The Relationship Between Hurricane Intensity and Economic Damage in the United States

Emily Palmer

Spring 2014

Introduction

Early in the morning on August 29, 2005, Hurricane Katrina hit New Orleans. The next day, newspapers across the nation proclaimed it the “Killer Storm”, “Our Tsunami”, a “Sea of Sorrow”, and that “It Only Gets Worse”. Before its landfall in New Orleans, Hurricane Katrina was a Category 5 hurricane, the most intense ranking, although it diminished to a lower category upon its landfall. Hurricane Katrina was the second most damaging storm in the United States since 1900, costing $81 billion dollars in present dollars (Pielke et al., 2008).

Another extremely destructive storm for its time was Hurricane Agnes. It struck Florida June 19th, 1972, and over the next six days made its way up to New York. At the time, Hurricane Agnes was the most destructive hurricane to hit the United States. Adjusting the damage to the current year, it caused $18.4 billion in economic losses. However, there was one key difference between these two storms. While Hurricane Katrina was rated as the most intense ranking for hurricanes before its landfall, Hurricane Agnes was rated as the least intense category, and during some times in its life it was not strong enough to be classified as a hurricane.

In the 20th century, there were several examples of intense hurricanes that did not produce excessive damage. Hurricanes Diana (1984), Emily (1993), and Bret (1999), were all the same intensity as Katrina at its landfall, but produced considerably less damage.

The year Katrina hit, 2005, was a year with an increase in the number of hurricanes to make landfall in the United States. This lead to speculation that hurricanes were occurring more often, and leaving more destruction behind. In 2005, there were 28 named storms in the Atlantic Basin, fourteen of which were hurricanes, seven of those major hurricanes, three rated category 5. This exceeded the previous record of the number of hurricanes that occurred each year by 33%

(Holland, 2007), leading to the belief that hurricanes were becoming more frequent, destructive and intense.

Hurricane Katrina was a strong storm that caused extensive damage. Hurricane Agnes was a weak storm that caused extensive damage. These are just two examples, but what is the overall pattern? Given that wind speeds are a determining factor in rating hurricanes, one might assume that as wind speed gets higher, destructiveness would increase. However in these examples, that is not true. The 20th century has seen numerous changes: coastal areas have become more populated, warning systems have become more accurate, and on average, people own more possessions that can be damaged, all of which have an effect on the damage caused. It is possible that these changes have impacted the relationship between intensity and damage Hurricane damage changes over the years, as does hurricane frequency and intensity. With populations along the coast high and dense, it is extremely unlikely that a hurricane could hit now without causing any damage (Pielke et al., 2008). The question of this research is then this: is there a relationship between intensity (as measured by pressure and the Saffir-Simpson Scale) and destructiveness (as measured by economic losses)? If so, is such a relationship strong or weak? Has the strength of the relationship changed over time? In other words how closely related are damage and intensity?

Some scientists attribute some of these changes to global climate change or increases in accumulation of greenhouse gases. However, the discussion of climate change is outside the scope of this paper. This paper will not relate the results of this research to climate change, although it is possible that it is a factor in the changes.

Hurricanes are extremely complex and affected by numerous influences. There are many factors that play a part in a hurricane's intensity and the damage it causes. Understanding the science of hurricane formation is the basis for understanding the factors that contribute to their destructiveness. Also, reviewing trends that have been found so far in both hurricane intensity and destruction is important to gain historical perspective. It is important to see how each individual factor has changed over time before one can look at the multitude of variables involved. Similarly, predictions about the future frequency and intensity of hurricanes are important to understand what might happen in the future. Lastly, adjusting values of economic destruction for past hurricanes must be done to compensate for those factors that have changed and be able to compare them to today's standards. Only after understanding all of this can we accurately examine how the relationship between a hurricane's intensity and its damage has changed over time.

Science of Hurricanes

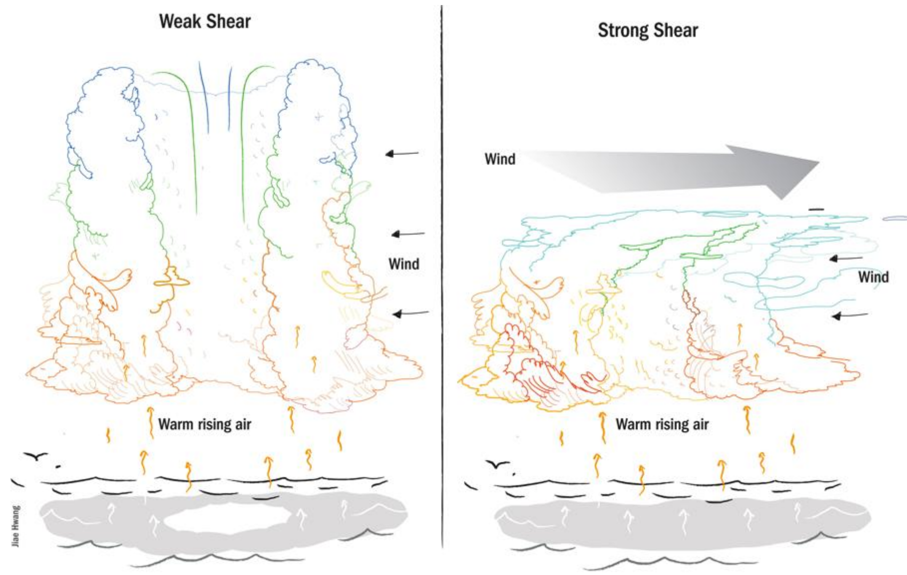
In order to understand the relationship between hurricane intensity and destructiveness, one must start by knowing what a hurricane is. Hurricanes are low-pressure, rotating tropical storms that cause major destruction to coastal communities at their landfall. A tropical storm is classified as a hurricane when its sustained winds reach over 74 mph. Storms with sustained winds under that are known as tropical storms (<74mph) or tropical depressions (<38mph) depending on their maximum wind speed. Hurricanes form between 5 and 30 degrees North latitude, and rotate and move westward in the Northern Hemisphere.

Almost all hurricane activity that affects the United States takes place in the North Atlantic Basin. Hurricane season runs from June 1^{st} to November 30^{th}. While other basins, especially the Northwestern Pacific Ocean, see more hurricane activity, the Atlantic Basin has a (relatively) reliable historical record of hurricanes from 1900 to present, although it is possible that it is not characteristic of all hurricane basins. (Landsea et al., 1996). To see the relationships changing through time, it is important to have a relatively long record focused on one basin. Therefore, the research in this paper looks only at data of hurricane damage and intensity in the Atlantic Basin.

Conditions Necessary for Hurricane Formation

To start analyzing the relationship between hurricane intensity and destructiveness, it is important to start with hurricane formation. Hurricanes are fueled by energy in the ocean. Hurricanes originally form from existing disturbances in the atmosphere above the ocean; most commonly waves of winds blowing towards the west originating near Africa, but occasionally cyclone-like storms that form outside the tropics. Over 60% of tropical storms begin from these atmospheric waves, and account for 85% of the most destructive hurricanes (Landsea, 1993). These waves have a cooler temperature compared to the surrounding ocean, causing a favorable environment for hurricane formation. Hurricanes require sea surface temperatures of 27ºC to form. The warm ocean water evaporates, rises, and condenses, releasing energy, and forms clouds and thunderstorms. Thus, moist air is also necessary for hurricane formation. The major hurricane producing areas usually have about 80% humidity, although changes in humidity do not produce a noticeable effect on the intensity of hurricanes (Emanuel 1987). The beginning of the hurricane then begins to rotate counterclockwise due to the rotation of the earth. As hurricanes travel over the ocean, more moist air condenses, powering the hurricane. Equally, once a hurricane hits land, the energy from the ocean water is gone, and the hurricane dissipates. Hurricane Katrina, for example, was a category 5 storm before hitting land. It changed back to a category 3 hurricane soon after landfall.

Hurricanes require low vertical wind shear to form. Wind shear is the difference in wind speed between levels of the atmosphere. Picture 1 shows this effect. A greater difference in wind speed would result in a higher vertical wind shear. If there was greater wind speed higher in the atmosphere, or stronger wind shear, it would end the possibility of a hurricane gaining the height necessary to sustain its rainclouds, as the difference in wind speed would disrupt the clouds. With low wind shear, the rainclouds can build vertically, and then begin rotating around a low-pressure area.



Picture 1

Factors that determine intensity

Hurricane intensity is not the same as its destructiveness. Intensity can be thought of as the power within the storm itself, whereas destructiveness, discussed later, is the damage caused by the storm. The factors explained below vary for each hurricane and are thus important to understand before relating them to the damage.

The pressure of a hurricane largely determines its intensity, which is directly correlated to the wind speed it generates (Emanuel, 1987). In other words, the lower the pressure, the higher the wind speeds. Pressure differences cause winds, and so larger pressure differences cause higher winds. Hurricanes generate pressures commonly ranging from 900 to 980mb, which is much less than the normal atmospheric pressure of 1013.25mb. Storms with pressures much lower than the surroundings can have stronger winds. More intense hurricanes almost always have lower pressure. Pressure, therefore, can be seen as a good measure for the intensity of the storm, and will be used in this paper alongside wind speed as a measure of the intensity of the storm.

The sea surface temperature (SST) of the ocean also plays a large part in the intensity of hurricanes, as temperature affects both pressure and wind speed. As stated above, tropical cyclones require a SST of 27ºC or higher to form. In addition to that, small changes in SST lead to quite large changes in intensity. In theory, an increase of 1ºC will lead to 5% higher wind gusts. (Emanuel, 2005) and a 3ºC will result in a 30-40% pressure drop (Emanuel, 1987). Since 1970, SSTs have increased by 1ºC.

Wind speed is also important to both understanding a hurricane's intensity, as well as classifying a tropical storm. The Saffir-Simpson scale, developed in 1971, is the official ranking system for the intensity of hurricanes. It is on a 1-5 number basis, with 5 being the most intense. Nowadays, it is based solely on the maximum sustained winds of the hurricane. The peak wind gusts of a hurricane can be 10-25% stronger than the maximum sustained winds. (NOAA) The Saffir-Simpson scale is also used as an indirect way to predict damage, as shown in Table 1.

Saffir-Simpson Hurricane Wind Scale

Category	Wind Speed (mph)	Predicted Damage
1	74-95	**Very dangerous winds will produce some damage:** Well-constructed frame homes could have damage to roof, shingles, vinyl siding and gutters. Large branches of trees will snap and shallowly rooted trees may be toppled. Extensive damage to power lines and poles likely will result in power outages that could last a few to several days.
2	96-110	**Extremely dangerous winds will cause extensive damage:** Well-constructed frame homes could sustain major roof and siding damage. Many shallowly rooted trees will be snapped or uprooted and block numerous roads. Near-total power loss is expected with outages that could last from several days to weeks.
3	111-130	**Devastating damage will occur:** Well-built framed homes may incur major damage or removal of roof decking and gable ends. Many trees will be snapped or uprooted, blocking numerous roads. Electricity and water will be unavailable for several days to weeks after the storm passes.
4	131-155	**Catastrophic damage will occur:** Well-built framed homes can sustain severe damage with loss of most of the roof structure and/or some exterior walls. Most trees will be snapped or uprooted and power poles downed. Fallen trees and power poles will isolate residential areas. Power outages will last weeks to possibly months. Most of the area will be uninhabitable for weeks or months.
5	> 155	**Catastrophic damage will occur:** A high percentage of framed homes will be destroyed, with total roof failure and wall collapse. 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.

(http://www.nhc.noaa.gov/aboutsshws.php)

Table 1

The Saffir-Simpson scale is not entirely reliable. Originally it was based on a combination of pressure, wind speed and storm surge values. It changed to be solely based on wind speeds in the late 1970s. This has led to an inconsistency in the historical records that use this scale. For measures of pressure and wind speed, records are also not completely consistent. Before 1950, airplanes monitoring hurricanes were not launched; before 1970 satellite pictures were not taken of the hurricanes; and before 1997 the instruments used to collect data were not as precise as the ones currently available (Norcross 2007). Thus it is hard to exactly measure the intensity of older storms on the record.

Despite the problems with the Saffir-Simpson scale, it is still used today as the measure for a hurricane's intensity, and often used to compare historical storms. In this research, the Saffir-Simpson Scale as well as pressure will be used as measures of intensity.

Looking back at Hurricane Katrina and Hurricane Agnes in relation to wind speed and pressure shows again the large difference in intensity of the two storms. Hurricane Katrina was a category 5 storm before it hit, then dissipated to a category 3 storm at its landfall. It had a pressure of 920mb and maximum wind speeds of 127mph. In contrast, Hurricane Agnes was a category 1 storm, and along some of its lifespan was a tropical storm. It had a pressure of 980mb and 85mph winds, a significantly higher pressure and lower winds than Katrina.

ENSO

The El Niño-Southern Oscillation (ENSO), which includes El Niño and La Niña, is a cycle that affects hurricanes. It also affects the interpretation of hurricane trends. ENSO is one of the factors that indirectly affect the intensity of hurricanes in the North Atlantic Basin. It is important to clarify that it is not ENSO itself that affects the intensity, but it is the effects of ENSO that cause hurricane intensity to change.

ENSO is when the ocean temperature off the coast of Peru and Ecuador is warmer (El Niño) or colder (La Niña) than usual. El Niño occurs when winds that blow eastward across the Pacific Ocean weaken and are not able to push the warmer waters offshore. Thus the cooler deeper water in the ocean does not rise to the surface. La Nina produces the opposite effects. The winds grow stronger allowing more cold water to rise. Since hurricanes are strongly affected by sea surface temperatures, these cycles impact hurricanes greatly.

ENSO produces effects opposite in the Atlantic Ocean to the Pacific Ocean. El Niño conditions contribute to increased hurricane activity in the Pacific Basins, and decreased activity in the Atlantic Basin (Pielke and Landsea, 1999). During El Niño in the Atlantic Ocean, there is increased vertical wind shear because of increased winds in the upper troposphere, and greater wind shear results in a smaller possibility for hurricane formation. During La Niña years, this wind shear effect is decreased, leading to a higher likelihood of hurricane formation and development during La Niña. There is a 66% chance that at least two hurricanes will strike in the Atlantic Basin during La Niña years compared to a 28% chance during El Niño years. The hurricanes that do strike during La Niña years are more likely to be major hurricanes (categories 3-5). The chance that there will be at least one major hurricane is 63% during La Niña and 23% for El Niño. (Pielke and Landsea, 1999) Thus ENSO has a large effect on hurricanes and can influence how intense hurricanes can become. Depending on which cycle ENSO is in during the year of a hurricane's formation could possibly affect the relationship between intensity and destructiveness.

Effects of Hurricanes/ Damage caused by Hurricanes

Hurricanes cause billions of dollars in damage. In this paper, hurricane destructiveness is defined as the economic damage associated with the hurricane. Where does this damage come from? The economic losses from hurricanes mainly come from a hurricane's storm surge, its winds, the floods it causes, and tornadoes that sometimes occur. In researching the correlation over time between hurricane intensity and destructiveness it is important to understand what factors cause the actual damage, and how they have changed over time.

Storm surges associated with tropical cyclones are accountable for the majority of the damage caused by hurricanes (Burt and Stroud, 2004). Storm surges are vertical walls of water that are lifted up by the immense winds of the hurricane. This wall, which can rise to around 20 feet, floods the coast and can cause damage to houses, cars, and people. In addition to flooding, water is dense, so when it comes crashing to the coast, the force of the water hitting causes damage. The low pressure at the center of the hurricane has only a small effect on the storm surge. Storm surges are also affected by incline of the continental shelf, or the shallow land before the deep ocean, and the angle at which the hurricane approaches the shore. Although quite damaging, storm surges are difficult to predict, and are hard to measure precisely, so are not a good measure for the intensity of the storm. However, part of the damage caused by each storm is due to the storm surge, a larger storm surge would cause more damage than a small one.

For a storm to be considered a hurricane, it must have winds above 74 mph. Winds this high can be extremely dangerous, and cause damage to structures. Debris that is loose becomes projectiles, which can hit people, or cause even more damage to buildings. The Saffir-Simpson Scale uses wind speeds to predict the damage that a hurricane will cause because with higher winds, more secure structures are at risk of being damaged. However winds are not always accurate to predict the economic damage caused, as the examples of Hurricane Katrina and Agnes show.

Hurricanes cause massive amounts of rain. Combined with the storm surge, hurricanes often leave behind immense floods. A large amount of the economic damage hurricanes cause is due to floods. Homes can be completely submerged, causing structural damage, cars can be damaged, and although it is not counted as economic losses, floods from hurricanes cause half of the deaths associated with a hurricane. The extent of floods does not depend on the winds, and weaker storms can occasionally cause more flooding than stronger storms.

Almost every hurricane that makes landfall creates at least one tornado (Spratt et al., 1997). Tornadoes are smaller rotating storms with much higher winds. The damage they cause is primarily from the high winds. Tornadoes are more localized, while hurricanes can span hundreds of miles. Nevertheless, tornadoes caused by hurricanes do contribute to the overall damage from a hurricane.

Changes in Potential Damage

While all the causes of damage remain the same, many of the things that can be damaged have changed over the past 100 years. Populations along the coast have increased by 33 million or 28 percent between 1980 and 2003 (Crosset 2004). Population density along the coast has also increased by 28 percent, and this is predicted to increase in the future. With more people living closer together in areas susceptible to hurricanes there is a greater chance that a hurricane will do more damage, as there is more property available to be damaged. Florida, one of the states with frequent hurricane landfalls, has one of the highest number of housing units per square mile. There has also been a change in the types of houses built along the coast. Trailer homes are becoming more common along the coasts (Cutter 2011). Trailer homes are much more vulnerable to hurricanes than frame houses. Weaker hurricanes can do damage to trailer homes, whereas they would not do as much damage to houses. With an increase in trailer homes, there could be a possible increase in the destructiveness of weaker storms compared to the past.

Researched Trends and Predictions

To gain an accurate picture of the relationship between damage and intensity one must examine trends and predictions relating to different measures of intensity and destruction. How have these factors changed independently? Some factors have stayed the same, while others have increased or decreased. These will then be combined to look at correlation in the research.

Trends are very difficult to measure for hurricanes. There are countless factors that affect how strong hurricanes become. Sometimes short-term trends are actually due to factors such as ENSO. Also climate changes slowly. The historical record we have, including its flaws, only goes back about a century. The last decade or two is a very short time span for any trends that show to be very reliable. Knutson et al. explain the difficulty in researching various hurricane trends:

> Large amplitude fluctuations in the frequency and intensity of tropical cyclones greatly complicate both the detection of long-term trends and their attribution to rising levels of atmospheric greenhouse gases. Trend detection is further impeded by substantial limitations in the availability and quality of global historical records of tropical cyclones. Therefore, it remains uncertain whether past changes in tropical cyclone activity have exceeded the variability expected from natural cause. (Knutson et al., 2010)

The trends that have been researched so far have been controversial. This is largely due to the complexity of the issue. There have been numerous and often conflicting studies about these trends. In addition, the studies that have detected a trend do not necessarily agree if this trend is only due to natural causes or results from human disruption. Some trends also appear to be cycles. If in fact hurricanes have been increasing in intensity recently, it could just be the upward curve in a normal cycle. In addition, many articles researching trends were written around 2005, a year with an increased number of destructive storms, which will most likely distort the data.

Intensity

How has intensity of hurricanes changed over time? Intensity can be considered in many different ways. The Saffir-Simpson scale is officially used to differentiate between tropical storms, hurricanes, and major hurricanes. Pressure and wind speed are other ways to separately look at how strong, or intense, a hurricane is. Although there has been much research into past occurrences, there is a lot of interest in how the future climate might look. It is predicted that the maximum wind speed of hurricanes will increase 2-11% globally by the end of the century, resulting in an increase of intensity (Knutson et al., 2010).

Major Hurricanes

There has been a great deal of research on different trends regarding hurricanes, even though many factors influence the data. There is much that has been done regarding major hurricanes (categories 3,4 and 5). Webster et al. (2005) stated that there has been an increase in the number of category 4 and 5 hurricanes. Elsner et al. (2008) also say that there has been a 30-year increasing trend of major hurricanes, and that this is likely due to increasing sea surface temperatures. Grey and Landsea (1996) disagree saying the measures Webster et al. used for intensity are exaggerated, and the increase is not as large as they stated, showing the complexity of measuring trends.

Major hurricanes may be more common in the future. It is predicted that the number of major hurricanes each year may even double; models predict an 81% increase in the number of category 4 and 5 hurricanes in the next 80 years (Bender et al., 2010). The wind speed and pressure of hurricanes are also predicted to increase, leading to stronger, more intense storms (Knutson 2008).

Frequency

Has the general frequency of hurricanes increased? Predictions for frequency in general are different than predictions for frequency of intense hurricanes. There is general agreement that the number of hurricanes per year is not increasing, but decreasing or remaining the same (Landsea 1996, Pielke 2005). An older study showed that there has been a five-decade decrease in the number of hurricanes that occurred each year in the Atlantic Basin (Landsea, 1996). However global hurricane frequency has not changed in recent years.

The future predictions for frequency might not be what one would expect. Opposite from intensity, it is predicted that the frequency of tropical cyclones will either remain unchanged or decrease. Different models predict that the frequency of tropical cyclones should decrease by 6-34% by 2100 (Bender et al., 2010).

Why would the frequency of hurricanes decrease? One possible reason for this predicted decrease relates to wind shear. The warming that could cause sea temperatures to rise could also lead to an increase in the vertical wind shear. This predicted increase (Knutson et al., 2008) would lead to potential hurricanes to be blown apart before they could establish. In other words, it is predicted that there will be more major hurricanes, but fewer hurricanes overall.

Destruction

Trends in monetary losses must be measured using some means of adjustment, as explained below. Using two adjustment methods, Pielke et al. (2005) found that there was no trend in economic damage since 1900. However, it has been shown that La Niña years show more damage for hurricanes in the Atlantic Basin with an average loss per storm of $1,600 million compared to $800 million in El Niño years.

The potential destructiveness of a hurricane can be predicted by a model established by Emanuel (2005). This measure is known as the power dissipation index, which is defined as the "integral over the lifetime of all storms of the surface wind speed cubed". This measure depends on both frequency and intensity as well as the length of the hurricanes. The power dissipation index, or potential destruction has increased over the last 30 years (Emanuel, 2005). It is interesting to note that while the recorded damage has shown no trend, the measured potential destructiveness has increased. Emanuel goes to theorize that this is because his method included hurricanes that never hit land while Pielke's research only deals with hurricanes that make landfall (Pielke 2005).

One study predicts that global damage caused by hurricanes will increase. They state that the average damages caused each year will double by 2100 (Mendelson et al 2004).

Deaths due to hurricanes have been decreasing. Since 1900 the average annual deaths caused by hurricanes have decreased by 79% (Goklany, 2009). Goklany theorizes that this is possibly due to better access to technology and money to deal with such extreme weather events. It is interesting to note that while economic damage has not changed, death rates have gone down.

Normalization

Normalization is when data recorded in the past are adjusted so they can be compared to today's standard. Normalization is vital to being able to analyze monetary losses from hurricanes. As half of the data used in this research is economic losses (the other half is intensity), normalization is necessary for this research. Much has changed since 1900, when records from hurricanes started to be more reliably kept. Normalization allows one to estimate the damage that would be caused if a past storm made landfall today. The data that will be used in this research will be normalized using a method established by Collins and Lowe (Pielke et al., 2008). It normalizes the economic damage from hurricanes that make landfall along the U.S Gulf and Atlantic coasts (the Atlantic Basin coasts). Economic damage is defined as "the direct losses associated with a hurricane's impact as determined in the weeks (and sometimes months) after the event" (Pielke et al., 2008). Collins and Lowe's method adjusts for three factors: inflation, wealth, and housing units. A multiplier is found for each factor, and then those are multiplied with the un-normalized data recorded in the year of the storm. Their normalization method uses the equation $D_{current\ year} = D_y * \ I_y * W_y * HU_y$ where $D_{current\ year}$ is the normalized damage, D_y is the reported damage in the year of the hurricane, I_y is the inflation multiplier for the year of the storm, W_y is the wealth multiplier for the past year, and HU_y is the housing unit multiplier for the year of the storm for the county of the storm. Their method differs from previous normalization methods in that it uses coastal county housing units instead of population for the affected counties. This is because they believe that the number of areas at risk of damage has increased faster than the population growth in the same areas.

Collins and Lowe's first factor is inflation, (I_y). Inflation is the decrease of the value of a currency over time. Without adjusting for inflation, storms in the past would automatically seem less destructive than storms now, as money is worth less currently. To normalize for inflation, Collins and Lowe used the implicit price deflator for gross domestic product (IPDGDP) provided by the Bureau of Economic Analysis. This is then turned into a ratio of the IPDGDP of the current year to the IPDGDP for the year of a particular storm that made landfall. This ratio is then multiplied by the recorded losses for that hurricane.

The next value adjusted for is wealth per housing unit, or household (W_y). Over the years households on average have gained more value, either the buildings themselves are built with more expensive material, or the goods inside are worth more and are more numerous. National wealth is defined as "the estimate of current-cost net stock of fixed assets and consumer durable goods produced each year by the U.S. Department of Commerce's Bureau of Economic Analysis (Pielke 2008). Normalizing for wealth per household instead of wealth per capita is important because it is the households that sustain the economic damage, not the people.

Adjusting for wealth per housing unit is more complex. First the ratio of national wealth for the year of the hurricane to the current year is found. Then it is divided by the inflation multiplier as explained above. So far, this is the same as finding wealth per capita, or the real wealth multiplier, but it still must be adjusted for each household. To do that, a ratio of the estimate of total U.S. housing units for the year of the hurricane to the current year is formed. Then the real wealth multiplier is divided by the ratio of number of households, normalizing wealth per household.

The final means of adjustment that Collins and Lowe use is number of county households, or housing units (HU_y). This is done by each county the storm affects. With a higher number of households, there is a greater risk that a storm will cause more damage. When adjusted for, storms that hit highly populated areas can be compared to storms that hit less populated areas. Also, this takes into account the growth of cities and towns over time. Household information is found from US Census data since 1940, and before then was estimated using populations and linear extrapolation. To adjust for households, a ratio of county housing units of the current year to the year the storm made landfall is created. This is the housing unit multiplier.

To normalize the data of destructiveness by economic losses, all three of the previous adjustments must be combined. The normalized damage equals the reported losses in the year of the storm, times the inflation multiplier, times the wealth per housing unit multiplier, times the housing unit multiplier. Or using the equation: $D_{current\ year} = D_y * \ I_y * W_y * HU_y$. Together, this creates a value for destruction that can be compared to any hurricane regardless of the year or location it hit.

Research Design

Previous studies on hurricanes have focused on detecting trends in individual factors or predicting future trends. This research will focus on seeing how closely related intensity and destruction are, and if that relationship has changed over time. The strength of relationships in this research is measured using the coefficient of determination, or r^2 value. The r^2 value also describes how the variation in the independent variable accounts for the variation in the dependent variable.

Pressure will be used as one of the measurements for intensity as it is one of the most accurate and reliable measure for intensity (Knaff and Zehr, 2007). Data for pressure were obtained from a report by Blake et al. in 2011.

The official ranking of the storm will also be used as a measure of intensity. This will be measured using the Saffir-Simpson Scale. It will be used because it is the official ranking system for hurricanes, is available for the time frame considered in this paper, and includes wind speeds in its measurement. It will be interesting to see if the scale's use for predicting damage will be useful after analyzing its strength of correlation with damage. It will also be interesting to see if the correlation is different than the one of pressure and damage. As wind speed and pressure are closely related, it would be expected that they would produce similar results. The data of categories was obtained from Pielke et al. in 2008 that listed all hurricanes since 1900.

Economic damage in dollars was chosen as a measurement for destructiveness because it is the most consistent measure and can easily be normalized to be usable by current day standards. Casualties were not included in destructiveness both because of the moral reason that human life cannot be assigned a dollar value and that earlier records may not be as reliable. The data for economic damages were taken from a study by Pielke et al. (2008) using economic data that were normalized by a method established by Collins and Lowe.

Results and Discussion

Relationship Between Intensity and Economic Destruction

In this research, intensity was measured using both pressure and the Saffir-Simpson scale. Destruction was measured in normalized US dollars for economic losses. The relationship between pressure and economic losses is exhibited in Figure 1. The strength of the relationship is measured using the coefficient of determination, or r^2 value, that was generated from the equation for exponential regression. In this case, this value describes how well a certain variation in pressure will explain the variation in the damage. It also describes how well the curve fits the data points. It was found that a linear regression did not fit the data as well as an exponential

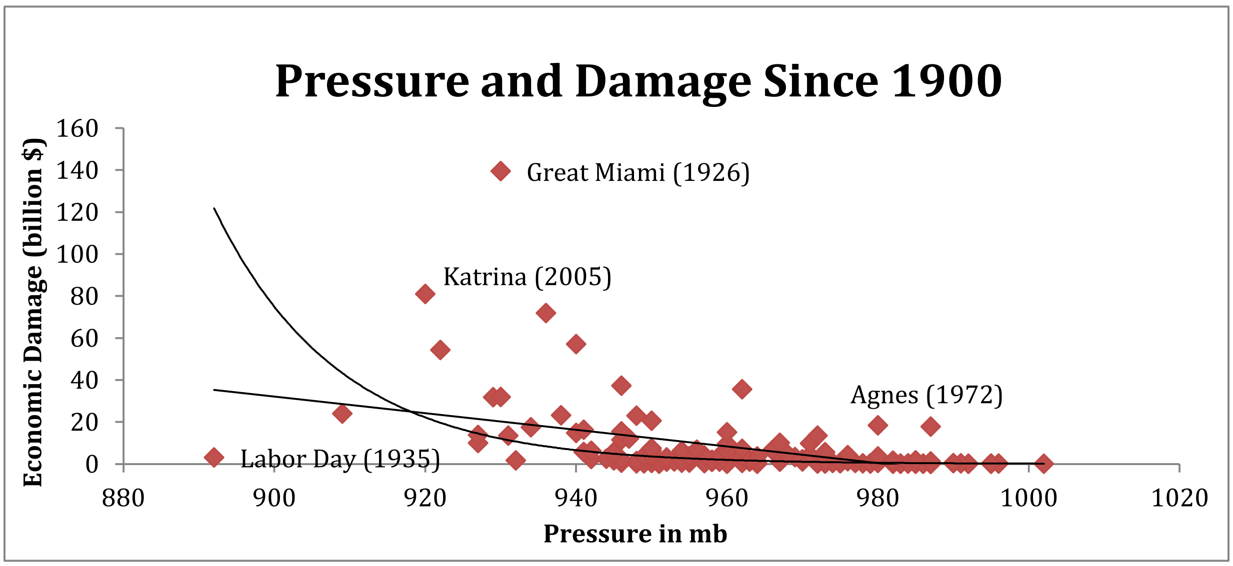


Figure 1

regression, as can be seen from the graph below. The strength of the relationship was also greater for the exponential regression than linear, an r^2 value of .433 for the exponential regression compared to .205 for the linear regression. Therefore, the following comparisons between intensity and pressure will use exponential regression. In the data set, there were some hurricanes that had normalized damages of zero dollars, which was caused from rounding and the normalization process. To create an exponential regression, these hurricanes had to be removed from the data set.

It might seem strange that damage decreases as pressure rises. But remember that lower pressures cause stronger storms. Any chart with pressure and damage then must have this negative relationship.

From this process, it was found that pressure and damage have a strong relationship. The r^2 value of this relationship was .433. This is a quite strong relationship, variation in pressure depicted by the exponential line accounts for 43% of the variation in damage. Especially considering the natural variation hurricanes have, this shows a strong relationship between intensity and destruction.

As Figure 1 shows, the higher the pressure, the closer to the line the damage lies. The storms with the lowest pressure are further spread out from the line. To analyze this further, hurricanes were divided into categories of low and high-pressure storms by the median pressure value, 960 mb. These were then analyzed separately to find the different strengths of relationships. It was found that the hurricanes with lower pressure were further from the curve than the storms with higher pressure, with r^2 values of .25 for low-pressure storms compared to .34 for high-pressure storms. This relationship is shown in Figures 2A and 2B.

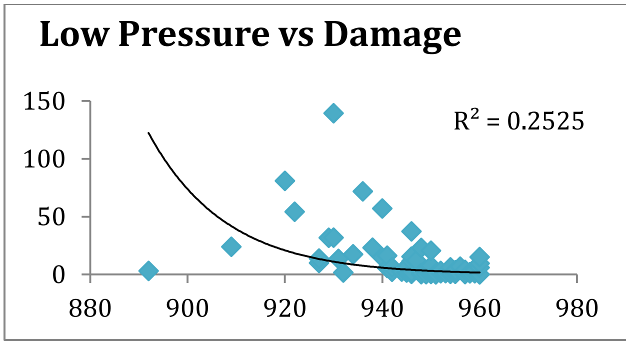


Figure 2A

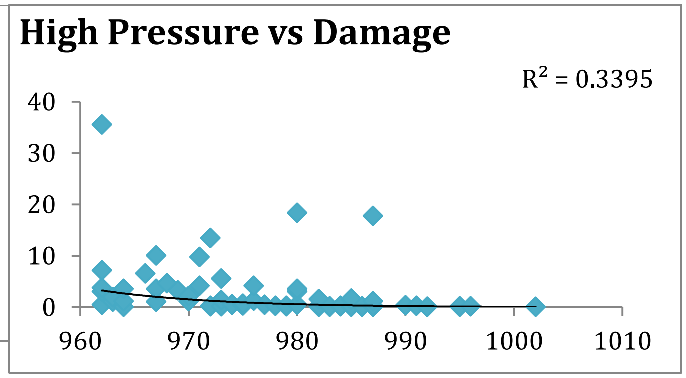


Figure 2B

From this, it makes sense that Hurricane Katrina caused significant damage, as it was a low-pressure storm. Hurricane Agnes, on the other hand can be seen as an anomaly, as it was a high-pressure storm with significant damage.

Category and Economic Losses

The other measure of intensity used in this research was the Saffir-Simpson category for each hurricane. It proved to have a very strong relationship with pressure, with an r^2 value of .74. This shows that it is a slightly different measure than pressure and because of this, both measures of intensity were used.

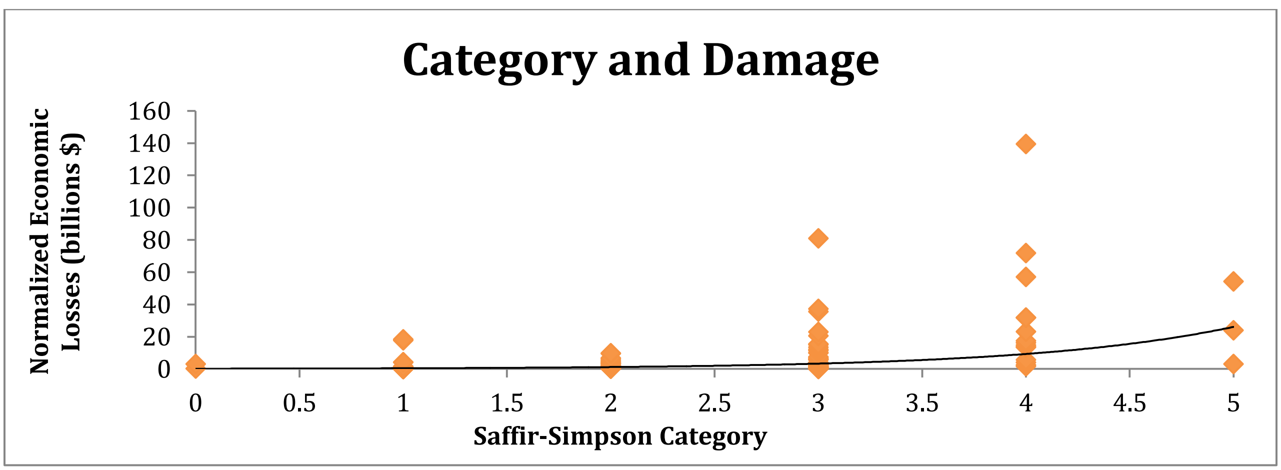


Figure 3

The relationship between the Saffir-Simpson category of a hurricane and its economic damage, as seen in Figure 3, also has a relatively strong relationship with damage, with an r^2 value of .38. This is a slightly weaker than the relationship between pressure and damage. This could lend support to why pressure is a better indication of intensity than the Saffir-Simpson Scale. It could also have a weaker relationship because unlike pressure, the category of the hurricanes only has whole number steps, whereas pressure is a continuous variable.

Relationship of Pressure and Damage Over Time

The original question of this research was to see how the relationship of intensity and damage has changed over time. To do this, the hurricanes were divided by year into the same four sections used for frequency. The relationships of pressures and damages are presented below in Figures 4 A-D.

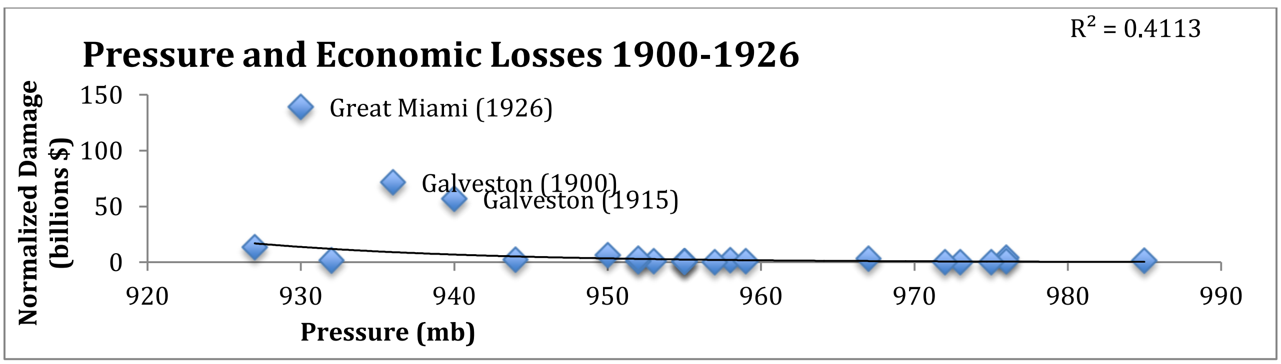


Figure 4A

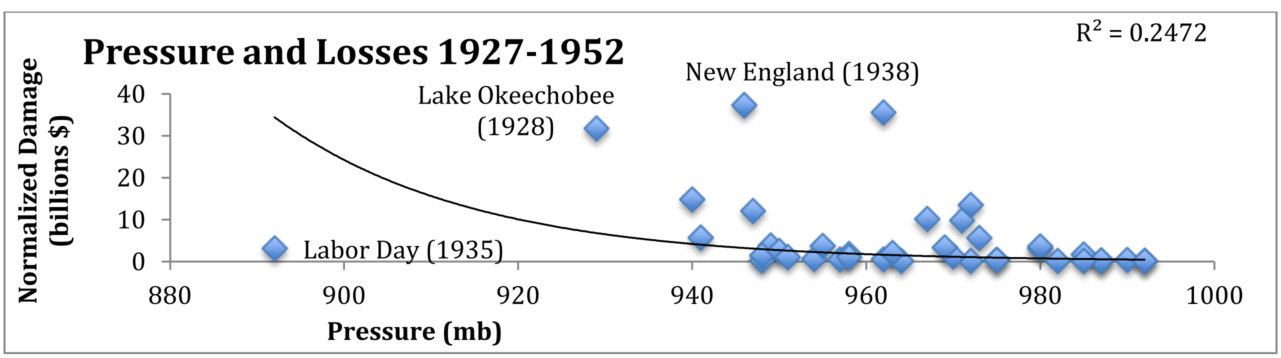


Figure 4B

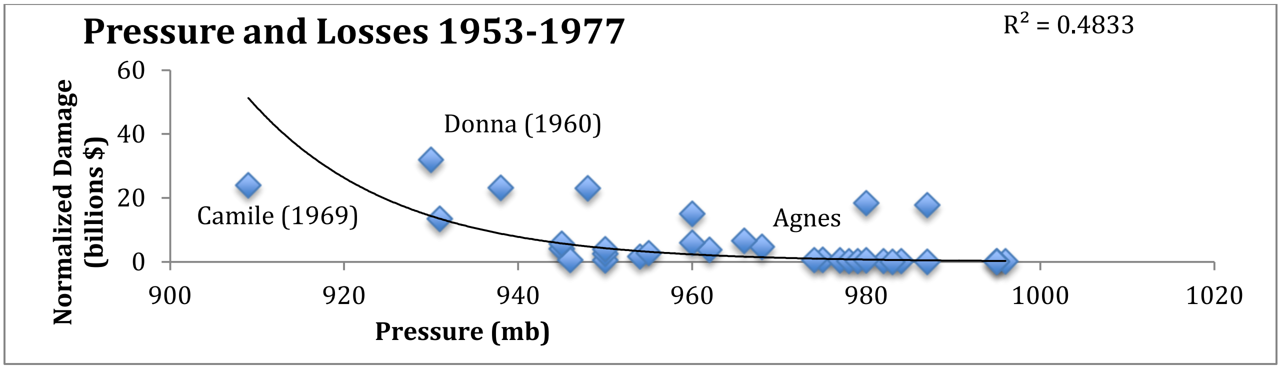


Figure 4C

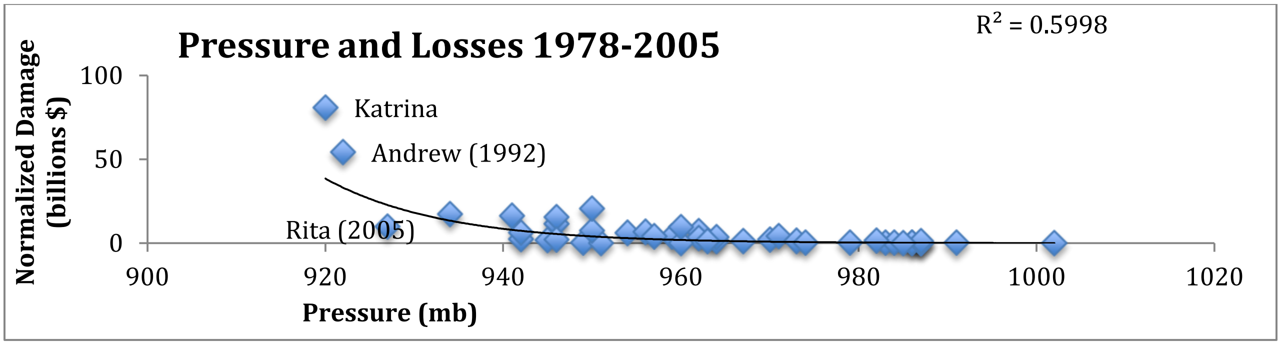


Figure 4D

The strength of the relationship between each section can be seen to be growing. This is with the exception of the second section, from 1927 to 1952. During this time period, there were almost no low-pressure hurricanes. This could be a possible cause for why the relationship is so weak. This is also why we will consider there to be an upward trend in the strength of the relationship from 1900 to present.

The relationship of pressure to damage for all sections combined had an r^2 value of .43. The first section had an r^2 value of .41, the second, anomalous, section with an r^2 value of .25, the third with .48, and the fourth with .59. Without looking at the second section, the values are .43, .48, and .59, show a clear increase over time. The last and most current section, from 1978-2005, shows the strongest relationship between pressure and damage, with the exponential regression explaining almost 60% of the damage of all hurricanes that made landfall during that time, an extremely high percentage. If this trend continues into the future, we can expect the weaker storms, with higher pressure, to cause little damage, and the stronger storms to cause much more damage.

Model for Predicting Damage from Pressure

The equation that calculated the correlation between pressure and damage for all years was also used to create a model. This model is intended to predict the damage sustained by a hurricane given its barometric pressure.

It is important to note that this model is not entirely accurate. Since the relationship does not have an r^2 value of 1, where all points would fit the line, it cannot completely predict exactly each storm. There are several storms that do not fit the equation at all, for example the Labor Day hurricane in 1935 had a pressure of 892, one of the lowest recorded in history. This storm hit the Florida Keys, a sparsely populated small strip of land, before weakening and making landfall again. By the time it made landfall on mainland Florida, it had weakened to a category 2 hurricane. These are probable reasons as to why it has such low damage for its pressure.

However, this is a general model that can predict the approximate damage of a hurricane given its pressure. It could perhaps be more accurate to create a model from the equation from the fourth section of time, as there is a stronger relationship there, and it could be that this trend could increase in the near future.

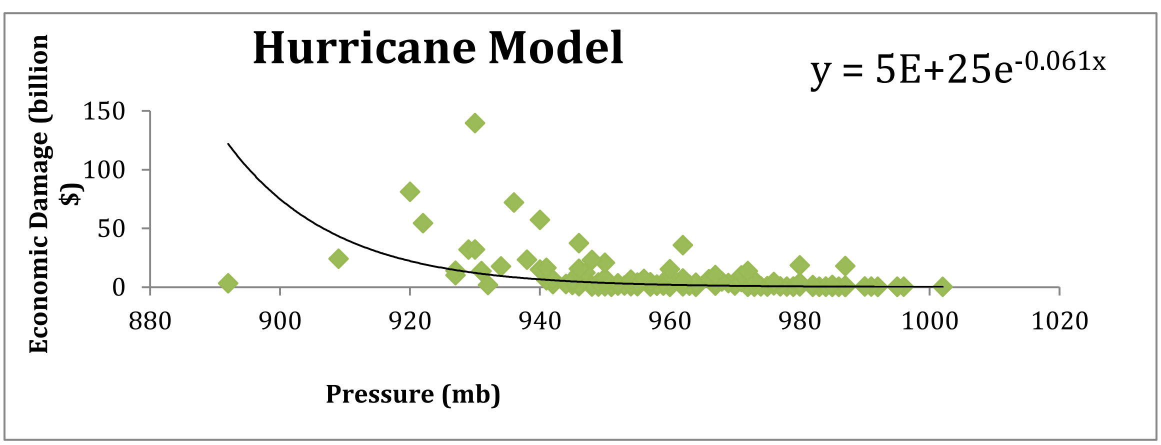


Figure 5

The graph in Figure 5 is the same as the original graph for pressure and damage. However, this chart includes the equation the model was based on. The equation for this model may look a little odd. Translated from the above, the equation is, $y = 5 \times 10^{25} e^{-0.061x}$. The value of 5×10^{25} is the y intercept of equation, meaning what the damage would be if the pressure were zero. Luckily it is impossible to have a pressure of zero in a hurricane, so that damage would never occur. Typical hurricane pressures are in the 900s, much higher than zero. The $e^{-0.061x}$ describes the slope of the line of the model. If pressure, *x*, goes up 1mb, damage, *y*, will be multiplied by $e^{-0.061x}$. In other words, for every 1mb increase, the damage will decrease by 6.1%.

Pressure (mb)	Damage (billion $)
890	132.17
920	21.20
950	3.40
980	0.55
1010	0.09

Table 2

This equation will show, for a given pressure, *x*, what the damage, *y*, would be. Table 2 shows the predicted damage in billions that is likely to occur for the given pressures.

This model can also elaborate the differences in damage for a change in pressure. Table 3 shows the given change in losses in billions for a 20mb change in pressure. For a change of pressure between two low pressures, the resulting change in predicted damage is extremely high. The change in damage from a change in two high pressures is less. This holds with the fact that pressure and damage fit an exponential curve.

Change in Pressure(mb)	Damage (billions $)
890-900	85.88
910-930	25.35
930-950	7.48
950-970	2.21
970-990	0.65
990-1010	0.19

Table 3

Frequency of Hurricanes

In terms of patterns of trends of intensity and destruction, the findings of this research supported those reported in the literature. There was no clear trend in either intensity over time or damage over time, for the time period with data available (1900-2005). This was in agreement with previous studies cited above. However, the change in frequency of hurricanes was different from those mentioned in the literature. The hurricanes were separated into four sections of roughly 25-year spans. The number of hurricanes for each section was then counted, and presented in Figure 6. To be clear, results presented here include hurricanes that have made landfall in the United States, and excludes those that remained in the ocean or hit Central America.

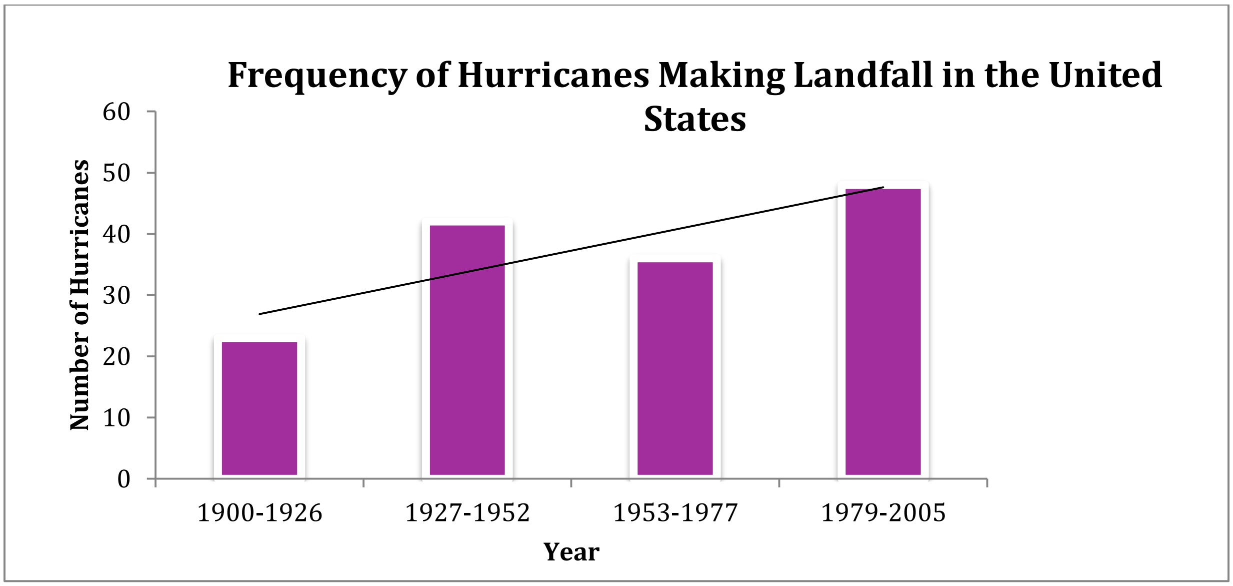


Figure 6

As can be seen from the Figure 6, once divided up into sections, the number of hurricanes has increased over the 100-year span. This directly contradicts Landsea's (1996) and Pielke et al.'s (2005) report that stated that the frequency of hurricanes was decreasing. It could be that if the hurricanes were divided up into smaller sections, or adjusted for ENSO, it might result in a downward trend.

The number of major hurricanes (categories 3, 4, and 5) over the years is also of interest. The number of major storms that have occurred in each section, as shown in Figure 7, has a general upwards trend, but not significant enough to be of note

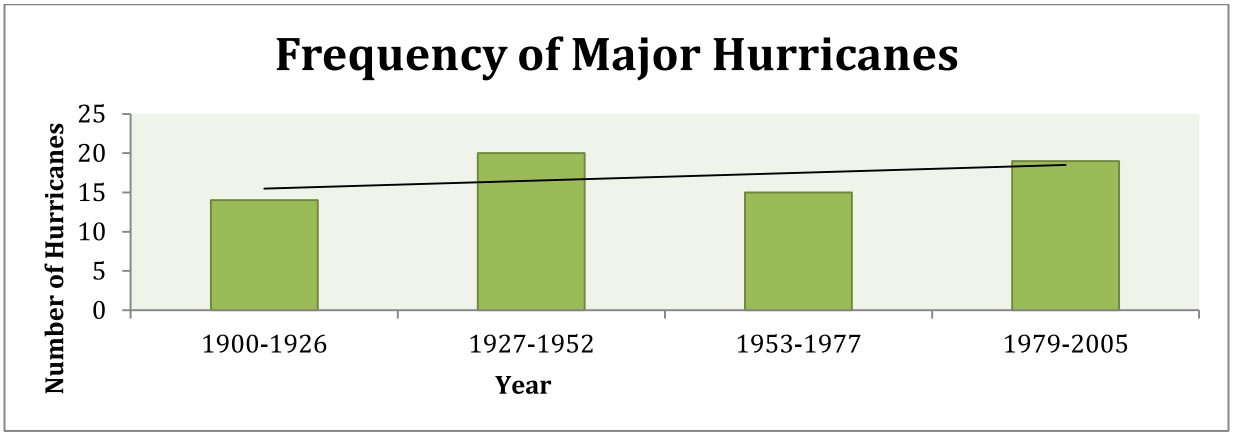


Figure 7

Because the number of total hurricanes and major hurricanes each year varies, it is necessary to look at the proportion of major hurricanes to all hurricanes occurring in each section. This can be seen in Figure 8. Even with all of the major storms that occurred during the 2005 hurricane season, there is still a decreasing trend of how many major hurricanes there are for the total storms. However, the proportion is not decreasing very rapidly, as the low slope of the trend shows. If this relationship is true and continues, even though there will probably be more storms overall, fewer of those storms will be major hurricanes.

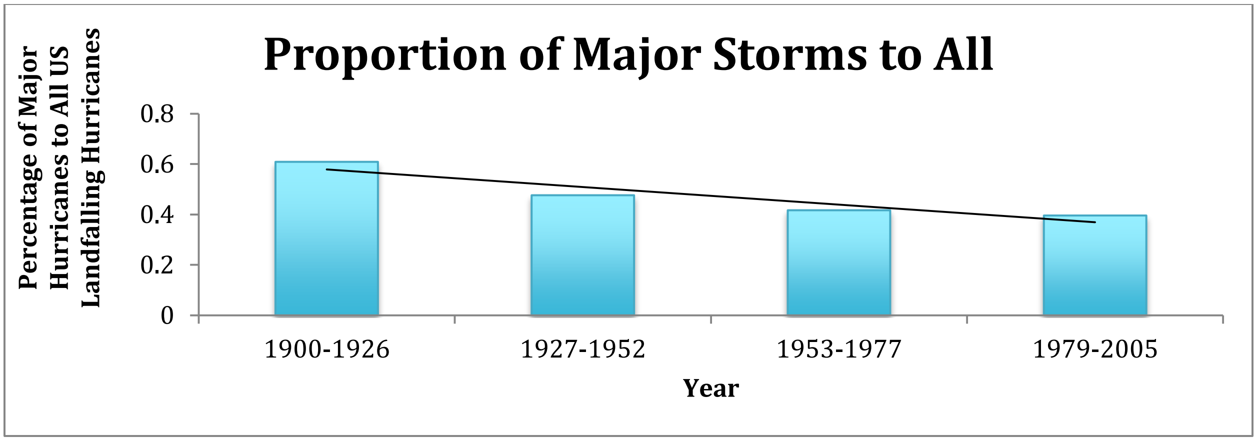


Figure 8

Discussion and Conclusion

This research examined the relationship between intensity and destruction of hurricanes. This research has enabled us to analyze this relationship in many ways. First of all, this research looked at the strength of the relationship between intensity and damage. It was found that there is in fact a very strong relationship between intensity and damage. However, the official measure of intensity, the Saffir-Simpson scale, does not explain as much of the damage as the pressure of a hurricane does. Implications of this include that it might be wise to change the official ranking of the storm to use pressure instead. This also means that stronger storms are very likely to have more damage than weaker ones. This would mean that weather predictions should stress safety measures when intense storms are predicted to make landfall.

The largest uncertainty in this research was the lack of reliable data. As accurate tools to collect variables such as pressure and wind speed have only been developed recently, there has not been that long of a time span to study. Also, most years only see a couple hurricane strikes, as many hurricanes develop in the ocean. Research in the future could benefit from having a larger data set.

To further examine the relationship between intensity and damage, the strength of the relationships between pressure and damage were compared among four 25-year sections. It was found that there has been a trend of increasing strength of the relationship over the time period of study. This would mean that low-pressure, intense storms are becoming consistently more damaging, and high-pressure, weaker storms are becoming consistently less damaging. These results show that it is now less likely that a weak, high-pressure hurricane would cause a large amount of damage. Given the numerous changes in infrastructure along the coasts since 1900, it was suspected that there would be some change in this relationship. The increase in mobile homes, especially, was expected to weaken the relationship as weak storms could still cause extensive damage to trailer homes. However this was not the case. Perhaps the development in creating houses that can withstand stronger hurricanes, as well as more advanced warning systems to more of the population, has led to this stronger relationship. It could also be that as technology for collecting hurricane data has improved, the recent data is more reliable. Because of the increasing strength of the relationship between pressure and damage, weather forecasters should be able to predict the damage caused by a given hurricane more accurately. Further research could examine the reasons behind the increasing strength of this relationship and see if the trend would be accurate continuing into the future.

Regarding the frequency of hurricanes, it was found that whereas there has been an increase in the frequency of all hurricanes, there has been a decrease in the proportion of major hurricanes. This can have large implications for those who live on the coast. If this trend continues, it would mean that the inhabitants of the coast can expect to see more hurricanes, but fewer of those hurricanes will be major.

Further research could examine if there has been a similar increase in all hurricanes and a decrease of the proportion of major hurricanes in all hurricanes in the Atlantic Basin, not just the ones that make landfall in the United States. These analyses could also be applied to other hurricane basins. Is this trend only apparent because there have been fewer hurricanes making landfall? An additional question would address why this research contradicts research already done by professionals in the field such as Landsea 1996 and Pielke 2005. Possible reasons could include the research design and set up.

The final result of this research was the creation of a model to predict damage given a hurricane's pressure. Having models to predict damage is extremely helpful to those on the coast, both the inhabitants and emergency responders. Having an estimate of the damage caused by a hurricane before it makes landfall can help hurricane preparedness, such as evacuations and other precautionary measures. This model is not an entirely accurate predictor for damage however, as it only takes into consideration the pressure of a hurricane. Other factors certainly play a role in the damage a hurricane causes, and since the damage used to create this model has been normalized, it doesn't take into consideration a hurricane hitting a highly populated area, where it would cause more damage. Future research into predicting hurricane damage is extremely important, as it has the possibility to save countless lives and prevent millions of dollars in damage.

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