

Earth System Science Theme Action Plan 2008

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Overview

Planet Earth is a complex, interconnected system. Earth System Science seeks to build an understanding of the whole system by increasing our knowledge of its component parts and the ways that they interact to create the complex Earth System. The Earth System Science Theme (<http://www.nerc.ac.uk/about/strategy/documents/theme-report-earth-system.pdf>) is therefore very broad with an overarching goal of using fundamental science to improve our understanding of the earth and its functions.

The Earth System Science Theme links to all other themes, but perhaps most particularly to the Climate System theme. These two theme leaders have worked closely on developing their Theme Action Plans. In general the physical and biogeochemical components of the climate system that operate on time scales of the next few decades are considered within the Climate Theme. Components of the Earth System affecting climate predominantly on longer time scales, including biogeochemical feedbacks involving atmospheric trace gas composition, will in general be addressed jointly between the Climate and Earth System Science themes.

The individual actions outlined in this Theme Action Plan (TAP) will be addressed within a broad Earth System approach. The breadth of the theme covers essentially all aspects of NERC science areas and hence the whole of the NERC community.

The NERC Strategy launched in November 2007 identifies the various challenges associated with the Earth System Science Theme and these are expanded on in the Earth System Science Theme Report published earlier in 2007. Earth System Science (ESS) is a very wide-ranging theme. Three broad challenges are identified within the Theme Report and within each are a series of more detailed sub-challenges/issues it is recommended be addressed. These challenges and sub-challenges are;

1. Providing Forewarning Of Abrupt Climate Change.
 - Changes in ocean ecosystems in response to increasing ocean acidity
 - Destabilisation of methane hydrates under global warming
 - Forewarning of abrupt climate change
2. Improve knowledge of the interaction between the evolution of life and the Earth.
3. Quantify forces and feedbacks that drive the Earth System. Challenge 3 is divided into the following sub challenges:
 - 3.a Global Biogeochemical Cycles
 - 3.b Dynamics of the earth's interior and their manifestation at the surface
 - 3.c Terrestrial processes and their interaction within the Earth System
 - 3.d Ocean processes and their interaction with the Earth System
 - 3.e Cryospheric change and its interaction with the Earth System
 - 3.f Atmospheric composition
 - 3.g What do records of past environments reveal about the operation of the Earth System?

Activities under all of these challenges are already being undertaken to some extent by NERC within Responsive Mode, Research Programmes and existing activity within NERC Research and

Collaborative Centres' strategic research programmes (hereafter Research Centres). Some of this activity will be considered where relevant to this TAP, but it is not intended at this time to comprehensively review all this activity. In the case of major ongoing research programmes (e.g. SOLAS, QUEST) the outcome of these programmes will inform the development of future TAPs.

- The actions proposed within this TAP are all identified within the NERC Strategy and the underlying Earth System Science Theme Report.

This first TAP identifies three primary areas as priorities for investment:

- Changes in ocean ecosystems in response to increasing ocean acidity;
- Destabilisation of methane hydrates under global warming and methane cycling;
- Stability of major ice sheets and effects on sea level and flooding.

Although it is proposed that each of these initiatives will be led under the Earth System Science banner, all three have components of other themes from the NERC strategy within them and other theme leaders have been involved in the process of developing these activities.

Action 1: Ocean Acidification

1.1 Rationale

Atmospheric CO₂ concentrations are increasing as a result of human activity and are likely to continue to do so in the future, although the future levels of CO₂ are uncertain. In response to this rise, the oceans are taking up more CO₂ and becoming more acidic. The associated increases in ocean acidity over coming decades are likely to be at a rate and on a scale that is unprecedented in at least the last 20 million years. It is likely that large areas of the ocean could become undersaturated with respect to at least aragonite (one of two common polymorphs of biologically produced calcium carbonate) within this century. Under such conditions, organisms creating aragonite skeletons face serious challenges. This acidification will clearly have major impacts on ocean biogeochemistry and biodiversity, but impacts will extend beyond this to the whole Earth System via impacts on air-sea gas exchange and sedimentation of material through the oceans. The scale and nature of the effects of acidification on marine systems and more widely are very poorly known.

The issue of ocean acidification now has a high profile after the recent publication of the Royal Society report on the issue and the 2007 IPCC report. The UK research community has played a very prominent role in this area to date. It is, however, not a major focus for any of NERC current research programmes – for example, there is a rather limited focus on this issue in the Oceans 2025 programme. Within the programme planned here, activities in this field being undertaken within Research Centres will be integrated within a larger ocean acidification research programme.. There are now important policy questions associated with ocean acidification related to levels of future CO₂ stabilisation and the scale of the global change challenge associated with ocean acidification, and hence it is anticipated that several Living with Environmental Change (LWEC) partners will wish to engage with this activity.

The UK currently has world-class skills available to tackle this important and scientifically challenging issue and has been a global leader in this field. There are currently timely opportunities for collaborations in this area with European partners.

1.2 Objectives

The overarching objective of this action is to reduce uncertainties in the predictions of effects of ocean acidification on ocean biogeochemistry and ecosystems and their interactions with other components of the Earth System. The focus will be on both pelagic and benthic communities. Acidification-induced changes will have ramifications throughout the system and hence the programme will need to embrace an Earth System Science perspective to succeed. To help achieve this, a third focus will be on studies of past periods of ocean acidification within the paleo-record which can provide a valuable insight into the way the Earth System responded in the past and may do in the future. The anticipated improved predictive capability will allow NERC to provide effective advice to policy makers on the potential magnitude and timescale of risks and to allow for development of appropriate mitigation and adaptation strategies.

This issue is of global significance, but the NERC initiative will be geographically focused on parts of the Arctic, N.E. Atlantic (including north European shelf) and Antarctic waters and hence includes areas relevant to the NERC Polar Strategy. This geographic focus is logical because

- The polar regions are where major changes in acidity and carbonate saturation state are predicted to occur first
- there are a number of vulnerable and important calcifying organisms living in these areas
- it can easily build on existing UK experience working in these areas
- logistics of access to these environments are relatively straightforward and cost effective from the UK.

This geographic limitation does mean that some other important communities under threat from ocean acidification will not be considered within the Research Programme, including warm water corals.

The NERC research programme will (in collaboration with European partners) consider impacts on pelagic and benthic ecosystems and it is envisaged that the overall programme would focus on five components, including one that is a potential new National Capability (NC) component.

1. Improve estimates of ocean CO₂ uptake and associated acidification, particularly since the North Atlantic is a key global oceanic CO₂ sink.
2. Evaluate the impact of acidification on ocean biogeochemistry such as in terms of nutrient and metal speciation.
3. Improve understanding of impacts of acidification on key surface water phytoplankton species, including coccolithophores and other calcareous phytoplankton. This will include a requirement for continued research on the fundamentals of the calcification mechanism. Quantify the impacts of these changes in phytoplankton composition for ocean biogeochemistry (e.g. role of calcium carbonate as ballast for sinking material) and the broader Earth System (e.g. effects on air-sea exchange of key climatically relevant trace gases including CO₂, DMS, NH₃).
4. Provide evidence from the paleo record of past changes in ocean acidity and resultant changes in marine species composition and Earth System function including, for instance, changes
 - during possible paleo analogues for a high CO₂ world (the Paleocene-Eocene Thermal Maximum PETM and KT boundary 55 and 66Mya),
 - since the last glacial maximum as CO₂ has risen and
 - during the last 100 years as anthropogenic effects have begun.

Some components of this work at least will require collaboration with the UK IODP programme.

5. Identify likely impacts of acidification on benthic communities. Benthic communities will be vulnerable to ocean acidification which may remove or stress certain specific species and hence alter the ecosystem. It is planned here to focus on the continental shelf and slope region. This will include research on impacts on deep sea cold water coral communities which are extensive around and almost unique to the UK and Scandinavian shelf margin and potentially very vulnerable to acidification.

The Biodiversity Theme has strong requirements to quantify effects on populations, species and communities, in order to identify vulnerable groups and allow ecosystem level analyses and predictions to be made. The Biodiversity TAP, therefore, has a specific contribution to this activity establishing acidification thresholds, sensitive life history stages and evaluation of abilities to acclimatise to small pH changes across a wider taxonomic range using laboratory-based studies and field simulations.

Other organisations have an interest in the vulnerability of fish stocks in UK waters to acidification and partnerships with these organisations will be explored.

A diverse range of activities will be undertaken, ranging from research ship based surveys and monitoring on commercial ships, through mesocosm studies, to laboratory physiology work. Modelling studies of acidification and its effects will be used to link these components and also to include the other global change pressures such as temperature rise and resultant stratification changes that will occur in parallel with ocean acidification, emphasising the importance of considering this within an Earth System Science perspective. The modelling component of the work will link to the Hadley Centre marine modelling work. Several components of the action would be suitable for PhD studentships contributing to NERC's training goals.

The research programme is ambitious, but there is considerable UK expertise to address these challenging scientific issues. The effective coordination of the research will allow the overall impacts across the Earth System to be addressed resulting in a truly innovative scientific programme. This research programme, particularly if coordinated with activity by European colleagues (see later), will be world-leading.

1.3 Proposed Annual Funding and Implementation Mechanism

Existing Activity

There is some ongoing research activity within the Research Centres particularly BAS, NOCS, PML and SAMS funded both by NERC and from other sources..

Additional Support

The work required to deliver this action is large and complex and so the research programme will be developed and led by NERC in collaboration with European and UK partners. This action is led by the Earth System Science TAP as it is directly relevant to Challenges 1, 3a and 3g of the Earth System Science Theme Report, but it also has strong links to other Themes, particularly the Biodiversity TAP, which will also contribute funding towards the delivery of this action. In the UK an opportunity exists to develop a collaborative programme with LWEC partners, and international collaborations will also be explored.

The scale of planned or proposed activity in other countries emphasises the importance and timeliness of this issue. The UK has played a prominent role in this area to date and the activity planned here aims to allow NERC to develop a world-leading programme in this area.

The primary funding mechanisms will be research grants, consortia grants and studentships, retaining flexibility to engage the widest NERC community from HEIs as well as Research Centres,

while requiring participants to contribute fully to the overall programme goals. NERC will need to ensure the effective integration of the programme components and the linkage to other international programmes.

Action 2 Methane

2.1 Rationale

The Earth System Science Theme Report includes a specific challenge associated with potential destabilisation of the vast methane hydrates reservoirs (possibly containing 500-10,000 Gt of methane which spans the range of total coal, oil and gas reserves) as a tipping point for global climate change. Methane hydrates are also of interest to the energy industry as a potential energy reservoir and as a hazard during drilling. Hence research in this area is also relevant to the Sustainable Use of Natural Resources Theme. These hydrate reservoirs (methane/water ice like structures) are only stable within a specific temperature and pressure range and hence increases in temperature (due to global warming) or decreases in pressure (e.g. submarine landslides) clearly have the potential to destabilise these reservoirs, leading to large scale methane release. Methane is currently the second most important greenhouse gas after CO₂, with a much higher global warming potential than CO₂, hence an increase in methane release rates can lead to warming, further destabilisation of methane and hence to further warming, a positive feedback cycle. There is evidence that a process like this may have occurred in the past at the Paleocene-Eocene Thermal Maximum and possibly on other occasions (and would have also probably initiated ocean acidification after oxidation to CO₂, and hence is relevant to Action 1 as well). However, detailed studies of the Quaternary ice core record suggest that the major warming events over this time scale have not been primarily driven by methane.

Predictions of the future risk of methane hydrate destabilisation are uncertain because of a lack of fundamental understanding of their distribution, magnitude and stability. There are major methane hydrate reservoirs in the deep ocean, which are thought to be relatively stable to climate change, and in permafrost where they are potentially unstable, although probably on a rather long time scale. There are smaller (but still substantial) methane hydrate reservoirs in shelf systems that are potentially the most unstable in the face of likely climate change. In some cases it is predicted that if destabilised, the methane will migrate upward and then re-stabilise within the sediments or remain in place, although thermodynamically unstable.

There is a further range of important issues relating to methane in addition to those of methane hydrates. It is the second most important greenhouse gas and levels have increased in the industrial era, but its rate of increase decreased considerably in the 1990s for reasons that are not understood. In part this reflects quite intense cycling and oxidation of methane within sediments and the water column so that methane release to the atmosphere is a small component of a larger cycle. Globally wetlands are a large, uncertain and climate sensitive source and change in wetlands may have played a role in driving glacial-interglacial methane concentrations and climate change, but the mechanisms and impacts of the various complex interactions between temperature and water supply in this process are not understood.

Understanding the methane cycle is also important because of its role as an OH radical sink in the atmosphere which in turn influences ozone cycling and raises issues about the long term trends in atmospheric oxidising capacity. Ozone is a greenhouse gas and also influences human, animal and plant health.

Globally methane has diverse sources and, while the total source strength is quite well known from atmospheric measurements, the relative importance of individual sources is uncertain. This will

become an issue given government commitments to reduce greenhouse gas emissions and hence there is interest from LWEC partners including DEFRA and from the Hadley Centre. An improved knowledge of the biogeochemical cycle of methane is relevant to the Climate Theme and Sustainable Use of Natural Resources Theme as well as to the Earth System Science Theme.

2.2 Objectives

There is significant research activity within the UK on methane hydrates and on the contemporary methane cycle, and collaboration could be improved.. As a first step to better coordination and development of novel research direction, it is planned to create a Methane Network to run for 3 years. In the future this may lead to bids for responsive mode funding and possibly a research programme in a future TAP.

2.3 Proposed Annual Funding and Implementation Mechanism

The proposed programme of work will directly address Challenge 1 on the destabilisation of methane hydrates under global warming and will contribute to addressing Challenges 3a, 3c, 3f and 3g.

Methane hydrates.

Existing Activity in Research Centres and NERC Research Programmes

There is already BGS research in this area funded in part by NERC and EPSRC in association with U. Leicester. There is also a consortium grant within the NERC International Polar Year programme studying potentially unstable hydrates off Svalbard. There is work being done under QUEST and IODP related to the Permian-Eocene Thermal Maximum, when large-scale methane release may have taken place, and research led by BAS associated with the QUEST DESIRE programme looking at methane through the last glacial cycle using ice core records. There is also considerable research at Heriot Watt University which is closely linked to the Petroleum Industry and hence relevant to the Research Council Energy Programme. There is little UK activity in relation to methane hydrates within continental permafrost. Research on permafrost may best therefore be done in partnership with countries with direct access to such environments.. BGS airborne mapping capability can contribute to studies of the distribution of permafrost.

Methane cycle.

Existing Activity in Research Centres and NERC Research Programmes

There is an ongoing programme of CEH activity on the methane cycle, most of it focussed in the UK including both field scale measurements and larger scale aircraft studies used to estimate UK emissions. QUEST is developing a contemporary methane model, linked to Hadley Centre model development.

Additional Support.

Methane Network. There is currently significant and diverse research activity on methane and methane hydrates in the QUEST programme and in Research Centres (see above) which should continue as well as research activity within the HEI sector. Much can be achieved by improved coordination of these programmes via a Network specifically charged with focussing activity on meeting the Strategy Challenges of the Earth System Science and Sustainable Use of Natural Resources Themes. This will involve both hydrate and the broader methane cycle researchers as well as LWEC and other partners. The outputs of this network should be of direct relevance to LWEC partners and the outcomes of this better coordinated activity should lead to some exciting new scientific insights into the contemporary, paleo and future global methane cycle and encourage the participants to consider the issues within a long term and large scale Earth System Science perspective. This investment will therefore deliver innovative scientific outputs and added value from existing investments by NERC and others and raise NERC's profile in this area. This

network may subsequently develop a coordinated research programme which could become part of later TAPs.

Action 3 Ice Sheets

3.1 Rationale

Sea levels are currently rising and the rate of rise is projected to increase. Ice sheet melting is an important and very uncertain component of this projected rise. Some projections suggest that possible global warming scenarios could lead to irreversible decline of the major ice sheets. The large scale interactions between the cryosphere, oceans and atmosphere are fundamental drivers of the climate system and hence of biogeochemical cycles throughout the Earth System. Improved modelling of ice sheets within their models is also a priority for the Hadley Centre and hence they have a strong interest in this theme. Policy makers including LWEC partners also require improved projections of sea level rise over the next century and beyond for a wide variety of infrastructure and hazard planning purposes. The UK has internationally recognised expertise in this area and improved satellite capability offer opportunities for significant advances in the near future. Activity in this research area is intimately linked to the NERC Polar Strategy. For all these reasons this area is being considered as a research priority.

Local sea level rise depends in part on global sea level, changes in the gravity field, local elevation level change, ice sheet melting and ocean thermal expansion. All are important and uncertain to various degrees, but recognising ice sheet and glacier stability as a particularly important and uncertain long term regulator of sea level rise leads to the focus here. Currently glaciers dominate this signal (dominated by the large glacial masses in Alaska, the Antarctic Peninsula and the Himalayas), but their total volume is relatively small compared to the major ice sheets and hence the ice sheets dominate the uncertainty in longer term projections of sea level rise and attendant flooding hazard. Glacial stability is also of concern in terms of sustaining natural resources and local flooding hazard in regions such as the Himalayas and even parts of Europe. The recent IPCC Fourth Assessment was unable to quantify the possibility of major destabilisation of the Greenland and West Antarctic Ice Sheets in its projections of sea level rise, although such destabilisation is a real possibility and poses the risk of an increase in both the rate and magnitude of sea level rise. Such ice sheet collapse may also impact the thermohaline circulation and climate.

An improved understanding of ice sheet stability is therefore important for future projections of sea level rise and is a specific challenge within the Climate, Earth System Science and Natural Hazards Themes. This proposed action is led through the Earth System Science Theme but is jointly proposed from the three themes. It is directly relevant to Challenges 1 (forewarning of abrupt environmental change), 3d, 3e and 3g within the Earth System Science Theme, being specifically identified within Challenge 3e. The focus of the proposed activity is on the stability of the West Antarctic Ice Sheet (WAIS) and the Greenland Ice Sheet, which are widely accepted to be the two areas of most concern. However, some of the improved understanding of ice sheet stability more generally should also contribute to improved understanding of glacial retreat. The issues of major uncertainty are rather different for the WAIS and Greenland and thus the proposed research activity will potentially involve research in both polar regions. In each case significant scientific advances are required in understanding fundamental processes involving ice sheet dynamics and their interactions with the underlying bed and/or ocean.

The primary issue in the case of the WAIS is to understand how the grounding line of the current ice sheet will retreat, and this may be primarily controlled by interactions of ocean water with the ice sheet. The nature and causes of recent changes in the oceans around Antarctica which control the ocean/ice sheet interaction are very uncertain. Understanding these changes and likely future

changes is a key issue. In Greenland there are three main uncertainties that need to be addressed, since the causes of recent loss of ice mass are uncertain. The first is surface mass balance, i.e. precipitation versus melting. The second is the behaviour of the ice sheet itself, i.e. ice sheet hydrology and in particular the role of melt water lubrication of basal flow. The third is melting at the front end of tidewater glaciers and ice sheets and the role of interactions with the ocean. This diversity of processes and their links to global scale processes makes this area of research an exciting Earth System Science challenge.

3.2 Objectives

Research activity in these hostile regions is difficult and requires complex and thorough planning and coordination with other international partners. Technology developments may be needed to facilitate some of this work. It is therefore planned to undertake a large scale scoping study in 2008/9 with the aim of presenting a detailed plan for a research programme for consideration by SISB in the second Earth System Science TAP on ice sheet stability and sea level rise.

This scoping study will be charged with identifying current and future planned UK activity in both polar regions and with outlining a world leading research programme that utilises UK scientific capability most effectively to narrow the current large range of uncertainties of the ice sheet component of future sea level rise and the resultant effects on sea level rise, on a timescale of decades to the next few hundred years. The scoping study will consider if the programme should involve both polar regions and the appropriate balance of effort between modelling, fieldwork on the contemporary ice sheet and studies to understand the past behaviour of the ice sheets. This scoping study will also be able to consider the outcome of a major BAS led proposal to the EU "Ice2sea", which will involve some UK partners and which could contribute significantly to research activity in this area.

4. National Strategy for Earth System Modelling

It is clear that from the end of the QUEST programme some activity will be required to allow the continued use and development of some key Earth System models. An audit of UK Earth System Models will be led by the Climate Theme and with Earth System Science Theme participation. Based on the results, a national strategy and implementation plan for Earth System Modelling will be developed. The audit and strategy development are discussed fully within the Climate System TAP.

5. Forward Look to Second Theme Action Plan and Subsequent Investment

During consultations to date, many exciting possible future research areas have been suggested, often with some overlap between them. A scoping meeting is planned for later in 2008 to discuss the development of an initiative on the interaction between the evolution of the planet (including the interactions between the earth's interior and the surface environment) and of life on it (Challenge 2 in the Earth System Science Theme Report).

The development of additional or alternative research themes will be considered as consultations with the HEIs, Research Centres and Users continue.

6. Training

As noted within the document, there are several components of the planned investment that could involve PhD studentships and hence contribute to training. In addition several programmes of Summer Schools have become established and contribute significantly, not only in subject specific training of the next generation of environmental scientists, but also in providing broadening of the PhD student's experience and the opportunity to develop networks of collaborators amongst young

scientists. NERC has supported students to attend international Summer Schools run by ERCA and SOLAS and NERC will provide the modest resources to continue to support 10 students attending these courses. In addition NERC established an Earth System Science Summer School almost 10 years ago, supported initially by a direct grant to the host institutions (UEA and Reading) and more recently within the QUEST programme grant. It is proposed that this Summer School continue and the resources become a part of NERC's core business at the same level of support as in recent years. NERC should continue to monitor the success of these summer schools and conduct a review at regular interval of the provision, perhaps every five years.

7. International

Earth System Science is by its nature international and this is reflected at least in part by the NERC support of IGBP Project Offices relevant to this theme - SOLAS, CLIVAR and GLOBEC. There is also planned partial support of Data Management within the GEOTRACES programme. The UK is also a partner in the major international IODP and there are plans for international ice core drilling which BAS are involved with. There are also existing commitments to the joint international programmes DIMES and Rapid-Watch and these will contribute directly to Challenges within the Earth System Science Theme. The continuation of all these activities is important to maintain the high UK profile within Earth System Science.