RAPID-WATCH – Will the Atlantic Thermohaline Circulation Halt?[1]

H. Bryden, D. Marshall, R. Sutton, R. Wood and J. Marotzke, with M. Srokosz[2]

Summary

RAPID-WATCH (2007-2014), building on RAPID[3], will deliver a decade-long time series of the strength and structure of the Atlantic Meridional Overturning Circulation (MOC[4]). These observations, in conjunction with other relevant research and data, will be used to determine and interpret recent changes in the Atlantic MOC, to improve assessment of the risk of rapid climate change due to MOC change, and to investigate the potential for predictions of the MOC and its impacts on climate. This work will be carried out in collaboration with the Hadley Centre in the UK, and strengthened through international partnerships, to address a fundamental stakeholder concern: "should we be worried about rapid climate change due to rapid MOC change?" As such, RAPID-WATCH is designed to deliver a robust and scientifically credible assessment of the risk to the UK and European climate due to a rapid change in the MOC. Additionally, it will assess the need for a long-term observing system that could detect major MOC changes, narrow uncertainty in projections of future change, and possibly initialise an "early warning" prediction system.

Objectives

- To deliver a decade-long time series of calibrated and quality-controlled measurements of the Atlantic MOC from the RAPID-WATCH arrays.[5]
- To exploit the data from the RAPID-WATCH arrays and elsewhere to determine and interpret recent changes in the Atlantic MOC, assess the risk of rapid climate change, and investigate the potential for predictions of the MOC and its impacts on climate.

1. Scientific background

Large variations in the Earth's climate have occurred in the past according to paleo records. Some changes in the last 100,000 years were rapid, with 10°C changes in Greenland temperature occurring over periods of 5 to 25 years (Broecker & Denton, 1989; Dansgaard et al., 1993). These are generally attributed to changes in the strength of the Atlantic MOC. The Atlantic MOC carries warm upper waters northward, which cool on their journey, giving up heat to the atmosphere. In the subpolar and polar regions the surface waters become cold and salty enough to sink forming cold deep waters, which return southward (Ganachaud & Wunsch, 2002). The Atlantic MOC is estimated to be ~17 Sv and transports 1.3 PW of heat northward, equal to a quarter of the maximum poleward heat transport of the combined global atmosphere-ocean heat transport required to balance the global heat budget (Bryden & Imawaki, 2001). Switching off the MOC could lead to rapid cooling of the northern Atlantic.

The remarkable stability of the Earth's climate for the past 8,000 years has coincided with, and arguably contributed to, the development of civilisation from prehistoric nomadic tribes to modern industrial society. By increasing the amount of CO_2 in the atmosphere, will we perturb the climate out of its stable state? Due to its role in past rapid climate change, the Atlantic MOC is a focus for understanding present and future climate change. Coupled ocean-atmosphere climate models generally agree that the Atlantic MOC will decrease as CO_2 builds up in the atmosphere (Cubasch et al., 2001; Gregory et al., 2005). GCM simulations suggest the slowdown is gradual, but at some stage a threshold may be crossed, leading to rapid shutdown (as seen in intermediate complexity models; Rahmstorf et al., 2005). GCM simulations show that this could result in reductions of 4 to 8°C in air temperatures over the northern Atlantic and northwest Europe (Vellinga & Wood, 2002).

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[1] In other, earlier documents referred to as RAPID2 for brevity and convenience.

[2] Bryden – National Oceanography Centre, Southampton; Marshall, Sutton – Reading University; Wood – Hadley Centre, Exeter; Marotzke – Max Planck Institut für Meteorologie, Hamburg; Srokosz – RAPID Science Coordinator.

[3] For background on the existing RAPID programme see http://www.noc.soton.ac.uk/rapid/rapid.php

[4] This is also referred to as the thermohaline circulation (THC) – the THC is the major component of the MOC, but the MOC is what can be measured directly.

[5] Rather than continually refer to the RAPID and RAPID-WATCH arrays, this is abbreviated to the RAPID-WATCH arrays here and in what follows.

The potentially large impacts of rapid MOC change mean that it is essential to identify changes in the North Atlantic that may be happening now. Observations suggest a cessation in the formation of lower North Atlantic Deep Water (NADW) in the Norwegian Sea (Østerhus & Gammelsrod, 1999), a decrease in the amount of cold dense overflow of deep waters through the Faroe Bank Channel (Hansen et al., 2001), and a freshening of northern Atlantic surface and deep waters (Curry et al., 2003; Dickson et al., 2002) during the latter decades of the 20th century. There is also evidence for decreased northward flow of upper waters through the subpolar gyre (Häkkinen & Rhines, 2004; Lherminier et al., 2006).[6] At 25°N "snapshot" measurements over the past 50 years suggest that the MOC has slowed by 30% and the structure of the overturning circulation has changed so that the southward transport of lower NADW has halved and the southward recirculation of upper waters in the subtropical gyre has doubled (Bryden et al., 2005). Assimilation of ocean observations made since 1992 into an ocean general circulation model, to make a state estimation of the global ocean circulation, suggests the Atlantic MOC has declined by 2.3 Sv over 12 years since 1992 (Wunsch & Heimbach, 2006). Thus observations indicate a recent and sizeable slowdown in the Atlantic MOC.

Yet North Atlantic sea surface temperatures (SSTs) have increased dramatically since the mid 1970's. Can we reconcile warmer SSTs with a slowdown in the MOC? There are currently three explanations (not necessarily independent) for warmer Atlantic SSTs. First, the warming may be a direct result of radiative heating due to the greenhouse effect resulting from increased atmospheric CO_2 (IPCC, 2001). Second, warmer SSTs could be associated with a high North Atlantic Oscillation (NAO) index. This index, measuring the strength of the westerly winds over the northern Atlantic, has increased substantially from low values in the 1970's to recent higher values. The low frequency response is expected to be warmer SSTs (Visbeck et al. 2003) and possibly a stronger MOC (Latif et al. 2006). Third, warmer SSTs may be due to the Atlantic Multidecadal Oscillation (AMO), a natural oscillation of 50 to 100-year period found in coupled climate models that links a strong MOC to warm SSTs (Delworth & Mann, 2000). The warmer SSTs in the past 25 years have led some to suggest that the MOC is presently in a strong phase (Knight et al., 2005).

The conflicting evidence for and against a recent weakening of the Atlantic MOC underscores the crucial importance of observing it continuously. In the debate that followed Bryden et al.'s (2005) report of a 30% slowdown of the MOC between 1992 and 2004, there was a consensus that sustained high frequency observations of the MOC are essential for understanding the nature and causes of MOC change and the effects on regional climate. That consensus was summarised in a *Nature* (2006) editorial.

RAPID, working with international partners, initiated such a monitoring project in 2004 with time-series measurements of the basin-scale MOC at 26.5°N and western boundary measurements to observe how a changing deep-water formation signal will propagate through the Atlantic. This monitoring will continue for 4 years to 2008 and should document the size and structure of the subannual variability in the Atlantic MOC and the propagation of anomalies originating in the subpolar regions along the western boundary. These initial measurements should allow us to determine whether the estimates of MOC strength based on synoptic shipboard data (Bryden et al., 2005) are within the range of subannual variability of the MOC. With only four years of data the new estimate of subannual variability will still be subject to a large degree of uncertainty. Extending the time series will reduce the uncertainty in the subannual variability, and allow an initial estimate of the interannual variability.

Here we propose to continue the monitoring for an additional 6 years to 2014 to acquire a decadal record of MOC variability. Many climate observing systems (especially in the ocean) are funded in short-term "research" mode, and loss of continuity of funding leads to gaps in time series which can damage understanding of climate trends.[7] From a 10-year record, we will be able to compare the

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[6] N.b. in coupled models neither high-latitude freshening (Wu et al., 2004), nor a change in the subpolar gyre (Landerer et al, 2006), are valid proxies for MOC change.

[7] E.g. see http://gosic.org/GCOS/GCOS_climate_monitoring_principles.htm

interannual variations in the MOC with changes in Atlantic circulation, deep-water formation, and overflows, and relate them to longer-term observations of SST, NAO and AMO. The observational estimates of MOC variability can be compared with variability in coupled climate models (which individually exhibit substantially different amplitude and structure in MOC variability) in order to test the models. Finally, with a 10-year record of MOC strength and structure, there will a higher signal to noise ratio as the subannual and interannual variability is quantified, so we should be able to assess whether there is a statistically significant decadal trend in the strength of the MOC above that variability. With the longer record, we may be able to detect early evidence of anthropogenic MOC changes (Vellinga & Wood 2004).

Closely allied to making the decade-long observations of the MOC, there is a clear need for research to exploit and interpret the observations in order to address major scientific and policy questions about the MOC. Synthesis activities are required to provide a consistent analysis of changes in the entire Atlantic Ocean. Model and data studies are required to: identify the causes of recent changes in the MOC; investigate the implications of MOC observations for estimates of the risk of rapid MOC change; and investigate the potential for predictions of MOC change and its impacts on UK, European and global climate. Taking advantage of the investment in model development under RAPID, such studies are vital to extract the full value of the MOC observations.

2. Strategic context

The United Nations Framework Convention on Climate Change (UNFCCC) aims to avoid dangerous anthropogenic interference with the climate system. Rapid climate changes are widely interpreted as dangerous, because the speed of change (and possible reversal of direction) can make adaptation difficult (Hulme 2003). The potential for irreversible changes (e.g. MOC hysteresis behaviour, Rahmstorf et al., 2005) is important in considering greenhouse gas stabilisation policy and ‘overshoot’ scenarios (Mastrandrea & Schneider 2006). These issues are likely to be at the forefront in negotiations toward the Second Commitment Period of UNFCCC, starting in 2012.

To-date, little quantitative information is available on the likelihood of rapid or irreversible changes in the MOC for particular levels of greenhouse gases. The few studies (e.g. Challenor et al. 2006, Schlesinger et al. 2006) are based on simplified models, and their results often seem at odds with experience from the smaller number of experiments possible with more comprehensive GCMs, which suggest that such events are very unlikely during the 21st Century (e.g. Cubasch et al, 2001). Therefore RAPID-WATCH will integrate the observations with a spectrum of models to assess the probability of irreversible MOC change.

One possible response to the risk of rapid MOC change is to accept a certain level of risk but to be prepared to implement adaptation measures if such an event were to occur. A predictive or ‘early warning’ capability would facilitate adaptation (e.g. by providing a lead time in which to defend against rapid sea level rise in the North Atlantic margins). Therefore RAPID-WATCH will explore the feasibility of interannual to decadal MOC prediction.

A critical future decision is whether the evidence and risk assessment merit a sustained operational monitoring system for the MOC. To inform this decision it will be important to set out clearly the full range of scientific and societal benefits that can be expected from the observing system, the timescales on which they can be expected to accrue, and the cost-efficiency of the observing system design. RAPID-WATCH will investigate the case for a cost-effective, long term MOC observing system to meet the needs of reducing uncertainty in projections, detecting change and initialising MOC forecasts.

RAPID has established links with policy makers (e.g. DEFRA), users and stakeholders (e.g. UKCIP, MCCIP) through its Knowledge Transfer facilitator and by having representatives from these communities on its Steering Committee. RAPID-WATCH will build on these links, to ensure its scientific results are used to address their needs. Scientifically RAPID has strong collaborative links with the Hadley Centre, and this collaboration will be explicitly strengthened to address both scientific and strategic questions (see Section 6).

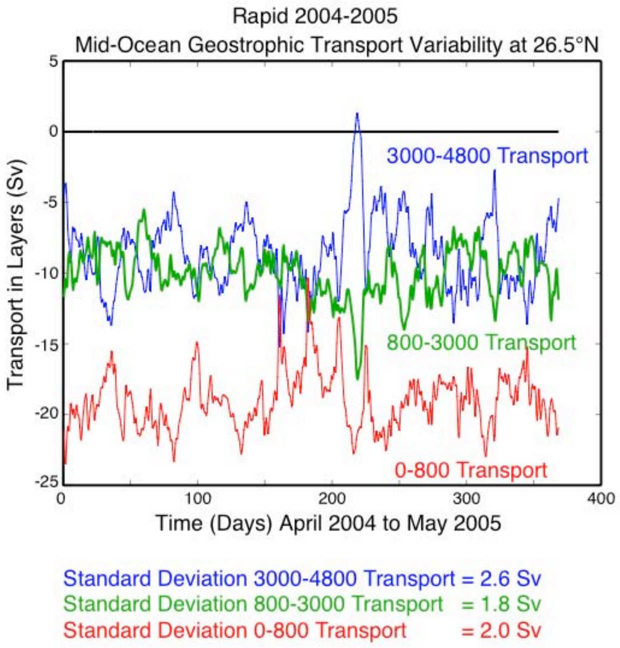
3. The RAPID-WATCH observing system

- Objective: *To deliver a decade-long time series of calibrated and quality-controlled measurements of the Atlantic MOC from the RAPID-WATCH arrays.*

Under RAPID, a prototype monitoring system has been designed and deployed to continuously monitor the strength of the MOC in the N. Atlantic. By the end of RAPID (2008), four years of in-water observations will have been made in collaboration with NSF and NOAA scientists. This is too short a duration to characterise interannual variability against which potential rapid changes might be detected and assessed. Therefore it is proposed to extend the observations to 2014. Both the 26.5˚N and WAVE (Western Atlantic Variability Experiment – observing the Deep Western Boundary Current) arrays are included in this proposal, subject to performance evaluation in 2007 (see discussion in 3.3. and 3.5 below). At this time (spring 2006) one year of data is available from the 26.5˚N array (2004-2005), and there are no data from WAVE, as the first recovery is scheduled for summer 2006. Detailed scientific justification for monitoring the MOC was given in the original RAPID proposals so here the focus is on the continued monitoring.

3.1 The 26.5˚N array

Geostrophic estimates of the N. Atlantic MOC require continuous endpoint monitoring of density at the eastern and western boundaries, and establishment of a reference level. This approach has been used before, though not in a systematic attempt to continuously monitor the MOC. For example, Whitworth (1983) monitored Drake Passage transport, Lynch-Sieglitz et al. (1999) estimated Florida Strait transport during the Last Glacial Maximum, and Lynch-Sieglitz (2001) used marginal density information to infer both modern and past circulations. The 26.5°N section has the fundamental advantage that the northward western boundary current flow is confined in the Florida Straits and can be measured relatively easily by submarine cable through the existing long-term US NOAA programme (e.g. Larsen, 1992; Baringer & Larsen, 2001) and regular calibration cruises. The Ekman transport can be estimated from the wind field. Thus monitoring the entire MOC is equivalent to monitoring the depth profile at which the flow through the Florida Straits returns southward. Currently, about half this return flow is found at depths between 1000m and 4000m (e.g., Roemmich & Wunsch, 1985); dramatic shoaling of this return path would be equivalent to a collapse of the MOC. Design studies using two high-resolution models (Hirschi et al., 2003, Baehr et al., 2004) have shown this monitoring strategy to be feasible. The 26.5˚N array was first deployed in spring 2004 and successfully recovered and redeployed in spring 2005 (Cunningham, 2005; Cunningham & Rayner, 2005). Data from the first year's deployment are being are now being processed and analysed and early results presented at the EGU (Kanzow et al., 2006) are summarised here in the temporal variability of mid-ocean geostrophic transports in three layers, 0-800m, 800-3000m, and 3000-4800m (see figure). While there is still additional processing and analysis to be done, it is clear that the 26.5°N array has fulfilled its objective to monitor the time-varying basin-wide geostrophic circulation for 2004-2005.



The monitoring array presently consists of 18 moorings and 8 bottom landers (measuring temperature, salinity, currents, and pressure) at the eastern and western boundaries of the Atlantic and the mid-Atlantic ridge (see Annexe and Cunningham & Rayner, 2005, for details). There is some redundancy built into the present array so that no single mooring failure can compromise the continuous monitoring. Until the end of RAPID (2008) the present array design will continue. Here it is proposed that the array will continue to be recovered and redeployed each year from 2008 to 2014, with redesign subject to evaluation (section 3.3). During the period of the deployment there will be two transatlantic hydrographic, calibration cruises undertaken by NOCS (in 2009, as part of Oceans 2025[8], and in 2014, beyond the end of Oceans 2025, though included in future planning), as was done in 2004, when the array was first deployed. These cruises will also extend the series of hydrographic observations made previously at that latitude (1957, 1981, 1992, 1998, 2004), the basis of the Bryden et al. (2005) results, and allow the continuous results obtained from the 26.5˚N array to be confirmed in 2009 and 2014 using the more traditional observing strategy.

3.2 The WAVE array

To have confidence in an observing system designed to monitor the basin-wide MOC, it is necessary to demonstrate that the measured signal is representative of processes spanning a wide latitude range of the North Atlantic. The WAVE array complements the 26.5ºN array by providing information to the north of the Gulf Stream, closer to high-latitude sources of variations in the MOC. Indications from model experiments (e.g., the RAPID-funded Williams project) indicate the need for at least one monitoring line that lies clearly in the subpolar gyre to the north of the Gulf Stream, since the Gulf Stream can act as a barrier to MOC anomalies on short time-scales.

The WAVE array presently consists of three lines spanning the Deep Western Boundary Current along the western margin of the North Atlantic, southeast of Cape Cod, Halifax and Grand Banks. The lines each have 6 bottom pressure recorders/inverted echo sounders and 5 temperature/salinity moorings. The Cape Cod line is the Toole "Line W", for which all but the bottom pressure recorders and some additional T-S sensors are provided by Woods Hole with NSF funding. In common with the 26.5˚N array, the key measurements are of the boundary pressure and density anomalies, consistent with the idea that these most strongly constrain the MOC. The WAVE array was first deployed in 2004 and is to be recovered and redeployed in summer 2006 and at 2-year intervals thereafter. The aims are to determine the coherence of the observations between one latitude and another, to test our understanding of the mechanisms by which the MOC adjusts through boundary wave propagation (e.g., Kawase 1987, Johnson & Marshall 2002, Getzlaff et al. 2004) and hence our ability to interpret data collected from a single section such as 26.5˚N. Knowledge of these adjustment mechanisms will also be important for the design of a MOC forecasting system.

3.3 Evaluating the observing system

Under RAPID, the performance of the 26.5˚N and WAVE arrays will be evaluated in 2007 to determine the optimal design for continued monitoring based on the first two years of data available then. Decisions will be made as to whether to continue monitoring with the current design or with a modified design, and whether to "thin" the arrays, reducing both instrument and deployment / re-deployment costs. Decisions will depend on the scientific results from the RAPID monitoring, and will seek to avoid jeopardising the value of the time series that are being built up. Here it is proposed that a further evaluation will be made in 2011, with a view to any future monitoring system moving to an operational phase beyond 2014. To move to operational status will require a strategic decision that the system is needed to provide early warning of MOC changes, to initialise MOC predictions, and to inform policy. RAPID-WATCH will provide the underpinning science for that decision.

3.4 Dependencies

For the observing system to succeed there are a number of dependencies summarised here:

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[8] Oceans 2025 is the NERC Marine Centres' proposed strategic programme 2007-2012 (*sub judice*).

Partnership with NSF and NOAA:
NSF and NOAA in the USA currently fund key aspects of the monitoring system in close strategic partnership with NERC. In particular, NOAA fund the Florida Straits cable measurements and the associate calibration cruises at 26.5˚N, together with inverted echo sounder measurements at the western boundary. NSF fund work by Johns (Miami) and Toole (WHOI) that is critical to the 26.5˚N array and WAVE, respectively (see Annexe). If MOC measurements are to continue as currently implemented these components must be continued in some form and NERC has accordingly engaged NOAA and NSF in discussions. NOAA funded measurements are part of their on-going programme and expected to continue beyond 2008. Johns and Toole will submit bids in 2007 to NSF for the continuation of their measurements, after NERC have made a decision on the present proposal (see also discussion in section 3.5).

Link to Oceans 2025 programme at NOCS and POL:
The Oceans 2025 programme (*sub judice*) will provide support for the PIs, and for the analysis and interpretation of the data (under Themes 1 and 10). The 26.5˚N trans-oceanic hydrographic cruise in 2009, plus analysis and interpretation of the data acquired, is included in Theme 1 (the cruise in 2014 is beyond the end of Oceans 2025, and would need to be included in any follow-on programme). In parallel with the monitoring proposed here, in Theme 8 technology will be developed to improve instrument and mooring reliability and data communications (via satellite telemetry). These developments will impact the design of the array, leading to possible cost saving and more efficient operations. Similarly, there is potential to improve reliability and reduce operational costs by employing new technology such as full-depth gliders. Glider technology is not yet at the stage where it can make full ocean depth measurements, but over the period of this programme (2007-2014) it may reach that potential.

3.5 Implementation scenarios for the observing system

NERC has requested a range of scenarios for funding the monitoring system and this is addressed here. An informed choice can only be made after the 2007 array evaluation (3.3).

Scenario 1: Continue with 26.5˚N and WAVE arrays in present form: This is the only scientifically credible option at present given limited data available from the 26.5˚N section and no data available from WAVE. The first opportunity to make a sound choice between the remaining options will be in 2007 following the first evaluation of the arrays (see 3.3).
Scenario 2: "Thin" one or both of the 26.5˚N and WAVE arrays: Any decision to thin the arrays to reduce the degree of redundancy at acceptable risk levels will be taken during the first evaluation of the arrays in 2007 based on the first two years of data.
Scenario 3: Continue the 26.5N array in present form, but not WAVE: This would provide the MOC time series at 26.5˚N, but no information on the MOC to the north of the Gulf Stream. Given recent model results indicating that the Gulf Stream can act as a barrier to MOC anomalies, this could limit the ability to provide early warning of rapid change in the MOC at high-latitudes.

Two further scenarios might need consideration after 2007, depending on US funding decisions:
Scenario 4: NSF funding discontinued for Johns: Some of this work is a critical component of the 26.5˚N section at the western boundary and would need to be sustained, possibly through savings obtained by "thinning" the arrays following the evaluation in 2007.
Scenario 5: NSF funding discontinued for Toole: A decision would need to be taken whether to continue with Line W through savings made elsewhere or by redeploying RAPID instruments from another line (probably the middle of the three WAVE lines; see Annexe).

In parallel, work will continue (e.g. at the Hadley Centre, in ongoing RAPID projects and in Oceans 2025) on exploiting "proxy" observations from other sources (e.g. ARGO, altimetry) to constrain the MOC estimates (building on Vellinga & Wood, 2004). While proxies may eventually allow less costly operational monitoring (from 2014), the 10-year MOC time series provided by RAPID and RAPID-WATCH will be needed to validate the use of "proxy" observations.

4. Exploitation of the observational data: synthesis, risk and the potential for prediction

- Objective: *To exploit the data from the RAPID-WATCH arrays and elsewhere to determine and interpret recent changes in the Atlantic MOC, assess the risk of rapid climate change, and investigate the potential for predictions of the MOC and its impacts on climate.*

This part of the RAPID-WATCH programme will be carried out via an open call for specific research proposals addressing one or more of the following key science questions.

1. *How can we exploit data from the RAPID-WATCH arrays to obtain estimates of the MOC and related variables?*

Optimal estimates of the ocean circulation can be obtained only by combining observations collected under RAPID and other observational programmes (e.g. JASON, ARGO, ASOF, Oceans 2025 Themes 1 & 10) with ocean circulation models which capture the underlying dynamics. This synthesis gives: a dynamically-consistent description of the evolving state of the Atlantic that can be used to identify and analyse patterns of MOC variability; estimates of derived quantities such as the MOC streamfunction and poleward transports of heat and freshwater; initial states for climate predictions; a framework for identifying systematic ocean model errors, optimizing parameters and improving parameterizations; and a rigorous framework for refining the MOC monitoring system.

There are currently two distinct approaches taken to ocean data-model synthesis. The ECCO project (Stammer et al., 2003) employs state estimation methods (Wunsch 1996) but, due to the computational overhead, is restricted to coarse spatial resolutions at which many critical processes are unresolved. In contrast MERCATOR, FOAM, SODA (Carton et al., 2000) and the RAPID-funded Haines & King project, employ simpler assimilation methods at eddy-permitting resolutions. The use of high-resolution regional models introduces additional complexities (e.g. open boundary conditions; Zhang & Marotzke, 1999). Present data assimilation methods also adopt much shorter covariance scales than the separation of the stations in the 26.5˚N array, thus posing particular challenges for the successful synthesis of data from the array. RAPID-WATCH will seek to: understand the properties of different assimilation methods, in particular with respect to evolution of the MOC; determine how to best incorporate new data collected by RAPID-WATCH (e.g. integral quantities, such as MOC strength at 26.5˚N) that have not been routinely assimilated in the past; identify which observations provide the strongest constraints on the MOC and related parameters to inform the ongoing refinement of the RAPID-WATCH (and wider) monitoring system. The FOAM system run by the National Centre for Ocean Forecasting (NCOF) provides a context in which ideas can be tested, in a range of model resolutions from 1° to 1/9° (see http://www.metoffice.gov.uk/research/ncof/foam/index.html).

2. *What do the observations from the RAPID-WATCH arrays and other sources tell us about the nature and causes of recent changes in the Atlantic Ocean?*

As noted in section 1, there is evidence that, since the mid 1970s, the MOC has been decreasing at the same time as North Atlantic SSTs have been increasing. While ocean synthesis activities are essential to develop a consistent picture of recent changes in the Atlantic, equally important is the need to interpret changes in terms of specific ocean-atmosphere-cryosphere processes. A credible recent history of the MOC is also a prerequisite for developing an MOC prediction system. RAPID-WATCH will seek to: identify the relationships between particular ocean observations (specifically those from the RAPID-WATCH arrays) and basin-scale changes in the MOC; apply new MOC observations to evaluate models; identify the relationship between changes in the gyre circulation (e.g. Häkkinen & Rhines, 2004), in the Nordic and Arctic Seas, and changes in the MOC, also addressing changes in the northward transports, and storage, of heat and fresh water; determine the roles of air-sea fluxes of heat, fresh water and momentum, sea ice changes, and run-off (Greenland Ice Sheet and rivers) in driving observed MOC changes; identify the component of Atlantic Ocean change that is attributable to anthropogenic forcing, and separate this signal from natural variability. The focus will be primarily on the MOC evolution over the last 50 years and this work will interact with and complement work being carried out under Theme 1 of Oceans 2025.

3. *What are the implications of RAPID-WATCH array data and other recent observations for estimates of the risk due to rapid change in the MOC?*

Estimating the probability of rapid change in the MOC is a very challenging problem, principally because we lack perfect models of the climate system. However, useful estimates can be obtained by using an ensemble of models (e.g. IPCC 2001) or model versions (Murphy et al, 2004). The effective sample of models can be enlarged through the use of statistical emulator techniques (Challenor et al, 2006). In any ensemble based approach a critical issue is how to weight different models. Here, the evaluation of models against observations plays a central role (e.g. Murphy et al, 2004). Therefore RAPID-WATCH will seek to: investigate how observations of the MOC can be used to constrain estimates of the probability of rapid MOC change, including the magnitude and rate of change, using methods such as Bayesian calibration (Kennedy and O'Hagan, 2001); develop traceable, process-based, metrics to relate estimates based on different classes of model (e.g. EMIC versus GCM); make sound statistical inferences about the real climate system from model simulations and observations (building on work under RAPID[9]; e.g. Goldstein & Rougier, 2005); consider hitherto under-explored dimensions of model uncertainty such as sensitivity to resolution. Research on the probability of rapid MOC change will exploit the capacity building work currently in progress in several RAPID projects (e.g. those led by Challenor and Gregory), in the HiGEM project (which has developed a high resolution climate model), the MUCM (Managing Uncertainty in Complex Models) project, and at the Hadley Centre (Murphy et al., 2004; Wood et al. 2006).

In addition to an estimate of probability, risk assessment requires knowledge of impacts. Previous research indicates that changes in the MOC can lead to substantial changes in North Atlantic climate, affecting temperature, precipitation, and sea level (e.g. Manabe & Stouffer, 1988; Vellinga & Wood, 2002; Levermann et al, 2005). More recently, high-resolution regional models have been used to investigate impacts at smaller spatial scales (Jacob et al, 2005; RAPID-funded Hoskins & Blackburn project). RAPID-WATCH will build on this research in order to support the development, with the Hadley Centre, of more detailed scenarios for rapid climate change. This work will include: assessment of model uncertainty in climate impacts, and characterisation of impacts that have received little attention, e.g. changes in the frequency of extremes.

4. *Could we use RAPID-WATCH and other observations to help predict future changes in the MOC and climate?*

There is evidence that changes in the MOC, and related climate impacts, may be predictable on decadal timescales (Griffies and Bryan, 1997; Collins et al, 2003; Collins et al, 2006). This raises the possibility of developing an MOC prediction system, which could potentially provide a valuable early warning of rapid climate change. Even if the predictability of the MOC itself is limited, climate impacts are expected to lag the MOC; thus detection of a substantial change in the MOC could provide the basis for a useful climate prediction. A full prediction system for the MOC and its climate impacts would most likely be based on ensemble integrations using one or more coupled ocean-atmosphere models, initialized using the products of ocean synthesis. It is beyond the scope of RAPID-WATCH to develop such a system; instead RAPID-WATCH will explore the potential for such predictions by investigating: the degree of predictability in the MOC and the skill of MOC hindcasts; the quantitative and time-dependent (lead-lag) relationships between changes in the MOC and changes in climate; ensemble design for sampling uncertainty (from initial conditions, model choice and scenarios) in MOC predictions; the interaction between the influence of ocean initial conditions and the influence of changing external forcing; the observational requirements for MOC predictions. For this work RAPID-WATCH will again work closely with the Hadley Centre where a prototype decadal prediction system has recently been developed (Smith et al, 2006).

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[9] Also RAPID-related international network on Probability, Uncertainty, Climate and Modelling funded under NERC's International Opportunities Fund.

5. Deliverables and delivery mechanisms

5.1 Deliverables

Based on the observations and exploitation of the observations, RAPID-WATCH will deliver:

- An observed time series of the MOC and associated variables from 2004-2014, and interpretation of the observations in the broader context of Atlantic and European climate.
- A tested design for a cost-efficient and robust system suitable for operational monitoring of the MOC.
- An assessment of the scientific (and in broad terms, socio-economic) benefits of an MOC monitoring system, including estimated timescales on which the full benefits would be realised. To include applications for: detection and attribution of unusual MOC change, reducing uncertainty in MOC projections, initialising MOC predictions (early warning system).
- A robust and scientifically credible assessment – specifically informed by the RAPID and RAPID-WATCH observations, modelling and synthesis – of the risk to the UK, Europe and other regions of a rapid change in the Atlantic MOC affecting our climate. This will address the probability, rate and expected magnitude of MOC-related rapid climate change, and associated uncertainties.

5.2 Delivery mechanisms

RAPID-WATCH science will be delivered as a combination of work by NERC marine centres, and a directed element open to competition (see section 4 above). The time series of the MOC (see section 3) will be delivered by NOCS and POL under RAPID-WATCH and Oceans 2025 funding (see section 3.4). Aspects of the science in section 4 are complementary to studies proposed under Oceans 2025, and it is anticipated these will interact to the benefit both programmes. Collaboration with the Hadley Centre and NCOF programmes in climate change, decadal predictions and data assimilation will ensure that RAPID-WATCH contributes to the development of an operational prediction system (in itself beyond the scope of this proposal).

The design for a cost-efficient and robust system suitable for operational monitoring of the MOC will be delivered through a workshop to be held in 2011, led by the PIs of the observing system work, and including independent international and national experts. The output will be a report specifying the design for an operational system.

To deliver a robust and credible risk assessment and to evaluate the need for a long-term MOC observing system will require RAPID-WATCH to work closely with users and stakeholders; in particular the Hadley Centre and DEFRA. Panels of experts (scientists, user and stakeholders; both from the UK and abroad) will be asked to make the assessment and evaluation, by examining the latest results from RAPID-WATCH in the context of other available research results at the time. The risk assessment and evaluation of the need for a long-term MOC monitoring system will be made early in 2012. This will allow time for an operational system to be in place by 2014 without a gap in the observational time series.

6. Collaboration with other UK programmes to deliver policy-relevant science

RAPID-WATCH is a crucial element of a broader UK effort to answer key policy-relevant science questions on the future of the MOC. This broader effort includes the Hadley Centre, NCOF and Oceans 2025 programmes, and research activities in these programmes provide substantial complementarity and gearing to RAPID-WATCH. Specifically:

The Hadley Centre programme includes a focus on delivering estimates of the probability of rapid MOC change for various future greenhouse gas scenarios, primarily through ensembles of 'standard-resolution' GCM experiments. This will be complemented by Oceans 2025 Theme 1 WP 1.4, which uses larger ensembles of computationally cheaper models to provide a fuller exploration of model parameter space. RAPID-WATCH work will focus on exploiting the observational datasets (section 4) to reduce uncertainty ranges in MOC projections from these ensembles, and on building a traceable multi-model ensemble tailored to estimating risks of major MOC change (section 4, question 3). This exploits capacity- and community-building work under RAPID.

Understanding recent climate changes around the North Atlantic (section 4, question 2) is an important area where further progress is needed to provide interpretation to policymakers (see section 2). This topic also has the potential to provide improved observational constraints on probabilistic MOC projections. Work in this area in the Hadley Centre programme focuses on attribution and mechanism-based analysis of recent observations using coupled models, while Oceans 2025 Theme 1 WP 1.1 proposes high resolution ocean model runs to isolate the ocean's response to surface flux changes. As this scientific area is open to a variety of approaches, some overlap of topics is expected with these programmes and is considered appropriate.

The Hadley Centre's experimental decadal climate prediction system (Smith et al. 2006) will be used to produce a global decadal climate forecast once per year, while NCOF produces daily ocean analyses from FOAM, using models with resolutions down to 1/9°. Both systems can be run in reanalysis / hindcast mode. The FOAM and decadal prediction systems provide facilities in which new data assimilation methods can be tested and the impact of new observations can be assessed; subject to resource constraints the Met Office will provide technical support to facilitate agreed collaborative projects with researchers using the RAPID-WATCH observations to improve state estimation and forecasting of the MOC within these systems (section 4, question 1, 2 & 4). RAPID-WATCH research into the predictability of the MOC, ensemble design, and the observational requirements for MOC prediction (section 4.4) will, in turn, feed into improvements in the Hadley Centre's prediction system.

There will be a requirement for proposals to the open call (section 4) to demonstrate how they will contribute to the above broader context.

Thus RAPID-WATCH research will be carried out in close scientific collaboration with the Hadley Centre and will be able to exploit existing links to make its results quickly available to the UK policy community, particularly DEFRA, UKCIP and MCCIP. Knowledge transfer will be treated as an integral part of RAPID-WATCH, rather than an 'add-on' or post-process.

7. International context

The UK has taken an international lead in studying the possibility of rapid climate change due to changes in the MOC. RAPID has established strong international collaborations from the outset and has underpinned these collaborations through joint international funding agreements – the first NERC programme to do so. For both the 26.5˚N and WAVE monitoring projects joint funding decisions were undertaken by RAPID (NERC) in the UK and NSF in the United States, and involved NOAA collaborators. More recently a joint funding call involving RAPID (NERC) in the UK, RCN in Norway and NWO in the Netherlands, led to co-funding of several international consortia. RAPID has also had strong, but more informal, links with scientists in Germany. Discussions about future activities indicate that there is a willingness to continue joint studies beyond the end of the present programme in 2008.[10] For example, NOAA, through the Climate Program Office, is committed to long-term observations of the ocean in the context of GEOSS, including aspects of the 26.5˚N observation programme. RAPID-WATCH will also make use of other observations being made in the Atlantic under international programmes (e.g. IPY, ASOF; which are seeking to answer related questions further north in the Atlantic and Arctic Ocean). More broadly, RAPID-WATCH will contribute to one of the overarching challenges identified at the 2004 CLIVAR workshop on Atlantic predictability — the development of a system for decadal climate prediction — by addressing the allied need for an MOC observing system.

8. NERC priorities and context

This proposal builds on the NERC investment in RAPID, reflecting the priorities articulated in the NERC 2005-2008 delivery plan and endorsed following Council's consideration of the NERC marine sector review. In addition to those critical components noted in 3.4, other possible aspects of

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[10] RCN anticipates future European cooperation in this area of science being through ERANET, others envisage continuing or strengthening cooperation as under RAPID.

the future (yet to be agreed Oceans 2025) investments in NERC Marine Centres (e.g. the Ellett hydrographic line and ARGO float deployments) are complementary to RAPID-WATCH, providing the broader context for understanding the Atlantic circulation. Furthermore, there are complementary studies funded by NERC's IPY programme to be carried out in the Arctic Ocean, the source of key freshwater inputs to the MOC. In addition, RAPID-WATCH will work with the NCAS II programme (2006-2011), which addresses Euro-Atlantic variability and predictability on decadal time-scales and the development of the next generation of coupled models.

Carbon transport and storage by the ocean is another key component of NERC's science, as evidenced by QUEST and Oceans 2025 objectives. The MOC is involved in these processes through its role in large-scale transport and mixing. Improved observations, understanding and modelling of the MOC will elucidate the ocean's role in the carbon cycle, and contribute to both QUEST and Oceans 2025, by providing physical constraints on the transport of carbon.

Data management would build on the framework established under RAPID by the NERC designated data centres (BODC, BADC – see http://www.bodc.ac.uk/projects/uk/rapid/).

9. Building and maintaining the community

RAPID has successfully built a community of scientists working across observational, paleo and modelling fields. As there is a clear benefit to rapid climate change studies in continuing to bring this community together through workshops and meetings, RAPID-WATCH will seek to optimise NERC's investment in RAPID by appropriate focussed workshops involving this broad community.

10. Resources sought and budget – provided separately

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Glossary
AMO = Atlantic multi-decadal oscillation
ARGO = international programme for a global ocean array of temperature/salinity profiling floats
ASOF = Arctic Sub-arctic Ocean Fluxes programme
CLIVAR = Climate Variability programme of the World Climate Research Programme
DEFRA = Department for the Environment, Food and Rural Affairs
DWBC = deep western boundary current
EB = eastern boundary
ECCO = Estimating the Circulation and Climate of the Ocean
EMIC = Earth model of intermediate complexity
ERANET = European Research Area Network – for cooperation in and coordination of research activities
FOAM = Forecasting Ocean Assimilation Model (UK Met. Office)
GCM = general circulation model
GCOS = Global Climate Observing System
GEOSS = Global Earth Observing System of Systems
HiGEM = High resolution Global Environmental Modelling (NERC-funded project)
IPY = International Polar Year
JASON = US-French radar altimeter mission
MAR = mid-Atlantic Ridge
MERCATOR – French ocean data assimilation and forecasting project
MCCIP = Marine Climate Change Impacts Partnership
MOC = meridional overturning circulation
MUCM = Managing Uncertainty in Complex Models, a RCUK-funded programme
NADW = North Atlantic deep water
NCAS = NERC Centres for Atmospheric Science
NCOF = National Centre for Ocean Forecasting – a UK partnership between the Met Office, NOCS, PML, POL, and the Environmental Systems Science Centre, Reading
NERC = Natural Environment Research Council
NOAA = National Oceanic and Atmospheric Administration, USA
NOCS = National Oceanography Centre, Southampton
NSF = National Science Foundation, USA
NWO = Netherlands Organisation for Scientific Research
Oceans 2025 = research programme 2007-2012 proposal to NERC from NERC Marine Centres (*sub judice*)
PI = principal investigator
PML = Plymouth Marine Laboratory
POL = Proudman Oceanographic Laboratory
QUEST = Quantifying and Understanding the Earth System – a NERC directed programme
RCN = Research Council of Norway
RAPID = NERC's Rapid Climate Change directed programme
RAPID2 = proposed successor to RAPID (earlier working title)
RAPID-WATCH = Rapid Climate Change – Will the Atlantic Thermohaline Circulation Halt? Proposed successor to RAPID (full title)
RCUK = Research Councils UK
SODA = Simple Ocean Data Assimilation
SST = sea surface temperature
THC = thermohaline circulation
UKCIP = UK Climate Impacts Programme
UNFCCC = United Nations Framework Convention on Climate Change
WAVE = Western Atlantic Variability Experiment
WB = western boundary

Annexe – array details

26.5°N

Description of array as deployed during 2005: Figure 1 shows the mooring array locations as deployed during 2005. Figures 2, 3 and 4 show the mooring configurations that are now thought to be stable for the remainder of RAPID to 2008. Due to fishing damage on WB4, and loss of MMPs (McClean Moored Profilers) there are some changes to these moorings for 2006. The description that follows is based on the upcoming Spring 2006 deployment.

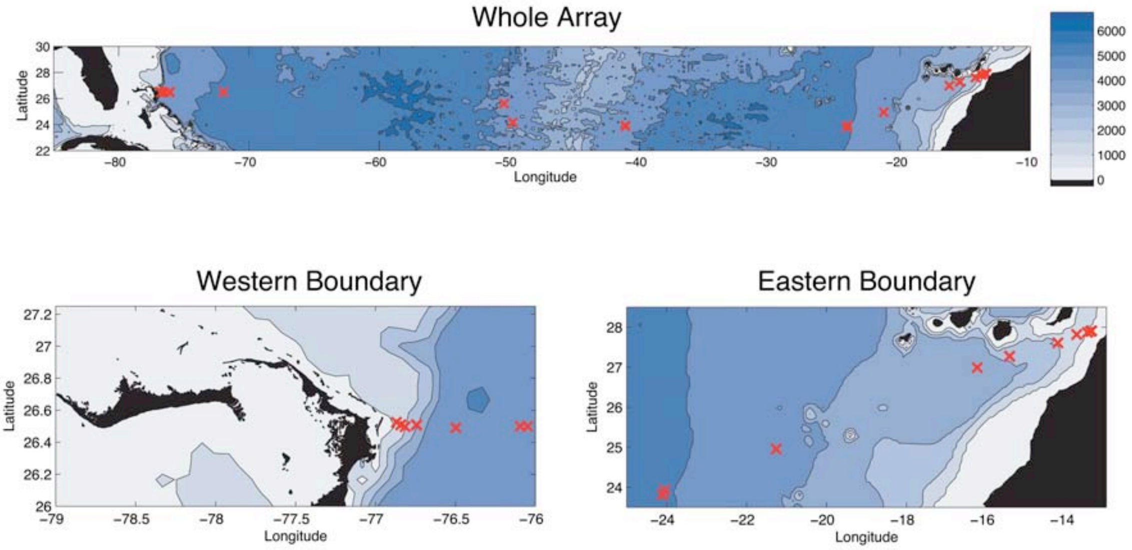

Figure 1. 26.5N mooring locations

Western array at 26.5°N (Figure 2): **WB2** is the pivotal mooring, as close to the western "wall" as possible in 3900m depth, with 13 CTDs and 7 CMs (current meters) and crucially, telemetry. **WB1** is similar to **WB2**, but without telemetry, and will be placed (2006) in about 1400m depth with 8 CTDs and 9 CMs, to obtain thermal-wind shear estimates across the continental slope. **WB4** is similar to **WB2**, but without telemetry, and will be placed at the outer edge of the DWBC core. Note that WB4 is planned to be a full depth mooring, but in 2005 only survived for a few days and the mooring shown in Figure 2 is a half depth emergency replacement and will be replaced by a full depth mooring in Spring 2006. It will obtain thermal-wind shear estimates across the strong current. An upward-looking **ADCP** (from the existing instrument pool) will be deployed in 500m water depth, to capture the shallow Antilles current. **WBL1** and **WBL2** are dual bottom pressure recorders mounted in a bottom lander. These were first deployed in 2005 and are designed for a two-year deployment and will be recovered in Spring 2007. Two further bottom pressure landers will be deployed at these sites in 2006 giving year-long overlapping bottom pressure records. This overlap will allow the construction of continuous bottom pressure records, uninterrupted by mooring recoveries and also allow removal of instrument effects. The need to deploy a third bottom pressure lander close to WB1 is being investigated currently. All the WB moorings will be serviced annually, using Miami as the base.

In addition, the WB array contains a Miami mooring (**Johns B**), close to **WB2**, currently deployed under NSF funding. This mooring is required as the back-up to the critical “tall mooring” **WB2** (just as **EB2** acts as a back-up to **EB1** on the eastern boundary, see below).

MAR array at 26.5°N (Figure 3): **MAR1** and **MAR4** are full depth moorings on either side of the MAR, with distributed CTDs on MAR1 and an MMP and CTDs on MAR4. Note that in 2006 the MMP on MAR4 will be replaced by CTDs. Their backup moorings, **MAR2** and **MAR3**, need only cover the depths below the ridge crest and are therefore equipped with 4 and 6 CTDs respectively. The MAR moorings also have near bottom CMs. **MARL1** and **MARL2** are dual bottom pressure recorders mounted in a bottom lander, and will be refurbished as described for WBL1 and WBL2.

Eastern array at 26.6°N (Figure 4): **EB1** in 5000m depth is the pivotal mooring, consisting of 24 CTDs – the counterpart to **WB2**. **EB2** is the backup and has a profiling MMP, and 4 CTDs. Owing to the more gently sloping topography, compared to the western boundary, the potential of incurring a significant bottom triangle error even from slowly moving water is considerable. To minimise leakage, moorings **EBHi** to **EBH5** obtain density profiles near the sloping bottom, over 500 vertical metres. Each of these 7 moorings has between 1 and 6 CTDs. An upward-looking **ADCP** is deployed at 500m water depth, to capture shallow boundary currents. **EBL1** and **EBL2** are dual bottom pressure recorders mounted in a bottom lander, and will be refurbished in 2006 as described for WBL1 and WBL2. **EBP1** and **EBP2** and pressure inverted echo sounders mounted in bottom frames, deployed in November 2005 with a planned lifetime of 5 years before recovery. These instruments have an acoustic telemetry system and each time the EB array is visited the latest data sets from these instruments is downloaded.

The monitoring array described above presently consists of 18 moorings and 8 bottom landers (measuring temperature, salinity, currents, and pressure). The presence of the mid-Atlantic ridge complicates the endpoint monitoring of the MOC, because a pressure drop may exist across the ridge. Separate monitoring of the sub-basins to the east and west below the ridge crest is therefore necessary until sufficient data have been obtained to determine whether or not these moorings are required permanently. In addition the density on the sloping shelf-break topography on the eastern and western continental boundaries, from deep water to shallow depths, is monitored to obtain continuous observations at fixed depths. This provides an alternative vertical sampling strategy to the full ocean depth “tall moorings,” and also helps solve the “bottom triangle” problem. This approach needs to be evaluated once sufficient data are available.

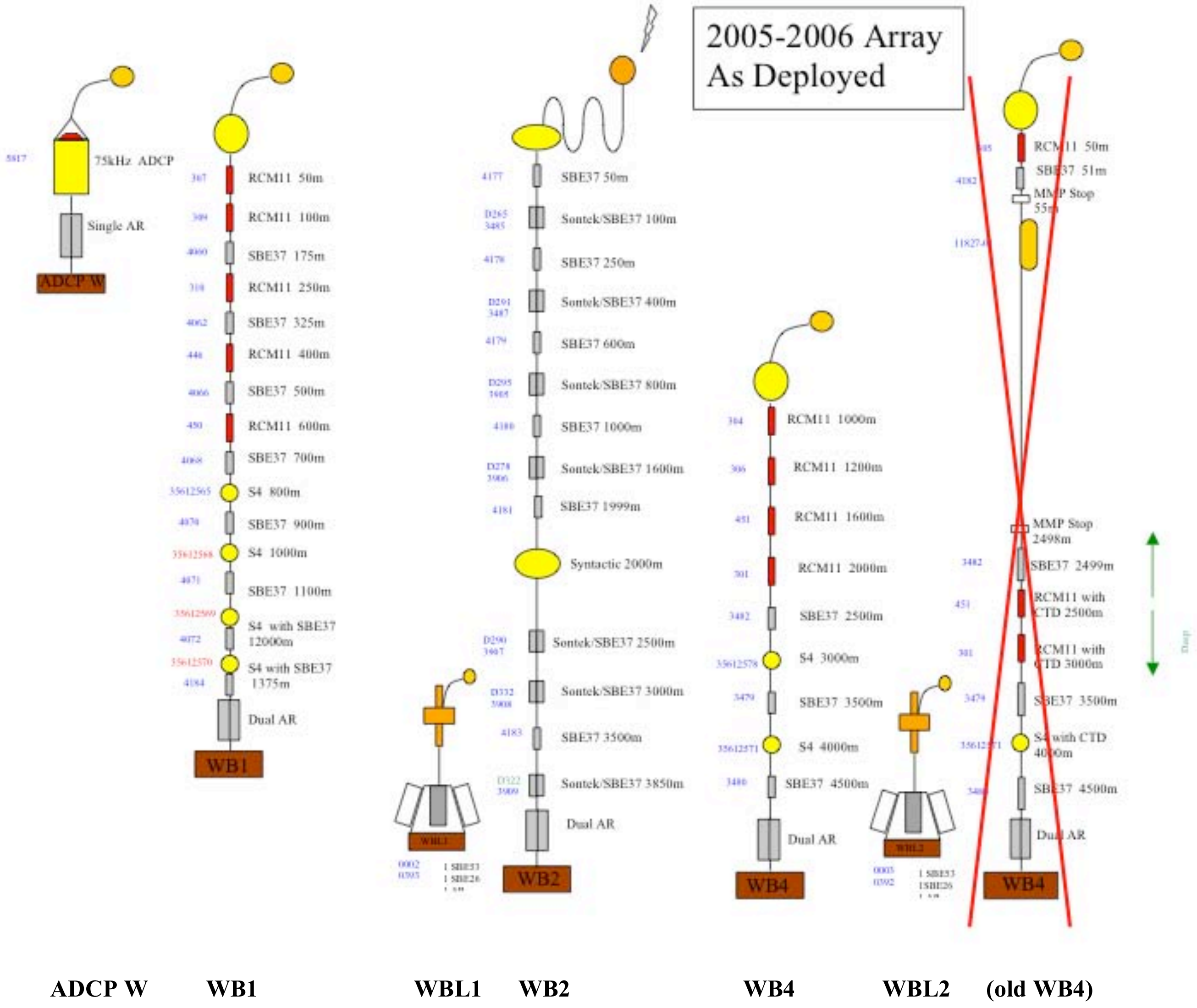

Figure 2. WB array

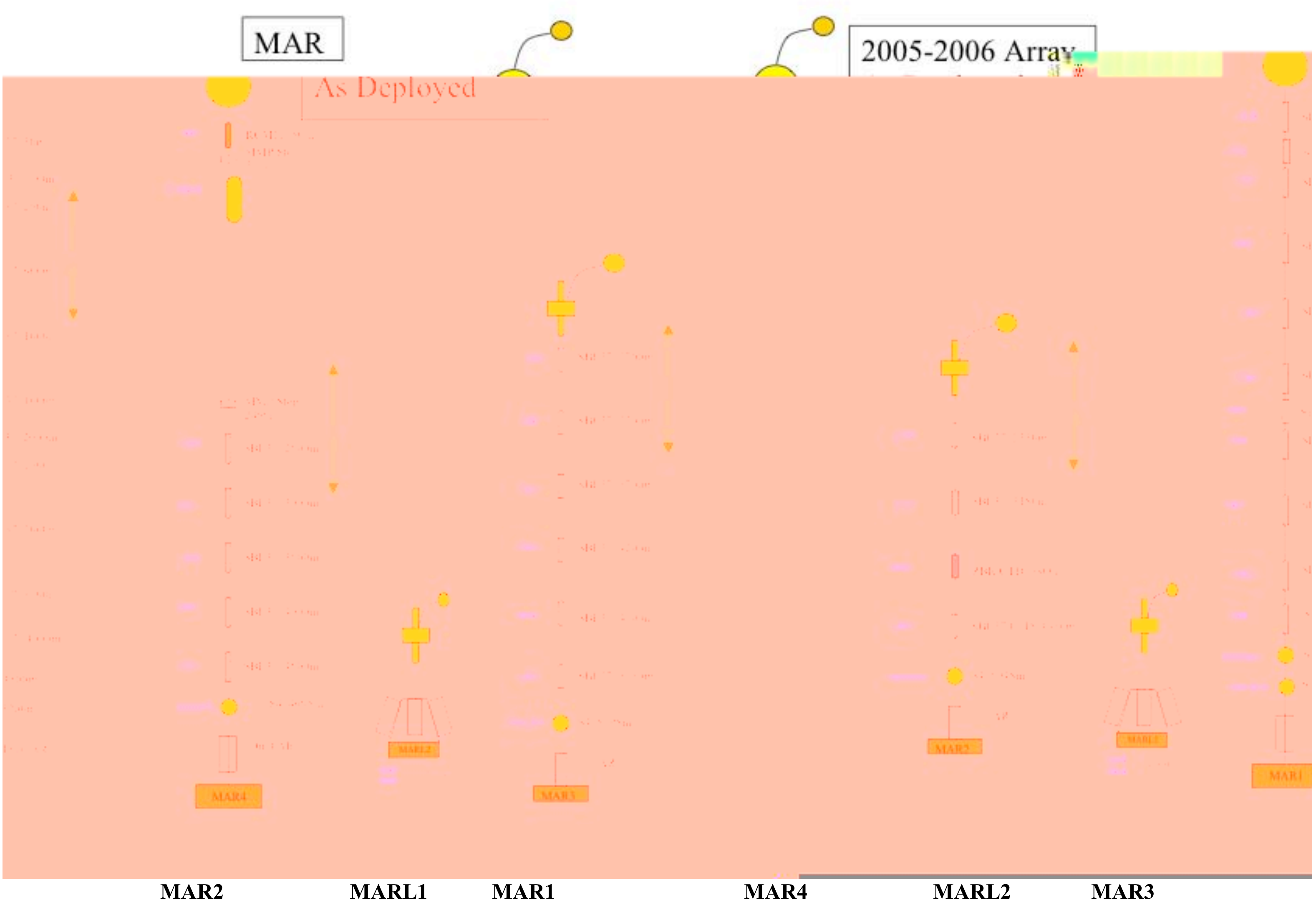

Figure 3. MAR array

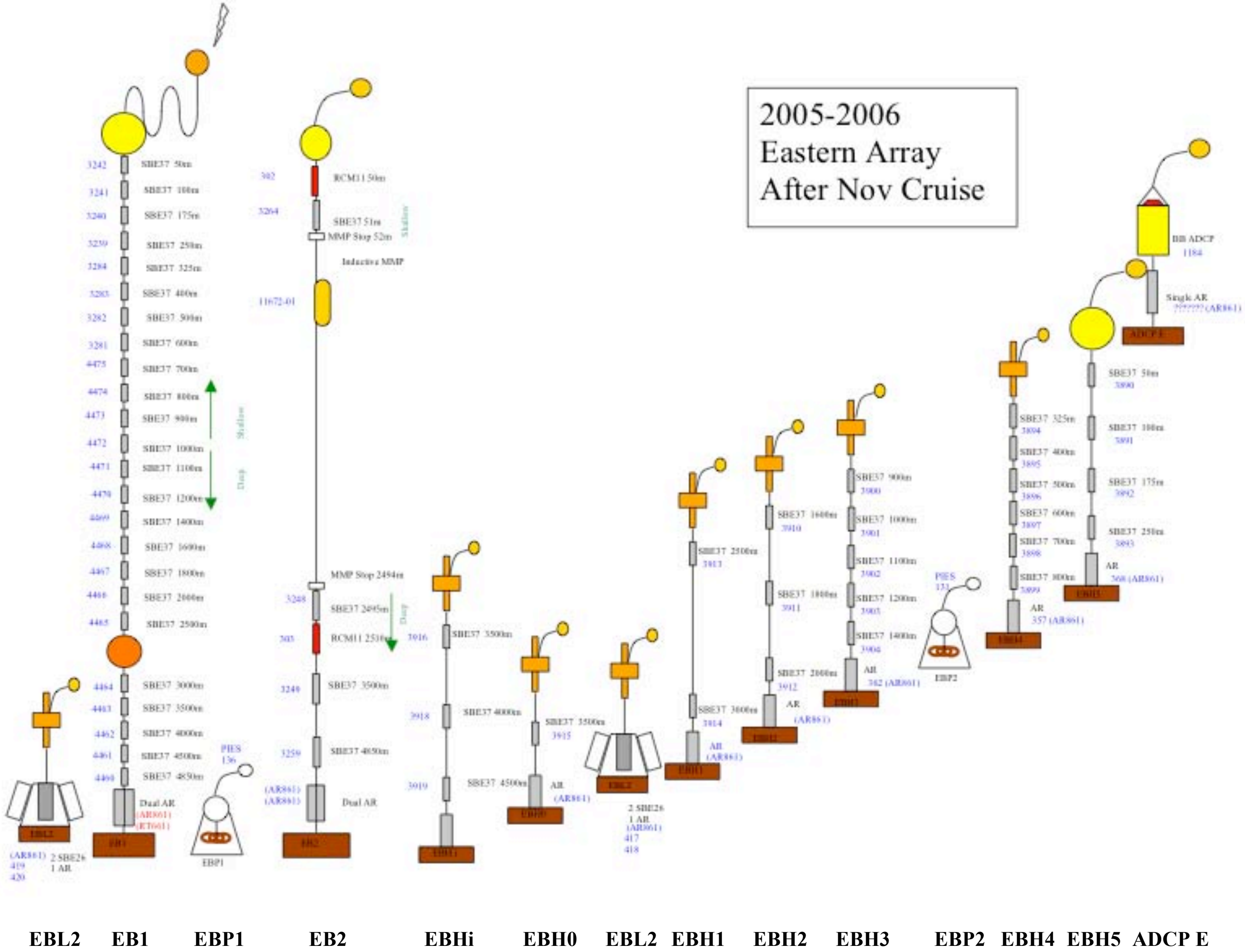

Figure 4. EB array

WAVE (Western Atlantic Variability Experiment)

Description of array as deployed during 2004: Figure 5 shows the lines A, B, and W as deployed under RAPID (2004-2008) and Figure 6 shows the bottom pressure recorder/mooring configuration along each line. Each of these lines is aligned with overlying JASON altimeter tracks.

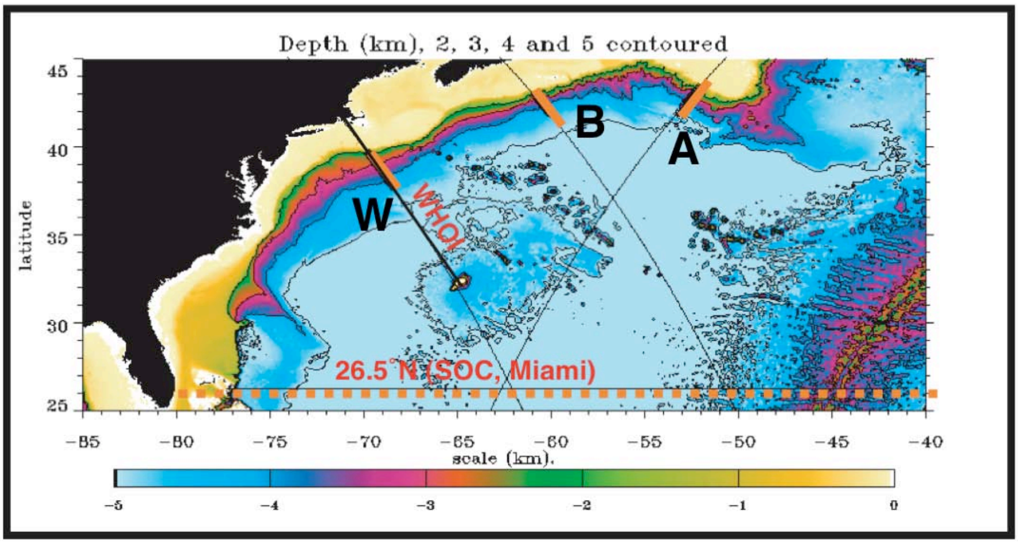

Figure 5. WAVE bottom pressure recorder/mooring array lines A, B and W (solid orange lines). Also shown are the 26.5N line (dotted orange line), altimeter tracks (thin black lines), and bathymetry (colour shading).

Lines A and B (Grand Banks and Halifax): Bottom pressure recorders/inverted echo sounders (mounted in bottom landers) are deployed at target depths of 1800m (A0/B0), 2200m (A1/B1), 2700m (A2/B2), 3200m (A3/B3), 3700m (A4/B4) and 4100m (A5/B5). Moorings are deployed at all but the innermost locations (A0/B0). The moorings A1/B1, A3/B3 and A5/B5 extend over the full height of the array to a depth of 1800m, with CTDs/CTs at 100m intervals over the lowest 400m (A1/B1) or 500m (A3/B3/A5/B5) and at the heights of the remaining bottom pressure recorders thereafter. These instruments were first deployed in August 2004 and will be serviced at two yearly intervals.

Line W (Woods Hole – Bermuda): This line is primarily NSF-funded, led by John Toole (WHOI), and consists a mix of conventional current meter and moored profiler moorings, complemented by semi-annual hydrographic sampling across the slope and Gulf Stream. The specific contribution of RAPID to this array is the addition of 6 bottom pressure recorders/inverted echo sounders at the same target depths as lines A and B and some additional CTD sensors. The bottom pressure recorders were first deployed in April 2004 and will be serviced every two years, although the moorings are serviced by Woods Hole more frequently.

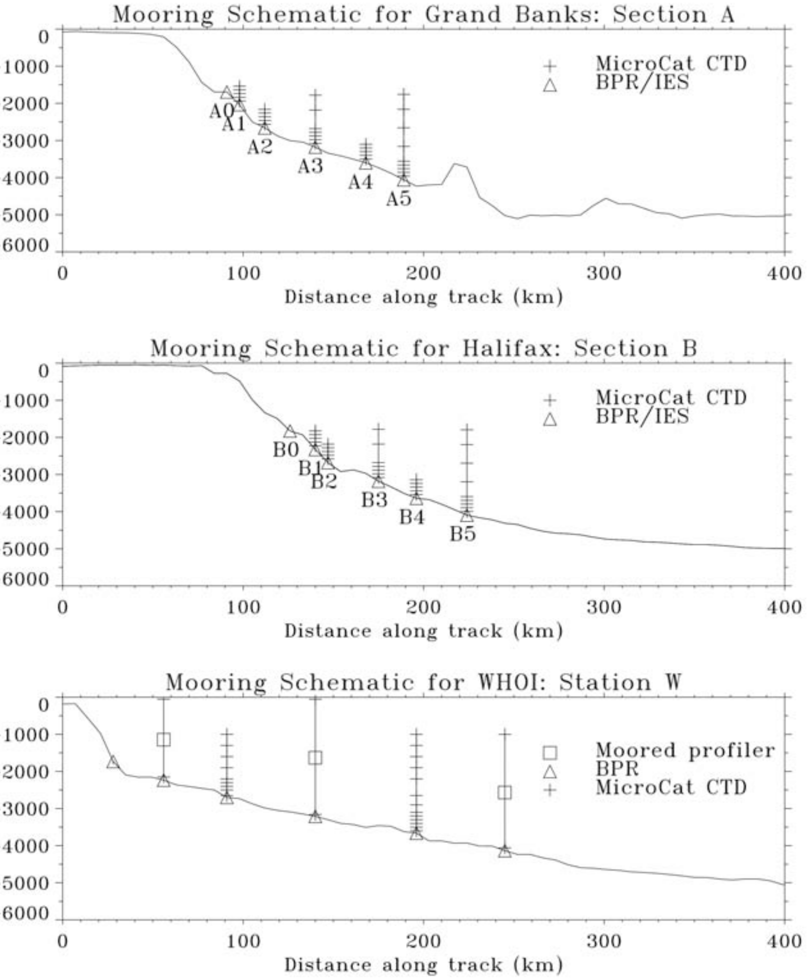

Figure 6. Bottom pressure recorder/mooring configurations along each of the WAVE array lines.