A signature of persistent natural thermohaline circulation cycles in observed climate

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[1] Analyses of global climate from measurements dating back to the nineteenth century show an 'Atlantic Multidecadal Oscillation' (AMO) as a leading large-scale pattern of multidecadal variability in surface temperature. Yet it is not possible to determine whether these fluctuations are genuinely oscillatory from the relatively short observational record alone. Using a 1400 year climate model calculation, we are able to simulate the observed pattern and amplitude of the AMO. The results imply the AMO is a genuine quasi-periodic cycle of internal climate variability persisting for many centuries, and is related to variability in the oceanic thermohaline circulation (THC). This relationship suggests we can attempt to reconstruct past THC changes, and we infer an increase in THC strength over the last 25 years. Potential predictability associated with the mode implies natural THC and AMO decreases over the next few decades independent of anthropogenic climate change. **Citation:** 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.

1. Introduction

[2] The AMO [*Kerr*, 2000] is a coherent pattern of multidecadal variability in surface temperature centred on the North Atlantic Ocean. It has been linked with the occurrence of Sahel drought [*Folland et al.*, 1986; *Rowell et al.*, 1995], variability in Northeast Brazilian rainfall [*Folland et al.*, 2001], North American climate [*Sutton and Hodson*, 2005] and river flows [*Enfield et al.*, 2001], and the frequency of Atlantic hurricanes [*Goldenberg et al.*, 2001]. Marked fluctuations of this pattern occurred in the 20th century, with intervals between successive peaks and troughs of roughly 65 years [*Schlesinger and Ramankutty*, 1994; *Mann and Park*, 1994]. A link with variability in the THC has been suggested [*Delworth and Mann*, 2000], as the mean THC transports sufficient heat northward (~1.2 PW at 30°N) [*Ganachaud and Wunsch*, 2000] to warm the Northern Hemisphere by several °C [*Vellinga and Wood*, 2002]. Assessments of whether the AMO is a long-lived phenomenon, and whether it is related to the THC, are hindered by relatively short global climate records and insufficient subsurface ocean data. Palaeoclimate proxies suggest AMO variability extending back over several centuries [*Mann et al.*, 1995; *Gray et al.*, 2004], but these have uncertainties [*Folland et al.*, 2002]. As such, long simulations from numerical climate models are needed to investigate multidecadal variability. Spatially coherent modes have been found in some models [*Delworth et al.*, 1993; *Timmermann et al.*, 1998; *Delworth and Mann*, 2000], although with limited success in capturing the pattern of the AMO. Here we look for the AMO and THC links in a 1400 year simulation with the HadCM3 climate model [*Gordon et al.*, 2000], isolating internal variability by using constant levels of external climate forcing.

2. The Observed AMO

[3] Characteristic AMO fluctuations can be seen in a multidecadal index of mean North Atlantic sea-surface temperature (SST) anomalies (Figure 1a), similar to that used by *Enfield et al.* [2001] and *Sutton and Hodson* [2005]. AMO variability is pronounced: its range (0.49°C) is larger than either the range of interannual to decadal variability (0.46°C) or the integrated trend over the period 1870–1999 (0.38°C). The index shows persistent warm (pre-1900, 1930s–1950s) and cool (1900s–1920s, 1960s–1980s) phases typically lasting a few decades, as well as the onset of a warm phase in the 1990s. Significant associations exist between North Atlantic SSTs and surface temperatures in other regions (Figure 1b). Our analysis reproduces the link with parts of the North Pacific shown by *Enfield et al.* [2001] and *Sutton and Hodson* [2005] using SST data alone. Combined land and sea data, however, indicates additional links with temperatures over western North America, Europe and Africa, and southern Asia, suggesting the AMO is coherent over much of the northern hemisphere. Southern hemisphere links, in contrast, show generally less significance and lack a clear pattern.

3. Simulated THC and Climate

[4] To examine the behaviour of the 1400 year simulation, we gauge the strength of the simulated THC as the maximum of the zonal mean meridional overturning streamfunction in the Atlantic at 30°N, close to the latitude of maximum Atlantic northward heat transport (Figure 2a). The average decadal mean THC (16.4 Sv) (1 Sv $\equiv 10^6 m^3 s^{-1}$) and meridional heat transport at 30°N (0.96 PW) compare well with observational estimates [*Ganachaud and Wunsch*, 2000], and are highly correlated with a coefficient of 0.81. Wavelet analysis [*Torrence and Compo*, 1998] of the

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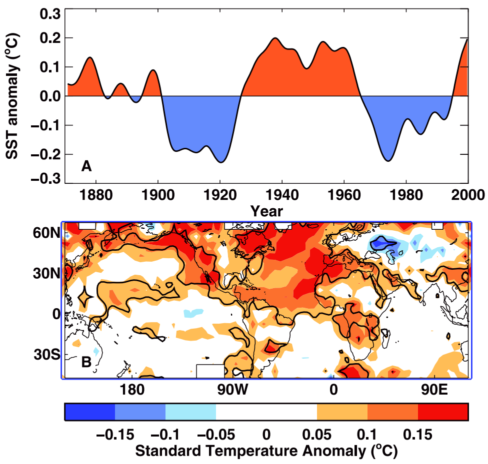

Figure 1. (a) AMO index derived from detrended area-weighted mean North Atlantic SST anomalies by using a Chebyshev filter with a half-power period of 13.3 years. SST data are from the HadISST data set [*Rayner et al.*, 2003]. (b) Surface temperature anomaly associated with one positive standard deviation of the AMO index, calculated by regression of surface temperatures with the index and scaled by its standard deviation. Combined land and sea-surface temperature data are from an optimally interpolated version of the HadCRUTv data set [*Jones et al.*, 2001]. The solid contour bounds regions significant at the 90% limit of a two-sided t-test accounting for auto-correlation using the method of *Folland et al.* [1991].

THC index (Figure 2b) shows a band of significant variability near periods of 100 years persisting through most of the simulation, indicating the model produces many cycles of a repeating mode of THC variability with this time scale. This is confirmed by the THC power spectrum (Figure 2c), which shows significant power between 70 and 120 years.

[5] The climate signal associated with the centennial THC mode is detected using a joint MTM-SVD [*Mann and Park*, 1994, 1999] analysis of the decadal overturning streamfunction and surface temperature (Figure 3). This technique derives the patterns of significant modes of covariability at phases of a typical cycle within frequency bands. Similarity between the mean streamfunction and its variability shows the THC mode represents changes in the speed of the entire circulation. This is associated with a coherent large-scale temperature pattern with widespread warm anomalies in the Northern Hemisphere when the THC is at a maximum. This pattern first diminishes (through 90°), then re-establishes in the opposite sense at a THC minimum (180°), when much of the Northern Hemisphere is anomalously cool. Comparison of the simulated positive phase (Figure 3a) with the observed positive AMO pattern (Figure 1b) shows considerable similarity in the North Atlantic and North Pacific Oceans, western North America, north-western Africa and the Mediterranean region. Where the patterns are of opposite sign, such as northern North America and central Eurasia, there is low significance in the observational analysis. The magnitudes of the observed and simulated variability are compared using decadal mean temperatures in the North Atlantic (0°–80°W, 0°–80°N). Standard deviations of 10 consecutive 130 year periods of simulated low-pass filtered (half power at about 45 years) mean temperatures range from 0.07 to 0.13°C, comparable with the 0.14°C derived from detrended observations.

[6] The regression of simulated global and Northern Hemisphere mean decadal temperatures with the THC are 0.05 ± 0.02 and 0.09 ± 0.02°C Sv^{-1} respectively, implying potential peak-to-peak variability of 0.1 and 0.2°C. Lagged correlations show both large in-phase covariability and anti-correlations at leads and lags of about 50 years (Figure 4a). Thus the simulated THC-AMO variability is quasi-periodic, evolving coherently for typically half a cycle; 50 years after a peak (trough) in the THC, statistically a cold (warm) phase would be anticipated.

4. THC Reconstruction and Forecast

[7] The likely link between the THC and the AMO implies historical climate can give a guide to past THC strength. Simulated northern North Atlantic SST anomalies are a good predictor of the THC anomaly (correlation of 0.71), but leave some residual variability (Figure 4b). The equivalent index calculated from observed SSTs was used as the predictor in the model-derived THC-SST relationship to reconstruct past THC variability, with the statistical limits of the residuals giving an estimate of uncertainty (Figure 4c). These limits show phases of strong (1950s and present day) and weak (1910s and 1970s) anomalies of definite sign at the level of confidence used (85% confidence interval). In addition, predictability of the simulated AMO and THC makes a model-based THC forecast for the next few decades possible. We use a method of analogues, seeking instances in the simulation when the decadal THC anomaly becomes larger than the reconstructed present-day level (0.63 Sv), and tracking its subsequent evolution. This produces an ensemble of 8 segments representing possible

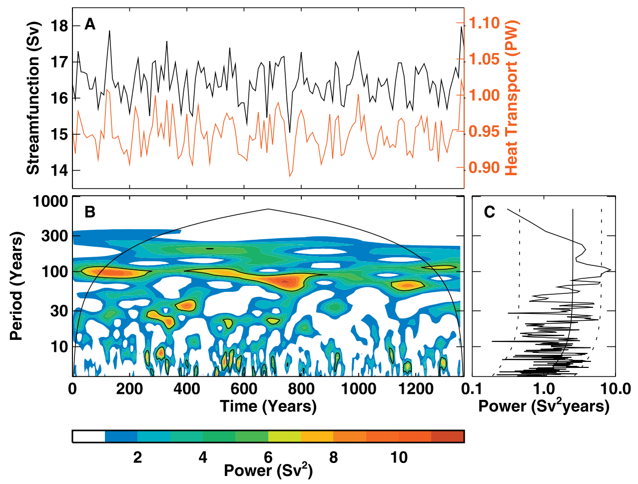

Figure 2. (a) Decadal mean THC index (black), and meridional heat transport at 30°N (red). (b) Wavelet analysis of the annual mean THC index using a continuous Morlet transform. Statistical significance at the 95% confidence interval is indicated by the contour. Curves bound the region where power is estimated from partial waves. (c) Power spectrum of the annual mean THC index. 95% confidence intervals are shown by the dashed curves.

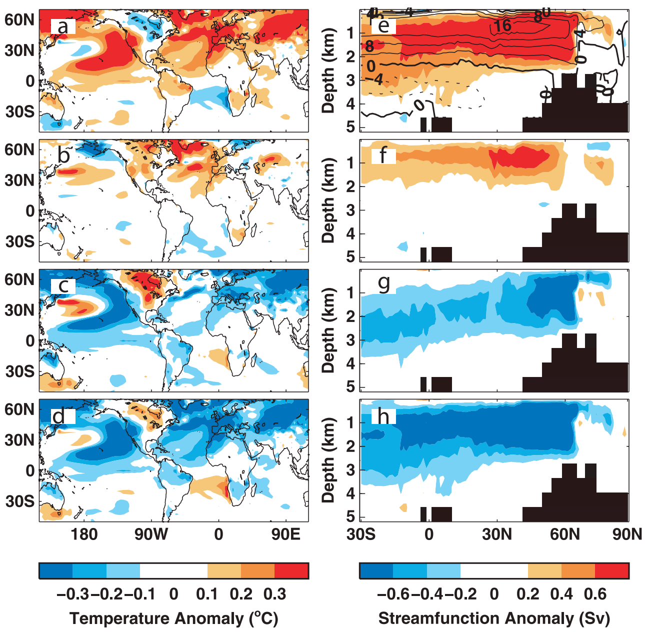

Figure 3. Joint MTM-SVD analysis of simulated decadal mean surface temperature and Atlantic overturning streamfunction for model years 400 to 900. Panels a–d show the signal in surface temperature anomaly in the frequency band from (70 years)$^{-1}$ to (180 years)$^{-1}$, at phases of 0°, 60°, 120°, 180° respectively. Zero phase corresponds to maximum mean Northern Hemisphere temperature. Panels e–h show the corresponding phases of the covarying signal in streamfunction anomaly in the same band. In panel e, the climatological streamfunction is shown by contours, such that the mean THC and anomalous THC strength are positive (clockwise). Negative contours are dashed.

THC strengths for the next 35 years (Figure 4c). All the members of this ensemble show a downturn in the strength of the THC within a decade of the present day, suggesting that the THC is currently at or near a peak and likely to diminish thereafter. Further, each analogue segment becomes negative in the next 3 decades, reaching an average minimum of −0.70 Sv, similar to reconstructed levels for the minima of the 1910s and 1970s.

5. Discussion and Conclusions

[8] Our 1400 year model simulation exhibits multidecadal climate variability with a similar pattern and amplitude to that of the AMO in observations. Together with the similarity of the simulated 70–120 year period to the observed 65 year period, and the range of periods derived from palaeodata (40–130 years) [*Delworth and Mann*, 2000; *Gray et al.*, 2004], this suggests the model simulates a realistic AMO. Its presence over many centuries in the model supports the suggestion from observations and proxy data that the AMO is a genuine repeating mode of global-scale internal climate variability. This is consistent with analyses showing the lack of a forced AMO signal in the ensemble of 1860–2000 HadCM3 simulations used by *Stott et al.* [2000], which otherwise accounts for almost all observed global-scale temperature variability by natural and anthropogenic forcings.

[9] The results also highlight the likelihood of a link between the AMO and the strength of the THC. Further evidence of this link comes from a 580 year experiment with a version of our model with the same atmospheric formulation but representing only the top 50 m of the ocean. This does not possess an AMO, demonstrating that the deep ocean is necessary to produce the AMO. The mechanism of the simulated AMO-THC mode is diagnosed fully by *Vellinga and Wu* [2004].

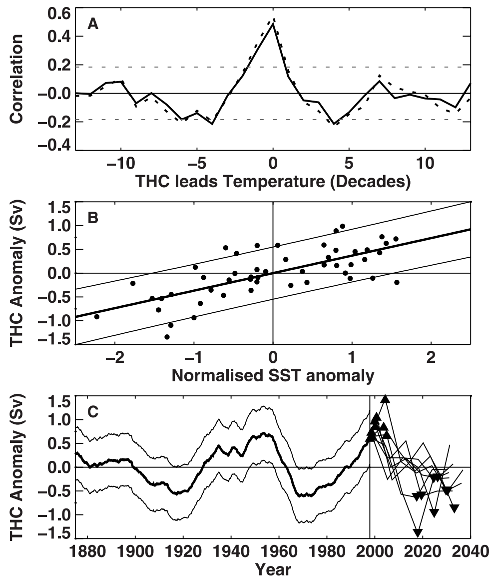

Figure 4. (a) Cross-correlations of decadal global (solid curve) and Northern Hemisphere (dotted) mean surface temperatures with the THC index for 1400 years of simulation. 95% confidence limits are shown as dotted horizontal lines. Negative values on the abscissa indicate temperature leading the THC. (b) Decadal THC anomalies (Sv) for the 50 decades used in Figure 3 as a function of a normalised index of mean northern North Atlantic SST anomaly (points). The index is an area-average (100°W–20°E, 35°–80°N) weighted by the local signal to noise variance ratio to reduce the influence of noisy marginal areas. The least-squares fit (thick line) is also a good fit for the remaining 900 years. 85% confidence intervals of the residuals are shown by thin curves. (c) Reconstruction of the THC (thick curve) and its uncertainty limits (thin curves), inferred using the regression and residual limits in Figure 4b and quadratically detrended running decadal mean SSTs from HadISST. The observed SSTs are weighted, meaned and normalised as the model SSTs. Dates refer to decadal mid-points. Also shown are the 8 forecast segments corresponding to the model THC after rises through the reconstructed 1993–2002 value (0.63 Sv). Assuming an AMO period closer to the 65 years estimated from observations than the 100 years in the simulation, the segments are contracted so 6 decades of model THC produce a forecast for 35 years. Upward- and downward-pointing triangles denote maxima and minima respectively of the THC ensemble members.

[10] The simulated temperature changes associated with THC variability cannot fully explain the 0.6°C of 20th century warming seen in both global and Northern Hemisphere mean temperature [*Folland et al.*, 2002], but are large enough to modify estimates of the rate of anthropogenic climate change. Such signals are even more significant in the pre-industrial era when variability was smaller [*Mann et al.*, 1995], and are of similar size to estimated very low frequency (>50 years) variability over the last millennium after accounting for external forcings [*Crowley*, 2000].

[11] The modelled AMO-THC link suggests we can make an SST-based reconstruction of past THC changes. This shows distinct strong and weak phases in the 20th century. Of particular note is the significant strengthening implied from the 1970s to the present day, suggesting that the observed North Atlantic deep freshening trend [*Dickson et al.*, 2002] and decreased strength of the Faroe bank channel overflow [*Hansen et al.*, 2001] are not linked with THC weakening [*Curry and Mauritzen*, 2005].

[12] The quasi-periodic nature of the model's AMO suggests that in the absence of external forcings at least, there is some predictability of the THC, AMO and global and Northern Hemisphere mean temperatures for several decades into the future. We utilise this to forecast decreasing THC strength in the next few decades. This natural reduction would accelerate anticipated anthropogenic THC weakening, and the associated AMO change would partially offset expected Northern Hemisphere warming. This effect needs to be taken into account in producing more realistic predictions of future climate change.

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