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Key Points:

- Ocean heat uptake evolves nonlinearly when CO_2 is reduced after an increase
- This is due to the nonlinear behavior of AMOC and its overshoot
- Ocean heat uptake depends nonlinearly on the initial state

Supporting Information:

- Figure S1
- Figure S2
- Text S1 and S2 and Tables S1–S3

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Nonlinearity of ocean heat uptake during warming and cooling in the FAMOUS climate model

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Abstract Atmospheric CO_2 concentration is expected to continue rising in the coming decades, but natural or artificial processes may eventually reduce it. We show that, in the FAMOUS atmosphere-ocean general circulation model, the reduction of ocean heat content as radiative forcing decreases is greater than would be expected from a linear model simulation of the response to the applied forcings. We relate this effect to the behavior of the Atlantic meridional overturning circulation (AMOC): the ocean cools more efficiently with a strong AMOC. The AMOC weakens as CO_2 rises, then strengthens as CO_2 declines, but temporarily overshoots its original strength. This nonlinearity comes mainly from the accumulated advection of salt into the North Atlantic, which gives the system a longer memory. This implies that changes observed in response to different CO_2 scenarios or from different initial states, such as from past changes, may not be a reliable basis for making projections.

1. Introduction

Climate change due to anthropogenic carbon emissions has long-term impacts such as coastal flooding due to sea level rise [*Nicholls and Cazenave*, 2010]. To avoid some of these effects, it could be decided in the future to attempt to actively remove carbon from the atmosphere, provided that the necessary engineering tools have been developed and can be deployed cost effectively. Such technology is already envisioned in many low-emissions policy scenarios such as RCP2.6 [*Meinshausen et al.*, 2011], although the possibility for much larger rates of artificial removal is very uncertain. Part of the due diligence that must be done as society considers how to respond to the challenges of future climate change is a need to better understand how the climate system might respond to rapid artificial removal of atmospheric CO_2 and the consequent decline in radiative forcing.

To investigate the effects of carbon removal on the climate, numerical models have been used under different atmospheric CO_2 evolution scenarios [*Wu et al.*, 2010, 2011; *Boucher et al.*, 2012; *MacDougall*, 2013]. The scenario most often used is an idealized increase of atmospheric CO_2 by 1% each year for 140 years until it reaches four times the preindustrial level (1%CO2 or "ramp-up") followed by a symmetrical decrease of atmospheric CO_2 back to the preindustrial value (−1%CO2 or "ramp-down") and subsequent stabilization at that level. Other scenarios such as an increase of CO_2 by 2% followed by −2%CO_2 have also been used [*Cao et al.*, 2011]. In the coupled Atmosphere-Ocean Global Climate Models (AOGCMs) forced with such scenarios, the ocean plays a key role because it takes up most of the heat and has a large thermal inertia. This has major effects on the evolution of atmospheric temperature and on sea level rise due to thermal expansion, both key metrics of future climate change.

Although the evolution of the radiative forcing is symmetrical during the two phases (ramp-up and ramp-down), many climate variables do not display such symmetry in their evolution. This asymmetry has been shown in several AOGCMs for ocean variables such as ocean heat content and sea level, both linked to the evolution of ocean temperature [*Boucher et al.*, 2012; *Bouttes et al.*, 2013].

To explain such behavior, we can consider a simple abrupt 4×CO2 experiment in which CO_2 is instantaneously increased to four times the preindustrial level. Much of the behavior of global heat uptake, and the associated sea level rise, can be understood in terms of its long time scale of response to forcing change. This is much longer than that of surface air temperature and is associated with the large heat capacity of the deep ocean. Consequently, under the Representative Concentration Pathway RCP2.6 aggressive mitigation scenario, while surface air warming ceases after about 2050 (responding to the decline in anthropogenic forcing), ocean heat uptake continues at a similar rate through the 21st century. The different time scales of climate response to

Table 1. CO_2 Concentrations Set in the FAMOUS Simulations[a]

Experiments	CO_2 Years 1–140	CO_2 Years 141–280
Ramp-up ramp-down	1%CO2	−1%CO2
Ramp-up followed by stabilization	1%CO2	4 × CO2
0.25×	0.25 × CO2	
0.5×	0.5 × CO2	
2×	2 × CO2	
4×	4 × CO2	
6×	6 × CO2	
8×	8 × CO2	
2× from 4×	4 × CO2	2 × CO2
1× from 4×	4 × CO2	1 × CO2
0.5× from 4×	4 × CO2	0.5 × CO2
0.25× from 4×	4 × CO2	0.25 × CO2

[a]The reference CO_2 level (indicated as "CO2") is the preindustrial value of 280 ppm. After year 280 the CO_2 concentration is kept at the preindustrial level in all simulations except the ramp-down followed by stabilization (CO_2 kept at 4 × CO2).

forcing change are revealed in the abrupt4×CO2 experiments, which are included in the Coupled Model Intercomparison Project Phase 5 (CMIP5) and Phase 6 (CMIP6) Diagnostic, Evaluation, and Characterization of Klima (DECK) protocols [*Meehl et al*., 2014].

If the system was linear, i.e., if the response to any sum of forcings equalled the sum of the responses to the individual forcings, ocean heat uptake in response to scenario of time-varying forcing could be predicted from the response to an experiment under any other scenario of time-varying forcing with sufficient length to exhibit all the relevant time scales. This is the basis for the linear "step-response" method [*Good et al*., 2011, 2013]. The abrupt4×CO2 experiment is particularly convenient here as it separates responses over different time scales effectively. Linearity also implies that the response to any forcing is proportional to the size of the forcing.

If nonlinearities exist, however, this implies additional processes which cannot be analyzed fully in a single abrupt CO_2 experiment. To evaluate such nonlinearities, the linear step-response prediction for a transient forcing scenario may be compared with AOGCM simulation for the same scenario. Where significant differences are found between the two, this indicates that the system is not exactly linear [*Good et al*., 2011, 2012]. *Bouttes et al*. [2013] applied this method for global mean heat uptake, under a scenario where CO_2 was increased steadily for 140 years and then abruptly decreased to preindustrial conditions. They found that the step-response prediction (based on the abrupt4×CO2 response) performed well for the ramp-up phase (approximate linearity) but less well for the abrupt decrease when CO_2 is removed from the atmosphere, indicating nonlinearity.

The present study explores nonlinear ocean heat uptake behavior in more detail to understand the physical mechanisms responsible for the nonlinearities. To detect and understand these nonlinearities under carbon removal and forcing decline, we use the FAMOUS AOGCM to run simulations, analyze the causes of nonlinearities, and identify ways to improve predictions with the step model. In particular we test the impact of the initial state of the system before the removal of carbon.

2. Methods

2.1. Climate Model and Experiments

The FAMOUS AOGCM [*Jones*, 2003; *Smith et al*., 2008] is a low-resolution version of Hadley Centre Coupled Model, version 3 (HadCM3) [*Gordon et al*., 2000]. It has an ocean component with a resolution of 3.75° longitude by 2.5° latitude with 20 levels and an atmosphere with a resolution of 7° longitude by 5°latitude. It is similar to its parent model HadCM3 in both structure and climate simulations [*Smith et al*., 2008] but runs about 20 times faster. Its transient climate response is 2.5°C, and the Atlantic meridional overturning circulation (AMOC) has been shown to be bistable under freshwater fluxes [*Hawkins et al*., 2011]. The primary experiment, which we aim to understand, is a "ramp-up ramp-down" scenario (Table 1, described in section 1). All experiments are driven by specified atmospheric concentrations. Results are given as anomalies with respect to a fixed-forcing preindustrial control experiment.

2.2. Step-Response Model

To predict the global climate model (GCM) evolution under a given scenario, the step model [*Good et al*., 2011, 2013], which is used to analyze the nonlinearities, relies on a convolution of the given forcing scenario with the response of the GCM to scenario of a "step change" in forcing. The step-response model assumes that the response y_i to the scenario at a year i can be obtained from the sum of the responses to step forcing changes in consecutive years:

$$y_i = \sum_{j=0}^{i} w_{i-j} x_j \tag{1}$$

with x_j being the response of the same variable in year j of the step experiment. The w_{i-j} scales the response from the step experiment (x_j) to match the annual step change in radiative forcing in year (i–j) of the scenario (denoted ΔF_{i-j}):

$$w_{i-j} = \frac{\Delta F_{i-j}}{\Delta F_s} \tag{2}$$

where ΔF_s is the radiative forcing change in the CO_2 step experiment. All quantities are expressed as anomalies with respect to a constant-forcing control experiment.

3. Results

3.1. Nonlinearity of the Ramp-Down Simulation in FAMOUS

The evolution of global mean surface air temperature and ocean temperature under the ramp-up ramp-down scenario (section 2.1 and Table 1) is shown in Figure 1 (solid black line for the FAMOUS model result, the ensemble mean of four integrations, as described in the supporting information). The longer response time scale of ocean temperature (compared to surface air temperature) is seen in that the ocean temperature peaks around 100 years after the CO_2 peak and declines only slowly.

To predict the GCM response to the ramp-up ramp-down scenario, we use the linear step-response (SR) model, with the response (x_j in equation (1)) given by the abrupt4×CO2 experiment (Table 1 and Figure S1 in the supporting information, the ensemble mean of four integrations), whose results were described by *Bouttes et al*. [2013]. We denote this prediction SR-4× (Figures 1a, 1c, and 1e, solid red line). As found by *Bouttes et al*. [2013], the SR-4× prediction performs well for the ramp-up phase, for both atmospheric and ocean temperature (Figure 1). For ocean temperature, the root mean square error of annual means of the prediction (SR-4×) compared to the GCM simulation during the ramp-up phase is 0.003°C, which is smaller than the interannual standard deviation of the control (after detrending to remove climate drift) of 0.039°C. This implies that the ramp-up physical response at the rate we examine here and over the range we examine may largely be understood from the abrupt4×CO2 experiment.

During the ramp-down and subsequent stabilization phases, however, the ocean temperature decrease is slower in the SR-4× prediction than the GCM (Figure 1c). The root mean square error of annual means of the prediction during the stabilization phase (years 280 to 499) is 0.064°C, larger than the standard deviation of the control (0.039°C). The predicted surface air temperature is, correspondingly, slightly too high at the end of the stabilization phase. The AMOC evolution is also not correctly represented with a smaller increase and no overshoot, i.e., an increase of the AMOC strength to a level above the control and subsequent decline (Figure 1e). Previous work [*Wu et al*., 2011] has established that an AMOC overshoot such as this could have significant impacts on European weather and climate.

Using the variability within the ensembles of ramp-up ramp-down and 4×CO2 experiments, we confirm that the time-mean air temperature and ocean temperature during years 400–499 (stabilization phase) are significantly different between the SR-4× prediction and the GCM evolution (see supporting information). This is evidence of the nonlinearity of the response of the system to forcing.

To identify where the nonlinearities arise in the ocean during the ramp-down, we compare the zonally averaged latitude-depth cross sections of temperature change in the GCM and SR-4× prediction at $t = 280$ years (end of the ramp-down phase) (Figure 2). The SR-4× prediction overestimates the heat content in the upper ocean (above 2000 m) and slightly underestimates it below (Figures 2a and 2b). The difference is mainly due to changes in the Atlantic (Figures 2c and 2d). Since the nonlinear behavior is largely found in the Atlantic, it may be associated with the AMOC. The prediction of the latter with the abrupt4×CO2 experiment appears to be too sluggish and shallow compared to the AOGCM during the ramp-down (Figures 2e and 2f).

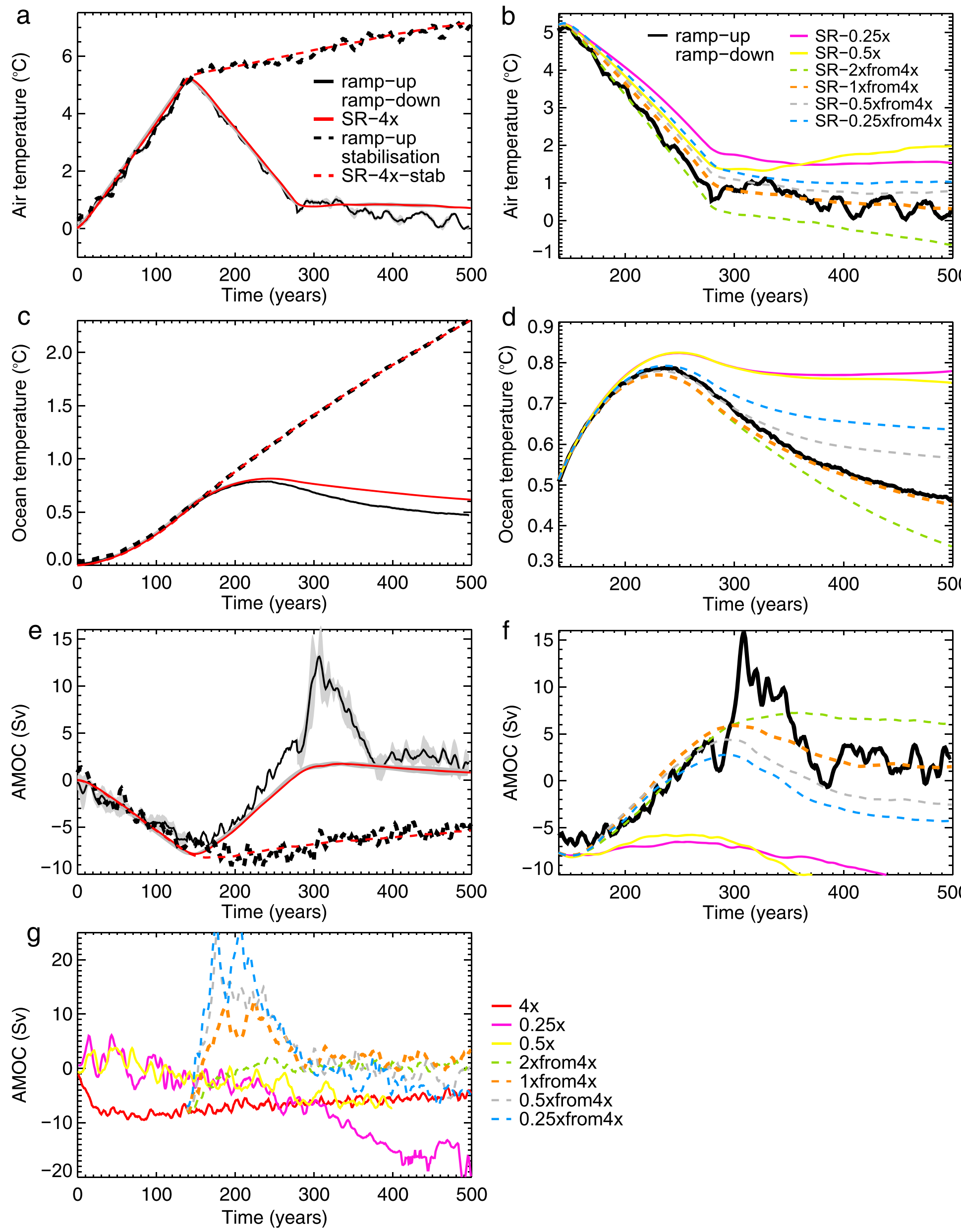

Figure 1. Evolution of (a, b) global mean air temperature (°C), (c, d) global mean ocean temperature (°C), and (e, f) AMOC strength (Sv) (all variables relative to the parallel control simulation) for the ramp-up ramp-down scenario (solid) and ramp-up followed by constant 4×CO2 (dashed), as simulated by the GCM (black) and the step model predictions (colors). Predictions of the ramp-up ramp-down or ramp-up stabilization using the 4×CO2 experiment (red) (Figures 1a, 1c, and 1e). Predictions during the ramp-down phase (from year 140) with step model predictions using step experiments starting from 1×CO2 (solid colored lines) or 4×CO2 (dashed lines) (Figures 1b, 1d, and 1f). (g) Evolution of the maximum strength of the AMOC (Sv) relative to the parallel control simulation for the abrupt step experiments starting from 1×CO2 (solid lines) or 4×CO2 (dashed lines). For the GCM ramp-up ramp-down simulation and the prediction with the 4×CO2 experiment, the mean of the four ensemble members is indicated by the solid lines and the standard deviation by the grey shading.

To analyze the nonlinear behavior, it is helpful to consider the responses to the CO_2 ramp-up and CO_2 ramp-down separately. The ocean temperature response during the ramp-down period is a combination of lagged responses to all previous forcing changes. That is, the ocean is still responding to the CO_2 ramp-up, as well as to the subsequent CO_2 ramp-down. The error of the prediction from the step model with the 4×CO2 simulation (SR-4×) during the ramp-down (Figure 1) could therefore be associated with long-term responses to the CO_2 ramp-up or shorter-term responses to the CO_2 ramp-down.

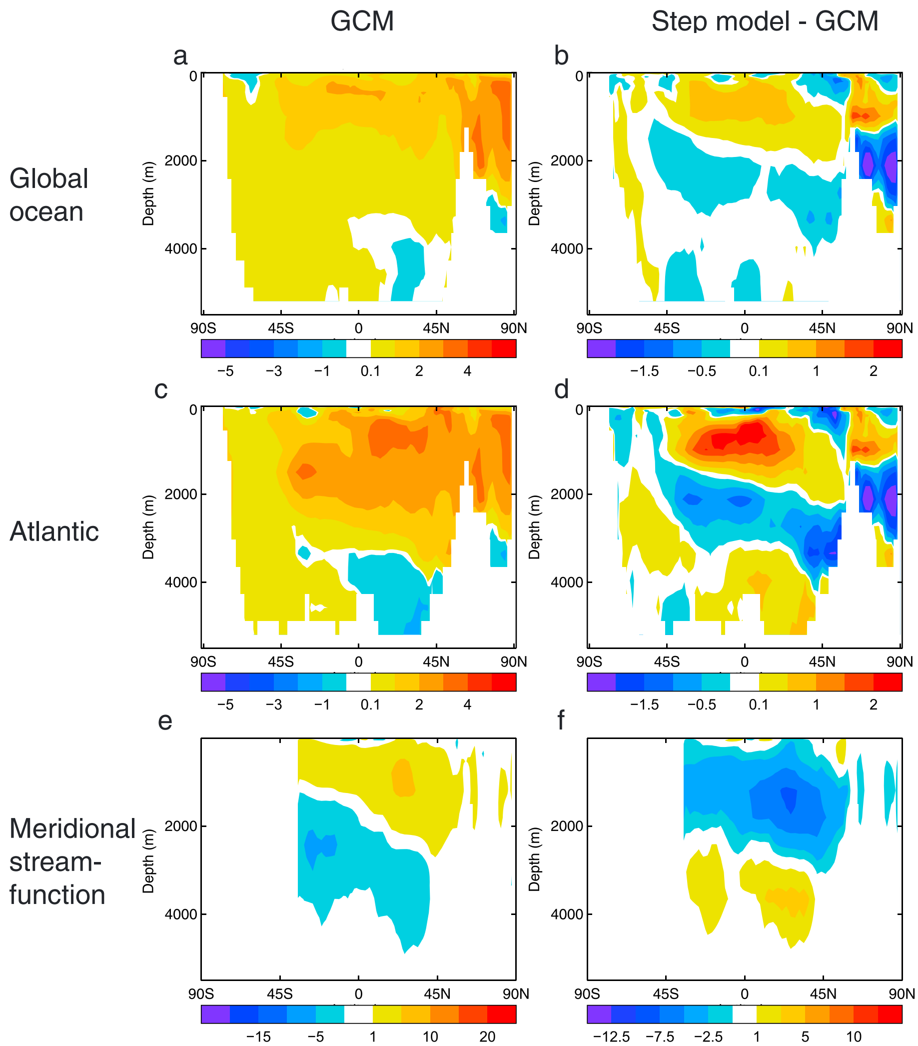

Figure 2. Differences of zonally averaged ocean temperature (°C) for (a and b) all oceans and (c and d) the Atlantic and (e and f) of the meridional stream function (Sv). Change between years 280 and 0 for the ramp-up ramp-down experiment (Figures 2a, 2c, and 2e) and difference between the step model prediction using 4×CO2 and the GCM (Figures 2b, 2d, and 2f).

We first examine the long-term lagged response to the ramp-up. This is seen in an experiment where CO_2 is ramped up and then held constant ("ramp-up stabilization," Table 1 and Figures 1a, 1c, and 1e, dashed lines). The SR-4×-stab prediction captures this lagged response accurately. This implies that the prediction errors in Figure 1 are instead associated with responses to the CO_2 ramp-down.

3.2. Nonlinearity Associated With Changes in AMOC

To help understand the ramp-down phase, we use several more abruptCO2 experiments (Table 1), spanning a range of initial and final CO_2 levels. These include one set initialized from the 1×CO2 (280 ppm) control state, with a range of final CO_2 levels: 0.25×CO2, 0.5×CO2, 2×CO2, 4×CO2, 6×CO2, and 8×CO2. A second set of abruptCO2 experiments was initialized from year 140 of the abrupt4×CO2 experiment, with CO_2 abruptly decreased to 2×CO2, 1×CO2, 0.5×CO2, or 0.25×CO2 (Figure S1).

To examine further if the nonlinear ocean cooling is associated with the AMOC, we investigate the relationship between ocean heat loss and the AMOC during the stabilization phase (i.e., at preindustrial CO_2 concentrations). We define the cooling rate coefficient α as follows:

$$\frac{dH}{dt} = -\alpha H \tag{3}$$

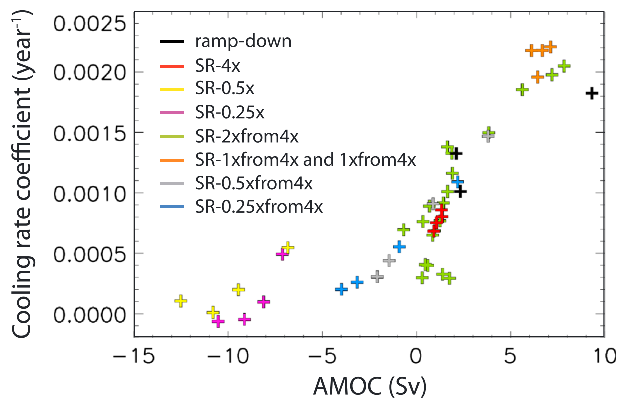

Figure 3. Cooling rate coefficient α (year^{-1}) versus AMOC strength (Sv) for the ramp-up ramp-down simulation (black), the 1×from4× simulation (orange), and the step-up and step-down experiments (colors). The AMOC and cooling efficiency are 50 year means from each nonoverlapping 50 year segment in the stabilization phase (after year 280, when CO_2 is back to the preindustrial level) except for the 1×from4× experiment for which the mixed layer spin-up of the first 30 years was excluded.

where H is the ocean heat content anomaly (relative to the control); i.e., we assume that the rate of heat loss is proportional to the heat content, if everything else is the same (cooling must tend to zero as H tends to zero). Although changes in ocean circulation can induce change in ocean heat uptake, this effect is small compared to the effect of changing the radiative forcing (see supporting information) and has been neglected in equation (3). As Figure 3 shows, the cooling rate coefficient in the GCM experiments following a reduction of CO_2 (evaluated from 50 year means during the stabilization phase) depends on the AMOC strength: the ocean cools more efficiently with a strong AMOC; an increase of around 7 Sv (sverdrup) of AMOC from the control state increases the cooling rate by a factor of 3. Hence, the prediction will be inaccurate when the step model is used with an abrupt experiment that has a different AMOC strength, and hence cooling efficiency, compared to the GCM simulation that we try to predict (such as the ramp-down for instance).

We use each of the GCM experiments with abrupt CO_2 reduction to simulate the ramp-down phase, and add it to the SR-4× prediction of the CO_2 ramp-up, since this has been shown to be accurate. For the ramp-down phase, the step model predictions SR-0.5× and SR-0.25× use the GCM experiments 0.5× and 0.25× (Table 1). In 0.5× and 0.25×, the AMOC strength remains relatively constant for around a century and then decreases (Figure 1g). In the step model prediction this gives a relatively constant AMOC followed by a decrease (Figure 1f, see pink and yellow solid lines), whereas it actually increases in the GCM ramp-down simulation. The prediction is worse for SR-0.5× than SR-0.25× because the AMOC decrease is relatively similar in both abrupt experiments for the first ~250 years, but in the step model the response of 0.5×CO2 is multiplied by 2 to scale with the change of radiative forcing. Consistent with the weak AMOC and consequently small cooling rate coefficient, SR-0.5× and SR-0.25× give greater disagreement than SR-4× with the GCM temperature changes (Figures 1b and 1d). These step model predictions also feature more warming in the upper ocean due to the reduced circulation, which exacerbates the overestimation of the quantity of heat in the ocean (Figure 1d).

Much better results are obtained, however, when 1×from4× (a cooling experiment from a warm state, Table 1) is used in the SR prediction of the response to the CO_2 ramp-down. This experiment has initial and final CO_2 levels matching those at the start and end of the CO_2 ramp-down. In the case of SR-1×from4×, both the AMOC evolution, including the overshoot, and the ocean temperature evolution are in close agreement with the GCM simulation (dashed orange lines in Figures 1b, 1d, and 1f).

3.3. What Controls the AMOC Behavior and Nonlinearity?

In the ramp-up ramp-down experiment, the overshoot of the AMOC is due to the buildup of high salinity in the subtropical gyre during the ramp-up. At the beginning of the ramp-down, the circulation intensifies due to the atmospheric temperature decreases from the decline of CO_2. The saline water from the subtropical gyre is then transported northward [*Wu et al.*, 2011; *Jackson et al.*, 2013]. The sudden increase of salinity results in higher density in the area of deep convection leading to the AMOC overshoot.

To account for the overshoot during the ramp-down, the short-term component of the step model prediction needs to have the memory of the salinity buildup. This cannot happen if the warm phase causing the salinity anomaly at low latitudes does not exist. Using an upward step from the control to predict the ramp-down (as in SR-4×) fails to reproduce the overshoot because it does not start from a warm state with the salinity anomaly needed to trigger the overshoot.

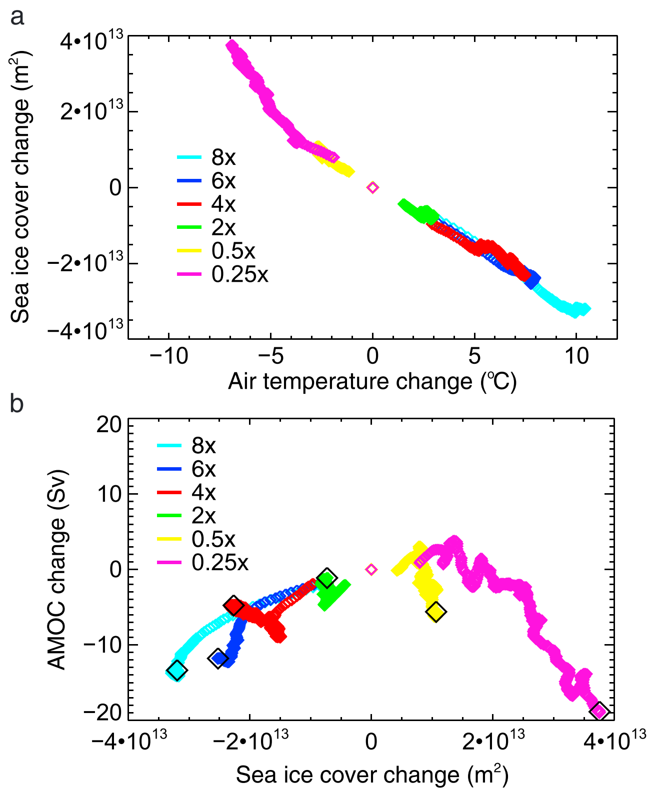

Figure 4. (a) Sea ice cover change in the Northern Hemisphere (m^2) as a function of global mean air temperature change (°C) and (b) changes of AMOC strength (Sv) as a function of sea ice cover in the Northern Hemisphere (m^2) for the different step-up and step-down simulations starting from 1×CO2 shown relative to the control. The black diamonds indicate the end of each simulation.

On the other hand, the memory of the salinity buildup is achieved when using abrupt step-down experiments starting from a warm state (from 4×CO2) in the step model (see dashed lines in Figures 1b, 1d, and 1f, SR-2×from4×, SR-1×from4×, SR-0.5×from4×, and SR-0.25×from4×). The best result is obtained for SR-1×from4×, for which not only the initial state of the short-term component accounts for the salinity buildup but also the change of radiative forcing is similar to the one in the ramp-down, from 4×CO2 to 1×CO2.

When the step model uses abrupt step-down experiments from 1×CO2 (cooling experiments, SR-0.25× and SR-0.5×), the AMOC prediction is inaccurate because the AMOC exhibits two different regimes of change divided by a thermal threshold [*Oka et al.*, 2012] linked to the area covered by sea ice, which is a monotonic decreasing function of the surface air temperature change (Figure 4a). The AMOC strength decreases with decreasing sea ice in warm climates but decreases with increasing sea ice in cold climates (Figure 4b). The extension of sea ice in the cooling experiments insulates the upper ocean in the areas of convection, which is reduced or stopped. Hence, the ramp-down component of the prediction in SR-0.25× and SR-0.5× gives a weakening of the AMOC (Figure 1g) rather than a strengthening.

4. Conclusions

Artificially removing carbon from the atmosphere could be attempted in the future to avoid the negative impacts of climate change. However, in FAMOUS the response of the climate system to reduction of CO_2 forcing is not the exact opposite of the response to increase of CO_2 forcing. This nonlinearity can be characterized and studied by comparing FAMOUS with the results from using a simple step model which relies on a linear convolution of the response to an abrupt experiment, such as 4×CO2, with any other forcing scenario.

There are strong nonlinearities in the evolution of the Atlantic meridional overturning circulation (AMOC) in FAMOUS, affecting ocean heat content changes. The behavior of the AMOC is linked to changes in sea ice cover in the North Atlantic and salinity advection from the subtropical gyre and can be divided into three cases: (1) above 1×CO_2 the AMOC decreases if CO_2 increases (warming); (2) below 1×CO_2 the AMOC decreases if CO_2 decreases (cooling); and (3) starting from above 1×CO_2 (cooling from warm state) there is an overshoot of the AMOC if CO_2 decreases, i.e., the AMOC recovers to more than its original strength, then declines again.

Due to these nonlinearities, the response of the AMOC and ocean heat content to reducing CO_2 depends on the starting state. When CO_2 is ramped up and then down, the rate of heat loss by the ocean during the ramp-down is intensified by the overshoot of the AMOC strength and larger than would be predicted by the response to a CO_2 increase from the starting state.

It is likely that the quantitative results are model dependent, especially the sea ice thresholds, but that similar behaviors will be simulated by other GCMs. For instance, the asymmetry of AMOC evolution between warming and cooling is also apparent in GCM simulations with varying solar forcing [*Schaller et al*., 2014]. A model intercomparison project (Good et al., in preparation) will help with constraining the uncertainty in these nonlinearities. The qualitative differences in the evolution of the climate system in the different cases imply that results obtained in one case might not be relevant to infer changes in other cases, for example, using results from climate change under RCP scenarios (warming) to infer past changes during deglaciations (warming from a colder state) or inversely. This also points to the need to carefully consider the choice of model and its setup in experiments to examine hypothetical forcing reduction in the future, especially where reduced complexity models are deployed.

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