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Research Article

The Spatial Pattern of the Sun-Hurricane Connection across the North Atlantic

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The authors define the spatial response of hurricanes to extremes in the solar cycle. Using an equal-area hexagon tessellation, regional hurricane counts are examined during the period 1851–2010. The response features fewer hurricanes across the Caribbean, Gulf of Mexico, and along the eastern seaboard of the United States when sunspots are numerous. In contrast fewer hurricanes are observed in the central North Atlantic when sunspots are few. The sun-hurricane connection is as important as the El Niño Southern Oscillation toward statistically explaining regional hurricane occurrences.

1. Background

Hurricanes are severe tropical cyclones characterized by heavy rain, winds, and extremely low surface pressures, with maximum sustained winds of at least $33\,\mathrm{m\,s^{-1}}$. They can be compared theoretically to huge heat engines, where heat transfer from warm seas fuel sustained convection and tremendous release of latent heat. Their development and intensification are dependent on their immediate environment. Changes in water vapor [1], steering currents [2], and sea surface temperatures [3] affect hurricane intensity. Recently, Elsner and Jagger [4] and Elsner et al. [5] have shown that variations in upper-tropospheric temperature in response to changes in ultraviolet radiation also affect hurricanes.

The idea for a direct connection between the sun and tropical cyclones ($18\,\mathrm{m\,s^{-1}}$) dates back to the 19th century. In one of the first volumes of *Nature*, Meldrum [6] reports a relationship between Indian Ocean tropical cyclone frequency and sunspots over the period 1847–1872, noting that cyclone number, size, and duration were all enhanced at solar maximum compared to minimum. A year later Poey [7] would find a similar result for Caribbean storms. Citing memorable Cuba-landfalling hurricanes of 1751, 1780, and 1837, he noted that all coincided with sunspot maxima. Forecasts upwards of 70 years have been developed using solar output as a predictor for North Atlantic hurricane activity; Willett [8], using sunspot numbers, correctly predicted a relative decrease in Atlantic and Gulf Coast hurricane frequency from 1960 to1990, followed by an increase from 1990 to 2020.

Cohen and Sweetser [9] performed a spectral analysis of North Atlantic hurricane frequency from 1871 to 1973 with sunspot numbers from 1750 to 1963. Of their more interesting results were 11-year periodicities in both the annually averaged sunspot totals and seasonal hurricane counts at 11.0 and 11.3 years, respectively. Again, however, no description of a physical mechanism was put forward, and the spectral analysis method employed did not differentiate whether it was in or out of phase.

More recently, Elsner and Jagger [4] showed that the annual counts of US-affecting hurricanes are negatively related to high sunspots. Poisson regression modeling revealed that, after accounting for known climate covariates important to hurricane frequency in the North Atlantic, September sunspot number (SSN) was negatively related to seasonal hurricane counts. An SSN value of 100 sunspots yielded a 26% reduction in the probability of a US hurricane. The relationship was found to be weak but consistent and statistically significant for the entire duration of the HURDAT records, reaching back into the mid-19th century. For instance, 1886 and 2001 are seasons featuring a low SSN (21.4 sunspots) and a high SSN (150.7 sunspots), respectively, and their corresponding seasonal US-affecting hurricanes total 7 and 0.

The sun-hurricane connection (hereafter, SHC) presented in Elsner and Jagger [4] indicates fewer intense hurricanes over the Caribbean and Gulf of Mexico when sunspots were high. The finding is in accordance with the heat-engine theory of hurricanes [10], 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 ultraviolet radiation. All else being equal, changes in surface or outflow temperature should produce a change in tropical cyclone maximum winds: colder (warmer) surface and warmer (colder) outflow temperatures correspond to a decrease (increase) in tropical cyclone winds and, by extension, the number of tropical cyclones reaching hurricane intensity.

The SHC has even been found to be relevant at the daily timescale [5]. Quantile regression revealed that high solar activity over the western Caribbean leads to a $-4.3 \pm 1.86\,\mathrm{m\,s^{-1}}$ mean reduction in daily maximum wind speed and a 90th percentile storm wind reduction from 65.9 to $48.1\,\mathrm{m\,s^{-1}}$, or 27%.

Of interest to the present work, Elsner and Jagger [4] note that high numbers of sunspots correspond with higher intensities in the eastern tropical Atlantic. The geographic difference, the authors contend, is the result in limiting factors for cyclone intensity. The western tropical Atlantic features high oceanic heat content compared to the eastern tropical Atlantic, rendering the upper-tropospheric warming from increased solar activity the limiting factor in the west. The east, where oceanic heat content is limited, shows increased sea-surface temperatures when the sun is active [11, 12]. This indicates a spatially heterogeneous response in hurricane intensity and frequency from solar activity. The SHC may be prevalent elsewhere over the North Atlantic ocean basin. Needed is a more spatially explicit assessment of the SHC over the North Atlantic basin.

In this paper we define the regional responses in hurricane frequency to changes in solar activity. We use a hexagon grid tessellation [13] of the North Atlantic basin and count the number of hurricanes in each region conditional on September sunspot number. The data used in this study are introduced in Section 2. In Section 3, we show the procedure for counting the number of hurricanes passing through each region. In Section 4, we condition these seasonal counts on highs and lows of the solar cycle. In Section 5, we compare earlier to later portions of the hurricane records to demonstrate coherency in the overall pattern. In Section 6, we examine the influence of geographic scale on the sun-hurricane connection. In Section 7, we apply the sampling approach and mapping method used in Section 4 but, for El Niño/La Niña seasons, showing a signal similar in magnitude to that observed with solar activity. A summary and conclusions are presented in Section 8.

2. Data

The best-track dataset contains the six-hourly center locations and intensities of all known tropical cyclones across the North Atlantic basin, including the Gulf of Mexico and Caribbean Sea. The dataset is called HURDAT (HURricane DATa). It is maintained by the US National Oceanic and Atmospheric Administration at the National Hurricane Center. Tropical cyclone center locations are given in geographic coordinates (in tenths of degrees). The intensities, representing the one-minute near-surface ($\sim$10 m) wind speeds, are given in knots ($1\,\mathrm{kt} = 0.5144\,\mathrm{m\,s^{-1}}$). The minimum central pressures are given in millibars ($1\,\mathrm{mb} = 1\,\mathrm{hPa}$). The data are provided in six-hourly intervals starting at 00 UTC (Universal Time Coordinate). The version of HURDAT used here contains cyclones over the period 1851–2010. Updated information is available online via http://www.nhc.noaa.gov/pastall.shtml#hurdat. Information on the history and origin of these data is found in Jarvinen et al. [14]. For this study, HURDAT is limited to observations of hurricane-force intensity ($\geq$64 knots). Qualifying extratropical and subtropical storm observations are excluded.

For each cyclone, the HURDAT observations are six hours apart. For spatial analysis and modeling, this can be too coarse, as the average forward motion of hurricanes is $6\,\mathrm{m\,s^{-1}}$ (12 kt). Therefore, the data is imputed using interpolation to one hour. Wind speeds are smoothed using a third-degree polynomial, capturing most of the fluctuation in cyclone intensity without overfitting to the random variations and consistent with the 5 kt precision of the raw wind speed [15].

Solar activity is described via monthly mean international sunspot numbers as made available by the National Geographic Data Center (ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SUNSPOT_NUMBERS/INTERNATIONAL/monthly/MONTHLY). It was originally constructed by Solar Influences Data Analysis Center, World Data Center at the Royal Observatory of Belgium. Reliable monthly observations extend back to 1749. Swiss astronomer Johann Rudolph Wolf introduced a daily measurement technique that accounts for total spots observed and the quantity of their clusterings. The dataset addresses observational error by incorporating a weighted average of cooperating observations.

The El Niño Southern Oscillation (ENSO) is a coupled ocean-atmospheric phenomenon whose impact on hurricanes is well established. The Southern Oscillation Index (SOI) anomalies represent the normalized air pressure difference between Darwin and Tahiti. The change in equatorial Pacific SST leads to an atmospheric pressure imbalance whose far-reaching effects produce wind shear in the North Atlantic Main Development Region (MDR) during El Niño phases. Monthly values of the SOI are obtained from the UK Climatic Research Unit (http://www.cru.uea.ac.uk/cru/data/soi/). For technical descriptions of the SOI anomalies data, see Allan et al. [16] Können et al. [17] Ropelewski and Jones [18]. SOI data begin January 1866.

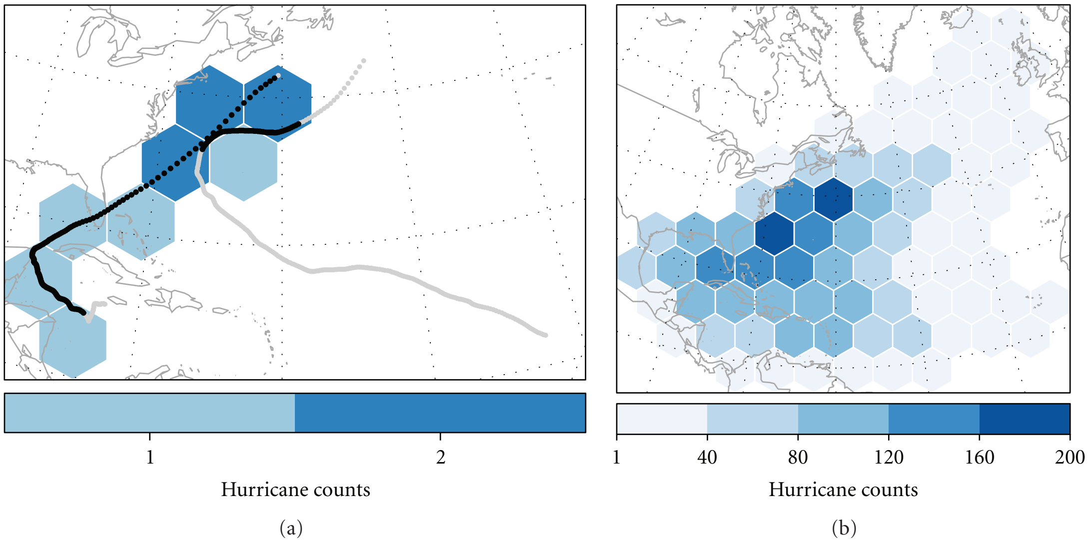

Figure 1: North Atlantic hurricane counts. (a) Hourly interpolated tropical cyclone positions for Florida-landfalling Wilma and open-ocean Irene from the 2005 season. Points in gray (black) indicate a wind speed below (at or above) minimum hurricane intensity (i.e., 64 knots). For each region, the number of hurricanes that pass through it is recorded. A hurricane gets counts once regardless of how long it remains inside the region. (b) Regional hurricane counts for the study period 1851–2010.

3. Tracks to Grids

We first grid the tropical cyclone track data. We use the procedure detailed in Elsner et al. [13], creating a hexagon tessellation over the North Atlantic. While rectangular grids can also be used for this study, hexagons more efficiently pack the domain and better capture the directional variability of hurricane tracks.

For each region, the number of hurricanes that pass through it is recorded. Figure 1(a) shows hourly track points for two hurricanes and the set of hexagon regions affected by them. A hurricane gets counted once regardless of how long it remains inside the region.

Figure 1(b) shows hurricane counts over the entire study period (1851–2010) using the counting method illustrated in Figure 1(a). Highest counts occur off the US East Coast, southeast of the Outer Banks of North Carolina, with a maximum of 200 hurricanes over the 160-year period in that region.

4. High versus Low Solar Activity: 1851–2010

Having constructed a spatial framework, we next examine hurricanes by region based on solar activity. We use sunspot numbers for the month of September (hereafter, SSN) as an indicator of solar activity during the peak of the North Atlantic hurricane season. This is reasonable as monthly sunspot numbers do not vary much from one month to the next. The temporal autocorrelation of all monthly sunspot numbers from January 1851 through December 2010 at a lag of one month is $r = +0.93$. Eighty-seven percent of the variance in monthly sunspot numbers is explained by the number in the previous month. The high value tells us that a high sunspot number observed in one month is very likely

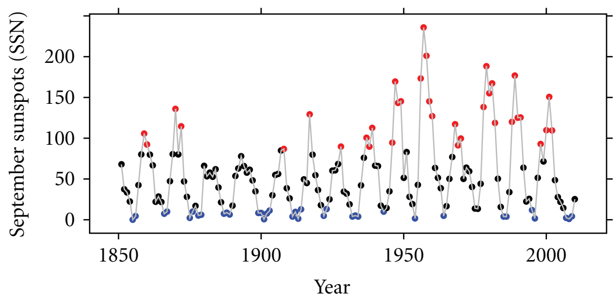

Figure 2: Time-series of September sunspot number (SSN) for the period 1851–2010. The 22nd and 78th percentiles are color-coded as blue and red points, respectively.

to be preceded and succeeded by a high sunspot number. A high sunspot number in September, for instance, will likely be neighbored by a high sunspot number in August and October, the three-month peak of the North Atlantic hurricane season. Therefore, we use September sunspots to examine the North Atlantic SHC.

Our interest is the regional pattern of hurricane activity in years of high and low sunspot numbers. Thus, we examine the time series and hurricane data using two sets of years: thirty-five years with the fewest sunspots and thirty-five years with the most sunspots. This corresponds to the 22nd and 78th percentiles of SSN seasons (see Figure 2). The mean September SSN during low (high) sunspot years is 5.9 (130.8).

Regional counts are determined for years with low and high SSN. Low SSN years (Figure 3(a)) feature regions with 40+ hurricanes extending from off the northern US East Coast southwestward into the Gulf of Mexico and northern

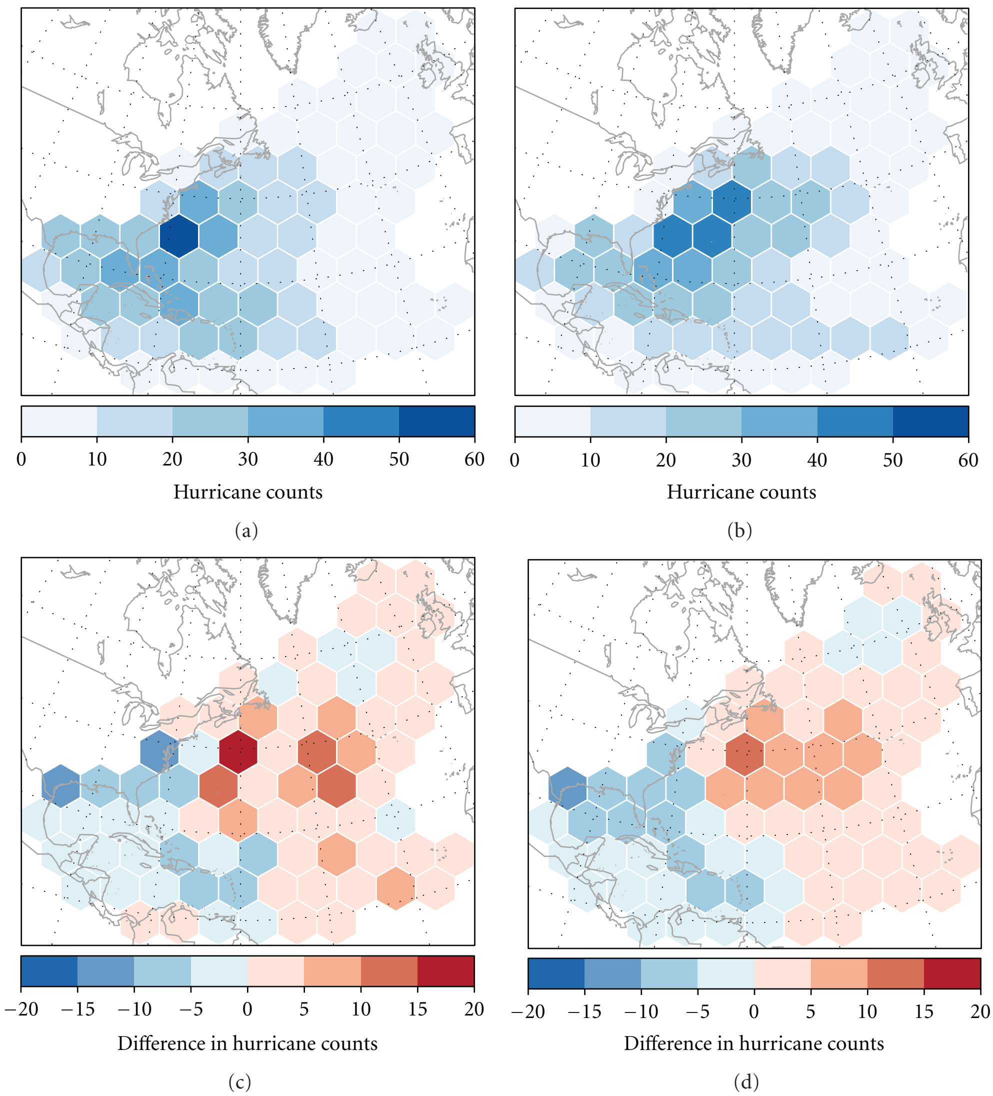

Figure 3: September sunspots (SSN) and regional hurricane counts. (a) Regional North Atlantic hurricane counts for the thirty-five lowest SSN seasons over the period 1851–2010. (b) The same, except for the thirty-five highest SSN seasons. (c) Their difference plot (i.e., high minus low). Negative (positive) values indicate regions where fewer (more) hurricanes are observed during high SSN seasons compared to low. (d) A spatially smoothed plot of count differences, where the raw count difference of each region has been averaged with the average of its (maximum of) six neighbors.

Antilles, with a regional maximum of 52 hurricanes off the North Carolina Outer Banks. High SSN years (Figure 3(b)) show higher counts (40+) in central Atlantic regions. However, fewer hurricanes are observed in the North Carolina Outer Banks region. We then subtract the low SSN season counts from the high SSN season counts (Figure 3(c)). Negative (positive) values indicate regions with fewer (more) hurricanes during seasons with high SSN. The most negative region lies in the northwest Gulf of Mexico, showing 15 fewer hurricanes. The most positive region is the region to the southeast of the grid containing Nova Scotia, featuring 16 more hurricanes.

Figure 3(d) is a spatially smoothed plot of count differences, where each region is averaged with the average of its (maximum of) six neighbors. This spatially weighted averaging is a rudimentary technique to account for high (low) regional counts having neighbors with high (low) regional counts, a geostatistical phenomenon referred to as spatial autocorrelation. Moran's I, a measure of spatial autocorrelation for grid data [19], is defined as

$$I = \frac{N}{s_o} \frac{y^T W y}{y^T y}, \quad (1)$$

where N is the number of regions (i.e., grids), y is the vector of values on the regions where the values are deviations from the mean, W is a weights matrix, and the superscript T indicates the vector transpose operator. The spatial weights matrix W is constructed by first identifying region neighborhoods. As constructed here, a hexagon region has a maximum of six neighbors and a minimum of one neighbor.

Neighbors are identified using contiguity. Regions that share a common border are neighbors. Moran's I here is the least-squares linear slope between neighborhood averages of regional raw count differences upon regional raw count differences. The slope can range from -1 to $+1$; the former indicates absolute dispersion (e.g., a checker-board pattern), and the latter indicates absolute correlation. The computed slope coefficient is +0.51 ($P < 0.01$), indicating a fairly large and significant amount of spatial autocorrelation.

Returning to Figure 3(c), the regional hurricane count differences between low and high SSN seasons range in magnitude from -15 to +16 hurricanes, for a spread of 31 hurricanes. The hurricane count increase (decrease) in the eastern (western) tropical Atlantic corroborates previous findings by Elsner and Jagge [4]. However, a central Atlantic and southeast US East Coast signal is also prevalent. The bounding box used in Elsner and Jagge [4] had a northward maximum extent of 30°N. Based on the spatially averaged result in Figure 3(d) which highlights groups of like count difference regions, the pattern extends just south of Nova Scotia around 40°N. The East Coast decrease in counts during high SSN seasons is similar in magnitude to the Caribbean and Gulf patterns.

The regional nature of the SHC into the central Atlantic and US East Coast is a new finding. However, a statistical model for US-affecting hurricane counts employed in Elsner and Jagger [4] does use SSN as a predictor. The coefficient on the statistically significant predictor is negative, indicating that the probability of a US-affecting hurricane decreases as SSN increases. Fewer East Coast hurricanes during high solar activity found here further explain their finding.

5. High versus Low Solar Activity: Early and Late Records

There is an amplitude modulation in SSN, with the more recent decades featuring more sunspot peaks (Figure 2). Some of the highest September peaks within the 1851–2010 study period have occurred since 1947, recording a SSN of 169.4 sunspots. As a result, the median year for the high SSN seasons sample is 1959, while the mean year for low SSN seasons is 1912. Hurricane positions, intensities, and occurrences are reasonably more reliable as technology has improved, so it is possible that the spatial signal we show in Section 4 is a consequence of the difference in years sampled. To check the robustness of the pattern shown in Figure 3, we examine the modern portions of the respective high and low SSN seasons within the thirty-five season sample.

In the thirty-five season sample from the previous section, there are seven low (1985, 1986, 1995, 1996, 2007, 2008, 2009) and seven high (1989, 1990, 1991, 1998, 2000, 2001, 2002) SSN seasons whose median years are 1996 and 1998, respectively. The previous twenty-eight season sets had median years of 1902 and 1953, respectively. We therefore compare the seven most recent season sets of high and low SSN to see if the SHC pattern is consistent over time.

Figure 4 shows the regional patterns for Figure 4(a) earliest twenty-eight and Figure 4(c) seven most recent high and low SSN hurricane count differences; Figures 4(b) and 4(d) are their respective spatially smoothed plot of count differences, where each region is averaged with the average of its (maximum of) six neighbors. For the early (late) portions, the sample season mean of low SSN is 6.4 (4.1) sunspots; the sample season mean of high SSN is 131.7 (127.2) sunspots. The count differences in each epoch appear to be similar, marked by an eastern (western) increase (decrease) in hurricane counts when solar activity is high.

The range of count differences for the early period is -12 to +10 hurricanes which compares with a range of -5 to +6 hurricanes during the later period. Pairing the two periods' regions, Pearson's product-moment correlation test between their raw count differences (a and c) yields a correlation coefficient of $r = +0.50$ ($P < 0.01$), indicating spatial coherence in the patterns. The same statistical test between the spatially smoothed count differences (b and d) yields a correlation coefficient of $r = +0.72$ ($P < 0.01$). The Moran's I values for the early and late periods are +0.38 ($P < 0.01$) and +0.44 ($P < 0.01$), respectively. Therefore, the increase in the SHC pattern correlation (+0.50 to +0.72) can be attributed to the fairly large amount of spatial autocorrelation present in the regional hurricane counts. Despite temporal inhomogeneities, the pattern of regional hurricane frequency featuring more (less) Caribbean and US East Coast hurricanes when the sun is less (more) active is robust across the decades.

6. Scale and the SHC

In the analysis above, we use regions with an area of 483,379 km^2. This is approximately the area formed by a circle with radius 392.3 km, comparable to the 75th percentile radii (407.0 km) of the outer closed isobar from North Atlantic tropical cyclones over the period 1988–2002 [20]. Here we examine how the count difference pattern between high and low solar activity changes as the region area is altered.

Figure 5 is a reproduction of Figure 3 using four different geographic scales. The regions correspond to regional area sizes (a) four, (b) two, (c) one-half, and (d) one-quarter times the original used. Qualitatively, we see that the east/west relationship is consistent despite differences in regional magnitudes.

Using the raw hurricane count differences from seasons of low and high SSN, we count the number of regions that have fewer hurricanes and divide by the total number of regions. This ratio expressed as a percentage provides a way to quantitatively compare the overall pattern at different scales. 37% of the regions (Figure 3(c)) show fewer hurricanes during high SSN seasons relative to low. In comparison, we find values of 42% (Figure 5(a)), 42% (Figure 5(b)), 36% (Figure 5(c)), and 36% (Figure 5(d)) for scales changed from smallest to largest. The percentages are within a few points of each other, indicating scale is not a major concern for the results presented in previous sections.

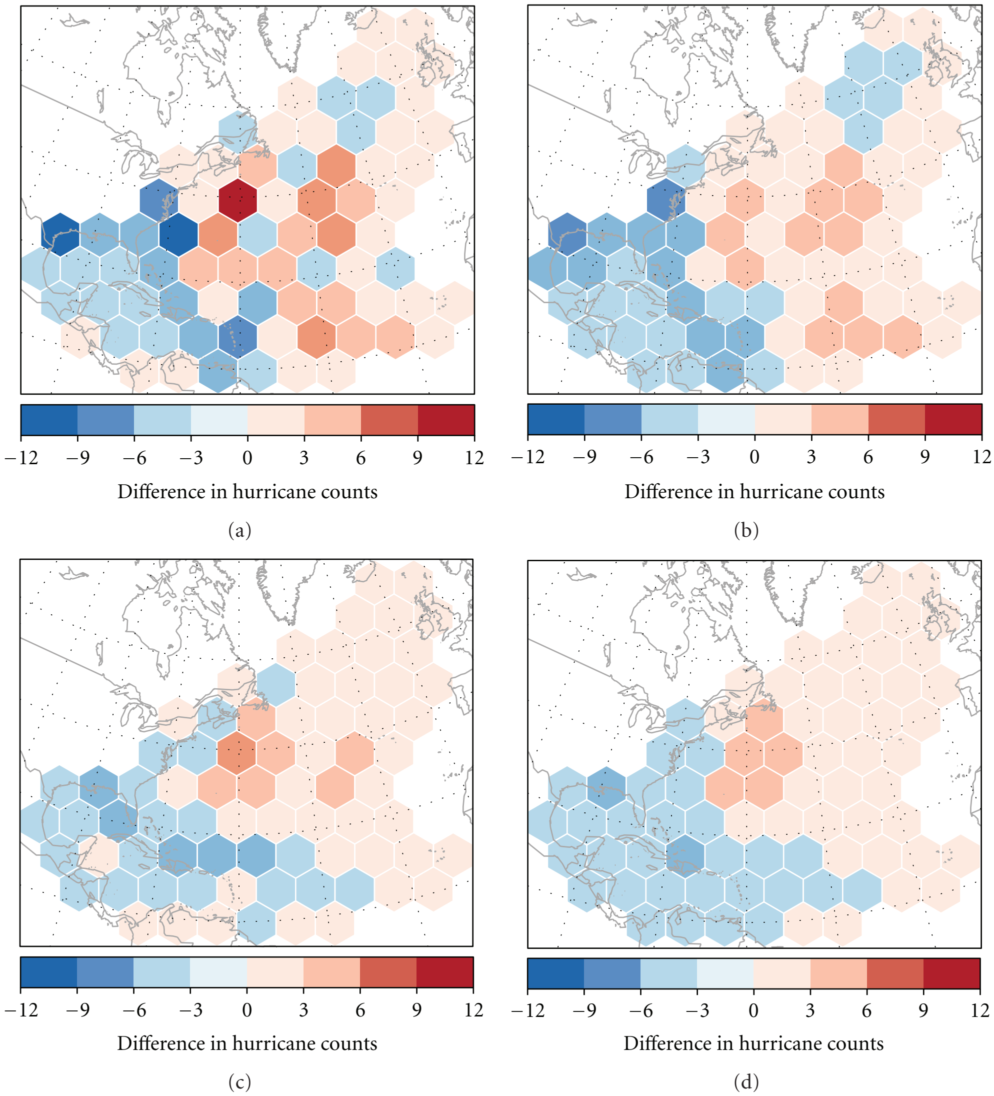

Figure 4: September sunspots (SSN) and regional hurricane count differences, early and late. (a) Regional North Atlantic hurricane count differences between the twenty-eight earliest high and low SSN seasons from a thirty-five storm seasons sample. Negative (positive) values indicate regions where fewer (more) hurricanes are observed during high SSN seasons compared to low. (b) A spatially smoothed plot of count differences, where each region's raw count difference has been averaged with the average of its (maximum of) six neighbors. (c) Same as (a), but for the seven most recent sets of high and low SSN seasons. (d) Same as (b), but for the seven most recent high and low SSN seasons.

7. The Spatial ENSO Hurricane Pattern

As a final comparison, we repeat the analysis from Section 4 using an index for ENSO. The El Niño Southern Oscillation (ENSO) is an oscillating climate pattern of atmospheric and oceanic coupling. El Niño (La Niña) is the abnormal warming (cooling) of equatorial East Pacific sea-surface temperatures, leading to a weakening (strengthening) of the normal western and central equatorial Pacific trade winds. During El Niño, stronger upper-level winds over the western Atlantic [21] create an environment unfavorable for tropical cyclones, resulting in a decrease in hurricane frequency over the region [22].

We sample hurricane data from 1866 to 2010 for thirty-five seasons of lowest and highest SOI values, respectively; or the 24th and 76th percentiles of SOI data. The sample season mean of low (high) SOI is −4.00 (+3.61) s.d. Figure 6 shows hurricane counts for (a) low SOI (El Niño) seasons, (b) high SOI (La Niña) seasons, (c) count differences (El Niño minus La Niña), and (d) a spatially smoothed version of (c) where each regional value is the average between the original count difference and the average of its (maximum of) six neighbors. Negative (positive) values indicate regions where fewer (more) hurricanes are observed during El Niño seasons compared to La Niña seasons.

The hurricane count differences between low SOI and high SOI seasons (Figure 6(c)) range in magnitude from −26 to +2 hurricanes. While virtually all of the Atlantic shows decreased counts, the largest magnitude regions reside in

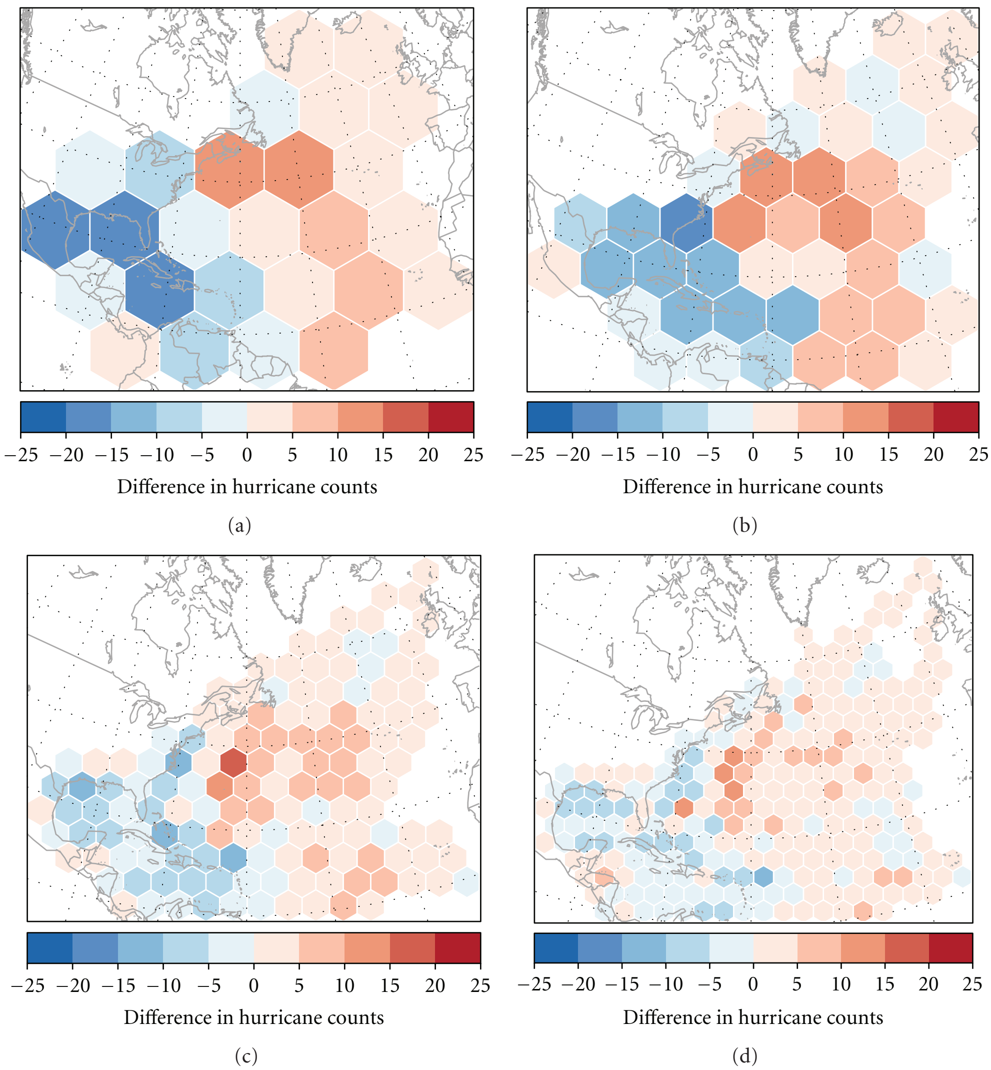

FIGURE 5: September sunspots (SSN) and regional hurricane counts under varying region sizes. (a) Regional North Atlantic hurricane count differences for the thirty-five highest and lowest SSN seasons from 1851 to 2010 for region sizes of 1,991,921 km^2, (b) 995,961 km^2, (c) 249,870 km^2, and (d) 124,935 km^2.

the western half of the tropical Atlantic main development region (20°N–10°N; 20°W–85°W). As expected, the spatial pattern of hurricane count decrease in the Western tropical Atlantic corroborates previous findings from Gray [22]. The spread between high and low SOI seasons in the frequency difference of 28 hurricanes is comparable to—if slightly less than—the spread of 31 hurricanes between high and low SSN seasons. This indicates that SSN is as important statistically toward explaining hurricane occurrences as ENSO.

8. Summary and Conclusions

Here we use a hexagonal tessellation of the North Atlantic to examine the regional frequency of hurricanes in contrasting years of the solar cycle. A spatially coherent pattern emerges that features fewer (more) hurricanes across the Caribbean and along the US East Coast during high (low) sunspot years. The finding is consistent with Elsner and Jagger [4] who demonstrated a statistically significant improvement in a model of seasonal US-affecting hurricane activity by including SSN as a covariate. A new finding is that the pattern is prevalent across other regions (US East Coast and north-central Atlantic) in the North Atlantic basin. The spatial pattern is robust using hurricane records back to 1851. The pattern is also consistent at multiple geographic scales. For comparison we use the approach using SOI data to show that SSN has a comparable effect on regional hurricane occurrence to that of ENSO.

The results shown here raise further questions about the nature of the SHC. As previously mentioned, Elsner and Jagger [4] speculate on the geographic differences in hurricane frequency as being driven by limiting factors (i.e., sea-surface temperatures versus upper-tropospheric temperatures). Sea-surface temperatures (SST) can be considered as a first-order requirement and changes in upper-tropospheric temperatures as a conditioning effect upon hurricane intensity and

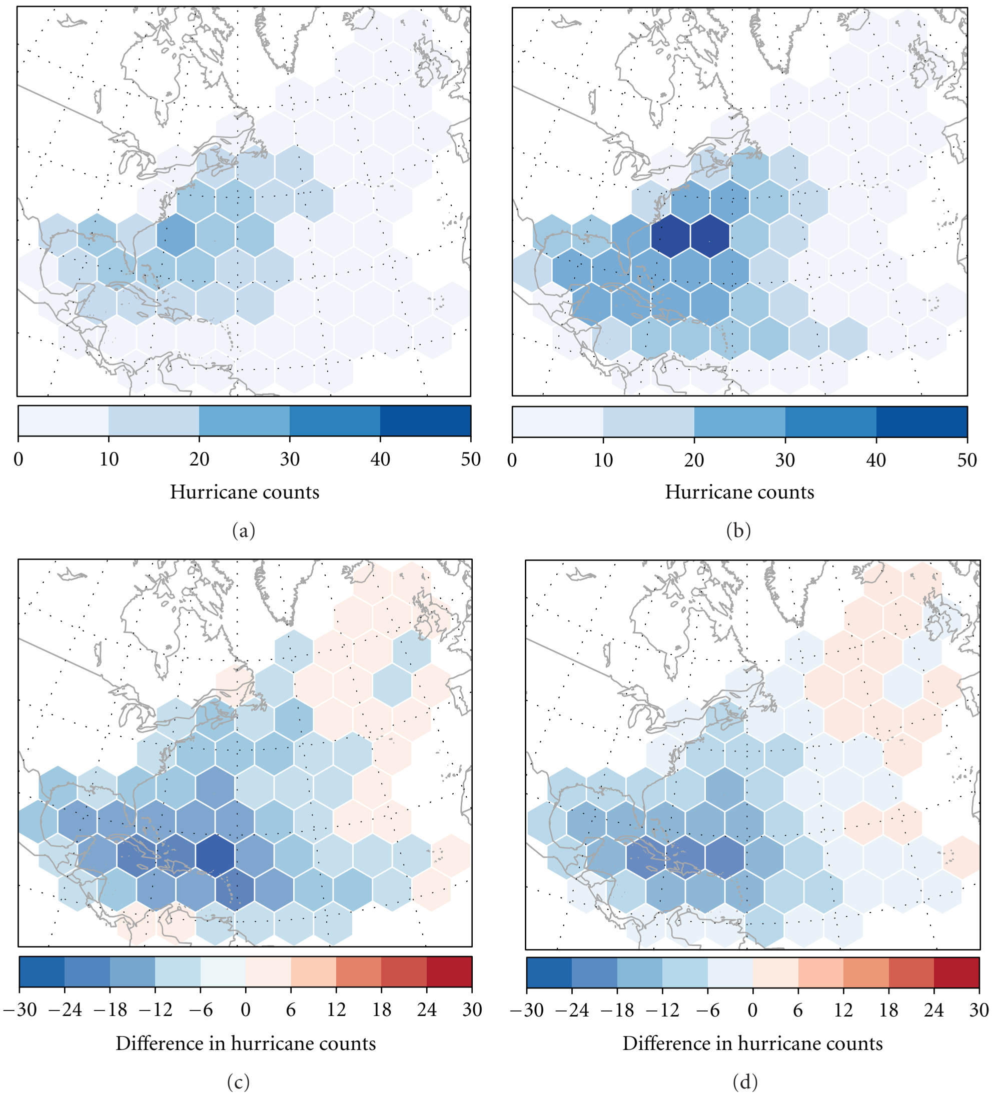

Figure 6: August through October averaged SOI anomalies and regional hurricane counts for 1866 to 2010. (a) Regional North Atlantic hurricane counts for the thirty-five lowest SOI (i.e., El Niño) seasons from 1866 to 2010. (b) The same, except for the thirty-five highest SOI (i.e., La Niña) seasons. (c) Their difference plot (El Niño minus La Niña). Negative (positive) values indicate regions where fewer (more) hurricanes are observed during El Niño seasons compared to La Niña seasons. (d) A spatially smoothed version of subplot (c) where the raw count difference of each region has been averaged with the average of its (maximum of) six neighbors.

counts. However, increased solar activity increases SST in the tropical North Atlantic [11, 12]. Therefore, where heat content is marginal, the limiting effect of warmer upper-tropospheric temperatures is outpaced by the encouraging effect of warmer SST when the sun is active. So while the difference in hurricane counts (Figure 3(d)) extends our knowledge of the spatial extent of the SHC, it also affirms this bicameral effect from increased solar activity in the central Atlantic and the southeast US East Coast. A space-time regression model capable of distinguishing the contributions from individual climate variables like ENSO and solar activity can be developed to predict regional hurricane counts.

The pattern could also be the result of hurricane tracking in response to the SHC. Increased hurricane counts in the southeast Atlantic may indicate that hurricanes are developing earlier due to warmer seas and leaving the deep tropics due to β-drift [23]. The result is more hurricanes recurving into the central and north-central Atlantic. A conceptual model is as follows: increased upper-tropospheric temperatures in response to increased solar activity [24–26] increase the static stability over the upper levels of the tropical cyclone. The cap prevents upwardly-propagating gravity waves—common in tropical cyclones [27]—from radiating normally out of the central dense overcast into the stratosphere [28] and, instead, shunting it radially away from the center of circulation [29]. The increase in the transport of angular momentum away from the vortex core [30–32] results in a broader circulation that tracks more poleward due to increased β-drift. In order to investigate this possibility, it will be necessary to develop a model that can be used to describe and predict hurricane tracks.

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