Multidecadal variability of Atlantic hurricane activity: 1851–2007

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[1] An analysis of Atlantic hurricane data (HURDAT), using a hurricane activity index that integrates over hurricane numbers, durations, and strengths during the years 1851–2007, suggests a quasi-periodic behavior with a period around 60 years superimposed upon a linearly increasing background. The linearly increasing background is significantly reduced or removed when various corrections were applied for hurricane undercounting in the early portion of the record. The periodic-like behavior is persistent in uncorrected HURDAT data as well as in data corrected for possible missing storms. The record contains two complete cycles: 1860–1920 and 1920–1980. The 2004 and 2005 hurricane seasons were unusual in that two intense hurricane seasons occurred in consecutive years. The probability for this happening in any given year is estimated to be less then 1%. Comparing the last 28 years (1980–2007) with the preceding 28 years (1953–1980), we find a modest increase in the number of minor hurricanes (category 1 and 2); however, we find no increase in the number of major hurricanes (category 3–5). The hurricane activity index is found to be highly correlated with the Atlantic Multidecadal Mode (AMM). If there is an increase in hurricane activity connected to a greenhouse gas induced global warming, it is currently obscured by the 60 year quasi-periodic cycle.

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1. Introduction

[2] On the basis of hurricane thermodynamics [*Emanuel*, 1986] it is plausible to expect hurricane strength to increase with increasing sea surface temperature while keeping all other parameters important for hurricane generation [*Gray*, 1968; *Simpson et al.*, 1998; *Goldenberg et al.*, 2001] constant. Some recent papers already claimed detection of such an increase [*Emanuel*, 2005, *Webster et al.*, 2005; *Holland and Webster*, 2007] while others reported little or no trend [*Solow and Moore*, 2002; *Landsea*, 2005; *Pielke*, 2005; *Klotzbach*, 2006; *Landsea et al.*, 2006; *Nyberg et al.*, 2007; *Kossin et al.*, 2007]. Any "observed" increase of hurricane activity might be due to a real increase in hurricane numbers, duration or wind speed, or due to an improvement in observational capabilities, or both. In this paper we apply simple statistical methods to the NOAA HURDAT record of storm activity in the North Atlantic basin between 1851 and 2007 to investigate a possible linear trend, periodicity and other features of interest.

2. Data

[3] The NOAA National Hurricane Center maintains a record, referred to as HURDAT (www.aoml.noaa.gov/hrd/Data_Storm.html), containing all North Atlantic tropical cyclones since 1851. The HURDAT data set is used to investigate tropical cyclone activity in the North Atlantic basin. In the following analysis no changes were made to the data except in the section dealing with suggested corrections for missing storms. The HURDAT data are known to be of variable quality [*Landsea*, 1993] because of improvements in observational methods and instrumentation, and methods of analysis over the archive length. Early records rely heavily on ship observations (data prior to about 1945), while later data are based predominantly on aircraft reconnaissance flights (since about 1945) and satellite observations (starting in the mid 1960s). Several sets of corrections to the data have been suggested that will be discussed later.

3. Method

[4] Accumulated cyclone energy (ACE) has been used as a measure of individual cyclone and entire tropical cyclone season activity. Defined [*Bell et al.*, 2000] as a normalized sum of maximum observed wind speed (in knots) squared, v_{max}^2, over the lifetime, T, of the considered cyclone

$$ACE = A \sum_T v_{max}^2 \quad (1)$$

The ACE characterizes the kinetic energy of an individual cyclone integrated over the cyclone's life-time, T. The normalization constant, A, is taken to be 10^{-4} for v_{max} in knots. The sum in the above equation runs over the cyclone duration, T, in six hour intervals. The ACE for a given year

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Table 1. Example of HAX Calculation for 2007 Hurricane Dean[a]

Dean 2007	S	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	HAX
HAX coefficients	0.5	1	2	3	4	5	
Number of 6-h intervals	7	10	1	2	10	4	
Contribution to HAX	3.5	10	2	6	40	20	81.5

[a]HAX coefficients (line 2) for given storm categories (line 1) are multiplied by the number of 6-h intervals (line 3) in which Dean was classified as a storm of a given category. The products (line 4) are summed over all categories to provide the HAX value (81.5) for Dean.

characterizes the combined storm activity including the number of storms, their duration and strength (as long as the maximum wind speed is at least 35 knots).

[5] We introduce a simplified version of the ACE which we call the hurricane activity index (HAX), defined in the following manner:

$$\mathrm{HAX} = 0.5\mathrm{S} + \mathrm{H}_1 + 2\mathrm{H}_2 + 3\mathrm{H}_3 + 4\mathrm{H}_4 + 5\mathrm{H}_5 \qquad (2)$$

where S is the number of six hour periods of duration of tropical storm strength, H_1 is the number of six hour intervals of duration of hurricane category 1 (Cat 1) on the Saffir-Simpson scale; H_2 is the number of six hour periods of duration of a hurricane of Cat 2, and similarly H_3, H_4, and H_5 designate the numbers of six hour periods of Cat 3, Cat 4, and Cat 5 hurricanes. The hurricane activity index is calculated for each storm in the HURDAT database (see Table 1 for an example) and then the storms are added to produce the HAX for a considered year. The index can be summed over a definite spatial region or time period. In our analysis we consider the hurricane index evaluated for the whole North Atlantic and for a given calendar year. The HAX, as well as the ACE, is closer to characterizing the total energy of the storms rather then the storms' separate characteristics.

[6] The choice of coefficients in the HAX definition is motivated partly by simplicity. The coefficient set is based on the Saffir-Simpson hurricane category scale with the values related to kinetic energy. For the coefficients to be proportional to the square of the maximum wind speed and normalized so that the H_2 coefficient equals two, the coefficients would be 0.59, 1.35, 2.0, 2.7, 3.9, and 5.3 (see Table 2 for details). If the mass and velocity distribution would be the same for all hurricanes, the HAX would be proportional to the total energy of the hurricane integrated over the hurricane's lifetime. Since the equality of mass and velocity distributions is obviously not valid, the rounding of the coefficients will not produce a significant additional error. For convenience we round the coefficients to the nearest integer except that the tropical storm category coefficient is set to 0.5. As a result of the normalization the HAX is a dimensionless number equal to one for a hurricane category 1 lasting one six hour period, equal to two for a hurricane category 2 of six hours duration, etc. Thus it is easy to assign the HAX value to any hurricane or a portion thereof. A comparison of individual hurricanes becomes transparent and easy to interpret. Conclusions derived in the following are independent of rounding the HAX coefficients. By being related to the maximum wind speed squared, the HAX is for all practical purposes equivalent to the ACE (the ACE/HAX correlation coefficient for annual unsmoothed data for years 1851–2007 is 0.99), however, the HAX is easier to calculate and easier to interpret. In the HAX formulation, each hurricane is fully characterized by a set of six numbers (S, H_1, H_2, H_3, H_4, H_5) giving the number of six hour time periods for a given storm to be classified in a particular category.

4. Analysis

[7] It is not the purpose of the current paper to determine the physical reasons for the observed changes in hurricane activity. However, it has been suggested that global warming [*Emanuel*, 2005; *Webster et al.*, 2005; *Holland and Webster*, 2007] or internal variability of the atmosphere-ocean system [*Schlesinger and Ramankutty*, 1994] manifested through the Atlantic Multidecadal Oscillation [*Kerr*, 2000; *Nyberg et al.*, 2007] or the Atlantic Meridional Mode (AMM) [*Bell and Chelliah*, 2006; *Kossin and Vimont*, 2007] may play a role. Effects of variability in aerosol

Table 2. Tropical Cyclone Category (Column 1); Minimum, Maximum, and Mean Wind Speed (Column 2 to 4); Mean Wind Speed Squared (Column 5); HAX Coefficients Normalized to Two for Cat 2 (Column 6); and the HAX Rounded Coefficients as Used in This Work (Column 7)[a]

Category	v_{min}	v_{max}	v_{mean}	v_{mean}^2	HAX Coefficient Exact	HAX Coefficient Rounded	Coefficient for v_{mean}^3
Storms	39	73	56	3136	0.59	0.5	0.32 (0.5)
Cat 1	74	95	84.5	7140	1.35	1	1.10 (1)
Cat 2	96	110	103	10,609	2.00	2	2.00 (2)
Cat 3	111	130	120.5	14,520	2.74	3	3.20 (3)
Cat 4	131	155	143	20,449	3.86	4	5.35 (5)
Cat 5	156		168	28,224	5.32	5	8.68 (9)

[a]The wind speed is in miles per hour. The mean wind speed of a Cat 5 hurricane is assumed to be 12 m/h above the minimum speed required for a Cat 5 hurricane. Coefficients are dimensionless numbers (ratio of v_{mean}^2 for a given category to v_{mean}^2 for Cat 2 hurricanes) normalized to 2 for hurricanes Cat 2. The last column provides coefficients for an index proportional to v_{mean}^3 (not used in this study but suitable for characterizing a hurricane destructive power; *Emanuel* [2005]). Values in parenthesis are rounded to the nearest integer, except that the coefficient for storms is set to be 0.5.

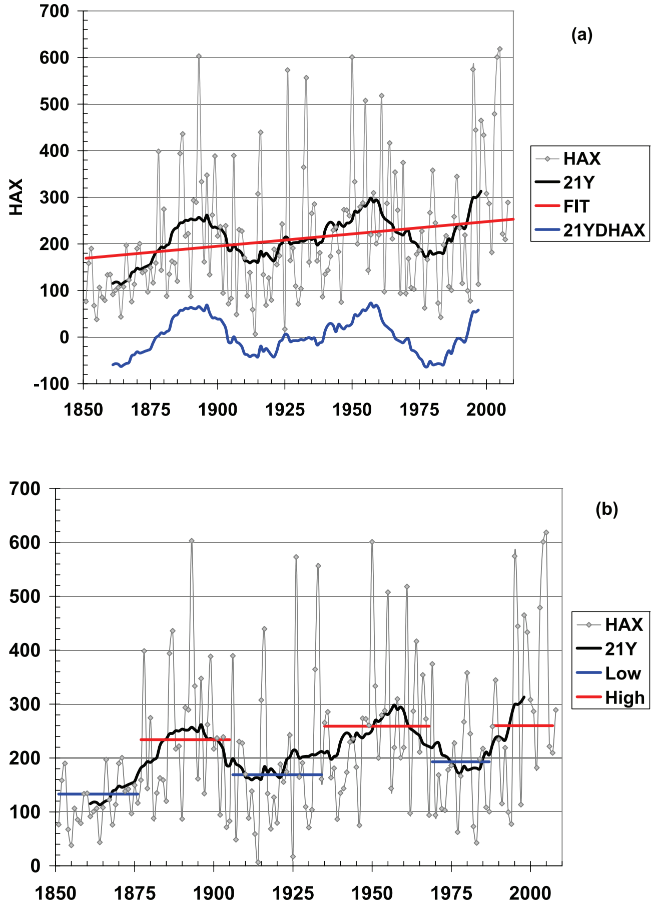


Figure 1. (a) Annual hurricane activity index (diamonds) and its 21-year running mean (black curve) suggests a linear trend with an increase of about 0.6/yr (red line). The detrended HAX (blue curve) preserves a quasi-periodic oscillation with a period of about 60 years. (b) Alternating periods of high (red line segments) and low (blue segments) hurricane activity.

concentration [*Chylek et al.*, 2007; *Evan et al.*, 2008; *Wong et al.*, 2008] and solar insolation [*Scafetta and West*, 2007] on SST and hurricane activity cannot be excluded as well.

4.1. Linear Trend

[8] Figure 1a shows the annual HAX evaluated for each individual year within the 1851–2007 time span as well as the 21-year running average (black line) to remove the short-term variability and to average over possible short-term non-systematic observational errors. Although there is considerable variability in the running mean, a quasi-periodic behavior superimposed upon a monotonically rising background is apparent.

[9] Because of the short time span of data available, the apparent linear trend depends on the choice of the end points of a series. To minimize the effect of arbitrarily selected end points, we estimate the slope of the trend by choosing the beginning and end points to be located on the same phase position of the curve, e.g., both points close to the relative maximum or minimum of the curve. Using the 1860–1984 interval (from the first to the last relative minimum) we obtain a slope of 0.5 HAX/yr. From the time interval 1893–2007 (from the first to the last relative maximum) we obtain a slope of 0.7 HAX/yr. Thus the data suggests that the HAX has been increasing at the average rate of about 0.6/yr between 1851 and 2007. A slope of 0.6/yr could be caused by one Cat 1 hurricane lasting longer by about 3.6 hours each year, or one Cat 2 hurricane lasting by 1.8 hours longer, etc. The observed linear trend in the hurricane index is very likely a combination of a possible real increase in hurricane activity (a larger number of hurricanes, a longer hurricane lifetime, or a higher wind speed), and by an improved ability to observe hurricanes since we have used uncorrected HURDAT data.

4.2. Periodicity

[10] The lower curve in Figure 1a (blue in on-line edition) is the HAX detrended to show more clearly the quasi-periodic behavior. Since the observational errors in the data

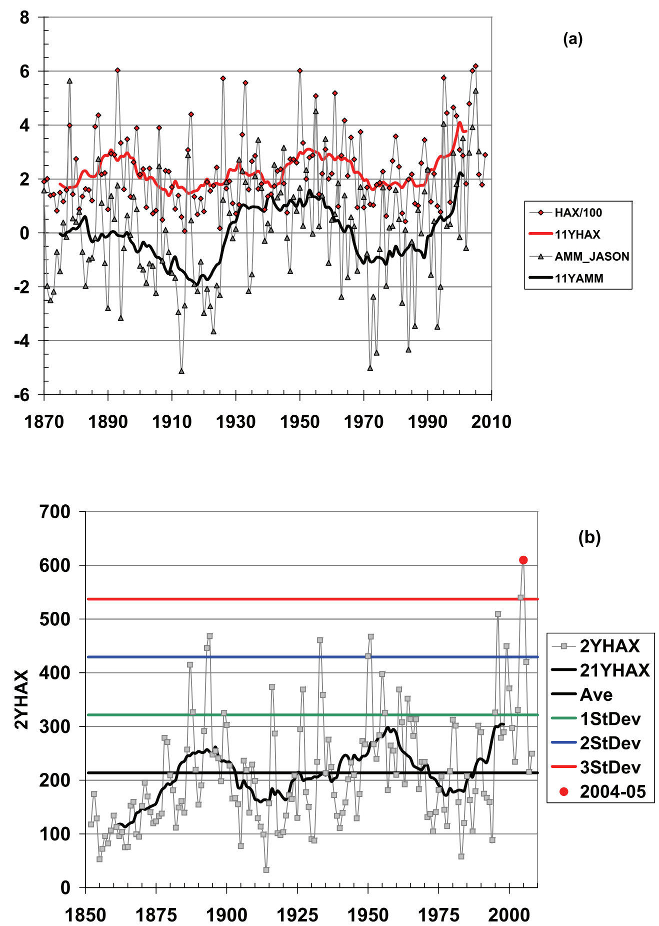
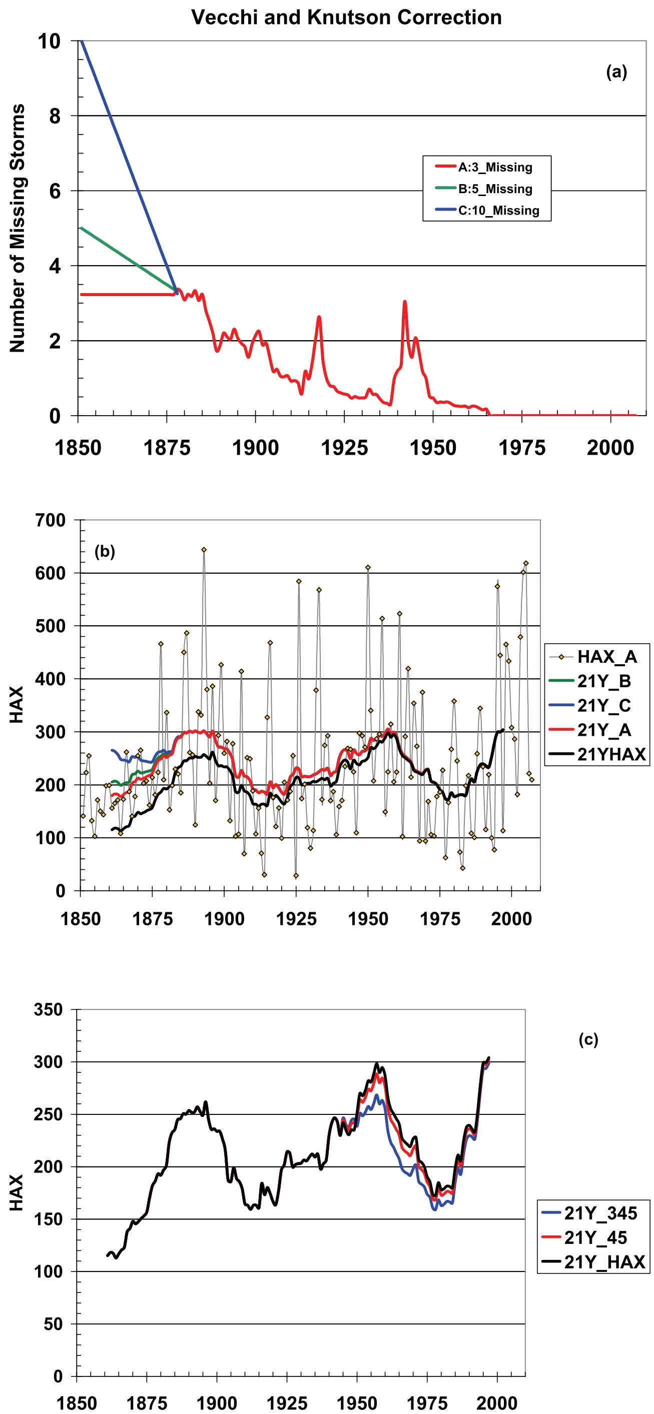


Figure 2. (a) The Atlantic Multidecadal Mode (AMM) index averaged over the months of July to November for a given year (individual points) and its 21-year running average (red curve). The hurricane activity index (HAX) has been divided by 50 (21-year average; black line) for convenience of graphing. (b) The HAX 2-year mean values (squares); 21-year running average (black curve); 1851–2007 mean (black line); and mean plus 1 (green), 2 (blue line), and 3 (red line) standard deviations. The red circle is the 2004–2005 HAX average.

Table 3. Correlation Coefficients Between 21-Year Running Averages of HAX and the AMM Index (Column 2) for Given Time Periods, Between the HAX and Number of All Storms Listed in HURDAT Data (Column 3), and the HAX and Number of Hurricanes (Column 4)[a]

	HAX/AMM	HAX/All Storms	HAX/All Hurricanes
1871–2007	0.75 (0.58)		
1851–2007		0.68	0.79
1950–2007	0.94 (0.65)	0.73	0.83

[a]Numbers in parenthesis in column 2 are correlation coefficients for unsmooth annual values.



are not expected to be periodic, they should not be responsible for the observed periodic-like behavior. It would require an implausible error behavior to increase the 21-year averaged HAX from its value of 120 in 1860s to over 260 in 1890 and then again to suppress it to about 150 in 1910. It is therefore reasonable to expect that the observed quasi-periodic behavior of the HAX as depicted in Figure 1 is a real characteristic of changing hurricane activity rather than an artifact of imperfect observations.

[11] We observe (Figure 1b) multidecade periods in which the HAX is alternatively below and above the long-term mean. The HURDAT record contains six such periods, and we are currently in an above average period. Since the data contain only two complete cycles of hurricane activity, it is not possible to predict with any certainty that the swings will be repeated in the future.

[12] To estimate an approximate period for the hurricane activity index, we consider a 60 year segment of HAX data (1850–1910) and calculate the autocorrelation coefficient with the rest of the time series with varying time lag. We find the maximum correlation for a time lag of 63 years. Segments of 45, 50 or 55 years lead to basically the same result, with a maximum correlation for a lag time between 60 to 64 years. The post 1980 years are on a rising part of a quasi-periodic curve with the post 2000 years approaching a relative maximum that is expected to occur between 2010 and 2013 if the 60 to 63 year periodicity prevails in the current cycle. Past proxy hurricane reconstructions [*Miller et al.*, 2006] suggest that the approximate 60 year periodicity might extend back a few hundred years.

[13] The time variation of the HAX and the AMM is very similar (Figure 2). The correlation coefficient between the unsmoothed annual values of the HAX and AMM within the years 1950–2007 is 0.65 and the correlation rises (as expected when using multiyear averages) to 0.94 for 21-year running averages (Table 3). The corresponding correlation coefficients for the years 1870–2007 are 0.58 for the annual values and 0.75 for 21 years averages.

4.3. Exceptional Years 2004 and 2005

[14] The years 2004 and 2005 were exceptional in the sense that these were the only two consecutive years with extremely high HAX values in the HURDAT data set. High HAX values over 600 were also reached in 1893 and 1950,

Figure 3. (a) Corrections to the HURDAT data proposed by *Vecchi and Knutson* [2008] showing how the number of missed hurricanes is deemed to have varied over time. The number of missing storms is extended linearly up to year 1851, as shown corresponding to 3.2 (case A), 5 (case B), and 10 (case C) missing storms in 1851. (b) The HAX time series (21-year running averages) corresponding to the uncorrected HURDAT data and the three cases (A, B, and C) of the Vecchi-Knutson correction. (c) Uncorrected HAX (black curve) from HURDAT data and correction to a possible overestimate of the wind speed simulated by (1) decreasing hurricanes Cat 4 and 5 between the years 1955 and 1990 by one category (red curve) and (2) decreasing hurricanes Cat 3, 4, and 5 by one category (blue curve). The oscillating character of the HAX curve is not removed by corrections.

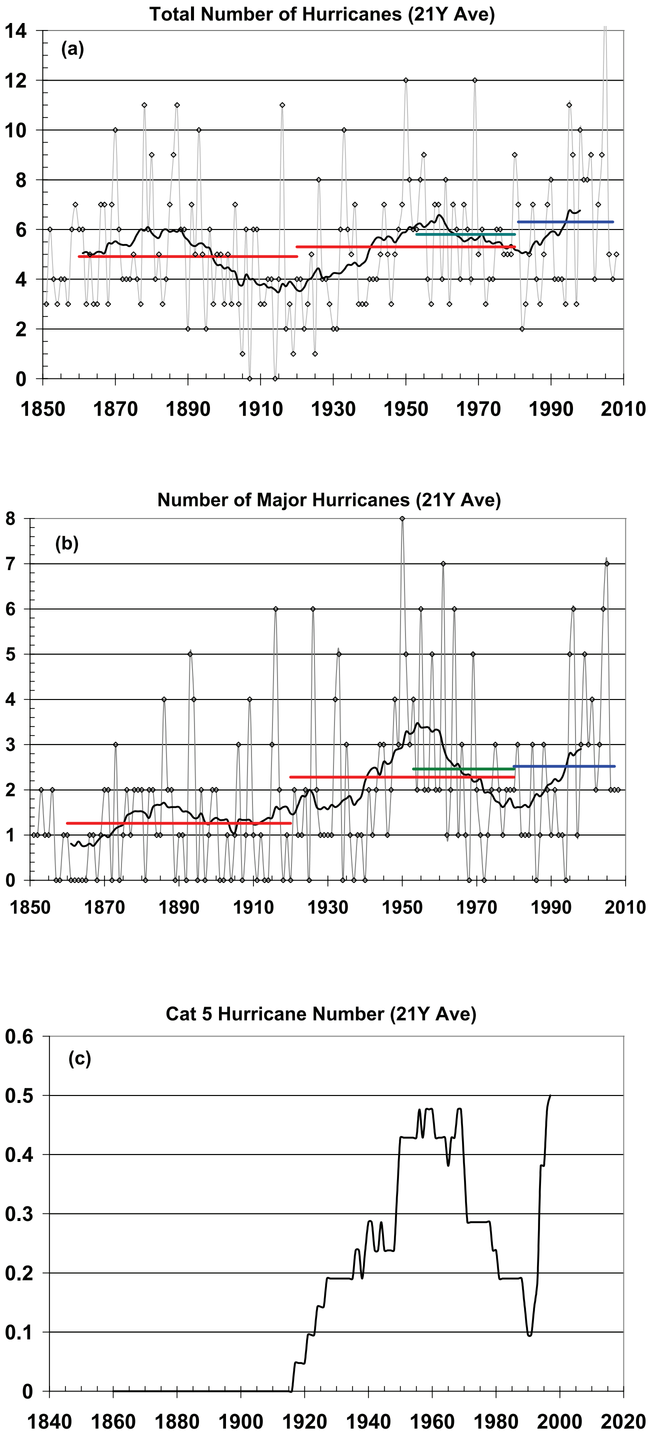


Figure 4. (a) Total number of hurricanes during the 1851–2007 period, (b) number of major hurricanes, and (c) number of hurricanes of Cat 5. Individual points are annual values, black line is the 21-year running average, and the red segments are averages for stated time periods. No category 5 hurricanes before 1928 suggest that the hurricane strength (maximum wind speed) was underestimated during the early years of the hurricane record.

however, each of these cases were followed by a year with a more average hurricane activity (HAX value around 300). The years 2004 and 2005 represent the first occurrence in the 157 year record of two very high hurricane activity (HAX of 601 and 618) years next to each other. Thus what is unusual in the recent hurricane activity is not high activity in an individual year, but high activity in two consecutive years. This is a feature that is independent of any changes in the observational capability. The two-year average (2004 and 2005) of the HAX is more than three standard deviations above the average 2-year HAX value (Figure 2b).

4.4. Corrections to HURDAT Data

[15] To compensate for missing storms during the early years of the HURDAT record several corrections to the HURDAT data have been proposed [e.g., *Vecchi and Knutson*, 2008; *Chang and Guo*, 2007; *Landsea*, 2007; *Mann et al.*, 2007; *Holland*, 2007, 2008]. All the proposed corrections do decrease the linear trend, however, none of

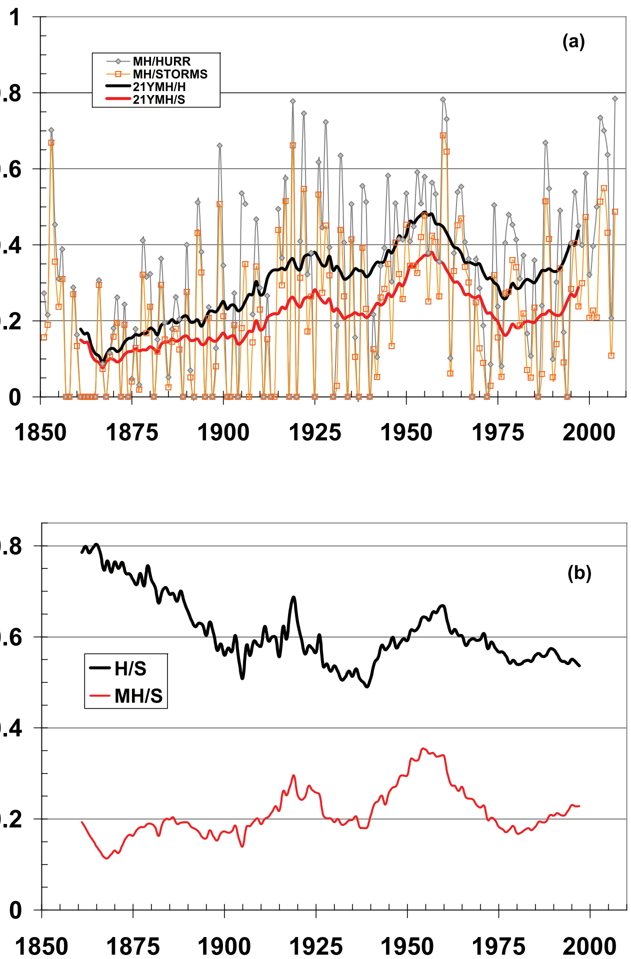


Figure 5. (a) Ratio of the HAX values of major hurricanes to all hurricanes and to all tropical storms and hurricanes. Individual points are annual data, black lines are 21-year running averages for the ratio with respect to all hurricanes, and red lines are corresponding 21-year running averages with respect to all storms. (b) Ratio of number of hurricanes (black line) and major hurricanes (red line) to the total number of storms.

Table 4. Percentage Contribution of Cyclonic Storms (S) and Hurricanes (H_1 to H_5) of Stated Category to the HAX Within a Given Time Period

	S/HAX (%)	H_1/HAX	H_2/HAX	H_3/HAX	H_4/HAX	H_5/HAX
1851–2007	26.4	27.3	20.9	14.1	9.2	2.1
1950–2007	24.6	26.4	16.9	13.9	14.3	3.9
1965–2007	27.9	28.3	15.2	11.3	13.0	4.3
1880–1937	29.2	24.2	25.0	15.5	5.4	0.7

them remove the oscillating character. To demonstrate this we use as an example the correction of *Vecchi and Knutson* [2008] for the number of missing storms and the Landsea and Holland suggestion [*Landsea*, 1993; *Holland*, 2008] that the maximum wind speed might have been overestimated in 1950–1990 time period.

[16] In the Vecchi-Knutson scheme the proposed number of missing storms deduced from the modeling of ship observations during the post 1870 years varies continuously in time (Figure 3a) and compensates for the lack of observations during the World Wars. To translate the number of missing storms to the HAX index, we approximate a missing storm to be on average a hurricane category two lasting approximately ten six hour periods. This means a correction to the HAX value of 20 for each missing storm. We also extend the Vicchi-Knutson correction to the time period before 1870 by assuming that the number of missing storms during pre-1870 remains the same as the 1870–1880 average (case A in Figure 3), that the number of missing storms increases linearly to 5 missing storms in 1851 (case B), and that the number of missing storms increases linearly to 10 in 1851 (case C). The annual values of the hurricane activity index (HAX) calculated from the adjusted data are shown in Figure 3b. The results are similar to the detrended HAX calculated from the raw (uncorrected) HURDAT data (Figure 1). The correction lowers the linear trend, however, the quasi-periodic character remains. The existence of a peak in hurricane activity around 1890 is not sensitive to the exact form of the correction. The peak remains when we vary the number of missing storms in 1851 between 3 and 10.

[17] *Landsea* [1993] and *Holland* [2008] suggested that the maximum wind speed of major hurricanes as listed in the HURDAT data might have been overestimated during the approximate time period 1950–1990. Holland argues that the underestimate is due to the use of the Dvorak method to deduce the wind speed from the estimated central pressure. We assess the sensitivity of the HAX values to a possible overestimate of wind speed by (1) reducing hurricanes cat 4 and 5 by one category within the time span of 1955–1990, and (2) similarly reducing the hurricanes cat 3, 4 and 5 by one category. Although the HAX peak in the 1950s is slightly reduced (Figure 3c) the basic oscillating character of the HAX, characterizing the total integrated energy, remains unchanged. Similarly, any of the other suggested corrections only shift or tilt the HAX curve and leaves the oscillating character of the HAX unchanged.

4.5. Hurricane Numbers

[18] To compare the number of hurricanes within definite time intervals, we have to eliminate the quasi-periodic oscillation in hurricane activity by selecting the time periods corresponding to the same relative phase of the oscillating record. For our comparison we select two time intervals, each containing one full cycle from 1860–1920 and 1920–1980. Considering these two adjacent 60 year time periods, the average total number of hurricanes per year in the raw (uncorrected) HURDAT data set is about 0.3 hurricanes higher during 1920–1980 than during 1860–1920 (Figure 4a). If this difference is due to an underestimation of the hurricane number in an earlier period, then the underestimate during the years 1860–1920 should be not more than 0.3 hurricane per year compared to 1920–1980 period. If the difference is due to an increase in hurricane activity, then the average number of hurricanes in the 1920–1980 period was by no more than 0.3 per year higher than in 1860–1920.

[19] The average number of observed major hurricanes (hurricanes category three, four and five) increased by about 1.1 major hurricanes per year (Figure 4b) during 1920–1980 compared to 1860–1920. A part of this increase may be real with the remainder being due to underestimating the hurricane strength in the years 1860–1920. The increase in the number of observed major hurricanes is over three times larger than the increase of all hurricanes. The fact that no category 5 hurricane was observed before the year of 1928 (Figure 4c) suggests that observational deficiency in determination of the maximum wind speed in early years have played a significant role in the apparent increase of major hurricanes from 1920–1980.

[20] To corroborate the suggestion that underestimation of the hurricane strength may play an important role in early hurricane records, Table 4 shows the relative contribution of hurricanes of a given category to the total hurricane activity index. The early (1880–1937) and the modern (1950–2007) periods have approximately the same relative contributions from tropical storms and Cat 1 hurricanes. However, the early period has a significantly higher proportion of Cat 2 hurricanes (compared with the modern period), and significantly lower contribution of Cat 4 and Cat 5 hurricanes. This suggests that the strength of major hurricanes might have been underestimated and consequently some of the hurricanes of Cat 4 and 5 may have been reported as Cat 2 (or Cat 3). The HAX ratio of major to all hurricanes and the ratio of major hurricanes to all hurricanes and storms (Figure 5a) shows the peak structure similar to that of the same ratios of the hurricanes numbers (Figure 5b). In the total HAX as shown in Figure 1, however, the peak between 1920 and 1930 is almost eliminated because of a relatively low contribution from weaker storms during the same time. Correlation coefficients between the HAX and number of all storms and all hurricanes are listed in Table 3.

4.6. Hurricane Rapid Intensification

[21] We define rapid intensification as an increase of hurricane category by at least two during a 12 hour time

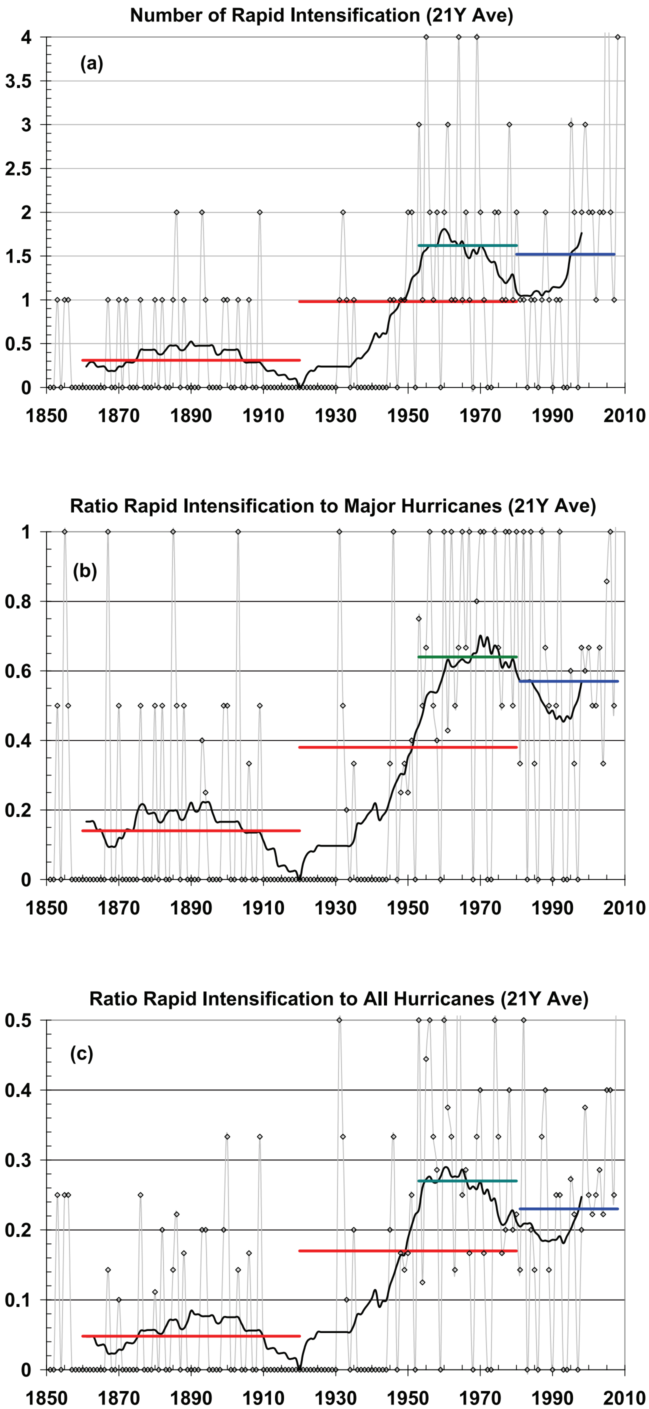


Figure 6. (a) The number of hurricanes with rapid intensification, (b) ratio of hurricanes with rapid intensification to major hurricanes, and (c) ratio of hurricanes undergoing a rapid intensification to all hurricanes. The points are annual data, black curves are 21-year running averages, and linear segments are averages for time periods specified in the text.

period. The number of hurricanes undergoing a rapid intensification increased from 0.34 hurricanes per year during the 1860–1920 time period to about 0.91 hurricanes per year during 1920–1980 (Figure 6a). The ratio of hurricanes with rapid intensification to major hurricanes increased from 0.14 to 0.38 (Figure 6b) during the same period, and the fraction of all hurricanes undergoing a rapid intensification increased from 0.05 to 0.17 (Figure 6c). Thus the record suggests that rapid hurricane intensification has been more common during the 1920–1980 years compared to 1860–1920. However, the storms are much better sampled today than they would have been in the late 19th and early 20th century and the hurricane category was probably underestimated in earlier times. There is an improved ability to detect rapid intensification later in the record. A recent decrease in cases of rapid intensification may be an artifact due to possible overestimation of the maximum wind speed [*Landsea*, 1993; *Holland*, 2008] during 1950–1990 period.

4.7. Recent Time

[22] The recent increase in hurricane activity seems to be undisputable. Its implications have already received considerable attention [*Goldenberg et al.*, 2001; *Solow and Moore*, 2002; *Landsea*, 2005; *Pielke*, 2005; *Webster et al.*, 2005; *Landsea et al.*, 2006; *Holland and Webster*, 2007]. Comparing the very recent time period, 1995–2007, with the preceding 1970–1994 time span shows a large increase (over 100%) in the hurricane activity index (Figure 7). However, the observed quasi-periodic oscillation (Figure 1) suggests that the comparison should be made for time sections with similar relative phase. The last minimum in the hurricane activity (HAX) occurred around 1980. Since then the activity has been increasing as shown in Figure 1. To detect a possible increase in activity beyond that expected from the quasi-oscillating behavior we compare the time intervals 1980–2007 and 1953–1980, namely the 28 year intervals before and after the 1980 minimum (Figure 7). We find an increase in the HAX of about 12% between the 1953–1980 and 1980–2007 periods. Similarly, comparing the last few years 2000–2007 with the corresponding years on the hurricane activity time series, namely, the years of 1950–1957, we observe a 9% increase in the hurricane activity index (compared to 100% increase between 1970–1994 and 1995–2007 time spans). At this

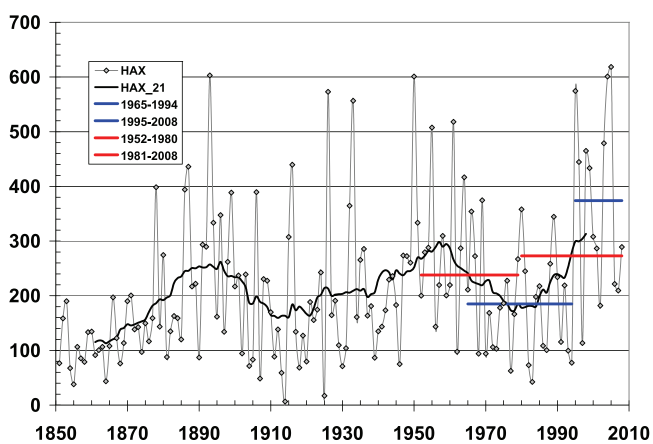


Figure 7. The HAX for the recent (1950–2007) time period. Individual points are annual values, and the black line is a 21-year running average. Red segments are averages for 1970–1995 and 1995–2007, and blue segments are averages for 1953–1980 and 1980–2007.

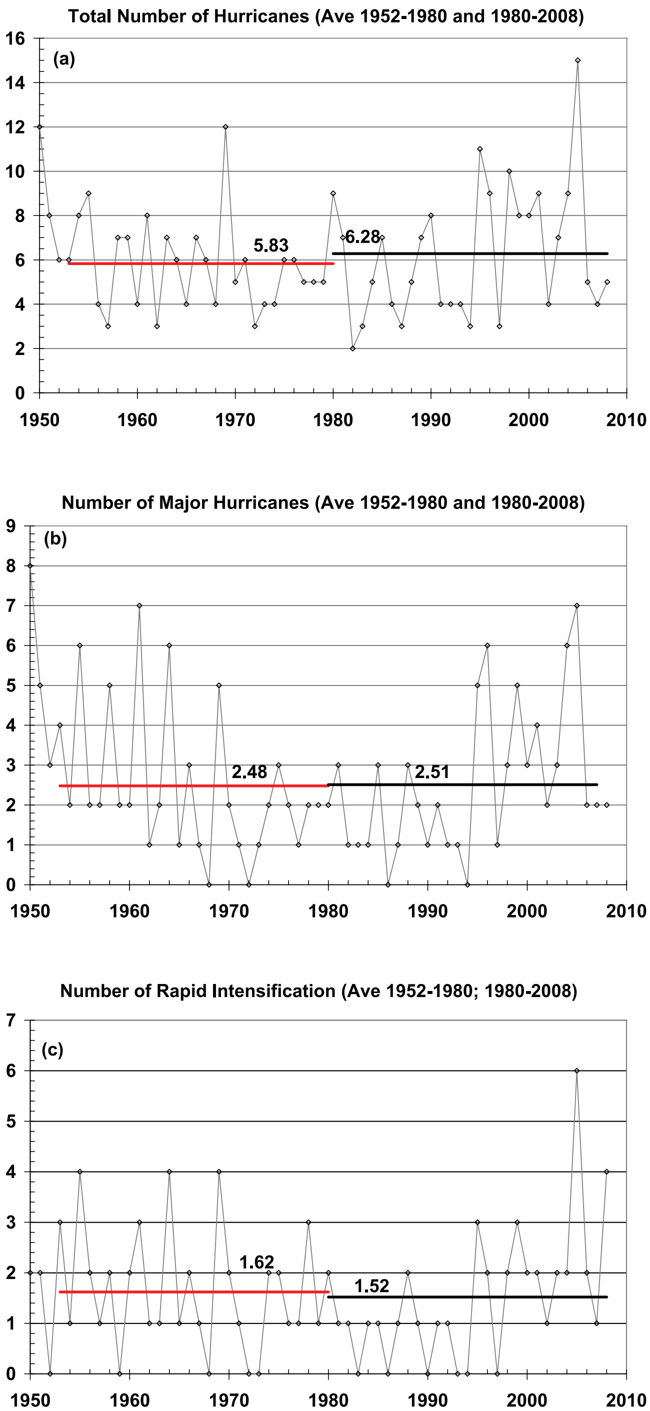


Figure 8. The number of hurricanes for the last 28 years (1980–2007) is compared with that for the preceding 28 years. (a) The number of total hurricanes, (b) the number of major hurricanes, and (c) the number of hurricanes undergoing a rapid intensification. Individual points are annual values, and line segments are averages for specified time periods.

point it is not clear what fraction of these 12% and 9% increases is real and what is due to improved observations.

[23] The average number of hurricanes in all categories increased from 5.8 hurricanes per year in 1953–1980 to 6.3 in 1980–2007 (Figure 8a). However, the average number of major hurricanes (category 3, 4, and 5) and the number of hurricanes undergoing a rapid intensification remained effectively unchanged (Figures 8b and 8c).

5. Summary and Discussion

[24] We have introduced the hurricane activity index (HAX), as a simplified version of the Accumulated Cyclone Energy (ACE), to provide a way to easily combine the effects of the number of North Atlantic storms, their duration and intensity. The index characterizes the energy of the storm integrated over the storm's duration, and is then summed over all storms in a given year to get the annual value.

[25] The uncorrected HURDAT data (1851–2007) as well as corrected for possible missing hurricanes suggest a quasi-periodic oscillation of hurricane activity with a period around 60 years. This periodic-like behavior is likely connected to one of the oscillating patterns of the atmosphere-ocean system, such as the Atlantic multidecadal oscillation [*Landsea et al.*, 1999] or the Atlantic Multidecadal Mode (AMM) [*Kossin and Vimont*, 2007].

[26] The last minimum in hurricane activity occurred around 1980. We are currently near a peak of hurricane activity assuming the past periodic-like 60 year cycle persists. A decrease in hurricane activity can be expected some time after 2010.

[27] The years 2004 and 2005 were unusual because these two years of high hurricane activity (HAX > 600) occurred consecutively. If this is a result of a random process, it can be expected to happen about once in 100 years.

[28] The observed frequency of rapid hurricane intensification increased significantly during the years 1920–1980 compared to 1860–1920. It is probable that a major part of this increase is due to improved observations rather than a real increase in rapid intensification cases. Although we observe a dramatic increase of hurricane activity from the 1970s to the years 1995–2007, most of this increase is attributed to a 60 year quasi-cyclic behavior.

[29] Comparing the last two 28 year long periods, located symmetrically on the oscillating time series with respect to the 1980 minimum, we have seen a modest increase of minor hurricanes, no change in the number of major hurricanes, and a decrease in cases of rapid hurricane intensification. If there is an increase in hurricane activity connected to a greenhouse gas induced global warming, it is currently obscured by the 60 year quasi-periodic cycle. We cannot of course exclude a possibility that the AMM cycle is at least partially affected by global warming in addition to the deep ocean circulation. If the cyclic nature of hurricane activity persists, we can expect additional active seasons for the next few years with a decreasing trend taking over a few years after 2010.

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