MCCIP ARC Science Review 2010-11
Atlantic Heat Conveyor (Atlantic Meridional Overturning Circulation)

MCCIP Marine Climate Change Impacts Partnership

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EXECUTIVE SUMMARY

The meridional overturning circulation (MOC) is part of a global ocean circulation that redistributes heat from Equatorial to Polar regions. In the Atlantic the MOC carries heat northward (the Atlantic Heat Conveyor) which is released to the atmosphere and maintains UK temperatures between 3 to 5°C higher than elsewhere at similar latitudes. However, the present strength and structure of the MOC may not continue. The 2007 IPCC assessment report (IPCC, 2007) suggests that there is less than 10% chance of abrupt changes during the 21st Century, but that there is greater than 90% chance that MOC will slow by an average of 25% compared to pre-industrial levels, offsetting some of the warming over the European sector of the North Atlantic, and contributing to the rate of sea-level-rise. Daily observations using the RAPID MOC mooring array at 26.5°N are providing a continuous and growing time-series of the MOC strength and structure, but the five year record is at present too short to establish trends in the annual mean MOC. Other observations do not at present provide a coherent Atlantic wide picture of MOC variability, and there is little evidence of any long-term slowing. Ocean assimilation models suggest a slowing over the past decade of around 10%. However, models still have many problems in representing ocean circulation and conclusions of change are very uncertain.

FULL REVIEW

Introduction

The Atlantic Meridional Overturning Circulation (AMOC) comprises a net northward flow of warm water in the upper ~1 km, overlying a net southward flow of cold water. The AMOC carries up to 25% of the northward global atmosphere-ocean heat transport in the northern hemisphere (Bryden and Imawaki, 2001), progressively losing heat to the atmosphere en route. Changes in the AMOC, uncompensated by the atmospheric circulation, may impact western European climate, which is strongly influenced by AMOC heat transport.

Since 2004 we have been able to continuously monitor the AMOC and associated northward heat transport through measurements from the 26°N mooring array of the "Rapid Climate Change" (RAPID) Research Programme of the Natural Environment Research Council (NERC) (www.noc.soton.ac.uk/rapidmoc/) (Figure 1). These data

reveal energetic short-term variability (Cunningham *et al.*, 2007), but we cannot yet identify slower (decadal) variability or trends in the AMOC because the timeseries is only half a decade long.
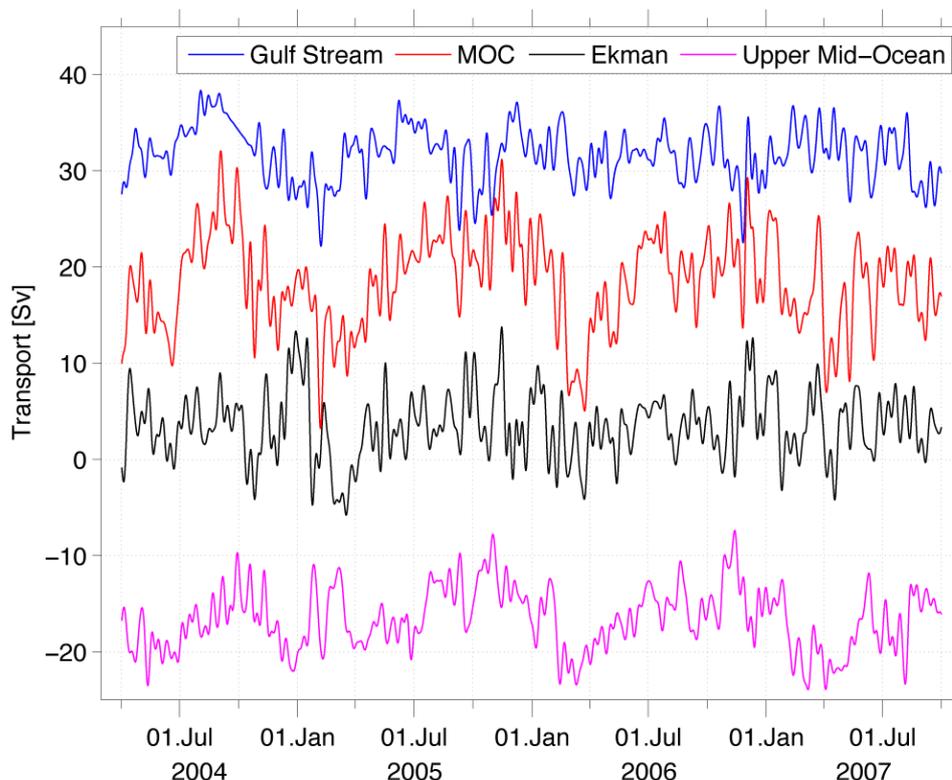

Figure 1: Twice daily time series of Florida Straits transport (blue), Ekman transport (black), upper mid-ocean transport (magenta) and reconstructed AMOC transport (red). Transports in Sv, positive northward (1 Sv = 10^6 m^3s^{-1}). Florida Straits transport is based on electromagnetic cable measurements. Ekman transport is based on QuikScat winds. The upper mid-ocean transport is the vertical integral of the transport per unit depth down to 1100 m. Overturning transport is the sum of Florida Straits, Ekman and upper mid-ocean transport (Cunningham et al., 2007). The mean ± standard deviation of Gulf Stream, Ekman, upper-mid ocean and overturning transports are 31.7±2.8 Sv, 3.5±3.4 Sv, -16.6±3.2 Sv and 18.5±4.9 Sv respectively. These data products (and several other relevant quantities) and the gridded files used in their computation are freely available without restriction at www.noc.soton.ac.uk/rapidmoc. All calibrated instrument records may be obtained from www.bodc.ac.uk. We encourage download and analysis of the data.

Climate model predictions suggest that the AMOC could slow by up to 30% over the coming decades (Figure 2) in response to rising atmospheric CO_2 levels (Gregory *et al.,* 2005). The relationship between AMOC strength (as measured as a volume flux) and northward heat transport is strong, with studies demonstrating that most variability in the former can be related to changes in the latter, for a given location (e.g. Wen *et al.*, 2010; Dong *et al.*, 2009; Baehr *et al.*, 2007). Therefore, a change in AMOC strength is not only expected to exacerbate sea-level rise in the North Atlantic (Yin, *et al.*, 2009), but also impact climate at the global scale via teleconnections (Vellinga and Wood, 2007). Kuhlbrodt, *et al.*, 2009 recently undertook an integrated assessment of the risks associated with a major reduction of the AMOC.
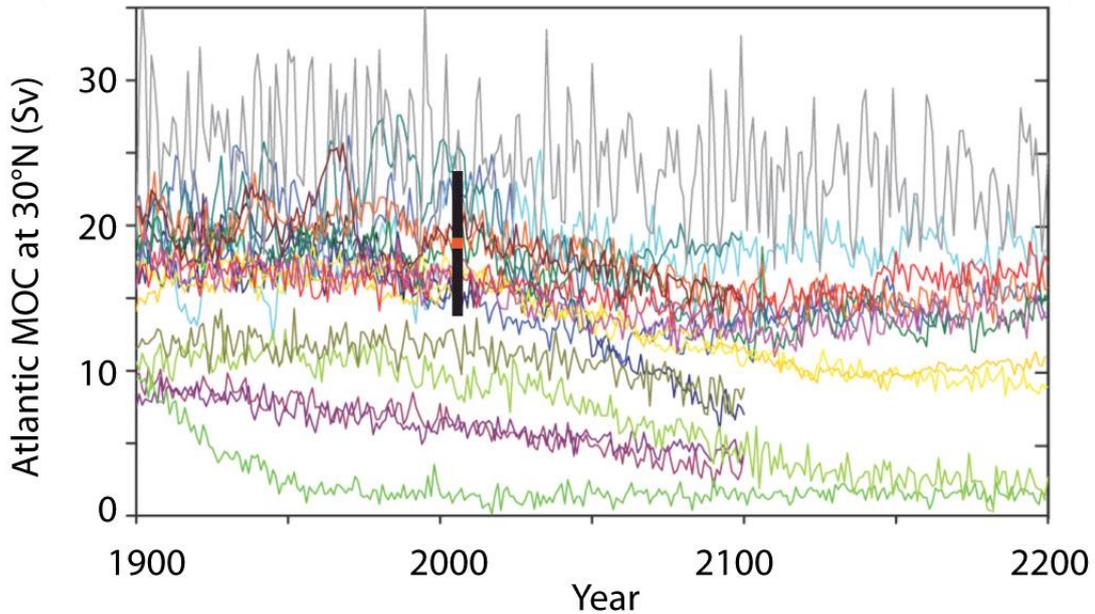
Figure 2: *Evolution of the Atlantic meridional overturning circulation (AMOC) at 30°N in simulations with the suite of comprehensive coupled climate models from 1850 to 2100 using 20th Century Climate in Coupled Models (20C3M) simulations for 1850 to 1999 (axis begins at 1900) and the SRES A1B emissions scenario for 1999 to 2100. Some of the models continue the integration to year 2200 with the forcing held constant at the values of year 2100. Observational estimate of the mean AMOC and its variability observed at 26.5°N for 3.5 years from 1st April 2004 (black bar). The mean AMOC for this period is 18.5 Sv with a standard deviation of ±4.9 Sv (for twice daily values). Three simulations show a steady or rapid slow down of the AMOC that is unrelated to the forcing; a few others have late-20th century simulated values that are inconsistent with observational estimates. Of the model simulations consistent with the late-20th century observational estimates, none shows an increase in the AMOC during the 21st century; reductions range from indistinguishable within the simulated natural variability to over 50% relative to the 1960 to 1990 mean. Adapted from IPCC, 2007.*

1. What is already happening?

What do observations tell us about the changing AMOC?

Observation-based estimates of the AMOC

The AMOC can be estimated from hydrographic measurements on basin-wide, full-depth sections. Estimates of AMOC intensity at 26°N (Bryden, *et al.*, 2005) from five hydrographic sections between 1957 and 2004 suggest a slowing of the AMOC of 6 Sv, with a change of 4 Sv from 1992 to 2004. Snapshot estimates of the AMOC from hydrographic sections alias ocean variability (Ganachaud, 2003), and for single section analysis an error of around 6 Sv is considered appropriate. The slowing inferred by Bryden *et al.* (2005) is within this error but was accompanied by water mass property changes that they argued are consistent with a slowing of the AMOC. Using CTD stations and mooring observations near the western boundary taken between 1980 and 2004, Longworth, 2007 estimates a long-term decrease in the AMOC over this period of about 2 Sv. Lherminier, *et al.*, 2007report a 2 Sv slowing of the AMOC in the northeast Atlantic from hydrographic sections in 1997 and 2002. In contrast Lumpkin, *et al.*, 2008 do not find a change in the AMOC at 48°N from five hydrographic sections taken between 1993 and 2000.

Continuous monitoring of the AMOC at 26.5°N began in April 2004 with the installation of a transatlantic mooring array, designed as a pre-operational monitoring system to replace expensive and rare hydrographic sections (Cunningham, *et al.*, 2007, Kanzow, *et al.*, 2007). The annual mean AMOC from April 2004 was 18.7 Sv

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with a standard deviation of 5.6 Sv (Figure 1). Data recovered since 2007 are presently being analysed and will be published in course to extend the series to the present day. The array effectively monitors the annual mean AMOC with an accuracy of 1.5 Sv, so any secular trend in the coming decades can be measured against the 2004-2005 baseline.

Observations of associated oceanographic processes and impacts

Long-term salinity trends may be a key indicator of AMOC change (Wu, *et al.*, 2004). Peterson, *et al.*, 2006 summarize the processes responsible for Arctic and northern North Atlantic freshening over several decades (to the early new millennium), while Holliday, *et al.*, 2008 report a recent reversal of this freshening trend (since around 2000) in northeast Atlantic and the Nordic Seas. Over the same period, overflow transports have not notably changed. Olsen, *et al.*, 2008 show that overflow across the Greenland-Scotland Ridge has been rather stable over the period 1948-2005. Generally, the flux of the deep western boundary current (DWBC) as measured by current meter arrays is found to be steady (Schott, *et al.*, 2006). An exception is off Cape Farewell, Greenland, where the boundary current may show some decadal variability (Bacon and Saunders, 2009).

Convective activity in the Labrador Sea may have just undergone an important change. Yashayaev and Loder, 2009 and Våge, *et al.*, 2008 report recent resumption of deep convection in Labrador Sea, in winter 2007/08, after more than a decade of suppressed convection. Changes in the properties of water exported from the Labrador Sea are readily identified propagating downstream in the boundary currents (Curry, *et al.*, 1998), suggesting a direct link with the evolution of the AMOC.

Recently, direct association of the AMOC with thermohaline forcing has motivated reconstructions that are based on surface heat and freshwater fluxes alone. By this approach, the AMOC is inferred to have weakened from the 1990s to the early 2000s, by ~3 Sv (Grist, *et al.*, 2009; Josey, *et al.*, 2009).

At present, the utility of these observations is limited to understanding local changes. A broader physical understanding of AMOC variability may be attained once we can reliably assimilate these disparate observations into ocean models. However, even our highest resolution ocean models are in some respects rather flawed, particularly in the representation of overflows (Saunders and Cunningham, 2008), to such an extent that assimilation may not yet add much value at high latitudes and in the deep ocean.

Proxies for past changes in the AMOC

Broecker and Denton, 1989 originally proposed that sudden changes in the AMOC caused past abrupt climate change in the Atlantic sector, in the form of the "Dansgaard-Oeschger" cycles that are a prevalent feature of glacial climate. Although the phenomenon of rapid AMOC collapse/recovery in the glacial past has since received much attention (McManus, *et al.*, 2004, Schmittner, 2005), an alternative view of abrupt climate change invokes interplay between ice sheets and the atmospheric circulation that subsequently impacts the AMOC (Wunsch, 2006).

These three classes of observations provide us with a wide range of information on changes in the AMOC, but little consensus on what has been happening in the past, both recent and distant.

What do models tell us about the changing AMOC?

Past AMOC changes and future projections have been addressed with a range of models and methodologies.

Assimilation of observations in ocean model hindcasts

In ocean models of relatively coarse horizontal resolution (~1°), a range of techniques have been developed for the assimilation of observations. Results from the "Estimating the Circulation & Climate of the Ocean" (ECCO) project (see http://www.ecco-group.org/index.htm), indicate the AMOC slowed between 1993 and 2004, at the rate of 0.19 ± 0.05 Sv/yr (Wunsch and Heimbach, 2006). Based on an alternative data assimilation system, ECMWF operational reanalysis, Balmasada, *et al.*, 2007 find decadal anomalies of around ±4 Sv and a decline by 6-8 Sv from the mid 1990s to 2006. A German project, GECCO Köhl and Stammer, 2007 has a fairly steady increase of the AMOC, by ~4 Sv, from the 1960s to the mid-1990s, followed by a short period of decline that may be part of a longer decadal variation.

High-resolution ocean model hindcasts

Eddy-permitting and eddy-resolving simulations (~1/4°)are more typically forced with realistic atmospheric boundary conditions, so drifts are more likely, but the drifts can be separately diagnosed (Marsh, *et al.*, 2005). Based on the eddy-permitting Ocean Circulation & Climate Advanced Model (OCCAM), Marsh, *et al.*, 2008 find little change of the AMOC over 1985-2004, but a clear step change in northward heat transport around 1997/98 associated with extensive warming of the mid-latitude North Atlantic in the late 1990s. Using an eddy-permitting ocean model based on the new NEMO framework, with higher resolution (1/10°) in the key region around southern Africa, Biastoch, *et al.*, 2008 establish a subtle influence of the Indian Ocean on decadal variability of the North Atlantic MOC, over 1958-2001.

More generally Marsh, *et al.*, 2009 emphasize the influence on hindcast AMOC changes of horizontal resolution, between eddy-permitting and eddy-resolving (1/4° and 1/12°, globally). Largest differences between both mean structure and temporal variability of the AMOC arise in mid-latitudes, where ocean eddies are most energetic. By comparison with observations, they conclude that the eddy-resolving version of OCCAM provides a more realistic AMOC hindcast. The latest comparison of model and observations is presented in Figure 3, which shows AMOC strength at 26°N in the 1/12° OCCAM model alongside the published estimates of the AMOC in 1992, 1998 and 2004 (Bryden, *et al.*, 2005) and the first 3.5 years of RAPID array estimates (http://www.noc.soton.ac.uk/rapidmoc/).

The RAPID-estimated AMOC exceeds that in OCCAM during summer, but variability is similar in both model and observations. The longer OCCAM time series (1988-2006) provides an opportunity to place earlier one-time AMOC estimates in the context of variability on a range of timescales. Baehr, *et al.*, 2009 also find a close correspondence between the observed and modeled AMOC variability for the ECHAM5/MPI-OM coupled model (and the ECCO-GODAE state estimation). This is encouraging in the context of estimating natural variability in climate simulations and for detecting changes in the AMOC.
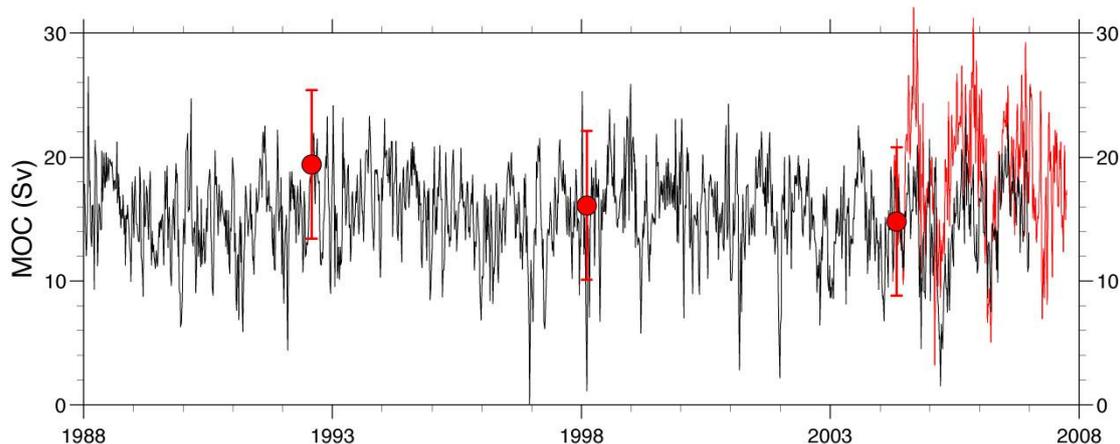
Figure 3. *Time series of 5-daily AMOC strength at 26°N in the 1/12° OCCAM model, 1988-2006 (black line, as Marsh et al., 2009), alongside published estimates of the AMOC in 1992, 1998 and 2004, with published error bars (Bryden, et al., 2005), and RAPID array estimates twice daily from 2 April 2004 to 1 October 2007 (red line, www.noc.soton.ac.uk/rapidmoc).*

Climate models and the AMOC influence on climate

Climate models can provide insights on the mechanisms that cause AMOC variability. Links between climate variability and AMOC changes in coupled climate models have been sought since evidence for decadal oscillations first emerged in the early 1990s (Delworth, *et al.*, 1993). While it has been argued that the AMOC, associated heat transport, and variability thereof, may actually have rather little influence on European climate (Seager, *et al.*, 2002), the consensus is that AMOC variability does influence climate through associated slow variations in sea surface temperature (SST).

Latif, *et al.*, 2004 established empirical relationships between north-south SST gradients and AMOC strength in climate models, on decadal timescales. Latif, *et al.*, 2006a these relationships to SST observations, concluding that the AMOC has increased since the 1980s, in association with a positive phase of the Atlantic Multi-decadal Oscillation (AMO). The AMO, and by implication the underlying AMOC variability, is believed to exert considerable influence on Atlantic sector climate (Knight, 2005, Hetzinger, 2008). However, attribution of recent climate variability to AMOC changes is still at a very early stage. The detection of a possible anthropogenic influence on the AMOC has also been investigated with climate models (e.g., Vellinga and Wood, 2004; Baehr, *et al.*, 2007). Such studies provide further justification for long-term monitoring, as an anthropogenic trend may only be detected after at least a decade of continuous observations.

AMOC predictability and decadal forecasting with climate models

Following from Griffies and Bryan, 1997, extensive research on decadal predictability of the AMOC has established that, under some circumstances, the AMOC may be predictable up to a decade ahead (see review by Latif, *et al.*, 2006b). Two different systems have so far been developed for decadal climate forecasting (Smith, *et al.*, 2007 Keenlyside, *et al.*, 2008). However, while Smith, *et al.*, 2007 show that more accurate depiction of internal variability in the global ocean (through assimilation) significantly improves the prediction of global-mean temperature in decadal climate hindcasts, this is paradoxically not the case in the North Atlantic.

An overall conclusion is that models do not yet provide us with a consensus on recent change in the AMOC. In the specific case of ocean models, differences may be associated with choice of:

- model type (in particular, the vertical coordinate)

- resolution (non eddy-permitting, eddy-permitting, eddy-resolving)

- parameters and parameterizations (diapycnal mixing, eddies, overflows)

- experimental design (with or without assimilation)

- boundary conditions (surface, lateral)

2. What could happen in the future?

Recent projections, using a new generation of climate models, support the assessment presented in UKCIP02 and suggest that the MOC will weaken gradually in response to increasing levels of greenhouse gases (Figure 2). The models examined in the IPCC AR4, excluding those with a poor simulation of the present day MOC, suggest reductions of between 0 and 50% in the MOC by 2100, under the SRES A1B (UKCP09 Medium) emissions scenario. An ensemble of HadCM3-based coupled models, similar to the one used to generate the UKCP09 probabilistic projections, shows a slightly narrower range of weakening under an idealised scenario of CO_2 increase (Figure 4). The effects of the gradually weakening MOC on UK climate are included in the UKCP09 climate projections. No comprehensive climate model, when forced with one of the SRES emissions scenarios, produces a complete or abrupt MOC shutdown in the 21st century, consistent with the models shown in Figure 4. However models in general do not allow for the possibility of increased fresh water supply due to rapid ice flow from the Greenland ice sheet, which has been observed in recent years; such extra fresh water could result in further MOC weakening.

The simulations of rapid MOC changes that have been seen generally come from less complex climate models; such models are computationally cheaper and so the range of possible behaviours can be explored more fully than with the comprehensive climate models used in UKCP09, but, being simpler, the models may omit key processes affecting the stability of the MOC. Assessing the evidence overall, the IPCC AR4 concludes that it is very likely (>90% chance) that the MOC will weaken gradually over the 21st century in response to increasing greenhouse gases, but very unlikely (<10% chance) that an abrupt MOC change will occur in that time. Longer term changes cannot be assessed with confidence at this stage. The effects of any rapid MOC changes (beyond the expected gradual weakening seen in most climate model simulations) would be superimposed on any manmade global climate change that had already taken place. Some of the MOC effects, for example any cooling over the UK, would oppose those due to man. Others, however, would reinforce the global man-made signal — for example additional summer drying, and sea level rise reinforcing that due to thermal expansion.

The figures derived from hypothetical MOC shutdown experiments such as those discussed above show that an MOC shutdown, while very unlikely, could produce climatic effects as large as, or larger than, the effects of increasing greenhouse gases. Thus research to improve our understanding of the probability of such events, and to improve the prospects for early warning, continues to be a priority. Recent developments in both models and observations have improved our fundamental

understanding of what controls the MOC, and in time this can be expected to narrow the uncertainty over the future of the MOC.
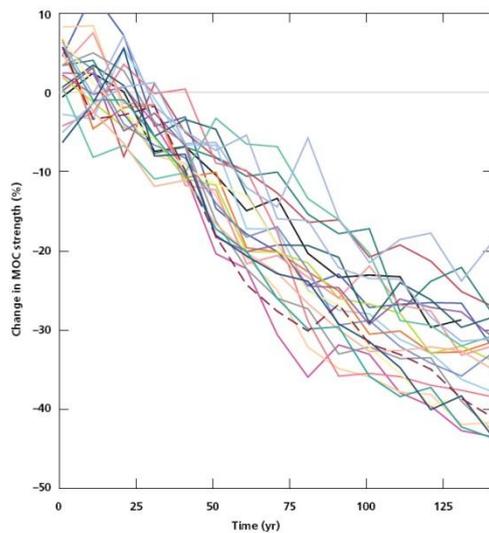

Figure 4: Model simulations of the change in MOC strength under an idealised 1%-per-annum increase of CO_2 concentrations. Twenty-two simulations are shown, from a HadCM3-based perturbed physics ensemble similar to the one used to generate the UKCP09 projections. MOC change is expressed as a percentage of its value in the corresponding control run. (Courtesy M. Vellinga.)

3. Confidence in the science

What is already happening: **Medium**
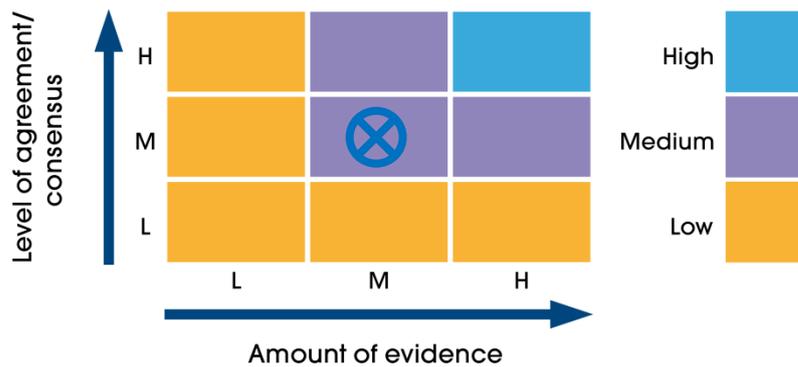
What could happen: **Medium**
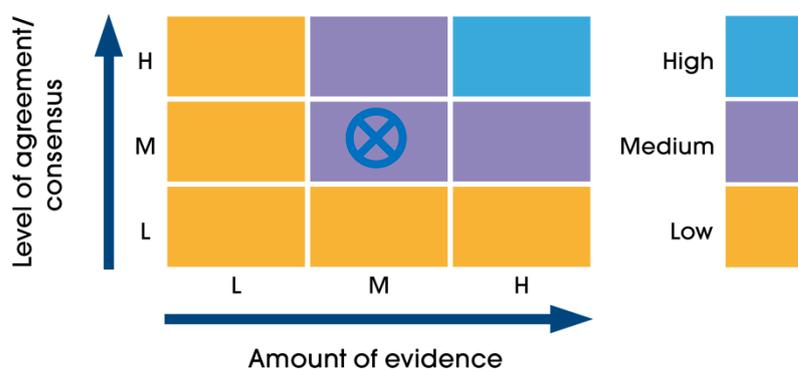
Our confidence in answering the question 'What is happening now?' has risen, since the 2007-2008 ARC, given the extended length of the RAPID 26°N mooring time series. In fact, confidence in what is happening in the immediate time frame (say the

last year or so) is actually high, given the accuracy of the monitoring approach. However, we have assessed here the confidence in what is happening to the longer-term (i.e. decadal) trend, which is of most relevance to society with respect to potential AMOC slowdown, and any possible climatic impacts. Recent projections of future AMOC strength show a consensus of agreement between climate models regarding the sign of change to the AMOC this century. A slow down of between 0 and 50% is considered very likely (>90% chance) by 2100.

4. Knowledge gaps

The top priority knowledge gaps that need to be addressed in the short term to provide better advice to be given to policy makers are:

1. *Ocean Observations and Monitoring:* Fundamentally we require a set of benchmark observations of the AMOC that can provide the necessary full depth, continent-to-continent dynamical constraints at different latitudes throughout the Atlantic for verifying assimilations, coupled climate model hindcasts and for ocean initialization for climate forecasts (Figure 5) (Cunningham *et al.*, 2009).
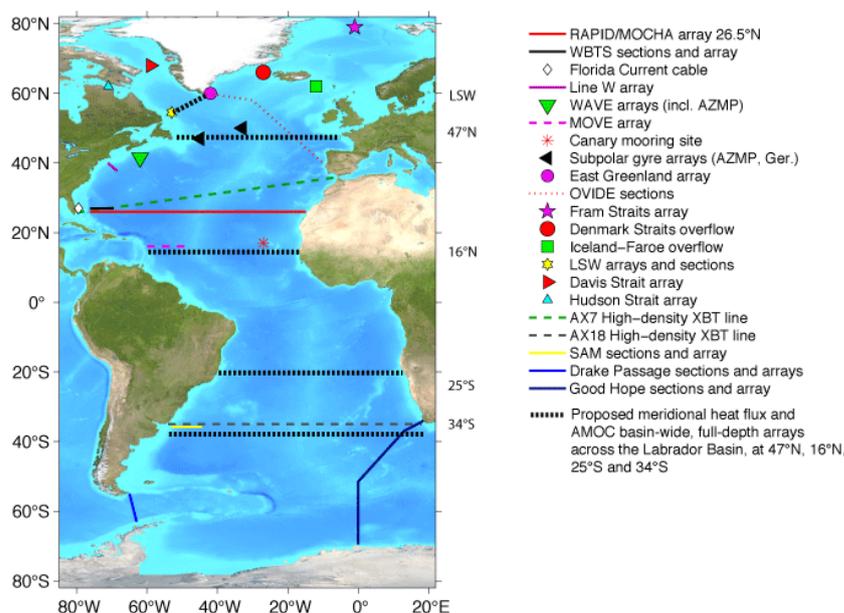

Figure 5: Observational programs presently measuring components of the AMOC, and proposed meridional het flux and AMOC basin-wide, full depth arrays (black dashed).

2. *Ocean Models and Past Reconstruction.* Ocean models should be increasingly used to gain a better understanding of past AMOC changes and the present state of the AMOC. In the near future, we can expect further simulation and analysis with eddy-resolving ocean models that achieve ever more realistic pathways, vertical structure and properties (Hecht and Smith, 2009). However, the modeling community must strive to improve key details of model AMOC (e.g., depth of NADW outflow, see Saunders and Cunningham, 2008).

3. *Climate Models and Decadal Forecasting.* Following the pioneering work of Smith *et al.*, 2007 and Keenlyside *et al.*, 2008, further development of decadal climate forecasting should:

- place more emphasis on the issue of initializing the AMOC state appropriately
- be underpinned by continuing research on decadal predictability of the AMOC
- address different assimilation strategies

5. Socio-economic impacts

Given that almost all climate model projections of future climate incorporate the most probable change to the AMOC this century, i.e. a partial slow down, the majority of socio-economic impacts to the UK and Europe are already summarised through the analysis of changes to primary climatic conditions (i.e. air temperature, precipitation patterns, sea level rise, all of which contain some AMOC-related signal within the broader, and larger, greenhouse gas response).

A broad body of work, however, has addressed impacts relating to the lower-probability, higher-impact, risk of a complete shutdown, some of which attempts to isolate socio-economic consequences.

Initial work in this field, e.g. Higgins and Vellinga (2003), investigated impacts of an AMOC-absent climate system relative to a pre-industrial climate, meaning that any confounding effects on impacts via greenhouse gas warming were unaccounted for. More recently, coupled climate, vegetation and ecosystem modelling experiments have been performed whereby the earth system is allowed to evolve under greenhouse gas emission scenarios, followed by large AMOC perturbation. This approach enables the quantification of AMOC shutdown impacts against the more realistic setting of an unperturbed global warming (called "amoc_ghg"), rather than the pre-industrial climate.

An analysis of the climatic impacts in an amoc_ghg situation using the UK Hadley Centre coupled climate model is given in Vellinga and Wood (2007). A similar experiment, using a different climate model, is summarised by Kuhlbrodt *et al.*, (2009) and is extended to include marine and terrestrial ecosystem model responses. In their experiment, Kuhlbrodt *et al.* (2009) allow IPCC greenhouse gas emission scenarios to progress and then reduce, assuming co-ordinated political intervention on emissions during the 22nd century. In one simulation an added perturbation of gradual fresh-water addition is introduced, resulting in an AMOC collapse part way through the 22nd century: a comparison of the responses in this simulation with the others allows isolation of the additional impacts relating to the AMOC. The key results, likely to be of socio-economic importance, from this study are summarised here:

- **Sea-level Rise:** An additional sea level rise of ~80cm around European coasts is evident in the AMOC-collapse simulation by 2150. By the end of the 21st century, the additional AMOC-related sea level rise is 50cm. If this is superimposed upon an approximate estimate of a 'regular' greenhouse gas sea level rise for the same period, ~50cm, the additional financial requirement for European land protection and population relocation would be US$670 million per year, using calculations based on Stern (2007). The sign and magnitude of these sea-level rises are comparable with other investigations into the response of North Atlantic sea level to abrupt changes in the AMOC (e.g. Vellinga and Wood, 2007; Levermann et al., 2005).

- **Crops:** In all simulations, including the AMOC-collapse scenario, the total area suitable for crop production in Europe increases, despite stresses introduced relating to water shortage. This response can be related to the dominance of

carbon fertilisation as the primary forcing agent for crop efficiency and yield, for the region as an average: by 2150, European annual cereal production, estimated by the vegetation model coupled to the climate model, approximately doubles, even when the AMOC collapses.

- **Marine Net Primary Production (NPP):** By 2150 North Atlantic NPP is seen to markedly decrease in the 'regular' greenhouse gas simulation by around 70% compared with 1990 levels. The response in the AMOC-collapse scenario is similar, but the magnitude of the decrease is only slightly larger, despite the absence of the AMOC. The similarity in responses is related to the reduced tendency for mixing in the upper ocean and the associated depletion of nutrients towards the surface; the larger decrease in NPP for the AMOC-collapse scenario seems related to a reduction in north-eastward nutrient transport through the Faroe-Shetland region associated with a retarded North Atlantic Current.

- **Fish:** The application of high-resolution regional ocean - ecosystem modules in this study, simulating cod larvae and juvenile survival rates in the prime spawning area north of Norway, demonstrated that a 35% reduction in the AMOC led to a widespread decrease in cod distribution, compared to the present day. The decrease is thought to be related to local ocean circulation changes, resulting in the advection of cod juveniles and larvae into regions where they are unable to survive. Parameterizing this effect under global warming scenarios shows that whilst in a 'regular' greenhouse warming scenario, with a partial AMOC slow down, cod harvesting remains largely unchanged (due to successful recruitment of new generations), an AMOC collapse super-imposed on this scenario leads to marked reductions in cod harvest as the North Atlantic population diminishes.

Further important socio-economic exposures related to the AMOC do exist which are not addressed in Kuhlbrodt *et al.*, (2009). One prominent such impact is change to energy demand and consumption. With respect to Western Europe, patterns of temperature change under an AMOC collapse within a simulated greenhouse-warming world, suggest that summer temperatures may remain warmer than pre-industrial conditions, although the magnitude of warming is reduced. During winter, however, an AMOC collapse may be sufficient to cool Western Europe below the pre-industrial reference temperature. Vellinga and Wood (2007) demonstrate in one such climate model experiment that the mean winter Central England Temperature in 2049-2059 after a hypothetical AMOC collapse embedded within an IS92a warming scenario is approximately 3°C, 1°C colder than pre-industrial conditions. Further analysis of this scenario also revealed a tripling of the frost season. Such impacts would almost certainly influence energy demands, although as of yet no quantitative assessment has been undertaken.

Robust investigations of what impacts would likely be felt by the UK marine environment *per se* in the event of abrupt changes to the AMOC are presently lacking in the literature and at best would be speculative given presently-published information. This can be attributed to the relative recentness with which feasible coupled ocean-atmosphere computer experiments can be performed having the necessary geographical resolutions and, perhaps more so, to the immediacy of funding investigations, first, into potential impacts with respect to regional atmospheric and terrestrial climate with their first-order effects upon human population. We hope that as technological resources and funding opportunities develop further this important knowledge deficit can be addressed by the scientific community.

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