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Northward intensification of anthropogenically forced changes in the Atlantic meridional overturning circulation (AMOC)

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[1] Extensive modeling studies show that changes in the anthropogenic forcing due to increasing greenhouse gases might lead to a slowdown of the Atlantic meridional overturning circulation (AMOC) in the 21st century, but the AMOC weakening estimated in most previous modeling studies is in depth space. Using a coupled ocean atmosphere model (GFDL CM2.1), this paper shows that in density space, the anthropogenically forced AMOC changes over the 21st century are intensified at northern high latitudes (nearly twice of those at lower latitudes) due to changes in the North Atlantic Deep Water (NADW) formation. In contrast, anthropogenically forced AMOC changes are much smaller in depth space at the same northern high latitudes. Hence projecting AMOC changes in depth space would lead to a significant underestimation of AMOC changes associated with changes in the NADW formation. The result suggests that monitoring AMOC changes at northern high latitudes in density space might reveal much larger signals than those at lower latitudes. The simulated AMOC changes in density space under anthropogenic forcing can not be distinguished from that induced by natural AMOC variability for at least the first 20 years of the 21st century, although the signal can be detected over a much longer period. **Citation:** Zhang, R. (2010), Northward intensification of anthropogenically forced changes in the Atlantic meridional overturning circulation (AMOC), *Geophys. Res. Lett.*, *37*, L24603, doi:10.1029/2010GL045054.

1. Introduction

[2] Changes in the Atlantic meridional overturning circulation (AMOC) could have a profound impact on global climate [*Vellinga and Wood*, 2002; *Zhang and Delworth*, 2005; *Stouffer et al.*, 2006b]. A slowdown of the AMOC strength in the 21st century is simulated extensively by climate models forced with projected increases of greenhouse gases, due to increased freshwater flux and reduced ocean to atmosphere surface heat flux over the North Atlantic Deep Water (NADW) formation sites in response to increasing greenhouse gases [*Manabe et al.*, 1991; *Wood et al.*, 1999; *Gregory et al.*, 2005; *Schmittner et al.*, 2005; *Stouffer et al.*, 2006a; *Delworth and Dixon*, 2006; *Meehl et al.*, 2007]. As noted in both the Intergovernmental Panel on Climate Change Fourth Assessment (IPCC AR4) and the US Climate Change Science Program (CCSP) report [*Meehl et al.*, 2007; *Delworth et al.*, 2008], over the course of the 21st century, the modeled AMOC strength at 30°N is projected to weaken by about 25% to 30% on average, in response to increasing greenhouse gases.

[3] The anthropogenically forced AMOC changes in most previous studies are estimated in depth space. The AMOC consists of both the wind driven part and the part associated with the NADW formation. A recent study [*Zhang*, 2010] suggests that the typical estimation of AMOC in depth space at mid and high latitudes is not a good measure of the part associated with the NADW formation; natural AMOC variations associated with the NADW formation have significant meridional coherence in density space with the subpolar AMOC variations leading the subtropical AMOC variations by a few years, and the amplitude of natural AMOC variations in density space is much larger than that in depth space at northern high latitudes. Will the difference due to the estimation of AMOC in density space vs. in depth space [*Zhang*, 2010] also be present in anthropogenically forced AMOC changes? This paper addresses this question using a coupled ocean atmosphere model (GFDL CM2.1). The statistical assessment is also conducted to compare anthropogenically forced AMOC changes with natural AMOC variability.

2. Description of the Coupled Ocean-Atmosphere Model and Experiments

[4] The model used in this study is the fully coupled ocean-atmosphere global general circulation model (GFDL CM2.1) developed for IPCC AR4 [*Delworth et al.*, 2006]. In the control simulation, the climatological mean maximum Atlantic overturning streamfunction in density space is about 25.7 Sv ($1Sv = 10^6\ m^3 s^{-1}$) and located around 51.5°N, similar to estimates using the observed hydrographic data [*Talley et al.*, 2003]. North of 45°N, the steep isopycnals below 200m are almost perpendicular to the isobars, and the southward deep flow of NADW moves along these steep isopycnals [*Zhang*, 2010]. In depth space north of 45°N, the northward and southward transports compensate each other within the same depth layer, disguising the maximum AMOC near NADW formation sites and resulting in a climatological mean maximum of 23.7 SV at lower latitudes (42.5°N). The simulated climatological mean Atlantic overturning streamfunction at 26.5°N at 1100 m depth is about 18 Sv, similar to that observed directly using RAPID arrays [*Cunningham et al.*, 2007]. This paper employs a very long (3000-year) control simulation to estimate the strength of natural AMOC variability in order to assess the statistical significance of anthropogenically forced AMOC trends.

[5] The GFDL CM2.1 was employed to simulate the 21st century climate change for three scenarios with low (B1), medium (A1B), and high (A2) rates of greenhouse gas emissions respectively. This paper is focused on these three scenarios to study anthropogenically forced AMOC changes

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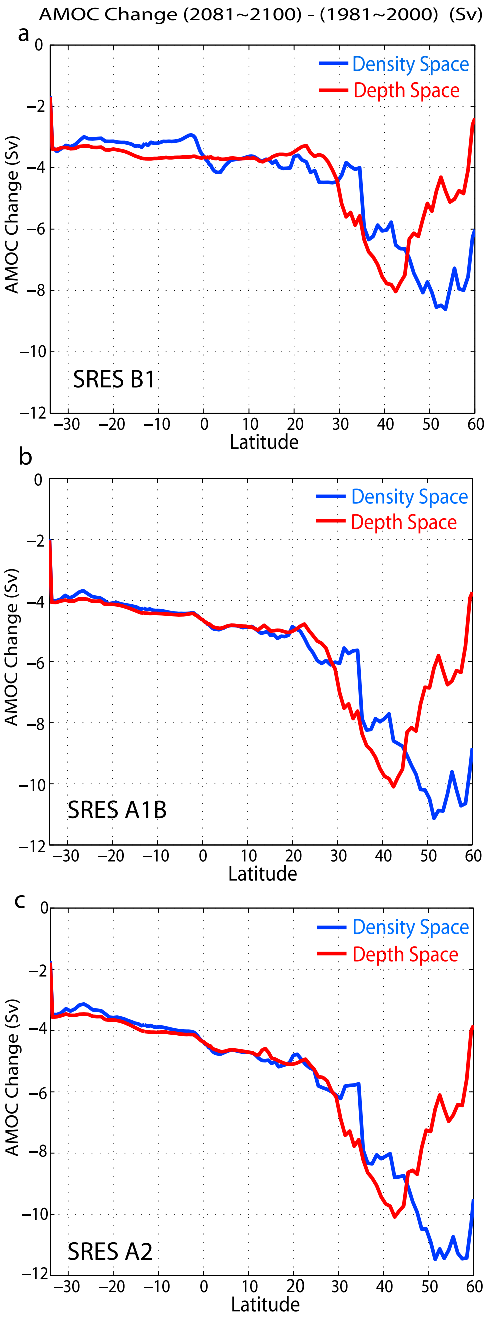


Figure 1. Simulated AMOC changes as a function of latitude for the period (2081–2100) relative to the period (1981–2000) for scenarios (a) B1, (b) A1B, and (c) A2 in density space vs. in depth space.

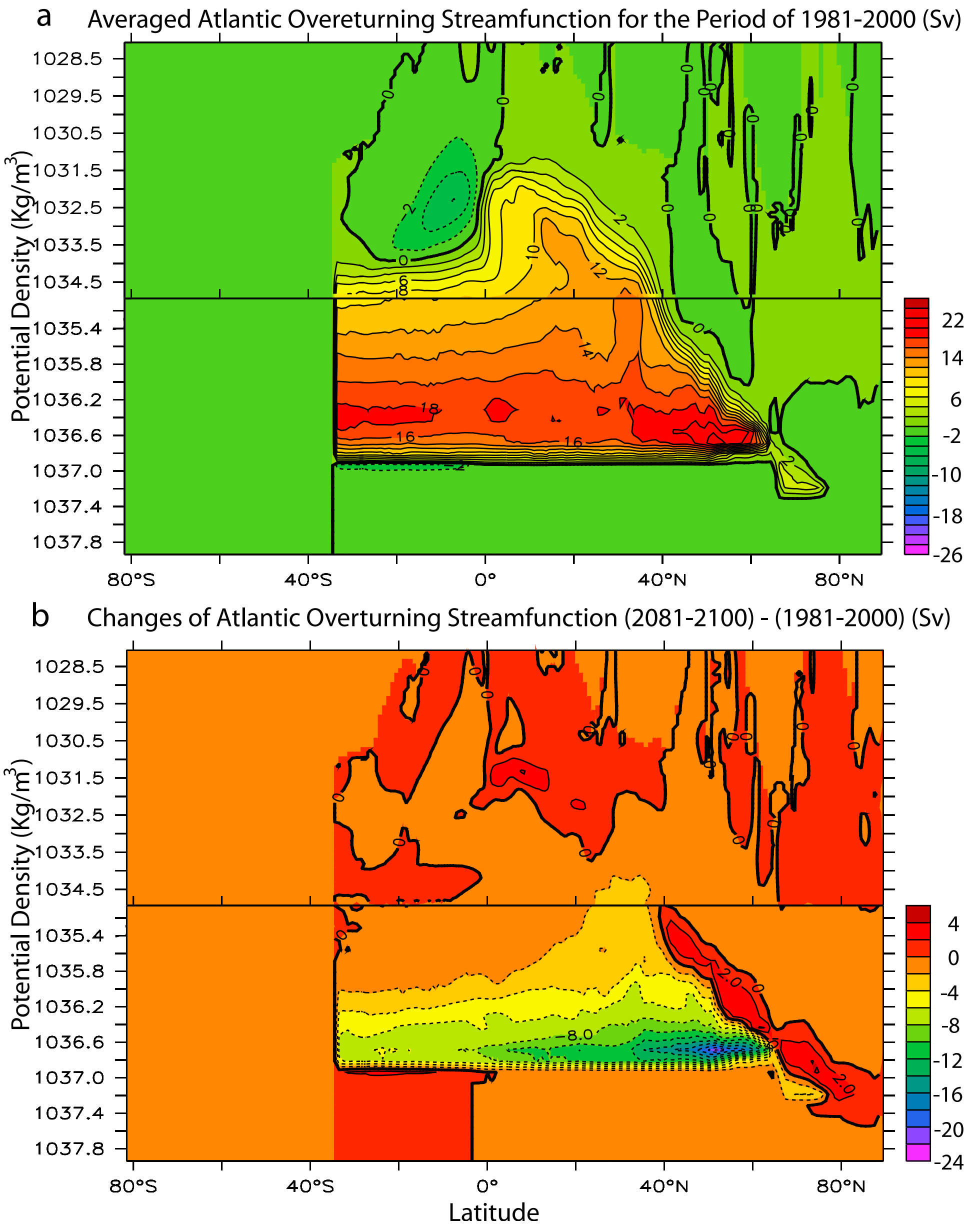
in the 21st century. To compare simulated AMOC changes over the course of the 21st century, the paper also employs a 5-member ensemble 20C3M experiment using GFDL CM2.1, i.e., each member is started with a different initial condition from the control simulation, and forced by the same estimates of changes in the radiative forcing from 1861 to 2000 [*Knutson et al.*, 2006]. The 5-member ensemble mean from the 20C3M experiment are used to compute the climatology for the period (1981–2000). In this paper, the AMOC Index at each latitude is defined as the maximum annual mean zonal integrated Atlantic overturning streamfunction of the whole column in potential density (referenced to 2000 m) space or in depth space respectively.

3. Anthropogenically Forced AMOC Changes in Density Space Versus in Depth Space

[6] Over the course of the 21st century, the simulated AMOC changes are intensified at northern high latitudes (nearly twice of those at lower latitudes) for all three scenarios (B1, A1B, and A2) in density space, but are much smaller in depth space at the same northern high latitudes (Figure 1). For scenarios A1B and A2 (Figures 1b and 1c), the AMOC weakening in density space reaches about 11 Sv (nearly 50%) at northern high latitudes, but only about 6 Sv (nearly 33%) at 26.5°N. On the other hand, in depth space, the amplitude of AMOC weakening starts to decrease north of 43°N and drops back to about 6 Sv at 52°N (Figures 1b and 1c). The AMOC weakening in B1 has a similar behavior but smaller in amplitude than in A1B and A2 (Figure 1a). As suggested by *Zhang* [2010], the typical estimation of AMOC in depth space at mid and high latitudes does not represent the part of the AMOC associated with the NADW formation accurately.

[7] The northward intensification of the Anthropogenically Forced AMOC changes in density space (Figure 1) is closely tied to changes in the NADW formation. In all three scenarios, although the AMOC does not shutdown by the end of the 21st century, the Labrador Sea deep convection shuts down by year 2050. For example, a strong Labrador Sea deep convection exists during the period (1981–2000) with an annual mean mixed layer depth (MLD) of about 1200m in the 5-member ensemble mean from the 20C3M experiment. However, the MLD becomes less than 100m for the second half of the 21st century in all scenarios. The deep convection in the Nordic Sea and the Irminger Sea is also weakened but does not shutdown over the course of the 21st century in all scenarios. The increase of greenhouse gases leads to increased freshwater flux and reduced ocean to atmosphere surface heat flux over these NADW formation sites, thus reduced surface density and increased vertical stratification there, resulting in the weakening or even shutdown of the deep convection. The shutdown of the Labrador Sea deep convection in response to increasing greenhouse gases has also been found in previous modeling studies [*Wood et al.*, 1999; *Stouffer et al.*, 2006a].

[8] The simulated Atlantic overturning streamfunction in density space averaged for the period (1981–2000) shows a strong vertical recirculation just south of NADW formation sites (Figure 2a), contributing to the maximum AMOC there. This recirculation cell is very sensitive to changes in the NADW formation, and is substantially weakened for the period (2081–2100) in scenario A1B, causing very large anthropogenically forced AMOC weakening at northern high latitudes (Figure 2b). In A1B, the maximum reduction of the Atlantic overturning streamfunction over the course of the 21st century reaches about 22 Sv at the density level 1036.7 kg/m^3 near 52°N. This maximum reduction in the Atlantic overturning streamfunction is much larger than the reduction in the maximum AMOC Index shown in Figure 1b, because the maximum AMOC at northern high latitudes is not only weakened but also moves upward to a lighter density level over the course of the 21st century, i.e., the NADW becomes less dense in response to increasing greenhouse gases.


a Averaged Atlantic Overeturning Streamfunction for the Period of 1981-2000 (Sv)

b Changes of Atlantic Overturning Streamfunction (2081-2100) - (1981-2000) (Sv)

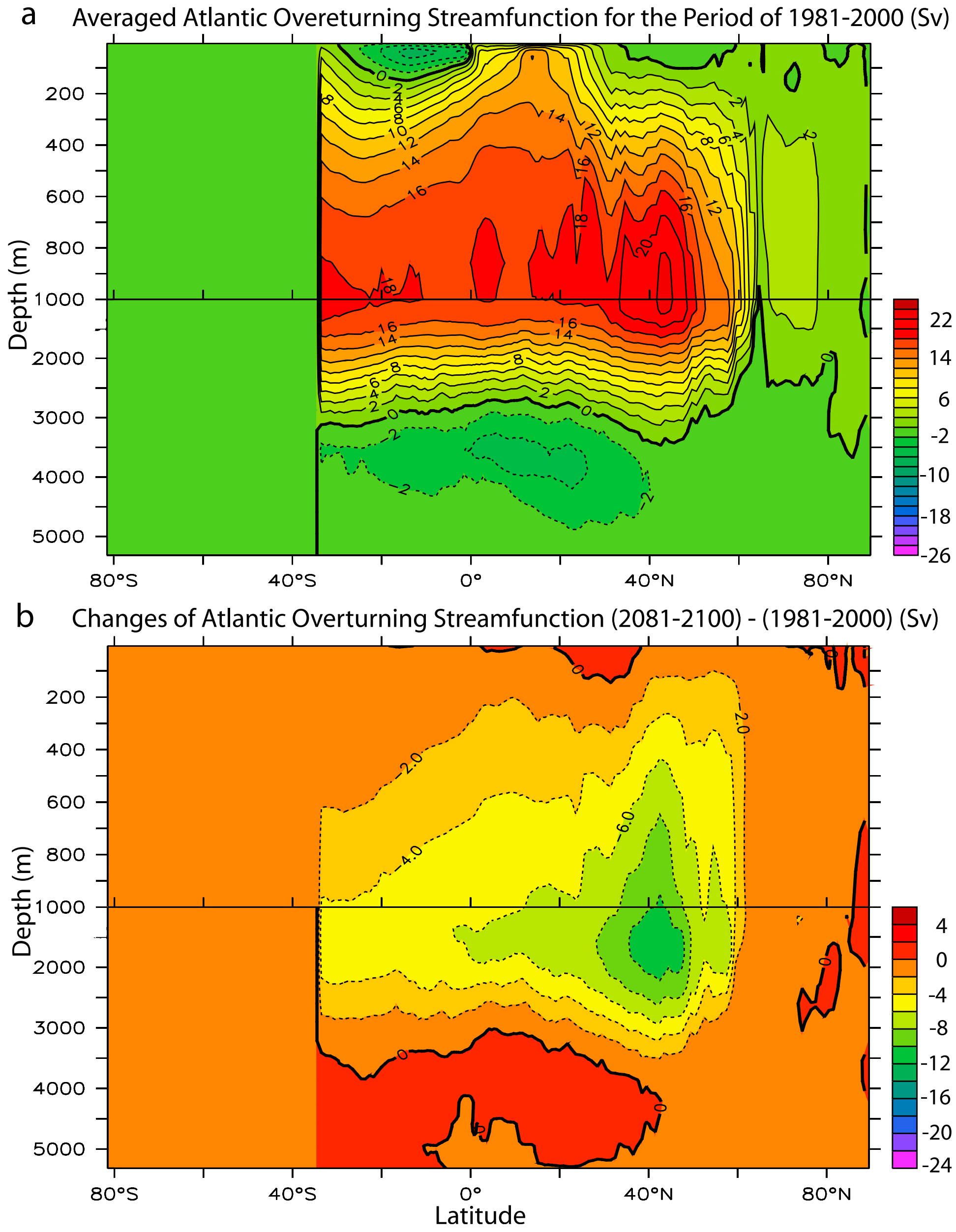
Figure 2. Simulated Atlantic overturning streamfunction and changes in density space as a function of latitude. (a) Atlantic overturning streamfunction averaged for the period (1981–2000). (b) Changes for the period (2081–2100) relative to the period (1981–2000) for scenario A1B.

[9] In contrast, in depth space, the maximum AMOC for the period (1981–2000) is located at lower latitude (about 43°N, Figure 3a). North of 45°N, the steep isopycnals below 200m are almost perpendicular to the isobars, thus the northwardand southward transports compensate each other within the same depth layer, disguising the strong recirculation at northern high latitudes just south of NADW formation sites [*Zhang*, 2010]. The maximum reduction of the Atlantic overturning streamfunction over the course of the 21st century is about 11.5 Sv at 1500m near 42°N (Figure 3b), much smaller than that found in the density space (22 Sv, Figure 2b).

[10] In summary, here the simulated substantial AMOC weakening at northern high latitudes in density space over the 21st century is mainly due to the combined effects of the shutdown of the Labrador Sea deep convection and the weakening of the deep convection in the Nordic Sea and the Irminger Sea. Meanwhile, the anthropogenically forced AMOC weakening at northern high latitudes in depth space is much smaller, and can not reflect the substantial AMOC changes induced by changes in the NADW formation. The result also suggests that monitoring AMOC changes at northern high latitudes in density space might reveal much larger signals than those at lower latitudes.

4. Assessment of Simulated AMOC Trends in the 21st Century

[11] Are the simulated AMOC changes under anthropogenic radiative forcing in the 21st century distinguishable from natural AMOC variability? To answer this question, the simulated AMOC trends in density space over various


a Averaged Atlantic Overeturning Streamfunction for the Period of 1981-2000 (Sv)

b Changes of Atlantic Overturning Streamfunction (2081-2100) - (1981-2000) (Sv)

Figure 3. Simulated Atlantic overturning streamfunction and changes in depth space as a function of latitude. (a) Atlantic overturning streamfunction averaged for the period (1981–2000). (b) Changes for the period (2081–2100) relative to the period (1981–2000) for scenario A1B.

periods of the 21st century in all three scenarios are assessed by comparing with AMOC trends induced by natural AMOC variability in the 3000-year control simulation over the same periods. For example, the simulated 100-year AMOC trends for the entire 21st century in all three scenarios are compared with the statistics of 100-year AMOC trends derived from 30 non-overlapping segments from the 3000-year control simulation of GFDL CM2.1 (Figure 4a). The AMOC trend of each segment is derived through the linear regression of AMOC on time. The 100-year AMOC trends over the 21st century clearly stand out from that expected from natural variability at all latitudes in all three scenarios (Figure 4a).

[12] The simulated AMOC trends over the period 2001–2050 are statistically significant for scenarios A1B and B1, but not for scenario A2, by comparing with AMOC trends derived from 60 non-overlapping 50-year segments from the control simulation (Figure 4b). The smaller response in A2 is mainly due to the stronger sulphate aerosol prescribed in A2 during 2001–2050. The response in A2 becomes much larger during 2051–2100 due to the rapid increase in greenhouse gases and the decrease in sulphate aerosol. The difference in prescribed total radiative forcing between A1B and B1 is smaller during 2001–2050 but much larger in 2051–2100, resulting in a slight larger response after the first 50 years but a much larger response after 100 years in A1B than in B1 (Figures 4a and 4b). The response in B1, A1B, and A2 is also affected by natural variability, especially over shorter periods.

[13] Over the period 2001–2030, only the trends in A1B at northern mid and high latitudes clearly stand out from that

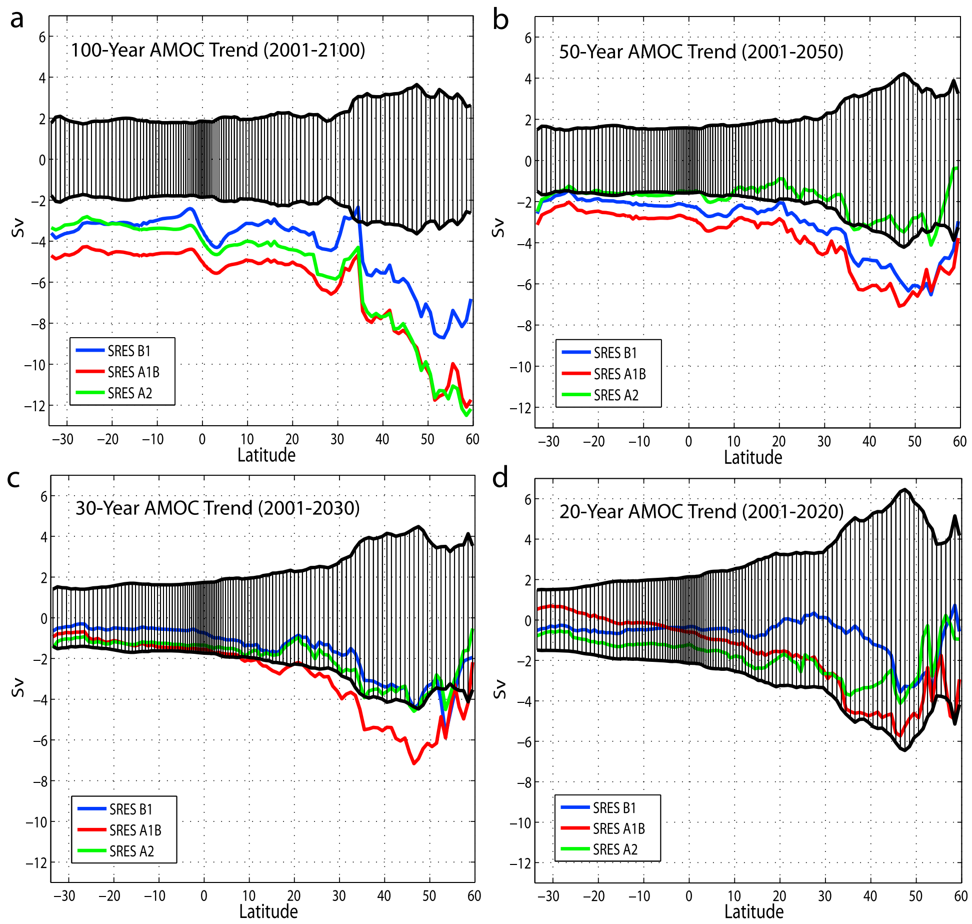


Figure 4. Assessment of simulated AMOC Index trends in the 21st century in density space. (a) Hundred-year trend (2001–2100). (b) Fifty-year trend (2001–2050). (c) Thirty-year trend (2001–2030). (d) Twenty-year trend (2001–2020). AMOC trends within areas covered with thin black lines are not statistical significant at the 95% level using the 2-tailed Student's t-test, by comparing with AMOC trends derived from non-overlapping segments of the same length of periods from the 3000-year control simulation respectively. Areas covered with thin black lines represent the range of AMOC trends expected to arise from natural AMOC variability.

expected from natural variability, by comparing with AMOC trends derived from 100 non-overlapping 30-year segments from the control simulation (Figure 4c). The simulated AMOC trends over the period 2001–2020 in all three scenarios can not be distinguished from those induced by natural AMOC variability at all latitudes, by comparing with AMOC trends derived from 150 non-overlapping 20-year segments from the control simulation (Figure 4d). The results are consistent with the previous study that the detection times for anthropogenically forced AMOC changes in A1B at 26°N are on the order of several decades to a century [*Baehr et al.*, 2007]. Furthermore, the results here indicate that the detection times for anthropogenically forced AMOC changes in A1B at northern high latitudes in density space might be shorter than those at lower latitudes (Figure 4c).

5. Conclusion and Discussion

[14] Using a coupled ocean atmosphere model (GFDL CM2.1), this paper shows that in density space, the anthropogenically forced AMOC changes over the 21st century are intensified at northern high latitudes (nearly twice of those at lower latitudes), but much smaller in depth space at the same northern high latitudes. The northward intensification of the anthropogenically forced AMOC weakening is caused by changes in the NADW formation at northern high latitudes. The results suggest that studying AMOC changes in depth space would lead to a significant underestimation of AMOC changes associated with changes in the NADW formation, and monitoring AMOC changes at northern high latitudes in density space might reveal much larger signals than those at lower latitudes. The results also show that simulated AMOC trends in density space under anthropogenic forcing can not be distinguished from those induced by natural AMOC variability for at least the first 20 years of the 21st century, although they can be detected over a much longer period.

[15] There are large uncertainties of the amplitudes of simulated AMOC changes in response to increasing greenhouse gases in different models [*Gregory et al.*, 2005; *Meehl et al.*, 2007]. One caveat of this study is that the results are based on one coupled climate model (GFDL CM2.1), and needs to be reinvestigated in other coupled climate models in future studies. In particular, it would be worthwhile to check whether the northward intensification of AMOC changes in density space is robust across different models in future studies. Another caveat is that the three scenario

simulations (B1, A1B, A2) for the 21st century do not include any changes in solar irradiance or volcanic aerosols in the atmosphere which could potentially affect the solutions.

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