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Can the Atlantic Ocean drive the observed multidecadal variability in Northern Hemisphere mean temperature?

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[1] While the Northern Hemisphere mean surface temperature has clearly warmed over the 20th century due in large part to increasing greenhouse gases, this warming has not been monotonic. The departures from steady warming on multidecadal timescales might be associated in part with radiative forcing, especially solar irradiance, volcanoes, and anthropogenic aerosols. It is also possible that internal oceanic variability explains a part of this variation. We report here on simulations with a climate model in which the Atlantic Ocean is constrained to produce multidecadal fluctuations similar to observations by redistributing heat within the Atlantic, with other oceans left free to adjust to these Atlantic perturbations. The model generates multidecadal variability in Northern Hemisphere mean temperatures similar in phase and magnitude to detrended observations. The results suggest that variability in the Atlantic is a viable explanation for a portion of the multidecadal variability in the Northern Hemisphere mean temperature record. **Citation:** Zhang, R., T. L. Delworth, and I. M. Held (2007), Can the Atlantic Ocean drive the observed multidecadal variability in Northern Hemisphere mean temperature?, *Geophys. Res. Lett.*, *34*, L02709, doi:10.1029/2006GL028683.

1. Introduction

[2] The warming of the 20th century Northern Hemisphere mean surface temperature (NHT) has not been monotonic, even when smoothed by a 10–20 year low-pass filter. As is well-known, temperatures reached a relative maximum near mid-century, from which they cooled into the 1970's, after which warming recommenced. Radiative forcings due to solar variations, volcanoes, and aerosols have often been invoked as explanations for this non-monotonic variation [*Stott et al.*, 2000]. Internal variability is another possible contributor to such hemispheric multidecadal variability. The Atlantic Ocean is typically considered as the mostly likely source of internal variability on this time-scale, through interactions between the poleward heat and salt fluxes due to the thermohaline circulation (THC), the deep convective activity in the subpolar Atlantic, and the export of sea ice from the Arctic [*Delworth et al.*, 1997; *Dima and Lohmann*, 2007]. It has been shown that Atlantic sea surface temperature (SST) variations have significant impacts on the multidecadal climate variability over North America and Europe [*Sutton and Hodson*, 2005]. The question is whether the Atlantic variations are strong enough to contribute significantly to NHT variability. In support of the plausibility of this mechanism, *Knight et al.* [2005] find in the HadCM3 climate model that variations in the Atlantic THC are correlated with variations in NHT and global mean surface temperature at low frequency. Regression with the THC yields 0.09 ± 0.02 K/Sv (1 Sv = 10^6 m^3/s) for the NHT and a smaller global mean signal of the same sign (0.05 ± 0.02 K/Sv) in their model, values large enough to make these Atlantic variations one possible source of the non-monotinicity in these hemispheric and global temperature indices.

[3] In this paper, we use a coupled ocean-atmosphere model recently developed at the Geophysical Fluid Dynamics Laboratory of NOAA (GFDL) to further explore this potential role of Atlantic variability in the multidecadal variation of 20th century NHT. By redistributing heat within the Atlantic ocean of our climate model, we constrain the model to follow the observed, detrended multidecadal variations in the North Atlantic during the 20th century. This model generates variations in NHT similar to those obtained by detrending the observations. The results indicate that it is possible that Atlantic multidecadal variability has played an important role in the non-monotonic NHT evolution during the 20th century. They also imply that one cannot infer from the high correlation between the observed multidecadal variability in detrended NHT and the North Atlantic that the latter is necessarily directly forced by external radiative perturbations.

2. Model Descriptions

[4] The model used is the latest version of the GFDL global coupled ocean-atmosphere model (CM2.1; see http://nomads.gfdl.noaa.gov/CM2.X) [*Delworth et al.*, 2006]. In order to evaluate the global-scale impact of Atlantic multidecadal temperature fluctuations, we construct a modified version of CM2.1, in which the fully dynamic ocean component over the Atlantic (34°S–66°N) is replaced by a slab with uniform heat capacity, interacting with the atmosphere only through exchanges of surface heat fluxes. Ocean basins outside the Atlantic remain fully dynamic. A climatological heat flux adjustment representing the effect of horizontal heat transport convergence in the ocean and heat exchange between the surface and deep ocean is prescribed over the slab Atlantic so as to maintain observed seasonally varying SSTs. This climatological heat flux is then perturbed with a prescribed anomalous heat flux that redistributes heat meridionally only within the Atlantic with zero spatial integral. The anomalous heat flux is of the form $A(t)B(x, y, \tau)$, with a spatial pattern $B(x, y, \tau)$ that is a function of time of year τ, but with a time-dependent amplitude $A(t)$ designed to force the model to approximate

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the observed detrended multidecadal SST variability in the Atlantic from 1901 to 2000. This perturbation can be thought of as imposing a time series of anomalous northward Atlantic ocean heat transport across the equator. An ensemble of 10 simulations is generated. All radiative forcings are kept constant at their 1860 levels. We refer to the simulations using this modified model as the 'Atlantic-Constrained Experiment (ACE)'. The detailed experimental setup is described by *Zhang and Delworth* [2006], where the effects of the imposed heat redistribution within the Atlantic on the tropical circulation, Sahel summer rainfall, and the Indian summer monsoon are described. *Zhang and Delworth* [2006] also describe how the ensemble mean of the SST anomalies averaged over the entire North Atlantic in these simulations agrees in phase and amplitude with the observed detrended area mean SST anomalies in this region, helping to validate the experimental design.

[5] For comparison with these ACE simulations, we also discuss an ensemble of 5 simulations conducted with CM2.1, using estimates of changes in climate forcing agents (solar irradiance, volcanoes, anthropogenic greenhouse gases, ozone, aerosols, and land cover) from 1861 to 2000 [*Knutson et al.*, 2006], as made available to the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment (AR4). We refer to these as the 'Radiatively Forced Experiment (RFE)'.

3. Comparing Modeling Results With Observations

[6] For the observational analyses, a linear trend has been removed over the period 1901–2000. Removing a second, third, or fourth order polynomial gives qualitatively similar results. It should be emphasized that the detrending does not necessarily decompose the time series into forced and internal variability components. Here we consider the limiting case in which redistribution of heat within the Atlantic forces in full the deviations from linearity. In reality, it is likely that both internal variability and radiative forcing contribute to the observed deviations.

[7] The observed detrended annual mean northern hemispheric mean surface temperature time series (hereinafter, DNHT) is shown in Figure 1a. Surface temperature over land is from CRU-TS_2.1 data, Climate Research Unit, University of East Anglia, United Kingdom; SST over ocean is from HADISST data [*Rayner et al.*, 2003]. Also shown in Figure 1a are the results from ACE (after applying a low-pass filter to both time series, with a frequency response that drops to 50% at the 10-year cutoff period; all subsequent time series are similarly filtered). The modeled DNHT is in phase with the model's North Atlantic multidecadal variations, which, in turn, follow the observed detrended North Atlantic variations by experimental construction. The specified North Atlantic variability in ACE is capable of generating DNHT of similar phase and magnitude as observed, and the observed DNHT generally remains within one standard deviation (as estimated from the 10 ensemble members) of the modeled ensemble mean (Figure 1a).

[8] We have also calculated the DNHT with the North Atlantic excluded. Both observed and modeled ensemble mean time series are similar to those shown in Figure 1a. The ratio of the standard deviation of the filtered DNHT time series with the North Atlantic excluded to that with the North Atlantic included ranges from 0.93 to 1.02 for different ensemble members, while it is 1.00 for the observation.

[9] Figure 1b compares the same observed DNHT signal with the ensemble mean from the Radiatively Forced Experiment (RFE). The ensemble mean serves to remove much of the internal variability, thus providing an estimate of the role of radiative forcing in producing the non-monotonic NHT evolution. This model generates a forced signal that also has similar phase and amplitude to the observations. These results clearly illustrate the difficulty of separating effects of Atlantic variability and radiative forcing from the observational record of DNHT.

[10] The DNHT signal in Figures 1a and 1b is averaged over both land and ocean. Figures 1c and 1d also shows the DNHT signals averaged only over northern hemisphere (NH) land, and only over NH ocean respectively. For both modeling results (ACE and RFE), the land-only mean and ocean-only mean are very similar to the NH mean over both land and ocean. The observed land-only mean and ocean-only mean differ somewhat in phase and amplitude. The agreement with ACE is better over ocean, while the agreement with RFE is better over land.

[11] The Southern Hemisphere (SH) mean surface temperature does not respond as strongly as the NH to the imposed multidecadal Atlantic variability in ACE; the SH/NH ratio of the standard deviations range from 0.49 to 1.09 in the ensemble, with a mean of 0.72. The detrended response of the SH mean surface temperature is also small in RFE; we find a range of 0.39 to 0.64 with a mean of 0.52 for the SH/NH ratio of the standard deviations. These can be compared to the value of 0.42 in the observations. The multidecadal variability of the detrended SH mean temperature is smaller than that for the NH in both observations and modeling results, although the ratio in ACE is somewhat larger than observed. This may suggest that some fraction of this multi-decadal signal is, in fact, generated by NH-centered radiative forcing, but we also suspect that this ratio can be sensitive to the meridional distribution of the imposed heat transport in the Atlantic Ocean. Despite this discrepancy, the SH responses are small enough that, as shown in auxiliary material[1] Figures S1a and S1b, the observed multidecadal variations of detrended *global* mean surface temperature generally match with the modeling results from ACE and as well as from RFE.

[12] Figure 2 shows the geographical pattern of the surface temperature difference, after detrending, between the relatively cool period of 1961–1990 and the relatively warm period of 1931–1960 (displayed as cool minus warm). Over the North Atlantic the ensemble mean of ACE (Figure 2b) has a similar spatial pattern as that observed (Figure 2a), a result of the experimental design. The cooling spreads over the Northern continents bounding the North Atlantic (especially eastern North America and Europe (Figure 2b)). The modeled warming over the Sahel region from ACE is mainly due to reduced rainfall associated with a southward shift of the Intertropical Convergence

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2006GL028683.

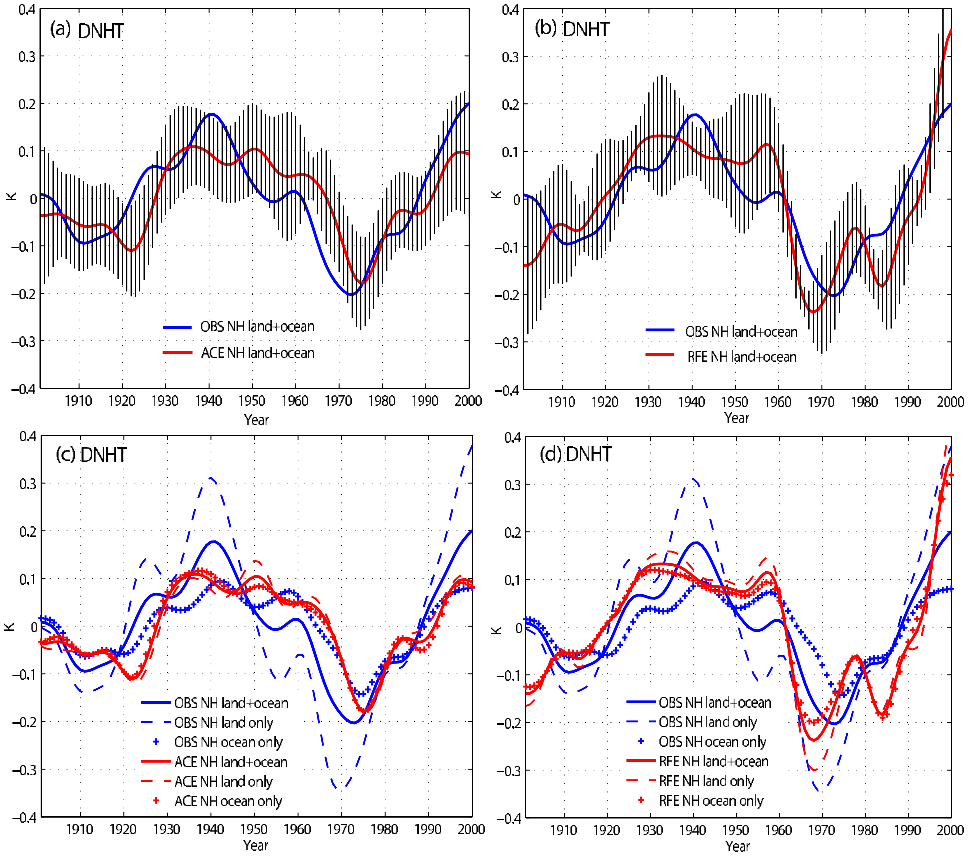

Figure 1. Observed and modeled low-pass filtered annual mean time series. (a) Ensemble mean ACE detrended northern hemispheric (NH) mean surface temperature (K) (over both land and ocean) compared to observations. (b) Same as Figure 1a but for RFE. (c–d) Same as Figures 1a and 1b but also including detrended NH mean surface temperature time series (K) only over land, and only over ocean. Observed surface temperature over land is from CRU-TS_2.1 data, Climate Research Unit, University of East Anglia, United Kingdom; SST over ocean is from HADISST data [*Rayner et al.*, 2003]. The areas covered with black lines show the ±1 standard deviation about the ensemble mean calculated from 10 members of ACE in Figure 1a and 5 members of RFE in Figure 1b, respectively. The Matlab function 'filtfilt' was used for zero-phase filtering of all time series in this paper, with a Hamming window based low-pass filter and a frequency response that drops to 50% at the 10-year cutoff period. To reduce end effects, the beginning and end of the time series are extrapolated to have zero slopes at the end points.

Zone generated by the North Atlantic cooling [*Zhang and Delworth*, 2006]. The ensemble mean of RFE (Figure 2c) shows a more uniform cooling over the northern hemisphere. Over northernmost Asia, neither experiment captures the observed warming, indicating a model deficiency or that some other mechanism not included in the models might also have contributed to this observed warming over northernmost Asia. As shown in auxiliary material Figures S2 and S3, the individual ACE ensemble members show substantial differences in their spatial patterns. In particular, some realizations generate warming over Northern Asia.

[13] We do not attempt here the challenging task of using the observed spatial pattern of this cooling episode to test which of these two ensembles fits best with the observed pattern. To be physically relevant, a spatial fingerprinting study will have to take into account the uncertainty in the radiative forcing as well as the uncertainty in the heat redistribution within the Atlantic that we impose. Our concern here is to focus on NHT so as to motivate more detailed studies of this sort, and in the process demonstrate that one cannot infer from the high correlation between the observed multidecadal variability in DNHT and detrended North Atlantic SSTs that the latter is necessarily predominantly forced by external radiative perturbations.

[14] Although both types of modeling experiments produce a time series of DNHT similar to that observed, the underlying mechanisms are very different. In ACE, a pattern of heat flux anomalies is imposed over the slab North Atlantic, with a 3.4 W/m^2 annual mean area mean reduction between the cool period and the warm period. This corresponds to a reduction of the northward Atlantic ocean heat transport across the equator of 0.141 PW. The specified heat flux change over the slab North Atlantic is closely balanced by the change in the net surface air-sea heat flux given the low frequencies considered and modest heat capacity of the slab. The anomalous Northern Hemispheric mean surface heat uptake (0.121 PW) is dominated by the North Atlantic contribution (0.141 PW), with much smaller amount of heat extracted from the North Pacific (0.011 PW) and North Indian oceans (0.006 PW) (Figure 3). One might expect with the colder mean temperature that part of this flux perturbation over the northern hemisphere surface would be

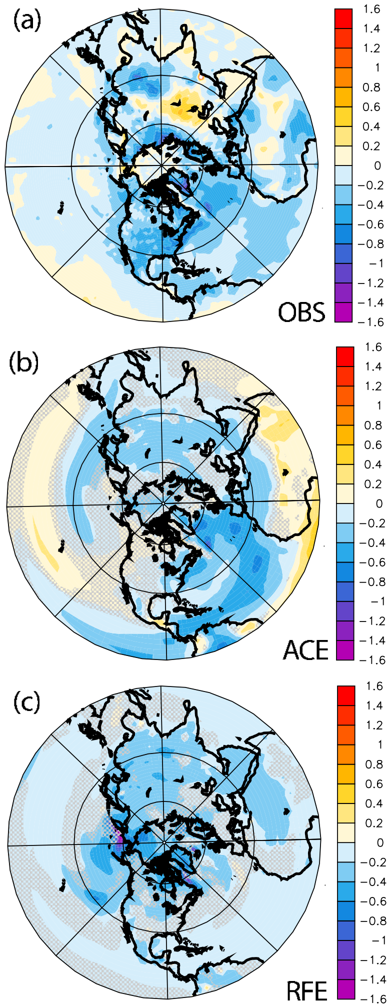

Figure 2. Detrended northern hemispheric annual mean surface temperature difference (K) between the cold period (1961–1990) and the warm period (1931–1960): (a) observation, (b) ensemble mean ACE, and (c) ensemble mean RFE. The values at the stippled areas are not statistically significant at the 90% level with the 2-tailed Student's *t*-test. Estimate of variance of the detrended northern hemispheric surface temperature difference is based on 20 non-overlapping 100-yr segments from the 2000-year control runs of CM2.1 (assumed independent).

balanced by an increase in the net downward radiative flux at the top of the atmosphere. Instead, we find that the net radiation at the top of the atmosphere provides a positive, albeit small, feedback (0.016 PW upward flux integrated over the northern hemisphere) with the imbalance primarily accounted for by an increase in the zonal-integrated northward atmospheric heat transport (0.137 PW) across the equator (Figure 3). In ACE, the reduction in the northward cross-equatorial ocean heat transport is mainly compensated by an increase in the northward cross-equatorial atmospheric heat transport.

[15] The above processes are in contrast to the results from RFE, in which net radiation changes at the top of the atmosphere integrated over the northern hemisphere cool the system during the cool period by 0.061 PW as compared to the warm period. To balance this heat perturbation at the top of the atmosphere, a total of 0.044 PW of heat is extracted from the Northern Hemisphere surface (mainly from the North Atlantic, North Pacific, and North Indian oceans), and the change in the cross-equatorial northward atmospheric heat transport is much smaller (Figure 3).

[16] We have conducted additional idealized integrations with a model in which the entire ocean is replaced by a slab model. The global integral of the imposed heating at the base of the slab was constrained to be zero but its distribution was altered in the different experiments, to study the importance of the spatial structure of the heating on the resulting temperature response. In these perturbed experiments, a total heating (0.2 PW) was applied over either the tropical or extratropical North Atlantic; the compensating cooling was applied over either the rest of the globe, or over the South Atlantic alone. Preliminary results suggest that heating over the North Atlantic extratropics appears to be effective in warming NHT. A pattern of *extratropical* North Atlantic heating compensated by uniform cooling elsewhere results in the same sign response in NHT to that in ACE (Figure 4a). The spatial pattern shown in Figure 4 is computed as the 40-yr-averaged differences between the control and perturbed experiments (Control-Perturbed). A warmer midlatitude ocean leads to a reduction of low cloud cover and an increase in absorbed shortwave radiation in the model. The fact that cloud feedback appears to play some role in the large-scale temperature response to oceanic heat redistribution is an important caveat to these results, since the ability of models to realistically simulate clouds and their response to forcing changes is highly uncertain.

[17] These all-slab ocean integrations also suggest that the pattern of SH surface temperature response is sensitive to the manner in which the compensating heat flux is distributed spatially. In particular, if one compensates the extratropical North Atlantic heating uniformly over the South Atlantic alone, there is a strong response over the South Atlantic (Figure 4d); if the compensating heat flux is uniformly distributed over the rest of the globe, the South Atlantic response is greatly reduced, and the pattern of SH surface temperature response is very different (Figure 4b). However, in both experiments the NH surface temperature responses (Figures 4a and 4c) show very similar sign and

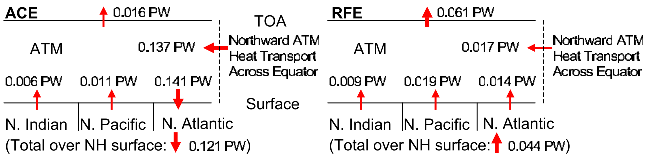

Figure 3. Schematic diagram of Northern Hemisphere annual mean heat flux change across the surface, top of the atmosphere (TOA), and equator between the cool (1961–1990) and warm period (1931–1960) from (left) ACE and (right) RFE. The downward (upward) arrow across the Surface corresponds to a net heat taken from (released into) the atmosphere. The horizontal arrow across the vertical dash line refers to the zonal-integrated northward atmospheric (ATM) heat transport across the equator. For the heat flux change in RFE, the trend of the 20th century is removed before the calculation.

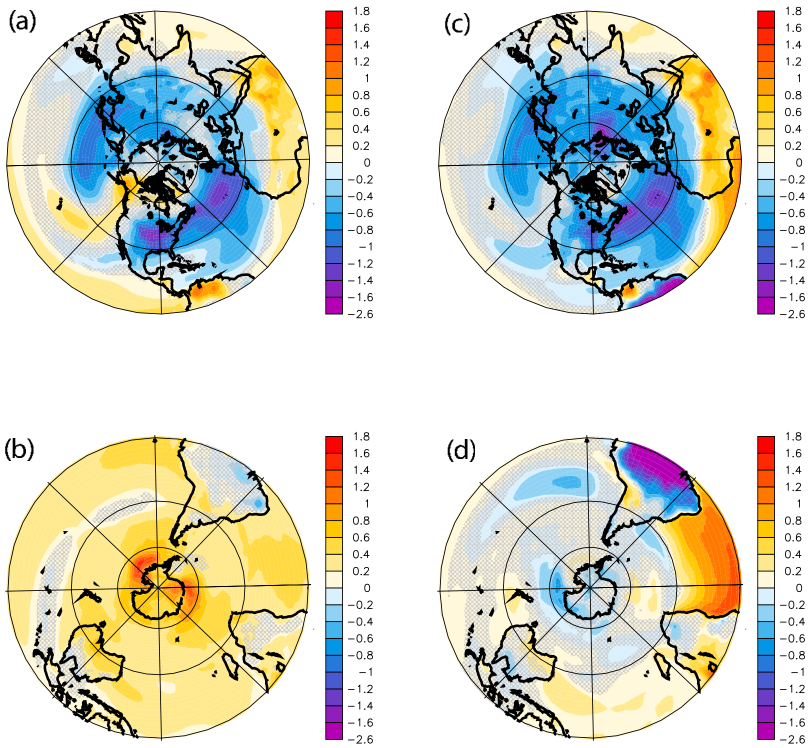

Figure 4. Annual mean surface temperature differences (K) between the control and perturbed experiments (Control-Perturbed) using the slab ocean model (40-yr-average). (a–b) Total heating (0.2 PW) was uniformly applied over extratropical North Atlantic (30–60°N); the compensating cooling was uniformly applied over the rest of the globe in the perturbed experiment. (c–d) Total heating (0.2 PW) was uniformly applied over extratropical North Atlantic (30–60°N); the compensating cooling was uniformly applied over the South Atlantic (0–30°S) alone in the perturbed experiment. Figures 4a and 4c display the Northern Hemisphere; and Figures 4b and 4d display the Southern Hemisphere, respectively. The values at the stippled areas are not statistically significant at the 90% level with the 2-tailed Student's *t*-test.

pattern to the ACE results (Figure 2b), suggesting that the NH surface temperature response is robust and not very sensitive to the spatial distribution of the compensating heat flux and the SH response.

[18] The ACE simulations generate strong correlations between North Atlantic and South Atlantic multidecadal variability, similar to that shown in Figures 4c and 4d. Each member of the ensemble produces a negative correlation, whereas the observed correlation for the detrended, low-pass filtered North and South Atlantic means is slightly positive. This disagreement potentially provides evidence against the dominance of the Atlantic variability mechanism. However, these all-slab ocean integrations suggest that this model deficiency might be alleviated by using a different structure in the heat compensation. They also suggest that the NH response is not very sensitive to the pattern of compensation in the SH. Simulations in which the North Atlantic is forced by fresh water perturbations also typically show a smaller SH response than in the ACE ensemble [*Zhang and Delworth*, 2005]. The design of the ACE simulations does not allow us to modify the oceanic heating outside of the Atlantic, and evidently results in unrealistically large South Atlantic SST anomalies.

4. Conclusion and Discussion

[19] Understanding the causes of the multidecadal departures from monotonic warming is important for the prediction of future climate change. In this paper, we find that a model in which Atlantic multidecadal variations are specified is capable of producing a time series of detrended northern hemispheric mean surface temperature with similar phase and amplitude as observed, as a result of a simple meridional redistribution of heat within the Atlantic. Our results reinforce the result of *Knight et al.* [2005] that Atlantic multidecadal variability can potentially play an important role in the evolution of Northern Hemisphere mean temperatures. Our methodology is different from Knight et al.; rather than focusing on a freely running coupled model, we manipulate the heat redistribution in the Atlantic Ocean so as to match the observed time series of detrended Atlantic temperatures, and then find that the model matches the detrended northern hemisphere mean surface temperatures as well.

[20] In the Atlantic-Constrained Experiment (ACE), the implied Atlantic ocean heat transport reduction across the equator between the cool period and the warm period is 17.5% of the observed climatological Atlantic ocean heat transport across the equator (0.8 PW) [*Trenberth and Caron*, 2001]. Assuming a linear relationship between this heat transport and the Atlantic THC strength, and given the estimate of the climatological Atlantic THC of about 18 Sv [*Talley et al.*, 2003], the implied Atlantic ocean heat transport reduction across the equator in ACE corresponds to ~3 Sv. The cooling (0.14 ± 0.07 K) in the northern hemispheric mean surface temperature between these two

periods produced by ACE indicates a sensitivity of ~0.050 ± 0.02 K/Sv (here the uncertainty is one standard deviation estimated from the 10 ensemble members), on the same order but smaller than that found with the HadCM3 model [*Knight et al.*, 2005].

[21] We find in supplementary experiments with a slab ocean model that heating over the North Atlantic extratropics is particularly effective in influencing Northern Hemisphere surface temperatures. The NH surface temperature response in this model is not very sensitive to the spatial distribution of the compensating heat flux in the SH and thus to the SH temperature response. Preliminary analysis suggests that cloud feedbacks appear to play some role in this response, and uncertainties in cloud feedbacks may be very relevant to the robustness of these results.

[22] Nothing in our results suggests that the underlying long-term warming trend has a significant component due to internal Atlantic variability. In ACE, the southern hemispheric variability is smaller than the northern hemispheric variability, and the North and South Atlantic variability are out of phase. In contrast, the observed century-long warming trends are comparable in magnitude in the two hemispheres and are of the same sign in the North and South Atlantic. A comparison of observations and modeling results of the long-term warming trends in the fully coupled model are described by *Knutson et al.* [2006]. Our results are directed towards understanding the low-frequency departures of the Northern Hemisphere mean temperature from a uniform warming trend.

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References

Delworth, T. L., S. Manabe, and R. J. Stouffer (1997), Multidecadal climate variability in the Greenland Sea and surrounding regions: A coupled model simulation, *Geophys. Res. Lett.*, *24*, 257–260.

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

Dima, M., and G. Lohmann (2007), A mechanism for the Atlantic multidecadal variability, *J. Clim.*, in press.

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.

Knutson, T. R., et al. (2006), Assessment of twentieth-century regional surface temperature trends using the GFDL CM2 coupled models, *J. Clim.*, *10*, 1624–1651.

Rayner, N. A., D. E. Parker, E. B. Horton, C. K. Folland, L. V. Alexander, D. P. Rowell, E. C. Kent, and A. Kaplan (2003), Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century, *J. Geophys. Res.*, *108*(D14), 4407, doi:10.1029/2002JD002670.

Stott, P. A., S. F. B. Tett, G. S. Jones, M. R. Allen, J. F. B. Mitchell, and G. J. Jenkins (2000), External control of 20th century temperature by natural and anthropogenic forcings, *Science*, *290*, 2133–2137.

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

Talley, L. D., J. L. Reid, and P. E. Robbins (2003), Data-based meridional overturning streamfunctions for the global ocean, *J. Clim.*, *16*, 3213–3226.

Trenberth, K. E., and J. M. Caron (2001), Estimates of meridional atmosphere and ocean heat transports, *J. Clim.*, *14*, 3433–3443.

Zhang, R., and T. L. Delworth (2005), Simulated tropical response to a substantial weakening of the Atlantic thermohaline circulation, *J. Clim.*, *18*, 1853–1860.

Zhang, R., and T. L. Delworth (2006), Impact of Atlantic multidecadal oscillations on India/Sahel rainfall and Atlantic hurricanes, *Geophys. Res. Lett.*, *33*, L17712, doi:10.1029/2006GL026267.

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