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How the AMOC affects ocean temperatures on decadal to centennial timescales: the North Atlantic versus an interhemispheric seesaw

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Abstract This study investigates how variations of the Atlantic meridional overturning circulation (AMOC) affect sea surface temperature (SST) within the simulations of the coupled model intercomparison project phase 5. In particular, we explore whether the SST response is interhemispheric in nature, specifically as reflected in the Atlantic SST Dipole index, or whether the response is localized more in the North Atlantic Ocean. In the absence of direct observational data, this Dipole index has been proposed to approximate AMOC variations over the duration of the instrumental temperature record. We find that typically, on timescales between decadal and centennial, the SST Dipole index correlates with the AMOC with coefficients ranging from 0.2 to 0.7, typically with a 0–6 year lag, and thus explains less than half of the AMOC variance. In just two models this value slightly exceeds 50 %. Even for the models with the highest correspondence between the AMOC and the Dipole index, the correlation between the two variables is controlled mainly by SST variations in the North Atlantic, not the South Atlantic, both for the model control and historical simulations. Consequently, in nearly all models, the North Atlantic SST provides a better indicator of AMOC variations than the Atlantic Dipole. Thus, on decadal to centennial timescales AMOC variability affects mainly the North Atlantic Ocean, with the sensitivity of the North Atlantic SST between 40 and 60°N, given by the multi-model average, of about 0.3 °C per 1 Sv of AMOC change, explaining roughly one third of the SST variance.

Keywords AMOC · SST Dipole · AOGCMs

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1 Introduction

Variations of the Atlantic Meridional Overturning Circulation (AMOC) are believed to be an important driver of decadal to multi-decadal climate variability (e.g. Sutton and Hodson 2005; Knight et al. 2005; Zhang and Delworth 2006; Álvarez-Garcia et al. 2008; Seager et al. 2010; Semenov et al. 2010; Mahajan et al. 2011, for a recent review see Srokosz et al. 2012). In particular, it has been suggested that AMOC variations control or at least contribute to the Atlantic Multidecadal Variability (AMV), also referred to as the Atlantic Multidecadal Oscillation (AMO), see (Ting et al. 2011; Zanchettin et al. 2014). One important aspect of this connection is whether the AMOC variability affects sea surface temperatures (SST) mainly in the Northern Hemisphere or its impacts extend to the Southern Hemisphere as well. Accordingly, the goal of this study is to investigate this and other key aspects of the SST response to AMOC variations in climate models.

A number of observational and modeling studies investigating the AMOC have linked an interhemispheric SST dipole, designed to reflect interhemispheric seesaw changes in SSTs, to fluctuations in the overturning circulation (Latif et al. 2006; Keenlyside et al. 2008). This temperature dipole is observed on multi-decadal and longer timescales, is separate from the interannual to decadal Northern Hemisphere tri-polar pattern (Visbeck et al. 1998), and is generally consistent with the observed interhemispheric signature of the AMV.

While some studies use the dipole as a way of removing the global warming signal from the North Atlantic SST (Latif et al. 2004; Keenlyside et al. 2008), others employ the dipole as an index to investigate AMOC changes (Latif et al. 2006; Kamyokwsi 2010). In particular, in the absence of direct measurements of the AMOC extending beyond

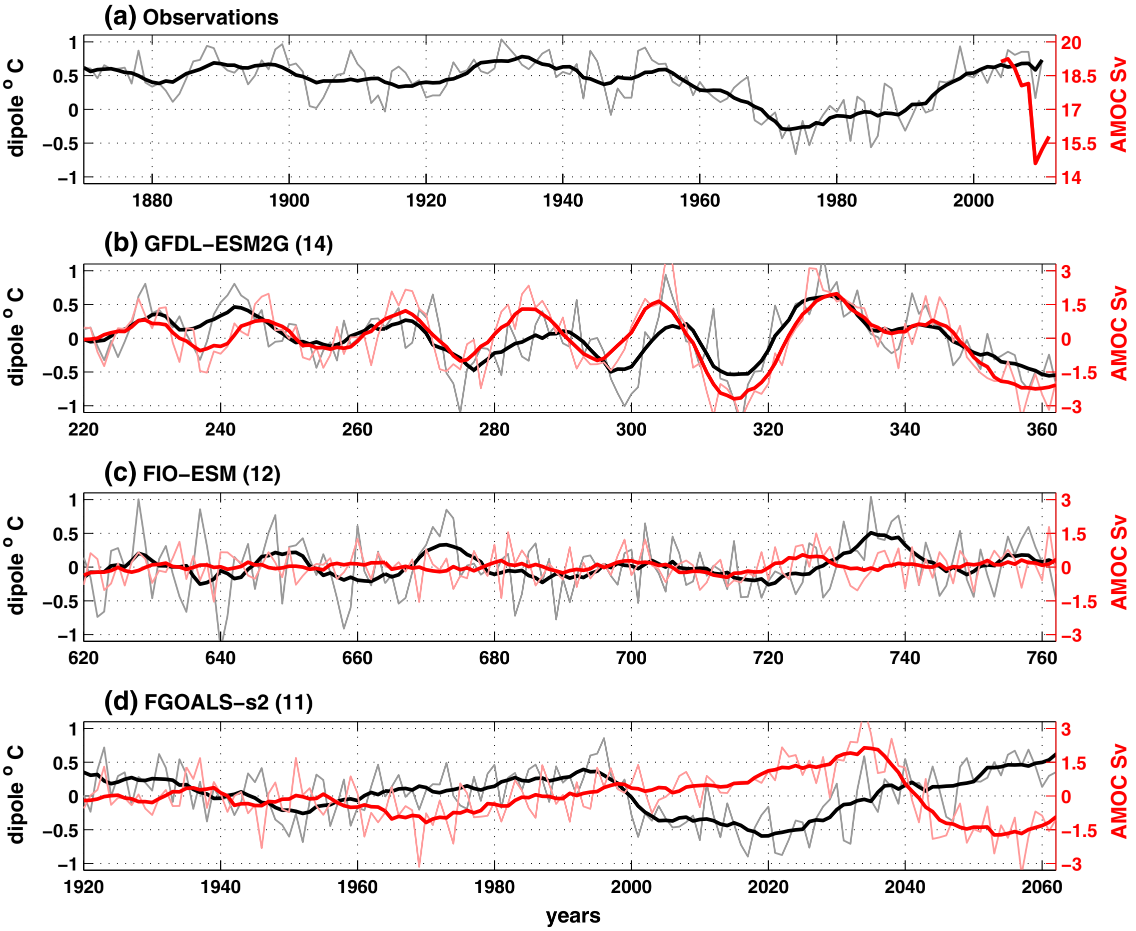

Fig. 1 **a** The observed Atlantic SST Dipole computed from HadISST (*black line*) and the AMOC volume transport at 26.5°N (*red*) from the RAPID-MOCHA project. **b**–**d** Examples of variations in the Atlantic Dipole (*black*) and the AMOC at 30°N (*red*, anomalies from the time mean) in the piControl simulations of the CMIP5 multi-model dataset showing a very broad range of behavior. Years in **b**–**d** are based on internal model years which are arbitrary as there are no changes in the radiative forcing. Even though the magnitude of decadal to multi-decadal changes in the simulated Atlantic SST Dipole indices is not unlike the observed, their temporal variations may be very different. *Thick lines* are decadal running means while *thin lines* are annual means

the past decade (RAPID, Cunningham et al. 2007), Latif et al. (2006) suggested using changes in the interhemispheric difference in temperature, the Atlantic SST Dipole Index (Fig. 1a), as a proxy for changes in the AMOC. To estimate the temperature difference, they computed a difference between mean SSTs for two selected regions in the Northern and Southern Atlantic respectively (see Sect. 2).

Evidence of an interhemispheric dipole of sea surface temperature (SST) in the tropical Atlantic Ocean comes from different observational and modeling sensitivity studies, as well as paleoclimate data. For example, the global expression of the AMV includes SST anomalies of the opposite sign in the Northern and Southern Atlantic. In modeling studies, Vellinga and Wood (2002) and Zhang and Delworth (2005) identified a dipole response in Atlantic SST while investigating perturbation freshwater 'hosing' experiments in the North Atlantic Ocean aimed at a full shutdown of the AMOC. After the shutdown, the Northern Atlantic cools and the Southern Atlantic warms. Typically, the warming south of the equator is restricted to the tropics and subtropics with the largest warming in the Benguela Current region. In a different approach, Knight et al. (2005) investigated the co-variability of the AMOC and SST in Hadley Centre Coupled Model, version 3 (HadCM3), a global coupled climate model. A dipole mode was found involving Southern Hemisphere subtropical temperatures and broad Northern Hemisphere SST that underwent an oscillation with a periodicity between 70 and 180 years. On much longer, millennial timescales, the out-of-phase variations in the climate of the Northern and Southern Hemispheres are tentatively identified in the records of abrupt climate changes (e.g. Blunier and Brook 2001).

Other studies however call into question the existence of an SST dipole mode, at least within the observed

Table 1 The model names, experiment durations (in years), AMOC mean strengths and other characteristics of the model control simulations

	Model name	Length (years)	Mean AMOC (Sv)	NH SST	Lag (years)	SH SST	Lag (years)	Dipole	Lag (years)
1	ACCESS1-0*	500	15.7	0.32	2	−0.37	−25	0.39	1
2	ACCESS1-3*	500	17.4	0.36	2	0.38	−39	0.32	1
3	bcc-csm1-1	500	16.4	0.58	1	(−0.28)	0	0.58	1
4	BNU-ESM	559	28.4	0.53	3	(−0.26)	3	0.55	3
5	CanESM2 *	996	14.9	0.34	1	−0.23	−2	0.38	0
6	CCSM4	501	19.6	0.43	2	0.39	50	0.33	18
7	CNRM-CM5	850	14.2	0.68	5	−0.58	−20	0.50	−15
8	CSIRO-Mk3-6-0	500	19.1	0.77	3	−0.35	−14	0.73	3
9	EC-EARTH	452	15.7	0.24	−1	(−0.39)	44	0.38	43
10	FGOALS-g2*	700	22.9	0.41	−1	0.25	−36	0.23	−1
11	FGOALS-s2	500	20.4	0.41	35	−0.45	30	0.52	33
12	FIO-ESM	800	12.9	0.22	15	0.18	−5	0.19	20
13	GFDL-CM3*	500	19.0	0.68	1	(−0.16)	50	0.52	0
14	GFDL-ESM2G	500	22.0	0.84	2	0.28	−35	0.77	2
15	GFDL-ESM2M*	500	21.4	0.50	2	(−0.23)	18	0.37	2
16	GISS-E2-R	525	17.6	0.77	2	(−0.18)	−17	0.59	3
17	HadGEM2-ES	550	14.7	0.68	2	0.24	−34	0.60	1
18	inmcm4*	500	16.7	0.36	−18	(0.17)	34	0.35	−18
19	IPSL-CM5A-LR	1,000	8.7	0.44	7	−0.24	−43	0.40	8
20	MIROC-ESM	531	13.6	0.47	6	0.32	−49	0.47	5
21	MIROC5	570	17.9	0.72	2	−0.39	32	0.52	3
22	MPI-ESM-LR*	1,000	19.3	0.67	1	0.22	7	0.56	0
23	MPI-ESM-MR*	1,000	16.9	0.65	2	0.23	−5	0.51	3
24	MPI-ESM-P*	1,156	18.7	0.61	1	−0.21	15	0.56	1
25	MRI-CGCM3*	500	14.2	0.59	5	(−0.27)	31	0.44	4
26	NorESM1-M*	501	29.7	0.53	3	−0.27	−50	0.41	5

The AMOC is evaluated at 30°N (in Sv). The maximum lag-correlations between of the NH SST, SH SST and the Atlantic Dipole index against the AMOC and the corresponding lags are also shown. Positive correlations at positive lags indicate that the AMOC strengthening precedes an SST warming. Model names marked with an asterisk are those that have data available for the historical (post-1850) simulations. Values given in brackets are not significant at the 90 % level as determined by a two-sided Student's *t* test

temperature record. They argue that SST variability in the South Atlantic is separate from that originating in the North Atlantic Ocean (Houghton and Tourre 1992; Enfield and Mayer 1997; Enfield et al. 1999). Specifically, the SST signature of the AMV as found in the observations is much greater in the Northern Hemisphere than in the Southern Hemisphere (Enfield et al. 2001; Sutton and Hodson 2005).

In the present paper we will use the CMIP5 (Coupled Model Intercomparison Project Phase 5) multi-model ensemble dataset to determine whether there is a strong connection between AMOC variations and the interhemispheric SST dipole at multi-decadal time scales and if one could indeed use the Atlantic Dipole as an index for AMOC variability on decadal to centennial (or perhaps multi-centennial) timescales. The CMIP5 control simulations provide a natural framework to answer these and related questions. For comparison, we will also use historical simulations, even though they are too short to fully analyze the models' AMOC variability typically dominated by decadal to multi-decadal frequencies.

2 Data and methods

The models used in this study are taken from the dataset of the CMIP5 (Taylor et al. 2012). The piControl experiments are used as they contain sufficiently long simulations and have constant 1850 levels of greenhouse gases and other external forcing (Taylor et al. 2009). Models with fewer than 400 years of data are ignored, which leaves a total of 26 models. The duration of those runs varies from 452 to 1,156 years. The names of the models and lengths of the experiments are provided in Table 1. In addition, the historical experiments (1850–2005), when available, are also analyzed for a subset of the models (indicated in Table 1 by an asterisk). These latter experiments are all of only 156 years in length.

The CMIP5 coupled models use different ocean components, which include isopycnal models (e.g. GFDL-ESM2G, NorESM1-M) and terrain following coordinate models (e.g. inmcm4), however the majority of ocean models are level coordinate models. The ocean component resolutions range from 0.4° (NorESM1-M) to 2° (IPSL-CM5A-LR).

For the purposes of this study, the strength of the AMOC is defined by the maximum value at 30°N, close to the latitude of the RAPID array of 26.5°N. When the overturning streamfunction was not available for a particular model, the integrated volume transports were calculated on the model's native grid by integrating velocity fields along model grid points closest to 30°N. These calculations are based only on the Eulerian-mean flow, which should not affect the main results of the study.

To evaluate the Northern Hemisphere Atlantic (NH) and Southern Hemisphere Atlantic (SH) SSTs, we follow Latif et al. (2006) and use the two regions bounded by the boxes [60°W–10°W, 40°N–60°N] and [50°W–0°E, 60°S–40°S]. To compute the Atlantic SST Dipole index we simply subtract the latter from the former. Note that the region we use for computing the NH SST (40–60°N) is smaller than the region typically used for defining the AMV index (0–60°N).

For most of the results shown, temporal filtering is performed on the data to restrict the investigation to decadal to multi-decadal variability. The band-pass filtering of the AMOC and SST time series in the band between 10 and 100 years is performed by computing the difference between 100- and 10-year running means; other types of filters were tested but did not affect the outcome. The relatively short lengths of the control simulations in many models (Table 1) limit the statistical significance of periods longer than 100 years. Regression maps shown in Fig. 5 are computed on the band-pass filtered data. Statistical significance tests are performed using a two-sided Student's *t*-test with the effective degrees of freedom determined by the decorrelation timescale of the data.

In addition, for eight models having greater than 800 years of model output available, we also use a low-pass filter with a cut-off of 400 years to produce regression maps in Fig. 6. Although these results are at the margins of statistical significance, they are still informative and useful, providing information on the connection between the AMOC and SST on longer, multi-centennial timescales.

3 Results

The AMOC in the CMIP5 dataset shows a very broad range of behavior from one model to the next. The mean AMOC at 30°N varies from 8.7 Sv (IPSL-CM5A-LR) to 29.7 Sv (NorESM1-M), see Table 1, while the observations from RAPID-MOCHA give 17.5 ± 5.1 Sv (Cunningham et al. 2007; Johns et al. 2011; Smeed et al. 2013; Fig. 1a) ($1\,\text{Sv} = 10^6\,\text{m}^3\,\text{s}^{-1}$). The strength of the AMOC variability in the models also has a large spread across the dataset, with the variance of the decadal means ranging from 0.07 Sv (FIO-ESM) to 1.38 Sv (GFDL-ESM2G). The available AMOC observations are too short to estimate this variance for decadal and longer timescales.

Some of the models exhibit strong multi-decadal variability in the AMOC, while other models show little decadal variability with no dominant frequency (Fig. 1b–d). Computing the power spectra indicates that most of the models produce AMOC variations with dominant periods in the 8–80 year range (Fig. 2).

The strength of the connection between the Atlantic Dipole and the AMOC also varies greatly across the models. Maximum lagged correlations between the two indices (Fig. 3) can be as high as 0.77 (GFDL-ESM2G, Fig. 1b) or as low as 0.19 (FIO-ESM, Fig. 1c). All but two of the models show a maximum correlation greater than 0.3 in magnitude, and half of the models are above 0.5 (25 % of the variance explained).

The lag between the Atlantic SST Dipole index and AMOC variations at 30°N falls between 0 and 6 years for a majority of the models, with positive anomalies in the AMOC preceding positive values of the Dipole (Fig. 3). However, there are a few exceptions. For example, FGOALS-s2 has the Dipole index 33 years out of phase with the AMOC (Fig. 1d), predominately due to cooling in the North Atlantic Ocean. Two models, inmcm4 and CNRM-CM5, have peaks in the Atlantic Dipole some 20 years before the AMOC maximum.

While the Atlantic Dipole does appear to have a relatively robust connection to the AMOC, especially at favorable lags, we will now investigate the individual contributions of the NH SST and the SH SST to the Dipole index and compare their respective roles.

In most of the models the NH SST shows a generally similar response in the lag correlations as the Atlantic Dipole (the warming of the northern Atlantic lags the AMOC intensification by 0–6 years, see Fig. 3). These lags are similar to those found in Roberts et al. (2013) but in a smaller subset of models. In contrast, correlations between the AMOC and the SH SST on these timescales are not consistent (Table 1). Although many models show a statistically significant link between these two variables, only two models exhibit a correlation greater than 0.4 (CNRM-CM5, FGOALS-s2); neither of these models however display a true dipole-like SST behavior characterized by well-defined temperature anomalies of different sign in opposite hemispheres.

In general, the timing of the SH SST peak with respect to the AMOC varies strongly from one model to the next

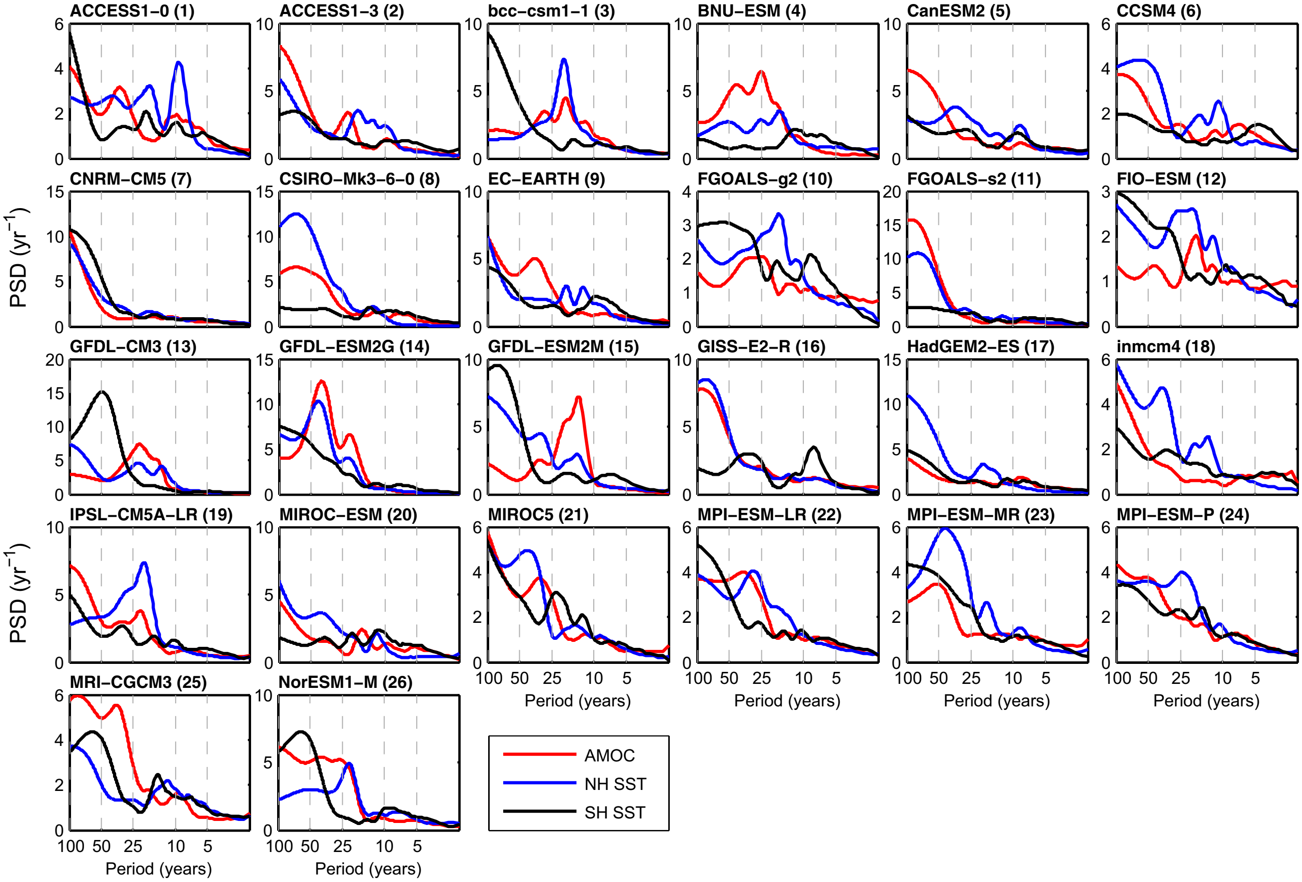

Fig. 2 Normalized power spectra of the AMOC Index at 30°N (*red*), and of variations in the NH SST (*blue*) and the SH SST (*black*). Note significant differences in the spectra across the models, and between the three variables. A number of models share dominant spectral peaks between the AMOC and NH SST, but rarely between the AMOC and the SH SST

(Fig. 3). For example, in many models the SH SST cools after the AMOC peak, albeit at different lags (CCSM4, FGOALS-s2, MPI-ESM-P, NorESM1-M), while other models show warming after the AMOC peak (CNRM-CM5, ACCESS1-0, CSIRO-Mk3-6-0, MPI-ESM-LR).

In many models the spectra of the NH SST and the AMOC share similar dominant peaks, which gives more evidence that variations in the North Atlantic SST and the AMOC are connected (e.g. bcc-cm1-1, GFDL-CM3, GFDL-ESM2G, IPSL-CM5A-LR), see Fig. 2. This result is consistent with a recent study of Ba et al. (2014), who used a smaller subset of 10 models from an earlier intercomparison and considered the relationship between the AMV and the AMOC. The SH SST does not tend to have similar spectral peaks with the AMOC, which is not what one should expect if there were a strong relationship between the SH SST and the AMOC.

Consistent with these relationships between the AMOC and hemispheric SSTs, the maps of SST regression onto the AMOC (for the maximum lag-correlation between the AMOC and the Atlantic Dipole Index) reveal qualitatively similar patterns of broad warming in the Northern Hemisphere with either no signal or weak cooling in the South (Fig. 4). The exact location of the strongest warming varies across the models but there is a broad agreement that it occurs in the latitudinal band between 40°N and 60°N.

Note that in four models the broad warming of the North Atlantic is accompanied by a strong, albeit localized cooling in the Nordic Seas (CCSM4, EC-EARTH, IPSL-CM5A-LR, MRI-CGCM3). This cooling can be related to model deficiencies in simulating deep convection in that region or to how accurately the models simulate the North Atlantic subpolar gyre and the path of the North Atlantic Current.

Several models develop a weak localized cooling off the African South West Coast, in the region of the Benguela Current. The spatial pattern of the cooling in the HadGEM2-ES model is very similar to results found previously (Knight et al. 2005; Vellinga and Wood 2002) using the HadCM3 model. This could be the result of HadGEM2-ES and HadCM3 having the same ocean model. A similar SST anomaly south of the equator is evident in five other

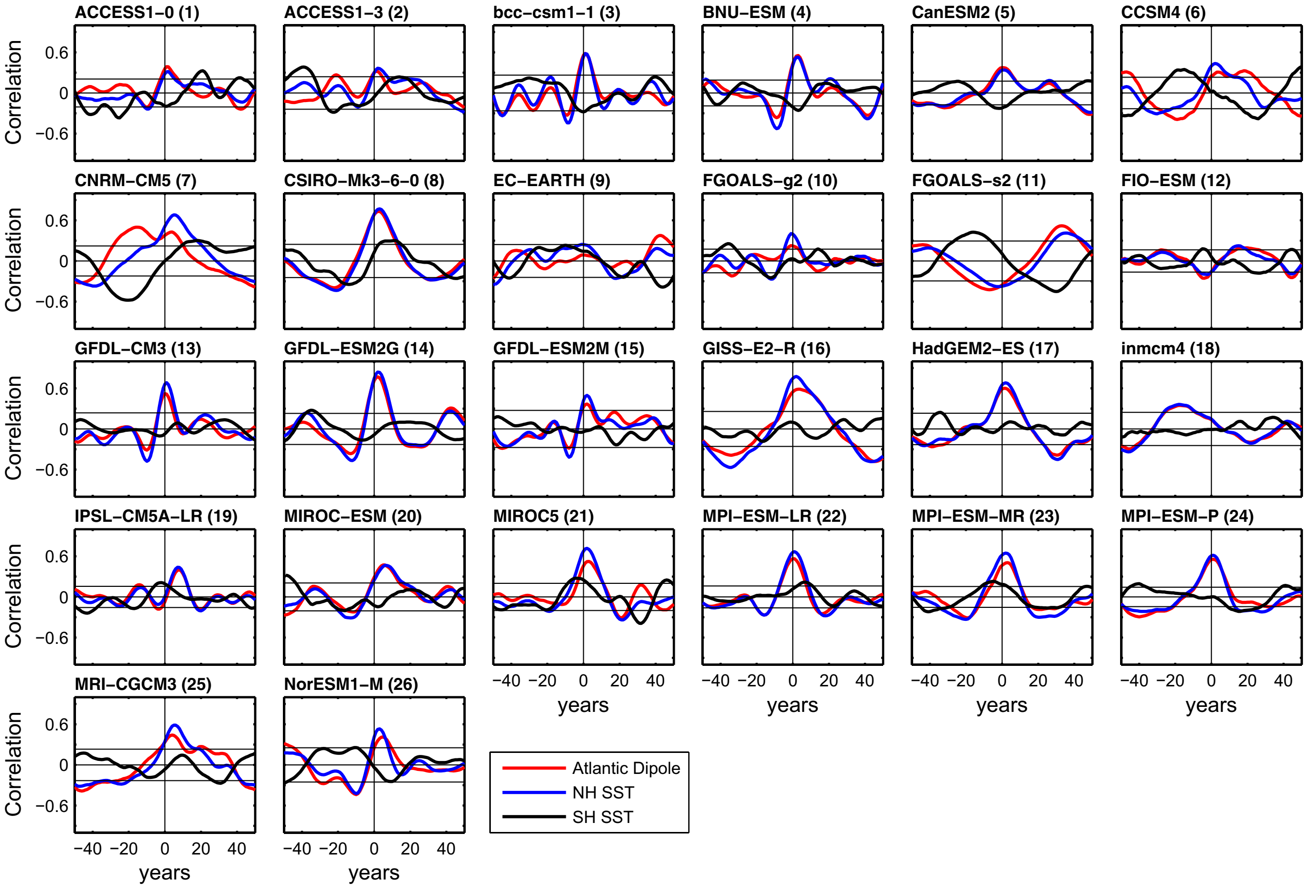

Fig. 3 Lag correlations of the AMOC against the NH SST (*blue*), the SH SST (*black*) and the Atlantic Dipole (*red*). Positive correlations at positive lag indicate AMOC changes lead SST changes. Most models show a strong link between the AMOC and NH SST variations (with the latter lagging the former), and a weak or no link between the AMOC and the SH SST. *Thin horizontal lines* indicate the 90 % significance levels

models with varying strengths (FGOALS-g2, FGOALS-s2, MPI-ESM-LR, MPI-ESM-MR, NorESM1-M).

Thus, on decadal to centennial timescales there are significant differences in the AMOC relationship to SST variations in the Northern and Southern Hemispheres (Figs. 2, 3, 4), which includes the weak or even zero impact of AMOC variations on the SH SST. As a result, in the majority of the models (19 out of 26) the NH SST alone correlates better with the AMOC than the Atlantic Dipole does; in fact many models show improvements in the correlations of up to 20 % when using the NH SST alone (Fig. 5). Only in five models does the AMOC have a slightly higher correlation with the Atlantic Dipole than with the NH SST (ACCESS1-0, BNU-ESM, CanESM2, EC-EARTH, FGOALS-s2).

Could an interhemispheric seesaw pattern of the SST response to AMOC variations emerge at longer timescales, for example multi-centennial? We have investigated this question using eight CMIP5 models with more than 800 years worth of data available. A low-pass filter is used with a cut-off of 400 years instead of the band pass approach used previously. Although on the margins of statistical significance, these calculations are still informative. Of the eight models, only one model shows a true dipole like pattern (CNRM-CM5; Fig. 6). Moreover, half of the models investigated show a warming of the South Atlantic concurrent with the warming of the North Atlantic Ocean, but the signal in the Southern Hemisphere remains highly inconsistent between the models.

Since one of the goals of using the Atlantic SST Dipole was to approximate AMOC variations over the duration of the instrumental record, in addition to the analysis performed on the control simulations we have also investigated the use of the Atlantic Dipole index in the historical (post-1850) CMIP5 simulations, which incorporate the observed natural and anthropogenic forcings. Only 12 models had data from the historical experiments available (those models are indicated by an asterisk in Table 1). Instead of a band pass filter used in most of the previous analysis, now we use a 10-year low-pass filter, which better preserves longer frequencies. For comparison we also use

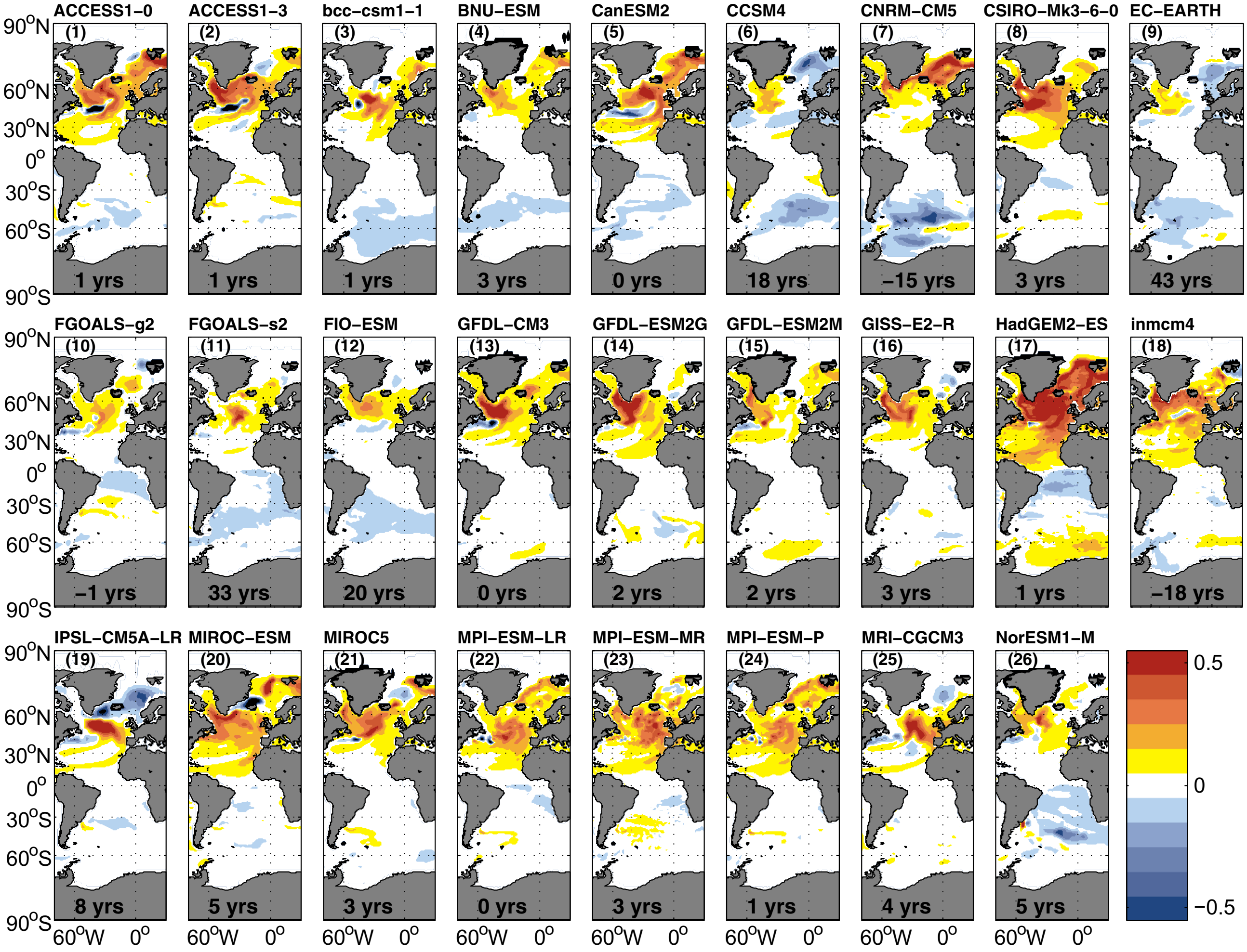

Fig. 4 Regressions of SST onto the AMOC index (evaluated at 30°N) at the lag corresponding to the maximum correlation between the AMOC and the Atlantic Dipole (the best lag). SST changes for a 1 Sv increase in the AMOC are shown. *Numbers at the top of each panel* indicate the models number (Table 1); *numbers at the bottom of the panels* indicate the lag (in years) of the Dipole Index with respect to AMOC variations. Units are °C Sv^{-1}. The maximum SST response is found in the northern Atlantic, typically between 40 and 60°N. The Southern Atlantic exhibits no or very week signal

an isolated NH SST anomaly computed by subtracting the global mean SST from the full North Atlantic SST.

We find that again the Atlantic Dipole performs worse than the isolated NH SST anomaly (Fig. 7). This is because in many simulations the North Atlantic and South Atlantic SSTs have different temporal behavior as apparent from Figs. 2 and 3. Changing the location of the southern region to 0–20°S when computing the Dipole index (as in Roberts et al. 2013) improves the correlations between the Dipole and the AMOC slightly for a few models, but the isolated NH SST anomaly still provides a better indicator of AMOC variations, as the Southern Hemisphere contribution interferes with the AMOC–SST link. Thus, the isolated NH SST index appears to do a better job in separating the SST signal associated with the AMOC from that due to the global warming trend.

4 Conclusions and discussion

In this study, long control simulations of the CMIP5 dataset as well as several historical (post 1850) simulations have been used to investigate the relationship between the AMOC and sea surface temperature in the Atlantic Ocean on decadal to centennial timescales. We find a large diversity in how the models simulate AMOC and SST variations, including their magnitude, dominant periods and the relative timing. We also find little connection between SST variability in the Northern and Southern Hemispheres even for non-zero lags. However, there is consistent agreement across the models that the North Atlantic Ocean warms a few years following the peak of the AMOC. Just three of the models show a warming in the North Atlantic preceding the peak in the AMOC (by roughly 1 year, EC-EARTH,

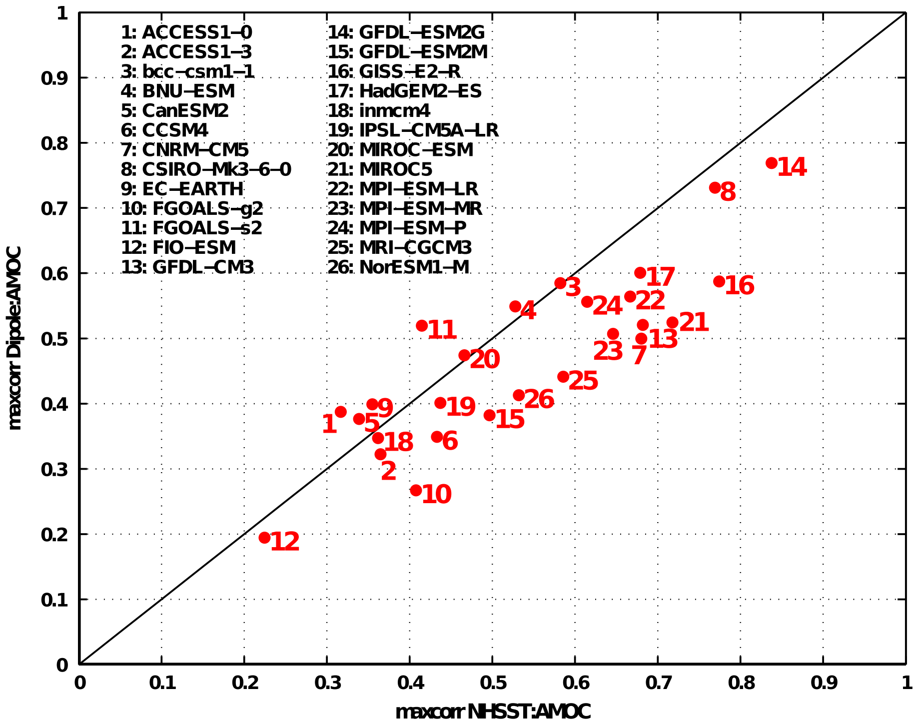

Fig. 5 Maximum lag correlations between AMOC variations and the Atlantic SST Dipole (ordinate) plotted against the lag correlation between the same AMOC index and the NH SST (abscissa). For points below the *diagonal line* the NH SST is a better approximation to the AMOC than the Atlantic Dipole. Consequently, within a significant majority of the models, taking into account South Atlantic SSTs makes the Atlantic Dipole index a less accurate indicator of AMOC variations than using just the Northern Hemisphere SSTs

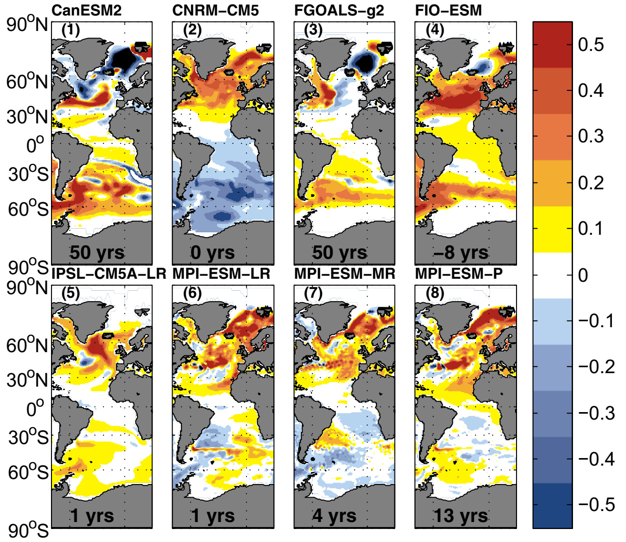

Fig. 6 As in Fig. 4, but with a 400-year low pass filter applied to the data, and only for models with more than 800 years of data available. Units are °C Sv^{-1}. This plot suggests that even for multi-centennial timescales, the Southern Atlantic SST response to AMOC variations is inconsistent between the models, while a truly interhemispheric seesaw pattern emerges only in one model (CNRM-CM5)

FGOALS-g2, inmcm4), whereas one model develops a slight cooling during the AMOC peak (FGOALS-s2).

While the relationship between the AMOC and the North Atlantic SST is largely consistent across the models, the relationship of the AMOC and the Southern Hemisphere Atlantic SSTs temperatures shows little to no consistency. On the timescales of interest, from decadal to centennial and even multi-centennial, the interhemispheric variations in SST appear to be dynamically important only in a small subset of the models. For instance, one model develops a cooling in the SH SST prior to the positive AMOC peak and the subsequent NH SST warming (CNRM-CM5). This could be a signature of a long oscillation connecting the two hemispheres with a period extending over a century. Overall, the link of the Atlantic SST Dipole index to the AMOC on these timescales is weaker across the models than the link between the AMOC and the North Atlantic SST.

SST regression maps (Fig. 4) confirm that on such timescales, AMOC variations have the largest impact on the Northern Hemisphere, even though typically they still explain less than 50 % of the SST variance; only in three models do they explain up to 60–70 % of the variance. In general, the impact of AMOC variations on the Southern Atlantic Ocean is weak, not robust and present only in a handful of models. Consequently, using the Atlantic SST Dipole as a measure of the AMOC even at the best lags can result in the reduction of the correlations by as much as one third as compared to using the NH SST (Fig. 5). Thus, the North Atlantic SST emerges as a better indicator of the AMOC variability, as evidenced by the fact that the majority of points in Fig. 5 lie below the figure's diagonal. Those few models that do show correlations of the AMOC to the Dipole Index slightly higher than to the NH SST are the

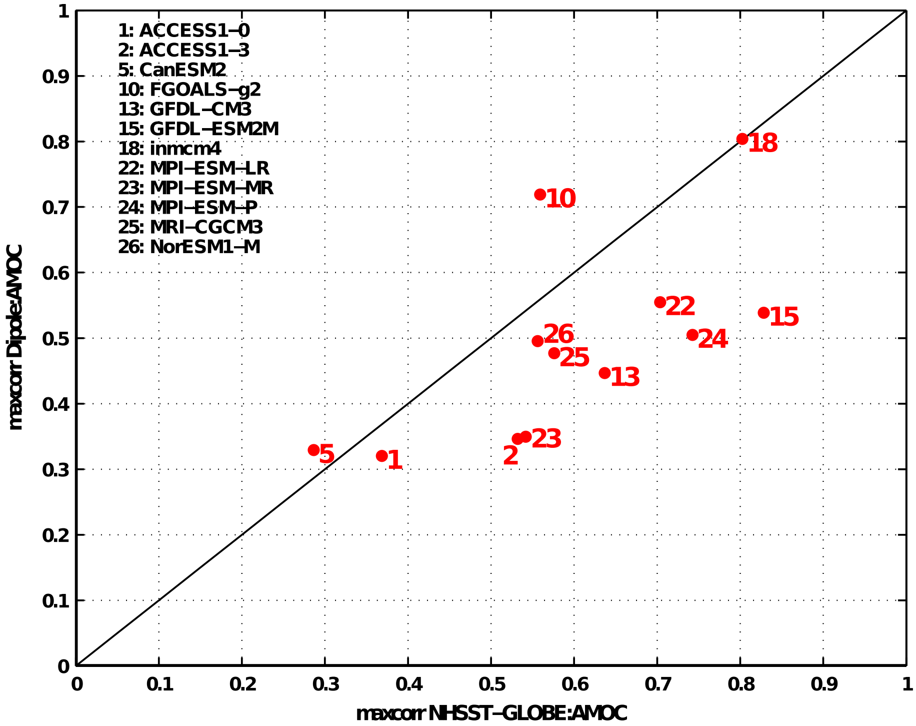

Fig. 7 As in Fig. 5, but for ten historical (post-1850) simulations. The NH SST has been replaced by an isolated NH SST anomaly (defined as the NH SST minus Global mean SST). Since the majority of points are located below the *diagonal line*, the isolated NH SST anomaly provides a better approximation to the AMOC than the Atlantic SST Dipole

models with a generally low correlation between ocean surface temperatures and the AMOC.

Among the analyzed models, the GFDL-ESM2G model has the strongest relationship between the AMOC and the NH SST, with a correlation coefficient of 0.84 at a 2-year lag. However, it remains unclear which models simulate the connection between ocean surface temperatures and the AMOC most realistically. Much longer observations of the AMOC are necessary to constrain these values. In fact, the Atlantic Dipole Index produced by FGOALS-s2 (Fig. 1d) is dominated by longer-term variability and visually looks very much like the observed index (Fig. 1a); however, in this model the AMOC actually lags the NH SST, which contrasts the vast majority of other models.

Several different choices for the Southern Atlantic box were used to investigate the sensitivity of our results to the definition of the Atlantic Dipole index. While slightly higher correlations with the AMOC were obtained for a few models using a southern box defined between 0 and 20°S [as done recently by Roberts et al. (2013)], the intermodel spread was much larger than the spread due to different boxes. This highlights the large differences in how the models simulate the AMOC behavior and the importance of multi-model studies in diagnosing the SST changes associated with AMOC variability. Likewise, the results discussed in this study are not sensitive to the exact location of the Northern Atlantic boxes, nor the exact way in which the AMOC strength is estimated. We have investigated these sensitivities but found no major changes in the results.

The connection between the AMOC and the Atlantic SST Dipole at periods significantly longer than 100 years could not been fully investigated, as the majority of the models do not have long enough simulations. Nevertheless, for the few models with simulations spanning greater than 800 years we find that even on multi-centennial timescales the NH SST still remains a better indicator of the AMOC variability.

In the present study, we estimate that the mean sensitivity of the North Atlantic SSTs in the region between 40° and 60°N (this is the region typically affected by the AMOC the most) is about 0.3 °C per 1 Sv of AMOC change, as given by the multi-model average. However, the fraction of SST variance explained by the AMOC, in this multi-model average, is only about one third.

Another question to consider is what this study implies for the connection between the AMOC and the Atlantic Multidecadal Variability (AMV). On the one hand, our results support the notion that a significant, albeit not too large a fraction of the AMV should be related to AMOC variations. In fact, we find that the region of the maximum SST response to AMOC simulated by the models, south of Iceland and Greenland and east of Canada, generally coincides with the region of the strongest AMV signal in the observations. However, finding a robust SST response of the Southern Atlantic to AMOC variation in the North on decadal to centennial timescales remains illusive, as evidenced by weaker correlations between the AMOC and the Atlantic SST Dipole and generally weak and varied SST response in the Southern Hemisphere.

Finally, our results suggest that using the interhemispheric temperature difference as a means to separate fluctuations in the North Atlantic SST driven by the AMOC from those that are radiatively forced as part of global warming signal (Keenlyside et al. 2008) is not optimal. In fact, within historical (post-1850) simulations, we find that subtracting global mean SST, rather than the temperature of a Southern Hemisphere regional box, from the North Atlantic SST provides a better approach.

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