Detecting thermohaline circulation changes from ocean properties in a coupled model

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[1] Significant changes of the thermohaline circulation (THC) are likely to cause abrupt climate change. Here we intend to find a simple measure to detect changes in THC through examining several factors proposed to control the THC variations using a coupled climate model. These factors are equatorial-South Atlantic upper Atlantic ocean temperature, Southern Ocean freshening, inter-basin sea surface salinity contrast, and meridional steric height gradient. Three experiments are analyzed – a present-day control run, a freshwater hosing run and a 1% CO2 run. Results show that if freshwater flux is the primary cause, all examined factors can predict the THC changes. If both thermal and haline forcings are involved, only the Atlantic meridional steric height gradient gives a consistent measure of the THC variations. A new result presented here is that the inter-basin sea surface temperature contrast between North Atlantic and North Pacific is found to be an indicator of THC changes. INDEX TERMS: 1620 Global Change: Climate dynamics; 4352 Oceanography: Physical: General circulation; 4215 Oceanography: General: Climate and interannual variability; 1635 Global Change: Oceans (4203).


1. Introduction

[2] Reorganization of the global thermohaline circulation (THC) is the only well proposed mechanism responsible for the past abrupt climate change that has been reviewed in depth by an expert group [Committee on Abrupt Climate Change et al., 2002]. THC involves a global scale three-dimensional water mass transport along with the atmospheric heating and cooling processes in which the warmer upper water is converted into dense deep water in the northern North Atlantic and around the periphery of the Antarctic. These highly localized deep convective activities could be fully suppressed by an outburst of a freshwater flood, especially in the North Atlantic. The shutdown of the THC could induce significant cooling in the North Atlantic region, thus triggering a cooling event.

[3] Although variations of the global THC are suggested to be important for climate change, detection of the THC change remains a challenging task. The challenge arises from our inability to obtain continuous three-dimensional global data. Consequently, strengths of the THC are often inferred from the variation of important factors that can cause changes of the THC steady state. These factors include: the meridional gradient of the zonally averaged steric height [Hughes and Weaver, 1994; Thorpe et al., 2001], inter-basin salinity contrast [Stocker et al., 1992; Seidov and Haupt, 2003], the southern ocean freshening [Saenko et al., 2003], and the warming of tropical Atlantic upper ocean [Rühlemann et al., 1999]. Other factors that can also affect the THC are: diapycnal mixing [Munk, 1966; Bryan, 1987], Southern Ocean winds [Toggweiler and Samuels, 1998], and geothermal heating [Huang, 1999].

[4] The goal of this paper is to explore some of the factors controlling the steady-state THC that can effectively reflect the THC response to century-long transient climate change. To accomplish the goal, we perform a set of experiments using a coupled climate model – the National Center for Atmospheric Research’s Community Climate System Model version 2.0 (NCAR’s CCSM2.0). Results from this research will increase our ability to detect the changes in THC and project its future status.

2. Model and Experiments

[5] The model used in this study is the NCAR’s CCSM2.0 [Kiehl and Gent, 2004; Holland, 2003]. Its atmospheric component is the NCAR Community Atmospheric Model (CAM2) at T42 resolution and 26 hybrid levels vertically. The ocean model is a version of the Parallel Ocean Program (POP) developed at Los Alamos National Lab with 1° horizontal resolution and enhanced meridional resolution (1/2°) in the equatorial tropics, and with 40 vertical levels. The sea ice model is the Community Sea Ice Model (CISM4) with the Elastic-viscous-plastic dynamics, a subgrid-scale thickness distribution, and energy conserving thermodynamics. The land model is the Community Land Model (CLM).

[6] Three experiments are analyzed: the CCSM millennial present day control run (CON) from year 500 to 699, a freshwater hosing run (HOS), and a 1% CO2 transient climate run (TRC). The last two experiments are specifically designed to investigate the relation of THC with changes of various oceanic variables for the past and future climate, and therefore to determine the prominent factors that most efficiently reflect the THC change.

[7] In the HOS experiment, a 0.1 Sv (1 Sv = 106 m3 s-1) additional freshwater flux is uniformly distributed in the northern North Atlantic between 50° and 70°N, which mimics a freshwater pulse during the last deglaciation. This additional freshwater flux represents a 50% increase in net freshwater input into this region relative to the control experiment. In TRC experiment, the atmospheric CO2...
increases 1% per year compound. These two experiments are branched from the CON run at year 500. The TRC run is integrated for 150 years where CO2 doubles at year 70 and quadruples at year 140. The HOS run is integrated with the additional freshwater flux for 100 years, and that flux is then switched off for another 100 years.

3. Results
3.1. Variation of MOC

Since the meridional overturning circulation (MOC) of Atlantic is dominated by THC, hereafter, we use MOC to represent THC. The mean MOC strength, the maximum value of the Atlantic meridional stream function, in CON is 15.7 Sv, agreeing well with observed estimates [e.g., McCartney and Talley, 1984]. In comparison with that in CON, MOC weakens by 4.4 Sv in HOS averaged over years 580–599, and by 1.5 (2.9) Sv in TRC when CO2 doubles (quadruples). Empirical orthogonal function analysis of the Atlantic meridional stream function shows that the production of the North Atlantic Deep Water and the Antarctic Bottom Water varies in an opposite sign in both CON and HOS runs (figure not shown) – when the production of the former is stronger, the latter is weaker, and vice versa, consistent with the bipolar seesaw theory of Broecker et al. [1999]. In TRC, the production of both waters varies in the same direction – as CO2 increases, the formations of both are reduced.

The meridional heat transport (MHT) north of the equator is proportional to the MOC strength – a weaker MOC transports less heat into North Atlantic (figure not shown). The MHT reduction at 24°C/176N, a location with an abundance of repeated observations, is 0.17, 0.05 and 0.09 PW (1 PW/1015 W) for HOS averaged over years 580–599, and for CO2 doubling and quadrupling, respectively. In the South Atlantic, the northward MHT reduces by 0.15 PW in HOS. In TRC, the MHT reduction induced by the weaker MOC is compensated by the CO2 induced warming effect. The resulting MHT is almost the same as in CON.

3.2. Upper 1 km Mean T in South Atlantic

Comparing with Figure 1a, as MOC spins down, the upper 1000 meter equatorial-South Atlantic ocean temperature (T_up, Figure 1b) increases in HOS. A opposite situation occurs for a stronger MOC. These are consistent with Rühlemann et al. [1999] and Stocker [2002] in that a weaker MOC transports less heat from South Atlantic to North Atlantic. In TRC, the weaker MOC is also related to a higher T_up. However the increase in T_up is much larger than that in HOS. This higher T_up increase is primarily attributed to the CO2 induced warming. In CON, the MOC induced T_up variation is small. Therefore, T_up could give us a good signal to detect the MOC changes for future climate only if the direct CO2 contribution on T_up could be removed.

3.3. Southern Ocean Freshwater Forcing

Saenko et al. [2003] proposed that the MOC strength in steady state is controlled by freshening in the Southern Oceans. As for the MOC, MHT and associated air-sea heat...
flux anomalies are all proportional to the southward moisture transport from subtropical to subpolar regions in the Southern Hemisphere. In our two transient climate runs (Figure 1c), the freshwater flux into the Southern Oceans (a proxy of the poleward water vapor transport) increases dramatically in TRC, and there is only a small change in HOS compared to CON. In comparison with Figure 1a, fresher subpolar Southern Oceans are related to a weaker MOC in TRC, in contrast with Saenko et al.’s conclusion. However, the Antarctic deep water production is reduced and the Southern Ocean upwelling also increases (figure not shown), agreeing with Saenko et al. To further investigate the discrepancy between our model and Saenko et al., two new sensitivity experiments are conducted: A. the freshwater flux in the CON run is replaced by that in the TRC run; B. the freshwater flux in the TRC run is replaced by that in the CON run. In the other word, the CO$_2$ induced thermal effect was removed in experiment A, and the CO$_2$ induced hydrological change was removed in experiment B. Results from these two experiments show that MOC strengthens in A relative to CON, and weakens further in B relative to TRC. Thus, the CO$_2$ induced warming effect on deep convective activity overcomes the Southern Ocean freshening in TRC, producing an overall weaker MOC in our model.

Although the variations of the freshwater flux into the Southern Oceans is small in CON, the relation between MOC and this freshwater flux is consistent with Saenko et al. In HOS, the warming of the equatorial-South Atlantic induces a small increase in the freshwater flux into the Southern Oceans, but the much larger freshwater forcing in northern North Atlantic leads to a weakened MOC. Thus the effect of the freshwater flux changes in the Southern Oceans under transient climate on MOC could be offset by other factors.

### 3.4. MOC and Inter-basin SST, SSS Contrast

Seidov and Haupt [2003] pointed out that the inter-basin sea surface salinity (SSS) contrast between North Atlantic and North Pacific (10 to 60°N) controls the strength of the steady-state MOC. A stronger salinity contrast causes a stronger MOC. In our transient climate runs, the North Atlantic freshening in HOS decreases this salinity contrast to 0.34 ppt from 0.79 ppt in CON (Table 1), resulting in a weaker MOC, agreeing well with Seidov and Haupt. In TRC, this salinity contrast has no change when CO$_2$ doubles, and increases to 0.81 ppt when CO$_2$ quadruples. This increase is related to a weaker surface freshening in the North Atlantic, and a stronger one in the North Pacific (Table 1). Since the net freshwater loss actually increases in both oceans, the overall freshening in these two oceans is due to CO$_2$ induced ice melting. The exported melt-ice water from the Arctic is the major contributor to the freshening in North Atlantic. The local melt-ice water dominates the Pacific freshening with minor contribution from Arctic ice export via Bering Strait driven by biased model wind. The MOC weakening as CO$_2$ increases in TRC (Figure 1a) implies that the overall warming and freshening in the North Atlantic, suppressing the deep convective activity there, dominates the increased inter-basin salinity contrast, producing a weaker MOC.

Table 1. Mean SST, SHF, SSS and SFWF in NA and NP

<table>
<thead>
<tr>
<th>Case</th>
<th>SST °C</th>
<th>SHF w/m²</th>
<th>SSS ppt</th>
<th>SFWF Sv</th>
</tr>
</thead>
<tbody>
<tr>
<td>CON</td>
<td>20.0 ± 0.06</td>
<td>-6.5 ± .4</td>
<td>35.14 ± .03</td>
<td>-325 ± .007</td>
</tr>
<tr>
<td>HOS</td>
<td>19.4 ± 0.05</td>
<td>-4.3 ± .2</td>
<td>34.71 ± .02</td>
<td>-292 ± .005</td>
</tr>
<tr>
<td>2- CO$_2$</td>
<td>20.8 ± 0.03</td>
<td>-4.8 ± .2</td>
<td>35.13 ± .01</td>
<td>-351 ± .003</td>
</tr>
<tr>
<td>4- CO$_2$</td>
<td>21.7 ± 0.07</td>
<td>-3.7 ± .3</td>
<td>35.07 ± .01</td>
<td>-376 ± .002</td>
</tr>
</tbody>
</table>

* SST stands for sea surface temperature, SSS for sea surface salinity, SHF for net surface heat fluxes, SFWF for net surface freshwater fluxes. The sign convention for SHF and SFWF is that positive indicates ocean gaining heat or freshwater. NA (NP) stands for North Atlantic (Pacific) between 10 and 60°N. 2- CO$_2$ (4- CO$_2$) represents CO$_2$ doubling (quadrupling). Numbers in this table are averaged over NA or NP, and the same time average as in Figure 1e is applied here. The numbers after the ± signs are the standard deviations.

3.5. MOC and Meridional Steric Height Gradient

Steric height is defined as vertically integrated density. A linear relation between MOC strength and meridional steric height gradient has been found by many authors [e.g., Hughes and Weaver, 1994; Thorpe et al., 2001]. Comparing with that in CON, the zonally averaged steric height, a density integration from surface to 2750 m, is reduced more significantly in mid-high latitude North...
Atlantic due to freshwater forcing than that in mid-latitude South Atlantic due to less northward heat transport, resulting in a decreased meridional steric height gradient and a weaker MOC in HOS (Figure 1e). In TRC, the change in steric height is almost uniform meridionally, resulting in a smaller change in meridional steric height gradient, and a smaller MOC change than that in HOS. A regression plot (Figure 1f) further demonstrates that as meridional steric height gradient decreases, MOC weakens for all three cases. But the coefficient of the linear regression between MOC and meridional steric height gradient is 17 Sv per cm/deg-lat in HOS and CON, and that increases to 29 Sv in TRC. This higher regression coefficient in TRC is caused by an increased net evaporation in subtropical South Atlantic, resulting in a weaker steric height decrease there.

4. Discussion and Conclusions

[17] In contrast with Hirschi et al. [2003] who suggested the use of moorings across a longitude-depth section and zonal wind stress to obtain continuous MOC measurement, here we have tried to find an indirect measure to detect the THC changes using NCAR’s CCSM2.0 since a direct and sustained measurement of the THC is not available from observations. Three experiments are analyzed - a CON run, a TRC run with 1% CO₂ increase per year, and a HOS run with an additional 0.1 Sv freshwater flux into the northern North Atlantic.

[18] Our results show that MOC response to transient climate changes is a result of several competing processes. In the model, MOC weakens when CO₂ increases, agreeing with many climate models [Cubasch et al., 2001]. Surface warming and freshening in North Atlantic, suppressing deep convective activity there, are the primary cause for a weaker MOC. The increased poleward moisture transport in the Southern Hemisphere and the increased sea surface salinity contrast between North Atlantic and North Pacific tend to strengthen the MOC, but are overcome by changes in the North Atlantic, resulting in a moderate MOC reduction. This result is in line with several recent studies of the MOC response to climate change scenarios [Dixon et al., 1999; Mikolajewicz and Voss, 2000; Thorpe et al., 2001]. In the HOS run, the additional freshwater flux causes a freshening in the North Atlantic, a decreased surface salinity contrast, and a slight increase in poleward moisture transport in the Southern Hemisphere. The first two lead to a greater weakening of the MOC than in the TRC run.

[19] Factors examined here to detect the MOC changes are the equatorial-South Atlantic upper ocean temperature, Southern Ocean freshening, sea surface salinity contrast between North Atlantic and North Pacific, and meridional steric height gradient. Variations in these factors will change the steady state of MOC. Our study indicate that the effect of some of these factors on MOC strength is dominated by others under transient climate conditions. If the freshwater input into the ocean is the primary cause, all examined factors can be used as an indicator to detect MOC changes. If the thermal forcing is the primary cause, only the meridional steric height can be used. A new factor found in this research is the sea surface temperature contrast between North Atlantic and North Pacific which can be used to detect MOC changes for the two forced runs.

[20] Next, we will sort out more detailed underlying physics influencing the effectiveness of these factors on transient MOC changes. And the results in this study are also going to be compared with other coupled climate models.

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