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Changes in subduction in the South Atlantic Ocean during the 21st century in the CCSM3

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[1] The Community Climate System Model version 3 is used to analyse changes in water mass subduction rates in the South Atlantic Ocean over the 21st century. The model results are first compared to observations over 1950–2000, and shown to be rather good. The subduction rates do not change significantly over the 21st century, but the densities at which water masses form become significantly lighter. The strong westerly winds in this region do not change much, which suggests small changes to the rate at which the Atlantic sector of the Southern Ocean takes up heat and carbon dioxide over the 21st century. **Citation:** Goes, M., I. Wainer, P. R. Gent, and F. O. Bryan (2008), Changes in subduction in the South Atlantic Ocean during the 21st century in the CCSM3, *Geophys. Res. Lett.*, *35*, L06701, doi:10.1029/2007GL032762.

1. Introduction

[2] Water mass formation in the Atlantic sector is an important component of Southern Ocean ventilation. Components of both Subantarctic Mode Water (SAMW) and Antarctic Intermediate Water (AAIW) are formed in this basin, see *Sloyan and Rintoul* [2001] for example, and much of the Antarctic Bottom Water is formed in the Weddell Sea. This region is important because it takes up a lot of heat and CO_2 from the atmosphere. Therefore, an important question is how water mass formation will change over the 21st century, especially if formation rates weaken, and the South Atlantic can't take up as much heat and CO_2 as it does at present? There are conflicting published answers to this question. *Russell et al.* [2006] analyze future changes in the Southern Hemisphere from the latest GFDL climate models. They suggest that the ocean may take up more CO_2 in the future, because of a small increase in the strong westerlies over the high latitude Southern Ocean. *Le Quere et al.* [2007] estimate from observations that the Southern Ocean sink of CO_2 has weakened between 1981 and 2004 at a faster rate than expected from just the reduced solubility as CO_2 increases. They attribute this additional weakening to the observed increase in the Southern Ocean westerlies.

[3] Possible changes in South Atlantic water mass formation will be analyzed using simulations from the Community Climate System Model version 3 (CCSM3). The justification is that SAMW and AAIW are simulated much better in the ocean components of climate models used in the IPCC fourth assessment report than in previous reports, see *Sorensen et al.* [2001, Figure 2], for example. Very recently, *Sloyan and Kamenkovich* [2007] have made a detailed study of the SAMW and AAIW simulation in eight of the climate models used in the IPCC fourth assessment report. The CCSM3 is one of the three best models in simulating the density structure of the Antarctic Circumpolar Current, the AAIW salinity minimum in the Indian Ocean, and the simulation of SAMW and AAIW in general. Their study is only of present day simulations, and shows results mostly from the southern Indian and Pacific Oceans. In this paper, we show results just from the South Atlantic Ocean, and include projections of future changes over the 21st century.

2. The CCSM3 Model and Integrations Analysed

[4] The CCSM3 is a general circulation climate model that couples atmosphere, land, ocean, and sea ice components. An overview and a description of its present day climate simulation using T85 (1.4°) atmosphere and land resolution, and a nominal 1° ocean and sea ice resolution are given by *Collins et al.* [2006]. First, two long control integrations with 1870 values of greenhouse gases were run. Then a total of nine 20th century integrations, that branched from the control runs at different times, were run for 130 years; 1870–1999. These 20th century integrations were all forced using observed variations of solar input, volcanic and other aerosols, and observed values of greenhouse gases such as CO_2. The 21st century integrations continued for 100 years from the end of the 20th century runs, and spanned years 2000–2099. The runs analyzed in this paper all used the A1B SRES scenario for the projected future increase in CO_2, which increases from 370 ppm in 2000 to 690 ppm in 2100. There were seven members in this ensemble of 21st century integrations, and much more detail on all these runs is given by *Meehl et al.* [2006, section 2].

3. The 20th Century South Atlantic Simulation

[5] This section will be very brief, and the reader is referred to the recent *Sloyan and Kamenkovich* [2007] study for a more thorough analysis of SAMW and AAIW in present day simulations from eight climate models including the CCSM3.

[6] Figure 1a shows the zonal average salinity in color and the potential density contour lines in white in the South Atlantic down to 1.5 km from the *Levitus et al.* [1998] data. It shows the salinity minimum that defines AAIW going from the surface at 50°–55°S, reaching a maximum depth of about 840 m near 35°S, and then rising to a depth near 680 m equatorward of 20°S. Figure 1b shows the same fields, but for the ensemble mean of 20th century runs between 1950–1999. It has a similar subsurface salinity

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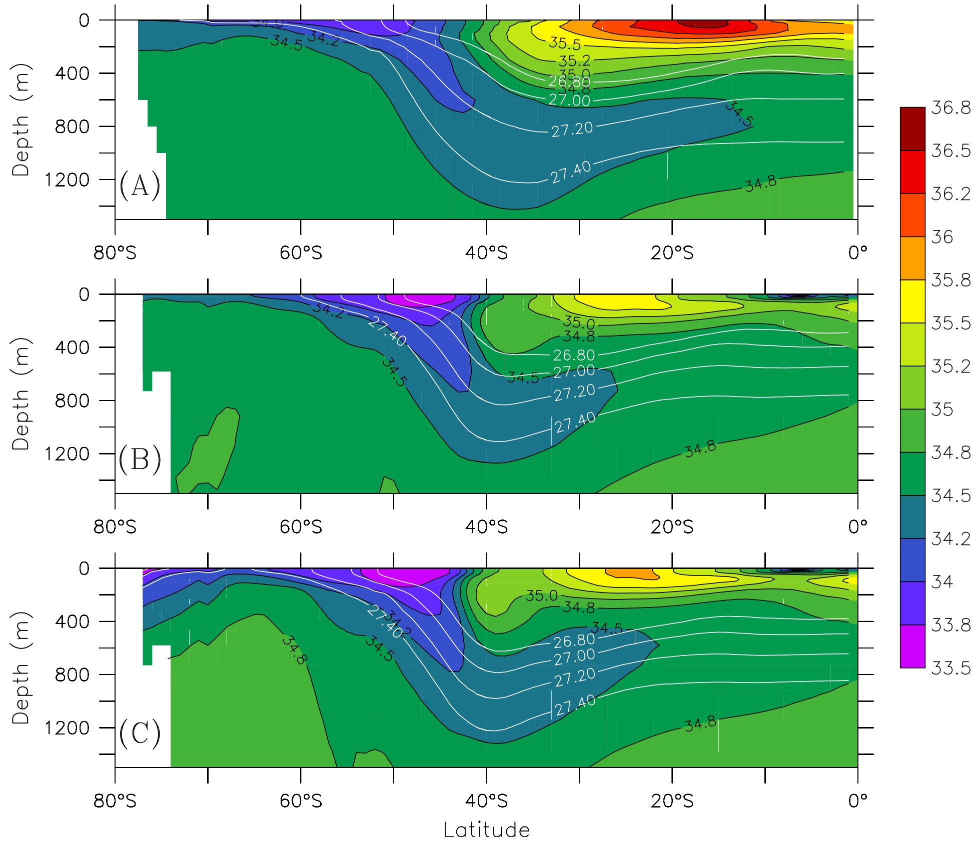

Figure 1. Plot of zonal average salinity and density contours in the South Atlantic: (a) *Levitus et al.* [1998] data, (b) CCSM3 ensemble average ⟨1950–1999⟩, and (c) CCSM3 ensemble average ⟨2080–2099⟩.

distribution, with the salinity minimum at the surface near 45°–50°S, reaching a maximum depth of about 830 m near 40°S, and then rising to a depth of about 700 m equatorward of 30°S. Thus, the salinity is about 0.2 psu fresher than observations near the surface at 55°S, and 0.1 psu more saline at depth equatorward of 30°S.

[7] In observational studies, the location of the salinity minimum is always taken as the σ = 27.2 isopycnal. A very nice feature of the CCSM3 simulation is that the salinity minimum below 300 m is also characterized by the same isopycnal. A quantitative measure of the model error is the depth of the σ = 27.2 isopycnal and the average salinity on this isopycnal at 30° and 50°S. These values are 730 m and 34.45 psu at 30°S in the model, and 825 m and 34.37 psu in the *Levitus et al.* [1998] data. At 50°S, the values are 150 m and 33.92 psu and 165 m and 34.06 psu in the model and observations, respectively. These errors imply that the model temperature is >1° C too cold around 150 m at 50°S, and <1°C too warm around 730 m at 30°S. Overall, we conclude that the simulation of water mass formation in the South Atlantic in CCSM3 is rather good. This gives confidence that the model will show realistic changes in the 21st century integrations.

4. Water Mass Formation Changes During the 21st Century

[8] We first look at the changes in salinity and potential density over the 21st century, and their variability across the ensemble of 21st century runs. Figure 1c shows the zonal average salinity and potential density in the South Atlantic for the ensemble mean of 21st century runs between 2080–2099. It shows that AAIW becomes fresher, and the associated isopycnals deepen considerably, over the 21st century. Contrasting changes in the surface ocean occur elsewhere: the Weddell Sea freshens significantly, but the area around 25°S becomes more saline.

[9] The solid line in Figure 2a shows the ensemble and zonal average of the σ = 27.2 isopycnal depth at 30°S versus time between 1870–2100, and Figure 2b shows the same for salinity on the 27.2 isopycnal. The shading shows the standard deviation across the ensemble. The depth of the 27.2 isopycnal shows variability on the order of 10 m between 1870–1980, but then begins to deepen monotonically. The deepening starts late in the 20th century, but then continues strongly throughout the 21st century, so that the depth reaches 810 m in 2100, compared to the average of 720 m for 1870–1980. Figure 2b shows similar changes with time for salinity on the 27.2 isopycnal. The average value, with small variability, is nearly 34.45 psu over 1870–1980, but then starts to get fresher and this continues over the 21st century to a value of 34.41 psu at 2100. The standard deviation shows that both the deepening and freshening of the 27.2 isopycnal are highly significant compared to the ensemble variability.

[10] The upper 1 km of the ocean warms throughout the South Atlantic region, with a near-surface temperature rise of 1–2°C. However, Figure 2 shows that the 27.2 isopycnal

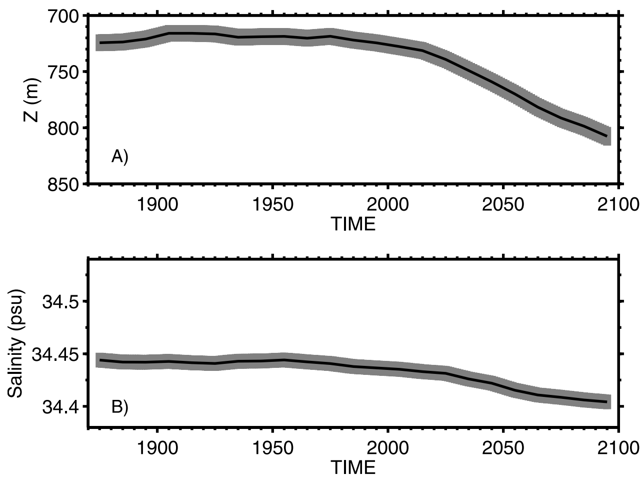

Figure 2. Plot of (a) depth of the σ = 27.2 isopycnal, and (b) salinity on 27.2 at 30° in the South Atlantic versus time 1870–2100. The line is the ensemble mean, and the shading is the ensemble standard deviation.

deepens sufficiently that the temperature on it actually goes down a little.

[11] The measure of water mass formation rates used is to diagnose the subduction across the base of the ocean mixed layer as a function of potential density, see *Karstensen and Quadfasel* [2002]. The model mixed layer depth is the depth where the local buoyancy gradient equals the maximum bulk buoyancy gradient calculated between the surface and any depth, see *Large et al.* [1997, p. 2427]. First, the annual maximum depth of the mixed layer is averaged over a particular decade to calculate the depth, *H*. Subduction is then calculated with respect to this depth under the assumption that most water mass formation occurs in winter when the mixed layer depth is a maximum. It is also assumed that using the decadal average value does not alias the interannual variability. The total subduction is calculated as,

$$Sub(\sigma) = -\oint_{\sigma-\Delta\sigma/2}^{\sigma+\Delta\sigma/2} [\mathbf{u}\cdot\nabla H + w]dA, \qquad (1)$$

where $\mathbf{u}$ and w are the decadal averaged horizontal and vertical velocities at the depth *H*. The total subduction is an integral of the local positive subduction over the area defined by the adjacent isopycnals $\sigma - \Delta\sigma/2$ and $\sigma + \Delta\sigma/2$, where $\Delta\sigma = 0.2$.

[12] Figure 3 shows the transport of subducted waters for $24.9 < \sigma < 27.5$ in each decade between 1870–2100 from one of the 20th and 21st century runs. The blue line is the average value for $\langle 1870\text{–}1999 \rangle$, and the red line the average value for $\langle 2000\text{–}2099 \rangle$. For $24.9 < \sigma < 26.3$, the subduction transports are relatively small, and do not change much over the 21st century. However, there are significant changes for $26.3 < \sigma < 27.1$, which is the density range at which SAMW and AAIW are formed in the CCSM3. The largest changes are a 3 Sverdrup (Sv) increase at σ = 26.8, and a 4 Sv decrease at σ = 27.0, with much smaller increases of <1 Sv at σ = 26.4 and 26.6. The total subduction transport in this density range is about 15 Sv, which is close to the observational estimate of *Karstensen and Quadfasel* [2002], and the inverse model estimate of *Sloyan and Rintoul* [2001]. Total subduction in this density range does not change significantly over the 21st century.

[13] Figure 4 shows how the subduction is divided into the lateral and vertical velocity components at the higher densities in the range $26.5 < \sigma < 27.3$ versus time 1870–2100 from the same 20th and 21st century run as Figure 3. The lateral component dominates the vertical component in all these density classes due to the frontal characteristic of this region, in agreement with the results of *Karstensen and Quadfasel* [2002]. In fact, the vertical component is negative at σ = 26.8 and 27.0. Figure 4 shows that the total

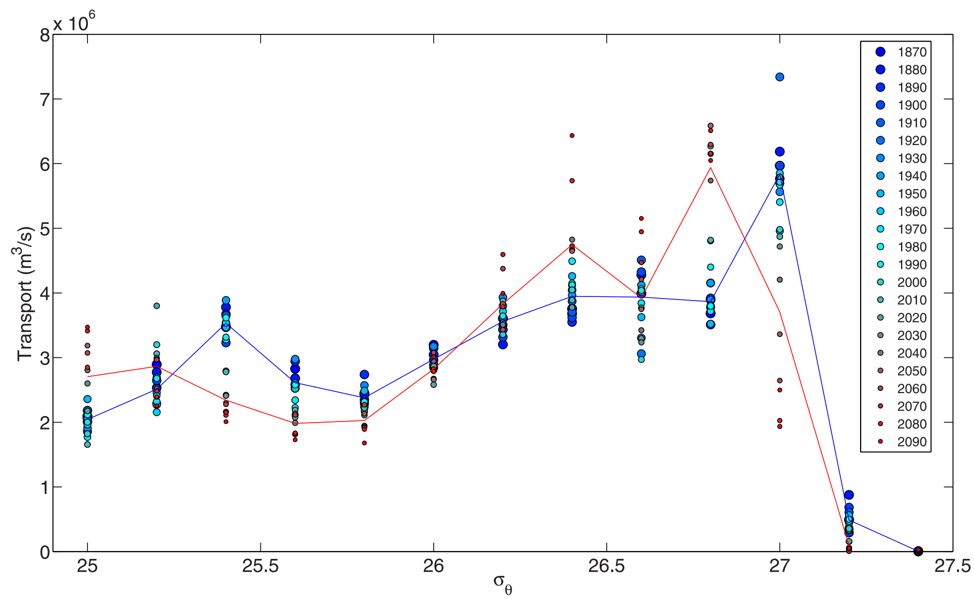

Figure 3. Transport of subducted waters for each decade between 1870–2100 versus density $24.9 < \sigma < 27.5$ in one 20th and 21st century run. The blue line shows the average $\langle 1870\text{–}1999 \rangle$, and the red line the average $\langle 2000\text{–}2099 \rangle$.

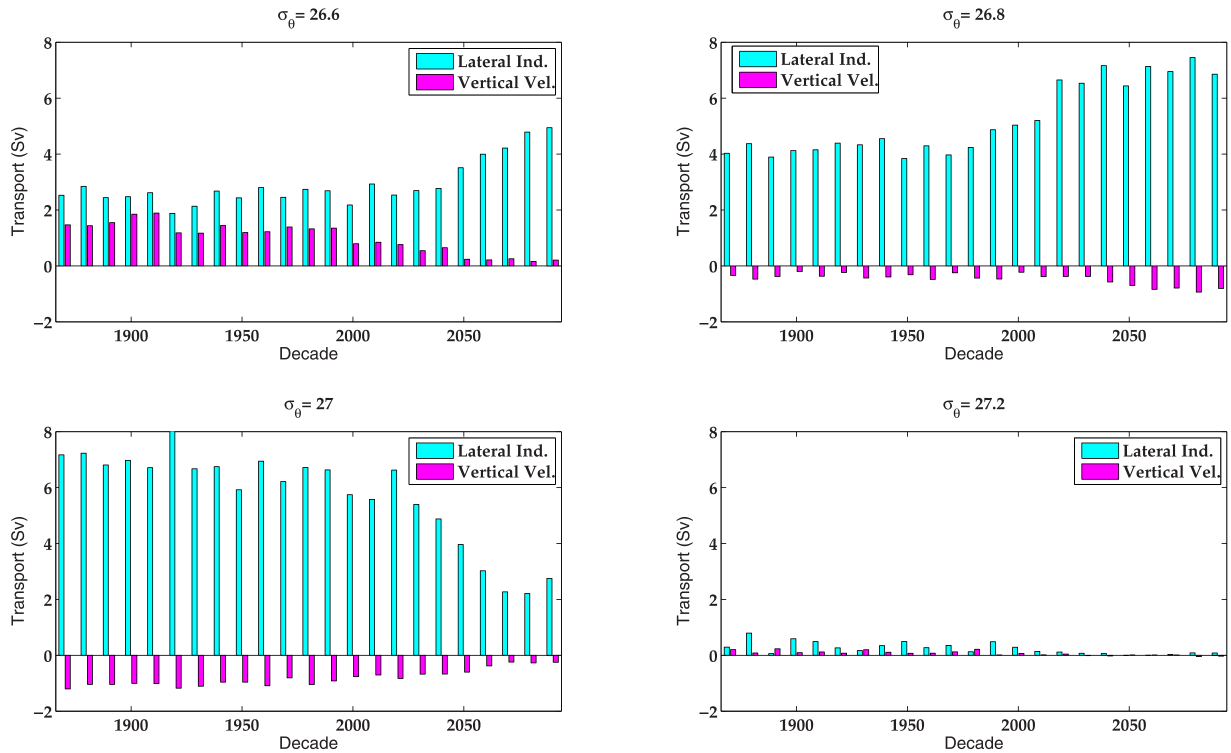

Figure 4. Plot of the lateral and vertical velocity subduction rates for $26.5 < \sigma < 27.3$ in the South Atlantic versus time 1870–2100 in one 20th and 21st century run.

subduction rates increase at σ = 26.6 and 26.8 over the 21st century, but decrease at σ = 27.0 and 27.2. There is very little subduction at σ = 27.2 after about 2040 for this A1B scenario run. This again shows that the total subduction rates of SAMW and AAIW do not change much over the 21st century, but move to a significantly lower density by about $\Delta\sigma$ = 0.2.

[14] Figure 5a shows the decadal maximum mixed layer depth *H*, and the density at this depth from the same 21st century run for ⟨2000–2009⟩, and Figure 5b shows the same fields for ⟨2090–2099⟩–⟨2000–2009⟩. There is relatively little change in the maximum mixed layer depth over the 21st century, although the location of the deepest mixed layer near 40°S moves a little to the south. However, there is a consistent change to lighter densities throughout the South Atlantic. The largest change of $\Delta\sigma$ = 0.5 occurs between 30° and 40°S where the ⟨2000–2009⟩ density is around σ = 26.0. South of 45°S, there is a consistent change to a lighter density by $\Delta\sigma$ = 0.2 all across the South Atlantic, which covers the formation region of SAMW and AAIW. Figure 5b shows how the areas of different density classes at the base of the maximum mixed layer change over the 21st century. Additional calculations show that the changes in subduction over the 21st century at the higher densities shown in Figures 3 and 4 are mostly due to the changing areas of the density intervals over which the integral is taken, with the integrand in equation (1) staying nearly constant.

5. Conclusions

[15] There are four main conclusions from this study:

[16] a) The CCSM3 simulation in the South Atlantic, and of AAIW properties in particular, is good enough to give confidence in the model's projected changes over the 21st century.

[17] b) There is natural variability, but small trends, in the ocean simulation up to 1980. Then changes and trends appear, which continue throughout the 21st century. These changes under the A1B scenario forcing are very significant with respect to both variability within each run, and the variability across the ensemble of 21st century runs.

[18] c) In the South Atlantic, the isopycnals become deeper and the water on them becomes a little fresher and colder over the 21st century. Isopycnals getting deeper and salinity decreasing on isopycnals is exactly the interior ocean signal that *Bindoff and McDougall* [1994] showed would result from warming and freshening at the ocean surface.

[19] d) Analysis of the subduction across the maximum mixed layer depth shows that the total SAMW and AAIW formation rates do not change significantly over the 21st century. However, by 2100 these water masses are

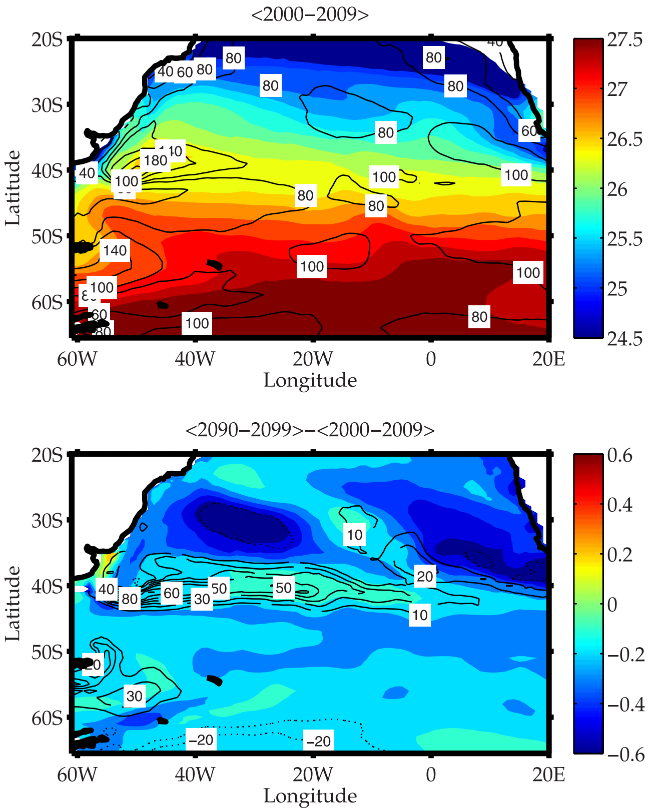

Figure 5. Density, in color, at the annual maximum mixed layer depth, black contours, in the 21st century run: (a) ⟨2000–2009⟩ and (b) ⟨2090–2099⟩–⟨2000–2009⟩.

formed at significantly lighter densities by $\Delta\sigma = 0.2$ than in 2000. This pattern of change in subduction rates is consistent across the ensemble of CCSM3 21st century A1B integrations.

[20] Thus, the CCSM3 suggests that the uptake of heat and CO_2 in the South Atlantic over the 21st century will not be affected by reduced rates of water mass formation. This conclusion is supported by analyses of water mass transformation rates at the ocean surface and passive tracers done on the same model runs, which are not shown. *Russell et al.* [2006] analyze future changes in the Southern Hemisphere from the latest GFDL climate models. They suggest that the ocean may take up more CO_2 in the future, because of a small increase in the strong westerlies over the high latitude Southern Ocean. These westerlies increase by only 2–3% in the South Atlantic sector over the 21st century in the CCSM3, which is not statistically significant, although the maximum does move slightly polewards. Thus, this mechanism for increased ocean uptake does not occur in the CCSM3. Note again that *Le Quere et al.* [2007] suggest that increased winds have led to reduced CO_2 uptake over 1981–2004. Finally, the question of whether the Southern Ocean continues to take up the same fraction of CO_2 emissions in the future can only be calculated in a model with a full carbon cycle. *Fung et al.* [2005] show results from such a model embedded in an earlier version of this climate model, CSM1.4. They show that, even if future ocean circulation changes do not affect the uptake of CO_2, whether the ocean continues to take up the same fraction of emissions depends upon the rate of atmospheric CO_2 increase and the reduced solubility due to rising sea surface temperatures. Unfortunately, future projections with a carbon cycle component have not been performed with the CCSM3.

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