Bistability of the Atlantic overturning circulation in a global climate model and links to ocean freshwater transport

E. Hawkins[1], R. S. Smith[1], L. C. Allison[1], J. M. Gregory[1,2], T. J. Woollings[1], H. Pohlmann[2] and B. de Cuevas[3]

The possibility of a rapid collapse in the strength of the Atlantic meridional overturning circulation (AMOC), with associated impacts on climate, has long been recognized. The suggested basis for this risk is the existence of two stable regimes of the AMOC ('on' and 'off'), and such bistable behaviour has been identified in a range of simplified climate models. However, up to now, no state-of-the-art atmosphere-ocean coupled global climate model (AOGCM) has exhibited such behaviour, leading to the interpretation that the AMOC is more stable than simpler models indicate. Here we demonstrate AMOC bistability in the response to freshwater perturbations in the FAMOUS AOGCM - the most complex AOGCM to exhibit such behaviour to date. The results also support recent suggestions that the direction of the net freshwater transport at the southern boundary of the Atlantic by the AMOC may be a useful physical indicator of the existence of bistability. We also present new estimates for this net freshwater transport by the AMOC from a range of ocean reanalyses which suggest that the Atlantic AMOC is currently in a bistable regime, although with large uncertainties. More accurate observational constraints, and an improved physical understanding of this quantity, could help narrow uncertainty in the future evolution of the AMOC and to assess the risk of a rapid AMOC collapse.
NOTE: This is the author's version of the paper with a correction and addition of extra unpublished results to Fig. 3.

1. Introduction

The Atlantic meridional overturning circulation (AMOC) is an important component of the climate system. It transports heat and salt northwards from the tropics via the near-surface Gulf Stream and North Atlantic Current. At high latitudes this heat is released to the atmosphere, ensuring that the water cools and becomes more dense, subsequently sinking and returning southwards at depth. One mechanism for disrupting this circulation is through the addition of extra freshwater to the North Atlantic, which causes the seawater to become less dense and less able to sink, thus slowing the circulation.

The pioneering work of *Stommel* [1961] first suggested that this density driven circulation in the Atlantic Ocean has two equilibrium states, either 'on' or 'off'. If the climate is altered, a transition may occur between these states which is not reversible by returning the climate to its previous regime (this irreversibility is termed 'hysteresis'). Atlantic paleoclimate records suggest very rapid changes in climate have occurred in the past; these events are believed to be linked to sudden changes in the strength of the AMOC due to the input of freshwater from melting ice-sheets [*Broecker et al.* 1985; *Bond et al.* 1997].

A warmer climate in the 21st century is likely to increase the freshwater input to the North Atlantic through additional precipitation over the ocean, increased river runoff, and a small contribution from the melting of Greenland [e.g., *Wood et al.* 1999; *Gregory and Huybrechts* 2006]. In turn, a gradual weakening in the strength of the AMOC is projected by AOGCMs, although there is considerable uncertainty in the magnitude of the change [*Meehl et al.* 2007]. However, if the 'on' state of the AMOC ceased to be stable under future climate conditions, it might collapse into an 'off' state with severe and wide ranging climatic impacts, especially for Europe [e.g., *Vellinga and Wood* 2002; *Kuhlbrodt et al.* 2009]. Determining the risk of such a rapid change occurring in the future critically depends on whether the AMOC exhibits bistable behaviour and if so, whether the real ocean is currently close to a critical threshold for collapse [*Knutti and Stocker* 2002].

Box models of the AMOC and a range of simpler climate models do exhibit bistability and/or sudden transitions between stable 'on' and 'off' states of the AMOC [e.g., *Stommel* 1961; *Manabe and Stouffer* 1988; *Gregory et al.* 2003; *Lenton et al.* 2009]. In particular, a multi-model comparison showed that a range of Earth-system Models of Intermediate Complexity (EMICs) exhibited rapid transitions, bistability and hysteresis in the AMOC [*Rahmstorf et al.* 2005]. However, such a collapse of the AMOC in the near future is considered very unlikely [*Meehl et al.* 2007], mainly because state-of-the-art AOGCMs have not shown the presence of two stable states of the AMOC. A possible explanation for this increased stability is that the presence of a dynamical atmosphere in AOGCMs, missing in many EMICs, is crucial to accurately describe the stability behaviour of the AMOC [*Schiller et al.* 1997; *Monahan* 2002; *Yin et al.* 2006]. An alternative explanation considers the net northwards freshwater transport by the AMOC at the southern boundary of the Atlantic as a stabilizing influence in most AOGCMs [e.g., *Rahmstorf* 1996; *Drijfhout et al.* 2011].

Testing for hysteresis is extremely challenging in AOGCMs due to computational constraints. However, in Section 2 we describe specific experiments designed to test for AMOC hysteresis in the FAMOUS AOGCM. Section 3 demonstrates the presence of AMOC hysteresis in FAMOUS, and we consider a possible indicator of bistability in Section 4. Evidence from ocean reanalyses is used to suggest that the real ocean is currently in a bistable regime in Section 5 and we conclude and discuss the results in Section 6.

2. FAMOUS and experimental design

Here we make a specific search for bistability of the AMOC in the FAMOUS AOGCM. A search for this behaviour in AOGCMs is normally impractical because of the computational expense, a hurdle which FAMOUS can overcome because of its relatively coarse resolution.

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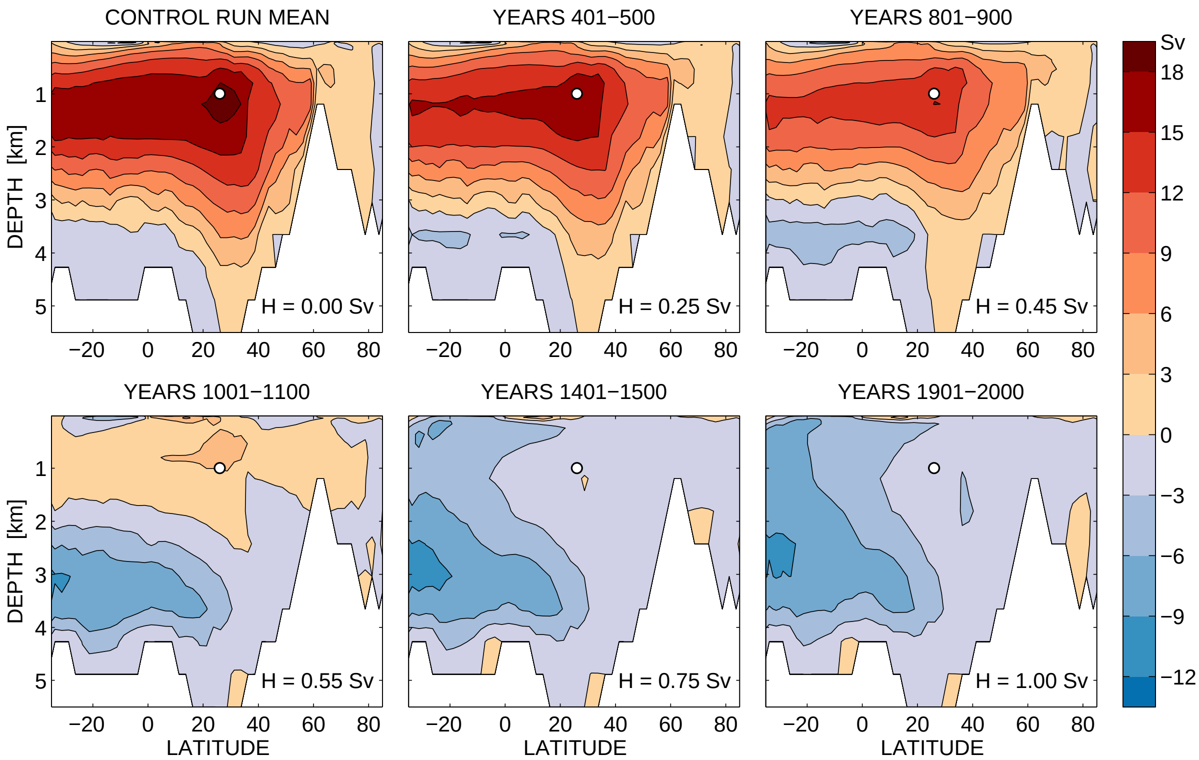

Figure 1. The FAMOUS AMOC streamfunction in Sv. Top left panel: the control run mean. Other panels show time means of various portions of the transient increasing hosing simulation, labelled with the hosing value (H) at the end of the time period indicated. The white dots show the position of the AMOC index shown in Fig. 2A.

2.1. The FAMOUS AOGCM

FAMOUS [*Smith et al.* 2008] is a lower resolution and re-tuned version of the third Met Office Hadley Centre AOGCM [HadCM3; *Gordon et al.* 2000]. Importantly, these AOGCMs do not use flux adjustments. FAMOUS has an atmospheric component with a horizontal resolution of $5^\circ \times 7.5^\circ$, with 11 vertical levels. The ocean component has a horizontal resolution of $2.5^\circ \times 3.75^\circ$, with 20 vertical levels. The computational speed of FAMOUS allows simulations to be performed at over 100 model years per wall-clock day, making it suitable for lengthy simulations.

The climate of a 4000-year stable control simulation of FAMOUS is in reasonable agreement with the observed climate [*Smith et al.* 2008]. However, there is a winter cold bias in the North Atlantic which may make the salinity contributions to the density larger than observed in that region. Deep water formation regions are found in the Irminger and Nordic Seas [*Smith and Gregory* 2009].

The AMOC in the control simulation of FAMOUS has a maximum strength of 19Sv ($1\text{Sv} \equiv 10^6\,\text{m}^3\text{s}^{-1}$) at around 26°N, consistent with many other AOGCMs [*Meehl et al.* 2007] and with recent observations at this latitude [*Cunningham et al.* 2007].

2.2. Experimental design

We follow a similar experimental design to a previous multi-EMIC comparison of AMOC hysteresis [*Rahmstorf et al.* 2005], allowing a direct comparison to be made. FAMOUS is significantly more complex than the EMICs generally used in the AMOC hysteresis literature, providing a three-dimensional simulation of both atmosphere and ocean, including internally generated temporal variability over periods from days to millennia and physically detailed representations of important evolving processes such as clouds, precipitation and atmosphere-ocean feedbacks. In particular, the leading mode of atmospheric variability in the Atlantic sector - the North Atlantic Oscillation - is well represented in FAMOUS (Fig. S1). Note that AMOC bistability has also been demonstrated for SPEEDO (*Severijns and Hazeleger* 2010), which has a comparable level of atmospheric complexity to FAMOUS (S. Drijfhout, pers. comm.).

Our simulations include a long control experiment and a comparison transient 'hosing' experiment, where additional freshwater is artificially applied to the extra-tropical North Atlantic. The flux of freshwater is increased slowly from zero to $H = 1$Sv over 2000 years, and subsequently reduced back to zero over another 2000 years. The hosing then becomes negative, i.e. freshwater is extracted, and the simulation is continued for another 800 years with increasingly negative hosing until $H = -0.4$Sv.

Additional simulations keeping H fixed for at least several hundred years were started from various points during both the transient increase and decrease experiments.

For all hosing experiments additional freshwater is added to the ocean surface in the 20°N-50°N band of the North Atlantic as a negative salinity flux. The same quantity of freshwater is removed from the rest of the global surface ocean evenly to conserve global salinity. This hosing region is chosen to allow a direct comparison with the previous study examining hysteresis in a range of EMICs [*Rahmstorf et al.* 2005], and to avoid applying the freshwater over the deep water formation regions directly. Overall, more than 56,000 years of simulations were completed (Fig. S2), all with pre-industrial levels of greenhouse gases. The steady state simulations were performed in parallel; this same strategy would be useful for investigating AMOC hysteresis in other climate models.

3. Hysteresis in the AMOC

As the hosing increases in the transient experiment, the strength of the AMOC decreases, and a reversed AMOC cell with a strength of around 10Sv forms in the South Atlantic (Fig. 1). The strength of the AMOC at 26°N drops rapidly from around 17Sv to 0Sv as the rate of hosing reaches

$H \approx 0.4$Sv, and continues decreasing slowly as the hosing increases further. As the rate of hosing is subsequently reduced, the AMOC at 26°N remains small until the rate of hosing is almost zero, when it rapidly increases to 20Sv (Fig. 2A). This behaviour is suggestive of hysteresis.

However, the apparent hysteresis could be an artefact of the speed of the transient changes in hosing. With fixed hosing rates in the range $H = 0.15 - 0.22$Sv, both a stable AMOC 'on' state and a stable 'off' state are seen, depending on which transient simulation they were started from, confirming the presence of hysteresis (Fig. 2A, Fig. S2). For hosing values smaller than this range the AMOC remains 'on', and it persists in the 'off' state for values larger than this range.

If the hysteresis loop were traversed infinitesimally slowly, we would expect the transitions to be made exactly at the boundaries of the bistable range (following the dashed lines in Fig. 2A). The non-zero rate at which H is changed in practice means that the collapse does not happen until H has passed the top of the range, and likewise the recovery occurs after H has gone below the bottom of the range.

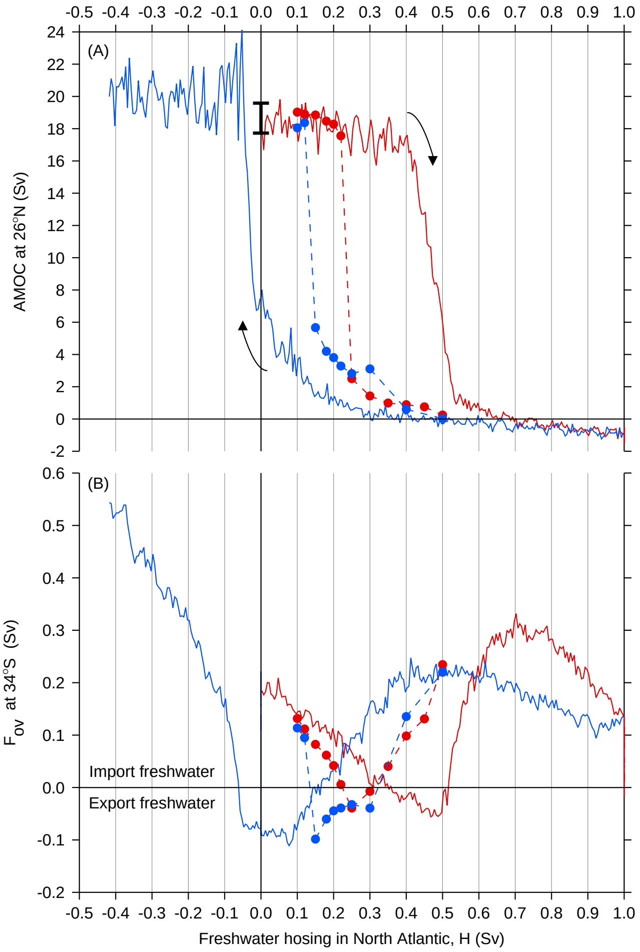

Figure 2. (A) The strength of the AMOC at 26°N as a function of the hosing applied, for increasing hosing (red) and decreasing hosing (blue). The coloured symbols represent the equilibrium AMOC state for various constant hosing values. The black error bar indicates the maximum to minimum range of annual mean AMOC values from the first 5 years of the RAPID-WATCH observations at 26°N [*Cunningham et al.* 2007], demonstrating that FAMOUS produces a realistic AMOC at these latitudes. (B) The net freshwater import into the Atlantic (F_{ov}) by the AMOC in the transient (solid lines) and equilibrium (filled circles) simulations.

In a range of EMICs, *Rahmstorf et al.* [2005] found hysteresis regimes at a wide range of hosing values ($H = 0.1 - 0.5$Sv) and FAMOUS is within this range. However, the width of the hysteresis regime ranges within $0.2 - 0.5$Sv in those EMICs, but FAMOUS has a much narrower hysteresis width of around 0.07Sv.

As a simple illustration of the implications of these results, the projected change in freshwater input from increases in precipitation and river runoff at the end of the 21st century amount to around 0.1Sv in the North Atlantic region in the HadCM3 AOGCM [*Wood et al.* 1999] and similarly in FAMOUS (not shown). This projected rate of change of additional freshwater input to the North Atlantic is similar to the rate of change in our transient experiment. The contribution from the melting of Greenland is expected to be much smaller (around 0.01Sv) [*Gregory and Huybrechts* 2006].

Overall, these modelling results suggest that a warmer climate, and associated hydrological cycle changes, could plausibly induce a bistable regime in the AMOC.

4. Indicators of the multiple equilibrium regime

We next consider whether the sudden AMOC collapse seen in FAMOUS is potentially predictable. If so, this could allow the development of a early warning system of such a collapse in the real climate system.

We consider the suggestion that that the net freshwater import by the overturning circulation in the Atlantic (F_{ov}) is a useful physical indicator of the presence, or not, of a bistable regime [*Rahmstorf* 1996; *de Vries and Weber* 2005; *Dijkstra* 2007; *Huisman et al.* 2010]. For a particular latitude Φ,

$$F_{ov}(\Phi) = -\frac{1}{S_0}\int_{-D}^{0} \overline{v^*}(z,\Phi)\langle S(z,\Phi)\rangle dz, \qquad (1)$$

where $S_0 = 35$psu is a reference salinity, z represents depth, $\overline{v^*}$ is the zonal integral of the northward baroclinic ocean velocity [*Drijfhout et al.* 2011], $\langle S(z,\Phi)\rangle$ denotes the zonal mean salinity, and D is the depth of the ocean bottom (see Supp. Info.). The freshwater input by the AMOC into the Atlantic is defined at the southern boundary, i.e. $\Phi = 34$°S. Note that this quantity is also called M_{ov} in the literature.

A simplistic view of the relevance of F_{ov} to the stability of the AMOC is as a measure of Stommel's salt-advection feedback [*Stommel* 1961; *Rahmstorf* 1996]. If F_{ov} is positive then the AMOC exports salt; in this case, a small decrease in the strength of the AMOC would export less salt, encouraging a recovery of the AMOC (i.e. a negative feedback) as a higher salinity tends to promote deep mixing and a stronger AMOC. However, if F_{ov} is negative then there is a positive feedback, reinforcing any decline in the strength of the AMOC.

The sign of F_{ov} has been demonstrated to be a reliable indicator of the stability of the 'on' state of the AMOC in global ocean-only models and an EMIC [*de Vries and Weber* 2005; *Dijkstra* 2007; *Huisman et al.* 2010], but not yet in an AOGCM of this complexity.

In the FAMOUS transient simulation with increasing hosing, F_{ov} is positive for low values of the hosing (a stable AMOC), but becomes negative (indicating bistability) at $H = 0.35$Sv, i.e. before the rapid collapse occurs (Fig. 2B). In the equilibrium simulations started from the 'on' state (filled red circles), F_{ov} is negative for similar H to those where hysteresis occurs and positive elsewhere, before and after the rapid collapse. This suggests that a similar argument may apply in FAMOUS, although the physical mechanisms will be explored in greater detail in further work.

In the 'off' state, such a simple argument for the usefulness of F_{ov} as an indicator may not be appropriate [*Huisman*

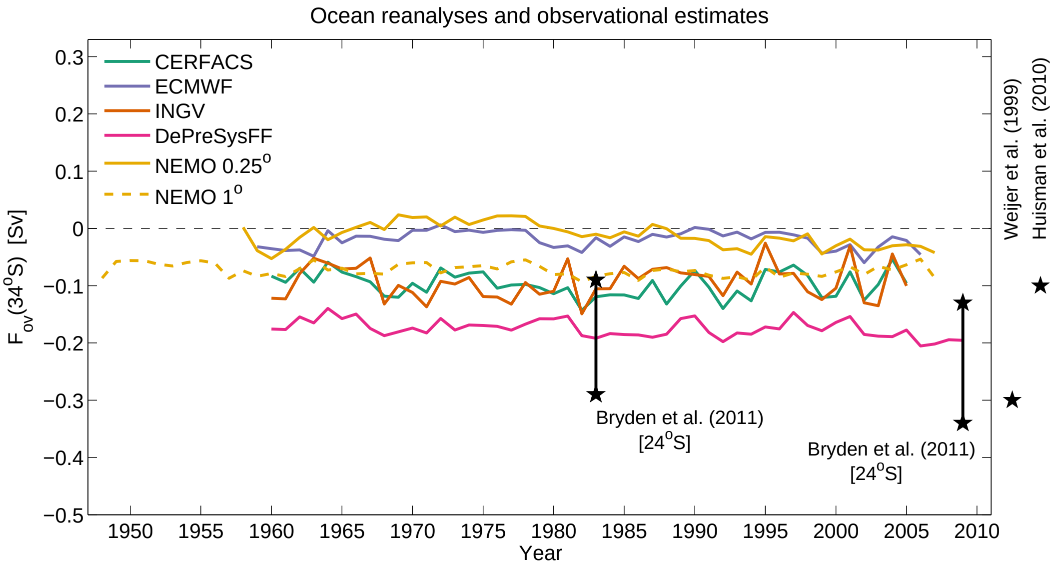

Figure 3. F_{ov} estimated from different ocean reanalyses and observational estimates as labelled. The mean of N realisations from the ENSEMBLES project is shown for INGV ($N = 3$), CERFACS ($N = 9$) and ECMWF ($N = 5$) [*Weisheimer et al.* 2007; *Doblas-Reyes et al.* 2009]. An additional single realisation is shown for a new DePreSys assimilation [after *Smith et al.* 2007]. All four of these analyses use full observations, rather than anomalies, to constrain the ocean state. Estimates from ocean-only simulations with NEMO 0.25° and 1°, forced with atmospheric observations, are also shown [*Barnier et al.* 2006]. The black stars indicate two climatological estimates from observations [*Weijer et al.* 1999; *Huisman et al.* 2010] and observations from ship transects at 24°S in 1983 and 2009, using two different methods [*Bryden et al.* 2011]. **Please note that this is a corrected version of the published figure, and that the Bryden et al. results are not in the published version of the paper.**

et al. 2010]. However, there is some evidence that it is relevant: as the rate of hosing is reduced in the FAMOUS transient experiment (blue solid line in Fig. 2B), F_{ov} becomes negative (suggesting bistability) before the recovery of the AMOC. Furthermore, it has been suggested that the rate of change of the total freshwater transports are more relevant for the 'off' state (*Sijp et al.* 2011). The mechanisms governing the stability of the 'off' state will also be examined in further work.

5. Warning signals in the real ocean

The findings with FAMOUS suggest that the transient evolution of F_{ov}, and particularly the sign of F_{ov}, could be a potentially observable indicator of AMOC bistability. Existing observation-based estimates for the recent time-mean of F_{ov} [*Weijer et al.* 1999; *Huisman et al.* 2010] are shown in Fig. 3. These observations consistently suggest that F_{ov} is negative, but they are rather uncertain on the magnitude. Recent observations from two ship transects in 1983 and 2009 at 24°S also indicate that F_{ov} is negative (*Bryden et al.* 2011).

Further evidence can be derived from ocean reanalyses using a range of AOGCMs, constrained by assimilating the historical observations of salinity and temperature [*Weisheimer et al.* 2007; *Doblas-Reyes et al.* 2009] or forced with atmospheric observations [*Barnier et al.* 2006]. These first estimates of the recent time evolution of F_{ov} (Fig. 3) show generally negative values for F_{ov}, suggesting the present-day ocean is in a bistable regime, but they are not consistent on the magnitude of F_{ov}, or its variability. However, given the wide range of estimates for the strength of the AMOC in these AOGCMs (*Pohlmann et al.* 2011), this agreement on the sign of F_{ov} is rather surprising. The two NEMO simulations suggest that ocean model resolution may be important.

Note especially that F_{ov} is generally negative for DePreSysFF [after *Smith et al.* 2007], which is based on the HadCM3 AOGCM. However, *Drijfhout et al.* [2011] showed that HadCM3 has a positive value of F_{ov} in its control state. This implies that assimilating the observations into this AOGCM causes the net freshwater transport to swap direction to a state consistent with a bistable regime. Determining the reasons for this will be valuable to assess the reliability of these results.

Another useful characteristic of F_{ov} as an effective indicator of bistability is that it has a higher signal-to-noise than the AMOC in FAMOUS (compare the time series in Figs. 2A and B), potentially allowing an early detection of any long-term changes. The estimates from the ocean reanalyses do not generally show any significant trends, but the DePreSysFF analysis indicates a less stable AMOC before the mid-1980s (Fig. 3).

6. Conclusions and discussion

We have performed specific experiments to look for AMOC hysteresis in a coupled AOGCM and analysed observational estimates of the freshwater transport in the Atlantic. The main findings are as follows:

1. We have demonstrated AMOC hysteresis in the FAMOUS coupled AOGCM. Although FAMOUS has a relatively coarse resolution compared to state-of-the-art AOGCMs, it is arguably the most physically comprehensive dynamical climate model to be shown to exhibit a bistable regime.

2. The sign of the net freshwater transport across 34°S by the AMOC may be an indicator of the presence of a bistable regime in FAMOUS. Further work will aim to understand the physical processes responsible.

3. Estimates for the net freshwater transport by the AMOC in a range of different ocean reanalyses are consistently negative, tentatively suggesting that the real ocean may currently be in a bistable regime.

One key issue to address is that FAMOUS, in common with many other AOGCMs [*Drijfhout et al.* 2011], shows a positive value for F_{ov} in its control climate (Fig. 2B), which is opposite to the observations. There are at least three possibilities for this: (i) the observational estimates are flawed, (ii) the value of F_{ov} switched from being positive to negative before the 1950s, or (iii) the AOGCMs are not realistically representing the transports of salinity. Determining which of these reasons are important for the differences in net freshwater import into the Atlantic between the observations and AOGCMs is highly relevant to assessing the likelihood of bistability in the real climate system. Additional observations of the net freshwater import into the Atlantic could also help constrain the risk of a future rapid collapse of the AMOC and the resulting impacts on climate.

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Supplementary Information

FAMOUS atmospheric variability

An important difference between FAMOUS and the various EMICs which have previously been used to analyse AMOC hysteresis is the presence of a dynamical atmosphere in FAMOUS, allowing a representation of clouds, precipitation and atmosphere-ocean coupling on scales from days to decades. In particular, variability in the state of the North Atlantic Oscillation (NAO) is thought to have a large impact on the state of the AMOC [*Latif et al.* 2006], but this variability is not present in EMICs.

To illustrate the magnitude and spatial patterns of atmospheric variability in FAMOUS over the Atlantic sector, we compare the winter (DJF) monthly mean sea level pressure (MSLP) characteristics of FAMOUS and the ERA-40 reanalysis [*Uppala et al.* 2005] (Fig. S1). The patterns of variability are very similar, especially the spatial structure of the North Atlantic Oscillation (NAO) in EOF1, although the pattern is centered slightly further north in FAMOUS.

The standard deviation of an NAO index (defined as the difference between monthly sea level pressure in Iceland and the Azores) is around 6hPa in FAMOUS, within the range of other AOGCMs (5-10hPa), and around 15% less than seen in observations [*Osborn* 2004].

Individual equilibrium simulations

Fig. S2 shows the AMOC at 26°N for the different constant hosing integrations performed. These are initiated both as the hosing is increasing ('ON') and when it is decreasing ('OFF').

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In both cases the 0.10 and 0.12Sv hosing runs recover to near the control value. For hosing larger than 0.25Sv, the MOC remains 'off'. However, the $0.15, 0.18, 0.20$ and 0.22Sv runs initiated as the hosing is increasing remain in an 'on' state, whereas those initiated as the hosing is decreasing remain in an 'off' state, demonstrating bistability.

It is also worth noting that the AMOC in several integrations started from the collapsed state undergo transient recovery and collapse on millennial timescales. This behaviour will be explored in further work.

Defining F_{ov}

The freshwater transport by the overturning circulation across a latitude Φ is defined by *Drijfhout et al.* (2011) as,

$$F_{\text{ov}}(\Phi) = -\frac{1}{S_0}\int_{-D}^{0} \overline{v^*}(z,\Phi)\langle S(z,\Phi)\rangle dz, \tag{1}$$

where $\langle S(z,\Phi)\rangle$ is the zonal mean salinity, S_0 is a reference salinity, D is the depth of the ocean, and $\overline{v^*}$ represents the zonal integral of the baroclinic velocity,

$$v^* = \langle v\rangle - \tilde{v}, \tag{2}$$

where $\tilde{v}$ is the mean northwards velocity and $\langle v\rangle$ is the zonal mean northwards velocity, across latitude Φ. The baroclinic velocity (v^*) is considered, excluding the barotropic velocity ($\tilde{v}$) because we are concerned specifically with the salinity transport by the overturning circulation.

References

Drijfhout, S. S., S. L. Weber, and E. van der Swaluw (2011), The stability of the MOC as diagnosed from model projections for pre-industrial, present and future climates, *Clim. Dyn.*, *in press*, doi:10.1007/s00382-010-0930-z.

Latif, M., C. Böning, J. Willebrand, A. Biastoch, J. Dengg, N. Keenlyside, U. Schweckendiek, and G. Madec (2006), Is the thermohaline circulation changing?, *J. Climate*, *19*, 4631 – 4637.

Osborn, T. J. (2004), Simulating the winter North Atlantic Oscillation: the roles of internal variability and greenhouse gas forcing, *Clim. Dyn,*, *22*, 605–623, doi:10.1007/s00382-004-0405-1.

Uppala, S. M., et al. (2005), The ERA-40 re-analysis, *QJRMS*, *131*, 2961–3012, doi: 10.1256/qj.04.176.

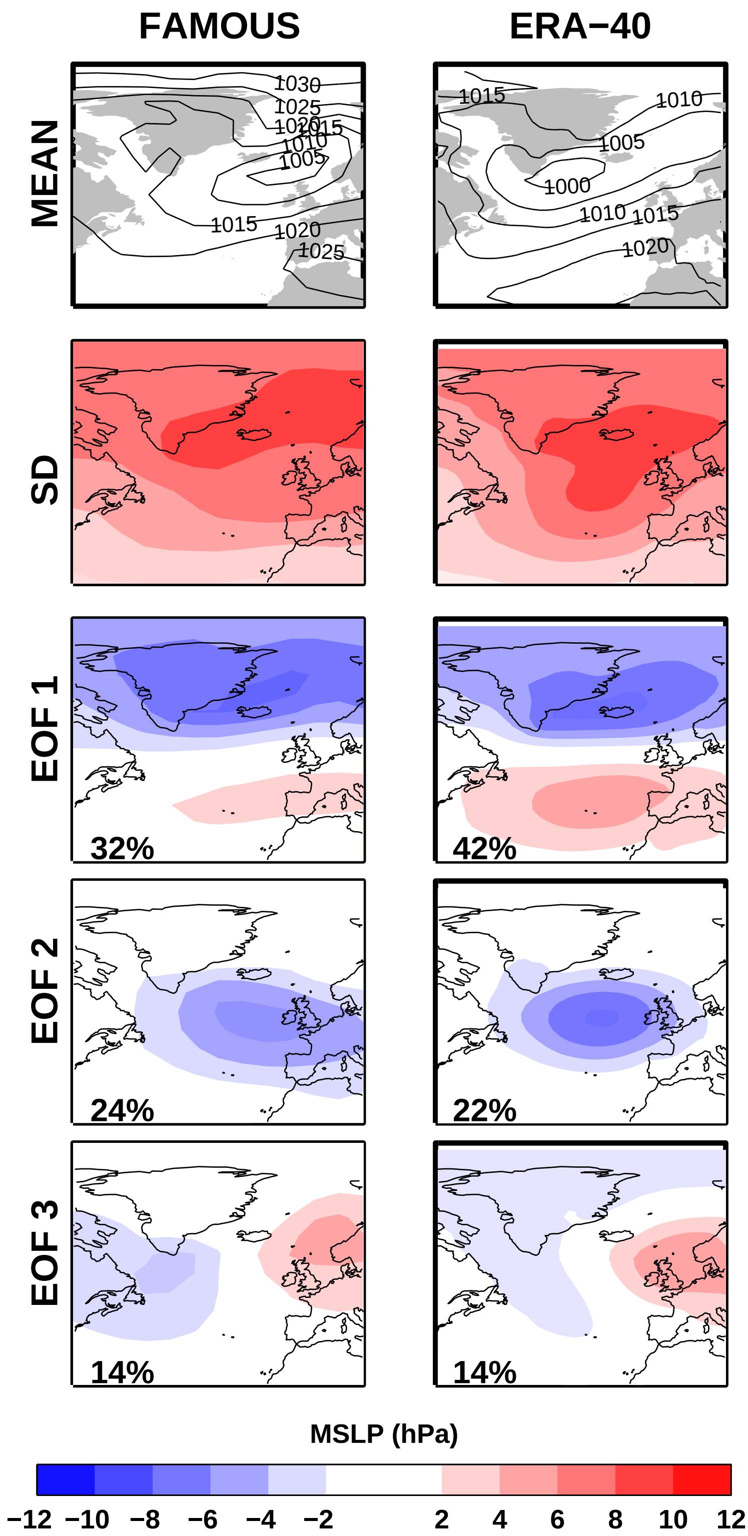

Figure S1: A comparison of winter (DJF) monthly mean sea level pressure (MSLP) characteristics of FAMOUS and the ERA-40 reanalysis. The EOF panels indicate the percentage of MSLP variance explained.

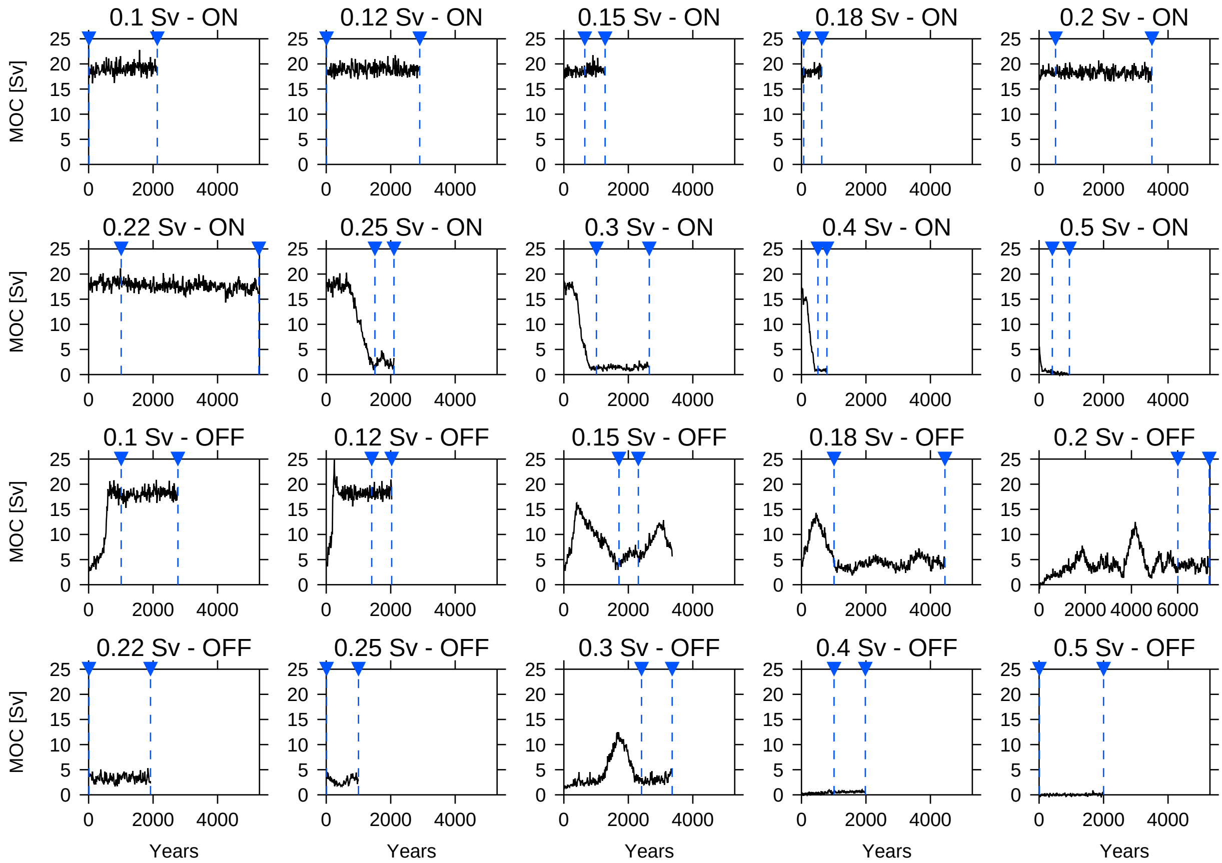

Figure S2: The time series of the AMOC at 26°N for the various hosing experiments as labelled, initiated from both the on and off states. The blue arrows indicate the time periods selected as stable to estimate the equilibrium values for the AMOC.