Land-ocean interactions and climate change – insights from the ELOISE projects

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1 Introduction

Over the last decade, the 55 projects in the ELOISE cluster have contributed to the international body of knowledge about land-ocean interactions in the coastal zone. Europe's scientific community has bridged disciplines in a wide range of study areas – coastal seas and estuaries, society and the natural environment, and biogeochemical cycling through atmospheric and aquatic systems. Perhaps the most significant achievement of the programme was the formalisation and consolidation of a European scientific infrastructure for coastal zone research, developing research tools and methodologies relevant to the region, and contributing accessible and coherent data for better coastal zone management.

A progress review of ELOISE with an analysis of its key findings has been compiled by Herman et al. (2003). That review explains the process of constructing the ELOISE cluster and the rationale for project inclusion. Just as the process of cluster development was one of evolution, so also is the process of scientific understanding of the role of coastal systems in the earth system. The original science plan (Cadée et al., 1994) highlighted global change and human impacts as research-framing priorities. Since the inception of the ELOISE project, climate change has risen much higher on the international policy and scientific agendas. Although the scope of most projects did not explicitly include an analysis of the implications of climate change, either as causal factors in the processes being studied or in terms of their impacts on climatic processes, much information generated in the ELOISE process makes a valuable contribution to climate change science.

This report critically evaluates the suite of projects within the ELOISE cluster from the perspective of their importance for climate change science. As in many areas, the issue is often not one of generating data, nor even necessarily of accumulating more information (processed data). The aim is to add to knowledge – appraising the information that is already available, testing it against today's context, and learning from it.

2 Climate Change – the context

What is climate change?

In the words of the IPCC's Third Assessment Report (2001), '*The Earth's climate system has demonstrably changed on both global and regional scales since the pre-industrial era, with some of these changes attributable to human activities.*' The collective picture is one of a warming world, with rising sea levels, longer growing seasons, shifting ecological assemblages and ranges, and more frequent storminess.

The climate system is a complex interplay between the atmosphere, the oceans and ice-sheets, and land systems, both the biosphere and geosphere. As such, the remit of ELOISE projects can be mapped firmly within the scope of climate change science (Figure 1). The corollary is that climate change is just one aspect of the dynamic system to which the ELOISE scientists are contributing knowledge and understanding.

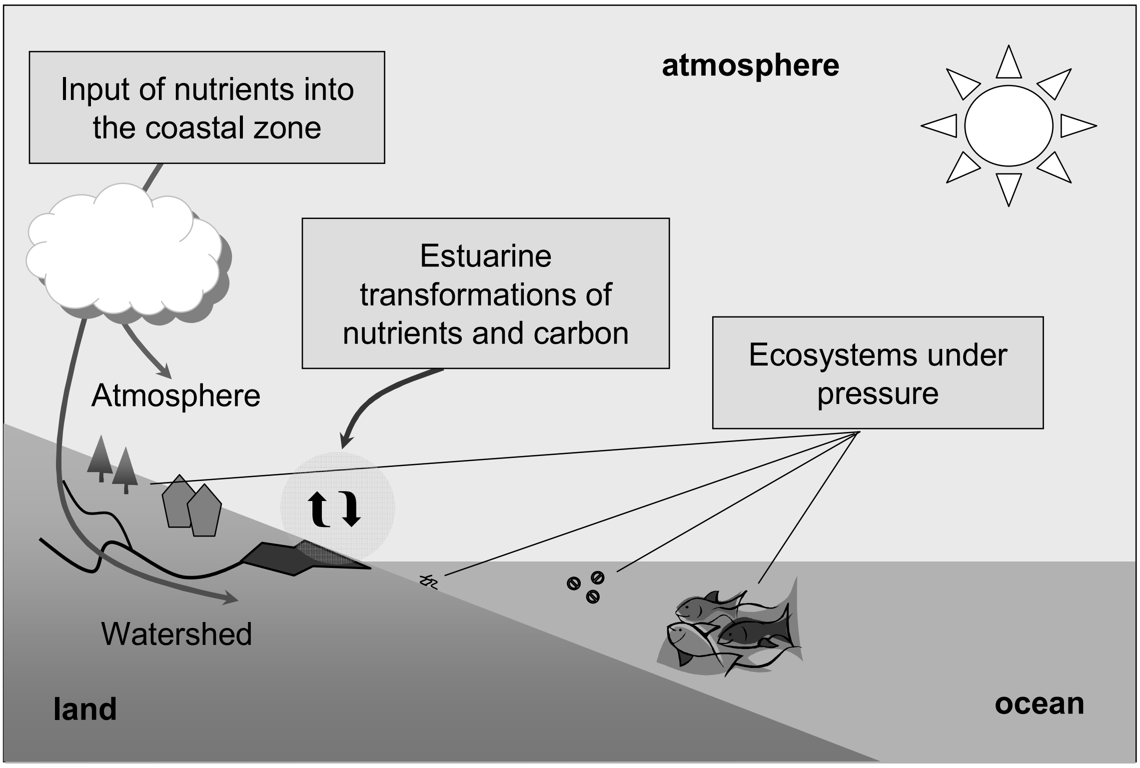


Figure 1 Principle themes of ELOISE projects address key interfaces in the climate system – land, ocean, atmosphere and life.

The concept of an equilibrium mode is important in climate science. The general state of the global climate is one of stability: the coupled components of the global climate system act in balance with one another. The incoming solar radiation is in balance with outgoing terrestrial radiation. When the climate system responds to radiative forcing (i.e., climate forcing that alters the energy balance of the Earth system, such as orbital variations, fluctuations in solar radiation, volcanic activity, and changes in the atmosphere's chemistry like the current anthropogenic increase in greenhouse gases), this equilibrium is temporarily disturbed. In order to restore equilibrium, the global climate alters. Thus for the climate system to retain overall balance, that balance must be a dynamic process, adjusting with ever-changing responses to the forcing perturbations.

Given the inertia within the climate system, the full impacts of the present climate forcing may not become apparent for hundreds of years, but the changes observed even over the last few decades have had a discernable impact on marine and terrestrial ecosystems. Regional climate change has also impacted elements of the hydrological cycle. Changes in stream flow and precipitation have led to increased frequency and severity of floods and droughts. Both coastal ecosystems and coastal hydrology feature strongly in the ELOISE portfolio, which aims to provide vital information about the state of the environment and its critical processes now, and also the consequences for the overall interplay that may be expected by changing those processes.

What are the tools and building blocks of climate change science?

The 'raw materials' of climate change science are data on temperature, precipitation and humidity, wind and air pressure, and solar irradiance. These weather parameters become climate change data when they are combined to show temporal and spatial patterns. Today's climate has been set in the perspective of long term climate records pieced together in palaeoclimatological studies, which rely on proxy measures for the fundamental data. This study of climate and climatic change in the period before instrumental measurements or historical records of observations were available draws on data from ice cores, tree rings, and the analysis of sediments.

Beyond this empirical analysis of past trends, the greater emphasis in recent years has been on understanding the underlying systems that control and drive climate. General circulation models (like those of NCAR in the USA, and the UK's Hadley Centre model) are like weather prediction models in that they parameterise these driving forces (the patterns of atmospheric and oceanographic motion), but they do so on a global scale (Hadley Centre, 1999). This aspect of climate change science relies on an understanding of ***radiative*** processes (i.e., the transfer of radiation by absorption, reflection, etc.); ***dynamic*** processes relating to the transfer of energy among components of the Earth system (e.g., by diffusion, advection or convection); and what can broadly be classed as ***surface processes***. This latter category, in which land-ocean interactions are very important, along with the effects of albedo and surface-atmosphere exchanges, is the area of most potential overlap of climate change science with the science themes of ELOISE projects. It is possible that some of the 'raw materials' data generated during the ELOISE programme may also be of wider use, if appropriately catalogued and managed. For instance, local and regional downscaling of general circulation models and other climate change modelling tools is greatly facilitated by access to and comparison with such smaller scale data sources. In general, however, the most significant contribution of the programme as a whole to the science of climate change and (in today's favoured jargon) of the Earth system is likely to be in the area of surface processes.

How does climate change manifest itself in the coastal zone?

The world's coastal zones experience climate change in several ways. The most obvious impact on the coastal zone of the current global warming is sea-level rise. Global mean sea level has increased at an average rate of 1-2 mm during the past century (IPCC TAR 2001), but the manifestation of this global change is variable in Europe, being enhanced or attenuated by isostatic processes of the Earth's crust following the last glaciation. Nevertheless, increasing vulnerability of ecosystems and human systems in the coastal zone is expected.

Changes in oceanic circulation patterns on multiple scales are evident. Best known controllers of global climate are the El Niño Southern Oscillation, and the North Atlantic Oscillation that plays a major role in Europe's climate. These are projected to display altered frequency and intensity in future.

Meteorological patterns will change as a result of shifts in the global heat balance. For the coastal zone, this (together with the changes in the behaviour of the oceans) is likely to mean more storminess, with greater storm surges and a modified wave climate regime.

These changes will drive transformations in the processes of sediment transport and deposition that are so important in the coastal zone, and also provoke changes in its ecosystems, including the human systems. ELOISE projects address the present situation in the coastal zone, providing the most robust multidisciplinary baseline to date, but several projects focusing on understanding and modelling processes also permit the assessment of projections into the future of impacts arising from many forcing factors, including climate change. The following section provides a categorisation of ELOISE projects according to their significance in contributing to the understanding of climate change and the potential for their use in adapting to or mitigating climate change. The appendix to this document lists a collation of the existing peer-reviewed ELOISE publications that are relevant to climate change, using this categorisation.

3 ELOISE projects categorised

'Building blocks' Projects and Tools for Climate Change Management:

Several projects in the ELOISE portfolio contribute baseline information that makes an invaluable contribution to the understanding of the surface processes mentioned above, informing society's approaches to climate change adaptation and mitigation, while others have developed observation or modelling tools that would allow climate-induced changes to the physical and ecological forms and processes of the coastal zone to be detected and perhaps managed.

ESCAPE outputs contribute greatly to the understanding of the marine sulphur and carbon cycles and more specifically, their linked interactions in coastal ecosystems. Both sulphur and carbon cycles are highly relevant to climate change studies, with carbon dioxide being the main contributor to the greenhouse effect (global warming), while sulphur compounds are an important source of cloud condensation nuclei, and are thus involved in regulating cloud albedo (global cooling). The project focused on a single plankton genus, *Phaeocystis*, which can dominate entire ecosystems during its blooms. Its species generate the climate active compound dimethylsulphide (DMS), and its blooms may act as sinks for atmospheric CO_2. One of the ESCAPE outputs is a conceptual model to allow an estimation of the impact of *Phaeocystis*-dominated ecosystems on global climate. The latest generation climate/Earth System models require precisely this type of information about the fundamental elemental cycles. The research presented at the double symposium at the University of Groningen in 1999 (CEES/University of Groningen, 1999; Stefels, 2000) addressed the issue of climate relevance, and was an important step towards drawing together the emergent research in this particular 'building block' area.

The contribution of **BIOGEST** is its focus on the coupling of estuaries and the atmosphere, and on several climate-active biogases. Estuaries, as areas rich in decaying organic matter, produce large quantities of CO_2, their anoxic sediments are a source of methane, and their generally high nutrient loading enhances the production and release of N_2O, another greenhouse gas. On the other hand, primary productivity consumes carbon dioxide, and eutrophic (nutrient-enriched) conditions favour the production of DMS and carbonyl sulphide, which increase cloud albedo. The interplay among these climate-active species, and the regional contribution to the global budget of biogases (see in particular Frankignoulle and Borges, 2001; Frankignoulle et al, 1998), are both vital contributions to the basic understanding of the climate system.

As already mentioned, climate science needs a long-term perspective. The **MOLTEN** project explores the changes in estuarine and coastal systems arising from human activities through history. Most monitoring programs in the region have only run for a few decades, leaving open the question of when the changes began and what really is the extent of anthropogenic alteration. Palaeoecological analysis of sediments can uncover the long-term effects of nutrient enrichment and how it has affected ecosystem functioning over time. These insights into changes in structure of various parts of coastal and estuarine ecosystems are fundamental for establishing the baseline and time-scale of long-term ecological change.

The **INCA** project established hydrological and water quality databases for a range of key European ecosystems, and developed a process-based dynamic model for selected river catchments across Europe. It looked at the fluxes and cycling of nitrogen on many timescales, linking plants, soil and stream processes. This integrated land/biosphere/atmosphere approach allows the impacts of climatic change, along with other processes, to be assessed. It adds to the understanding of the behaviour of N_2O in the coastal zone, and it also addresses critical upscaling problems, from site to catchment scale. Limbrick et al. (2000) have applied the model to the UK's River Kennet catchment using the widely accepted Hadley Centre climate change scenarios, and were able to satisfactorily draw conclusions about future water resource changes and the implications for catchment ecology.

The scaling issue is recognised as a critical hindrance in the translation of climate change science. The project **MMS2000$^+$** was a response to this shortcoming. Many coastal zone monitoring systems are intended for use on a local or national scale, and this project facilitated the exchange of data for use on a regional scale. While meteorological parameters tend to be less locally focused, the integration of climate data with real-time *in-situ* measurements from their many sources is the challenge MMS2000+ addressed, together with developing operational data-assimilation models to produce useful impacts forecasts. Over the last decade, the SeaNet workshop has consolidated this effort across Europe, and evolved in response to other initiatives, such as EuroGOOS, the ocean component of the Global Climate Observation System.

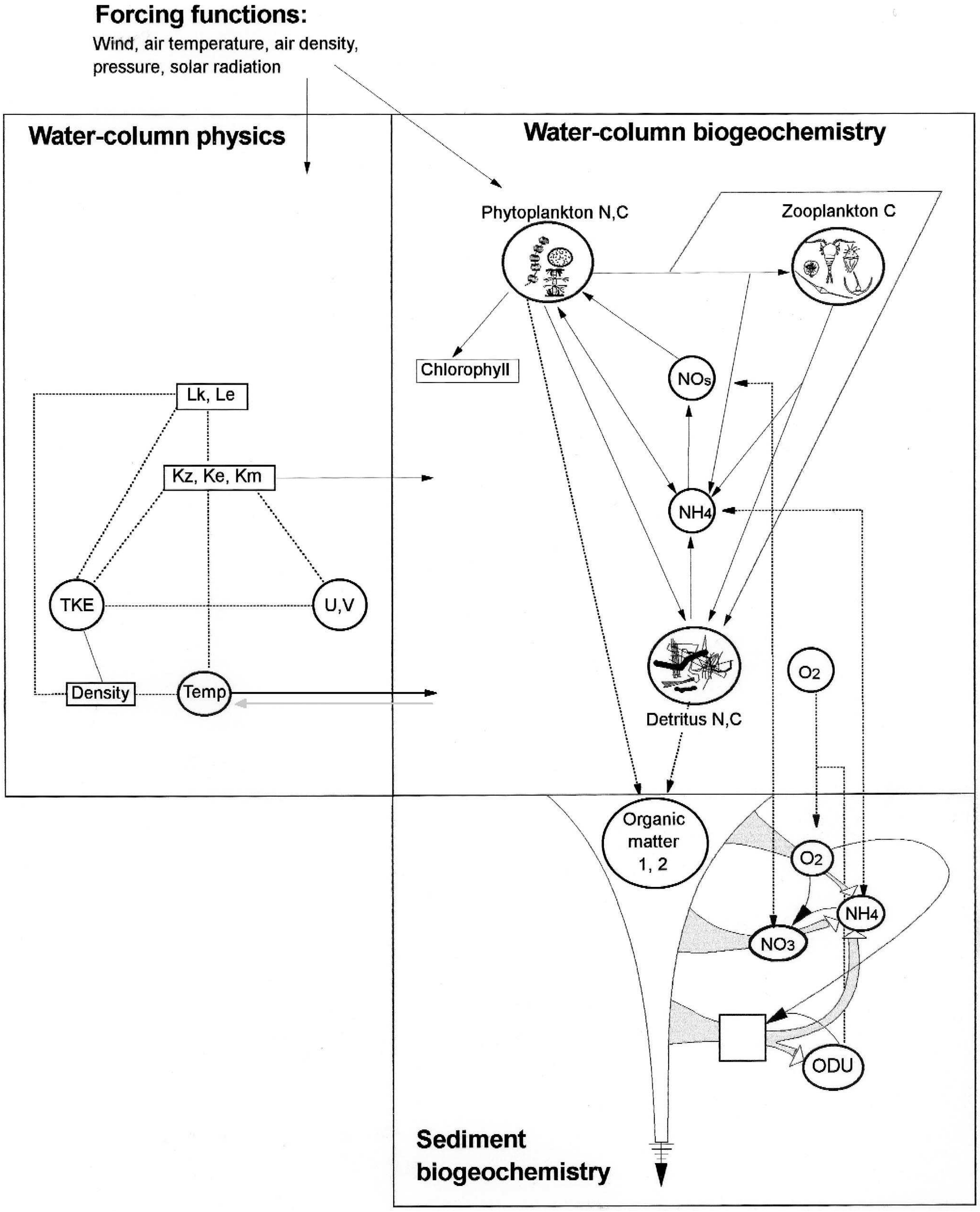
METROMED studied and modelled the key processes driving the exchange and storage of particulate material and the biogeochemical cycles in the coastal zone. The data are also useful as initial or boundary/validation conditions for hydrodynamic models such as those used in regional climate impacts studies. A key contribution is the linking of both hydrographic conditions and meteorological forcing in the transport and dispersion processes. **PHASE** researchers also addressed the interactions between physical forcing functions (e.g., wind, solar energy and tidal energy) and biogeochemical fluxes in shallow coastal waters. (See Figure 2). The importance of physical forcing through the water column (with high frequency variability) on the biogeochemical processes in shallow coastal waters and the benthos was very poorly understood, and this project therefore contributes significantly to the understanding of climatic impacts (see Serra et al. (2003) for a consideration of the comparative effect of weather extremes). Again, a further useful contribution is its aim to upscale from the processes studied to a general integrated coastal zone model.

The **F-ects** project looked at the complicated feedback and feed-forward loops that link the establishment and success of phytobenthic communities with water quality and physical oceanographic parameters. A focus of the project was the prediction of the evolution of phytobenthic ecosystems and their reactions to anthropogenic and climatic disturbances (Bergamasco et al., 2003).

Similarly, the focus of **KeyCop** was the investigation and modelling of key processes that affect the fluxes and cycling of carbon, nutrients and other trace substances, generally on a small scale, but under different physical (stratification) and chemical conditions. As already mentioned, understanding the fundamentals of carbon biogeochemistry is an important building-block in climate change science. The potential value of KeyCop lies in the fact that the local process modelling in the study has been designed to be integrated into large-scale models, and an important contribution is its data management protocols that were designed with interconnectivity in mind. Like MMS2000+, this project can link in with global earth observation information networks that contribute to the detection of climate change and its impacts.

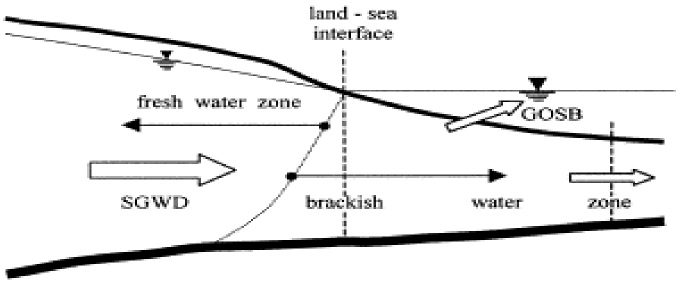
The general objective of **RANR**, similar to that of INCA, was to develop improved procedures for regional analysis of the export of nitrogen from land to sea. Its starting point was to identify the minimum amount of information that is required for such analyses (Forsman et al., 1998 outlines the methodological approach). Like other nitrogen studies, it addressed denitrification and the production of N_2O, but its greater value for climate change studies is its approach to developing modelling tools. By taking a process-oriented and mechanistic approach, it integrated water transport processes with nitrogen cycling, in such a way that visualisation technologies and extrapolation tools (e.g., from catchments to regions) can be used and tested.

Figure 2 Schematic representation of the fully coupled model; encircled are the prognostically modeled components, enclosed by rectangles are derived components (from Soetaert et al., 2000)



The focus of the SubGate project was the transfer of solutes and gases across the sediment-water interface. (See Figure 3). One of the principle species studied was methane, and this project thus adds to the fundamental knowledge base for carbon cycling and climate change. It explicitly links surface water quality in coastal seas with submarine groundwater fluxes and transport processes.

Figure 3. Schematic representation of submarine groundwater discharge (SGWD) and groundwater outflow at the sea bottom (GOSB) (Kaleris et al, 2002).



The functioning of intertidal systems reflects changes in the coastal zone in general. The main organisms underpinning this functioning are the algae and seagrasses, which support the whole food web, such that changes to intertidal ecosystems greatly influence our natural environment and coastal zone economies. **HIMOM** aims to systematically combine methods, the Hierarchical Monitoring Methods, to determine the status and changes in that system. By providing a conceptual framework that accommodates both simple ground measurements and remote sensing of basin-scale systems, the project lays the foundation for the ongoing investigation of long term changes.

Manifestations of climate change:

Important manifestations of climate change occur in the coastal zone. Knowing what climate change will mean on a local scale, in terms of altered functioning of coastal ecosystems and changes in coastal forms and processes is critically important. Several ELOISE projects have the common aim of developing robust systems for assessing the quality of vulnerable coastal systems, and as such, they may be useful tools for detecting and managing climate change-induced degradation and transformation.

ECOFLAT's study of carbon and nutrient cycling processes within tidal flat ecosystems potentially contributes baseline knowledge for climate science (e.g., van de Koppel et al., 2001). However, its predictive mathematical models of the key processes, mechanistically related to the main forcing factors in tidal flat systems, have been developed with the aim of addressing the scale mismatch between local-scale processes and their estuary- or regional-scale consequences. As such, these model outputs can be used to detect and explore the implications of global change. Similarly, **EUROSAM** linked a range of ecological process models with hydrodynamic models to make a predictive tool that addresses the likely responses of various saltmarsh ecosystems to environmental changes (e.g., sea level rise, increased pressure from human activities). To date, however, the project outputs have been focused more on valuation of the studied saltmarsh ecosystems than on any critical appraisal of their vulnerability and the scope for adaptation to environmental change.

ISLED's focus was on defining and describing the responses (both physical and biological) to sea-level rise in saltmarsh ecosystems. Losses of these ecosystems have been very severe in past decades (Dijkema, 1984), as a result of many human-induced pressures, and these losses are now being addressed in part. However, fundamental knowledge about saltmarsh accretion and erosion processes has been lacking, as has information on the characteristics and diversity of the ecosystem itself, and the main aim of this project was to consolidate that knowledge. This project has recognised that by the time accelerated sea-level rise has had its effects on vulnerable coastal ecosystems, it may be too late to respond. Thus a valuable aspect of this project was its exploration of other human-induced coastal changes as an experimental analogue of climate change (e.g., Hazelden and Boorman, 2001). This means that accelerated sea-level rise as a result of global warming will now be easier to assess, and its impacts on important ecosystems may more effectively be pre-empted.

Looking in detail at a single climate-sensitive ecosystem gives the greater baseline knowledge that is necessary for understanding climate change and its impacts. The goal of the **M&MS** project is to define the habitat requirements of seagrasses in the European coasts, the present threats to the sustainability of the ecosystem they form, and their resilience to disturbance (Duarte, 2002). By exploring the extent to which the isotopic composition of carbon, nitrogen and sulphur in seagrasses reflects the degree of human disturbance, this project also potentially provides a means of detecting climate change impacts.

The **DUNES** project compiled an effective database of the present state of selected European dune systems, and simplified their multiple processes and features into a workable integrated 'checklist' system combined with novel remote-sensing image processing. The main aim was to appraise the direct effects of human activity on dune vegetation and stability. However, its attention to the effects of intermittent processes, rather than assuming steady, linear change in these systems, is an important advance from the perspective of climate change knowledge, given that projections are for greater variability in storm and surge conditions. A further strength of the project is that its methodology allows for intra- and extra-regional comparisons of dune systems, potentially facilitating the knowledge transfer and 'learning-by-analogy' that are fundamental to adaptive social behaviour, rather than mere reactivity to climate change.

The possible impact of climate change on the distribution and population dynamics of cod and eelpout has been addressed by **CLICOFI**. From its outset, considerations of climate change science informed the project (e.g., Blust et al., 1993; and Schellnhuber and Sterr, 1993). Like most ELOISE projects, it was deeply multi-disciplinary, drawing together long-term retrospective climate data, time-series of fish population dynamics, and information about physiological processes and genetics. This approach means that the manifestation of climate change can be explored through the improved understanding and modelling of the temperature-sensitive responses of the studied species from molecular right through to population level.

BASIS explicitly aims to provide an integrated case-study of the likely magnitude of global changes on regional to sub-regional scales. Knowledge of the likely consequences of global changes for terrestrial, freshwater and marine ecosystems in the Barents region is extended to an assessment of the impacts on human systems dependent on them, with the aim of determining the necessary conditions for the region's sustainable development. Climate change is an explicit element of the change addressed, albeit not the sole change, but the cross-sectoral, multidisciplinary approach of this study means that the outputs of this study are potentially highly valuable in exploring the manifestations of climate change. Like CLICOFI, it explores the implications of climate change on fisheries; it also defines how global change can be detected in major terrestrial natural resources. Such regional-level deeply integrated studies will be useful in future if they can specify the extent to which human and natural systems can adapt to changes. In particular, given that very pronounced impacts of global warming are occurring in the high latitude regions, and many of these impacts relate to coasts and coastal management, the contribution of BASIS is important.

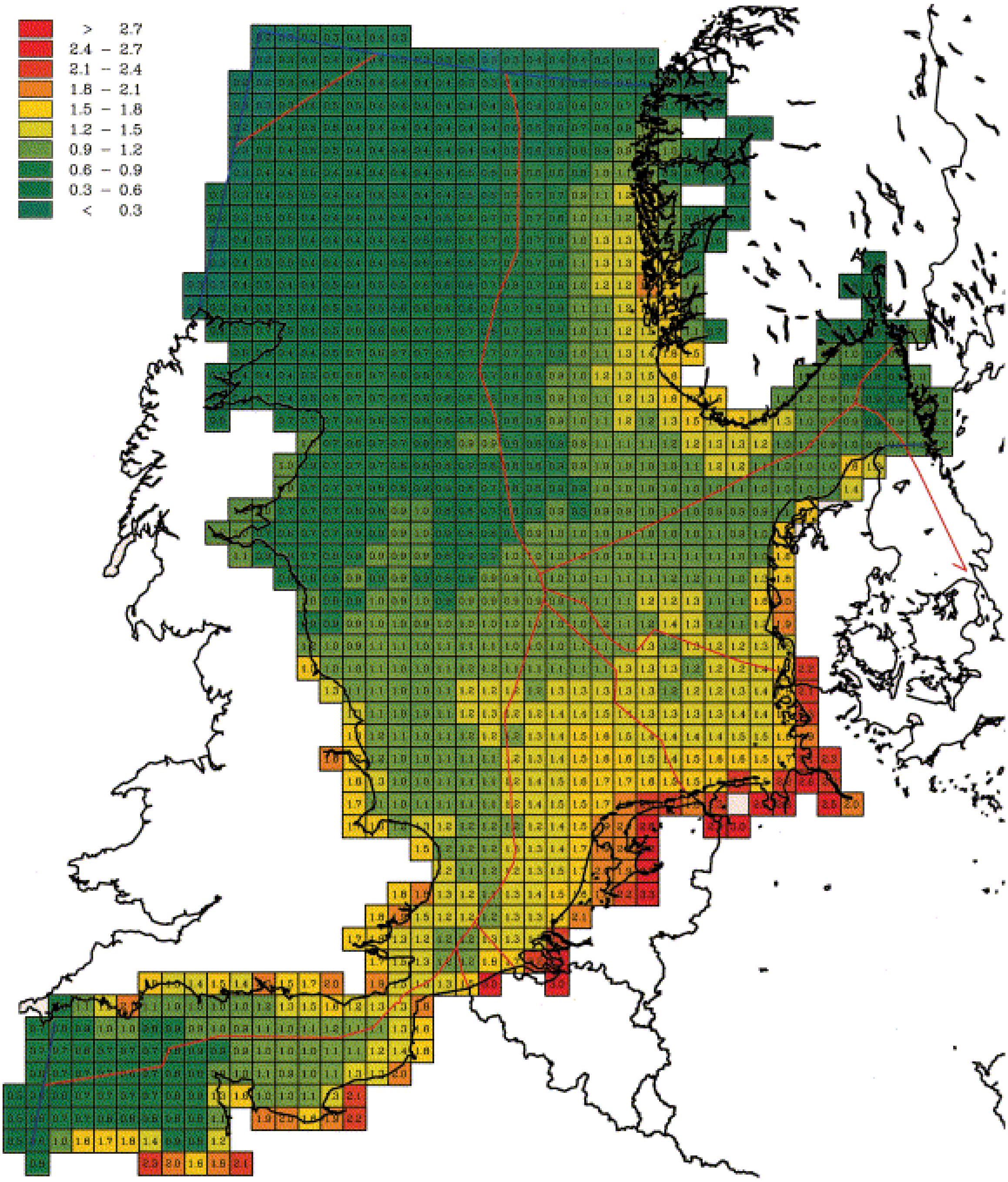
Human impacts:

Teasing apart impacts due to accelerated climate change and those due to other human activities is conceptually difficult, and indeed from the perspective of promoting concerted sustainability action, probably unnecessary. The set of projects described in this section have the common aim of addressing human modification of the coastal zone, including climate-induced change. Several of these projects recognise the ubiquity of climate change as *both* causal factor and consequence of the processes being studied. Often climate change is targeted for specific attention because it has the potential to aggravate or synergise with a particular process. In other instances, climate change is taken into consideration as a forcing control.

The influences on nitrogen removal in Europe's estuaries are explored in **NICE**. Climatic variables (in particular, differences in temperature, length of growing season, and solar irradiance) are important direct controlling factors, but climate change also has implications for the tidal flushing regime and the biota, also studied in this project, as other key factors determining nitrogen fluxes. The interplay between nitrogen and carbon cycling means that nitrogen management interventions in the coastal zone induce changes in the global balance of carbon dioxide and N_2O (e.g., Welsh et al., 2000, 2001), with implications for climate change. More in-depth investigations of seasonality in nutrient cycling have been carried out (Risgaard-Petersen and Ottosen, 2000; Rysgaard et al., 1998), potentially giving higher temporal resolution to climate change impact projections. An interesting premise of the project is that the fate of anthropogenic nitrogen in the aquatic environment is as much a socio-political problem as an environmental one, and the approach taken for the project design has the potential to give valuable insights for future climate change science. A critical issue is the extent to which knowledge from one location or context can be applied to others. In NICE, cross-comparability was an explicit methodological aim, for instance, with the climate effects evaluation drawing on a north/south comparison accommodating different tidal regimes.

ANICE also investigated the cycling of nitrogen in the coastal zone, with a focus on atmospheric inputs. The problem of atmospheric nitrogen inputs (both nitrate and ammonium) is increasingly recognised, and anthropogenic emissions are expected to increase further (e.g., Galloway et al., 1995). The inclusion of aerosol into the nitrogen modelling is an important advance, bridging with climatological studies. Indeed, ANICE was an innovative combination of empirical and modelling work, and it addressed both the larger scale (atmospheric inputs of nitrogen to the North Sea) and the local scale, with a more detailed assessment of the effects of nitrogen on the coastal area in the southern North Sea. This is shown if Figure 4, below.

Figure 4. The total atmospheric nitrogen deposition to the North Sea in 1999. (Depositions - ton N per km²). The results reflect to a large degree the distribution of the source areas around the North Sea, but also the distribution of precipitation is important. For example, the large depositions at the Norwegian coast reflect the high precipitation amounts due to the mountains in this region (Hertel et al, 2002).



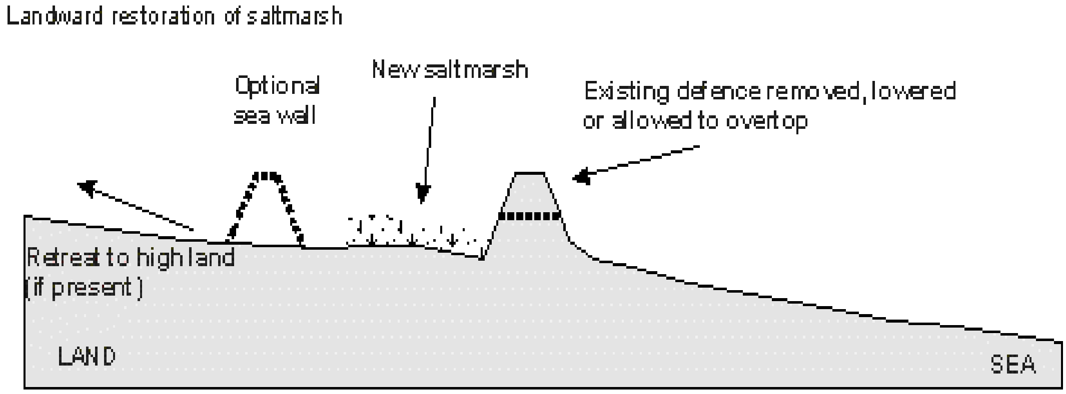
Both those studies focus on the causes of eutrophication in the coastal zone. **CHABADA** sought ways to detect and address changes in Mediterranean coastal zone community composition in response to such external factors. The suite of modelled and molecular techniques used to assess changes in diversity is intended to be of use whatever the nature of the alterations of the microbial community. **EULIT** also explored population responses to ecosystem change and nutrient enrichment, but of littoral flora and fauna, rather than bacteria. Again, human activities are shown to lead to altered species interactions and succession patterns, and this type of information, scaled across Europe, is important for climate change impacts analyses. Eutrophication is also a key theme in the **EROS21** project, and the studied river-ocean system of the northwestern Black Sea is a highly altered system. Society's modifications of water flow, chemical composition and sedimentation in the Danube and Dnjestr rivers have been severe. Seasonal patterns in productivity have been determined, along with supporting meteorological data, again linking anthropogenic pressures with climate-related forcing of ecosystem processes.

EUROCAT, like BASIS, aimed to develop a multi-disciplinary sustainability approach for coastal zone science. While it collated and appraised data on sources and fluxes of different compounds (nutrients and other trace elements) for several European catchments, its focus on integrating these data with related socio-economic data (pertaining to users and consumers of the natural resources and coastal zone functions) lends it the potential for greater applicability, not least in climate change impacts assessment. By bringing together natural science models and socio-economic tools, it aims to provide a broadly usable management tool of interest to a wide spectrum of users (those involved in policy, planning and regulation of coastal zone management) at multiple scales.

The consequences of climate change will have mixed impacts on different communities (in both human and natural systems), and EUROCAT offers the potential to seek out optimalities in managing emissions and environmental processes in terms of ecological potential and socio-economic benefit. This is exemplified by the research undertaken in the UK's catchment, the Humber Estuary (HUMCAT). HUMCAT considers managed realignment of coastal flood and erosion defences as a central component of the various policy options for attenuation of nutrient emissions. Managed realignment involves the deliberate breaching of engineered defences to allow the coastline to recede to a new line of defence further inland (see Figure 5.). It is intended to be used as part of an on-going re-assessment of sea defence and coastal protection strategies in the UK in response to the threat of climate change.

The analysis takes as a core starting assumption that managed realignment policy will be an important component of any future planning for the Humber estuary and the catchment. But the key insight highlighted is that managed realignment (and its impact in terms of increased intertidal habitat) carries with it a number of positive externality effects. It creates more habitat with potential biodiversity, amenity and recreational values; a more extensive nutrient and contaminants storage capacity; and a carbon sequestration function. All these potential economic benefits are in addition to its sea defence/coastal protection benefits in terms of increased flexibility in response to sea level rise and climate change and therefore reduced maintenance costs.

Figure 5. Manages Realignment (Source: English Nature)



From an economic efficiency perspective, the first test of managed realignment requires the scheme or programme to demonstrate net economic benefit, i.e., that compared to a traditional hard engineering "hold the line" sea defence strategy, managed realignment yields an efficiency gain in terms of net benefit or lower overall costs. The analysis demonstrates that for a range of managed realignment schemes around the Humber estuary and tidal rivers, there is a net economic benefit. In this case study, the costs of realignment over a 25 year time period or more are outweighed by the benefits created in terms of savings in maintenance costs and the positive environmental externality effects.

The HUMCAT research concludes that:

- managed realignment, if implemented on a reasonably large scale, could be an effective way of improving the water quality of the Humber estuary. In the scenarios considered, farming practices throughout the more than 25,000 km^2 of the catchment would have to be radically changed in order to achieve reductions in concentrations of nutrients throughout the estuary comparable to those realised by creating 75 km^2 of new intertidal area around the estuary and tidal rivers by realignment of flood defences;

- managed realignment has a number of environmental benefits (habitat creation, carbon sequestration, etc.), the value of which can more than offset of the costs associated with this option and can result in substantial positive net present values.

The following ELOISE projects also extend from an analysis of the impacts of environmental change on society towards demonstrations of how society is attempting to address climate change-related impacts on the environment.

In the expectation of accelerated sea-level rise, the outputs of **DELOS** have immediately accessible benefits to society. Flood and coastal defence investment is a major use of public funds across Europe, and it exemplifies the tensions between the natural and human systems in the coastal zone. Low-crested structures are those coastal defences that are regularly overtopped by waves, and the DELOS project aimed to provide a synthesis of the effects and effectiveness of these artificial breakwaters and reefs. Its validated and calibrated models are important advances in forecasting the effect of low crested defence structures on the littoral environment.

Under conditions of climate change and sea-level rise, transformation of the coastline is inevitable. Increasing erosion of coastal cliffs is projected. From society's perspective, cliff collapses are a hazard, and uncertainty about the triggers of serious collapse leads to technical difficulties for land use planners, limiting the use of coastal lands. The **PROTECT** project has researched techniques to identify cliffs at risk of imminent collapse, to allow predictions to be made of the timing and extent. In adapting to climate change impacts, this type of applied understanding of natural processes is vital.

HUMOR also addresses the implications of the ongoing degradation of coastal areas across Europe, and has attempted to understand – and predict – the medium to long-term evolution of coastal morphology (over months to years) and its interplay with human actions in the coastal system. Its modelling tools link the complex, multi-scale, often nonlinear dynamics of coastal hydrological and sediment processes which shape the coastline with the human interventions and impositions on the littoral zone (ports and harbours, dredging, and so on). This project thus has tremendous potential to contribute to the science of integration and sustainability.

The **OROMA** project addresses changes in coastal bathymetry and the related processes of erosion, sediment transport and deposition. Its innovations are new tools for mapping and presenting morphodynamics over large areas in nearly real time. Such tools have the potential to be vital parts of the climate change management toolkit.

Indirect links to Climate Change:

The remaining set of about half of the projects in the ELOISE programme only have indirect relevance to climate change science. As already emphasised, the objectives and science remit of ELOISE (the interfaces and mutual influences of land, air, ocean, biosphere and anthroposphere) are fundamentally aligned with climate change and earth system science, but for several reasons, the research outputs of the following projects are less directly applicable.

One of these projects, **ROBUST** (a precursor study to F-ects), addressed the way ecosystems cope with environmental change. It focused on 'buffering capacities', arising from both physical and biological processes in coastal lagoon ecosystems (of sea-grasses, macroalgae and microbial communities). Its mechanistic study may allow vulnerability assessments to be made, but its focus was on understanding processes *within* the system, and external or enhanced climatic forcing was largely beyond the scope of the research.

Several projects looked at understanding the scale and impacts of pollution and other human alterations of the environment. **POPCYCLING** produced a mass balance model for anthropogenic pollutants; **TOROS** explored the biological processes pertaining to trace metal regulation of primary productivity; **MAMCS**, **MOE** and **MERCYMS** addressed the serious problems of mercury and heavy metal pollution, and as such have little direct connection to climate change research. However, the baseline temperature and irradiation data generated in these projects may be of use, and this should be borne in mind in dissemination.

Several projects exploring the relationships between nutrient supply, biodiversity and primary productivity have already been described in the previous sections. Other ELOISE projects in this area have contributed to more fundamental understanding, with less attention to external (climatological) forcing. **MEAD** and **SIGNAL** both contribute baseline data for atmospheric deposition, with particular attention to the anthropogenic enhancement of nutrient supply. **COMWEB**'s key task was fundamental research on food web structure and functioning; **BASIC** aimed to identify the short timescale controls on cyanobacterial communities; and **BIOCOMBE** also addressed the consequences of changes in biodiversity and community dynamics on ecosystem functions. All these projects contributed towards the development of assessment criteria for the state of ecosystems, and the parameterisation of response functions for use in modelling those systems. While this knowledge is vital, is it several steps away from being integrated into climate change science.

Despite the great uncertainties that remain in nutrient and pollutant biogeochemistry, that science is comparatively well-advanced in contrast with the understanding of sources, nature and fates of dissolved organic material in the coastal zone. **DOMAINE** addressed these fundamental questions, while **DOMTOX** investigated the potential for organic nutrient species to promote the growth of harmful or nuisance blooms in the coastal environment. **COMET** also focused on the characterisation of the organic material, contributing to the understanding of its behaviour and interaction with other dissolved species in the aquatic environment. This knowledge will ultimately be consolidated into the understanding of biogeochemical cycles (this is already underway; for example, the organic component of atmospheric aerosol is being considered in ANICE), but until that happens, very little can be inferred about its connections with climate change.

Eurotroph and **DANLIM** both test hypotheses about the role of anthropogenic drivers in eutrophication, and integrate the changes in biota with physical processes. **NTAP** and **Oaerre** explicitly link physical and biological processes to aid understanding of the scale and patterns of eutrophication. **DANUBS, STREAMES, MANTRA-East** extend this knowledge in the development of models for use in integrated management tools. Like most other projects in this section, the questions being addressed by these tools are either too local in scale or too specific in remit to be consolidated into climate change models, and conversely, climate change manifestations may be too weak to be a significant forcing variable for inclusion in these models.

COSA, investigating the biocatalytic effects of sands, is rather an outlier in terms of this analysis, with little immediately evident connection to climate change. The remaining projects in the ELOISE programme, however, despite their lack of direct links, have furthered the process of integration of science, and have generated prototype tools of the sort that will facilitate society's responses to the environmental changes related to global climate change.

The **BEAM** project is one of few large scale initiatives that recognise the difficulties of understanding and managing multiple interacting effects. By looking at combination and synergistic effects of multiple pollutants, this project represents a real advance in risk assessment methodology. Given that climate change will act in synchrony with other global changes (e.g., rising temperatures coinciding with greater particulate loadings in the atmosphere and higher nitrogen emissions as a result of the greater human population), a meta-appraisal of this process may well be of great value in terms of its potential for framing methodologies for multi-forcing impacts.

The final set of projects comprises tool-development projects to help sustainable decision-making and action-taking. **BBCS** was a cross-sectoral sustainability study on a small regional scale, researching improved ways to bring the natural and human systems into the same environmental analysis; **DITTY** similarly took a cross-sectoral approach in its efforts to develop an integrated IT tool for environmental management. **CoastView** and **TIDE** developed support tools using models of morphological and ecological dynamics, with a strong focus on visualisation and parameterisation. All these innovations represent important progress for sustainable action in our highly complicated Earth system.

4 Non-ELOISE European projects related to climate change and coastal management

In addition to the ELOISE projects, there are several European funded projects not within the ELOISE cluster which have examined the interactions between climate change and the coastal zone in Europe, and which can complement and add to the work undertaken within the ELOISE projects. The **SURVAS** project is an example of one such project. The SURVAS project found that while there is a consensus for mitigation of climate change within the European Union, proactive adaptation aimed at reducing a systems vulnerability to climate change either through minimising risk or maximising adaptive capacity is much more patchy and variable: "concern about sea-level rise, including the level of preparation, varied greatly across Europe; a few northern countries are already preparing for accelerated sea level rise, while many southern countries are ignoring observed 20th Century rise, let alone preparing for projected accelerated rise" (Nicholls and Klein, 2004).

The most notable of the non-ELOISE projects examining the interactions between climate change and the coastal zone is the **DINAS-COAST** project. The DINAS-COAST project has undertaken a dynamic and interactive assessment of national, regional and global vulnerability of coastal zones to climate change and sea level rise. DINAS-COAST is an integrated modelling project that builds on expertise and methods developed in climate modelling, coastal morphology and ecology, economics, environmental geography and computer science in order to assess potential impacts and vulnerability to sea-level rise (McFadden et al., 2003; see figure 6).

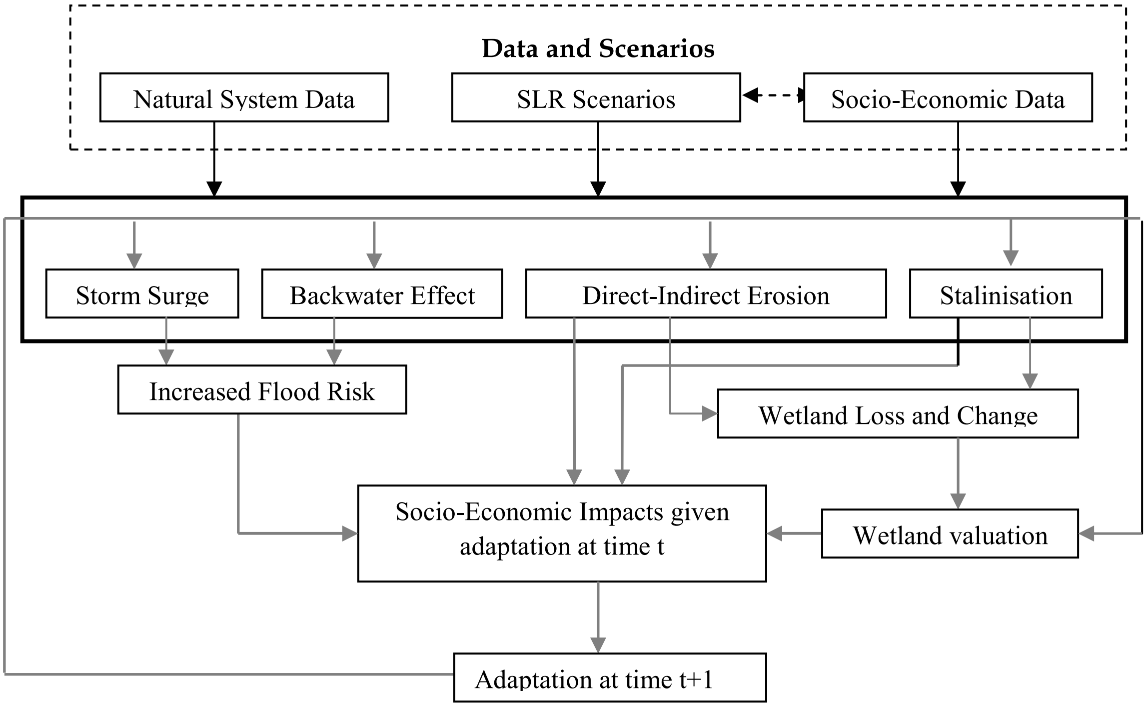


Figure 6: Schematised methodology of DINAS-COAST (Source: McFadden et al., 2003)

The DINAS-COAST project has developed a dynamic, interactive and flexible assessment tool on a CD-ROM, called DIVA (Dynamic Interactive Vulnerability Assessment) which is to be of practical use to policymakers and other stakeholders. DIVA enables its users to produce quantitative information on a range of coastal vulnerability indicators, for user-selected climatic and socio-economic scenarios and adaptation policies, on national, regional and global scales, covering all coastal nations. These mitigation and adaptation scenarios can then be visualised and analysed on high quality thematic geographic maps using a map server (developed by DEMIS b.v., The Netherlands). The user can compose maps by adding map layers and by setting properties for the display of the layers, as well as by adding data for thematic layers. It is hoped that DIVA will enable its users to explore the effects on coastal vulnerability of climate change mitigation on the one hand and adaptation in coastal zones on the other; identify cost-effective policies that combine mitigation with adaptation; set priorities for international co-operation with respect to climate change and development; and to use the quantitative output on coastal vulnerability to sea-level rise for further scientific and policy analysis.

Looking to future research, **Euro-limpacs** is a new project which began in January 2004, designed to assess the effects of future global change on Europe's freshwater ecosystems. One of the central activities of this project is the development of an innovative toolkit for integrated catchment analysis and modelling to simulate hydrological, hydrochemical and ecological processes at the catchment scale for use in assessing the potential impact of global change under different climate and socio-economic scenarios (Euro-limpacs, 2004). There will also be development of a unified system of ecological indicators for monitoring freshwater ecosystem health, and new methods for defining reference conditions and restoration strategies. The aim is that these will take into account the probable impacts of future climate change and the need for a holistic approach to restoration based on habitat connectivity.

5 Conclusions

The major objectives outlined in the ELOISE science plan were:

- understanding the significance of the coastal zone in global change
- appraising human impacts on coastal seas
- finding a strategic approach for sustainable coastal zone management
- developing a robust framework for Europe's coastal zone science.

Here, we revisit those objectives, briefly appraising the extent of the contribution of ELOISE projects in the light of today's understanding of climate change and its expected impacts on the region.

Understanding the coastal zone

The concerted efforts of pan-European science over the last decade have undeniably led to major advances in the understanding of ecosystem processes. From a climate change perspective, the most important progress has been made in the contribution to the understanding of the great cycles of nutrients and carbon through key reservoirs (land, biosphere, ocean and atmosphere), and the causes and extents of indirect impacts and non-linear interactions. Also important is the inclusion of this knowledge into process models and scenarios.

Human impacts

A common theme in all the ELOISE projects is recognition that human activities change water chemistry and aquatic ecosystems. Most projects have focused on appraising those changes (recognising that many of those changes have negative impacts on the natural systems that compete for coastal zone space with human society). The physical boundary conditions of coastal systems are vulnerable to climate change, yet human interventions will shape the extent to which the natural environment can re-establish a stable equilibrium. A potentially important aspect that the ELOISE programme addresses only very superficially is the fact that the deeper knowledge of human impacts uncovered here leads to further questions of the evaluation and prioritisation of options for adaptation or mitigative action. Of course these questions are a matter for society as a whole, not just for scientists, but scientists are in a unique position to make judgments about the value of different ecosystems (c.f. O'Neill, 1993), and ELOISE should be seen as a vehicle for a concerted input to these wider debates.

Integration for sustainability in the coastal zone

Long time-scale changes were not explicitly in the original ELOISE remit, but we now have the best–ever "present state" analysis. Some projects have explicitly looked at the links between the natural and human systems, integrating socio-economic analysis with the natural sciences. The development of integrated management tools across the spatial continuum from land to sea, addressing loadings and forcings of different types, are an attempt to manipulate the impacts of human activities in a positive way, to counteract unsustainable negative impacts. The *pressures-impacts-responses* framework for the interface between human activities and natural systems that is common to many of the ELOISE projects allows for knowledge transfer among the projects, with more robust comparison and testing across regions and sub-systems, and confers the potential benefit of ensuring that these tools can more efficiently interface with the latest generation of modular climate impacts modelling tools (e.g., the Tyndall Centre's Community Integrated Assessment Model, and the projected Europe-wide E-VIA; see Leimbach and Jaeger, 2004).

Frameworks for the future

The fundamental value of process models has already been mentioned. In terms of global climate modelling, some ELOISE outputs do indeed make a contribution, but only inasmuch as the basic science is translated from 'raw' knowledge into parameterised process functions (e.g., for the interconnections between sulphur cycling in plankton blooms and cloud formation). The potential importance of ELOISE projects in the emergent integrated approaches to natural science has also been mentioned. There is a vital need for a focus on compatibility in scale and resolution of outputs. Next-generation climate impact modelling relies on "plug and play" models which ELOISE could provide. The bringing together of 'tailor made' models into a distributed framework is today's priority, and research advances in institutions that have been involved in ELOISE programme may be vital in allowing the translation of research outputs into management-oriented models.

The issue of scaling (both up and down, in time and space) has also been identified, and significant moves towards addressing the technical and conceptual difficulties have already been made, in a consolidation workshop (ELOISE, 2003), and in ongoing applications of the project outputs. Where management and decision-support tools are used, these should be monitored and critically appraised over the longer term, to see to what extent they stay applicable under changing conditions.

A common theme in many projects is that they are fundamental ('pure') research – and indeed, fundamental questions about the functioning and form of the coastal zone remain unanswered. End users, including those who will implement responses to future climate change, need to know about the processes explored in ELOISE, but they need this knowledge to be translated. Whether end users are climate modellers, local managers or Europe's policy makers, a 'critical path' of translation from the raw science to usable outputs is needed. In some cases, there may be very few intermediate steps, but in many others, the end users are very distant. ELOISE has tackled this dilemma in several interfacing projects, bringing scientists into the process of developing informed management tools. The dissemination and consolidation of the science outputs must recognise the vital need for this type of appropriate, multi-level communication of important results.

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Appendix – Climate Change Relevant Publications from ELOISE Projects (with ELOISE attribution codes)

'Baseline' Observations – Role of CZ in CC	Manifestation of Climate Change	Tools
ESCAPE: Archer et al., 2000	BASIC: Stal et al. (2003)	METROMED: Karageorgis et al., 2000
NICE: Rysgaard et al., 1998; 1999; Thornton et al., 1999 ; Miles & Sundbäck (2000); Sundbäck et al. (2000); Risgaard-Petersen & Ottosen (2000)	CLICOFI: Dippner & Ottersen (2001); Pörtner (2001); Pörtner et al. (2001)	NICE: Serodio & Catarino (2000)
PHASE: Granata et al. (2001); Duarte et al. (1998); Gacia et al. (2002)	BASIS: Valkama & Kozlov (2001); Cornelissen et al. (2001); Kozlov (2000); Kozlov & Berlina (2002)	PHASE: Burchard & Petersen (1999)
RANR: Grimvall et al. (2000); Kronvang et al. (2001)	DANUBS: Zessner et al. (2004)	RANR: Larsen et al. (1999); Forsman et al. (2003); Müller-Wohlfeil et al. (2001)
BASIC: Albertano et al. (1999); Staal et al. (2003)	**Human Impacts of Climate Change**	CLICOFI: Sirabella et al. (2001)
CLICOFI: Pörtner et al. (2000); van Dijk et al. (1999); Hardewig et al. (1999)	RANR : Kronvang et al. (1999);	ECOFLAT: Van de Koppel et al. (2001)
ISLED: Boorman et al. (2001)	BASIS: Lange & Cohen (1999)	DUNES: Edwards et al. (1997); Laranjeira et al (1999)
ANICE: De Leeuw et al. (2002)	BBCS: Jansson (1997); Jansson & Stålvant (2001)	EROS-21: van Eeckhout & Lancelot (1997)
ROBUST: Giordani et al. (1997); Welsh et al. (1999)	DUNES: Willams & Bennett (1996)	OAERRE: Lee (2002)
ECOFLAT: Barranguet et al. (1997); Hamels et al. (2004)		
POPCYCLE: Wania et al. (1998); Wania et al. (1998)		
DUNES: García-Mora et al. (1999)		
BIOGEST : Van der Nat & Middelburg (1998) ; Borges & Frankignoulle (1999); Van der Nat & Middelburg (2000); Abril et al. (2000); Frankignoulle & Borges (2001); Middelburg et al (2002);		
EROS-21: Amouroux et al. (2002);		
INCA: Gallart et al. (2002); Machefert et al. (2002)		
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