Evidence in support of the climate change–Atlantic hurricane hypothesis

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[1]   The power of Atlantic tropical cyclones is rising rather dramatically and the increase is correlated with an increase in the late summer/early fall sea surface temperature over the North Atlantic. A debate concerns the nature of these increases with some studies attributing them to a natural climate fluctuation, known as the Atlantic Multidecadal Oscillation (AMO), and others suggesting climate change related to anthropogenic increases in radiative forcing from greenhouse-gases. Here tests for causality using the global mean near-surface air temperature (GT) and Atlantic sea surface temperature (SST) records during the Atlantic hurricane season are applied. Results show that GT is useful in predicting Atlantic SST, but not the other way around. Thus GT "causes" SST providing additional evidence in support of the climate change hypothesis. Results have serious implications for life and property throughout the Caribbean, Mexico, and portions of the United States. **Citation:** Elsner, J. B. (2006), Evidence in support of the climate change–Atlantic hurricane hypothesis, *Geophys. Res. Lett.*, *33*, L16705, doi:10.1029/2006GL026869.

1. Introduction

[2] A significant concern about the consequences of climate change is the potential increase in tropical cyclone activity [*Emanuel*, 2005; *Pielke et al.*, 2005; *Trenberth*, 2005; *Webster et al.*, 2005; *Elsner et al.*, 2006]. Theoretical arguments [*Emanuel*, 1987] and modeling studies [*Knutson and Tuleya*, 2004] indicate that hurricane intensity should increase with increasing global mean temperature. Direct observational verification of such a linkage is lacking, but *Emanuel* [2005] shows that Atlantic sea surface temperature (SST), which is correlated with global mean near-surface air temperature (GT), helps explain the recent upswing in frequency and intensity of Atlantic tropical cyclones. Yet others, who acknowledge the relationship between SST and hurricane activity, argue that the low frequency fluctuations in Atlantic SST called the Atlantic Multidecadal Oscillation (AMO) are a consequence of natural cycles related to the thermocline circulation [*Pielke et al.*, 2005; *Goldenberg et al.*, 2001]. Here I apply tests for causality using GT and SST records during the hurricane season and find that GT is useful in predicting SST, but not the other way around.

2. Data

[3] I obtain monthly global temperature (GT) anomalies (1961–1990 base period) from the Intergovernmental Panel on Climate Change (IPCC) from the Climatic Research Unit (CRU) [*Folland et al.*, 2001]. The anomalies in degrees C are accurate to ±0.05°C for the period since 1951. I obtain monthly values of Atlantic sea surface temperature (SST) from the U.S. NOAA-CIRES Climate Diagnostic Center. The data are a blend of the Hadley model SST values and interpolated SST values from the U.S. National Oceanic and Atmospheric Administration (NOAA). Values are given as anomalies in degrees C from the climatology based period of 1951–2000 [*Enfield et al.*, 2001]. The anomalies are spatially averaged over the North Atlantic Ocean. For this study, the GT and SST anomalies are time averaged over the main Atlantic hurricane season months of August through October for 135 consecutive seasons from 1871–2005.

[4] I also derive a total power dissipation index (PDI) from the Hurricane Database (HURDAT or best-track) maintained by the National Hurricane Center. HURDAT is the official record of tropical storms and hurricanes for the Atlantic Ocean, Gulf of Mexico and Caribbean Sea. HURDAT consists of the 6-hourly position and intensity (maximum wind speed at an altitude of 10 m) estimates of tropical cyclones back to 1851 [*Neumann et al.*, 1999]. For storms in the period 1931–1956, the 6-hr positions and intensities were interpolated from twice daily (00 and 12 UTC) observations. I compute the PDI by cubing the maximum wind speed for each 6 hr observation. I consider only observations where the tropical cyclone is at hurricane intensity (33 m s^{-1}) or above and sum the cubed wind speeds over the entire hurricane season for the years 1871–2005. Annual values of this total PDI depend on the duration, frequency, and intensity of the strongest hurricanes. I transform the annual total PDI to normality by taking the cube root. The Anderson-Darling test (a modification of the Kolmogorov-Smirnov test giving more weight to the distribution tails) provides a P value of 0.704 indicating no reason to reject the hypothesis of normality for the transformed index. Values of the cube root of the total PDI have units of m s^{-1}.

3. Competing Hypotheses

[5] Figure 1 illustrates the two competing hypotheses concerning Atlantic hurricanes. The climate change hypothesis asserts that changes in radiative forcing resulting from increased greenhouse gas build up in the atmosphere increases GT and causes Atlantic SST to rise at least during the hurricane season months of August through October. On the other hand, the AMO hypothesis asserts that natural changes in the deep water circulation of the Atlantic Ocean drive hurricane season SST resulting in changes to both hurricane activity and GT. Under both hypotheses local SST plays a direct role in helping to power hurricanes by providing moist enthalpy and instability. Thus the point of

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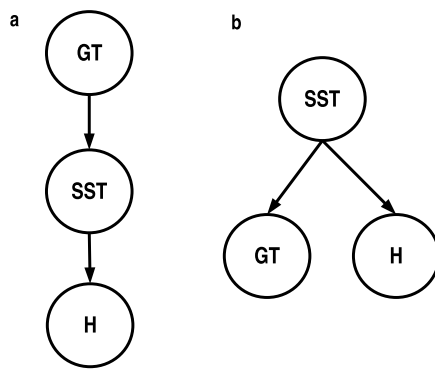
Figure 1. Two networks illustrating competing hypotheses concerning the causes of recent increases in Atlantic hurricane activity. (a) Climate change hypothesis network whereby global temperature (GT) predicts Atlantic sea surface temperature (SST) which in turn predicts hurricane activity (H). (b) AMO hypothesis network whereby SST predicts both GT and H.

departure for the two competing hypotheses is the causal connection between GT and Atlantic SST. The climate change hypothesis suggests the causality goes from GT to Atlantic SST whereas the AMO hypothesis implies it is the other way around.

[6] Figure 2 shows the time series of August–October averaged values of GT and Atlantic SST. The linear correlation between the two series is a significant 0.82 with a 95% confidence interval of (0.75, 0.88). Warmer global temperatures are associated with warmer Atlantic SST. However causality cannot be assessed from correlation alone. Instead, tests of causality can be made by determining whether one time series is useful in predicting another. More specifically, causality in the Granger sense [*Granger*,
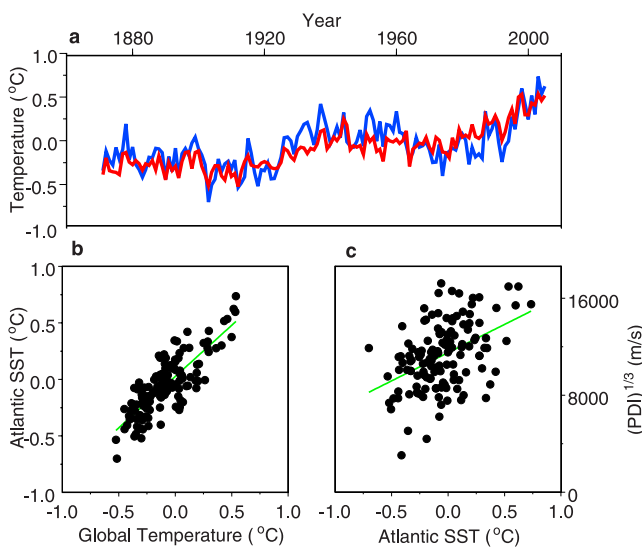

Figure 2. Global mean near-surface air temperature (GT) and North Atlantic sea surface temperature (SST) anomalies. The GT (AMO) anomalies are in red (blue). (a) Time series of August–October averaged values of SST and GT. (b) Scatter plot of GT and SST. (c) Scatter plot of SST and the cube root of the PDI. The straight lines in the scatter plots indicate the linear best fit relationship.

Table 1. Granger Causality Tests (Global Temperature and Atlantic SST)[a]

Model	Residual Df	Df	F Value	Pr(>F Value)
Test 1: SST as the Response				
Full	130			
Reduced	131	1	7.072	0.0088
Test 2: GT as the Response				
Full	130			
Reduced	131	1	0.910	0.3419

[a]Variables are the global mean near-surface air temperature (GT) and the North Atlantic sea surface temperature (SST) both averaged over the hurricane season months of August–October. Both series are differenced to eliminate non-stationarity before the tests are applied. The full models contain lagged values of both SST and GT whereas the reduced models contain only lagged values of the response variable (SST in Test 1 and GT in Test 2). Df stands for degrees of freedom and the F value is the ratio of the model mean square to the residual (error) mean square. It is used to decide whether the model as a whole has statistically significant predictive capability. Pr(>F value) is the probability of finding an F value as extreme or more extreme under the null hypothesis that the model has no predictive capability. A value of Pr(>F) less than 0.05 means I reject the reduced model.

1969; *Kaufmann and Stern*, 1997] can be tested statistically by comparing two sets of models involving lagged values of the predictor variable. This contrasts with standard regression models from which causality cannot be directly inferred.

4. Granger Causality

[7] A variable X is said to Granger-cause a variable Y if it can be shown that time series values of X provide statistically significant information on future values of Y. The test works by first regressing Y on lagged values of Y to determine the maximum lag for Y (reduced model). Then Y is regressed on lagged values of Y and lagged values of X for lags out to the maximum lag (full model). The full model is compared to the reduced model using an F-test to see if lagged values of X statistically improve upon the reduced model. If there is significant improvement in the full model by adding the X variable, then we say that X Granger causes Y. Here I am interested in determining the Granger causality between two variables, call them X and Y, so more formally I define two statistical models as

$$Y_t = \alpha_1 Y_{t-1} + \beta_1 X_{t-1} + \epsilon_t \qquad (1)$$

$$X_t = \gamma_1 Y_{t-1} + \delta_1 X_{t-1} + \eta_t, \qquad (2)$$

where Y_t (X_t) is the value of Y (X) at year t. The terms ϵ_t and η_t are the model residuals in the regression. The models are shown here only for lag = 1 year, but they can be extended to higher orders by adding additional terms (lagged values and their associated coefficients). More details on the Granger causality tests in the context of a climate study are given by *Mosedale et al.* [2006].

[8] I perform two separate tests with the results taken together providing clues about causality. The first involves predicting Atlantic SST from GT using time lagged values of SST and GT as predictors. In this case, SST is the response variable. The second involves predicting GT from

Table 2. Granger Causality Tests (Atlantic SST and Hurricane Activity)[a]

Model	Residual Df	Df	F Value	Pr(>F Value)
		Test 1: SST as the Response		
Full	130			
Reduced	131	1	1.278	0.2604
		Test 2: PDI as the Response		
Full	130			
Reduced	131	1	4.306	0.0400

[a]Variables are the North Atlantic sea surface temperature (SST) and the annual total power dissipation index (PDI) of Atlantic basin hurricanes. Both series are time differenced to eliminate non-stationarity before the tests are applied. The full models contain lagged values of both SST and PDI whereas the reduced models contain only lagged values of the response variable (SST in Test 1 and PDI in Test 2).

Atlantic SST (again using time lagged values of SST and GT). In this case GT is the response variable. For each test, I entertain two regression models. The full model contains lagged values of the response and the explanatory variables and the reduced model contains lagged values of only the response variable. I eliminate non-stationarity by time differencing both series before applying the tests. Results are given in Table 1 for lag = 1 year. The first test determines whether GT adds any prediction information to a model for Atlantic SST. The F value is large and significant ($P = 0.0088$) indicating that lagged values of GT are indeed useful in predicting SST. The second test determines whether SST adds any information to a prediction model for GT. In this case, the F value is quite small and insignificant ($P = 0.3419$) indicating that lagged values of Atlantic SST are not useful in predicting GT. The results are significant for these same tests using lags 1 through 9. In summary, GT can be used to predict Atlantic SST, but not the other way around. Thus I conclude that GT causes SST in the Granger sense.

[9] The role of SST in modulating hurricane activity is well established statistically and physically. The warm ocean provides the heat and moisture to sustain hurricane-force winds against friction and entropy. Thus I expect that Atlantic SST causes greater hurricane activity and that the causality be detectable in the Granger sense. I examine this assertion using the same test procedure as outlined above where I use the power dissipation index (PDI) as a measure of Atlantic hurricane activity to account for intensity and duration of the storms. The total PDI is computed as the sum of the third power of the maximum sustained wind speed over all observations above hurricane intensity (33 m s^{-1}) and over all hurricanes during the year. The statistical relationship between Atlantic SST and the total PDI (transformed by taking the cube root) is shown in Figure 2. Results of the causality test, given in Table 2, verify that indeed Atlantic SST Granger causes hurricane power (as defined by the total PDI) and not the other way around.

5. Conclusions

[10] Results from the Granger causality tests are consistent with the hypothesis that as climate change causes the atmosphere and, in turn, the seas to warm, the ocean stores more energy that is converted to hurricane wind. Of course, a warm ocean is necessary but insufficient for hurricanes. While others have recently argued that the warming of the oceans shows a clear signature of external forcing [*Barnett et al.*, 2005; *Trenberth and Shea*, 2006], the present analysis is the first to directly relate climate change to hurricane activity. The relationship between climate change and hurricanes may not extend to other tropical cyclone regions where ocean circulations during the tropical cyclone season may play the dominant role in warming (and cooling) the ocean surface. Understanding how climate modulates hurricane destructiveness is crucial to society, particularly as coastal populations swell [*Pielke et al.*, 2005]. The large increase in power dissipation of hurricanes over the past several decades together with the results presented here suggest cause for concern.

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