GEOPHYSICAL RESEARCH LETTERS, VOL. 35, L20705, doi:10.1029/2008GL035463, 2008

Coherent surface-subsurface fingerprint of the Atlantic meridional overturning circulation

Rong Zhang[1]

Received 24 July 2008; revised 16 September 2008; accepted 19 September 2008; published 24 October 2008.

[1] Satellite altimeter data shows a weakening of the North Atlantic subpolar gyre during the 1990s, which is thought as an indicator of a slowdown of the Atlantic meridional overturning circulation (AMOC). However, whether the recent slowing subpolar gyre is a decadal variation or a long-term trend remains unclear. Here I show that altimeter data is highly correlated with instrumental subsurface ocean temperature data in the North Atlantic, and both show opposite signs between the subpolar gyre and the Gulf Stream path. Such a dipole pattern is a distinctive fingerprint of AMOC variability, as shown for the first time by a 1000-year coupled ocean-atmosphere model simulation. The results suggest that, contrary to previous interpretations, the recent slowdown of the subpolar gyre is a part of a multidecadal variation and suggests a strengthening of the AMOC. The ongoing satellite and subsurface temperature measurements could be used to monitor future AMOC variations sensitively. **Citation:** Zhang, R. (2008), Coherent surface-subsurface fingerprint of the Atlantic meridional overturning circulation, *Geophys. Res. Lett.*, *35*, L20705, doi:10.1029/2008GL035463.

1. Introduction

[2] Monitoring the AMOC variability is crucial for assessing future rapid climate changes. Instantaneous surveys across 25°*N* indicate a long-term slowdown of the AMOC [*Bryden et al.*, 2005], but these snapshots could be aliased by large intra-annual variations [*Cunningham et al.*, 2007]. Satellite sea surface height (SSH) data shows a weakening of the North Atlantic subpolar gyre during the 1990s [*Häkkinen and Rhines*, 2004], which is thought as an indicator of a slowdown of the AMOC [*Bryden et al.*, 2005]. However, due to the lack of satellite data before 1978, whether the recent slowing subpolar gyre is a decadal variation or a long-term trend remains a challenging question [*Häkkinen and Rhines*, 2004]. *Böning et al.* [2006] using ocean general circulation model (OGCM) simulations also suggests that the recent slowing subpolar gyre reflects a slowdown of the AMOC, but it is a part of the decadal variability and the subpolar transport index might be used to monitor AMOC variations. If the altimeter SSH anomalies in the North Atlantic are associated with AMOC variations, they may be linked to some AMOC fingerprints in the subsurface North Atlantic. I explore such relationship with both the altimeter SSH and instrumental ocean temperature data [*Le Traon et al.*, 1998; *Levitus et al.*, 2005], and modeling results from a 1000-year control simulation using a fully coupled ocean-atmosphere model (GFDL CM2.1) [*Delworth et al.*, 2006]. The details are described in the auxiliary material.[1]

2. Analyses of Observed Anomalies

[3] Empirical orthogonal function (EOF) analyses were performed for the observed annual mean anomalies of SSH and subsurface temperature at 400m (Tsub) in the extratropical North Atlantic respectively, for their overlapping period of 1993–2003. The leading mode (EOF1) of observed SSH anomalies has a dipole pattern, i.e., opposite sign between the subpolar gyre and the Gulf Stream path (Figure 1a), similar to that found previously [*Häkkinen and Rhines*, 2004]. The EOF1 of observed Tsub anomalies shows a very similar dipole pattern (Figure 1b). The Principal Components of the leading mode (PC1) of observed SSH and Tsub anomalies (Figure 1e) both show very similar interannual variations, as well as a decadal increasing trend (i.e., increased SSH and warmer Tsub in the subpolar gyre, and decreased SSH and colder Tsub near the Gulf Stream path). The SSH PC1 and Tsub PC1 are highly correlated (r = 0.98), significant at 99% level. The high correlation between the two independent datasets (Altimeter SSH and instrumental Tsub, each derived with tremendous effort) suggests that both datasets are quite reliable.

3. Analyses of Modeled Anomalies From a 1000-Year Control Simulation

[4] In the 1000-year control simulation, the annual mean SSH PC1 and Tsub PC1 show strong decadal variability and are also highly correlated (r = 0.85, Figure 1f), significant at 99% level. The modeled SSH EOF1 and Tsub EOF1 both show the dipole pattern (Figures 1c and 1d), i.e., increased SSH and warmer Tsub in the subpolar gyre and decreased SSH and colder Tsub near the Gulf Stream path. The dynamic SSH anomalies (induced by variations of ocean circulation and surface fluxes) and the steric SSH anomalies (induced by changes in the density within an ocean column) are in phase with each other and each contributes about half of the total SSH anomalies. The modeled EOF1 of the upper ocean heat content (UOHC) (0–700m) also shows a similar dipole pattern (Figure S1), and the UOHC PC1 is highly correlated with the Tsub PC1 (r = 0.99, Figures S6a and S6b). The modeled AMOC Index has significant correlations (at 99% level) with SSH PC1 (r = 0.64) and Tsub PC1

[1]Geophysical Fluid Dynamics Laboratory, NOAA, Princeton, New Jersey, USA.

0094-8276/08/2008GL035463$05.00

[1]Auxiliary materials are available in the HTML. doi:10.1029/2008GL035463.

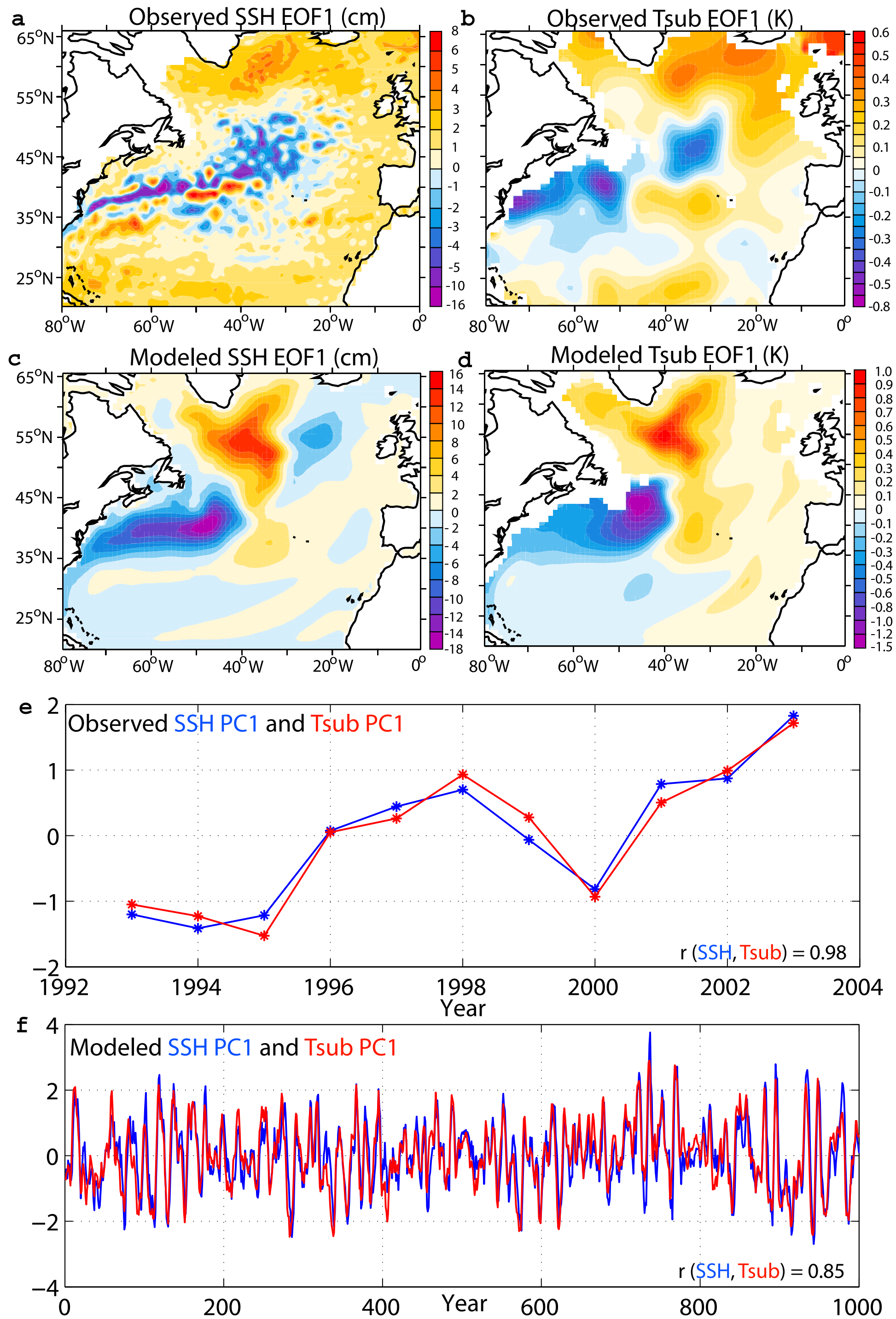

Figure 1. Observed and modeled annual mean anomalies of SSH and Tsub. (a) Observed SSH EOF1 (cm, 30%) and (b) observed Tsub EOF1 (K, 33.4%) for 1993–2003. (c) Modeled SSH EOF1 (cm, 21.24%) and (d) modeled Tsub EOF1 (K, 24.8%) from GFDL CM2.1 1000-year control integration. (e) Observed SSH PC1 (blue) and Tsub PC1 (red) during 1993–2003 (normalized). (f) Modeled SSH PC1 (blue) and Tsub PC1 (red) from GFDL CM2.1 1000-year control integration (normalized). Note the different scales in Figures 1a and 1c and Figures 1b and 1d. No filter is applied to any time series in this paper.

(r = 0.81) (Figures 2a and 2b). Here the AMOC Index is defined as the maximum of zonal integrated annual mean overturning streamfunction in the Atlantic at 40°N, which has a standard deviation of 1.8Sv ($1Sv = 10^6 m^3\ s^{-1}$). The regressions of Tsub and UOHC anomalies on the AMOC Index (Figures 2d and S2) show very similar dipole patterns, i.e., warmer Tsub and increased UOHC in the subpolar gyre and colder Tsub and decreased UOHC near the Gulf Stream path when the AMOC is stronger.

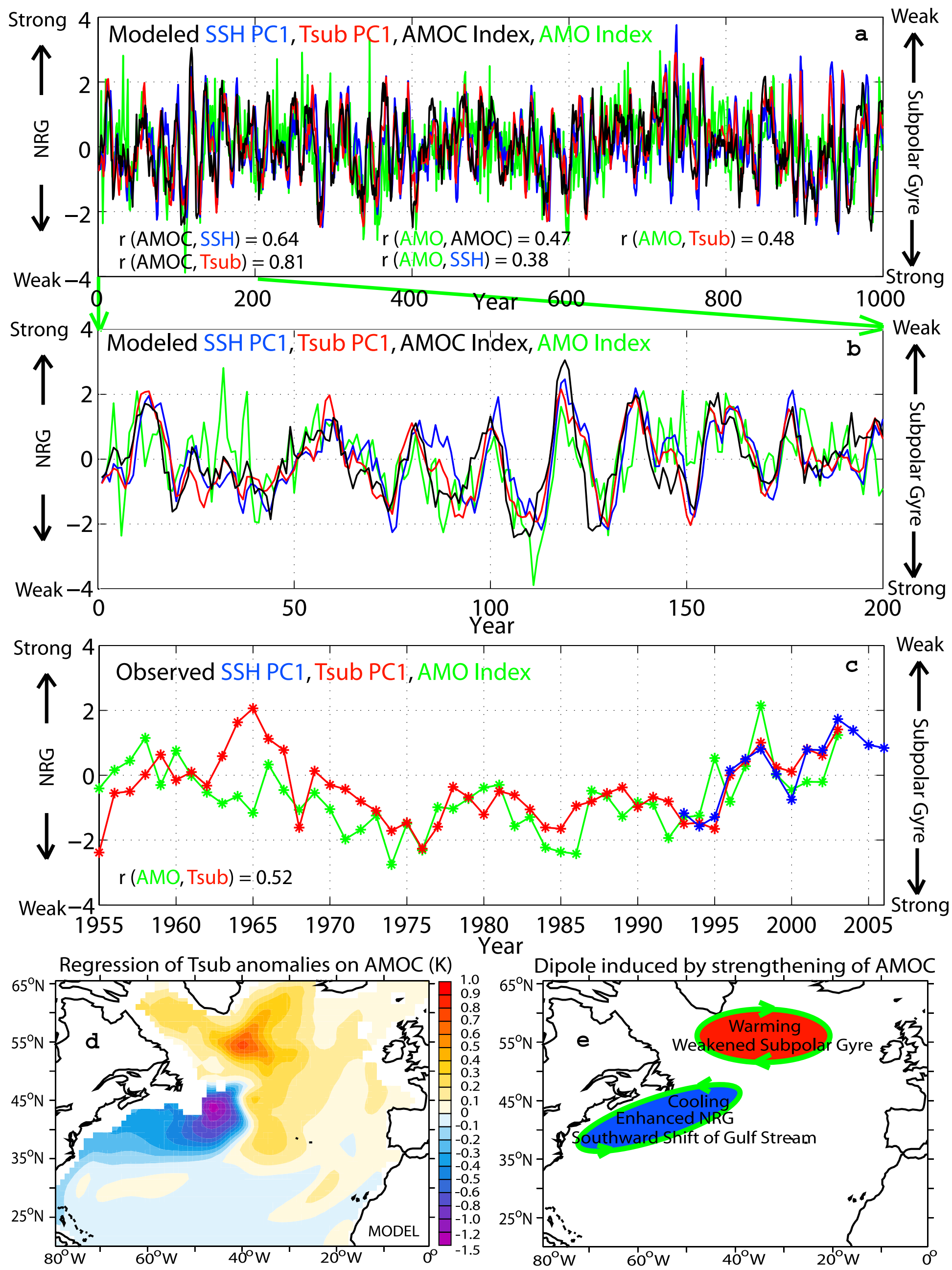

Figure 2. Modeled and observed anomalies. (a) Modeled SSH PC1 (blue), Tsub PC1 (red), AMOC index (black), and AMO Index (green) from GFDL CM2.1 1000-year control integration (normalized). The standard deviation (SD) of modeled AMOC index is 1.8Sv. The SD of modeled AMO index is 0.16K. (b) Same as Figure 2a, but enlarged for the first 200 years. (c) Observed Tsub PC1 (red) and AMO Index (green) for 1955–2003, and observed SSH PC1 (blue) for 1993–2006 (normalized), all anomalies are relative to the climatology mean of 1993–2003. The long-term trend of the instrumental subsurface data is removed. The SD of observed AMO index is 0.18K. Positive anomalies in Figures 1a–1c correspond to a weakening in the subpolar gyre and a strengthening in the NRG. (d) Regression of Tsub anomalies (K) on the AMOC Index from GFDL CM2.1 1000-year control integration. The regression corresponds to 1 SD of the AMOC Index (1.8Sv). (e) Schematic diagram of the dipole pattern induced by the strengthening of the AMOC.

[5] In the control simulation, the above dipole pattern is due to variations of the strength of the subpolar gyre, the northern recirculation gyre (NRG) north of the Gulf Stream, and the shift of the Gulf Stream path, all linked to AMOC variations (Figure 2e). The stronger AMOC is associated with a stronger deep western boundary current (DWBC), which leads to the strengthening of the cyclonic NRG and a southward shift of the Gulf Stream path (Figure S3), consistent with previous modeling and observational studies [*Thompson and Schmitz*, 1989; *Joyce et al.*, 2000; *Zhang*

and Vallis, 2006, 2007; *Peña-Molino and Joyce*, 2008]. The strengthening of the cyclonic NRG and southward shift of the Gulf Stream lead to an upper level divergence of oceanic advected mass and heat flux, thus cooling in the subsurface and decreasing in the SSH there. This is consistent with a previous study [*Kelly and Dong*, 2004] showing that in the Gulf Stream region interannual and decadal subsurface temperature anomalies are primarily caused by variations in ocean advection, rather than by changes in wind-induced air-sea heat fluxes.

[6] In the control simulation, the enhanced AMOC lags stronger deep convection in the Labrador Sea or in the Nordic Sea (two major North Atlantic deep convection sites in modern climate) by several years, i.e., the advection time scale of the deep current from the deep water formation regions to the interior North Atlantic. When the denser deep current propagates into the south and east of Greenland a few years later, it increases the vertical stratification below the surface and thus limits the depth to which the mixed layer can penetrate. The resulting reduction of mixed layer depth in the subpolar gyre leads to accumulation of water at surface and thus increased SSH. The higher SSH in the center of the gyre relative to surroundings leads to an anomalous anticyclonic circulation there (Figure S3), i.e., a weakening of the subpolar gyre. *Levermann and Born* [2007] also found that an increase in the Greenland-Scotland ridge overflow leads to an increase of density of waters south of the ridge, thus decreasing the density gradient across the subpolar gyre and weakening the subpolar gyre. The weakening of the subpolar gyre leads to a convergence of oceanic advected mass and heat flux, thus warming in the subsurface and further increasing in the SSH there. The positive temperature and salinity feedbacks induced by changes in the subpolar gyre *Levermann and Born* [2007] further weaken the subpolar gyre. The modeled subpolar gyre anomalies locate further southwest compared to that observed, thus the modeled anomalies over the Gulf Stream region do not extend further northeast as that observed (Figures 1a–1d). This is because the modeled climatology mean mixed layer depth is shallower in the Irminger Sea and deeper towards the southwest than that observed. Nevertheless, both observed and modeled subpolar gyre anomalies are centered at south and east of Greenland, not in the Labrador Sea.

[7] Here the modeled out-of-phase relationship between the AMOC and the subpolar gyre strength is opposite and a challenge result to the traditional in-phase relationship found in previous Ocean-Only (OGCM) modeling studies, such as *Böning et al.* [2006]. The OGCM simulations [*Böning et al.*, 2006] do not have coupled surface boundary conditions as in reality and restore the sea surface salinity to climatology; the northern boundary is also restored to climatology to eliminate variations of overflow from the Nordic Sea. The very different boundary conditions might be the cause of the opposite results between the two types of models. Here the modeled out-of-phase relationship is consistent with an earlier study [*Manabe and Stouffer*, 1999] showing that when the AMOC is weakened, the subpolar gyre is stronger. The model used by *Manabe and Stouffer* [1999] is completely different and independent from the GFDL CM2.1 used here, but both models have realistic coupled surface boundary conditions, which are very important for AMOC variations.

4. Comparison of Modeling Results With Observations

[8] The above modeling results suggest that the dipole pattern in the leading mode of SSH, Tsub, and UOHC anomalies is a distinctive fingerprint of the AMOC decadal variations. The strengthening of the AMOC is associated with the strengthening of the NRG (decreased SSH and colder Tsub near the Gulf Stream path) and the weakening of the subpolar gyre (increased SSH and warmer Tsub in the subpolar gyre). The leading modes of observed SSH and Tsub anomalies with a similar dipole pattern thus suggests similar AMOC decadal variations (Figures 1a, 1b, and 1e), and might be used as proxies for variations of the AMOC, the NRG, and the subpolar gyre. EOF analyses were performed for the instrumental subsurface data for a longer period (1955–2003), and the long-term trend is removed because the anthropogenic radiative forcing generates a monotonic warming trend in the subtropical subsurface [*Levitus et al.*, 2001]. The long-term subtropical warming trend is centered at the subduction region off the US east coast, opposite to the recent cooling there during the 1990s. The subpolar Tsub and UOHC anomalies have no significant long-term trend, hence the detrended data is not statistical significantly different from the original data over the subpolar region. The observed Tsub EOF1 and UOHC EOF1 over this longer period both show similar dipole patterns (Figures S4a and S4b). The observed Tsub PC1 shows a multidecadal variation and matches well with the observed SSH PC1 computed for 1993–2006 (Figure 2c). This result suggests that the recent slowdown of the subpolar gyre is a part of a multidecadal variation in the North Atlantic: during the 70–80's, the subpolar gyre was stronger, and the NRG and the AMOC were weaker; during the 50–60's and the recent decade, the subpolar gyre was weaker, and the NRG and the AMOC were stronger. *Böning et al.* [2006] using OGCM simulations also suggests that the recent slowing subpolar gyre reflects a decadal variability, but their AMOC-subpolar gyre phase relationship is opposite to that found here. The smaller amplitudes of observed SSH EOF1 and Tsub EOF1 (Figures 1a–1d) suggest that the low frequency AMOC variations in reality might have a smaller standard deviation than that modeled (1.8 Sv).

[9] The weakening of the AMOC during the 70–80's inferred from the observed Tsub PC1 (Figure 2c) lagged the observed reductions of Labrador Sea deep convection induced by Great Salinity Anomalies events at the early 70's and 80's [*Dickson et al.*, 1988; *Curry et al.*, 1998] by several years. During the recent decade, the peak of the AMOC at 1998 inferred from observed PC1s of Tsub and SSH (Figure 2c) lags the observed peak of Labrador Sea deep convection around 1994 [*Yashayaev et al.*, 2007] by several years. The above lags are consistent with the advection time scale of the deep current from the Labrador Sea to the interior North Atlantic [*Yashayaev et al.*, 2007]. The very recent peak of the AMOC at 2003 inferred from observed Tsub PC1 and SSH PC1 (Figure 2c) might be due to the strengthening of Nordic Sea deep convection several years before, consistent with the observed peak of Faroe

Bank Channel overflow from the Nordic Sea into the Atlantic at 2003 [*Steffen et al.*, 2008]. This Faroe Bank Channel overflow reflects Nordic Sea deep convection strength several years before. A recent modeling study [*Hawkins and Sutton*, 2007] also shows that changes in the Nordic Sea deep convection leads AMOC variations by a few years. Changes in the Nordic Sea deep convection could also be very important for AMOC variations. The observed SSH PC1 suggests that the AMOC has declined from its peak at 2003 during the last few years (Figure 2c).

5. Independent Verification and Discussions

[10] Instrumental records also show large-scale multidecadal variations in the Atlantic sea surface temperature (SST). The observed detrended multidecadal SST anomaly averaged over the entire North Atlantic, often called the Atlantic Multidecadal Oscillation (AMO) Index [*Enfield et al.*, 2001; *Sutton and Hodson*, 2005], has been linked to AMOC variations [*Knight et al.*, 2005]. During a positive AMO phase, the North Atlantic mean SST is warmer relative to that of the South Atlantic due to the increased northward oceanic heat transport associated with a stronger AMOC [*Knight et al.*, 2005]. The comparison of observational and modeling results suggests that AMOC variations are in phase with the observed AMO [*Zhang*, 2007]. If the leading mode in SSH, Tsub, UOHC anomalies is a distinctive fingerprint of AMOC decadal variations, it should be related to the AMO Index as well, which turns out to be true in both modeling results and observations (Figure 2). In the 1000-year control simulation, the AMO Index has significant correlations (at 99% level) with the AMOC Index ($r = 0.47$), Tsub PC1 ($r = 0.48$), and SSH PC1 ($r = 0.38$) (Figures 2a and 2b). The observed AMO Index, derived from the same instrumental dataset [*Levitus et al.*, 2005], has significant correlations with the observed Tsub PC1 ($r = 0.52$, at 95% level, Figure 2c) for the period 1955–2003. The AMO Index is in phase with subpolar Tsub variations and anti-phase with Tsub variations near the Gulf Stream path in both modeling results and observations (Figure 2).

[11] Hence the observed AMO Index provides an indirect observational verification of the modeled out-of-phase relationship between changes in the AMOC and the subpolar gyre strength, independent from the GFDL CM2.1 model. The AMOC variations inferred from the observed Tsub PC1 are consistent with those inferred from the observed AMO index. The observations show that the AMO Index is out-of-phase with the subpolar gyre strength (Figure 2c). The GFDL CM2.1 coupled model simulates this important relationship as that observed (Figures 2a and 2b), because the AMOC variations are out-of-phase with the variations of the subpolar gyre strength in the model. If changes in the AMOC were in-phase with changes in the subpolar gyre strength as some previous study suggested [*Bryden et al.*, 2005], then the AMO Index, which is in-phase with the AMOC variations, would be in-phase with the subpolar gyre strength and this is contrary to the observations. Here the longer instrumental subsurface timeseries (1955–2003) suggests that, contrary to the previous interpretations [*Bryden et al.*, 2005], the recent slowdown of the subpolar gyre is a part of a multidecadal variation, not a long-term trend. This result itself is based on the observed high correlation between SSH and subsurface temperature, and does not depend on the GFDL CM2.1 modeling results.

[12] The AMO is thought to have important impacts on Atlantic hurricane activities and European and North American climate [*Enfield et al.*, 2001; *Goldenberg et al.*, 2001; *Sutton and Hodson*, 2005], thus it is crucial to identify an AMO regime shift. The multivariable approach, i.e., whether the AMO Index, SSH and Tsub PC1s change simultaneously in the same direction, will give much more confidence in identifying the regime shift. The relationships identified here and the fact that they are reproduced in a millennium control simulation using a state-of-art coupled model bring significant new evidence that the observed AMO is linked to AMOC variations [*Delworth and Mann*, 2000; *Knight et al.*, 2005; *Zhang*, 2007] rather than merely a 20th century artifact of changes in radiative forcing [*Mann and Emanuel*, 2006]. This result suggests that AMOC variations might have played an important role in the multidecadal variations of the Atlantic hurricane activities and European and North American climate.

[13] The simulated leading Principle Components of Tsub and SSH have much higher correlations with the AMOC Index than the AMO Index (Figures 2a and 2b), probably because the SST-based AMO Index is more likely to be affected by various atmospheric forcings apart from AMOC variations. The results suggest that the historical subsurface temperature data could be used for reconstructing AMOC variations in the past. The ongoing satellite SSH observations and subsurface temperature measurements (such as the ARGO program) could be used to monitor AMOC variations sensitively in the coming decade.

[14] **Acknowledgments.** I thank Kirk Bryan, Thomas L. Delworth, and Syukuro Manabe for helpful discussion. The altimeter products were produced by SSALTO/DUACS and distributed by AVISO with support from CNES.

References

Böning, C. W., M. Scheinert, J. Dengg, A. Biastoch, and A. Funk (2006), Decadal variability of subpolar gyre transport and its reverberation in the North Atlantic overturning, *Geophys. Res. Lett.*, *33*, L21S01, doi:10.1029/2006GL026906.

Bryden, H., H. R. Longworth, and S. A. Cunningham (2005), Slowing of the Atlantic meridional overturning circulation at 25°N, *Nature*, *438*, 655–657.

Cunningham, S. A., et al. (2007), Temporal variability of the Atlantic meridional overturning circulation at 265°N, *Science*, *317*, 935–938.

Curry, R. G., M. S. McCartney, and T. M. Joyce (1998), Oceanic transport of subpolar climate signals to mid-depth subtropical waters, *Nature*, *391*, 575–577.

Delworth, T. L., and M. E. Mann (2000), Observed and simulated multidecadal variability in the Northern Hemisphere, *Clim. Dyn.*, *16*, 661–676.

Delworth, T. L., et al. (2006), GFDL's CM2 global coupled climate models. Part I: Formulation and simulation characteristics, *J. Clim.*, *19*, 643–674.

Dickson, R. R., J. Meincke, S.-A. Malmberg, and A. J. Lee (1988), The 'Great Salinity Anomaly' in the northern North Atlantic 1968–1982, *Prog. Oceanogr.*, *20*, 103–151.

Enfield, D. B., A. M. Mestas-Nuñez, and P. J. Trimble (2001), The Atlantic Multidecadal Oscillation and its relation to rainfall and river flows in the continental U.S., *Geophys. Res. Lett.*, *28*, 2077–2080.

Goldenberg, S. B., C. W. Landsea, A. M. Mestas-Nuñez, and W. M. Gray (2001), The recent increase in Atlantic hurricane activity: Causes and implications, *Science*, *293*, 474–479.

Häkkinen, S., and P. B. Rhines (2004), Decline of subpolar North Atlantic circulation during the 1990s, *Science*, *304*, 555–559.

Hawkins, E., and R. Sutton (2007), Variability of the Atlantic thermohaline circulation described by three-dimensional empirical orthogonal functions, *Clim. Dyn.*, *29*, 745–762.

Joyce, T. M., C. Deser, and M. A. Spall (2000), The relation between decadal variability of subtropical mode water and the North Atlantic Oscillation, *J. Clim.*, *13*, 2550–2569.

Kelly, K. A., and S. Dong (2004), The relationship of western boundary current heat transport and storage to midlatitude ocean-atmosphere interaction, *Earth's Climate: The Ocean-Atmosphere Interaction*, *Geophys. Monogr. Ser.*, vol. 147, edited by C. Wang, S.-P. Xie, and J. A. Carton, pp. 347–363, AGU, Washington, D. C.

Knight, J. R., R. J. Allan, C. K. Folland, M. Vellinga, and M. E. Mann (2005), A signature of persistent natural thermohaline circulation cycles in observed climate, *Geophys. Res. Lett.*, *32*, L20708, doi:10.1029/2005GL024233.

Le Traon, P.-Y., F. Nadal, and N. Ducet (1998), An improved mapping method of multisatellite altimeter data, *J. Atmos. Oceanic Technol.*, *15*, 522–534.

Levermann, A., and A. Born (2007), Bistability of the Atlantic subpolar gyre in a coarse-resolution climate model, *Geophys. Res. Lett.*, *34*, L24605, doi:10.1029/2007GL031732.

Levitus, S., J. I. Antonov, J. Wang, T. L. Delworth, K. W. Dixon, and A. J. Broccoli (2001), Anthropogenic warming of Earth's climate system, *Science*, *292*, 268–270.

Levitus, S., J. Antonov, and T. Boyer (2005), Warming of the world ocean, 1955–2003, *Geophys. Res. Lett.*, *32*, L02604, doi:10.1029/2004GL021592.

Manabe, S., and R. J. Stouffer (1999), The role of thermohaline circulation in climate, *Tellus, Ser. A*, *51*, 91–109.

Mann, M. E., and K. A. Emanuel (2006), Atlantic hurricane trends linked to climate change, *Eos Trans. AGU*, *87*(24), doi:10.1029/2006EO240001.

Peña-Molino, B., and T. M. Joyce (2008), Variability in the Slope Water and its relation to the Gulf Stream path, *Geophys. Res. Lett.*, *35*, L03606, doi:10.1029/2007GL032183.

Steffen, M. O., B. Hansen, D. Quadfasel, and S. Osterhus (2008), Observed and modelled stability of overflow across the Greenland-Scotland ridge, *Nature*, *455*, 519–522.

Sutton, R. T., and D. L. R. Hodson (2005), Atlantic Ocean forcing of North American and European summer climate, *Science*, *309*, 115–118.

Thompson, J. D., and W. J. Schmitz (1989), A limited-area model of the Gulf Stream: Design, initial experiments, and model-data intercomparison, *J. Phys. Oceanogr.*, *19*, 791–814.

Yashayaev, I., M. Bersch, and H. M. van Aken (2007), Spreading of the Labrador Sea Water to the Irminger and Iceland basins, *Geophys. Res. Lett.*, *34*, L10602, doi:10.1029/2006GL028999.

Zhang, R. (2007), Anticorrelated multidecadal variations between surface and subsurface tropical North Atlantic, *Geophys. Res. Lett.*, *34*, L12713, doi:10.1029/2007GL030225.

Zhang, R., and G. K. Vallis (2006), Impact of great salinity anomalies on the low-frequency variability of the North Atlantic climate, *J. Clim.*, *19*, 470–482.

Zhang, R., and G. K. Vallis (2007), The role of bottom vortex stretching on the path of the North Atlantic Western Boundary Current and on the Northern Recirculation Gyre, *J. Phys. Oceanogr.*, *27*, 2053–2080.

R. Zhang, Geophysical Fluid Dynamics Laboratory, NOAA, 201 Forrestal Road, Princeton, NJ 08540, USA. (rong.zhang@noaa.gov)