GEOPHYSICAL RESEARCH LETTERS, VOL. 27, NO. 12, PAGES 1743-1746, JUNE 15, 2000

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

James B. Elsner

Department of Geography, Florida State University, Tallahassee, Florida

Thomas Jagger[1] and Xu-Feng Niu

Department of Statistics, Florida State University, Tallahassee, Florida

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 extratropical 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.

1. Introduction

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. The five-year period beginning with 1995 saw 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 [*Elsner and Kocher*, 2000; *Elsner et al.*, 2000]. Results of these studies indicate 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 taken 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, but the observational bias is smallest for the strong storms considered here. 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 (SLPs) for southwestern Iceland.

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 1.9 with a variance of 3.24 over the period 1886–1996. 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

Table 1. Poisson statistics.

Intensity	n	$\bar{x}$	$(\text{s.d.})^2$	R	R_c	
$\geq$ 100 kt	202	2.04	3.20	1.57	1.17	Reject
$\geq$ 120 kt	75	0.76	0.82	1.08	1.28	Accept

Values are the number of storms (n), annual mean ($\bar{x}$), variance [$(\text{s.d.})^2$], ratio (R), critical ratio (R_c), and decision (last column) 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.

[1]Now at MathSoft, Seattle, Washington.

Paper number 2000GL011453.
0094-8276/00/2000GL011453$05.00

between successive hurricanes are exponentially distributed. The exponential distribution results from 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. Scatter is reduced by averaging interarrival times in clusters of successive events. 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 to visualize the changing rates of significant hurricane activity. Interarrival times are shortest during 1940s, 50s, and 60s and longer before and after.

The rejection of a Poisson process for major hurricanes ($\geq$100 kt) suggests the possibility of a process having varying rates (i.e., variable-rate Poisson process). The time-series plot in Figure 1 indicates that changes in the rates of major hurricane activity might be abrupt rather than slowly changing [*Wilson*, 1997]. Though *Landsea et al.* [1996] show a negative *straight line* trend through the annual counts of major hurricanes since the middle 1940s, a careful examination indicates a downward shift in the level of activity [*G.S. Lehmiller*, pers. comm., 1996]. Figure 2 shows the cumulative frequency of major hurricanes over time. Apparently, rather sudden shifts in the rates separate periods of lower activity from periods of higher activity.

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:

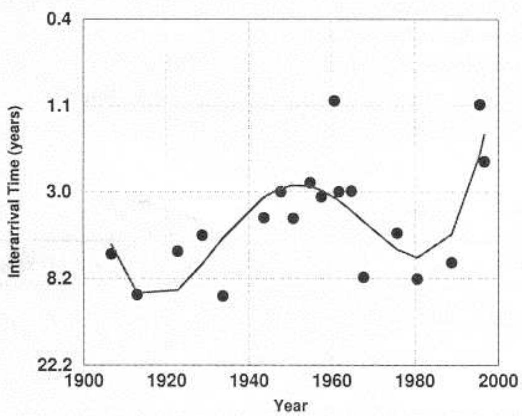

Figure 1. Interarrival times (logarithmic scale) averaged within clusters of four events versus time of the event. The events are defined as major hurricanes with winds in excess of 120 kt. The line represents a polynomial regression of the points. The distribution of the residuals is symmetric.

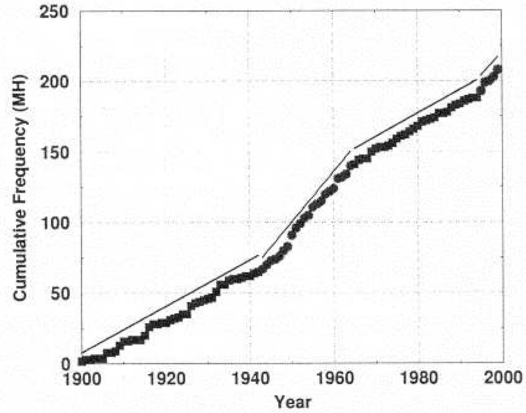

Figure 2. Cumulative frequency of the annual number of major hurricanes over the North Atlantic for the period 1900–99. The graph shows the regression line (displaced along the y-axis) through the points for each regime identified by the change-point analysis. Regression statistics are given in Table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

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

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

$$Y_i = \beta_0(l) + \beta_1(l)S_i(l) + \epsilon_i(l), \qquad (1)$$

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

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

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 that 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 in 1965 to more modest levels of activity. A return to a more active regime is indicated starting in 1995. Though these years represent the most likely years of rate shifts in the frequency of major hurricanes, the actual change point could have occurred over a few-year interval either before or after the year indicated. 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 2 displaced 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 through 1994. Over the last five years the rate of major hurricanes has returned to 3.4 per year. The change-point model detects shifts in the rates of occurrence regardless of their physical or non-physical origins. The change at 1943 is due in part to improvement in our capabilities to observe these storms.

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* [1999]. 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 amplitude of the NAO is largest during the boreal winter, but the signal is present during spring and summer [*Rogers*, 1990].

Table 2. Regression statistics.

	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

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 influenced by an observational bias.

Table 3. Mean hurricane activity and sea-level pressures (SLPs).

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

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 over southwestern Iceland.

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 (weaker NAO). This compares to the subsequent period characterized by lower average SLPs (stronger NAO) and less frequent major hurricanes. The most recent period indicates a return to higher SLPs over Iceland and more major hurricanes.

The association of the NAO with major hurricane 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 indicates that this is not the case. 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). This suggests an interannual relationship between the NAO and the occurrence of major hurricanes that is worthy of further investigation.

A plausible physical mechanism behind the association between the NAO and hurricanes centers on the geographic positioning of the subtropical high and its influence on trade wind strength. When the Icelandic low is weaker (higher pressures), the subtropical high is shifted farther to the west and south, closer to the Caribbean Sea. This relaxes the trade winds across the main development region for hurricanes. Under this regime, tropical waves embedded in the trades and moving westward across the western North Atlantic are more likely to intensify as they encounter westerlies from a monsoon trough or a favorable phase of the

Madden-Julian oscillation [see *Maloney and Hartmann*, 2000]. On the other hand, when the Icelandic low is stronger (lower pressures), the subtropical high tends to be stronger and shifted toward the northeast. This freshens the trade winds across the eastern and central tropical North Atlantic, and carries the premature disturbances across Central America into the eastern North Pacific. In fact, *Elsner and Kocher* [2000] show an inverse relationship between tropical cyclone activity over these two tropical cyclone basins (eastern North Pacific and North Atlantic) that is statistically related to the strength of the NAO.

4. Summary

A statistical analysis of major hurricanes over the North Atlantic basin reveals active and inactive periods 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, possibly through changes in trade wind strength. 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 grants ATM-9618913 and ATM-9417528, and the Risk Prediction Initiative of the Bermuda Biological Station for Research grant RPI-99-001.

References

Chang, I., G.C. Tiao, and Chen, C. Estimation of time series parameters in the presence of outliers. *Technometrics*, **30**, 193–204, 1988.

Elsner, J.B., and Schmertmann, C.P. Improving extended-range seasonal predictions of intense Atlantic hurricane activity. *Wea. Forecasting*, **8**, 345–351, 1993.

Elsner, J.B., and Kara, A.B. *Hurricanes of the North Atlantic: Climate and Society*. Oxford, New York, 488 pp, 1999.

Elsner, J.B., Liu, K.-b., and Kocher, B. Spatial variations in major U.S. hurricane activity: Statistics and a physical mechanism. *J. Climate*, in press.

Elsner, J.B., and Kocher, B. Global tropical cyclone activity: A link to the North Atlantic oscillation. *Geophys. Res. Lett.*, **27**, 129–132, 2000.

Keim, B.D., and Cruise, J.F. A technique to measure trends in the frequency of discrete random events. *J. Climate*, **11**, 848–855, 1998.

Landsea, C.W., Nicholls, N., Gray, W.M., and Avila, L.A. Downward trends in the frequency of intense Atlantic hurricanes during the past five decades. *Geophys. Res. Lett.*, **23**, 1697–1700, 1996.

Maloney, E.D., and Hartmann, D.L. Modulation of hurricane activity in the Gulf of Mexico by the Madden-Julian oscillation. *Science*, **287**, 2002–2004, 2000.

Neumann, C.J., Global overview. *Global Guide to Tropical Cyclone Forecasting*, Greg J. Holland, Ed., World Meteorological Organization, Rep. TCP-31, 1.1–1.56. [Available from World Meteorological Organization, Case Postale 2300, CH-1211 Geneva 2, Switzerland.], 1993.

Rogers, J.C. Patterns of low-frequency monthly sea level pressure variability (1899–1986) and associated wave cycle and frequencies. *J. Climate*, **3**, 1364–1379, 1990.

Serreze, M.C., Carse, F., and Barry, R.G. Icelandic low cyclone activity: Climatological features, linkages with the NAO, and relationships with recent changes in the northern hemisphere circulation. *J. Climate*, **10**, 453–464, 1997.

Wilson, R.M., Comment on 'Downward trends in the frequency of intense Atlantic hurricanes during the past 5 decades,' by C.W. Landsea et al. *Geophys. Res. Lett.*, **24**, 2203–2204, 1997.

Wilson, R.M., Statistical aspects of major (intense) hurricanes in the Atlantic basin during the past 49 hurricane seasons (1950–1998): Implications for the current season. *Geophys. Res. Lett.*, **26**, 2957–2960, 1999.

J. B. Elsner, Department of Geography, Florida State University, Tallahassee, Florida 32306, USA. (e-mail: jbelsner@elsner.coss.fsu.edu)

T. Jagger, Department of Statistics, Florida State University, Tallahassee, Florida 32306, USA.

X.-F. Niu, Department of Statistics, Florida State University, Tallahassee, Florida 32306, USA.

(Received January 28, 2000; accepted March 30, 2000.)