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Evidence linking solar variability with US hurricanes

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ABSTRACT: The relationship between US hurricanes and solar activity is investigated empirically. First, a relationship between the probability of a US hurricane and the solar cycle is shown conditional on sea surface temperatures (SST). For years of above normal SST, the probability of three or more US hurricanes decreases from 40 to 20% as sunspot numbers (SSN) increase from lower to upper quartile amounts. Second, since SST is in phase with the 11-year total solar irradiance cycle but upper-air temperature is in phase with ultraviolet radiation changes on the monthly time scale, an anomaly index of SSN is constructed. The index is significantly correlated with US hurricanes and major US hurricanes over the period 1866-2008. The chances of at least one hurricane affecting the United States in the lowest and highest SSN anomaly seasons are 68 and 91%, respectively. A similar relationship is noted using hurricane records spanning the period 1749-1850, providing independent corroborating evidence linking solar variability to the probability of a US hurricane. Copyright © 2010 Royal Meteorological Society

KEY WORDS UV radiation; sunspots; ozone; multivariate regression; sea surface temperatures; thermodynamics

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1. Introduction

Hurricanes, capable of filling the entire vertical extent of the troposphere, transfer large amounts of energy from the ocean to the atmosphere via latent heat released from the condensation of rising moist air. But their development and intensification are highly dependent on ambient influences. Changes in atmospheric water vapour composition (Emanuel, 1991), steering currents (Dong and Neumann, 1986), and sea surface temperatures (SST) (Holland, 1997) affect tropical cyclone intensity (for an overview, see Wang and Wu, 2004). Recently, it has been found that variations in upper-air temperature resulting from fluctuations in ultraviolet (UV) radiation from the sun can also affect tropical cyclone intensity (Elsner and Jagger, 2008 (hereafter, EJ08)).

Actually, the idea of a solar connection to tropical cyclones is almost a century and a half old (Meldrum, 1872; Poey, 1873), but the relationship has recently been re-examined. EJ08 show that the annual US hurricane counts are significantly related to solar activity. The relationship results from fewer intense tropical cyclones over the Caribbean and Gulf of Mexico when there are many sunspots. The finding is in accordance with the heat-engine theory of hurricanes, which predicts a reduction in the maximum potential intensity in response to warming in the atmospheric layer near the top of the hurricane. An active sun warms the lower stratosphere and upper troposphere through ozone absorption of additional UV radiation. In short, increased solar activity – associated with more sunspots – means more UV radiation reaching the Earth's upper atmosphere. The extra radiation warms the air aloft and decreases the temperature differential between high and low elevations resulting in less available potential energy for hurricane intensification (Elsner *et al*., 2010). But increased solar activity also contributes to warming of the ocean and altering of the atmospheric circulations, thus complicating the role solar variability plays in modulating hurricane activity.

The purpose of this paper is to (1) further examine the evidence for a sun–US hurricane relationship on the interannual time scale, and (2) show that the relationship is detectable in data that pre-dates the modern record. In doing so, the study provides additional evidence that the relationship is likely the result of changes in upper-level temperature caused by variation in UV radiation. This treatment is statistical, and no attempt is made to directly address the hypothesized causal mechanisms, as is done in Elsner *et al*. (2010).

The paper begins in Section 2 with background information about solar variability and its possible relationship with hurricane activity. In Section 3, the data used in the study are described. In Section 4, we examine the sun–hurricane relationship using data since 1851. The intra-seasonal variability in solar activity is proposed as a better way to describe the sun–hurricane relationship. This is shown using a table of ranked years and, more comprehensively, with a Poisson regression model. In Section 5, the technique of ranking years according to the magnitude of the change in intra-seasonal solar activity is used on a set of US hurricane counts dating back to 1749. The results are consistent in showing an increase in US hurricane probability for years with large sunspot

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number (SSN) anomalies, featuring relatively low numbers of sunspots during the hurricane season and high numbers immediately before and after the season.

2. Background

Sunspots are visible disturbances on the surface of the sun resulting from intense magnetic fields associated with the geographic switching of magnetic poles which occurs, on average, every 11 years (Schwabe cycle) as part of the solar magnetic cycle. Higher outgoing total solar irradiance (TSI) occurs during periods of increased SSN. While TSI in a given cycle varies by only 0.1% in magnitude for all radiation wavelengths, UV and extreme UV (EUV) have been shown to vary by more than 10% (Hoyt and Schatten, 1997). Increases in upper-tropospheric (above 200 hPa) temperature have been shown to occur during solar activity maxima (Labitzke, 2002; Pap and Fox, 2004), with tropical tropopause temperatures also increasing with increased UV radiation (Hood, 2003). Higher solar activity has also been linked with increased global SST. Upper ocean temperatures were shown to increase during periods of increased solar activity over most of the tropical oceans (White *et al.*, 1997). In fact, Elsner *et al.* (2008) develop a model for North Atlantic SST that includes a term for the 11-year cycle.

The maximum potential intensity (MPI) theory postulates that, in an idealized thermodynamic environment, a hurricane's intensity is proportional to the thermodynamic efficiency between input energy (entropy gain from ocean/atmosphere interaction) and outflow venting (mechanical dissipation) (Miller, 1958; Emanuel, 1991; Holland, 1997; Bister and Emanuel, 1998). An increase (decrease) in surface (upper-tropospheric) temperature would increase the thermodynamic potential energy available for convection, all else being equal. The effect of upper-tropospheric and oceanic warming from increased UV exposure presents a bicameral climate effect upon hurricane intensity: warming at the surface increases a hurricane's potential intensity, whereas warming aloft decreases the potential mechanical dissipation and therefore hurricane intensity.

An active sun (many sunspots) might lead to warmer SST over regions where hurricanes form (due to additional shortwave energy absorbed by the surface). But it will more immediately lead to a warmer upper troposphere over these same regions (due to additional UV radiation absorbed by ozone). Since, according to the heat-engine theory, warming at the surface acts to enhance cyclone intensification while warming aloft acts to inhibit intensification, the influence of the sun on hurricanes is masked when using simple analyses. A way around this problem is to control for one or the other of the variables.

EJ08 do this geographically by examining the sun–hurricane relationship only for hurricanes over the western part of the tropical North Atlantic basin. Over this region, ocean heat content is nearly always high enough for tropical cyclogenesis, so the limiting thermodynamic factor is upper tropospheric temperatures (UTT). Indeed, they find a significant negative relationship between daily SSN and hurricane intensity over this part of the North Atlantic. Because of the region's already sufficiently warm ocean, the extra energy from an active sun limits intensification via a warmer upper troposphere. Thus EJ08 are able to detect a solar signal on the hurricane occurrence by geographically controlling for SST.

Over the western Atlantic including the Caribbean Sea and Gulf of Mexico where optimal oceanic heat content for cyclogenesis is spatially and intra-seasonally expansive, the limiting thermodynamic factor for a tropical cyclone to reach maximum intensity is the temperature of the atmosphere near the tropopause. Since this covariate is inversely related to MPI, we note that an active sun warms the lower stratosphere, thereby decreasing potential intensity. Indeed, the correlation between seasonally averaged SSN and temperatures near the tropopause over the domain is consistently positive based on atmospheric data over the period 1948–2006 (EJ08). In contrast, the daily SSN is positively correlated with daily averaged tropical cyclone intensity for cyclones over the eastern Atlantic.

The present work examines the sun–hurricane relationship by constructing an index that accounts for the low- and high-frequency variability inherent in the solar cycle. Though findings here corroborate those of EJ08, a potential bicameral role of the sun is examined through the construction of an SSN anomaly index of in-season and out-of-season values. The inclusion of almost 100 years of additional North Atlantic hurricane records back to 1749 (Chenoweth, 2006) confirms the robustness of the interannual sun–hurricane relationship.

3. Data

The National Hurricane Center (NHC) houses the North Atlantic-basin hurricane database (HURDAT, or Best Track), containing dates, tracks, wind speeds, and minimum central pressure values as available, providing the best available modern hurricane information dating back to 1851 (Landsea *et al.*, 2004). With refining work begun by Jose Fernandez-Partagás (Partagás and Diaz, 1996), over 5000 additions and alterations have been approved by the NHC Best Track Change Committee in an effort to improve the accuracy of storm data between 1851 and 1910 (AOML-NOAA, 2008). Through the 2008 hurricane season, HURDAT identifies 1362 unique North Atlantic storms (>18 m s^{-1}) and 819 individual hurricanes (>33 m s^{-1}), 283 of which struck the US mainland.

Monthly mean SSN for this study are the International Sunspot Number as made available by the National Geographic Data Center, which was originally constructed by Solar Influences Data Analysis Center, World Data Center, at the Royal Observatory of Belgium (Van der Linden, 2009). Reliable monthly observations extend back to 1749. The Swiss astronomer Johann Rudolph Wolf introduced a daily measurement technique that observes both total spots and the quantity of their clusterings. The dataset addresses the observed error by incorporating a weighted average of cooperating observations.

Other covariate data include the North Atlantic oscillation (NAO), North Atlantic SST, and the Southern Oscillation index (SOI). The NAO May to June monthly index values (mean of −0.35 and standard deviation of 1.02) are courtesy of the Climatic Research Unit, and are calculated from sea level pressures at Gibraltar and at a station over southwest Iceland (Jones *et al.*, 1997). More information about the NAO as a covariate for US hurricane activity is provided in Elsner and Jagger (2006). Monthly SST anomalies averaged from June to November (mean of 0.01 °C and standard deviation of 0.20 °C) are departures from the long-term average for 0° to 70°N, and are linearly detrended. The SST data are provided and maintained by the Physical Sciences Division of the Earth System Research Laboratory, NOAA, and are derived from the Kaplan SST dataset (Kaplan *et al.*, 1998). The SOI averaged from June to November (mean of −0.09 and standard deviation of 0.92) is defined as the normalized sea-level pressure difference between Tahiti and Darwin, and is obtained also from the Climatic Research Unit.

A record of US hurricanes pre-dating those listed in HURDAT are available in Chenoweth (2006). This cross-referenced compendium of North Atlantic hurricanes improves upon previous compilations (Tannehill, 1938; Poey, 1855; Ludlum, 1963; Redfield, 1863), providing individual storm positions and dates through cross-referencing and validating individual entries using newspaper accounts, weather diaries, and ships logbooks for the period of 1700–1850. Chenoweth (2006) identifies 383 unique storms and 289 hurricanes, 127 of which affected the US mainland. The archive was digitized for use as a database of individual storm locations in Scheitlin *et al.* (2010) and we use this digitization here.

In summary, the present study considers the evidence for a sun–hurricane relationship by dividing the data into pre- and post-1851. The post-1851 data use the HURDAT records for US hurricane counts and the covariate information as described above. However, the monthly SST data begin in 1856 and the monthly SOI data begin in 1866, so adjustments are made accordingly. The pre-1851 analysis uses the Chenoweth (2006) archive for US hurricane counts and the covariate information is limited to monthly SSN.

4. The sun–hurricane relationship since 1851

4.1. Seasonal variability

As previously mentioned, one of the purposes of the present work is to re-examine the evidence shown in EJ08 for a sun–hurricane relationship. EJ08 assume a Poisson model for US hurricane counts and the model includes SST and SSN as covariates. Here, we make the same Poisson assumption and look at the bivariate relationship between US hurricanes and the SSN conditional on above- and below-normal SST.

Figure 1 shows the probability distribution of US hurricanes conditioned on values of August to October SSN for seasons of above-normal and below-normal SST, based on upper and lower tercile SST values averaged from June to November, respectively. For each hurricane count, the percent bar represents the probability of that many US hurricanes given the data and the Poisson distribution. For above-normal SST values among lowest terciled August to October SSN, the probability of no US hurricanes is 9%. This probability increases to 20% for highest tercile SSN. Conversely, the probability for exactly four US hurricanes is 13 and 6% for lowest and highest tercile SSN, respectively. Likewise, the probability of three or more US hurricanes occurring dwindles from 40 to 22%.

In years of lowest tercile SST values among the lowest tercile August to October SSN, the probability of no US hurricanes is 17%. This probability increases to 39% for the highest tercile SSN. Note that these probabilities are greater than those for warm years, but also demonstrate the same inverse relationship for increasing SSN. Conversely, the probability for exactly four US hurricanes is 7 and 1% for the lowest and highest tercile SSN, respectively. Likewise, the probability of three or more US hurricanes dwindles from 26 to 6%. Note that the higher storm count probabilities are less than for those of the warm years. With maximum hurricane intensity dependent on SST (e.g. Emanuel, 1991; Holland, 1997; Henderson-Sellers *et al.*, 1998), the decrease in overall US hurricane probabilities from warm SST to cold SST is expected.

Another way to consider the relationship between SSN and US hurricanes as modulated by SST is through the conditional correlation. Figure 2 shows the correlation between SSN and US hurricane counts at different percentiles of SST. The correlation (Pearson product moment) over all years is −0.13, as indicated by the leftmost point. The correlation is based on a sample size of $N = 153$ years. Each storm season is considered independent, and the standard error on the overall correlation estimate is 0.139, providing a 90% confidence interval on the correlation value of (−0.264, +0.01). The confidence interval is shown by the width of the gray band.

The next point on the graph to the immediate right is the correlation between hurricane counts and SSN after removing the coldest 20% (20th percentile) seasons. The 20th percentile SST value constitutes an anomaly of −0.17 °C. The correlation changes negligibly, but with reduced sample size the confidence band widens. The plot shows that the correlation does not change much for the coldest 50% of seasons. However, when 60% of the coldest seasons are removed, the correlation decreases to −0.24 with a 90% confidence interval of (−0.429, −0.027), based on a sample size of 61 years. The correlation continues to decrease as only the warmest years remain. With sample size decreasing accordingly, the

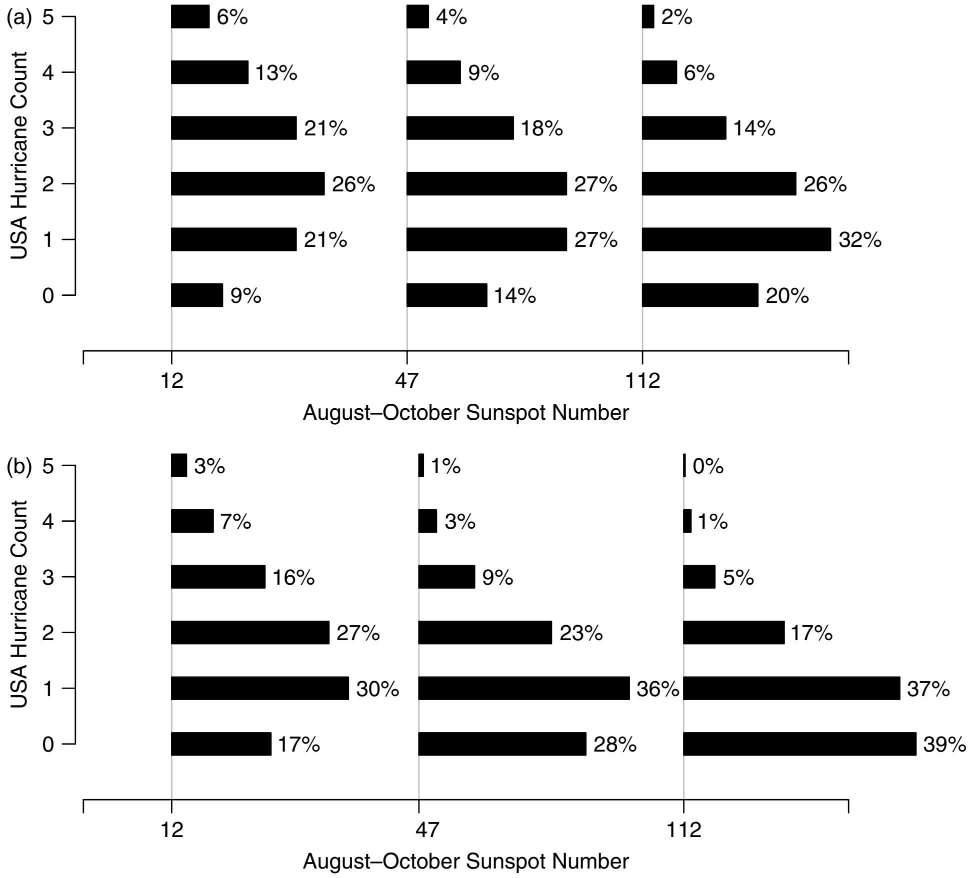

Figure 1. Probability distribution of US hurricanes conditional on terciled August to October SSN values for years of (a) upper- and (b) lower-tercile August to October Atlantic SST anomalies. Sunspots are displayed as the averages of their respective terciles. Data span the period 1856 to 2008.

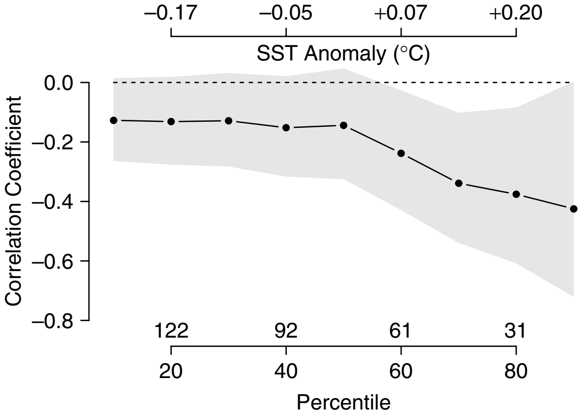

Figure 2. Correlation between August and October SSN and US hurricane counts. The correlations are computed at increasing percentiles of August through October averaged SST for the period 1856 to 2008. The shaded region represents the 90% confidence band at each computed value. The number of years over which the correlation is based is shown above the abscissa.

confidence bands expand, but the relationship between the US hurricane counts and August to October SSN remains statistically significant. The strengthening negative correlation indicates that the relationship between hurricane activity and SSN is tightest when ocean temperatures are warmest. Warmer core-season SSTs provide a fertile developing ground for tropical development. As such, suppressed tropical development from high August to October SSN is most evident at this time.

4.2. Intraseasonal variability

As mentioned, the proposed sun–hurricane relationship is a result from changes in upper-level temperatures due to changes in UV radiation, thermodynamically decreasing the amount of energy for wind generation. Hood (2003) shows that the tropopause temperature response to changes in UV radiation is maximum at the 100 hPa layer around 16 km, which is commensurate with the tropical thermal tropopause and hurricane cloud height extent. Hurricane cloud heights can extend upward to the tropical tropopause layer. A warming of 0.5 K at the 100 hPa level (Hood, 2003) results in a relative temperature difference (between inflow and outflow) of only about 1%, but a relative decrease in CAPE of about 10%, according to the theory of Emanuel (1994). These thermodynamic changes decrease the relative wind speed by about 5%, which translates to a 3 m s^{-1} weakening of a 50 m s^{-1} hurricane (Elsner *et al*., 2010). In short, increased solar activity – associated with sunspots – means more UV radiation reaching the Earth's upper atmosphere. This is corroborated by UV/upper-level temperature studies (Hood, 2003) and solar activity/ozone production increases (Angell, 1989; Calisesi and Matthes, 2007). The extra radiation contributes to warming the air aloft (via the exothermic response from ozone photodissociation), thus decreasing the temperature differential between high and low elevations that would otherwise foster vertical motion and cloud height growth. This thermodynamic explanation is in line theoretically with the observed changes in hurricane intensity concurrent with the diurnal cycle and net radiation changes (Hobgood, 1986; Gray, 1998). As mentioned, however, increased solar activity also contributes to the warming of the oceans (White *et al.*, 1997, 1998), thus complicating the role solar variability plays in modulating hurricane activity.

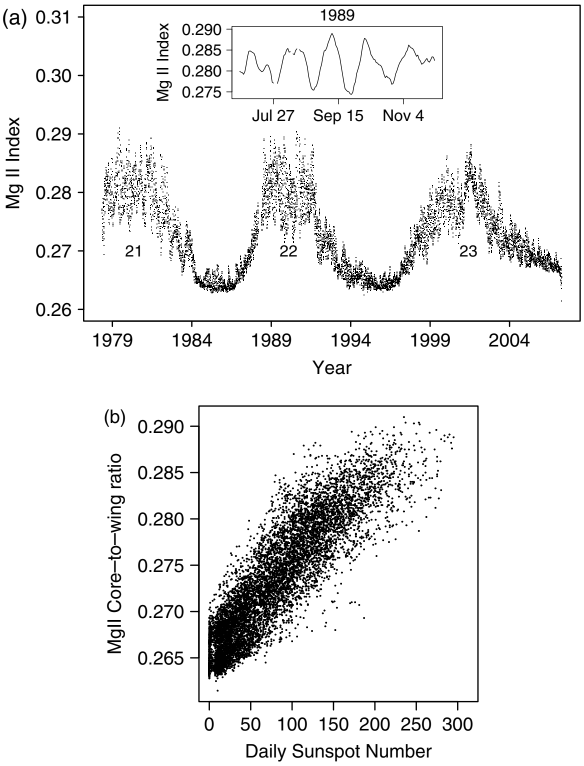

Figure 3. Solar Mg II index values. (a) Time series of the daily solar Mg II index. The series begins on 7 November 1997 and ends on 14 October 2007 (10 578 days). Values are plotted as points. Values below the 11-year peaks indicate the solar cycle number. Horizontal axis is labelled on 1 July of the year. The inset graph shows the Mg II index values as a time series over the hurricane season of 1989. Values are connected as a curve. Breaks in the curve indicate missing values. There are 1331 missing values (12.6% of the days). (b) Scatter plot of daily sunspot number and MgII core-to-wing ratio. The correlation between the two variables is 0.9.

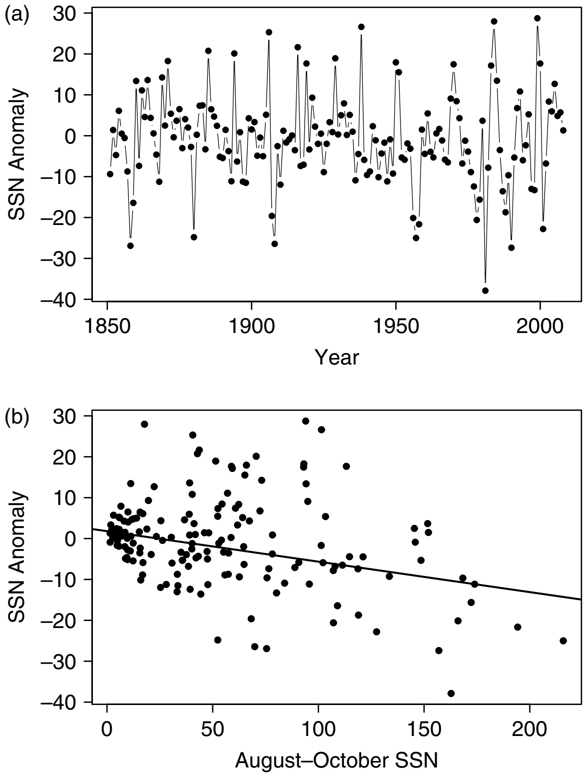

Figure 4. Seasonal sunspot number (SSN) anomalies as defined by the difference in sunspot numbers during May, June, July, November and sunspot numbers during August, September, October. (a) Time series of the anomaly and (b) scatterplot of August to October SSN *versus* SSN anomalies. Negative anomalies are largest for larger values of SSN. The trend has a value of −0.08 ± 0.02 (s.e.) with dimensionless units.

Solar UV radiation at wavelengths near 200 nm is important for ozone production in the Earth's upper stratosphere. Variation in the amount of this radiation is best measured by the Mg II core-to-wing ratio (Mg II index) (Heath and Schlesinger, 1986; Lean *et al.*, 1997; Viereck and Puga, 1999; Viereck *et al.*, 2001) and is shown in Figure 3(a). The time series reveals the well-known 11-year Schwabe cycle and short-term fluctuations (near 27 days) caused by the asymmetric distribution of active rotating solar regions (plages and sunspots). The short-term fluctuations are especially pronounced near solar maxima (Mg II index values exceeding 0.27). Although accurate estimates of UV radiation are available only since the advent of satellite measurements, the record of sunspots dates back to the 18th century. The relationship between daily sunspot number and Mg II index is quite strong (the correlation between the two variables is 0.9), allowing us to use sunspot numbers as a reasonable proxy for UV radiation (see Figure 3(b)).

The impact on UTT from changes in UV radiation is a fast process. Hood (2003) notes that tropical tropopause (∼15 km) temperatures vary in phase with incoming UV radiation at a zero-day phase lag, or immediately. Given such, UV radiation/UTT fluctuations are better represented on a shorter time scale than the solar influence on warming the oceans, which occurs at a monthly to multi-annual timescale. Thus, if EJ08 are correct, we should be able to detect an immediate solar influence on hurricanes by using changes in UV radiation caused by the 27-day solar rotational period.

We do this by defining solar activity during the hurricane season as anomalous if the August to October SSN is substantially different from the SSN during the months of May to July and November. Formally, let $\mathrm{SSN_{anom}} = \mathrm{SSN_{MJJN}} - \mathrm{SSN_{ASO}}$, where $\mathrm{SSN_{MJJN}}$ is the sunspot number averaged over May, June, July, and November, and $\mathrm{SSN_{ASO}}$ is the sunspot number averaged

Table I. | SSN anomalies and US hurricanes: 1851–2008.

SSN Anomaly	US	MUS	Year	NAO	SOI	SST
+28.7	3	1	1999	+1.21	+0.43	+0.19
+27.9	1	0	1984	−1.01	−0.22	−0.26
+26.6	2	1	1938	+0.31	+1.19	+0.29
+25.3	4	1	1906	−1.72	+0.99	−0.05
+21.7	4	2	1916	−1.88	+1.06	−0.06
+20.8	1	1	1885	+0.96	−1.23	+0.01
+20.1	2	1	1894	+0.7	−0.29	−0.27
+19.0	2	1	1929	+0.31	+0.3	−0.12
+18.3	3	1	1871	−1.94	+0.23	+0.01
+17.9	3	2	1950	−0.24	+1.59	+0.01
+22.6	**2.5**	**1.1**	**1927**	**−0.33**	**+0.4**	**−0.03**

SSN Anomaly	US	MUS	Year	NAO	SOI	SST
−37.9	0	0	1981	−0.76	0.41	−0.07
−27.4	0	0	1990	−0.39	−0.31	+0.07
−26.9	6	0	1858	+0.15	–	−0.17
−26.4	1	0	1909	+1.38	+0.58	−0.06
−25.0	1	1	1957	−0.82	−0.6	+0.14
−24.8	4	1	1880	−0.67	+0.75	+0.13
−22.8	0	0	2001	−0.71	−0.18	+0.25
−21.7	1	1	1958	−0.17	−0.14	+0.21
−20.6	0	0	1978	+0.26	+0.01	−0.19
−25.4	**1.4**	**0.3**	**1947**	**+0.12**	**+0.16**	**+0.02**

Years are listed according to the value of the ten most negative SSN anomalies (top) and ten most positive (bottom). Corresponding columns include the number of US hurricanes (US), major US hurricanes (MUS), the NAO as a May to June average anomaly, the SOI as a June to November average anomaly, and SST as a June to November average anomaly. Averages over the 10 years are given in bold.

over August through October. Negative (positive) anomalies indicate that solar activity during the hurricane season is greater (less) than the solar activity during the months prior to and after the season. In general, positive anomalies arise during hurricane seasons when the Schwabe cycle is near a peak but sunspot numbers are relatively low during August, September, or October in response to the phase and intensity of the 27-day solar rotation. Negative anomalies arise during hurricane seasons when the Schwabe cycle is near a trough but sunspot numbers are relatively high during August, September, or October (Figure 4b). Thus there is a inverse relationship between total SSN and the SSN anomaly as defined here. The SSN anomaly index has a mean of −0.80 and standard deviation of 11.37. A time series of the SSN anomaly since 1851 has been provided (Figure 4a).

While the hurricane's violent vertical transport of moisture and energy overrides the ambient atmospheric temperatures, changes in temperatures at outflow levels (upper troposphere) alter the available potential energy for given vertical motion. EJ08 found a significant relationship between 150 hPa temperatures and SSN. As SSN increases, so does 150 hPa temperature. The SSN anomaly as described here offers a potential extra-terrestrial proxy for inflow and outflow temperature modification: thus, a seasonal thermodynamic profile. This is because the SSN averaged over the peripheral months of the hurricane season (May, June, July, November) captures the position of the 11-year Schwabe cycle, which is related to SST variability (Dima *et al.*, 2005), and the SSN averaged over the core hurricane season months (August, September, October) captures the position of the 27-day cycle, which is related to upper-air variability from changes in UV radiation. By taking the difference of these two averages, we combine the effects into a single covariate, which we hypothesize is related to the probability of US hurricanes. Hurricane seasons characterized by a positive SSN anomaly (warmer inflow temperature and colder outflow temperatures) should correspond to greater hurricane activity.

Table I lists the top and bottom 10 hurricane seasons according to the value of the SSN anomaly using the years 1851–2008. The list includes the observed number of US and major US hurricanes by year along with anomaly values of other covariates which are known to be related to hurricane activity. These covariates include the NAO averaged over May and June prior to the hurricane season, the SOI averaged over the hurricane season months of June through November, and the SST averaged over June through November. The NAO is a precursor signal for hurricane steering (Elsner and Jagger, 2006) and the SOI is an indicator of the El Niño-Southern Oscillation and, therefore, wind shear and subsidence over the tropical Atlantic. Data for the SOI is available only back to 1866.

Of the top ten positive anomaly years, 2 years featured four US hurricanes and 3 years featured three. There was at least one US hurricane in each of the top ten anomalous years. In contrast, four of the bottom 10 years had no US hurricanes and 3 years had only one. The mean US hurricane rate for positive SSN anomaly years is 37% higher than the overall mean US rate (1.82 hurricanes per year). For negative differences, mean US counts were 56% lower. Mean major US (MUS) hurricanes demonstrated a 72% increase (positive) and a 53% decrease (negative), respectively, in departure from mean seasonal MUS hurricanes (0.64 hurricanes per year). Mean values of the SST and SOI anomalies are clearly not able to explain the difference in hurricane rates; however, the NAO might be a confounding variable. This is examined next in the context of a multivariate regression model.

4.3. A seasonal model incorporating the SSN anomaly

To examine the intra-seasonal SSN anomaly as a predictor for US hurricanes, we need a multivariate setting. This is achieved through the development of a regression model. Separate models are developed for hurricanes and major hurricanes that make landfall in the United States. The Poisson regression is a form of statistical regression used to model count data, such as the annual number of US hurricanes. The Poisson regression assumes that the

Table II. | Poisson regression of US hurricanes.

Term	Estimate	Dev.	Res. df	Res. Dev.	p-Value
		US hurricanes			
NULL	0.498	–	142	180.756	
NAO	−0.176	12.166	141	168.589	0.005
SOI	+0.157	6.254	140	162.336	0.022
SST	+0.665	4.186	139	158.150	0.034
SSN_{anom}	+0.028	6.447	138	151.703	0.011
		Major US hurricanes			
NULL	-0.604		142	152.929	
NAO	−0.190	5.654	141	147.275	0.073
SOI	+0.256	5.936	140	141.338	0.022
SST	+1.144	4.424	139	136.914	0.030
SSN_{anom}	+0.047	6.624	138	130.290	0.010

Regression parameters using all US hurricanes as the response (top) and all major US hurricanes as the response (bottom) for 1866–2008. The columns include the parameter estimate, the deviance (Dev.), the residual degrees of freedom (Res. df), the residual deviance (Res. Dev.) and the p-value. The p-values are based on F-tests for differences in group means. All p-values are less than 0.1, indicating the significance of the term to the model after accounting for the terms already in the model.

response variable H (annual number of US hurricanes) has a Poisson distribution with a single parameter λ, which is the annual rate of US hurricanes. The logarithm of the annual rate is modelled using a linear combination of covariates. The model coefficients are determined using the method of maximum likelihood. The model covariates include May to June NAO index as an indicator of hurricane steering, the June to November SOI as an indicator of Atlantic basin wind shear and subsidence, June to November SST as an indicator of ocean heat content, and the SSN anomaly as defined above. With the exception of the SSN anomaly, the covariates are identical to those used in Elsner and Jagger (2006) for predicting US hurricane activity.

The NAO index is the sea-level pressure difference between the permanent Icelandic Low and semi-permanent Azores High. An inverse relationship between the NAO index and US hurricanes was found in Elsner and Kocher (2000). When the Azores High is located farther to the north and east and is stronger (i.e. high NAO index values), hurricanes that form over the central North Atlantic tend to get steered away from the United States. The SOI is another sea-level pressure difference (Tahiti minus Darwin, Australia) that has been shown to vary in phase with North Atlantic hurricane activity (Gray, 1984).

Low values of the SOI correspond with warm eastern equatorial Pacific SST (i.e. El Niño conditions). This warm water tends to shift the focus of Pacific deep tropical convection eastward, leading to sheering winds and subsidence over the North Atlantic basin. North Atlantic hurricane activity also varies in phase with SST. Warm waters provide a breeding ground for genesis and intensification of tropical cyclones, with temperatures below 26 °C generally too cool for supporting organized tropical deep convection (Gray, 1968).

Table II lists model parameters and analysis of deviance for a model with the number of US hurricanes as the response variable from 1866 to 2008. The coefficient on the SSN anomaly term indicates a positive relationship with hurricane frequency, consistent with the relationship proposed from the analysis of Table I. Model covariates are added sequentially to the model. Model parameters and analysis of deviance for the first three covariates were originally shown to be statistically significant in EJ08. The SSN anomaly is determined to be the second most important variable (based on the magnitude of deviance) toward explaining the US hurricanes. The model for major US hurricanes is similar, but here the SSN anomaly term is the most important variable.

Note that the SSN anomaly covariate is significant after accounting for the NAO. In a general circulation model, Shindell *et al.* (2001) find a shift to low index values of the NAO as a response to reduced solar irradiance. This would contribute to an increase in US hurricane probability, as the paths they take are directed through the Caribbean Sea. In fact, the correlation between June values of SSN and the NAO (1866–2008) is +0.14 (p-value $= 0.1$), suggesting that some of the solar influence on hurricanes might be through solar-forced changes to the NAO. More work on this area is needed.

Model adequacy is checked by examining the residual deviance after all terms are included. For the hurricane model, the residual deviance is 151.7 with 138 degrees of freedom (df). The p-value as evidence in favour of model adequacy from a χ^2 distribution with this quantile value and this df is 0.2, indicating no strong evidence against model adequacy. The p-value on the residual deviance of the major hurricane model is 0.7, again providing no evidence against model adequacy.

Figure 5 illustrates the model-predicted changes in US hurricane frequency with respect to the extremes of

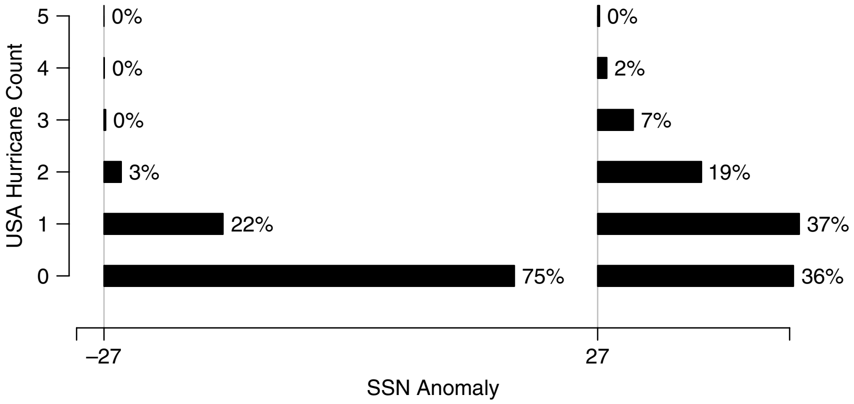

Figure 5. Predicted probability distribution of US hurricanes. Predictions are made using a Poisson regression for values of SSN anomalies corresponding to the 1st and 99th percentiles while keeping the other three covariates at neutral values. The model is based on data from the period 1866–2008.

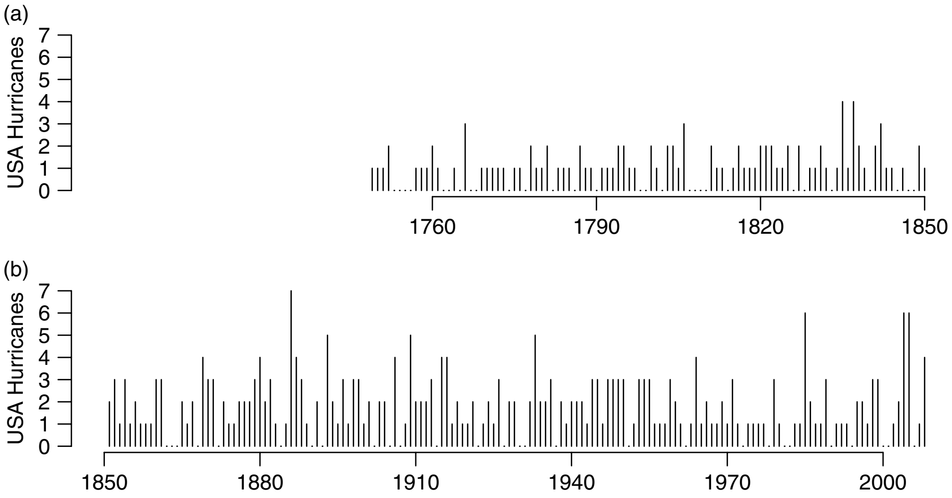

Figure 6. Annual US hurricane counts for the periods (a) 1749–1850 and (b) 1851–2008. Data from 1851 through 2008 are from HURDAT and the data prior to 1851 are from the Chenoweth (2006) historical hurricane archive.

SSN anomalies while assuming neutral conditions for the NAO, SST, and SOI. A zero-count US hurricane season is more than 3 times as likely to occur in a low SSN anomaly season (32%) than high (9%). The chances of at least one major hurricane affecting the United States in the lowest and highest SSN anomaly season are 10 and 39%, respectively.

5. The sun–hurricane relationship prior to 1851

Above, we showed that an index that quantifies a portion of the intra-hurricane season sunspot variability is quantitatively related to US hurricane and major hurricane frequency controlling for the other climate variables known to affect hurricanes. The SSN anomaly index captures, to some extent, the combination of low frequency variation associated with the 11-year Schwabe cycle and the 27-day solar rotation. This is important as it allows us to examine the relationship farther back in time with the availability of long records of sunspot numbers and old records of hurricanes over the western part of the North Atlantic basin. In this section, we consider the sun–hurricane relationship back to 1749, which is the start of accurate monthly sunspot counts with the International Sunspot Number, and make use of a portion of the Chenoweth (2006) Atlantic hurricane archive.

Figure 6 shows the time series of US counts since 1749 where the counts from the Chenoweth (2006) archive are appended to the HURDAT counts used in the previous section. Hurricane intensity entries in the archive listing a US mainland state or region are qualified as 'USA hurricane'.

Historical archives are less comprehensive than modern records. So differences in hurricane rates between the modern (HURDAT) and historical (Chenoweth archive) storm records can largely be explained by differences in completeness of the records. Given the nature of the collection of pre-1851 observations, knowledge of cyclone location and occurrence was a function of shipping traffic path frequency and meteorologically attuned populations. As such, for each year there is probability of at least one hurricane making landfall which is not in the record and this probability is almost certainly larger at the beginning of the record than towards the end accounting for, at least partially, the upward trend over this period. Thus we assume that the collection of hurricane counts prior to 1851 is an under-representation of the actual counts.

This under-count notwithstanding, here we are interested in the variability in available counts from one year to the next. We can assume that this variability is largely unaffected by trends caused by missing cyclones. In fact, the autocorrelation function computed using the counts from 1749 to 1850 is similar to that computed using the counts from 1851 to 2008. Moreover, it is certainly not likely that observational limitations correlate with the solar cycle.

Overlapping portions of the Chenoweth archive and SSN data provide a 102-year segment from which we can further examine the sun–hurricane relationship. The two busiest years in the series are the 1835 and 1837 seasons, with each reporting four hurricanes impacting the United States. There are 73 seasons that record at least one US hurricane, and the mean number of recorded hurricanes is 1.04 per year, giving an annual probability of 28% of at least one hurricane occurrence. This compares with the modern record mean (1.79 hurricanes per year) and annual probability of at least one hurricane occurrence (53%).

Table III lists the top and bottom ten hurricane seasons according to the value of the SSN anomaly using the years 1749–1850. The list includes the estimated number of US hurricanes by year. No direct observations for Atlantic SSTs, the ENSO, or the NAO are available for these early years. Of the top ten positive anomaly years, one year featured four recorded US hurricanes and five years featured two US hurricanes. With the exception of 1774, there was at least one US hurricane in each of the top ten anomalous years. In contrast, eight of the bottom ten years had fewer than two US hurricanes, although 1835 featured four.

The mean US hurricane rate is 42% higher in the ten positive SSN anomaly years compared to the ten negative anomaly years (the 1851–2008 mean difference is 79%, respectively). However, note that the mean year for the positive anomalies is 1786, 28 years earlier than the mean year for the negative anomalies (1814). Since the idea is for fewer missed hurricanes as time goes by, the actual difference in hurricane rates is probably greater than shown here and closer to what is found over the period 1851–2008. Thus, despite the inherent limitations in the older hurricane data, there is a detectable solar signal that mirrors the signal found in the more recent records, featuring a higher probability of US hurricanes when the SSN anomaly is positive and large.

Table III. | SSN anomalies and US hurricanes: 1749–1850.

SSN anomaly	USA	Year
+37.6	2	1781
+32.9	1	1749
+26.6	1	1771
+24.9	2	1794
+23.4	2	1838
+22.5	2	1778
+22.1	1	1789
+19.5	2	1752
+19.3	0	1774
+16.9	4	1837
+24.5	**1.7**	**1786**

SSN Anomaly	USA	Year
−72.7	0	1847
−52.8	1	1839
−33.8	1	1769
−25.9	4	1835
−24.6	2	1787
−20.3	1	1759
−16.9	0	1786
−16.6	1	1850
−15.0	1	1824
−14.6	1	1846
−29.3	**1.2**	**1814**

Years are listed according to the value of the ten most negative SSN anomalies (top) and ten most positive SSN anomalies (bottom). Corresponding columns include the number of US hurricanes (USA). Averages over the 10 years are given in bold.

6. Summary and conclusions

Here we examined the evidence for a sun–hurricane relationship for hurricanes affecting the United States, which was identified recently by EJ08. We first looked at seasonal activity and noted a consistent inverse relationship between the probability of a US hurricane and SSN. The relationship occurs for both warm and cold years as defined by Atlantic SSTs. Since it has been argued that the sun–hurricane relationship arises from changes in upper tropospheric temperature associated with variations in the UV radiation (Elsner *et al.*, 2010), next we showed the strong correlation between SSN and a core-to-wing ratio as a satellite-derived measure of the UV flux.

Since the SST responds on a slower timescale to changes in total solar irradiance, we derived a SSN anomaly that captures a portion of the intra-hurricane season variability in solar activity by subtracting the SSN averaged over August through October from the SSN averaged over May, June, July, and November. The SSN anomaly is used to divide the hurricane record from 1851 to 2008 into top and bottom years with respect to the 20 most anomalous values. As expected, years with positive SSN anomalies featuring high peripheral month sunspot numbers but low in-season numbers have, on average, significantly more (79%) US hurricanes. This relationship was checked over all years by controlling for SST, the ENSO cycle, and the NAO in a multivariate Poisson regression model. The SSN anomaly was shown to be statistically significant in models for US hurricanes and US major hurricanes after accounting for the other climate variables.

The evidence for a sun–hurricane relationship was further bolstered by showing that a similar relationship between the SSN anomaly and US hurricanes (years of high SSN anomaly have more US hurricanes) is detectable in an archive of Atlantic hurricanes dating back to 1749. This lends additional support to the contention that solar variability influences hurricane activity and provides support for the utility of older, less reliable, hurricane records for examining hurricane–climate relationships. Consequently, we feel that this work makes an important new contribution by showing that the sun–hurricane relationship, discussed in EJ08 using mostly 20th century data, does not disappear when examined by another 100 years of data. The work will be extended by examining whether the relationship can be seen in other tropical cyclone basins.

Our thermodynamic hypothesis explaining the observed correlation between hurricanes and the solar activity is likely incomplete. As mentioned, increased solar irradiance tends to trend the NAO towards positive anomalies, which reduces the chance that a hurricane will reach the Unites States. Also, under an active sun the stratosphere warms unevenly, with the most pronounced warming occurring at lower latitudes. As a result, stratospheric winds are altered, which could end up changing the strength of tropical cyclones (van Loon *et al*., 2004; Meehl *et al*., 2009; van Loon *et al*., 2007; van Loon and Shea, 1999). Our hunch is that circulation changes could influence weaker tropical cyclones but the intensity of the stronger hurricanes is influenced more by the thermodynamic changes above and below the hurricane. More work in this area is needed.

At the time of writing, the 2010 hurricane season is set to occur during the onset stage of Solar Cycle 24, with a running average estimate of about 30 sunspots over the duration of the hurricane season. Using monthly sunspot predictions for from NOAA/Space Weather Prediction Center, the 2010 hurricane season could feature an SSN anomaly of approximately −5, or around the 32nd percentile of SSN anomaly activity. Utilizing a model similar to that used in Figure 5 and assuming the other three climate values at neutral values (they are clearly not), an SSN anomaly of −5 corresponds to a 46% chance of two or more US hurricanes, 8% lower than the climatological average (54%) for two or more US hurricanes.

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