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Atlantic Meridonal Overturning Circulation

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KEY HEADLINES

- The AMOC is key to maintaining the mild climate of the UK.
- The AMOC is predicted to decline in the 21st century in response to a changing climate.
- Past abrupt changes in the AMOC have had dramatic climate consequences.
- There is growing evidence that the AMOC has been declining for at least a decade, pushing the Atlantic Multidecadal Variability into a cool phase.
- Short term fluctuations in the AMOC have proved to have unexpected impacts, including being linked with severe winters and abrupt sea-level rise.

1. INTRODUCTION

1.1 The AMOC in the climate system

The Atlantic Meridional Overturning Circulation (AMOC) is a system of currents that carries warm, shallow water northwards and returns cold, deep water southwards (Figure 1). This exchange of warm water with cold water which results in the largest transport of heat by any ocean, the maximum of which occurs near 30°N in the subtropical North Atlantic (Bryden and Imawaki, 2001). This ocean heat transport is a key element of the redistribution of heat by the climate system. North of 30°N, the ocean releases its heat to the atmosphere. It is this release of heat by the ocean and the delivery of this heat towards the land by the prevailing winds that is particularly crucial to maintaining the relatively mild climate of the British and Irish Isles and northwestern Europe in comparison to similar maritime climates, such as the west coast of North America. For example, located at similar latitudes and distances from the ocean, Dublin is over 4°C warmer than Seattle in winter (McCarthy *et al.*, 2015a). The ideas of the ocean maintaining the mild climate of the British and Irish Isles UK date back to Maury (1855) who popularised the idea that the Gulf Stream was responsible for the mild climate. His nomenclature of 'The Gulf Stream' (or sometimes, its extension 'The North Atlantic Current/Drift') live on popularly. However, while the Gulf Stream is the main conduit of the warm, shallow upper branch of the AMOC, without the cold, deep return (i.e. without the AMOC) the heat transported by the ocean would be much diminished.

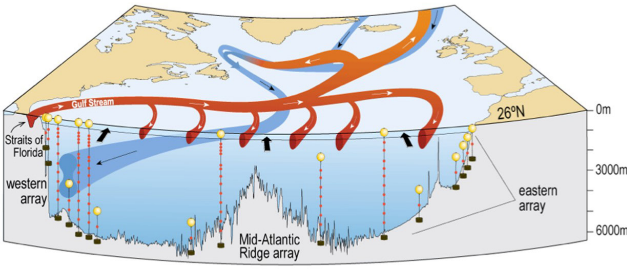

Figure 1. The AMOC north of 26°N. Red colours indicate warm, shallow currents and blue colours indicate cold, deep return flow. The RAPID array at 26°N is also highlighted. Modified from Church (2007).

1.2 Centennial to Millennial: Past collapses and future projections

In the earth's long history, the climate has moved into and out of ice ages on numerous occasions. Beyond the rhythmic and predictable ice ages associated with changes in the earth's orbit, it has been proposed that dips or collapses in the strength of the AMOC were associated with glacial periods (Broeker, 1991). Large, rapid and random fluctuations in the climate of the past saw temperature changes of up to 20°C

(Dansgaard *et al.*, 1993). Such chaotic oscillations have led to the AMOC being implicated in these changes, as simple models of the AMOC, such as Stommel (1961), allow for noisy fluctuations between 'on' and 'off' states. While more complex, modern models of the AMOC, such as the CMIP5 (Coupled Model Intercomparison Project, 5th iteration) models used in IPCC (Intergovernmental Panel for Climate Change) 5th Assessment Report, do not have chaotic oscillations in AMOC strength, the AMOC's potential involvement in abrupt climate change has sharpened interest in its dynamics.

An abrupt collapse of the AMOC in the near future is not generally predicted but a slowdown in the AMOC due to anthropogenic climate change is widely predicted (Figure 2). Regardless of the emissions scenario, the IPCC predict that an AMOC slowdown is 'very likely' (90-100% probability) over the coming century in response to man-made climate change (IPCC, 2013). Warming and increased precipitation in the high latitudes is predicted to increase the stability of the water column and inhibit the formation of the deep, cold branch of the AMOC. In spite of consistency in the prediction of an AMOC decline, the magnitude nature of this decline varies widely between models (Figure 2).

1.3 Decadal oscillations

Decadal climate variability is a striking feature of the climate of the North Atlantic and bounding land masses. Most prominently, the Atlantic Multi-Decadal Variability (AMV) is a feature of North Atlantic sea-surface temperatures (SSTs) where positive (negative) phases correspond with anomalously warm (cool) SSTs across the whole subpolar North Atlantic—approximately 45°-60°N. The AMOC is believed to be the driver of the phases of the AMV by controlling subpolar gyre heat content. This has been shown in a number of modelling studies e.g. Delworth and Mann (2000) and using indirect observations (Gulev *et al.*, 2013 McCarthy *et al.*, 2015b). Direct observations of the AMOC of sufficient length do not exist to rigorously prove the link.

There are many climate impacts of the AMV. A negative/cool phase last occurred in the 1970s and 1980s. This was associated with reduced rainfall, and consequent famine, in the Sahel region of Africa (Zhang and Delworth, 2006), drier summers in northwest Europe including the UK (Sutton and Dong, 2012) and has been associated with the mid-20th century dip in global temperatures (Muller *et al.*, 2013). This previous cool phase of the AMV is the best indicator of the types of changes that are likely to occur in response to a declining AMOC in the coming century, until AMOC decline outstrips what has previously been experienced.

The mid-1990s saw a shift to a warm phase of the AMV. This was associated with increased numbers of hurricanes affecting the Caribbean (Goldenberg *et al.*, 2001) and a reversal of the precipitation and temperature patterns associated with the preceding negative phase. The 1990s saw profound changes in the subpolar gyre, with a contraction of the extent of the gyre (Häkkinen and Rhines, 2004) and a reversal of the freshening trend that had dominated since the 1960s (Holliday *et al.*, 2008). It is likely that these basin scale changes are entwined with the wider system of the AMOC, but a full understanding is not yet complete.

1.4 Challenges to the AMOC's role in the climate system

It is worth noting that there have been challenges to the role

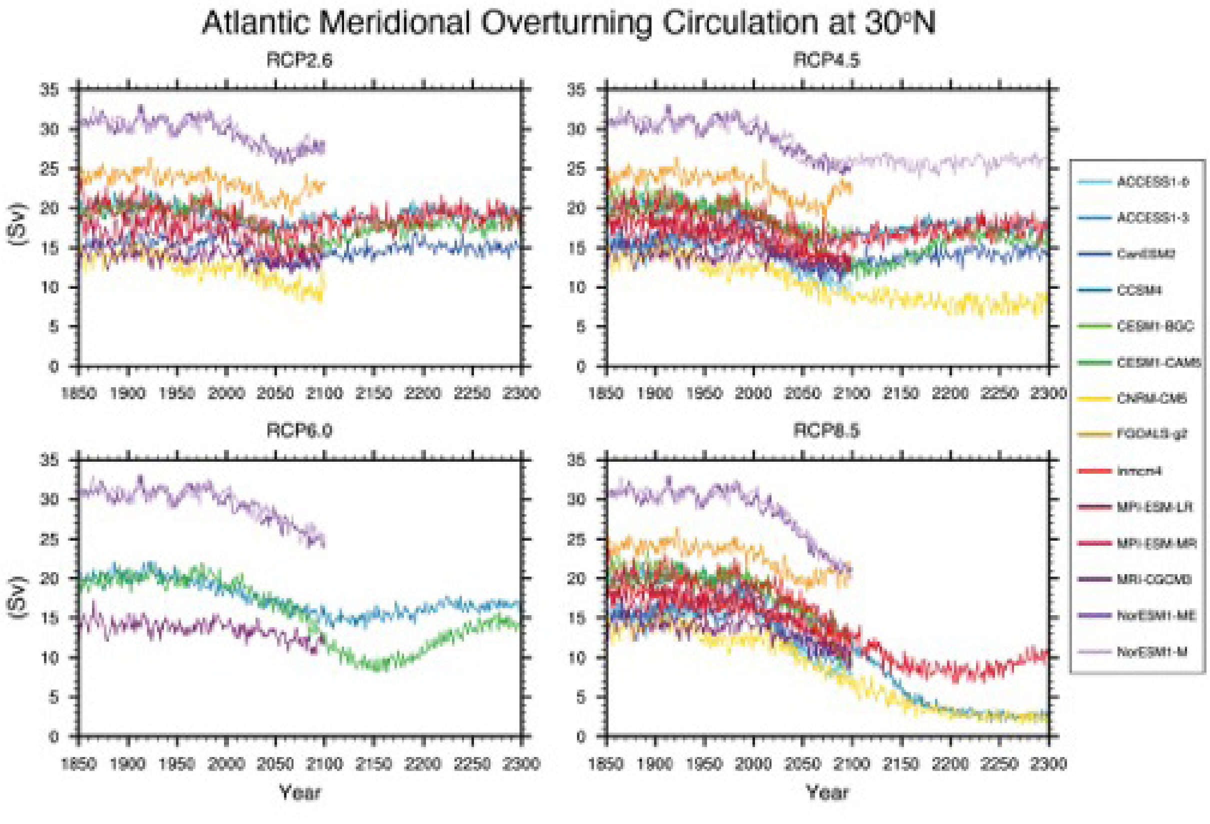

***Figure 2**: Future projections of AMOC strength from a suite of CMIP5 models. RCP is Representitive Concentration Pathway (e.g. RCP 8.5 is intended to result in a net top of atmosphere radiative imbalance of 8.5 W m−2 in the year 2100), with higher numbers indicating higher emissions scenarios. The y-axis is in units of Sverdrups (1 Sv = 106 m3 s-1).*

of the AMOC in climate and the role of the AMOC in the AMV in particular. A strong challenge to the fundamental role of the AMOC and ocean heat transport in maintaining Europe's mild climate came from Seager *et al.* (2002). They posited that the prevailing winds enhanced in the south-westerly direction due to orographic steering from the Rocky Mountains and seasonal release of heat from the ocean, was sufficient to maintain the mild climate of north west Europe. However, this argument neglects the fact that climate models that simulate a collapsed AMOC consistently show European cooling as a consequence (e.g. Jackson, 2015). Another counterpoint is to look at decadal variability. As important as the Rocky Mountains are in maintaining south-westerly air flow towards Europe, they cannot contribute to decadal variability. Therefore, the AMV in itself emphasises the role of the AMOC in the climate system.

However, the role of the AMOC in driving the AMV has itself been challenged. As mentioned, direct observations of the AMOC of sufficient length do not exist to prove this link and so we rely on numerical models and proxy data for support. Booth *et al.* (2012) challenged the role of ocean heat transport in decadal variability, which they said could be explained by indirect aerosol effects with no need for a dynamic ocean. More recently, Clement et al. (2015) looked at experiments with slab ocean models and found that AMV patterns could be reproduced, again without a dynamic ocean. Both of these challenges have already had responses defending the role of the AMOC (e.g. O'Reilly *et al.*, 2016) but the arguments are worth bearing in mind.

Direct observations of ocean heat transport and the AMOC at key locations are designed to settle the debate about the AMOC's role in climate. Continuous, basinwide measurements near the location of the maximum ocean heat transport in the North Atlantic began in 2004 with the UK-led RAPID project (Cunningham *et al.*, 2007). A system of moored instruments and cable measurements, the RAPID array directly measures ocean transport across 26.5°N in the North Atlantic (McCarthy *et al.*, 2015c, Figure 1). Over the past 12 years, this project has revolutionised understanding of AMOC variability from seasonal to decadal variability. With the addition of other basin wide arrays such as the OSNAP array in the subpolar North Atlantic and the SAMBA array in the South Atlantic, our understanding of the AMOC and its role in climate is due to advance in the coming decades.

2. TOPIC UPDATE

2.1 Extreme winter conditions

At the time of the last MCCIP review, unprecedented inter-annual variability in the AMOC had been observed by the RAPID array (McCarthy *et al.*, 2012), when AMOC strength dropped by 30% for a period of 18 months. Following this initial drop in the years of 2009/10 there was a second dip in strength, confined to the winter, in 2010/11. This pattern of double dips (two winters of consecutively low AMOC) is one that has been simulated in an ensemble of ocean hindcast models, including double dips in the consecutive winters of 1968/69 and 1969/70 as well as 1977/78 and 1978/79 (Blaker et al., 2015). The mechanism linking the two events was ocean re-emergence (Taws *et al.*, 2011). The SST pattern in winter 2010/11 was strong enough to push the North Atlantic Oscillation (NAO) into a second successive negative state that winter (Buchan *et al.*, 2014) resulting in the coldest winter in the UK since 1910 and costing the economy an estimated £13 billion in lost revenues (The Independent, 2010). The fact that the correct initialisation of the SSTs in 2010 led to a skilful seasonal forecast of the negative NAO associated with this cold winter (Maidens *et al.*, 2013) indicates that the winter of 2010/11, and potentially the winters of 1969/70 and 1978/79 (the latter being the infamous 'Winter of Discontent') may have been more predictable than most cold winters, and consequently easier to prepare for. The entwining of the AMOC in these processes emphasizes the potentially important societal role that relatively short term changes in the AMOC can have.

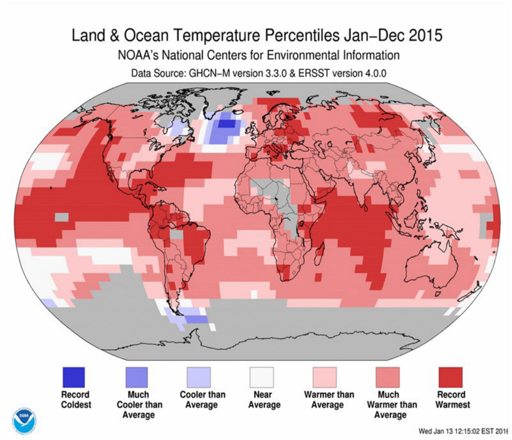

***Figure 3**: Temperature anomaly percentiles for 2015. From www.ncdc.noaa.gov.*

2.2 A new cold Atlantic phase

Based on observations from the first 8.5 years of the RAPID programme, Smeed *et al.* (2014) published the first observations of a multiyear decline in the AMOC. The record now stretches to 11.5 years and while the AMOC is still weak, it appears that the rate of decline has not continued (Smeed et al., 2016). SSTs in the subpolar North Atlantic have been strikingly cold in the past few years (Figure 3). Some of the most extreme cold SSTs were associated with extreme air-sea heat fluxes (Duchez *et al.*, 2016) and are have already diminished. Robson *et al.* (2016) and Jackson *et al.* (2016) highlight that the Atlantic has been shifting to a cool phase since 2005. A number of authors had predicted this shift to cooler Atlantic temperatures e.g. Klower *et al.* (2014) and Hermanson *et al.* (2014). The cooling of the Atlantic is consistent with entering a negative AMV phase, although it is too early to definitively say the conditions represent a negative AMV. The impacts of a negative AMV have already been described and there is some evidence that these are being borne out. Hurricane activity has declined (Klotzbach *et al.*, 2015) and, in spite of 2015 being the warmest year on record globally, Ireland, where the impact of Atlantic changes are often first felt, experienced a cooler year than the 1980-present average (Met Éireann, 2015).

2.3 Predicted hiatus in sea-ice decline

In addition to new records for the highest global temperatures, recent years have been notable for ever declining Arctic sea-ice extents. A slowing AMOC means less heat transported into the Arctic and this has led a number of authors predicting a slowing of Atlantic sea ice loss in concert with this (Zhang, 2015; Yeager *et al.*, 2015). It is worth noting that this has not been observed yet—indeed 2016 was tied for the second lowest Arctic sea-ice extent. The slow effects of reduced ocean heat transport is not expected to emerge for 5-10 years (Yeager *et al.*, 2015).

2.4 Sea level rise

Previous MCCIP reports have emphasised a potential extra 80 cm rise in sea level around UK coasts in the case of a collapsed AMOC. Developments Recent research into the links betweenin sea-level rise and the AMOC of late have focused on the east coast of the United States but are worth mentioning briefly here.

On inter-annual timescales, Goddard *et al.* (2015) demonstrated how the weakening in the AMOC in 2009/10 was linked with a large surge in sea level along the east coast of the United States. Based on this event, they noted a 13 mm sea-level rise in New York for every Sverdrup (1 Sv = 106 m^3 s^{-1}) of AMOC decrease. Were a drop in the AMOC to coincide with a storm surge event, widespread coastal flooding along this densely populated coastline could result.

On decadal timescales, periods of accelerated sea-level rise along the eastern seaboard of the US have been observed in the 1950s (Sallenger *et al.*, 2012) and in the last ten years. The timings of these accelerations are associated with transitions to negative AMV states that McCarthy et al. (2015b) link to changes in ocean circulation associated with the AMOC.

2.5 Renewed credibility of a collapsing AMOC?

The IPCC report in 2013 stated that a collapsed AMOC was unlikely (<5% probability) based on the CMIP5 suite of models. This ties in with the fact that while simple models of the AMOC showed bistability (an 'on' and an 'off' state), more complex, current generation models did not. Valdes (2011) points out that this generation of models may be artificially stable and recent results by Mecking *et al.* (2016) have shown that a next generation model (HadGEM3) does show a stable 'off' state. Work by Hansen *et al.* (2016) and Rahmsdorf *et al.* (2015) has suggested that ongoing melting in the Arctic could provide a sufficient perturbation to the formation of the deep, cold branch of the AMOC and that a contemporary shutdown of the AMOC is possible, with dramatic climate consequences. The reconstruction of Rahmsdorf *et al.* (2015) indicates that the AMOC has been in decline throughout the 20th century and that further melting of the Greenland iIce sheet could contribute to a further weakening. On the other hand, studies have found that the impact of high latitude melt on the AMOC is not yet detectable (Böning *et al.*, 2016). While increased melting in the Arctic has the potential to disrupt the AMOC, no consensus has been reached on how the ongoing changes in the Arctic will affect the AMOC. Nonetheless, it remains to be seen whether the next generation of climate models will add further credibility to the potential of an AMOC collapse.

3. HOW OUR UNDERSTANDING HAS DEVELOPED OVER THE PAST DECADE?

The past ten years have seen major changes in the AMOC itself and in our understanding of the AMOC. In 2005, Bryden et al. published findings from five hydrographic sections at 24ºN in the North Atlantic. They showed a 30% decline in the AMOC over the past 50 years. The authors acknowledged the lack of measurements but the fact was that at the time, there were no other basin-wide estimates of the AMOC. This data-poor picture of the ocean has changed rapidly over the past decade. At the time of publication of Bryden *et al.* (2005), the RAPID array was already in the water (since 2004) to provide the first continuous, basin-wide estimates of the AMOC. The first year's results from the RAPID array showed that the magnitude of variability seen in Bryden *et al.* (2005) could be observed over the space of a few weeks (Cunningham *et al.*, 2007). In 2007, the Argo array of profiling floats passed the 3000 float milestone enabling unprecedented sampling of the subsurface ocean. Quantitative links between the AMOC and ocean heat content were now possible.

The level of variability observed by the RAPID array was unexpected, not only on sub-annual timescales, but also on seasonal (Kanzow *et al.*, 2010) and inter-annual timescales (McCarthy *et al.*, 2012), with the 30% drop in the strength of the AMOC in 2009/10 a particular surprise. The AMOC in ocean models had not been examined on such short timescales previously but, when they were, they were found to do a good job simulating the observed variability. It emerged that much of the inter-annual and shorter term variability observed in the first 10 years of RAPID was wind driven and could be captured by models ranging from two-layered (Zhao and Johns, 2014) to the more complex high resolution models (e.g. Blaker *et al.*, 2015).

When Smeed *et al.* (2014) described a multi-year decline in the AMOC, the increased quality of observations led to much more confidence than in the results of Bryden *et al.* (2005). The decline in the AMOC since the mid-2000s is supported by observations of Labrador Sea density changes (Robson *et al.*, 2014) and by reanalysis data (Jackson *et al.*, 2016). Together with a substantial cooling of the subpolar North Atlantic, this has lead to gathering evidence that we are entering a negative AMV phase, driven by a declining AMOC.

These decadal trends have proved the most difficult for models to capture. While a suite of CMIP5 models show a long-term decline in the AMOC, decadal variability is not well represented (Roberts *et al.*, 2014). The long-term projections from state-of-the-art climate models is one thing that has not changed much in ten years. The models predict a decline in the AMOC going into the 21st century in the 5th IPCC assessment report in 2013, much as they did in the 4th assessment report in 2007.

It is possible to say that doomsday scenarios involving AMOC collapse have received a revival in the past ten years. Once the preserve of simple dynamical models or paleo-oceanographers interpreting sparse temporal data such as ice cores, more and more complex models (e.g. from Hawkins *et al.*, 2011, to Mecking *et al.*, 2016) are showing that AMOC may well have stable 'on' and 'off' states. Much of the focus has been on the control by salinity on the stability of the AMOC and especially the sign of the ocean's freshwater flux into the Atlantic through its southern boundary but growing body of literature is investigating the role of enhanced Arctic melting on the AMOC (e.g. Hansen *et al.,*2016; Böning *et al.*, 2016).

Most studies do not support an imminent AMOC collapse but the last ten years has confirmed that the AMOC is declining. Already the subpolar gyre is cooling indicating suggesting a return to a negative AMV. It is possible that summers in the UK over the coming decade will be drier than the last, with benefits for outdoor recreation. Prediction of individual summers is a difficult task—and some widely reported predictions of so-called 'barbecue summers' that failed to materialise exist—but one might venture that the UK will get more use out of its barbecues in the next decade than the last, if this negative AMV phase materialises as it did in the 1970s. Such upshots would not be without their downsides as drier summers would put increased strain on water resources in the south of England. Precipitation effects—such as drier summers in the UK—associated with a negative AMV will take a while to become evident given the variable nature of precipitation. Further afield, the greening of the Sahel region of Africa that occurred during the warm AMV phase from the mid-1990s could be reversed. Droughts have already been recorded in the region in 2010 and 2012, increasing the chance of conflict and famine.

4. EMERGING ISSUES (CURRENT AND FUTURE)

4.1 Duration of a decline

For how long will the decline in the AMOC be sustained?

Smeed *et al.* (2014) noted that the rate of change was significantly faster than the long-term trend predicted by climate models as a response to anthropogenic warming (IPCC, 2013) and suggested that the change was more likely related to decadal-scale internal variability that has been identified in longer time series of sea-surface temperature (Kerr *et al.*, 2000). If the transition is to a negative AMV state, should we expect relatively cool conditions to persist for a number of decades? The predictability of the AMOC and associated Atlantic changes is a key issue. The availability of direct observations of the AMOC from the RAPID array allow for the direct validation of predictons such as the cooling of the Atlantic due to a weakening of the AMOC in the coming years predicted by Hermanson *et al.* (2014).

4.2 Mechanisms and extent of changes

What is causing changes in the AMOC and is the change coherent throughout the Atlantic? A number of studies have suggested that shorter-term variability (up to inter-annual time scales) is primarily forced by the winds (Zhao and Johns, 2014) and is not meridionally coherent. Longer-term changes are expected to reflect changes in ocean buoyancy and to have greater coherence over latitude. Robson *et al.* (2014) hypothesized that the change was forced by reductions in the density of deep water formed in the Labrador Sea that started in the late 1990's.

Atmospheric aerosols and greenhouse gases are expected to influence the long term trends in the AMOC in different ways. Greenhouse gases are expected to weaken the overturning by warming and freshening high latitudes. However, atmospheric aerosols, including volcanic aerosols, sulphates and particulate carbon, can act to strengthen the AMOC by altering high latitude to low latitude density gradient by cooling or evaporation (Delworth and Dixon, 2006; Menary *et al.*, 2013). How robust the oft-repeated claim that the AMOC will weaken in response to increased anthropogenic emissions is thus a competition between these two forcings.

4.3 The relative roles of atmosphere and ocean in decadal climate variability

What are the relative roles of the atmosphere and ocean in changing North Atlantic heat content on multi-year timescale? There is consensus that the 2009-2010 downturn of the AMOC affected the heat content of the North Atlantic Ocean (Cunningham *et al.*, 2013) but the impact of the longer-term reduction has not yet been clearly identified. There has also been some debate about the relative roles of ocean heat transport and atmospheric fluxes in the variability of the sea-surface temperature distribution. Recent analyses of observations have affirmed the role of ocean heat transport (McCarthy *et al.*, 2015b; O'Reilly *et al.*, 2016). Alternatively, some coupled climate model studies have suggested that long-term variability of North Atlantic SST is driven solely by atmospheric forcing (Clement *et al.*, 2015).

4.4 Accurate simulation of changes in numerical models

Forced- ocean only models do simulate variability consistent with observations (e.g. Blaker *et al.*, 2015) but AMOC variability in coupled climate simulations does not seem to be able to replicate observed variability. Roberts *et al.*, 2014 showed that the internal (i.e. non-forced) inter-annual and multi-annual variability in all but two of the 14 CMIP5 models studies were significantly less than has been observed in the RAPID time series. It is clear that accurate observations of meridional heat transport have an important role in model verification.

There is a large dependence on climate models for climate change forecasts and a number of issues are of relevance to the representation of the AMOC in climate models. are of relevance. The horizontal resolution of the ocean in the CMIP5 suite of climate models was not sufficient to resolve ocean eddies. The eddy field is important for heat and freshwater transports, especially in key locations such as the Agulhas leakage (Biastoch *et al.*, 2008) and is important for air-sea interaction. The numerical representation of deep water formation processes in key locations, transport across important locations such as the Greenland-Scotland ridge and mixing/entrainment processes does not result in sufficiently deep North Atlantic Deep Water. Hence the lower branch of the overturning circulation is too shallow. Finally, the lack of a dynamic cryosphere in these models could lead to the crucial freshwater input from the Arctic not being represented correctly. Some of these issues are being addressed in the next stage of the CMIP project and the impact of these model improvements on the representation of the AMOC will be important to our understanding of future AMOC changes.

4.5 What insights will observations at other latitudes provide?

Until recently the 26°N array provided the only trans-basin estimate of Atlantic overturning but a number of other initiatives are in development (Nature News, 2013). Since 2014, the OSNAP program (Lozier *et al.*, 2016) (http://www.o-snap.org/) has a pilot array across the sub-polar gyre. The first compete data will be retrieved fromorm the OSNAP array in 2016 and comparisons with the subtropical RAPID array will be made in following years. Another basinwide array, called the SAMBA array, is being developed at the southern boundary of the Atlantic, estimating heat and freshwater fluxes into the Atlantic that are crucial for the stability of the AMOC.

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