Global Warming, the AMO, and North Atlantic Tropical Cyclones

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Increases in key measures of Atlantic hurricane activity over recent decades are believed to reflect, in large part, contemporaneous increases in tropical Atlantic warmth [e.g. *Emanuel*, 2005]. Some recent studies [e.g. *Goldenberg et al*, 2001] have attributed these increases to a natural climate cycle termed the "Atlantic Multidecadal Oscillation" (AMO), while other studies suggest that climate change may instead be playing the dominant role [*Emanuel*, 2005; *Webster et al*, 2005]. Using a formal statistical analysis to separate the estimated influences of anthropogenic climate change from possible natural cyclical influences, we find that anthropogenic factors are likely responsible for long-term trends in tropical Atlantic warmth and tropical cyclone (TC) activity. We also conclude that late 20th century tropospheric aerosol cooling has offset a substantial fraction of anthropogenic warming in the region and has thus likely suppressed even greater potential increases in TC activity.

The multidecadal oscillatory pattern in Atlantic sea surface temperature (SST) referred to as the "AMO" was first isolated by *Folland et al* [1986], and confirmed by subsequent analyses of observational [e.g. *Mann and Park*, 1994; *Schlesinger and Ramankutty*, 1994] and longer-term "proxy" climate data [e.g. *Delworth and Mann*, 2000]. Modeling studies [e.g. *Delworth et al*, 1993; *Delworth and Mann*, 2000; *Knight et al*, 2005] have isolated a plausible mechanism related to the intrinsic multidecadal variability of the North Atlantic thermohaline circulation ("THC").

Inconsistencies exist, however, with regard to the potential role of the AMO in tropical Atlantic warmth and hurricane activity. Recent analyses arguing for a significant such role define the AMO as a residual after linearly detrending North Atlantic SST data available back through the late 19th century [e.g. *Goldenberg et al*, 2001]. These analyses impute a significantly greater AMO influence on tropical North Atlantic SST than do climate model simulations [e.g. *Knight et al*, 2005] or analyses employing multivariate signal detection methods to separate possible long-term oscillatory patterns from trends in observational data [e.g. *Mann and Park*, 1994]. If the AMO were indeed responsible for anomalous recent tropical North Atlantic warmth, moreover, the THC should have exhibited a trend towards anomalous strength in recent decades, since model simulations indicate that tropical North Atlantic surface warmth associated with the AMO is in phase with the strength of the North Atlantic THC [see e.g. Fig. 3 *Knight et al*, 2005]. Yet the only direct oceanic measurements available suggest a decrease, not an increase, in the THC between the late 1950s and the past decade [*Bryden et al*, 2005].

Global Mean SST forcing

Defining the AMO as the residual pattern after linear detrending assumes that any internal oscillation is superimposed on a linear background trend. Yet neither observed nor modeled 20th century global mean series exhibit a linear trend. It is more plausible to assume that North Atlantic SST trends result from a combination of background large-scale warming, believed to be largely radiatively forced [e.g. *Crowley*, 2000], and an internal "AMO" signal that projects onto regional SST trends. We employ a statistical model based on this assumption to test the hypothesis that tropical Atlantic SST variability contains an AMO signal:

$$T(t) = \alpha_0 G(t) + R_0(t) \qquad (1)$$

The net SST variability $T(t)$ is represented by tropical Atlantic HadISST2 SST observations [*Rayner et al*, 2003] from 1870-2004 averaged over the season (Aug-Oct or 'ASO') most relevant to tropical cyclone (TC) formation, and over the main development region ('MDR') of 6-18N, 20-60W. $G(t)$ represents global mean SST over the same ASO seasonal window and time interval, and $R_0(t)$ is the residual which should, in principle, contain any "AMO" contribution. Implicit in our analysis is the assumption that the "AMO" does not project significantly onto $G(t)$. While *Knight et al* [2005] find a very small non-zero AMO projection onto global mean SST (0.05^{o}C peak amplitude), this is negligible compared to the secular trend in $G(t)$ of approximately 0.8^{o}C. Southern Hemisphere (SH) mean SST should be even more free of AMO impacts, but the estimated observational error for the SH series is unacceptably large over the 19th and early 20th century (see supplemental online material: http://www.meteo.psu.edu/~mann /eos06, henceforth 'supplementary'). Owing to constraints discussed below, we confine our analysis to the time interval 1870-1999.

Using the decadally-smoothed (see supplementary for details) $T(t)$ and $G(t)$ series, the regression (eq. 1) yields α_0=0.93±0.12 (p<<0.001; reduced degrees of freedom associated with decadal smoothing have been taken into account and a one-sided hypothesis test has been used). The single predictor $G(t)$ resolves 70% of the decadal variance and roughly two thirds of the net warming in $T(t)$ (see Figure 1a). The residual $R_0(t)$ (Figure 1c) has an annual (decadal) standard deviation of 0.19°C (0.11°C), and its spectrum (see supplemenatry for details) indicates a multidecadal (timescale>30 year) spectral peak significant at the p<0.01 level relative to the traditional null hypothesis of climatic "red noise" (Figure 1d). The argument for an AMO signal in tropical Atlantic SST rests upon this statistical feature. This feature, however, proves not to be robust.

When we eliminate the last 50 or even 40 years of data, the multidecadal spectral peak becomes statistically indistinguishable from red noise (see supplementary). The apparent multidecadal cycle therefore derives its statistical significance from the pronounced negative trend in $R_0(t)$ beginning in the 1950s and persisting through the 1980s. Yet, this pattern of late 20th century cooling has been attributed in past work to Northern Hemisphere anthropogenic tropospheric aerosol forcing [e.g., *Crowley*, 2000]. Model estimates [*Hansen et al*, 2005] indicate that this forcing is especially pronounced over the MDR during the crucial ASO season wherein the net estimated cooling is -1.12°C, while the global mean ASO cooling is -0.71°C, indicating a regional enhancement of -0.41°C for the MDR.

Regional Aerosol Forcing

To represent potential enhancement of ASO tropospheric aerosol cooling over the MDR, we included the estimated Northern Hemisphere anthropogenic tropospheric aerosol forcing series available through 1999 [*Crowley*, 2000] as an additional predictor $S(t)$:

$$T(t) = \alpha\, G(t) + \beta\, S(t) + R(t) \qquad (2)$$

Linear regression with eq. 2 yields a revised estimate α=1.7±0.17 (p<<0.001), implying a projection of global warming onto the MDR (Figure 1a) that is significantly greater than the global mean. The estimated value of β=0.79±0.16 °C/W/m^2 (p<<0.001) however indicates that aerosol cooling has substantially offset much of the latter 20th century warming. The -0.50°C estimated regional enhancement of aerosol cooling (Figure 1a) is close to the model-based estimate (-0.41°C) cited above.

The bivariate statistical model resolves 85.5% of the decadal variance in $T(t)$ including most of the net warming (Figure 1b). To independently assess the skill of the statistical model, we regressed on only the first 100 years (1870-1969), predicting the evolution over the subsequent 30 years (1970-1999). The model parameters (α=1.64±0.20, p<<0.001; β=0.57±0.23 °C/W/m^2, p<0.01) are found to be consistent with those obtained above, and the actual evolution of $T(t)$ over the subsequent 30 year interval is skillfully predicted by the statistical model (Figure 1b).

The residual $R(t)$ (Figure 1c) for the bivariate regression has a reduced annual (decadal) standard deviation of 0.17°C (0.08°C). More significantly, its spectrum shows no multidecadal peak (Figure 1d). Similar results are obtained using global combined land air and SST temperature for $G(t)$, either ASO or annual mean (see supplementary).

Connections with Tropical Cyclone Activity

A measure of total power dissipation by TCs (the power dissipation index or "PDI") has been shown by *Emanuel* [2005] to be well correlated with MDR ASO SST over the last half century, during which tropical cyclone wind measurements are most reliable. Although wind estimates prior to the 1940s are problematic, detection of the existence of TCs is less so, as in the absence of aircraft and satellites to warn them off, ships often encountered storms at sea, at least peripherally. A reasonably reliable record of North Atlantic TC occurrence is thus available back into the late 19th century [*Jarvinen et al*, 2005]. This record, like the PDI index, shows a strong long-term relationship with tropical Atlantic Aug-Oct SST (Figure 2). The linear correlation between the decadally smoothed series, r= 0.73 (p<0.001 for decadally smoothed data, and a one-tailed hypothesis test) indicates that the overall trend and more than half of the total decadal variance in

TC numbers can be resolved by SST variations (we obtain r=0.61; p<0.001, if we use our bivariate statistical model for $T(t)$ in place of $T(t)$ itself). $R(t)$ which must include any "AMO" contribution, explains an insignificant 4% (Figure 2) of the decadal TC variance (r=0.20, p>0.1 for a one-sided test). It might be argued that other factors potentially associated with the AMO (e.g. changes in vertical wind shear in the tropical North Atlantic) could be responsible for the observed TC changes [e.g. *Goldenberg et al*, 2001]. We rejected this possibility after examining the residual time series that results from removing the statistical fit of our bivariate model for $T(t)$ from the annual TC series. The residual shows no evidence of a multidecadal spectral peak (see supplementary). We thus infer that any factors unrelated to SST which might influence TC activity also do not exhibit any detectable multidecadal cyclicity.

Implications for Future Changes

There is a strong historical relationship between tropical Atlantic SST and TC activity extending back through the late 19th century. There is no apparent role of the AMO. The underlying factors appear to be the influence of (primarily anthropogenic) forced large-scale warming, and an offsetting regional cooling overprint due to late 20th century anthropogenic tropospheric aerosol forcing. These findings have implications for potential impacts of various alternative possible future anthropogenic forcing scenarios on Atlantic TC trends.

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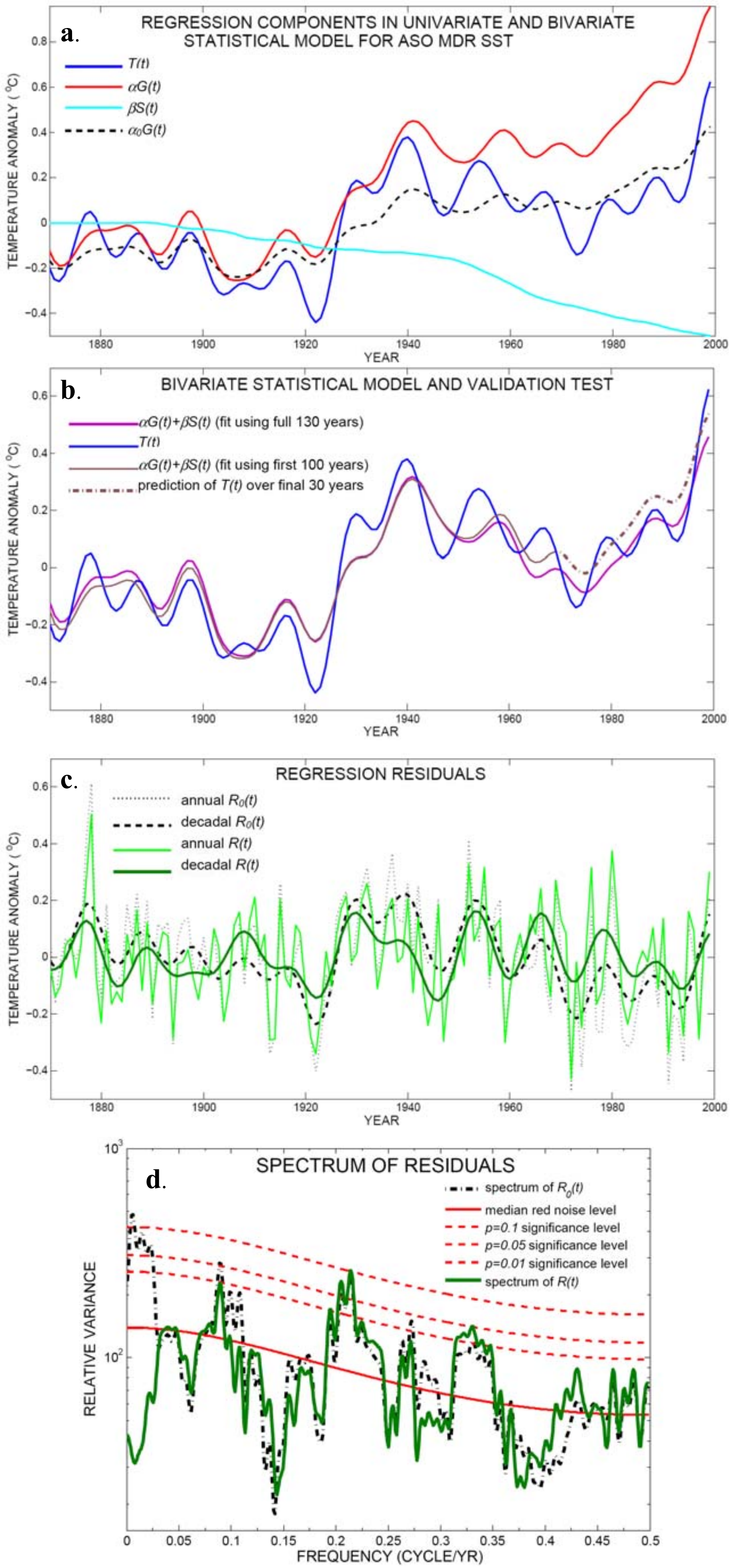
FIGURE CAPTIONS

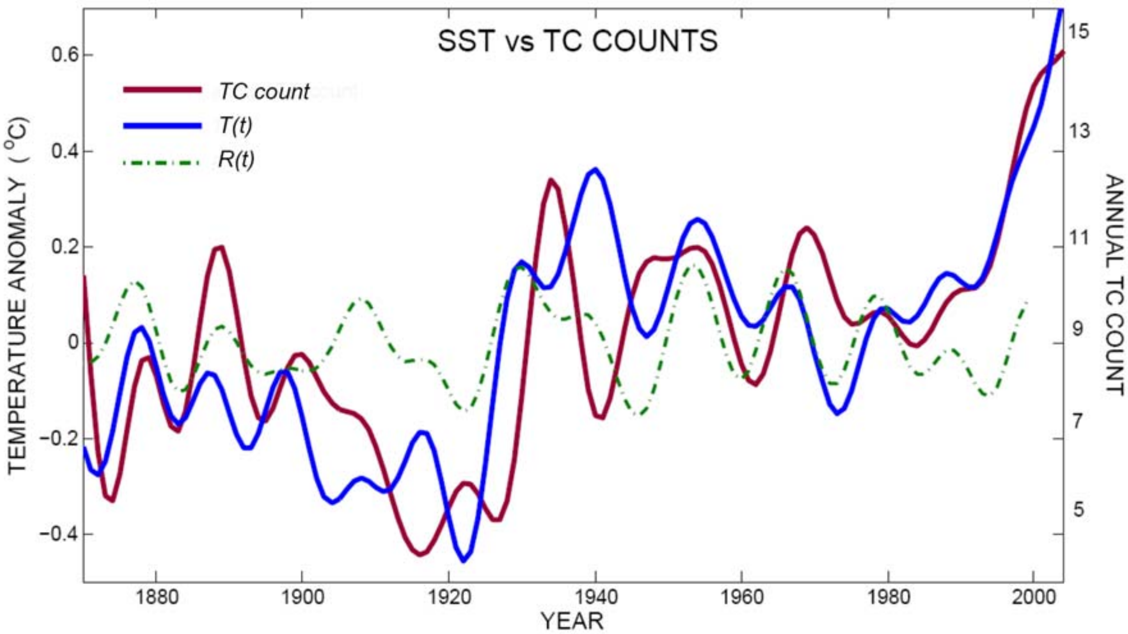
Fig. 1. Analyses of SST series. (a) decadally-smoothed ASO MDR SST series T(t) and estimated components for both (i) univariate regression (eq. 1 in text) using ASO global mean SST [$\alpha_0 G(t)$] and (ii) bivariate regression (eq. 2 in text) including component associated with ASO global mean SST [$\alpha G(t)$] and regional enhancement of anthropogenic tropospheric aerosol cooling [$\beta S(t)$]. (b) Bivariate statistical model (eq. 2 in text) for T(t) based on sum of both regression components shown in 'a'. Shown also is the fit of the regression model based on the restricted interval 1870-1969 and the prediction of T(t) over the subsequent 30 years (1970-1999) based on that regression model. (c) annual and decadally-smoothed univariate [$R_0(t)$] and bivariate [R(t)] regression residuals. (d) Power spectrum of of univariate [$R_0(t)$] regression residuals, with estimated red noise level and associated p=0.1,0.05, and 0.01 significance levels. Shown for comparison is the spectrum for the bivariate regression residual [R(t)]. See 'supplementary' for further details.

Fig. 2. Comparison of decadally-smoothed TC numbers with decadally-smoothed ASO MDR SST series T(t) and decadally-smoothed bivariate regression residual series R(t).



a.
REGRESSION COMPONENTS IN UNIVARIATE AND BIVARIATE STATISTICAL MODEL FOR ASO MDR SST
T(t)
αG(t)
βS(t)
α0G(t)
TEMPERATURE ANOMALY (°C)
YEAR
b.
BIVARIATE STATISTICAL MODEL AND VALIDATION TEST
αG(t)+βS(t) (fit using full 130 years)
T(t)
αG(t)+βS(t) (fit using first 100 years)
prediction of T(t) over final 30 years
c.
REGRESSION RESIDUALS
annual R0(t)
decadal R0(t)
annual R(t)
decadal R(t)
d.
SPECTRUM OF RESIDUALS
spectrum of R0(t)
median red noise level
p=0.1 significance level
p=0.05 significance level
p=0.01 significance level
spectrum of R(t)
RELATIVE VARIANCE
FREQUENCY (CYCLE/YR)

FIGURE 1



SST vs TC COUNTS
TC count
T(t)
R(t)
TEMPERATURE ANOMALY (°C)
ANNUAL TC COUNT
YEAR
0.6
0.4
0.2
0
−0.2
−0.4
15
13
11
9
7
5
1880
1900
1920
1940
1960
1980
2000

FIGURE 2