Proposal for a Thematic Programme:

Abrupt Climate Change and the Stability of the Thermohaline Circulation

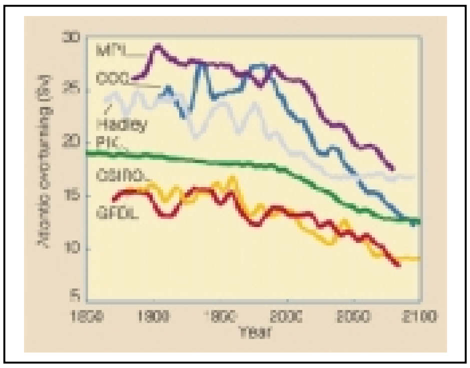
J. Marotzke, R. Dickson, J. Slingo, A. Watson, R. Wood, and members of a Working Group

SUMMARY

Ocean-atmosphere interactions in the North Atlantic are responsible for heat transports that keep the UK 5-10°C warmer than it would otherwise be. This is caused by the ocean's thermohaline circulation (THC), driven by temperature and salinity differences. However, existing THC patterns might not continue: climate models suggest that the increasing atmospheric greenhouse-gas burden could dramatically weaken the THC and associated circulation systems within a few decades. Furthermore, palaeo-data indicate large and rapid variability in North Atlantic THC strength during the past 20,000 years, and recent observations on the extent and thickness of Arctic sea-ice show that a new regime shift may already be underway. This observation-based programme will investigate the dynamics and sensitivity of the North Atlantic THC, and the climatic consequences of potential changes. It will focus on delivering: (i) the establishment of efficient and cost-effective systems for detecting and quantifying THC change; (ii) the identification of the main northern high-latitude drivers of the THC; (iii) an improved fundamental understanding of interactions of THC dynamics with the atmosphere and cryosphere; (iv) quantitative palaeo-estimates of past THC changes; (v) advances in conceptual understanding of the THC. Models are essential to the programme: they will be used to investigate mechanisms controlling the strength of the THC; to provide scenarios for risk assessment of the impact of THC changes on climate; to synthesise field data; and to assist the design of programme field work and longer-term observational strategies. The proposed programme builds on the existing strengths of the UK community in oceanographic research and climate modelling, and will be tied closely to related international efforts. In particular, it will provide the main UK contribution to a collaboration with Norway on high-latitude ocean and climate research encouraged by the Prime Ministers of both countries (Wadhams and Nicholls, 1999). NERC support required is £16.9m over 5 years. A key overall deliverable would be the identification of the critical observations that would eventually need to be part of a quasi-operational observing system. Moreover, this programme would produce recommendations for future climate model development, to increase confidence in projections of THC and climate change.

Background

Annual-mean air temperatures over the northern North Atlantic and western Europe are considerably higher than elsewhere at the same latitude. This is due to a complex ocean-atmosphere interaction, which includes the vast amount of heat (about 10^{15} W) carried northward by the THC. The THC consists of deep convection induced by surface cooling at high latitudes, sinking to depth, and upwelling of deep waters at lower latitudes, with horizontal shallow and deep currents feeding these vertical flows. The deep convection and sinking in the North Atlantic (in the Labrador and Greenland Seas) have no counterpart in the North Pacific Ocean, where northward heat transport is consequently much weaker. However, the Atlantic THC has not always been like today's. Palaeoclimate records prove that massive and abrupt climate change has occurred in the Northern Hemisphere, especially during and just after the last Ice Age (Broecker and Denton, 1989, Dansgaard et al., 1993), with THC change as the most plausible driver. Simple conceptual models explain the basic mechanism behind such change (Stommel, 1961). Similar change might occur in the future. Model results suggest that the human-induced increase in the atmospheric concentration of CO_2 and other greenhouse gases will lead to a dramatic reduction in THC strength in the Atlantic (e.g., Manabe and Stouffer, 1993; Wood et al., 1999), which will modify substantially the projected rate of climate change over western Europe. Furthermore, it is possible that the changes in the strength of the THC will occur rapidly, perhaps over just 10-20 years. Such large, fast climate change (hereafter, 'abrupt climate change') would make adaptation to, and mitigation of, the impacts exceedingly difficult for the affected countries. Therefore, the probability of such changes must be assessed. However, while most climate models indicate that there will be THC weakening, there is considerable spread between their projections (see inset, from Rahmstorf, 1999, showing THC strength as simulated by various climate research centres around the world), and at least one model shows no change at all (Latif et al., 2000; not shown in inset). Hence, the climate research communities, both oceanographic and atmospheric, are faced with both a challenge and an opportunity. There is a risk that the Atlantic THC will undergo changes that will result in substantial and rapid climate change for western Europe, but we cannot reliably quantify this risk.



The critical knowledge gaps

Our current knowledge is insufficient to determine the likelihood of abrupt climate change, or even to answer some simple questions with confidence. For example, why was the THC in glacial times apparently subject to large instabilities, but in the present interglacial has been considerably more stable? Did the giant ice sheets dramatically amplify a climate signal that has persisted into the interglacial, but at a suppressed amplitude? Or does the relative quiescence of the present interglacial primarily result from a change in the atmospheric forcing applied to the ocean, or perhaps a change in ocean processes, the nature of which may have altered because of decreased sea ice coverage or a higher sea level? First-order advances are needed. In particular;

- Present observations of the THC are insufficient to detect whether it is changing. Thus a significant weakening of the THC may already be in progress, unnoticed. However, there is clear evidence of long-term hydrographic changes in the deep northern overflows (which help to drive the THC) and the Labrador Sea; potential early warning signs.
- Changes in strength and structure of the THC are forced by the atmosphere, especially the strength and location of the storm track. We do not know with any certainty how climate change will affect the heat and freshwater budgets associated with the storm tracks, although we already know that the recent trend towards positive North Atlantic Oscillation (NAO) states has had a substantial effect (Dickson et al., 2000).
- The mechanisms believed to control the strength of the THC include: the northward flux of warm and salty Atlantic surface water; the freshwater flux out of the Arctic; the speed and density of the deep overflows crossing the Greenland-Scotland Ridge; open-ocean convection; mixing near the ocean margins, including the sea surface; ice-ocean and atmosphere-ocean interactions; freshwater input from the atmosphere and rivers. These processes and transports are poorly observed and understood, and are only crudely represented in the present generation of climate models.
- Though a range of climate models suggests that greenhouse warming can lead to THC weakening, these models all have relatively crude spatial resolution in their oceanic components. It has never been demonstrated that the THC can undergo dramatic weakening in ocean climate models of the resolution and sophistication that we believe are needed to reproduce quantitatively observed features of ocean circulation, such as the narrowness of fronts and boundary currents.
- While key processes controlling THC response in models are beginning to be identified (e.g., freshwater transport into the North Atlantic), few observationally-based constraints are available against which those model processes can be tested.
- Possible impacts of rapid changes in the THC on the climate of western Europe are not known with confidence.

Scientific objectives

The programme would be devoted to observing the time evolution of the THC, to understanding what factors might change the THC, and to assessing the climatic consequences of such changes. The aim would be to quantify under what conditions a weakening of the THC would occur, as an essential precursor to predicting *when* this may happen. Observations will be provided that are crucial for testing simulations of THC strength and climate change. The programme's main objectives are:

1) To establish a system to continuously observe the strength and structure of the THC.
2) To obtain long-term direct observations of water, heat, salt, and ice transports at critical locations in the northern North Atlantic, using efficient and cost-effective systems; and to quantify the atmospheric inputs to these transports.
3) To perform process studies of mixing at northern high latitudes.
4) To study the formation and transport of sea ice in and through the regions critical for THC dynamics.
5) To develop and use high-resolution regional models to synthesise the observational data.
6) To apply a hierarchy of modelling approaches towards understanding the processes that connect changes in ocean convection and its atmospheric forcing to the large-scale transports relevant to the modulation of climate.
7) To investigate, using model experimentation, the atmosphere's response to large changes in Atlantic northward heat transport, in particular changes in storm track, storm frequency, storm strengths, and energy and moisture transports.
8) To use palaeo-proxies for quantitative model-testing and to explore the extent to which palaeo-data can provide direct information about the THC.

The linkages between these objectives arise as follows. The THC is the central phenomenon whose strength and structure ultimately must be predicted, and hence must be continuously observed (1). Heat and water fluxes in the Nordic Seas (2) are powerful influences on the THC. Mixing processes (3) are crucial in establishing how these fluxes interact with each other and the large-scale flow. Sea ice is critical for the water budget in the Nordic Seas and has undergone recent dramatic change (4). New modelling approaches are needed to synthesise all these observations and processes (5). The high-latitude processes must be linked dynamically to the THC strength – combining (1) with (2) – (5); however, this programme could not muster the resources to collect the new observations needed to firmly establish these connections. But the programme will support modelling studies and 'data mining' that could suggest pathways for these poorly known linkages (6). Objectives (1) – (6) are strongly focused on observations and processes in the present ocean. Objective (7) connects these ocean processes to the response of the atmosphere, assuming that the THC could indeed weaken dramatically (7); apart from sea level change, it is mostly atmospheric processes that *directly* influence societies. As large, abrupt climate change did not occur during the era of instrumental records, models must be tested against quantitative palaeo-evidence of past abrupt changes in climate and the THC (8). These individual objectives and indications of their feasibility are now discussed one by one.

1) Observing the THC overturning rate:

The stability of the THC and its role in abrupt climate change are the defining characteristics of this programme. If we are to develop predictive capabilities for the THC, we must observe its strength and structure as a fundamental requirement, akin to the necessity to observe the equatorial Pacific if one wants to forecast El Niño. It is the ocean heat transport (and hence the THC) around 25°-35°N that is most relevant for western European climate, because much of this heat is given off to the atmosphere between 35° and 50°N, from where it is transported north-eastward toward Europe by the atmosphere. The strategy for observing the THC relies on dynamic height considerations: mass transport between any two points depends only on the pressure difference between these points. The meridional mass transport across the entire Atlantic, as a function of depth, is a reasonable working definition for the THC. Estimating the THC thus would require the continuous observation of density and pressure at eastern and western boundaries of an east-west section. Simple and straightforward as this idea might be, it has been implemented to limited extent only (Whitworth, 1983; Lynch-Stieglitz et al., 1999). Marotzke et al. (1999) tested this idea in their general circulation model (GCM), while Kanzow (2000) performed array design studies for moorings dedicated to monitoring integrated transports in the western North Atlantic.

We propose that this thematic programme supports a continuous THC observing array near the heat transport maximum of the THC. One choice of latitude might be 25°N, which has the advantage that the western boundary current (flow through Florida Strait) can be measured relatively straightforwardly by cable (existing long-term programme by the US, e.g., Larsen, 1992) and regular calibration cruises. This would leave observing the relatively quiescent interior section, to be accomplished with a series of moorings on the western end, off the very steep drop east of the Bahamas, and on the more gently sloping eastern end. Which mooring design should be applied depends in part on emerging technological developments. A tall mooring should be equipped with a CTD-acoustic current measurement profiler, taking roughly one profile per day. This technology appears to just have reached maturity (J. Toole, 2000, pers. comm.). On either end, several of these moorings, over differing water depths, would be required. In addition, a significantly greater number of (much cheaper) moorings could be deployed with CTD, pressure sensors, and current meters only close to the (sloping) bottom, allowing estimation of near-bottom flows and non-geostrophic eddy-noise in the density field. The pressure sensors and current meters would give added information for estimating the part of the flow that is not in thermal wind balance but is instead dominated by high-frequency barotropic dynamics (e.g., Lee and Marotzke, 1998). To test the boundary array, two ship-based transoceanic sections would be required, toward the beginning and the end of the deployment period.

2) Long-term transport observations at high latitudes:

Observing change in the THC overturning rate is an essential foundation, but not the whole requirement. If our models are to be developed to the point of predicting such changes – and if we are ultimately to mitigate their socio-economic impacts on an appropriately regional basis – we need to learn more about which upstream processes and regions are the source of the observed changes. Present-day observations show significant decadal changes in the temperature of the warm Atlantic currents flowing towards the Arctic Ocean and in the outflows of freshwater and ice from the Arctic Ocean. Both of these recent changes have been observed to affect the characteristics of the cold deep overflows which cross the Greenland-Scotland Ridge southwards to “drive” the THC. Further, the modelling effort in support of the recent EC-VEINS Project indicates that an increase in the southward flux of freshwater through Fram Strait is able, in a few years, to reduce the intensity of the THC in the North Atlantic. However, models are not necessarily reliable, since we have no direct measurements of some of the key ocean fluxes involved including the net poleward flux of heat and salt to the Arctic Ocean through the three main gateways (Fram Strait, Barents Sea and Bering Strait) and the net equatorward flux of ice and freshwater through its two main pathways (southward along the East Greenland shelf and through the Canadian Arctic Archipelago). Model improvement depends on obtaining these measurements, and on doing so over a long enough period to capture their variability. Since the most advanced models now suggest that certain of the ocean fluxes at different Arctic gateways may be linked in their time-dependence, these measurements ultimately need to be made simultaneously and for a long time (1-2 decades).

Measurement techniques now exist to cover all the necessary components of the problem. Some, such as the speed and hydrographic character of the deep northern overflows are now routinely covered by conventional instruments. These may simply require the funding to continue present efforts, which are affected by termination and losses. For others, such as the sub-ice systems designed to measure and partition the ice and freshwater fluxes leaving Fram Strait, modern techniques exist but are expensive and/or unproven. Although the measurement of all key fluxes affecting the THC will need to be an international effort (with contributions from the US, Canada, Norway, among others, expected), the UK already has experience and lead-expertise in several key components. Examples are *inter alia*, long-term observations of the deep northern overflows (CEFAS and FRS, Aberdeen), novel moored profiling techniques for sub-ice hydrography (POL), novel techniques in tracer chemistry (UEA, PML, SOC), multi-decadal time series on Atlantic hydrography (FRS), sub-ice water mass-following capability using AUTOSUB (SOC), and the dynamics and climatic consequences of sea-ice variability in the Greenland Sea (SPRI). These examples are illustrative only and are not intended to be exclusive.

It may prove difficult to partition the upstream influences on the THC of all heat, ice, and freshwater fluxes into their separate components in a quantitative way, but establishing their relative importance is crucial. Many of the transformation processes at high latitudes take place at small spatial scales, but the integral properties of the mixing probably depend on regional scale patterns of surface buoyancy flux and on the underlying stratification. Hence there is a need to determine the heat and water budgets (mean and variability); of necessity, this programme must concentrate on the Nordic Seas, while attempting a budget for the Labrador Sea would not be realistic. Establishing budgets would involve all the direct measurements in the Nordic Seas, including the mixing processes discussed in section 3, and the model-data synthesis efforts detailed in section 4.

3) Mixing processes at northern high latitudes:

Mixing processes such as convective and non-convective vertical mixing, interaction with topography (boundary mixing), sea-ice interactions, and the dynamics of overflows are known to be important for the THC but are poorly understood. These processes all have short space and time scales, making it impossible to model them from first principles in coupled GCMs. The effects of these processes must be parameterised, but only if the process is well understood does this approach have predictive skill. Without proper understanding, the parameterisation simulates the present state, but not the response to forcing changes.

We still do not know much about the location of small-scale stirring in the ocean interior, but measurements (Ledwell et al. 2000, Polzin et al., 1997) and theory (Munk and Wunsch, 1998) suggest that interactions with rough boundaries dominate. Vertical mixing is expected to stimulate the THC, (Bryan, 1987), but the implications of mixing occurring mostly at boundaries has only begun to be explored (Marotzke, 1997). Thus for example, the present generation of ocean GCMs frequently do not simulate well the properties of North Atlantic Deep Water (NADW). The main reason for this is that interaction with the boundaries and entrainment of surrounding water at the overflows is impossible to model from hydrodynamic principles except at very fine resolution. Confidence in predictions of how NADW may change in the future, or has changed in the past, is therefore low. Recent measurements indicate a surprisingly large non-convective vertical mixing rate in the Greenland Sea (Watson et al., 1999). Again, the reason is unknown, but disturbances generated by topographic interactions are likely candidates. Deep convection in the Labrador and Greenland Seas varies from year to year and decadally, possibly in response to the NAO (Dickson et al., 2000). Labrador Sea convection is responsible for the formation of a major cold water mass in the North Atlantic, and it seems very likely that change in the rates of convection there, if sustained for decades, will affect the character of the THC. Convection in the Greenland Sea presumably influences the character of the Denmark Strait overflow water, and is itself influenced by ice flux and ice melt coming from the Arctic Ocean.

We propose that the new programme should support experiments to increase the understanding of the key mixing processes in the Nordic Seas, such as convective and non-convective mixing, and their influence on the circulation in the Nordic Seas and the overflows. Tracer and direct turbulence measurements are powerful and mutually supporting techniques for this.

4) Sea ice formation and transport:

Arctic sea ice volume has shrunk dramatically over the past decades (Vinnikov et al., 1999; Johannessen et al., 1999; Rothrock et al., 1999). The influence of this decline on the freshwater budget of the Nordic Seas is unknown but may be critical. It is crucial to know the net freshwater flux from the Arctic Ocean to the Nordic Seas, in form of both sea ice and low-salinity surface water. The sea ice emerging from Fram Strait plays two different roles in the THC process. Ice which is transported onwards through Denmark Strait, either in frozen or melted form in the East Greenland Current, goes on to participate directly in the North Atlantic surface circulation with possible involvement in Labrador Sea convection, and may be the origin of events such as the “Great Salinity Anomaly” that have been documented in the North Atlantic (Dickson et al., 1988). Given the importance of freshwater forcing to the stability of the THC, such events might presage change in the circulation. Ice which melts within the Greenland Sea and which is transported into the central part of the gyre, for example by the Jan Mayen Current, plays a role in stimulating or suppressing local sea ice formation in the central gyre, thus affecting the winter salt flux from ice formation and the consequent vigour of convection. The influx of ice through Fram Strait into the Nordic Seas varies on interannual and decadal timescales (Kwok and Rothrock, 1999). Hence, its extent, thickness, speed and thus flux must be observed continuously. In this respect the joint use of satellite imagery (giving extent and motion field) and thickness measuring methods is vital. Thickness can be measured routinely by moored upward sonar and possibly synoptically by anticipated new satellite techniques such as radar or laser altimetry.

5) Regional model-data synthesis:

Even the most intensive observational campaign in oceanography provides insufficient sampling to extract all the information one needs to understand processes and budgets. Observational data must be augmented with information from numerical models, which express the conservation laws governing ocean circulation. This programme will support work that provides model-data syntheses based on the intensive field campaigns. The emphasis should be on regional models with high spatial resolution. Although the basic principles are relatively well understood (Bennett, 1992; Wunsch, 1996), and mesoscale ice-ocean models have been developed (e.g. Backhaus and Kämpf, 1999), data assimilation of this type has not been performed routinely. For example, the largely North American Labrador Sea Deep Convection Experiment (The Lab Sea Group, 1998) had a significant modelling component, but no comprehensive model-based data synthesis has yet been performed. Hence, data from the Labrador Sea Deep Convection Experiment may well serve as a test bed for the type of synthesis envisioned here, in collaboration with PI’s from that experiment. A particularly important fundamental aspect of regional modelling arises through the need to specify lateral boundary conditions. In the data assimilation mode, these conditions can be estimated from the model and the observations. Such an approach has been implemented in a low-resolution model (Zhang and Marotzke, 1999), but considerable further exploration is required.

6) Atmospheric forcing of ocean convection, and resulting large-scale ocean transports:

Many fundamental questions remain unanswered concerning the physics that controls the stability of the THC. Coupled GCMs are useful tools to address this problem, but their computational expense limits both the physics that can be resolved and the number of sensitivity studies that can be performed. Two recent studies of the THC response to increasing atmospheric greenhouse gases in a run of the HadCM3 coupled model illustrate this. Wood et al. (1999) emphasise the importance of poorly resolved processes such as Labrador Sea convection and sill overflows in controlling the model response, whereas Thorpe et al. (2000) emphasise the importance of large scale atmospheric feedbacks (interbasin water transport) in stabilising the model THC, consistent with Latif et al. (2000). The two views are not necessarily contradictory, but the first implies a need for high resolution modelling of the overflows to assess the robustness of the HadCM3 results, whereas the second suggests a need to examine the robustness of the basin-scale processes, for which a lower resolution GCM or even more highly parameterised model might be appropriate. Particular processes which may be important include the adjustment of the THC to forcing of the deep water source (possibly in response to the NAO), through boundary waves and currents (Kawase, 1987; Marotzke and Klinger, 2000); response of the THC to variations in the two deep water sources – would both have to be switched off to trigger a significant THC weakening? (Döscher and Redler 1997); inhomogeneity of interior mixing (Polzin et al., 1997; Marotzke, 1997). Low-resolution models have been used to propose some large scale parameters which may be critical controllers of the THC and its stability, e.g. large-scale dynamic height contrasts or deep density differences between North and South Atlantic (Hughes and Weaver, 1994; Rahmstorf, 1996; Marotzke and Klinger, 2000; Thorpe et al., 2000), or the integrated fresh water budget of the Atlantic basin (Wang et al., 1999). A range of modelling approaches, of appropriate degrees of complexity, will be used to assess the robustness of such processes in the present generation of climate models.

7) Atmospheric response to massive changes in ocean heat transport:

Ultimately, it is the atmosphere's response to THC changes – changes in climate and weather patterns – that influences societies, not so much the oceanic changes themselves (with the important exceptions of sea level change and influence on ecosystems). In particular, changes in North Atlantic storm track, storm frequency, storm strengths, and energy and moisture transports are crucial for western European climate. Therefore, this programme will support studies that assess the impact of a massive THC weakening on climate. Previous work with coupled models (e.g. Manabe and Stouffer, 1988; M. Vellinga, 2000, pers. comm.) showed a large-scale cooling of the Northern Hemisphere, possible Southern Hemisphere warming, and changes to the main precipitation zones in the tropics. Low-resolution atmosphere-only GCMs have been used to study the response to large changes in North Atlantic sea surface temperature (SST, e.g., Rind et al., 1986; R. Alley et al., 2000, pers. comm.). But these results must be confirmed with higher-resolution atmospheric models, having much more realistic storm track representations, and for different scenarios (e.g., North Atlantic heat transport, rather than SST, changes).

8) Use of palaeo-proxies:

The only occurrences of abrupt climate change predated the beginnings of instrumental climate records, so our understanding must be tested against palaeo-data. A wealth of indicators of past climates exists, but a major effort is needed to confront models with these observations quantitatively. Direct palaeo-information about ocean circulations is harder to obtain but possible. The isotopic composition of foraminifera which carries a combined T/S signal has recently been used as a density proxy, and the changing slope of reconstructed isopycnals across Florida Straits shows reduced Gulf Stream flow 20,000 years ago (Lynch-Stieglitz et al., 1999). Several proxies in foraminifera relate to the nutrient content of surface and bottom waters, indicating ventilation rate when applied to deep water. Temporal changes are then related to changes in vigour of circulation. Radionuclide-based ages of deep waters may also be reconstructed for past times, another indicator of circulation strength. A direct estimate of flow speed is provided by grain size studies (McCave et al., 1995), and although this is presently not calibrated in absolute flow speed, it does reveal changes in speed consistent with other proxies (Bianchi and McCave, 1999).

The oceanic palaeo-record mostly has much lower temporal resolution than ice cores, although some records for the past 10 ka in the Norwegian Sea offer a resolution down to ~5 years, enabling changes at NAO frequencies to be detected. In addition, laminated sediments offering annual resolution occur in fjords and other restricted environments. Even though palaeo-proxy data are often point measurements whereas models mostly have large grid-boxes, palaeo-time series offer anchor points to test and tune ocean models. Implementation of widely used palaeo-proxies into model simulations already has produced a series of meridional ocean palaeo-circulation transects (e.g., Rohling and Bigg, 1998; Schmidt, 1998). These allow for an improved interpretation of the palaeo-records and help in the design of algorithms for transforming palaeo-data to meteorological variables. Palaeoceanographic modelling and data assimilation are therefore important elements of this programme.

There is emerging evidence that North Atlantic climate and ocean circulation of the past 10,000 years were less stable than previously assumed (Bond et al., 1997). For example, new SST-proxy data from the NW Atlantic show that waters north of the Gulf Stream experienced warming during the "Little Ice Age" (LIA) of the 16th to 19th centuries (Keigwin and Pickart, 1999). Moreover, THC fluctuations have been suggested as the cause of the LIA (Broecker, 2000). As longer instrumental records become available and climatic proxy records are analysed, the presence of a multi-decadal modulation of the NAO becomes apparent. Using multi-proxy palaeo-records (terrestrial and marine) of high-resolution sites covering the last millennium in the North Atlantic region will elucidate the interplay between decadal and multi-decadal climate variability and the THC. The LIA will thus serve as a more accessible test-bed for understanding the massive THC-climate interactions at the end of the glacial.

Other performance targets

We aim to attract 50 high-quality proposals, over two funding rounds, with funding for about half of them, a considerable proportion of which will collect new field data. We expect the programme to fund about 25 PDRAs and 25 tied students.

Specific deliverables

- Advice on observing systems for quantifying the THC and its variability, including beginnings of implementation.
- Identification of main drivers of THC variability.
- Identification of consequences for climate of abrupt THC change, including scenarios for risk assessment.
- Assessment of the ability of climate models to simulate the THC and its variability, and recommendations for model development to reduce uncertainty in future THC projections.

Timeliness and relevance to the UK

This thematic programme addresses an urgent scientific and societal problem. If the increase in greenhouse gases leads to a dramatic weakening of the THC, drastic action might be required in the very near future. Thus, answers to the scientific questions posed above must be found quickly. The UK is a major beneficiary of the moderating influence of Atlantic THC heat transport, and could be expected to be among the countries hardest hit by a substantial change in the THC. This proposal builds on the strengths of the UK ocean and climate research community. Funding this programme now would establish a leading role of UK science in research on abrupt climate change.

Relevance to NERC science strategies and Board priorities

- In *Looking Forward*, NERC identifies the interactions and feedbacks between the components of the climate system – in this case, the ocean, the atmosphere, and sea ice – as a key science area.

- NERC's marine science strategy targets the development of robust predictive capabilities for natural ocean variability as a generic goal, and forecasting ocean behaviour as a future priority.
- NERC's marine science strategy poses the question: "How does the physical and bio-geochemical behaviour of the coupled ocean-atmosphere system affect climate and other aspects of global change, both natural and anthropogenic? (ocean monitoring; climate change and extreme weather events; remote sensing applications; release and uptake of greenhouse gases; planetary sustainability)."
- NERC's Marine Science and Technology Board strongly endorsed the outline bid for this programme.
- NERC's earth science strategy targets the dynamics of climatic and environmental change, including the study of ultra-rapid events, reconstruction of oceanic circulation, time-dependent modelling of climatic change, understanding impacts of past climate changes (especially rapid changes), and assessing risks and mitigating impacts of future change.
- NERC's atmospheric science strategy identifies climate variability and predictability as one of its key scientific areas.

User community and beneficiaries

A broad range of disciplines will benefit from the programme, including physical and tracer oceanography, boundary-layer meteorology, atmospheric and oceanic modelling, palaeoceanography, and sea ice research. The town meeting on abrupt climate change in London on 19 May 2000 was attended by around 130 scientists and agency representatives from all these disciplines. Users will be the climate community at large, including the communities dealing with climate predictability and prediction, and those dealing with the impacts of climate change. The programme will provide an underpinning for future climate predictability work and will provide scenarios for risk and impact assessment by social and political scientists. In particular, this programme will feed interactively into the recently funded Tyndall Centre for Climate Change Research, which will focus on prevention, mitigation, and adaptation strategies. A strong involvement of the Hadley Centre is anticipated beyond R. Wood's authorship on this proposal, and collaborative links will be sought at an early stage with organisations such as DETR, Environment Agency and the UK Climate Impact Assessment (including identification of their specific needs).

Required Technology Development:

1) *Observing mixing processes*. A number of new techniques are now becoming available for practical application and promise substantial and rapid progress over the near future. UK scientists are prominent in developing these techniques. They include (a) tracer measurements, including tracer release experiments and transient tracer studies to quantify water mass formation rates (e.g., Watson et al., 1999); (b)Time series of CTD moorings to enable study of internal waves, transient and seasonal signals; (c) moored whole water samplers to enable the study of time series of water properties.
2) Provision of cheap bottom-moored profiling CTD systems for sub-ice work. One of the most difficult yet most important measurements is that of freshwater fluxes under the ice (e.g., along the East Greenland shelf). The freshwater lies mostly immediately below the ice and must be reached by the instruments. Hitherto this has been impractical using moorings because of the risk of having moored equipment snagged and destroyed by passing ice. UK, German, and Canadian groups have designed and built cheap systems whose utility and performance would need to be further developed.
3) Ice movement: Use of new designs of ice drifters and satellite communication (Wadhams et al., 1999).
4) Model development: This programme will closely interact with, and greatly benefit from, current and planned UK initiatives in model development: (1) the existing Hadley Centre coupled model, for simulations spanning up to 1000 years; (2) a planned Earth System Model consisting mainly of GCM components, for timescales up to 100 years; (3) a planned intermediate-complexity model for simulating timescales up to 100,000 years.
5) Developments in satellite observations: Radar altimeters on ERS-2 (to 82ºN) and TOPEX (to 66ºN) provide measurements of sea surface topography over ice-free and ice-covered regions; ERS-2 also provides sea surface temperature measurements. These measurements will be continued on future missions including EnviSat (2001-) and Jason (2001). Gravity missions GRACE (2001-) and GOCE (2003-) will measure the marine geoid to an accuracy which, when combined with altimetry, will provide direct estimates of the time-mean surface ocean circulation. Another ESA mission, SMOS, is designed to provide estimates of sea surface salinity, with a spatial resolution of 60km. Two new altimetric missions will obtain high-latitude measurements of the mass balance and fluxes of land and marine ice. The NASA IceSat mission (2001-) uses a laser altimeter to estimate changes in surface elevation to 86ºN. ESA's CryoSat (2003-) uses novel processing to constrain its radar footprint providing high-precision estimates of land ice and sea ice topography to latitudes of 88ºN.

Management issues and scientific collaboration

The standard model for managing and overseeing a thematic programme will apply, with one important exception. The task of establishing a continuous THC observing array would require too large and careful a co-ordination to arise as a "grass-roots" enterprise, through individual proposals responding to the Announcement of Opportunity (AO). Either the observing array is to be developed by a consortium (membership invited through the AO), or the components could be specified explicitly in the Science Plan, with the chance for researchers to bid for certain pieces. In addition, funds will have to be set aside for making model results available to the UK community, in particular synthesis/data assimilation results. Their storage and effective dissemination and use is nontrivial and may require a small but dedicated facility. Field data will be archived at the BODC and will be made available to interested researchers following a brief embargo period (e.g., 2 years).

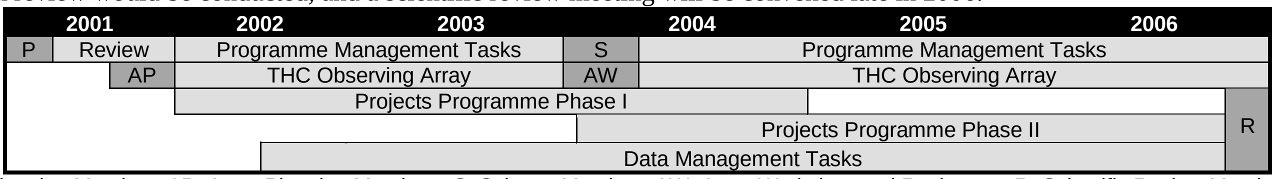
The Steering Committee and the Science Co-ordinator (employed by the programme), will ensure that links are developed to existing and planned programmes with related activities, to provide added value to the science and to avoid duplication of efforts. Existing programmes include COAPEC, ARCICE (both NERC), NOCLIM (Norway), CONVECTION, TRACTOR, VEINS, MAIA (all EU), ARGO, ERS2, TOPEX, Florida Straits monitoring (all international) and various modelling ventures.

Planned programmes include PRESCIENT, AUTOSUB\ICE (both NERC), OPEC2 (EU), CLIVAR (various national components), ENVISAT, JASON, GRACE, GOCE, SMOS, ICESAT, CRYOSAT (all international).

A high priority will be given to developing the UK–Norway initiative into a genuine scientific collaboration of mutual benefit. Strong links have been established at scientific and funding-agency levels. There will be common membership of the national steering committees, a joint working-group will develop a collaborative scientific strategy, and ultimately a joint workshop or conference will be held. This programme's strong emphasis on ocean observations, and its modelling focus on the robustness and realism of internal atmospheric and oceanic processes – rather than on the coupled interactions – distinguish it from the existing COAPEC programme. Both approaches are necessary to achieve the long-term goal of improved THC projections. In turn, the emphasis on field work in the Nordic Seas and on time series observations in the North Atlantic make this programme complementary to the ARGO float programme. The latter, while providing global coverage, is not expected to sample boundary currents well enough to measure the THC (the zonally integrated flow).

Indicative timetable

The following timetable is an example of the way the programme might run. Commencement of funding could be in 2001, leaving adequate time for the establishment of a steering committee and the announcement and review process. The end of the programme would be in 2006, with the THC observing array being maintained throughout. The science projects would be carried out in two overlapping phases; a significant number of research projects are expected to continue into Phase II. A mid-term review would be conducted, and a scientific review meeting will be convened late in 2006.



P: Planning Meeting   AP: Array Planning Meeting   S: Science Meeting   AW: Array Workshop and Review   R: Scientific Review Meeting

Resources sought

As there will be a heavy emphasis on establishing time-series observations, a significant expenditure in instruments and moorings is expected in the first two years of the programme. The proposed budget for the core programme is based on a scenario for a system at 25°N, consisting of 8 tall profiling moorings, 20 near-bottom systems, 6 current meter moorings, and two hydrographic sections (note that these systems need to exist in duplicate, to allow continuous observations while instruments are repaired, re-calibrated, etc., on land). Other field work costs are based on the equivalent of 10 profiling moorings (again in duplicate) and 1 hydrographic line per year of 30 days each. (These platforms are merely used as placeholders representing time series and ship-borne measurements, respectively.) Apart from the 7 hydrographic lines (5 pro forma and 2 concrete), neither core nor field work costs involve scientific staff cost, which are assumed to be contained in the 21 funded projects (each budgeted nominally with 1 PDRA, 1 tied student, and partial support for a technician or programmer). Ship time is also listed separately but is included, at a rate of £6K per day, because (1) the full cost of the programme should be shown, (2) it is not yet clear which funding model for ship time will apply; (3) a foreign ship may have to be chartered, depending on availability and opportunity. Costs are included for data management and distribution. Programme management assumes a full-time science co-ordinator and standard administrative support within NERC. Data management assumes two full-time persons for most of the runtime (one for handling observations, one for handling synthesis results), with a budgeted increase toward the end to allow for some continuation after the 'formal' end of the programme. For simplicity of presentation, a match of the start date with the financial year is assumed.

All numbers in k£	FY01/02	FY02/03	FY03/04	FY04/05	FY05/06	Total
Awards (21)	700	700	1470	770	770	4410
THC Observing Array	2194	1551	76	76	451	4348
Field work	1730	1730	400	400	400	4660
Ship time	600	600	300	300	460	2260
Programme management	120	120	120	120	120	600
Data management	60	120	120	120	240	660
Total	5404	4821	2486	1786	2441	16938

This proposal was prepared with additional advice from attendees and non-attending registrants at the NERC-funded Town Meeting, all of whom were alerted to the web site posting of a draft version.

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