictions of thermocline structures are a result of our limited knowledge of, and/or parameterisation of, mixing processes in the presence of vertical density gradients. For instance, turbulence closure schemes need additional, often location-dependent, manipulation of the turbulent diffusivity within vertical density gradients to try to account for the effects of non-resolved processes (e.g. Canuto *et al*., 2001).

On the shelf and into the coastal zone, marine sediments shape the seabed and the coastline, and play an important role in the dynamics of benthic and pelagic ecosystems. Through the actions of accretion, erosion and transport, sediments define most of our coastline. Their deposition and resuspension by waves and tidal currents in estuarine and offshore environments controls seabed morphology. Fine sediments, which act as reservoirs for nutrients and contaminants and as regulators of light transmission, have significant impact on water chemistry and on primary production. Therefore improved understanding of sediment dynamics in coastal waters has relevance to a broad spectrum of marine science ranging from physical and chemical processes, to the complex biological and ecological structures supported by sedimentary environments.

Close to the seabed, sediment dynamics involve the intimate interactions and feedbacks between the flow, the bedforms and the mobile sediments. For example, flow separation and vortex generation due to flow over ripples on the seabed influence sediment suspension. However, the presence of mud in predominantly sandy beds tends to suppress the ripple formation and thereby change the whole dynamics of sediment entrainment. These processes are fundamental and the development of process-based models describing these interactions is essential both for the description of sediments throughout the water column and for large scale sediment transport modelling.

When sediments are entrained into the water column, impacts on water quality in coastal and estuarine waters arise. Suspended particulate matter mediates primary productivity (through control on the absorption of light), biogeochemical cycling, and pollutant dispersal (Souza *et al* 2001). Our ability to model coastal primary production is currently hampered by descriptions of sediment suspension and water column optics that are too simple. Thus a prerequisite for the management of water quality in coastal waters is an understanding of the properties of such material.

The transport of sediments either by suspension in the water column or moving along the bed as bedload, impacts over time on the bathymetry. The ability to predict bathymetric evolution is a key requirement for coastal managers, particularly as our environment changes. This requires the development of improved numerical models and also the high-resolution datasets necessary for rigorous model assessment. Model development has in the past been hampered by the lack of such data, but a recently developed capability to collect continuously, high resolution maps of coastal morphology using ground based radar has solved this. Such a monitoring scheme will provide, for the first time, separation of episodic impacts from the slowly-varying background processes.

At our coastline, understanding the risks presented by combinations of extreme events is vital for their successful mitigation and management. An important tool in the management of episodic flood events is an enhanced forecasting capability, with a better quantification of uncertainty. Improved operational models (Flather & Williams, 2004) lead to better risk management, and the provision of the best guidance to government and local authorities regarding policies for coastal defence. Furthermore, a complete description of storm impact requires details of the inundation process (Bates & Hervouet, 1999), and suitably linked models are essential to emergency planners. The long term impacts on inundated ecosystems and habitats are also important, and relevant to national policy on shoreline management. The development of reliable inundation tools has an international dimension for those regions affected by hurricanes and tropical cyclones.

Looking to the future, global warming may increase the frequency and intensity of extreme events (e.g. Houghton, 2005). In the marine context, increased flooding due to larger and more frequent storm surges (combined with larger waves and increased rainfall) could have a major impact on economic and social systems (Lowe *et al*., 2001), as well as fragile ecosystems in vulnerable areas. The devastation following the Sumatra-Andaman tsunami in 2004 demonstrated the need to understand and mitigate against such high impact, low probability events (Defra, 2005), using that knowledge to develop warning systems based on multi-hazard instrumentation. Although the risk of a tsunami affecting the UK is very low, we need to fully understand the credible source mechanisms (considered in Theme 5), propagation pathways, suitability of numerical methods for representing the source, and the wave transformation as it approaches the shoreline.

WP 3.1 (POL) Global impacts of shelf seas

Aims and rationale

At the margins of the shelf seas steep shelf-slope bathymetry has impacts on ocean circulation and the transmission of signals around the ocean basins (Hughes & Meredith, 2006), while dense water formation and cascades at the shelf edge are thought to be important for water mass formation (Ivanov *et al*., 2004) and for the off-shelf transport of organic and inorganic carbon (e.g**.** Wollast & Chou, 2001; see also Fig. 1). WP 3.1 aims to quantify the water fluxes between the shelf and open ocean globally, including the development of methods to incorporate shelf effects into global models. Greater understanding of the whole carbon cycle will benefit from combining this work on down-slope fluxes of water (and its constituent dissolved carbon) with work in Theme 5 (down-slope transports of sediments and particulate carbon).

Specific objectives

i) Quantify and predict dense-water formation, cascading, slope mixing, their effects in the ocean.
ii) Determine constraints that the ocean margin imposes on adjacent ocean circulation and fields.
iii) Quantify and predict shelf seas' contribution to global biogeochemical budgets:
  - Ocean-margin fluxes and budgets of P, N, C, production and CO_2
  - The shelf-ocean carbon "pump" (Yool & Fasham, 2001) and its dependence on context
  - The shelf seas' role in large scale transport, especially of freshwater and pollutants.

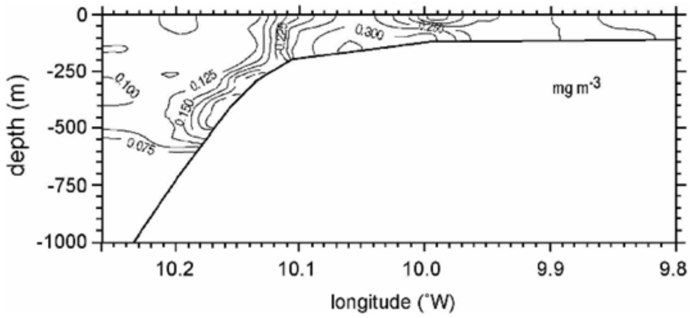

Fig. 1 (after Hill *et al*., 1998).

An observed cascade off the Malin shelf, seen in terms of the chlorophyll (mg m^{-3}) trapped within the dense water. The patchy, episodic nature of such cascade events makes it difficult to capture or parameterise the resulting carbon fluxes in models.

Approach and methods

Dense water, cascades, turbulence and down-slope mixing have been / will be measured by others in the Antarctic (Theme 1 and *SASSI*), Mediterranean outflow in the Gulf of Cadiz (*GO*, 2006-09, 50% EU-funded), over Rockall Bank (Theme 10), Faroe-Shetland Channel (2005), and in the Arctic (*ASBO* and Theme 1). These processes will be investigated by using a range of models from semi-analytic (Shapiro & Hill, 1997) to 3D unstructured grids (ICOM; Pain *et al*., 2005) and non-hydrostatic (Xing & Davies, 2006). We will evaluate the sensitivity of cascading to topography, and to ambient and initial conditions, and how slope mixing and its effects vary with context, forcing and internal waves. Validated 3-D models will be used to estimate fluxes in areas with observations (Ivanov *et al*., 2004), and their contribution to oceanic water masses relative to the original volume of water formed at the shelf edge. Sensitivity to climate factors will be modelled.

We will investigate the strong effect of topography on ocean circulation form (Salmon, 1998) and stability (Benilov *et al.*, 2004), the return of shelf-ward baroclinic flow via mixing and in boundary layers, and the diversion of limited depth-integrated flow along the continental slope (dynamical issues building on and going beyond projects in NERC-QUEST). In idealized ocean-shelf basins, we will use finite-difference and unstructured grids (e.g. ICOM, Theme 9) and investigate what global models require to model near-margin circulation, what aspects of shelf representation are important, what reduced models remain sufficient and the utility of the unstructured grid approach. Parameterized slope mixing effects will be shown in an established ocean model (1/4° North Atlantic sub-domain of NEMO; Theme 9). We will investigate the contribution of global shelves to total ocean energy dissipation and in enabling overturning.

A global coastal-ocean hydrodynamics-ecosystem modelling *system*, based on POLCOMS-ERSEM (Theme 9), is being developed (for QUEST to 2009). ERSEM has already been tested in very varied shelf and deep-sea locations (Blackford *et al*., 2004). We will further:

- Develop appropriate representation of key shelf sea processes. For shelf-seas' biochemical contribution in a coarse-resolution ocean model, and parameterisations of net shelf effects where shelves are not resolved (e.g. in GENIE), we will experiment with model resolution and collaborate with PML and NOCS regarding (ecosystem) model complexity.
- Investigate key transport pathways of carbon off shelf seas in relation to the seasonal cycle of stratification and mixing (ventilation).
- Study sensitivity to widely varied atmospheric/oceanic forcing and model parameterizations, using a 50 yr hindcast (ERA40 forcing) and future climate scenarios (HadGEM forcing; Theme 9). The long runs will help to study long-term balances, e.g. net carbon or nutrient accumulation. Model verification will be carried out in Theme 9, using key data sets (e.g. SES, OMEX).

Summary WP 3.1 research plan and deliverables

2007–09	• Data sets to test models' skill to represent cascades and slope mixing. • Develop a model to predict entrainment, mixing, sensitivity to initial and ambient conditions. • Water mass flux estimates in representative locations, and contribution to circulation. • Parameterisations of physical processes in shelf seas for global models
2007–10	• Demonstration of the effect of slope-mixing parameterization in an ocean-basin model

2009–11	• A –50 to +50 year assessment of the shelf seas' role in global carbon budgets. • Published model system (in 2010).
2010–12	• Shelf-sea contribution to the global carbon budget.

WP 3.2 (POL) Horizontal patchiness in vertical mixing in stratified shelf seas

Aims and rationale

As a boundary to vertical mixing, the thermocline affects much of the ecology and biochemistry of seasonally-stratifying shelf seas (e.g. Richardson *et al*., 2000; Sharples *et al*., 2001). WP 3.2 aims to address vertical mixing processes at the thermocline that are either poorly-understood or have inadequate parameterisations in models. Horizontal patchiness of vertical mixing is now known to be driven by varying seabed topography, indicating a need for a non-hydrostatic approach (Moum & Nash, 2000; Dewey *et al*., 2005). Recent data (Fig. 2) illustrates potentially important topographic effects on primary production. The thickness of the surface homogenous layer is also often poorly represented in shelf models, and yet is a key control on the light experienced by primary producers in the thermocline. Possible drivers of this are the effects of spatial and temporal patchiness in meteorological driving through Langmuir circulation (Smith, 1998; Noh *et al*., 2004), which plays a currently uncertain role in the development and structure (particularly the depth) of the thermocline, and horizontally-patchy inertial shear (Itsweire *et al*., 1989).

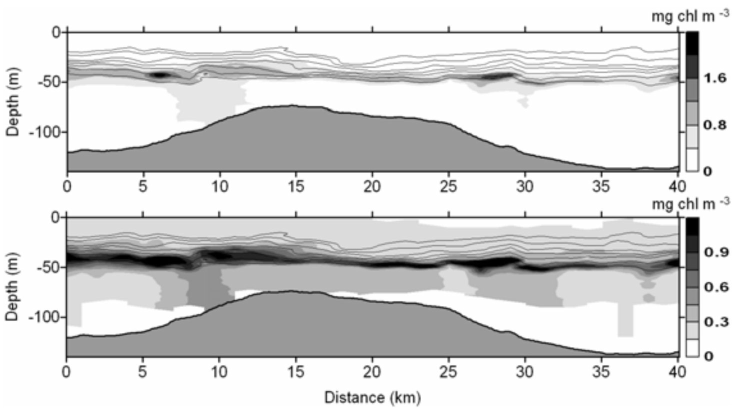

Fig. 2 (Sharples, Celtic Sea, 2005).

Transect of temperature (every 1°C) and chlorophyll (shaded, mg m^{-3}) along a typical bank. Both panels show the same data. The lower panel chlorophyll scale is skewed to highlight bottom layer concentrations. Note the high biomass in the thermocline and bottom layer at the bank edges, possibly driven by lee-wave mixing. These patterns are not correctly simulated by present shelf models.

Specific objectives

i) Quantify discrepancies between POLCOMS (with the GOTM turbulence scheme) and observations of thermocline depths/strengths and diapycnal fluxes.
ii) Determine the causes of these discrepancies in terms of modelled and observed responses to meteorological forcing and in terms of the potential for patchy internal mixing.
iii) Quantify the importance of non-hydrostatic processes at the thermocline over typical shelf topographies.
iv) Carry out ship-based process studies focusing on the patchiness of mixing through the shelf thermocline.
v) Quantify the consequences of thermocline patchiness over a whole shelf sea, alongside recommendations for process, bathymetry, and model resolution required to simulate the more important consequences.

Approach and methods

A high resolution (~1.8km) shelf wide application of POLCOMS (developed from Holt & James 2006) will provide the shelf scale context for exploring the parameterization of small scale processes. This model will be run from 1995-2005 to encompass the large number of undulating CTD (Scanfish) sections made by CEFAS (Brown *et al*., 2003) and recent data collected by POL (e.g. Fig. 2). These data will be used as a direct assessment of model performance at ~1 km resolution. Use will also be made of high resolution sea surface temperature and ocean colour data in collaboration with RSDAS. The importance of non-hydrostatic effects will be assessed by using an existing high-resolution non-hydrostatic model (Xing & Davies, 2006) in both hydrostatic and non-hydrostatic modes over typical shelf seabed topographies. The comparison will be carried out with existing data, and later with targeted process study data. A simple biogeochemical module will be included in the non-hydrostatic model to allow comparisons with basic biological fields (e.g. Fig. 2) and a preliminary assessment of the importance of non-hydrostatic effects on biogeochemistry.

There is particular need to rationalise the often disparate data types that the modelling and observational communities work with. Using the experience gained through the model-observation comparisons, the necessary observational data required to test key model predictions will be identified. As well as simple model-observation comparisons of resultant fields (e.g. temperature) we will focus on more fundamental properties, such as internal wave energy fluxes and turbulent dissipation rates. Two interdisciplinary research cruises (jointly with SAMS) will be conducted, with process studies to target the required data. POL will be responsible for coordinating the first of these cruises (24 days in the Celtic Sea), while the second cruise in 2009 will be led by SAMS (Hebrides and Malin). At-sea methods will include standard CTD and moorings, free-fall vertical turbulence profilers, towed CTD (Scanfish), towed temperature-fluorometer chain (high-resolution thermocline structure, with Theme 8), turbulence measurements from autonomous vehicles (with Theme 8), and satellite imagery. The work will be closely linked to WP 3.7 (horizontal dispersion rates in shelf seas in response to patchy vertical mixing) and WP 3.8 (ecological patchiness related to variability in the physical environment), both carried out by SAMS.

Summary WP 3.2 research plan and deliverables

2007–08	• Collate observational data and carry out 1995-2005 POLCOMS run. • Begin hydrostatic/non-hydrostatic comparisons.
2008	• Celtic Sea (summer) cruise. • Begin assessment of model-observation discrepancies over the NW European shelf.
2009	• Malin Sea cruise. • Complete configuration of hydrostatic model. • Begin comparisons of cruise process study results with POLCOMS and non-hydrostatic models.
2010–11	• Complete POLCOMS-observation comparisons. • Begin work on 2-D (x-z slice) coupled physical-biological non-hydrostatic, high-resolution model. • Apply 2-D model to a shelf sea bank as seen in observations.
2011–12	• New models and parameterisations of fine-scale processes (with Theme 9).

WP 3.3 (POL) Bottom boundary processes

Aims and rationale

Sediment transport process models underpin our ability to predict the entrainment of sediments into the water column (WP 3.4) and the transport of sediments for forecasting seabed and coastal morphodynamic evolution (WP 3.5). The difficulty in achieving accurate process models lies with the complex inter-dependence of sediment processes in the bottom boundary layer. Near the bed the fundamentals of sediment transport are governed by interactions between the sediment transport triad; the bed, the hydrodynamics and the mobile sediments. These three components interrelate, being mutually interactive and interdependent.

To make significant advances in the area of boundary layer sediment transport processes, we require co-located simultaneous measurements of the triad. This has traditionally been difficult to achieve. However, recent developments at POL using high frequency underwater acoustics has led to a suite of instruments which provide high spatial and temporal resolution measurements of all three components of the triad *in situ*. Linked with complementary advances in laser technology the combination provides an observational framework capable of assessing and advancing the latest sediment transport models available (e.g. Davies & Thorne, 2005). We propose to use these combined opto-acoustic systems, which will be developed further under Theme 8, to collect novel measurements of sediment processes in a range of environments, leading to significant advances in our understanding of, and modelling capability in, coastal sediment transport.

Specific objectives

i) Assess process based models over different sediment types, cohesive to non-cohesive.
ii) Investigate intra-wave and turbulence processes, over flat and rippled beds to improve process based sediment transport models; parameterisation of the process modelling output for input into large scale area models
iii) Advance the description and parameterisation of the impact benthic biota has on sediment transport processes (jointly with PML).

Approach and methods

A series of process studies will be carried out, coupling multi-frequency ABS (measuring vertical profiles of near-bed suspended sediment concentration and particle size), 3D-acoustic ripple profilers (ARP, providing very high resolution measurements of the bedforms), and 3-axis acoustic coherent Doppler velocity profilers, CDVP (providing turbulence and intra-wave velocity profiles). Combining these acoustics with optical instruments, such as OBS (optical backscatter) and LISST (Laser In-Situ Scattering and Transmissometery) to measure particle size distribution and concentration, should allow us to characterise different particles, *i.e.* sands and flocs. All this instrumentation is presently being built onto the autonomous seabed tripod STABLE III (Sediment Transport And Boundary Layer Equipment), following a recently successful NERC capital bid. STABLE III is expected to become available in 2006/7. For some of the field experiments we will use the Liverpool Bay Coastal Observatory (SO 11), to take advantage of the larger-scale context.

Utilising STABLE III a number of high resolution measurements of suspended sediments, flow and bedforms (Williams *et al*., 2004) will be collected on homogeneous and heterogeneous seabeds. The intention is not to simply choose sites which are non-cohesive quartz, for which most sediment transport formulae have been developed, but to also investigate sites with mixed bed sediments and beds which are biologically active(Widdows, *et al*., 2000). The aim is to examine the relationship between bed stress, bedforms and sediment transport for the different sedimentary regimes and to investigate such effects as bed stabilisation or destabilisation due to the bed type. Process based models will be both assessed and developed to represent and understand the basic sediment mechanisms. Parameterised outputs from these process models will be used as the inputs into large scale area models. (Thorne *et al*., 2003, Davies & Thorne, 2005).

Summary WP 3.3 research plan and deliverables

2007–09	• Analyse data from the DeltaflumeII and Dee 05/6 experiments to provide improved predictors of bedforms under waves and currents. • Assess the impact the bedforms have on the nature of vertical mixing.
2008–10	• Use the Dee 06-08 and LEACOAST2 06/07 experiments to measure sediment processes over different bed types. • Use the data to formulate improved formulations of bed roughness, reference concentration and nearbed suspended load.
2010–11	• Parameterise sub-grid scale sediment processes and include in high resolution coastal models, POLCOMS and TELEMAC
2011–12	• With WP3.5, model future scenarios of increased sea levels and wave heights and provide an assessment of the impact on sediment transport around the UK coastline.

WP 3.4 (POL) Suspended particulate material, transport, and water column optics

Aims and rationale

Processes controlling properties of sediments in suspension (e.g. flocculation and disaggregation) determine both the residence time of sediments in suspension (and so the potential transport rate) and the penetration of light through the water column. A range of impacts from coastal sediment transport, seabed and coastal morphology, through to pollutant transport and the primary productivity of coastal waters are controlled by the behaviour of sediments in the water column. However, there is a recognised need for significant improvements in our capability to model the processes and their impacts, beyond the presently limited accuracy and applicability of widely-used empirical approaches (e.g. Gordon & Morel, 1983). Pressing problems in the context of improving operational modelling around the UK coastline are the transport rates of sediments from estuaries into the coastal zone, and the impact that the sediments have on water opacity and the rates and distribution of primary production. For instance the combined ERSEM/POLCOMS modelling system not only fails to correctly reproduce the sediment distribution within the eastern Irish Sea, but it also uses a very simple optical model in which light absorption is just proportional to SPM, which in consequence will fail to reproduce the correct primary production.

The proposed work will address the dynamics of suspended sediment behaviour in the context of sediment supply to the coastal zone from estuaries, and of coastal water column optical properties. The overall aim is not only to improve our modelling accuracy of coastal suspended sediment transport, but also to develop a new description of sediment suspension and water opacity that will improve simulation of coastal primary productivity. The work will closely interact with WP 3.3.

Specific objectives

i) Acquire new knowledge of the dynamics of sediment flocculation and its impact on suspended particulate material (SPM) in shelf seas and estuaries.
ii) Provide preliminary formulations for aggregation-disaggregation and test these formulations using shelf sea models of the Eastern Irish Sea.
iii) Develop our understanding of the processes that affect the sediment fluxes between estuaries and the adjacent shelf sea.
iv) Derive and apply formulations of the effects of SPM on optical attenuation and absorption and assess their potential impact on primary productivity using existing models.

Approach and methods

We will carry out a series of process studies consisting of intensive measurements of turbulence, SPM concentration, particle size, light attenuation and absorption throughout the water column. To achieve this we will use a combination of shear probes, both in free fall and AUV mode (with Theme 8), ADCP, ADV, OBS, LISST and in-situ hyper-spectrometers and scatterometers. The work will be carried out within the Liverpool Bay Coastal Observatory (SO11), providing both the larger oceanographic context and a range of typical oceanographic regimes (e.g. estuary, ROFI, vertically-mixed coastal water, and seasonally-stratified shelf sea).

Particle size, concentration and settling velocities will be measured alongside turbulence properties (Reynolds stresses, turbulent production and dissipation) to find the appropriate formulations to describe aggregation and disaggregation (Winterwerp, 2002; Sanford *et al.*, 2005). Sediment transport in Liverpool Bay will be quantified by combining direct measurements and high resolution sediment transport models of the eastern Irish Sea, including the estuaries. The resulting knowledge of transport paths will allow calculation of the sediment fluxes between the estuaries and the Liverpool Bay ROFI. Commercial and new (through Theme 8) optical instruments will be used to measure the spatial and temporal variability in optical properties. Combining that information with concurrent observations of SPM will lead to a new dynamic model of water opacity as a function of coastal sediment processes. The effects of this new model on primary production will be assessed using the POLCOMS-ERSEM model in both 1D (vertical process study) and 3D modes.

Summary WP 3.4 research plan and deliverables

2007–10	• Carry out experimental studies annually in the Dee to provide benchmark data sets. • Assess and improve sediment transport models.
2007–09	• Use the Dee data to develop improved parameterisations of particle aggregation/disaggregation for modelling the transport suspended particulate matter, SPM.
2009–10	• Apply improved optical models to assess the effect that SPM has on primary production, using existing numerical models (e.g. POLCOMS-ERSEM).
2010–12	• Using the data sets and improved modelling, develop a coupled physical-sediment-optics-bio hi-resolution model of Liverpool Bay and connecting estuaries.

WP 3.5 (POL) Coastal morphodynamics and bathymetric evolution

Aims and rationale

Our ultimate goal is to combine accurate models of coastal sediment dynamics with knowledge of how changes in sea level, flooding, and storm events will impact our coast. Before we can do this we need to improve our understanding of transport processes for both coarse and fine sediments on scales relevant to coastal management and how these are integrated into long-term changes in coastal morphology. However, it is widely recognised that the prediction of coastal morpho-dynamics is often hampered by a lack of well-resolved (in time and space) quantitative observations over long enough time-scales required to understand the present status and recent changes in a system (e.g. Southgate *et al.*, 2003). We aim to address this lack of data and understanding in a specific case study, focusing on the large-scale consequences for bathymetric evolution in the coastal zone, arising from the integral effects of processes studied in WP 3.3 and WP 3.4.

Specific objectives

i) Identify key sediment transport pathways in the coastal zone and assess the performance of existing morphodynamic models against collected data. Identify appropriate modelling methodologies for coastal evolution.
ii) Assess the relative importance of short-term episodic events (*e.g.* storms) and continuous slow evolution in determining coastal morphology.

Approach and methods

The Dee Estuary will be used for the field case, with the advantage of having the larger scale hydrodynamic context provided by the Liverpool Bay Coastal Observatory (SO 11). The whole estuary has already been surveyed at high resolution using airborne LIDAR by the EA and NERC-ARSF. A new method of acquiring high temporal and spatial resolution bathymetry of the evolving mouth of the Dee Estuary uses a recently-developed land-based X-band radar system (Bell *et al*., 2006). We will also acquire further repeat LIDAR and echosounder surveys. The unprecedented spatial and temporal detail will allow identification of areas of erosion and deposition and mobile bedforms such as sandwaves. These data will then be used to assess sediment transport models e.g. Li and Amos (2006), implemented in 3D hydrodynamic models such as POLCOMS. Bedload as well as suspended sediment transport will be implemented. The data will also be used to investigate the role of extreme events (storms) impacting on the coastal environment, against the background bathymetric evolution due to tides and the affects of dredging and other engineering works. Thus we will be able to separate the relative effects of slow and episodic change.

Summary WP 3.5 research plan and deliverables

2007–12	• Acquire long-term (years) time series of high resolution (days and 10s metres) bathymetries over limited areas from X-band radar • Acquire larger area (less frequent) LIDAR and echosounder surveys • Carry out ongoing analysis of combined datasets.
2007–09	• Assess existing bathymetric data and produce model grids. • Implement POLCOMS and sediment transport modules including bedload transport to provide an enhanced POLCOMS model.
2008–10	• Evaluate available morphodynamic models against new data to select an appropriate model to describe the morphodynamic evolution of the Dee
2011–12	• Produce a 7-year hindcast of the bathymetric evolution of the Dee estuary to be compared with high-resolution data. • Assess the model capability and possible future scenarios (with WP3.3).

WP 3.6 (POL) Causes and impacts of extreme events

Aims and rationale

There is a requirement to both increase our skill at forecasting surges and flooding in the short term, and to develop our understanding of the dynamics of extreme events and the likely impacts of future changes in our climate. Based on these needs, WP 3.6 has the following aims:

- Improve our forecasting tools for surges and coastal flooding, with better tide/surge/wave models and a coupling of fluvial/estuarine/coastal models.
- Define the envelope of possible extreme sea levels around the UK resulting from a range of future climate scenarios.
- Predict the response of the shoreline to an increase in the frequency and intensity of storm events.
- Quantify the risk of tsunami impact in UK coastal waters, and understand the regional oceanographic properties that control tsunami propagation on a wide continental shelf (e.g. how would a tsunami from La Palma, a generation process to be studied by Theme 5, propagate across the UK shelf).

Specific objectives

i) Develop an appropriate system of sea level data assimilation for the operational modelling suite within the Storm Tide Forecasting System (STFS), including a robust and effective real-time quality control for the sea level data used in assimilation studies.
ii) Establish a prototype forecasting system based on short period ensembles, which can provide a statistical constraint on forecasts.
iii) Assess the consequences to forecasts of regional noise in sea level signals.
iv) Investigate the response of coastal and estuarine systems to flood events resulting from combined extremes (e.g. surge and rainfall).
v) Quantify how extreme sea level has changed, and is likely to change in future climates, around the European and other continental shelves.
vi) Assess the differing characteristic responses of other continental shelves, and identify areas of particular vulnerability to future increases in extreme sea level. This will also provide a global perspective of flood risk and sea level variability.
vii) Build upon preliminary Defra funded research to quantify tsunami risk to the UK.

Approach and methods

We will improve the initial conditions of tide/surge models using a broad range of assimilation options including local adjustment, optimal interpolation and Kalman filtering (e.g. Canizares *et al*., 1998). An optimised approach for operational systems will be developed. We will investigate how the ensemble information in an ensembles-based forecasting system should be presented: using the archive of forecasts and actual observations, a number of techniques including artificial intelligence (e.g. Lawry, 2004) will be to develop reliable forecasting rules. We will also use an existing fine resolution coastal baroclinic model (POLCOMS) to study the seasonal impact of steric effects and density-driven circulation on surge measurements and on local mean sea levels. In research that complements the FREE program, we will couple coastal models to estuarine and fluvial models that include floodplain inundation. We will compare a hierarchy of approaches from linked 2D coastal - 2D river models, through to unstructured models with advanced wetting-drying capability.

Data from tide gauges in the UK and global network (GLOSS), together with information from a range of both regional and basin-scale barotropic and baroclinic numerical models, will be used to study how extreme sea levels have changed in the recent past, and if changes in extremes correspond to, or are different than, changes in mean sea levels. Findings will compared to those suggested by climate model simulations of interannual sea level variability. Information on future meteorology from regional climate models will be used as input to surge models to simulate future extreme sea levels, thereby enabling assessment of changes in flood risk. The research will make use of, and will further develop, advanced extreme value statistical methods on the joint probability of waves and water levels, in collaboration with the University of Lancaster. Nested models will also be applied to investigate the dissipation of tsunami energy at the UK shelf break and across the shelf, which is a key component in developing a potential national tsunami warning capability.

Summary WP 3.6 research plan and deliverables

2007–08	• Methods for real-time quality control of assimilation data. • Begin collecting short period ensemble surge archive. • Establish 2D coupled coastal-fluvial models. • Configure global barotropic model for sea level studies using ERA40 reanalysis dataset. • Examine steric effects on seasonal sea level with regional baroclinic model.
2008–09	• Assimilation studies for operational surge model using advanced techniques. • Develop methodology for ensemble synthesis and dissemination. • Develop full 3D baroclinic coastal-fluvial models. • Run global model using Hadley Centre timeslices. • Analysis of long term sea level data and application of advanced spatial statistics. • Develop expressions for sea surface deformation for La Palma tsunami scenario.
2009–10	• Perform comparisons of the coastal-fluvial inundation models for a number of scenarios in key estuaries with barotropic and baroclinic models. • Set up unstructured Atlantic model for shelf surge characterization. • Model the La Palma tsunami and examine the run-up effects due to shoaling and shelf amplification. • Begin unstructured, finite volume estuarine inundation modelling work.
2011–12	• Complete modelling studies, write papers and arrange delivery of all transferables to the operational agencies.

Topographic Regime Control over Shelf Sea Systems

Contribution to Theme 3 by the Scottish Association for Marine Science

Background

Coastal and shelf waters are influenced by inputs from the open ocean, from land and from the atmosphere. Interactions between the physics, sedimentology, biochemistry, and ecology then act to distribute, dilute, modify, and absorb those inputs. Our understanding of these interactive processes underpins our capability to forecast and predict the shelf sea response to natural and anthropogenic influences. Yet we know that there are processes and interactions that are not well described by models, some that we presently have no way of incorporating into models, and some that we are only just beginning to recognize as important components of the coastal/shelf sea system. Identifying and quantifying these inter-disciplinary interactions, using integrated programmes of modelling and observations, is fundamental to providing robust tools for management and understanding of the shelf and coastal marine environment.

We propose to address some of the key processes that link the physical dynamics of shelf seas to the pelagic and benthic ecosystems and, ultimately, the cycling of nutrients and carbon. The global importance of shelf seas in cycling carbon is well recognised (Verity *et al*., 2002; Rippeth, 2005); however, much spatial heterogeneity exists with different regions functioning as CO_2 sources and sinks (Wang *et al.*, 2005). The underlying goal is to improve the parameterisation and simulation of these processes in the current and future generations of operational shelf sea models, and hence better quantify the contribution of shelf seas to global carbon budgets (through the continental shelf pump; Tsunogai *et al*. 1999) and improve predictions of changes induced by natural and human perturbations. In particular it is becoming increasingly apparent that irregular topography may be a key driver in the functioning of shelf systems. Our goals are to:

- Improve our understanding of the processes that determine the horizontal scales and variability of mixing on the continental shelf in contrasting topographic regimes, and of how these processes affect the transfer of water properties along and across the shelf (WP 3.7)
- Investigate how spatial variability in mixing and water properties influences microbial functional group composition and therefore the production and transformation of organic carbon within the upper water column (WP 3.8).

- Quantify the influence of shelf topography on benthic-pelagic coupling through mixing-driven export flux and by generating heterogeneity in benthic processes and associated biogeochemical carbon cycling (WP 3.8).
- Map sediment, and hence carbon, transport on the shelf through radiochemical and geochemical analyses (WP 3.9).

The backbone of this Research Unit (jointly with WP 3.2) will be multi-disciplinary cruises to topographically contrasting shelf regimes: a topographic high (or bank), a topographic low (or deep), and adjacent flat areas of shelf. Proposed sites are Hawes Bank and Muck Deep in the Sea of the Hebrides, and Labadie and Jones Banks in the Celtic Sea. Physical flow regimes will be described in detail by models and observations, from the ~10 km scale to the variations in turbulent properties over 10-100 m. Hydrodynamic and sediment transport modelling and *in situ* physical flow and benthic mapping in WP 3.7 and WP 3.9 will then inform the details of subsequent ecosystem and pelagic/benthic coupling investigations (WP 3.8).

WP 3.7 (SAMS) Role of topography in determining the spatial variability in horizontal dispersion

Aims and rationale

Tracer and budget studies show that mixing and exchange of oceanic and coastal water take place on the shelf. Topographic features, such as banks, slopes and troughs are expected to enhance both horizontal and vertical mixing on scales of a few kilometres, too small to be fully resolved by present shelf models but not by the next generation. Processes that drive the mixing between terrestrial runoff and oceanic water, e.g. tidal stirring and straining (Simpson *et al.*, 1990), inertial currents (Mackinnon & Gregg, 2005), eddy activity and internal waves (Inall *et al.*, 2001*;* Nash & Moum, 2005), are still inadequately parameterized or simulated. Furthermore, horizontal diffusion and dispersion processes are often included in numerical models simply to maintain numerical stability; increasing model resolution, however, means that in the future these processes must be explicitly included or parameterised.

Internal waves are generally assumed to dominate velocity and density variations on scales <100m. Two-dimensional geostrophic horizontal turbulence ("vortical modes") exists at similar, and larger, scales and is relatively well understood. However, the dispersive effect of the interaction between vortical modes and patchy internal wave mixing is not well understood. Recent evidence suggests that not only do vortical modes exist at km scales, but that a component of the geostrophic turbulence may be related to the gravitational collapse of patchy internal wave mixing events (Sundermeyer *et al*., 2005), and that shear dispersion, from a combination of vertical mixing and vortical mode shear, may contribute significantly to horizontal dispersion (Dale *et al*., 2005).

Both internal wave (Inall *et al*., 2005; Moum & Nash, 2000) and vortical mode activity (Sundermeyer *et al*., 2005) are enhanced by topography. We will therefore investigate topographic regime control on horizontal dispersion mediated by internal wave/vortical mode interactions on the continental shelf.

Specific objectives

i) Assess and quantify how horizontal dispersion through shelf seas is affected by irregular seabed topography.
ii) Deliver an understanding on what the rate limiting processes are in the horizontal dispersion and exchange and mixing rates of stratified shelf waters.

Approach and methods

Cruise-based field work will produce a suite of observed parameters allowing us to characterize the local mixing regime at each study site. CTD, moored and vessel-mounted ADCP surveys will provide information on the background density and velocity fields. We propose to use dye, injected at depth, to trace the interleaving and horizontal mixing of water masses; the fluorescent dye will be tracked using a tuned fluorometer, mounted on board an AUV. Microstructure observations, both from profiling instruments and AUV (Theme 8, and potential for SOFI), will describe the turbulence field. These measurements will be augmented by analyzing lowered ADCP measurements for the finescale response in order to infer turbulent diffusivities (Polzin *et al.*, 2002). Bed-mounted ADCP data will also be analysed, using structure function methods to derive estimates of turbulent dissipation. The proposed field observation programme, therefore, will directly measure the dispersion and mixing of water and, by mapping the ambient flow, density and turbulence fields, allow us to relate and parameterize the mixing in terms of the velocity and density fields.

Prior to the research cruise programme commencing, each site will be modelled using the current operational POLCOMS model and a more sophisticated non-hydrostatic model, e.g. MITgcm. The model results will be used to inform and guide the observational programme.

This research is closely linked POL WP 3.2, and will be conducted with close collaboration between SAMS and POL. Clearer understanding of the physics of mixing on the shelf will feed directly into pelagic and benthic system studies and their cyclical coupling.

Summary WP 3.7 research plan and deliverables

2007–08	• Initial idealised modelling studies of stratified flows over banks and deeps. (POLCOMS and MITgcm)
2008–11	• Fieldwork related timing: A better understanding of the causative processes of horizontal dispersion and mixing in shelf waters.
2010–11	• Derivation of parameterizations for horizontal transport and exchange of water masses along and across the shelf resulting from topographically controlled spatially variable mixing.
2011–12	• Apply and test horizontal mixing parameterisation schemes to current generation (at that time) operational models.

WP 3.8 (SAMS) Pelagic and benthic biogeochemical processes: response to spatial variability in topographically controlled mixing

Aims and rationale

Shelf seas may contribute 25-50% of global ocean CO_2 draw down (Rippeth, 2005). However, the biological processes governing the fixation and transfer and fate of carbon on the shelf remain surprisingly poorly quantified. A major impediment to biogeochemical modelling of carbon flux is the inadequate understanding and representation of pelagic microbial community structure and related multi-element cycling in response to non “Redfield” nutrient ratios (Doney, 1999), with further modelling studies (Allen *et al*. 2004) highlighting the role of turbulence in regulating microbial carbon production and export. An improved understanding of the physical and nutrient controls of different planktonic functional groups in terms of their rates of growth, the grazing pressure they experience, trophic transfer and export flux is critical to better understanding of ecosystem function and carbon cycling in shelf seas. Furthermore, understanding the fate of this sedimenting carbon and the processes contributing to benthic remineralisation and topographically generated transport is critical to the quantification of shelf carbon cycling, which remains a major challenge in marine geochemistry (Aller & Blair 2004).

Specific Objectives

i) To determine how topographically generated horizontal and vertical mixing and its influence on nutrient ratios will influence the distribution and density of different phytoplankton, bacterial and micro/meso zooplankton functional groups and hence the rate and quantity of primary production, trophic transfer and the quantity and quality of carbon deposition to the benthos.

ii) To assess the role of inputs of high quality labile carbon associated with specific topographical features in fuelling high rates of benthic particle reworking and solute transport, promoting microbial mediated remineralisation and increased rates of benthic recycling of inorganic nutrients.

iii) To investigate the role of sea bed topography in modifying cross shelf carbon transport processes, creating areas of enhanced deposition and erosion.

Approach and methods

In the pelagic zone, ship-based fieldwork will assess a suite of parameters (including phytoplankton taxonomy, bacterial abundance and functional group, picoplankton, micro and mesozooplankton abundance and biomass, dissolved inorganic nutrients and dissolved/particulate organic matter, pigment analysis and DIC). This will allow us to spatially characterise the microbial community and its carbon biomass and any characteristics such as the appearance of harmful species in relation to topographically influenced variability in the physical and chemical environment. We shall determine the major rate processes of primary and bacterial production, respiration, trophic transfer of particulate and dissolved C and N and relate these to the physical/biological/chemical characteristics of the water column. Deck-board nutrient manipulation experiments on microbial communities will be used to assess the specific factors limiting productivity in different mixing regimes. Laboratory and deck-board studies with oscillating grid generated turbulence will provide better understanding of how turbulence/nutrient interactions influence the rate processes that govern production, transport and export of carbon (Alcaraz *et al*., 2002; Peters & Marrase, 2000).

Sediment trap studies and nutrient analysis will be employed to assess the pelagic-benthic export flux. We propose to use both ^{234}Th and ^{210}Pb/^{210}Po in the water column and particulate matter to determine the export flux from the pelagic to benthic zone. We will also try to explicitly link productivity in the photic zone with biogenic particle flux to the sea floor through the study of bacterial proxies in the form of halophilic, oil-degrading bacteria associated with phytoplankton / phytodetritus. Recent research has identified that very closely related strains of this bacterial group can be found in both pelagic and benthic zones (Green *et al*, in prep.), suggesting coupling between the pelagic and benthic microbial communities. By the use of culturing techniques and molecular analysis (DGGE, 16S clone libraries and 16S sequencing), we will assess the qualitative and quantitative distribution of our microbial proxies through the water column and in the upper benthic layers and hence determine the source of phytodetrital benthic carbon in different topographic regimes.

Bloom composition may influence quality of sedimenting material with consequences for benthic organism activity, organic matter decomposition and recycling. Benthic metabolism and remineralisation pathways will be examined *in situ* and ship-board to determine rates and contribution to nutrients and other biogeochemical fluxes and re-supply to the water column. Benthic organisms play a key role in controlling redistribution and burial of settling material and thereby influence the redistribution, early diagenesis, and ultimate incorporation of carbon and other biogenic components into the sediment record (Green *et al*., 2002, 2004). However, different mixing regimes are not geochemically equivalent (Sun *et al*., 2002) and explicit coupling of sedimentary process with biological mechanisms is an essential step in the improvement of current ecosystem models (Blackford, 1997). In order to constrain some of these factors, we will use multiple tracer methods to examine spatial differences in bioturbation (^{210}Pb, ^{137}Cs, ^{234}Th, Chl-a, luminophores) and bioirrigation responses (*in situ* and using ship board incubations) of the benthos to the changing nature and quality of organic matter supply associated with seabed geomorphology.

Topographic banks that are expected, through mixing, to modulate carbon export flux are further hypothesised to influence benthic carbon transfer. In addition, depressions may trap older particulate material laterally advected by coastal currents. Furthermore, material may be drawn away from the shelf and down slope, resulting in the export of shelf production to deeper water. By comparing modelled and observed ^{210}Pb and ^{234}Th export fluxes with measured sediment inventories it will be possible to identify areas of sediment focussing and erosion at the topographically different regions and hence inform understanding of particle flux in these regions with respect to vertical and lateral transport (Shimmield *et al*., 1995, Smith *et al*., 2003).

Summary WP 3.8 research plan and deliverables

2007	• Initial cruise, west coast Scotland to determine bloom characteristics and carbon flux, retrieval of sediment cores to determine organic supply, type and redistribution in areas of topographic change. • Establish methodology for monitoring bacterial proxies of bethic-pelagic coupling
2007–09	• Quantification of the phytoplankton community structure and function, carbon export flux and benthic remineralisation in areas of complex topography.
2008	• Celtic Sea cruise (25 days), sample collection, shipboard experiments, *in situ* measurements, and work up molecular data. • Synthesis and reporting of observational and experimental data.
2008–11	• Assessment of the role of topography in generating carbon sinks and sources in shelf regions.
2008–12	• Determine the role of topography in governing the distribution of planktonic functional groups, rates of production, trophic transport and export of carbon.
2009	• Cruise to banks and deep holes, west of Scotland, collection of samples, shipboard experiments, *in situ* measurements, and work up molecular data.
2010–-11	• Report & publish distribution and utility of proxies (2010) and integration to topography (2011).
2011	• Deliver a better understanding of the processes that govern the distribution of planktonic functional groups and the related rates of production, trophic transport and export of C.
2012	• Synthesis, providing an improved mechanistic understanding of topography and turbulence generated physical-pelagic-benthic interactions and their influence on benthic processes, regeneration rates and carbon storage

WP 3.9 (SAMS) Topographic controls on sediment transport pathways on the shelf

Aims and rationale

Modern continental shelves represent ~5% of the Earth's surface. Sediments on the UK shelf are presently being redistributed by the post-glacial rise in sea level. Relating seabed sediments and hydraulic processes is thus problematic, and shelf sediment processes are not well understood. Through acoustic surveys, coring, and geochemical tracers we propose to investigate sediment transport pathways and the localised influence of topography on a region of the western UK shelf.

Sediments play a key role in transporting both carbon and contaminants along and across the shelf; however, sediment transport paths are complex and not clearly understood. The hydrodynamic regime of the shelf has a fundamental influence on sediment redistribution; other, less well understood are the bathymetric controls on sediment movement. Shelf depressions can act as sediment sinks, focusing fine-grained deposition in a mid-shelf setting, whilst bathymetric highs can produce localized zones of current enhancement producing erosion and net sediment export, or provide 'lees' from tidal dispersion allowing deposition to occur. Sediment bedforms themselves, such as sand waves, can produce local hydrodynamic effects but also provide an indication of the gross bed-load transport direction (Kenyon *et al.,* 1981).

Acoustic mapping, such as multibeam sonar, offers insights into modern and historical sediment transport pathways by providing highly detailed geomorphology on the shelf (Howe *et al.,* 2003*;* Landvik *et al.,* 2005). Since the last glaciation, ice streams established routes of net sediment export from the continent to the shelf break which, in some cases, have remained active during the present Holocene transgression (Stoker & Bradwell, 2005).
Contaminants associated with the sediment, such as stable lead ($^{206}Pb/^{207}Pb$) isotopes, and anthropogenic radionuclides are unique markers which offer an ideal opportunity to use them as tracers for sediment provenance, and transport on the shelf. Here we propose to use such tracers to gain a comprehensive understanding of pathways of contamination of the shelf.

Specific objectives

i) Survey and interpret the complex post-glacial physiography of the shelf and observe any influences on sediment transport pathways.

ii) Investigate the age and provenance of modern UK shelf sediments and analyse their post-depositional history.
iii) Investigate and utilise specific geochemical tracers to denote sediment, and therefore contaminant transport pathways on the shelf.

This work will link with WP 3.3 and WP 3.4 on the physical dynamics of sediment transport and the effect on optical properties of the water column, and WP 3.10 on modelling benthic habitats to determine ecosystem function in a variety of sediment types. It is also expected to provide useful information on sediment pathways to the Biscay canyons studied in Theme 5.

Approach and methods

Initial acoustic survey of two regions of the UK shelf (multibeam sonar, side scan sonar and a sub-bottom profiler), focussing on the Sea of the Hebrides. This region is ideal for WP 3.9 as it contains not only some of the deepest points of the UK shelf, originating as glacial incisions, but also sediment (morainal) and bedrock-derived bathymetric highs. Benthic sampling will use short corers (e.g. multi-mega corers) to sample the sediment-water interface and longer, gravity cores will be used at sites where the sediment cover can provide a longer (post-glacial) record of sediment deposition across the region (e.g. the finer-grained sediment within the depressions and any localised lees surrounding the shelf banks). The cores will be investigated for texture and geochemistry, in particular using geochemical markers to reveal sediment composition, provenance and source. By combining the detailed acoustic survey and coring with published regional sediment transport maps (e.g. BGS) a highly detailed dataset will be produced on the localised and regional influences of topographic features on sediment transport across the shelf.

Summary WP 3.9 research plan and deliverables

2007–09	• Initial sediment mapping, legacy data (BGS) • Initial estimates of bedload transport and benthic boundary conditions. • Survey (Phase I): side-scan and multibeam imaging, to prepare acoustic map. • Survey (Phase II) : coring, for initial sedimentology.
2009–11	• Core analysis – sedimentology and geochemistry – identification of geochemical tracers. • Dataset complete
2011	• Compilation of legacy, acoustic and core datasets into sediment process and pathways map. • Parameters passed to partner institutions.
2012	• Publication of physiographic and sediment transport map: including a comprehensive understanding of sediment–borne contaminant transport pathways on the shelf and a better understanding of continental shelf carbon pump.

Consequences of Climate Change and Anthropogenic Activity on Ecosystem Functioning of Estuaries, Coasts and Shelf Seas

Contribution to Theme 3 by Plymouth Marine Laboratory

Background

Between now and 2025, increased precipitation, temperature, seawater acidity and storm events, plus changes in agricultural practice, are predicted to alter the transport of suspended material and the supply of nutrients to coastal waters (Tappin *et al*., 2002). In addition, habitat modification through land reclamation, coastal development and resource extraction are likely to increase. Coastal and estuarine ecosystems are important for the provision of food, employment and recreation, and as home to a significant amount of the UK's biodiversity (Defra, 2002).

Larger estuaries and their surrounding coasts are often areas of high population density and considerable economic activity that are of great importance to international and national trade (Defra, 2002). As such, they have been subjected to pollutants, including radioactive waste, trace metals and organic inputs, as well as morphological changes due to dredging and engineering modifications such as land reclamation and the construction of harbours and training walls. Estuaries are at particular risk as the pressures for development, and maintenance, of docks, recreational facilities and housing will continue to squeeze this unique habitat.

We will improve understanding of how the UK coastal environment responds to climate change, development and natural disasters, thereby helping to develop a sustainable national economy. By providing Defra and conservation agencies with information on the relative functional importance of different benthic habitats, we will provide tools to assist the management of activities that damage the sea bed (dredging, spoil disposal, aggregate extraction, fishing etc). Providing data on the impact of seawater acidification will enable scientists to assess the environmental risks associated with the sub-seabed sequestration of carbon dioxide. We will contribute to the knowledge-base required for implementation of the European Water Framework Directive.

The research also directly addresses two of NERC's fundamental science questions: how can we integrate biogeochemical cycles into physical and geological models, with particular attention to processes at critical interfaces? and what are the impacts of climate change on continental shelves, and their implications for coastal-zone management? (NERC, 2002). To improve predictive capabilities needed for effective management and protection of coastal ecosystems, we will:

- Quantify biological, physical and chemical interactions in estuarine, coastal and shelf sea ecosystems, with emphasis on the mechanisms driving key processes at marine interfaces.
- Describe how such interactions and processes are distributed through space and time.
- Develop the knowledge and understanding necessary for predicting the likely consequences of climate change and anthropogenic activity on ecosystem functioning.

The aims of this Research Unit will be delivered through a combination of data generation and model development. The research will be conducted in three related work packages. WP 3.10 will identify the organisms responsible for mediating key processes at environmental interfaces and will quantify their effects. The data and understanding gained from this activity will be scaled up in WP 3.11 to address scientific questions and management issues operating at the level of whole ecosystems. WP 3.12 will use the knowledge gained to develop a capability to predict the potential impacts of climate change and anthropogenic activities on estuaries and coastal waters, whilst WP 3.13 (originally in another Theme) focuses on the biogeochemical processes affecting pollutant pathways and their human health implications.

WP 3.10 (PML) Biological processes affecting ecosystem function: key organisms and mechanisms in a physico-chemical context

Scientific aims and rationale

In shallow coastal seas and estuaries strong coupling exists between the benthic and pelagic systems and this coupling could be instrumental in setting rates of ecosystem function. For example, the sediment can supply up to 80% of the nitrogen required by phytoplankton in shallow (<50m) coastal seas (Dale & Prego, 2002) and can also act as a nitrogen sink through burial in sediment reservoirs and loss via denitrification (Tappin, 2002); sediments therefore play a key role in the removal of anthropogenically derived nitrate (Nedwell *et al.*, 1999). However, both biological and chemical processes are poorly quantified in existing benthic models. Significant interactions between large infaunal organisms and nitrogen cycling have been demonstrated by a number of authors (e.g. Widdicombe & Austen 1998; Howe *et al*, 2004). Whilst many studies have quantified the impact of bioturbating species on nutrient flux, few have provided reliable data on the rates of nutrient transformation via denitrification and anammox. This information gap is a major constraint on the development of benthic models: studies designed to fill it are urgently needed. A key mechanism by which bioturbation alters nutrient cycling is by changing the abundance and distrib-ution of key microbial groups responsible for nutrient transformation (Papaspyrou, *et al.*, 2006 &

2005; Dollhopf, 2005). Whilst previous studies have observed correlations between total bacterial activity and ecosystem processes (Gilbert *et al*., 1998), the relationships between bioturbating macrofauna, microbial functional diversity and ecosystem function have yet to be quantified.

The importance of biological processes in sediments is not limited to nutrient cycling. The presence of biota within cohesive sediments can also act to either stabilise or to destabilise the sediment depending on the identity and function of the organisms present (Widdows & Brinsley, 2002). By reducing local current flow, increasing deposition and reducing turbidity, some biota, e.g. mussel beds and saltmarsh plants, may alter bed levels by in excess of 1 m and their sediment stabilising effects are obvious. However, the effects of other organisms are more subtle and their impact needs to be quantified in terms of effects on sediment erodability and changes in bathymetry (e.g. bio-stabilisation by benthic diatoms and vegetation and destabilisation via increased turbulence in the benthic boundary layer and bioturbation by burrowing and deposit feeding animals).

Estuarine and coastal ecosystems also contain numerous suspension feeding species that are capable of removing significant amounts of particulate material from the water column before being deposited as faeces. The relationship between the seston and suspension feeders is two-way in that the concentrations and compositions of suspended materials can both affect and be affected by the activities of these organisms (Hawkins *et al*., 1998). As suspension-feeding organisms have the potential to interact with particle transport and biogeochemistry it is essential that the contributions of such organisms are included in ecosystem process models (e.g. Bacher *et al*., 2003; Duarte *et al*., 2003). Clearly, in low energy environments, the identity and distribution of benthic animals can profoundly affect the subtidal sediment resuspension, with lowest erosion thresholds coinciding with the most intense mixing of the sediment column by bioturbation activity.

In cohesive sediments, bioturbation is an important driver in ecosystem function. However, coarser, more permeable sediments may be dominated by physical processes such as water column hydro-dynamics and interstitial water flow (de Beer *et al.* 2005). Ripples at the sediment-water interface induce alternating pressure gradients which drive water into, and draw water out of, interstitial spaces in the sediment. This interfacial advection carries particles, oxygen and nutrients into the sediment where they encounter microbial communities on the surfaces of sediment particles. The net result is that penetration into the sediments greatly exceeds that predicted by models based on molecular diffusion or bioturbation, and rates of microbially mediated processes may be far greater than might be predicted from estimates of microbial biomass.

Specific objectives

i) Describe and quantify the biological processes and mechanisms underlying sediment erodability and nutrient flux.
ii) Determine the impact of biological processes on the benthic-pelagic balance of nutrients and sediments.
iii) Determine the relative importance of physical and biological processes to rates of ecosystem function across different sediment types.

Approach and methodology

We will identify the impact of bioturbating organisms on the activity, function and composition of microbial communities through laboratory based manipulative experiments and field observations. The experiments will involve collecting key bioturbating species from the field and establishing them in cores of natural sediment in PML's mesocosm facility. Using this facility we have a proven ability to maintain sediment communities under conditions that are representative of the environ-ment from which they have been taken (eg. Kendall *et al*, 1995). Once established in the mesocosm, the burrowing activities of bioturbators can be observed and samples taken for microbial analysis. To estimate microbial production we will use the method of Dixon & Turley (2001). For identifying the microbial species and functional types, DNA and RNA will be extracted from the sediments associated with known bioturbatory structures e.g. burrows and expulsion mounds, and phylo-genetic marker libraries will be used to identify microbial communities. By artificially mimicking the individual impacts of bioturbators, such as burrow ventilation and ammonia production, we will also determine the relative importance of individual processes in structuring microbial communities.

The impact of benthic organisms on sediment stability and transport will be determined using existing flume technology (Widdows *et al,* 2004; 2005). The flumes will be employed in a series of manipulative laboratory and field experiments to quantify the effect of different species (bio-stabilisers and bio-destabilisers) in estuarine and coastal sediments. We will also assess the effect of suspension-feeding organisms on particle transport and biogeochemistry by establishing models for each main class of suspension feeder. These will predict how feeding, biodeposition, excretion, and growth vary in response to environmental changes, seston availability and composition. Novel elements will include resolving the relative processing of living phytoplankton, non-phytoplankton organics and the remaining inorganic matter, where shellfish and other suspension-feeders are known to select between these dietary components. The importance of estuarine turbidity maxima and resuspension and transport of particles due to tides, freshwater runoff and waves will be determined. Measurements will be made of standard variables (e.g., velocity, salinity, temperature, suspended sediment concentration, pH, dissolved oxygen), waves (using bed-mounted velocity, OBS and depth recorders) and turbulence (using ADV and SCAMP instrumentation). These data will be used to develop novel models of sediment transport and nutrient flux to better describe the impact of bioturbation on the benthic-pelagic balance of nutrients and particle transport.

Impacts of physical disturbances (waves, rainfall and storms) on sediments and their mediation by biota will be determined. Specifically, are mud banks progressively more difficult to erode with depth because of consolidation, or easier to erode because of reduced influence of micro-phytobenthos? Intertidal sediment erodability down vertical sediment profiles will be measured using *in situ* core-sectioning techniques and mini-flumes (Bale *et al.*, 2006), and will be related to physical, chemical and biological properties of the sediment, as well as desiccation associated with diurnal, spring-neap cycles and seasonal timescales. Field studies and manipulation experiments will quantify the impact of rainfall and waves on erodability of sediment and the interactions with biota acting as ecosystem engineers (with POL, WP 3.3). Data from these studies will be assimilated within models of sediment transport.

In mobile sandy sediments, biotic processes are assumed to be less important than physical processes: we will assess the relative contribution of bioturbation and permeable sediment processes to ecosystem functioning in shallow coastal seas. Data will be obtained from fieldwork in winter, post spring bloom and summer, on an extensive area of intertidal sand flat in the Isles of Scilly.

Summary WP 3.10 research plan and deliverables

2007–11	• Experimental studies to quantify the role of ecosystem engineers in hydro-bio-sedimentary process.
2007–09	• Use existing and novel data to develop dynamic models of how suspension feeders interact with their environments, particularly their influences on pelagic to benthic fluxes of particles and nutrients.
2007–12	• Use the experimental data to develop a conceptual model describing the mechanisms by which macro-organisms impact nutrient flux through the mediation of microbial communities.

WP 3.11 (PML) Implications of biotic processes for ecosystem functioning at spatial scales relevant for management

Scientific aims and rationale

The seafloor is a complex mosaic of different sediment habitats. The abundance and distribution of organisms and the rates of many key ecosystem processes are affected by habitat type (Widdicombe & Austen, 2005; and references within). Therefore, an ability to predict the regional distribution of sediment habitats would enable prediction of the impacts of environmental or anthropogenic change on the functioning of coastal and estuarine ecosystems. Heterogeneity exists within habitats, as the distribution and activity of functionally important organisms are not consistent throughout space or time (e.g. Rowden *et al*., 1998; Widdicombe & Austen, 2005); this is true for both macro-organisms and bacteria. It is essential that this heterogeneity is included as an intrinsic part of models used to predict ecosystem function at regional scales. In addition to biological processes, fluxes of nutrients and sediments in coastal ecosystems can be constrained by, or facilitated by physical phenomena such as frontal regimes, water-column stratification, upwelling, advection and mixing. Physical processes can exhibit great variability in time and space, particularly in shallow estuarine and coastal waters, and consequently can generate strong variability at similar scales to biological processes (Uncles, 2003). Current models of sediment and solute transport cannot yet effectively replace expensive and time consuming field observations.

Specific objectives

i) Model and predict the distribution of sediment habitats.
ii) Quantify spatial and temporal variability in the biological processes responsible for nutrient cycling and sediment transport.
iii) Determine and quantify the environmental factors that affect the balance between benthic, anthropogenic and pelagic nutrient regeneration and assess the impact of changes in this balance on pelagic primary productivity.

Approach and methodology

Field data will be collected in near-shore coastal and embayment areas, and estuaries and estuarine plume regions, in order to determine the dependence of sediment suspension, sediment distributions, bed types and habitats on sediment availability and forcing due to waves, tides and density-driven and wind-driven currents. Estuarine circulation, salt intrusion and salinity stratification will be investigated in relation to estuarine morphology, tidal forcing, freshwater buoyancy inputs, weather, vertical mixing and seiching phenomena. We will also investigate the behaviour of high concentration sediment suspensions (0.1 to ~10 g l^{-1}) in estuaries and their production by tidal currents, wind and waves, high runoff events, and accumulation mechanisms in the estuarine turbidity maximum and intertidal areas. The knowledge gained through these studies will enable us to apply the latest theories of estuarine and coastal morphology to a wide range of environments and test the validity of current models of sediment distribution. We will develop these and additional models to explain large-scale sediment distributions and long-term estuary and coastal evolution, as well as more localised features, such as channel and intertidal mudflat shapes.

The spatial and temporal variability in abundance of large, functionally-important organisms will be determined at a number of sites in estuaries and coastal areas close to Plymouth. Spatially-referenced samples will be taken every 2 months over the course of the first 2 years, after which sampling will be reduced. Concurrently, samples will be taken to determine the rates of associated key ecosystem processes such as: nutrient flux, denitrification, bacterial activity and sediment stability/cohesion. Short term (24-48 hr) and long term (seasonal) variability in the activity and impact of key species on ecosystem processes (nutrient flux, nutrient transformations, biogas production and sediment cohesion) will be assessed using mesocosm experiments.

We will incorporate biological impacts (sediment stabilisation / destabilisation and the removal of suspended material through suspension feeding) into models of long and short term changes in estuarine morphology, which include the feedback between tidal currents and the bathymetry. This incorporation of biological processes and environmentally realistic critical erosion and deposition thresholds (with appropriate spatial and temporal changes) will improve parameterisation of benthic-pelagic exchanges in the POLCOMS, BELPLUME and other models. These models will be validated using data generated from measurement of short term (hours - days) and long term (months - years) changes in intertidal sediment levels using a novel self-logging, optical sediment level sensor developed at PML.

Summary WP 3.11 research plan and deliverables

2007–11	• Generate spatially and temporally referenced data set containing information on the abundance and distribution of key organisms, environmental conditions and ecosystem function.

2008–10	•	Carry out experimental sediment studies to quantify the impact of key organisms on nutrient flux across a range of temporal scales.
2009–12	•	Model the effects on nutrient cycling of changing the balance of nutrient regeneration processes.

WP 3.12 (PML) Environmental impacts of global change on ecosystem function in estuaries and coastal seas

Scientific aims and rationale

Climate change will have significant physical and biological effects on estuaries and coastal zones (Tappin *et al*., 2002). Increased precipitation, extreme events and changing sea levels would lead to greater sediment inputs, freshwater volumes and water-column stratification, as well as sediment erosion that will alter estuarine and coastal morphology. Rising temperatures are already altering species composition (Lawrence & Soame, 2004), with the potential to alter biotic influences on sediment dynamics – and hence modify the morphology of intertidal mudflats and saltmarshes.

As atmospheric increases in CO_2 diffuse into the ocean, seawater becomes more acidic (Caldeira & Wickett, 2003). This may have substantial impacts on the biological processes of coastal and estuarine ecosystems (Turley *et al.*, 2005). Concerns about the greenhouse effect have led to proposals for CO_2 mitigation. One method currently being suggested is to inject CO_2 into sub-seabed porous reservoir rocks, which is technically viable and has been employed at the Sleipner West gas field in the Norwegian sector of the North Sea since 2000. Whilst geological storage appears to be a practical tool in reducing emissions (Gibbens *et al*. 2005), little is known about the long term issues which will arise from underground storage of CO_2. Sub-seabed leaks are possible over time and ocean currents may carry acidified water to vulnerable areas nearer to shore.

Specific objectives

i) Describe and quantify the impact of environmental change on the biological processes and mechanisms underlying sediment erodability and nutrient flux.
ii) Determine the impact of pH change on the health and structure of body tissues (respiratory, reproductive and digestive) in marine organisms, as well as key physiological processes such as acid-base regulation and reproductive development.
iii) Use newly parameterised models to assess the relative risks for coastal and estuarine ecosystems associated with different carbon sequestration strategies.

Approach and methodology

We will determine the effect of persistent events (spring-neap tidal cycles) and intermittent events (storms) on hydro-bio-sedimentary interactions, using recording instrument packages (waves, currents, T, S, SPM, PML's optical sediment sensors) to quantify the balance between erosion and accretion, and consequently intertidal morphology. We will examine whether ecosystem engineers (bio-stabilisers - macrofauna, macroalgae, saltmarsh plants; and bio-destabilisers – burrowing bivalves, crustaceans) will be capable of sustaining intertidal habitats and coastal defences in response to climate change and anthropogenic activity. The effects of high concentration suspensions (and their associated density gradients) on estuarine mixing, and the dispersion of contaminants, will be assessed; in particular, the roles of flood-ebb mixing asymmetry due to 'tidal straining', mixing suppression and floc settling. We will construct sediment budgets that illustrate the relationships between floc settling, water-column turbidity and current speeds. A major outcome of this work will be to improve prediction of the transport and fate of soluble (or quasi-soluble) constituents and contaminants.

Climate change could alter regional productivity because reductions in river flow will change the balance between benthic, riverine and regenerated nutrients. We will determine flux rates and concentrations of dissolved nutrients over seasonal periods (e.g. Rees *et al*., 1995) in a gradient of conditions in the Western Channel (linked to SO 10), from the estuary to the continental shelf break. Moored and shipboard instrumentation will be used in combination with nutrient analysis and stable and radioisotopes (Rees *et al* 1999; Shaw *et al* 1999; Woodward & Rees 2001). These data will be used to validate and improve coastal ecosystem models in Theme 9 and subsequently to forecast the implications of climate change.

Using the seawater acidification experimental facility recently developed at PML, we will assess the impact of changing pH on the health (e.g. tissue damage, acid base regulation) and reproductive potential (e.g. gamete development, fertilisation success and larval survival) of key functional benthic invertebrates. This will complement other acidification studies by SAMS in Theme 6 (WP 6.9). The experimental pH values used will address both ocean acidification and the environmental consequences of leakage from proposed CO_2 storage sites. As well as determining the vulnerability of marine ecosystems to pH change, data from these experiments will be used to parameterise and validate ecosystem models (developed in Theme 9). The models will be run to assess the ecological consequences of leakage from sub-seabed carbon sequestration. There is the opportunity that SOFI support might be used to extend the range of organisms used for the acidification studies.

Summary WP 3.12 research plan and deliverables

2007–10	• Experimental studies to quantify organism and ecosystem vulnerability in response to seawater acidification.
2010–12	• Model the effects of climate change on sediment transport and coastal defence. • Model the effects of climate change on nutrient cycling and primary productivity. • Assess the use of macro-organisms as biological indicators of environmental change. • Model the relative environmental risks of carbon sequestration strategies.

WP 3.13 (PML) Pollutant pathways

Scientific objectives

i) To investigate how biogeochemical processes control the exposure and uptake of natural and synthetic toxicants into biota and the food web.
ii) To develop molecular models to predict the processes that control exposure.

Rationale and approach

The complexity and challenges in assessing chemical exposures have recently been highlighted by the Royal Commission on Environmental Pollution (RCEP, 2003). The Commission identified the need for better prognostic tools, the importance of screening environmental pathways and life-cycles, and noted the vast diversity of potentially damaging agents and their complex mixtures. WP 3.13 will develop, test and refine protocols to address these challenges. For example, recent research at PML on the antimicrobial agent triclosan has shown that its photolysis to a potentially bioaccumulative and toxic dioxin is more rapid in saline waters (where the product is more persistent) than in freshwaters. It is proposed to develop molecular models which more realistically quantify contaminant life-cycles and exposure assessments. Triclosan will be used as a test substance together with other personal care products (including fragrances such as synthetic musks and pharmaceuticals with default PEC:PNEC ratios exceeding one – such as paracetamol, ibuprofen and mefenamic acid: Jones *et al.*, 2002). Phenol-based endocrine disrupters (e.g. bisphenol A) will also be evaluated (Liu *et al.*, 2004) and technologies for managing their life-cycles investigated. Choice of further substances will evolve and will respond to projected outputs from REACH and other scheduled chemical evaluation programmes on emerging pollutants.

Reactive nano-particles also pose a perceived toxicological threat and will be addressed. Our recent studies have confirmed that C60 Buckminster fullerenes reduce lysosomal stability in mussel haemolymph cells. However, methods to evaluate environmental behaviour and exposure routes are currently lacking; we propose to develop them.

The question of safeguarding the environment and human health from biogenic (i.e. entirely natural) contaminants is also important. Although evolution has selected biochemical defence mechanisms for most natural biologically-active compounds, this is not universal (see Royal Commission report) and some are genotoxic e.g. phytotoxin from bracken and tannins. PML proposes to investigate transport pathways from rivers to estuaries and the potential routes of uptake for selected natural toxins, including phytoplankton toxins from harmful algal blooms.

Conventional techniques, such as high resolution chromatography, coupled with mass spectrometry will be used to quantify contaminants and to investigate transport pathways and biological uptake. These proven methods will also be used to validate a series of rapid assessment, immunoassay techniques recently developed at the PML (Galloway *et al.,* 2002; Fillmann *et al.,* 2002). These novel approaches will also be applied to biological fluids (e.g. invertebrate blood and urine) to measure bioavailability (Fillmann *et al.,* 2004) and solid phase micro-extraction will be employed to assay colloidal interactions (King *et al.,* 2004). Research on nano-particles will initially involve technique development for isolation and quantification. Differentiation between synthetic and biogenic analogues will build on recent research at PML (with Japanese collaborators) to isolate individual compounds by GC and subject accumulated fractions to accelerator mass spectrometry for ^{14}C dating. Simulation modelling will integrate these activities within the larger framework of theoretical toxico-pathology (Moore *et al.,* 2004), using variable Kd simulations to improve prediction of pollutant behaviour and uptake mechanisms.

Summary WP 3.13 research plan and deliverables

2007-12	• Develop appropriate analytical techniques for natural and synthetic contaminants and nano-particles. • Experimental, environmental and theoretical investigations into biogeochemical processes that control exposure and uptake of toxins. • Develop simulation and prognostic models that reflect transport, availability and uptake of contaminants of concern into cells. • Develop high-throughput “dipstick” technologies for biogenic and pollutant toxins identified as important in a human risk context.

Theme 3 Synthesis and Concluding Material

Oceans 2025 synergies and wider links

The three laboratories involved in Theme 3 cover a range of expertise in physics, biochemistry, ecology, and sediment dynamics, allowing the development of inter-disciplinary questions and experiments. Both POL and SAMS have capability in ship-based observations of physical processes in shelf seas; Oceans 2025 allows these groups to combine their efforts towards gaining a more complete description of the patchiness of shelf seas by combining work on the distribution of vertical mixing (POL) with parallel experiments on horizontal transport and diffusion (SAMS). There are supportive links between the observationalists in all three laboratories and the numerical modellers in POL, in terms of existing models (POLCOMS), recently-developed models (particularly non-hydrostatic) and, via Theme 9, new model developments as part of Oceans 2025.

Inter-disciplinary observations in shelf seas will bring together physical oceanographic capabilities at POL and SAMS with the pelagic and benthic ecosystem skills at SAMS. In particular, SAMS’ experience with bottom landers and *in situ* benthic production measurements will be allied strongly with the physical measurements of patchiness in relatively deep (100m) shelf waters. We expect fruitful interaction between the benthic ecosystem work at SAMS (open, deep shelf *in situ* studies during cruises) and at PML (shallower, coastal studies with long time series and more detailed seasonal data, and mesocosm laboratory experiments), not only in terms of methods development but also (depending on differences in sediment types and ecologies) in terms of understanding ecosystem function. Combining POL's background in coastal sediment physics with the work at PML on benthic fauna as seabed engineers will greatly enhance the scope and outputs of the sediment component of Theme 3. POL's sediment dynamics studies will cover the range from small-scale processes up to nearshore scales of a few km, while the work by SAMS on shelf sediment transport pathways will connect the coastal zone with the rest of the shelf.

Synergies with other Themes in Oceans 2025 and existing collaborations with other UK and international research groups are summarised in Tables 1 and 2 below.

Table 1. Main links between Theme 3 and other parts of Oceans 2025

Theme 1	Ocean models, global sea level response to climate change
Theme 2	Data quantifying the impact of seawater acidification on marine ecosystems will be generated in Themes 2 and 3. Despite the sources of acidification being different (Theme 2 - atmospheric absorption; Theme 3 – potential leaks from carbon storage) the knowledge generated will be of mutual benefit.
Theme 5	Process studies and estimates of particulate carbon fluxes will inform modelling in WP3.1. WP3.1 will provide a global context for Theme 5 work on canyon processes. WP3.9 will provide information on sediment pathways in the Celtic Sea.
Theme 6	Access to Theme 6 interpretation of POLCOMS multi-decadal runs; information provided to Theme 6 on the potential impacts of climate change on coastal/shelf ecosystems.
Theme 8	Technology developments due to be used in fieldwork (autonomous vehicle turbulence measurements, towed thermistor/fluorometer chain, optical and acoustic methods for sediment dynamics and transports).
Theme 9	Theme 3 to provide Theme 9 with new process models/descriptions to include in existing and new models.
Theme 10	SO 4: An annual hydrographic survey of NE European shelf waters (Ellett Line; dating back to 1975) will be used both for a combined cruise and as historical data. SO 10: Data produced to address issues relating to spatial and temporal variability in coastal ecosystems will also contribute to the objectives of Western Channel Observatory SO 11: The Liverpool Bay Coastal Observatory will be the site of much of the sedimentology fieldwork.
BODC (NF1)	Use of archived data, supplying data for archival, liaison over archival formats for new data types (e.g. from new instrumentation via Theme 8)

Table 2. Main existing science collaborations between Theme 3 and other research groups (UK and international) not part of Oceans 2025.

UK

British Geological Survey (BGS)	Potential tsunami sources in European waters, ground-based LIDAR, environmental impacts of CO_2 sequestration, seabed sediment distributions
Centre for Ecology & Hydrology (CEH)	Impact of inundation on floodplain ecology, hydrocarbon degradation through bacteria and bioturbation
Hadley Centre	Wave/surge extremes in future climate, climate modelling
HR Wallingford	Effect of short wavelength transformations on tsunamis (estuarine processes consortium)
QUEST/MARQUEST	Use and extension of QUEST model deliverables
Univ of Bristol	Artificial Intelligence techniques for prediction, FRMRC, coupled coastal-fluvial inundation models
Univ of Durham	Seismic sections and their analysis
Univ of East Anglia	Antarctic shelf-slope interaction; ecosystem modelling, bottom boundary layer measurements, Argos remote sensing Morphology
Univ of Essex	Turbulent mixing and phytoplankton photoacclimation
Univ of Exeter	Simulated rainfall and sediment erosion. Impact of ocean acidification on fish physiology
Univ of Lancaster	Spatial statistics of extreme values
Univ of Leeds	Estuarine dynamics
Univ of Liverpool	Morphodynamic modelling
Univ of Plymouth	Cascading, sediment dynamics, flocs in sediment dynamics, linking biotic activity to ecosystem functioning, natural variance structure of physical oceanographic characteristics linked to landscape scale patterns infaunal distribution, organism physiological response to increased pH
Univ of Sheffield	Wave remote sensing
Univ of Southampton	Submarine hazards and catastrophic events. Intertidal crabs as ecosystem engineers

Univ of Strathclyde	*In situ* marine optics
Univ of Wales, Bangor	Turbulence measurements in coastal/shelf seas, CASIX carbon flux model development, modelling cohesive sediments and the bottom boundary layer
International	
Baltic Sea Research Institute (Germany)	Modelling turbulence and wave-current interaction
EU	Collaboration through EU projects on surge climate and integrated multi-hazard warning systems (DMI, DNMI, RIKZ, SHOM, Univ of Bologna).
Delft Hydraulics (Netherlands)	Modelling of sand-mud mixtures and biological effects
NIOZ (Netherlands)	Internal waves and slope mixing
Norwegian Inst for Water Research	Joint research on the environmental effects of seawater acidification)
UC Santa Barbara	Optical measurements of suspended particles
USGS (USA)	Sediment modelling

Theme-wide stakeholder relevance and Knowledge Transfer activities

Theme 3 focuses on quantifying shelf sea and coastal processes that are poorly represented or missing from current hydrodynamic and ecosystem models. The data and understanding gained through this research will not only be used to parameterise existing models, but also to conceive, develop and validate novel conceptual and numerical models – intended for use as support tools for managing human activity in the coastal and estuarine environment, and providing the basis for longer-term predictions of the environment's response to change. The follow-through from strategic science to policy and management application will be achieved through the existing, strong relationships that POL, SAMS and PML already have with government departments and agencies (e.g. Defra, SEERAD, JNCC, EN, SNH, SEPA, CCW the Met Office and Hadley Centre, and DTI), local authorities, non-governmental organisation (e.g. WWF), and the private sector.

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

Policy/application issues	**Main stakeholders with interests**	**Relevant Theme 3 science**
EU Water Framework Directive, the Marine Bill, aggregate extraction/dredging, flood warning systems, tsunami threat and instrumental warning systems, coastal defence and managed retreat schemes	Defra, SEERAD, EA, SEPA, CCW, EN	Dispersion and mixing; sediment transport; improved forecasts of coastal flooding
Improved operational models (Storm Surge Forecasting Service) ensemble forecasts, reducing uncertainty	Met Office and NCOF	Integrated shelf sea models
End user feedback on operational systems for flood warnings, long term data via the UK Tide Gauge Network; water quality monitoring	EN, SEPA, UK Local Authorities, National Trust	Flood risks, coastal erosion and water quality
Developing ecosystem approach for fisheries; patchiness in shelf seas; establishing Marine Protected Areas; use of dredged material and sediment stability	Defra/CEFAS and SEERAD/FRS	Patchiness of mixing and dispersion; models of sediment transport , water quality and ecosystems
Sediment transport information for dredging activities	Port authorities (e.g. Mostyn for Dee)	Sediment dynamics in estuaries/coastal waters
Pollution dispersal; environmental impacts of CO_2 leaks from geological storage sites	Oil industry, Defra, DTI	Hydrodynamic and acidification models
Threat to and changes in coastal and estuarine environments; development of indices to identify change; maintaining healthy ecosystems; marine conservation policy	EN, SNH, CCW, JNCC, NGOs, local authorities, other coastal zone managers	Ecosystem models
Coastal defence and relevant engineering decisions (eg replacing Thames barrier)	Defra; local authorities	Future extreme events
Tracking contaminants in the coastal oceans	Defra, OSPAR, European Environment Agency, EA	Pollutant pathways
Health related implications of human consumption of	Food Standards Agency	Uptake of toxicants into

contaminated fish and shellfish		marine shellfish

All the NERC marine Centres in Theme 3 have obtained, and will continue to obtain, private sector and governmental funding for research that meets specific research-user needs. Such commissioned research is not presented here; nevertheless, it is the direct consequence of NERC strategic funding. Oceans 2025 will provide the underpinning capabilities, expertise and facilities to continue meeting user needs in future, whilst itself delivering data, information and understanding directed at 'real time' national needs. Major stakeholders were consulted in preparing the proposal, and many components have involved additional discussions with research users. To ensure effective communication between scientists and research users throughout the programme, a Stakeholders Consultation Group will be established for Theme 3 (and other Themes) early in 2007, to meet at 6-9 monthly intervals

Public outreach will continue to be mediated through open days; school liaison and projects; work experience; enhanced web-sites; public lectures; participation in exhibitions, National Science Week events and the annual BA Festival of Science; and active interactions with the media (via press releases, TV and radio interviews).

Strategic Ocean Funding Initiative (SOFI)

Up to 10% of the research science funding for Oceans 2025 will be made available to UK universities and other academic institutions eligible to receive NERC support. Such funding will be awarded for research that is complementary to the Oceans 2025 science Themes, in defined topic areas in a series of funding calls (first call to be announced in 2007). For Theme 3, the following SOFI opportunities have been identified:

- Improved technologies to determine particle size concentrations and fractal parameterisations
- Development of underwater video systems
- Turbulence measurements from AUVs
- Impacts of seawater acidification on marine invertebrates (also with links to Theme 6).

Consolidated fieldwork

One dedicated major NERC ship cruise (Celtic Sea 24 days), shared cruise time with SO 4 (Ellett Line, Malin Shelf, 7 days), and 35 days of SAMS shelf-vessel *RV Calanus* (Malin Shelf) are planned jointly between POL and SAMS. Collaborative fieldwork between PML and POL will be carried out on hydro-bio-sedimentary processes in the Dee estuary within the Liverpool Bay Coastal Observatory (SO 11).

Summary of Theme-wide outcomes

- A +/- 50 yr (hindcast and forecast) assessment of the shelf seas' role in the global carbon budget
- Quantification of interactions between biota and climatic factors (rainfall, waves, currents) and their impact on sediment habitats.
- Algorithms of hydro-bio-sedimentary processes for improved estuarine / coastal models
- With Theme 9, new parameterisations for mixing and transports in stratified environments, including recommendations for the necessary bathymetric resolution in models.
- Quantitative analysis of the patchiness of coastal and shelf sea carbon and nutrient cycling.
- Predictions of the likely consequences of higher CO_2 for coastal marine ecosystems.
- With Theme 9, parameterisations of the effects of marine bioturbators on sediment stability suitable for large scale shelf models.
- Predictions of the likely changes to the UK coastline as a result of climate change.

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Acronyms

ABS Acoustic Backscatter Sensor
ADCP Acoustic Doppler Current Profiler
ADV Acoustic Doppler Velocimeter
AUV Autonomous Underwater Vehicle
BELPLUME Brixham Environmental Laboratory Plume Model
BODC British Oceanographic Data Centre
CASIX Centre for Observation of Air-Sea Interactions & Fluxes
CCW Countryside Commission for Wales
EA Environment Agency, UK
EN English Nature
ERA40 Meteorological data from the European Centre for Medium Range Weather Forecasting 40yr re-analysis
ERSEM European Regional Seas Ecosystem Model (coupled to POLCOMS)
FREE Flood Risk from Extreme Events (NERC programme)
FRMRC Flood Risk Management Research Consortium
FRS Fisheries Research Services, Scotland
FTE Full Time Equivalent
GENIE Grid-Enabled Integrated Earth system model
GLOSS Global Sea Level Observing System
GOTM General Ocean Turbulence Model (provides turbulence scheme for POLCOMS)
HAB Harmful Algal Bloom
HadGEM Hadley Centre Global Environmental Model
IACMST Inter-Agency Committee on Marine Science and Technology
ICOM Imperial College Ocean Model
JNCC Joint Nature Conservancy Council
LIDAR Light Detection and Ranging
LISST Laser In-Situ Scattering & Transmissometry instrument
MarLIN Marine Life Information Network
MARQUEST Marine Biogochemistry and Ecosystem Modelling Initiative of QUEST
MITgcm MIT general circulation model (non-hydrostatic)
NCOF National Centre for Ocean Forecasting
CDVP Coherent Doppler Velocity Profiler
CEFAS Centre for Environment, Fisheries & Aquaculture Science
CTD Conductivity-temperature-depth instrument
Defra Department for the Environment, Food & Rural Affairs
DGGE Density Gradient Gel Electrophoresis
DMI Danish Meteorological Institute
DNMI Norwegian Meteorological Institute
DTI Department for Trade and Industry
NEMO Nucleus for European Modelling of the Oceans
NERC-ARSF NERC Airborne Remote Sensing Facility
OBS Optical Back Scatter
OMEX Ocean Margins Exchange Experiment
PML Plymouth Marine Laboratory
POL Proudman Oceanographic Laboratory
POLCOMS POL Coastal Ocean Modelling System (3D model of the NW European shelf)
QUEST Quantifying and Understanding the Earth System (NERC programme)
RIKZ National Institute for Coastal and Marine Management Netherlands
ROFI Region of freshwater influence
RSDAS Remote Sensing Data Analysis Service (PML)
SAMS Scottish Association for Marine Science
SASSI Synoptic Antarctic Shelf-Slope Interactions Study
SCAMP Self Contained Autonomous Microstructure Profiler
SEERAD Scottish Executive Environmental Rural Affairs Department
SEPA Scottish Environment Protection Agency
SES Shelf Edge Study
SHOM Hydrographic and Oceanographic Services, France
SOES School of Ocean Sciences, Southampton University
SNH Scottish Natural Heritage
STFS Storm Tide Forecasting System
WCO Western Channel Observatory
WWF Worldwide Fund for Nature