Reviewer #1 (Comments to Author):

The manuscript presents a modeling study on the increase of the Atlantic ocean heat content over the 20th century using an ocean-ice model with prescribed surface fluxes. The modeling results suggest that the increase of the Atlantic ocean heat content over the mid-20th century is mainly due to the increase in the Westerly wind over the Southern Ocean and thus enhanced northward ocean heat transport across 30S over the same period. The conclusion is based on a coarse resolution ocean-ice model without coupled air-sea interaction and eddy activities, and inconsistent with previous coupled modeling studies showing the increase of the anthropogenic greenhouse gases is the dominate mechanism for the increase of the Atlantic ocean heat content. The manuscript needs to include more analyses and more comparison with the observation to substantial the conclusion. I can not recommend the paper be accepted for publications in Geophysical Research Letters in its current form. I hope the following comments be helpful to the manuscript.

We would like to thank the reviewer for the thoughtful comments and suggestions. The manuscript is now revised substantially based on these comments. In the revised manuscript, the ocean heat content changes in the North and South Atlantic are now added and discussed (comment #1). We cite and discuss important relevant literatures (comment #2). The two-dimensional spatial pattern of the long-term trend in Atlantic Ocean heat content is compared between the model simulation and available observations (comment #3). Due to paucity of observations in the South Atlantic, however, we could not perform a comprehensive model-data comparison away from the Gulf Stream area. Boning et al. [2008], and Farneti and Delworth [2010] are now cited and discussed to further stress the limitations in this study (comment #4). Pleas find below our reply to each comment from the reviewer.

1, *Please also show the time series of the simulated ocean heat content change averaged for the North Atlantic (NA) and the South Atlantic (SA) respectively. This is another way to test the proposal mechanism of ocean heat transport. If the increase of the Atlantic ocean heat content over the mid-20th century is mainly caused by the enhanced northward ocean heat transport across 30S, then the increase in the NA ocean heat content should lag that in the SA due to the propagation/advection of the signal from SA to NA, and the amplitude of ocean heat content* *increase should be smaller in the NA than in the SA due to the dissipation. However, the observation (Levitus et al. 2009) shows that the increase of the NA ocean heat content started earlier than that in the SA, and the amplitude of the increase is much larger in the NA than in the SA, seems inconsistent with the proposed mechanism. Please discuss the phase relationship and amplitude of the simulated increase of ocean heat content in both basin (NA and SA), and how do they compare with the observation?*

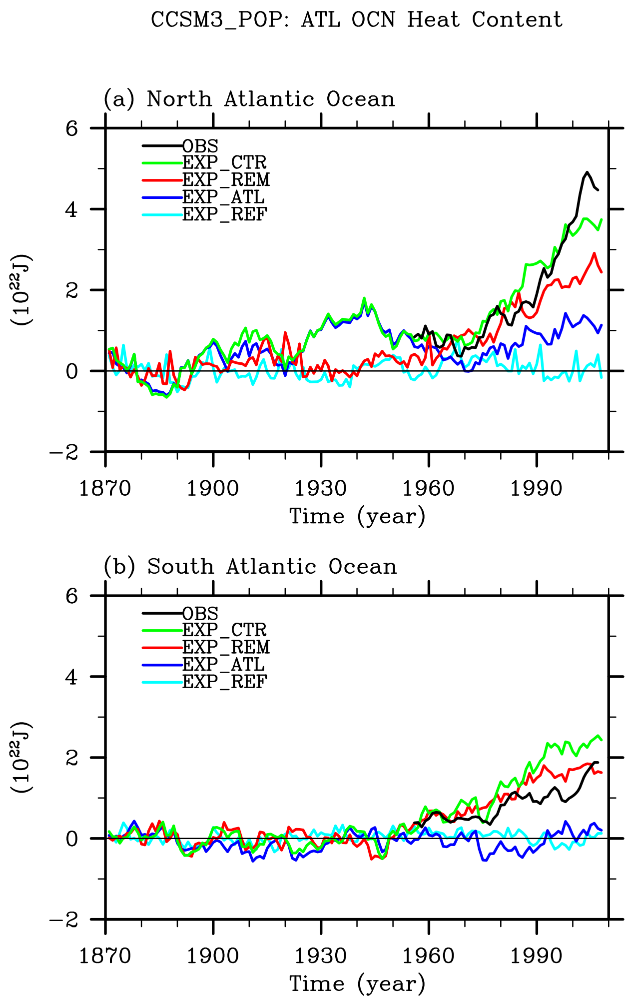

Figure A1. Simulated (a) North and (b) South Atlantic Ocean heat content changes in the upper 700m in reference to 1871-1900 obtained from the four model experiments. The thick black lines in (a) and (b) are the observed heat contents of the North and South Atlantic, respectively, reproduced from Levitus et al. [2009].

The above figure (Figure A1) shows the simulated (a) North Atlantic and (b) South Atlantic Ocean heat content change in the upper 700m in reference to the 1871-1900 period obtained form the four model experiments. The observed heat content is recomputed from Levitus et al. [2009] for the North Atlantic (equator – 75^{o}N) and South Atlantic (30^{o}S to equator), and is referenced in such a way that it matches with the simulated heat content in EXP_CTR averaged during 1955-1964 for a better visual comparison with the simulations. The simulated North Atlantic Ocean heat content in EXP_CTR increases moderately during the 1930s - 1940s, and then decreases during the 1940s - 1970s, after which it increases substantially much like the Atlantic Multidecadal Oscillation (AMO) from observations. Between the 1970s and 2000s, it increases by 3 ~ 4$\times 10^{22}$ J. This large increase is reasonably close to the observed North Atlantic Ocean heat content increase of 4 ~ 5$\times 10^{22}$ J during the same period [Levitus et al., 2009], suggesting that the model experiment (EXP_CTR) reproduces reasonably well the heat budget trend of the North Atlantic Ocean after the 1960s.

On the other hand, if the northward heat transport in the South Atlantic at 30^{o}S is allowed to vary in real time by considering the fully transient surface fluxes south of 30^{o}S while keeping the surface fluxes over the Atlantic Ocean at their 1871-1900 levels (EXP_REM), the North Atlantic Ocean heat content increases by ~ 2 $\times 10^{22}$ J during the 1970s – 2000s explaining a moderate portion of the observed trend. In this case, however, the multidecadal signal during the 1930s – 1970s, which is clearly simulated in both EXP_CTR and EXP_ATL is completely missing. The absence of this multidecadal signal in EXP_REM and its presence in EXP_ATL suggest that the multidecadal swing in EXP_CTR prior to the 1970s is caused by processes internal to the Atlantic Ocean. During the 1970s – 2000s, on the other hand, remote processes (i.e., increased inter-ocean heat transport from the Indian Ocean) seem to have contributed more than internal processes to the large increase in the North Atlantic heat content.

The simulated South Atlantic Ocean heat content in EXP_CTR remains unchanged until the 1960s, after which it increases monotonically. Between the 1970s and 2000s, it increases by ~ 2 $\times 10^{22}$ J, overestimating the observed South Atlantic Ocean heat content increase of 1 ~ 2 $\times 10^{22}$ J during the same period. As in EXP_CTR, the South Atlantic Ocean heat content in EXP_REM is also characterized by a monotonic increase after the 1960s, with a smaller amplitude of 1 ~ 2 $\times 10^{22}$ J during the 1970s – 2000s. In the case of EXP_ATL, however, there is no apparent change in the South Atlantic heat content throughout the 20th century.

In summary, the simulated ocean heat content trend in the North Atlantic since the 1950s is in a reasonable agreement with the observations. However, the heat content of the North Atlantic is much complicated by what appears to be a locally-driven multidecadal oscillation, much like AMO from observations (ERSST3) as shown in the figure below (Figure A2a). As a result, a clear lead-lag relationship of the ocean heat content between the North and South Atlantic is not found. The simulated ocean heat content trend in the South Atlantic seems to overestimate the observed heat content trend since the 1950s. This mismatch in the South Atlantic could be partly resulted from a lack of observational data in the South Atlantic region. This point is discussed in our reply to the reviewer's comment 3 below.

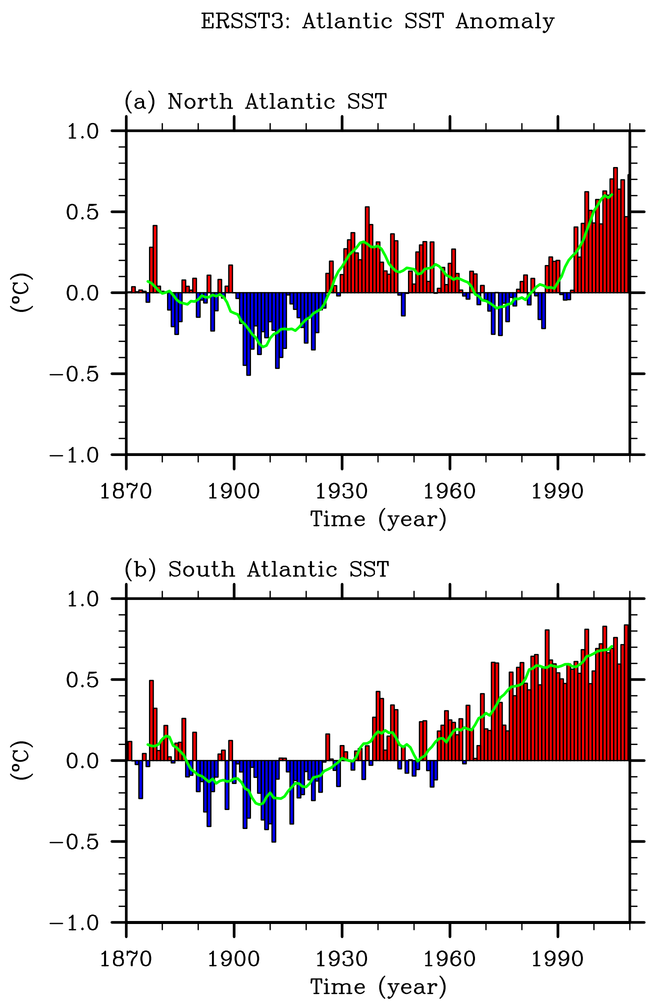

Figure A2. Observed (a) North (0^o – 60^oN) and (b) South Atlantic (30^oS – 0^o) SSTs during the instrumental period, obtained from ERSST3. The green line in each plot is obtained by performing a 11-year running average.

The simulated ocean heat contents of the North and South Atlantic are now discussed in section 7. Figure A1 is now included as Figure S3.

2, *The manuscript should cite more previous studies on the ocean heat content increase since the mid-20 century, such as Barnett et al. 2001; Barnett et al. 2005. Previous coupled modeling studies show that the increase of the anthropogenic greenhouse gases could induce similar Atlantic ocean heat content increase as that observed, without the need of the enhanced northward ocean heat transport across 30S. How does the results in this manuscript reconcile with those previous modeling studies?*

Previous coupled modeling studies by Barnett et al. [2001] and Barnett et al. [2005] are now cited. Barnett et al. [2005] stated in the abstract that "*Changes in advection combine with surface forcing to give the overall warming pattern*". Figure 4 of Barnett et al. [2005] shows that advection is equally important as surface forcing for the warming of the North Atlantic Ocean between 1940 and 1999 in their coupled model simulation. As discussed above, our model simulations also show that both local (EXP_ATL) and remote (EXP_REM) processes contribute to the increased North Atlantic Ocean heat content increase in EXP_CTR since the 1950s, thus in agreement with Barnett et al. [2005].

However, Figure 4 in Barnett et al. [2005] shows that the warming of the South Atlantic Ocean between 1940 and 1999 is largely due to surface forcing. This appears to be inconsistent with our model simulations because we find that local processes play a minor role in the warming of the South Atlantic Ocean since the 1950s as discussed above. We would like to point that this disagreement between Barnett et al. [2005] and our study may partly originate from different definition of the South Atlantic Ocean in the two studies. In our study, the South Atlantic Ocean is defined as the Atlantic Ocean from 30^{o}S to the equator, whereas in Barnett et al. [2005], the South Atlantic also includes the part of the Southern Ocean between 77^{o}S and 30^{o}S (The southern boundary of the South Atlantic is stated in Figure 1 of their previous paper, Barnett et al. [2001]). Since the South Atlantic is defined differently in the two studies, it is inconclusive whether the inter-ocean heat transport from the Indian Ocean increases in the coupled model simulation of Barnett et al. [2005] and thus contributes to the warming of the South Atlantic Ocean.

Additionally, now we cite and discuss in the introduction two previous studies [Palmer and Haines 2009; Grist et al. 2010] that used historical hydrographic observations and models to show that the ocean heat transport convergence played an important role in the warming of the Atlantic Ocean during the past decades.

3, *Please show the 2-dim spatial pattern of Atlantic ocean heat content change (long term trend) and compare that with the observation. Are the modeled and observed spatial patterns similar to each other? This analysis can also test the proposed mechanism.*

It is a challenging task to compute the 2D spatial pattern of the observed long-term trend in ocean heat content for the entire Atlantic due to the paucity of observational data south of the equator. This is particularly true during the pre-XBT era (1955-1966). However, even during the XBT-era (since 1967), only limited number of ship track data are available in the South Atlantic Ocean. For instance, Figure A3 shows the number of total observations at 300m during (a) 1955-1981 (total 27 years) and (b) 1982-2008 (total 27 years) for each $1^o \times 1^o$ grid box obtained from NODC (the same dataset used in Levitus et al. [2009]). The regions with less than five observations for the given 27-year periods are marked with white color.

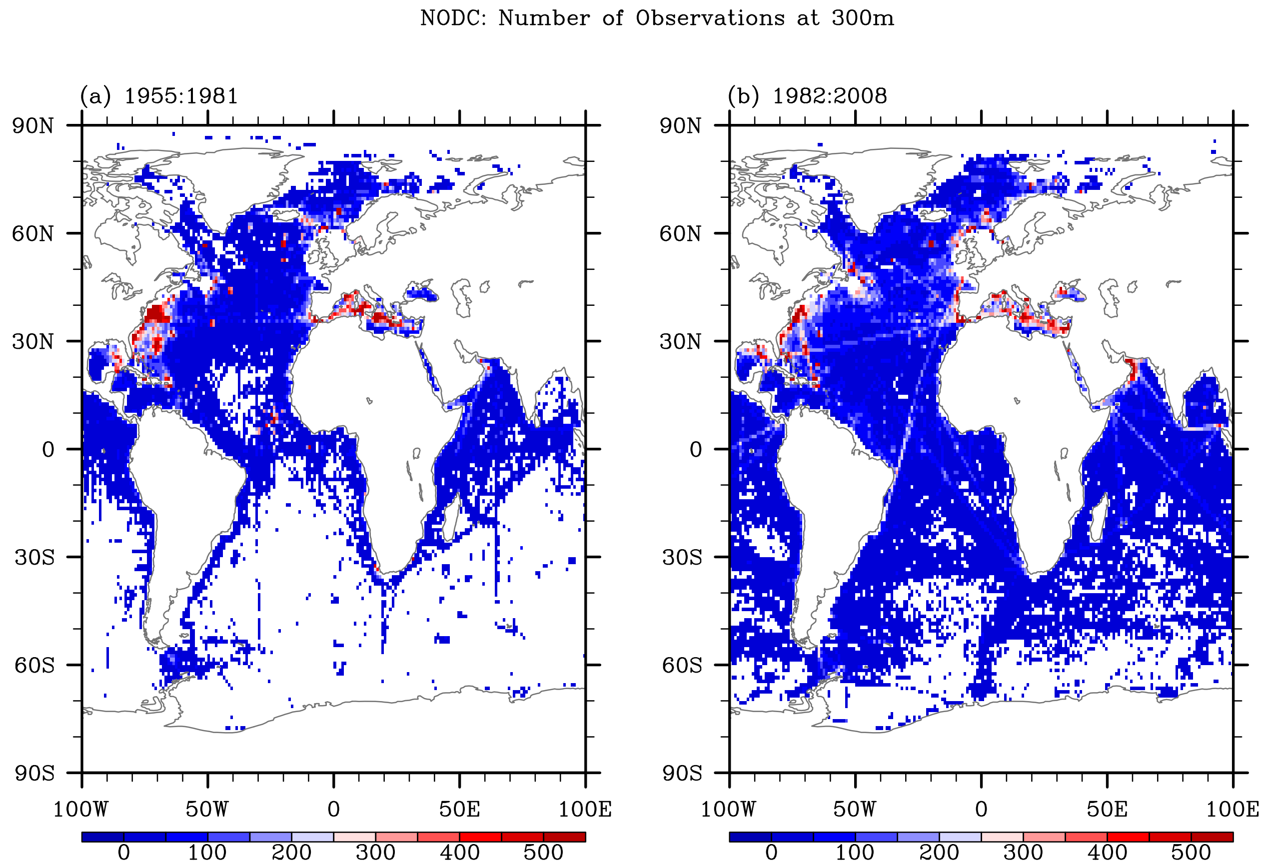

Figure A3. Number of total observations at 300m during (a) 1955-1981 and (b) 1982-2008 for each $1^o \times 1^o$ grid box obtained from NODC. The regions with less than five observations for the given 27-year periods are marked with white color.

Figure A4 shows the linear trend of the ocean heat content in the upper 700 m between 1955 and 2008 obtained from (a) the control simulation (EXP_CTR) and (b) observations (NODC). In Figure A4b, the observed trends in the regions with less than five observations at 300m during 1955-1981 or during 1982-2008 are marked with white color. The model experiment (EXP_CTR) successfully reproduces a large warming trend in the observations over the Gulf Stream region around 40^oN. The model shows a similar large warming trend immediately south of the South Atlantic Ocean around 40^oS, which cannot be validated due to lack of observations around that region.

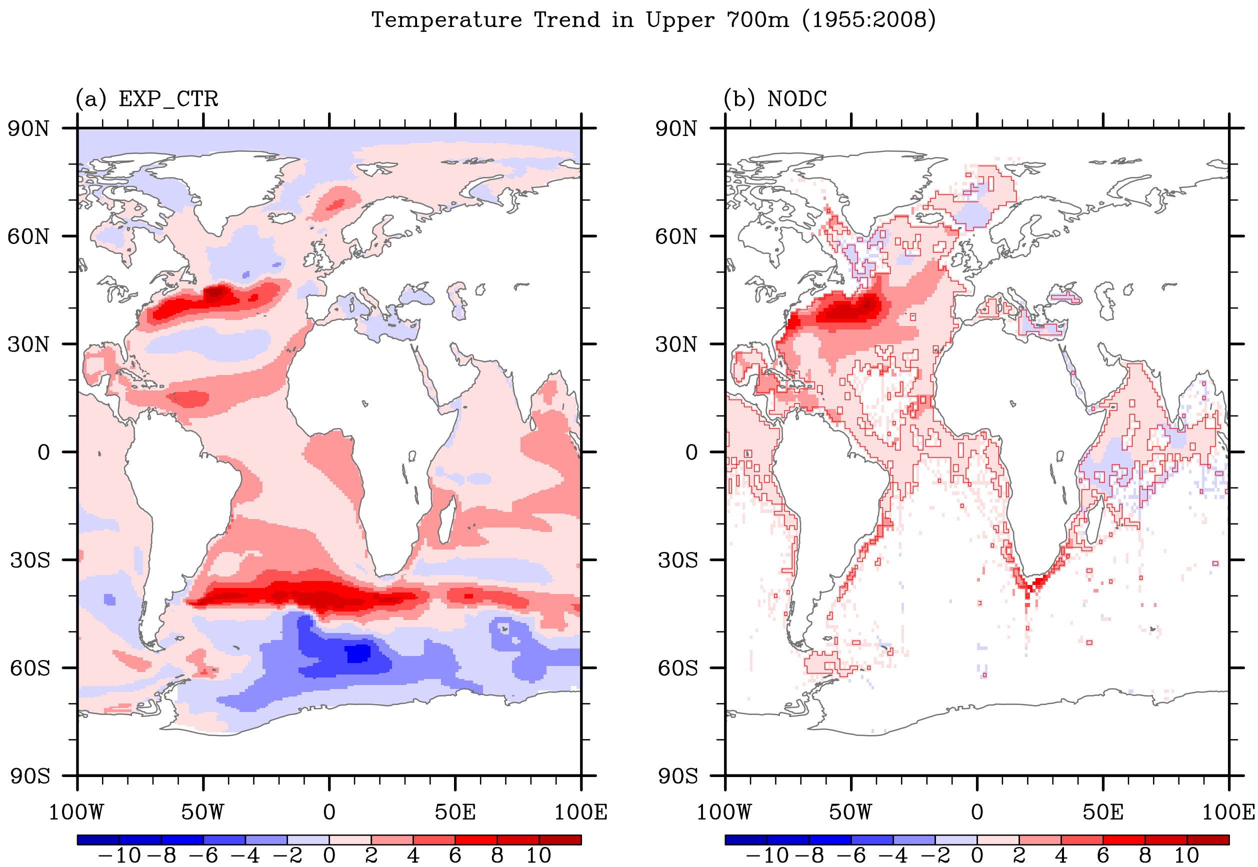

Figure A4. Linear trend of the ocean heat content in the upper 700m between 1955 and 2008 obtained from (a) the control simulation (EXP_CTR) and (b) observations (NODC). In (b), the observed trends in the regions with less than five observations at 300m during 1955-1981 or during 1982-2008 are marked with white color.

Since it is hard to perform a comprehensive model-data comparison away form the Gulf Stream region, we feel that Figure A4 is not very informative to include in the manuscript.

4, *Recent observational study [Boning et al. 2008] shows that the transport in the Antarctic Circumpolar Current (ACC) and the meridional overturning in the Southern Ocean are INSENSITIVE to the intensification of Southern Hemisphere westerly winds over the past decades, in contrast to coarse-resolution model studies. In contrast, the streamfunction change shown in Fig. S2(b) of the manuscript suggests that the ACC is increased in response to the intensification of Southern Hemisphere westerly winds. The manuscript should cite this relevant paper and discuss the discrepancy.*

Boning et al. 2008, The response of the Antarctic Circumpolar Current to recent climate change, Nature Geoscience, 1, 864-869.

Boning et al. [2008] is now cited and discussed in section 7. Now, we also add the following sentence about the limitation of this study in section 7: “Therefore, we fully acknowledge that the simulated AMOC increase at 30^{o}S during the 1950s – 2000s could be an overestimate.”

5, *In a recent paper [Farneti and Delworth, 2010] shows that in the fine-resolution eddy-permitting model, the AMOC change induced by changes in southern hemisphere westerly winds is greatly reduced compared with simulations in the coarse-resolution model, because changes in poleward eddy fluxes largely compensate for the enhanced northward Ekman transport in the Southern Ocean. The manuscript should cite this relevant paper and discuss the discrepancy.*

Farneti, R., and T. L Delworth, 2010: The role of mesoscale eddies in the remote oceanic response to altered Southern Hemisphere winds. Journal of Physical Oceanography, 40, doi:10.1175/2010JPO4480.1.

Farneti and Delworth [2010] is now cited and discussed. Limitations in our model simulation are also stated in section 7.

6, *The observation shows that the Atlantic ocean has warmed more than the Pacific ocean since the mid-20th century. However, this can also be caused partially by other factors, such as the low frequency variability presented in the Pacific ocean (PDO) which leads to a broad cooling over the north central and western Pacific since 1976.*

Potential impact of PDO on the differential inter-ocean warming is now mentioned in section 7.

7, *The simulated AMOC index (Fig. 2b) is inconsistent with the phase of the observed Atlantic Multidecadal Oscillations (AMO) index which often thought to be positively correlated with the AMOC.*

If we define the AMO as the low-frequency North Atlantic SST, the AMO contains both secular trend and multidecadal signal (Figure A2a). The multidecadal signal of the AMO is largely restricted in the North Atlantic and probably driven from the North Atlantic sinking regions. As discussed earlier, we think that the simulated AMOC at 30^{o}S (Figure 2b) largely contributes to the secular trend of the AMO, not the multidecadal signal. Therefore, we think that the simulated AMOC at 30^{o}S does not have to be correlated with the multidecadal signal of the AMO. This issue is discussed in section 7.

8, *Page 10, Line 9-11, the manuscript states that the results are in agreement with the observations of inter-ocean transport [Biastoch et al. 2009]. However, the observational data (altimetry SSH) used in Biastoch et al. [2009] is very short, only from 1995 to 2004, can not be used to judge the simulated change since mid-20th century.*

"Observation" is now removed from this sentence.