Stability of the Atlantic meridional overturning circulation: A model intercomparison

Andrew J. Weaver,[1] Jan Sedláček,[2] Michael Eby,[1] Kaitlin Alexander,[1] Elisabeth Crespin,[3] Thierry Fichefet,[3] Gwenaëlle Philippon-Berthier,[3] Fortunat Joos,[4,5] Michio Kawamiya,[6] Katsumi Matsumoto,[7] Marco Steinacher,[4,5] Kaoru Tachiiri,[6] Kathy Tokos,[7] Masakazu Yoshimori,[8] and Kirsten Zickfeld[9]

Received 4 September 2012; revised 24 September 2012; accepted 24 September 2012; published 24 October 2012.

[1] The evolution of the Atlantic Meridional Overturning Circulation (MOC) in 30 models of varying complexity is examined under four distinct Representative Concentration Pathways. The models include 25 Atmosphere-Ocean General Circulation Models (AOGCMs) or Earth System Models (ESMs) that submitted simulations in support of the 5th phase of the Coupled Model Intercomparison Project (CMIP5) and 5 Earth System Models of Intermediate Complexity (EMICs). While none of the models incorporated the additional effects of ice sheet melting, they all projected very similar behaviour during the 21st century. Over this period the strength of MOC reduced by a best estimate of 22% (18%–25%; 5%–95% confidence limits) for RCP2.6, 26% (23%–30%) for RCP4.5, 29% (23%–35%) for RCP6.0 and 40% (36%–44%) for RCP8.5. Two of the models eventually realized a slow shutdown of the MOC under RCP8.5, although no model exhibited an abrupt change of the MOC. Through analysis of the freshwater flux across 30°–32°S into the Atlantic, it was found that 40% of the CMIP5 models were in a bistable regime of the MOC for the duration of their RCP integrations. The results support previous assessments that it is very unlikely that the MOC will undergo an abrupt change to an off state as a consequence of global warming.
Citation: Weaver, A. J., et al. (2012), Stability of the Atlantic meridional overturning circulation: A model intercomparison, *Geophys. Res. Lett.*, *39*, L20709, doi:10.1029/2012GL053763.

1. Introduction

[2] In the 4th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR4) the Atlantic Meridional Overturning Circulation (MOC) was described as being *very unlikely* to undergo an abrupt (over the period of a decade or two) shutdown in the 21st century [*Meehl et al.*, 2007b]. This assessment was based on a basic understanding of processes involved in past abrupt changes of the MOC [e.g., *Clark et al.*, 2002; *Alley et al.*, 2003], focused model intercomparison projects [e.g., *Gregory et al.*, 2005; *Rahmstorf et al.*, 2005; *Stouffer et al.*, 2006] as well as coupled model simulations conducted as part of the third phase of the Coupled Model Intercomparison Project (CMIP3) [*Meehl et al.*, 2007a]. The IPCC AR4 further argued that it was too early to make an assessment regarding the stability of the MOC beyond the 21st century.

[3] Concomitant with and subsequent to the release of the AR4, the US Climate Change Science Program (CCSP) initiated the preparation of 21 synthesis and assessment products designed to provide decision makers in the United States the latest information on a variety of climate-related scientific issues of strategic national importance. One of these, Synthesis and Assessment Product (SAP) 3.4 [*Climate Change Science Program*, 2008], focused on the issue of Abrupt Climate Change. In SAP 3.4, *Delworth et al.* [2008] reaffirmed the assessment of *Meehl et al.* [2007b] that it is very unlikely that the Atlantic MOC will abruptly change in the 21st century, even though the MOC was expected to weaken by a best estimate of 25%–30%. However, they further concluded that it was also unlikely that global warming would lead to a MOC collapse beyond the end of the 21st century, although they were not able to completely exclude this possibility.

[4] As originally discussed in the pioneering work of *Stommel* [1961], *Rooth* [1982] and *Bryan* [1986], salt transported poleward in the North Atlantic provides a potentially destabilizing advective feedback to the MOC. That is, if the strength of the MOC were to reduce, then less salt would be transported into the North Atlantic thereby encouraging further reduction in its strength. The existence of this slow, salt advection feedback is critical to the presence of stable multiple equilibria of the MOC [see *Rahmstorf*, 1996]. Further analysis has determined that the sign of net freshwater flux transported by the MOC into the Atlantic across 30°–32°S serves as a key measure of this salt advection feedback and hence an indicator of the potential existence of multiple

[1]School of Earth and Ocean Sciences, University of Victoria, Victoria, British Columbia, Canada.
[2]Institute for Atmospheric and Climate Science, ETH, Zurich, Switzerland.
[3]Georges Lemaître Centre for Earth and Climate Research, Earth and Life Institute, Université Catholique de Louvain, Louvain-La-Neuve, Belgium.

Corresponding author: A. J. Weaver, School of Earth and Ocean Sciences, University of Victoria, Victoria, British Columbia, Canada. (weaver@uvic.ca)

0094-8276/12/2012GL053763

[4]Climate and Environmental Physics, Physics Institute, University of Bern, Bern, Switzerland.
[5]Oeschger Centre for Climate Change Research, University of Bern, Bern, Switzerland.
[6]Research Institute for Global Change, JAMSTEC, Yokohama, Japan.
[7]Department of Earth Sciences, University of Minnesota, Twin Cities, Minneapolis, Minnesota, USA.
[8]Atmosphere and Ocean Research Institute, University of Tokyo, Tokyo, Japan.
[9]Department of Geography, Simon Fraser University, Vancouver, British Columbia, Canada.

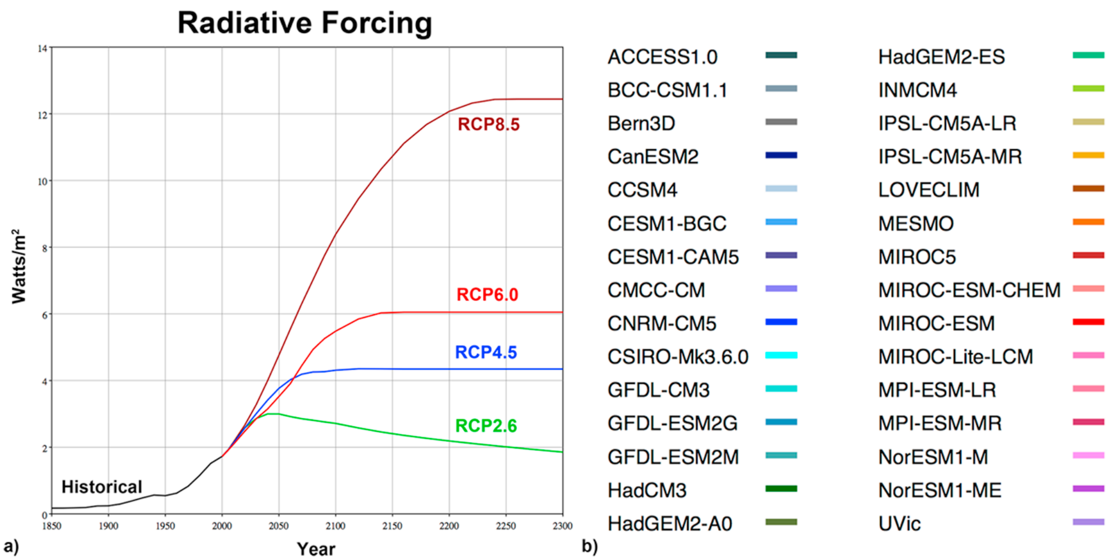

Figure 1. (a) Net radiative forcing in Watts/m^2 over the historical period (1850–2005), 21st century (2006–2100) and the RCP extension period (2100–2300). In the EMIC experiments that continued on until 3000, the radiative forcing was held constant at 2300 values. (b) Colour legend used in Figures 2 and 3. The five EMICs are: Bern3D, LOVECLIM, MESMO, MIROC-Lite-LCM, UVic.

equilibria [*Rahmstorf*, 1996; *Gregory et al.*, 2003; *de Vries and Weber*, 2005; *Dijkstra*, 2007; *Weber et al.*, 2007; *Huisman et al.*, 2010; *Drijfhout et al.*, 2011; *Hawkins et al.*, 2011]. A negative freshwater flux associated with the zonally-integrated baroclinic flow across 30°–32°S indicates net salt import to the Atlantic by the MOC. This in turn reveals the presence of the potentially destabilizing salt advection feedback and hence the existence of multiple equilibria. That is, the system is in a bistable regime. Conversely, if the freshwater flux is positive, the system is in a monostable regime.

[5] Since the publication of both the IPCC and CCSP assessments a number of studies have argued that many of the CMIP3 models might be overly stable [e.g., *Hofmann and Rahmstorf*, 2009; *Drijfhout et al.*, 2011]. This is significant since if the models are predominantly in a monostable regime for the present climate, then they will invariably project a MOC that would reestablish itself after a small perturbation caused it to weaken. At the same time, observations suggest that the present-day Atlantic is in a bistable regime [*Weijer et al.*, 1999; *Huisman et al.*, 2010; *Hawkins et al.*, 2011]. As the potential climatic and societal impact of an abrupt change of the MOC would be profound [*Kuhlbrodt et al.*, 2009], determining the stability properties of the MOC in models is a matter of some importance. In light of the availability of a new collection of model results from the fifth phase of the Coupled Model Intercomparison Project (CMIP5) [*Taylor et al.*, 2012] as well as from an intercomparison project involving Earth System Models of Intermediate Complexity (EMICs) conducted in support of the IPCC 5th Assessment Report, it is evidently timely to re-examine the stability of the MOC within this new generation of models.

2. Description of the Model Experiments

[6] The results from 30 Atmosphere-Ocean General Circulation Models (AOGCMs), Earth System Models (ESMs) and EMICs were analysed for this study. The models followed the CMIP5 protocol [*Taylor et al.*, 2012] for their historical integrations from 1850 to 2005 (see http://cmip-pcmdi.llnl.gov/cmip5/). During this period, changes in both natural and anthropogenic forcing (including land surface changes) were prescribed. From 2006 to 2300, the models were forced with specified trace gas and aerosol concentrations or emissions following, and consistent with, the Representative Concentration Pathways (RCPs) detailed in *Moss et al.* [2010]. These RCPs are distinguished by either their eventual stabilization level of anthropogenic radiative forcing (RCP4.5 and RCP 6.0) or, in the case of RCP2.6 and RCP8.5, their radiative forcing at 2100 (Figure 1a). Preindustrial baselines are defined here as the 1850–1900 average, except for a few models which started in 1851 or 1860. In this case, the 1851–1900 and 1860–1900 averages were used, respectively.

[7] All of the models completed the RCP4.5 integration to year 2100. Only 26 of them completed RCP8.5, 21 undertook RCP2.6 and 18 RCP6.0. Several of the models completed the RCP extensions to year 2300 (see Table 1). While velocity and tracer output were available from many of the CMIP5 model simulations, the maximum strength of the Atlantic MOC was updated to the CMIP5 database by fewer of them. In the analysis that follows, for each model, a single timeseries of the Atlantic MOC was obtained by averaging over all members of any submitted model ensemble. For the EMICs this was also done in the calculation of the baroclinic freshwater transport by the MOC into the Atlantic (F_{ov}) across 30°–32°S. Only the first complete ensemble member was used in the calculation of F_{ov} for the CMIP5 models.

[8] The five participating EMICs are as follows: Bern3D (B3) from the University of Bern; LOVECLIM v1.2 (LO) from the Université Catholique de Louvain; MESMO v1.0 (ME) from the University of Minnesota; MIROC-lite-LCM (ML) from the Japan Agency for Marine-Earth Science and Technology; UVic v2.9 (UV) from the University of

Table 1. Models for Which the Flux of Freshwater Into the Atlantic (F_{ov}) at 30° or 32°S Was Calculated[a]

Model Name	Country	Model Type	RCP(s) Used and the Final Year to Which Integration Occurred in Parentheses	Regime
ACCESS1.0	Australia	CMIP5	4.5 (2100); 8.5 (2100)	Bistable
BCC-CSM1.1	China	CMIP5	4.5 (2300); 6.0 (2100); 8.5 (2300)	Bistable
Bern3D	Switzerland	EMIC	2.6 (3000); 4.5 (3000); 6.0 (3000); 8.5 (3000)	Multiple
CanESM2	Canada	CMIP5	2.6 (2300); 4.5 (2300); 8.5 (2100)	Monostable
CCSM4	USA	CMIP5	4.5 (2300)	Monostable
CESM1-BGC	USA	CMIP5	4.5 (2100); 8.5 (2100)	Monostable
CESM1-CAM5	USA	CMIP5	4.5 (2300); 6.0 (2300); 8.5 (2100)	Monostable
CMCC-CM	Italy	CMIP5	4.5 (2100); 8.5 (2100)	Bistable
CNRM-CM5	France	CMIP5	2.6 (2100); 4.5 (2300); 8.5 (2300)	Monostable
CSIRO-MK3.6.0	Australia	CMIP5	2.6 (2100); 4.5 (2300); 6.0 (2100); 8.5 (2300)	Monostable
GFDL-CM3	USA	CMIP5	2.6 (2100); 4.5 (2100); 6.0 (2100); 8.5 (2100)	Bistable
GFDL-ESM2G	USA	CMIP5	2.6 (2100); 4.5 (2100); 6.0 (2100); 8.5 (2100)	Monostable
GFDL-ESM2M	USA	CMIP5	2.6 (2100); 4.5 (2100); 6.0 (2100); 8.5 (2100)	Multiple
HadCM3	UK	CMIP5	4.5 (2035)	Monostable
HadGEM2-AO	South Korea	CMIP5	2.6 (2100); 4.5 (2100); 6.0 (2100); 8.5 (2100)	Monostable
HadGEM2-ES	UK	CMIP5	2.6 (2300); 4.5 (2300); 6.0 (2100)	Monostable
INMCM4	Russia	CMIP5	4.5 (2100); 8.5 (2100)	Monostable
IPSL-CM5A-LR	France	CMIP5	2.6 (2300); 4.5 (2300); 6.0 (2100); 8.5 (2300)	Bistable
IPSL-CM5A-MR	France	CMIP5	2.6 (2100); 4.5 (2100); 8.5 (2100)	Bistable
LOVECLIM	Belgium	EMIC	2.6 (3000); 4.5 (3000); 6.0 (3000); 8.5 (3000)	Monostable
MESMO	USA	EMIC	2.6 (3000); 4.5 (3000); 6.0 (3000); 8.5 (3000)	Multiple
MIROC5	Japan	CMIP5	2.6 (2100); 4.5 (2100); 6.0 (2100); 8.5 (2100)	Bistable
MIROC-ESM-CHEM	Japan	CMIP5	2.6 (2100); 4.5 (2100); 6.0 (2100); 8.5 (2100)	Bistable
MIROC-ESM	Japan	CMIP5	2.6 (2100); 4.5 (2300); 6.0 (2100); 8.5 (2100)	Bistable
MIROC-Lite-LCM	Japan	EMIC	2.6 (3000); 4.5 (3000); 6.0 (3000); 8.5 (3000)	Monostable
MPI-ESM-LR	Germany	CMIP5	2.6 (2300); 4.5 (2300); 8.5 (2300)	Multiple
MPI-ESM-MR	Germany	CMIP5	2.6 (2100); 4.5 (2100); 8.5 (2100)	Bistable
NorESM1-M	Norway	CMIP5	2.6 (2100); 4.5 (2300); 6.0 (2100); 8.5 (2100)	Monostable
NorESM1-ME	Norway	CMIP5	4.5 (2100)	Monostable
UVic	Canada	EMIC	2.6 (3000); 4.5 (3000); 6.0 (3000); 8.5 (3000)	Bistable

[a]Not all models had maximum Atlantic MOC information available on the CMIP5 database. Columns 1–3 provide the model name, its country of origin and whether it is an EMIC or a CMIP5 model, respectively. The 4th column gives information on the RCPs used by each model and the final year of integration using that RCP (in parentheses). The 5th column indicates whether the model is always in a bistable or monostable regime for all RCPs. The entry *Multiple* indicates that at least for one RCP, the model moves from a bistable to a monostable regime or vice versa (see text for details).

Victoria. Each of these EMICs extended the RCP integrations to 3000 with radiative forcing held constant from 2300–3000 at the 2300 values.

3. Results

[9] The behaviour of the MOC in all models is similar over the 21st century (both CMIP5 and EMIC) under all radiative forcing scenarios (Figure 2). All models project a weakening of the MOC during the 21st century with a multi-model average of 22% (18%–25%; 5%–95% confidence limits) for RCP2.6, 26% (23%–30%) for RCP4.5, 29% (23%–35%) for RCP6.0 and 40% (36%–44%) for RCP8.5. None of the models reveal a shutdown of the conveyor during the 21st century. As also noted in previous analyses with both simple models [*Stocker and Schmittner*, 1997] and more complicated ESMs [*Meehl et al.*, 2012], the response of the MOC, and any potential slow spin down, depends on both the magnitude and rate of increase of the radiative forcing. For example, in *Gregory et al.* [2005] a strong correlation was found between the MOC's control strength and its weakening after 140 years of integration with atmospheric CO_2 levels increasing by 1% per year (i.e., until $4xCO_2$ was reached with a radiative forcing of about 7.4 W/m^2). Here we find a strong correlation in the case of RCP8.5 (Figure 3b), which has the radiative forcing corresponding most closely to that used in *Gregory et al.* [2005]. However, for RCP6.0, RCP4.5 and RCP2.6 this correlation breaks down (Figure 3a and Figure S1 in the auxiliary material).[1]

[10] During the RCP extension period from 2100–2300, the strength of the MOC either stabilizes or starts to recover in all the models that completed the RCP2.6, RCP4.5 and RCP6.0 simulations over this period. Only under the RCP8.5 scenario does the MOC spin down in two models. This eventually occurs before 2200 in CNRM and after 2700 in Bern3D (Figure 2). However, both of these models also start with the weakest Atlantic MOC during the preindustrial time (Figure 3a).

[11] As noted in the introduction, the freshwater flux by the MOC into the Atlantic through 30°–32°S (F_{ov}) provides an important indicator as to whether the MOC is in a monostable or bistable region. This freshwater flux across any particular latitude is given by:

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

where v is the northward velocity, the overbar denotes its zonal integral, the asterisk denotes its departure from the vertical average (i.e., the baroclinic component) and

[1]Auxiliary materials are available in the HTML. doi:10.1029/2012GL053763.

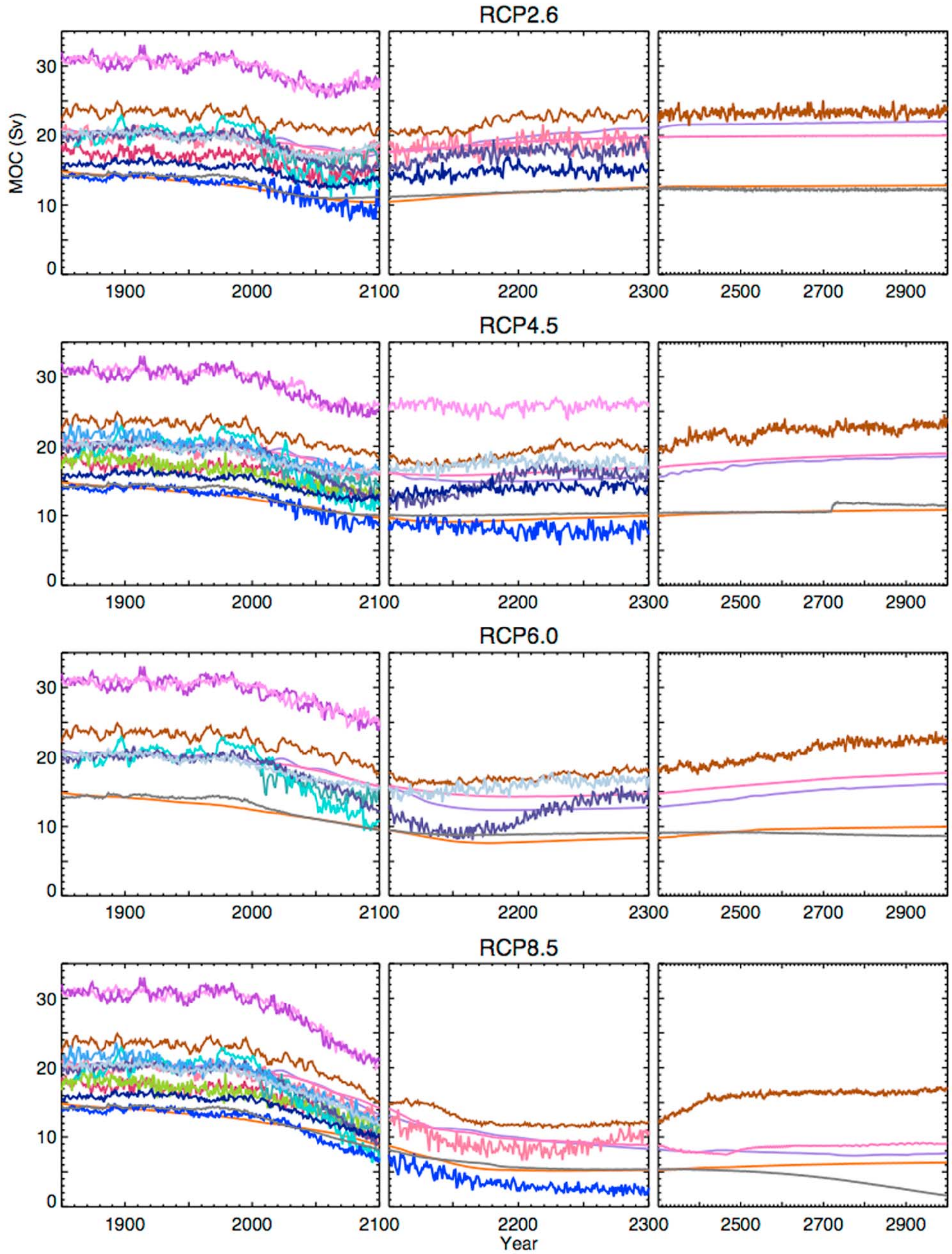

Figure 2. Maximum strength of the Atlantic Meridional Overturning Circulation (AMOC) in Sv (1 Sv ≡ $10^6 m^3 s^{-1}$) for the 5 EMICs and the 12 CMIP5 models (see Figure 1b for a colour legend). Each row shows the AMOC strength from (left) 1850–2100, (middle) 2100–2300 and (right) 2300–3000 for a different Representative Concentration Pathway: (first row) RCP 2.6; (second row) RCP 4.5; (third row) RCP 4.5; (fourth row) RCP 8.5.

the $\langle\ \rangle$ denotes a zonal mean. That is, $\overline{v^*}(z)$ is the zonally-integrated, northward baroclinic velocity and $\langle S(z)\rangle$ is the zonally-averaged salinity. Here S_0 is a reference salinity (selected to be 35 psu) and H is the depth of the ocean.

[12] The freshwater flux F_{ov} across 30°–32°S for each of the models under each RCP is shown in Figure 4. All but four of the models (Bern3D, GFDL-ESM2M, MESMO, MPI-ESM-LR – Figure S2 in the auxiliary material) reveal that F_{ov} is of the same sign throughout the entire length of the integrations across all RCPs. Eleven of the models always have $F_{ov} < 0$ (bistable regime) and fifteen of the models always have $F_{ov} > 0$ (monostable regime) at all time and for all RCPs.

[13] In GFDL_ESM2M, F_{ov} oscillates about $F_{ov} = 0$ during the historical period due to natural variability inherent to the system. However, during the later part of the 20th century, F_{ov} becomes less than zero (bistable regime) for all RCP scenarios out to 2100. In the case of MPI-ESM-LR, RCP2.6 and RCP4.5 always remain in the bistable regime (with $F_{ov} < 0$). RCP8.5, on the other hand, trends into positive (monostable) territory from 2100 to 2300. Two of the EMICs also have F_{ov} change sign during the course of their integrations. In MESMO, RCP8.5 eventually moves from $F_{ov} > 0$ (monostable regime) to $F_{ov} < 0$ (bistable regime), while all other RCP integrations remain in the monostable regime. In Bern3D, all of the RCP integrations begin with

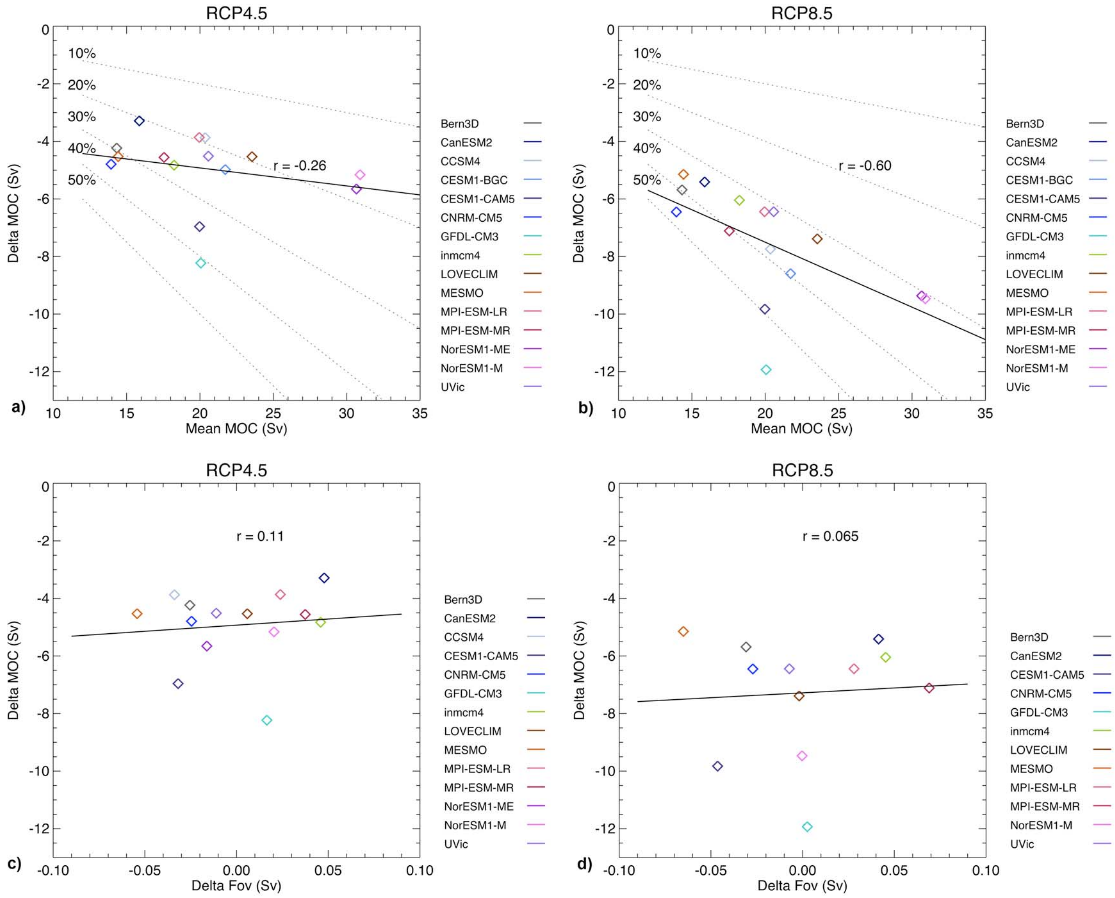

Figure 3. Change in the maximum strength of the AMOC (Sv), calculated as the difference between the 2081–2100 average and the preindustrial average, as a function of the maximum strength of the preindustrial AMOC. (a) RCP4.5; (b) RCP8.5. It is also shown as a function of the change in F_{ov} over the same averaging period. (c) RCP4.5; (d) RCP8.5. The best linear fit is also shown in all figures.

$F_{ov} > 0$, but in the case of RCP4.5, RCP6.0 and RCP8.5, they eventually cross over into the bistable regime. RCP2.6 remains in the monostable regime but F_{ov} slowly drifts towards zero as the integration proceeds to year 3000. RCP8.5 reveals interesting behaviour in this model, one of only two that eventually has a MOC spin down. By about 2600, F_{ov} becomes positive again and continues to grow in an unbounded fashion by year 3000. This suggests that in Bern 3D, the collapsed state is monostable towards the end of the integration.

4. Discussion and Conclusions

[14] In our experiments we have not imposed a freshwater forcing to examine the hysteresis and multiple equilibria behaviour of the MOC under constant radiative forcing (e.g., as in *Stocker and Wright* [1991], *Rahmstorf et al.* [2005], and *Stouffer et al.* [2006]). Rather, we have explored the behaviour of the MOC under changing, and ultimately sustained radiative forcing [e.g., *Manabe and Stouffer*, 1988; *Plattner et al.*, 2008]. The rationale for doing this was not to use F_{ov} as a predictor of the transient, radiatively forced behaviour of the MOC, but instead to determine whether or not the salt-advection feedback would be present to allow for multiple equilibria under any given radiative forcing. That is, we wished to determine whether or not models were in general overly stable and preferentially lay in the monostable regime, unlike observations. As such we focused our attention on the meridional streamfunction zonally-integrated across the Atlantic.

[15] We analysed the behaviour of the MOC in 30 models of varying complexity under four different Representative Concentration Pathways. The model responses were similar over the 21st century. All models showed a weakening of the Atlantic MOC but none showed an abrupt change to an off state. As noted in the carefully designed partially coupled experiments of *Gregory et al.* [2005], the reduction of the AMOC in global warming experiments is mainly driven by changes in surface thermal flux rather than surface freshwater flux. As such, we might not expect to see a correlation between the change in F_{ov} and the change in AMOC strength between the end of the 21st century and preindustrial times. This is indeed the case for all RCPs considered here (Figures 3c and 3d and Figure S1 in the auxiliary material). Nevertheless, the sign of F_{ov} is still an important indicator of the sign of the salt-advection feedback required for the existence of multiple equilibria of the AMOC.

[16] Beyond 2100, only two models eventually exhibited an eventual spin down of the MOC but even this shutdown occurred gradually, and not in an abrupt fashion. Previous criticism regarding a tendency for models to be overly stable appears not to be the case in the CMIP5 and EMIC models

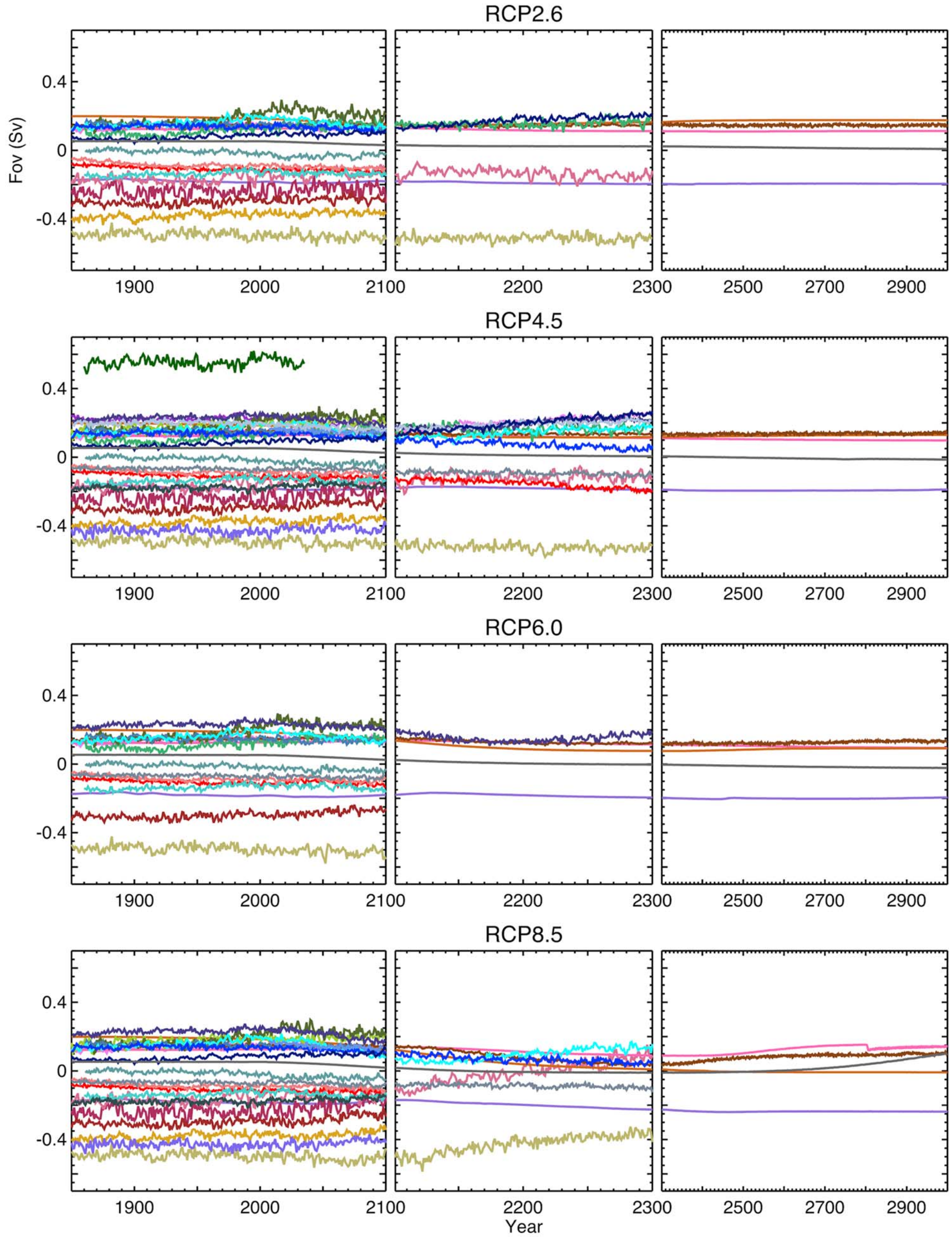

Figure 4. Flux of freshwater in Sv (1 Sv ≡ $10^6 m^3 s^{-1}$) into the Atlantic (F_{ov}) across 30°S for the 5 EMICs and across 32°S for the 25 CMIP5 models (see Figure 1b for a colour legend). Each row shows F_{ov} from (left) 1850–2100, (middle) 2100–2300 and (right) 2300–3000 for a different Representative Concentration Pathway: (first row) RCP 2.6; (second row) RCP 4.5; (third row) RCP 4.5; (fourth row) RCP 8.5.

examined here. Forty percent of the CMIP5 models analysed were in a bistable regime of the MOC during the RCP integrations. Taken together, this analysis tends to strengthen previous assessments that it is very unlikely that the MOC will undergo an abrupt transition during the 21st century. In fact, no model exhibited an abrupt transition even beyond the 21st century.

[17] Abrupt change of the MOC was certainly a pervasive feature of the last glacial cycle [*Clark et al.*, 2002; *Alley et al.*, 2003]. However, unlike today, vast reservoirs of freshwater were present in the Laurentide and Fennoscandian Ice Sheets and associated proglacial lakes. Sudden releases of this freshwater via either ice sheet surging, ice berg calving or meltwater discharge would affect the surface densities of the North Atlantic and could initiate a fast convective feedback that might ultimately lead to a MOC collapse. While none of the models examined in this study included an interactive Greenland Ice Sheet, *Jungclaus et al.* [2006], *Mikolajewicz et al.* [2007], *Driesschaert et al.* [2007], and *Hu et al.* [2009] all found only a slight temporary effect of increased melt water fluxes on the AMOC. This was either small compared to the effect of enhanced poleward atmospheric moisture transport in a warmer mean climate or only noticeable in the most extreme scenarios. It appears that significant ablation of the Greenland ice sheet greatly exceeding even the most aggressive of current projections would be required

[*Swingedouw et al.*, 2007; *Hu et al.*, 2009] to initiate an abrupt collapse of the MOC as a consequence of global warming.

[18] **Acknowledgments.** We are grateful to comments that we received from two anonymous reviewers. AJW, ME and KA are grateful for ongoing support from NSERC through its Discovery Grant, G8 and CREATE programs. TF and EC acknowledge support from the Belgian Federal Science Policy Office. We are particularly indebted to the enormous efforts of the CMIP5 organizational team and modelling groups.

[19] The Editor thanks two anonymous reviewers for their assistance in evaluating this paper.

References

Alley, R. B., et al. (2003), Abrupt climate change, *Science*, *299*, 2005–2010, doi:10.1126/science.1081056.

Bryan, F. O. (1986), High latitude salinity effects and interhemispheric thermohaline circulations, *Nature*, *323*, 301–304, doi:10.1038/323301a0.

Clark, P. U., N. G. Pisias, T. F. Stocker, and A. J. Weaver (2002), The role of the thermohaline circulation in abrupt climate change, *Nature*, *415*, 863–869, doi:10.1038/415863a.

Climate Change Science Program (2008), *Abrupt Climate Change. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research*, U.S. Geol. Surv., Reston, Va.

Delworth, T. L. et al. (2008), The potential for abrupt change in the Atlantic meridional overturning circulation, in *Abrupt Climate Change. A report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research*, pp. 258–359, U.S. Geol. Surv., Reston, Va.

de Vries, P., and S. L. Weber (2005), The Atlantic freshwater budget as a diagnostic for the existence of a stable shut down of the meridional overturning circulation, *Geophys. Res. Lett.*, *32*, L09606, doi:10.1029/2004GL021450.

Dijkstra, H. A. (2007), Characterization of the multiple equilibria regime in a global ocean model, *Tellus, Ser. A*, *59*, 695–705, doi:10.1111/j.1600-0870.2007.00267.x.

Driesschaert, E., T. Fichefet, H. Goosse, P. Huybrechts, I. Janssens, A. Mouchet, G. Munhoven, V. Brovkin, and S. L. Weber (2007), Modeling the influence of Greenland ice sheet melting on the Atlantic meridional overturning circulation during the next millennia, *Geophys. Res. Lett.*, *34*, L10707, doi:10.1029/2007GL029516.

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.*, *37*, 1575–1586, doi:10.1007/s00382-010-0930-z.

Gregory, J. M., O. A. Saenko, and A. J. Weaver (2003), The role of the Atlantic freshwater balance in the hysteresis of the meridional overturning circulation, *Clim. Dyn.*, *21*, 707–717, doi:10.1007/s00382-003-0359-8.

Gregory, J. M., et al. (2005), A model intercomparison of changes in the Atlantic thermohaline circulation in response to increasing atmospheric CO_2 concentration, *Geophys. Res. Lett.*, *32*, L12703, doi:10.1029/2005GL023209.

Hawkins, E., R. S. Smith, L. C. Allison, J. M. Gregory, T. J. Woollings, H. Pohlmann, and B. de Cuevas (2011), Bistability of the Atlantic overturning circulation in a global climate model and links to ocean freshwater transport, *Geophys. Res. Lett.*, *38*, L10605, doi:10.1029/2011GL047208.

Hofmann, M., and S. Rahmstorf (2009), On the stability of the Atlantic meridional overturning circulation, *Proc. Natl. Acad. Sci. U. S. A.*, *106*, 20,584–20,589, doi:10.1073/pnas.0909146106.

Hu, A., G. A. Meehl, W. Han, and J. Yin (2009), Transient response of the MOC and climate to potential melting of the Greenland ice sheet in the 21st century, *Geophys. Res. Lett.*, *36*, L10707, doi:10.1029/2009GL037998.

Huisman, S. E., M. den Toom, H. A. Dijkstra, and S. Drijfhout (2010), An indicator of the multiple equilibria regime of the Atlantic meridional overturning circulation, *J. Phys. Oceanogr.*, *40*, 551–567, doi:10.1175/2009JPO4215.1.

Jungclaus, J. H., H. Haak, M. Esch, E. Roeckner, and J. Marotzke (2006), Will Greenland melting halt the thermohaline circulation?, *Geophys. Res. Lett.*, *33*, L17708, doi:10.1029/2006GL026815.

Kuhlbrodt, T., et al. (2009), An integrated assessment of changes in the thermohaline circulation, *Clim. Change*, *96*, 489–537, doi:10.1007/s10584-009-9561-y.

Manabe, S., and R. J. Stouffer (1988), Two stable equilibria of a coupled ocean-atmosphere model, *J. Clim.*, *1*, 841–866, doi:10.1175/1520-0442(1988)001<0841:TSEOAC>2.0.CO;2.

Meehl, G. A., C. Covey, T. Delworth, M. Latif, B. McAvaney, J. Mitchell, R. Stouffer, and K. Taylor (2007a), The WCRP CMIP3 multimodel dataset, *Bull. Am. Meteorol. Soc.*, *88*, 1383–1394, doi:10.1175/BAMS-88-9-1383.

Meehl, G. A. et al. (2007b), Global climate projections, in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by S. Solomon et al., pp. 747–845, Cambridge Univ. Press, New York.

Meehl, G. A., et al. (2012), Climate system response to external forcings and climate change projections in CCSM4, *J. Clim.*, *25*, 3661–3683, doi:10.1175/JCLI-D-11-00240.1.

Mikolajewicz, U., M. Vizcaíno, J. Jungclaus, and G. Schurgers (2007), Effect of ice sheet interactions in anthropogenic climate change simulations, *Geophys. Res. Lett.*, *34*, L18706, doi:10.1029/2007GL031173.

Moss, R. H., et al. (2010), The next generation of scenarios for climate change research and assessment, *Nature*, *463*, 747–756, doi:10.1038/nature08823.

Plattner, G.-K., et al. (2008), Long-term climate commitments projected with climate-carbon cycle models, *J. Clim.*, *21*, 2721–2751, doi:10.1175/2007JCLI1905.1.

Rahmstorf, S. (1996), On the freshwater forcing and transport of the Atlantic thermohaline circulation, *Clim. Dyn.*, *12*, 799–811, doi:10.1007/s003820050144.

Rahmstorf, S., et al. (2005), Thermohaline circulation hysteresis: A model intercomparison, *Geophys. Res. Lett.*, *32*, L23605, doi:10.1029/2005GL023655.

Rooth, C. (1982), Hydrology and ocean circulation, *Prog. Oceanogr.*, *11*, 131–149, doi:10.1016/0079-6611(82)90006-4.

Stocker, T. F., and A. Schmittner (1997), Influence of CO_2 emission rates on the stability of the thermohaline circulation, *Nature*, *388*, 862–865, doi:10.1038/42224.

Stocker, T. F., and D. G. Wright (1991), Rapid transitions of the ocean's deep circulation induced by changes in surface water fluxes, *Nature*, *351*, 729–732, doi:10.1038/351729a0.

Stommel, H. (1961), Thermohaline convection with two stable regimes of flow, *Tellus*, *13*, 224–230, doi:10.1111/j.2153-3490.1961.tb00079.x.

Stouffer, R. J., et al. (2006), Investigating the causes of the response of the thermohaline circulation to past and future climate changes, *J. Clim.*, *19*, 1365–1387, doi:10.1175/JCLI3689.1.

Swingedouw, D., P. Braconnot, P. Delecluse, E. Guilyardi, and O. Marti (2007), Quantifying the AMOC feedbacks during a $2 \times CO_2$ stabilization experiment with land-ice melting, *Clim. Dyn.*, *29*, 521–534, doi:10.1007/s00382-007-0250-0.

Taylor, K. E., R. J. Stouffer, and G. A. Meehl (2012), An overview of CMIP5 and the experimental design, *Bull. Am. Meteorol. Soc.*, *93*, 485–498, doi:10.1175/BAMS-D-11-00094.1.

Weber, S. L., et al. (2007), The modern and glacial overturning circulation in the Atlantic Ocean in PMIP coupled model simulations, *Clim. Past*, *3*, 51–64, doi:10.5194/cp-3-51-2007.

Weijer, W., P. M. de Ruijter, H. A. Dijkstra, and P. J. van Leeuwen (1999), Impact of interbasin exchange on the Atlantic overturning circulation, *J. Phys. Oceanogr.*, *29*, 2266–2284, doi:10.1175/1520-0485(1999)029<2266:IOIEOT>2.0.CO;2.