THE NERC MARINE CENTRES' STRATEGIC RESEARCH PROGRAMME 2007-2012

Theme 1: Climate, Ocean Circulation, and Sea Level

The ocean is the sleeping giant of the Earth system - that may have been woken by human activities, with potential to affect millions of people through coastal flooding and cause dramatic change in climate. Through fieldwork, analysis and modelling, Theme 1 will provide detailed knowledge of how the Atlantic, Arctic and Southern Oceans are responding to, and driving, climate change. In combination with geodetic studies, it will also improve our ability to predict global sea level and UK land movements in the century ahead.

Theme 1 comprises three Research Units and nine Work Packages:

The Atlantic and Southern Ocean in a changing climate (National Oceanography Centre, Southampton). *NOCS Theme Leader: Peter Challenor p.challenor@noc.soton.ac.uk*

- WP 1.1 Recent climate change and the state of the ocean
- WP 1.2 Atlantic circulation and transports
- WP 1.3 Physical-biogeochemical budgets and mixing in the Southern Ocean
- WP 1.4 Risk assessment of 21st century climate change

Arctic and Boreal Seas in a rapidly changing climate (Scottish Association for Marine Science). *SAMS Theme Leader: Ray Leakey rjl@sams.ac.uk*

- WP 1.5 Past and present variability of the northern limb of the MOC
- WP 1.6 The effect of climate change on the Arctic marine system

Geodetic oceanography, polar oceanography and sea level (Proudman Oceanographic Laboratory). *POL Theme Leader: Chris Hughes cwh@pol.ac.uk*

- WP 1.7 The ocean adjustment process
- WP 1.8 Arctic Ocean climate change
- WP 1.9 Sea level and vertical land movement

Theme 1: Climate, Ocean Circulation, and Sea Level

Strategic setting

The ocean plays a key role in the global climate system as the Earth's major reservoir and pathway for heat, freshwater and carbon, and has a direct impact on coastal populations as a result of sea level change. Global climate change is likely to have a particularly strong impact in the North Atlantic, which has undergone a major warming and a possible reduction (by ~30%) in the strength of its meridional overturning circulation (MOC) in recent decades. Furthermore, the high latitude North Atlantic has freshened dramatically since the 1960s and major changes in the Arctic are presently underway (e.g. a historic minimum of summer sea ice extent in 2005). Palæoclimate records and numerical models show that the North Atlantic MOC is particularly vulnerable to perturbations in the freshwater budget, leading to potentially rapid changes in European climate.

The prime cause of current global warming is the rise of atmospheric CO_2, mainly from the burning of fossil fuels. This rise would be 50-100% higher were it not for the large carbon sink provided by the ocean. However, the regional distribution and climate sensitivity of the oceanic carbon uptake is uncertain – in particular, CO_2 fluxes in the Atlantic sector of the Southern Ocean and the Arctic are poorly determined. To manage international obligations on carbon budgeting under the Kyoto Protocol, it is necessary to quantify these fluxes and assess their effects.

Reliable predictions of the future climate of the UK, coastal sea level rise and changes in the ocean carbon sink all critically depend on sustained observations of changes in the ocean - and determination of ocean feedbacks on the climate system. These predictions will improve strategies to mitigate the effects of climate change; for example flood defence planning. They will also provide societal benefits relating to agricultural practice, energy usage and water security. Whilst UK marine scientists need to continue to communicate the serious consequences of human-driven global warming, they must do so from soundly-based knowledge of the causes of changes in ocean physics and biogeochemistry, and their impacts on climate and sea level.

The research proposed here is well linked with the international effort in similar areas, through cooperative observational programmes; for example, the RAPID arrays, the ice monitoring project DAMOCLES, and model intercomparison projects such as CMIP. These links provide access to a much wider body of research, extending both the scope and importance of Theme 1 studies. In turn, we provide key inputs to the Intergovernmental Panel on Climate Change (IPCC, the major inter-national assessment of climate change and its impacts), and actively participate in global research programmes such as CLIVAR and the IPY. The proposed work builds on the strengths of the Centres involved, providing a natural progression to their current research.

Theme-wide science aims

Through fieldwork, analysis and modelling, we will investigate recent, ongoing and future changes in the Atlantic, Arctic and Southern Oceans. In particular, we address three urgent questions:

1. How is the pole-to-pole Atlantic MOC changing and what impact do the changes have on the ocean and our climate?
2. What are the effects of climate change on the marine Arctic environment?
3. What are the processes controlling past, present and future rates of sea level rise?

These issues provide the basic rationale for Theme 1, and relate to the following main science aims and Centre contributions:

Issue 1: The Atlantic and Southern Oceans in a changing climate (NOC, POL, SAMS)

i) To reduce the uncertainties concerning possible weakening of the Atlantic MOC and its consequences for deep ocean storage of heat and carbon (closely linked with the NERC RAPID programme and the RAPID II proposal).

ii) To accurately estimate recent and ongoing changes in the surface fluxes of heat, freshwater, and momentum, with a focus on the North Atlantic and the Atlantic sector of the Southern Ocean, and to relate these to the major observed changes in ocean state.

iii) To estimate new property budgets and transports (heat, freshwater, carbon, ACC), including their variability, and to measure and model mixing processes, in the Atlantic sector of the Southern Ocean.

iv) To reconstruct high resolution records of change at ocean margins and shelves in the northern North Atlantic, using proxy records from Quaternary sediment and biogenic archives.

v) To integrate into the wider Earth system context new knowledge of ocean processes and predicted Atlantic MOC changes on decadal-to-centennial timescales (closely linked with the NERC QUEST programme).

NOC	• Evaluation of observed and simulated changes in air-sea interaction since the 1950s • Evaluation of the extent to which changes in Atlantic heat and freshwater content in recent decades are due to changes in surface fluxes • Analysis of Atlantic MOC observations obtained at the 26°N monitoring array, interpreted using high-resolution model simulations • New observations across the North Atlantic subpolar gyre at around 55°N, the South Atlantic subtropical gyre at 30°S, and western Drake Passage • Determination of variability in the Pole-to Pole Atlantic MOC, and its implications for the storage of heat and carbon in the deep ocean, using observations and models • Evaluation of variability in ACC transport and properties through analysis of ongoing annual occupations in central Drake Passage • Analysis of property budgets in the Atlantic sector of the Southern Ocean using inverse methods • Analysis of mixing in the Southern Ocean, which will be used to evaluate new parameterisations of mixing in ocean models • Intercomparison of the centennial Atlantic MOC response to rising CO_2 in climate models with three different classes of ocean model • Decadal forecasts of the Atlantic MOC using new climate models • Uncertainty analysis of predicted changes in the Atlantic MOC and associated impacts, using a suite of climate and earth system models • Optimisation of ocean monitoring strategies based on model prediction and uncertainty analysis
POL	• Analysis of ocean adjustment to external forcing, leading to re-design of Atlantic MOC monitoring arrays • Spectral and physical characterization of sea level and bottom pressure variability in Drake Passage, leading to the recommended best method of monitoring the ACC for long-term change
SAMS	• New observations of the northern limb of the MOC across the Iceland-Scotland Ridge, and an evaluation of its connectivity between the northern North Atlantic and the Nordic Seas • High resolution records of change at ocean margins and shelves in the northern North Atlantic during the late Quaternary will be examined for inter basin MOC connectivity through the transmission of Rapid Climate Change events

Issue 2: Arctic and boreal seas (SAMS, POL)

i) To test scenarios concerning the influence on European seas of a summer ice-free Arctic Ocean, coupling physical changes with ecosystem responses

ii) To improve predictions of the combined effect of sea ice dynamics and ocean mixing on the biogeochemistry and carbon fluxes of the Arctic shelf seas, and the implications for the carbon budget of the Arctic basin.

SAMS	• Development of a multi-sensor satellite algorithm for sea ice classification, leading to sea ice classification maps that provide near-daily coverage in the Fram Strait area • Evaluation of POLCOMS and the CICE module in a high latitude shelf domain using new Arctic observations of seasonal changes in water mass transport and modification as a result of changes in sea ice extent and concentration • New observations in the Arctic of pelagic and benthic processes, specifically to identify potential climate-driven feedbacks (e.g. changing sea ice) on the marine ecosystem.

SAMS (cont)	• A tested and refined, coupled biological-physical model for ice edge processes within Arctic shelf and oceanic waters, used to predict how changes to Arctic sea-ice and water column structure will influence the ecosystem, and the subsequent biologically derived carbon export	
POL	• Evaluation of the sensitivity to climate change of water mass transformation processes in the Arctic • Determination of processes contributing to sea level change in the Arctic	

Issue 3: Sea level change, including geodesy and geophysics (POL)

i) To help solve the ‘enigma’ of 20th century sea level change, so that the sum of contributing climatic factors (steric change, glacial variations, etc.) accounts for the observations
ii) To validate global and regional sea level changes of the 20th century hind-casted by climate models, in order to derive confidence in model predictions for the 21st century
iii) To apply modern geodetic techniques (e.g. advanced tide gauges, GPS, Absolute Gravity, space altimetry and gravity) to new measurements of global and regional sea and land level changes
iv) To extend the sea level change database for the past few centuries by combining instrumental measurements with information from archaeological, geological and geochemical sources.

POL	• Combined geodetic estimates of current and past sources of sea level change • Development of an optimal procedure for combining geodetic time series for vertical land movement, leading to a definitive new map of UK land movement

The Atlantic and Southern Ocean in a Changing Climate

Contribution to Theme 1 by the National Oceanography Centre, Southampton

[5% of this Research Unit is considered to be Category 1 in the NERC definitions of different funding modes; Annex 6 of Overview]

Background

The prediction of future climate is difficult and uncertain. If we are to successfully mitigate or adapt to the effects of climate change, accurate climate forecasts are vital. Much of the present uncertainty arises from our limited understanding of the ocean’s role in the climate system (IPCC, 2001), particularly in terms of its exchange of heat and CO_2 with the atmosphere. The ocean’s large capacity to store and transport heat makes it a dominant factor in the timing and location of climate change. The UK is vulnerable to rapid warming or cooling due to changes in the North Atlantic. Anomalous Atlantic warming may outpace global warming, or, paradoxically, we might experience a period of regional cooling. Modelling studies and palæoclimate records suggest that the amount of freshwater entering the North Atlantic determines which scenario will emerge. Adaptation to such dramatic change is crucially dependent on early warning through the combined use of high quality observations and state-of-the-art models. Our observations, such as repeat hydrography (Bryden *et al* 2005) and the RAPID arrays, have revealed signs of substantial changes in the strength of the Atlantic Meridional Overturning Circulation (MOC). However, we cannot yet say with full confidence that the observed MOC decline will continue, nor can we give probabilities for future risks from such a decline.

NOC (formerly SOC) is one of the world leaders in observing and modelling the ocean and in estimating the fluxes between the atmosphere and the ocean. It has led UK participation in the World Ocean Circulation Experiment (WOCE) and Climate Variability and Predictability programme (CLIVAR), hosted the WOCE and CLIVAR international project offices, and contributed significantly to the results of these major endeavours. NOC scientists have the necessary expertise to further enhance UK capabilities to describe, explain and predict the changes underway in our oceans and hence the climate of our planet. Several of the investigators involved in this work are presently contributing to the 2007 IPCC Assessment and we expect that the research proposed here will underpin future IPCC assessments. Theme 1 will contribute towards: a coordinated effort to develop the UK capability for ocean forecasting (NCOF); fundamental research on the biogeochemical interaction of the surface ocean and lower atmosphere, including the air-sea flux of CO_2 (UK SOLAS and CASIX); reduced uncertainty in the risk of rapid climate change (RAPID II); better quantification and understanding of the Earth system (QUEST); and improved climate forecasts from the Hadley Centre.

The pace of global warming is largely dependent on the extent to which the world ocean can absorb CO_2 and excess heat. Cumulative uptake of anthropogenic CO_2 amounts to almost half of the anthropogenic emissions so far (Sabine *et al* 2004). Anthropogenic influence on global ocean heat content is now distinguishable from natural variability (Barnett *et al* 2005). The upper North Atlantic and the high-latitude Southern Ocean have warmed rapidly since the 1950s (Levitus *et al* 2005; Meredith & King, 2005), while other regions show smaller but still significant increases in temperature.

Changes in high latitudes are particularly relevant as these are regions of intense surface exchange and transport of CO_2 into deep waters through a combination of high wind speeds, low temperatures, deep mixing, and links to a vigorous overturning circulation. Moreover, model studies indicate a vulnerability of the Atlantic Meridional Overturning Circulation (MOC) to changes in budgets of freshwater and heat for this region (Gregory *et al* 2005). Recent variations in CO_2 uptake are becoming apparent (Le Quéré *et al* 2003); there is evidence for a dramatic freshening of the subpolar North Atlantic over the last decades (Curry & Mauritzen, 2005) which is due in part to increased net precipitation (Josey & Marsh, 2005), and observations suggest a substantial slowing of the MOC after the 1990s (Bryden *et al* 2005).

It is now imperative that we establish with greater accuracy the role of the changing ocean in the climate system. Only then can we account correctly for feedback processes and reduce uncertainty in the predicted extent of climate change over coming decades.

Aims and rationale

The scientific aims of this Research Unit are summarized as follows:

- To accurately estimate recent and ongoing changes in the surface fluxes of heat, freshwater, and momentum, with a focus on the North Atlantic and the Atlantic sector of the Southern Ocean, and to relate these to the major changes in the observed ocean state;
- To establish whether the Atlantic MOC is slowing down, and to relate this to changes in regional storage of heat, freshwater and carbon;
- To help develop more accurate parameterisations for our predictive ocean models by quantitatively investigating diapycnal and isopycnal transport processes using observations; To combine our best models with new statistical methodologies for risk assessment to reduce uncertainty in multi-decadal climate forecasts relevant to the UK.

This work is timely not only because climate change is a pressing societal issue, but also because recent scientific developments (new estimates of fluxes from ships, the RAPID arrays, and new climate prediction models and statistical techniques) now make significant progress possible. Such progress depends crucially on synergy between coordinated observations and experiments with a range of models. The observational programme is carefully designed to give a pole-to-pole description of the Atlantic Ocean, from the Southern Ocean to the Arctic. The approaches and methods necessary to achieve these aims are outlined in more detail in Work Packages 1.1 - 1.4 below. They involve analysing changes in air-sea flux fields from 1950 to the present day (WP 1.1) and using cruise data at three latitudes in the Atlantic and across the Drake Passage (see Figure 1). In addition, data from the RAPID arrays as well as from Argo profiling floats, satellites and the new flux datasets will be used to infer the overturning circulation and associated changes in heat, freshwater and carbon budgets (WPs 1.2 & 1.3). We will develop new model parameterisations for mixing in the Southern Ocean where current model deficiencies are largest (WP 1.3) and use these in our new NEMO-based ocean-only and coupled models (Theme 9), in order to identify the drivers of MOC variability and its consequences for the transport of heat and carbon. A comprehensive analysis of past and present changes, both observed and simulated, together with a detailed account of the main transport processes involved, will help to reduce uncertainty in our numerical models.These models will be used to estimate potential future changes of the ocean and their impact on the atmosphere, while advanced statistical methods will be employed to explore uncertainty in the predicted changes, with a special focus on UK climate (WP 1.4).

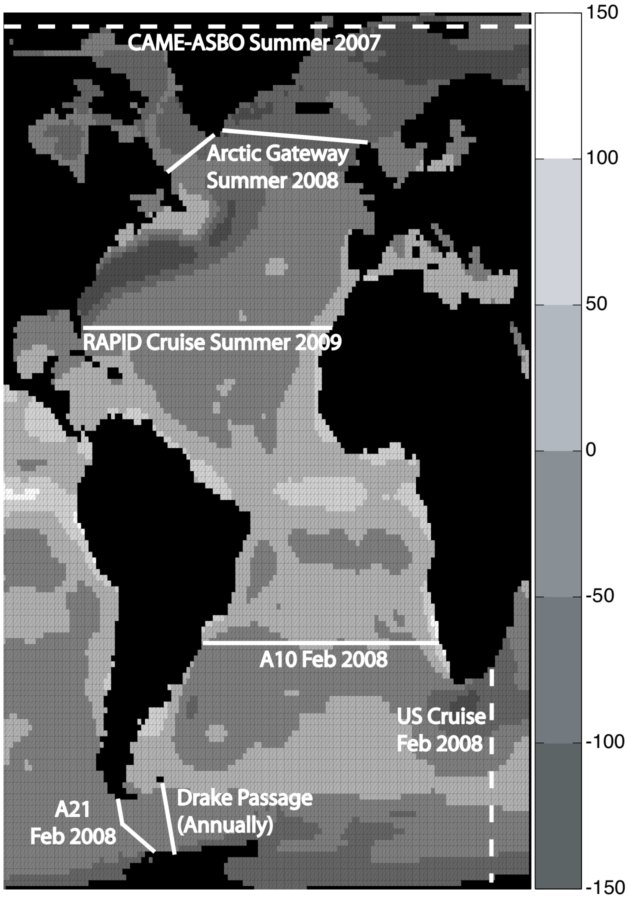

Figure 1. Hydrographic sections (solid white lines) to be occupied under Theme 1 of Oceans 2025 and related cruises (dashed white lines), over-layed on the NOC annual mean net air-sea heat flux field (positive values indicate ocean heat gain, units Wm^{-2}).

WP 1.1 (NOC) Recent climate change and the state of the ocean

Specific objective

To accurately estimate recent and ongoing changes in the surface fluxes of heat, freshwater, and momentum, with a focus on the North Atlantic and the Atlantic sector of the Southern Ocean, and to relate these to the major changes in the observed ocean state.

Approach and methods

We will use observations and model output to determine the extent to which major changes in ocean properties over the last 50 years, particularly in the North Atlantic and Southern Ocean, are caused by changes in the air-sea fluxes of heat, freshwater and momentum. This work will build on our previous experience of the development, evaluation and analysis of air-sea interaction datasets (e.g. Josey *et al* 1999; Grist & Josey, 2003) and make use of the next generation of ocean models being developed under Theme 9. The surface flux results from WP 1.1 will feed into studies of the large-scale circulation in the North Atlantic and Southern Oceans (WP 1.2 & 1.3), and the coupled model analyses (WP 1.4).

WP 1.1a Observations of climate change at the air-sea interface

A new multi-decadal NOC flux dataset based on *in situ* observations, with uncertainty estimates, will be developed under SO 9 (Climate-quality surface marine dataset development). Analysing this together with other long period datasets that utilise atmospheric model reanalysis fields (e.g. NCEP/ NCAR, ECMWF, OAFlux), we will identify changes in the air-sea flux and underlying meteorological fields over the last 50 years, and evaluate new coupled model simulations (see WP 1.4a). A combined analysis of several datasets will give increased confidence in the observed changes. The reanalysis fields are needed to extend the analysis of changes to regions of high latitude water mass formation (where ship sampling density is low). Using the different datasets we will determine where significant multi-decadal changes in the fluxes of heat, freshwater and momentum have occurred, and explain these in terms of both the forcing meteorological variables and the trends in large-scale patterns of atmospheric variability. The benefit of employing fields from SO 9 for part of our analysis is that they provide a temporally consistent dataset developed using our knowledge of how ship reporting errors have varied with time (e.g. Kent & Kaplan, 2006).

We will evaluate the accuracy of each flux dataset using advances in the observing system (e.g. surface flux reference sites, including new data in the Norwegian Sea discussed below), satellite data (from SO 9) and large scale constraints (e.g. hydrographic estimates of ocean heat transport). Underpinning the development of new flux datasets in SO 9, we will seek to improve parameterisations of exchange processes, targeting in particular the dependence of latent heat and CO_2 fluxes on wind and sea state conditions under high wind speeds - exchanges that are poorly understood at present. In close collaboration with CASIX we will combine research cruise measurements and satellite observations, building on NOC expertise in obtaining and interpreting direct measurements of the air-sea fluxes (e.g. Drennan *et al* 2005) and exploiting a three year (2006-09) continuous time series of flux data obtained at Station Mike in the Norwegian Sea (at 66°N 2°E) under separate funding (UK SOLAS project HiWASE - High Wind Air-Sea Exchanges).

WP 1.1b Model simulations of climate change in the ocean

In parallel with the analysis of observation-based datasets we will analyse global runs of the NEMO ocean model at 1/4° (provided by Theme 9). Additional nested runs at 1/12° resolution will be used to most accurately represent the ocean circulation in the NW Atlantic (where model errors are generally largest). The model will be forced with the NOC surface fluxes and reanalysed surface meteorological fields (NCEP/NCAR and possibly ECMWF) for 1950 onwards. We will undertake a full analysis of the changes in the simulated state of the North Atlantic in recent decades. Using observational datasets (including historical and new hydrographic sections from WP1.2 and WP1.3, available gridded hydrographic datasets such as the World Ocean Atlas, and satellite altimetry from SO 9) we will also assess the models' ability to provide a realistic account of recent changes in the state of the North Atlantic - an approach which we have pioneered (Marsh *et al* 2005a,b). The robustness of our results will be investigated further by comparing simulations forced by different atmospheric conditions including the ERA40 and NCEP reanalyses. The various model runs will provide dynamically consistent estimates of changes in the ocean interior, particularly the transport and storage of heat, freshwater and carbon, over the last 50 years. This will aid interpretation of observational datasets that are separated in space and time (e.g. Bryden *et al* 2005).

WP 1.1c Identifying the causes of recent climate change in the ocean

Using water mass transformation diagnostics (e.g. Marsh *et al* 2005b) we will relate the observed and simulated changes in ocean state (WP 1.1b) directly to the observed variations in the surface flux fields (WP 1.1a). As changes in large-scale ocean circulation are also likely to have played a significant role in the observed temperature and salinity changes, research under WP 1.1b will include model-based investigations of changes in the North Atlantic circulation. These studies will be extended here in the form of sensitivity experiments to separate the influences of surface flux and circulation changes on ocean heat and freshwater content. Using altimetry and gravity data from GOCE and GRACE, we will investigate circulation changes in the 'altimeter era' (1985 to present). We will also diagnose annual heat and freshwater budgets in key regions of the North Atlantic since 1950 using the ocean model simulations, complemented by an investigation of more recent changes using Argo float data (SO 5) and altimeter estimates of steric height changes (linked with sea level work at POL: WP 1.8, WP 1.9). Our analysis will determine the extent to which the observed ocean changes (e.g. warming of upper layers in mid-latitudes; Levitus *et al* 2005), are a direct response to changing atmospheric conditions. In addition, simulations of coupled ocean-ice-atmosphere models (provided by Theme 9 and used in WP 1.4a) will be analysed to give estimates of the relative amplitudes of fluctuations and patterns of variability, with and without increasing atmospheric CO_2 over the historical era. We will then look for fingerprints of anthropogenic change with the aim of separating such trends from fluctuations due to natural variability. We will focus on simulated changes in North Atlantic heat content, extending the work of Barnett *et al.* (2005).

Summary WP 1.1 research plan and deliverables

2008	• Completed simulation of changes in the ocean over the period 1950 - 2006 obtained by running NEMO globally at 1/4° resolution (and with a nested 1/12° North Atlantic grid) using NCEP/NCAR (and possibly ECMWF) derived surface flux fields (WP 1.1b)
2009	• Analysis of changes in surface fluxes over the last 50 years from the new multidecadal NOC flux dataset and available reanalysis datasets (WP 1.1a)
2010	• Evaluation of changes in ocean temperature and salinity over 1950-2008 in the various model simulations and in available hydrographic datasets (WP 1.1b,c)
2012	• Completed analysis of the extent to which the modelled/observed changes in the ocean since 1950 are due to changes in air-sea interaction (WP 1.1c) • Key publications for citation in anticipated 5th Assessment Report of the IPCC, with some Theme 1 scientists directly involved in the IPCC writing (all WPs).

WP 1.2 (NOC) Atlantic circulation and transports

Specific objective

To establish whether the Atlantic MOC is slowing down, and to relate this to changes in regional storage of heat, freshwater and carbon.

Approach and methods

Bryden *et al*. (2005) showed that the strength of the MOC at 26°N had slowed from 23 Sv in 1957 to 15 Sv in 2004. This observation raises a number of questions. Are we seeing a decrease in the MOC possibly presaging a collapse in the circulation and a consequent rapid climate change? Are we observing part of a long-term variation where the MOC will recover? Is this decline restricted to 26.5°N or does it extend over the whole Atlantic? Or is the observed signal simply the result of aliased high frequency variations? In this work package we address these questions.

WP 1.2a The MOC at 26.5°N

We will analyse observations of the MOC from the RAPID-MOC array at 26.5°N (SO 3) to quantify its temporal variability on scales from seasonal to interannual. This will provide a definitive baseline dataset for understanding MOC dynamics and forcing. Only by observing the MOC over decades can we quantify its natural variability so that trends may be separated from natural fluctuations. We will obtain a vital base line data set against which the performance of coupled climate models (in WP 1.1 and WP 1.4) may be assessed.

To test the monitoring array using an independent method, MOC estimates will be obtained from trans-oceanic sections at five-year intervals. The SOC James Rennell Division conducted a 26.5°N cruise as part of its Core Programme in 2004 and we will analyse two further transatlantic cruises (SO 3), to be taken in 2009 and 2014, extending the time series of high precision physical and chemical measurements at this section to 57 years. With observations from the 2009 section included in our existing analysis of variations in the size and vertical structure of the MOC and the changing property structure of the sub-tropical Atlantic at 26.5°N, we will quantify different modes of MOC variability (e.g. those driven by the Florida Current, Ekman transport, baroclinic interior circulation and barotropic transport fluctuations) on seasonal, inter-annual and eventually decadal timescales. We expect the flux variability of heat and other properties to be dominated by the fluctuating velocity field (Jayne & Marotzke, 2001). We will derive estimates for fluxes of heat, freshwater, carbon and other tracers across 26.5°N, by combining the MOC time series with section-wide hydrographic measurements. WP 1.2c will synthesise the array and section measurements with other hydrographic observations, models and air-sea flux studies. We will use the array measurements to quantify the effect of aliasing seasonal and interannual variability on the hydrographic observations, and carry out a rigorous investigation of the sources of uncertainty.

WP 1.2b The MOC in the subpolar gyre and exchanges with the Arctic

Recent observations show an increase in the freshwater flux from the Arctic Ocean and Nordic Seas to the Atlantic (Curry & Mauritzen, 2005) and a reduction in the flux of Lower North Atlantic Deep

Water in the Deep Western Boundary Current (Bryden *et al* 2005; Bacon, 1998), coincident with evidence for net melting of the Greenland ice cap in the last decade. These changes are poorly understood. We therefore propose a hydrographic section between Scotland, Greenland and Canada, at about 55˚N, occupying both the WOCE AR7W section across the entrance to the Labrador Sea and the WOCE AR7E section between Cape Farewell (southern tip of Greenland) and Scotland. Tracers, including oxygen isotopes and barium, will be measured to determine the sources of freshwater. The data will be combined with historical hydrographic and mooring data across AR7E&W, including the Ellett Line (SO 4), Argo float data (SO 5), and surface flux measurements (WP 1.1 / SO 9). We will calculate the contemporary annual mean and seasonal cycle for fluxes of heat and freshwater across the section, and investigate their interannual variability.

We will use these results to determine changes with time and location of freshwater and heat transports across the section. This will enable us to determine whether the additional freshwater input to the North Atlantic over previous decades is to be found in boundary currents, and if so, whether the Canadian Archipelago or the Greenland-Scotland ridge is the main conduit, and whether surface or deep flows are implicated. Observations indicate that while the flux of LNADW has decreased, the overflow source fluxes have not changed significantly. Therefore, we will determine whether changes in horizontal density gradients, caused by changes in overflow properties, are responsible for the downstream decrease in DWBC strength. Additionally, the proposed cruise will provide the first modern, synoptic estimate of high-latitude carbon fluxes, which will further strengthen the supporting links to UK and international Arctic IPY efforts, as well as to QUEST and SOLAS. Synthesis of these measurements with models and air-sea flux studies is addressed in WP 1.2c.

WP 1.2c Decadal variability in the pole-to-pole Atlantic MOC, and the storage of heat and carbon

Here we will integrate air-sea fluxes and *in situ* observations throughout the Atlantic with a range of models, to quantify decadal trends in the MOC and transport and storage of heat and carbon, and to identify the mechanisms generating the observed changes. With measurements from the Arctic Gateway section (WP 1.2b), the 26.5˚N section (SO 3), the Southern Boundary section (WP 1.3a), and from CAME-ASBO work in the Arctic, we will calculate Atlantic pole-to-pole estimates of heat, freshwater and carbon transports. The analysis will also include data from the AMT section (SO1), the repeats of the Extended Ellett line (SO 4), the WAVE array (SO 3) and Argo data (SO 5). Most of our sections will repeat or closely repeat sections occupied in the 1990s or earlier. By comparing new estimates of the MOC and northward heat transport with earlier estimates, we will ascertain the geographical extent of observed trends at 26.5°N (Bryden *et al* 2005) and whether they continue throughout the next decade, or are natural oscillations. Local and remote forcing of the MOC will be investigated by building on our considerable experience in the synthesis of observations and simulations of the MOC at 26°N (Hirschi *et al* 2003, Marsh *et al* 2005b).

We will compare observations from the array with simulations of MOC strength and structure in the ongoing 1/12° simulation of OCCAM and new 1/4° simulations with NEMO, including a 1/12° nested Atlantic model (Theme 9). Through critical comparison of simulated MOC variability on a range of timescales with that observed at 26°N we will relate MOC variability there to circulation changes to the north and south, and hence establish the influence of remote forcing on the dynamics and physical properties at the mooring array. This analysis will be carried out jointly with POL, who propose a range of model experiments alongside analysis of the 26°N and DWBC monitoring arrays, and with SAMS, who will investigate the MOC near the Greenland-Iceland-Scotland Ridge.

Measuring the large number of physical and chemical measurements required on the long hydrographic sections will be a major undertaking. There will be an opportunity for the academic community to enhance the data either by adding new variables to the measurement suite, or by providing needed measurements such as CFC and carbon. Relevant expertise exists in the UK university community and will be sought through SOFI.

Summary WP 1.2 research plan and deliverables

2008	• Arctic Gateway Section (WP 1.2b)
2008-12	• Annual quantification of MOC from analysis of RAPID-MOC data (WP 1.2a)
2009	• Analysis of exchange between Atlantic and high-latitude northern ocean basins (WP1.2b)
2010	• Estimate of total CO_2 inventory, providing a baseline for future direct estimates of CO_2 change (WP 1.2c) • Analysis of 26.5°N cruise carried out under SO 3 in 2009 (WP 1.2a)
2012	• Pole-to-pole description of the size, structure and variability of the MOC and of the ocean sources and sinks of carbon dioxide (WP 1.2c) • Key publications for citation in anticipated 5th Assessment Report of the IPCC, with some Theme 1 scientists directly involved in the IPCC writing (all WPs)

WP 1.3 (NOC) Physical-biogeochemical budgets and mixing in the Southern Ocean

Specific objective

To establish regional budgets of heat, freshwater and carbon, and to develop more accurate parameterisations for our predictive ocean models by quantitatively investigating diapycnal and isopycnal transport processes using observations.

Approach and methods

Vast, though poorly known, amounts of anthropogenic CO_2 (~20 Pg, Sabine *et al* 2004) are believed to have been absorbed into the Antarctic mode and intermediate waters. Much of this uptake is achieved in the ACC, involving the upwelling of North Atlantic Deep Water, its northward transport by a delicate balance between Ekman drift and eddies, followed by subduction as mode waters. Models suggest that the rate of CO_2 uptake is sensitive to changes in the wind and to changes to the eddy fluxes (Mignone *et al* 2005).

To predict climate change, it is essential that we know the size of this carbon sink, and understand the processes that control it. Even the exchanges of heat and freshwater between the Atlantic and Southern Oceans are poorly known. We will combine observations and modelling to quantify and understand the processes controlling property fluxes and trends in the Atlantic sector of the Southern Ocean, where the Atlantic overturning circulation is partially closed as it meets the ACC. The observational effort will be fully integrated with the international CLIVAR/Carbon repeat hydrography program, and with the DIMES initiative to study mixing rates and processes; this work has been accepted as a contribution to IPY. The budgets and mixing rates inferred from field measurements will be used to both evaluate and improve our numerical models.

WP 1.3a Transports and fluxes in the Atlantic sector of the Southern Ocean

We will reoccupy the WOCE section A10 across the South Atlantic at 30°S. This cruise will be carried out in conjunction with an occupation of A21 across the Drake Passage (further W than the SO 3 cruises) and a US section from Africa to Antarctica (WOCE I6). We will repeat A21 rather than our regular SO 3 track because the cruises on the SO 3 track do not have tracer or carbon measurements. This will create a box in the Southern Ocean/South Atlantic. The combined effort will be a coordinated two-ship operation, with the intention that the Drake Passage section (A21) will be simultaneous with the US 30°E section. If that is not achieved, seasonal changes in upper-ocean properties will combine with the large volume transport of the ACC to increase uncertainty in the inverse analysis - a weakness of previous calculations (e.g. Rintoul, 1991). Data from a Spanish cruise across the South Atlantic (possibly around 45°S), and a German cruise on the Greenwich meridian will be valuable additions to our analysis.

We will diagnose a regional circulation scheme and basin-scale budgets of physical and biogeochemical properties by means of a box-inverse analysis of these new observations, following the methods of McDonagh & King (2005). Where appropriate, we will employ direct current measurements, including shipboard and lowered ADCP. Cautious use will be made of chemical tracers to constrain the analysis: dissolved silicate, which has high contrasts in concentration across the domain, is the most likely to be useful. We will consider the consistency of the circulation scheme with previous analyses and Argo float trajectories, and combine the inferred circulation with biogeochemical tracers to diagnose the carbon budget.

WP 1.3b Seasonal, interannual and decadal variability

In addition to the one-time synoptic experiment, we will maintain the annual Drake Passage (DP) time series, proposed for continuation under SO 6. This has been occupied in 11 out of 13 years from 1993 to 2005. Cunningham *et al.* (2003) point out the significant seasonal variation in heat flux across the DP repeat section, equivalent to several tenths of a petawatt. We will test the sensitivity of the inverse calculation to interannual and decadal variability by including all occupations of the Drake Passage section, as well as other occupations of 30°S (1993, 2003) and 30°E (1996). We will carry out an inverse of winter conditions by using winter Argo data (SO 5) to modify upper ocean temperature and salinity profiles in the hydrographic sections. Our analysis will be further informed by examination of seasonal and interannual variability in models. As the cruises defining our box are exact repeats of sections occupied during WOCE we will use these to identify decadal changes in physical and transient tracer properties and the carbon inventory.

WP 1.3c Measurement and parameterisation of mixing

Meridional property fluxes within the upper layers are restricted by the closed contours of mean geostrophic flow that pass through Drake Passage. Tracers can only cross these contours through ageostrophic flow such as Ekman drift or through eddy fluxes. Coarse resolution models (e.g. Mignone *et al* 2005) have shown the sensitivity of CO_2 uptake to these eddy fluxes. Presently such models parameterise these eddy fluxes crudely. Moreover, the MOC over the ACC is sensitive to the diapycnal mixing rates (Karsten *et al* 2002). Existing parameterisations used in numerical models do not give the enhanced deep diapycnal mixing already inferred in this region (Naveira Garabato *et al* 2004).

We intend to build on past work on OCCAM 1/4° (Lee & Coward, 2003) and 1/12° (Lee *et al* 2006), and diagnose isopycnal mixing of tracers and eddy advective 'bolus' transports in eddy-resolving runs involving nested NEMO 1/12°(and global NEMO 1/12°). These results will be used to estimate the parameterised isopycnal eddy fluxes that should be employed in coarser resolution models. Very high resolution process runs planned in Theme 9 will be used, together with detailed observations of flow over rough topography (Naveira Garabato, already funded), to develop parameterisations of diapycnal mixing for use in models such as NEMO.

These estimates of isopycnal and diapycnal mixing will be validated by model simulations of the DIMES tracer release experiment, releasing passive tracer into the high resolution NEMO configured with the new diapycnal mixing. Model mixing will also be validated against: i) net mixing over the enclosed region implied by the inverse model; ii) mixing inferred from LADCP data on the sections; and iii) mixing along 60°S, being studied in a cruise planned by Naveira Garabato that may involve direct microstructure measurements.

Summary WP 1.3 research plan and deliverables

2008	• Southern Ocean Cruises, A10 and A21 (WP 1.3a)
2010	• New estimates of the diapycnal mixing implied by vertical exchange of tracer properties in the box inverse calculation and from LADCP data (WP 1.3a,c)
2011	• New estimates of air-sea fluxes of heat, freshwater, carbon and other biogeochemical tracers, and between the Atlantic sector of the Southern Ocean and neighbouring ocean basins (WP 1.3a)
2012	• Analysis of interannual and decadal variability (WP 1.3b) • Improved mixing parameterisation in ocean models (WP 1.3c) • Key publications for citation in anticipated 5th IPCC Assessment Report, with some Theme1 scientists directly involved in IPCC writing (all WPs)

WP 1.4 (NOC) Risk assessment of 21st century climate change

Specific objectives

i) To integrate into the wider Earth system context new knowledge of ocean processes and predicted Atlantic MOC changes on decadal-to-centennial timescales.

ii) Using our best models combined with new statistical methodologies for risk assessment, to reduce uncertainty in multi-decadal climate forecasts relevant to the UK.

Approach and methods

There is currently much uncertainty as to how the Atlantic MOC will respond to global warming from increasing levels of atmospheric greenhouse gases. Climate models show a wide range of responses (IPCC, 2001), attributed to varying influences of warming and freshening on the MOC. In some models, MOC decline is arrested through the stabilising feedback of enhanced salt advection from low latitudes (Latif *et al* 2000). Atlantic salinity, and perhaps THC stability, is controlled by a combination of oceanic and atmospheric processes (Gordon, 1986; Broecker, 1997). Through variations in the dominance of different processes and feedbacks, predictions appear highly contingent on ocean model type. There is some evidence that the MOC is more stable to climate change in coupled models with a largely isopycnic ocean component (Latif *et al* 2000) than in models with a z-coordinate ocean component, although a formal intercomparison has yet to be carried out. On decadal timescales, it has been suggested that the MOC may be predictable (Collins & Sinha, 2003) while natural variation of the MOC on a multi-decadal timescale may obscure an anthropogenic trend for several decades (Knight *et al* 2005). Greater uncertainty surrounds future changes in the ocean carbon cycle (IPCC 4th Assessment, in prep.). Most challenging of all are exotic risks such as the destabilisation of the methane hydrates, ubiquitous in continental shelf sediments, which could lead to a catastrophic release of methane.

WP 1.4a Centennial prediction and decadal forecasting of the MOC and climate

We will use control and forced experiments with new, coupled models (Theme 9) to elucidate the response of the Atlantic MOC to increasing atmospheric CO_2 levels, effects of MOC changes on European climate, and the mechanisms involved. By comparing experiments with models featuring ocean components with three different types of vertical coordinate, we will for the first time formally address the dependence of MOC response on ocean model type. This will help the international community reach consensus on possible future changes in the Atlantic, the timescales on which such changes might occur, and on the processes involved. We will also use the climate models for decadal MOC forecasting, running simulations that span the modern observational era and the next 2 to 3 decades. Successful simulations of recent change in the Atlantic MOC are a prerequisite for forecasting decadal changes. Having evaluated the realism of simulated MOC change up to the present, and established model hindcast skill following standard methods (Collins & Sinha, 2003), we will simulate future changes (to at least 2025), and quantify uncertainty using the ensemble approach. This work will benefit from links with WP 1.2, SOFI-funded atmospheric modelling expertise (Theme 9) and assimilation work planned for RAPID II. Through more in-depth analysis of the coupled model simulations, we will investigate processes that drive multi-decadal variability of the Atlantic THC and link changes in the North Atlantic to European climate.

WP 1.4b The changing ocean in an Earth system context

Using computationally efficient Earth system models (e.g. GENIE), we will explore the role of the changing ocean in the global context. With such models, we can address the sensitivity of changes in climate and the biogeochemical cycles to parameterisations of key ocean processes, such as diapycnal mixing. The results of ensemble simulations will be combined with novel, rigorous statistical methods to quantify the uncertainty of predicted changes in climate and the oceanic carbon cycle. Emulator technology (e.g. Challenor & Marsh, 2006), being developed through the RCUK basic technology programme *Managing Uncertainty in Complex Models*, gives us a tool for making probabilistic forecasts even for complex models. Challenor *et al* (2006) demonstrated that these techniques can be used to estimate the risk of the MOC collapsing by 2100. We will continue to work with these methods to investigate the probability of future climate events, initially using GENIE, but we intend to extend this technology to more complex climate models. As models develop, we will extend our uncertainty analysis to cover MOC strength, CO_2 uptake and the stability of methane hydrates (linked to Theme 5b). Advanced statistical methods will then be used to develop optimal strategies for monitoring: a) changes in ocean circulation at 26°N (SO 3) and at the Extended Ellett Line (SO4); b) changes in water masses as sampled by Argo floats (SO 5); and c) changes in biogeochemical tracers along the AMT (SO 1).

Summary WP 1.4 research plan and deliverables

2009	• Improved mechanistic understanding of the vulnerability of the MOC and associated transports to a changing climate (WP 1.4a)
2010	• Formal intercomparison of MOC response to increasing CO2 in climate models differing only in type of ocean component (WP 1.4a)
2011	• Forecasts of multi-decadal changes (to 2025) of the THC and ocean climate in the Atlantic sector, plus uncertainty analysis (WP 1.4.a) • Recommendations for future monitoring strategy and prediction of (statistically significant) future expected anthropogenic impacts on MOC, ocean carbon cycle and climate (WP 1.4b)
2012	• Quantitative risk assessments of MOC shutdown, major changes of ocean CO_2 uptake, and hydrate instability, by probabilistic prediction with models of varying complexity (WP 1.4b) • Key publications for citation in anticipated 5th Assessment Report of the IPCC, with some Theme 1 scientists directly involved in the IPCC writing (all WPs).

Change in Arctic and Boreal Seas in a Rapidly Changing Climate *Contribution to Theme 1 by the Scottish Association for Marine Science*

[18% of this Research Unit is considered to be Category 1 in the NERC definitions of different funding modes; Annex 6 of Overview]

Background

The circulation of surface waters of the northern North Atlantic and Nordic Seas, the sub-polar gyre, has undergone significant variability in recent decades. The interconnectivity of oceanic and terrestrial climates is undisputed (e.g. IPCC, 2001), so understanding the time scales of local ocean climate variability will prove invaluable to north European governments as they plan for the defence of the region against the extremes of climate change. The changes in the sub-polar gyre and in particular the heating of the northern transport, coupled with an increased atmospheric heat flux, are causing rapid melting of Arctic sea-ice. This melting has altered the pelagic ecosystem structure and function and the flux of CO_2 into the water column. This Research Unit will i) re-assess recent and ancestral changes in the northward flux of heat and salt, and ii) quantify and predict the effects of changing sea-ice on the Arctic marine ecosystem and biogenic carbon cycle.

Model predictions for the 21st century suggest that changes in the distribution of North Atlantic salinity may lead to a slowing down of the MOC (e.g. Dickson *et al* 2003). The flow of freshwater southwards along the Greenland coast in recent decades has lead to a progressive freshening of the sub-polar gyre (e.g. Curry & Mauritzen, 2005), which in turn can affect its intensity by reducing the rate of deep water convection in the Labrador Sea (Stramma *et al* 2004). Salinity and temperature on the eastern side of the North Atlantic, between Faroe and Shetland, are increasing but short term variations are intimately linked to the interaction between circulation in the sub-polar and sub-tropical gyres (e.g. Hátún *et al* 2005). Model predictions (Kauker *et al* 2005) and hindcasts of the wind stress curl (Skagseth, 2004) reveal that part of the variability in transport of the MOC in Nordic Seas correlates across the Greenland-Scotland Ridge. Recent effort has focussed on the southward flux of freshwater across the eastern part of the ridge (ASOF, 2005). Here we focus on the northward flux of heat and salt across the western part.

It is well established that the marine sediments of the NW European Atlantic margin contain geological records of climatic change and its linkages to global thermohaline circulation (Knutz & Cartwright, 2003; Øvrebø *et al* 2006). At timescales of millennia and longer, the marine geological record of this passive margin provide crucial evidence of the variability of the MOC and its relationship to climate change. At shorter timescales, high resolution records can preserve evidence of rapid climate change events (Mayewski *et al* 2004) that have occurred during the present Holocene interglacial (Alley *et al* 1997). Detailed studies of palaeo-records of MOC activity across this region have to date focussed on the longer-term geological records (Stoker *et al* 2005). This is partly a reflection on the characteristic glacio-marine and downslope style of sedimentation across the margin. However, recent programmes such as RAPID, NORPAST-2 (Norway), and ENAM and STRATAGEM (EU) have ably demonstrated regions of enhanced bottom-current sedimentation along the margin that could provide temporally and spatially detailed records of MOC activity. Here we focus on that activity during the late Quaternary using textural and geochemical proxies from the marine sediments of the northeast Atlantic margin.

Climate-driven changes in the physical oceanography of the shelf seas of the Eurasian Arctic influence Arctic biogeochemical cycles, including the biogenic carbon flux and marine ecosystem (Skjevlan *et al* 1989). Sea ice directly influences the flux of carbon to phytoplankton by altering the PAR, changing the mixed layer depth and ventilation process, and creating a barrier to air-sea exchange. It also influences phytoplankton indirectly through the release of nutrients and viable microbial populations on melting. However attempts to model carbon flow through sea-ice microbial communities are rare and tend to be focused on coastal waters (Vezina *et al* 1997). Reduced sea ice cover is likely to increase light, mixing and phytoplankton growing season, resulting in increased primary production and reduced sea-ice algal production; however, such changes are highly dependent on regional and local changes in upwelling, mixing and salinity which, in turn, are influenced by the dynamics of the marginal ice zone (MIZ) (Sakshaug, 2004). These changes will alter the pelagic (ie. water column) community structure and vertical export flux to the seabed with associated consequences for the benthic communities, remineralization and burial of organic matter (Klages *et al* 2004). Benthic-pelagic coupling, including nutrient regeneration and subsequent entrainment into surface waters, is clearly an important component of the carbon cycle in these shallow Arctic shelf seas; however, such processes have yet to be adequately determined and included in Arctic ecosystem and biogeochemical models. Here we focus on improved quantification and incorporation of sea-ice and benthic processes into a coupled biological-physical model of ice-edge biogeochemical processes in Arctic shelf waters.

Scientific aims and rationale

This Research Unit aims to assess the significance of, and improve measurements of, present day changes of the northern limb of the MOC in the context of geological change. It also aims to greatly enhance our ability to predict how changes to Arctic sea ice and water column structure influence ecosystem structure and function, and subsequent biologically-derived carbon export.

The study of the MOC will involve a combination of desk study from an archive of international datasets, the installation of new instrumentation, the validation of a new satellite based salinity sensor, and the analysis of new and existing cores. It will be centred on, but extend north and south of, the Iceland - Scotland Ridge. The Arctic work package requires an integrated, multidisciplinary programme of observational and experimental research encompassing sea ice physics, physical oceanography, pelagic ecology, pelagic and benthic biogeochemistry, remote sensing and instrumentation. The research will be undertaken in the western Arctic shelf and northern Svalbard, and will underpin the construction, testing and refinement of a coupled physical-biological mathematical model. Both work packages will be undertaken with, and enhanced by, active engagement from the wider UK and international community.

WP 1.5 (SAMS) Past and present variability of the northern limb of the MOC

Specific objectives

i) Establish the connectivity of the surface flow of the MOC across the Iceland - Scotland Ridge and determine any correlation with external forcing
ii) Use modern hydrographic measurements to calibrate and interpret ancestral MOC flow using palaeo-proxy data.
iii) Examine any inter basin MOC connectivity through the transmission of RCC events across the northern transect as measured in the palaeo-sediment archived records.
iv) Install a thermosalinograph on a ferry that regularly crosses the MOC, and to validate flux observations using other in situ measurements and satellite remote sensing

Approach and methods

A mounting body of evidence is revealing that the transport of the MOC varies significantly over time scales of months to millennia. The northward flow of heat and salt across the Iceland - Scotland Ridge affects the climate of Northern Europe and the Arctic. The following questions about the MOC that are tractable within the time scale of Oceans 2025 are addressed here: what can archived datasets reveal about the forcing and pathways of surface flows? can palaeo-proxy records reveal variability of the MOC and can any rapid climate change events be detected between basins? and what is the true northward flux of salinity in the MOC across the ridge?

WP 1.5a Mining instrumental records of Atlantic water transport to investigate connectivity and forcing

One of the most important pathways for the inflow of warm, saline Atlantic Water is the northern limb of the MOC extending from the latitude of Scotland to the Arctic Ocean; it acts as the major conduit between the Atlantic and the Arctic accounting for 90% of the northward transport of heat and mass, and about 30% of the return flow (Hansen & Østerhus, 2000). SAMS will focus on the connectivity of the NE Atlantic and the Nordic Seas and exploit, in collaboration with national and international partners, the valuable long-term oceanographic time-series of modern thermohaline flow from a number of key locations (e.g. Ellett Line, Faroe-Shetland Channel, Svinøy Section) spanning up to 50 years. These time series, previously used to estimate the magnitude and variability of Atlantic Water transport, will be combined with drifter tracks (Argo, Global Drifter Center), meteorological hindcasts (NCEP/NCAR, ECMWF, Norwegian Met Office), satellite radar altimetry (TOPEX/Poseidon, ERS, Envisat) and numerical model output [e.g. MICOM (planned with Uni. Bergen), HOPE-C (existing collaboration through MOEN), and NEMO (linking into Theme 9, WP3)] to investigate transport mechanisms and the implied connectivity in basin exchanges (Nilsen *et al* 2003).

Linkage of data sets targeted at the Atlantic inflow complements the observations of Arctic export planned in WP 1.2b (NOC). This approach will be integrated into a Norwegian-led IPY initiative that has been endorsed and incorporated into an international cluster of the integrated Arctic Ocean Observing System (iAOOS).

WP 1.5b Palaeoceanographic records of MOC activity

At present, palaeoceanographic records of North Atlantic Overturning remain geographically dispersed across the northwestern North Atlantic (McCave, 2002, Weltje & Prins, 2003). By sampling in the regions of established oceanographic time-series in the northeastern North Atlantic it is proposed to develop a stronger link between the modern instrumental and the palaeo-record of the MOC. By examining records from diverse depositional environments across established hydrographic sections (e.g. Ellett line – across the UK shelf, the Rockall basin and bank) it is anticipated that records can be obtained showing variability within the MOC across a wide geographic area (Cortijo *et al* 2000). These records will provide resolution over a number of temporal scales, (e.g. high-resolution Holocene-age records from the shelf; pre-Holocene, lower-resolution records from the deep-sea). Using the high sedimentation rates (up to 100 cm per 1000 yr) of bottom-current enhanced deposition found across the transect, Holocene climatic events such as the Little Ice Age and the Medieval Warming Period (RCC events of Mayewski *et al* 2004) could become detectable and, perhaps ultimately traceable between basins allowing the chronology and influence of RCC events to be resolved. This 'time-slice' approach relies heavily on the use of established palaeo-proxy data such as sediment grain size for bottom-current variability, ^{18}O and ^{13}C, Mg/Ca, Sr/Ca for temperature and salinity of bottom waters and the rigorous use of ^{14}C and ^{210}Pb to constrain the chronology of the cores.

To relate the palaeo-record with the instrumental datasets of MOC, we will use short undisturbed sediment cores to establish the modern benthic conditions at, or near the sea floor. Palaeo-proxies such as Cd/Ca, Ba and carbon isotopic composition will be used to reconstruct past productivity and nutrient availability. Pre-existing core records, notably those from the Norwegian Margin and the Faroe-Shetland Channel, will also be examined negating the need for repeated sampling cruises.

WP 1.5c Installation and validation of a thermosalinograph across the MOC

SAMS will collaborate with colleagues from Europe and America to measure the surface flux of mass and salt in the MOC across the Iceland – Scotland Ridge (the eastern end of the GSR). At present trawl-proofed ADCPs deployed by FRS, Aberdeen and the Färoese Fisheries Laboratory (FFL) monitor the flux of surface water to the north and south of Färoe (Østerhus *et al* 2006). Since these moorings cannot measure surface salinity they are supplemented with occasional CTD sections. SAMS will measure directly 90% of the total MOC on *MS Norröna*, a passenger ferry that travels weekly from Norway and Denmark to Iceland via Färoe and Shetland (see Rossby & Benway, 2000, for a similar installation). When URI recently installed an ADCP on *Norröna*, they added T-junctions to the ship's cooling system to facilitate a thermosalinograph. Data will be streamed to SAMS via satellite and wireless connections, made available to users through a website and archived at BODC. Water intake will be controlled to prevent fouling in harbours (Theme 8 activity: the technology will also be used on a Scottish ferry). Supporting instrumentation (ADCPs, Homer) will be deployed under the track of the ferry on the Iceland-Färoe Ridge to validate the system. Data from the SBE21 will ground-truth ESA's new SMOS (Soil Moisture and Ocean Salinity) satellite, scheduled for launch in early 2007. SMOS is a passive microwave interferometric radiometer measuring L-band radiation (21cm - 1.4GHz) emitted from the Earth's surface with a resolution of 35 km. Salinity mapping by SMOS will be supplemented with SST mapping by passive microwave (AMSR-E or SSMIS, all-weather) and optical/infrared (MODIS, cloud-free periods) satellite sensors. Stakeholders (specifically FRS, FFL and IMR, Bergen) will help with the on board maintenance of the SBE21.

We will collaborate with European and American partners in establishing a formal network of sensors to monitor the northern limb of the MOC (first attempted as an EU Framework VI proposal). Opportunities exist for university groups to put a complementary meteorological / carbon flux package on the ship. This is a NERC Category 1 activity (establishment and validation of a new monitoring line).

Summary WP 1.5 research plan and deliverables

2007	• Core site selection; piston coring; investigation of the pre-existing datasets (WP 1.5b).
2008	• Data extraction and recovery of ocean model output (WP 1.5a). • Installation of thermosalinograph; deployment of ADCPs and Homer; acquisition of SMOS data (WP 1.5c).
2009	• Analysis of data sets (WP 1.5a). • Core sedimentology, particle size analysis, initial multi-element geochemistry (WP 1.5b). • Continued ADCPs, Homer, SMOS data; initial estimates of heat and salt fluxes; develop web site (WP 1.5c) • Analysis products of coherence between oceanographic, ancillary and model data sets (WP 1.5a) • Validation of SMOS salinity data (WP 1.5c)
2010	• Synthesis of results and publications (WP 1.5a). • Detailed core geochemistry (^{18}O, initial ^{14}C); sortable silt analysis; further piston coring (if needed) (WP 1,5b)

	• Continued data acquisition; possible additional sensors (2nd Seacat, fluorescence, nutrients) (WP 1.5c)
2011	• Construction of time-slices and comparison with hydrographic datasets (WP1,5c).
2012	• Publication of papers, dissemination of results. • A record of the ancestral MOC activity, between depositional basins in the northeastern Atlantic (WP 1.5b) • Validated surface fluxes of salinity and heat across the Iceland-Scotland Ridge (WP 1.5c)

WP 1.6 (SAMS) The effect of climate change on the Arctic marine system

Specific objectives

i) To improve understanding of how changing sea ice and water column structure influence ecosystem structure and function, and subsequent biologically derived carbon export, by delivering novel and comprehensive observational data sets on biogeochemical parameters from Svalbard shelf waters and the western Barents Sea.

ii) To construct, test and refine a coupled physical-biological model to predict, for Arctic waters, how changes in sea ice and water column structure influence ecosystem function and subsequent biologically derived carbon export.

iii) To develop a multi-sensor algorithm for sea ice classification, using a combination of current and future satellite sensors, to provide sea ice data to extrapolate ice driven model outputs over larger spatial scales.

Approach and methods

The Intergovernmental Panel on Climate Change (IPCC) has identified that "*The Arctic is extremely vulnerable to climate change and major physical, ecological and economic impacts are expected to appear rapidly*". Several global climate models predict substantial Arctic warming, particularly in the Eurasian Arctic area (e.g. Delworth & Dixon, 2000). Current forecasts estimate a reduction of Arctic pack ice by the end of the century by ~ 20% in winter and 80% in summer, resulting in an associated northward retreat of the MIZ and widening of the seasonal ice zone (Johannessen *et al* 2002). This will, in turn, lead to an extended area of water column stratification across the Arctic shelves and deep ocean with associated significant increases in new production (Reigstad *et al*. 2002; Wassmann *et al* 2006). The effect of ice duration and extent on ecosytems can already be seen across the Arctic from comparisons of 'cold' (late ice melt and low latitude MIZ) and 'warm' (early ice melt and high latitude MIZ) years (Wassmann, 2002; Lovvorn *et al* 2005). For the Barents Sea, a recent modelling study suggests a current increase in primary production of >30% associated with warm years (Wassmann *et al* 2006). This climate driven interannual variability in plankton communities in Arctic shelf seas leads to associated variability in carbon flux (Sakshaug, 2004; Slagstad & Wassmann, 1997). WP 1.6 will use a combined observational, experimental and modelling approach to improve predictions of how such climate-driven changes in the Arctic environment will impact upon ecosystem function, biogeochemical cycling and vertical carbon flux.

Observational and experimental studies will be undertaken in ice-covered and open waters of the western Barents Sea and the northern Svalbard region for which our understanding of the physical oceanography is relatively well advanced, and where seasonal access via a UK ice-strength research vessel (*RRS James Clark Ross*) and installation of year-round *in situ* instrumentation are feasible. These studies will complement previous observational and experimental studies undertaken in the western/central Barents Sea (Wassmann, 2002) and will be used, along with published data sets and remotely-sensed data, to parameterise and test a coupled physical-biological model which will be developed, in collaboration with POL, in the UK. This model will allow comparison with similar modelling studies undertaken in Arctic waters, including the western/central Barents Sea (Wassman *et al* 2006); it will also advance the current state-of-the art by improved parameterisation of microbial rate processes, and by the incorporation of benthic and sea-ice biogeochemical processes and feedbacks. This approach, encompassing ship, instrument and modelling platforms, will provide the UK with an enhanced strategic capability to undertake, and be informed by, research on the consequences of rapid climate change in the Arctic.

Observational studies will involve two 32 day research cruises to Svalbard shelf waters undertaken during summer (June-August) 2007 and 2009. Each cruise will focus on the MIZ, the position of which in June-August varies from year to year but generally lies to the north of Svalbard. On each cruise a suite of observations will be undertaken at sites along a shelf transect from fully ice covered to open water conditions. These observations will include:

- Physical parameters: sea-ice thickness, concentration and extent (satellite imagery and moorings), water column structure (salinity, temperature) and mixing, PAR, horizontal exchanges, cross shelf exchange processes and mixing.
- Sea-ice community and biogeochemical parameters: sea-ice algal, bacterial and protozoan composition, abundance and biomass. Primary and bacterial production. Inorganic nutrients, particulate (POC-N) and dissolved (DOC-N) organic carbon and nitrogen, and biogenic sulphur compounds (DMS).
- Pelagic community and biogeochemical parameters: phytoplankton, bacterioplankton, protozoo-plankton and metazoan zooplankton composition, abundance and biomass; primary and bact-erial production, respiration and nutrient uptake; inorganic nutrients, POC-N, DOC-N & DMS
- Benthic community and biogeochemical parameters: abundance, biomass, composition and metabolic carbon demand of meio-, macro- and megafauna. Quantification of vertical carbon flux (226Ra/210Pb/210Po/234Th particulate, dissolved, sediment, sediment trap material), sediment accumulation and mixing rates.

In addition to the above observations, examination of grazing, microbial production and benthic-pelaic coupling will be necessary to improve understanding of ecosystem and biogeochemical processes, and thereby model functionality, as follows:

Grazing. Phytoplankton communities tend to be grazed by either protozoans or metazoan zooplankton (predominantly copepods) with the importance of the latter dependent upon timing. Under a scenario of reduced sea ice cover, phytoplankton productivity is predicted to increase, with the major grazers being protozooplankton rather than large copepods (*Calanus* spp.), which have yet to ascend from diapause (Hansen *et al* 2003). The ability of *Calanus* spp. to respond to changing conditions in the Arctic is critical not only to the higher trophic levels, due to the potential impact on Arctic fisheries, but also to ecosystem function as a whole. If grazer dominance shifts from mesozooplankton to protozooplankton, vertical carbon fluxes are likely to be reduced. There are still relatively few studies of zooplankton grazing in Arctic waters (Hansen *et al* 1996; Verity *et al* 2002) yet a recent model suggests that the balance of grazing pressure may be critical for vertical carbon flux (Wassmann *et al* 2006). Our experiments will focus on elucidating the relative importance of micro- and metazoan grazers.

Microbial production. The limiting effect of nutrients on pelagic microbial communities is complicated by potential nutrient/temperature co-limitation of microbial populations observed at low temperatures and substrate concentrations (Pomeroy & Wiebe, 2001). This area of current debate is of relevance given the low temperatures encountered in polar waters and the importance of both marine and terrestrial derived dissolved organic nutrients within Arctic waters (Middelboe & Lundsgaard, 2003; Amon, 2004). There is further uncertainty concerning the relationships between phytoplankton and bacterioplankton which are at times uncoupled in Southern Ocean waters due to high protozoan bacterivory (Bird & Karl 1999; Duarte *et al* 2005). The combined effects of temperature and nutrients may have significant influence on lower trophic levels of Arctic waters yet have received little attention. Our experiments will focus on the co-limitation of microbial production by nutrients and temperature.

Benthic-pelagic coupling. Around 50% of Arctic marine primary production is ungrazed and directly exported to deeper water (Sakshaug, 2004). However, this vertical flux of particulate organic carbon is highly variable (7.5-14 $gCm^{-2}y^{-1}$ at 200 m water depth) and very susceptible to changes in MIZ conditions (Wassman *et al* 2004; 2006). Recent studies reveal that sediment oxygen consumptions for sediments NE and E of Svalbard in the Barent Sea are much lower than those W and S of Svalbard, reflecting differences in carbon supply to these areas (Hulth *et al* 1994). Furthermore, Glud et al(1998) indicates that Arctic benthic communities are limited by carbon availability, not by low temperatures. In addition to the quantification of vertical C flux, sediment accumulation and mixing rates, we will examine benthic remineralisation and nutrient fluxes to calculate nutrient entrainment into surface waters. *In situ* measurements of oxygen consumption will be made using the Profilur lander and rates compared with those from ship-board core incubations to determine how community composition affects respiratory demand (Piepenburg *et al* 1995). Concurrently the Elinor lander will be used to measure *in situ* fluxes of carbon and nitrogen across the benthic boundary layer. The origins and lability of carbon will be determined using $\delta^{13}C$ and $\delta^{15}N$ isotope ratios, and lipid/pigment concentration respectively (Lovvorn *et al* 2005).

To place these observations in a larger temporal and spatial context we will also undertake instrumented measurements[1] throughout the year in Storfjorden, an extensive area of shelf sea to the south of Svalbard. Storfjorden is a relatively well constrained area of relatively low advection with contrasting water masses. Sea ice coverage at Storfjorden varies from year to year, but has typically melted by the end of May. To assess ice coverage, thickness and timing of blooms the fjord will be instrumented with moorings containing sediment traps, fluorometers, salinity and temperature probes, ADCP, ULS and PAR sensors. The moorings will be deployed in summer 2007, maintained throughout 2008 (by collaboration with the Norwegian Polar Institute) and recovered in summer 2009 enabling two seasons of ice formation and melt to be monitored.

Development of a physical-biological model will be achieved, in collaboration with POL, by utilising an established ecosystem model (for example Hansen *et al* 2003) reconfigured to include variable CN flow (Doney, 1999) through lower pelagic trophic levels (phytoplankton, bacteria, protozoa and zooplankton), including carbon export flux. The biological model will be linked to the POLCOMS 3-D physical model. The resulting coupled model will be developed to include sea ice-pelagic interactions and pelagic-benthic coupling (using the ERSEM benthic model).

Scaling up of the model to regional and annual levels will be achieved by: a) using data available from the literature and our international partners; b) using remote-sensed data including satellite passive microwave (SSM/I, AMSR-E and SSMIS), optical/infrared (MODIS) and SAR (Envisat, ALOS PALSAR and Radarsat-2) and ice thickness data collected by underwater vehicles (through collaborations with university partners); and c) simulations with the global NEMO including biogeochemistry (carried out in NOC Themes 1 and 9).

Summary of WP 1.6 research plan and deliverables

2007	• Arctic research cruise to Svalbard and western Barents Sea with mooring deployment. • Model construction
2008	• Novel observational and experimental data sets on key physical and biogeochemical variables from summer 2007 cruise. • First peer reviewed publications • Mooring maintenance and turn around (with NPI). • Complete model construction and commence parameterisation.
2009	• Arctic research cruise to Svalbard and western Barents Sea with mooring retrieval • Complete model parameterisation.
2010	• Novel observational and experimental data sets on key physical and biogeochemical variables from summer 2009 cruise.
2011-12	• Model refinement and delivery of model output. • Sea ice classification map giving near-daily coverage of the Fram Strait area (NW Greenland to E of Svalbard) from 70N to 85N.

[1] A request for required mooring equipment will be made to the NERC marine equipment pool.

Geodetic Oceanography, Polar Oceanography and Sea Level

Contribution to Theme 1 by the Proudman Oceanographic Laboratory

Background

Over the last decade of the 20th century, global mean sea level rose at a rate of ~ 3 mm per year (Woodworth *et al* 2004; Cazenave & Nerem, 2004), faster than the 1-2 mm/yr rates reported for the past 100 years. Model predictions suggest a mid-range sea level rise by 2080 of ~ 45 cm, with associated increased flooding. In a constant coastal protection scenario, Nicholls (2002) predicts that this would increase the total number of people affected by coastal flooding from 36 million to 310 million,.The importance of an accurate assessment of future sea level change, and of the associated uncertainties, is clear. Such an assessment requires an understanding of the past, present, and likely future causes of sea level change (ocean dynamics, changes in ocean density or mass), and of land movement (Glacial Isostatic Adjustment, tectonics, atmospheric and oceanic loading, groundwater pumping etc.).

Two central difficulties limit our ability to predict sea level change. The first, enunciated by Munk (2002), concerns the difficulty of balancing mass and volume budgets in order to explain past sea level change. While sea level rose by about 18 cm over the 20th century, observed changes in ocean heat content are not adequate to explain this, suggesting that a large proportion of the sea level change is due to a change in ocean mass. However, geodetic constraints (measurements of Earth rotation, polar wander, and change of earth oblateness) appear to be inconsistent with the required movement of mass from polar regions which would be implied were this due to melting of icecaps. This 'enigma' must be solved, not only for the total 20th century sea level change, but also on shorter time scales, if we are to have faith in future predictions of global mean sea level change.

The second concerns the difficulty of predicting regional patterns of sea level change. While the model predictions presented in IPCC (2001) showed some agreement for global mean sea level change, there was little or no agreement for regional patterns. The satellite altimeter record shows intricate patterns of sea level change over the past 10 years (e.g. Cazenave & Nerem, 2004), with regional variations significantly larger than the global mean. and the (relatively coarse resolution) model predictions of IPCC (2001) suggest that regional variations will be almost as important as the global mean even on century timescales.

Research into sea level change naturally focuses on related geodetic quantities: sea level, land level, gravity, and ocean bottom pressure. POL has expertise, and is responsible for ongoing monitoring, in the *in situ* measurement of all of these. In addition, we have experience dealing with satellite altimetry and satellite gravity measurements, and are exploiting these datasets along with the *in situ* data. Particularly exciting are gravity data from the GRACE satellites, which are producing maps of large scale changes in ocean bottom pressure and land hydrology, and from the forthcoming GOCE mission (2007 launch), which will produce a high resolution (about 100 km) geoid as a reference surface for sea level. In addition, a Global Geodetic Observing System (GGOS) is currently under construction and will provide complementary global in-situ data with capabilities complementary to GRACE, in addition to further satellite data. This is a natural complement to the Global Coastal Observing System (GCOS) and Global Ocean Observing System (GOOS).

This geodetic viewpoint provides particular insights into ocean dynamics and monitoring systems, such as the POL contribution to monitoring the flow through Drake Passage (SO 6), and the Atlantic Meridional Overturning Circulation (MOC: WAVE, SO 2). These are two regions recognised within CLIVAR and GOOS as of special importance to the global ocean circulation and its role in climate. Sea level, bottom pressure, and other ocean boundary measurements have proved to be particularly well-suited to such monitoring in the Southern Ocean (e.g. Hughes *et al* 1999; Meredith *et al* 2004, Meredith & Hughes, 2005), and to understanding the dynamics of flows interacting with topography (Hughes & de Cuevas, 2001; Hughes, 2005). In parallel with our work to understand the aspects of sea level change associated with ocean dynamics, we will apply these insights where they contribute to understanding of other climate-related aspects of ocean circulation. The particular focus is determined by the need to engage fully with the NERC RAPID and RAPID II programmes, and to contribute to the success of the International Polar Year (IPY).

The Arctic is of particular interest, for both sea level and thermohaline circulation. There are good historical sea level data from the Russian sector (Proshutinsky *et al* 2004), which show coherent sea level fluctuations and a rate of rise similar to the global mean. In addition, water mass transformations in the Arctic make an important contribution to the northern limb of the thermohaline circulation. The Arctic is changing rapidly (ACIA, 2005): it has warmed at twice the global mean rate over the last 30 years (Peterson & Vose, 1997); sea ice cover has decreased by 10-15% since the 1970s (Cavalieri *et al* 1997), and is expected to decrease further (Stroeve *et al* 2005). Relevant processes associated with sea level change and water mass transformations are not, however, typical of the open ocean. Some 60% of the Arctic Ocean is shelf sea, and the influence of sea ice is strong. We will use POL shelf sea and sea ice modelling expertise to improve understanding of sea level and water mass transformation in the region, whilst also providing SAMS with a modelling tool for work on wider Arctic issues including ecosystems dynamics.

POL capabilities relevant to Theme 1 include hosting the Permanent Service for Mean Sea Level (PSMSL; National Facility 1 in Oceans 2025 bid) and the National Tidal and Sea Level Facility (NTSLF), and contributing Atlantic and Southern Ocean tide gauges to the Global Sea Level Observing System (GLOSS).. Related research into coastal flooding and the modelling of tides and storm surges to predict high frequency coastal sea level signals is covered in Theme 3. POL scientific work and data has featured strongly in IPCC reports (Church et al 2001).

Scientific aims

The overall aims of the POL contribution to Theme 1 are to:

- Understand past and present contributions to global sea level change, and their uncertainties.
- Understand the processes controlling regional variations and uncertainty in sea level change.
- Determine which processes contributing to sea level change are accurately represented in models and what further work must be done to ensure more accurate predictions.
- Determine the best means of monitoring the Atlantic MOC and flow in the Southern Ocean
- Determine the contribution of shelf sea processes and sea ice dynamics to sea level change and water mass transformations in the Arctic Ocean.

These aims are covered by three Work Packages, as detailed below. Results will feed into the IPCC 5th Assessment Report, narrowing the uncertainties of climate change, and informing related governmental policy decisions. This work will also contribute to various Global Observing Systems (Coastal, Geodetic, and Ocean), to help refine their strategies, and will provide underpinning science for the NERC Flood Risk from Extreme Events (FREE) programme.

WP 1.7 (POL) The ocean adjustment process

Specific objectives

i) To determine how sea level and ocean bottom pressure adjusts to changes in ocean forcing and to internal ocean variability.
ii) To assess the processes responsible for regional sea level variations and the capability of models to predict these changes
iii) To make recommendations on the best way to monitor the Atlantic MOC and the flow through Drake Passage

Approach and methods

While the ocean mass and volume budgets are important climate indicators, it is not global mean sea level which causes flooding, but local coastal relative sea level. In addition to regional loading effects, this is also affected by ocean dynamics, operating on all timescales from minutes (tsunamis) to centuries (thermohaline circulation). This WP focuses on open ocean dynamics. Complementary work focusing on shelf sea and estuarine dynamics is covered by Theme 3 (WP 3.3: Causes and impacts of extreme events). Modelling results from WP 3.3 will be used to reduce 'noise' in the tide gauge measurements of long period changes, and the understanding of long period mean sea level change from this WP will feed into the understanding of trends in extreme events in WP3.3.

In addressing the question "how does the ocean adjust to change?", we focus on adjustment in the major geodetic variables of ocean bottom pressure and sea level, covering both forced and internally-generated change (since both are likely to be present in observations). The issue is directly relevant to ocean monitoring strategies, since sea level and bottom pressure measurements provide strong integral constraints on the ocean circulation (Hughes *et al* 1999; Hughes & de Cuevas, 2001; Hughes, 2005).

More specific issues are: how do sea level and bottom pressure changes occur at sites remote from the region of forcing or local internal variability? does heat flux into the ocean simply produce a local expansion and associated sea level change, or does it induce a dynamical response which results in a non-local change? does dense water injected into the deep ocean by a high latitude convection event produce circulation changes (and associated pressure and sea level signals) at lower latitudes on timescales much shorter than the advective timescale?. These are essentially classic Rossby adjustment problems (e.g. Gill, 1982), but extended to circumstances in which Rossby waves, topographically-controlled waves, nonlinear interactions with mean flows, and eddies, can all be sustained. Our approach is to: i) determine the extent to which linear wave theory can explain the adjustment process in observations and model data; ii) diagnose the role of buoyancy advection; and iii) investigate momentum advection and eddy fluxes.

We will address the causes of observed changes in the satellite altimetry record, in observations from SO 3 (Atlantic MOC, both the NOC array at 26.5ºN, and the POL WAVE array), particularly the bottom pressure and related measurements, from SO 6 (Drake Passage) and SO 7 (UK GLOSS), and in models such as those run in NOC Theme 1, the Hadley Centre, and the NERC RAPID and RAPID II programmes. Three aspects will be addressed:

WP 1.7a Sea level change and ocean dynamics

What are the causes of the observed patterns of sea level change in the altimetric record, tide gauge data, and in model simulations? Holgate & Woodworth (2004) concluded that global coastal sea level rose faster than global mean sea level in the 1990s, and speculated that this might be explained by the more rapid propagation of waves around ocean boundaries than across the ocean interior, a mechanism proposed by Hsieh & Bryan (1996). Hughes & Meredith (2006) have shown that sea level signals are coherent over very long distances along the continental slope, at periods shorter than annual, but Huthnance (2004) has noted that a surprisingly low bottom friction is necessary if wave propagation is to account for these large-scale correlations. Similarly, variability in zonal jets is becoming apparent in observations (e.g. Maximenko *et al* 2005) and model studies (e.g. Richards *et al* 2006); clearly visible in sea level as features typically 300-600 km across, and varying on time scales up to at least decadal. There are a variety of mechanisms which could produce such jets, both linear and nonlinear. We will investigate the dynamics of these signals in models which reproduce them, and the extent to which they can be represented in relatively coarse resolution climate simulations.

The most obvious contribution to sea level change is heat flux, which causes expansion of the oceans. In collaboration with the Hadley Centre and NOC, we will investigate the extent to which this can explain patterns of sea level change by a simple advective mechanism. An artificial tracer will be added to the NOC model runs performed for Theme 1, proportional to the heat flux anomaly (similar experiments are also being run by the Hadley Centre). By comparing the model sea level anomaly with that which would be predicted from the distribution of this tracer, we will be able to determine the extent to which this simple mechanism is responsible for sea level change in the models. There is also a secondary dynamical effect of density change, in that it induces currents which produce a dynamical adjustment process, reflected in both movements of the thermocline and bottom pressure changes. We will use linear theory and simple model process studies to assess the importance of these secondary effects (which may be dominant in some places, eg at high latitudes).

This comparison of models and altimetry, with an underlying dynamical framework, will make it possible to attribute different patterns of sea level change in different model simulations to different physical processes, permitting a clearer diagnosis of the reasons for the differing predictions of climate simulations, and pointing to steps needed to improve the models.

WP 1.7b Atlantic MOC

The question of how the North Atlantic responds to a change in the formation of deep water at northern latitudes is related to the question of whether boundary waves are important in the sea level adjustment problem. We will pursue a similar analysis of this problem, making use of the RAPID and RAPID II observations and the complementary work by POL and NOC in SO 3. This work will feed insights from the sea level work into the various RAPID collaborations we have with NOC, BAS, and the Universities of Liverpool and Reading, as well as adding targeted model process studies appropriate to this region. By understanding the adjustment process in this region, and the space and time scales on which it varies, we will be able to refine the design of the MOC observing system for future deployments (and, indeed we aim to provide advice leading to refinements of the SO 3 deployments within the lifetime of this programme), to produce a better-targeted and more cost-effective system. This part of Theme 1 involves strong collaboration with NOC.

WP 1.7c Southern Ocean

Bottom pressure and sea level measurements to the south of the ACC are crucial to accurate monitoring of the Antarctic circumpolar transport (Hughes *et al* 2003; Meredith & Hughes, 2005), and the 17 years of BPR deployments (continued in SO 6: Drake Passage) and longer sea level records from the Antarctic Peninsula (to be maintained as part of SO 7: UK GLOSS) are now capable of providing insights into interannual transport changes (Meredith *et al* 2003; 2004). The adjustment process in question here is to determine what happens after the initial barotropic adjustment (which has now been clearly identified) in this system for which the baroclinic adjustment process is clearly highly nonlinear (e.g. Rintoul *et al* 2001). Comparisons between the long altimeter and tide gauge/BPR records, together with model diagnostics, will be used to address this question, in which the role of eddy-mean flow interactions is expected to be important. Eddy-resolving, idealised process studies will be used, particularly (in collaboration with NOC) following Hogg & Blundell (2006), who suggests an eddy-mean flow mechanism which can produce internal decadal variability, as well as regulating the response to forcing. We will use our improved dynamical understanding to make recommendations concerning the best strategy for ongoing monitoring of the ACC.

Summary WP 1.7 research plan and deliverables

Southern Ocean work will be ongoing, with annual Drake Passage cruises (SO 6). Similarly, analytical and model/observational diagnostic work will continue through the lifetime of the programme. Particular milestones and deliverables are:

2007	• GOCE satellite launch
2008	• Initial NOC model runs available. • WAVE array redeployment (SO 3)
2009	• Preliminary MOC monitoring array redesign to be provided
2010	• WAVE array redeployment (SO 3) • Causes of regional sea level change in model data identified
2011	• Synthesis of sea level process understanding • Final recommendation for MOC monitoring array • Final recommendation for future of Drake Passage monitoring

WP1.8 (POL) Arctic Ocean climate change

Specific objectives

i) To estimate the sensitivity to climate change of water mass transformation processes and downslope flows in the Arctic Ocean

ii) To understand the processes responsible for Arctic sea level change

Approach and methods

The large extent of shelf sea, and the prominent role of ice in the Arctic, mean that quite different processes are expected to be important in Arctic sea level change and the Arctic limb of the MOC. As part of a RAPID project, POL is developing an ocean-sea ice model to investigate processes controlling dense water formation and transport in the Barents Sea. The ocean component is the POL Coastal Ocean Modelling System (POLCOMS) and the ice component is the Los Alamos sea ice model (CICE). We will enlarge this model to cover the entire Arctic at a 10-km resolution, while adding parameterisations for smaller-scale processes. Model development work will also include support for SAMS WP 1.6 in coupling POLCOMS with an ecosystem model. POL work with this model will cover two aspects, the role of Arctic shelves in water mass transformation, and sea level modelling, as described below.

WP 1.8a Arctic shelves and water mass transformation in the Arctic

Arctic freshwater and heat budgets have changed significantly over the past decades, but the reason for these changes and their climatic implications (e.g. via the Atlantic overturning) are still under debate (e.g. Saloranta & Haugan, 2001; Gerdes *et al* 2003; Dickson *et al* 2002; Karcher *et al* 2005). While atmospheric forcing and volume transport of Atlantic Water into the Arctic are key controls of Arctic hydrography, processes particular to Arctic Ocean dynamics are also important: for example, water mass transformations associated with atmospheric cooling and formation of sea ice in leads and polynyas on Arctic shelves. Leads and polynyas are the sites of the largest surface heat losses in the Arctic (Maykut, 1982) and the creation of dense brines in these features, after down-slope cascading and mixing with ambient waters, may help to maintain the cold Arctic halocline (Aagaard *et al* 1981) and to form intermediate and Arctic deep waters that will later modify the properties of GIN Sea waters participating in the MOC (Aagaard *et al* 1991). Deep ocean ventilation by shelf convection in the Arctic has been estimated to contribute 40% of the deep overflows from the GIN Sea into the North Atlantic (Rudels *et al* 1999). Neither leads and polynyas nor cascading processes are resolved in POLCOMS-CICE and so a parameterisation will be used, based on an idealised lead/polynya flux model developed by us (Maqueda *et al* 2004). Cascading and downslope mixing parameterisations will, in turn, be incorporated in POLCOMS-CICE by means of a bottom layer transport scheme (Shapiro *et al* 2003). An interesting approach to the parameterisation of frazil/pancake ice is suggested by work on granular flows (Grey *et al* 2003), and there would be the opportunity for this to be developed by a SOFI-funded collaboration.

Our Arctic Ocean modelling work will benefit from the following agreed collaborations: 1) In support of the BAS contribution to the IPY ASBO Project, we shall include passive tracers, both artificial (e.g. age, dye) and realistic (e.g. oxygen isotopes), in our simulations, to help discriminate between melt water and river runoff. 2) We have links with the Canadian IPY Circumpolar Flaw Lead System (CFL) Project. If CFL is funded, we shall use CFL data for model validation and will use the model to investigate the role that the reduction in the central Arctic ice pack has on the development and maintenance of the circumpolar lead. 3) We shall carry out fieldwork with SAMS in the area of Storfjord[2], with the aim of estimating mixing of dense waters formed in the fjord's polynya and their contribution to oceanic overturning. Slope mixing was the focus of a POL/SAMS/NIOZ field experiment in the Faroe-Shetland Channel in September 2005 and a instrumental array similar to the one used in that study is proposed in Storfjord. 4) Our modelling and field experiments will also benefit from links with the Western Arctic Shelf-Basin Interactions

[2] SAMS plans to carry out a second field experiment in the shelf area north of Svalbard. POL collaboration in this cruise is possible.

(SBI) programme, and the IPY-Climate of the Arctic and its Role for Europe (IPY-CARE) consortium, in which POL is a participant.

WP 1.8b Arctic sea level

Arctic sea level appears to be rising at about the global average rate, although ~26% of this variation is not explained by recent balance assessments (Proshutinsky *et al* 2004). Changes in river run-off (Peterson *et al* 2002), Greenland ice melting (Rignot & Kanagaratnam, 2006), and rates of formation and transport of water masses (e.g. by a weakening of the MOC) could upset the current trend. Given the sparseness of Arctic sea level measurements, a combination of observations and modelling is needed to quantify the sources and modes of sea level variability. Analysis of tide gauge data along the Eurasian Arctic indicate that short-time-scale and interannual sea level variations are strongly coherent across the Arctic (Hughes & Stepanov, 2004), but the associated dynamics are not yet clear. At longer periods, the regional distribution of sea level changes shows a net sea level rise on the shelves, but a fall in the Central Arctic, presumably due to a different steric response of the coastal sea (fresher and warmer) versus the open ocean (Proshutinsky *et al* 2004). With the aid of our model, we shall evaluate the relative contributions of changes in surface pressure, winds, freshwater input and water temperature and their impact on sea level rise. This work will link to IPY-endorsed project ‘Sea level and tidal science in the polar oceans’ (PIs PL Woodworth & CK Shum).

Summary of WP 1.8 research plan and deliverables

2007	• Cruise to Storfjord (SAMS led, in WP1.6) • Arctic Ocean coupled ice-ocean model produced • Support for SAMS model development and ecosystem model coupling (for WP1.6)
2008	• Polynya and downslope flow parameterisations produced • Model experiments in support of CFL System experiment, if funded
2009	• Main Arctic model runs, Arctic model dataset produced
2010	• Model and data analyses (with SAMS cruise data), and additional model runs
2011	• Estimate of sensitivity of Arctic Ocean to polynya formation and downslope flows produced • Estimate of different contributions to Arctic sea level change produced

WP 1.9 (POL) Sea level and vertical land movement

Specific objectives

i) To determine the causes of global sea level change and vertical land movement
ii) To produce the definitive map of vertical land movement in the UK
iii) To extend the historical tide gauge record
iv) To test the realism of climate model predictions of sea level change

Approach and methods

WP1.9 focuses on the total volume and mass budget of the oceans, which is an important indicator of the ocean’s role in climate change, and a strong test of model capabilities. We will investigate the factors contributing to past and present day sea level change, particularly in the UK, where we will continue to monitor land level using GPS (and, in future, GALILEO), and absolute gravity, at selected tide gauge and other sites chosen to provide the most useful geophysical information. The UK is well-served by information on vertical land movement (tide gauges, and dating of a range of geological indicators, in addition to the techniques mentioned above). However, interpretation of GPS data is complicated by uncertainties in maintenance of terrestrial reference frames, which are most clearly addressed by comparison with absolute gravity measurements (Teferle *et al* 2006). The relevant signals in the UK are of the order 1 mm/yr, and require long time series and careful attention to error budgets and noise spectra in order to produce an optimal combination for interpretation (Williams, 2003; Williams *et al* 2004; Van Camp & Williams, 2005). In WP 1.9, we will extend our analysis and measurements, using global DORIS data and GRACE satellite gravity data to make the best determination of vertical crustal motion in the UK. From this we will produce the definitive map of UK vertical land movement. There is the opportunity for this work to be aided by a SOFI-funded collaboration, using Interferomentric Synthetic Aperture Radar to relate point measurements at particular sites to the pattern of local land deformation, hence determining whether the point measurement is representative of the wider area.

Melting of icecaps does not simply produce a constant sea level change across the globe. For example, melting of the Greenland Ice Sheet (which has shown a dramatic acceleration in recent years: Rignot & Kanagaratnam, 2006) produces a sea level rise which is smaller near the UK than in the southern hemisphere, because of the changed gravitational attraction and loading effect of Greenland and the ocean, and actually produces a sea level drop around Greenland (Mitrovica *et al* 2001). This means that different sources of ocean mass produce different characteristic fingerprints of relative sea level change in the tide gauge records. POL has geodetic expertise in loading calculations needed to determine these effects (Bos & Baker, 2005; Fratepietro *et al* 2006; Stepanov & Hughes, 2004, Hughes & Stepanov, 2004), and will work with university groups to interpret the tide gauge record (this collaboration would be facilitated by a SOFI bid to contribute to the application of geodetic capability to the sea level question).

To determine whether sea level rise has accelerated since the 19th century, data archaeology will be used to supplement the currently available tide gauge records, as in Woodworth (1999). It is hoped that new techniques of estuarine core analysis (Gehrels *et al* 2005) will produce long records in regions of the world where long tide gauge records do not exist (this work is currently the subject of a consortium bid to NERC between POL, NOC, the Hadley Centre and four university partners).

While we are limited to the tide gauge data and geological reconstructions for multidecadal time series, the accurate satellite altimetry record is approaching 15 years (almost 20 yr by the end of this programme). Time series of vertical land movement based on GPS and DORIS are also approaching the same length in places. A measure, based on satellite laser ranging, of the Earth's dynamic oblateness (J_2), which is a coarse resolution measure of the redistribution of mass between poles and tropics, is available from the 1980s onwards. Since 2002, the GRACE satellites have been producing higher resolution mass distributions, from which it is possible to measure the change in total ocean mass (Chambers *et al* 2004) and its distribution at ocean basin level at least. The transfer of mass from land to ocean will have different fingerprint patterns in each of these measurement types, making it possible to assess their consistency. We will compare these measurements, together with hydrographic estimates of change in ocean density in order to make the connection between ocean bottom pressure and sea level. From this, we will produce estimates of the mass exchange processes between land and ocean, on the timescales available for analysis, to resolve the 'enigma' for recent years. The results will be compared with model estimates, such as those from the Hadley Centre, to assess the degree of realism of the models. Conversely, the model data will be used to assess the observational error budget due to lack of resolution or sampling. This work is closely allied to WP1.8, in which the regional effects of ocean dynamics will be assessed.

Summary of WP 1.9 research plan and deliverables

At least annual absolute gravity measurements at three primary sites, with possible extension to sites identified in future, together with maintenance visits to POL-owned GPS sites.

2009	• Optimal procedure for combining geodetic time series for vertical land movement
2010	• Estimates of spectral characteristics and associated uncertainty estimates for sea level
2011	• Produce the definitive map of UK vertical land movement • Combined geodetic estimates of current and past sources of sea level change

Theme 1 Synthesis and Concluding Material

Oceans 2025 synergies and wider links

The Oceans 2025 structure will provide major benefits from the joint research activities to be carried out between NOC, POL and SAMS. The three Centres have a long history of working together on climate-related activities, which will be strengthened. For example both NOC and POL are partners in the NERC EO Centre of Excellence, CASIX, whose mission is to estimate the ocean - atmosphere flux of CO_2 using satellite data. CASIX will work in close collaboration, with Theme 1. Other linkages include the extended Ellett Line (SO 4) which has been run jointly over the last few years by NOC and SAMS, and joint Arctic work by SAMS and POL. All three Centres are active in the International Polar Year (2007-09).

In Theme 1, SAMS and POL will collaborate closely on the Arctic application of coupled models (POLCOMS/CICE, POLCOMS/ERSEM) to improve understanding of the physical processes that control Arctic ecosystems in a rapidly changing climate. The observations and modelling carried out by NOC will provide the global context for the Southern Ocean and Arctic analyses undertaken at POL and SAMS. In turn, collaboration between POL and NOC will lead to better ACC and MOC monitoring strategies. POL work on regional sea level change will use NOC model studies, and the NOC modelling will include an artificial 'heat flux' tracer explicitly to address the breakdown of sea level change by physical processes. SAMS new monitoring line along the Iceland-Scotland Ridge will complement the existing RAPID sections further south and west. This integrated approach will provide a much fuller description and understanding of the pole-to-pole MOC and its role in the Earth system than would have been possible through separate research efforts.

Synergies with other Themes in Oceans 2025 are shown in Table 1. All three Centres also have extensive relevant national and international collaborations and partnerships, including involvement in NERC consortia, directed programmes and EU programmes (summarised in Table 2).

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

Theme 2	Observations and simulations of changes in carbon storage and transport throughout the Atlantic sector (NOC) and Arctic (SAMS-POL) will inform, and be informed by, the fieldwork and process modelling proposed in Theme 2 ("Marine biogeochemical cycles") which in particular will address the storage of carbon by the biological pump.
Theme 3	Studies of changes in mean sea levels take place alongside those of higher frequency sea level variability and extreme events (tides, surges, tsunamis etc.) included in Theme 3. Changes in the large-scale ocean carbon cycle (NOC) and the development of coupled physical-biological modelling for the Arctic (SAMS and POL) are linked to the shelf-sea modelling component of Theme 3 ("Shelf and coastal processes").
Theme 5	Observations of mixing in the Southern Ocean and the use of new observations to develop and improve mixing parameterisations in ocean models (NOC) is linked to the parts of Theme 5 which address mixing associated with submarine canyons on the continental slope. Predictions of future changes in clathrate stability in a warming ocean (NOC) is linked with the "Continental margins" component of Theme 5.
Theme 8	Theme 1 will inform and benefit from "Technology Development", directly through improvements in telemetry, and indirectly through the contribution of Theme 8 to the SO components of Theme 10. Development of communication and control system for *Nörrona.*
Theme 9	The large-scale ocean and coupled models required in Theme 1 (eg for the NOC contribution) are being developed in "Next Generation Ocean Prediction Systems". A suite of model experiments has been agreed between Themes 1 and 9, and the observations and analyses of Theme 1 will feed back into the development of the models in Theme 9. The global NEMO model will provide context for the Arctic model (SAMS).
Theme 10	SO 1: Observations of physical and biogeochemical properties on the Atlantic Meridional Transect will complement the NOC observations in Theme 1, providing a composite dataset which will be used to evaluate NOC global model simulations in the Atlantic sector.
	SO 3: The RAPID arrays, which include the 26.5°N array and the WAVE array, will supply data on the state of the Atlantic MOC to NOC (WP1.2) and POL (WP1.7). SO 4: Reoccupations of the Ellett line will provide the data needed to further establish variability of the northern limb of the MOC (SAMS, WP 1.5). SO 5: Measurements by Argo profiling floats will be used by NOC to develop new circulation schemes and property budgets for the subpolar gyre (WP1.2b) and the Southern Ocean (WP1.3a); Argo will provide critical

	estimates of upper ocean variability to inform interpretation and analysis of one-time sections, and SAMS (WP1.5) to estimate Atlantic Water inflow to the Nordic Seas. SO 6: Annual observations of ACC transports and properties in Drake Passage will be used by NOC to evaluate variability (WP1.3) and by POL (WP1.7) to improve ACC monitoring strategies. SO 7: UK GLOSS will inform work on changing sea level (POL, WP1.9). SO 9: Observations from voluntary observing ships and satellite data will improve estimated surface fluxes used by NOC (WP1.1). SO 13: Observations from the Arctic Shelf Time Series will supply data on long-term changes in sea ice and water column variables in Arctic shelf waters, SAMS (WP1.6) and POL (WP1.8).
NF 1 BODC	Use of archived data, provides long-term data archive throughout Theme 1; critical support for quality control of Argo data in SO 5
NF 2 PSMSL	The POL sea level work critically depends on the availability of long time series of sea level change from the PSMSL .

Table 2. Main existing science collaborations between Theme 1 and other research groups (UK and international) not part of Oceans 2025

UK Institution	Collaboration (identifying related WPs)
BAS	ACC monitoring, property budgets in Atlantic sector of Southern Ocean, Antarctic climate change, IPY CAME-ASBO Consortium; UK DIMES partners; Biogeochemical long-term monitoring in polar coastal waters; WAVE MOC monitoring, Antarctic sea level changes, International IPY GLOSS programme. (WP1.3, WP1.7, WP1.9)
FRS, Aberdeen	CTD and moored ADCP data in the Färoe-Shetland channel; Norrona stakeholder (WP1.5)
Hadley Centre/ UK Met Office	NEMO modelling (physics & biogeochemistry), RAPID model intercomparison, CHIME model, decadal MOC forecasting, probabilistic forecasting with complex models; UK Argo expert group; Evaluation of decadal variability in HADCM3 and successor models by comparison with observations; IPY CAME-ASBO Consortium; Global sea level variability. (all WPs)
Univ Cambridge	Sea ice thickness data (from underwater vehicles); Development of algorithms for extraction of sea ice parameters from satellite data. (WP1.6)
Univ. College London	NERC IPY ASBO Consortium, RAPID “ARTHER” project (both with UCL–CPOM), Hydrographic datums (WP1.2, WP1.7)
Univ. of Durham	RAPID model intercomparison, RCUK programme “Managing Uncertainty in Complex Models”; Geological sea level studies. (WP1.4, WP1.9)
Univ. of East Anglia	36°N Consortium project, GENIE, Tyndall Centre, RAPID “ARTHER” project, CASIX partner; SOLAS projects DOGEE and HiWASE; 26N Carbon budget; UK DIMES; analysis of Drake Passage repeat hydro data. (WP1.2, WP1.3, WP1.4, WP1.5, WP1.6, WP1.8)
Univ. of Edinburgh	CASIX partner; Benthic process studies & modelling of carbon burial efficiency; (Edinburgh Earth Observatory); Development of algorithms for sea ice parameters from satellite data. (WP1.6)
Univ. of Liverpool	36°N Consortium project; Dissolved organic nutrients at 26N; WAVE MOC monitoring and interpretation; geological sea level studies (WP1.2, WP1.3, WP1.7, WP1.9)
Univ. of Newcastle	SOLAS project DOGEE, earth loading, altimetry, space gravity (WP1.2, WP1.3, WP1.9)
Univ. of Nottingham	Vertical land movements (GPS, DORIS) (WP1.5)
Univ. of Plymouth	CASIX partner, Sea level change studies (WP1.2, WP1.3, WP1.7)
Univ. of Reading	RAPID model intercomparison, decadal forecasting of the MOC with coupled models, IPY CAME-ASBO Consortium; Methods for assimilation of Argo data, WAVE MOC monitoring and interpretation, GOCE satellite gravity and oceanography (WP1.1 - WP1.8)
Univ. of Sheffield	RAPID model intercomparison, RCUK basic technology programme Managing Uncertainty in Complex Models (WP1.4)
Univ. of Southampton	UK DIMES experiment, GENIE, Tyndall Centre, Spatio-temporal modelling of ARGO data (WP1.1 - 1.4)
Univ. of St Andrews	Oxygen isotope and foraminiferal analyses; zooplankton acoustics; microfossil geochemistry and assemblages. (WP1.5, WP1.6)
Univ. of Wales, Bangor	IPY CAME-ASBO Consortium; Turbulence measurements , collaborative sea-ice research (WP1.6)

Consortia/IPY Clusters (national and international)

ArcOD	Arctic Ocean Diversity (IPY cluster) (WP1.6)
ATMOPOL	IPY initiative focusing on multi-national co-ordination of atmospheric contaminant monitoring in Polar Regions. (WP1.6)

Baffin-Labrador Ecosystem Impacts	Climate Change Impacts on Marine Ecosystems in the Baffin-Labrador Region (Canadian IPY proposal - Erica Head) (WP1.6)
CAME-ASBO	IPY Consortium Project (WP1.2)
CASIX	Centre for Air Sea Interaction and Fluxes (WP1.2, WP1.3)
CoAAT (Norway)	Norwegian IPY consortium investigating Atlantic Water inflows (WP1.5)
DAMOCLES	Integrated EU programme with 47 partners from Various EU countries Identifying changing sea ice and physical oceanography in the Arctic Seas (WP1.6)
ESSAR	Ecosystem Studies in Arctic Regions (IPY cluster) (WP1.6)
EUROCLIM	Maintenance of sea ice database for climate studies as part of EUROCLIM consortium. (WP1.6)
GENIE	Grid Enabled Integrated Earth System Model (NERC Consortium) (WP1.4)
PAM-AME	The pan Arctic cluster for climate forcing of the Arctic marine ecosystem (IPY cluster led by Norwegian Polar Institute, University Manitoba and SAMS) (WP1.6)
PAME	Polar Aquatice Microbial Ecosystems (IPY cluster led by Univ. of Bergen and SAMS) (WP1.6)
QUEST/MARQUEST	Use and extension of QUEST model deliverables (WP1.4, WP1.5, WP1.6)
RAPID Monitoring	Consortium includes MPI (Hamburg), WHOI, NOAA/AOML, Univ. Miami. (WP1.2, WP1.7)
Tyndall Centre	UK Climate Impacts/mitigation consortium (WP1.4)

Additional links include those with groups in the Alfred Wegner Institute, Bedford Institute of Oceanography, Bjerknes Centre for Climate Research, CSIRO (Australia), ESA, Färoese Fisheries Laboratory, Geophysics Institute (Bergen), Geological Survey of Norway, IFREMER (Brest), Institute of Marine Research (Bergen), IOS (Canada), JAMSTEC, LODyC (Paris), Norwegian Polar Inst., Ohio State University, UNIS Svalbard, the University of Tromsø, and WHOI.

Theme-wide stakeholder relevance and Knowledge Transfer activities

Stakeholder relevance and Knowledge Transfer are built-in to the Oceans 2025 programme: all the Marine Centres involved have obtained, and will continue to obtain, both private sector and governmental funding for applied research that meets specific research-user needs. Such commissioned research is not presented here; nevertheless, it is the direct consequence of previous NERC strategic funding, and Oceans 2025 will provide the underpinning capabilities, expertise and facilities to continue to make that possible, whilst also itself delivering data, information and understanding directed at ‘real time’ national needs. In preparing Theme 1, major stakeholders were consulted, and many components have involved additional discussions with research users.

The information generated by Theme 1 will be of direct relevance to UK (and global) climate change programmes, policy makers, government departments, NGOs and the public. The main international outlet for knowledge generated in this sub-theme will be refereed papers in the scientific literature. These will be targeted on questions relevant to the IPCC, and we anticipate a significant contribution to the IPCC 5th Assessment Report. Globally, this constitutes the main forum for provision to governments of scientific advice on matters of climate change. Likewise our results will inform UK policy makers in preparing for the future consequences of climate change.

Stakeholders in this category are science-user interfaces such as UKCIP, the newly formed MCCIP, government departments such as Defra and, in the academic community, the Tyndall Centre. A key stakeholder concern in recent years, addressed within Theme 1, is likelihood and magnitude of future abrupt THC-related climate change. Our links with the Hadley Centre (which has been consulted during the writing process) will ensure that our results are used to improve their predictions of future climate . A further example is the use of improved predictions of sea level rise to help Defra, the Environment Agency, the Northern Ireland Rivers Agency, and Scottish Water to plan flood defences. The modelling of tides and storm surges, and coastal flooding (in Theme 3), and the NTSLF, are inter-related with the sea level work in this theme. The work will also help underpin the NERC FREE programme.

We will feed Theme 1 science into society via enhanced appreciation by the public and NGOs of the role of the oceans in climate change. This will include dissemination of our findings through media, public lectures, open days and schools. We will also assist our university partners in training the next generation of scientists via taught courses and postgraduate research degrees.

Theme 1 will hold annual workshops which will circulate amongst the three laboratories. In addition two open workshops, specifically targeted at stakeholders (Hadley Centre, FRS, Defra), will be held in 2010 and 2012.

Strategic Ocean Funding Initiative (SOFI)

Up to 10% of the research 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). SOFI opportunities that have been identified for Theme 1 are shown in Table 3. These are areas where the Centres could benefit from expertise which exists in the UK academic community.

***Table 3**. SOFI opportunities identified in Theme 1.*

WP	Opportunity
1.2, 1.3	Measurements of additional hydrographic and chemical variables on long hydrographic transects
1.4	Expertise in interpretation of numerical models of the atmosphere. (also links to Theme 9)
1.5	Meteorological and / or carbon flux sensors on board *MS Nörrona*
1.5	Oxygen isotopes as an aid to reconstructing palaeo water mass temperature and salinity
1.6	Chemical characterisation of sea ice dissolved organic material
1.6	Dissolved and particulate inorganic carbon measurements and interpretation
1.6	Sediment microbial community composition and activity
1.7	Interferometric Synthetic Aperture Radar to relate point measurements at GPS, tide gauge, or absolute gravity sites to the pattern of local land deformation.
1.7	To enable application of geodetic capability to the sea level question
1.9	Collaboration on various applications of granular flow research.

Consolidated fieldwork

NOC proposes three cruises in 2008. The Arctic Gateway cruise is a section across the Atlantic at about 55°N. The Southern Ocean/South Atlantic experiment comprises a trans-Atlantic section at 30°S (repeat of WOCE A10) and an occupation across the Drake Passage (WOCE A21). These should be carried out at the same time as a US section from South Africa to the Antarctic continent at 30°E. Coordination with the Spanish re-occupation of WOCE A11 (around 45°S) is less critical.

SAMS (WP1.6) proposes two 4-5 week research cruises in the Arctic north of Svalbard, during summer (June-August) of 2007 and 2009, eg using *RRS James Clark Ross.* These cruises will be and closely co-ordinated with other IPY Arctic cruises, and one will be jointly with POL (WP1.8). SAMS (WP1.5b) propose to undertake piston coring across established hydrographic sections such as the Extended Ellett line, in 2007/08 and possibly also in 2009/10. Over 2007-2010, SAMS (WP1.5c) propose to install a Ferrybox system on the *MS Norröna*, to monitor the flux of the MOC across the Iceland - Scotland Ridge.

POL (WP1.8) proposes to participate on one of the SAMS cruises, in the area of Storfjord, to observe mixing of dense waters formed in the fjord's polynya and their contribution to oceanic overturning.

Note that some of the Theme 1 activities proposed by NOC and POL depend on fieldwork funded under Theme 10: re-occupation of the Atlantic 26°N section and maintenance of the MOC and WAVE arrays (SO 3); annual repeated measurements in Drake Passage (SO 6); Arctic shelf time series measurements (SO 13).

Summary of Theme-wide outcomes

Relating back to the three cross-cutting issues identified in the Introduction, the main Theme 1 outcomes are expected to be as follows:

Issue 1: The Atlantic and Southern Oceans in a changing climate

- Pole-to-pole descriptions of the size, structure and recent variability of the Atlantic MOC and definition of an optimal monitoring strategy (NOC, POL, SAMS).
- Explanation of the extent to which changes in the state of the North Atlantic and Southern Oceans over the last 50 years are due to changes in air-sea fluxes (NOC).
- Inverse method estimates of Southern Ocean property (heat, freshwater and carbon) budgets and an optimal monitoring strategy for the ACC (NOC, POL).
- New estimates of mixing rates in the Southern Ocean and more accurate mixing parameterisations for use in ocean and climate models (NOC).
- High resolution records of change at ocean margins and shelves in the northern North Atlantic during the late Quaternary (SAMS).
- Model-based risk assessments of future MOC shutdown, major changes of ocean CO_2 uptake, and hydrate instability, leading to reduced uncertainty and more effective monitoring of these elements of the earth system (NOC, SAMS).

Issue 2: Arctic and Boreal Seas

- An integrated understanding and ability to predict the effects of climate change on Arctic ecosystems and biogenic carbon flux , achieved via international collaboration within the context of IPY (SAMS, POL).
- Determination of the sensitivity of the Arctic Ocean to polynya formation and downslope flows (SAMS, POL).
- Determination of the causes of Arctic sea level variability (POL).

Issue 3: Sea level change, including geodesy and geophysics

- Determination of the causes of global and regional sea level change and vertical land movement (POL).
- The definitive map of vertical land movement in the UK (POL).
- An extended historical tide gauge record (POL).
- Tests of the realism of climate model predictions of sea level change (POL).

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Acronyms

ACC	Antarctic Circumpolar Current
ACIA	Arctic Climate Impact Assessment
ADCP	Acoustic Doppler Current Profiler
ALOS	Advanced Land Observing Satellite
AMSR-E	Advanced Microwave Scanning Radiometer for EOS
AOML	Atlantic Oceanographic and Atmospheric Lab.
ARGO	The international profiling float programme
ARTHER	Arctic Regulation of the Thermohaline Circulation
ASBO	Arctic Synoptic Basin-wide Oceanography
ASOF	Arctic SubArctic Ocean Fluxes
BAS	British Antarctic Survey (NERC)
BODC	British Oceanographic Data Centre
BIO	Bedford Institute of Oceanography (Canada)
BPR	Bottom Pressure Recorder
CAME	Canadian Arctic Margin Expedition
CARE	Climate of the Arctic and its Role for Europe
CASIX	Centre for Air Sea Interaction and Fluxes
CEH	Centre for Ecology and Hydrology (NERC)
CFC	Chloro-Fluro Carbons
CFL	Circumpolar Flaw Lead System project
CHIME	Coupled Hadley-Isopycnic Model Experiment
CICE	The Los Alamos Sea Ice model
CLIVAR	International research programme addressing climate variability
CMIP	Coupled Model Intercomparison Project
CSIRO	Australian National Research Organisation
CTD	Conductivity, Temperature and Depth
DAMOCLES	Developing Arctic Modelling and Observing Capabilities for Longterm Environmental Studies
Defra	Department for the Environment and Rural Affairs
DMS	Dimethylsulphoxide
DOC	Dissolved Organic Carbon
DON	Dissolved Organic Nitrogen
DIMES	Diapycnal and Isopycnal Mixing Experiment in the Southern Ocean
DOGEE	Deep Ocean Gas Exchange Experiment (SOLAS)
DORIS	Doppler Orbitography and Radio-positioning Integrated by Satellite
DP	Drake Passage
DWBC	Deep Western Boundary Current
ECMWF	European Centre for Medium Range Weather Forecasting
ENAM	European North Atlantic Margin
ERA40	ECMWF reanalysis
ERSEM	European Regional Seas Ecosystem Model
ESA	European Space Agency
FFL	Färoese Fisheries Laboratory
FREE	Flood Risk from Extreme Events
FRS	Fisheries Research Services (Aberdeen)
GALILEO	European GPS type system
GCOS	Global Coastal Observing System
GENIE	Grid Enabled Integrated Earth System Model
GGOS	Global Geodetic Observing System
GIN	Greenland Iceland Norway (Sea)
GLOSS	Global Sea Level Observing System
GOCE	Gravity and Ocean Circulation Explorer
GOOS	Global Ocean Observing System
GPS	Global Positioning System
GRACE	Gravity Recovery and Climate Experiment
GSN	Geological Survey of Norway
GSR	Greenland-Scotland Ridge
HADCM3	Hadley Climate Model 3
HiWASE	High Wind Air-Sea Exchanges (SOLAS
HOPE-C	Hamburg Ocean Primitive Equation model (C-grid)
HYCOM	Hybrid Coordinate Ocean Model
IAOOS	integrated Arctic Ocean Observing System
IFREMER	Inst Français de Recherche pour l'Exploitation de la Mer
IMR	Institute of Marine Research, Bergen
InSAR	Interferometric Synthetic Aperture Radar
IOS	Institute of Ocean Sciences (Canada)
IPCC	Intergovernmental Panel on Climate Change
IPY	International Polar Year
JAMSTEC	Japan Marine Science and Technology Center
LADCP	Lowered acoustic doppler current profiler
LFI	Land Fast Ice
LNADW	Lower North Atlantic deep water
LODyC	Laboratoire d'Océanographie Dynamique et de Climatologie, France
MARQUEST	Marine Biogeochemistry and Ecosystem Modelling (QUEST Consortium)
MCCIP	Marine Climate Change Impacts Programme
MICOM	Miami Isopycnic-Coordinate Ocean Model
MOC	Meridional Overturning Circulation
MODIS	Moderate Resolution Imaging Spectroradiometer
MOEN	Meridional Overturning Exchange with Nordic Seas
MPI	Max Planck Institut, Hamburg
NAO	North Atlantic Oscillation
NCAR	National Center For Atmospheric Research
NCEP	National Center For Environmental Prediction
NCOF	National Centre For Ocean Forecasting
NEMO	Nucleus European Model Ocean
NERC	Natural Environment Research Council
NIOZ	Netherlands Institute for Sea Research
NOAA	National Oceanic Atmospheric Admin. (US)
NOC	National Oceanography Centre, Southampton
NORPAST-2	Past Climates of the Norwegian Region
NPS	Naval Postgraduate School
NTSLF	National Tidal and Sea Level Facility
OAFlux	An ocean-atmosphere flux product from WHOI
OCCAM	Ocean Circulation and Climate Advanced Model
PALSAR	Phased Array L-band Synthetic Aperture Radar
PAR	Photosynthetically Available Radiation
POC	Particulate Organic Carbon
POL	Proudman Oceanographic Laboratory
POLCOMS	POL Coastal Ocean Modelling System
PON	Particulate Organic Nitrogen
PSMSL	Permanent Service for Mean Sea Level
QUEST	Quantifying and Understanding the Earth System
RAPID	NERC rapid climate change programme
RAPID-MOC	The 26°N RAPID monitoring array (SO2)
RCC	Rapid Climate Change
RCUK	Research Councils UK
SAMS	Scottish Association for Marine Science
SBE21	Seabird Electronics Inc. thermosalinograph
SEASAW	Sea Spray, Gas Fluxes and Whitecaps (SOLAS)
SMOS	Soil Moisture and Ocean Salinity (satellite)
SOC	Southampton Oceanography Centre (now NOC)
SOES	School of Ocean and Earth Sciences, NOC
SOFI	Strategic Ocean Funding Initiative
SOLAS	Surface Ocean - Lower Atmosphere Study
SAR	Synthetic Aperture Rada
SSM/I	Special Sensor Microwave/Imager
SSMIS	Special Sensor Microwave Imager/Sounder
STRATAGEM	Stratigraphic Development of the Glaciated European Margin
TAR	Third Assessment Report
THC	Thermohaline Circulation
TIC	Total Inorganic Carbon
TOPEX	Altimetric Satellite mission
UCL	University College, London
UKCIP	UK Climate Impacts Programme
ULS	Upward-Looking Sonar
URI	University of Rhode Island, New York
WAVE	Western Atlantic Variability Experiment
WCRP	World Climate Research Programme
WHOI	Woods Hole Oceanographic Institute
WOCE	World Ocean Circulation Experiment