

Impacts of climate change on the Atlantic Heat Conveyor

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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 (AMOC) carries heat northward (the Atlantic Heat Conveyor) which is released to the atmosphere and maintains UK temperatures between 3 to 5°C higher than they would otherwise be. However, the present strength and structure of the MOC may not continue. The IPCC Fourth Assessment Report (IPCC, 2007) concludes that there is greater than 90% chance that the AMOC will slow by up to half by 2100, compared to pre-industrial levels, offsetting some of the warming over the European sector of the North Atlantic, and contributing to the rate of Atlantic sea-level-rise. The IPCC also concluded that there is less than 10% chance of abrupt changes during the 21st Century. Daily observations using the RAPID MOC mooring array at 26°N are providing a continuous and growing time series of the AMOC strength and structure, the time series is not yet sufficiently long to determine if there is a long-term trend in the AMOC. There was a significant reduction in the AMOC in 2009-2010 that has since recovered. The relationships between the AMOC reduction and the anomalous winter weather over the UK at the same time are not yet understood. 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. Despite substantial progress over recent years in understanding and modelling the AMOC, projections of its future fate are still subject to significant uncertainty.

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. Variability in the AMOC is highly correlated with the northward ocean heat flux (Johns *et al.*, 2011), which strongly affects the climate of Western Europe and other regions bordering the North Atlantic.

Since 2004, we have continuously monitored the AMOC and associated northward heat transport through measurements from the 26°N mooring array, supported by the Rapid Climate Change (RAPID) Research Programme of the Natural Environment Research Council (NERC) (www.rapid.ac.uk) (Figure 1). The latitude of 26°N was chosen because it is close to the latitude at which the northward heat transport in the Atlantic Ocean is at a maximum (Trenberth and Caron,

2001). There are three components to the AMOC. Firstly monitoring of the AMOC at 26°N is facilitated because the Gulf Stream transport is confined to the Florida Strait and has been monitored since 1982 using undersea electromagnetic cable measurements (Baringer and Larsen, 2001). A second part of the AMOC is the shallow wind driven transport, referred to as the Ekman flow. This is measured by satellite scatterometers. The third part is 'mid-ocean' circulation from the Florida Strait to the coast of Africa and this is monitored by the RAPID team at the National Oceanography Centre, Southampton.

Climate model projections suggest that the AMOC could slow by up to 30% over the coming decades (Figure 2) in response to rising atmospheric CO₂ levels (Gregory *et al.*, 2005). The slowing is caused by increasing buoyancy forcing (warming and addition of fresh-water) at high latitudes that reduces the density of the deep, southward-flowing limb of the AMOC (Gregory *et al.* 2005). Results from the more recent 'CMIP5' models¹ show changes of similar magnitude (Weaver *et al.*

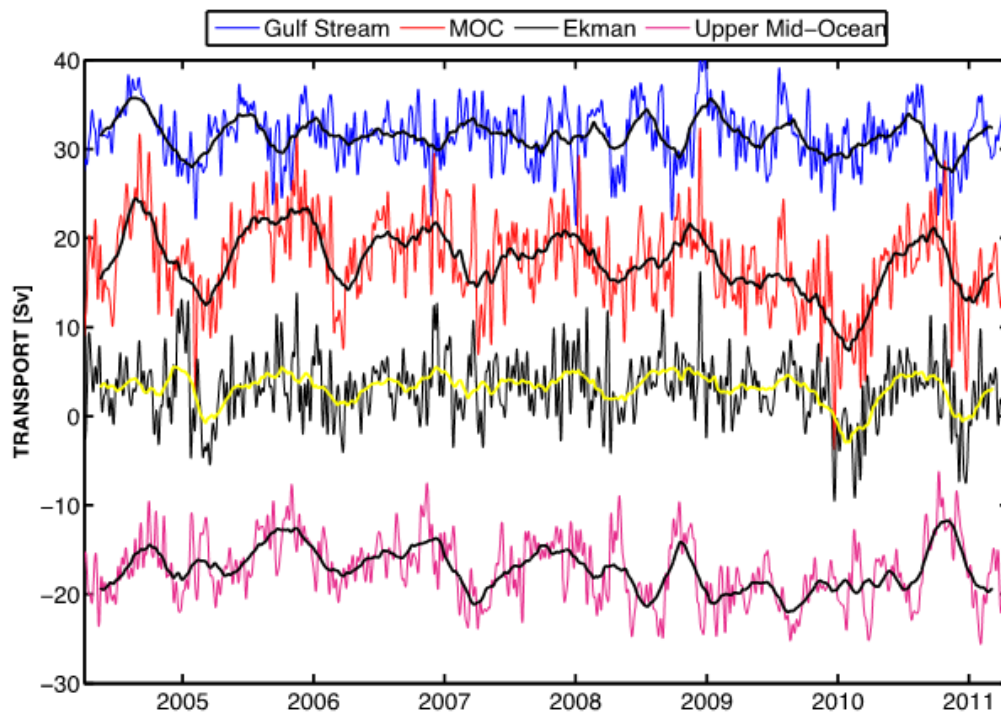


Figure 1: Time series of the AMOC transport (red) from McCarthy *et al.* (2012). The AMOC is the sum of the Florida Straits transport (blue), Ekman transport (black), and upper mid-ocean transport (magenta). Transports in Sv, positive northward ($1 \text{ Sv} = 106 \text{ m}^3 \text{ s}^{-1}$). The data are filtered with a 10 day low pass filter. Also shown in black (yellow for Ekman transport) is the same data with a 90 day low pass filter. The upper mid-ocean transport is the vertical integral of the transport per unit depth down to 1100 m. These data products (and other relevant quantities) are freely available at www.rapid.ac.uk/rapidmoc. All calibrated instrument records may be obtained from www.bodc.ac.uk. We encourage download and analysis of the data.

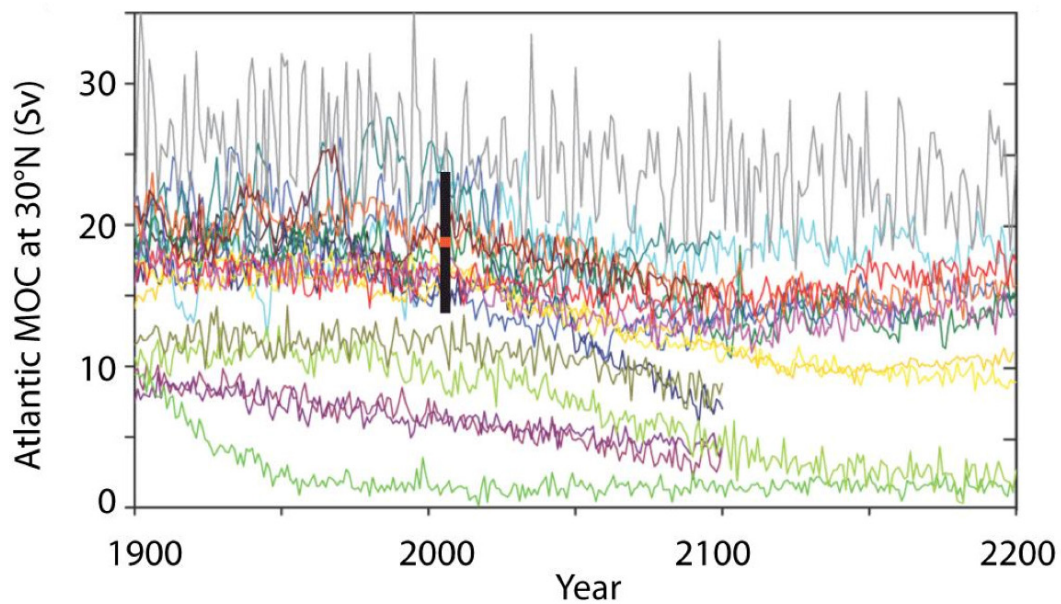


Figure 2: Evolution of the Atlantic meridional overturning circulation (AMOC) at 30°N in simulations with the suite of comprehensive coupled climate models from 1850 to 2100 using 20th Century Climate in Coupled Models (20C3M) simulations for 1850 to 1999 (axis begins at 1900) and the SRES A1B emissions scenario for 1999 to 2100 (A scenario of rapid growth peaking in mid 21st century and declining thereafter). 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 $\pm 4.9 \text{ Sv}$ (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.

2012). The spread among models in the amount of AMOC weakening remains large. The relationship between AMOC strength (quantified 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. Baehr *et al.*, 2007; Dong *et al.*, 2009; Wen *et al.*, 2010). Therefore, a change in AMOC strength is not only expected to exacerbate sea-level rise in the North Atlantic (Yin, *et al.*, 2009; Pardaens *et al.*, 2011), but also impact climate at the global scale via teleconnections (Vellinga and Wood, 2007). An integrated assessment of the risks associated with a major reduction of the AMOC was presented by Kuhlbrodt *et al.*, 2009.

In a range of models, the AMOC has been shown to have bi-stable modes of circulation, such that it can switch from on to off, and a threshold beyond which the AMOC becomes unsustainable and collapses. Theoretical studies suggest that the fresh water transport by the AMOC at the southern end of the Atlantic determines whether the AMOC is in such a bi-stable regime (Dijkstra, 2007; Drijfhout *et al.*, 2011). Recently observations (Bryden *et al.*, 2011) have shown that the AMOC transports freshwater out of the Atlantic, suggesting that the circulation is capable of multiple equilibria. Many of the climate models used in IPCC AR4 had an AMOC fresh water transport into the Atlantic, suggesting that they were biased towards a too stable state (Huisman *et al.*, 2010). However several of the more recent CMIP5 models have an AMOC fresh water transport that is in the same direction as observed; none of these models show an AMOC collapse in the 21st Century, though some show a spin-down in the 22nd Century under strong greenhouse gas forcing (Weaver *et al.*, 2012).

WHAT IS ALREADY HAPPENING?

What do observations tell us about the changing AMOC?

a. Observation-based estimates of AMOC

Continuous monitoring of the AMOC at 26.5°N began in April 2004 with the installation of a transatlantic mooring array. Seven full years of measurements have enabled an examination of the inter-annual variability of the AMOC (McCarthy *et al.*, 2012). While earlier results (Cunningham *et al.* 2007) highlighted substantial seasonal and shorter timescale variability, there was no significant inter-annual variability during the first 5 years of monitoring. The mean AMOC from 1 Apr 2004 to the 31 March 2009 was 18.5 Sv with the annual means having a standard deviation of only 1.0 Sv. From 1 April 2009 to 31 March 2010, the annually averaged MOC strength was just 12.8 Sv, representing a 30% decline from the 2004-2009 average. This downturn persisted from early 2009 to mid-2010. The change was partly due to extreme Ekman transport from December 2009 to March 2010 associated with a negative phase of the North Atlantic Oscillation, but mainly due to a longer

timescale strengthening of southward gyre transport above 1100 m. This can be interpreted as a change in the balance between the overturning circulation and the horizontal gyre circulation above 1100m.

Initial indications are that the AMOC returned values closer to the earlier years in 2011, but the next update on the time-series is not expected to be available until 2013.

A significantly longer time series is needed before the RAPID array can be used to identify any long-term trends in the AMOC. However, some estimates have been made from historical hydrographical measurements. Bryden *et al.* (2005) analysed five trans-Atlantic hydrographic sections conducted at 26°N between 1957 and 2004 that suggested a slowing of the AMOC of 6 Sv. 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 not significant given 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.* (2007) report a 2 Sv slowing of the AMOC across a hydrographic section from Portugal to Greenland between 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. Hobbs and Willis (2011) have also estimated northward heat transport at 41°N from ARGO and altimetry data. They too find no significant trend between 2002 and 2010.

b. 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. The freshening trend was passed on to the system of deep overflow and entrainment (Dickson *et al.*, 2002) and there is evidence that freshening has ended and may also have reversed in these deeper waters (Sarfanov *et al.*, 2010; Dye *et al.*, 2012). In the Denmark Strait overflow short-term (a few months) but large (>0.05) deviations in salinity have been observed and related to wind forcing north of Iceland (Holfort and Albrecht, 2007; Hall *et al.*, 2011). Over the same period, overflow transports have not notably changed. Using a model that validates well against observations and includes significant subdecadal variations in overflow at the Faroe Bank Channel, Olsen *et al.* (2008) show that overflow of the Greenland-Scotland Ridge has been rather stable over the period 1948-2005.

¹The Coupled Model Intercomparison Project Phase 5 (CMIP5) provides a framework for internationally coordinated climate change experiments. It is expected that some of the scientific questions that arose during preparation of the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) will through CMIP5 be addressed in time for evaluation in the Fifth Assessment Report (AR5, scheduled for publication in late 2013).

Some interannual to multi-year variations have been seen in the size of Denmark Strait overflow both at the sill and downstream (Macranders *et al.* 2005, Dickson *et al.*, 2008). However, Dickson *et al.* (2008) could find no trend (1995–2005) in the transport of the plume of the Denmark Strait overflow and Jochumsen *et al.* (2012) recently found no significant trend (1996–2011) in the Denmark Strait overflow at the sill itself but noted a trend to cooler overflow waters. The model analysis of Sandø *et al.* (2012) concludes that the interannual variability of GSR overflow transport reflects to a large degree variations of inflow forced by an NAO-like wind pattern. Generally, however, 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, 2010).

Convective activity in the Labrador Sea may have undergone an important change. Yashayaev and Loder (2009) and Våge *et al.* (2009) report the resumption of deep convection in the Labrador Sea, in winter 2007/08, after more than a decade of suppressed convection. In the same winter convective mixing to 1 km depth was observed in the Irminger Sea by de Jong *et al.* (2012). This was significantly deeper than observed in their preceding observations that started in 2002. Changes in the properties of water exported from the Labrador Sea are readily identified propagating downstream in the boundary currents (Curry *et al.*, 1998; Peña-Molino *et al.*, 2011), suggesting a direct link with the evolution of the AMOC.

Recent theoretical studies suggest that whether or not the AMOC is in a bi-stable state (with an alternative, ‘AMOC-off’ state) may depend on whether the AMOC carries fresh water into or out of the Atlantic. Observations (Bryden *et al.*, 2011) now suggest that the AMOC is in a bi-stable mode, such that the AMOC could in principle switch into an off state with no deep overturning. However, the size of perturbation that would be needed to induce such a switch has not been determined.

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. Recent developments in estimating the state of the AMOC through data assimilation are described in Section 2.

c. 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 events 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).

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.

a. Assimilation of observations in ocean and climate model hindcasts.

In ocean models of relatively coarse horizontal resolution ($\sim 1^\circ$), a range of techniques have been developed for the assimilation of observations to produce estimates of past AMOC variability. Results from the Estimating the Circulation and 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, Balmaseda, *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.

Recently data assimilation has been used to produce ocean state estimates in higher resolution ($\sim 0.25^\circ$) models (Carton and Giese, 2008; Haines *et al.*, 2013). Haines *et al.* (2013) compare in detail the AMOC structure in one such analysis with the RAPID array, and find overall good agreement in the structure of the flow, although there are some differences with the meridional heat transports deduced from the array. Operational data assimilation products used for ocean forecasting and seasonal prediction are now also run at this resolution and are capable of capturing the AMOC anomalies observed by the RAPID array in winter 2009/10 and 2010/11, suggesting the potential to use currently available observations to initialize the North Atlantic for climate predictions.

b. High-resolution ocean model hindcasts

Eddy-permitting ($\sim 1/4^\circ$) and eddy-resolving ($\sim 1/10^\circ$) simulations are typically forced with realistic atmospheric boundary conditions and initialized from some estimate of the ocean state, with the result that care must be taken to separate the ocean response from initial model drifts (Marsh *et al.*, 2005). Based on the eddy-permitting Ocean Circulation and 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 ($1/10^\circ$) 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 ($1/4^\circ$ and $1/12^\circ$, 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.

c. 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). AMOC variations, particularly on longer timescales, have been shown in many models to have a major influence on climate and sea level (e.g. Vellinga and Wood, 2002; Knight *et al.*, 2005; Pohlmann *et al.*, 2006; Pardaens *et al.*, 2011; Woollings *et al.*, 2012). There is also observational and model evidence that variations in Atlantic SST, such as could arise from AMOC variations, can influence a range of climate indices, including European temperature and rainfall in both winter and summer, Atlantic hurricanes, and rainfall in regions as diverse as the Sahel, North and South America (e.g. Knight *et al.*, 2005; Hodson *et al.*, 2010; Sutton and Dong, 2012), although of course the AMOC is not the only influence on European climate (e.g. Seager *et al.*, 2002).

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) linked 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. Recently, aerosol forcing rather than AMOC variability has been proposed as a possible cause of recent North Atlantic SST changes (Booth *et al.*, 2012); however, this remains controversial.

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). These studies suggest that several decades of AMOC observation may be necessary for robust detection of anthropogenic trends. Addition of other variables may in principle reduce the detection time by increasing the signal to noise ratio (Vellinga and Wood, 2004), but current models do not provide a robust (model-independent) design for a more rapid detection variable that could be deployed confidently in the real world (Roberts and Palmer, 2012).

d. 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). A number of systems have been developed for interannual to decadal climate forecasting (Smith *et al.*, 2007; Keenlyside *et al.*, 2008; Matei *et al.*, 2012). 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. Progress has been made in initialising the North Atlantic for such forecasts (Dunstone and Smith, 2010; Matei *et al.*, 2012), but further work is needed to realize the potential of AMOC predictability.

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?

Recent projections, using a new generation of climate models (used in the CMIP5 model intercomparison and to be reported in the IPCC's 5th assessment report in 2014) suggest that the MOC will weaken gradually over the 21st Century in response to increasing levels of greenhouse gases (Weaver *et al.* 2012). This is consistent with previous generations of climate model, as reported for example in the IPCC 4th Assessment report (AR4, Figure 2). The models examined in the IPCC AR4, excluding those with a poor simulation of the present day MOC, suggested 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 CO₂ increase (Figure 3, Jackson *et al.*, 2012). The CMIP5 models (Weaver *et al.*, 2012) have been run through a new set of future scenarios known as Representative Concentration Pathways (RCPs). This makes direct comparison with the AR4 results difficult. Weaver *et al.* (2012) find AMOC reductions over the 21st Century of 18-25% for the lowest-forcing RCP, and 36-44% for the highest-forcing RCP, across the range of models for which data was available to them (ranges quoted are 5-95% confidence limits).

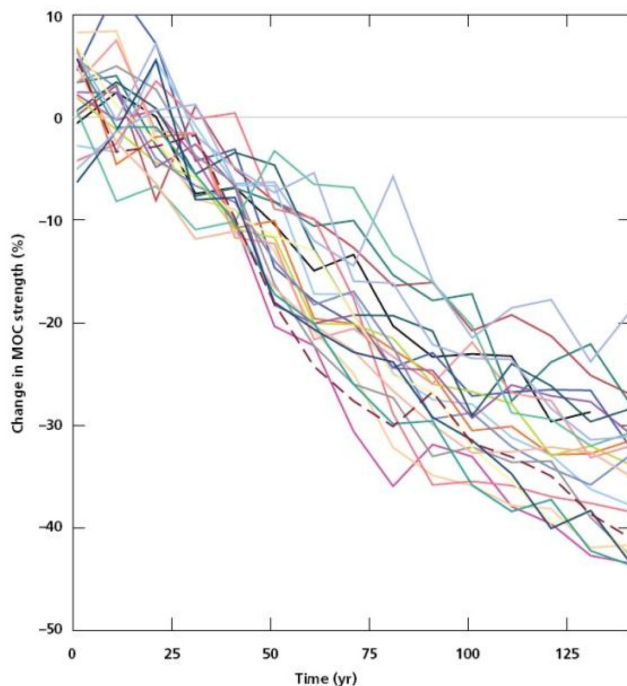


Figure 3: Model simulations of the change in MOC strength under an idealised 1%-per- annum increase of CO_2 concentrations. Twenty-two simulations are shown, from a HadCM3-based perturbed physics ensemble similar to the one used to generate the UKCP09 projections. MOC change is expressed as a percentage of its value in the corresponding control run. (Courtesy M. Vellinga.)

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 or RCP emissions scenarios, produces a complete or abrupt MOC shutdown in the 21st Century. However a few more recent models show a gradual spin-down of the AMOC over the 22nd Century under strong greenhouse gas forcing. 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 (Fichefet *et al.*, 2003).

The simulations of rapid MOC changes that have been seen have generally come from less complex climate models. Such models are computationally cheaper, so the range of possible behaviours can be explored more fully than with the comprehensive climate models used in UKCP09; however, the models may omit key processes affecting the stability of the MOC. Assessing the evidence overall, the IPCC AR4 concluded 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 could not be assessed with confidence at that stage. The effects of any rapid MOC changes (beyond the expected gradual weakening seen in most climate model simulations) would be superimposed on any man-made 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 (Vellinga and Wood, 2007).

Recent evidence has reawakened interest in the possibility of threshold behaviour in the AMOC. Hawkins *et al.* (2011) showed that a comprehensive, if low resolution climate model exhibits threshold behaviour in the AMOC similar to that seen in simpler models, and it has been suggested that comprehensive climate models may have a bias in their simulation of fresh water transport into the Atlantic basin by the AMOC that makes the AMOC too stable (e.g. Huisman *et al.*, 2010). However, this bias is less common in the more recent CMIP5 models (Weaver *et al.*, 2012). Overall the possibility of the AMOC crossing a threshold in the next few centuries is an active research topic, but there remains no evidence from the most comprehensive climate models that such an event is likely in the 21st Century.

Another potential behaviour of the AMOC has recently been discovered under a hypothetical scenario of a future reduction in atmospheric greenhouse gases (such as might result from an aggressive programme of carbon removal from the atmosphere). Some models suggest that in such a scenario the AMOC would recover from its weakened state and overshoot its unperturbed value, due to an accumulation of saline water in the subtropical Atlantic. The strong AMOC could delay the recovery of northern hemisphere temperatures for several decades after greenhouse gases have returned to pre-industrial values (Wu *et al.*, 2011).

Overall, recent developments in both models and observations such as those described above 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.

3. 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:

- 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 coupled climate model hindcasts and for ocean initialization for climate forecasts (Figure 5) (Cunningham *et al.*, 2009).
- 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 modelling community must strive to improve key details of model AMOC (e.g. depth of NADW outflow, see Saunders and Cunningham, 2008).
- Climate Models and Decadal Forecasting.** Following the pioneering work of Smith *et al.* (2007), Keenlyside *et*

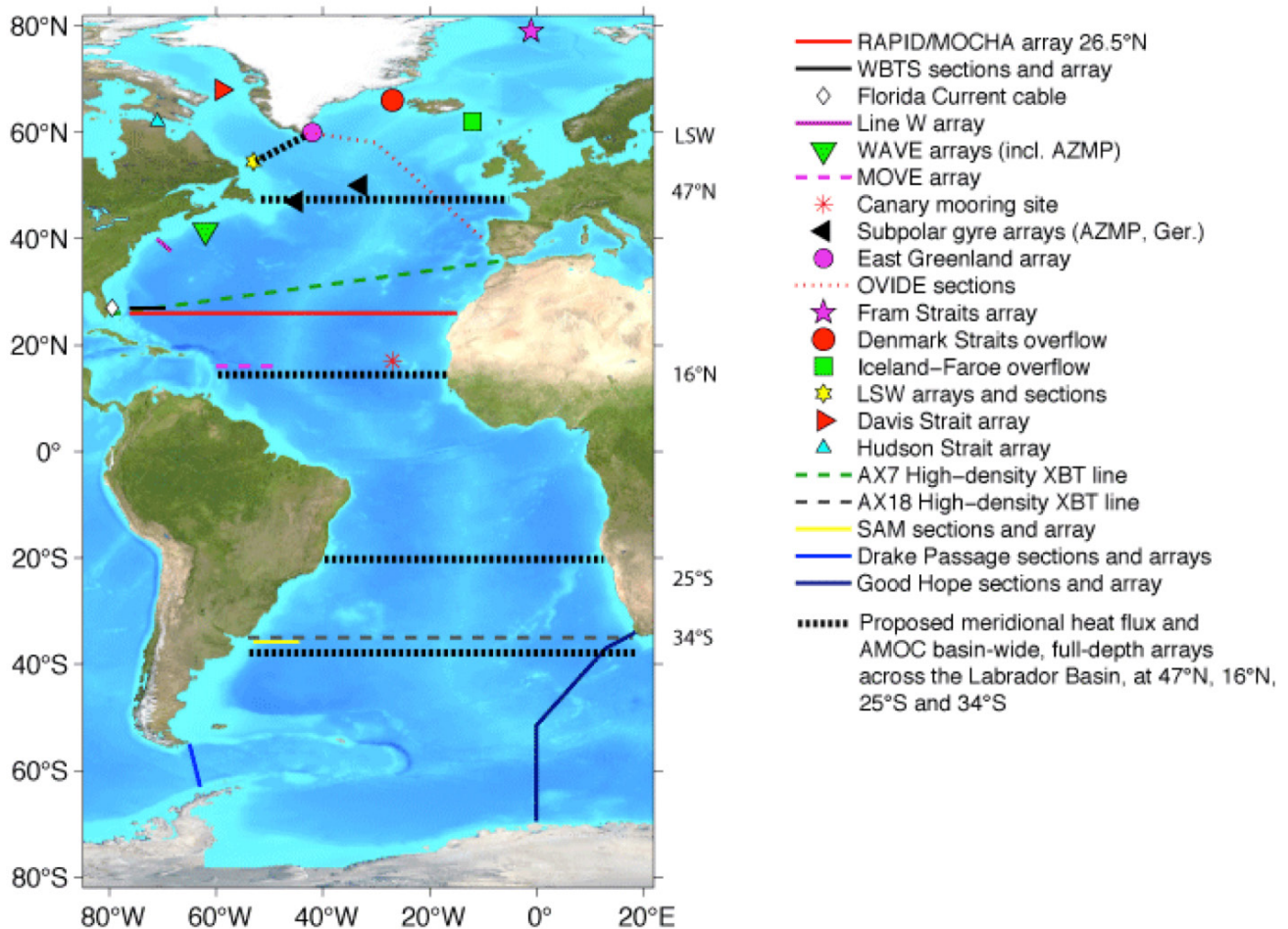


Figure 4: Observational programs presently measuring components of the AMOC, and proposed meridional heat flux and AMOC basin-wide, full depth arrays (black dashed).

al. (2008) and Matei *et al.* (2012), 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;
- develop strategies for initialization of derived quantities such as the AMOC;
- improve assessment and early warning of AMOC thresholds, including quantifying the resilience of the AMOC if a threshold is passed temporarily; and
- develop a better understanding and greater confidence in regional impacts.

4. 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 (2004), 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 a gradual fresh-water perturbation is added, to mimic melt-water from the Greenland Ice Sheet. This results 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 around US\$670 million per year, using calculations based on Stern (2007). The sign and magnitude of this sea-level rise is 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. We note that the effect on NPP depends crucially on how the nutrient advection changes, this is highly model dependent as Hofmann *et al.* (2011) describe.

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

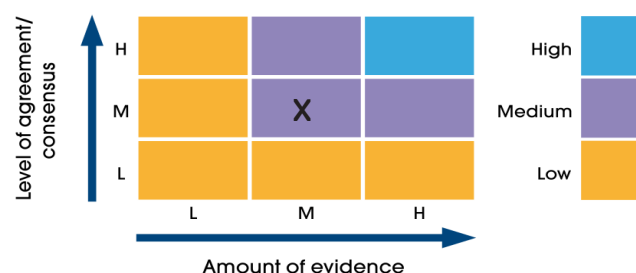
new generations), an AMOC collapse superimposed on this scenario leads to marked reductions in cod harvest as the North Atlantic population diminishes.

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 length. 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.

5. CONFIDENCE ASSESSMENTS

What is already happening?



Our confidence in answering the question 'What is already happening?' 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 in the last three years) 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.

What could happen?

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.



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