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NORTH ATLANTIC OCEAN RESPONSE TO FUTURE ANTHROPOGENIC FORCING IN A COUPLED GCM

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1. Introduction

Because of the large impact of the North Atlantic Ocean circulation (especially the thermohaline circulation or THC) on regional and global climate, its response to increased greenhouse gases has attracted considerable attention. The THC weakens under increased CO_2 levels in most coupled general circulation models (GCMs) (e.g., the GFDL model, the HadCM3, the NASA GISS model, the Canadian model, the Hamburg model ECHAM3/LSG, and the NCAR PCM) and in some intermediate-complexity models. On the other hand, the THC changes little in a few coupled GCMs, including the Hamburg model ECHAM4/OPYC3 and the NCAR CSM. Many of these coupled GCMs (except the HadCM3, CSM and PCM, and GISS model) use flux adjustments.

A stable THC was possible in the ECHAM4/OPYC3 because salty surface water was advected into the North Atlantic sinking region which compensates the effects of local warming and freshening (Latif et al. 2000). In the CSM, the Northwest Atlantic became warmer and more saline with little change in surface ocean density (Gent 2001). In the models with a weakened THC, both freshening effect of increased precipitation and river runoff and thermal effect of local warming on surface ocean density play a role, although their relative importance during different stages of the weakening varies with individual models (Dixon et al. 1999). The freshwater forcing is expected since increased precipitation at northern mid- and high-latitudes is a common response of most GCMs to increased greenhouse gases. Many GCMs also produce surface warming over the North Atlantic Ocean under increased CO_2; the thermal effect is thus also expected. Some coupled GCMs, however, produce little warming (Wood et al. 1999; Boer et al. 2000) or substantial cooling (Russell and Rind 1999; Dai et al. 2001a) over the North Atlantic sinking region at the time of CO_2 doubling. In these cases, the local thermal effect is negligible or even works to enhance the THC in the cooling cases. Nevertheless, all these models produce a weakened THC. This suggests that local thermal effect is not needed to slow down the THC.

Here we report the North Atlantic Ocean circulation changes during the next two centuries in the Parallel Climate Model (PCM) forced by projected greenhouse gases and sulfate aerosols under a business as usual (BAU) and a CO_2 stabilization (STA) scenario (Dai et al. 2001a). The PCM is a coupled ocean-atmosphere GCM without flux adjustments, with horizontal resolution of $\sim 2.8^o$ in the atmosphere and $\sim 2/3^o$ in the ocean (Washington et al. 2000). Five ensemble runs are used for 1870-2099 results and one run extends to 2199 (Dai et al. 2001b).

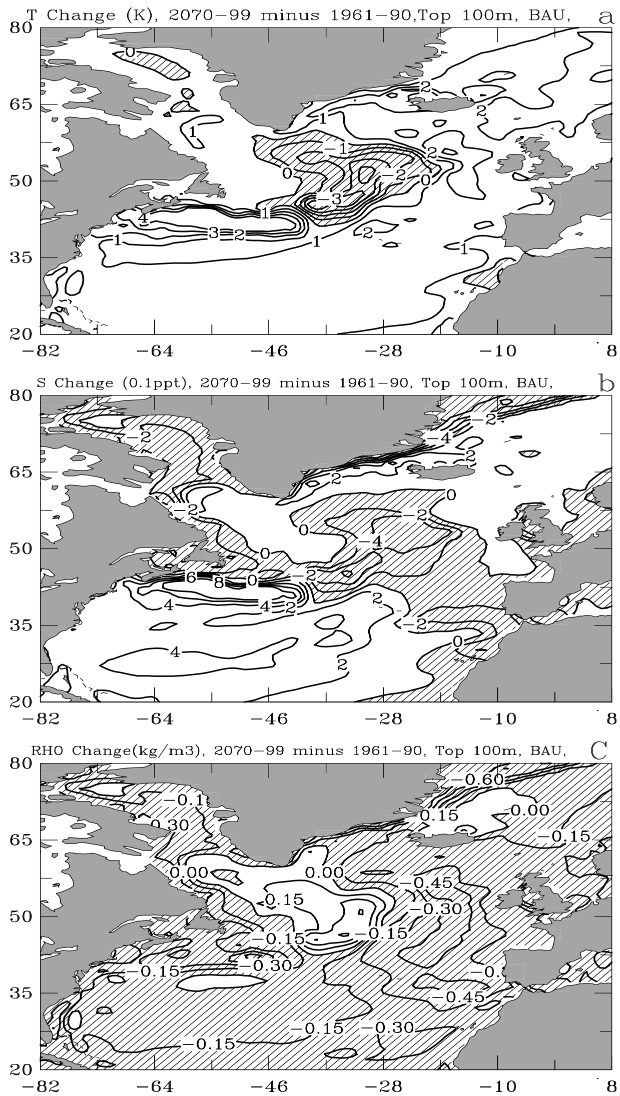

Fig. 1: Changes in top 100m-averaged North Atlantic Ocean annual temperature (a), salinity (b) and density (c) from 1961-90 to 2070-99 in the PCM ensemble simulations in the BAU case. Hatched is negative.

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2. Results

Fig. 1a shows that from 1961-1990 to 2070-2099 there is a warming of ~1–3^{o}C in the surface (top 100m) North Atlantic Ocean, except for a region around 17–38^{o}W and 46–56^{o}N where a cooling of 1–4^{o}C occurs. This cooling, which extends to ~1.5 km depth, results largely from an eastward shift of the central North Atlantic Drift current (Fig. 2). Surface ocean salinity also increases substantially (by up to 1 ppt) over the subtropical North Atlantic due to increased evaporation, but it decreases by 0.2–0.4 ppt in the cooling area. The resultant change in ocean density is a decrease over most of the North Atlantic (Fig. 1c). This reduces the North Atlantic deep water formation, especially in areas south of Iceland and around ~43–52^{o}N and 42–52^{o}W where deep water formation is large in the model at current conditions.

The central North Atlantic Drift current is shifted eastward by ~9^o longitude from 1961-1990 to 2070-2099 (Fig. 2; similar change patterns extend down to ~1.5 km, but is not evident in a multi-century control run). This change cuts off a flow of subtropical warm water into the center of the above cooling region, resulting in a regional cooling around this area (Fig. 1a). Associated with this cooling, there are large decreases in the 21st century in surface air temperature, surface latent and sensible heat fluxes, convective precipitation, and lower tropospheric lapse rate over the cooling region (Dai et al. 2001b).

The eastward shift of the Drift current appears to result from enhanced southwestly surface winds (or wind stress, which in turn results from sea level pressure changes) around 36–40^{o}N and 38–70^{o}W (Fig. 3). This enhanced wind stress extends the northern end of the Gulf Stream eastward, allowing the current to turn to northeast around 31^{o}W instead of 40^{o}W.

Zonally-averaged meridional overturning circulation (or THC) in the Atlantic sector weakens by ~20% from 1961-1990 to 2070-2099 and by an additional 10% from 2070-2099 to 2170-2199 in the BAU case, as shown by the meridional stream function in Fig. 4. The clockwise overturning cell of the upper ocean also becomes increasingly shallow, while the bottom anti-clockwise cell gains strength and depth. It should be noticed, however, that similar change patterns (with much smaller magnitude of change rate, cf. Fig. 5) are also evident in a 4-century control run. It was suggested that a lack of an ocean bottom boundary model in the ocean GCM contributes to the drifts in the overturning cells (Gent 2000).

The weakening of the upper overturning circulation or the THC is also shown by the 1950–2199 time series of the maximum stream function shown in Fig. 4

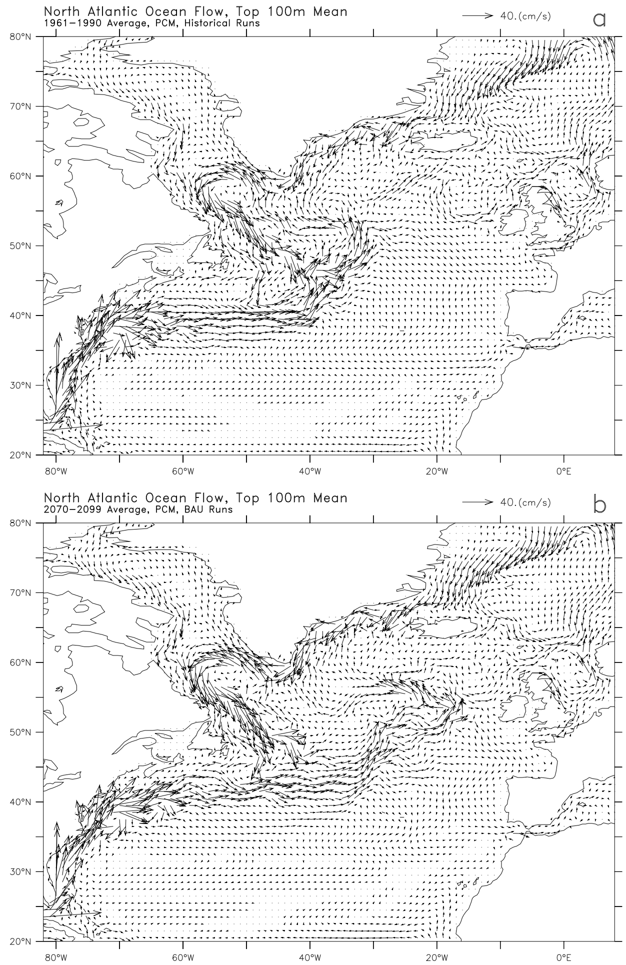

Figure 2: Top 100m-averaged ocean currents for 1961-1990 (a) and 2070-1999 (b, for the BAU case) in the North Atlantic.

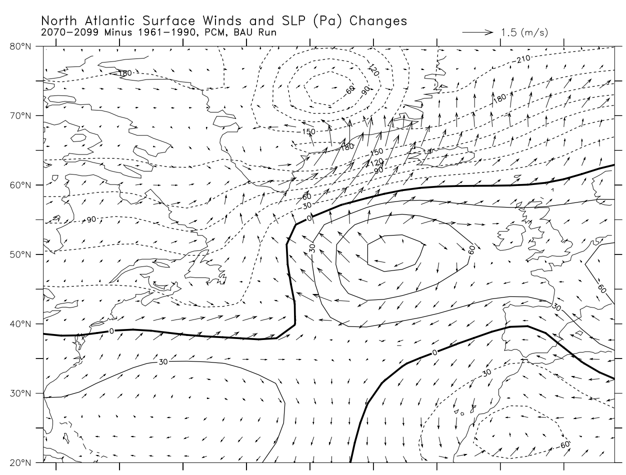

Figure 3: Changes in annual sfc. winds (arrows) and sea level pressure (contour intvl.=30 Pa, dashed are negative) from 1961-99 to 2070-99 in the BAU case.

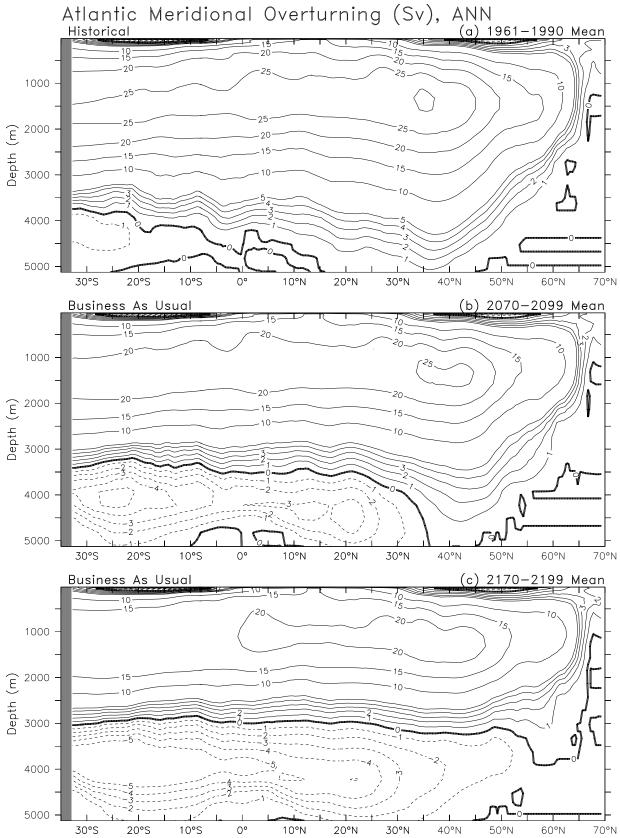

Figure 4: Zonally-averaged annual meridional overturning stream function (Sv, 1 Sv=10^6 m^3 s^{-1}) for Atlantic sector for 1961-1999 (a), 2070-2099 (b) and 2170-2199 (c) in the BAU case.

(averaged over 32–38^{o}N and 1.1–1.6 km depth) and the volume transport within the top 1 km of the North Atlantic Ocean at 40^{o}N (Fig. 5). It is evident that the decreases in these two quantities are significantly larger than any variations in the control run by the late 21st century. Similar change patterns (but with reduced magnitudes) are also seen under the STA scenario.

In summary, the meridional overturning circulation weakens at a rate much larger under the BAU scenario than in the control run. This weakening results from reduction of deep water formation in the areas south of Iceland (due to thermal effect of surface warming) and around ∼43–52^{o}N and 42–52^{o}W (due to both thermal and freshening effects). The northern end of the Gulf Stream also extends eastward by ∼9 longitude by 2070-2099, resulting an eastward shift of the North Atlantic Drift current. This ocean circulation change results a regional surface and ocean (down to 1.5 km depth) cooling around 17–38^{o}W and 46–56^{o}N.

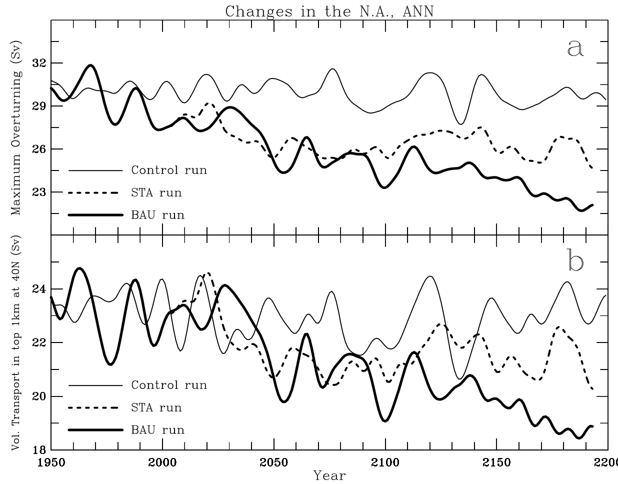

Figure 5: Time series for 1950-2199 of the maximum overturning (a) and volume transport in the top 1 km at 40^{o}N (b) in the North Atlantic Ocean for the control, STA and BAU cases.

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