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Secular and multidecadal warmings in the North Atlantic and their relationships with major hurricane activity

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ABSTRACT: Analysis of recent literature finds weaknesses in arguments to the effect that the Atlantic multidecadal oscillation (AMO) – roughly 50–90 year fluctuations in North Atlantic sea surface temperatures – is externally forced by anthropogenic aerosols and greenhouse gases rather than an internal climate mode, plus indications from other sources that the contrary may be true. We are led to the conclusion that the AMO is probably comprised of both natural and anthropogenic forcing in ways that preclude a physically based separation of the two, using the limited historical data sets. A straightforward quadratic fitting of trend to temperature data accounts for some of the 20th century nonlinearity in secular warming and separates the secular and multidecadal components of variability without inherent assumptions about the nature of the multidecadal fluctuations. Doing this shows that the 20th century secular ocean warming in the North Atlantic is about equal to the peak-to-peak amplitude of the multidecadal fluctuations. However, over the last quarter-century (1975–2000) the most recent multidecadal warming has been almost three times the secular sea surface temperature (SST) increase over the main development region (MDR) for major Atlantic hurricanes. In the last quarter-century the multidecadal increase in late summer Atlantic warm pool (AWP) size (area of SSTs in excess of 28 °C) has been 36%, and the secular increase, 14%. Projections to the year 2025 show that the cumulative change in summer warm pool size since 1975 will depend critically on whether a subsequent cooling in the multidecadal cycle occurs, comparable to the warming between 1975 and 2000 AD. This places a high premium on understanding to what extent the AMO is a man-made or a natural phenomenon. Copyright © 2009 Royal Meteorological Society

KEY WORDS Atlantic multidecadal oscillation; Atlantic hurricane activity; anthropogenic global warming

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1. Introduction

Multidecadal modulations of the global surface temperature record in the 20th century have alternately exaggerated or de-emphasized, over shorter periods, the century-long secular increase in temperature that has been increasingly attributed to anthropogenic global warming (AGW) (Intergovernmental Panel on Climate Change – IPCC; Houghton *et al*., 2001). Schlesinger and Ramankutty (1994) and Andronova and Schlesinger (2000) identified similar multidecadal variations in sea surface temperature (SST) as being most pervasive and energetic in the North Atlantic and showed that a global climate model forced only by external factors such as greenhouse gases and solar variations cannot reproduce the Atlantic variability, suggesting that they must arise instead from internal interactions of the climate system. These 20th century variations have since been called the Atlantic multidecadal oscillation (AMO; Kerr, 2000) and the AMO associations with Western Hemisphere rainfall, river flows and hurricanes have been documented by Folland *et al.* (1986); Rowell *et al.* (1995); Enfield *et al.* (2001); Folland *et al.* (2001); Goldenberg *et al.* (2001); McCabe *et al.* (2004); Sutton and Hodson (2005) and Knight *et al.* (2006). In the context of explaining the increase in major hurricane activity in the last decade several new studies have pointed to the possibility that the AMO is not a natural climate oscillation, but rather is forced by variable external factors related to AGW (Elsner, 2006; Mann and Emanuel, 2006; Trenberth and Shea, 2006). The nature of the AMO is a crucial question because it bears in a significant way on the sensitivity of droughts and hurricanes to AGW and on the proper separation of the secular warming from multidecadal fluctuations. In this paper we review the evidence from research in the past decade as it bears on this question, leading to a reformulation of how the secular and multidecadal components of the SST record may be separated so as to properly address their relative contributions to climate impacts.

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2. The case for external forcing

The traditional definition for the AMO index is the area average of SST over the North Atlantic (0–70 °N) with a linear trend removed (Enfield *et al.*, 2001). However, as argued by Trenberth and Shea (2006), it is probable that the actual trend associated with AGW is nonlinear, with an increasing warming rate in recent decades. Accordingly, they 'remove' the AGW signal by subtracting the global average SST time series (GSST) from the North Atlantic average. Doing so yields a detrended multidecadal residual with about 2/3 the amplitude of the linearly detrended AMO index and only a very small positive anomaly in recent years (their Fig. 3), accompanied by a large component of recent AGW. This is a valid procedure only if it is known *a priori* that the Atlantic contribution to the GSST signal is entirely anthropogenic, which of course is not known. Thus, by removing the GSST average, they also remove a part of the unforced Atlantic variability (the baby) along with global AGW changes (the bathwater). If, to avoid this problem, one removes instead a modified GSST' excluding the Atlantic sector, the results are not greatly changed, although the residual (AMO) amplitude is somewhat increased. However, because the imprint of AGW on global SST is highly nonuniform, it is not reasonable to suppose that the North Atlantic component of the AGW modulation is of the same amplitude as GSST (the Trenberth and Shea approach) or as GSST'. Moreover, the problem with either approach is that they ignore the fact that similar multidecadal variability is found over large areas of the North Pacific Ocean as suggested by contemporaneous correlations (Enfield *et al.*, 2001), and that the GSST curve contains similar oscillations (Andronova and Schlesinger, 2000). This can be cited as evidence that the entire Northern Hemisphere is being forced by multidecadal changes in aerosols, primarily as a result of human activity; but it can also be used to bolster the contrary argument that the AMO is natural and alters SST outside of the North Atlantic through atmospheric teleconnections. Consistent with the latter, Dima and Lohmann (2007) conclude that the global reach of the multidecadal signal probably results from forcing by the AMO, while Xie *et al.* (2008) present evidence from model experiments for tropical Atlantic-to-Pacific forcing at very low frequencies. The fact that a temperature signal in the world ocean forced by the AMO is even possible makes the Trenberth and Shea approach undesirable because it rests on the false premise that natural variations in one ocean do not affect those in another. A final drawback to the Trenberth and Shea approach is the implicit assumption that the Atlantic imprint of AGW is equal in amplitude to the global average, whereas the global distribution of anthropogenic warming is demonstrably nonuniform.

Mann and Emanuel (2006) do a similar analysis, regressing tropical Atlantic SST variability since 1870 on the GSST time series. In addition, however, they add as a second predictor the multidecadally varying estimates of radiative forcing due to atmospheric optical thickness based on aerosols (Sato *et al.*, 1993) and conclude that both the secular warming and the multidecadal signal in North Atlantic SST can be largely explained by the combined forcings. In effect, their analysis argues that most of the tropical Atlantic warming in recent decades is radiatively (externally) forced and that most of the tropical North Atlantic multidecadal variability in the 20th century is probably not an outgrowth of a natural (internal) climate mode. In using the GSST series in the regression, however, they are implicitly assuming, as Trenberth and Shea (2006) do, that the multidecadal oscillations in GSST are entirely anthropogenic and that any natural AMO-like variability has no projection onto the SST in other oceans. Moreover, the regression is based on estimates of radiative forcing since 1870, whereas the optical thickness estimates are thought not to be representative in the tropics prior to 1960 (Sato *et al.*, 1993). Lastly, it should be mentioned that Sato *et al.* (1993) attribute much of the optical thickness variability to natural causes (volcanic activity) as well as human induced aerosols. Hence, neither approach can claim to separate natural changes from anthropogenic changes, regardless of the nature of the AMO or its global projections.

Finally, Elsner (2006) statistically examines the question of causality between the AMO index (classically defined) and the global surface air temperature (GT) index using a Granger causality test. In that test, the 1-year lagged response of GT to AMO is assessed by computing the regression of GT(t) on GT(t-1) and AMO(t-1), and comparing the results to a regression of GT(t) on GT(t-1) alone, using an F-test. Comparing that result to the reverse test of AMO on GT, Elsner concludes that the data are consistent with GT causing the AMO but not the reverse. We have repeated the Elsner procedure using all 12 combinations of the AMO index based on three data sets for SST and four ways of estimating GT. The AMO index is computed using the extended Kaplan SST data (v2) (www.cdc.noaa.gov/cdc/data.kaplan_sst.html) (Kaplan *et al.*, 1998), the extended NOAA reconstructed SST (v2) (www.cdc.noaa.gov/cdc/data.noaa.ersst.html) (Smith and Reynolds, 2004) and the Hadley Centre's SST anomalies from Rayner *et al.* (2006). The GT series is based on four data sets developed by the Hadley Centre (www.cru.uea.ac.uk/cru/data/temperature) (Rayner *et al.*, 2003). Results of our testing are shown in Table I. In half of the cases we reproduce the Elsner result and in half we do not. The F-column includes the value of the test statistics for the hypothesis of no Granger causality between GT (input) and AMO (response), using the Elsner methodology. Failures to reproduce the Elsner result include a land-only dataset as well as a combined land–ocean dataset. The successes and failures break down according to whether or not a spatially varying variance adjustment was applied to the air temperature data at the grid cell level to correct for spatial inhomogeneity in sampling density (Brohan *et al.*, 2006). Reduction of sample-based spatial inhomogeneities in the raw data has the effect of increasing the signal-to-noise ratio of the time domain index averages, in much the way temporal smoothing does. Hence, the F-tests (variance ratios) used in the Granger method are affected. The suggestion from

Table I. Test statistics for the hypothesis of no Granger causality between GT as input (INDEP), and AMO as output (DEP) using Elsner methodology (no prewhitening); $p < 0.05$ are considered significant. The AMO data sets correspond to the extended Kaplan SST (1), extended NOAA SST (2) and Hadley Centre's SST (3), and the GT data sets are for Land air temperatures only (1), combined land air and SST (2), and the same two with a variance adjustment (3, 4).

Model	DEP	INDEP	F	p-value
1	AMO1	GT1	2.32	>.10
2	AMO1	GT2	2.36	>.10
3	AMO1	GT3	12.42	0.0006
4	AMO1	GT4	12.92	0.0005
5	AMO2	GT1	1.14	>.10
6	AMO2	GT2	1.19	>.10
7	AMO2	GT3	9.33	0.0027
8	AMO2	GT4	10.11	0.0018
9	AMO3	GT1	1.69	>.10
10	AMO3	GT2	1.76	>.10
11	AMO3	GT3	9.50	0.0025
12	AMO3	GT4	10.01	0.0019

this analysis is that the Elsner result is not robust against the varying errors and uncertainties inherent in the way the data sets are estimated.

Apart from these results, the Granger test as applied by Elsner suffers from an additional problem. The application of a 1-year lag to annualized data fails to account for the fact that the atmosphere (GT) reacts much more quickly to the ocean (AMO) than vice versa. Hence, while the ocean might require upwards of a year to adjust to the atmosphere, the atmosphere probably responds to the ocean in less than a season, essentially undetectable with a 1-year lag. If the two are coupled, the Granger test on annual data may show GT to be causal but will fail to show causality for the AMO. This is consistent with Elsner's result and suggests it is a flawed test of causality. The negative impact of improper sampling on Granger causality tests is pointed out by Freeman (1983). Because of this problem and the added difficulty presented by the variance adjustment in two of the GT time series, it is advisable to do a modified Granger causality analysis. The details of the modified analysis are found in Appendix A. The results show that causality cannot be rejected in either direction (Table AI).

3. The case for a natural internal climate mode

Evidence from observations, coupled global models and paleoclimatic proxy data cast further doubt on the conclusions of Trenberth and Shea (2006); Mann and Emanuel (2006) and Elsner (2006). Coupled models in the absence of external forcing, with stratified dynamical oceans that transport heat, consistently produce variability similar to the AMO (Delworth *et al*., 1993; Gray *et al*., 1997; Delworth and Mann, 2000; Latif *et al*., 2004; Knight *et al*., 2005), although they fail to reproduce some of the details. A recent paper by Dijkstra *et al*. (2006) presents a thorough summary of the model evidence to date and explores the AMO physics in a hierarchy of models. The model mechanisms typically involve fluctuations of the Atlantic meridional overturning circulation (AMOC), as previously suggested by Gray *et al*. (1997). Moreover, Dima and Lohmann (2007) find that observations are consistent with an AMOC mechanism combined with lagged fluctuations in sea ice export through the Fram Strait between Greenland and Norway. These mechanisms are consistent with a multidecadal oscillation that is most dominant in the Atlantic, as suggested by Schlesinger and Ramankutty (1994) and Enfield *et al*. (2001). However, many global coupled models have difficulty simulating the multidecadal variability in the tropical North Atlantic (Santer *et al*., 2006) and this is where Mann and Emanuel (2006) suggest that fluctuations are more radiatively driven than in the extratropics. If indeed the tropical and extratropical Atlantic vary multidecadally due to distinct mechanisms, it has yet to be explained why their respective variations have been so coherent over the 20th century.

Finally, the AMO proxy series of Gray *et al*. (2004), based on tree-ring chronologies dating to the 16th century, correlate highly with the instrumentally based AMO index and exhibit similar fluctuations throughout the time series. A proxy-based reconstruction by Delworth and Mann (2000) shows a similar centenary oscillation over the last several centuries. Paleo-proxy data alone, however, cannot distinguish between radiative forcing by aerosols (natural or otherwise) and internal climate variability in the coupled ocean–atmosphere system. Tree-ring fluctuations in previous centuries may have been likely natural but those in the 20th century may, indeed, be of mixed parentage. Enfield and Cid-Serrano (2006) demonstrate that a gamma distribution can be successfully fit to the multidecadal regime intervals in both the observed AMO index and the Gray *et al*. proxy series for previous centuries, and that the distribution parameters for the 20th century are consistent with those of earlier variability in the index. This suggests that AMO-like variability has existed long before anthropogenic greenhouse forcing and man-induced aerosol forcing became significant, and thus is likely to be, at least partly, a natural climate mode.

Finally, Kossin *et al*. (2007) have created a reanalysed hurricane database that accounts for artificial trends due to historical evolution of the way hurricanes are detected and classified since the early 1980s. They conclude that except for the North Atlantic there are no significant hurricane activity trends in any ocean basin, thus modifying the results of Webster *et al*. (2005) and Emanuel (2005) pointing to a global increase in hurricane activity. Very similar conclusions are arrived at by Klotzbach (2006). The fact that only the North Atlantic sees a significant trend suggests that most of the increase in North Atlantic hurricane activity is due to factors other than global temperature rise. The most obvious alternative is the AMO, as pointed out by Goldenberg *et al*. (2001).

4. Most likely character of the AMO

In spite of the difficulties with analyses that argue for an anthropogenically forced AMO, the anthropogenic production of sulfate aerosols, as opposed to other greenhouse gases such as CO_2, has been uneven, modulated by events such as World War II, the subsequent post-war industrialization, and efforts to curb pollution later in the century. These are known to affect surface warming (IPCC-AR4) and may indeed explain some of the multidecadal changes in SST. Moreover, a paleoclimate proxy calibrated against 20th century oscillations cannot independently verify that prior oscillations had the same amplitude, while model simulations of AMO-like activity do not reflect the 20th century amplitude (Knight *et al*., 2005). Nor does the occurrence of multidecadal climate impacts necessitate either a natural or anthropogenic mechanism; SST variations, whatever the cause, can lead to such impacts. Hence, we conclude that the question of how the AMO is forced is not settled, and that both natural and anthropogenic factors are probably involved. The validity of the hypotheses and their possible interplay must be sorted out with further work using models and proxy data, because the various instrumental records arguing either way are simply inadequate to the task. Both the aerosol forcing and the Atlantic SST appear to have both natural and anthropogenic components and therefore any physically based method of separation based on observations will necessarily not produce a clean separation along causal lines. Until a scientific consensus is reached, we believe that the best approach is to separate the monotonic and multidecadal components of temperature change in a straightforward manner using a method that does not involve implicit assumptions about the nature of the AMO. It is absolutely essential that such a separation cannot be viewed as one of the causes but as one of the timescales. Accordingly, the references to the AMO in this paper are not meant to connote a natural cycle, but rather, a hybrid blend of natural and anthropogenic variability in the 20th century and beyond.

5. An alternate formulation

We consider that Trenberth and Shea (2006) and Mann and Emanuel (2006) are quite correct about the desirability of defining the AMO in a way that accounts for the nonlinearity in AGW. This can be achieved effectively and simply by subtracting a least squares-fit quadratic function from the time series, of the form $T = \beta_0 + \beta_2 t^2$, where T is the North Atlantic temperature, t is a time index, β_0 is $T(t = 0)$ and β_2 is the coefficient of nonlinear warming rate. This method has the virtue of simplicity, makes no assumptions about the origins of multidecadal variability and loses no information at the ends of the series. The particular form chosen also has two added advantages: the low order is most appropriate for modelling a monotonic increase, while the absence of an order = 1 term meets the continuity constraint, $dT/dt = 0$ at $t = 0$, required to match the 20th century trend to the negligible trend during the 19th century. Because 19th century data are less reliable and since secular warming was negligible prior to the 20th century, we recommend using a multiyear average centred on $t_0 = 1900$ AD, meaning that $T = \beta_0$ prior to 1900 and $T = \beta_0 + \beta_2 t^2$ thereafter. Figure 1 illustrates the method when applied to the average sea surface temperatures anomalies (SSTA) of the North Atlantic during August–October (ASO), from the equator to 70 °N, using the extended Kaplan SST (v2) dataset.

It is reasonable to ask what the effect is of (a) using alternate global SST data sets, and (b) changing the start time (t_0) for the quadratic fit. Using three SST datasets to calculate the North Atlantic SST history (as before: extended Kaplan, Hadley and extended NOAA), we examine critical times in both the fitted trend and the multidecadal residual (1900, 1975 and 2000 AD), as well as their time differences. The average rms difference between datasets varies from 0.01 to 0.05 °C and for the critical 1975–2000 time differences discussed later, the rms spread is less than 0.03 °C. Hence, conclusions based on the quadratic fit and separation of time scales are not sensitive to the dataset used. Using the Kaplan dataset and alternate start times of $t_0 = 1880$, 1900 and 1920, the rms spread of values is also very similar. Hence, choosing reasonable alternatives for $t = 0$ has little effect on the results. The reliability of future extrapolations will be considered in the Section 7.

Table II presents decadal values of the North Atlantic (0–70 °N) SSTA increment $[T(t) - \beta_0]$ and warming rate ($2\beta_2 t$) since 1900, as given by the fitted quadratic in Fig. 1 applied to the Kaplan extended SSTA (v2). The total secular warming in the North Atlantic by 2000 AD is 0.35 °C with respect to 1900 AD. Also shown are the values when applied to the global averages

Table II. $T(t) - \beta_0$ rows: Decadal averages of temperature increase (°C) with respect to 1900 AD, for the quadratic trends of North Atlantic SST (NATL; 0–70 °N) and the global surface temperature (GT). dT/dy rows: decadal averages of the rate of increase in the quadratic trends (°C/decade). Years shown are the centre points of the averages.

	Year	1900	1910	1920	1930	1940	1950	1960	1970	1980	1990	2000
NATL	$T(t) - \beta_0$	0.00	0.01	0.02	0.04	0.06	0.09	0.13	0.18	0.23	0.28	0.35
	dT/dt	0.003	0.009	0.015	0.022	0.028	0.035	0.041	0.048	0.054	0.060	0.067
GT	$T(t) - \beta_0$	0.00	0.01	0.03	0.06	0.11	0.16	0.23	0.31	0.39	0.49	0.60
	dT/dt	0.004	0.016	0.027	0.038	0.049	0.060	0.072	0.083	0.094	0.105	0.116

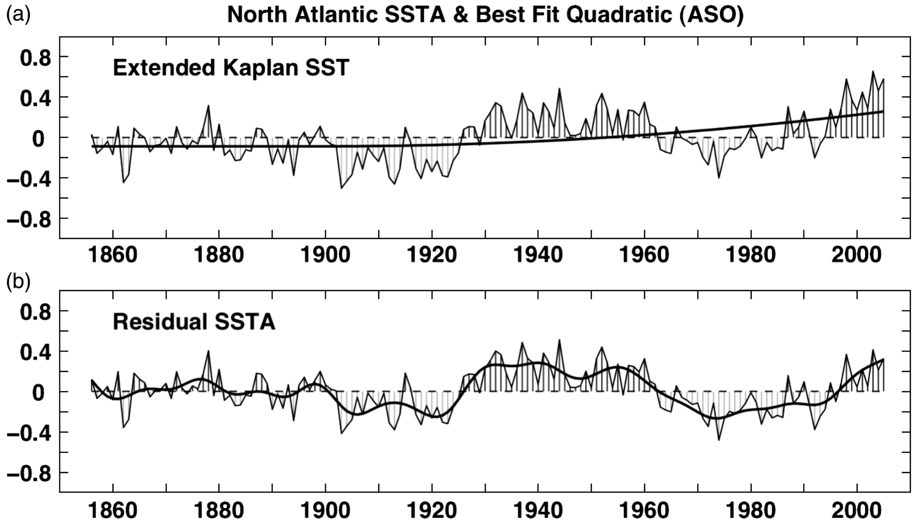

Figure 1. (a) Annual averages for August–October (ASO) of North Atlantic SSTA from 1856 to 2005, with a least squares quadratic trend fit $T = \beta_0 + \beta_2 t^2$ superimposed from 1900 AD to the present and $T = \beta_0$ prior to 1900 AD, where β_0 is the 10-year average of T centred on 1900 AD. (b) Residual difference between the SSTA in the (a) and the quadratic fit, with a decadal scale smoothing superimposed (8-pole Butterworth filter, forward and back, with half amplitude at 10 years). SSTA are from the extended $5° \times 5°$ Kaplan data set (www.cdc.noaa.gov/cdc/data.kaplan_sst.html).

of the Hadley Centre's variance adjusted combined land and marine surface temperature anomalies (GT = HadCRUT3v) (www.cru.uea.ac.uk/cru/data/temperature). These values are in line with IPCC estimates for global temperature increases in the 20th century. The warming rate for GT increases steadily from near 0 °C in 1900 AD to 0.12 °C/decade in 2000 AD. Note that the total warming in the North Atlantic SSTA is about 60% of the global surface warming that includes air temperatures.

It is instructive to map several quantities obtained when the quadratic fit is applied at each grid point of the Kaplan $5° \times 5°$ extended SSTA (Fig. 2). Figure 2 is shown for the late summer (peak) hurricane season, August–October (ASO), but the results are similar for annual averages. First is the quadratic increase in SSTA in 2000 AD with respect to 1900 AD [Fig. 2(a)]; the second is the 10-year averaged total SSTA centred on 2000 AD minus the average centred on 1900 AD (Fig. 2(b)); and the third is the 10-year averaged SSTA residual (after subtracting the quadratic fit) centred on 2000 AD minus the average centred on 1975 AD (Fig. 2(c)). The first two panels are alternate ways to display the global distribution of the secular increase in SST since 1900 AD: one as given by the quadratic fit, which excludes the multidecadal component, the other as a simple difference between decadal averages of total SSTA. The third represents the global distribution of the multidecadal component of SST warming during the 25 years from 1975 to 2000 AD, the decades centred in the most recent cool and warm phases of the AMO, respectively. The secular warming patterns (Fig. 2(a) and (b)) both resemble the global distribution of linear trend shown by Enfield and Mestas-Nuñez (1999), but they differ from the North Atlantic rotated empirical orthogonal function (EOF) discussed by Mestas-Nuñez and Enfield (1999) that led to the definition of the AMO index of Enfield *et al*. (2001) (see Section 7). The 1975–2000 warming pattern resembles the global distribution of the correlation of global gridded SSTA with the linearly defined AMO index (Enfield *et al*., 2001) as well as the rotated EOF of Mestas-Nuñez and Enfield (1999).

The patterns in Fig. 2(a) and (b), while similar to each other, display significant differences vis-à-vis Fig. 2(c) (the late 20th century increase). The latter distribution lacks the warming in the Indian Ocean and the South Atlantic, and lacks the cooling along the equator in the Pacific and south of Greenland. We attach special significance to these differences, because if the multidecadal component were *primarily* the product of variable radiative forcings associated with AGW (Mann and Emanuel, 2006), one would expect the recent warming pattern [Fig. 2(c)] to resemble that of Fig. 2(a) and (b). This is consistent with the notion that the North Atlantic multidecadal variability is not entirely anthropogenic, and thus supports the choice of a monotonic trend that does not presuppose the AMO's origin.

Figure 2(c) confirms that the multidecadal fluctuations indexed by the AMO phase change dominate most strongly in the North Atlantic but also project onto large regions of the Pacific, as shown by Enfield *et al*. (2001), and have virtually no imprint in the South Atlantic or Indian Oceans. Model studies of multidecadal South Atlantic SST response (Knight *et al*., 2005) and of meridional distributions of atmospheric and oceanic heat transport anomalies in the Atlantic (Zhang and Delworth, 2005) are consistent with the North Atlantic dominance and the relative lack of a response in the South Atlantic. The secular [Fig. 2(a)] and multidecadal [Fig. 2(c)] components have roughly equal basin-wide averages in the North Atlantic and in particular the tropical North Atlantic, while the secular component dominates in the Indian Ocean and portions of the eastern Pacific.

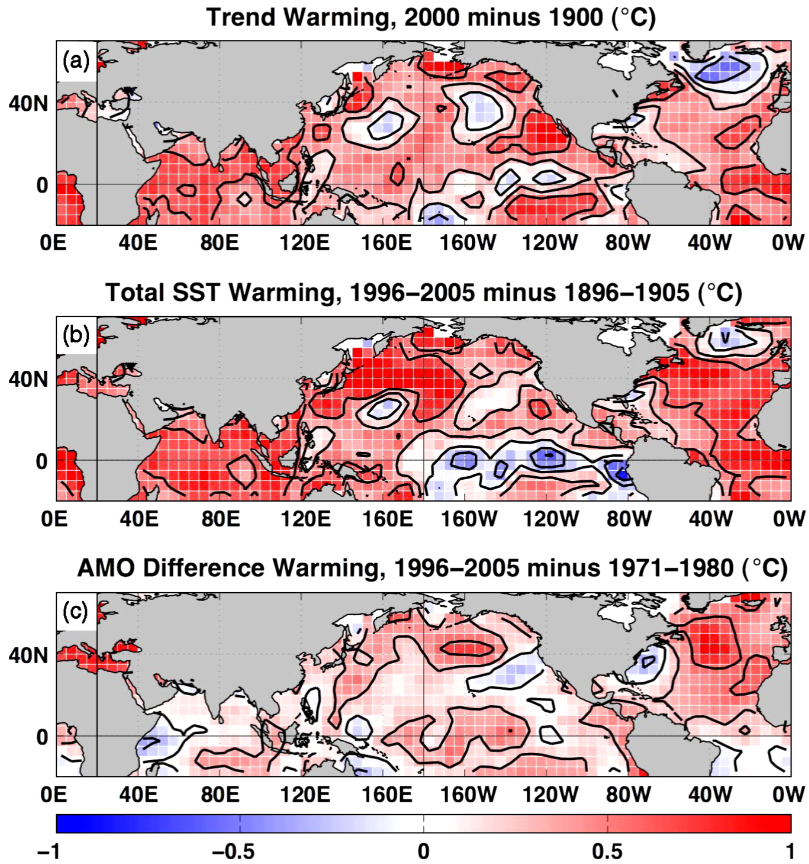

Figure 2. Global distributions of component SST warming for August–October. (a) The quadratic secular increase from 1900 to 2000 AD, excluding multidecadal variability. (b) The simple increase in total SSTA between decadal averages centred on 1900 and 2000 AD. (c) The increase in multidecadal SSTA [residual in Fig. 1(b)] between decadal averages centred on 1975 and 2000 AD. Contours are shown for 0.3 °C intervals. Dark shades are positive, light shades are near zero or weakly negative. SSTA are from the extended 5° × 5° Kaplan data set. This figure is available in colour online at www.interscience.wiley.com/ijoc

6. Past and future changes in the tropical North Atlantic SST

Let's consider how the secular and multidecadal trends [Fig. 2(a) and (c)] have affected average summer warm pool size since 1975, and from then into the future. To do this we focus on the effect of large-scale SST changes on the area of the Atlantic warm pool (AWP), because we wish to weight the analysis towards the region of highest absolute SST, which has the greatest impact on deep convective heating of the atmosphere. Warm pool variability has been linked to hurricane activity (Wang *et al.*, 2006, 2008) and roughly 80% of large (small) warm pools occur during the warm (cool) phases of the AMO (Table III). Thus, we add the respective 1975–2000 AD warming components over the main development region (MDR) (0.14 °C, 0.37 °C) to the average 1970–1980 SST distribution of the tropical North Atlantic in August–October and calculate the percentage of increase in AWP size using the 28 °C isotherm to determine the area (Fig. 3). The quadratic trend results in a 14% area increase, and the multidecadal warming in a 36% increase. The area increase due to the combined warmings (0.51 °C) is 54%.

In future decades, the nature of the AMO may have a rather profound impact on the thermal configuration of

Table III. Contingency table based on tercile classes of AWP size *versus* hurricane activity measured by total hurricane counts for the Atlantic basin. Data are for August–October, 1948–2005. Active (inactive) seasons are defined as having more than eight (fewer than seven) hurricanes and other years are 'neutral'. A large majority of active hurricane seasons occur when the AWP is large and more inactive than active seasons occur with small warm pools.

	Small AWP	Neutral AWP	Large AWP	Row total
Active	**7**	**5**	**14**	**26**
Neutral	**3**	**5**	**3**	**11**
Inactive	**10**	**8**	**3**	**21**

the tropical North Atlantic, one way or another. Based on an ensemble of nine models from the IPCC Fourth Assessment Report (AR4) that reproduce a reasonable AMOC, the North Atlantic SST warming should be about 0.25 C with a spread of ±0.75 °C, by 2020–2025 AD. Extrapolating the quadratic trend to the same period yields a 0.2 °C increase, not unlike the IPCC projection. Through superposition as done in Fig. 3, a 0.25 °C increase implies a decadally averaged AWP about 84% larger in 2025 than in 1970–1980, provided there is no reverse shift of equal magnitude in the multidecadal

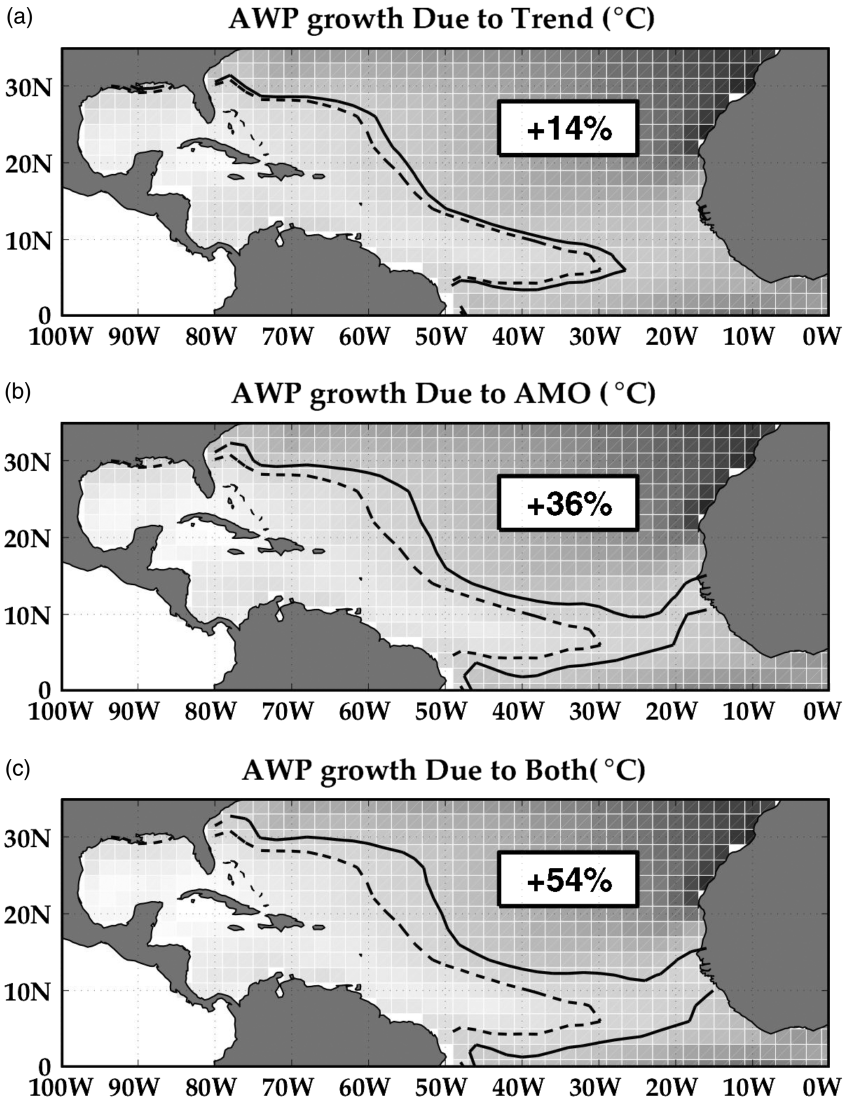

Figure 3. SSTA distributions for the 1970–1980, average SSTA plus three 1975–2000 AD increments of warming: 0.14 °C (a; secular component), 0.37 °C (b: multidecadal component) and 0.51 °C (c: total). The dashed contour for 28 °C shows the 1970–1980 average AWP, and the solid contour shows the same isotherm for the 1970–1980 average SSTA plus the increment. SSTA are from the 2° × 2° extended NOAA reconstructed SST (www.cdc.noaa.gov/cdc/data.noaa.ersst.html). Inset boxes indicate the percentage growth in AWP area.

component [Fig. 4(c)]. That would be 30% beyond the present increase. However, if the AMO is primarily due to natural climate forcing, as unforced coupled models and paleoclimate data suggest, the probability of a reverse shift to the 1970–1980 phase by 2025 is about 85% (Enfield and Cid-Serrano, 2006). A reverse shift of equal magnitude, superimposed on the secular increase, will result in a warm pool about 38% larger than 1970–1980, or 16% below the present level [Fig. 4(b)]. It is quite possible that future natural and anthropogenic warmings will not add linearly as shown here, but this simple calculation serves to illustrate the importance of settling the question of the nature of the AMO.

7. Discussion

Recent analyses by Trenberth and Shea (2006); Mann and Emanuel (2006) and Elsner (2006) arguing against a natural, internally forced AMO are problematic and their conclusions are weakened by contrary evidence from unforced coupled models and paleoclimate data. It is our position that the climate community has not yet determined how much of the multidecadal residual may be forced radiatively, as argued by Mann and Emanuel (2006), but that some portion of it is probably due to internal climate variations. Even to the extent that a radiative component exists, however, it is partly forced naturally, through volcanic activity (Sato *et al.*, 1993), as well as anthropogenically. This is a critical point, because it relates to the probability that multidecadal fluctuations similar to the 20th century AMO have a significant natural component and will likely continue into the future, modulating anthropogenic forcing and its climate impacts. By forcing an AGCM with historical solar and volcanic fluctuations, Shindell *et al.* (2003) show that volcanic aerosols contribute significantly to long-term coolings of global surface temperature, including a cooled

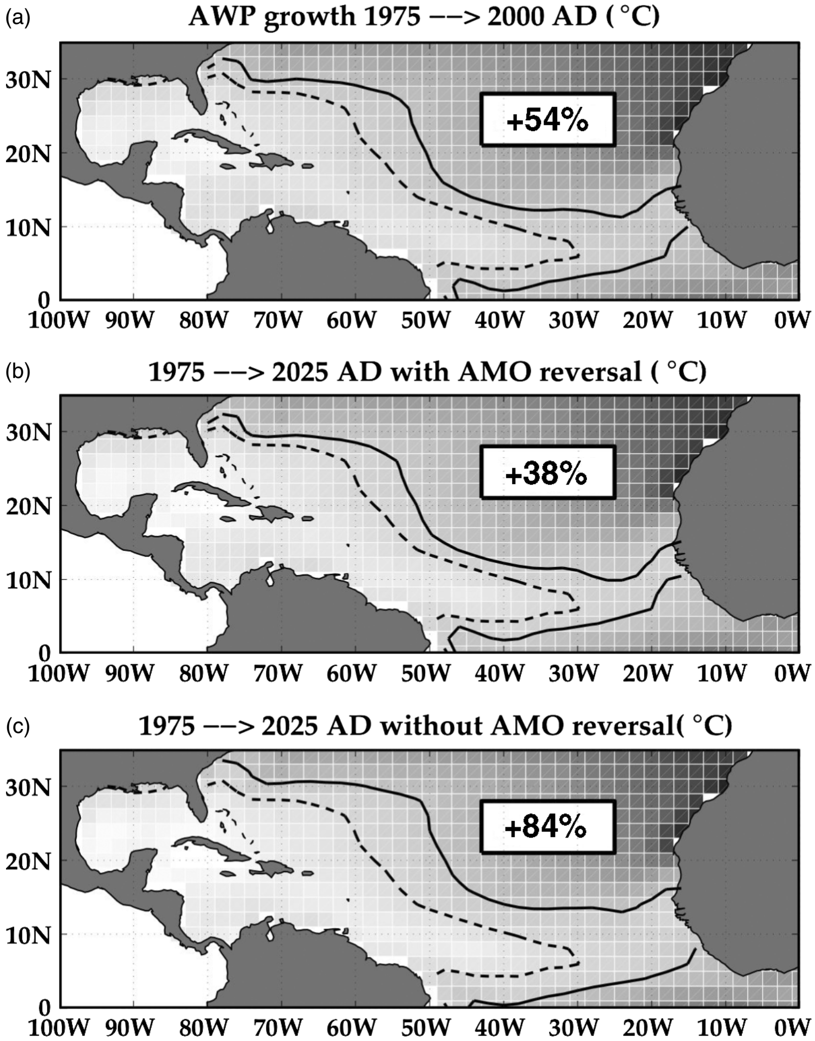

Figure 4. As in Fig. 3, Fig. 3(a) repeated here ([Fig. 4(a)] to show the total warm pool growth from 1975 to 2000 AD. (b) The cumulative AWP growth from 1975 to 2020 AD, assuming that an AMO reversal (of similar magnitude) occurs, superimposed on a projected 0.25 °C secular warming of North Atlantic SST from 2000 to 2020 AD. (c) The accumulated 1975–2020 AD growth of the AWP assuming that no reversal occurs. Inset boxes indicate the percentage growth in AWP area.

North Atlantic and a positive Arctic Oscillation anomaly. The latter is consistent with the pattern obtained by correlating the AMO index with gridded sea level pressure (not shown). Thus, it is not unreasonable that both internal ocean–atmosphere interactions and volcanic aerosols can lead to fluctuations in North Atlantic temperatures on multidecadal time scales.

Therefore, we argue that any separation of variability based on subtracting the global temperature time series and/or optical thickness will not isolate a purely anthropogenic signal. To avoid the complication and pretense of doing so, we recommend simply to remove a monotonic trend. To account for the nonlinear nature of secular warming, we recommend that historical time series be detrended with a simple quadratic algorithm. However, until such time as the nature of the AMO is definitively settled, the partitioning of recent warming should be characterized as secular *versus* multidecadal, not as anthropogenic *versus* natural.

The comparison of multidecadal and secular components of North Atlantic warming over the last quarter of the 20th century is appropriate because hurricane records are most accurate in the satellite era, but also because the societal impacts of changed hurricane frequencies are best considered on the generational time scale of human perception and institutional response. By judging the warming components through the lens of the AWP size, we find the recent quarter-century increase due to the multidecadal component to be about 2.6 times that of the secular component. This disparity can be expected to decrease in the future, as the secular component becomes proportionally larger under realistic scenarios for nonlinear global warming over the next generation.

Because hurricane activity responds to tropical Atlantic SSTA in the 20th century (e.g., Goldenberg *et al*., 2001; Wang *et al*., 2006), one might hypothesize that any warming of the tropical North Atlantic will impact the hurricane activity in similar fashion, regardless of whether the warming is secular or multidecadal (but see our cautionary note, below). Based on the previous discussion of future warm pool scenarios we can see how hurricane activity in the Atlantic might evolve in very different ways, depending on whether or not the AMO occurs naturally and reverts to a relatively cool state within the next decade or so.

However, much recent evidence suggests that global warming will affect the hurricane environment in very different ways than suggested by the simple linear reasoning above. Increasingly, anthropogenic warming may confound the understandings we have developed based on 20th century observations. This dilemma is illustrated by two studies that consider the effects of 1–2 °C secular warmings on hurricanes. As discussed in Henderson-Sellers *et al.* (1998), under future global warming scenarios the SST threshold for tropical storm genesis may go up from the current 26.5 to 28 °C if there is a 1.5 °C anthropogenic SST increase. This is because changes in the atmospheric stability from global warming may physically alter that boundary. In a second study, Knutson and Tuleya (2004) find that models that get the recent wind shear climatology correct either develop no change in tradewinds and shear in the future, or even an increase – implying that AGW-related hurricane activity could even be lessened. Such analyses suggest that the tropospheric mechanisms for the secular and multidecadal changes are different, and that the balance between anthropogenic (e.g., Knutson and Tuleya, 2004) and natural AWP-hurricane interactions (e.g., Wang *et al.*, 2007) will be increasingly modified under global warming.

Most recently, Vecchi and Soden (2007a) have shown that the IPCC multi-model ensemble projects an increase in vertical wind shear and moist static stability over the MDR towards the end of the 21st century. If true, this can be expected to lead to a gradual decrease in overall Atlantic tropical cyclone activity, exactly the opposite of our expectation from the 20th century relationship between warm pool variability and hurricane activity. The likely reason for this reversal emerges from several studies suggesting that differential warming in the several ocean basins may produce startlingly different impacts on the respective tropical cyclone environments than would be expected from local changes alone (Latif *et al.*, 2007; Vecchi and Soden, 2007b). It is therefore essential to better understand the mechanisms behind the natural and anthropogenic influences on TC activity and to develop prognostic models that correctly account for them.

Lastly, we should note that the AMO could eventually be modified by AGW if both interact with the AMOC, which appears likely. Numerical water-hosing experiments consistently show an AMOC decrease in response to AGW-related freshening of the North Atlantic (e.g., Schmittner *et al.*, 2005) while other studies show that the AMOC fluctuates in tandem with multidecadal cycles of North Atlantic SST (e.g., Knight *et al.*, 2005). Bryden *et al.* (2005) claim to have detected a recent decreasing trend in the AMOC, possibly due to AGW, but Cunningham *et al.* (2007) show that the Bryden *et al.* trend, based on five hydrographic sections across the North Atlantic, is uncertain due to unresolved variability on shorter time scales. The projection of future Atlantic hurricane activity onto SST trends (as in Fig. 4) may only make sense over the next two to three decades or until it can be established that the AMOC is indeed beginning to decrease as currently projected by the IPCC models.

It is absolutely essential for ongoing research, that the question of natural *versus* anthropogenic forcing of the AMO be settled. If the AMO is mainly natural, the effects of global warming on hurricanes stand to be partially offset over the next generation. If 20th century AMO fluctuations have been predominantly forced anthropogenically, as suggested by Mann and Emanuel (2006) and others, then a relaxation of the present rate of increase in hurricane activity may never occur. The stakes for society, one way or the other, could be enormous.

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Appendix A

We performed an improved test for causality using the methodology proposed by Pierce and Haugh (1977). Based on the cross-correlation function (CCF) between the series, this method advantageously accounts for the lagged dependency of the series beyond lag = 1. Since this CCF can be compromised by the autocorrelative structure of the individual series, which is very heavy in the presence of multidecadal changes, they recommend to prewhiten the series by computing the residuals from the corresponding ARMA model. We then compute the CCF of the residuals X_t and Y_t after fitting to each of them an adequate ARMA(p,q) model (Box *et al.*, 1994) of the form

$$\phi_X(B)X_t = \theta_X(B)\alpha_t, \qquad \text{or} : \alpha_{\mathrm{t}} = \theta_X(B)\phi_X(B)X_{\mathrm{t}} \quad (1)$$

$$\phi_Y(B)Y_t = \theta_Y(B)\beta_t, \qquad \text{or} : \beta_t = \theta_Y(B)\phi_Y(B)Y_t \quad (2)$$

where X = AMO, Y = GT, and ϕ (B) and θ (B) are the autoregressive and moving average operators (Box *et al.*, 1994) defined for the X_t and Y_t series, respectively. After the prewhitening process has been completed, we calculate the CCF of the residuals.

A further refinement of the procedure was proposed by Box *et al.* (1994). Instead of calculating the CCF using ARMA models for both X and Y, we prewhiten the causal series (input) and use the same parameterization to 'transform' the caused (output) series. So if X_t is the input series, using the parameterization of Equation (1) the residuals will be

$$\alpha_t = \theta_X(B)\phi_X(B)X_t \tag{3}$$

$$\beta_t = \theta_X(B)\phi_X(B)Y_t \tag{4}$$

Now we can test for the significance of the CCF of the residuals from Equations (3) and (4) for a given number of lags K, using the test statistic

$$S(K) = n(n+2)\sum_{k=0}^{K}\frac{r_{\alpha\beta}^2}{n+1} \sim \chi_K^2,$$

This test has the advantage of cumulatively considering all cross-correlations up to lag K. The method can be reversed to demonstrate the causality in both directions, prewhitening and transforming both series now with parameterization of Equation (2).

The results of the testing are shown in Table AI for the AMO causing GT and for GT causing the AMO using lagged values up to $K = 12$. All Chi-square tests are highly significant ($p < 0.001$), showing that the causality cannot be rejected in either direction. The test was also performed for lags of up to 6 and 24 years with similar results. In summary, both of our attempts at replicating the causality test have failed to convincingly reject the hypothesis that the AMO affects global temperature variability. This calls into question the premise implicit in the analyses of Mann and Emanuel (2006) and Trenberth and Shea (2006).

Table AI. Values of the Chi-square statistics for testing the hypothesis of no causality between input and output, using lagged values of up to 12 years. The p-values for all tests are <0.001.

Input\output	AMO input/GT output				GT input/AMO output			
	GT1	GT2	GT3	GT4	GT1	GT2	GT3	GT4
AMO1	58.5	57.5	57.3	59.1	42.7	43.3	70.7	60.4
AMO2	56.0	54.9	63.1	65.1	40.2	41.5	68.1	59.5
AMO3	55.8	54.8	48.4	50.7	43.4	44.2	61.1	49.2

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