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Secular Changes to the ENSO–U.S. Hurricane Relationship

James B. Elsner and Brian H. Bossak

Department of Geography, Florida State University, Tallahassee, Florida

Xu-Feng Niu

Department of Statistics, Florida State University, Tallahassee, Florida

Abstract. Analysis of the statistical relationship between annual U.S. hurricane activity and the El Niño-Southern oscillation (ENSO) is performed. The legitimacy of considering annual U.S. hurricane counts as a Poisson process is checked. Then, Poisson regression is used to model the ENSO-U.S. hurricane connection. A bivariate regression model verifies a significant negative correspondence between tropical Pacific sea-surface temperature (SST) and U.S. hurricane activity. When equatorial SSTs are cold, U.S. hurricanes are more likely. Secular changes to the ENSO-U.S. hurricane relationship are examined using moving regressions. A nonlinear downward trend in the relationship's strength is evident. Variations in sea-level pressures over the extra-tropical North Atlantic Ocean during months immediately prior to the hurricane season provide an explanation for a portion of this secular variability. Atmospheric synoptic conditions associated with the North Atlantic oscillation (NAO) result in hurricanes tracking parallel to southern latitudes en route to the United States.

1. Introduction

Under the El Niño (or warm) phase of the El Niño-Southern oscillation (ENSO), atmospheric convection over the western equatorial Pacific shifts eastward along with warm sea-surface temperatures (SSTs). Increased convection over the central equatorial Pacific creates stronger upper-level (200 hPa) winds and greater vertical shearing over the hurricane genesis and development regions of the tropical Atlantic [*Gray*, 1984; *Vitart and Anderson*, 2001; *Goldenberg et al.*, 2001]. The shear, combined with increased subsidence, inhibits the growth of pre-hurricane disturbances in the Atlantic. When these conditions persist there is a reduced threat of a coastal storm.

Factors that control the frequency of hurricanes are not necessarily the same as those that control where they track. During certain periods the tendency is for hurricanes to track parallel to latitudes between 10°N and 20°N, while during other periods the tendency is for storms to recurve into higher latitudes. To some extent, the degree to which the U.S. coast is vulnerable is related to factors associated with the predominance of straight-moving hurricanes. Thus the probability of a U.S. hurricane strike is a function of the factors that control their frequency as well as a function of the factors that control their movement. In order to understand factors that might have an influence on hurricane steering, it is useful to first examine changes to the strength of the ENSO-hurricane connection. In this work, secular variations to the ENSO-U.S. hurricane relationship are studied.

2. Poisson regression

A hurricane is a tropical cyclone with maximum sustained (one-minute) 10 m winds of 33 ms^{-1} (65 kt) or greater, with landfall occurring when all or part of the eye wall (the central ring of deep atmospheric convection, heavy rainfall, and strong wind) passes directly over the coast or adjacent barrier island. A U.S. hurricane is a hurricane that makes at least one landfall. A reliable list of the annual counts of U.S. hurricanes back to 1900 is available from the U.S. National Oceanic and Atmospheric Administration [*Neumann et al.*, 1999]. These data represent a blend of historical archives and modern direct measurements, but the annual time series appears stationary over the period [see *Elsner and Kara*, 1999]. The lag-one autocorrelation of annual counts is a negligible -0.02.

A χ^2 goodness-of-fit test is performed by assuming the distribution of counts is Poisson (null hypothesis) with a rate equal to the sample mean of 1.6 U.S. hurricanes per year. Since the empirical distribution has a minimum of 0 and maximum of 6, we divide the distribution into $n = 7$ parts and find the χ^2 value with $n-1$ degrees of freedom equal to 7.36 giving a p-value of 0.289. As such there is no evidence against the null hypothesis and we proceed to model the annual counts of U.S. hurricanes using Poisson regression [see also, *Parisi and Lund*, 2000].

To fit a model to the annual hurricane counts we use a generalized linear model. The relationship between $\mathrm{E}(Y_i) = \mu_i$ and $\beta_0 + \sum_{k=1}^{p} \beta_k x_k$ is specified by a link function $g(\mu_i)$, which is required only to be monotonic and differentiable. The canonical link function given by *McCullagh and Nelder* [1989] for the Poisson distribution is $g(\mu_i) = \log(\mu_i)$.

For the present analysis, let $\mu_i = \mathrm{E}(Y_i)$. Then

$$\log(\mu_i) = \beta_0 + \beta_1 x_i \quad (1)$$

is used to describe the relationship between μ_i and ENSO (x_i). The parameters in a generalized linear model are estimated by the maximum likelihood method. The deviance is a measure of the discrepancy between observed and fitted values. It serves as a generalization of the usual residual sum of squares for non-normal data.

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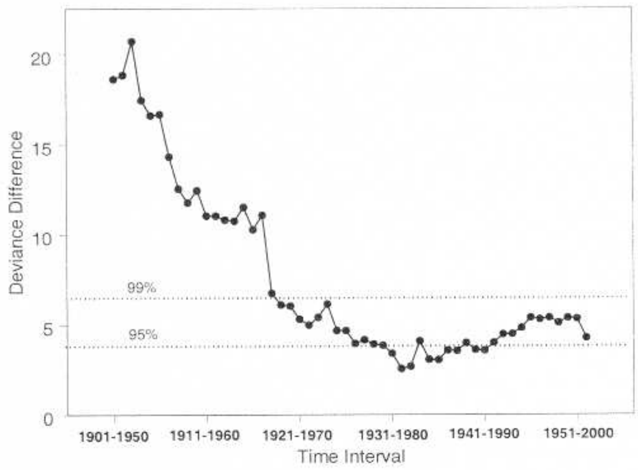

Figure 1. Difference in deviance values for Poisson regressions of U.S. hurricanes against CTI values using 50-year intervals in 1-yr overlapping steps. The magnitude of the difference in deviance indicates model fitness against the null model (no covariate) and thus the strength of the bivariate ENSO-U.S. hurricane connection.

A reliable time record of the Pacific ENSO is obtained by using basin-scale equatorial fluctuations of SSTs. Average SST anomalies over the region bounded by 6°N to 6°S latitude and 90°W to 180°W longitude are called the "cold tongue index" (CTI) [*Deser and Wallace*, 1990]. Values of CTI are obtained from the *Joint Institute for the Study of the Atmosphere and the Oceans* web site (www.jisao.washington.edu/science2.html) as monthly anomalies (base: 1950–79) in hundredths of a degree Celsius. Since the Atlantic hurricane season runs principally from August through October, a 3-month averaged (Aug–Oct) CTI from the data set is used. A significant relationship between CTI and U.S. hurricanes is noted. The annual count of hurricanes is higher when values of the CTI are lower (La Niña events).

The deviance difference between the null (no covariate) model and the model in (1) is 20.62 with a p-value of 5.59×10^{-6} using a χ^2 test. The larger the deviance difference, the stronger the bivariate ENSO-U.S. hurricane relationship. Thus it appears, as expected, that the ENSO has a statistically significant influence on the annual numbers of U.S. hurricanes during the 20th century. The relationship is strongest when using central equatorial Pacific SSTs as measured by the CTI for the model covariate. When CTI values indicate below normal equatorial SSTs, the probability of a U.S. hurricane increases. Model fit is examined with residual plots (not shown). The absolute deviance residuals show striations due to the discrete nature of hurricane counts; otherwise the plots reveal nothing to suggest a poor fit.

3. Secular changes

Secular variations to the ENSO-U.S. hurricane relationship on long timescales are investigated by applying Poisson regressions on successive 50-year overlapping time intervals. The 50-year intervals are moved one year at a time through the 101 year record and difference in deviance (deviance difference) values are plotted on a time axis in Fig. 1. Deviance differences corresponding to p-values of 0.05 (95% significance level) and 0.01 (99% significance level) are indicated by horizontal lines on the graph.

Results reveal variations in the strength of the ENSO-U.S. hurricane relationship. In particular, deviance differences are large and significant for regressions run on data from the earliest 50-year intervals, but smaller for regressions run on data from the later intervals. Values are somewhat higher again toward the end of the period indicating a recent return to a stronger relationship. Similar results, showing a decrease in the deviance-difference values through time and a recent slight increase, are obtained using intervals in the range between 20 and 60 years. Similar results are also obtained if linear correlation is used instead of deviance difference with values of the correlation ranging between −0.62 (strongest relationship) and −0.27 (weakest relationship).

A closer look at the change in the ENSO-U.S. hurricane connection can be seen in Fig. 2. Box plots of the relationship are displayed for two contrasting periods. The periods correspond to the largest (1902–51) and smallest (1931–80) deviance values of the Poisson regression as noted in Fig. 1. The abscissa is labelled in pentads of August through October averaged CTI values, where "MB" is much below average, "B" is below average, "N" is normal, "A" is above average, and "MA" is much above average. Notice that even during the period of weakest relationship, above normal values of the CTI (indicative of El Niño conditions) correspond with fewer U.S. hurricanes.

4. Physical hypothesis

Although much of the variation in the ENSO-U.S. hurricane relationship might be attributable to sampling variability [*Gershunov et al.*, 2000], it is instructive to look for physical causes. Physical mechanisms responsible for coastal hurricane strikes can be divided into two factors: (1) Factors that control the quantity of hurricanes that form over

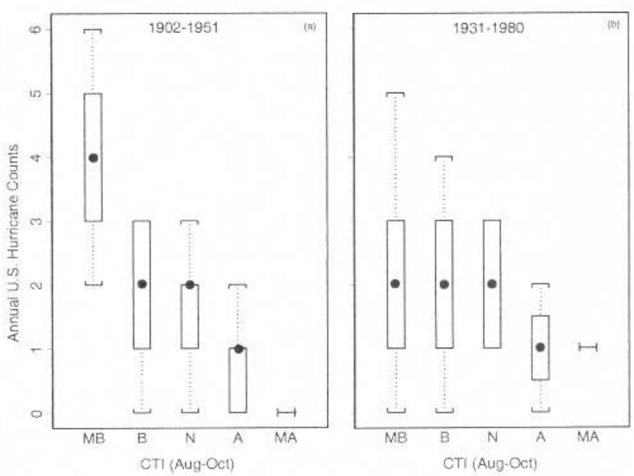

Figure 2. Box plots of annual U.S. hurricane counts as a function of the CTI separated into time intervals of (a) strong relationship and (b) weak relationship. The abscissa is labelled in pentads of August through October averaged CTI values, where "MB" is much below average, "B" is below average, "N" is normal, "A" is above average, and "MA" is much above average. Brackets indicate maximum and minimum values and boxes show the interquartile range. The annual U.S. hurricane count does not vary over the "MA" interval.

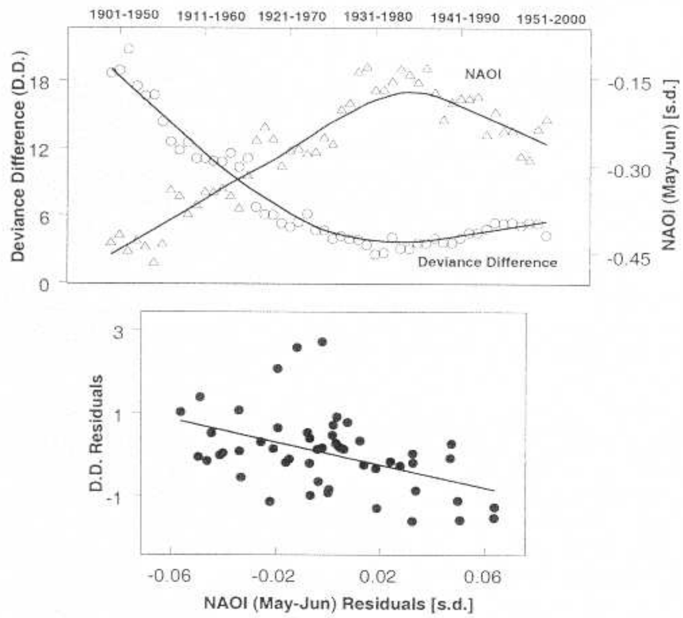

Figure 3. (a) Time-series plots of the deviance-difference values from moving Poisson regressions and the May-June NAOI averaged in 50-year overlapping intervals. The nonlinear trend line is from a locally weighted kernel smoother having a span of 75% of the data. (b) Scatter plot of the residuals from the nonlinear trend lines in (a). The straight line represents the linear least-squares regression fit to the points.

the North Atlantic during a given season, and (2) Factors that control where the hurricanes will likely track upon formation. ENSO is responsible for factors that contribute to hurricane formation and development, and thus the overall quantity of storms. When the equatorial Pacific is cooler than normal more hurricanes occur over the Atlantic, which increases the probability that the United States will get hit. Yet climate conditions can be such that the storms that form tend to steer clear of the U.S. coastline. *Elsner et al.* [2000], using historical and geological data [e.g., *Liu and Fearn*, 2000], suggest that sea-level pressure variations over the North Atlantic are responsible for routing strong hurricanes. In particular, when the North Atlantic oscillation (NAO) is characterized by an intensified Icelandic low there tends to be a greater threat of a major hurricane along the mid-Atlantic coast to New England (North Carolina to Maine). An NAO index (NAOI) is defined as the normalized pressure difference between the Azores and Iceland. When NAOI values are positive the North Atlantic subtropical high tends to be stronger and located over the eastern part of the ocean basin allowing hurricanes to recurve northward generally away from the United States. The situation is complicated by the fact that recurving hurricanes will, at times, strike the U.S. northeast.

Values of the NAOI, as calculated from Gibraltar and a station over southwest Iceland [*Jones et al.*, 1997], are obtained from the *Climatic Research Unit.* The values are first averaged over the pre- and early-hurricane season months of May and June. This is a compromise between signal strength and timing relative to the hurricane season. The signal-to-noise ratio in the NAO is largest during the boreal winter and spring, whereas the U.S. hurricane season begins in June. Fifty-year running means are computed and compared to the deviance-difference values from the running regression [Fig. 3(a)]. There is an obvious out-of-phase relationship. The nonlinear trend lines indicate that during earlier periods when the NAOI was low the strength of the ENSO-hurricane relationship was strong, whereas during later periods when the NAOI was higher the relationship was weak.

In order to make more meaningful comparisons it is necessary to remove the nonlinear trends in both time series using a local weighted smoother. A scatter plot of the relationship after the trends are removed is shown in Fig. 3(b). The ordinary least-squares regression line indicates a significant negative relationship (p-value on the regression slope $= 0.0008$). This analysis provides evidence for the NAO as an additional important factor in explaining U.S. hurricane activity on the decadal scale after accounting for ENSO.

5. Conclusion

ENSO influences hurricane formation through variations in upper-level vertical shear of the horizontal winds. The occurrence of hurricanes on the coast, however, is a function of their frequency *and* their tracks. While ENSO explains a portion of U.S. hurricane variability associated with hurricane frequency, it appears that the NAO is responsible for a portion of the variability associated with their tracks. The physical explanation of the NAO-U.S. hurricane connection is based on the positioning of the subtropical high [*Elsner et al.*, 2000; *Liu and Fearn*, 2000]. A negative NAOI is associated with a subtropical high that is weaker and displaced farther to the south and west. Under these conditions, hurricanes that form over the open waters of the North Atlantic get steered westward in the direction of the United States. Westward moving, straight tracking hurricanes are likely threats the United States south of approximately 35°N latitude. The correlation between the NAOI and the seasonal number of hurricanes making landfall from Texas to South Carolina is -0.273. The situation for understanding overall U.S. hurricane activity is complicated by the fact that recurving hurricanes under a strong NAO will sometimes make landfall along the mid-Atlantic states and New England. As an example, during the period of strongest ENSO-U.S. relationship (1902–51), the mean annual number of East coast (North Carolina to Maine) was only 0.24. This compares to a mean of 0.34 (an increase in annual landfall odds of 63%) during the 1931–80 period of weakest ENSO-U.S. hurricane relationship.

Quite reasonably then, climate periods during which atmospheric conditions are favorable for low-latitude, straight moving hurricane tracks, and recurving hurricanes remaining offshore, are periods during which the ENSO-U.S. hurricane relationship is strongest, as the frequency of U.S. landfalls in this case is primarily related to the overall basin-wide occurrence of hurricanes. This apparently was the case during the first two decades of the 20th century, but not since. Results from this research provide another piece to the puzzle of hurricane climate variability.

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

B. H. Bossak, Department of Geography, Florida State University, Tallahassee, Florida 32306, USA.

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

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