High-Frequency Variability in Hurricane Power Dissipation and Its Relationship to Global Temperature

BY JAMES B. ELSNER, ANASTASIOS A. TSONIS, AND THOMAS H. JAGGER

Results from a statistical analysis are consistent with recent numerical and observational studies showing that in a warmer environment increased hurricane intensity due to a warmer ocean might be partially compensated by decreased intensity due to greater atmospheric stability.

A major concern about global warming is the potential increase in tropical cyclone destructiveness resulting from more or stronger hurricanes (Shen et al. 2000; Pielke et al. 2005; Trenberth 2005). Theoretical arguments (Emanuel 1987) and modeling studies (Knutson and Tuleya 2004) indicate that hurricane intensity should increase with increasing global mean temperature. Observational verification of such a linkage is lacking, but Emanuel (2005) shows that Atlantic sea surface temperature (SST), which is correlated with global mean surface air temperature (GT), helps explain the recent upswing in frequency and intensity of Atlantic tropical cyclones (see also Webster et al. 2005). He defines the annual power dissipation index (PDI) as the integral of the third power of the maximum sustained wind speed over all 6-h observations at tropical storm intensity (18 m s^{-1}) or higher and over all tropical cyclones during the year and shows that a time series representing the low-frequency component of the annual PDI is highly correlated with a time series of similarly filtered annual values of the Atlantic SST. The PDI takes into account the frequency, strength, and duration of tropical cyclones. Here we use the PDI to further investigate its relationship to Atlantic SST in the high-frequency domain and we show that the positive influence of global temperature on Atlantic hurricanes appears to be limited to its connection with Atlantic SST.

There is a strong positive correlation between GT and Atlantic SST consistent with increasing greenhouse gases causing an increase in both SST (Levitus et al. 2000) and GT at both low and high frequencies. Yet there are reasons to expect that tropospheric warming might be related to hurricanes through

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changes in atmospheric shear and/or column stability independent of SST. For instance, the enhanced wind shear associated with El Niño, which is also a global warming event (Trenberth et al. 2002), will inhibit hurricane genesis (Gray 1984). Moreover, a numerical modeling study indicates the stabilization of the atmosphere's near-storm environment through warming that decreases hurricane intensity, thereby offsetting the increase in intensity due to higher SST (Shen et al. 2000). Thus, it is of interest to investigate whether there is observational evidence for this offsetting relationship. We do this here using partial correlation and regression analyzes.

DATA. We derive the 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 (Jarvinen et al. 1984; Neumann et al. 1999). For storms in the period of 1931–56, the 6-h positions and intensities were interpolated from twice-daily (0000 and 1200 UTC) observations. It is well known that hurricane data from the Atlantic basin are not uniform in quality owing to improvements in observational technology over the years. We adjust the pre-1973 wind speeds to remove biases using the same procedure as described in Emanuel (2005) and compute the PDI by cubing the maximum wind speed for each 6-h observation. We consider only observations where the tropical cyclone is at or above hurricane intensity (33 m s^{-1}) and sum the cubed wind speeds over the entire hurricane season for the years of 1947–2004 ($N = 58$ yr). For comparisons we perform the analysis using both the adjusted and unadjusted wind speeds. Annual values of the PDI depend on the duration, frequency, and intensity of the strongest hurricanes. We transform the annual PDI to normality by taking the cube root. Values of transformed PDI have units of meters per second. The Anderson–Darling test (a modification of the Kolmogorov–Smirnov test, giving more weight to the distribution tails) provides a P value of 0.307, indicating no reason to reject the hypothesis of normality.

We obtain monthly GT anomalies (1961–90 base period) from the Intergovernmental Panel on Climate Change (IPCC) online from the Climatic Research Unit (CRU; Folland et al. 2001). The anomalies are accurate to ±0.05°C for the period since 1951. We note that tropospheric temperatures measured from radiosondes have increased since 1958 by 0.09°C decade^{-1}, so that the long-term trend is upward and equivalent to that of the surface trend (Jones 1994). We obtain September values of Atlantic SST by averaging over a box bounded in latitude by 6° and 18°N, and longitude by 20° and 60°W from the National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR) reanalysis dataset (Kalnay et al. 1996; Kistler et al. 2001). The SST values are for September only to be consistent with those used in Emanuel (2005). We obtain Southern Oscillation Index (SOI) values as an indicator of El Niño–Southern Oscillation (ENSO). The SOI is defined as the normalized sea level air pressure difference between Tahiti and Darwin. The SOI is inversely correlated with the equatorial Pacific SST so that El Niño warming is associated with negative SOI values. Units are standard deviations. The monthly SOI values are obtained online from the CRU (Ropelewski and Jones 1987). The GT and SOI values are averaged over the main hurricane season months of August through October.

PARTIAL CORRELATION ANALYSIS. Partial correlation analysis is a procedure that allows us to determine the correlation between two variables after removing the effect of the third (controlling) variable. The equation for the partial correlation coefficient is

$$r_{12.3} = \frac{r_{12} - r_{13}r_{23}}{\sqrt{\left(1-r_{13}^2\right)\left(1-r_{23}^2\right)}},$$

which describes the correlation between variable 1 and 2 after controlling for variable 3. The simple correlation between variables 1 and 2 is denoted r_{12}, and the partial correlation between variables 1 and 2 controlling for (holding constant) variable 3 is denoted $r_{12.3}$. The equation is naturally extended to multiple control variables. Here P values of the correlations and partial correlations are obtained through linear regression. We save the residuals of a regression of variable 1 on variable 3 and the residuals of a regression of variable 2 on variable 3. We then perform a regression of the residuals of variable 1 on the residuals of variable 2. The partial correlation between variables 1 and 2 after controlling for variable 3 is the correlation between the residuals, and a test of the significance is performed using a one-tailed Student's t test on this correlation after taking into account the reduction in the degrees of freedom in the residuals. In the case of two control variables a multiple regression is applied to compute the residuals controlling for both variables. We employ partial correlation analysis using the PDI, SST, and GT values as defined in the "Data" section.

Figure 1 displays two networks relating the PDI to both GT anomalies and Atlantic SST. In the first network, SST intervenes between GT and the PDI. The values shown on the links are the partial correlations between the two node variables (circles) controlling for year. A list of correlations and partial correlations is given in Table 1. The partial correlation between GT and SST is +0.70, and the correlation between GT and PDI is +0.15. Because we are interested in the high-frequency variability, we control for year to remove the effect of trends in the data. Interestingly, the partial correlation between PDI and GT controlling for both year and SST is −0.24, consistent with the hypothesis that additional tropospheric warming decreases hurricane intensity (Shen et al. 2000). In the second network, GT intervenes between SST and the PDI. Here the partial correlation between PDI and SST controlling for year and GT is of the same sign, but is somewhat larger than the direct correlation, so we conclude that the effect of Atlantic SST on the PDI is enhanced when the negative influence of GT is removed. Results do not change if we include the weaker tropical cyclone data in the calculation of PDI. Moreover, the conclusions are the same if we compute the PDI using unadjusted wind speeds (see Table 1).

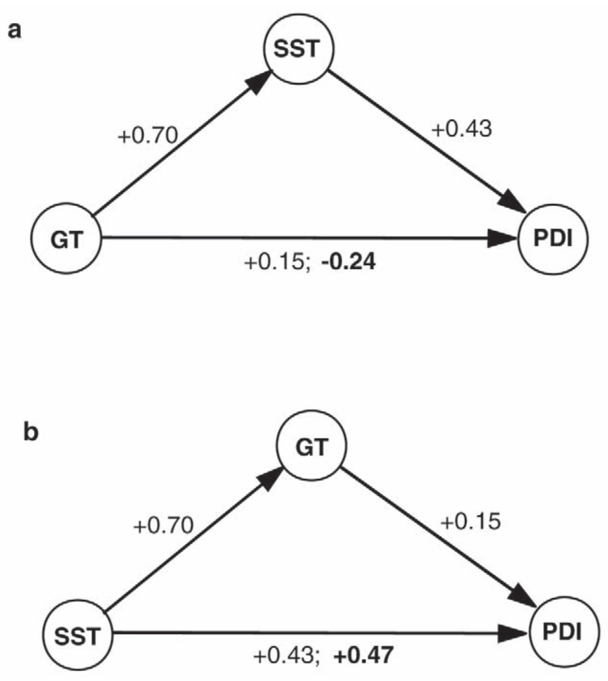

Fig. 1. Two networks relating the PDI to GT and tropical Atlantic SST. (a) SST intervenes between GT and the PDI; (b) GT intervenes between SST and the PDI. The values are the correlations between the linked variables. The bold value is the correlation between the two connected variables holding the third variable constant. In the first network the correlation values change sign when controlling for the third variable, indicating that the relationship between GT and PDI is not direct. In the second network the correlation values are of the same sign and approximately the same magnitude, indicating that GT is not needed in explaining the relationship between Atlantic SST and PDI.

HIGH-FREQUENCY VARIABILITY OF THE PDI. In order to investigate the high-frequency relationship between PDI and Atlantic SST we first fit a nonlinear trend to each of the signals by applying a regression smoother (Chambers and Hastie 1991) with a span of 44 yr. A smoothed value at a given year is obtained by fitting a weighted regression to the neighboring values within a chosen time span of the year, where the weights are a decreasing function of time from the given year. Figure 2 shows the raw and smoothed time series of annual hurricane PDI values. The coefficient of determination (R^2) between the smoothed PDI and smoothed SST series is 84%, indicating a strong relationship. Results are in agreement with those in Emanuel (2005) showing the unprecedented upswing in hurricane destructiveness related to rising Atlantic SST. The upswing is most pronounced starting with 1995 (Elsner et al. 2000). It has been suggested that low-frequency variability of Atlantic SST and hurricane activity result from

Table 1. Correlations and partial correlations. Variables are the PDI, GT, tropical Atlantic SST, and year (y). The correlation *r* between PDI and GT is in the row labeled PDI,GT. The partial correlation between PDI and GT controlling for year is in the row labeled PDI,GT.y. The partial correlation between PDI and GT controlling for both year and SST is in the row labeled PDI,GT.y,SST. The *P* values are obtained through regression analysis. For comparison, values in parentheses are based on computing the PDI using unadjusted wind speeds. Results are essentially the same.

Variables	correlation (*r*)	*P* value
PDI,GT	+0.349 (+0.024)	0.007
PDI,GT.y	+0.146 (+0.222)	0.275
PDI,GT.y,SST	−0.241 (−0.171)	0.068
PDI,SST	+0.472 (+0.425)	< 0.001
PDI,SST.y	+0.434 (+0.474)	< 0.001
PDI,SST.y,GT	+0.468 (+0.456)	< 0.001
GT,SST	+0.600 (+0.600)	< 0.001
GT,SST.y	+0.696 (+0.696)	< 0.001

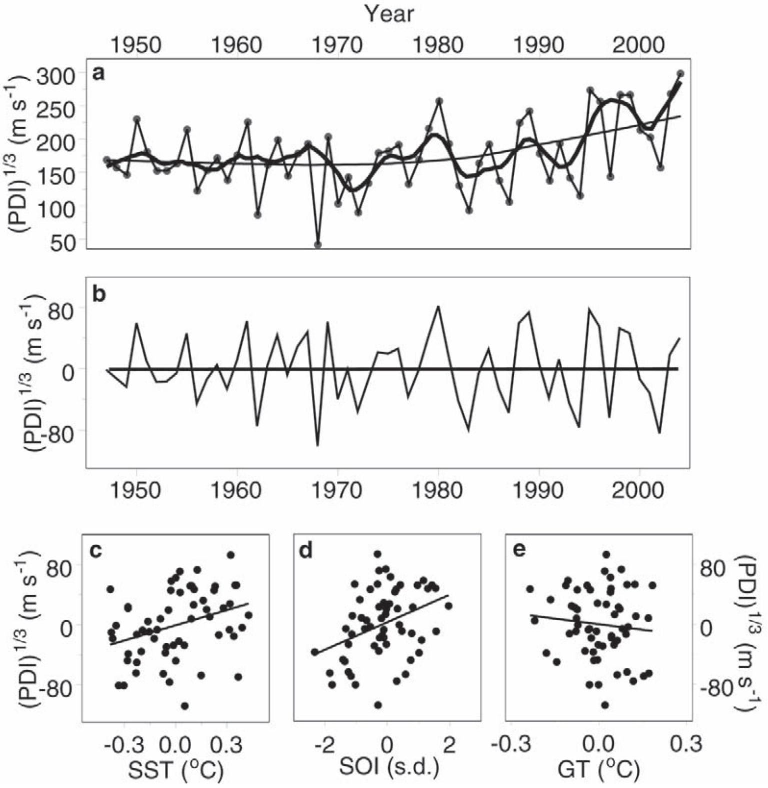

FIG. 2. Analysis of high-frequency variation in the PDI. (a) Time series of the PDI. Annual values (dots and light line), and the local regression smoother with a span of 44 yr (thick line) are shown. (b) Time series of the PDI residuals from the 44-yr local regression smoother (high-pass-filtered PDI). (c) Scatterplot of the high-pass-filtered PDI and high-pass-filtered SST. The linear regression line has a positive slope that explains 11% of the high-frequency variability (*P* value = 0.010). The *P* value represents a test of the null hypothesis of zero slope for the regression line. (d) Same as (c), except using SOI as the explanatory variable. The linear regression line has a positive slope (higher PDI during La Niña conditions) that explains 14% of the high-frequency variability (*P* value = 0.004). (e) Same as (c), except using GT as the explanatory variable. The linear regression line has an insignificant negative slope.

changes in the thermohaline circulation (Goldenberg et al. 2001).

Next we subtract the smoothed PDI (SST) curve from the raw PDI (SST) values. A time series of the PDI residuals shows regular high-frequency variation (Fig. 2b). A linear regression of the PDI residuals on the SST residuals results in a positive relationship (Fig. 2c) with a value of 11% for R^2. The positive regression slope is marginally significant ($P = 0.010$). Analysis of the regression errors confirms adherence to the underlying modeling assumptions. Thus, we show that tropical Atlantic SST is important in explaining both the low- and high-frequency component of the PDI. We find the R^2 values do not change using smoothing spans from 21 to 44 yr. The above procedures are repeated using basin-wide-averaged SST for the months of August through October with similar results.

ENSO is also an important regulator of Atlantic hurricane activity through modulation of wind shear (Gray 1984) and tropospheric warming (Tang and Neelin 2004) over the region where hurricanes develop. A regression of the PDI residuals on the SOI results in a significant positive relationship ($P = 0.004$), with the high-frequency component of the PDI explaining 14% of the variation (Fig. 2d). Because there is little correlation between the SOI and Atlantic SST residuals ($R^2 = 0.02$), a multiple regression of PDI on both variables explains 29% of the high-frequency variation in PDI. As anticipated from the above partial correlation analysis, we find only a weak negative relationship between the high-frequency variation of the PDI and global surface air temperature (Fig. 2e). However, the GT residuals are significant in the multiple regression model after accounting for both the SST and SOI, and the model explains 38% ($P < 0.0001$) of the high-frequency variation in the PDI. The sign on the GT coefficient in the model is negative, indicating that the influence of GT on Atlantic hurricane activity after accounting for both Atlantic SST and ENSO is to inhibit hurricane intensification consistent with the offset hypothesis.

CONCLUSIONS. Understanding the role climate plays in modulating hurricane destructiveness is crucial to society, particularly as coastal populations swell. The large increase in power dissipation of hurricanes over the past several decades is indeed troubling. Evidence presented here is consistent with numerical and observational studies showing that in a warmer environment increased hurricane intensity due to a warmer ocean might be partially compensated by decreased intensity due to greater atmospheric stability.

Using the best-available data we show that the relationship between hurricane power dissipation and SST is not confined to the decadal time scale, but extends to higher frequencies where other climate signals like ENSO are independently important in explaining annual fluctuations. We also investigate the question of the relationship between GT and hurricane power dissipation using partial correlation analysis, and show that after removing the effect of SST from GT the correlation between GT and hurricane power dissipation is negative. This indicates that the positive influence of global temperature on Atlantic hurricanes, possibly related to climate change, is limited to an indirect connection with tropical Atlantic SST.

Results from both the correlation analysis and the regression model lend support to the offset hypothesis (Shen et al. 2000) that increased hurricane intensity due to higher SST is partially compensated by decreased intensity due to greater atmospheric stability resulting from tropospheric temperatures that are warm relative to SST. It is well known from observations that increased column stability limits hurricane intensification (DeMaria et al. 2001; Emanuel et al. 2004).

Results are also consistent with the disequilibrium hypothesis of Tang and Neelin (2004). A disequilibrium state arising from a warmer troposphere over the North Atlantic basin (due to climate change and/or a Pacific El Niño event) relative to the normal relationship between tropospheric temperature and Atlantic SST leads to anomalously small mean potential intensity (Bister and Emanuel 1998) over the tropical Atlantic. In this case, the environment becomes less supportive of tropical cyclogenesis through a reduction in thunderstorm activity (Giannini et al. 2001).

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