Eos, Vol. 87, No. 24, 13 June 2006

EOS

EOS, TRANSACTIONS, AMERICAN GEOPHYSICAL UNION

VOLUME 87 NUMBER 24

13 JUNE 2006

PAGES 233–244

Atlantic Hurricane Trends Linked to Climate Change

PAGES 233, 238, 241

BY M. E. MANN AND K. A. EMANUEL

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, this article presents results indicating that anthropogenic factors are likely responsible for long-term trends in tropical Atlantic warmth and tropical cyclone activity. In addition, this analysis indicates that late twentieth 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 tropical cyclone activity.

AMO Revisited

The multidecadal oscillatory pattern in Atlantic sea surface temperature (SST), referred to as the AMO, was first isolated by *Folland et al.* [1986], and was 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;

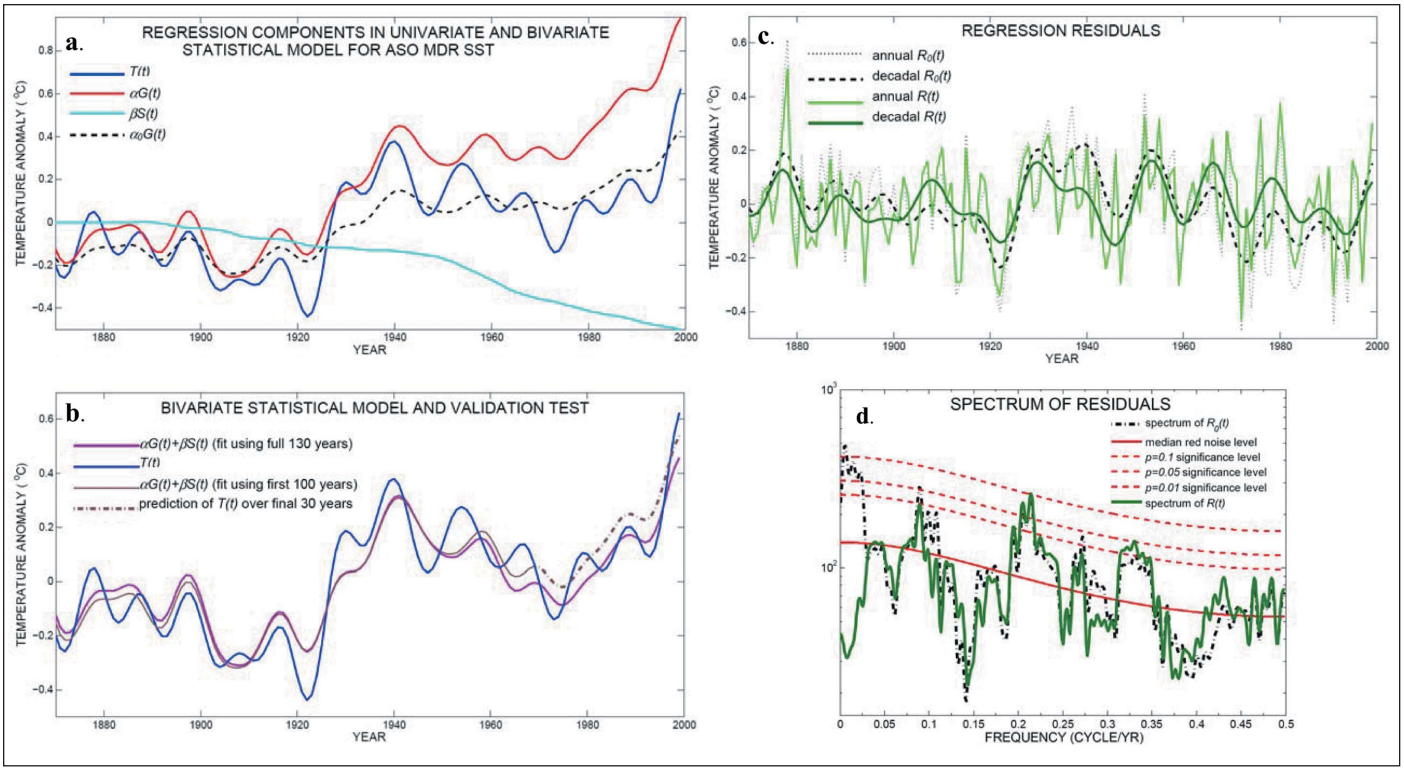

Fig. 1. Analyses of sea surface temperature (SST) series. (a) Decadally smoothed August-September-October (ASO) main development region (MDR) SST series T(t) *and estimated components for both (1) univariate regression [equation (1)] using ASO global mean SST [*αG(t)*] and (2) bivariate regression [equation (2)] including the components associated with ASO global mean SST [*αG(t)*] and the regional enhancement of anthropogenic tropospheric aerosol cooling [*βS(t)*]. (b) Bivariate statistical model [equation (2)] for* T(t) *based on the sum of both regression components shown in Figure 1a. 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 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 additional material for further details.*

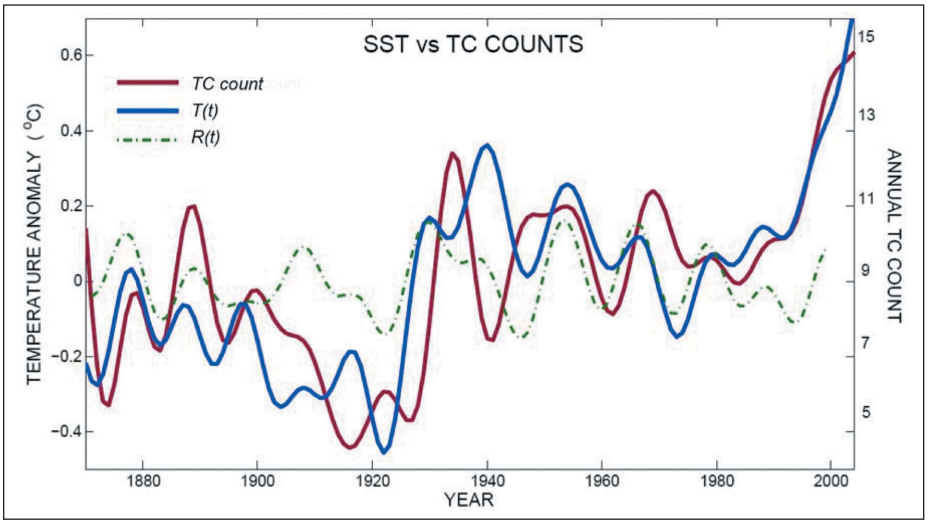

Fig. 2. Comparison of decadally smoothed tropical cyclone numbers with decadally smoothed ASO MDR SST series T(t) *and decadally smoothed bivariate regression residual series* R(t).

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 remnant after linearly detrending North Atlantic SST data available back through the late nineteenth century [e.g., *Goldenberg et al.*, 2001]. These analyses attribute the AMO as having a significantly greater influence on tropical North Atlantic SST than do climate model simulations [e.g., *Knight et al.*, 2005] or analyses using multivariate signal detection methods to separate possible long-term oscillatory patterns from trends in observational data [e.g., *Mann and Park*, 1994].

Moreover, if the AMO were indeed responsible for anomalous recent tropical North Atlantic warmth, the THC should have exhibited a trend toward 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., Figure 3 in *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 twentieth-century global mean temperature series exhibit a linear trend. It is more plausible [see *Trenberth and Shea*, 2006] 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. A statistical model based on this assumption can be used 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 using the tropical Atlantic HadISST2 observational SST dataset [*Rayner et al.*, 2003]. The SST data from 1870 to 2004 are averaged over the season most relevant to tropical cyclone formation (August–September–October, or ASO), and over the main development region (MDR) of 6°–18°N, 20°–60°W. $G(t)$ 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 this analysis is the assumption that the AMO does not project significantly onto $G(t)$. While *Knight et al.* [2005] find a very small nonzero AMO projection onto global mean SST (0.05°C peak amplitude), this is negligible compared with the secular trend in $G(t)$ of approximately 0.8°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 nineteenth and early twentieth centuries (see http://www.meteo.psu.edu/~mann/eos06, henceforth referred to as 'additional material'). Owing to constraints discussed below, the analysis is confined to the time interval 1870–1999.

Using the decadally smoothed (see additional material for details) $T(t)$ and $G(t)$ series, the regression [equation (1)] yields $\alpha_0 = 0.93 \pm 0.12$ (significance level $p \ll 0.001$; 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 percent 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 additional material for details) indicates a multidecadal (timescale > 30 years) 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 the last 50 or even 40 years of data are eliminated, the multidecadal spectral peak becomes statistically indistinguishable from red noise (see additional material). 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 twentieth century cooling has also 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, the estimated Northern Hemisphere anthropogenic tropospheric aerosol forcing series available through 1999 [*Crowley*, 2000] was included as an additional predictor $S(t)$:

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

Linear regression with equation (2) yields a revised estimate $\alpha = 1.7 \pm 0.17$ ($p \ll 0.001$), implying a projection of global warming onto the MDR (Figure 1a) that is significantly greater than the global mean. The estimated value of $\beta = 0.79 \pm 0.16$°C W^{-1} m^{-2} ($p \ll 0.001$), however, indicates that aerosol cooling has substantially offset much of the latter twentieth 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 percent of the decadal variance in $T(t)$ including most of the net warming (Figure 1b). To allow for an independent assessment of the skill of the statistical model, the regression was performed on only the first 100 years (1870–1969), and the resulting model parameters were used to predict the temperature evolution over the subsequent 30 years (1970–1999). The model parameters ($\alpha = 1.64 \pm 0.20$, $p \ll 0.001$; $\beta = 0.57 \pm 0.23$°C W^{-1} m^{-2}, $p < 0.01$) were 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 0.17ºC (0.08ºC). 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 additional material). In short, there is no evidence that a natural climate oscillation such as the AMO contributes to long-term tropical North Atlantic SST variations.

Connections With Tropical Cyclone Activity

A measure of total power dissipation by tropical cyclones (the power dissipation index, or PDI) has been shown by *Emanuel* [2005] to be well correlated with MDR ASO SST over the past 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 tropical cyclones is less so, because without aircraft and satellites to warn them off, ships often encountered storms at sea, at least peripherally. A reasonably reliable record of annual North Atlantic tropical cyclone counts is thus available back into the late nineteenth century [*Jarvinen et al.*, 2005]. This record, like the PDI index, shows a strong, long-term relationship with tropical Atlantic ASO 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 annual tropical cyclone counts can be resolved by SST variations ($r = 0.61$; $p < 0.001$ is obtained if the bivariate statistical model for $T(t)$ is used in place of $T(t)$ itself). $R(t)$, which must include any AMO contribution, explains an insignificant four percent (Figure 2) of the decadal tropical cyclone variance ($r = 0.20$, $p > 0.1$ for a one-sided test). In other words, the SST variability underlying increased Atlantic tropical cyclone activity appears unrelated to the AMO.

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 tropical cyclone changes [e.g., *Goldenberg et al.*, 2001]. This possibility was rejected after examining the residual time series that results from removing the statistical fit of the bivariate model for $T(t)$ from the annual tropical cyclone series. The residual shows no evidence of a multidecadal spectral peak (see additional material). Thus, it can be inferred that any factors unrelated to SST that might influence tropical cyclone activity also do not exhibit any detectable multidecadal cyclicity.

Implications for Future Changes

There is a strong historical relationship between tropical Atlantic SST and tropical cyclone activity extending back through the late nineteenth 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 twentieth century anthropogenic tropospheric aerosol forcing. These findings have implications for potential impacts of various alternative possible future anthropogenic forcing scenarios on Atlantic tropical cyclone trends.

Acknowledgments

We thank G. Schmidt, S. Rahmstorf, C. Folland, J. Knight, B. Santer, and K. Trenberth for comments on an early version of this manuscript, and we thank an anonymous reviewer for helpful comments on the manuscript. We thank G. Schmidt and L. Nazarenko for GISS (Goddard Institute for Space Studies) ModelE tropospheric aerosol SST cooling estimates and J. Knight for the U.K. Met Office SST data. Kerry Emanuel's contribution was supported by the U.S. National Science Foundation under grant ATM-0432090.

References

Bryden, H. L., H. R. Longworth, and S. A. Cunningham (2005), Slowing of the Atlantic meridional overturning circulation at 25°N, *Nature, 438,* 655–657.

Crowley, T. J. (2000), Causes of climate change over the past 1000 years, *Science, 289,* 270–277.

Delworth, T. L., and M. E. Mann (2000), Observed and simulated multidecadal variability in the Northern Hemisphere, *Clim. Dyn., 16,* 661–676.

Delworth, T. L., S. Manabe, and R. J. Stouffer (1993), Interdecadal variations in the thermohaline circulation in a coupled ocean-atmosphere model, *J. Clim., 6,* 1993–2011.

Emanuel, K. (2005) Increasing destructiveness of tropical cyclones over the past 30 years, *Nature, 436,* 686–688.

Folland, C. K., T. N. Palmer, and D. E. Parker (1986), Sahel rainfall and worldwide sea temperatures, *Nature, 320,* 602–607.

Goldenberg, S. B., C. W. Landsea, A. M. Mestas-Nuñez, and W. M. Gray (2001), The recent increase in Atlantic hurricane activity: Causes and implications, *Science, 293,* 474–479.

Hansen, J., *et al.* (2005), Efficacy of climate forcings, *J. Geophys. Res., 110,* D18104, doi:10.1029/2005JD005776.

Jarvinen, B. R., C. J. Neumann, and M. A. S. Davis (2005), A tropical cyclone data tape for the North Atlantic Basin, 1886–1983: Contents, limitations, and uses, NOAA Natl. Hurricane Cent., Miami, Fla.

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.

Mann, M. E., and J. Park (1994), Global-scale modes of surface temperature variability on interannual to century timescales, *J. Geophys. Res., 99(D12),* 25,819–25,833.

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.

Schlesinger, M. E., and N. Ramankutty (1994), An oscillation in the global climate system of period 65–70 years, *Nature, 367,* 723–726.

Trenberth, K.E., and D.J. Shea (2006), Atlantic hurricanes and natural variability in 2005, *Geophys. Res. Lett.*, in press.

Webster, P. J., G. J. Holland, J. A. Curry, and H. R. Chang (2005), Changes in tropical cyclone number, duration, and intensity in warming environment, *Science, 309,* 1844–1846.

Author Information

Michael E. Mann, Department of Meteorology, Pennsylvania State University, University Park; E-mail: mann@psu.edu; Kerry A. Emanuel, Program in Atmospheres, Oceans, and Climate, Massachusetts Institute of Technology, Cambridge.