NOTES AND CORRESPONDENCE

Return Periods of Continental U.S. Hurricanes

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ABSTRACT

This note estimates return periods of Atlantic basin hurricanes striking the continental United States. With Hurricane Katrina fresh on the public's mind, there is considerable interest in this topic. The return periods are estimated from historical data from the 1900 to 2006 period via extreme value methods and Poisson regression techniques. Despite the recent active 2004 and 2005 hurricane seasons, the authors do not find evidence of an increasing trend in hurricane strike frequencies.

1. Introduction

This note estimates return periods of Atlantic basin hurricanes striking the U.S. coastline from Texas to Maine. Return period information helps set building design standards and insurance rates and also helps establish climatological norms. Here, our purpose is to estimate how frequently the United States experiences certain hurricane wind speeds and central pressures; we also estimate return periods of some memorable storms including Camille (1969), Andrew (1992), and Katrina (2005).

Under a uniform storm arrival pattern (mathematically, this is called a time-homogeneous Poisson process), an L-year hurricane strike is observed on the average of once every L years. That is, a storm of equal or greater magnitude will strike on the average of once every L years. This interpretation is slightly off in our case because the arrival rates of hurricanes vary within a season. Exact interpretations of return periods are given in section 2.

The data in this study contain Atlantic basin hurricanes striking the continental United States during the period 1900–2006. A strike is said to occur when the hurricane's center of circulation crosses a continental landmass. In this study, the Florida Keys are viewed as part of the continental United States. The data were collected and cross-checked from various sources, including Neumann et al. (1999), Blake et al. (2005), Web pages supported by the National Oceanic and Atmospheric Administration (NOAA) and the National Hurricane Center (NHC), and the Hurricane Research Division's hurricane database (HURDAT) Reanalysis Project (http://www.aoml.noaa.gov/hrd/hurdat/ushurrlist18512005-gt.txt).

We select 1900 as the study starting date to ensure storm count accuracy. While some work aims to improve accuracy for U.S. hurricane data (Landsea et al. 2004) and adjust counts for undetected storms (Solow 1989a), the 1900–2006 data are generally considered reliable. To elaborate, towns on the coast were likely dense enough to avoid missing (undercounting) landfalling hurricanes after 1900 (Murnane et al. 2000). The wind speeds for storms from 1900 to 1914 and from 1980 to present are considered accurate and are based on work in the HURDAT Reanalysis Project. For storms striking from 1915 to 1979, no official wind speed estimates are currently available. For storms during this period, wind speeds were estimated from the wind–pressure relationships described in Landsea et al. (2004) if there is an available central pressure; in other cases, the midpoint of the wind speed range for each storm's Saffir–Simpson (SS) category was used. These midpoints (to the nearest 5 kt) are 75, 90, 105, and 125 kt for categories 1, 2, 3, and 4, respectively.

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This study examines striking (landfalling) hurricanes only; hurricanes that do not strike the continental United States or tropical storms and depressions are not considered. For the purpose of this study, "striking hurricanes" include storms that produce hurricane-force winds at the coast, but the center of the eye does not cross the coast (Hurricane Ophelia in 2005 is one example). As a convention, hurricanes making two distinct strikes are counted as separate events. (Hurricane Andrew in 1992, e.g., struck southern Florida, reintensified in the Gulf of Mexico, and then struck Louisiana.) There are 214 hurricane strikes in our data. These storms and their landfalling central pressures and wind speeds are listed in Table 1. Storms with wind speeds derived from a wind–pressure relationship are marked with an asterisk; storms whose wind speeds are category midpoints are marked with double asterisks. Wind speeds were rounded to the nearest 5 kt.

There are 7 storms in our dataset with landfalling wind speeds below 64 kt that are included because their landfalling central pressures resulted in hurricane conditions. These storms are included in the central pressure distribution fits but not in the wind speeds distribution fits. Likewise, there are 25 storms for which the central pressures are not available.

2. Methodology

Our mathematical methods use Poisson processes to describe the arrival times of the hurricanes and extreme value techniques to model the wind speeds and central pressures of the hurricanes at their time of strike. These specifications are then used to estimate return periods. We now discuss these modeling aspects briefly.

Poisson processes and their variants have been widely used to describe hurricane counts in various regions of the tropics (Mooley 1981; Thompson and Guttorp 1986; Solow 1989a,b; Parisi and Lund 2000). While we refer the reader to these works for the basics on Poisson processes in hurricane modeling and to Ross (1996) for more mathematical aspects, Poisson models describe hurricanes well because the two "Poisson axioms" are approximately satisfied: 1) two distinct hurricanes are very unlikely to strike simultaneously, and 2) the hurricane strike counts in disjoint time intervals are approximately independent.

On axiom 2) above, the existence of patterns in the annual Atlantic hurricane counts is hotly debated (see Bove et al. 1998; Goldenberg et al. 2001; Elsner and Jagger 2004, 2006). Figure 1 displays the annual landfalling hurricane counts over the period of record. The simplest model for these annual counts is an independent Poisson random sequence (Poisson white noise). However, any pattern in the Fig. 1 landfall counts

TABLE 1. U.S. hurricanes used in the study with their wind speeds (WS) and central pressures (CP).

Year	Month	Name	WS (kt)	CP (mb)
1900	Sep	Galveston	125	936
1901	Jul	—	70	983
1901	Aug	—	80	973
1901	Aug	—	80	973
1903	Sep	—	75	976
1903	Sep	—	80	977
1903	Sep	—	70	990
1904	Sep	—	70	985
1904	Oct	—	70	985
1906	Jun	—	70	986
1906	Jun	—	75	979
1906	Sep	—	80	977
1906	Sep	—	95	958
1906	Oct	—	105	953
1906	Oct	—	105	953
1908	May	—	55	989
1908	Jul	—	70	985
1909	Jun	—	85	972
1909	Jul	Velasco	100	959
1909	Aug	—	65	955
1909	Sep	Grand Isle	105	952
1909	Oct	—	100	957
1910	Sep	—	95	965
1910	Oct	—	90	941
1910	Oct	—	95	955
1911	Aug	—	70	985
1911	Aug	—	85	972
1912	Sep	—	65	988
1912	Oct	—	85	973
1913	Jun	—	65	988
1913	Sep	—	75	976
1913	Oct	—	65	989
1915	Aug	Galveston	115	945*
1915	Sep	—	65	988*
1915	Sep	New Orleans	130	931*
1916	Jul	—	110	948*
1916	Jul	—	75	**
1916	Jul	—	75	980*
1916	Aug	—	110	948*
1916	Oct	—	85	972*
1916	Nov	—	75	**
1917	Sep	—	100	958*
1918	Aug	—	105	955*
1919	Sep	—	130	927*
1919	Sep	—	125	**
1920	Sep	—	85	975*
1920	Sep	—	75	**
1921	Jun	—	80	979*
1921	Oct	Tampa Bay	110	952*
1923	Oct	—	70	985*
1924	Sep	—	70	985*
1924	Oct	—	75	980*
1925	Dec	—	75	**
1926	Jul	—	90	967*
1926	Aug	—	105	955*
1926	Sep	Great Miami	115	935*
1928	Aug	—	90	**

TABLE 1. *(Continued)*

Year	Month	Name	WS (kt)	CP (mb)
1928	Sep	Lake Okechobee	120	929*
1929	Jun	—	75	982*
1929	Sep	—	105	948*
1932	Aug	Freeport	120	941*
1932	Sep	—	80	979*
1933	Jul	—	75	**
1933	Aug	—	85	975*
1933	Aug	—	80	971*
1933	Sep	—	110	949*
1933	Sep	—	105	948*
1933	Sep	—	90	957*
1934	Jun	—	100	962*
1934	Jul	—	85	975*
1935	Sep	Labor Day	160	892*
1935	Sep	—	90	**
1935	Nov	—	85	973*
1936	Jun	—	65	987*
1936	Jul	—	95	964*
1936	Sep	—	90	**
1938	Aug	—	70	985*
1938	Sep	—	100	946*
1939	Aug	—	70	985*
1939	Aug	—	75	**
1940	Aug	—	85	972*
1940	Aug	—	85	970*
1941	Sep	—	100	958*
1941	Oct	—	80	975*
1941	Oct	—	90	**
1942	Aug	—	60	992*
1942	Aug	—	110	950*
1943	Jul	—	90	969*
1944	Aug	—	65	990*
1944	Sep	—	100	947*
1944	Sep	—	105	**
1944	Sep	—	105	**
1944	Oct	—	100	962*
1945	Jun	—	70	985*
1945	Aug	—	90	967*
1945	Sep	—	100	951*
1946	Oct	—	75	980*
1947	Aug	—	60	992*
1947	Sep	—	110	940*
1947	Sep	—	105	**
1947	Oct	—	75	**
1947	Oct	—	80	974*
1948	Sep	—	65	987*
1948	Sep	—	95	963*
1948	Oct	—	80	975*
1949	Jan	—	75	980*
1949	Aug	—	100	954*
1949	Oct	—	85	972*
1950	Aug	Baker	75	980*
1950	Sep	Easy	100	958*
1950	Oct	King	100	955*
1952	Aug	Able	70	985*
1953	Aug	Barbara	65	987*
1953	Sep	Carol	75	**
1953	Sep	Florence	70	985*
1954	Aug	Carol	90	**
1954	Aug	Carol	90	960*
1954	Sep	Edna	95	954*
1954	Sep	Edna	75	**
1954	Oct	Hazel	110	938*
1955	Aug	Connie	95	962*
1955	Aug	Diane	65	987*
1955	Sep	Ione	95	960*
1956	Sep	Flossy	85	975*
1956	Sep	Flossy	75	**
1957	Jun	Audrey	115	945*
1958	Sep	Helene	105	946*
1959	Jul	Cindy	60	993*
1959	Jul	Debra	70	984*
1959	Sep	Gracie	105	950*
1960	Sep	Donna	130	930*
1960	Sep	Donna	105	**
1960	Sep	Donna	105	**
1960	Sep	Ethel	75	981*
1961	Sep	Carla	130	931*
1963	Sep	Cindy	55	996*
1964	Aug	Cleo	85	968*
1964	Sep	Dora	90	966*
1964	Oct	Hilda	110	950*
1964	Oct	Isbell	85	974*
1965	Sep	Betsy	105	948*
1965	Sep	Betsy	105	**
1966	Jun	Alma	75	982*
1966	Oct	Inez	70	983*
1967	Sep	Beulah	110	950*
1968	Oct	Gladys	80	977*
1969	Aug	Camille	145	909*
1969	Sep	Gerda	75	980*
1970	Aug	Celia	115	945*
1971	Sep	Edith	80	978*
1971	Sep	Fern	80	979*
1971	Sep	Ginger	55	995*
1972	Jun	Agnes	75	980*
1972	Jun	Agnes	75	**
1974	Sep	Carmen	110	952*
1975	Sep	Eloise	105	955*
1976	Aug	Belle	75	980*
1977	Sep	Babe	55	995*
1979	Jul	Bob	70	986*
1979	Sep	David	85	970*
1979	Sep	David	90	**
1979	Sep	Frederic	115	946*
1980	Aug	Allen	100	945
1983	Aug	Alicia	100	962
1984	Sep	Diana	95	949
1985	Jul	Bob	65	1002
1985	Aug	Danny	80	987
1985	Sep	Elena	100	959
1985	Sep	Gloria	90	942
1985	Sep	Gloria	90	**
1985	Oct	Juan	75	971
1985	Nov	Kate	85	967
1986	Jun	Bonnie	75	990
1986	Aug	Charley	65	990
1987	Oct	Floyd	65	993

TABLE 1. *(Continued)*

Year	Month	Name	WS (kt)	CP (mb)
1988	Sep	Florence	70	984
1989	Aug	Chantal	70	986
1989	Sep	Hugo	120	934
1989	Oct	Jerry	75	983
1991	Aug	Bob	90	962
1992	Aug	Andrew	145	922
1992	Aug	Andrew	105	956*
1993	Aug	Emily	100	960
1995	Aug	Erin	70	984*
1995	Aug	Erin	85	973
1995	Oct	Opal	100	942
1996	Jul	Bertha	90	974
1996	Sep	Fran	100	954
1997	Jul	Danny	70	984
1998	Aug	Bonnie	95	964
1998	Sep	Earl	70	987
1998	Sep	Georges	90	981
1998	Sep	Georges	90	964
1999	Aug	Bret	100	951
1999	Sep	Floyd	90	956
1999	Oct	Irene	70	987
2002	Oct	Lili	80	963
2003	Jul	Claudette	80	979
2003	Sep	Isabel	90	957
2004	Aug	Alex	85	972
2004	Aug	Charley	130	941
2004	Aug	Charley	75	**
2004	Aug	Charley	75	**
2004	Sep	Frances	90	960
2004	Aug	Gaston	65	985
2004	Sep	Ivan	105	946
2004	Sep	Jeanne	105	950
2005	Jul	Cindy	65	991
2005	Jul	Dennis	105	946
2005	Aug	Katrina	70	984
2005	Aug	Katrina	110	920
2005	Sep	Ophelia	65	982
2005	Sep	Rita	100	937
2005	Oct	Wilma	105	950

* Wind speed derived from wind–pressure relationship.
** Wind speed equals midpoint of SS category.

would imply that the Poisson white noise assumption is suboptimal. Sample correlations in the year-to-year hurricane counts support the white noise assumption. Elsner and Bossak (2001) conclude that historical Atlantic hurricane counts (not just U.S. landfalling storms) are essentially stationary, nor is there any significant shift (changepoint) in hurricane rates (Elsner et al. 2004). Neither of these studies includes data from the very active 2004 and 2005 seasons.

Recent research allows the annual Poisson mean parameter, denoted by λ and also called an arrival rate, to depend on covariate factors such as time, the North Atlantic Oscillation (NAO), the Southern Oscillation index (SOI), and the Atlantic multidecadal oscillation (AMO) (see Van den Dool et al. 2006, and the references therein for how the NAO and AMO influence climate in North America). In addition to these covariates we also modeled the Bivariate El Niño–Southern Oscillation Time series (BEST). It is important to note that the BEST is a univariate time series and that "bivariate" refers to the fact that it is calculated from two data series (the SOI and Niño-3.4). (Data for the NAO, the SOI, the AMO, and the BEST were taken from links at http://www.cdc.noaa.gov/ClimateIndices/List/ and http://www.cru.uea.ac.uk/cru/data/pci.htm. The units of all covariates are in standard deviations.)

The number of storms occurring in year t of the study is modeled as a Poisson random variable with mean λ_t, where

$$\lambda_t = \exp(\beta_0 + \alpha t + \beta_1 \mathrm{NAO}_t + \beta_2 \mathrm{BEST}_t + \beta_3 \mathrm{SOI}_t + \beta_4 \mathrm{AMO}_t).$$

Here, α is a linear trend slope and the β_is are regression coefficients. Poisson regression methods are used to statistically fit and assess such models (Davison 2003 gives an overview). Elsner (2003), Elsner and Bossak (2004), McDonnell and Holbrook (2004), and Elsner and Jagger (2004, 2006) employ such techniques and find that the NAO is the only significant predictor among the NAO, the AMO, and the SOI.

In our Poisson regression fittings with the storm strike data through 2006, we also find that the estimates of α, β_3, and β_4 are statistically insignificant (judged as zero) at the 95% confidence level. This was gauged by an all-subsets regression technique; that is, every possible combination of factors was examined. Only the NAO and the BEST were statistically significant in our model. That some of the covariates are insignificant is perhaps not unexpected. In particular, hurricanes, our population of interest, are composed of the strongest of the tropical cyclones. Moreover, it is known that correlating extremes to covariates is more difficult than correlating means to covariates (McCormick and Qi 2000 make the notions precise). Hence, an analysis containing all tropical storms may stand a better chance in fingerprinting the AMO as a legitimate covariate influencing storm counts. It is also not surprising that the SOI is insignificant in the presence of the BEST; indeed, the SOI is one of the components of the BEST.

In short, the mean U.S. hurricane strike count from year t is modeled as

$$\lambda_t = \exp(\beta_0 + \beta_1 \mathrm{NAO}_t + \beta_2 \mathrm{BEST}_t). \qquad (2.1)$$

The NAO and the BEST values for year t were taken as the May–June averages; these values are plotted in Fig. 2 in anomalies of standard deviations. Both time series are modeled as zero mean Gaussian white noise with

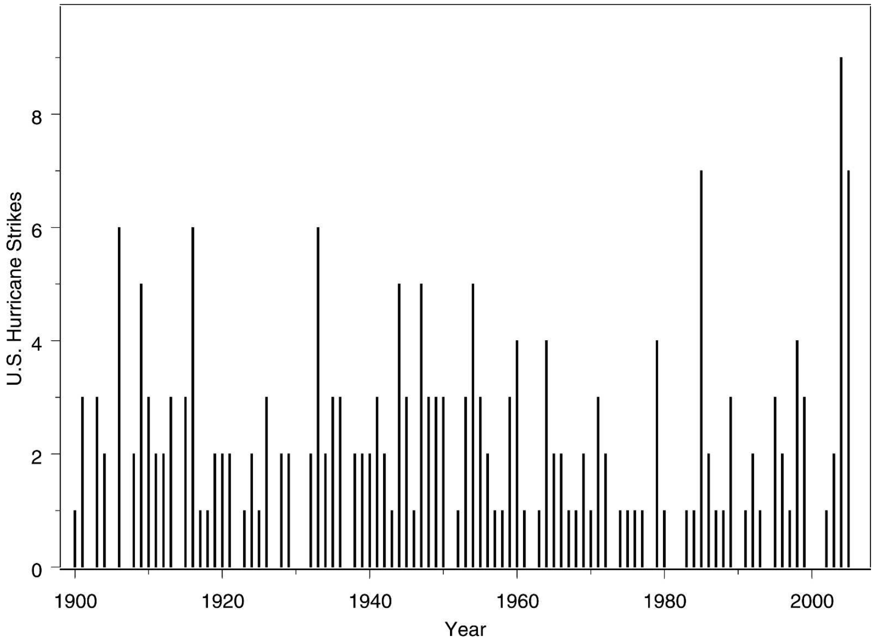

FIG. 1. Annual U.S. landfalling hurricane counts, 1900–2006 (counting multiple landfalls as separate storms).

variances $\sigma^2_{Z_{\text{NAO}}} = 0.881$ for $\{\text{NAO}_t\}$, and $\sigma^2_{Z_{\text{BEST}}} = 0.567$ for $\{\text{BEST}_t\}$. These models were selected by the model selection criteria and normality assessments in Brockwell and Davis (1991). Additionally, $\{\text{NAO}_t\}$ and $\{\text{BEST}_t\}$ show no clear correlation.

No significant trend in the hurricane counts is seen in the data through 2006. This result is consistent with Landsea (2005). The trend estimator and one standard error is $\hat{\alpha} = -0.0026 \pm 0.0023$, which has a p value of 0.28 (in a test of $\alpha = 0$ against $\alpha \neq 0$). An estimate of the long-run annual average of landfalling hurricanes is $\hat{\lambda} = n_{\text{yr}}^{-1}\Sigma_{t=1}^{n_{\text{yr}}}\hat{\lambda}_t$, which is about 2 storms per year. Here, $n_{\text{yr}} = 107$ is the number of years of observations.

Given that a hurricane has made landfall, the day of year that it strikes is modeled as a statistical draw from the probability density function $f_D(\cdot)$. This density is estimated from kernel density techniques:

$$\hat{f}_D(d) = \frac{1}{214}\sum_{i=1}^{214} h^{-1}K\left(\frac{d-d_i}{h}\right), \quad 0 \le d < 365, \tag{2.2}$$

where d_i is the day of year on which the ith storm struck (the year is not relevant), and K is a Gaussian kernel function defined by $K(x) = \exp\{-x^2/2\}/\sqrt{2\pi}$. Leap year effects imparted on the day of storm strike are negligible and hence ignored; the bandwidth $h = 33.80$ days was selected here [Parisi and Lund (2000) provide more details on kernel smoothing methods and the Atlantic hurricane arrival seasonality].

The final component in our model specifies the wind speed and central pressure distributions of the landfalling storms. Our fitted distributions will be based on peaks over threshold extreme value techniques (see Coles 2001; Wilks 2006 for overviews). Specifically, the wind speed and central pressure data are modeled with a generalized Pareto distribution for excesses, which has cumulative distribution function

$$\Pr(W_i - u \le x \mid W_i > u) = 1 - \left(1 + \xi\frac{x}{\sigma}\right)_+^{-1/\xi} \quad x \ge 0, \tag{2.3}$$

where W_i is the landfalling wind speed for the ith storm (see Embrechts et al. 1997; Coles 2001; Wilks 2006 for more on peaks over threshold methods and Pareto distributions). The parameters of this distribution are $\sigma > 0$ and ξ, and u is a fixed threshold that we take as 64 kt for the wind speeds. The notation uses $x_+ = \max(x, 0)$. Landfalling central pressures are modeled similarly, except that the Pareto distribution is fitted to $\{1002 - P_i\}$ ($u = -1002$ mb) to reverse the natural ordering in pressures. The estimated wind speed parameters and standard errors are $\hat{\sigma} = 32.751 \pm 2.712$ and $\hat{\xi} = -0.3122 \pm 0.039$; those for the central pressures are $\hat{\sigma} = 48.109 \pm 3.963$ and $\hat{\xi} = -0.4242 \pm 0.0377$. The method of maximum likelihood was used to estimate these parameters. The model fits the data reasonably well; specifically the thresholds $u = 64$ kt and $u = -1002$ mb were gauged as adequate via the mean ex-

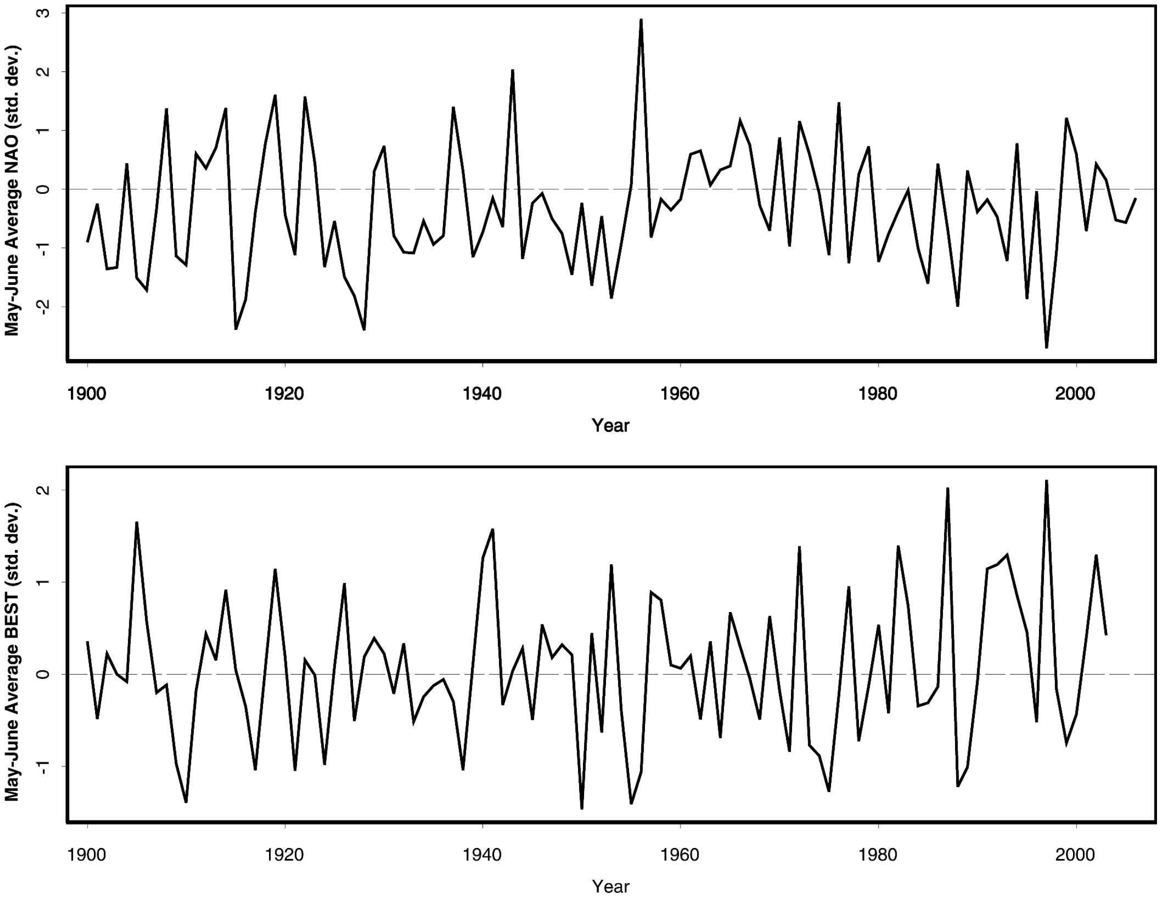

FIG. 2. May–June average (top) NAO and (bottom) BEST anomaly (std dev), 1900–2006.

cess plots of Davison and Smith (1990) and Parisi and Lund (2000). Implications of the negative ξs in the model fits are that wind speeds can be no larger than 169 kt and central pressures can be no lower than 888 mb at the storm strike time. These bounds do not apply to storms over open waters. The 169-kt bound is slightly less than the 185-kt bound used in Murnane et al. (2000). Time-varying Pareto parameters were considered but were not ultimately needed. In fact, simple linear regression fits of the striking wind speeds and central pressures on the year of arrival and the relative NAO and BEST levels did not reveal any significant relationships at the 95% significance level. Table 2 summarizes all parameters in our hurricane model.

Return periods can be estimated from the above model via simulation. For preciseness, the return period of a hurricane with a landfalling wind speed of w kt is defined as the expected time (a statistical average) that one must wait, starting from 1 January of a given year, until a hurricane with a wind speed of w kt or greater makes landfall.

A single simulation run must generate a fair draw of a "level w" return period. To do this, one first generates $\{\mathrm{NAO}_t\}$ and $\{\mathrm{BEST}_t\}$ over a suitably long time horizon (the length of this time horizon is not overly relevant for this discussion). From the two covariate series, one then generates a time series of λ_ts via (2.1). We then generate the number of storms N_t in each year t as a Poisson random variable with parameter λ_t. Given that

TABLE 2. Model parameter estimates with std errors.

Parameter	Estimate	Std errors
$\hat{\beta}_0$	0.5536	0.081
$\hat{\beta}_1$	−0.2281	0.072
$\hat{\beta}_2$	−0.2074	0.093
$\hat{\sigma}^2_{Z_{\mathrm{NAO}}}$	0.8814	
$\hat{\sigma}^2_{Z_{\mathrm{BEST}}}$	0.5668	
$\hat{h}$	33.80 days	
Wind speed $\hat{u}$	64 kt	
Wind speed $\hat{\xi}$	−0.3122	0.039
Wind speed $\hat{\sigma}$	32.751	2.712
Central pressure $\hat{u}$	1002 mb	
Central pressure $\hat{\xi}$	−0.4242	0.038
Central pressure $\hat{\sigma}$	48.109	3.963

TABLE 3. U.S. hurricane wind speed return periods and nonencounter probabilities.

Saffir–Simpson category	Wind speed (kt)	Return period (yr)	Nonencounter probability (one season)
1	64	0.9	0.17
2	83	1.3	0.37
3	96	2.0	0.55
4	114	4.7	0.78
5	>135	23.1	0.95

$N_t = k$ for a fixed year t, the day of arrival of the k storms within the calendar year is generated as the order statistics of k independent draws from the arrival time density in (2.2). For each storm, wind speeds and central pressures are then generated from the distributions fitted in (2.3). We do not vary these distributions for the day of storm arrival for the reasons discussed in Parisi and Lund (2000).

The above procedure will generate a random sequence of hurricane landfalling times and storm strength characteristics that realistically match those seen in the observed data. The waiting time for the simulation run is merely the first time that a hurricane with wind speeds of w or greater is encountered. By empirically averaging waiting time draws over many independent simulations—the number of which is taken as one hundred thousand to minimize sampling error—we arrive at an estimate of the wind speed w return period.

3. Results

Table 3 lists estimated return periods for storms of various wind speed magnitudes. For example, one waits an average of 0.9 yr for a Saffir–Simpson (SS) category 1 or stronger storm, which has wind speeds of 64 kt or higher, to make landfall (as measured from 1 January). The nonencounter probability listed is the estimated probability that no SS 1 storm or greater makes landfall in a calendar year. For example, the chance that no hurricane (SS 1 or higher) makes landfall in a given year is about 17%. Major storms (SS 3 and higher) have a return period of about 2.0 yr, with a probability of about 0.45 occurring annually (one or more landfalls in a given year). Table 4 displays estimated return periods for central pressures of the storms. Their interpretations are similar to the wind speed return periods.

TABLE 4. U.S. hurricane central pressure return periods and nonencounter probabilities. Classification by central pressures was discontinued in the 1990s.

Central pressure (mb)	Return period (yr)	Nonencounter probability (one season)
≥980	0.9	0.17
979	1.2	0.34
964	1.7	0.48
944	3.2	0.70
<920	12.7	0.92

TABLE 5. Regional return periods in years.

Saffir–Simpson category	FL	Gulf states (TX, LA, MS, AL)	East Coast (GA to ME)
1	1.7	1.6	1.6
2	2.4	2.1	2.4
3	3.3	2.8	4.2
4	6.5	5.6	28.7
5	23.4	37.1	NA

The covariates NAO and BEST are not overly important in the return period debate. For example, a Saffir–Simpson category 5 hurricane strike return period is 23.1 yr when these are taken into account, and 22.5 yr when they are ignored.

The return periods in Tables 3 and 4 apply to the continental United States as a whole. We have also partitioned the storms into three regions of strike location: the Gulf of Mexico (excluding Florida), the East Coast, and Florida. Return periods for these subregions are presented in Table 5 and have the same interpretations. Category 5 hurricanes striking the Atlantic coast north of Florida were deemed impossible by the fitted model.

Table 6 exhibits return periods of some memorable Atlantic basin storms by both striking wind speed and central pressure. That Katrina is roughly a 4-yr storm (based on wind speed, 13 yr based on central pressure) may seem surprisingly low, but perhaps not so when only the storm's meteorological characteristics are con-

TABLE 6. Return periods of some notable U.S. landfalling hurricanes.

Storm name	Wind speed (kt)	Return period (yr)	Central pressure (mb)	Return period (yr)
New Orleans (1915)	130	13.7	931	6.3
Labor Day (1935)	160	265.3	892	101.6
Betsy (1965)	105	2.9	948	2.9
Beulah (1967)	110	3.7	950	2.7
Camille (1969)	145	62.9	909	35.7
Hugo (1989)	120	6.7	934	5.3
Andrew (1992)	145	62.9	922	10.9
Charley (2004)	130	13.7	941	3.8
Katrina (2005)	110	3.7	920	12.7

sidered. As the central pressure is arguably a better measure of overall storm strength, central pressure return periods are probably better measures of overall severity.

The 1935 Labor Day Florida Keys storm was the most severe in our dataset. With a 265-yr wind speed return period and a 102-yr central pressure return period, it presses the fitted model boundaries. We believe this is due in part to the extreme southern latitude of this landfalling storm. Another storm of this intensity would likely again require a very southern landfalling latitude, with the Florida Keys or the Brownsville, Texas, region being the most likely hosts.

4. Summary

Return periods of continental U.S. hurricane strikes were estimated from Poisson processes and extreme value techniques. Incorporating the NAO, the BEST, the SOI, and the AMO does not seem to greatly impact return period estimates, with only the NAO and BEST influencing the results at all. The hypothesis that hurricane strike frequencies are increasing in time is also statistically rejected.

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