ARE ATLANTIC BASIN HURRICANE PROPERTIES CHANGING OVER TIME?

By

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In recent years, scientific studies have made linkages between global climate change and increasing hurricane frequency, but many of these studies have been criticized for their treatment of pre-satellite data and poor use of statistics. Additionally, existing literature focuses on hurricane frequency and the number of strong storms without considering other important hurricane properties of location, duration, intensity, and evolution time. Through the use of statistical tests (Poisson analysis, Z-test, and Kolmogorov-Smirnov test) on Atlantic Basin hurricane data via track and grid analyses, hurricane properties were closely examined. Strong multidecadal variability with defined waveforms was found to exist in hurricane frequency and spin-up times. While hurricanes were not determined to be increasing over time, the relative frequencies of strong hurricanes and the duration of strong storms appear to be increasing. Due to the incompleteness and short time period of reliable hurricane data, more data are necessary to better understand hurricane trends.

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INTRODUCTION

In the film "An Inconvenient Truth," Al Gore asserts that the number of Category 4 and 5 hurricanes has doubled in the past thirty years. Indeed, the film emphasizes the link between hurricanes and greenhouse gas emissions with its promotional image: the smoke emanating from the smokestack forms a satellite image of a hurricane. While this claim seems probable particularly with the film's debut just months after the news-making 2005 Atlantic hurricane season with Hurricanes Katrina and Rita among others, a growing number of scientists are reexamining the suggested link between global climate change and hurricane frequencies and intensities.

Hurricane properties include hurricane frequency, duration, location, intensity, and evolution time[1] and their changes over time. After the anomalous 2005 hurricane season, there was an influx of articles and research linking hurricanes and climate change. Unfortunately some of these articles do not rely upon robust, defendable statistics to make these linkages; although it may be effective to utilize scare tactics to encourage sustainable lifestyles that minimize contributions to global climate change, it is problematic if the science and statistics backing these claims are inaccurate. This project of analyzing historical hurricane tracks and spin-up times will help substantiate claims for what the storms mean for the future. With other scientists basing these links between global climate change and increased hurricane frequency and intensity on inadequate science, it allows global warming skeptics to stem further arguments regarding the validity of any claims made regarding the need for sustainability.

[1] Kossin 2007.

In addition, by applying more robust statistics and grid analysis to hurricanes, predictions and risk factors can be more accurately estimated. There are many social implications involved with these risk calculations. With a better understanding of the risks involved in certain Gulf Coast regions, for example, people will be able to better prepare for hurricane systems. Those who are most vulnerable to hurricanes are generally people who are already most economically and socially vulnerable: the poor and other marginalized individuals, specifically people of color. Thus, a more thorough understanding of hurricanes and their trends over time may help residents better prepare for hurricanes and minimize the damage and harm inflicted upon the disadvantaged.

To supplement existing studies on hurricanes, new statistical analyses on the official North Atlantic hurricane dataset were performed in efforts to answer the following questions for hurricanes in the Atlantic Basin from 1900-2007. Most current literature only address the first two questions.

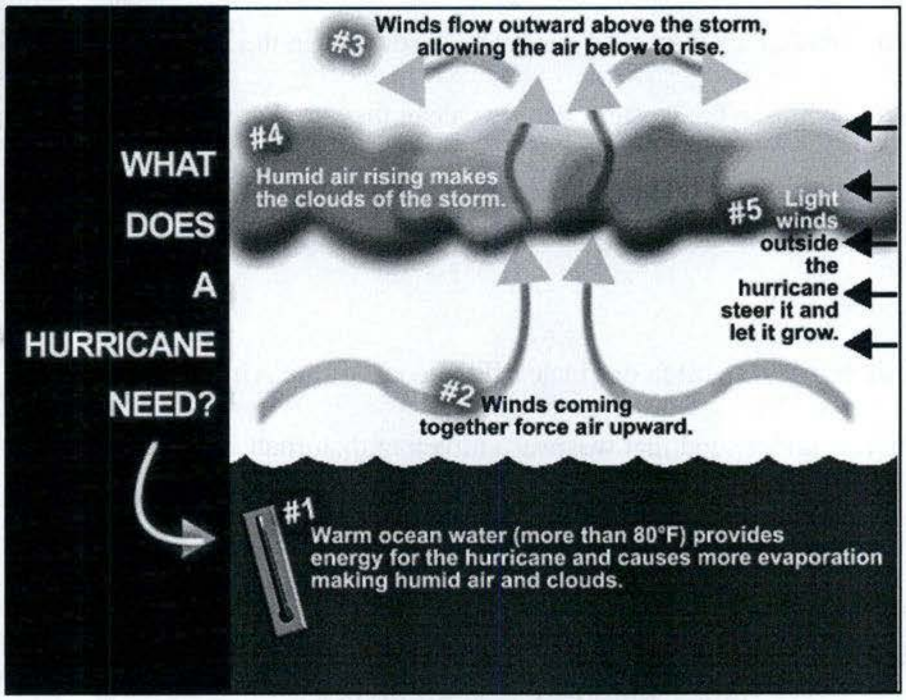
- Is hurricane frequency increasing with time?
- Is the frequency of strong (Category 4 and 5) hurricanes increasing with time?
- Is there evolution in hurricane spin-up times?
- Are there noticeable geographical shifts in Category 4 and 5 hurricanes over time?
- Are duration times of strong hurricanes increasing?
- Are hurricanes appearing in areas they historically did not frequent?

BACKGROUND

Hurricane Mechanics

Hurricanes are intense low-pressure systems that sustain high wind speeds. They develop over warm water (usually requiring at least 26.5°C), which fuels the cyclonic activity by allowing sufficient evaporation of water. When this water vapor rises in the air, it cools down as it goes up in elevation. The cooling causes the water vapor to condense, which in turn releases the latent heat that was used to evaporate the water in the first place. This energy and the Coriolis Effect, in which the earth's rotation causes particles of air to be deflected as it moves across the earth's surface, combine to produce a rotational force. **Figure 1** shows the process of hurricane formation.

Figure 1 Hurricane Formation[2]



[2] *Windows to the Universe*, University Corporation for Atmospheric Research.

Tropical disturbances are the first stage in the tropical cyclone life cycle, and they consist of a system of clouds and thunderstorms that show slight circulation and rotation without the presence of closed isobars or enclosed low-pressure systems.[3] These tropical disturbances can then develop into tropical depressions, in which there is at least one closed isobar. Tropical depressions are usually assigned a number, as the systems are not named until later stages of development. Tropical depressions have maximum surface wind speeds of 38 miles per hour, and when they continue to intensify and strengthen they develop into a tropical storm. Tropical storms are officially assigned names when the wind speeds are between 39 and 73 miles per hour. Once tropical storm wind speeds exceed 73 miles per hour, they are upgraded to hurricanes, typhoons, or tropical cyclones, depending on which part of the world the system exists. Tropical cyclones are known as hurricanes in the North Atlantic and the Gulf of Mexico while in the western Pacific Ocean they are known as typhoons.[4] When they exist off Australia or in the Indian Ocean, tropical cyclones are referred to as cyclones.[5]

Atlantic Basin hurricanes often originate off the coast of the African continent. Specifically, it is understood that westward traveling disturbances in the lower

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[3] Isobars are lines that connect points with the same atmospheric pressure. When isobars are closed, they enclose regions that have either higher or lower pressures than the surrounding areas. In the case of tropical depressions and hurricanes, enclosed regions have low pressure. Smith 2006:223-4.

[4] Smith 2006:225.

[5] Smith 2006:223.

troposphere[6] serve as "seedling" circulations for a large percentage of tropical cyclones over the North Atlantic Ocean[7]. Now known as African easterly waves, these disturbances have been established to originate over North Africa[8]. The mechanisms for these waves are generated by instabilities in the African easterly jet[9]. This jet results from a reversed temperature gradient over western and central North Africa in the lower troposphere when warmer temperatures over the Saharan Desert contrast with substantially cooler temperatures along the Gulf of Guinea coast.

From April or May until October or November, these easterly waves move toward the west across the Atlantic Ocean in the tradewind flows of the lower troposphere. The waves typically have a period of three or four days and a wavelength of 2000-2500 km[10], although the waves behave more as convectively active troughs along an extended wave train. While approximately sixty easterly waves are generated over North Africa each year, the number of waves formed does not appear to be correlated with the amount of tropical storm activity in the Atlantic Basin each year. About 60% of Atlantic tropical cyclones originate from easterly waves, but these waves account for 85% of the intense hurricanes[11]

Natural decadal variations may play a role in hurricane properties as well. The Atlantic Multidecadal Oscillation has a waveform with high and low cycles that are

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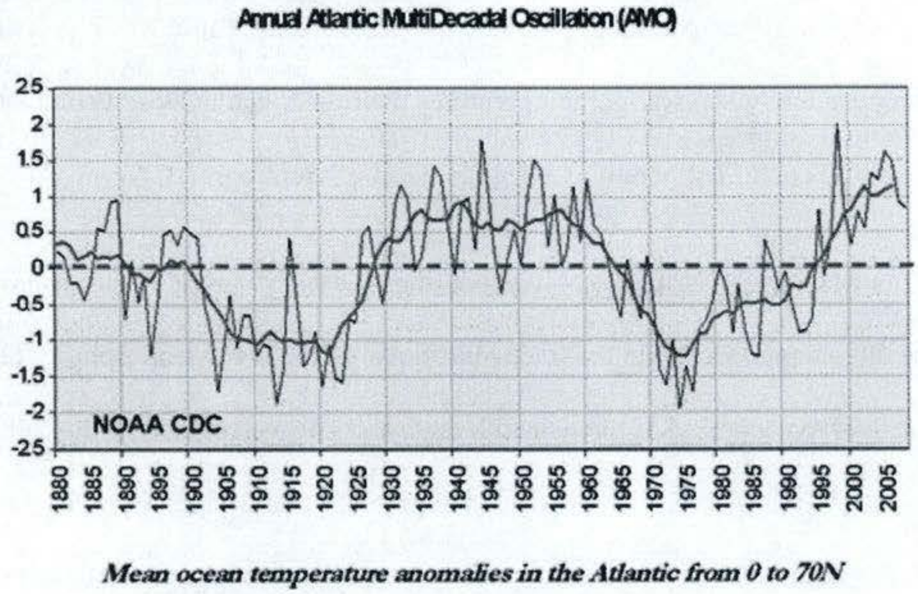
[6] From the ocean surface to about 5 km.
[7] Dunn 1940.
[8] Riehl 1945.
[9] Burpee 1972.
[10] Burpee 1974.
[11] Landsea 1993.

primarily expressed by changing sea surface temperatures (see **Figure 2**). Some scientists believe recent hurricane trends of increased hurricane activity largely result from this multidecadal oscillation[12].

Figure 2 Atlantic Multidecadal Oscillation[13]



The most common measurement of hurricanes is the Saffir-Simpson Hurricane Scale. This scale is an intensity-based rating of hurricanes, split into five categories: 1-5, based on certain wind speed ranges (see **Figure 3**). Because hurricanes typically build up their intensity with time, their Saffir-Simpson category often changes as they develop. Category 1 hurricanes are the least intense, with wind speeds of 74-95 miles per hour, while Category 5 hurricanes have winds greater than 155 miles per hour. The infamous Hurricane Katrina achieved a Category 5 with top wind speeds of 175 miles per hour.

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[12] *NOAA Magazine* 2005.

[13] National Oceanic and Atmospheric Administration, Climate Diagnostics Center.

Figure 3 Saffir-Simpson Hurricane Wind Scale[14]

Saffir-Simpson Scale	Category 1	Category 2	Category 3	Category 4	Category 5
Wind Speed (mph)	74 - 95	96-110	111-130	131-155	>155

Storm Tracking History

Hurricane detection relies heavily upon technological advances. Thus, the completeness of hurricane data varies with time and available detection methods. Prior to the development and active use of radio in 1910, the only sources of hurricane observation were landfall records and ship logs[15]. As a result, some storms were inevitably undetected while other storms that moved through shipping lanes and were observed by multiple ships had highly detailed records. It is important to note, however, that despite some storms that were undetected in this pre-radio era, without storm forecasting capabilities, ships likely more frequently crossed paths with storms[16]. Additionally, by using sulphur emissions as a proxy for ship density in oceans, major shipping lanes can be inferred, and these are located where most hurricanes tend to exist (see **Figure 4**). Thus, while there may have been some storms that were undetected, in terms of large storms and those that lasted longer, this number is likely small.

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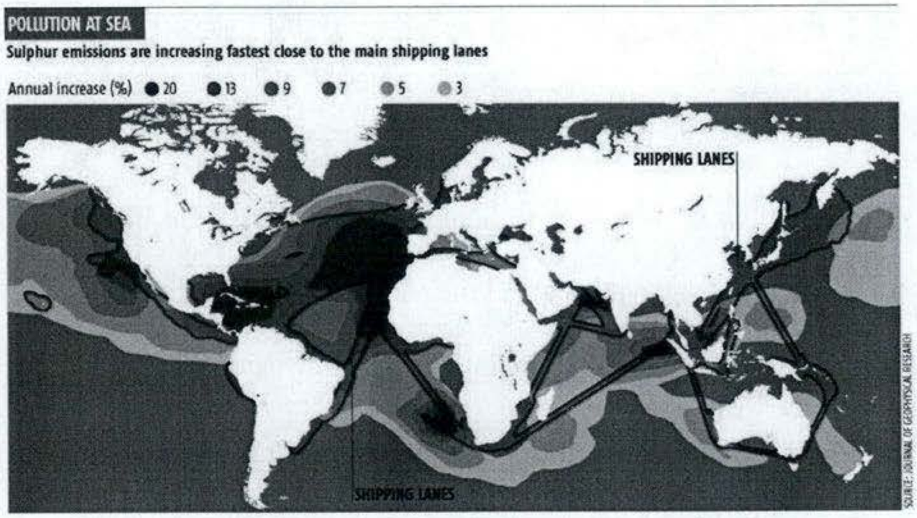
[14] National Weather Service: National Hurricane Center.
[15] Jarvinen 1988.
[16] Jarvinen 1988.

Figure 4 Sulphur emissions as proxy for shipping lanes[17]



With the use of radio technology after 1910, ships detecting storms contacted the mainland using wireless telegraph, and this message would be relayed to other nearby ships. With a radio network system, the records became more complete, as only storm systems that occurred very far from shipping lanes and that never reached land would be omitted from observation records.

Shortly after the end of World War Two, radar started to be used for storm detection. This allowed the detection efficiency of storms to approach 100%, thereby eliminating the issue of hurricane data incompleteness after 1950. With the advent of weather satellites in 1960, which continues to be used today for hurricane detection, more detailed storm observations have been made with visible and infrared sensors.

Due to the incompleteness of data before 1950, correction coefficients can be estimated to account for the actual number of storms. To correct and adjust errors in historical data, the National Oceanic and Atmospheric Administration (NOAA) has an

[17] *Journal of Geophysical Research*

ongoing Atlantic hurricane reanalysis project. This reanalysis project updates and adds information to data on historical hurricanes, and revisions are made to the official hurricane database for the Atlantic Basin, HURDAT. The most recent reanalysis revised data from 1921-1925[18].

Past Studies

Some scientists argue that warmer oceans caused by global climate change will increase the fuel available for hurricane formation in the future. Many of these analyses focus on warmer sea surface temperature in the Atlantic, but due to most intense hurricanes originating off the coast of Africa, these temperatures would not affect the number of hurricanes formed. Rather, the elevated sea surface temperature would cause amplification of already formed hurricanes.

Furthermore, global climate change will result in more than just increased sea surface temperatures. Other patterns are also expected to change and may result in phenomena such as increased shearing winds. Quinn Shiermeier, author of "Hurricanes are getting fiercer," asserts that shearing winds suppress cyclonic rotation in storms, thereby suppressing the formation of hurricanes.[19] While wind shear does not influence highly developed storm systems, shear does affect and prevent storms from fully developing.

There exists much debate in scientific articles regarding hurricane trends and the causes behind them. One review of recently published articles recognizes that even if Atlantic hurricane intensity and frequency as well as sea surface temperatures have

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[18] Landsea 2008.
[19] Schiermeier 2008.

both increased over the past thirty years, this correlation does not imply anthropogenic causes of hurricane increase.[20] Rather, the reviewer argues that excluding increased sea surface temperature, anthropogenic changes to the climate such as increased greenhouse gas emissions should be making the tropical environments less favorable for intense tropical cyclones. Furthermore, this literature review addresses the issue of some studies' reliance on "poor quality data,"[21] specifically in Emanuel's 2005 publication.

Interestingly, Emanuel's 2005 *Nature* article "Increasing destructiveness of tropical cyclones over the past 30 years" is the only citation listed on the official website for "An Inconvenient Truth" in conjunction with the assertion that recent hurricane behaviors are linked to anthropogenic global climate change.[22] Much of the criticisms of studies that report increased hurricane destructiveness are skeptical of the scientific quality. Since extracting trends from a dataset requires the use of past data that may not have been calibrated or recorded in methods consistent with modern data, there are dangers of misusing the past data.[23]

In particular, the use of tropical storm data from the past poses an even greater risk of incompleteness. Since tropical storms are smaller and often more ephemeral, they are more likely to have higher rates of data incompleteness than hurricanes. Due to the

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[20] World Climate Report
[21] World Climate Report
[22] http://www.climatecrisis.net/thescience/
[23] Atmospheric researcher Judith Curry has been criticized for using different and inconsistent protocols to conclude that doubling of category 4 and 5 storms in size and proportion since 1970 has occurred. Schiermeier 2008.

noisy nature of environmental data, when incomplete data are incorporated, trendlines and trends grow meaningless due to the large ranges of error. In addition, hurricanes are more significant because they have greater societal consequences than tropical storms. Thus, a focus on hurricanes is both more practical and more effective.

Existing hurricane studies often focus on frequencies and numbers, without much regard to other factors. Due to the significant financial damage caused by hurricanes, there are many studies focusing primarily on hurricane landfall statistics. Climatologist Kevin Trenberth argues that there should be more discussion about the intensity, duration, and size of hurricanes.[24] Therefore, the use of grid analysis and track analysis to assess trends of hurricane properties over both time and space will serve to supplement existing studies in storm frequency and set the stage for future analysis.

METHODS

Data

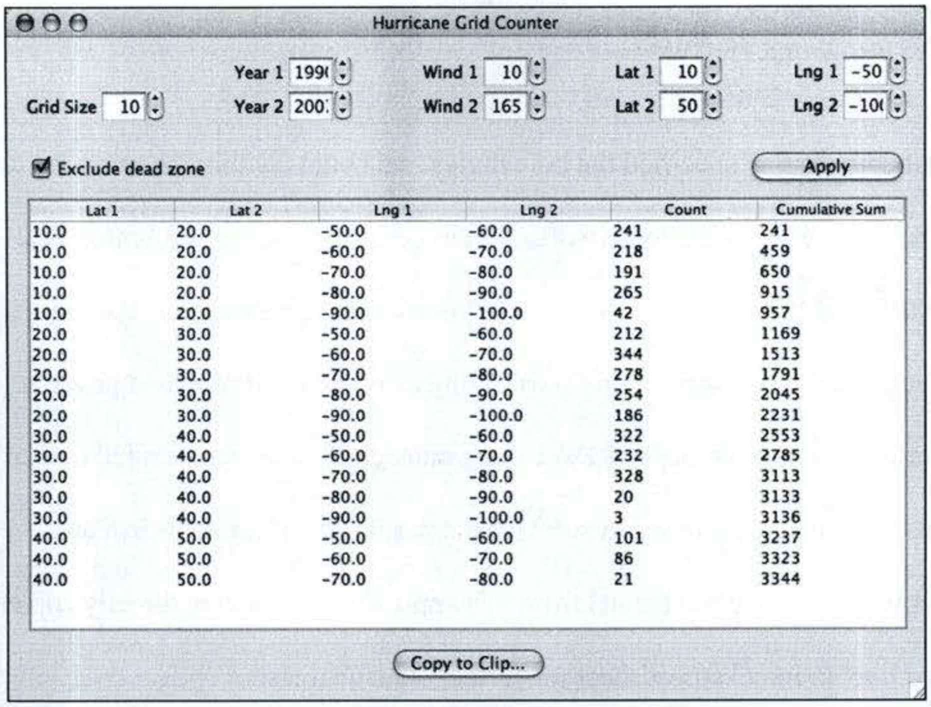
The analyses in this project were performed on data from HURDAT (HURricane DATa), a dataset initially compiled in 1984 by Jarvinen, et al. for the National Hurricane Center of the National Oceanic and Atmospheric Administration[25]. HURDAT includes all North Atlantic tropical storms and hurricanes from 1851 to the present, and contains storm track data at six-hour timesteps (0000, 0600, 1200, 1800 UTC). The track data comprises of location (latitude and longitude to the nearest tenth

[24] Heffernan 2008.
[25] Jarvinen 1988.

of a degree), wind speed, and central pressure for each storm at every timestep. The dataset also includes the maximum status of each storm during its duration (ie Category 4). Due to less advanced detection and observation, not all properties were recorded at these six-hour intervals in earlier decades, but various measured properties have remained consistent since 1970. In addition to the numerical database, visual storm tracks overlaid on maps are also available. The data are updated regularly with new hurricane seasons and through the ongoing reanalysis project.

To perform statistical analyses, the track data were exported into Microsoft Excel. Due to the enormity of data in HURDAT, a hurricane counter Java application was programmed to query specific data. This application included parameters for grid size, years, wind speeds, and latitudinal and longitudinal boundaries for which queries could be selected (see **Figure 5**).

Figure 5 Hurricane Grid Counter Application



Lat 1	Lat 2	Lng 1	Lng 2	Count	Cumulative Sum
10.0	20.0	-50.0	-60.0	241	241
10.0	20.0	-60.0	-70.0	218	459
10.0	20.0	-70.0	-80.0	191	650
10.0	20.0	-80.0	-90.0	265	915
10.0	20.0	-90.0	-100.0	42	957
20.0	30.0	-50.0	-60.0	212	1169
20.0	30.0	-60.0	-70.0	344	1513
20.0	30.0	-70.0	-80.0	278	1791
20.0	30.0	-80.0	-90.0	254	2045
20.0	30.0	-90.0	-100.0	186	2231
30.0	40.0	-50.0	-60.0	322	2553
30.0	40.0	-60.0	-70.0	232	2785
30.0	40.0	-70.0	-80.0	328	3113
30.0	40.0	-80.0	-90.0	20	3133
30.0	40.0	-90.0	-100.0	3	3136
40.0	50.0	-50.0	-60.0	101	3237
40.0	50.0	-60.0	-70.0	86	3323
40.0	50.0	-70.0	-80.0	21	3344

The grid size parameter specified the length of a cell (in latitudinal and longitudinal degrees) within the specified square grid network that was to be overlaid on the area bounded by the selected latitude and longitude boundaries. The starting and ending years provided a temporal range, and the wind speed parameters (mph) allowed for certain categories of the Saffir-Simpson Hurricane Scale to be selected. The geographical boundaries were used to limit the results to regions of the Atlantic Basin that were of interest. Additionally, there was a "dead zone" exclusion function that was built into the application. As the geographical boundaries were limited to a rectangular shape, inconsequential inland areas were inevitably included, and thus the exclusion function allowed for inland masses to be excluded from the grid result outputs. One predefined excluded region was between 31.31°N and 90°N and between

81.78°W and 180°W; a second exclusion region was between 39.23°N and 90°N and between 75.72°W and 180°W.

The output data display specified the boundaries and counts within the temporal range for each grid in the created grid network. As the grid network was calibrated to always begin at 90°S and 180°W, a few rows and columns in the grid near the queried geographical boundaries were sometimes trimmed from their designated grid size. Consistent with the format of HURDAT track data, each count represented one six-hour timestep in which there was a storm in the particular grid, rather than an individual storm. The output results from this application were then directly copied and pasted into an Excel spreadsheet for further statistical tests.

For this project, only data from 1900-2007 were used. At the time when this project commenced, the 2008 hurricane season had not yet passed, and thus 2007 was the most recent year with complete data.

Statistical Tests

The HURDAT data were analyzed to identify significant events, years, and trends in the storm data from 1900-2007. The data analyses employed three types of statistical calculations: Poisson analysis, z-test, and the Kolmogorov-Smirnov test.

Poisson analysis

Poisson statistics are used to calculate the probability of some number of events occurring within a certain unit of time, given a known average rate of the event's occurrence.[26] Poisson statistics are calculated with the following formula:

$$P_{(x)} = \frac{e^{-\lambda}\lambda^{x}}{x!}$$

$P_{(x)}$ = Probability that an event will occur *x* times
x = Integer number of events that are observed
λ = Average event rate

Poisson can only be applied with the assumption that each event occurs randomly and independently of one another. Hurricane locations are thus appropriately suited for Poisson analysis, as the trajectory of one hurricane typically does not influence where other hurricanes travel; hurricane locations are independent of one another.

Poisson was used in the grid analysis for this project to determine the probability that high event rates for certain hurricane properties would occur. By having a way to statistically assess abnormal event rates, significant anomalies in each grid could be identified with Poisson statistics. Poisson calculations have been applied to hurricanes in the past[27]; this method of grid analysis with different parameters, however, has not been performed.

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[26] Mendenhall 197-8.
[27] Wilson 1999.

Z-test

In this project, the z-test was used to compare the mean values between two samples. This test is a statistical calculation that uses the properties of a normal distribution bell curve to test a null hypothesis, which in this case was that the two samples were not significantly different. This test was performed when samples were suspected to be different; whether or not the null hypothesis could be rejected would help determine the level of the difference between samples.

To perform the z-test, the sample average and error in the mean were calculated for each sample in order to use the following z-test formula:

$$z = \frac{\bar{\chi}_1 - \bar{\chi}_2}{\sqrt{\left(\sigma_1^{\,2}\right) + \left(\sigma_2^{\,2}\right)}}$$

$\bar{\chi}_1$ = sample 1 mean

$\bar{\chi}_2$ = sample 2 mean

σ_1 = sample 1 error in the mean

σ_1 = sample 2 error in the mean

The mean was obtained by dividing the number of events of interest by the total number of events for each sample: $\chi = \frac{N}{D}$, where N = numerator (number of events of interest) and D = denominator (total number of events).

To determine the error in the mean, the respective counting errors for the numerator and the denominator from the mean calculation were first derived in order to calculate the dispersion. Counting errors for the event count and the total event count were determined by taking their respective square roots. By incorporating the counting errors, the averages for the numerator and denominator became: $N \pm \sqrt{N}$ and $D \pm \sqrt{D}$.

With these new averages, the dispersion could then be calculated. To do this, the largest and smallest possible means were determined, and the range between these two extremes was divided by two:

Largest potential mean value: $\left(\frac{N+\sqrt{N}}{D-\sqrt{D}}\right)$

Smallest potential mean value: $\left(\frac{N-\sqrt{N}}{D+\sqrt{D}}\right)$

Dispersion: $\left[\left(\frac{N+\sqrt{N}}{D-\sqrt{D}}\right)-\left(\frac{N-\sqrt{N}}{D+\sqrt{D}}\right)\right]\left(\frac{1}{2}\right)$

Subsequently, this dispersion was divided by the error in the denominator to yield the overall error in the mean:

$$\sigma=\left[\left(\frac{N+\sqrt{N}}{D-\sqrt{D}}\right)-\left(\frac{N-\sqrt{N}}{D+\sqrt{D}}\right)\right]\left(\frac{1}{2}\right)\left(\frac{1}{\sqrt{D}}\right)$$

This calculated value is thus the sigma (σ) that is required in the z-test equation.

The resulting z-value is the number of dispersion units between the two sample distributions. The larger the z-value, the more confidence there is in rejecting the null hypothesis that the two samples are the same. These z-values can also be looked up in a standard normal distribution table, in which z-values less than 3 can be referenced to identify the confidence with which the null hypothesis can be rejected. Important z-values are $z = 1.65$, in which the null hypothesis can be rejected with 95% confidence, and $z = 2.33$, in which the null hypothesis can be rejected at a 99% level.

Kolmogorov-Smirnov test

The Kolmogorov-Smirnov (K-S) test is an extremely powerful statistical test for comparing two samples or comparing a sample with its parent population. It does not require the samples to have normal distributions, as it relies on cumulative frequency distributions to determine a maximum difference between samples. Without being tied to normal distributions, the K-S test can reveal statistically significant differences between two samples that otherwise may not be statistically different with just the z-test or other tests.

The K-S test was calculated in Excel via an intermediate step of histogram plots. Using data arrays from two samples, the highest and lowest values were first determined. The histogram bin size was then selected, and bin boundaries were calculated from the lowest value to the highest value with each boundary increasing in equal increments by the specified bin size (see **Figure 6**).

Figure 6 Histogram bins

binsize	bins
2	0
	2
Maximum	4
40	6
Minimum	8
0	10
	12
	14
	16
	18
	20
	22
	24
	26
	28
	30
	32
	34
	36
	38
	40

Once the histogram bins were established, the Data Analysis tool was used in Excel in order to produce histograms and cumulative frequency distribution plots for both sample datasets. An output table was also generated, which included the bin boundaries, frequency of events at each bin, and the computed cumulative frequency percentages at each bin (see **Figure 7**).

Figure 7 Histogram outputs

Bin	Frequency	00Cumulative %
0	0	.00%
2	10	25.00%
4	15	62.50%
6	9	85.00%
8	1	87.50%
10	2	92.50%
12	2	97.50%
14	0	97.50%
16	1	100.00%
18	0	100.00%
20	0	100.00%
22	0	100.00%
24	0	100.00%
26	0	100.00%
28	0	100.00%
30	0	100.00%
32	0	100.00%
34	0	100.00%
36	0	100.00%
38	0	100.00%
40	0	100.00%

Since the bin sizes and breakpoints were shared between the two samples, the cumulative frequency percentages can be directly compared. The difference between these percentages at each bin is then calculated, and the maximum value of these differences between the two samples is designated as the Dmax (maximum distance). To determine the significance of the Dmax value, confidence levels must be calculated. If the goal is to show the two values as being statistically different with at least 95% confidence, the Dmax must be greater than or equal to the resulting value from the following equation:

$$95\% \text{ confidence} = 1.36\left(\sqrt{\frac{m+n}{mn}}\right)$$, where m = size of sample 1 and n = size of sample 2. For 99% confidence the threshold is higher;

$$99\% \text{ confidence} = 1.63\left(\sqrt{\frac{m+n}{mn}}\right).$$

Once Dmax values are calculated, the values are compared with these confidence levels to determine whether the two samples are significantly different. The larger the Dmax, the higher the likelihood that the samples are different.

Large-Scale Overview

To gain a better grasp of broad hurricane trends, graphs were first created to provide a visual representation of temporal and spatial data.

Large grid overlay

A large-scale grid network was created as a precursor to the later small grid analyses. Using the Hurricane Grid Counter, the Atlantic region was defined as the area between latitudes 10°N and 50°N and longitude 50°W and 100°W. This area was then divided into 10-degree by 10-degree square grids. Twenty grids resulted from this grid overlay, and they were assigned numbers 1-20, beginning with the southeast corner (see **Figure 8**). Since grids 18 - 20 were either entirely inland or very far north, they were omitted in this large-scale graphical representation[28].

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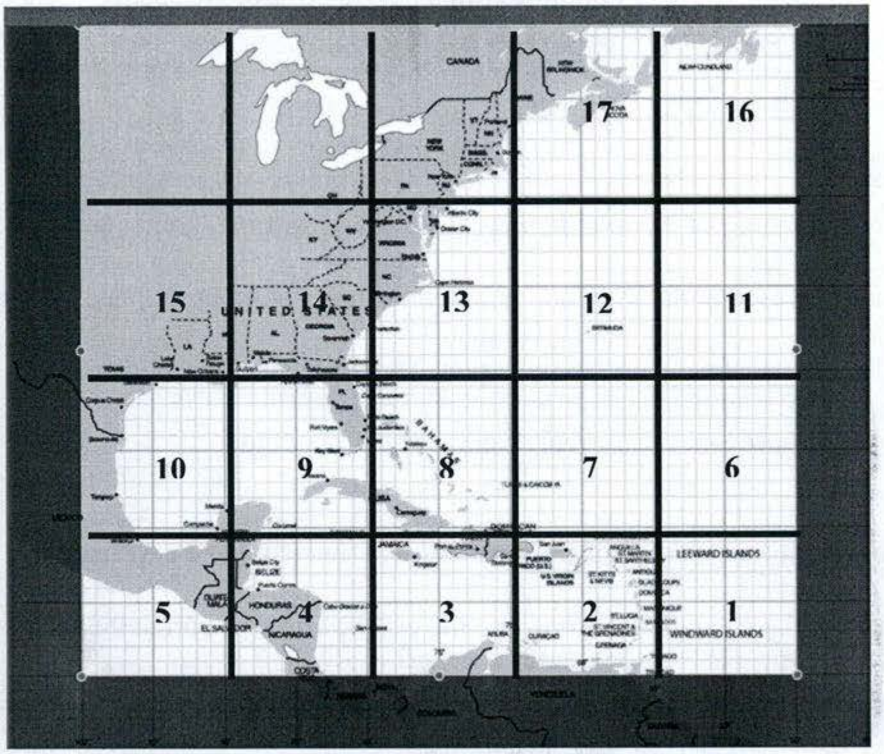
[28] Grid 15 includes portions of the Louisiana coast, and was thus included in this analysis.

Figure 8 Large-Scale Grid Network (10x10)[29]



In the Hurricane Grid Counter, the wind speed range was left at the default setting of 10mph – 165 mph to include all storms. The counter was applied once for each decade from 1900-2007[30]. For the yet incomplete 2000 decade, the time period 2000-2007 was used, and appropriate adjustments were made in later calculations.

For each grid, the number of storm counts per decade was compiled from the Hurricane Grid Counter outputs. These raw counts were then converted to relative percentages by decade; this was calculated by dividing the number of counts (measured in six-hour timesteps) per decade in the specific grid by the total decadal count in the entire Atlantic Basin region. These proportions of events that occurred

[29] Original map source: National Hurricane Center, NOAA.
[30] Decades in this project followed the pattern of 1900-1909, 1910-1919, etc.

within each grid were then graphed over the decades, and scatter plots were produced for each grid. A moving average trendline with a period of three was added to each scatter plot.

Storm count

To gain an understanding of the total number of storms over time, graphs were made to offer a visual representation. The total number of hurricanes was graphed by year and by decadal annual average on the same plot. The decadal annual average is the average number of hurricanes each year within a specific decade.

To determine whether the change in storm count over time could be explained by incomplete data in the pre-radio and pre-satellite era, a variety of correction factors were tested. The correction factors accounted for the percentage of undetected hurricanes in the earlier decades, and these factors were manipulated in attempts to achieve trends with different slopes over time. Two different correction factors were implemented: pre-1910 (before radio) and pre-1960 (pre-satellite). If the correction factors were unreasonably high in order to achieve an overall trend of no change over time, it suggests that there is an underlying systemic change that goes beyond the improvement of storm observation techniques.

Additionally, the raw numbers of Category 4 and 5 hurricanes per decade were plotted. The proportions of Category 4 and 5 hurricanes relative to the total storms in each decade were calculated and plotted as well.

With these large-scale understandings from the overview graphs, smaller-scale analyses could be performed with statistics.

Grid Analysis

Storm events vary both spatially and temporally. By creating grid networks with the help of the Hurricane Grid Counter, spatial variation could be controlled while storm properties were analyzed over time. Poisson statistics was used to identify significant decadal event rates in each grid. Similar to the procedure to create the initial 10x10 grid network, the Hurricane Grid Counter was used to establish smaller grid overlays in order to apply statistical analysis at a more local scale. After experimenting with various grid sizes, including 5x5, 3x3, 2.5x2.5, 2x2, 1.5x1.5, and 1x1, the 3x3 and 1x1 grids were selected as representative grid sizes to serve analysis needs. The previously designated Atlantic Basin boundaries (between latitudes 10°N and 50°N and longitudes 50°W and 100°W) were used.

Once the grid cells and decadal information for the 3x3 and 1x1 grids were queried and selected for in the Hurricane Grid Counter, the data were compiled for all storm events that occurred within each grid by decade. The Hurricane Grid Counter was utilized with its exclusion function, thereby excluding storm data and grids that were substantially inland.

For both 3x3 and 1x1 grid sizes, the Hurricane Grid Counter was used three times for each decade to query out 1) all storms, 2) only Category 3+ storms, and 3) only Category 4+ storms, based on wind speed ranges. Due to the relatively rare strong storms, especially when counting within small grid cells, Category 5 storms were not analyzed in these smaller grid cell networks. Poisson statistics are more effective when most grid cells have a nonzero count, so a subsequent analysis focused entirely on stronger (≥ Category 3) hurricanes through the use of larger grid sizes.

Once decadal counts for each decade were compiled for each grid cell, decadal averages were determined. Due to the current decade having only 8 years worth of data, an adjustment was made to project the 2000-2009 decadal count. The 2000-2007 data were multiplied by a correction factor of 1.25 to account for the two years without data, and the adjusted values were used for the decadal average calculations per grid. To simplify the Poisson analysis, the maximum decadal count for each grid was identified in Excel; this served as the observed event value in the Poisson statistic. Calculations were performed to determine the likelihood of these maximum counts occurring in each grid, using the decadal average for the specific grid as the expected average value. To make improbable events more apparent without the use of long decimal values, the inverse of the Poisson statistics were taken. Inverse values greater than 100 (1% chance that the event could happen based on the expected rate), as well as those greater than 1000 and 10,000 were noted. While Poisson statistics can identify abnormally high and abnormally low values, by calculating the statistic for only the maximum value per decade, the abnormally low values were disregarded. The years of these improbable events were also collected to later examine their temporal trends.

To better understand the trends of stronger storms (Category 3 and above; 111mph+), a larger-scale grid analysis was performed. Both a 5x5 and 10x10 grid network were used, and Category 3+, 4+, and 5 queries were specified for each decade and each network. With larger grid sizes, more grids would experience nonzero counts over the decades, and Poisson analysis could thus be more representative. Poisson calculations followed those of 1x1 and 3x3 grids.

Spin-Up Analysis

Threshold analysis

Spin-up data for each storm that reached hurricane status were compiled from HURDAT by decade in order to evaluate how hurricane lifetimes have evolved. Three specific spin-up characteristics were examined: the number of timesteps it took for each storm to develop from 1005mb pressure to a Category 1 status, the number of timesteps it took each storm to develop from Category 1 to Category 3, and the number of consecutive timesteps in which the hurricane remained at Category 4 or above. The threshold of 1005mb was established as a point that all storms reach before their pressures drop and they intensify as low-pressure systems to reach Category 1 status. Although the number of consecutive Category 4 and 5 timesteps is not a direct spin-up characteristic, it is connected to the overall question of how hurricane evolution has changed over time.

To generate proportions of time spent in each spin-up category relative to the total time the storm existed, the raw number of timesteps for each spin-up category was converted into a relative percentage, thereby allowing different storm systems to be directly compared: $\frac{\text{\# timesteps in spin-up}}{\text{\# total timesteps in storm life cycle}}$.

With these percentages for each storm, thresholds were determined for each type of spin-up. These thresholds, determined from visual examination of the data arrays and graphs, helped to simplify the complex spin-up data; with a threshold percentage, each decadal average is either above or below the threshold. Four different thresholds were selected for each spin-up to enable a broader range of analysis. Since the thresholds were not scientifically defined, having this range was beneficial in understanding the effects of large and small threshold values.

For the 1005mb to Category 1 spin-up, thresholds of < 0.25 (the storm spent less than a quarter of its time as a storm spinning up from 1005mb to Category 1), < 0.15, < 0.10, and < 0.075 were selected. The thresholds were maximum thresholds because there have been hypotheses that hurricane spin-up times are getting shorter. The storms that met these thresholds were counted in Excel, and these counts were later used for z-test statistical calculations.

After examining the Category 1 – Category 3 spin-up data, the same thresholds were selected, and counts were compiled by decade. For consecutive Category 4 and 5 timesteps, however, the thresholds were selected to be minimum thresholds, as the claims that hurricanes are increasing in intensity[31] would suggest longer periods of

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[31] Schiermeier 2008, Emanuel 2005.

Category 4 and 5 hurricanes. The percentage thresholds for consecutive Category 4 and 5 timesteps were thus designated to be > 0.10, > 0.20, > 0.25, and > 0.30.

Once the threshold counts for each decade and each spin-up category were organized and compiled, the data were prepared for z-test analyses in a table (see **Table 1**). Since the z-test requires an average for each decade, the number of storms reaching the threshold was divided by the total number of storms in the decade. While all hurricanes in this particular dataset reached at least a Category 1 status, not all storms reached Category 3 or above. Thus the number of storms meeting the threshold Category 1 – 3 spin-up was divided by the total number of storms that reached at least Category 3 in the decade, rather than the total number of storms that decade. The same operation was performed for Category 4 and 5 storms. This was done to prevent the many 'zero' percentages from skewing the averages, as many storms did not achieve Category 3 status.

To organize the calculations for the z-test, intermediate calculations were included in the table. The variables match the equations in the z-test methodology section.

Table 1 Z-test components

Decade	Total storms	Storms meeting threshold	% Storms meeting threshold ($\bar{\chi}$)	Counting error: N	Counting error: D	High end: range of mean	Low end: range of mean	Dispersion	Error in mean (σ)
1900	D	N	$\frac{N}{D}$	$\sqrt{N}$	$\sqrt{D}$	$\frac{N+\sqrt{N}}{D-\sqrt{D}}$	$\frac{N-\sqrt{N}}{D+\sqrt{D}}$	$\frac{\text{High end - Low end}}{2}$	$\frac{\text{Dispersion}}{\sqrt{D}}$
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮

Next, the averages ($\bar{\chi}$, the proportion of storms that meet the threshold) for each decade were plotted in a scatter plot. Different thresholds were plotted on the same graph as different series. A total of three plots were created, one for each of the spin-up categories. This was done to visually evaluate any trends over time. Once trends were suspected, the decades with notably high percentages reaching thresholds were grouped together and those with low percentages were grouped in order to analyze whether significant differences between fast and slow spin-up decades and long and short consecutive Category 4 and 5 storms exist. This grouping was done for each threshold in each spin-up category, and did not necessarily include all decades from 1900-2007. The decadal data from 1900 and 1910 were omitted from the grouping, as incompleteness in storm observations at that time may affect and skew this particular analysis.

These new decade groups were compiled, and another copy of the z-test table was generated for high and low decade compilations. The total number of storms and the number of storms that met the threshold for each decade in the decade group were added together respectively, and the subsequent table entries were completed. Then, the z-test was applied between the high and low groups for each threshold. Large z-values, particularly those greater than 2.33 to allow for 99% confidence that the two samples are not the same, were noted.

Array comparison

Using the same spin-up time percentages for each storm from the previous threshold analysis, the spin-up data were used to analyze the maximum differences between decade pairs using the K-S test. A compiled array of all data from 1900-2007 was also created to enable analysis between each decade and a long-term average. In order to build histograms in preparation for the K-S test, the inverse of the relative percentages were taken to allow the histogram bins to be integers. To analyze all possible pairs of decades, the maximum and minimum values from the entire dataset were found and set as boundaries for histogram bins. This was done so each decade would have consistent bins and output cumulative frequencies could be directly compared. Using the output histogram tables (see **Figure 7**) the Dmax values were calculated between each decade pair and between each decade with the long-term average. The 1900 and 1910 decades were not omitted in this array analysis because each decade was compared individually with another decade. The decades 1900 and 1910 were experimentally removed from the long-term average, and since the differences in the significance of Dmax values were not notable, they were kept in the long-term average calculations.

To determine the level of significance of the Dmax values, 95% and 99% confidence values were calculated between each decade pair and compared with their respective Dmax values. These confidence levels needed to be recalculated for each decadal pair because they are sample size-dependent.

Spatial Analysis

For all storms in the Atlantic Basin reaching Category 4 status or higher from 1900-2007, the storm tracks were visually examined on the UNISYS Atlantic Tropical Storm Tracking by Year website[32] to determine and record their locations when the storms first reached Category 4 status. The locations were simplified to four general regions: the Yucatán Peninsula, the Gulf Coast, East (including the east coast of the U.S. exclusive of Florida and the western Atlantic), and Florida (see **Figure 9**). These locations were generalized based on observing hurricane tracks over time, as storms typically distinctly travel one of these routes. Moreover, these are four key regions that can also provide insight into hurricane landfall.

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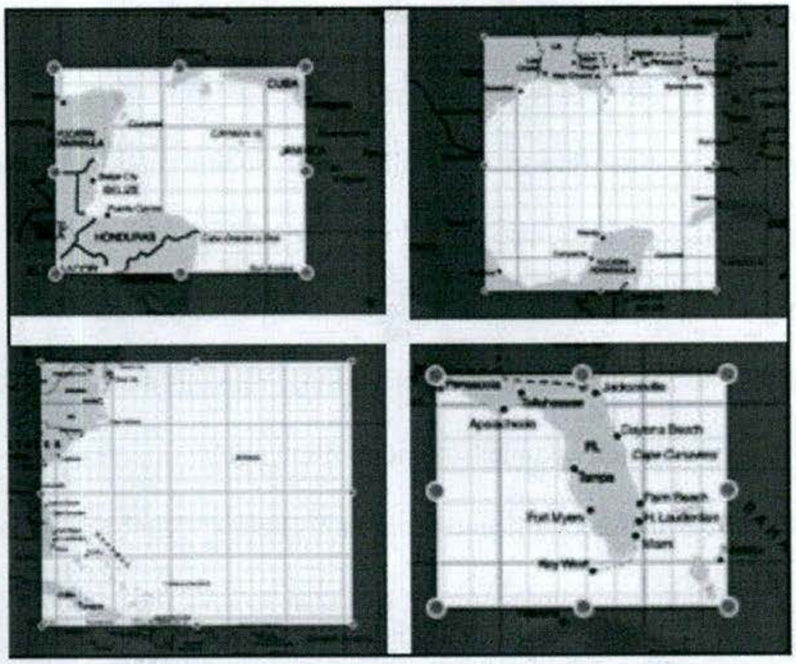
[32] These individual maps of tropical storms were compiled by the Tropical Prediction Center Best Track Reanalysis with data from Jarvinen, et al. 1984.

Figure 9 Spatial Analysis (clockwise from top left): Yucatán Peninsula, Gulf of Mexico, East, Florida



The spatial data of these Category 4 and 5 hurricanes were then compiled into decadal counts by region. Poisson statistics were applied to the 2000 decade to determine the likelihood of recent hurricane events. The 2000-2007 decade was treated both with and without the projection to the full decade, and a baseline was determined for each of the four regions, using data from 1900-1999. Additionally, for certain years with high intense storm counts in a given region, a Poisson analysis was performed for a single year, using the baseline decadal average and dividing it by ten to yield the annual average event rate. For the overall Atlantic Basin, Poisson statistics were also performed for notable decades and years for Category 4 and 5 storms.

Pressure Analysis

Since hurricanes are defined as intense low-pressure systems, central pressure values were analyzed. Since 1975, there have been central pressure records every six hours. Prior to 1975, the pressure records were sparse and irregular, so this analysis focused on the past 32 years from 1975 – 2007. The central pressure records were first compiled by year, and a histogram was created from the array of central pressure records in order to assess discontinuities in the distribution. From this distribution, a threshold of 965mb was determined as a measurement of intense storms. A new plot was then made to show the distribution of central pressures below 965mb. For these designated intense storms with central pressures of less than 965mb, the number of events per year was counted. Based on the distribution of intense storms over time, a z-test was performed comparing central pressures between 1975 – 1994 and 1995 – 2007.

RESULTS

The results from the data analyses are summarized below in the same order as they appear in the methodology.

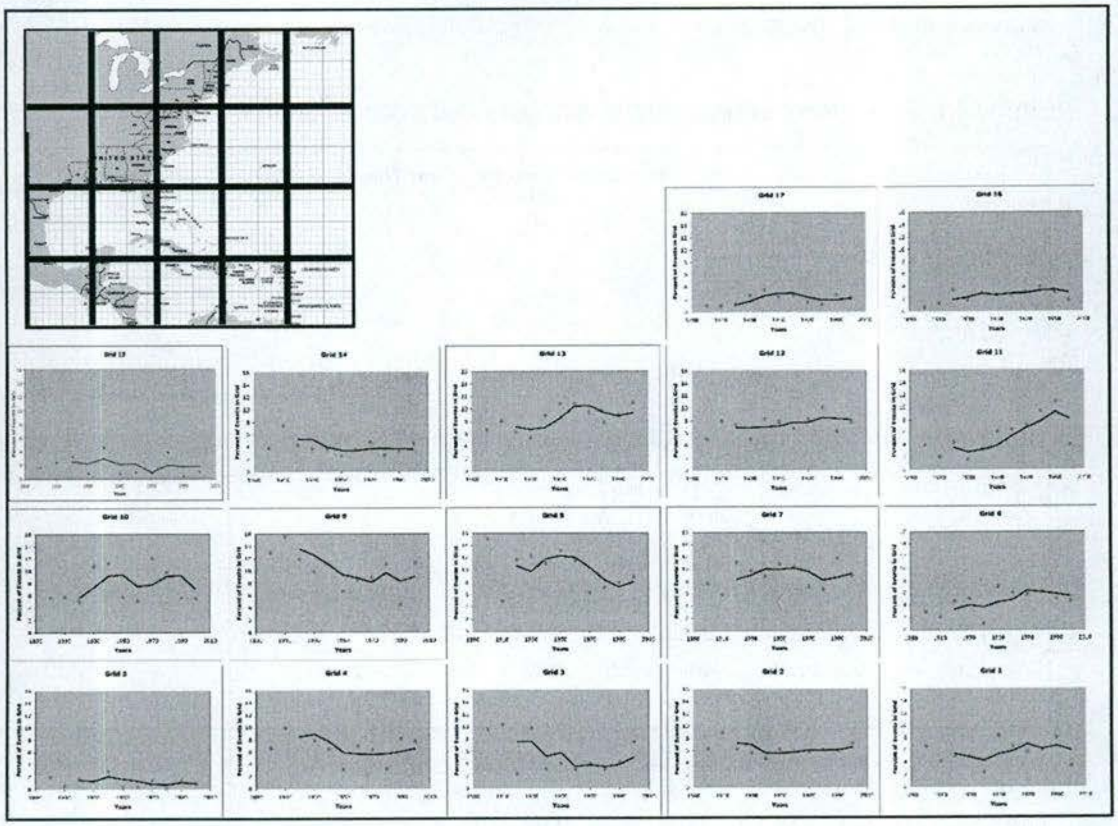
Large-Scale Overview

Large grid overlay

The large-scale grid analysis of the Atlantic basin, with 10-degree latitude by 10-degree longitude grid cells, demonstrates the spatial and temporal variability of hurricanes. As depicted in **Figure 10**, storm events are not constant over time or space.

If this were true, the proportions of storms in each grid would have remained constant, thus yielding horizontal lines with slopes of zero for each plot. However, with certain decades favoring some geographical regions over others, this graphical overview demonstrated the need for further analysis.

Figure 10 Proportion of hurricanes in specified grid per decade

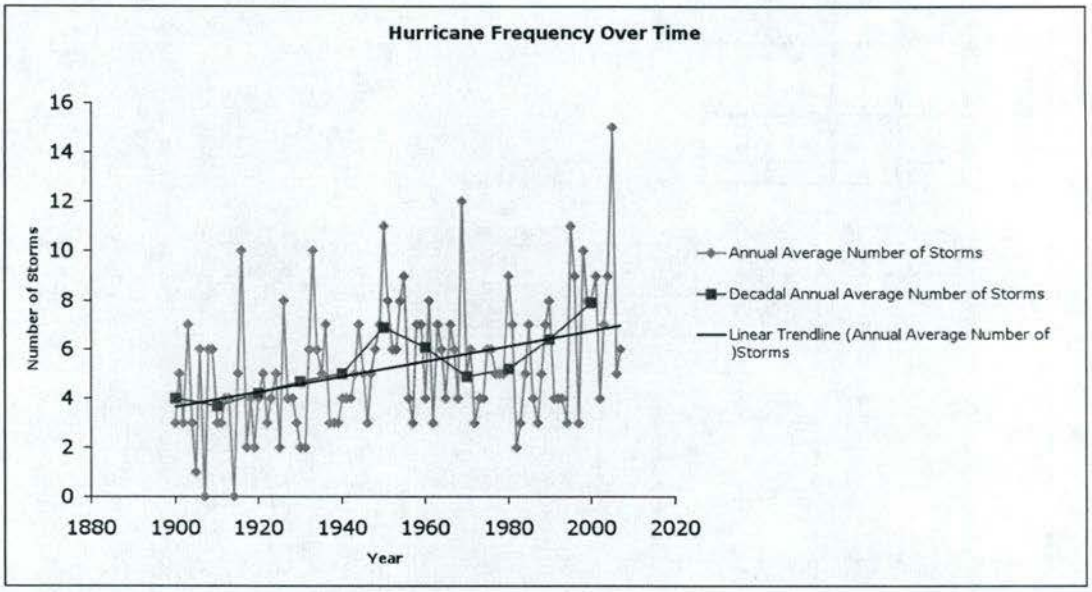


In **Figure 10** the 10x10 graphs are arranged spatially to represent their geographical location based on the inset grid network. The x-axis on each grid shows the decades from 1900-2007 and the y-axis shows the proportion of hurricane storm counts that occur within the grid for each particular decade. The axes are at the same scale for all seventeen grids, as this figure is intended to provide a quick understanding of the overall variation that exists at a temporal and a spatial scale.

Storm count

The graph of total storm count over time (**Figure 11**) displays clear interannual and interdecadal variation. The 1950s and 1960s had a high phase in storm frequencies, while the 1970s and 1980s experienced lower frequencies. The linear regression also depicts a gradual increase over time.

Figure 11 Total storm count: annual numbers and decadal annual averages



The pre-1910 data and pre-1950 data were corrected to account for missing storm data due to incomplete observations. Correction factors were exaggerated to determine how trajectories change with these adjustments. In **Figure 12** and **Figure 13** these graphs show selected correction factors for total storm count. Adjustment A) is the pre-1910 correction coefficient and B) is the pre-1950 correction coefficient; a coefficient of 1.1

means only 90% of storms were observed. Thus, multiplying pre-1910 data by 1.1 yields the potential average annual number of storms in the decade.

Figure 12 Adjusted Decadal Annual Average Storm Counts

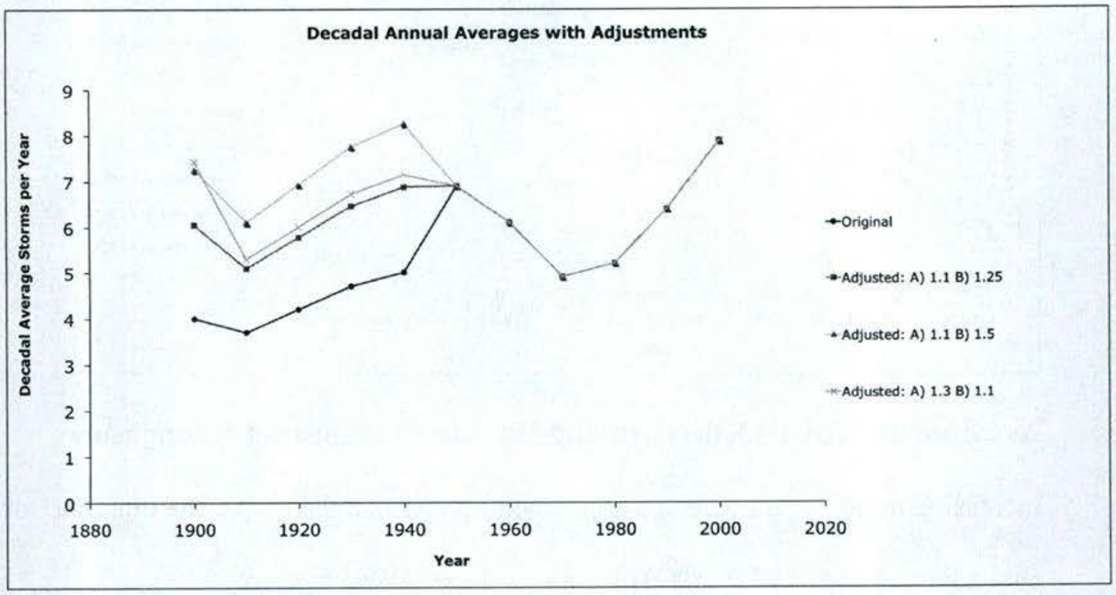
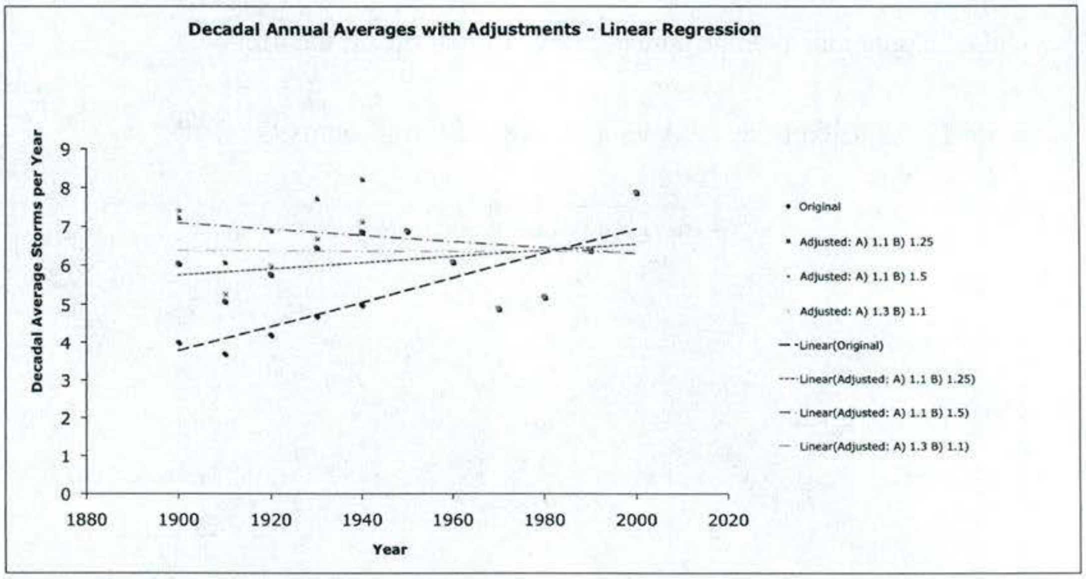


Figure 12 displays three different adjusted storm counts relative to the original uncorrected raw data. The post-1950 data are all uncorrected, as beginning with the use of satellite observation, all storms have been observed and recorded. To more clearly see the trajectories of each adjustment, linear trendlines were created for each adjustment (see **Figure 13**). The data points are no longer connected to highlight the trendlines.

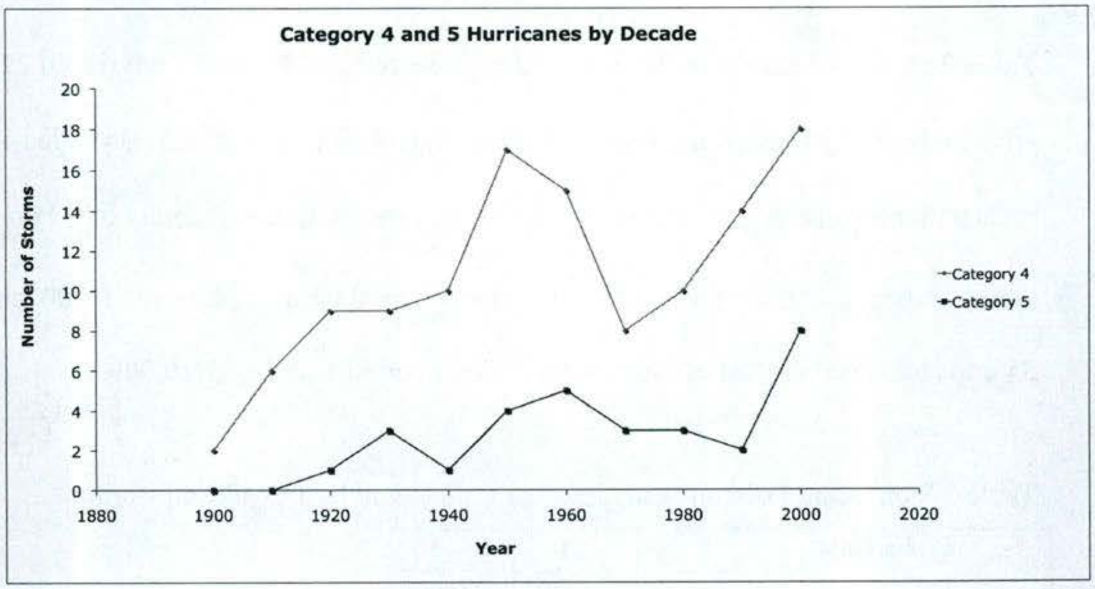
Figure 13 Adjusted Decadal Annual Average Storm Counts: Linear Regression



As evident in **Figure 13**, the three adjusted datasets evened out the originally increasing trend. Of the selected adjustments shown on the graph, the trendline for the data adjusted with A) 1.3 and B) 1.1 had a slope closest to zero.

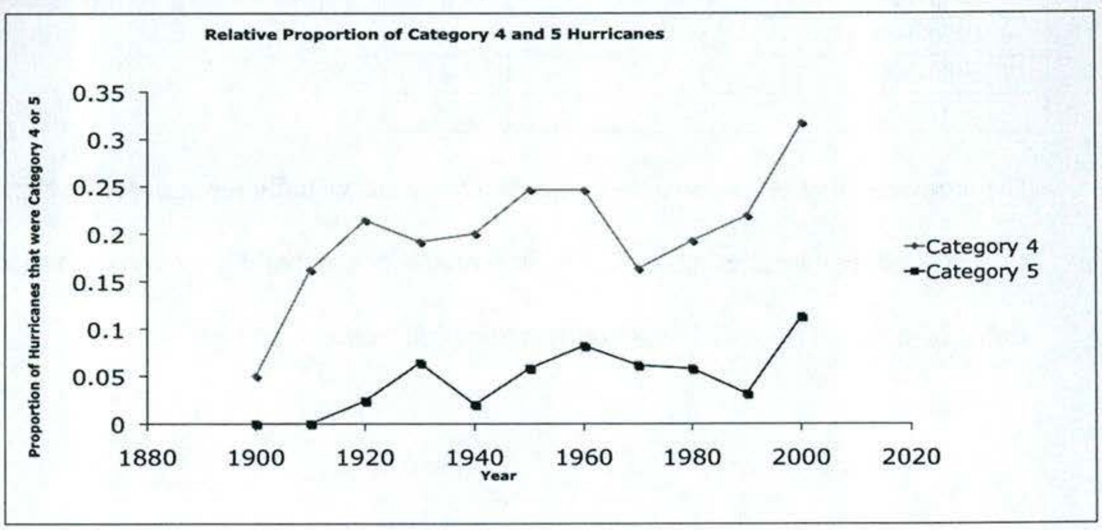
The graphs of Category 4 and 5 hurricanes per decade also demonstrate an increasing trend over time, with the number of Category 4 storms displaying a steeper increase than Category 5 storms. **Figure 14** shows the raw count of Category 4 and 5 hurricanes.

Figure 14 Category 4 and 5 Hurricanes over time



When the number of Category 4 and 5 storms are represented by proportions relative to the total number of storms per decade, similar trends exist (see **Figure 15**). The proportion of Category 4 and 5 storms appear to be increasing with time, with Category 4 storms increasing at a more rapid rate.

Figure 15 Relative Proportion of Category 4 and 5 Hurricanes Over Time



Grid Analysis

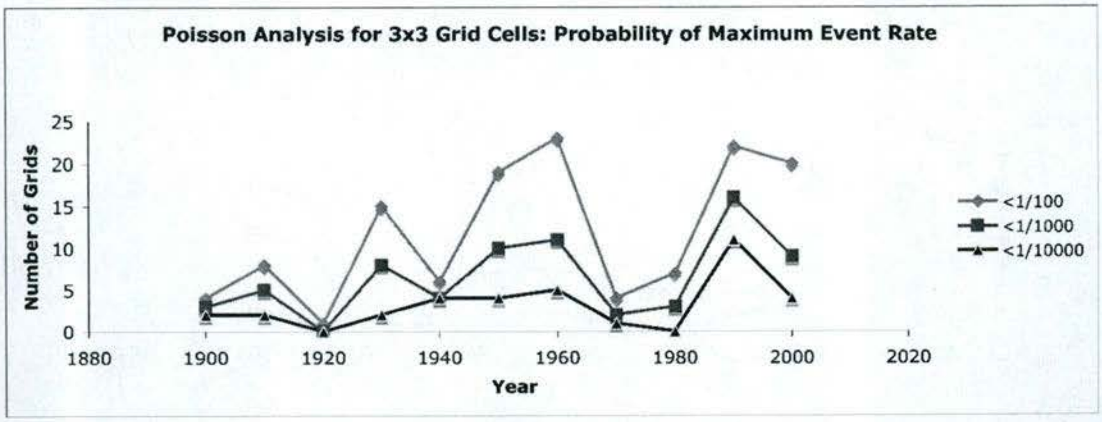
Table 2 shows the results of the 3-degree by 3-degree grid Poisson analysis. Of 210 grids in the 3x3 grid network, Poisson statistic calculations for all storms yielded 129 grids with maximum decadal event rates that occurred with a probability of ≤ 1%. Of these, 71 grids had maximum event rates that occurred with a chance of 1/1000, and 35 grids had maxima that occurred with a likelihood of less than 1/10,000.

Table 2 Significant Poisson Statistics: 3x3 Grid Count by Decade, all storms

Decade \ Probability	$< \frac{1}{100}$	$< \frac{1}{1000}$	$< \frac{1}{10000}$
1900-1909	4	3	2
1910-1919	8	5	2
1920-1929	1	0	0
1930-1939	15	8	2
1940-1949	6	4	4
1950-1959	19	10	4
1960-1969	23	11	5
1970-1979	4	2	1
1980-1989	7	3	0
1990-1999	22	16	11
2000-2007	20	9	4
Total	129	71	35

The temporal fluctuations visible in the data table are visually represented in **Figure 16**. The past two decades have rates of improbability comparable to that of the 1950s and 1960s; the 1970s and 1980s contrast this high trend.

Figure 16 Frequency of Significant Maximum Event Rates: 3x3 Grids, all storms

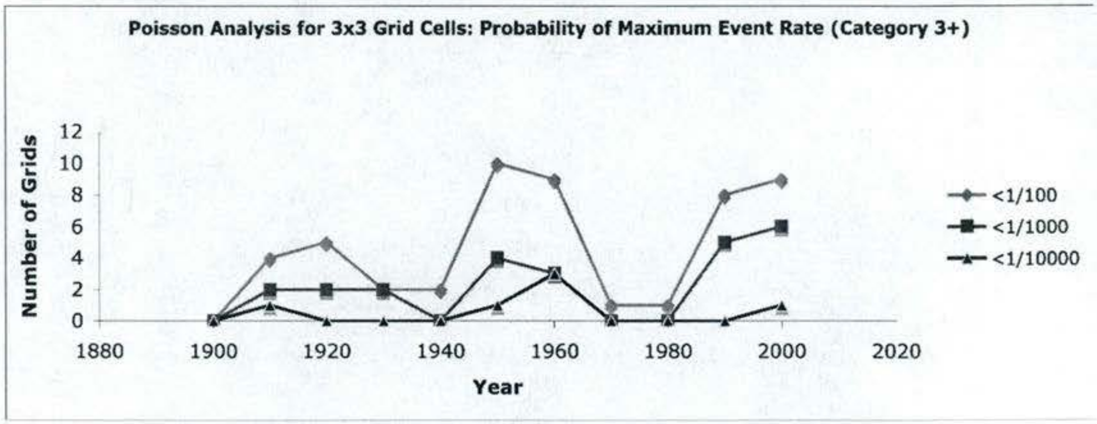


As expected, for Category 3+ and 4+ Poisson analyses at the 3x3 level, the stronger storm queries yielded proportionally more empty grid cells in each decade (see **Table 3**). Despite this, the Poisson analysis for category 3+ hurricanes by 3x3 grid still yielded decades that had notably high and notably low anomalous events, which generally correlated with the trend of overall storm events (see **Figure 17**).

Table 3 Significant Poisson Statistics: 3x3 Grid Count by Decade, Cat. 3+

Decade \ Probability	$< \frac{1}{100}$	$< \frac{1}{1000}$	$< \frac{1}{10000}$
1900-1909	0	0	0
1910-1919	4	2	1
1920-1929	5	2	0
1930-1939	2	2	0
1940-1949	2	0	0
1950-1959	10	4	1
1960-1969	9	3	3
1970-1979	1	0	0
1980-1989	1	0	0
1990-1999	8	5	0
2000-2007	9	6	1
Total	51	24	6

Figure 17 Frequency of significant maximum event rates: 3x3 grids, Cat. 3+



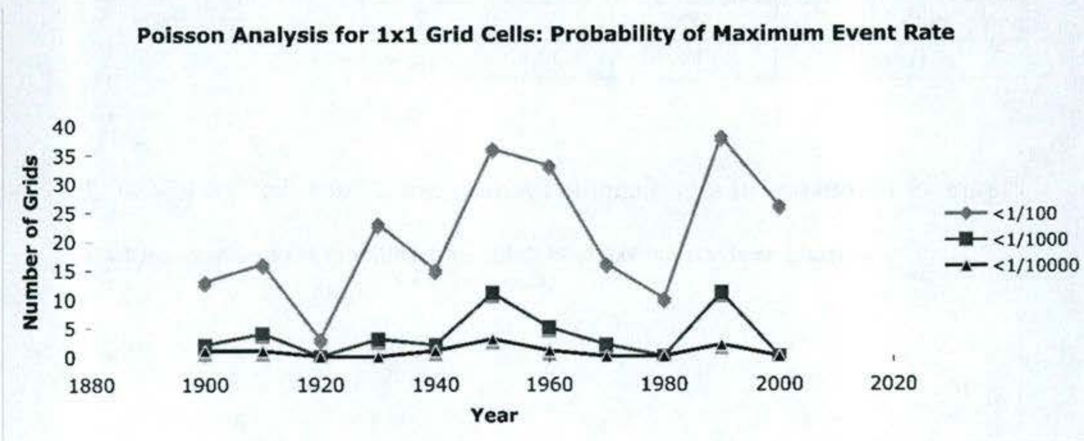
For the Category 4+ Poisson analysis for the 3x3 grids, there were even fewer significant maximum values, since most grids have zero events. Of the same 210 3x3 grids, only sixteen grids had maximum decadal events that occurred with less than 1% probability. Eight maximum values had likelihoods of less than 1/1000, and only one had a 1/10,000 probability maximum value.

Of 1598 grids in the 1-degree by 1-degree grid analysis, Poisson statistic calculations for all storms yielded 229 grids with maximum decadal event rates that occurred with a probability of ≤ 1% (see **Table 4**). Of these, 40 grids had maximum event rates that occurred with a chance of 1/1000, and 9 grids had maxima that occurred with a chance of less than 1/10,000. From the graph (**Figure 18**), the maximum event rate plot was most pronounced for probabilities less than 1%. The probabilities less than 1/10000 did not follow as notable a trend as those in the 3x3 grids.

Table 4 Significant Poisson Statistics: 1x1 grid count by decade, all storms

Decade \ Probability	$< \frac{1}{100}$	$< \frac{1}{1000}$	$< \frac{1}{10000}$
1900-1909	13	2	1
1910-1919	16	4	1
1920-1929	3	0	0
1930-1939	23	3	0
1940-1949	15	2	1
1950-1959	36	11	3
1960-1969	33	5	1
1970-1979	16	2	0
1980-1989	10	0	0
1990-1999	38	11	2
2000-2007	26	0	0
Total	229	40	9

Figure 18 Frequency of significant maximum event rates: 1x1 grids, all storms



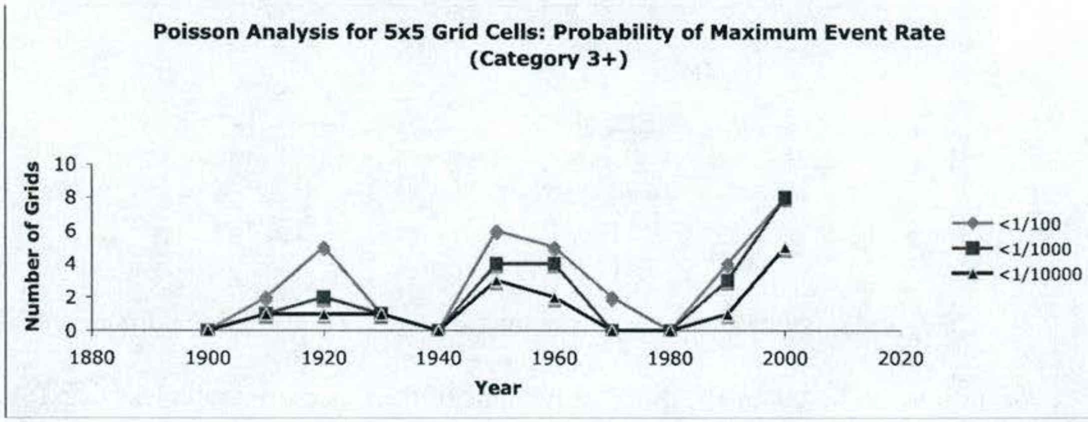
For Category 3+ storms in 1x1 grids, a total of sixteen grids had maximum values that occurred with less than 1% probability; none of these occurred with less than 0.1% probability. There were no significant events in the Category 4+ storms that had probabilities smaller than 1%.

The use of larger grid sizes enabled more clarity in the Poisson analysis. For Category 3+ storms in 5x5 grids, the distribution of improbable events over time seemed to mirror that of the smaller 3x3 and 1x1 grid overlays. (see **Table 5** and **Figure 19**)

Table 5 Significant Poisson Statistics: 5x5 grid count by decade, Cat. 3+

Probability / Decade	$<\frac{1}{100}$	$<\frac{1}{1000}$	$<\frac{1}{10000}$
1900-1909	0	0	0
1910-1919	2	1	1
1920-1929	5	2	1
1930-1939	1	1	1
1940-1949	0	0	0
1950-1959	6	4	3
1960-1969	5	4	2
1970-1979	2	0	0
1980-1989	0	0	0
1990-1999	4	3	1
2000-2007	8	8	5
Total	33	23	14

Figure 19 Frequency of significant maximum event rates: 5x5 grids, Cat. 3+



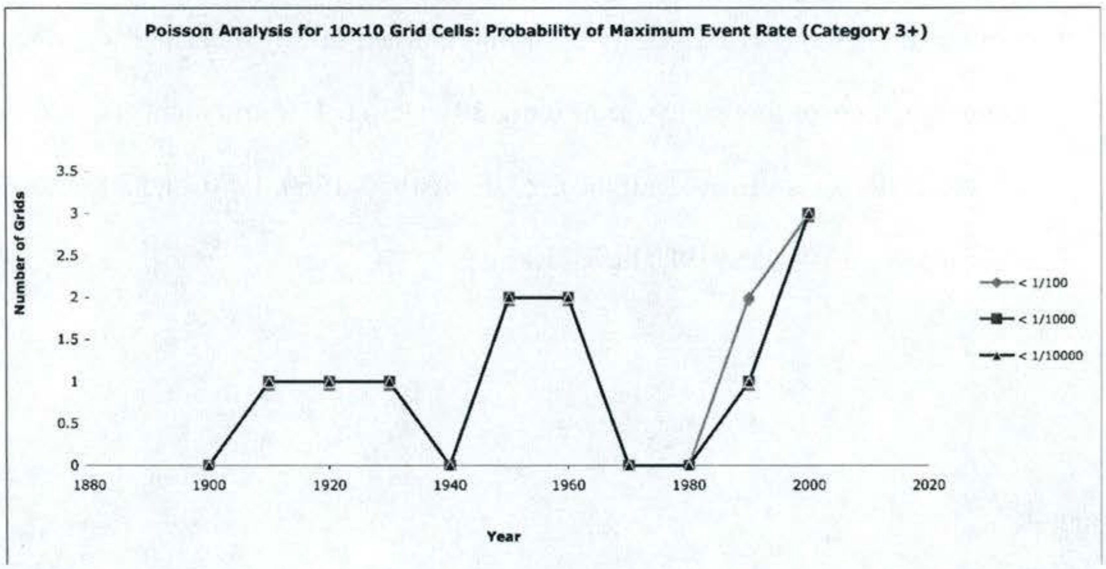
Even with grid sizes of 5x5, there were still many decades that experienced a maximum event rate of zero for Category 4 and 5 storms. With 10x10 grids, however, the Poisson analysis was more effective.

The 10x10 grids lined up with the preliminary 10x10 large-scale grids that were created for the overview. Of the seventeen grid cells of interest, twelve cells had maximum event rates for Category 3+ hurricanes that occurred with a likelihood of less than 1% (see **Table 6**). Eleven of these maxima had likelihoods of less than 0.01%, or 1/10,000. The decades of 1950-1960, as well as 1990-2007, were still relatively high in improbable events, while 1970-1980 was still fairly low. Thus, with eleven of the twelve grids that have maximum event rate probabilities of less than 1% also having likelihoods of less than 0.01%, the graph of grid frequency and the combined plot for 10x10 Category 3+ storms consists mostly of a single distribution rather than three or four series (see **Figure 20**). Despite low grid numbers, inter-decadal variation is still evident; the decades of 1950, 1960, 1990, and 2000 have high event rates and 1970 and 1980 have low rates.

Table 6 Significant Poisson Statistics: 10x10 grid count by decade, Cat. 3+

Decade \ Probability	$< \frac{1}{100}$	$< \frac{1}{1000}$	$< \frac{1}{10000}$
1900-1909	0	0	0
1910-1919	1	1	1
1920-1929	1	1	1
1930-1939	1	1	1
1940-1949	0	0	0
1950-1959	2	2	2
1960-1969	2	2	2
1970-1979	0	0	0
1980-1989	0	0	0
1990-1999	2	1	1
2000-2007	3	3	3
Total	12	11	11

Figure 20 Frequency of significant maximum event rate: 10x10 grids, Cat. 3+



Category 4+ Poisson statistics showed extremely high rates of low probability events in recent years compared to other decades (see **Table** 7). Category 5 hurricanes, however, did not display as stark a trend of highly improbable events. Only two grid cells experienced maximum Category 5 event rates with a less than 1% rate of occurrence, and only one of these cells had a rate of less than 0.1%. The cell that experienced a maximum count with < 0.1% probability saw the event in 1950; the other significant maximum event occurred in 1960.

Table 7 Significant Poisson Statistics: 10x10 grid count by decade, Cat. 4+

Decade \ Probability	$< \frac{1}{100}$	$< \frac{1}{1000}$	$< \frac{1}{10000}$
1900-1909	0	0	0
1910-1919	0	0	0
1920-1929	0	0	0
1930-1939	1	1	0
1940-1949	0	0	0
1950-1959	1	1	1
1960-1969	2	1	0
1970-1979	1	0	0
1980-1989	0	0	0
1990-1999	2	1	1
2000-2007	4	4	4
Total	9	7	5

Spin-Up Analysis

Threshold analysis

The scatter plots created to determine decadal groups displayed distinct high and low phases over time (see **Figure 21**, **Figure 22**, and **Figure 23**). The decadal groups and their respective z-values for each threshold are detailed in **Table 8**. The interdecadal variability of spin-up times is evident in the extremely high z-values.

Figure 21 Proportion of storms meeting minimum threshold: 1005mb - Cat. 1

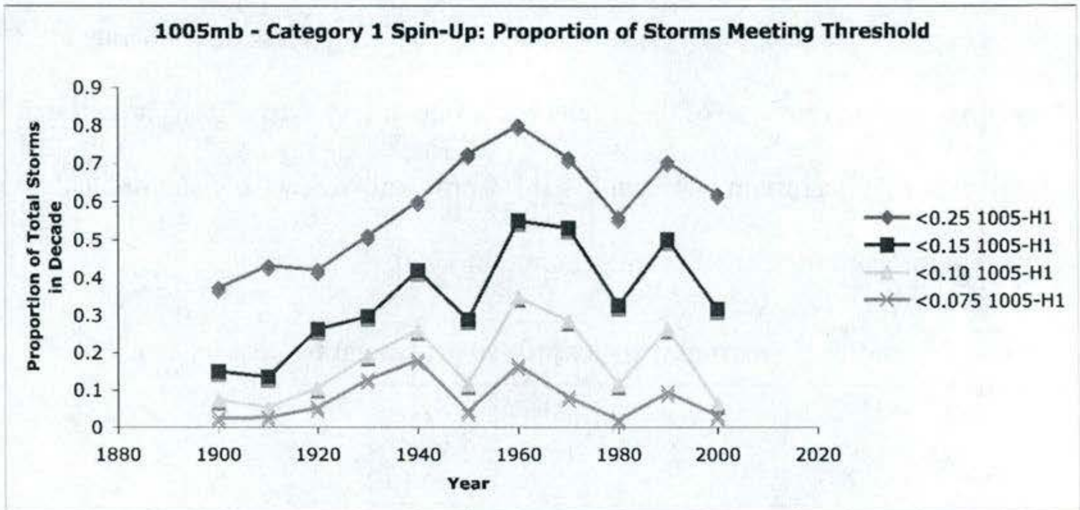


Figure 22 Proportion of storms meeting minimum threshold: Cat. 1-3

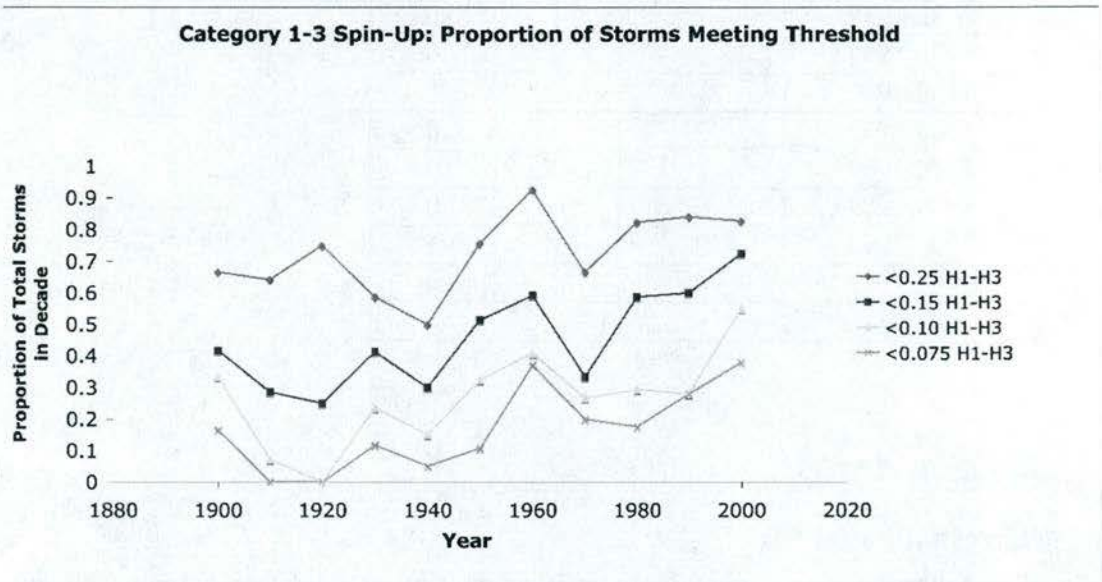


Figure 23 Proportion of Storms Meeting Maximum Threshold: Consecutive Cat. 4,5

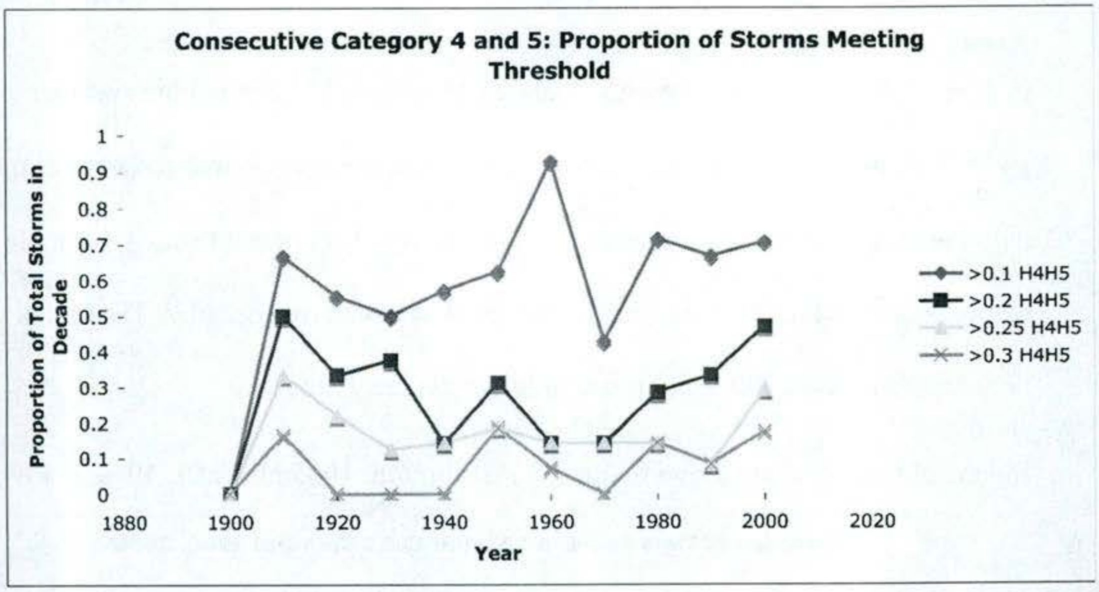


Table 8 Threshold spin-up times with decadal groups and z-values

Threshold	High Group	Low Group	Z-Value
1005mb – Cat. 1 <0.25	1950, 1960, 1970, 1990	1920, 1930, 1940, 1980	21.8
1005mb – Cat. 1 <0.15	1940, 1960, 1970, 1990	1930 1950, 1980, 2000	29.4
1005mb – Cat. 1 <0.10	1940, 1960, 1970, 1990	1930, 1950, 1980, 2000	41.1
1005mb – Cat. 1 <0.075	1940, 1960, 1970, 1990	1920, 1950, 1980, 2000	38.6
Cat. 1 - 3 <0.25	1950, 1960, 1980, 1990, 2000	1920, 1930, 1940, 1970	8.6
Cat. 1 - 3 <0.15	1930, 1950, 1960, 1980, 1990, 2000	1920, 1940, 1970	15.0
Cat. 1 - 3 <0.10	1930, 1950, 1960, 2000	1920, 1940, 1970, 1980, 1990	15.9
Cat. 1 - 3 <0.075	1960, 1990, 2000	1920, 1930, 1940, 1950, 1970, 1980	19.6
Consecutive Cat. 4, 5 >0.1	1960	1970	2.2
Consecutive Cat. 4, 5 >0.2	1920, 1930, 1950, 1980, 1990, 2000	1940, 1960, 1970	6.7
Consecutive Cat. 4, 5 >0.25	1920, 2000	1930, 1940, 1950, 1960, 1970, 1980	3.5
Consecutive Cat. 4, 5 >0.3	1950, 1980, 1990, 2000	1920, 1930, 1940, 1960, 1970	11.6

Array comparison

In general, for the K-S test spin-up analyses, the smaller histogram bin size of 1 yielded slightly more significant Dmax values than the histogram bin size of 2; thus only the results from the bin size of 1 will be reported. **Figure 24** shows a sample comparative cumulative frequency distribution between two decades. The Dmax value between 1960 and 2000 spin-up was significant (see **Table 9**).

Figure 24 Sample cumulative frequency distribution: 1005mb-Cat.1, 1960 & 1990

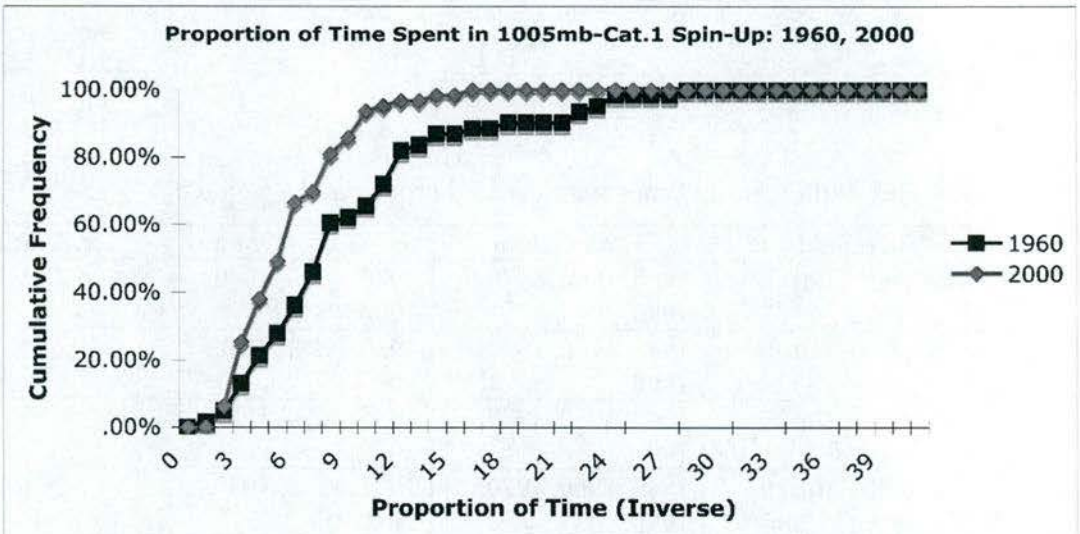


Table 9 displays the results from the K-S test, using a bin size of 1 for the cumulative frequency distribution. The number of significant Dmax values for each spin-up, based on comparisons with 95% and 99% confidence levels, is provided, as well as the decades in which these significant Dmax values occurred. The decades are listed in order from high numbers of significant values to low numbers of significant values. Each significant Dmax value is tied to two decades, as K-S tests assess the difference between two samples. The number inside the parentheses represents the number of

significant Dmax values that are associated with each particular decade. Some decades had significant Dmax values with the long-term average; although the long term average is not listed as its own decade, the significant value is included in decadal counts.

Table 9 Spin-up K-S test: Dmax summary

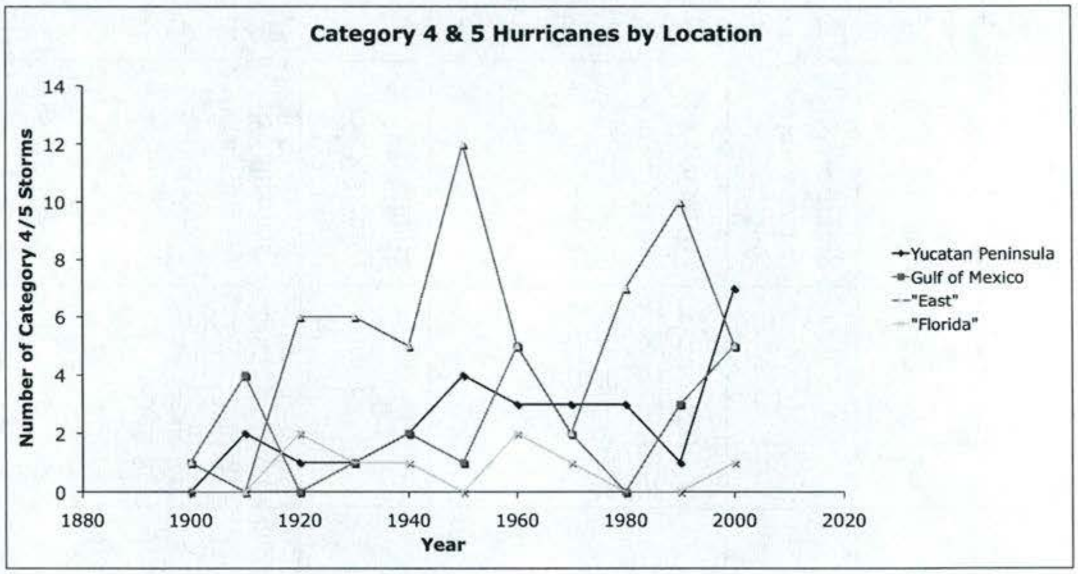
Spin-up	Significant Dmax values (95%)	Frequency of significant Dmax values by decade	Significant Dmax values (99%)	Frequency of significant Dmax values by decade
1005mb | Cat. 1	20	(8) 1960 (5) 1900; 1950 (4) 1910; 1990 (3) 1920; 1930 (2) 1970 (1) 2000	12	(6) 1960 (4) 1900 (3) 1920; 1990 (2) 1910; 1950 (1) 1930; 1970; 2000
Cat. 1 | Cat. 3	3	(3) 2000 (1) 1910; 1920; 1940	2	(2) 2000 (1) 1920; 1940
Consecutive Cat. 4,5	1	(1) 1960; 1970	0	

As shown in this summary table, 1960 emerges as a notable decade for 1005mb – Category 1 spin-up. With high Dmax values, 1960 is significantly different from eight other decades. For Category 1-3 spin-up, 2000 is associated with every significant Dmax value. The only significant difference found in this analysis for consecutive Category 4 and 5 storms is between 1960 and 1970.

Spatial Analysis

The decadal counts for each of the four regions (Yucatán Peninsula, Gulf of Mexico, East, and Florida) are graphed in **Figure 25**.

Figure 25 Locational Analyses of Category 4 & 5 Hurricanes



In addition to the decadal variations evident in **Figure 25**, the plots indicate that the regions do not cycle through high phases and low phases together. Rather, for much of the century, the East and the Gulf of Mexico have inverse relationships.

From the Poisson analyses, it was found that the probability of observing seven Category 4 or 5 storms in the Yucatán Peninsula region over a period of eight years, as was true from 2000-2007, was 0.00086, based on a baseline average of data from 1900-1999. The probability of observing five Category 4 or 5 storms in the Gulf of Mexico over eight years was 0.0098. In the Eastern region, the likelihood of twelve Category 4 or 5 storms occurring within a decade (1950) was 0.0027.

For Poisson analyses for years in which intense storms were concentrated in the same region, significant statistics exist for 2005 storms in the Gulf of Mexico and 1999 storms in the East. Three Category 4 or 5 storms occurred in the Gulf of Mexico in 2005; the likelihood of this occurring is 0.00095, or 1 in 1058. In 1999, four Category 4 or 5 storms occurred in the East. This event rate had a likelihood of 0.0016.

In the spatial analysis for all Category 4 and 5 hurricanes in the entire Atlantic Basin, the 2000 decade was the most significant. Since only eight years of data were available for the 2000 decade, the other decades were multiplied by 0.8 to estimate the event rate for an eight-year period. A new average was calculated, which was then used to calculate Poisson statistics. The anomalies for 2000-2007 and for 2005 were significant when compared with a baseline of 1900-1999 (see **Table 10**).

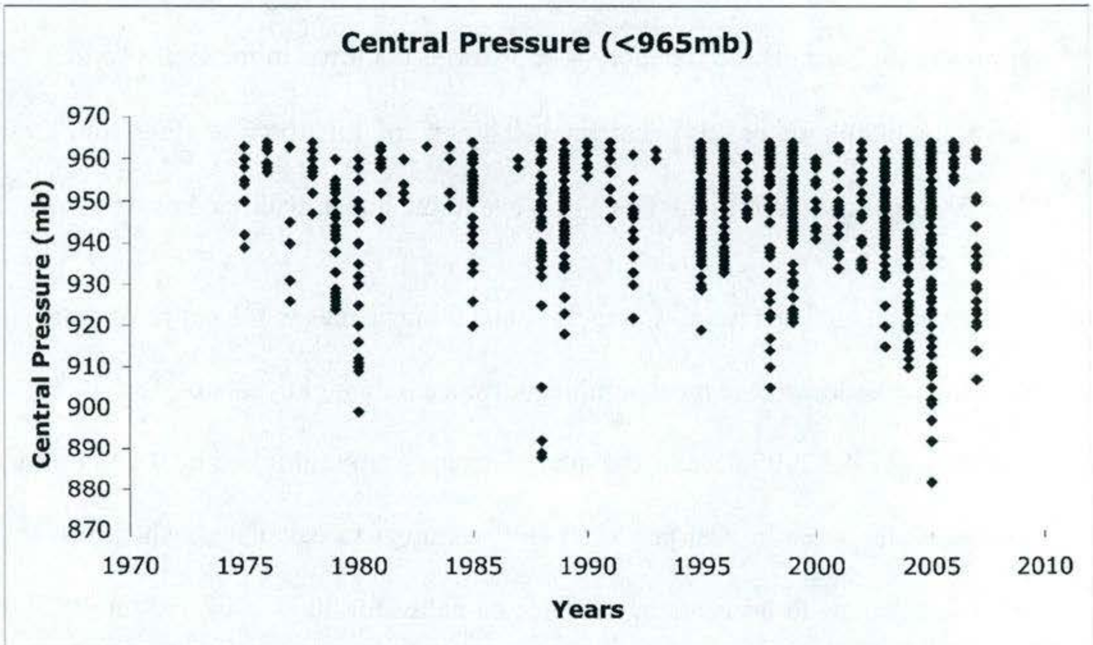
Table 10 Poisson Statistics: Atlantic Basin, Cat. 4&5

	Cat. 4 Storms	Cat. 4 Poisson Statistic	Cat. 5 Storms	Cat. 4 Poisson Statistic
2000-2007	18	$\frac{1}{11874}$	8	$\frac{1}{10671}$
2005	5	$\frac{1}{2119}$	4	$\frac{1}{70299}$

Pressure Analysis

A break in the scatter plot can be observed around 1994 in **Figure 26**. The years on either side of this gap were thus grouped and compared. From 1995 – 2007, the plot shows a higher concentration of points. After applying the z-test, the two sides of the gap shown in the plot had a significant z-value of 3.94.

Figure 26 Array of Central Pressure (<965 mb)



DISCUSSION

Interpretation of Results

From the data analyses performed on the hurricane track data, it was found that hurricanes are highly variable and more data are required to extract stronger trends. High decadal variation was evident at both large and small spatial scales, but some trends were observed. The central questions in this project are addressed below for a more in-depth analysis of the results.

Hurricane frequency

From the various analyses, it was concluded that hurricane frequency likely has not increased with time. While high correction coefficients were necessary to balance the increasing trend, small adjustments in these coefficients greatly affected the trajectory of hurricanes into the future. Additionally, the presence of pronounced decadal and interannual variations also interfered with the extraction of an overarching trend. Despite high storm frequencies in recent years, these high rates similarly occurred in the 1950s. The waveform of this multidecadal cycle appears to coincide with that of the Atlantic Multidecadal Oscillation, and if projections are correct, the Atlantic Multidecadal Oscillation is expected to peak at 2020[33]. Future analysis could identify whether the storm frequency peak will occur at that time as well. Currently there is inadequate data to determine whether hurricane frequencies have increased over time.

Category 4 & 5 frequency

The proportion of Category 4 and 5 hurricanes appears to be increasing with time, with Category 4 storms experiencing a starker increase than Category 5 storms. While data incompleteness was an issue in the other analyses performed, incompleteness was of a lesser concern with intense storms. Contrasting the higher rates of undetected tropical storms, strong Category 4 and 5 hurricanes are likely to have much lower rates of data incompleteness. With proportional data, therefore, the pre-satellite and pre-radio data are likely to be higher than expected, as weaker storms would be more likely to be undetected which would decrease the denominator in the proportional calculation. With potentially lower proportions of Category 4 and 5 hurricanes in the early decades than what appears in the dataset, it would strengthen the finding that the proportion of Category 4 and 5 hurricanes appears to be increasing over time.

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[33] Enfield et al. 2009.

Additionally, the likelihood that eighteen Category 4 and eight Category 5 storms have occurred from 2000-2007 is less than 0.01%. While this statistic is likely skewed by the 2005 season, in which its five Category 4 and four Category 5 hurricanes occurred with likelihoods of 0.047% and 0.0014% respectively, these events demonstrate the potential increase of more intense hurricanes, which brings about serious societal implications.

Spin-up time evolution

The spin-up analyses displayed evident interdecadal variation, and different thresholds yielded different trajectories into the future. These interdecadal waveforms were shown to be significant with the z-test, but were slightly different from the waveforms seen in the overall hurricane frequency. The 1005mb – Category 1 spin-up showed a distinctly shorter 20-year cycle in recent decades, and did not show signs of future increase.

The Category 1-3 spin-up had significant fluctuations between decades as well, and the high phases in the waveform generally had twice the threshold-meeting rate of that of the low phases. The variation among the different thresholds for this spin-up suggested a range of trajectories, as the stricter thresholds suggest a slight increase over time. With this variation between thresholds, more data are necessary to determine what long-term trends exist.

Geographical shift: Category 4 & 5

In recent years, there appears to be a change in where Category 4 and 5 hurricanes take place, but this result is likely skewed by the 2005 hurricane season. Category 4 and 5 hurricanes have increased in the Gulf of Mexico and the Yucatán Peninsula region in the past decade. With 0.086% likelihood that seven Category 4 or 5 storms were observed over a period of eight years (2000-2007) in the Yucatán Peninsula and 0.98% likelihood that five Category 4 or 5 storms would be observed in the Gulf of Mexico in an eight-year period, there exists some sort of change. However, more data are required to adequately assess the trend of intense storm geography.

Duration times of strong hurricanes

The pressure analysis indicates an increase in strong hurricane duration. Using low central pressure as a measurement for the intensity of storms, more timesteps at low pressure readings signal longer durations of strong storms. The high z-value contrasting low pre-1994 and high post-1994 data suggests an increase in intensity. However, fluctuations exist within each time period; for instance the high concentration of low pressure in 2003-2005 was met with a sudden drop in 2006 and 2007. Despite the data indicating an increase in intense storm duration over time, more data are needed to establish stronger trends.

Hurricane location

From the various grid analyses, it is evident that high multidecadal variation exists. While recent decades have seen increased numbers of significant event rates within many grid cells, it appears to be a cyclic pattern. Following the approximately 40-year cycle of a high and low phase that was observed in the overall storm counts over time, the small grid analyses also exhibited anomalous maximum event rate frequencies consistent with this cycle. As a result, further data are required to assess whether there is an overarching trend in anomalous events over time.

Limitations

Like other environmental phenomena, hurricanes are extremely complex. Due to the massive dataset and the complexities within it, there were several limitations to this project. The incompleteness of the dataset was a challenge, for although the database goes back to 1851, the data have only become more reliable in the past fifty years. With the reanalysis project having completed revisions for only the first few decades, it is possible that this partial reanalysis slightly influenced the results. The short span of data was also an issue, as with the multidecadal patterns that emerged from this analysis, there were generally not enough data beyond one cycle of the pattern to determine much significance in trends.

Due to the set grid network calibration point of 90°S and 180°W in the Hurricane Grid Counter, some grids near the specified boundaries were smaller than others, and this could possibly impact Poisson calculations. Errors were minimized by double-checking anomalous points to eliminate the possibility that an anomaly was caused by a differential grid size, but some of these cells could have been significant if the counts had been proportional to the cell size. Furthermore, when identifying maximum event rates for the Poisson grid analysis, while it simplified the analysis process, it neglected to consider the potentially other improbable events in that same grid. Some grids may have a few improbable events that are each more significant than the maxima in other grids, but because only the maximum was used, the grids were assumed to have only one significant improbable event.

With more advanced programming skills, the analyses could potentially have been more comprehensive. Many of the analyses required counting of anomalous events by hand, which takes more time and leaves more room for error. Additionally, with the infinite possibilities of statistical analysis, many important analyses were inevitably left out. These omissions, however, pave the path for future analysis within the hurricane dataset.

Future Analysis

This project experimented with various statistical tests to examine the large hurricane dataset. With these preliminary analyses, future studies can expand on the findings and apply similar techniques to other regions and other phenomena.

This particular project only analyzed data through 2007. Revisiting and reanalyzing the data at the end of the 2009 hurricane season would be beneficial, as another full decade of data could be directly compared with the other decades. Additionally, if or when the Atlantic Multidecadal Oscillation peaks, another analysis to compare it with hurricane decadal variations would be interesting. With continued climate and environmental change, these analyses could also be implemented to assess how hurricane properties have changed in relation to global changes.

As was evident in the differential results from varying thresholds and grid sizes, selection of these parameters can change the outcomes of statistical tests. The analyses in this project can be reapplied with different definitions of intense storms, new thresholds, and different grid sizes.

Finally, these analyses should be applied to Pacific Basin typhoons and other cyclones around the world. The analysis techniques can also be used to evaluate other phenomenon similar to tropical cyclones, such as tornadoes.

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