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United States and Caribbean tropical cyclone activity related to the solar cycle

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[1] The authors report on a finding that annual U.S hurricane counts are significantly related to solar activity. The relationship results from fewer intense tropical cyclones over the Caribbean and Gulf of Mexico when sunspot numbers are high. The finding is in accord with the heat-engine theory of hurricanes that predicts a reduction in the maximum potential intensity with a warming in the layer near the top of the hurricane. An active sun warms the lower stratosphere and upper troposphere through ozone absorption of additional ultraviolet (UV) radiation. Since the dissipation of the hurricane's energy occurs through ocean mixing and atmospheric transport, tropical cyclones can act to amplify the effect of relatively small changes in the sun's output thereby appreciably altering the climate. Results have implications for life and property throughout the Caribbean, Mexico, and portions of the United States.

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1. Introduction

[2] On average Atlantic tropical cyclones are getting stronger with a trend that is related to increases in oceanic heat content over the North Atlantic [*Emanuel*, 2005; *Webster et al.*, 2005; *Trenberth*, 2005; *Elsner*, 2007]. However, according to the heat engine theory, a hurricane's maximum potential energy is inversely related to the temperature at the top of the convective clouds in the central core [*Emanuel*, 1991; *Holland*, 1997]. A warming of the lower stratosphere, near the tropopause ($\sim$16 km altitude), resulting from increased ultraviolet (UV) radiation absorbed by ozone will decrease the convective available potential energy limiting the intensity of the cyclone. Variation in radiation between extrema of the solar cycle can reach as high as 10% or more in portions of the UV range. Here we examine whether there is a solar signal in the record of hurricanes affecting the United States. The focus on U.S. hurricanes is motivated by the reliability of records back into the 19th century and by their social and economic importance. In fact, hurricane damage in the United States averaged greater than $35 bn (U.S.) per year in the period 2002–2005.

[3] While the heat engine theory concerns hurricane intensity, we have hurricane counts (frequency) for U.S. hurricanes back into the 19th century. However frequency and intensity are not independent climatological characteristics. In fact, frequency implies a thresholding of intensity. If we count the number of tropical storms (frequency) we implicitly set the (threshold) intensity at 17 ms^{-1} or above. Similarly if we count the number of hurricanes, we implicitly set the threshold at 33 ms^{-1} or above. Since the number of hurricanes is constrained to be less than or equal to the number of cyclones at tropical storm intensity or higher, there is a monotonically decreasing relationship between tropical cyclone intensity and frequency.

[4] Moreover, the Gulf and eastern coastline of the United States can be considered a random boundary that ‘‘intercepts’’ tropical cyclones at random intensities. All else being constant, if the intensity of cyclones increases then the frequency of cyclones reaching hurricane intensity (or any intensity) increases as does the probability that one will cross the coastline at the hurricane intensity threshold or greater. Thus, it is reasonable to assume that a process that influences the intensity of a tropical cyclone will also have an influence on the frequency of a collection of cyclones at a given intensity or above along the coastline assuming all else stays the same. Under this reasoning it makes sense to consider the frequency of U.S. hurricanes even though our main interest is intensity.

2. Seasonal Model for Basin-Wide Tropical Cyclones

[5] We first consider basin-wide tropical cyclones. As a first approximation on the annual time scale, high ocean heat content, low values of wind shear, and westerly steering currents increase the risk of Atlantic hurricanes [*Gray*, 1968; *DeMaria et al.*, 2001; *Elsner*, 2003]. Indexes that track variations in these factors are used to construct skillful statistical models of hurricane activity and potential losses from storms that reach the coast [*Elsner and Jagger*, 2004; *Saunders and Lea*, 2005; *Jagger et al.*, 2008]. Table 1 gives the parameter estimates and the output of an analysis of deviance from a Poisson regression model (see Text S1 of the auxiliary material[1]) for Atlantic tropical cyclone counts (cyclones of intensity exceeding 33 ms^{-1}) using data that start at different years.[1] The dependent variable is basin-wide annual tropical storm and hurricane counts from the U.S. National Hurricane Center's HURricane DATabase (HURDAT). The model covariates include sea-surface temperature (SST) as an indicator of ocean heat content, the Southern Oscillation Index (SOI) as a remote indicator of shear, and the North Atlantic Oscillation index (NAO) as an indicator of steering currents (see Text S1).

[6] Signs on the coefficients are consistent with the current understanding of seasonal tropical cyclone variability

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Table 1. Coefficients and Analysis of Deviance of a Poisson Regression Model for Atlantic Tropical Cyclones[a]

Term	Est.	df	Dev.	Res. df	Res. Dev.	*P* Val.
			TS + H 1900–2006			
Null	+2.158			106	193.2	
NAO	−0.086	1	8.24	105	184.9	0.004
SOI	+0.138	1	5.41	104	179.5	0.020
SST	+0.859	1	64.4	103	115.1	<0.001
			TS + H 1914–2006			
Null	+2.116			92	175.3	
NAO	−0.096	1	9.31	91	166.0	0.002
SOI	+0.150	1	3.99	90	162.0	0.046
SST	+0.981	1	61.3	89	100.7	<0.001
			TS + H 1944–2006			
Null	+2.202			62	79.0	
NAO	−0.084	1	4.35	61	74.7	0.037
SOI	+0.146	1	5.80	60	68.9	0.016
SST	+0.817	1	27.4	59	41.4	<0.001

[a]The model uses the logarithm of the tropical cyclone rate as the canonical link function to a linear regression of the covariates. Coefficients of the model are estimated (Est.) from the maximum likelihood procedure. Covariates include the May–June averaged North Atlantic Oscillation (NAO) index in units of standard deviations, the August–October averaged Southern Oscillation Index (SOI) in units of standard deviations, and the August–October averaged SST in the main development area. For a one unit change in the covariate, the difference in the logarithms of expected tropical cyclone counts changes by the respective regression coefficient estimate holding the other covariates constant. Each covariate reduces the degrees of freedom (df) of the model by 1 and the significance of the covariate to the model is based on the amount by which the residual deviance is reduced (Res. Dev.) with its addition. Under the null hypothesis that a covariate is not important to the model, the residual deviance has a χ^2 distribution with 1 df. A small *P* value indicates the covariate is statistically important to the model after accounting for the variables already in the model. Covariates are added to the model sequentially from top to bottom in the table. Null refers to a model without covariates.

indicating more disturbances reaching tropical cyclone intensity with greater ocean heat content (positive SST coefficient), more cyclone intensification with less shear (positive SOI coefficient indicating La Niña conditions), and a greater number of cyclones tracking through the Caribbean with weaker pre-season NAO indicating a preference for storms to remain in the deep tropics (e.g., hurricanes Dean and Felix over the Caribbean Sea during 2007).

[7] Significance of the covariates is assessed by the drop in deviance resulting from the inclusion of the term in the model after accounting for the covariates already in the model. The deviance is defined as minus 2 times the log likelihood of the observed tropical cyclone count given the model. If the model is correct, then in the large-sample limit, the deviance follows a χ^2 distribution. The deviance is used here as a tool for assessing the significance of each covariate in the model. It is similar to the residual sum of squares in the analysis of variance from a linear regression model. A small *P* value indicates the covariate is a statistically important addition to the model. As shown in Table 1, all covariates in the model are statistically significant.

[8] It is noted that Poisson regression is not the same as a normal regression on the logarithm of counts. Moreover, with a Poisson regression you cannot explain all the variation in the observed counts; there will be unexplainable variation due to the stochastic nature of the process. Thus, given that the counts follow a Poisson distribution, even if the model precisely predicts the rate of cyclones, the set of predicted counts will have a degree of variability that cannot be reduced by the model (aleatory uncertainty).

[9] Model fit is examined using the χ^2 goodness-of-fit test. The test statistic is given as the sum of squared difference between the observed and expected counts divided by the expected count. The test statistic is 85.34 on 89 degrees of freedom (93 years minus 4 model parameters) for a *P* value of 0.6 using data starting with 1914. Thus the test provides no evidence against model adequacy. Similar results are noted for the model using data with start years of 1900 and 1944.

3. Seasonal Model for U.S. Hurricanes

[10] To make use of longer records extending back into the 19th century and to strengthen the model's utility for risk management, we next focus on U.S. hurricane counts. Table 2 shows the coefficients and an analysis of deviance for a similar Poisson regression model of U.S. hurricane counts from data having different start dates. The coefficients on the NAO, SOI, and SST are of the same sign as the basin-wide model and are all statistically significant.

[11] Since the statistical model includes SST, the missing thermodynamic variable in the heat-engine theory of hurricane intensity is upper troposphere temperature. We speculate that an increase in solar UV radiation during periods of strong solar activity will have a negative influence on tropical cyclone intensity as the temperature near the tropopause will warm through absorption of radiation by ozone modulated by dynamic effects in the stratosphere [*Labitzke and van Loon*, 1988; *Rind and Balachandran*, 1995; *Shindell et al.*, 1999; *Crooks and Gray*, 2005; *Salby and Callaghan*, 2007]. This effect will be most pronounced in regions of sufficient oceanic heat content and for stronger tropical cyclones.

[12] For solar activity we use the monthly total sunspot number (SSN) for September (the peak month of the

Table 2. Coefficients and Analysis of Deviance of a Poisson Regression Model for U.S. Hurricanes[a]

Term	Est.	df	Dev.	Res. df	Res. Dev.	*P* val.
			US H 1866–2006			
Null	+0.641			140	189.8	
NAO	−0.210	1	12.8	139	177.0	<0.001
SOI	+0.237	1	9.11	138	167.9	0.003
SST	+0.504	1	3.42	137	164.5	0.064
SSN	−0.003	1	5.09	136	159.4	0.024
			US H 1878–2006			
Null	+0.680			128	178.2	
NAO	−0.207	1	11.0	127	167.2	0.001
SOI	+0.270	1	11.6	126	155.6	0.001
SST	+0.490	1	3.14	125	152.4	0.076
SSN	−0.003	1	6.11	124	146.3	0.013
			US H 1900–2006			
Null	+0.628			106	136.1	
NAO	−0.216	1	10.4	105	125.7	0.001
SOI	+0.286	1	8.73	104	117.0	0.003
SST	+0.538	1	3.40	103	113.6	0.065
SSN	−0.004	1	5.59	102	108.0	0.018

[a]Same as Table 1, except U.S. hurricanes is the response variable in the Poisson regression model and September sunspot number (SSN) is an additional covariate.

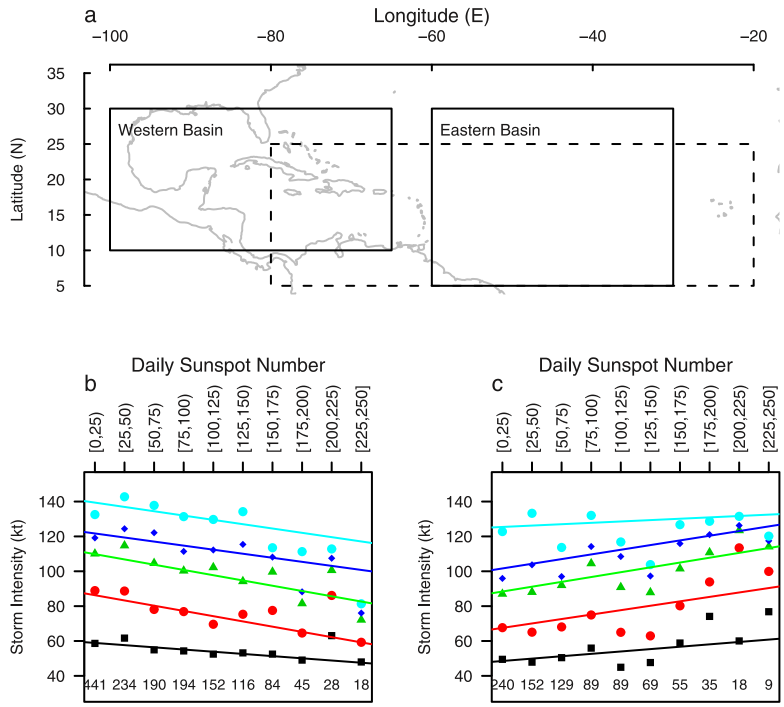

Figure 1. Region map and upper quantiles of hurricane intensity grouped by daily sunspot numbers. (a) Solid boxes delineate regions used to model daily tropical cyclone intensities. The dotted box delineates the averaging region for SST as an index of ocean heat content for the seasonal model of tropical cyclone activity. (b) Quantile values and regression model lines using daily tropical cyclone intensity in the western basin as the response and daily SSN as the covariate. Black is the 50th quantile (median), red is the 75th quantile, green is the 90th quantile, blue is the 95th quantile and cyan is the 99th quantile. Numbers above the abscissa are the sample sizes (number of days with sunspot numbers in the interval). (c) Same as Figure 1b, except for the eastern Atlantic basin.

hurricane season). Sunspots are magnetic disturbances of the sun surface having both dark and brighter regions. The brighter regions (plages and faculae) increase the intensity of the UV emissions. Sunspot numbers produced by the Solar Influences Data Analysis Center (SIDC), World Data Center for the Sunspot Index, at the Royal Observatory of Belgium are obtained from the U.S. National Oceanic and Atmospheric Administration. SSN is clearly significant in the model for U.S. hurricanes after accounting for the other three covariates (Table 2). The sign on the coefficient is negative indicating the probability of U.S. hurricanes decreases with increasing solar activity after accounting for the NAO, SOI, and SST. The coefficient magnitude indicates that for every additional 100 sunspots, the probability of a hurricane is reduced by a factor of 0.74.

[13] Results of including SSN as a covariate in the model are consistent with the heat engine theory and with the notion that increased UV radiation accompanying an active sun raises the temperature in the atmosphere at outflow levels of the cyclone. The P value from a goodness-of-fit test on the model that includes the SSN is 0.40 indicating no lack of fit. Correlation between the covariates range in absolute value from 0.05 to 0.19 with the highest occurring between SST and SOI and between SST and SSN.

4. Daily Tropical Cyclone Activity

[14] To examine this relationship between U.S. hurricanes and solar activity in more detail we consider daily tropical cyclone and solar data. We first spline interpolate the 6-hr positions and maximum wind speeds to hourly values [*Jagger and Elsner*, 2006] using the U.S. National Hurricane Center "best-track" data [*Neumann et al.*, 1999] for all tropical storms and hurricanes over the 63-year period 1944–2006. Tropical cyclones over the Caribbean Sea and near the United States were monitored with aircraft reconnaissance during this time period. We then compute a daily average tropical cyclone wind speed intensity from the spline interpolated values.

[15] Latent heat extracted from the warm ocean and released in deep convection intensifies tropical cyclones. But the intensity obtained by a particular cyclone depends on additional factors including low-level vorticity and wind shear [*DeMaria and Kaplan*, 1999]. These factors will confound attempts to identify a solar signal in the data. In order to provide some control for these variables, we correlate tropical cyclone intensity with solar activity using cyclones over a uniformly warm part of the western half of the basin and mainly within the deep tropics. The domain is bounded by 65 and 100°W longitude and 10 and 30°N latitude (Figure 1a). Oceanic heat content in this region is the largest during the hurricane season so the limiting thermodynamic variable is upper atmosphere temperature rather than SST.

[16] The rank correlation between daily SSN and daily averaged tropical cyclone intensity for all tropical storms and hurricanes in the domain over the period 1944–2006 is −0.11 ($P < 0.001$, 413 degrees of freedom). The signifi-

Table 3. Coefficients of a Quantile Regression of Storm Intensity on SSN[a]

Quantile	Estimate	S.E.	*t* Val.	*P* Val.
Q50	−0.025	0.006	−4.017	<0.001
Q75	−0.060	0.012	−4.908	<0.001
Q90	−0.061	0.014	−4.368	<0.001
Q95	−0.046	0.014	−3.461	0.001
Q99	−0.050	0.021	−2.342	0.019

[a]Values are estimates of the slope of a quantile regression of storm intensity on SSN over the western Atlantic basin. SSN is grouped in 25 count intervals. The slope estimate has units of ms^{-1}/SSN. The *P* value is the probability of a more extreme *t* value under the null hypothesis that the slope is zero. Q50, Q75, Q90, Q95, and Q99 are the 50th, 75th, 90th, 95th, and 99th percentiles (quantiles) of storm intensity.

cance includes a reduction in the degrees of freedom since daily intensities and SSN are serially correlated. Each storm is given one degree of freedom regardless of the number of days it stays in the domain. Although explaining a small amount of the variability, the result is consistent with results from the seasonal model showing an inverse relationship between hurricane intensity and solar activity. Figure 1b shows the upper quantiles of hurricane intensity by categories of daily SSN. The slopes from a quantile regression (Text S1) are negative at median cyclone intensities and above indicating an inverse relationship between solar activity and storm intensity. The relationship is generally stronger for the more intense cyclones (Table 3) and is consistent with the results from the seasonal model of U.S. hurricane counts.

[17] In marked contrast, the daily SSN is positively correlated with daily averaged tropical cyclone intensity for cyclones over the domain bounded by 30 and 60°W longitude and 5 and 30°N latitude. Figure 1c shows the upper quantiles of hurricane intensity by categories of daily SSN over the eastern part of the Atlantic basin. Here the slopes from a regression are positive at the median and higher quantiles indicating an direct relationship between solar activity and cyclone intensity over the central and eastern Atlantic.

5. Upper Troposphere Temperatures and SSN

[18] We speculate that over the western Atlantic including the Caribbean Sea and Gulf of Mexico where oceanic heat content is sufficiently large, the limiting thermodynamic factor for a tropical cyclone to reach its maximum potential intensity (MPI) is the outflow temperature near the tropopause. Since this variable is inversely related to MPI, we note that an active sun (more sunspots) warms the lower stratosphere and upper troposphere thereby decreasing the cyclone's potential intensity. Previous studies have shown a connection between the solar cycle and upper troposphere temperatures that is particularly strong during the Northern Hemisphere summer [*van Loon and Shea 2000*; *Zerefos et al.*, 2001; *van Loon and Labitzke*, 2000].

[19] To examine this linkage for the time and region of interest, we obtain seasonal averaged (August–October) upper atmospheric temperatures from the U.S. NCAR/NCEP reanalysis dataset [*Kalnay et al.*, 1996]. Seasonal mean temperature values at 200, 150, 100, 70, 50, and 30 hPa are averaged over the western part of the North Atlantic (see Figure 1) and correlated with SSN over the peak hurricane season (August–September). Table 4 shows the results of this correlation analysis at each level and for the layer average. The correlation between near-tropopause air temperature is positive throughout the layer and significantly so for the layer average. The mean response in air temperatures at 150 hPa is an increase of 0.5K for every 100 sunspots.

[20] Results indicate a relationship between solar activity and upper tropospheric/lower stratospheric temperatures consistent with our speculation that a cooler sun (fewer sunspots) results in a cooler outflow level surrounding the storm and thus greater cyclone intensity. The correlation analysis is repeated with similar results using data from radiosondes at sites from around the globe [*Free et al.*, 2005]. It should be kept in mind that although the reanalysis data go back to 1948, a statistical examination of a 10–12 year cycle is limited by the relatively few complete cycles (∼6) in this period. Moreover the reanalysis data may not be especially reliable at near-tropopause levels over regions where relatively few radiosonde measurements were available. The limited period of record and the confounding influence tropical cyclones have on their environment precludes us from using upper-air temperature directly in our model.

6. Summary and Discussion

[21] In this paper we demonstrate a statistically significant model for seasonal basin-wide tropical cyclone frequency. We then add SSN as a covariate to the same model applied to U.S. hurricane frequency and get a significant improvement as measured by the drop in deviance and a test of overall model adequacy. In fact, the SSN covariate is more significant than the SST covariate. The relationship between SSN and U.S. hurricane frequency is negative indicating that an inactive sun increases the probability of a U.S. hurricane after controlling for the NAO, SOI, and SST. Based on the leading theory of tropical cyclone intensity, all else being equal, hurricane intensity should increase with decreasing upper air temperature. We cite previous studies showing that increased solar activity increases upper troposphere/lower stratosphere tempera-

Table 4. Correlation Between Upper Air Temperature and SSN[a]

P (hPa)	r(T_{NCAR}, SSN)	*P* Val.	r(T_{NOAA}, SSN)	*P* Val.
30	+0.24	0.070	+0.32	0.027
50	+0.23	0.078	+0.18	0.206
70	+0.16	0.212	+0.11	0.459
100	+0.22	0.089	+0.21	0.152
150	+0.21	0.115	+0.32	0.025
200	+0.18	0.164	+0.26	0.075
Avg	+0.29	0.027	+0.28	0.055

[a]The correlation coefficient [r(T_{NCAR}, SSN)] is based on upper air temperatures from the NCEP/NCAR reanalysis data averaged over the western part of the North Atlantic (see Figure 1) from the hurricane season months of August–October (1948–2006). The correlation coefficient [r(T_{NOAA}, SSN)] is based on data from soundings (NOAA Radiosonde Atmospheric Temperature Products for Assessing Climate) averaged over the entire tropics between 30°N and 30°S latitude for the entire calendar year (1958–2006). The sunspot number (SSN) is the August–October total from daily counts. The *P* values are based on the null hypothesis of zero correlation. P is the pressure level and Avg is the correlation and associated *P* value after averaging the temperatures and SSNs over the layer from 30 to 200 hPa.

tures. Our own analysis of the temperature in this layer of the atmosphere over where cyclones intensify shows a statistically significant positive relationship to SSN. Finally we examine daily data and show that U.S. and Caribbean storminess tends to be more intense when sunspots are fewer consistent with our seasonal model and lending additional force to our argument of a solar signal in U.S. and Caribbean hurricane activity.

[22] An explanation for the geographic difference in the solar-hurricane relationship centers on the difference in the limiting factors associated with tropical cyclone intensity. Over the western Atlantic where the oceanic heat content is sufficient for cyclogenesis, upper-level outflow temperature appears to be the limiting factor with a warmer lower stratosphere acting as a "lid" on the tropospheric convection. In contrast over the eastern and central Atlantic where ocean heat content is limited, additional shortwave solar flux from an active sun provides the marginal increase in SST needed for cyclogenesis. In fact, a time series model of Atlantic SST contains a component corresponding to the solar cycle [*Elsner et al.*, 2008] with August–October SST values in the main development region generally higher (lower) during years of high (low) sunspot numbers.

[23] To better understand and predict how global warming might affect hurricanes it is necessary to consider the full range of natural factors responsible for variations in tropical cyclone activity. Here we identify a relationship with solar activity that explains a significant portion of the interannual variability in tropical cyclone frequency along the U.S. coast after accounting for oceanic heat, shear, and steering. Daily SSN are significantly negatively correlated to tropical cyclone intensity over the Caribbean especially for storms near their MPI. Indeed, results from a quantile regression model for daily intensity confirm the results of our seasonal model adding evidential support to the hypothesis of a solar-hurricane link.

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