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LETTER

Probabilistic projections of the Atlantic overturning

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Abstract Changes in the Atlantic overturning circulation have a strong influence on European temperatures, North American sea level and other climate phenomena worldwide. A meaningful assessment of associated societal impacts needs to be based on the full range of its possible future evolution. This requires capturing both the uncertainty in future warming pathways and the inherently long-term response of the ocean circulation. While probabilistic projections of the global mean and regional temperatures exist, process-based probabilistic assessments of large-scale dynamical systems such as the Atlantic overturning are still missing. Here we present such an assessment and find that a reduction of more than 50 % in Atlantic overturning strength by the end of the 21^{st} century is within the likely range under an unmitigated climate change scenario (RCP8.5). By combining linear response functions derived from comprehensive climate simulations with the full range of possible future warming pathways, we provide probability estimates of overturning changes by the year 2100. A weakening of more than 25 % is found to be very unlikely under a climate protection scenario (RCP2.6), but likely for unmitigated climate change. The method is able to reproduce the modelled recovery caused by climatic equilibration under climate protection scenarios which provides confidence in the approach. Within this century, a reduction of the

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Atlantic overturning is a robust climatic phenomena that intensifies with global warming and needs to be accounted for in global adaptation strategies.

1 Introduction

The Atlantic Meridional Overturning Circulation (AMOC) is a key component of the global climate system. Observational estimates find a poleward heat transport of about 1.3 ± 0.4 PW at 26°N (Johns et al. 2011), which accounts for about 85 % of global oceanic meridional heat transport at this latitude (Fasullo and Trenberth 2008). Future changes of the AMOC could affect the North Atlantic sea-level (Yin et al. 2009; Levermann et al. 2005) and carbon sink (Zickfeld et al. 2008) as well as the North Atlantic ocean ecosystem (Schmittner 2005), the position of the Intertropical Convergence Zone, the El-Nino southern oscillation and the Indian summer monsoon (Zhang and Delworth 2005). Analysis of the CMIP5 model ensemble reveals a wide model spread both in their equilibrium AMOC strength and in the projected reduction (Weaver et al. 2012). A probabilistic approach allows to capture the different long-term responses, combine these into a quantitative assessment and to systematically assess the associated uncertainties.

Here we investigate the magnitude of the AMOC decline that is forced by the global increase of greenhouse gases and the associated global warming (see Fig. S1). The rate of temperature increase associated with three of the four Representative Concentration Pathways (RCPs, Van Vuuren et al. (2011) is very rapid compared to natural temperature variations within the Holocene and projected to be most pronounced in the high northern latitudes (Stocker et al. 2013). The response to the resulting spatially diverse ocean heat-uptake (Kuhlbrodt and Gregory 2012) is found to dominate AMOC weakening across coupled climate models (Gregory et al. 2005; Gregory and Tailleux 2011; Sijp et al. 2012), which provides the basis for the highly simplified approach followed here.

2 Calibration procedure

In this study, we apply a linear response theory approach to express the AMOC change $\Delta M(t)$ to a climate forcing $F(t')$ by a convolution with a model-dependent response function $R(t-t')$:

$$\Delta M(t) = \int_0^t dt'\ F(t')\ R(t-t'). \tag{1}$$

This linear response theory was applied successfully to emulate global temperatures and precipitation change in response to greenhouse gas concentration changes (Good et al. 2011) and global sea-level rise including steric and ice-sheet contributions (Winkelmann and Levermann 2013; Levermann et al. 2014). The linear response approach is a time-dependent perturbation analysis method. Therefore, the temporal change in AMOC strength is related to the temporal change in the perturbation, in this case the first derivative of the global mean surface air temperature (GMT) $dT_{GMT}(t)dt^{-1}$. The analysis further needs to account for potential time delays as well as a long-term response to the forcing, since multi-decadal adjustment time scales of the AMOC are physically expected.

The response function may take any functional form which can, in principle, be deduced from an infinitely long time series of an arbitrarily forced simulation or from the response to a step-function forcing. Due to limited and specific data available we assume a specific functional form following the one identified by Winkelmann and Levermann (2013) for oceanic heat uptake. Our choice is justified ex post by its ability to reproduce the AOGCM's AMOC response to different warming scenarios.

The form $R(t) = M_0 \cdot t^{\alpha}$ yields the best results for $\alpha \approx -0.5$ which is the response function of the one-dimensional diffusion equation. We choose the value $\alpha = -0.5$, because the optimal value does not improve the fit significantly. It is important to note that this does not mean that the AMOC response is solely associated with vertical diffusion in the ocean, but rather that the influence of the change in global mean surface air temperature on the AMOC reduction can be described by

$$\Delta M(t) = M_0 \int_0^{t-\tau} \frac{dT_{GMT}(t')}{dt'} \cdot \frac{dt'}{\sqrt{t-t'-\tau}}, \tag{2}$$

where the scaling coefficient M_0 and the time-delay τ are independent calibration coefficients. Although AMOC equilibrium strength as well as reduction differ widely across the models, models with a stronger equilibrium AMOC tend to show a stronger reduction (see Fig. S4, Gregory et al. (2005) and Levermann et al. (2007)). Consequently, we assess the relative AMOC reduction with respect to the pre-industrial value (ΔM is given in percentage change). The time under the square root has been non-dimensionalized by division of one year and M_0 has the unit K^{-1}. It is important to highlight that such a linear response approach assumes a strong forcing to dominate the systems response as we find it to be the case for the GMT increase in the given RCP scenarios. No robust relation between AMOC weakening and GMT increase by 2100 over the model ensemble has been found (see Fig. S5), which implies that differences in the AMOC response do not contribute significantly to the ensemble spread in transient climate sensitivity and gives further confidence in our approach. Under less rigorous conditions, the relation between AMOC and GMT becomes considerably more complex (Zanchettin et al. 2010; Schleussner et al. 2014). Equation 2 is calibrated to eight individual models of the Coupled Model Intercomparison project (CMIP5, Taylor et al. (2012)) ensemble by minimizing the least-square differences for one realization of the RCP2.6, 4.5 and 8.5 scenarios over the 21st century equally weighted.

Since our method does not account for short term natural variability, all timeseries were low-pass filtered using a Hamming filter with a cut-off length of 20 years. The RCP scenarios are concatenated with the historical scenario for each model. The results are depicted in Fig. 1 and the corresponding parameter fits are provided in Table S1. The resulting time-delays that range from 23 to 34 years for all models except MRI-CGCM3 is consistent with basin-wide AMOC adjustment on an interdecadal time-scale (Johnson and Marshall 2002).

Our approach captures both the continuous AMOC weakening under the RCP8.5 scenario and its recovery under RCP2.6 and RCP4.5 that is present in most models, although some deviations between the model output and the fitting results are apparent. The AMOC recovery present for the RCP2.6 and RCP4.5 in several models is even more pronounced in the simulations until 2300 which was computed by four models (Fig. S2) and we find good agreement between our projections and the model output even far outside the calibration range for the CanESM2, CESM1-CAM5 and MPI-ESM-LR model.

The strongest deviations between the model and the emulation using (2) is found for the CNRM-CM5 model. For this model, the AMOC shows no clear scenario dependency for the RCP2.6 and RCP4.5 until 2100 and the weakening is overestimated for the RCP8.5 and underestimated for the RCP4.5 until 2300. Taken together, these deviations indicate

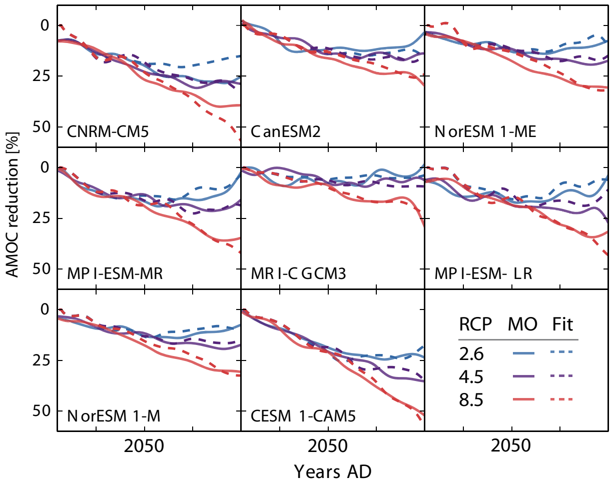

Fig. 1 Projections of the AMOC weakening over the 21st century based on Eq. 2 *(dashed)* compared to the AMOC as simulated by the corresponding comprehensive CMIP5 climate models *(solid line, MO=Model Output, low-pass filtered using a Hamming-filter with a cut-off length of 20 years)*. AMOC reduction is given relative to the pre-industrial period *(1850-1900)*

that other mechanisms, likely changes in the freshwater budget that are not captured by our simplified linear response function approach, are dominating on longer time scales in this model. For further analysis, we restrict our interpolation method to the period up to the year 2100.

3 Projections

Equation 2 was successfully calibrated to complex model output comprising a variety of different AMOC responses and can be used to interpolate in the vicinity of the existing model simulations to assess the probability distribution for future AMOC weakening under different emission pathways. To this end we use scenario dependent N=600 ensembles of GMT trajectories obtained from historically constrained MAGICC6-simulations (Meinshausen et al. 2009, see Supplementary Material for further details). AMOC trajectories are derived for each model parameter set based on the 600 GMT realizations by MAGICC6. Herein the time-delay is fixed for a given climate model and the scaling coefficient M_0 is randomly chosen from a normal distribution with mean and standard deviation determined by the calibration procedure. Results for the individual ensemble members are given in Table S4.

Median projections, the 50, 66 and 90 % percentiles as well as the underlying model ensemble trajectories are shown in Fig. 2 for different RCPs and detailed in Table 1. For the RCP2.6, we find the strongest AMOC weakening in the second half of the 21st century and a successive recovery to about 9 % relative to the preindustrial period (1850−1900). The likely range that comprises 66 % of all trajectories ranges from 5 % to 15 % weakening. As a consequence of the explicitly time-dependent response function and despite the time-delayed response, the AMOC stabilizes for monotonously rising temperatures under the RCP4.5 scenario at about 19 % (12 % − 30 %) below the pre-industrial value. By contrast, a continuous AMOC weakening is found for RCP6.0 and RCP8.5 with a median reduction

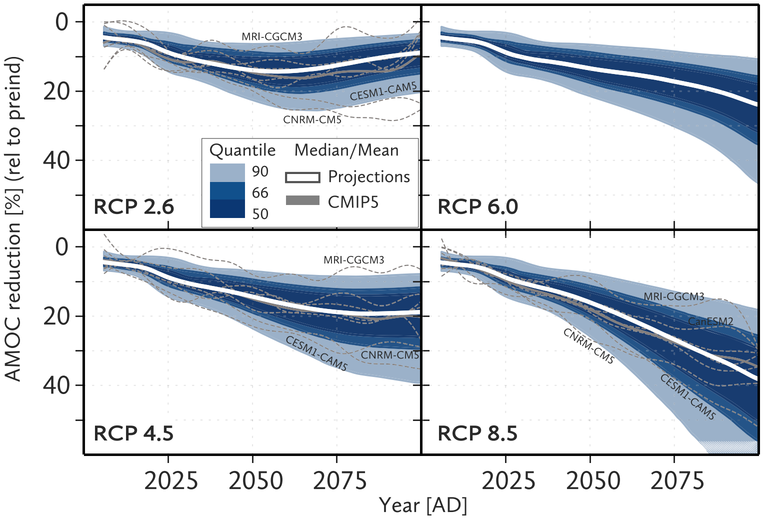

Fig. 2 Probabilistic Projections of the AMOC *(relative to the preindustrial period (1850-1900))* based on MAGICC6 GMT projections (see Fig. S3). The ensemble median as well as the 50, 66, and 90 % quantiles are indicated respectively. For comparison, the ensemble mean for the CMIP5 model ensemble is depicted in grey and individual models are overlayed as dotted lines *(low-pass filtered using a Hamming-filter with a cut-off length of 20 years)*. Models that deviate most strongly from the ensemble mean are labelled accordingly

of about 24 % (16 % − 35 %) and 38 % (25 % − 56 %), respectively. The uncertainty increases with increasing temperature. Note that our calibration range set by the underlying model ensemble does not comprise the full temperature projections of the MAGICC6 model under the RCP8.5, but is limited to a maximum of about 3.5 °C warming by 2070 relative to 1980−1999 levels. Thus, temperature trajectories above the upper limit of the likely range are extrapolating outside the calibration range and cannot be assessed.

4 Discussion and conclusions

The median projections of AMOC weakening in 2100 presented here match well with the ensemble average of the underlying CMIP5 model ensemble (RCP2.6: 9 %, RCP4.5: 20 %,

Table 1 Probabilistic assessment of the AMOC reduction for the different RCP scenarios in percentage reduction relative to the preindustrial AMOC strength (1850-1900). The likely range corresponds to the 66 %-percentile; the very likely range corresponds to the 90 %-percentile around the median of the distribution. Note that the upper limit of the RCP8.5 scenario lies outside the calibration range and can not be assessed

	Median	Likely Range	Very Likely Range
RCP2.6	9	5 – 15	3 – 20
RCP4.5	19	12 – 30	8– 39
RCP6.0	24	16 – 35	11– 46
RCP8.5	38	25 – 56	18 – *

RCP8.5: 35 %, see Fig. 2 and Table S2). This is not a trivial finding since the AMOC trajectories differ widely over the model ensemble (see Fig. 2). AMOC trajectories are a composition of the model specific AMOC response to GMT change as well as the GMT change in response to the emission pathways that differ between the models as a result of the model-dependent transient climate sensitivity (see Fig. S3 and Table S3). By resolving the AMOC response to the MAGICC6 GMT projections for each model parameter set we can assess the relevance of the model's GMT trajectory for the projected AMOC change (see Table S4). The CMIP5 ensemble spread is particularly large for the RCP2.6 (mean weakening: 9 %, standard deviation (std): 9 %) and is considerably lowered, if the model dependent GMT response is replaced by the MAGICC6 projections (std: 3 %). Accounting for the model dependent GMT response allows to narrow the uncertainty range in AMOC projections over the 21st century in particular for climate protection scenarios. The projections provided in this study are consistent with the assessment in the IPCC AR5 (Collins et al. 2013) and historically constrained Bayesian model studies (Urban and Keller 2010). In an emulator approach based on CMIP3 models, an AMOC reduction of about 11 % (22 %) for the RCP2.6 (RCP4.5) was found (Schleussner et al. 2011), which indicate some robustness of the results across methods but also model ensembles.

From our analysis, we would expect a delayed response of the AMOC to changes in GMT by about 23−34 years. A rapid increase in GMT has been observed since the 1980s and continuous AMOC observations suggest that the AMOC has weakened over the second half of the last decade (Smeed et al. 2013), which would correspond to a time-delay well within the identified range. However, since continuous AMOC observations are only available since 2004, a robust attribution of this trend to external climate forcing given the substantial internal variability on multi-decadal time-scales is not possible (Roberts et al. 2014).

Limitations of the approach relate to the representation of the AMOC in the model ensemble, the forcing in comprehensive climate models and a potential instability of the AMOC. While explicitly time-dependent, the linear response approach will yield a linear response of the AMOC with respect to the temperature forcing. If a weak temperature forcing initiates a collapse of the AMOC that is independent of the successive forcing the response will not be captured properly by the approach. This limitations is particularly relevant for low temperature scenarios. Furthermore, none of the models includes meltwater from the Greenland ice sheet. Meltwater influx from Greenland equivalent to about 10 cm global sea-level (Fettweis et al. 2013) has been found to lead to an additional AMOC reduction by about 5 % (Schleussner et al. 2011) and could prevent the recovery under the RCP2.6 and RCP4.5. As a consequence, a cessation of the AMOC within the 21^{st} century cannot be ruled out under unmitigated climate change and needs to be accounted for in future adaptation strategies.

While the median AMOC reduction in Fig. 2 shows a clear scenario dependence, the uncertainty that arises from the future climate response remains substantial. Compared to the mere model spread, the probabilistic approach allows for more elaborated statements on future AMOC reduction that might be useful in climate impact analysis such as projections of dynamic sea-level rise at the North American Atlantic coastline that has been found to be strongly affected by AMOC weakening (Yin and Goddard 2013; Bouttes et al. 2013; Slangen et al. 2014).

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