Changes in the Rates of North Atlantic Major Hurricane Activity During the 20th Century

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January 21, 2000

Index Terms: Major hurricanes, North Atlantic oscillation, change-point analysis, cumulative frequency

Abstract

The authors document and explain changes in the rates of North Atlantic major hurricanes over the 20th century. A change-point analyses identifies two contrasting regimes of activity. The regimes have significantly different occurrence rates that coincide with changes in the climate over the North Atlantic. In conjunction with the recent Arctic warming and a relaxation of the North Atlantic oscillation, it is speculated that we are beginning a new period of greater major hurricane activity across the North Atlantic.

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1. Introduction and approach

The frequency of major hurricanes across the North Atlantic (including the Caribbean Sea and Gulf of Mexico) has been lower over the past few decades compared to the long-term average. *Landsea et al.* [1996] indicate a half-century downward trend in occurrence, but point out that the 1995 season may have heralded a new regime of enhanced storminess. The five-year period beginning with 1995 has had 20 major hurricanes, the largest five-year total since the 1950s.

Recent studies have uncovered a statistical association between the North Atlantic oscillation (NAO) and tropical cyclones. Employing a factor analysis model, *Elsner and Kocher* [2000] demonstrate a relationship between an index of the NAO and the leading common-variance component of global tropical cyclone activity. Also, *Elsner et al.* [2000] show a correspondence between major hurricanes along the U.S. coastline and the intensity of the NAO. The relationship holds across a spectrum of time scales. When the NAO is in an amplified state, major hurricanes are more common along the eastern seaboard. These results imply that midlatitude climatic variations may play a greater role in modulating the tropics than hereforto considered while providing a fresh focus for additional hurricane climate research. Here we continue our investigation into the linkage between hurricanes and the NAO by examining the record of intense North Atlantic tropical cyclones.

Hurricane data are obtained from the best-track records [see *Neumann et al.*, 1993], which are a compilation of the six-hourly positions and intensities of tropical cyclones back to 1886. Major hurricanes are tropical cyclones with maximum sustained winds reaching 100 kt or greater—representing category three or higher on the Saffir-Simpson damage-potential scale. Records are most reliable after 1943, particularly for the weaker cyclones. Although the period of record for the present study is 1900–99 (N = 100 years), focus is on the second half of the 20th century. The emphasis is also on intense hurricanes. The essential results of this paper are not materially influenced by potential biases in the data record prior to 1944. After an examination of the major hurricane record, the study considers a possible connection to the North Atlantic oscillation (NAO). Data on the state of the NAO are obtained from the Climate Research Unit at the University of

East Anglia, UK. Values are monthly sea-level pressures (SLP) for southwestern Iceland.

The approach here is exploratory. First, the assumption that the occurrence of intense hurricanes follows a Poisson process is exploited to look at fluctuations in activity over the past 100 years. The method examines the characteristic of a scatterplot of the logarithm of average interarrival times between events over time. The cumulative frequency is then used to visualize shifting rates of major hurricanes. A change-point analysis is employed to determine the most likely years of shifts in activity. Over the reliable portion of the record, these years are used to composite related responses and a potential explanatory variable. The utility of the change-point model, over other more simplistic and subjective methods, is that it defines the years of change using the power of statistical confidence.

2. Secular changes

Major (or intense) hurricanes account for 38% of all North Atlantic hurricanes [*Elsner and Kara*, 1999]. The mean annual number of major hurricanes is 2.0 with a variance of 3.20. As a practical matter, their occurrence can be considered as a Poisson process [*Elsner and Schmertmann*, 1993; *Wilson*, 1999]. A characteristic of a Poisson process is the equality of population mean and variance. The ratio of the sample variance to the sample mean $[R = (\text{s.d.})^2/\bar{x}]$ is thus used to test for a Poisson process. The test is made by noting that the ratio (R) can be converted into a chi-squared random variable. Here we test the frequency of major hurricanes for the possibility of a constant-rate Poisson process at two hurricane intensity levels. Table 1 shows the test results for a null hypothesis (at $\alpha = 0.05$) that the distribution is Poisson for hurricanes of 100 kt or greater and for hurricanes of 120 kt or greater. For 100 kt hurricanes, R is greater than the critical value, R_c, guiding us to reject for a constant-rate Poisson process. This is not the case for 120 kt hurricanes where R is less than R_c.

With the occurrence of 120 kt intense hurricanes described as constant-rate Poisson, the interarrival times between successive hurricanes are exponentially distributed. The exponential distribution provides for a mixture of within-seasonal and cross-seasonal arrival times. As such, we employ standard regression on the natural logarithm of the interarrival times versus the cumulative number of days from the occurrence of the first intense storm. Noise in the data is reduced by averaging interarrival times in clusters of successive events. Here we use clusters of four events as suggested in *Keim and Cruise* [1998] based on the total number of events in the sample. A time-series plot of the average interarrival time on a logarithm scale versus time is shown in Figure 1. The solid line, representing a 4th-order polynomial regression, helps underscore the changing rates of significant hurricane activity. Interarrival times are shortest during 1940s, 50s, and 60s and longer before and after.

Another procedure, which considers the rates explicitly, is helpful in elucidating secular changes, or shifts, in major hurricane activity. The rate of major hurricane activity each year is obtained by using a five-year running linear regression on the cumulative frequency. Figure 2 shows the regression slopes as a time series. Values are plotted on the middle year of the five-year sliding window. The occurrence of major hurricanes prior to 1900 are used to obtain a value for 1900. Major hurricanes were more abundant during the middle decades of the 20th century with rates generally exceeding 3 storms per year. The decades of the 1970s and 80s have rates closer to 1.5 storms per year. This analysis confirms the temporal changes in major hurricane rates noted for 120 kt hurricanes and hints at another active period beginning more recently.

The rejection of a Poisson process for major hurricanes suggests the possibility of a process having varying rates (i.e., variable-rate Poisson process). The time-series plots in Figures 1 and 2 hint that changes in the rates of major hurricane activity might be abrupt rather than slowly changing [*Wilson*, 1997]. Though *Landsea et al.* [1996] shows a negative *straight line* trend through the counts of major hurricanes, a closer examination indicates a stepwise discontinuity [*G.S. Lehmiller*, pers. comm., 1996]. Figure 3 shows the cumulative frequency of major hurricanes over time. Rather sudden shifts in the rates separate periods of lower activity from periods of higher activity. Note the two methods above do not provide a procedure for unambigously identifying the likely year of change. Next we employ a different approach that does.

Given a time series of the annual counts of major hurricanes, a change point is detected at some year in the series if all values up to that year share a common rate and all years from that year onward share a different rate. Years in the period 1900–99 are labeled as 1–100. Let X_i be the number of intense hurricanes at year i and $Y_i = \log(X_i + 1)$. For each integer $l > 1$ to $m = N - 1$, define the step variable:

$$S_i(l) = \begin{cases} 0, & i < l \\ 1, & i \geq l. \end{cases}$$

In order to detect possible change points in the sequence $\{Y_i, i = 1, \ldots, 100\}$, we first fit a linear regression model to the Y_i as

$$Y_i = \beta_0(l) + \beta_1(l) S_i(l) + \epsilon_i(l), \tag{1}$$

where for a fixed l, the $\epsilon_i(l)$'s are assumed to be independent and identically distributed normal random variables with mean zero and variance $\sigma^2(l)$. Then we calculate the value

$$L(l) = \hat{\beta}_1(l) / se[\hat{\beta}_1(l)], \tag{2}$$

where $se[\hat{\beta}_1(l)]$ is the estimated standard error of $\hat{\beta}_1(l)$.

Then, let $L(l_1) = \max\{|L(2)|, |L(3)|, \ldots, |L(m)|\}$ and compare $L(l_1)$ with a critical value. For 100 observations, the critical value ($\alpha = 0.05$) is near 3.0 based on the simulation results of *Chang et al.* [1988]. If $L(l_1)$ is significant, we conclude that the response Y has a change point at l_1 with a rate shift $\hat{\beta}_1(l_1)$. Note that $L(l_1)$ is the year of the first detected change point. We repeat the procedure on a new response variable $Y_i^* = Y_i - \hat{\beta}_1(l_1) S_i(l_1)$ and the process is continued until no further change point can be detected.

The method identifies four change points during the 20th century. We take these four points and find only three are significant when the occurrence rates are estimated using a Poisson general linear model. Note that, although the entire record does not conform to a constant-rate Poisson process, shorter segments between the change points do. The first significant change occurs in 1943 as a shift upward in the rate of activity. This is followed by a downward shift to more modest levels of activity in 1965. A return to a more active regime is indicated starting in 1995. Though these values represent the most likely years of rate shifts, the actual change point could have occurred over a few-year interval either before or after. Major hurricane rates over the interval from 1900–42 and 1965–94, inclusive are not significantly different whereas the rate during 1900–42 is significantly different from the rate during 1943–64. The change-point model establishes periods of high and low major hurricane activity. The utility of this approach is that it provides a statistically defensible method of defining different periods of activity. The years can be used with confidence by others.

Here the periods are used to examine related activity and a possible association with changes in the climate. Table 2 shows the regression statistics, where the periods are defined by the objective change-point model. The regression lines are shown in Figure 3 displayed by 10 units up the vertical axis for visual inspection. The first period extends from the beginning of the record until 1942 and features an average rate of 1.65 major hurricanes per year. This rate jumps to 3.57 per year over the period 1943–64. Subsequently the rate returns to 1.67 per year. Over the last five years the rate of major hurricanes has returned to 3.4 per year.

It is critical to notice that the change-point model detects shifts in the rates of occurrence regardless of their physical or non-physical origins. Thus the change at 1943 is likely due, at least in part, to improvement in our capabilities to observe these storms. Since we find no additional change points over the unreliable period of 1900–42, an argument can be advanced that the first half of the 20th century belongs in the active period that ended in 1965, where the observational bias results in fewer storms in the record. Yet as support for a counter argument, it is noted that the rate of major hurricanes estimated from the unreliable period is practically equivalent to the rate during the reliable period of 1965–94, indicating that the configuration of climate can produce periods of activity (1965–94, for instance) that resemble a bias in the data. In either case, the analysis reveals two significant change points over the reliable period of record; the detection of which is not influenced by the earlier suspect period.

The shifts in major hurricane activity are significant and are accompanied by similar changes to other measures of tropical cyclone activity. Table 3 displays the frequency of hurricanes by category in each time period over the reliable period of record. Values are expressed in hurricanes per year for U.S. landfalling, tropical-only, and baroclinically enhanced hurricanes. The definitions of tropical-only and baroclinically-enhanced hurricanes are provided in *Elsner and Kara* [1996]. All three categories appear to have similar changes based on using the cutoff years of the change-point model. In particular during periods of heightened major hurricane activity, U.S. and tropical-only hurricanes are more frequent, while baroclinically-enhanced storms are less frequent.

3. A proposed link to the North Atlantic oscillation

Recent research has identified the North Atlantic oscillation as a possible proximal cause for changes in hurricane activity [*Elsner et al.*, 2000; *Elsner and Kocher*, 2000]. The NAO is a coherent north-south seesaw pattern in SLPs between Iceland and the Azores. When pressures are low over Iceland (Icelandic low) they tend to be high over the Azores (Azores high) and vice versa. The NAO (perhaps in conjunction with the Arctic oscillation) represents a significant regional climate fluctuation [*Lamb and Peppler*, 1987; *Wallace and Gutzler*, 1981; *Bjerknes*, 1964] and appears as an important pattern of global interannual variability [*Hurrell and van Loon*, 1997; *Mann and Park*, 1994]. The amplitude of the NAO is largest during the boreal winter, but the signal is present during spring and summer [*Rogers*, 1990].

The NAO is obviously tied to the behavior of the Icelandic low [*Serreze et al.*, 1997]. Table 3 shows the average SLP from southwestern Iceland during the three hurricane periods. Interestingly, there are corresponding changes. In particular, the near mid-century period of greater major hurricane activity and more tropical-only hurricanes is commensurate with higher SLPs over Iceland. This compares to the subsequent period when major hurricanes were less frequent and tropical-only hurricanes less abundant. The most recent period indicates a return to higher SLPs over Iceland and more major hurricanes.

The statistical significance of Iceland SLPs as a explanatory covariate to major hurricane activity is the subject of ongoing research. The association of the NAO with major hurricne counts over the different periods based solely on the mean values as shown in Table 3 can be misleading if the relationship is driven by a few exceptional years. Additional analysis that this is not the case is encouraging, however. Specifically, a Poisson generalized linear model of the annual major hurricane counts using Iceland SLP as the single covariate provides a t-value on the coefficient of 2.325 (two-sided p-value = 0.023), suggesting a relationship worthy of further investigation.

A plausible physical mechanism behind this association centers on the role of the intensity and positioning of the subtropical high. When Iceland pressures are low, the subtropical high tends to be strong and shifted toward the northeast. This allows midlatitude fronts to penetrate the tropics [perhaps in association with a stronger tropical upper-tropospheric trough (TUTT)] and inhibit the development and formation of Cape Verde storms while promoting the formation of baroclinically influenced storms [*Kimberlain et al.*, 2000]. In contrast, when the Icelandic low is weaker the subtropical high is shifted farther to the west and south where it more effectively blocks the intrusion of midlatitude weather systems.

It is possible that the movement of the subtropical high is related to changes in sea-surface temperatures. In fact, secular variations in principal large-scale SSTs over the North Atlantic during the past century indicate a cold ocean until about 1930 followed by warming through the 1950s with a return to cold conditions during the 1960s [*Kushnir*, 1994]. In fact, *Gray et al.* [1997] notes that major hurricane activity was much above normal over the 24-year period 1944–67 when the oceanic thermal haline circulation was strong and rainfall was above average over the Sahel region of western Africa. The cold conditions have recently given way to a warmer North Atlantic and Arctic [*Kerr*, 1999]. These northern North Atlantic SST variations are correlated to Iceland SLPs. Thus the NAO serves as a proximal cause to shifts in the rate of major hurricane activity with the ultimate cause linked to variations in SSTs. Another intriguing speculation is that changes in the stratosphere might trigger changes in the tropospheric NAO, perhaps induced by changes in ozone concentrations through slight variations in solar brightness or other factors.

4. Summary

A statistical analysis of major hurricanes over the North Atlantic basin reveals active and less active regimes based on differences in annual rates. A change-point model finds three statistically significant shifts in activity over the 20th century. The three change points divide the century into four periods of activity. Composite hurricane analyses indicate these periods effectively differentiate decadal-scale shifts in North Atlantic hurricane climate. This is true even if hurricane data before 1943 are considered unreliable. Sea-level pressures describing the climatic state of the Icelandic low provide some evidence for a physical linkage to the North Atlantic oscillation. Modeling studies should be able to unravel this connection in more detail. Disconcertingly, the last five years (since 1995) suggest a weaker Icelandic low and a return to greater major hurricane activity over the tropical North Atlantic.

Acknowledgments: This research was funded by the National Science Foundation (ATM-9618913 and ATM-9417528) and the Risk Prediction Initiative of the Bermuda Biological Station for Research (RPI-99-001).

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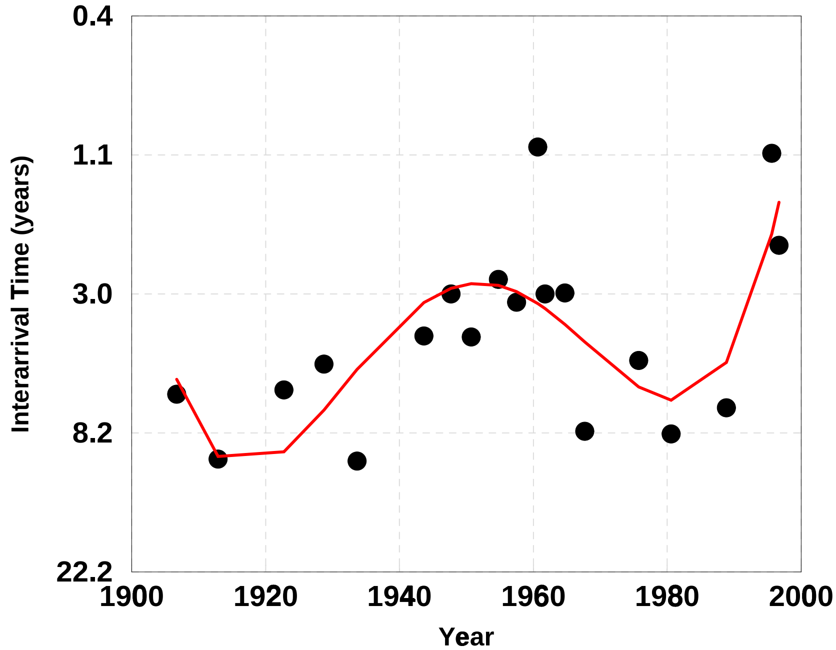

Figure 1: Interarrival times (logarithmic scale) averaged within clusters of four events versus time of the event. The events are defined as major hurricanes with winds in excess of 120 kt. The line represents a polynomial regression of the points. The distribution of the residuals is symmetric.

Table 1: Poisson statistics. Values are the number of storms (n), annual mean ($\bar{x}$), variance [(s.d.)^2], ratio (R), critical ratio (R_c), and decision based on a chi-squared test ($\alpha = 0.05$) for a constant-rate Poisson process. The test is performed on 100 kt or greater and 120 kt or greater hurricanes over the period 1900–99, inclusive.

Storm Intensity	n	$\bar{x}$	(s.d.)^2	R	R_c	Decision
$\geq$ 100 kt	202	2.04	3.20	1.569	1.170	Reject
$\geq$ 120 kt	75	0.76	0.82	1.080	1.284	Accept

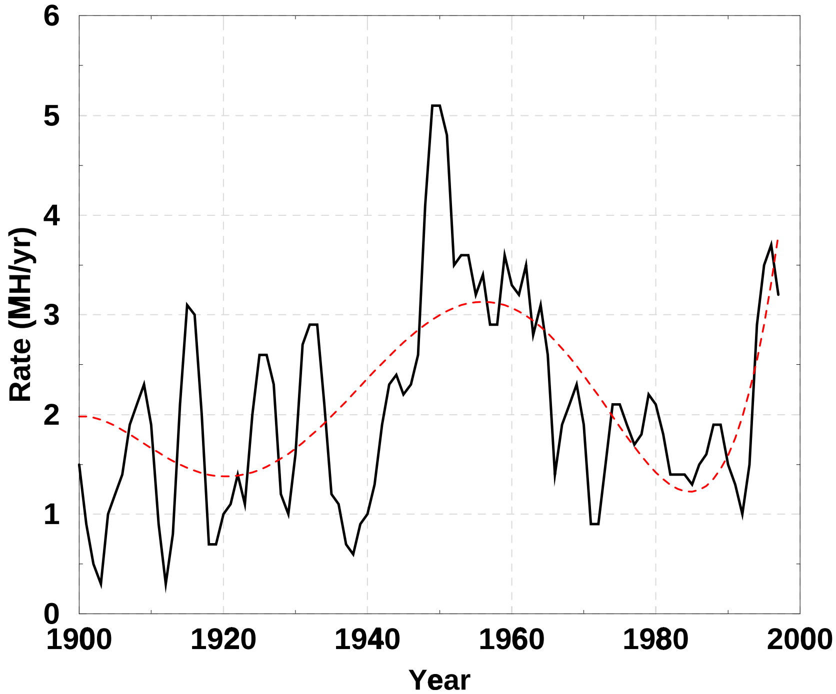

Figure 2: The annual rate of major hurricanes as determined by a five-year moving linear regression on the cumulative frequency over time. The dashed line represents a polynomial regression of the points.

Table 2: Regression statistics. Values are from the linear regressions on the cumulative frequency for the four periods identified in the change-point analysis. The rate is the regression slope and r is the correlation coefficient. Note that Period 1 may be an artifact of an observational bias.

	Years	n	Rate (MH/yr)	r
Period 1	1900–1942	43	1.65	0.995
Period 2	1943–1964	22	3.57	0.996
Period 3	1965–1994	30	1.67	0.997
Period 4	1995–1999	5	3.40	0.977

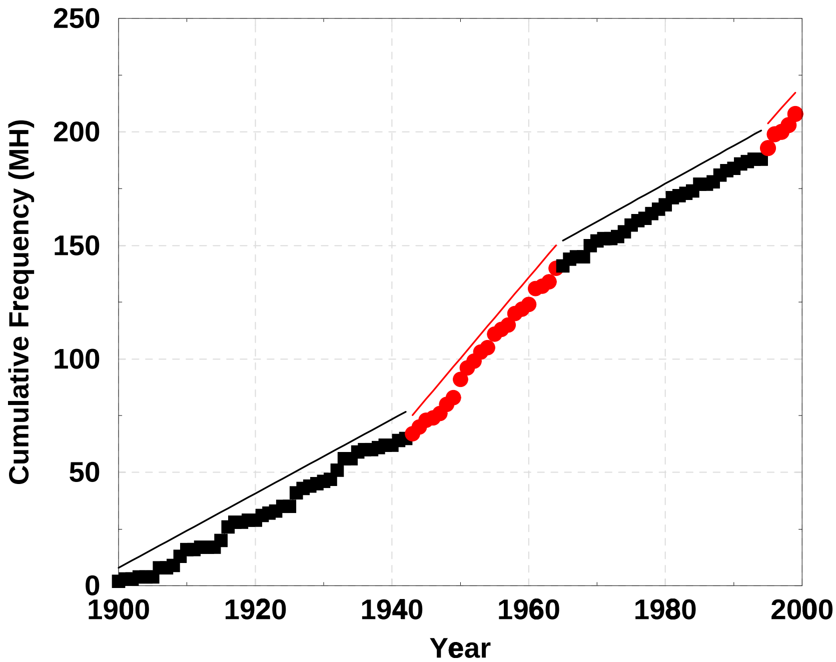

Figure 3: Cumulative frequency of the annual number of major hurricanes over the North Atlantic for the period 1900–99. The graph shows the regression line (displaced along the y-axis) through the points for each regime identified by the change-point analysis. Regression statistics are given in Table 2.

Table 3: Mean hurricane activity and sea-level pressures (SLPs). Values of hurricane activity are expressed in hurricanes per year for the categories of U.S., tropical-only (TO), and baroclinically-enhanced (BE). The SLPs (mb) are averaged from annual values for southwestern Iceland.

Category	1943–1964	1965–1994	1995–1999
U.S.	1.95	1.27	2.20
TO	4.86	1.80	6.00
BE	1.82	3.20	2.20
SLP	1005.8	1005.4	1006.5