TRENDS AND CHARACTERISTICS OF NORTH ATLANTIC TROPICAL CYCLONES

by

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1. INTRODUCTION

1.1 Research Problem

Human use of and developments on coastlines continue to increase. When tropical cyclones strike coastlines, they cause financial damage and create problems for human livelihood. To better prepare for such occurrences and to more accurately predict the damages of landfall, more research needs to be done on the characteristics of tropical cyclones and to address whether long-term changes exist.

Tropical cyclones thrive in areas with minimal vertical wind shear and warm ocean waters. It has been proposed that a changing climate will add additional heat to the oceans resulting in higher frequency of occurrence and more intense tropical cyclones (Emanuel 2005). Tropical cyclones making landfall present a large number of problems, especially for vulnerable coasts. The hypothesis that they may be increasing in strength and frequency should be investigated to determine if there are long-term changes in the frequency and intensity of North Atlantic tropical cyclones.

Tropical cyclones have been increasing in destructiveness in the past 30 years, and with this upward trend comes an increase in tropical cyclone destructive potential (Emanuel 2005). Climate change will cause tropical cyclones and windstorm damages to increase, with approximately 90% of North Atlantic tropical cyclone predictions showing increase in financial losses (Ranson et al. 2014). With the landfall of a tropical cyclone comes the threat of not only wind, but also storm surge and coastal flooding. The anthropogenic era (post-1970) has had an increase in the extremes of the storm types that are responsible for the majority of storm surge in New York City; flood heights have increased in part because of changes in tropical cyclone characteristics, leading to an increased risk of coastal inundation (Reed et al. 2015).

The North Atlantic Basin has reliable records since 1900, where there was sufficient coastal population to have a consistent count of tropical cyclone systems (NOAA 2015). With its long period of coverage and the expanding coastal population, the North Atlantic Basin is a good choice for this research domain in comparison to the other, less reliably observed, basins.

The impact of tropical cyclones on vulnerable coasts is a major concern. Increased flooding is observed, the intensity of tropical cyclones is increasing; wind speeds are increasing and predictions show increased fatalities and financial loss (Ranson et al. 2014). With populations increasingly moving toward the coasts and urban development sparing no expense on this highly sought-after land, there are more people in harm's way (Seo 2014). Evacuation methods and predictions are becoming more accurate and as a result fewer storm-related deaths are occurring, but there has also been a rapid increase in the amount of financial loss. Natural disaster losses along coastal strips and in cities have reached new financial dimensions, and with people being attracted to the coasts, risk only continues to increase (Kron 2013). Kron (2013) lists the top ten events worldwide according to financial loss and fatalities in the past 20 years; out of the ten events, eight of them occurred near a coast.

Research on tropical cyclones and their relationship with global warming is expanding, with trend analysis and damage reports being a major contributor to the discussion. Although this study will focus on the North Atlantic Basin, air and sea temperatures are increasing globally, people are moving to the vulnerable coastlines, and financial loss is growing (Kron 2013). Considering the requirements for a tropical cyclone to form, the threat is one that warrants continued research.

1.2 Research Questions

In this study I will address the following questions:

- Is there a trend in tropical cyclone frequency during the sample period (1900-2015)?
- Is there a trend in tropical cyclone intensity, measured using Accumulated Cyclone Energy (ACE), within the sample period (1900-2015)?
- Is there a temporal difference in tropical cyclone frequency and intensity in recent years (1970-2015) compared to the previous (1900-1969)?

2. LITERATURE REVIEW

2.1 Tropical Cyclones

A tropical cyclone can be defined as a cyclone that originates over tropical oceans and is driven principally by heat transfer from the ocean; they will generally develop over oceans with sea surface temperatures (SSTs) that exceed 26°C, but after formation often move out of these regions into higher latitudes (Emanuel 2003). Initially, a region of moist convection establishes a broad area of warming in the upper troposphere, lowering surface pressures (Holland 1997). Tropical cyclone genesis not only requires warm temperatures, but also the presence of the Coriolis force. Without Coriolis, the storm will not have the needed vorticity for formation; because of this, storms will not typically form below 5° latitude, where the Coriolis force is not strong. A favorable environment for cyclogensis would have minimal wind shear as well; strong wind shear can effectively "tilt" the system, not allowing it to reach its maximum potential intensity. The rate that a tropical cyclone can intensify is highly dependent on SST. There is an increasing trend of intensification rate with increasing SSTs, and the increasing trend of intensity becomes even more rapid when SSTs are is higher than 27°C; a tropical cyclone is only as strong as the ocean beneath it is warm (Xu et al. 2016) and its size (horizontal extent) is very sensitive to Coriolis and SSTs as well (Frisius 2015).

Tropical cyclones are commonly categorized by their wind speed using the Saffir-Simpson Wind Scale. Cyclones will be given a rating from one to five based on sustained wind speeds and potential property damages, where Category 3 and higher are considered major because of their potential for significant loss of life and damage (NOAA 2012). This scale has been very useful for notifying the public of potential tropical cyclone danger. The types of damage are just estimates, though damage is highly dependent on the building codes and regulations in place where the storm makes landfall. This scale does not address other related impacts, such as storm surge or rainfall-induced flooding.

TABLE 2.1: Saffir-Simpson Wind Scale (NOAA 2012).

Category	Sustained Winds	Types of Damage Due to Hurricane Winds
1	74-95 mph 64-82 kt 119-153 km/h	**Very dangerous winds will produce some damage:** Well-constructed frame homes could have damage. Large branches of trees will snap and shallowly rooted trees may be toppled. Damage to power lines and poles likely will result in power outages that could last a few to several days.
2	96-110 mph 83-95 kt 154-177 km/h	**Extremely dangerous winds will cause extensive damage:** Well-constructed frame homes could sustain major damage. Many shallowly rooted trees will be snapped or uprooted and block numerous roads. Near-total power loss is expected that could last from several days to weeks.
3 (major)	111-129 mph 96-112 kt 178-208 km/h	**Devastating damage will occur:** Well-built framed homes may incur major damage. Many trees will be snapped or uprooted, blocking numerous roads. Electricity and water will be unavailable for several days to weeks.
4 (major)	130-156 mph 113-136 kt 209-251 km/h	**Catastrophic damage will occur:** Well-built framed homes can sustain severe damage. Most trees will be snapped or uprooted and power poles downed. Power outages will last weeks to possibly months.
5 (major)	157 mph or higher 137 kt or higher 252 km/h or higher	**Catastrophic damage will occur:** A high percentage of framed homes will be destroyed. Fallen trees and power poles will isolate residential areas. Power outages will last for weeks to possibly months. Most of the area will be uninhabitable for weeks or months.

Another measure of storm strength is Accumulated Cyclone Energy (ACE), which originated from the Hurricane Destructive Potential (HDP) index. HDP is calculated by summing the squares of the estimated 6-hourly maximum sustained wind speeds for all periods in which the system is a hurricane. By also including when the system is at least named storm strength (39-73 mph winds) yields ACE. These indices represent a continuous distribution that accounts for the numbers of storms while also giving more weight to stronger and longer lasting systems (Bell et al. 2000). Power Dissipation Index (PDI) is calculated similarly to ACE, but uses the wind speed cubed instead of squared (Villarini and Vecchi 2013).

Tropical cyclone season in the North Atlantic is June 1st to November 30; within this timeframe, 97% of tropical cyclone activity occurs (NOAA 2015a). Season length can vary slightly from year to year though, and may even be extending or in direct relationship with other climatic variables, such as the El Niño Southern Oscillation (ENSO) or Pacific Decadal Oscillation (PDO). For example, La Niña conditions and a negative PDO may be indicative of a late-ending season (Karloski and Evans 2016). It could also be stated that if there was a particularly warm winter (or cold one) could influence an earlier (or later) start to the tropical cyclone season because of their dependency on SST thresholds.

Table 2.2 demonstrates the seasonal nature of tropical cyclone formation. January, February, March and April show very little activity. May is when formation becomes more common before officially entering the hurricane season on June 1.The season persists with high totals and averages of tropical storms and hurricanes and tapers off into December.

TABLE 2.2: Total and average number of tropical cyclones by month (1851-2015). * Indicates less than 0.05 (NOAA 2015b).

	Tropical Storms		Hurricanes		U.S. Landfalling Hurricanes	
Month	**Total**	**Average**	**Total**	**Average**	**Total**	**Average**
JANUARY	2	*	1	*	0	*
FEBRUARY	1	*	0	*	0	*
MARCH	1	*	1	*	0	*
APRIL	1	*	0	*	0	*
MAY	21	0.1	4	*	0	*
JUNE	87	0.5	33	0.2	19	0.12
JULY	118	0.7	55	0.3	25	0.15
AUGUST	378	2.3	238	1.4	77	0.48
SEPTEMBER	571	3.5	395	2.4	107	0.67
OCTOBER	336	2	201	1.2	53	0.33
NOVEMBER	89	0.5	58	0.3	5	0.03
DECEMBER	17	0.1	6	*	0	*
YEAR	1619	9.9	991	6	284	1.73

In Table 2.3 you can see that at the start of the hurricane season, direct hits tends to be in the southern part of the US, but as the season goes on, storms begin to make landfall at higher latitudes. Therefore, it is more common for southern coastal states to have hurricane landfall earlier in the season (June-August), and northern coastal states to have landfall later (August-October).

TABLE 2.3: Major Hurricanes direct hit by month for the coastline and individual states (1851-2015). State totals will not equal U.S totals and Texas and Florida totals will not necessarily equal sum of sectional totals since storms may be counted for more than one state or region (NOAA 2015c).

AREA	JUNE	JULY	AUG.	SEPT.	OCT.	ALL
U.S. Coastline (Texas to Maine)	2	5	26	46	17	92
Texas	1	2	10	9	0	19
North	1	1	3	4	0	7
Central	0	2	2	0	0	4
South	0	6	3	0	0	8
Louisiana	2	0	7	9	3	20
Mississippi	0	1	4	4	0	9
Alabama	0	1	1	4	0	6
Florida	0	2	6	19	10	37
Northwest	0	2	1	7	3	13
Northeast	0	0	0	1	0	1
Southwest	0	0	2	5	6	13
Southeast	0	0	4	8	3	15
Georgia	0	0	1	1	1	3
South Carolina	0	0	2	2	2	6
North Carolina	0	0	4	7	1	12
Virginia	0	0	0	1	0	1
Maryland	0	0	0	0	0	0
Delaware	0	0	0	0	0	0
New Jersey	0	0	0	0	0	0
Pennsylvania	0	0	0	0	0	0
New York	0	0	1	4	0	5
Connecticut	0	0	1	2	0	3
Rhode Island	0	0	1	3	0	4
Massachusetts	0	0	0	3	0	3
New Hampshire	0	0	0	0	0	0
Maine	0	0	0	0	0	0

Table 2.4 outlines all hurricane landfalls from 1851-2015. Of all Major Hurricane landfalls, 80% of them hit either Texas or Florida; 40% of all US hurricanes hit Florida. The effect of latitude on tropical cyclone longevity is apparent by the lack of storms

making landfall farther up the coast. There are no Major storms documented making landfall north of Virginia.

TABLE 2.4: Hurricane direct hits on the mainland US coastline and for individual states by Saffir-Simpson category from 1851-2015. State totals will not equal U.S totals and Texas and Florida totals will not necessarily equal sum of sectional totals since storms may be counted for more than one state or region (NOAA 2015d).

AREA		CATEGORY						Major Hurricanes
		1	2	3	4	5	ALL	
U.S. Coastline (Texas to Maine)		117	76	76	18	3	290	97
Texas		25	19	12	7	0	63	19
	North	13	8	3	4	0	28	7
	Central	7	5	2	2	0	16	4
	South	10	5	7	1	0	23	8
Louisiana		19	15	15	4	1	54	20
Mississippi		2	5	8	0	1	16	9
Alabama		12	5	6	0	0	23	6
Florida		44	33	29	6	2	114	37
	Northwest	27	16	12	0	0	55	12
	Northeast	13	8	1	0	0	22	1
	Southwest	16	8	7	4	1	36	12
	Southeast	13	13	11	3	1	41	15
Georgia		12	5	2	1	0	20	3
South Carolina		19	6	4	2	0	31	6
North Carolina		24	14	11	1	0	50	13
Virginia		9	2	1	0	0	12	1
Maryland		1	1	0	0	0	2	0
Delaware		2	0	0	0	0	2	0
New Jersey		2	0	0	0	0	2	0
Pennsylvania		1	0	0	0	0	1	0
New York		6	1	5	0	0	12	5
Connecticut		4	3	3	0	0	10	3
Rhode Island		3	2	4	0	0	9	4
Massachusetts		5	2	3	0	0	10	3
New Hampshire		1	1	0	0	0	2	0
Maine		5	1	0	0	0	6	0

A study examining the relationship between warm Atlantic SSTs and US tropical cyclone landfalls found that along the Gulf Coast and Southeast US cyclone landfall probability increases significantly under warm SST conditions (Dailey et al. 2009). The intensity of the storm when it makes landfall tends to correlate with where it originates; storms that form in the Gulf of Mexico have less opportunity to intensify before making landfall compared to those that originate in the north eastern Atlantic, which have a larger expanse of ocean over which they can increase in intensity.

2.2 Coastal Region

Coastlines are the most exposed regions of the world to tropical cyclones. Storm surges and fierce winds strongly impact fragile coastlines as well as the infrastructure. A third of the 23 costliest natural catastrophes from 2000-2011 were a result of hurricanes, and out of those 23 disasters 15 of them were in coastal areas (Kron 2013). It was concluded that, if global surface air temperatures rise 2.5 degrees Celsius, hurricane damages in the North Atlantic will increase by 63% (Ranson et al. 2014) with damage increases in the Southern Hemisphere being predicted as well (Seo 2014).

The US Atlantic coast stretches from Texas in the south to Maine in the north. In their Preparedness Guide (2011) NOAA outlines the primary threats that come with tropical cyclones. Storm surge and large waves produced by hurricanes pose the greatest threat to life and property along the coast, where storm surge is an abnormal rise in water generated by a storm’s winds, whereas storm tide is the rise in water level because of both the storm surge as well as the astronomical tide. The geography of the coastline can drastically impact the intensity of the surge and tide; shallower waters will generate larger waves inland, and can stretch hundreds of miles wide. Thunderstorms that occur in the rain bands around the hurricane can produce tornadoes, adding further wind threats and damage to the mix.

The east coast of the United States has seen increased damages from tropical cyclones in the anthropogenic era. New York City storm surges have grown and therefore the flood risk has greatly increased for the region, indicating higher need for advanced risk management strategies (Reed et al. 2015). Economic losses caused by tropical cyclones have increased by 4% annually from 1971-2005 (Schmidt et al. 2009).

Over the last 50 years, Atlantic tropical cyclone-related direct deaths total around 2,500; almost 90% of them resulted from excess storm water, either in the form of storm surge or flood events from rain (Rappaport and Blanchard 2016). Direct deaths have been decreasing with the increase of forecasting efficiency, but despite this, indirect deaths (fires, electrocution, vehicle accidents) are still taking many lives.

According to NOAA (2015d), only three category 5 storms have hit the US coastline; the Florida Keys Storm in 1935, Hurricane Camille in 1969, and Hurricane Andrew in 1992. The three deadliest storms were the Galveston storm of 1900 (Category 4), the Lake Okeechobee storm of 1928 (Category 4), and Hurricane Katrina in 2005 (Category 3). According to 2013 adjustments for inflation, the three costliest storms are currently Hurricane Katrina in 2005 (Category 3), Sandy in 2012 (post-tropical cyclone), and Hurricane Andrew in 1992 (Category 5).

2.3 Potential Impact of Climate Change on Tropical Cyclones

Possibly in correlation with rising tropical SSTs, tropical cyclones have been increasing in intensity and have had longer storm lifetimes since the 1970s (Emanuel 2005). Worldwide, frequency and intensity of tropical cyclones have shown much variability (Dwyer et al. 2015). Tropical cyclones are very sensitive to changes in oceanic conditions, with research in the Philippines stating a definite change in cyclone activity dependent on El Niño conditions (Corporal-Lodango et al. 2016). Tropical cyclones in the North Atlantic are not making landfall as frequently in El Niño years, as opposed to La Niñas (Klotzbach 2011).

The North Atlantic has seen heightened tropical cyclone activity likely related to warming sea surface temperatures (Holland and Webster 2007). The North Atlantic has recently seen higher levels of ACE and PDI, both of which are measures of tropical cyclone activity, likely in relation to the increasing tropical cyclone genesis counts observed (Murakami et al. 2014). An increase in PDI can tentatively be linked to increases in greenhouse gas emissions over the twenty-first century and changes in the quantity of atmospheric aerosols; these projections suggest an increase in tropical cyclone intensity and duration rather than an increase in frequency (Villarini and Vecchi 2013). Average tropical cyclone intensification rates show an increasing trend with warming sea surface temperatures, and about 79% of a storm's total lifetime is spent over sea surfaces temperatures of at least 27°C (Xu et al. 2016). With warming SSTs, this could open entirely new domains for tropical cyclone formation and landfalls.

Trend analysis in the North Pacific basin was positive for increasing tropical storm activity since the mid-1970s, and has previously shown a negative trend since the

1970s. A downward trend has been indicated in Australian data, and the Atlantic has yet to show a statistically significant long-term trend (Easterling et al. 2000). There is no homogeneous trend in the Western North Pacific data, however; the genesis numbers and intensity of storms are highly dependent on where they begin in the Pacific (Park et al. 2013). As global tropical cyclone activity continues to change in frequency and intensity, it is also migrating poleward. In both the Northern and Southern Hemisphere trends depict a poleward migration of maximum intensity by about one degree latitude per decade (Kossin et al. 2014). When considering the impact of CO_2 on North Atlantic tropical cyclone tracks, simulated changes in the large-scale steering flow on genesis location suggest a decrease in Gulf forming systems and an increase in mid-Atlantic forming storms, showing an overall trend of east-shifting cyclone tracks (Colbert et al. 2013). Contrary to some previous research, a global analysis in 2005 stated that no global trends had emerged in the frequency of tropical storms or hurricanes, with one exception: the North Atlantic (Webster et al. 2005).

The changes seen in tropical cyclone frequency, intensity, and location may be a result of global warming and human impacts. Intensities of Australian tropical cyclones under warmer than average conditions are slightly greater, although not statistically significant (Walsh and Ryan 2000) and tropical cyclone maximum intensities will likely increase in a warmer greenhouse world (Walsh et al. 2004). Tropical cyclone intensities will likely increase as the climate warms in response to human emissions of greenhouse gasses, and in the absence of strong reductions of these emissions, the intensity may increase substantially (Sobel et al. 2016).

2.4 Adaptation to Tropical Cyclones

Ellis, Sylvester, and Trepanier (2015) investigated temporal clusters of extreme hurricanes (extreme is defined as a 1/50 chance of occurrence for a specific area) making landfall along the Atlantic coast. They found that, along particular portions of the US coastline, there was temporal clustering present. When breaking down the coastline into four regions (Gulf, Florida, and SE and NE Atlantic) Florida and the Atlantic areas both displayed temporal clustering whereas the Gulf did not exhibit a spatial pattern. For the sake of adaptation they suggest further studies of temporal clustering to help prepare for future events.

Understanding the vulnerability of a coastal population is important in storm preparation and adaptation. Bian and Wilmot (2016) classified vulnerable populations as those who are elderly, carless, disabled, or living in very low elevation areas prone to flooding for 30 x 30 m areas for New Orleans, LA. Their small area assessment can help local agencies identify highly vulnerable areas and their distribution much more precisely.

3. DATA AND METHODS

3.1 Study Area

The geographical areas influenced by tropical cyclones are often referred to as tropical cyclone basins. The study area is the North Atlantic basin, which is defined as the North Atlantic Ocean, the Caribbean Sea, the Gulf of Mexico and a substantial portion of the adjacent coastal area (McAdie et al. 2009). Tropical cyclone genesis is typically North of 10°N latitude, extending from NW Africa to the North American coasts.

FIGURE 3.1: Map of the study area (NOAA 2015e).

3.2 Definitions

Some definitions are first required to be able to conceptualize the upcoming data and methods.

- Named Storm – total number of tropical storms (a storm with wind speeds of 39-73 mph (63-117 kmph)) and hurricanes in a particular year.
- Hurricane – a storm with wind speeds of 74 mph (119 kmph) or higher. Hurricane intensity is a function of wind speed and varies from 1-5 on the Saffir-Simpson Scale.
- Major Hurricane – a storm with winds of at least 111 mph (197 kmph). These storms have a Saffir-Simpson Scale ranking of 3, 4, or 5.
- ACE (Accumulated Cyclone Energy) – a wind energy index, defined as the sum of the square of the maximum sustained surface wind speed in a six-hour period. ACE is calculated for all tropical cyclones of at least tropical storm strength. ACE is measured in 10^4 knots^2 (3.4x 10^4 kmph^2). In this study total ACE for the season (June 1- November 30) is used as an example of tropical cyclone season intensity for each year.

3.3 Data

All data were obtained from the NOAA Hurricane Research Division storm database (NOAA 2015a). The Atlantic hurricane database (HURDAT) extends back to 1851. However, because of many tropical cyclones spending their lifetime over open ocean and never making landfall, many systems may have been missed in pre-satellite days. For hurricanes striking the US Atlantic and Gulf coasts, because of coastline population, storm observations reliably date back to 1900.

The National Hurricane Center began using daily satellite imagery in 1966, increasing reliability of coverage (McAdie et al. 2009). Before 1960, ship observations were the primary tool for detecting tropical cyclones; in 1960 the first polar orbiting satellites were used to detect storms, with geostationary satellites, dropsondes, and buoys becoming prevalent around 1970 (McAdie et l. 2009). As a result, instrumental offsets largely decreased around the 1970s as technology continued to improve (Levitus et al. 2009). The potential for instrumental offset was the deciding factor in, as well as analyzing the dataset as a whole (from 1900-2015), analyzing it in two periods (Period 1 being 1900-1969 and Period 2 being 1970-2015).

By breaking down the dataset into four different variables (Named Storms, Hurricanes, Major Hurricanes, and ACE) the study aims to investigate what may be subtle changes in the type and intensity of storms occurring as well as the overall frequency.

3.4 Statistical Analysis

3.4.1 Descriptive Statistics

Descriptive statistics (Median, Mean, Variance, Minimum, Maximum, and Standard Deviation) for all variables were calculated. This was done for the entire sample period (1900-2015) as well as the two break periods (1900-1969) and (1970-2015). Calculations of the frequency of storms that are Hurricanes and Major Hurricanes in the 1900-1969 set compared to the 1970-2015 set was also done.

3.4.2 Normality

Shapiro-Wilk's test for normality was run first. This is a common test for determining if the overall shape of a frequency distribution differs significantly from normal (Warner 2013); the type of frequency distribution (normal vs. non normal) usually determines whether parametric or nonparametric statistical measures will be used.

3.4.3 Difference of Means

An independent sample T-Test for difference of means between the 1900-1969 and 1970-2015 periods was used on all variables (Named Storms, Hurricanes, Major Hurricanes, ACE). This test is a parametric method, but is fairly robust to violations of normality. The test involves a comparison of mean scores between two groups, and is appropriate when the groups are between subjects or are independent (Warner 2013).

A Mann-Whitney test for difference of means between the 1900-1969 and 1970-2015 periods was also used on all variables (Named Storms, Hurricanes, Major Hurricanes, ACE). This is a nonparametric test that assumes independence between the two samples without the need for a normal distribution (Daniel 1990).

3.4.4 Trend Analysis

Kendall's tau test of the entire sample period (1900-2015) and for each variable (Named Storms, Hurricanes, Major Hurricanes, ACE) was used to determine if a statistically significant temporal trend exists. Kendall's tau was chosen because of its lack of need for a defined distribution. Kendall's tau is based on the ranks of observations (from -1 to +1); the closer Kendall's tau is to -1 or +1 the more highly correlated the variable is, where a result close to zero would indicate little relationship (Daniel 1990).

Theil-Sen's method of finding slope is sensitive to non-normality, is unbiased, and takes the median of the set of slopes as a simple linear regression technique (Sen 1968). It was calculated for all variables (Named Storms, Hurricanes, Major Hurricanes, ACE) over the entire sample period (1900-2015) to estimate linear trends.

4. RESULTS

4.1 Descriptive Statistics

The entire sample period consisted of 116 years of data. Here, the large range of the variables across time is apparent (Table 4.1). For example, the minimum number of named storms in a given year recorded was one, whereas the maximum was 28. The range decreases for hurricanes and major hurricanes in relation to their lower frequencies in compared to named storms. ACE, being a wind energy index, has a very large range as well, and relates to a higher/lower occurrence of all storms.

The descriptive statistics for period 1 (1900-1969) consisted of 70 years of data. Period 2 (1970-2015) consisted of 46. By breaking the data into these two categories, it appears that Period 1 (Table 4.2) and Period 2 (Table 4.3) have means that differ.

It should also be noted that the minimums and maximums vary between the two samples. Period 1 has a minimum of one named storm, whereas Period 2 did not see a year with fewer than four. Period 1 had a year without hurricanes, whereas Period 2 had a minimum of two hurricanes per year. The maximums between Period 1 and 2's Named Storms and Hurricanes also show variation. Period 1 had a maximum of 20 named storms and 15 hurricanes, whereas Period 2 had 28 and 15 respectively. The variation between the two periods with Major Hurricanes was less evident, as both had a minimum of zero and Period 1 a maximum of eight and Period 2 a maximum of seven. The ACE of Period 2's minimum was 17 compared to Period 1's three, although the maximums were very similar (Period 1: 259, Period 2: 250).

TABLE 4.1: Descriptive statistics for the entire period.

Statistic	Named Storms	Hurricanes	Major Hurricanes	ACE
Nbr. of observations	116	116	116	116
Minimum	1.000	0.000	0.000	3.000
Maximum	28.000	15.000	8.000	259.000
Median	10.000	5.000	2.000	83.500
Mean	10.060	5.474	2.241	91.526
Variance (n-1)	18.144	6.982	3.298	3204.669
Standard deviation (n-1)	4.260	2.642	1.816	56.610

TABLE 4.2: Descriptive statistics for period 1 (1900-1969).

Statistic	Named Storms	Hurricanes	Major Hurricanes	ACE
Nbr. of observations	70	70	70	70
Minimum	1.000	0.000	0.000	3.000
Maximum	20.000	12.000	8.000	259.000
Median	9.000	5.000	2.000	83.500
Mean	8.971	5.071	2.157	89.257
Variance (n-1)	13.767	6.067	3.613	3070.831
Standard deviation (n-1)	3.710	2.463	1.901	55.415

TABLE 4.3: Descriptive statistics for period 2 (1970-2015).

Statistic	Named Storms	Hurricanes	Major Hurricanes	ACE
Nbr. of observations	46	46	46	46
Minimum	4.000	2.000	0.000	17.000
Maximum	28.000	15.000	7.000	250.000
Median	11.000	5.500	2.000	81.500
Mean	11.717	6.087	2.370	94.978
Variance (n-1)	20.607	7.903	2.860	3460.911
Standard deviation (n-1)	4.540	2.811	1.691	58.830

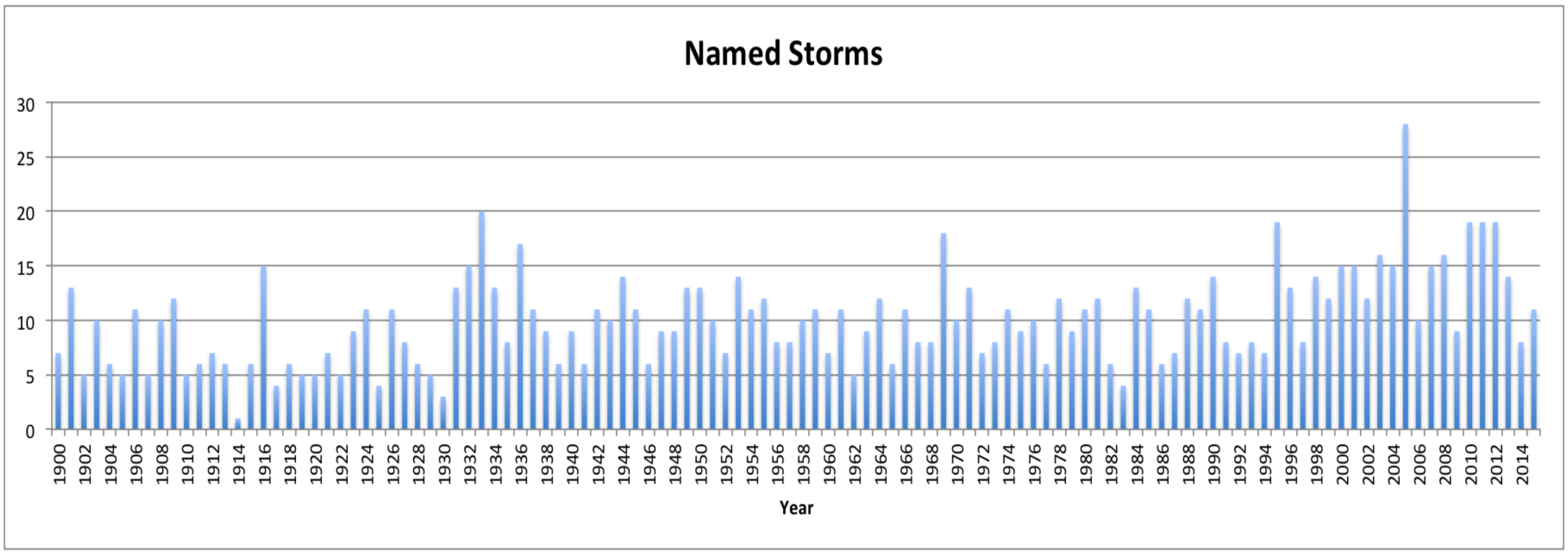

FIGURE 4.1: Time series of Named Storm frequencies 1900-2015.

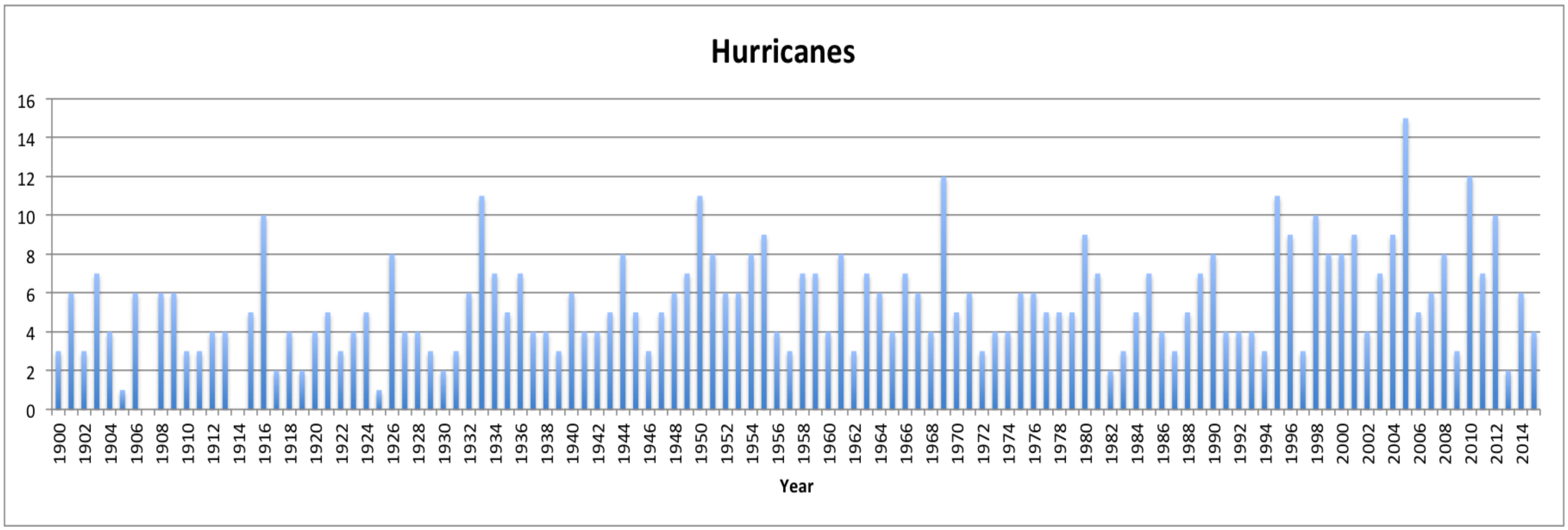

FIGURE 4.2: Time series of Hurricane frequencies 1900-2015.

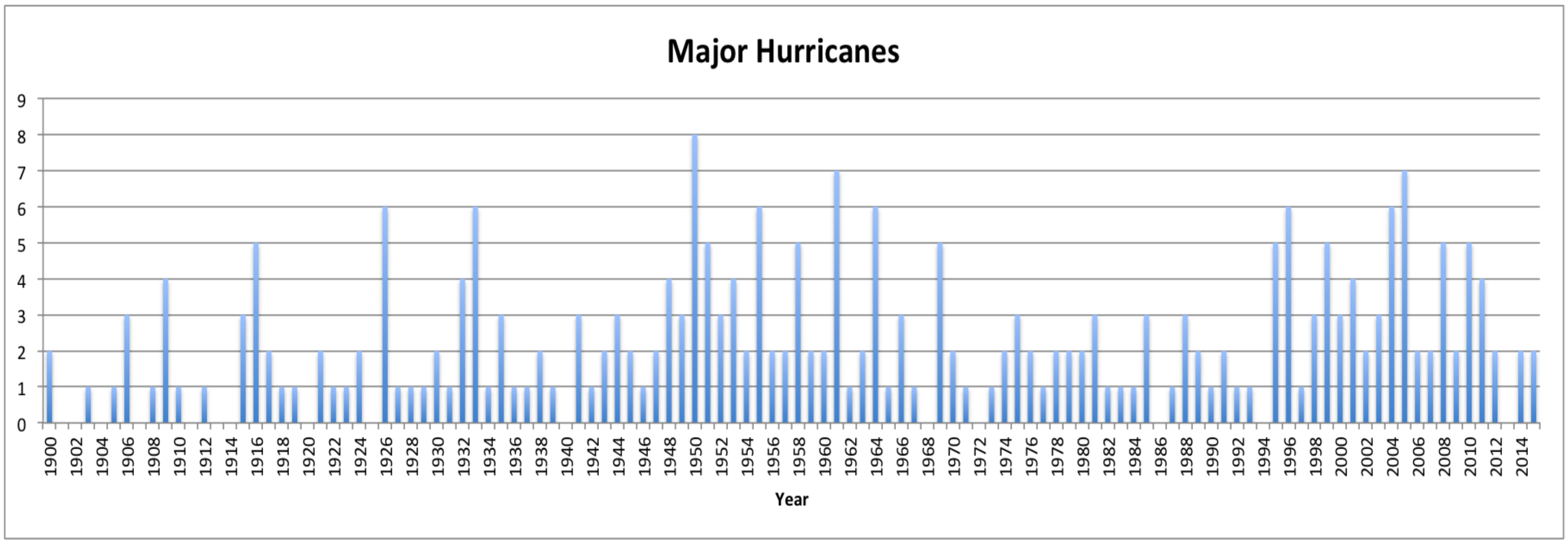

FIGURE 4.3: Time series of Major Hurricane frequencies 1900-2015.

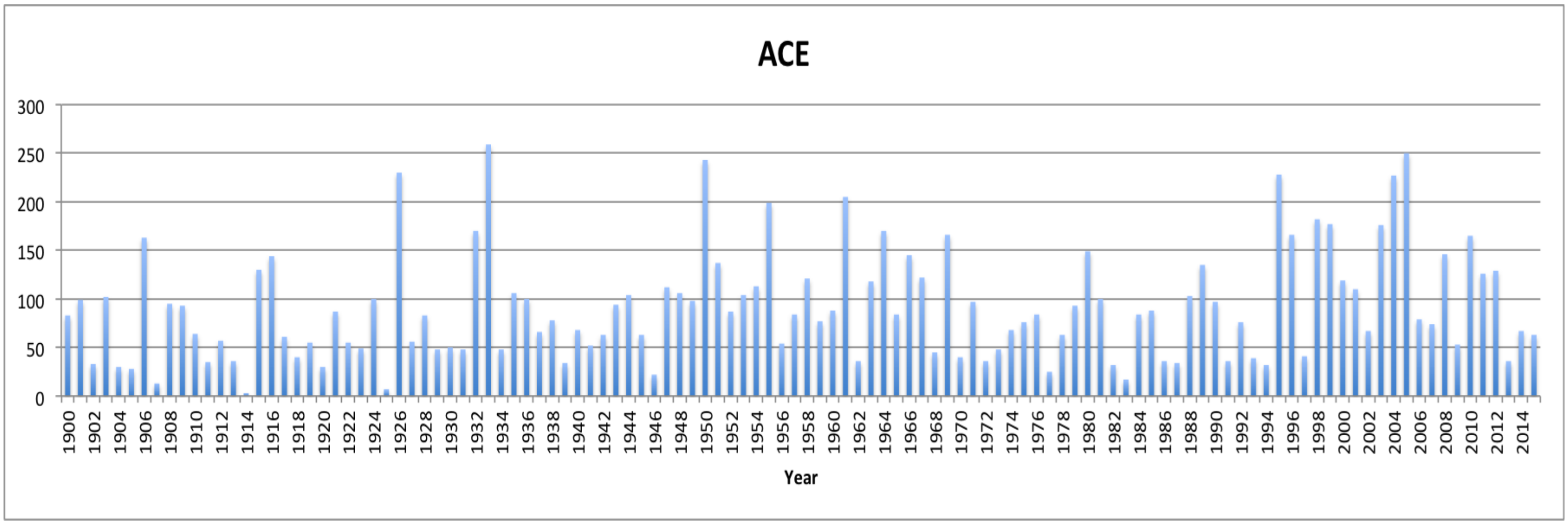

FIGURE 4.4: Time series of ACE values 1900-2015.

4.2 Normality Testing

A Shapiro-Wilk test of the entire sample (1900-2015) and the two periods (1900-1969, 1970-2015) was first run to determine normality. All variables displayed non-normal results, affirming that the frequency of storm occurrence is not normally distributed. The results for the entire sample (Table 4.4) are consistent with those found in the two sub-periods (Table 4.5 and 4.6).

TABLE 4.4: Normality test for entire period.

Shapiro-Wilk test	**Named Storms**	**Hurricanes**	**Major Hurricanes**	**ACE**
W	0.950	0.953	0.883	0.922
p-value (Two-tailed)	< 0.0001	< 0.0001	< 0.0001	< 0.0001

TABLE 4.5: Normality test for Period 1 (1900-1969).

Shapiro-Wilk test	**Named Storms**	**Hurricanes**	**Major Hurricanes**	**ACE**
W	0.964	0.960	0.869	0.922
p-value (Two-tailed)	0.044	0.026	< 0.0001	< 0.0001

TABLE 4.6: Normality test for period 2 (1970-2015).

Shapiro-Wilk test	**Named Storms**	**Hurricanes**	**Major Hurricanes**	**ACE**
W	0.931	0.933	0.895	0.914
p-value (Two-tailed)	0.009	0.011	0.001	0.002

4.3 Difference of Means

1. Two-tailed T-Test

With a robust sample size of 70 (Period 1) and 46 (Period 2), despite the lack of normality, a two tailed T-test was executed. All variables show a larger mean value in Period 2 when compared to Period 1. Named Storms and Hurricanes had statistically significant mean differences whereas Major Hurricanes and ACE did not (Table 4.7).

TABLE 4.7: Two-tailed T-test. H0, no difference of means; Ha, difference between the means is not zero. Bolded terms can reject the null, indicating that the means between the two periods are different.

Two-tailed T-Test	**Named Storms**	**Hurricanes**	**Major Hurricanes**	**ACE**
Difference	-2.746	-1.016	-0.212	-5.721
t (Observed value)	-3.565	-2.053	-0.615	-0.531
|t| (Critical value)	1.981	1.981	1.981	1.981
DF	114	114	114	114
p-value (Two-tailed)	**0.001**	**0.042**	0.540	0.597

2. Two-tailed Mann-Whitney

The Mann-Whitney test indicated that all variables showing increased means in Period 2 compared to Period 1. However, only Named Storms had statistically significant differences between the two periods, but Hurricanes, Major Hurricanes, and ACE did not.

TABLE 4.8: Two-tailed Mann-Whitney test. H0, no difference of means; Ha, difference between the means is not zero. Bolded terms can reject the null, indicating that the means between the two periods are different.

Two-tailed Mann-Whitney	**Named Storms**	**Hurricanes**	**Major Hurricanes**	**ACE**
U	1017.500	1298.500	1420.000	1547.500
Expected value	1610.000	1610.000	1610.000	1610.000
Variance (U)	31174.621	30817.379	29976.414	31384.621
p-value (Two-tailed)	**0.001**	0.076	0.274	0.726

4.4 Temporal Trends

Kendall’s tau test was used to identify temporal trends in variables over the entire time period (1900-2015) (Table 4.9). All variables displayed a statistically significant slope value, indicating a positive growth trend.

TABLE 4.9: Kendall’s tau trend test. H0 (no trend), Ha (there is a trend). All computed p-values are lower than the significance level, indicating there is a trend. The positive slope values indicate increasing numbers with time.

Kendall’s tau trend test	**Named Storms**	**Hurricanes**	**Major Hurricanes**	**ACE**
Kendall's tau	0.316	0.228	0.218	0.146
Sen’s Slope	0.053	0.023	0.01	0.34
p-value (Two-tailed)	< 0.0001	0.001	0.001	0.021

Inspection of graphs of the variables over time shows an upward trend, despite the noisiness of the data (Figure 4.5 - 4.8).

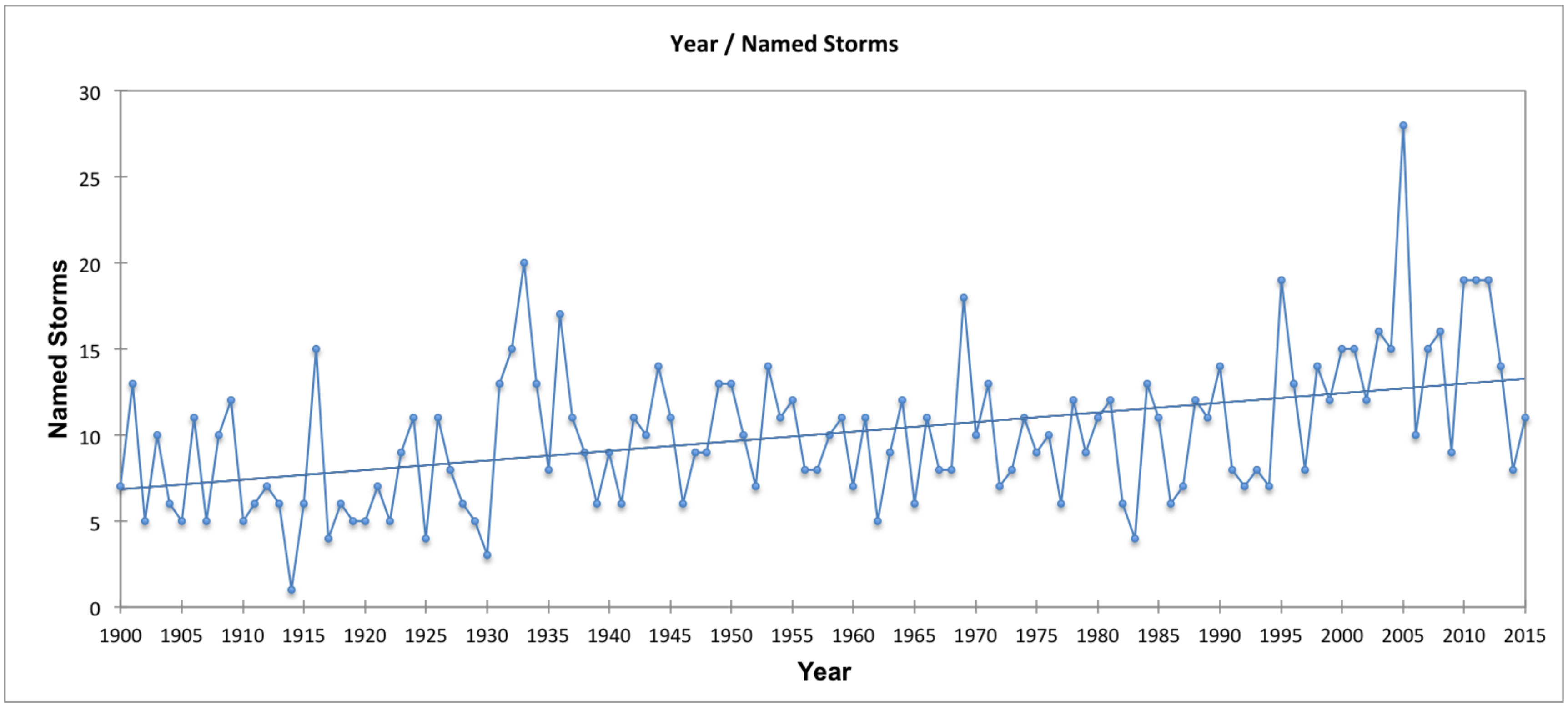

FIGURE 4.5: Trend of Named Storms, with a Sen's slope of 0.053.

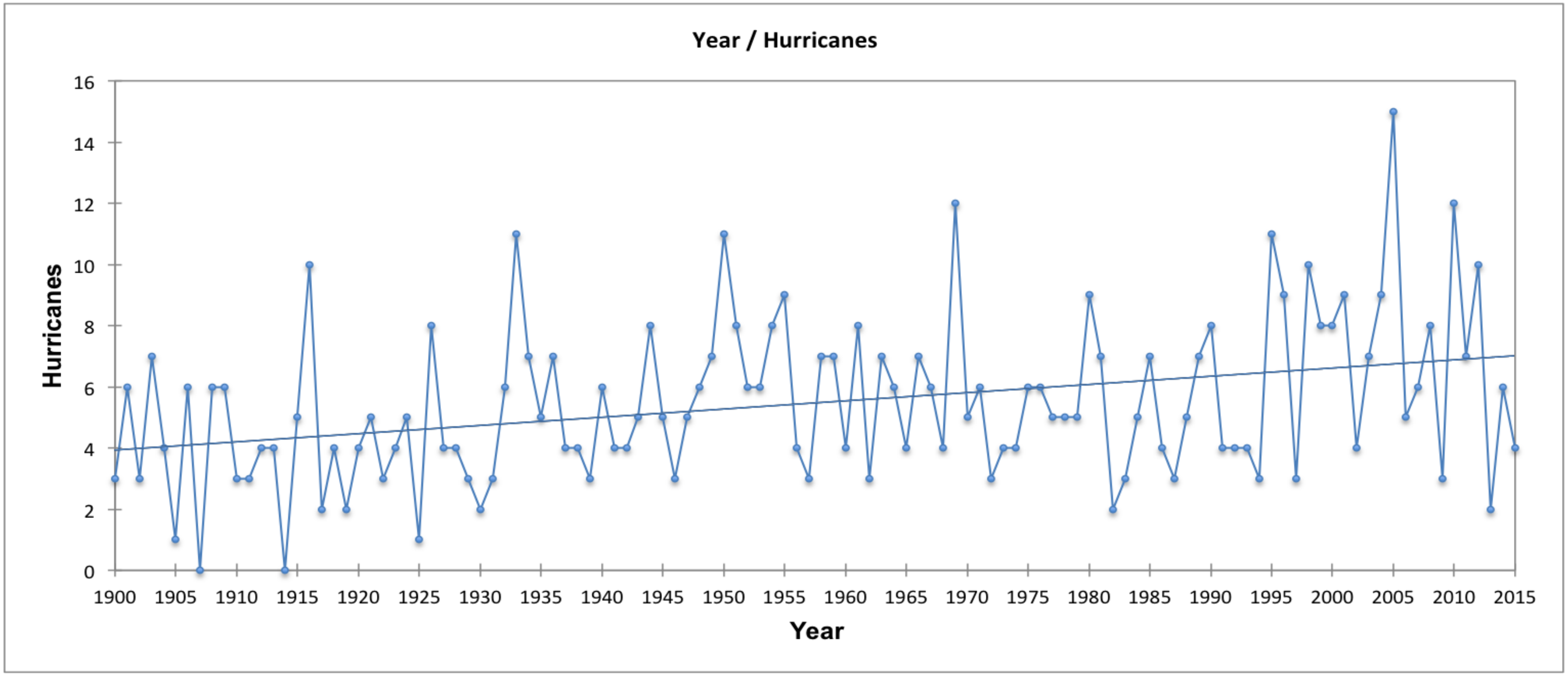

FIGURE 4.6: Trend of Hurricanes, with a Sen’s slope of 0.023.

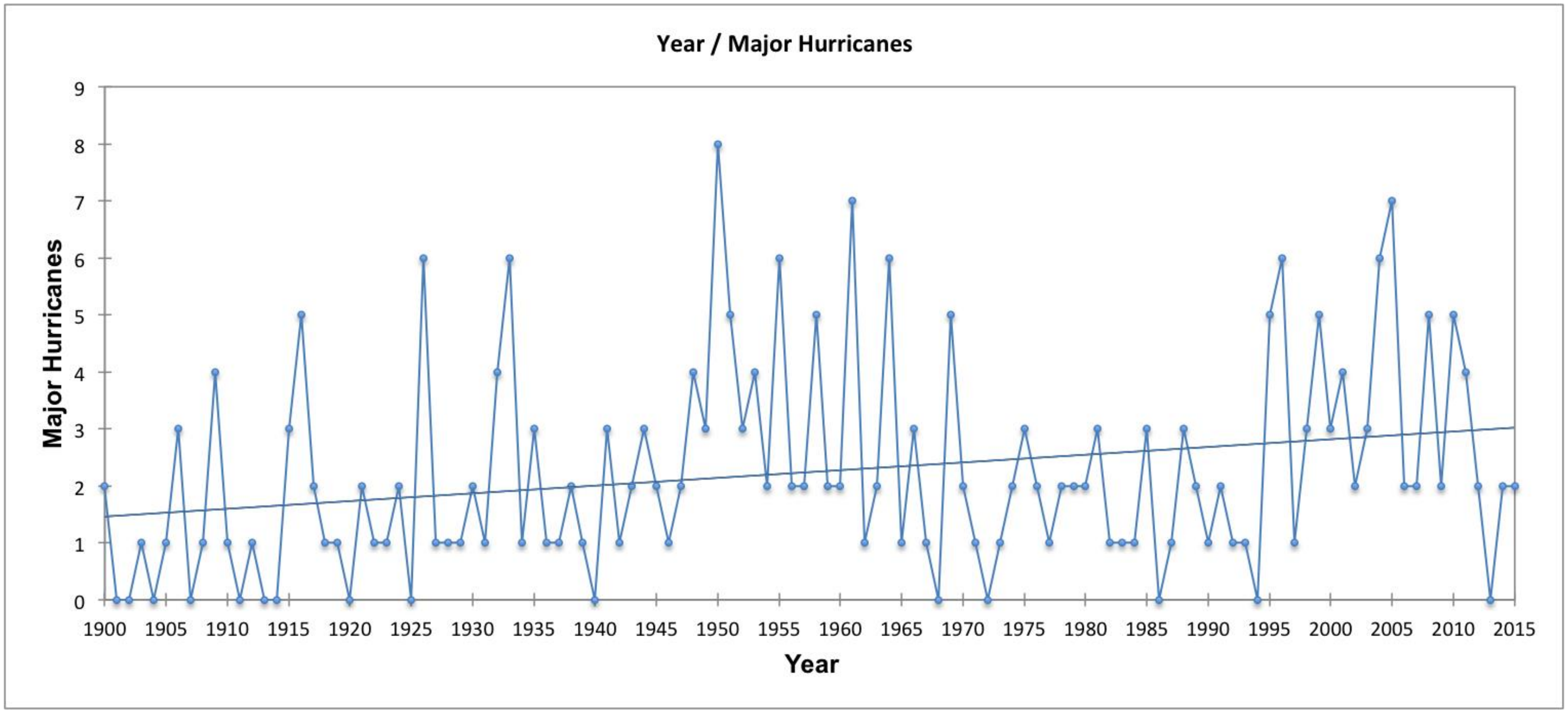

FIGURE 4.7: Trend of Major Hurricanes, with a Sen’s slope of 0.01.

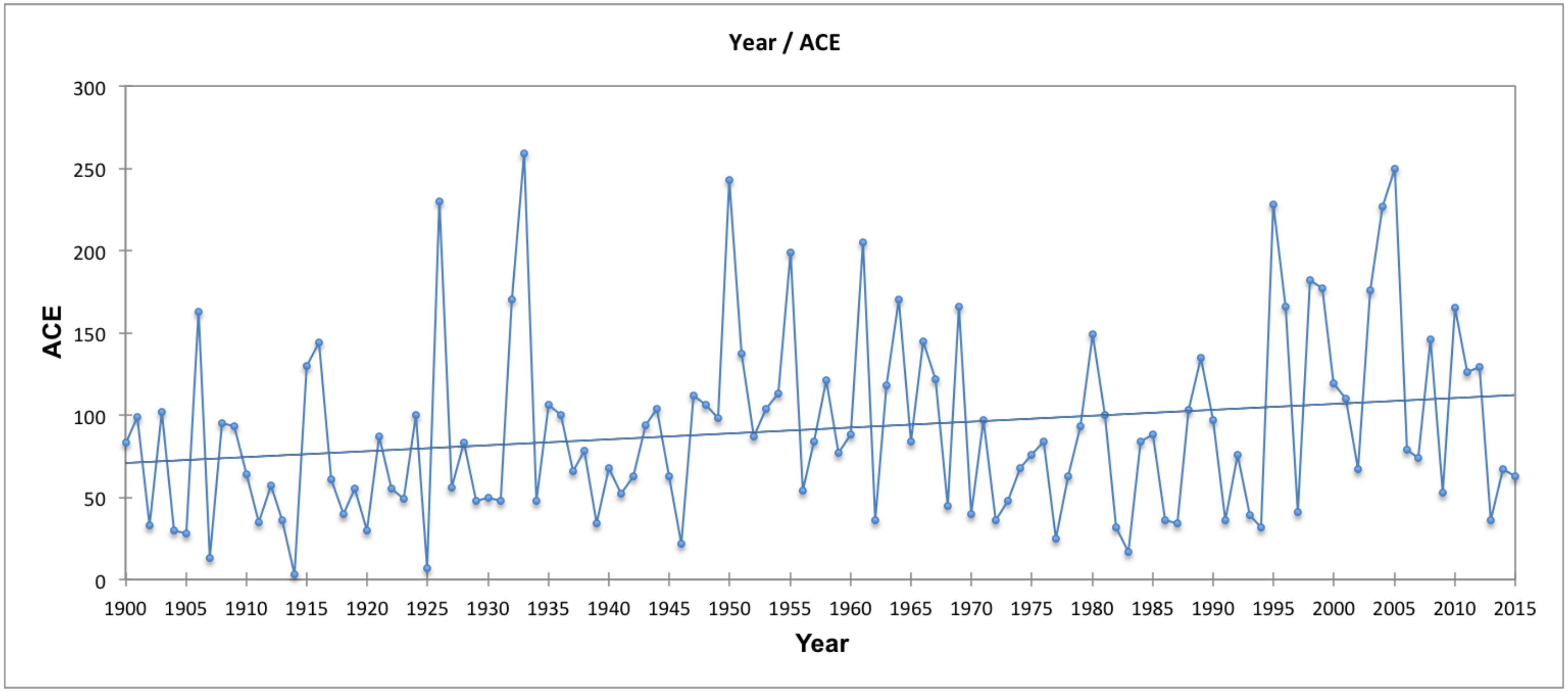

FIGURE 4.8: Trend of ACE, with a Sen’s slope of 0.34.

5. DISCUSSION

5.1 Descriptive Statistics

Since 1970, there has not been a year with fewer than four named storms, compared to a minimum of one storm per year pre-1970. When comparing means and specifically the Named Storms variable, storm frequency may appear to be increasing temporally because of better measurement techniques in recent years (Levitus et al. 2009). Historically, Hurricanes and Major Hurricanes are more likely to be recorded because of longer lifespans and higher intensity; even prior to advanced technology and satellite imagery, these events were more likely to be detected by humans. Named Storms, which appear to be increasing in frequency, often times die out before reaching Hurricane strength, and do so quickly. Without satellite imagery many of these storms may not have been recorded. Low intensity hurricanes (those that do not fall into the Major category) could fall victim to technology limitations when dating back pre-1970 as well.

5.2 Normality Testing

The results of the Shapiro-Wilk test determined that the dataset was not normally distributed. This result was the deciding factor in using the T-Test, which is robust enough in nature to account for non-normal data despite being parametric, and the Mann-Whitney and Kendall’s tau, both of which are nonparametric tests.

5.3 Difference of Means

1. Two-tailed T-test

When looking back to the descriptive statistics, Named Storms displayed a mean of 8.971 and 11.717 for Period 1 and 2, respectively. Hurricanes had 5.071 for Period 1 and 6.087 for Period 2. Named storms (with an observed value of -3.565) have means that not only differ, but also differ greatly between the two sample periods. The difference of means between Major Hurricanes and ACE did not signify statistically significant change between Period 1 and 2; Major Hurricanes and ACE means appear to remain consistent between the two samples, indicating little to no variation.

2. Two-tailed Mann-Whitney

In comparison to the T-test, the Mann-Whitney yielded similar results. This time though, only Named Storms was flagged for significance. All other variables (Hurricanes, Major Hurricanes, and ACE) did not show statistically significant variance between the means of the two periods. The Mann-Whitney test, being nonparametric, is more sensitive to analyzing non-normal datasets; because of this, the results are likely more accurate than those displayed by the T-test.

5.4 Temporal Trends

The Kendall's tau results displayed significant upward trends in all variables. In agreement with the previous explanation, Named Storms displayed the most pronounced trend, followed next by Hurricanes, which is now comparable to Major Hurricanes as well. ACE, although the noisiest of the variables, still displays a significant increasing trend. The "noise" factor can be attributed to the smaller sample size annually of

Hurricanes and Major Hurricanes in comparison to Named Storms. Hurricanes and Major Hurricanes historically have more accurate data records than Named Storms (NOAA, 2015); this becomes significant when evaluating the validity of the results. Named Storms has the most defined trend, with ACE having the least. Named Storms represent the least amount of noise of the variables, where ACE appears to have the most, further affirming the p-values (< 0.0001 vs. 0.021) and Kendall's tau (0.316 vs. 0.146). Although the trend displayed is less pronounced than that of Named Storms the accuracy of the data and likelihood of a "true" trend are much higher.

ACE is calculated every six hours that a system is at tropical storm strength, encompassing all of our variables, and at the end of each year is added together to give an annual number for how intense the velocity of all systems were. For every individual variable with observed upward trends in (Named Storms, Hurricanes, Major Hurricanes), it is expected that there will be an upward trend with ACE as well. The variation in ACE through time is a direct representation of the intensity of all storms for that year, meaning even if the total number of Named Storms is higher, the ACE may be lower if the next year had fewer Named Storms but more Major Hurricanes. The increasing trend in ACE is likely a product of the higher number of Named Storms recorded since 1970 (Murakimi et al. 2014).

6. CONCLUSIONS

This study's goals were to evaluate trends in tropical cyclone frequency and intensity from 1900-2015 as well as differences between the past (1900-1969) and more recent (1970-2015) storm occurrences; this goal was accomplished by conducting a statistical analysis of Named Storms, Hurricanes, Major Hurricanes, and ACE using the following methods:

1. Analysis of the descriptive statistics. From this analysis the minimum and maximum years of storm occurrence were observed, as well as a general measure of storm intensity using ACE. Through visualization of the descriptive statistics, and by plotting the frequency temporally, it was hypothesized that the data was not normally distributed. By breaking the data into two sub-periods, it was noted that the means between Period 1 (1900-1969) and Period 2 (1970- 2015) were not the same. The hypothesis of a lack of normality was the deciding factor in utilizing the Shapiro-Wilk test to evaluate the normality of all time series.
2. Normality testing. The Shapiro-Wilk test for normality was used on the entire sample period (1900-2015) as well as the two sub-periods. The results of this test stated that all data was non-normal with high statistical significance. Because of this, it was decided that nonparametric testing would be used moving forward.
3. A Two-tailed T-test and Mann-Whitney were used to test for a difference of means as a measure of variation between the two sub periods. The results of the T-test showed significant difference of the Named Storms and Hurricanes

variable between the two periods. The Mann-Whitney test only showed significance within the Named Storms variable. With the T-test being a parametric measure, and the Mann-Whitney a nonparametric one, the results of the Mann-Whitney can be regarded with higher confidence. The fact that the two tests agree on Named Storms increases that confidence as well.

4. A Kendall's tau analysis was used to test for trend. The results presented display statistical significance of positive trend in all variables. Named Storms displayed the strongest trend, with a tau of 0.316.

These results agree with previous research in showing a slight increasing trend in tropical cyclone activity over time, as well as an increase in overall storm season intensity (ACE) temporally.

Because of technology limitations pre-1970, the validity of the results pertaining to Named Storms is questionable. Although the trends in Hurricanes and Major Hurricanes are less pronounced, the likelihood that they are compromised by lack of technology is lower.

For future research many other variables could be added to the analysis. Sea surface temperatures, climate indices (ENSO, the North Atlantic Oscillation, or the Atlantic Multidecadal Oscillation for example), as well as comparisons of other active ocean basins could be analyzed to add to the discussion. Currently, there is still much speculation on exactly how and to what degree tropical cyclones will be impacted by climate change.

Vulnerable coastlines are going to continue being the primary victims to tropical cyclones; for the future of these areas, it is pivotal that research of this nature persists and that high quality records continue to be maintained.

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