Are Hurricanes Getting Worse?

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Abstract

After several destructive and deadly hurricanes in the last few years, there is growing concern that hurricanes are intensifying. Our paper examines this claim by modeling time series trends in the accumulated cyclone energy index (ACE) of tropical cyclones in the North Atlantic. We employ a linear model with regression splines that account for nonlinearity in our time series. Our model shows that predicted ACE trends downward between 1950 and 1990, upward in the 1990s, and downward again from 2000 until 2016. Based on our model, we cannot conclusively say whether hurricanes have intensified since 1950; however, we see that hurricane intensity is currently higher than average and that intensity has trended downward since 2000.

Introduction

The 2017 North Atlantic hurricane season ranks as one of the worst in United States history. Three storms—Hurricanes Harvey, Irma and Maria—together caused more than $270 billion in damage and 3,200 deaths in the United States and Puerto Rico.

In the wake of this historic hurricane season, scientists and media outlets have asserted that hurricane intensity is increasing. Our project examines the claim by studying the accumulated cyclone energy (ACE) of North Atlantic tropical cyclones.

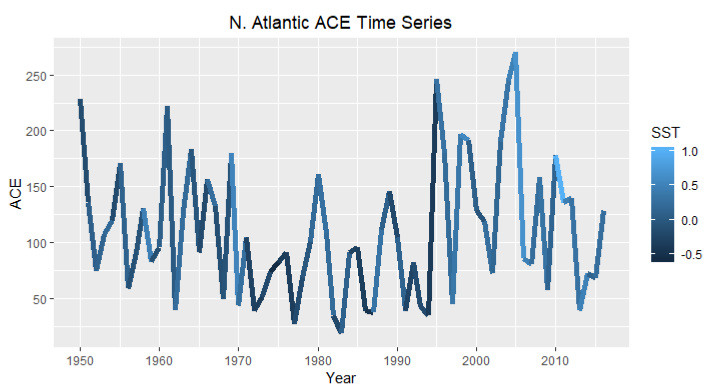

Figure 1

The ACE index is defined by Collins (2018) as

$$\text{ACE} = 10^{-4} \sum v_{max}^2,$$

where v_{max} is the estimated maximum sustained wind speed (in knots) and is calculated every six hours (at 0:00, 6:00, 12:00 and 18:00 UTC by convention). The sum is scaled down by a factor of 10000 for ease of computation. We chose this index because it is commonly used and it depicts both activity and intensity of a hurricane season in a given basin.

Our data consists of annual ACE and tropical North Atlantic sea surface temperature (SST) anomalies, both from the National Oceanic and Atmospheric Administration (NOAA) and in the years between 1950 and 2016. (At the time of this paper, the ACE for 2017 had yet to be calculated.) Both data sets have regular time intervals; thus, our data are structured as time series. An SST anomaly is a departure from mean ocean temperature. Figure 1 shows ACE and its corresponding SST anomalies. Empirically, we can see nonlinearity in our ACE data—a downward trend up until the 1980s, possibly due to Atlantic cooling, followed by an upward trend until about 2005. Figure 1 shows an overlap in Atlantic cooling and lower ACE indices. Moreover, we see a possible connection between ACE and North Atlantic SSTs: Low ACEs roughly correspond to lower-than-average SSTs, while high ACEs roughly correspond to higher-than-average SSTs.

Literature review

Many different factors can impact hurricane intensity. For example, Klotzbach (2006) found a statistically significant correlation between ACE, a measure of hurricane intensity, and N. Atlantic SSTs. Cubukcu (2000) also found both bathymetry, or ocean depth, and land-sea contrasts, to "play a role in reducing the intensity" of tropical cyclones.

Although global SSTs have been rising since the 1950s (EPA 2016), N. Atlantic SSTs have not followed such an upward trend. Consistently, neither have direct indicators of N. Atlantic hurricane intensity—*e.g.,* the power dissipation index (PDI) and the ACE. Villarini (2012) showed that both the ACE and PDI have trended downward between 1950 and 1985, and trended upward between 1985 and 2008. Klotzbach (2006) also found a significant increasing linear trend in the N. Atlantic ACE from 1986 to 2005.

In addition, Vecchi and Knutson (2008) argued that since many hurricanes before 1965 went undetected by the observing network of the day, an upward trend in hurricane intensity may not be accurately depicted by existing records. This is one reason to limit this study to only the hurricane seasons that coincide with the ACE.

Methods

We start with a linear model to indicate positive or negative trends in our time series data. Next, to determine whether there is persistence in lagged variables in our time series, we use the autocorrelation function (ACF) and determine the independence of each year in our time series. As Figure 2 shows, all the years are independent of each other, and the only highly correlated year is the current year. Thus, lags were not introduced into our model.

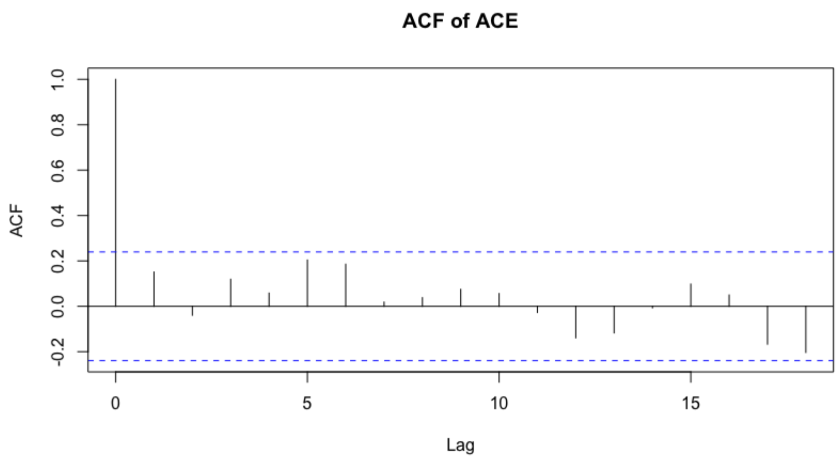

Figure 2

Moreover, given that our data has nonlinear elements, a basic linear model is rendered invalid. Thus, we introduce regression splines into our linear model. Sheather (2009) defines a regression spline as

$$(x-k)_+ = \begin{cases} x-k, & x > k, \\ 0 & \text{otherwise,} \end{cases}$$

with knot k being the joint between the two line segments. Note in Figure 3 that we set the knot to occur one year before the start of the decade; this enables us to set the first year of a new decade equal to 1.

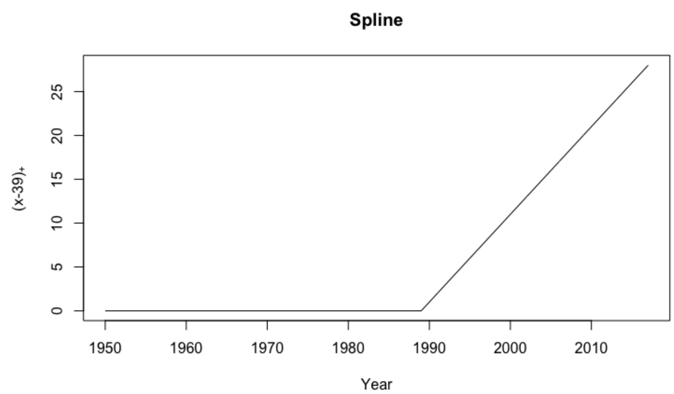

Figure 3

To select our model, we create a subset of knots in which k represents the number of years since 1950. We will then use use backward elimination and measure the significance of the knots using the Bayesian Information Criterion (BIC).

Table 1: Backward Elimination

Subset Size	Knot Location	BIC
6	9, 19, 29, 39, 49, 59	147.494
5	19, 29, 39, 49, 59	143.306
4	29, 39, 49, 59	139.134
3	39, 49, 59	135.095
2	39, 49	131.111
1	39	135.150

The lowest BIC occurs when our subset consists of knots 39 and 49. Thus, we incorporate two regression splines with knots at 39 and 49.

Model and Results

Our linear model with regression splines is given by

$$Y = X\beta + \epsilon, \text{ where}$$

$$Y = \begin{bmatrix} y_1 \\ \vdots \\ y_{67} \end{bmatrix}, \quad X = \begin{bmatrix} 1 & x_1 & (x_1 - 39)_+ & (x_1 - 49)_+ \\ \vdots & \vdots & \vdots & \vdots \\ 1 & x_{67} & (x_{67} - 39)_+ & (x_{67} - 49)_+ \end{bmatrix},$$

with $\epsilon \sim N(0, \sigma^2 I)$, β being a vector of coefficients, and Y being the log of the ACE. We choose to make the log of the ACE the response variable to better approximate linearity.

By plotting our model and a confidence band over our time series data, we see in Figure 4 that our predicted ACE trends downward between 1950 and 1990, upward in the 1990s, and downward again from 2000 until 2016.

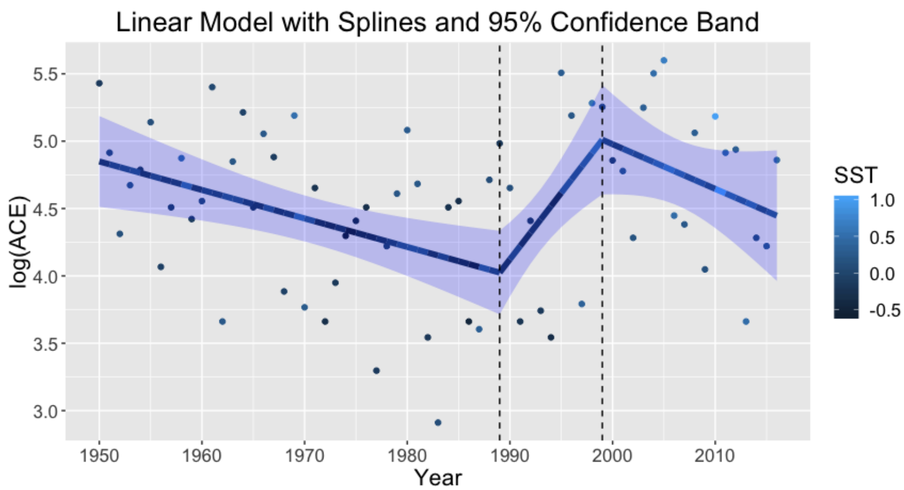

Figure 4

Table 2: Statistical Significance of Coefficients

	Estimate	Std. Error	t value	Pr(> $\|t\|$)
(Intercept)	46.0806	14.1744	3.25	0.0018
Year	-0.0211	0.0072	-2.94	0.0046
YearsM39Plus	0.1197	0.0327	3.67	0.0005
YearsM49Plus	-0.1317	0.0459	-2.87	0.0056

Next, we test our model for its validity. First, we see in Table 2 that the coefficients are statistically significant, with the largest p-value being approximately 0.0046. Second, the residuals in Figure 5 are highly scattered around the horizontal axis, showing that our linear regression model has an equality of variance. Third, the Q-Q plot in Figure 5 shows that the ACE is normally distributed, which justifies our assumptions of normality.

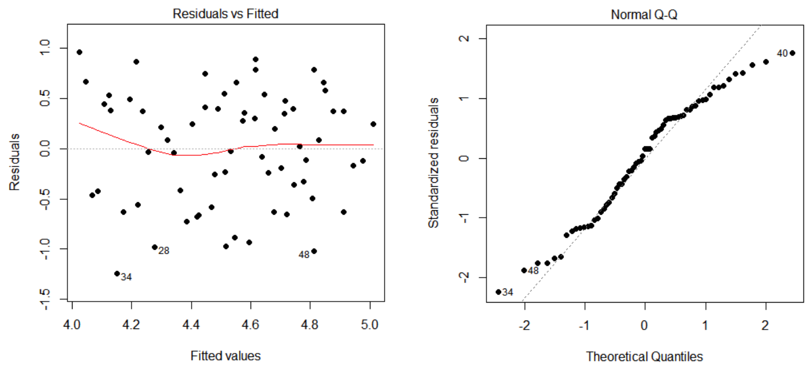

Figure 5

Conclusion

We went into this project to determine whether hurricanes in the North Atlantic have trended upward in intensity. Our model cannot conclusively answer this question. However, despite above-average hurricane intensity and unusually active seasons in the 2000s, accumulated cyclone energy has trended negatively since 2000.

That said, our model is limited in that it has shown trends in hurricane intensity but does not predict future trends. At most, our model affirms the trends we observe in our time series—decreasing between 1950 and 1989, increasing in the 1990s, and decreasing from 2000 until the present—and indicates that hurricane intensity is likely to remain above average but trend downward over the next few seasons.

Extended Studies

Sea surface temperatures are a strong predictor of hurricane intensity and are modestly correlated with ACE. Klotzbach (2006) showed a statistically significant correlation between them, and our calculations showed a correlation of 0.436 and a p-value of 0.0002. Figure 6 represents the ACE as a function of North Atlantic SSTs. Whether there is a strong fit to the data can be argued. There may be a better model than those used. If a correlation between SSTs and ACE can be established, then we can support the claim that hurricanes will eventually intensify again due to increasing global sea surface temperatures.

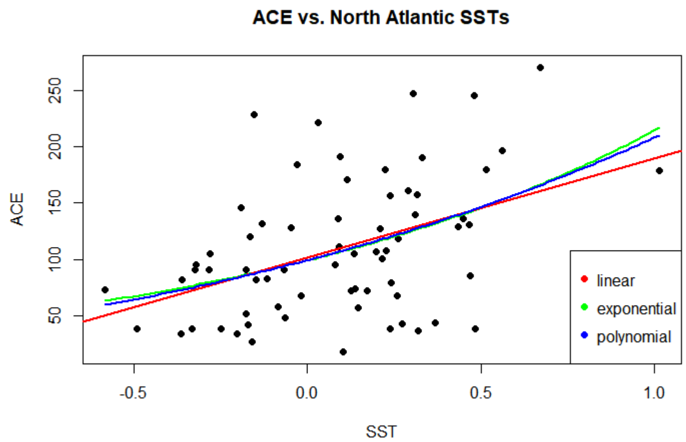

Figure 6

A similar measure to ACE is the PDI, which Emanuel (2005) defines as

$$\text{PDI} = \sum v_{max}^3,$$

where v_{max} is the maximum sustained wind speed at 10 meters above the ground. According to NOAA, PDI has decreased in recent years despite the increase in SSTs in the North Atlantic. Unlike the ACE, the PDI is not scaled down and is thus harder to compute. However, the PDI may be a better approximation of hurricane intensity, as it seems to place more emphasis on storm intensity due to the cube of the wind speed.

Another way to examine the intensity of hurricanes is to look at ACE in other basins. Klotzbach (2006) showed positive trends in ACE in the North Atlantic, North Indian, and South Indian basins, and negative trends in the Northeast Pacific, Northwest Pacific, and South Pacific basins. As in this project, we could use linear models with regression splines to model trends in hurricane intensity in other basins.

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