Have Aerosols Caused the Observed Atlantic Multidecadal Variability?

Rong Zhang[1], Thomas L. Delworth[1], Rowan Sutton[2], Daniel L. R. Hodson[2], Keith W. Dixon[1], Isaac M. Held[1], Yochanan Kushnir[3], John Marshall[4], Yi Ming[1], Rym Msadek[1], Jon Robson[2], Anthony J. Rosati[1], MingFang Ting[3], Gabriel A. Vecchi[1]

[1]GFDL, NOAA, Princeton, NJ, USA

[2]NCAS-Climate, Dept. of Meteorology, University of Reading, Reading, UK

[3]Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY, USA

[4]Dept. of Earth, Atmospheric and Planetary Sciences, MIT, Cambridge, MA, USA

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[1]Corresponding author address: Rong Zhang, GFDL, NOAA, Princeton, NJ 08540. Email: Rong.Zhang@noaa.gov

Abstract

Identifying the prime drivers of the twentieth-century multidecadal variability in the Atlantic Ocean is crucial for predicting how the Atlantic will evolve in the coming decades and the resulting broad impacts on weather and precipitation patterns around the globe. Recently Booth et al (2012) showed that the HadGEM2-ES climate model closely reproduces the observed multidecadal variations of area-averaged North Atlantic sea surface temperature in the 20th century. The multidecadal variations simulated in HadGEM2-ES are primarily driven by aerosol indirect effects that modify net surface shortwave radiation. On the basis of these results, Booth et al (2012) concluded that aerosols are a prime driver of twentieth-century North Atlantic climate variability. However, here it is shown that there are major discrepancies between the HadGEM2-ES simulations and observations in the North Atlantic upper ocean heat content, in the spatial pattern of multidecadal SST changes within and outside the North Atlantic, and in the subpolar North Atlantic sea surface salinity. These discrepancies may be strongly influenced by, and indeed in large part caused by, aerosol effects. It is also shown that the aerosol effects simulated in HadGEM2-ES cannot account for the observed anti-correlation between detrended multidecadal surface and subsurface temperature variations in the tropical North Atlantic. These discrepancies cast considerable doubt on the claim that aerosol forcing drives the bulk of this multidecadal variability.

1 Introduction

The observed 20th century multidecadal variations of area-averaged North Atlantic sea surface temperature (NASST) exhibit significant regional and hemispheric climate associations (Enfield et al. 2001; Sutton and Hodson, 2005; Knight et al. 2006; Zhang and Delworth, 2006; Zhang et al. 2007; Kushnir and Stein, 2010; Ting et al., 2011; Sutton and Dong, 2012). These variations are highly correlated with the multidecadal variations of the tropical North Atlantic SST and Atlantic hurricane activity (Goldenberg et al. 2001; Knight et al. 2006; Zhang and Delworth, 2006). In particular, tropical North Atlantic surface warming coincided with above-normal Atlantic hurricane activity during the 50-60's and the recent decade. These multidecadal NASST variations are often thought to be associated with Atlantic meridional overturning circulation (AMOC) variability (Delworth and Mann, 2000; Latif et al. 2004; Knight et al. 2005). On the other hand, some authors have suggested that they are at least in part driven by changes in the radiative forcing (Mann and Emanuel, 2006; Villarini and Vecchi, 2012). Various approaches have been proposed for quantitative attribution of NASST variations to a radiatively forced part and a part arising from AMOC variability (Kravtsov and Spannagle 2008; Ting et al. 2009; Zhang and Delworth 2009; Delsole et al. 2011; Wu et al. 2011; Terray 2012), and they show consistently that the role of internal variability cannot be ignored in multidecadal NASST variations.

Recently Booth et al 2012 (B12) showed that the HadGEM2-ES (Jones et al. 2011) climate model closely reproduces the amplitude and phase of the observed multidecadal variations of area-averaged NASST, especially over the 2nd half of the 20th century (Fig. 1). The multidecadal variations simulated in HadGEM2-ES are primarily driven by aerosol indirect effects that modify net surface shortwave radiation. On the basis of these results, B12 concluded that aerosols are a primary source of this multidecadal variability. However, B12 only compared the evolution of modeled and observed area-averaged NASST. In this study we show that there are major discrepancies between the HadGEM2-ES simulations and many observed changes in the North Atlantic. The discrepancies cast doubt upon the main conclusion of B12.

In section 2, the analysis methods and data used in this study are described. In sections 3-6 we compare the HADGEM2-ES simulations with observations over a range of variables. The purpose of these comparisons is to assess more completely how well the HADGEM2-ES simulations actually replicate the observed evolution of the North Atlantic over the 20th century. In section 3 we examine North Atlantic upper ocean heat content. In section 4 we examine the spatial patter of multidecadal SST changes. In section 5 we examine sea surface salinity (SSS) in the North Atlantic. In section 6 we examine subsurface temperature anomalies in the Tropical North Atlantic (TNA). Our conclusion is presented in section 7.

2 Description of Method and Data

In this study, the observed upper ocean heat content is derived from a yearly averaged dataset of objectively analyzed ocean temperature anomalies since 1955 (Levitus et al. 2009). The observed SSS data are from the pentadally averaged dataset of objectively analyzed ocean salinity anomalies since 1957 (Boyer et al. 2005). The observed SST is based on the HADISST dataset since 1871 (Rayner et al. 2003). The ensemble of four HadGEM2-ES historical simulations with all external forcing ("All Forcings") used in B12 are downloaded from the CMIP5 model output archive at http://cmip-gw.badc.rl.ac.uk. The ensemble of three "Constant Aerosols" HadGEM2-ES historical simulations (same as the first three members of the "All Forcings" except that anthropogenic aerosol emissions are fixed at 1860 levels) was provided to us by Ben Booth and Paul Halloran from the Met Office Hadley Centre (MOHC). We assume linearity in the sense that the ensemble mean difference (first three members) between "All Forcings" and "Constant Aerosols" HadGEM2-ES historical simulations is assumed to represent the net response to anthropogenic aerosols.

3 North Atlantic Upper Ocean Heat Content

Substantial warming trends in the upper ocean heat content have been observed in most ocean basins since the middle of the 20th century (Domingues et al. 2008; Levitus et al. 2009). Gleckler et al. (2012) using multiple observations (Domingues et al. 2008; Ishii and Kimoto 2009; Levitus et al. 2009) and external forced and unforced simulations from phase 3 of the Coupled Model Intercomparison Project (CMIP3), shows that the observed warming trend of upper ocean heat content in the North Atlantic (and other basins) over the second half of the 20th century is typically consistent with the response in these CMIP3 models to the sum of all external forcing. The results suggest that changes in anthropogenic forcing (especially increasing greenhouse gases) play an important role in the observed upper ocean warming trend.

In contrast to the observed heat content increase, the All Forcings HadGEM2-ES historical simulations exhibit no trend in the area-averaged North Atlantic upper ocean heat content (0-700m) between 1955 and 2004 (Fig. 2). The observed warming trend ($0.599 \times 10^{22} J/decade$) for the period of 1955-2004 is clearly inconsistent with the modeled trend (Fig. 2). Over the same period, the simulated trends for individual All Forcings ensemble members range from a minimum of $-0.141 \times 10^{22} J/decade$ to a maximum of $0.118 \times 10^{22} J/decade$, all much smaller than that observed. The HadGEM2-ES All Forcings simulations, which have strong aerosol effects, suggest that there is no net radiatively forced warming in the North Atlantic upper ocean over the 2nd half of the 20th century.

Using a different model (GFDL CM2.1), Delworth et al. (2005) shows that the surface waters cooled by aerosol effects can penetrate into the subsurface ocean through subduction, and persist in the subsurface for decades, thereby offsetting subsequent greenhouse gas induced subsurface warming. The cooled surface waters can reduce vertical stratification in the ocean thus have higher subduction rates (Marshall and Nurser, 1992). In HadGEM2-ES, over the 2nd half of the 20th century, the simulated subsurface aerosol induced-cooling is evidently so strong that it counteracted the subsurface greenhouse gas induced warming, resulting in a net subsurface cooling in the North Atlantic. The subsurface cooling lags the surface response by decades and even persists into the 1990's (not shown). On the contrary, in observations the subsurface temperature is dominated by warm anomalies over this period (Domingues et al. 2008; Ishii and Kimoto 2009; Levitus et al 2009).

In the ensemble-mean of the All Forcings HadGEM2-ES simulations, the simulated subsurface cooling trend offsets the surface warming trend, so there is almost no net heat content change integrated over the North Atlantic upper ocean (0-700m) for the 2nd half of the 20th century. In contrast, the ensemble of Constant Aerosols HadGEM2-ES historical simulations shows a clear warming trend in the North Atlantic upper ocean heat content (Fig. 2). In B12, the Constant Aerosols simulations are compared with All Forcings simulations to demonstrate the important role of anthropogenic aerosols in NASST. Here the comparison between these two sets of simulations also shows the important role of anthropogenic aerosols in causing the discrepancy between simulated and observed trends in the North Atlantic upper ocean heat content. This discrepancy with observations suggests that the aerosol effects are strongly overestimated over the North Atlantic in HadGEM2-ES.

4 Spatial Pattern of Multidecadal SST Changes

The pattern of SST changes associated with the prominent cooling of NASST that occurred in the late 1960s and 1970s is distinctly different in the HadGEM2-ES All Forcings simulations from that seen in observations, both within and outside the North Atlantic (Fig. 3a,b). The observed cooling is most pronounced in the subpolar and mid-latitude North Atlantic, while the model shows a more extensive cooling in the tropical North Atlantic than seen in observations. The observed abrupt cooling in the early 70's has the largest amplitude in the subpolar North Atlantic (Thompson et al. 2010) and coincided with a rapid freshening of the subpolar North Atlantic referred to as the "great salinity anomaly" (Dickson et al. 1988). This observed cooling in the subpolar North Atlantic is largely underestimated in HadGEM2-ES All Forcings simulations.

Outside the North Atlantic, the HadGEM2-ES All Forcings simulations show excessive cooling in the Barents Sea, North Pacific, tropical South Atlantic, Indian Ocean, and Southern Ocean compared to that observed (Fig. 3a,b). The net response to anthropogenic aerosols (Fig. 3c, difference between All Forcings and Constant Aerosols) is multidecadal cooling in most ocean basins. In contrast, the observed multidecadal SST changes are characterized by a dipole pattern in the Atlantic, suggestive of an important role for variations in the AMOC and related variations in Atlantic heat transport (Zhang and Delworth, 2005; Ting et al. 2009; Robson et al. 2012).

This discrepancy is also reflected in the 10-year low-pass filtered time series of SST anomalies averaged over the North Atlantic versus those averaged over the rest of the world ocean (Fig. 4). In observations, the low-pass filtered North Atlantic SST anomaly is characterized by a pronounced multidecadal variability, whereas the low-pass filtered SST anomaly averaged over the rest of the world ocean is dominated by an increasing trend with much weaker multidecadal variability (Fig. 4a). In particular, for the period of 1961-1980, although the observed North Atlantic SST was colder than the previous period of 1941-1960, the observed SST averaged over the rest of the world ocean did not exhibit a cooling (Fig. 4a). However, in the HadGEM2-ES All Forcings simulations, the low-pass filtered SST anomaly averaged over the rest of the world ocean shows a strong multidecadal variability, and the abrupt post-1960 cooling simulated in the North Atlantic SST is also present in the SST averaged over the rest of the world ocean (Fig. 4b). Although the simulated low-pass filtered North Atlantic SST anomaly resembles the observations (Fig. 4c), the simulated low-pass filtered SST anomaly averaged over the rest of the world ocean is quite different from the observations (Fig. 4d). The observed low-pass filtered SST anomaly averaged over the rest of the world ocean is outside the simulated ensemble spread for most of the 20th century (Fig. 4d). The results consistently suggest that the time-varying aerosols in HADGEM2-ES All Forcings simulations induce an unrealistic global scale multidecadal variability.

5 Subpolar North Atlantic Sea Surface Salinity anomalies

The simulation of the subpolar North Atlantic sea surface salinity (SSS) in the HadGEM2-ES All Forcings simulations also shows important differences to observations. In observations the subpolar North Atlantic SSS anomalies exhibit multidecadal variations that are coherent and in phase with variations in basin-mean and subpolar NASST (Fig. 5), with no long-term trend. In contrast, the subpolar North Atlantic SSS simulated in HadGEM2-ES shows a salinification trend, as well as variations that are largely out of phase with the observed subpolar NA SSS and also out of phase with the simulated basin-mean NASST variations over the second half of the 20th century (Fig. 5 and Fig. 4c). The simulated salinification trend in the subpolar North Atlantic is consistent with the response to aerosol forcing as shown in a previous study using GFDL CM2.1 (Delworth and Dixon 2006). The Constant Aerosols ensemble shows no significant salinification trend at the surface in the subpolar North Atlantic (Fig. 5), and the mean value of subpolar North Atlantic SSS over the period 1871-2000 is 0.2 PSU lower in Constant Aerosols simulations than that in All Forcings simulations, consistent with this interpretation.

The subpolar SSS changes are directly linked to changes in deep water formation and large-scale ocean circulation (Curry et al. 1998). The discrepancies in subpolar North Atlantic SSS again suggest the aerosol effects are strongly overestimated in HadGEM2-ES. In contrast, the observed coherent relationships between subpolar North Atlantic SSS/SST and basin-mean NASST variations are consistent with the notion that the AMOC plays an important role in the Atlantic multidecadal variability, as suggested by a number of climate model based studies (Delworth, et al. 1997; Robson et al. 2012).

6 Detrended Tropical North Atlantic Subsurface Temperature Anomalies

Zhang (2007b) showed that the observed multidecadal variations of Tropical North Atlantic (TNA) SST are strongly anticorrelated with those of TNA subsurface ocean temperature, with long-term trends removed. Therefore, mechanisms that are proposed to explain the observed multidecadal TNA SST variations should also be consistent with the observed anticorrelations between TNA surface and subsurface temperature variations. Further, we note that model results in Zhang (2007b) suggest that this out of phase relationship between surface and subsurface ocean temperature in the Tropical North Atlantic is a distinctive feature of AMOC variations.

Here we apply the same analyses as in Zhang (2007b) to the linear detrended TNA SST anomalies and subsurface temperature anomalies from the HadGEM2-ES All Forcings ensemble. The analyses here are not aimed to the question whether aerosol effects have been overestimated in the HadGEM2-ES, thus are different from the other discrepancies discussed in Section 3-5. The analyses in this Section are to test the hypothesis that the aerosol mechanism can account for the observed anticorrelation between the detrended TNA surface and subsurface temperature variations. The analyses are compared with the detrended observations and the ensemble of water hosing experiments using a CMIP3 coupled climate model (GFDL CM2.1, Delworth et al. 2006). In the ensemble of water hosing experiments, a strong freshwater flux anomaly is uniformly distributed over the subpolar North Atlantic for 60 years, and the AMOC weakens gradually in response. The changes in TNA temperature (surface and subsurface) in response to the freshwater forcing are indicative of the AMOC effects in the TNA. There is no need for detrending for the ensemble of water hosing experiments, as all radiative forcings are held constant in this ensemble.

As shown in Zhang (2007b), in the water hosing experiments the AMOC-induced anticorrelated changes between the TNA surface and subsurface temperature are clearly apparent in the spatial regression pattern of surface and subsurface temperature anomalies onto the TNA SST anomaly (Fig. 6a,d). The detrended observations also show anticorrelated changes, i.e. positive regression coefficients over most of the TNA surface and negative regression coefficients over most of the TNA subsurface (Fig. 6b,e). In contrast, the ensemble mean detrended results from the HadGEM2-ES All Forcings simulations show positive regression coefficients over the surface TNA, but almost no signals over most of the subsurface TNA (Fig. 6c,f). The vertical structure of the regression of the TNA ocean temperature anomalies onto the TNA SST anomaly (Fig. 6g,h,i) shows similar results. The TNA SST anomalies induced by aerosol forcing could slowly diffuse or subduct into the subsurface, but there is no obvious mechanism by which the time-varying aerosol forcing could give rise to subsurface temperature changes of opposite polarity to the SST anomalies on these time scales. Hence aerosol effects simulated in this All Forcings ensemble cannot account for the anticorrelated multidecadal SST and subsurface temperature variations in the detrended observations for the TNA.

In water hosing experiments, two dominant processes are excited rapidly by the AMOC weakening - surface southward displacements of the Atlantic ITCZ and subsurface thermocline deepening through the propagation of oceanic waves. These processes act together to produce opposite changes between the TNA surface and subsurface temperature (Zhang, 2007b). Similar AMOC-induced anticorrelated surface and subsurface TNA variations have also been found in NCAR CCSM3 coupled model simulations (Chiang et al. 2008). A recent study using high-resolution temperature records of the last deglacial transition from a southern Caribbean sediment core also shows that warmer subsurface temperatures correspond to colder surface temperatures and a weaker AMOC during the Younger Dryas (Schmidt et al. 2012). The analyses here suggest that the observed anticorrelated multidecadal TNA SST and subsurface temperature variations are consistent with the mechanism of AMOC variations, and inconsistent with the dominance of changes in aerosols. For example, during the 70-80's, the observed detrended TNA surface cooling and subsurface warming is consistent with a weaker strength of the AMOC when the Labrador Sea deep water formation was substantially reduced due to the "great salinity anomaly" events (Curry et al. 1998).

We have shown here that out of phase temperature variations are seen between the surface and subsurface in the TNA for both observations and in model simulations of AMOC changes. In contrast, this out of phase behavior is not seen in the HADGEM2-ES simulations. This suggests that the aerosol mechanism cannot account for the observed anticorrelated multidecadal TNA SST and subsurface temperature variations, regardless of whether the aerosol effects are overestimated. This discrepancy is inconsistent with the interpretation that aerosol forcing drives the bulk of the observed Atlantic multi-decadal variability.

7 Conclusions

In this paper we have tried to present a broad, multivariate comparison between the observed changes and those simulated in the HADGEM2-ES model. In this comparison, we have included not only SST in the North Atlantic, but also sea surface salinity and subsurface ocean temperature, as well as the vertical structure of temperature variations.

In summary, key aspects of the HadGEM2-ES simulation exhibit substantial discrepancies with observations. Discrepancies are seen in the North Atlantic upper ocean heat content, in the spatial pattern of multidecadal SST changes within and outside the North Atlantic, and in the subpolar North Atlantic sea surface salinity. These discrepancies are largely attributable to what appears to be excessively strong aerosol effects. It is also shown that the aerosol effects simulated in the HadGEM2-ES All Forcings ensemble cannot account for the anticorrelated multidecadal SST and subsurface temperature variations of the detrended observations for the tropical North Atlantic.

Anthropogenic and natural aerosols have likely played some role in forcing the observed Atlantic multidecadal variability (Evan et al. 2009; Chang et al. 2011; Villarini and Vecchi, 2012), and understanding the magnitude of their influence on the North Atlantic SSTs remains a key challenge. Aerosol indirect effects remain poorly understood owing to difficulties in representing sub-grid cloud processes in global climate models (Lohmann et al. 2010). The discrepancies pointed out in this paper call into question the claim of B12 that aerosols have been a dominant forcing of observed Atlantic multidecadal variability and the realism of the HadGEM2-ES simulations of the aerosol influence on North Atlantic SST.

We single out the HadGEM2-ES model for this critique to counterbalance the claims in Booth et al (2012) for the dominance of aerosol forcing for multi-decadal Atlantic variability. Whether it is possible for a model to exhibit comparably large indirect aerosol effects without the inconsistencies with observations outlined here remains to be seen.

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Figure Captions

1. Area-averaged North Atlantic SST (NASST) Anomaly (75-7.5°W, 0-60°N), adapted from Fig. 1b in Booth et al. (2012). Red Line: ensemble mean of HadGEM2-ES historical simulations with all external forcing ("All Forcings"). Black Line: Observations (HadISST). Orange shading: 1 std of ensemble spread of HadGEM2-ES All Forcings. All anomalies are relative to 1871-2000 mean.

2. North Atlantic upper ocean heat content anomaly. Red line: area-averaged North Atlantic upper ocean heat content anomaly (0-700m, 75-7.5°W, 0-60°N) from ensemble mean of HadGEM2-ES All Forcings simulations. Yellow shading: 1 std of ensemble spread of All Forcings. Green Line: ensemble mean from Constant Aerosols historical simulations. Black Line: observations. All anomalies are relative to 1955-2004 mean. The dash lines are linear trends for the respective variables. The 1955-2004 trend is $0.599 \times 10^{22} J/decade$ for observations and $0.003 \times 10^{22} J/decade$ for HadGEM2-ES All Forcings ensemble mean.

3. SST differences between the North Atlantic cold period (1961-1980) and the North Atlantic warm period (1941-1960). (a) Observations (b) HadGEM2-ES All Forcings ensemble mean (c) Ensemble mean difference between HadGEM2-ES All Forcings and Constant Aerosols.

4. Comparison of 10-Year low-pass filtered NASST anomaly (blue) with 10-Year low-pass filtered SST anomaly averaged for the Rest of the World Ocean (red). (a) Observations (HadISST) (b) ensemble mean of HadGEM2-ES All Forcings. Green shading: 1 std of ensemble spread for low-pass filtered NASST anomaly; yellow shading: 1 std of ensemble spread for low-pass filtered SST anomaly averaged for the Rest of the World Ocean. (c) low-pass filtered NASST anomaly from HadGEM2-ES All Forcings (blue) and observations (blue dash line) (d) low-pass filtered SST anomaly averaged for the Rest of the World

Ocean from HadGEM2-ES All Forcings (red) and observations (red dash line). The color shadings in (c,d) are the same as in (b).

5. Subpolar North Atlantic SSS anomaly (60°W-0°E, 50-65°N). Red Line: subpolar North Atlantic SSS anomaly from ensemble mean of HadGEM2-ES All Forcings simulations; Blue Line: subpolar North Atlantic SSS anomaly from ensemble mean of HadGEM2-ES Constant Aerosols simulation. Black Line: observed subpolar North Atlantic SSS anomaly (pentadally averaged), relative to 1957-2000 mean. Yellow Line: observed subpolar North Atlantic SST anomaly, relative to 1871-2000 mean. Green Line: observed North Atlantic basin-averaged NASST anomaly, relative to 1871-2000 mean. Thin red line: marking the 0.2PSU difference in the climatological mean subpolar North Atlantic SSS over the entire period 1871-2000 between HadGEM2-ES All Forcings and Constant Aerosols.

6. Regression coefficients of SST anomaly (a,b,c), subsurface ocean temperature anomaly (z=400) (d,e,f), and averaged Tropical North Atlantic (TNA) ocean temperature anomaly at different depths (g,h,i) onto the time series of the TNA SST anomaly, corresponding to 1 standard deviation of the TNA SST anomaly. (a, d, g) ensemble mean from water hosing experiments using GFDL CM2.1, year 1-60. (b, e, h) Using 10-year low-pass filtered observed data (OBS, 1955-2000) (c, f, i) Using 10-year low-pass filtered modeled ensemble mean from HadGEM2-ES All Forcings simulations, 1955-2000. The long-term trends have been removed for OBS and HadGEM2-ES. The brown box shows the TNA domain (0-14°N and 70°W-0°E) that is used for area average. (g,h,i) are normalized by the maximum absolute value of each regression respectively, and the green shading covers depths that are not statistically significant at the 90% level of non-zero correlation using the 2-tailed Student's *t*-test.

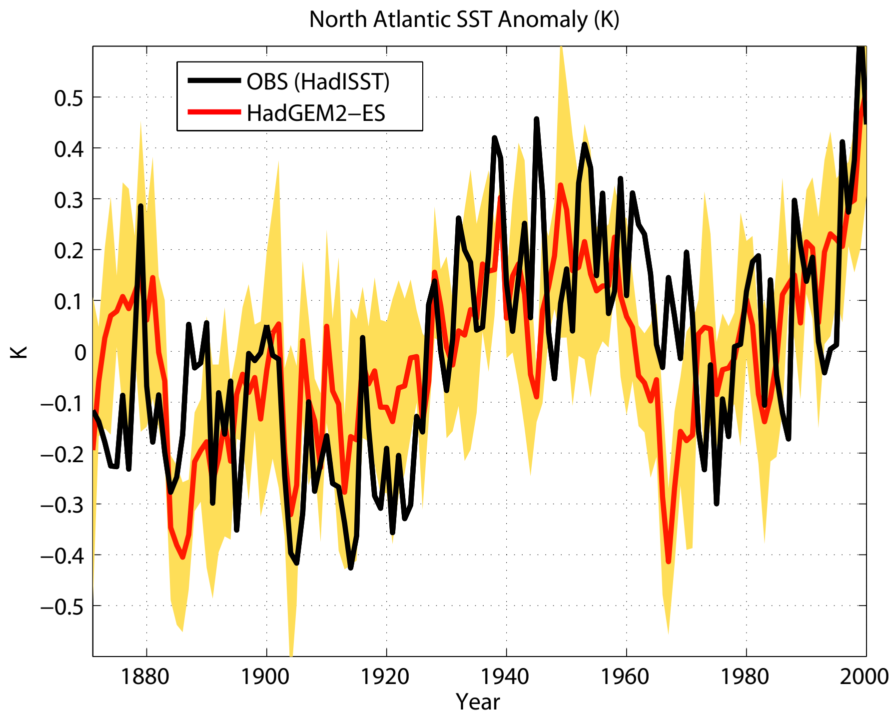

Figure 1: Area-averaged North Atlantic SST (NASST) Anomaly (75-7.5°W, 0-60°N), adapted from Fig. 1b in Booth et al. (2012). Red Line: ensemble mean of HadGEM2-ES historical simulations with all external forcing ("All Forcings"). Black Line: Observations (HadISST). Orange shading: 1 std of ensemble spread of HadGEM2-ES All Forcings. All anomalies are relative to 1871-2000 mean.

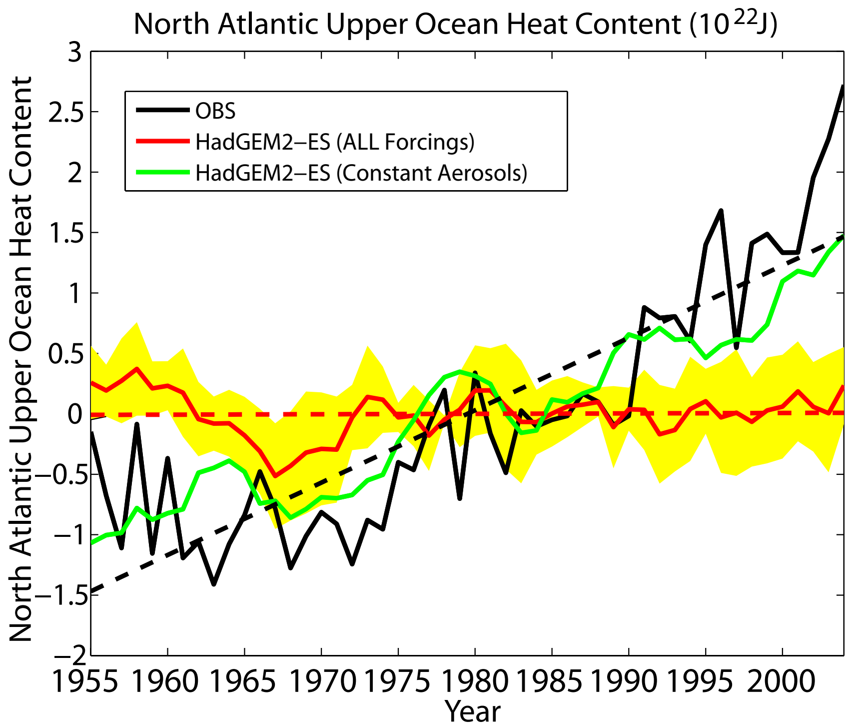

Figure 2: North Atlantic upper ocean heat content anomaly. Red line: area-averaged North Atlantic upper ocean heat content anomaly (0-700m, 75-7.5°W, 0-60°N) from ensemble mean of HadGEM2-ES All Forcings simulations. Yellow shading: 1 std of ensemble spread of All Forcings. Green Line: ensemble mean from Constant Aerosols historical simulations. Black Line: observations. All anomalies are relative to 1955-2004 mean. The dash lines are linear trends for the respective variables. The 1955-2004 trend is $0.599 \times 10^{22} J/decade$ for observations and $0.003 \times 10^{22} J/decade$ for HadGEM2-ES All Forcings ensemble mean.

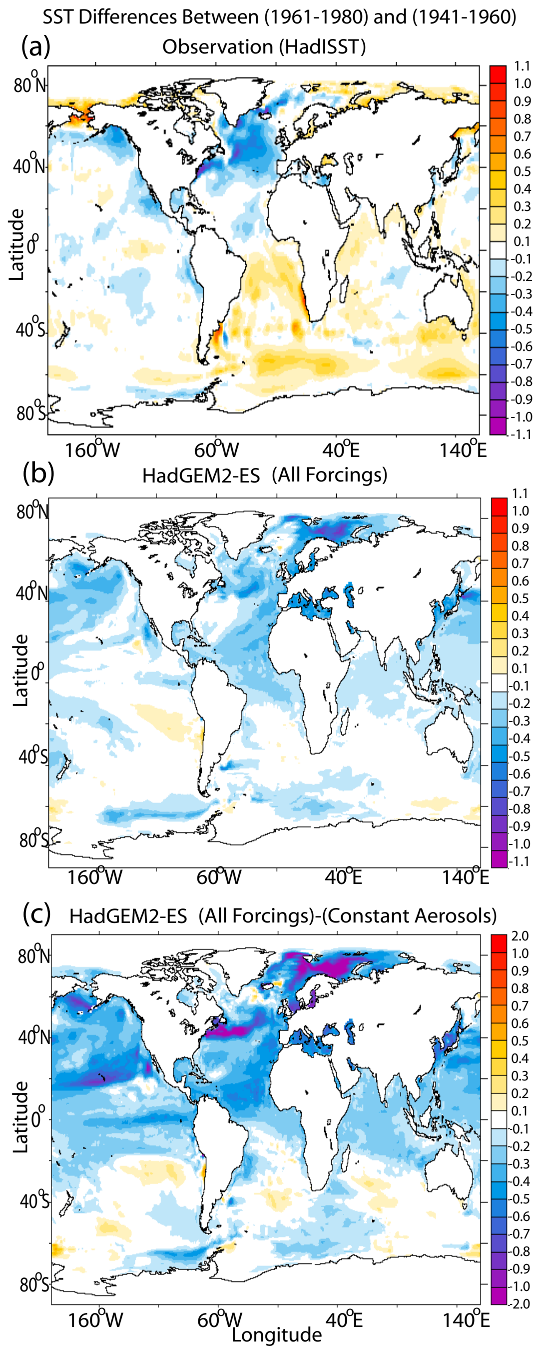

Figure 3: SST differences between the North Atlantic cold period (1961-1980) and the North Atlantic warm period (1941-1960). (a) Observations (b) HadGEM2-ES All Forcings ensemble mean (c) Ensemble mean difference between HadGEM2-ES All Forcings and Constant Aerosols.

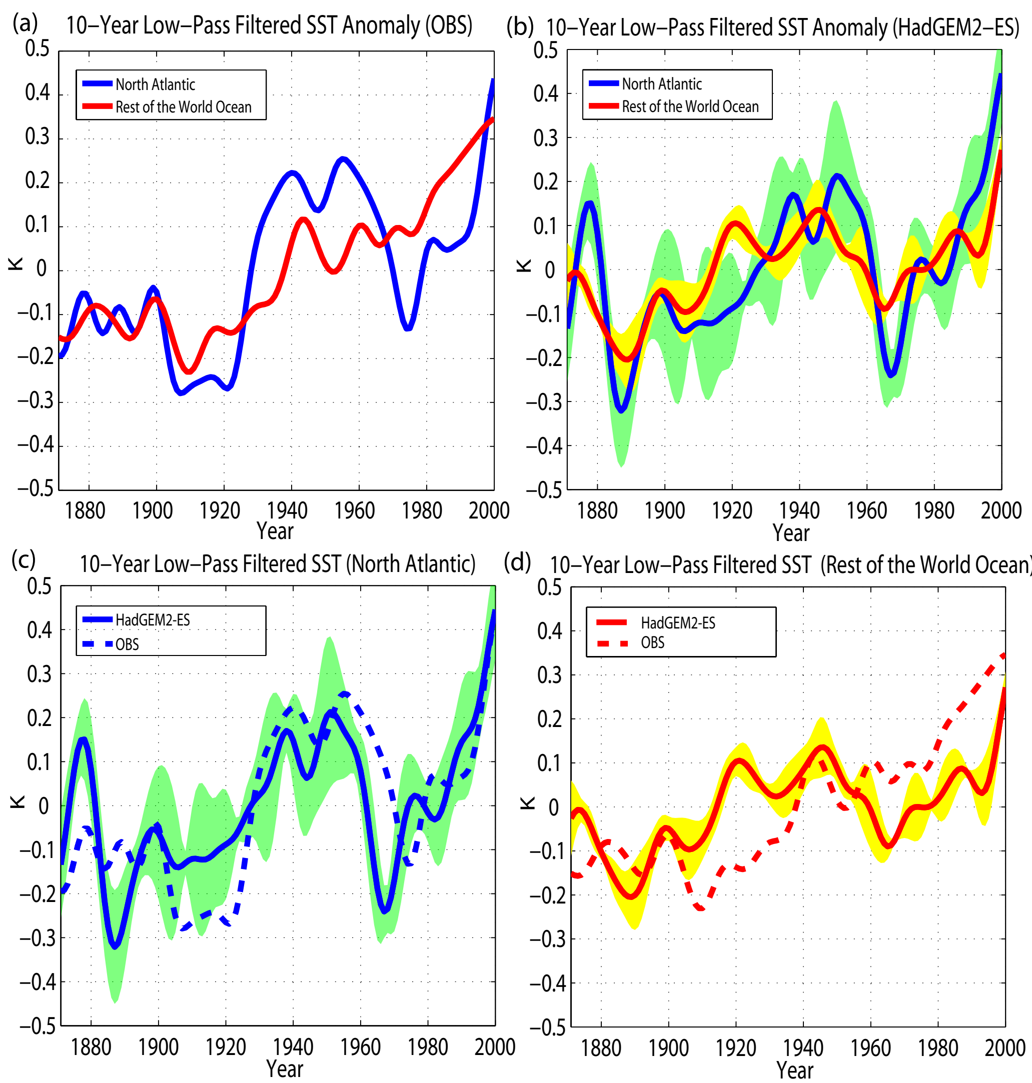

Figure 4: Comparison of 10-Year low-pass filtered NASST anomaly (blue) with 10-Year low-pass filtered SST anomaly averaged for the Rest of the World Ocean (red). (a) Observations (HadISST) (b) ensemble mean of HadGEM2-ES All Forcings. Green shading: 1 std of ensemble spread for low-pass filtered NASST anomaly; yellow shading: 1 std of ensemble spread for low-pass filtered SST anomaly averaged for the Rest of the World Ocean. (c) low-pass filtered NASST anomaly from HadGEM2-ES All Forcings (blue) and observations (blue dash line) (d) low-pass filtered SST anomaly averaged for the Rest of the World Ocean from HadGEM2-ES All Forcings (red) and observations (red dash line). The color shadings in (c,d) are the same as in (b).

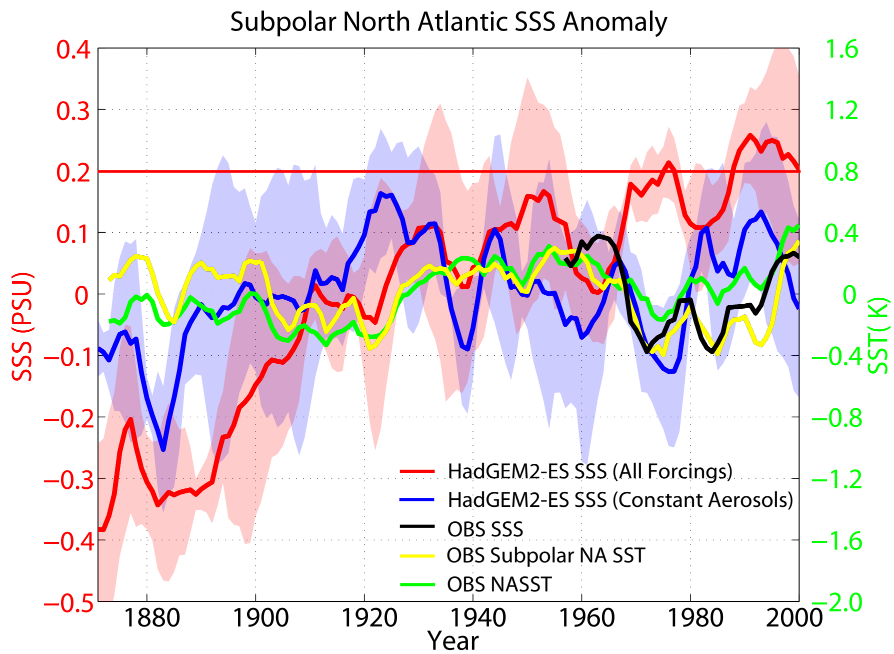

Figure 5: Subpolar North Atlantic SSS anomaly (60°W-0°E, 50-65°N). Red Line: subpolar North Atlantic SSS anomaly from ensemble mean of HadGEM2-ES All Forcings simulations; Blue Line: subpolar North Atlantic SSS anomaly from ensemble mean of HadGEM2-ES Constant Aerosols simulation. Black Line: observed subpolar North Atlantic SSS anomaly (pentadally averaged), relative to 1957-2000 mean. Yellow Line: observed subpolar North Atlantic SST anomaly, relative to 1871-2000 mean. Green Line: observed North Atlantic basin-averaged NASST anomaly, relative to 1871-2000 mean. Thin red line: marking the 0.2PSU difference in the climatological mean subpolar North Atlantic SSS over the entire period 1871-2000 between HadGEM2-ES All Forcings and Constant Aerosols.

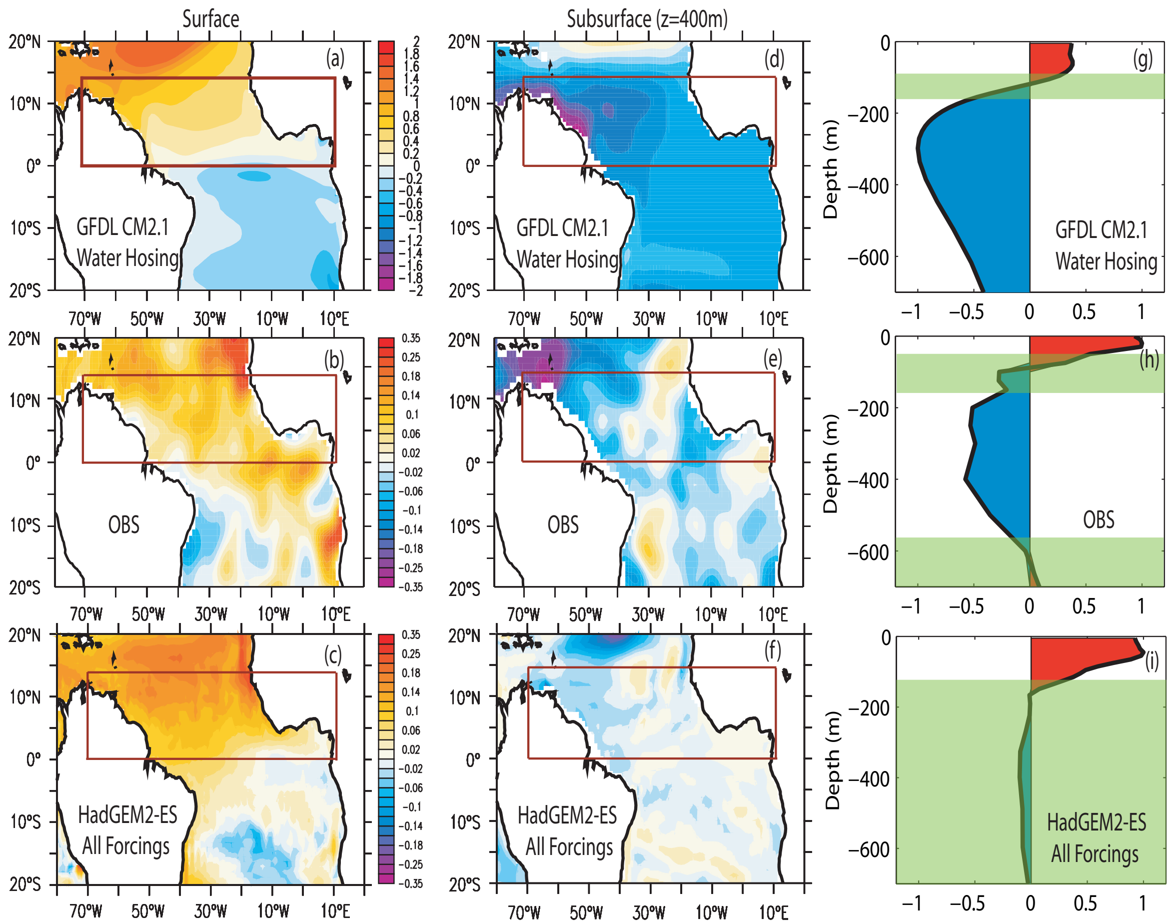

Figure 6: Regression coefficients of SST anomaly (a,b,c), subsurface ocean temperature anomaly (z=400) (d,e,f), and averaged Tropical North Atlantic (TNA) ocean temperature anomaly at different depths (g,h,i) onto the time series of the TNA SST anomaly, corresponding to 1 standard deviation of the TNA SST anomaly. (a, d, g) ensemble mean from water hosing experiments using GFDL CM2.1, year 1-60. (b, e, h) Using 10-year low-pass filtered observed data (OBS, 1955-2000) (c, f, i) Using 10-year low-pass filtered modeled ensemble mean from HadGEM2-ES All Forcings simulations, 1955-2000. The long-term trends have been removed for OBS and HadGEM2-ES. The brown box shows the TNA domain (0-14°N and 70°W-0°E) that is used for area average. (g,h,i) are normalized by the maximum absolute value of each regression respectively, and the green shading covers depths that are not statistically significant at the 90% level of non-zero correlation using the 2-tailed Student's *t*-test.