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Anticorrelated multidecadal variations between surface and subsurface tropical North Atlantic

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[1] In this paper for the first time I show that the multidecadal variations of observed tropical North Atlantic (TNA) sea surface temperature (SST) are strongly anticorrelated with those of the observed TNA subsurface ocean temperature, with long-term trends removed. I further show that the anticorrelated change between the TNA surface and subsurface temperature is a distinctive signature of the Atlantic meridional overturning circulation (AMOC) variations, using water-hosing experiments with the GFDL state-of-art coupled climate model (CM2.1). External radiative forced simulations with the same model do not provide a significant relationship between the TNA surface and subsurface temperature variations. The observed detrended multidecadal TNA subsurface temperature anomaly may be taken as a proxy for the AMOC variability. Various mechanisms proposed for the multidecadal TNA SST variations, which are crucial for multidecadal variations of Atlantic hurricane activities, should take into account the observed anticorrelation between the TNA surface and subsurface temperature variations. **Citation:** Zhang, R. (2007), Anticorrelated multidecadal variations between surface and subsurface tropical North Atlantic, *Geophys. Res. Lett.*, *34*, L12713, doi:10.1029/2007GL030225.

1. Introduction

[2] The observed 20th century multidecadal SST anomaly averaged over the North Atlantic after removing the long-term trend, often called the Atlantic Multidecadal Oscillation (AMO) [*Enfield et al.*, 2001; *Knight et al.*, 2005], has significant regional and hemispheric climate associations [*Enfield et al.*, 2001; *McCabe et al.*, 2004; *Knight et al.*, 2006; *Zhang and Delworth*, 2006; *Zhang et al.*, 2007]. The AMO index is highly correlated with the multidecadal variations of the TNA SST and the Atlantic hurricane activities [*Goldenberg et al.*, 2001; *Knight et al.*, 2006; *Zhang and Delworth*, 2006]. The observed TNA surface warming is correlated with above-normal Atlantic hurricane activities during the 50–60's and the recent decade. These multidecadal SST variations are often thought to be driven by the AMOC variability [*Delworth and Mann*, 2000; *Knight et al.*, 2005]. However, without knowing the AMOC variations over the past decades independently, such a hypothesis can not be verified. Direct observations of AMOC changes are controversial. Comparisons of five instantaneous surveys across 25°N since 1957 indicate a long-term slowdown of the AMOC [*Bryden et al.*, 2005]. Such observed snapshots might be aliased by observed large annual variations in the North Atlantic meridional heat flux [*Baringer and Molinari*, 1999]. Observations of the Deep Western Boundary Current indicate no basinwide slowdown in the recent decade [*Schott et al.*, 2006].

[3] The AMO and the multidecadal TNA SST variations have highly debated origins, i.e. some suggested that they are driven by changes in the radiative forcing [*Mann and Emanuel*, 2006]. If these multidecadal SST variations are associated with basin-scale AMOC variations, they may be linked to other signals in the North Atlantic basin, especially some AMOC fingerprints in the subsurface ocean. Does such a link exist? Are there any observed subsurface variables that can be taken as fingerprints of AMOC variations, but do not respond rapidly to changes in the radiative forcing? In this paper I show that the multidecadal variations of the observed TNA SST are strongly anticorrelated with those of the observed TNA subsurface ocean temperature, and strongly correlated with those of the observed sea surface salinity (SSS) over the subpolar North Atlantic, with long-term trends removed. The anticorrelated change between the TNA surface and subsurface temperature is a distinctive signature of the AMOC variations, as shown by the water-hosing experiments using the GFDL coupled climate model (CM2.1). The surface displacement of the Atlantic intertropical convergence zone (ITCZ) and subsurface thermocline adjustments, both excited rapidly by AMOC variations, together contribute to the above anticorrelated change. External radiative forced simulations with the same model do not generate rapid TNA subsurface temperature variations. Hence the detrended multidecadal TNA subsurface temperature anomaly may be taken as an AMOC fingerprint (not affected much by changes in the radiative forcing) through its inverse relationship with AMOC variations.

[4] Contrary to the rapid surface warming, there is a rapid subsurface cooling in the TNA in the recent decade, with long-term trends removed, indicating that the AMOC might have been strengthened since the mid 70's. This is consistent with the switch of the observed AMO index to a positive phase around the mid-1990s [*Enfield et al.*, 2001; *Goldenberg et al.*, 2001]. The multidecadal variability of the AMOC needs to be considered together with the long-term slowdown trend under debate [*Bryden et al.*, 2005]. Accurate monitoring of the variability of the TNA surface and subsurface temperature, and of the subpolar North Atlantic SSS may assist to assess the AMOC variability in the future.

2. Observed Anticorrelated Variations Between the TNA Surface and Subsurface

[5] The observed multidecadal anomaly of the TNA SST is strongly anticorrelated with that of the TNA subsurface

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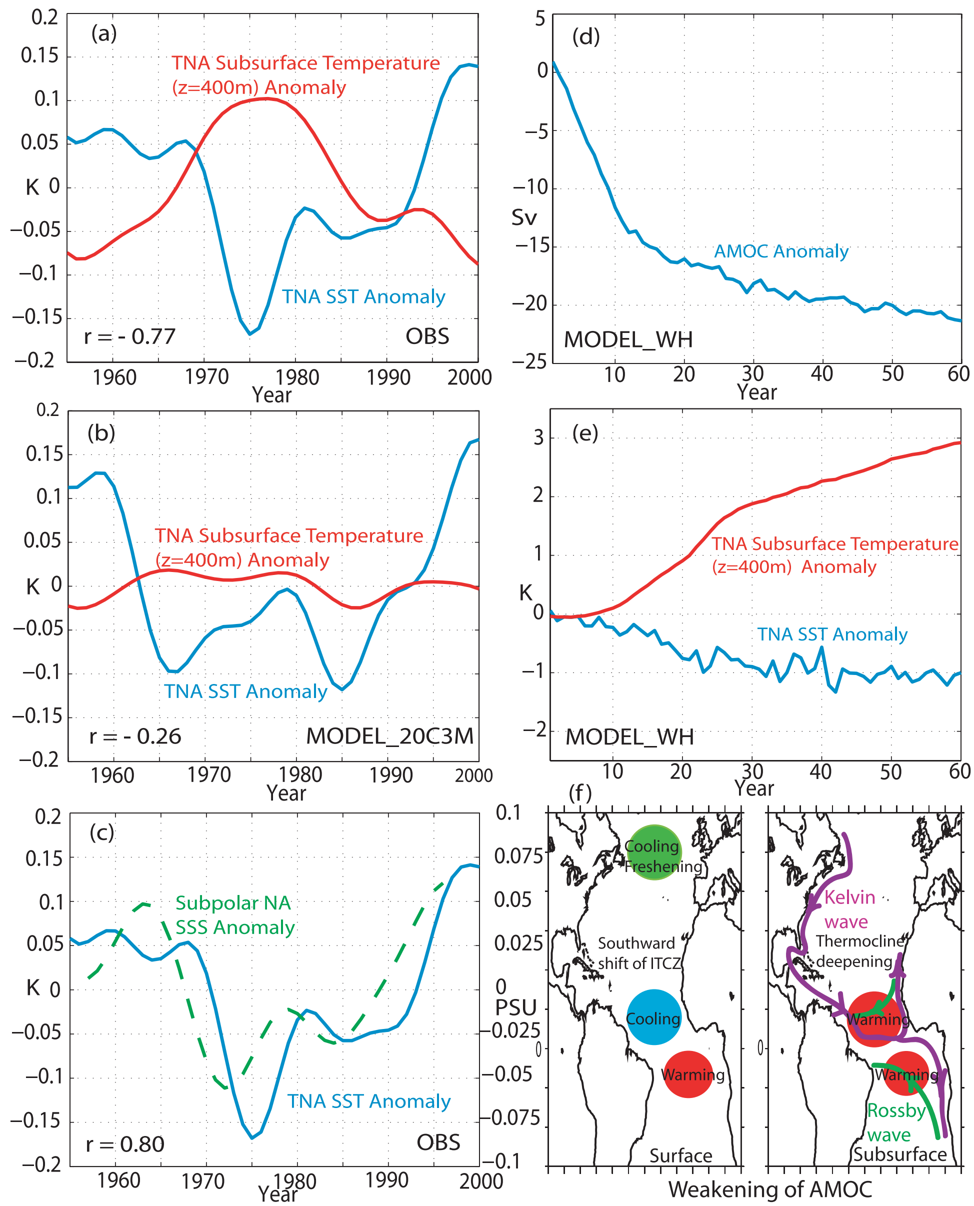

Figure 1. Observed and modeled time series. (a) Observed (OBS) SST anomaly (blue line) and subsurface ocean temperature anomaly (z = 400 m, red line) averaged over the TNA (0–14°N and 70°W–10°E). (b) Same as Figure 1a, but using modeled ensemble mean from MODEL_20C3M. (c) Observed TNA SST anomaly (blue line, left axis) and SSS anomaly (green dashed line, right axis) averaged over the subpolar North Atlantic (NA, 50°N–65°N). The observations are derived from the objectively analyzed datasets of ocean temperature and salinity anomalies [*Levitus et al.*, 2005; *Boyer et al.*, 2005]. The long-term trends have been removed for all time series. A low-pass filter is applied with a 10-year cutoff period. (d) Modeled ensemble mean AMOC anomaly (Sv) from MODEL_WH. The AMOC is defined as the maximum annual Eulerian mean overturning streamfunction over the domain 30°–80°N in the North Atlantic. (e) Modeled ensemble mean TNA SST anomaly (blue line) and TNA subsurface ocean temperature anomaly (z = 400 m, red line) from MODEL_WH. (f) Schematic diagrams of mechanisms: surface displacements of the Atlantic ITCZ and subsurface thermocline adjustments through the propagation of Kelvin waves and Rossby waves together contribute to the anticorrelated TNA surface and subsurface temperature anomalies. The weakening of the AMOC leads to a southward shift of the Atlantic ITCZ, TNA surface cooling, as well as thermocline deepening and subsurface warming in the TNA. The warming in surface and subsurface tropical South Atlantic are relatively weaker.

ocean temperature (Figure 1a, a maximum negative correlation r = −0.77 at zero lag), with long-term trends removed. The anticorrelation is significant at the 95% level using the 2-tailed Student's *t*-test and significant at the 90% level using the Monte Carlo test with the random phase method of resampling, i.e. resampling in the frequency domain to preserve the power spectrum and autocorrelation of the original data (auxiliary material).[1] Such significant anticorrelated multidecadal variations between surface and subsurface TNA indicate a coherent change in the ocean.

[1]Auxiliary materials are available in the HTML. doi:10.1029/2007GL030225.

The observed temperature anomalies are derived from the yearly averaged dataset of objectively analyzed ocean temperature anomalies for 1955–2000 [*Levitus et al.*, 2005]. To investigate this apparent inverse relationship, I analyzed an ensemble of 5 simulations conducted with the latest GFDL global coupled ocean-atmosphere model (CM2.1) [*Delworth et al.*, 2006], each with different initial conditions but forced with the same estimates of changes in the radiative forcing (solar irradiance, volcanoes, anthropogenic greenhouse gases, ozone, aerosols, etc.) from 1861 to 2000 [*Knutson et al.*, 2006], as made available to the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment (AR4). The ensemble is referred to MODEL_20C3M hereafter. The ensemble mean results from MODEL_20C3M (with long-term trends removed) show strong TNA surface cooling during the mid 60's and mid 80's (Figure 1b), mainly due to volcanic aerosols associated with the Agung (1963) and El Chichón (1982) eruptions. On the other hand, the observed TNA surface cooling peaked in the mid 70's, indicating that the modeled effect of aerosols may be overestimated. The subsurface anomaly in the model ensemble is very weak and there is no significant correlation between modeled TNA surface and subsurface anomalies (r = −0.26, Figure 1b and auxiliary material). Since the ensemble mean of MODEL_20C3M smoothes out internal variations and represents net radiative forced response, the results indicate that the above observed anticorrelated multidecadal variations can not be explained by changes in the radiative forcing.

[6] The observed multidecadal anomaly of the TNA SST is also strongly correlated with that of the subpolar North Atlantic SSS (Figure 1c), with long-term trends removed. The TNA surface cooling (warming) is accompanied by the subpolar surface freshening (salting), and the maximum correlation is r = 0.80 at a 2-year lag (significant at the 98% level using the 2-tailed Student's *t*-test and significant at the 95% level using the Monte Carlo test, auxiliary material), i.e. the subpolar SSS anomaly leads the TNA SST anomaly by ~2 years. The observed salinity anomalies are derived from the pentadally averaged dataset of objectively analyzed ocean salinity anomalies from 1955–1959 through 1994–1998 [*Boyer et al.*, 2005].

3. Simulated Anticorrelated Change Between the TNA Surface and Subsurface

[7] To explore whether the AMOC variations can induce anticorrelated changes between the TNA surface and subsurface temperature, I analyzed an ensemble of 5 water-hosing experiments conducted with the same coupled model (GFDL CM2.1), referred to as MODEL_WH hereafter. The control experiment uses constant radiative forcing of year 1860 and produces a stable, realistic, multicentury integration without flux adjustments [*Delworth et al.*, 2006]. In the 5 perturbed water-hosing experiments of the ensemble, an idealized strong freshwater forcing of 0.6 Sv (1 Sv = 10^6 m^3 s^{-1}) is uniformly distributed over the northern North Atlantic (55°–75°N, 63°W–4°E) for an entire 60-yr period to suppress the AMOC. The anomalies are defined as differences between the ensemble mean of the perturbed experiments and the climatology of the control experiment.

[8] In MODEL_WH, the weakening of the AMOC leads to a substantial subpolar surface cooling and thus a rapid southward shift of the Atlantic ITCZ, associated with an anomalous Hadley circulation that descends north of the equator and ascends south of the equator, providing an enhanced cross-equatorial northward atmospheric heat transport to compensate the subpolar surface cooling, similar to that found before [*Zhang and Delworth*, 2005]. Associated with the anomalous Hadley circulation/southward ITCZ shift are stronger northeast trade winds, greater surface evaporation and latent heat flux loss, and a surface cooling in the TNA. The TNA surface cooling is further amplified by intensified oceanic upwelling and poleward Ekman transport in response to the stronger northeast trade wind. The advection and propagation of cold air from extratropics also contributes to the relative stronger TNA surface cooling. Meanwhile, the southeast trade wind becomes weaker over the tropical South Atlantic, and contributes to a surface warming there, although such anomalous warming is relative weaker. The meridional gradient of SST anomalies further amplifies the ITCZ shift and the anomalous Hadley circulation, i.e. tropical air-sea interactions involving the ocean dynamics provide a positive feedback [*Zhang and Delworth*, 2005], similar to the simulated positive feedback between surface wind, evaporation and SST (WES feedback) [*Xie and Philander*, 1994; *Chang et al.*, 1997].

[9] In MODEL_WH, after 20 years of perturbation, the AMOC weakens rapidly from 23 Sv (climatology in the control experiment) to about 7 Sv, i.e. an anomaly of −16 Sv (Figure 1d). There are clear opposite changes between the TNA surface and subsurface (Figure 1e): the TNA surface is cooled down and the TNA subsurface is warmed up gradually, when the AMOC is weakened gradually. The TNA subsurface change is due to basin-scale thermocline adjustments, excited by changes in the AMOC. The adjustment takes place when coastal and equatorial trapped Kelvin waves propagate away from the subpolar North Atlantic region of changes of deep water formation, equatorward along the western boundary, eastward at the equator, and then split into two waves moving poleward along the eastern boundary [*Hsieh and Bryan*, 1996; *Johnson and Marshall*, 2002]. The weakening (strengthening) of the AMOC induces a thermocline deepening (shallowing) and thus a subsurface warming (cooling) along the paths of Kelvin waves, which is communicated into the interior ocean by the westward propagation of Rossby waves from the eastern boundary. The thermocline here refers to the internal thermocline outcrops in the subpolar gyre, not the shallower ventilated thermocline outcrops in the subtropical gyre. The coastal Kelvin wave propagates down to equator at a very fast speed, on the order of 1–2 years and the speed is underestimated due to the non eddy-resolving B-grid ocean component used in the GFDL coupled model [*Hsieh and Bryan*, 1996]. The Rossby waves move more rapidly at the tropics than at higher latitudes. Hence the TNA thermocline adjusts relatively quickly to changes in the AMOC. The South Atlantic thermocline deepens on much longer timescales and the rapid response to AMOC changes is weaker there, because the pressure anomaly decreases as the Kelvin wave moves equatorward and no sustained pressure gradients along the eastern boundary, i.e. the equatorial buffer mechanism [*Johnson and Marshall*, 2002].

[10] The two dominant processes excited rapidly by the AMOC variations - surface displacements of the Atlantic

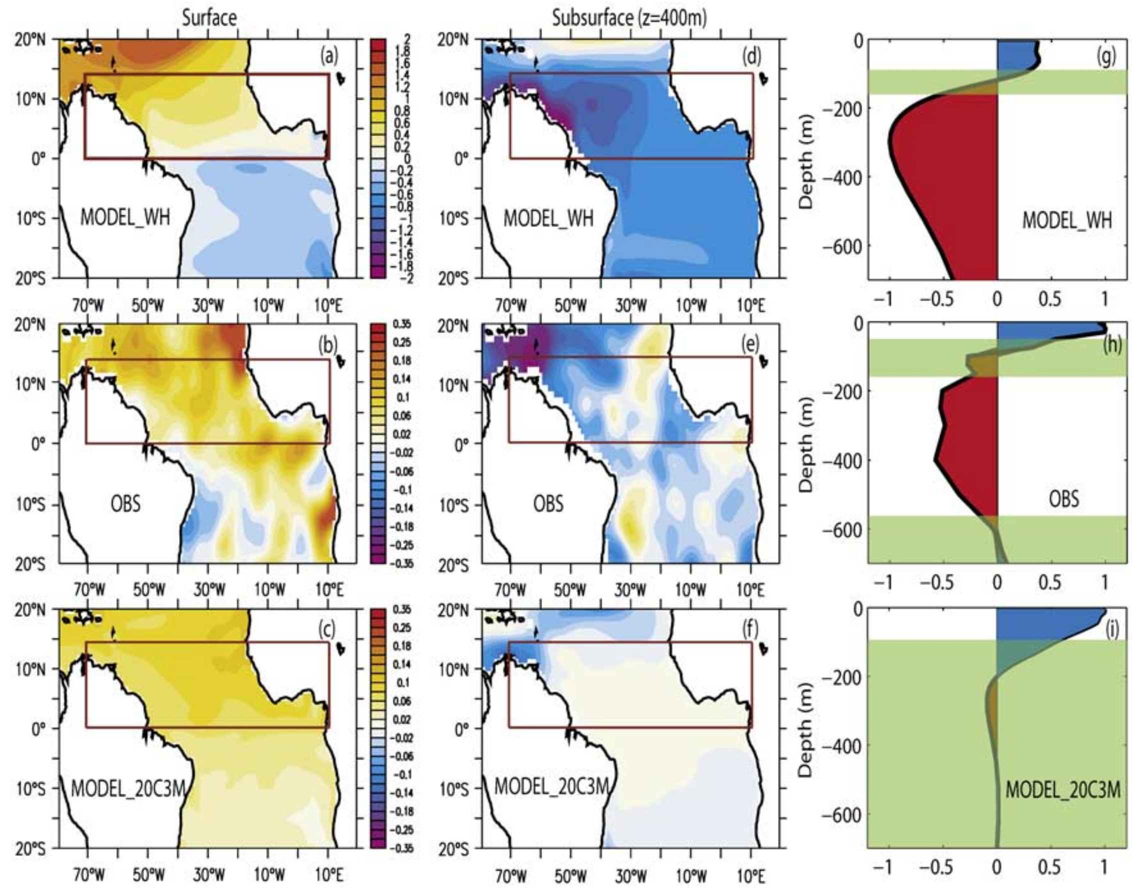

Figure 2. (a, b, c) Regression of the SST anomaly onto the time series of the TNA SST anomaly. (d, e, f) Regression of the subsurface ocean temperature anomaly (z = 400) onto the time series of the TNA SST anomaly. (g, h, i) Regression of the averaged TNA ocean temperature anomaly at different depths onto the time series of the TNA SST anomaly. All regressions correspond to 1 standard deviation of the TNA SST anomaly. Figures 2a, 2d, and 2g use the modeled ensemble mean from MODEL_WH, year 1–60. Figures 2b, 2e, and 2h use low-pass filtered observed data (OBS, 1955–2000). Figures 2c, 2f, and 2i use low-pass filtered modeled ensemble mean from MODEL_20C3M, 1955–2000. The long-term trends have been removed for OBS and MODEL_20C3M. The brown box shows the TNA domain (0–14°N and 70°W–0°E) that is used for area average. Figures 2g, 2h, and 2i 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.

ITCZ and subsurface thermocline adjustments through the propagation of oceanic waves, together contribute to opposite changes between the TNA surface and subsurface temperature (Figure 1f). The weakening (strengthening) of the AMOC leads to a southward (northward) shift of the Atlantic ITCZ, TNA surface cooling (warming), as well as thermocline deepening (shallowing) and subsurface warming (cooling) in the TNA. In the tropical South Atlantic, the thermocline deepening also contributes to the surface warming at upwelling zones, but both surface and subsurface responses are relative weaker.

[11] The AMOC-induced anticorrelated changes between the TNA surface and subsurface temperature can also be seen from the spatial regression pattern of surface and subsurface temperature anomalies onto the TNA SST anomaly, using results from MODEL_WH (Figures 2a and 2d), i.e. positive regressions over the TNA surface and negative regressions over the TNA subsurface. The idealized freshwater forcing in MODEL_WH is very strong, so that the AMOC changes and the TNA response are very strong, and the ensemble average further improves the signal-to-noise ratio. Hence the regressions from MODEL_WH corresponding to 1 standard deviation of the TNA SST anomaly (Figures 2a and 2d) are much larger than those observed (Figures 2b and 2e). The observations also show anticorrelated changes, i.e. positive regressions over most of the TNA surface and negative regressions over most of the TNA subsurface (Figures 2b and 2e). The observed surface and subsurface signals over the tropical South Atlantic are very noisy (Figures 2b and 2e), probably due to the above discussed weaker responses to AMOC changes there and much lower signal-to-noise ratios in observations. The weaker response in the tropical South Atlantic SST found in models is often insignificant in observations [*Mestas-Nuñez and Enfield*, 1999]. The results from MODEL_20C3M show positive regressions over the surface TNA, but almost no signals over most of the subsurface TNA (Figures 2c and 2f). The TNA SST anomaly induced by the radiative forcing could slowly diffuse or subduct into the subsurface, but there is no apparent mechanism causing a rapid opposite TNA subsurface change

to the SST anomaly. In addition, the 20th century AMOC change in MODEL_20C3M is not significant due to the opposite effects of increasing anthropogenic aerosols and greenhouse gases [*Delworth and Dixon*, 2006], and thus can not induce significant TNA subsurface response. The vertical structure of the regression of the TNA ocean temperature anomaly onto the TNA SST anomaly (Figures 2g, 2h, and 2i) shows significant anticorrelations between the TNA surface and subsurface temperature in both MODEL_WH and observations, but there is no significant subsurface response associated with the TNA SST anomaly in MODEL_20C3M.

4. Conclusion and Discussion

[12] The observational analyses here show that multidecadal variations of the TNA SST are strongly anticorrelated with those of the TNA subsurface ocean temperature, and strongly correlated with those of the SSS over the subpolar North Atlantic. Because the observed time series since the middle of the 20th century are short, Monte Carlo tests are performed and the above statistical links are still significant (auxiliary material). Nevertheless, future observations are needed to test the robustness of these links.

[13] The water-hosing modeling results here show that the anticorrelated change between the TNA surface and subsurface temperature is a distinctive signature of the AMOC variations. Since there are no significant rapid TNA subsurface variations to changes in the radiative forcing, the observed detrended multidecadal TNA subsurface temperature anomaly may be taken as a proxy for detrended AMOC variations. During the 70–80's, the observed TNA subsurface warming, along with the subpolar North Atlantic surface freshening (Figures 1a and 1c), indicate that the AMOC might have been in a weaker phase, concurring with the negative AMO phase. Conversely, during the 50–60's and the recent decade, the observed TNA subsurface cooling, along with the subpolar North Atlantic surface salting (Figures 1a and 1c), indicate that the AMOC might have been in stronger phases, concurring with the positive AMO phases. Previous studies [*Delworth and Mann*, 2000; *Knight et al.*, 2005] also suggested the link between the AMO index and AMOC variations, and AMOC is stronger in the recent decade as inferred from the observed detrended North Atlantic SST anomaly. However, the detrended North Atlantic SST anomaly has highly debated origins [*Mann and Emanuel*, 2006]. The detrended TNA subsurface temperature anomaly does not suffer from this debate, and may serve as an independent fingerprint of AMOC variations, through its inverse relationship with AMOC variations shown by the water-hosing experiments here.

[14] Due to the observed anticorrelation between the TNA surface and subsurface temperature anomaly, the AMOC variations inferred from the observed detrended TNA subsurface temperature anomaly independently are in phase with the TNA SST anomaly, indicating that the AMOC variations have played a role in the *phases* of observed multidecadal TNA SST variations. The contribution of AMOC variations to the amplitude of the TNA SST variations is unclear. Both changes in the radiative forcing and AMOC variations might contribute to the amplitude on the same order. The AMOC-induced TNA SST anomaly might be underestimated in MODEL_WH and increase with improved higher resolution models [*Zhang and Delworth*, 2005]. A quantitative attribution of contributions to the amplitude of the TNA SST variations between the two debated factors using modeling results here is not meaningful, due to the uncertainties of changes in the radiative forcing applied and the uncertainties of modeled amplitudes of SST anomaly driven by the radiative forcing and freshwater forcing. The quantitative attribution would be possible if the uncertainties are significantly suppressed with improved future observational and modeling efforts. Various mechanisms proposed for the multidecadal TNA SST variations, which are crucial for multidecadal variations of Atlantic hurricane activities, should take into account the observed anticorrelation between the TNA surface and subsurface temperature variations.

[15] The observed multidecadal variations of the TNA surface and subsurface temperature and the subpolar North Atlantic SSS are of the same order of magnitude as their own long-term trends respectively over the same period (Figures S1 and S2). The observed long-term warming trend of the TNA SST is well simulated by MODEL_20C3M (Figures S1a and S1c), indicating that tropical SST trends are dominated by the radiative forcing associated with increasing greenhouse gases. The long-term TNA subsurface warming trend may also be induced by the anthropogenic warming through slow diffusion and subduction processes (Figures S1b and S1d). The long-term freshening trend over the subpolar North Atlantic surface (Figure S2) may have contributed to the long-term slowdown of the AMOC [*Bryden et al.*, 2005]. However, observations of the Deep Western Boundary Current east of the Grand Banks show no basinwide AMOC slowdown in the recent decade [*Schott et al.*, 2006]. Contrary to the rapid surface warming, there is a rapid subsurface cooling in the TNA in the recent decade, when long-term trends are removed (Figure 1a), indicating a plausible strengthening in the AMOC since the mid 70's, which might have compensated the long-term slowdown trend. Both the multidecadal variability and the long-term trend of the AMOC should be considered for projections of future climate change.

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