(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. Despite 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 Representative 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 [illegible]VTh N T 3F[illegible]P[illegible]P[illegible]F*

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.

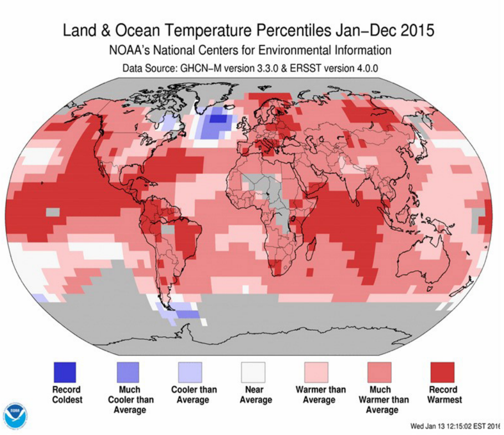

***Figure 3**: Temperature anomaly percentiles for 2015. From www.ncdc.noaa.gov.*

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 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. Recent research developments into the links between sea-level rise and the AMOC of late have focused on the east coast of the United States but are worth mentioning briefly here.

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