The Economic Effects of Hurricane-Induced Deforestation on the Timber Industry of the Southeastern United States

Evan Stanbro
Lewis & Clark College
Portland, OR

In partial fulfillment of the requirements for the Bachelors of Arts degree

Environmental Studies Program
Senior Thesis

May, 2013

Abstract:

In this paper, I seek to explore the economic ramifications of hurricane-induced deforestation on the timber industry of the southeastern United States. Annually, about 85 hurricanes form in the tropical regions around the world. From Australia to Bangladesh to the Gulf of Mexico, hurricanes strike and cause billions of dollars in property damage, leave millions of people homeless, and even cause thousands of fatalities. In the Atlantic basin, tropical storms form every summer off the coast of Africa and move west towards the United States. Many of these storms do not grow to become full-fledged hurricanes. However, every several years a monster category 4 or 5 hurricane forms in the Atlantic basin and strikes the southeastern United States, causing devastating effects. An often over-looked ramification of hurricanes, timber damage caused by a large hurricane can reach the billions. Over the next century, global climate change may have a large impact on hurricane magnitude, frequency and distribution. Thus, in this paper I analyze how hurricane activity may change by 2100 given an IPCC A1B climate change scenario. I apply model-projected 10% increases in hurricane wind speed and 20% increases in hurricane rainfall, and find that by 2100, average timber damage caused by a category 3, 4 or 5 hurricane could increase by $200 million. Due to salvage logging, government assistance, casualty loss deductions, and insurance, the timber industry as a whole appears to be resilient to such large increases in cyclonic deforestation. However, individual landowners without insurance may be at serious risk.

Table of Contents

Part I: Background on Hurricanes

(Pages 6-8)

Part II: The Physical Science of Hurricanes

(Pages 8-19)

Part III: The Economic Ramifications of Cyclonic Deforestation

(Pages 19-26)

Part IV: The Effect of Climate Change on Hurricane Activity

(Pages 26-34)

Part V: Future Economic Ramifications of Cyclonic Deforestation in Light of an IPCC A1B Scenario

(Pages 35-36)

Part VI: The Resiliency of the Timber Industry of the Southeastern United States to Increasing Cyclonic Deforestation

(Pages 36-40)

Introduction:

Global climate change will likely have a large impact on the planet over the coming century. As seasonal weather patterns are altered, entire ecosystems may change. Species will be forced to adapt to the transformations of the planet brought on by climate change. Likewise, society will also have to adapt to these transformations. Many industries around the world will be affected by climate change, and without adaptation and proper preparedness, these industries may collapse. Future climate change poses significant threats to one industry in particular; the timber industry of the southeastern United States. Over the next century, climate change may increase hurricane intensity, which may result in significant adverse effects for the timber industry of the southeastern United States.

Of all the natural phenomena that affect our planet, hurricanes are among the most spectacular, walking a fine line between destructive and beautiful. When atmospheric and oceanic conditions are just right, a raging meteorological monster known as a hurricane is born. From the Galveston hurricane of 1900, to Hurricane Sandy of 2012, hurricanes have been striking the southeastern United States nearly every year, paving a path of destruction along the way. When hurricanes strike they can wreak economic havoc on an area. The aggregate effect of the storm's surge, wind, and rain can cause billions of dollars in property damage, leaving millions of people homeless along the way. Economic ramifications of hurricanes are not merely attributed to just infrastructural damage though, but to an often unmentioned cause: cyclonic deforestation. When hurricanes make landfall in forested areas they can cause millions and even billions of dollars in damaged timber. Hurricane Katrina alone caused an estimated $5 billion in timber damage.

Under an IPCC A1B scenario, climate change may increase average hurricane wind speed by 10% and average hurricane rainfall by 20%. Increases this large may significantly increase cyclonic deforestation. Therefore, the timber industry of the southeastern United States must take preventative steps in order to mitigate the effects of cyclonic deforestation in the future.

In this paper, I set out to analyze the physical science of hurricanes, and how hurricanes affect forest ecosystems economically. I then explore how climate change, given an IPCC A1B scenario, may affect hurricane activity in the coming century. I then analyze how these changes in hurricane activity may increase average timber damage caused by a category 3, 4 or 5 hurricane. I then consider how resilient the timber industry of the southeastern United States is to increased cyclonic deforestation. Analyzing which elements of the timber industry make it more or less resilient to increased hurricane intensity allows me to make more generalizable laws about what makes any industry more or less resilient to future climate change. In this paper, I refer to tropical cyclones as hurricanes, as that is what they are called in the United States. However, it should be noted that in other regions of the world, hurricanes are referred to as cyclones and typhoons.

Part I: Background on Hurricanes

Global climate change began receiving attention in the 1970's and has slowly pushed itself to the forefront of the scientific community. Climate change has already had a noticeable impact on the earth, and will almost certainly have a much larger impact by the end of the 21st century. Climate change may alter seasonal weather patterns, disturb coral reefs, and change entire ecosystems. The ramifications of climate change will have a profound impact on various industries around the world. Future climate change poses significant threats to one industry in particular; the timber industry of the southeastern United States. Over the next century, climate change may increase hurricane magnitude and frequency, which may result in significant adverse effects for the timber industry of the southeastern United States. Figure 1[1] below shows the areas around the planet that are struck by hurricanes. As you can see, hurricanes have a large impact on many different areas around the globe.

Figure 1

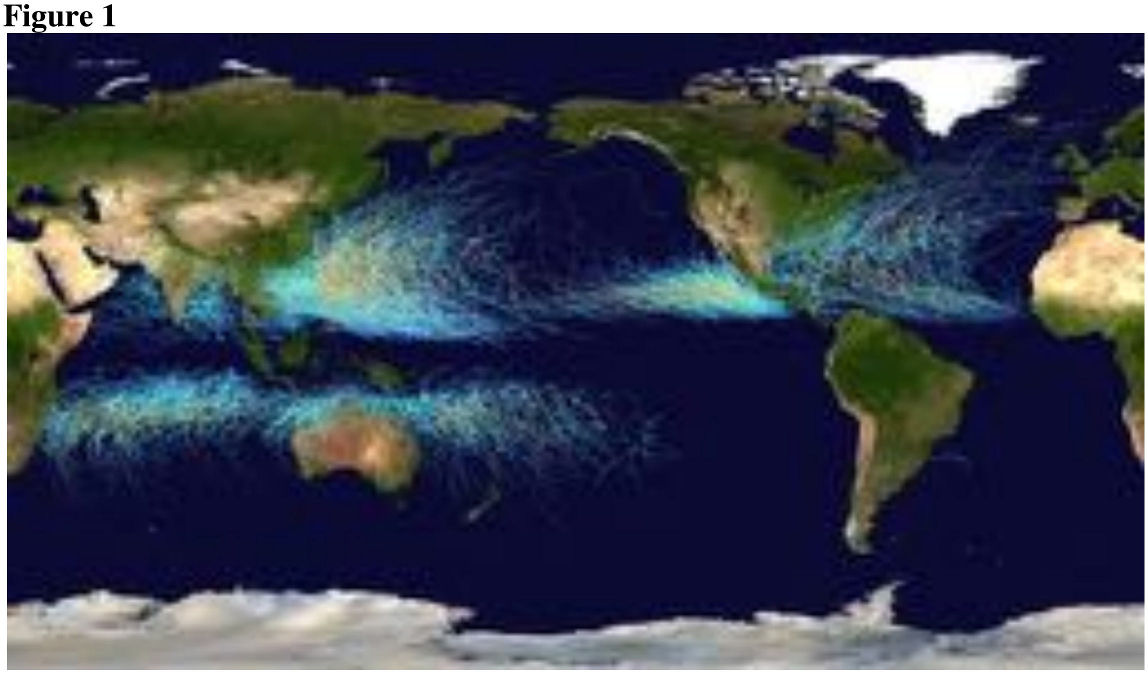

Figure 1: Best track path of hurricanes around the world. The lighter blue lines represent less intense hurricanes, while the orange and red lines represent category 4 and 5 hurricanes respectively.

[1]Figure 1 taken from https://www.google.com/search?hl=en&site=imghp&tbm=isch&source=hp&biw=1680&bih=819&q=hurrcane+history+tracks&oq=hurricane+history+tracks&gs_l=img. Accessed on 4/10/2013.

Worldwide, hurricane activity peaks in late summer, when the difference between temperatures aloft and sea surface temperatures is the greatest. However, each particular basin has its own seasonal patterns. In the Atlantic basin, hurricane season occurs from June to October, sharply peaking from late August through September. Every summer tropical storms form in Atlantic basin, but most of these storms do not grow to become full-fledged hurricanes. However, every several years a monster category 4 or 5 hurricane forms in the Atlantic basin and strikes the U.S. Figure 2[2] below shows the path of past Atlantic basin hurricanes. As you can see, most hurricanes form off the coast of Africa and move west across the Atlantic. When these hurricanes reach the mouth of the Gulf of Mexico, they usually begin moving north, and strike anywhere from Texas to New York.

Figure 2

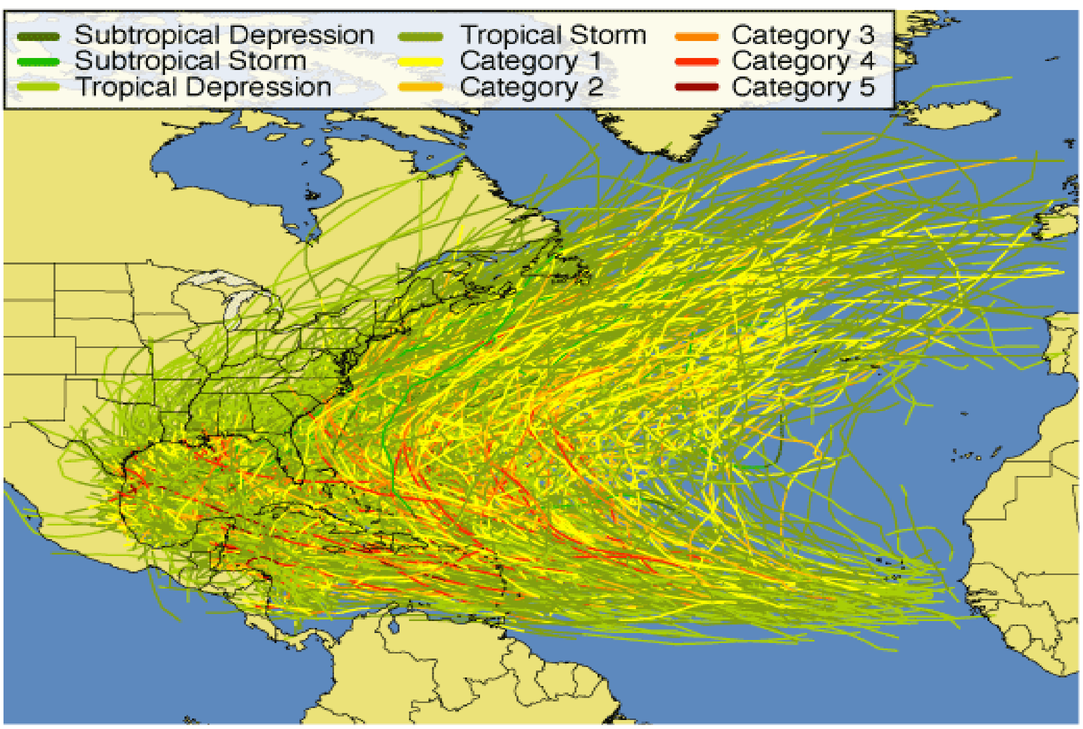

Figure 2: Best track path of Atlantic basin hurricanes.

---

[2] Figure 2 taken from https://www.google.com/search?hl=en&site=imghp&tbm=isch&source=hp&biw=1280&bih=664&q=hurricane+path+atlantic+basin&oq=hurricane+path+atlantic+basin&gs_l=img.3. Accessed on 3/12/2013.

Hurricanes are classified by their wind speed according to the Saffir-Simpson hurricane scale. In this paper, I analyze only category 3, 4 and 5 hurricanes, because storms smaller than this usually produce little to no timber damage. Table 1 below shows the Saffir-Simpson classifications for hurricanes.

Table 1

Classification	Wind Speed (mph)
Tropical Depression	0-38
Tropical Storm	39-73
Category 1	74-95
Category 2	96-110
Category 3	111-130
Category 4	131-155
Category 5	>156

Table 1: Saffir-Simpson hurricane scale.

Part II: The Physical Science of Hurricanes

The Birth of a Hurricane:

When just the right amount of things comes together, a deadly and destructive hurricane is born. In order for a hurricane to form, the following ingredients are necessary:

- Warm water (>80° F)
- Converging air masses
- Low wind shear[3]
- Rotation
- Condensation
- Coriolis Force[4]

[3] Wind shear is defined as a change in wind direction and speed between slightly different altitudes.

[4] Coriolis force is defined as an apparent force that as a result of the earth's rotation deflects moving objects (as projectiles of air currents) to the right in the northern hemisphere.

When two air masses converge, the warmer air mass rises because warm air is less dense than cold air. As air rises, its temperature decreases as pressure decreases. In response to the lower pressure, air expands, and water vapor in the air condenses into water droplets. Latent heat is released when water vapor condenses, because the phase change from gaseous H_2O to liquid H_2O is an exothermic process (Emanuel, 2005). This latent heat causes the cloud to continue to rise, keeping the air in the cloud warmer than its surrounding environment. The updraft finally encounters the tropopause, above which the temperature of the environment no longer decreases rapidly with altitude, and the air inside the cloud can no longer remain warmer than its surrounding environment (Emanuel, 2005). As the cloud continues condensing, some of the water vapor turns into ice. As this happens, the cloud can no longer support all of the mass, so the cloud begins to rain, snow or hail.

In a hurricane, air masses converge because a hurricane is a low-pressure system, and air naturally travels from high pressure to low pressure because of gravity (Emanuel, 2005) Thus, in a hurricane, winds near the ocean's surface carry warm, moist air towards the storm's center where atmospheric pressure is lowest. In a typical geostrophic current, the pressure gradient force is perfectly balanced and offset by coriolis force. However, because of friction, coriolis is slightly overcome, and air is slowly drawn in towards the low-pressure center of the storm as it rotates around the system. Figure 3[5] below illustrates geostrophic flow.

Figure 3

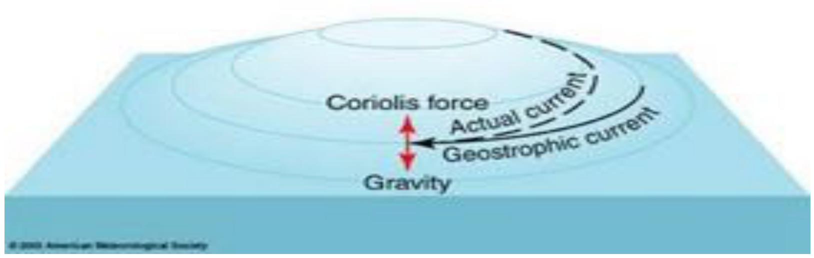

Figure 3: In a geostrophic current, the pressure gradient force is perfectly balanced and offset by coriolis force. However, because of friction, coriolis is slightly overcome.

---

[5] Figure 3 taken from Nasa at http://oceanmotion.org/html/background/geostrophic-flow.htm. Accessed on 3/12/2013.

Warm water is necessary for a hurricane to form because evaporation from the warm ocean surface is what fuels the storm. As air just above the surface of the ocean spirals in towards the center of the hurricane (where pressure is lowest), an enormous amount of energy is transferred from the ocean into the air. Evaporation of water is a very efficient way to transfer heat from one body to another. Thus, evaporation of seawater into the inflowing air is the most important source of heat driving a hurricane (Emanuel, 2005). Therefore, because warm water evaporates much more quickly than cool water, warm water is necessary for a hurricane to form. Cool water simply does not supply a hurricane with enough energy to maintain its force. Figure 4[6] below helps illustrate the formation of a hurricane. Note that air begins to cool as it spirals away from the hurricane in the upper levels of the storm.

Figure 4

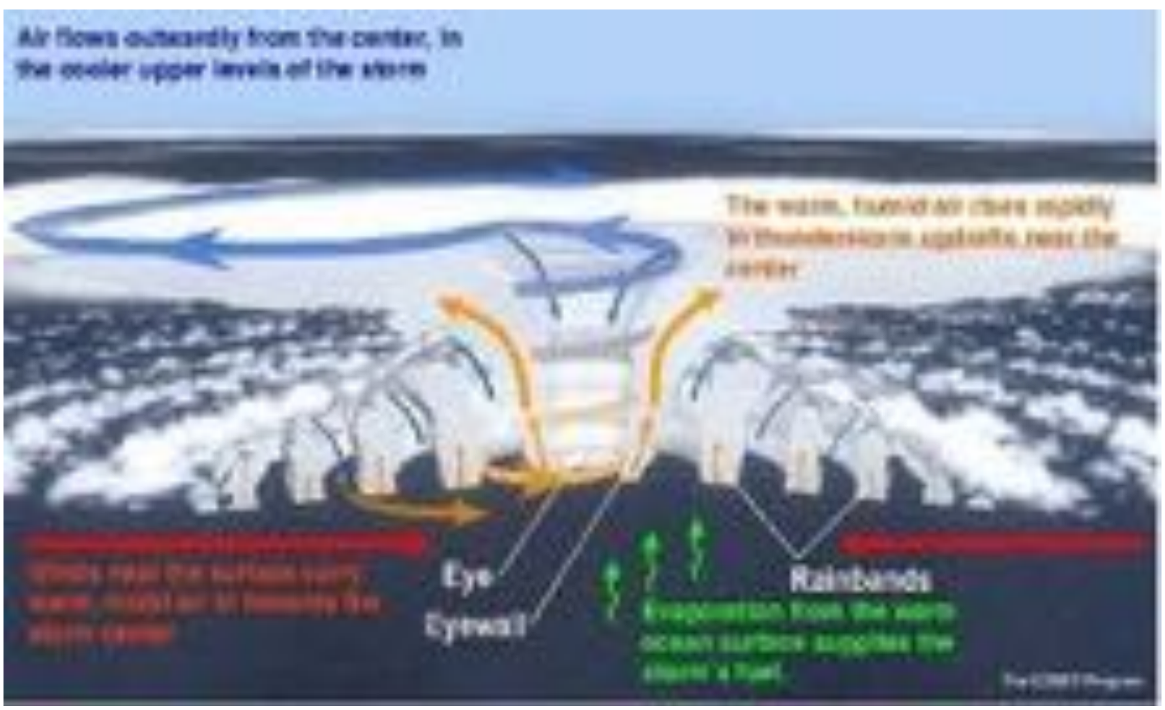

Figure 4: The formation and characteristics of a hurricane. Red arrows indicate very warm air, while blue arrows into cooler air.

---

[6]Figure 4 taken from USGS at http://coastal.er.usgs.gov/hurricanes/extreme-storms/hurricanes.php. Image credit to the USGS and the Comet Program. Accessed on 3/13/2013.

Satellite images allow us to see where heat and energy are distributed in a hurricane. Figure 5[7] below is a satellite image of Hurricane Katrina. Due to the enormous amount of energy gained from the inflowing air by evaporation, the center of the storm is the warmest part, and therefore contains the most energy. Further away from the eye, the storm becomes cooler, where the storm begins losing energy.

Figure 5

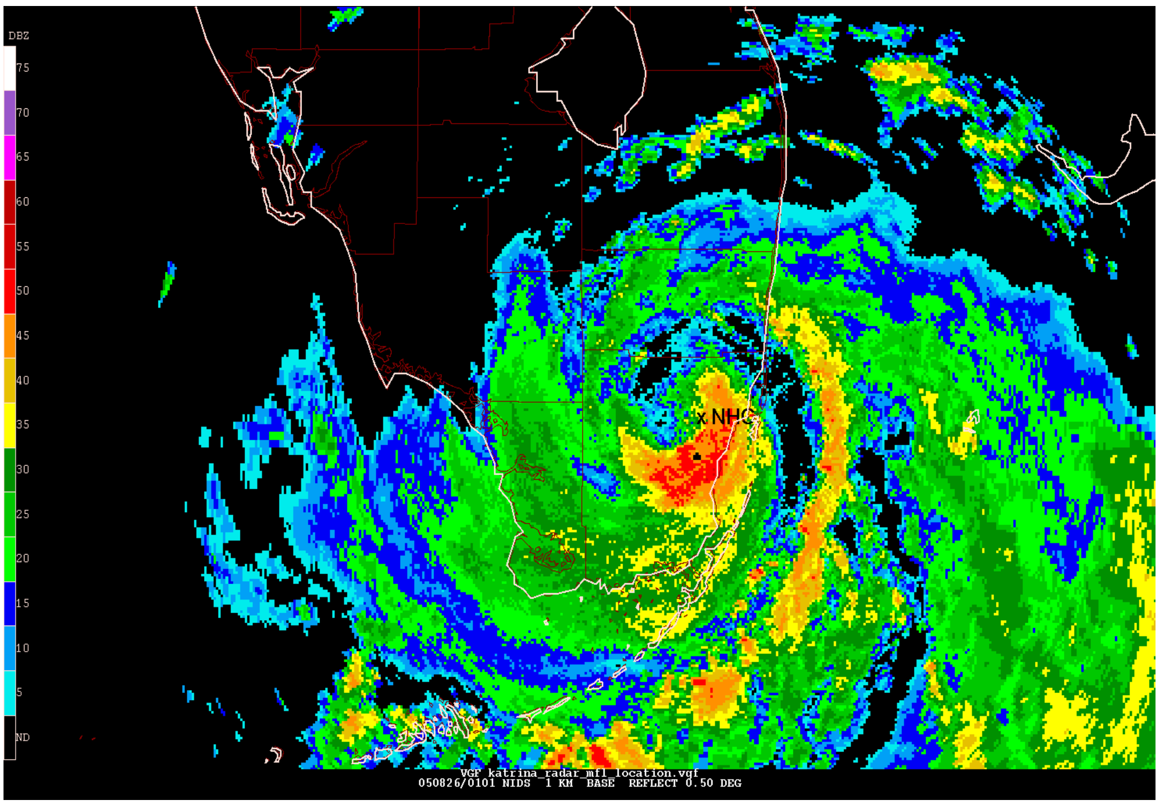

Figure 5: Radar reflectivity image from the Miami WSR-88D radar at 0100 UTC 26 August 2005, as the center of Hurricane Katrina passed over northern Miami-Dade County, Florida and near the NWS Miami Weather Forecast Office.

[7] Figure 5 taken from the National Hurricane Center's tropical cyclone report on Hurricane Katrina. Accessed on 3/20/2013.

Characteristics of a Hurricane:

When a hurricane is formed, the cyclonic rotation of air forms an eyewall, the outside edges of the storm's eye. Warm air rises up the eyewall, and disperses both towards and away from the eye at the top. The air that disperses towards the eye descends back down the eye, and the air that disperses away from the eye rotates out away from the center of the storm and eventually descends as well. Most of the air that travels up the eyewall flows outwardly away from the center. The following terms will help clarify the different parts of a hurricane:

Eye: calm center of the storm, with no wind or rain, with a diameter of ~ 30 miles.

Eyewall: outer edge of the eye, where air ascends in the storm. The eyewall is the area with the heaviest rains and the strongest winds.

Moat: the area outside the eyewall, with relatively calm conditions (low wind and rain).

Outer/Secondary Eyewall: the area outside the moat, with much higher winds and rainfall than the moat, but much less than the eyewall.

When a hurricane strikes a forested area, the eyewall and secondary eyewall cause the majority of the cyclonic deforestation, because these are the parts of the storm with the heaviest rains and the strongest winds. Although the eyewall is the most intense part of a hurricane, it often does not reach far inland, and may not cause as much damage as the secondary eyewall, which reaches much further inland.

Hurricane Intensity:

As the storm develops from a tropical depression into a full-fledged hurricane, the storm becomes more intense. As atmospheric pressure continues to drop, the storm becomes more intense, and wind speeds increase. Figure 6[8] below shows the atmospheric pressure and wind speed of hurricane Katrina through time. Note that as pressure decreases, wind speed increases, a characteristic common of all hurricanes.

[8] Wind speed and atmospheric pressure data for Figure 6 were taken from the National Hurricane Center's tropical cyclone report on hurricane Katrina. Accessed on 3/13/2013.

Figure 6

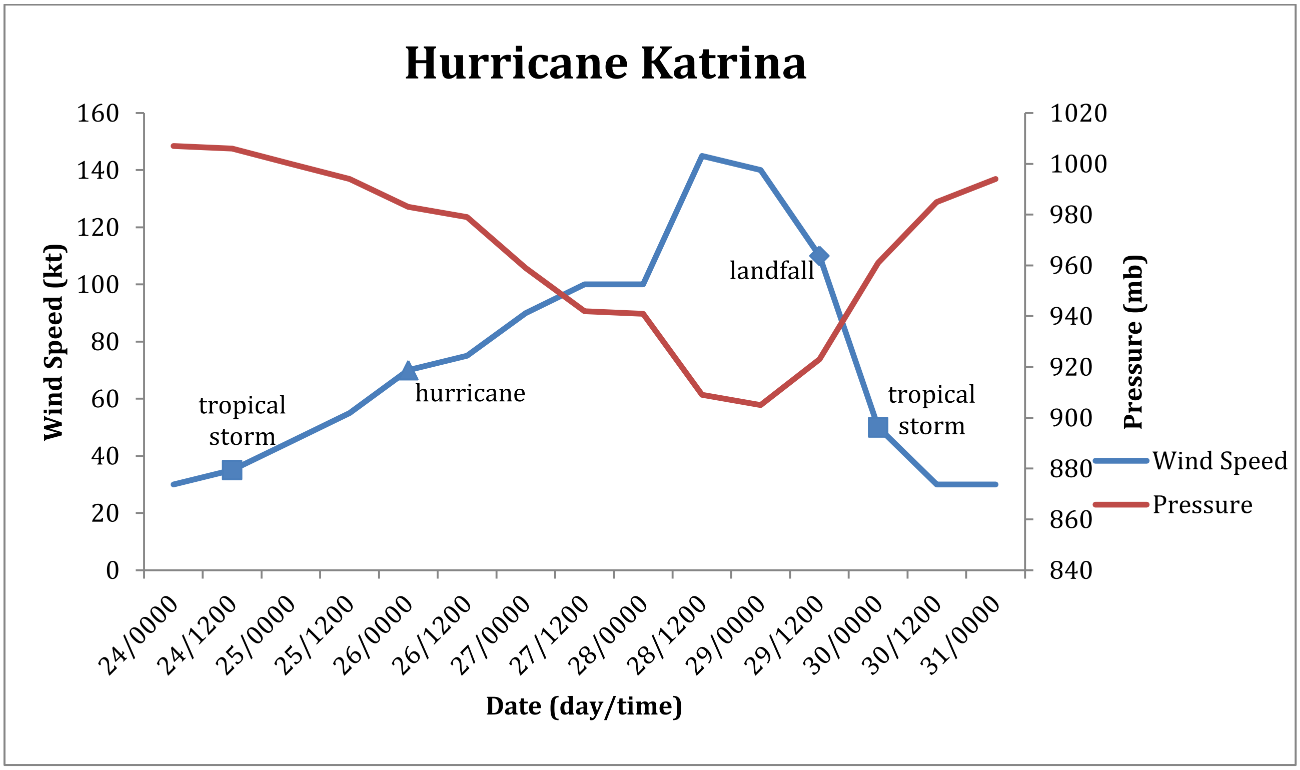

Figure 6: Hurricane Katrina wind speed (kt) and pressure (mb) through time.

Weakening a Hurricane:

Making Landfall

Hurricanes can be weakened or destroyed in a number of ways. Hurricanes gain their energy from warm ocean water; so when a hurricane encounters cooler waters the storm begins to weaken. For this same reason, hurricanes weaken rapidly upon making landfall, because the storm loses its source of energy once it leaves the ocean. Therefore, timber is most vulnerable near the coast, where winds are the strongest. Thus, most cyclonic deforestation occurs within a few hundred miles of the coast. Figure 7[9] below

[9] Data for Figure 7 were taken from the National Hurricane Center's GIS data archive. This data was then used in ArcGIS to create the image. Accessed on 3/11/2013.

illustrates the best track and wind swath of Hurricane Gustav as it moved through the Gulf of Mexico and made landfall in the Louisiana and Mississippi area. As figure 7 illustrates, Hurricane Gustav quickly dissipated upon making landfall, with the wind swath only reaching a few hundred miles inland.

Figure 7

Figure 7: Best track path and wind swath for Hurricane Gustav. Orange color represents wind swath.

Vertical Wind Shear

Increased vertical wind shear weakens hurricanes. This is because wind shear makes the storm circulation lose its circular symmetry, thus opening up the tight feedback loop of energy (Emanuel, 2005). When this loop is opened, energy is lost, and the storm loses intensity. If vertical wind shear is intense enough, it can blow apart a hurricane entirely. Shear can also force dry, low-energy air from the storm's environment to swirl into its core at middle levels, reducing the core entropy and weakening the storm; a process referred to as ventilation (Emanuel, 2005). As you will see in part IV, wind shear is an important part of climate change predictions.

Destructive Forces of a Hurricane:

Storm surge

When hurricanes make landfall in swampy or mangrove areas, storm surge can have adverse effects on forest ecosystems. However, this effect is usually minimal, and thus storm surge is not a large part of cyclonic deforestation. Therefore, I will focus on the two elements of hurricanes that are of the largest threat to cause significant cyclonic deforestation: wind and rain.

Wind

Wind is the most destructive force in a hurricane. Hurricanes can have maximum sustained wind speeds of 150 mph and beyond. These gale-force winds can cause extensive damage to forest ecosystems. Hurricane winds can damage limbs and even uproot trees entirely. Intense hurricanes are capable of completely flattening thousands of acres of forestland, causing millions of dollars in timber damage. Figure 8[10] below shows the progression of the wind speeds of Hurricane Katrina (August, 2005) and Hurricane Rita (September, 2005) through time. As you can see, both storms had peak wind speeds above 150 kt (172 mph), and both storms caused significant timber damage, as you will see in part III.

[10] Wind speed data for Figure 8 were taken from the National Hurricane Center's tropical cyclone reports on Hurricane Katrina and Hurricane Rita. Accessed on 3/13/2013.

Figure 8

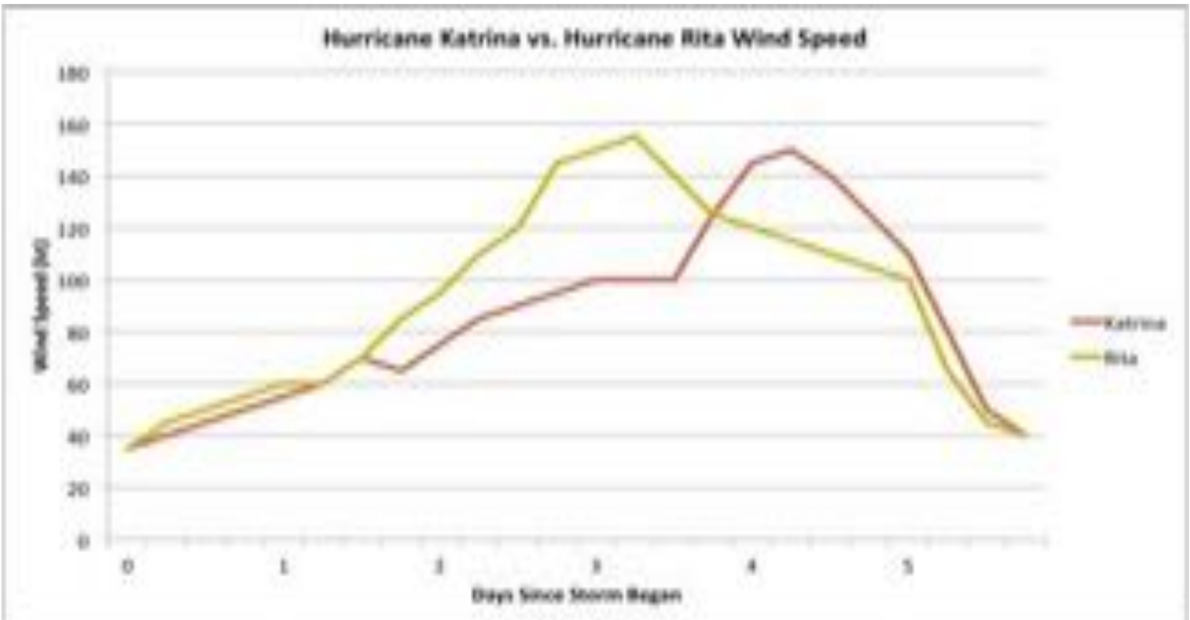

Figure 8: Wind speeds of Hurricane Katrina and Hurricane Rita through time.

Hurricanes can also cause tornadoes to form, which have destructive winds of their own. Hurricane Katrina spawned a total of 43 tornadoes. On 29-30 August, 20 tornadoes were reported in Georgia, 11 in Alabama, and 11 in Mississippi.[11] Tornadoes spawned by hurricanes can also cause extensive damage to forestlands.

Rain

Heavy rains are also a destructive force of hurricanes. When Hurricane Katrina struck New Orleans in August 2005, heavy rains combined with an intense storm surge to cause tremendous flooding that caused over $80 billion in property damage and killed over 1,800 people (Oswalt et al. 2008). Intense rainfall is also a crucial element in cyclonic deforestation. When the soil of a forested area becomes moist and flooded, the friction between soil and roots is decreased, and it becomes much easier for wind to

[11] Data taken from the National Hurricane Center's tropical cyclone report on Hurricane Katrina. Accessed on 3/13/2013.

uproot trees. Figures 9a[12] and 9b[12] below show the amount of rainfall from Hurricane Katrina at randomly selected locations in Alabama and Mississippi. Rainfall in Alabama reached above 3 inches in some places, while rainfall in Mississippi reached above 7 inches in several locations. This heavy rainfall played a huge role in the $5 billion timber damage caused by Hurricane Katrina.

Figure 9a

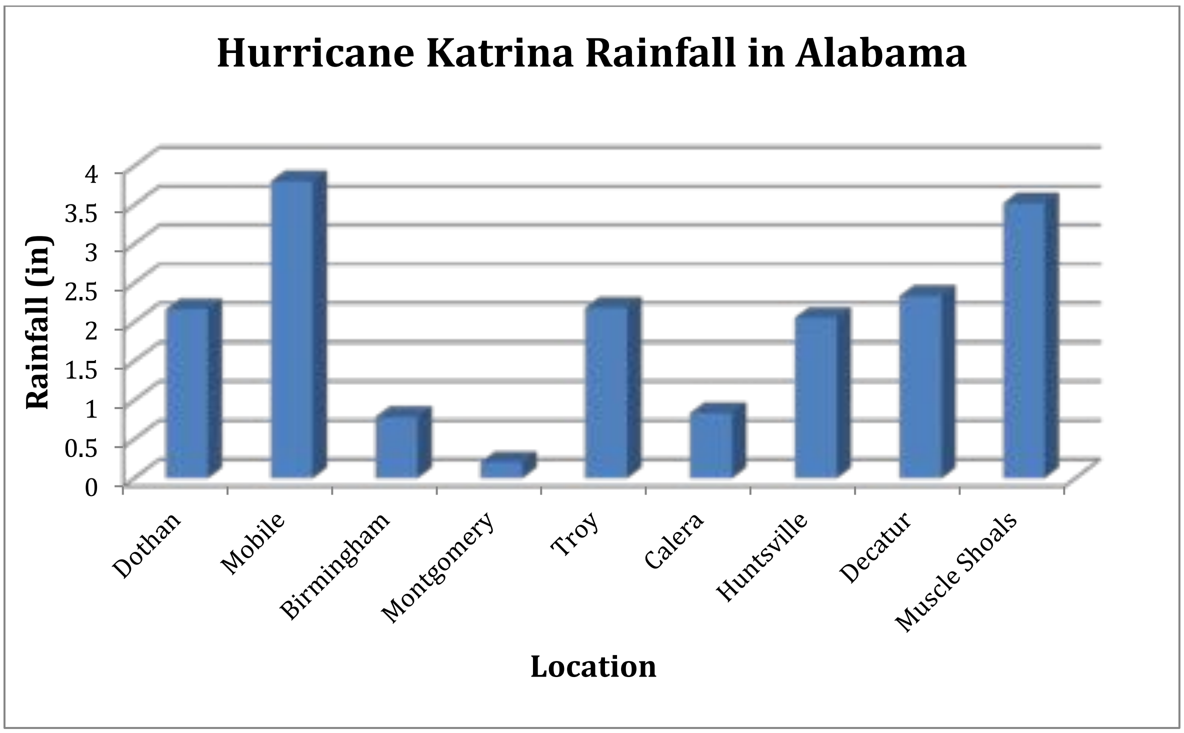

Figure 9a: Hurricane Katrina rainfall at select locations in Alabama.

[12] Data for figures 9a and 9b were taken from the National Hurricane Center's tropical cyclone report on Hurricane Katrina. Accessed on 3/12/2013.

Figure 9b

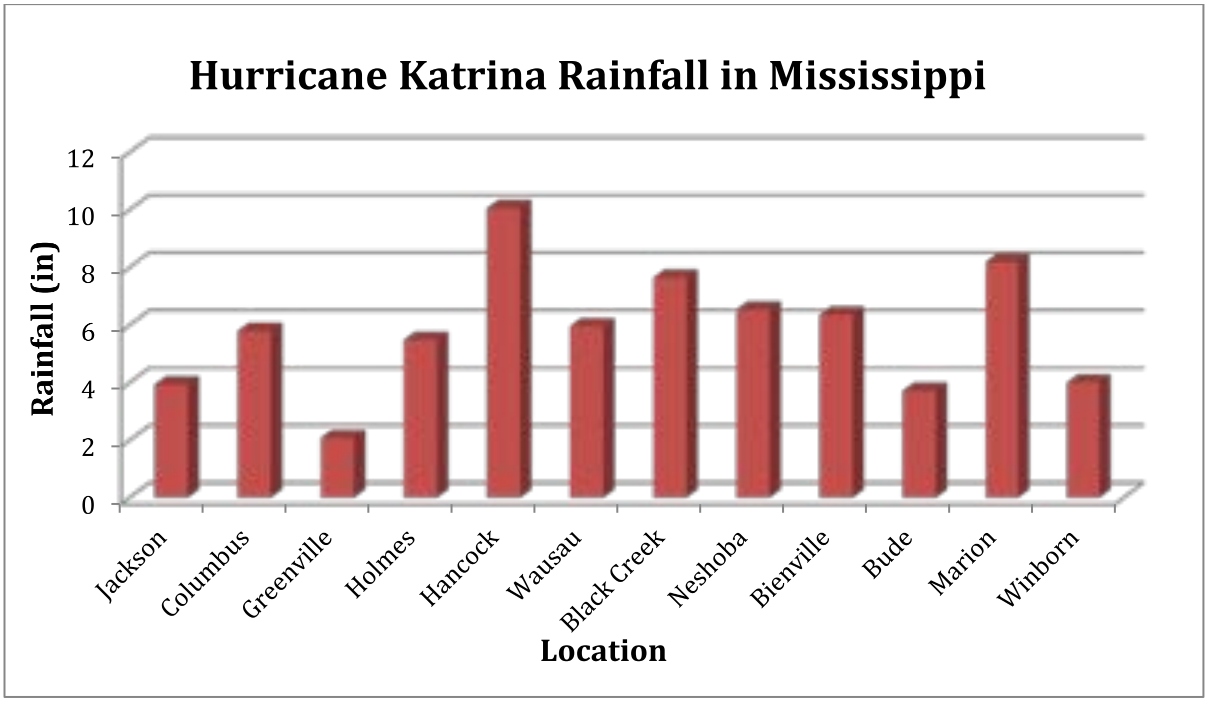

Figure 9b: Hurricane Katrina rainfall at select locations in Mississippi.

El Niño-Southern Oscillation:

ENSO is an oscillation of the ocean-atmosphere system in the tropical Pacific that affects global weather and climate. El Niño, the warm phase of ENSO, is a quasi-periodic (2-7 years) warming of ocean surface waters in the equatorial and eastern tropical Pacific and an eastward shift in convection from the western Pacific climatological maximum. Changes occur in the tropical trade easterlies, vertical wind shear, and ocean height. Cool ocean temperature anomalies are observed in the tropical western Pacific extending eastward into the subtropics of both hemispheres. La Niña refers to the less intense, anomalous cool phase of ENSO.

ENSO has a large affect on hurricane activity in the Atlantic basin. Gray (1984) found that of the 54 major hurricanes striking the United States coast from 1900-1983, only four occurred during the 16 El Niño years in contrast to 50 making landfall during the 68 non-El Niño years. This is a rate of 0.25 major hurricanes per year during El Niño events and 0.74 during non-El Niño years, almost a three to one ratio. In another study, O'Brien et al. (1998) found that during an El Niño year, the probability of 2 or more hurricanes making landfall in the U.S. is 28%. The probability of 2 or more U.S. hurricanes during the other two phases is larger: 48% during neutral years and 66% during La Niña[13]. Therefore, the timber industry is especially vulnerable to cyclonic deforestation during La Niña years.

Part III: The Economic Ramifications of Cyclonic Deforestation

Natural disturbances such as hurricanes strongly affect forest composition, structure and dynamics. When hurricanes make landfall in forested areas, they can damage hundreds of thousands of acres of timberland, causing hundreds of millions of dollars in timber damage. If this damaged timber is not salvaged and/or is not fully insured, the timber industry of the southeastern United States can lose millions of dollars in lost timber. When Hurricane Katrina struck the Gulf coast in August 2005, it swept through Louisiana, Mississippi and Alabama, causing a total timber damage of $5 billion (Oswalt et al. 2008). The impact of Katrina's winds resulted in the destruction of an average of 20 percent of the timber that was standing in the damaged area prior to the storm, with rates in areas near the coast as high as 35-40 percent.[14]

[13] Data taken from the Bulletin of the American Meteorological Society, Vol.79, No.11 (1998). Accessed on 3/6/2013.
[14] Data taken from the USDA Forest Service's Forest Inventory & Analysis Sheet following Hurricane Katrina. Accessed on 3/12/2013.

How Hurricanes Affect Forestlands:

Several factors influence how much deforestation any given hurricane will cause. As I just mentioned, rainfall and wind speed are both important elements of cyclonic deforestation. As well as rainfall and wind speed, landfall location is a crucial factor in determining how much cyclonic deforestation a hurricane will cause. If a large hurricane makes landfall in a forested area, there will likely be significant cyclonic deforestation. Thus, there are two important factors regarding landfall location: adjacent forest abundance and forest composition. Forest abundance is important because increased abundance increases the chances of deforestation. The more abundant the forestland is, the more trees there are to be damaged. Forest composition is very important because different tree species are more or less resilient to wind damage. Thus, different compositions of forestland will be more or less resilient to hurricane damage. Forest composition is also important because different tree species are more valuable than others, and this in turn affects the value of the damaged timber. Thus, wind speed, rainfall amount, forest abundance, and forest composition are the four crucial factors that determine the amount of deforestation caused by a given hurricane. These factors can be thought of in function 1 below. Any increase in wind speed, rainfall, or forest abundance will likely increase the amount of deforestation caused by a hurricane.

Function 1

Deforestation amount= f(wind speed, rainfall, forest abundance, forest composition)

Land Cover of the Southeastern United States

As you can see in function 1, land cover near the landfall location is very important. Figure 10[15] below shows that much of the southeastern United States is dominated by forestland. Over half of the land in Louisiana, Mississippi and Alabama is

[15] Figure 10 taken from https://www.google.com/search?hl=en&site=imghp&tbm=isch&source=hp&biw=1680&bih=819&q=land+cover+southeastern+United+States&oq=land+cover+southeastern+United+States&gs_l=img.3...2093. Image credit to the World Resources Institute and the USGS. Accessed on 4/10/2013.

forestland. Thus, any large hurricane that makes landfall in the southeastern United States is likely to cause extensive cyclonic deforestation.

Figure 10

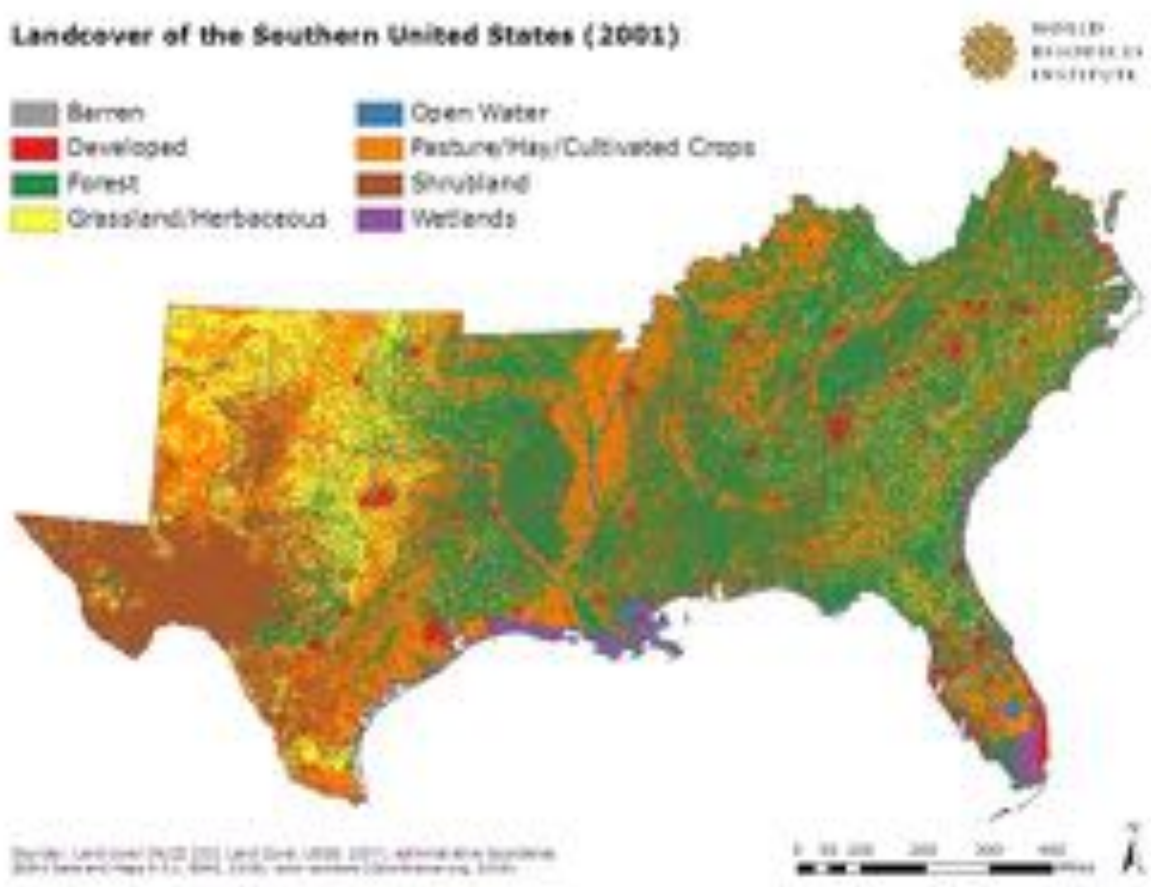

Figure 10: Landcover map of the Southern United States (2001).

Market Conditions of Damaged Timber:

The value of timber damaged by a hurricane adds another important element. Along with the amount of deforestation caused and the species of trees damaged, timber market conditions also affect the value of damaged timber. The timber market is very dynamic and is affected by a number of other markets, including the housing market. Timber prices fluctuate over time, and are often subject to available supplies of timber. The existing stock of timber influences the long-run quantity supplied in the market, which affects the price of timber. Since trees take a long time to grow, significant reductions in timber stocks can lead to an increased price shift due to increasing scarcity and increasing value of remaining stocks.

Sudden decreases in timber stocks can occur for a number of reasons, including timber damaged by hurricanes. Damaged timber stocks have vanishingly small opportunity costs and the liquidation of damaged timber stocks can create a large supply input that causes a negative price spike (Prestemon and Holmes, 2000). When a hurricane strikes, there is a small window of time in which damaged timber can be salvaged. Thus, immediately following a hurricane, timber markets are often flooded by salvage logging, leading to the negative price spike.

If the timber market is doing well, and timber prices are high, the value of damaged timber will be more than it would be if the market was not doing well. Therefore, market conditions are very important in determining not the amount of deforestation caused, but the value of damaged timber. These three factors can be thought of in function 2 below. Any change in these three factors will alter the value of damaged timber.

Function 2

Value of damaged timber= f(deforestation amount, tree species damaged, timber market conditions)

Cyclonic Deforestation of the Past:

Table 2 below shows the timber damage caused by six Atlantic basin hurricanes that struck the southeastern United States from 1989-2011. In total, these six hurricanes caused approximately $7.7 billion in timber damage. It is very difficult to determine average rainfall in a hurricane, because rainfall is often very unevenly distributed. Thus, in Table 2 I focus my attention on the role wind speed plays in cyclonic deforestation.

Note that wind speed is the maximum sustained wind speed at the time of landfall. Maximum sustained wind speed at the time of landfall is used because as mentioned in part II, wind speed quickly dissipates upon landfall. Therefore, most cyclonic deforestation occurs near the landfall location.

Table 2

Hurricane and Year	Hugo (1989)	Ivan (2004)	Katrina (2005)	Rita (2005)	Ike (2008)	Irene (2011)
Max Sustained Wind Speed (at landfall)	135 mph	121 mph	127 mph	115 mph	109 mph	86 mph
Landfall Location	South Carolina	Alabama	West Mississippi	East Texas	East Texas	North Carolina
Value of Damaged Timber (million)	$1,040	$610	$5,000	$833	$351	$80

Table 2: Timber damage caused by six Atlantic basin hurricanes that struck the southeastern United States.

In order to analyze the correlation between wind speed and timber damage, I plotted the wind speed and timber damage of the hurricanes in table 2 in figure 11 below. I chose to exclude Hurricane Katrina because Katrina caused an unusually high amount of timber damage that has not been seen in any other hurricanes. Therefore, it appears that Hurricane Katrina was an extreme exception to usual cyclonic deforestation. As you can see, maximum sustained wind speed at landfall is well correlated with amount of timber damage. As I hypothesized, increased wind speed leads to increased timber damage, and fits a trend line well (R^2=0.85122). Thus, if hurricane wind speeds are increased, the amount of timber damage caused by a large hurricane should increase as well.

Figure 11

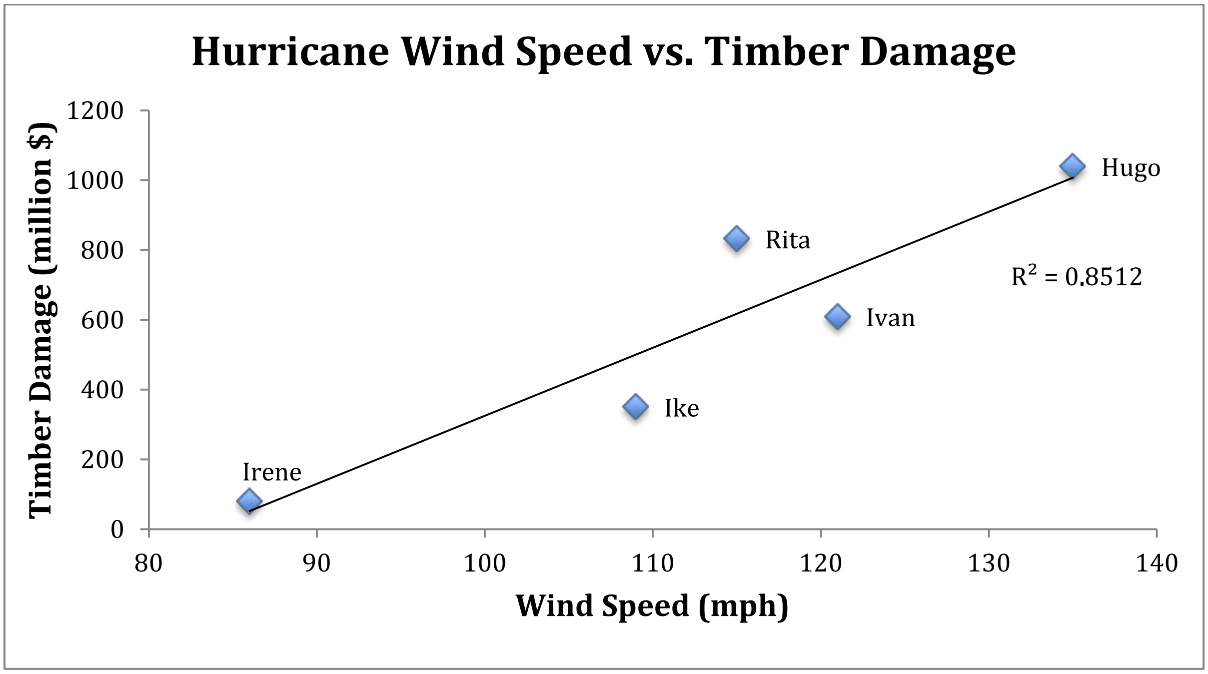

Figure 11: Correlation between hurricane wind speed and timber damage caused by five Atlantic basin hurricanes.

Figure 12 below shows the correlation between rainfall and timber damage with four Atlantic basin hurricanes. As you can see, there is also a correlation between rainfall and timber damage (R^2=0.4422), but the correlation is not as strong as it is with wind speed (R^2=0.85122). Wind speed and rainfall also appear to be correlated with each other. It appears that as wind speed increases in a hurricane, rainfall increases as well, as figure 13 below shows.

Figure 12

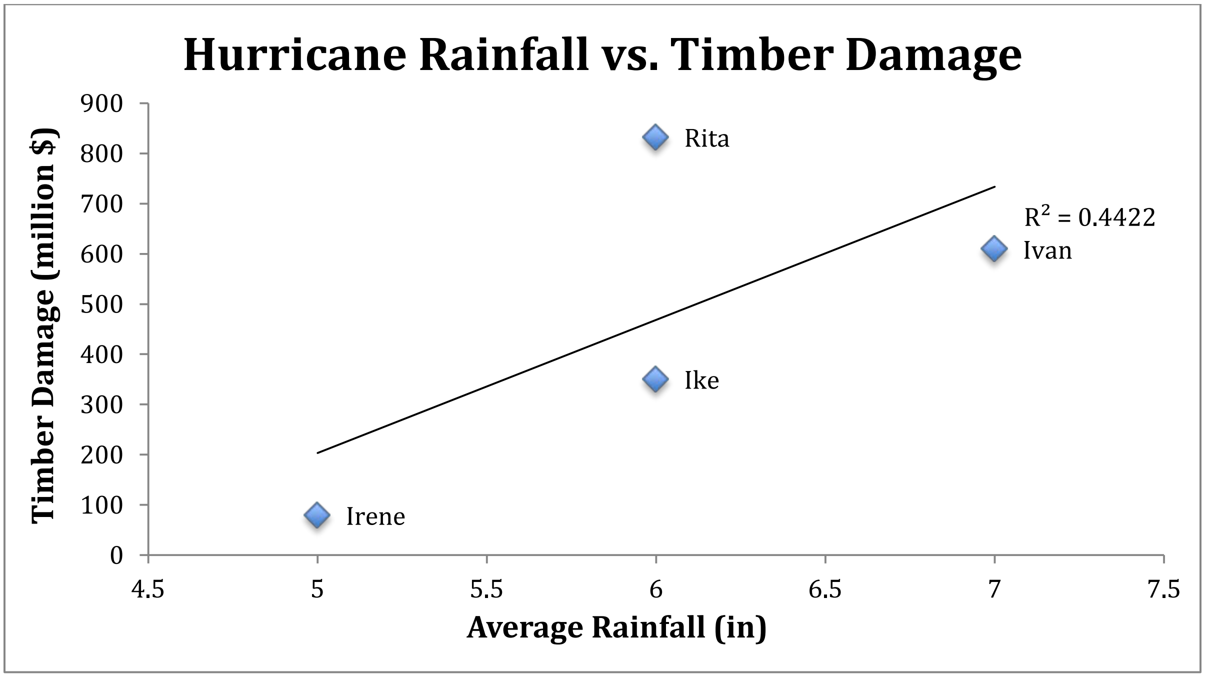

Figure 12: Correlation between hurricane rainfall and timber damage caused by four Atlantic basin hurricanes.

Figure 13

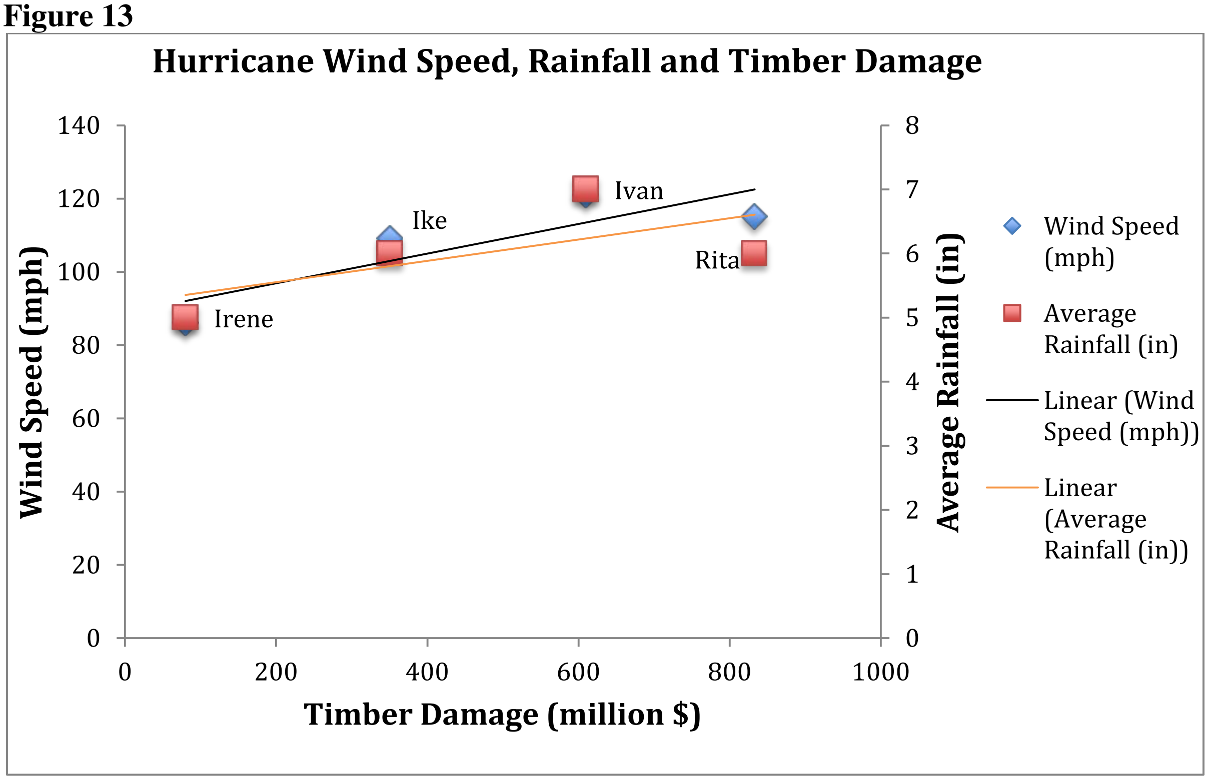

Figure 13: Hurricane wind speed, rainfall, and timber damage for four Atlantic basin hurricanes.

If timber damage is correlated with both wind speed and rainfall, then any increase in either variable should increase cyclonic deforestation. In part IV, I will apply model projected increases in hurricane wind speeds and hurricane rainfall rates to analyze how average timber damage caused by a category 3, 4, or 5 hurricane may increase by 2100 in the event of an IPCC A1B scenario.

Part IV: The Effect of Climate Change on Hurricane Activity

The effect global climate change will have on hurricanes in the Atlantic basin by the end of the 21^{st} century is unknown and controversial. In order to explore how climate change may alter hurricane activity in the future, analysis must be done on how climate change will affect the several environmental factors that influence the development of hurricanes. These factors include ocean sea-surface temperatures (SSTs), upper atmospheric temperatures, relative humidity, and wind shear.

It is popularly hypothesized that because climate change will lead to rising sea levels and increasing SSTs, there will be an increase in hurricane magnitude and frequency (Knutson, 2008). However, some models and projections predict that climate change may actually reduce hurricane magnitude and frequency because climate change will lead to increased vertical wind shear (Vecchi and Soden, 2007), one of the factors that weakens and destroys hurricanes.

One issue with predicting how climate change will affect hurricane activity in the Atlantic basin is that patterns in hurricane activity are very dynamic and happen over large time-scales. Some years produce few to no hurricanes, while others produce several intense hurricanes that cause billions of dollars in damage. In 2005, 15 hurricanes struck the Atlantic basin, including four category 5 storms.[16] These 15 hurricanes combined to make 2005 the most active Atlantic hurricane season in recorded history, shattering numerous records and causing an estimated $160 billion in damages. The following year, no hurricanes made landfall in the United States for the first time since 2001. Thus, patterns in hurricane activity are constantly fluctuating, making it very difficult to gauge what effect climate change has and/or will have. If climate change does increase hurricane magnitude in the Atlantic basin, there will be adverse ramifications on the timber industry of the southeastern United States. Even small increases in hurricane magnitude may greatly increase cyclonic deforestation, significantly increasing damaged timber.

Increased Hurricane Magnitude and Frequency Due to Increasing SSTs:

As I have previously stated in part II, evaporation of seawater into the inflowing air is the most important source of heat driving a hurricane. This is the cardinal reason why it is popularly hypothesized that increasing SSTs will lead to increasing hurricane intensity (Knutson, 2008). However, in order for this hypothesis to come true, hurricane intensity must be correlated with SSTs.

Observed records of Atlantic hurricane activity (Emanuel, 2007) show a strong correlation, on multi-year time-scales, between local Atlantic SSTs and the Power Dissipation Index. PDI is an aggregate measure of Atlantic hurricane activity, combining frequency, intensity, and duration of hurricanes in a single index. Both Atlantic SSTs and PDI have risen sharply since the 1970s, and appear to be very well correlated, which you can see in Figure 14 below.[17]

---

[16] The four category 5 storms to hit the Atlantic basin in 2005 were Emily, Katrina, Rita and Wilma.
[17] Figure 14 was taken from Emanuel (2007).

Figure 14

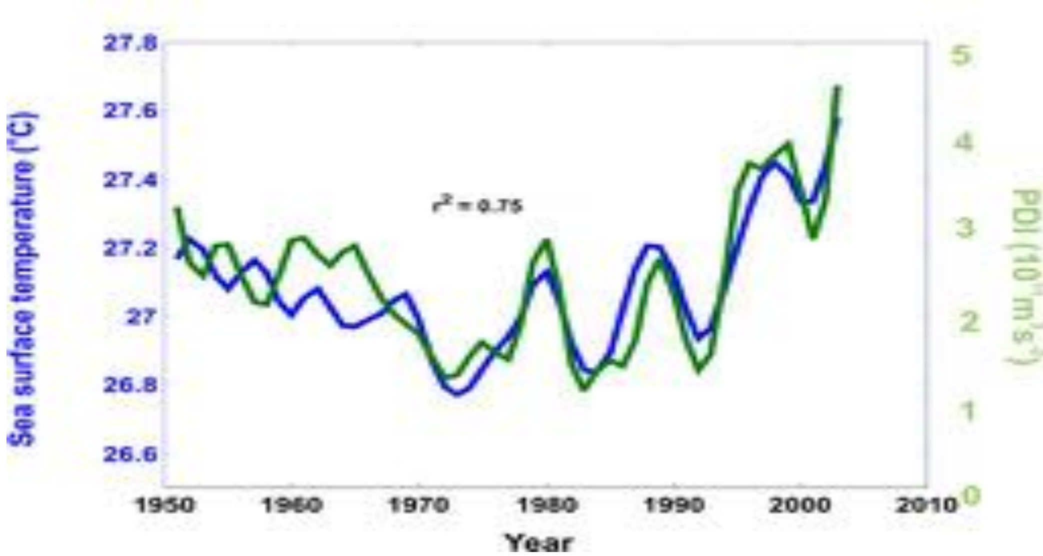

Figure 14: Time series of late summer tropical Atlantic SSTs (blue) and the PDI (green).

Large increases in tropical Atlantic SSTs projected for the late 21st century by the IPCC A1B scenario would imply very substantial increases in hurricane intensity; roughly a 300% increase in the PDI by 2100, as shown in Figure 15[18] below (Vecchi et al. 2008). However, others (Swanson, 2008) note that Atlantic hurricane PDI is also well correlated with other SST indices besides tropical Atlantic SST alone. In particular, Atlantic hurricane PDI is well correlated with indices of Atlantic SST relative to tropical mean SST (Knutson, 2008). This is a significant difference because the statistical relationship between Atlantic hurricanes and local Atlantic SST shown in the upper panel of Figure 15 would imply a very large increase in Atlantic hurricane PDI due to 21st century climate change, while the statistical relationship between the PDI and the alternative relative SST measure shown in the lower panel of Figure 15 would imply only modest changes of Atlantic hurricane PDI with climate change (Vecchi et al. 2008).

[18] Figure 15 was taken from Vecchi et al. (2008).

Figure 15

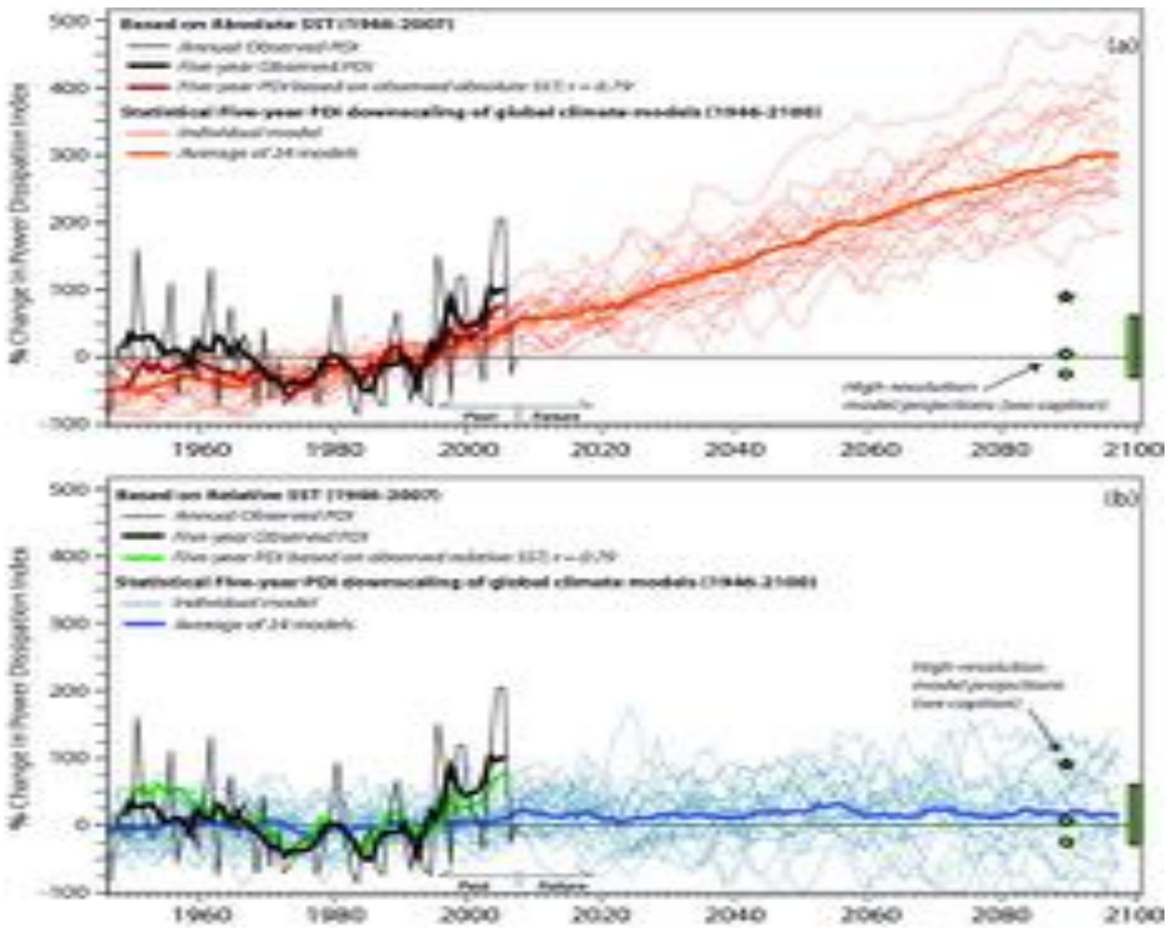

Figure 15: Two different statistical models of Atlantic hurricane PDI vs. SST. The upper panel statistically models hurricane activity based on "local" tropical Atlantic SST, while the bottom panel statistically models hurricane activity based on tropical Atlantic SST relative to SST averaged over the remainder of the tropics.

Has Climate Change Already Had An Effect on Atlantic Hurricanes?

The number of reported Atlantic hurricanes has risen sharply over the last 130 years (Vecchi and Knutson, 2008), making it seem clear that climate change has already had a significant effect on hurricane frequency. However, there is a major distinction between reported hurricanes and the actual overall number of hurricanes that occur, because not all hurricanes have been reported. Reporting methods have greatly changed since the 1960s with the use of satellite detection. Reporting methods pre 1960s consisted almost entirely of ship reports because many hurricanes do not make landfall. In the late 19^{th} and early 20^{th} century, ship traffic was sparse, and it is likely that many hurricanes were missed and never reported (Vecchi and Knutson, 2008). Therefore, the appeared sharp increase in hurricane frequency over the last 130 years is most likely linked to increased reporting, not global climate change.

In order to attempt to correct for these missed hurricanes, Vecchi and Knutson (2008) adjusted for an estimated number of missing storms, and found that there is a small nominally positive upward trend in tropical storm frequency from 1878-2006 (Figure 16 below[19]). However, statistical tests reveal that this trend is so small, relative to the variability in the series, that it is not significantly distinguishable from zero. Another study (Landsea et al. 2010) found that the rising trend in Atlantic tropical storm counts is almost entirely due to increases in short-duration (<2 day) storms alone. Such short-lived storms were particularly likely to have been missed by ships and never reported. Therefore, it does not appear that climate change has already had an effect on Atlantic basin hurricanes. However, as climate change carries on into the next century, effects on Atlantic basin hurricanes may begin to be observed.

Figure 16

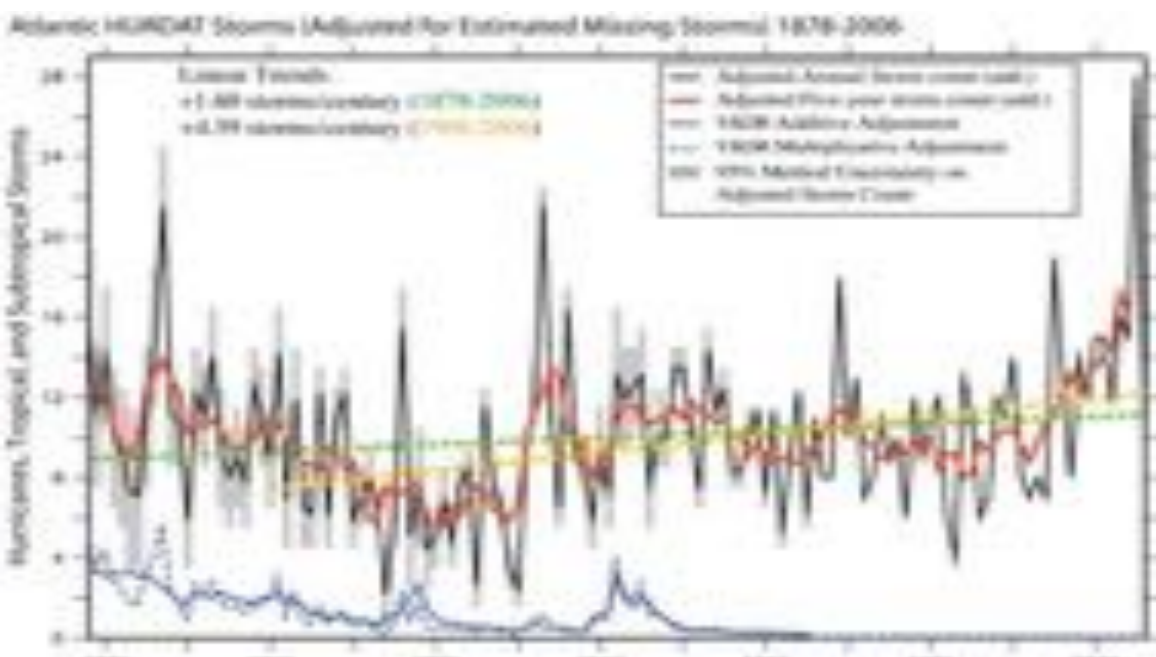

Figure 16: Reconstruction of Atlantic tropical storms (1878 to current) with adjustments during the pre-satellite era (1878-1965) based on weather reporting ship track density in the Atlantic. Blue curve shows the adjustment for estimated number of missing storms.

[19] Figure 16 was taken from Vecchi and Knutson (2008).

The Effect of Climate Change on Hurricane Rains:

There are several ways in which global climate change may alter hurricane intensity. The first way is that climate change may increase the duration and amount of hurricane rainfall. Increased hurricane rains will lead to an increase in soil moisture making timber more readily uprooted, therefore leading to increased cyclonic deforestation.

Knutson (2008) projects that by the end of the 21st century, global climate change will likely cause hurricanes to have substantially higher rainfall rates than present-day hurricanes, with a model-projected increase of 20% for average rainfall rates. A 20% increase in rainfall would likely cause a significant increase in cyclonic deforestation, especially in the areas hit by the hurricane's eyewall and secondary eyewall, where rainfall would increase the most.

During Hurricane Katrina, a large swath of 8-10 inches of rain fell across southeastern Louisiana and southwestern Mississippi, with a small area of 10-12 inches over eastern Louisiana, including 11.63 inches reported in Slidell, LA.[20] Heavy rainfall was also reported in southwestern Alabama, with some locations receiving 5 inches. Figure 17[21] below shows the geographic distribution of rainfall during Hurricane Katrina. As you can see, the heaviest rainfall is located near the storm's center, in the hurricane eyewall.

[20] Information taken from the National Hurricane Center's tropical cyclone report on Hurricane Katrina. Accessed on 2/26/2013.
[21] Satellite imagery of Figure 17 provided by NOAA. Image was taken from a powerpoint provided by Dr. William W. Locke at Montana State University. Accessed on 2/26/2013.

Figure 17

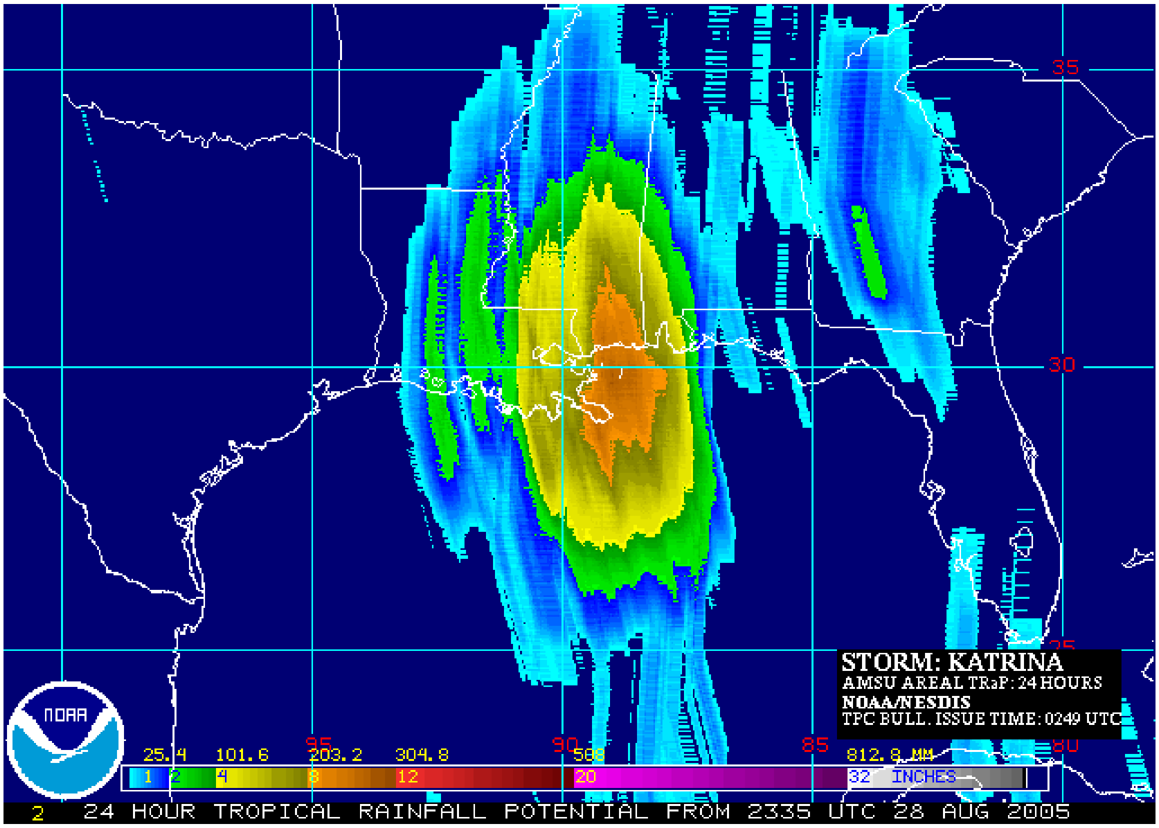

Figure 17: Satellite imagery of tropical rainfall during Hurricane Katrina.

A model-projected 20% increase in hurricane rainfall (Knutson, 2008) would be very significant given a hurricane the size of Katrina. If the rains caused by Hurricane Katrina were to be increased by 20%, much of the orange area in Figure 17 (8-10 inches) would increase into red (11-12 inches), an increase of about 2 inches. A 2 inch increase in rainfall during Hurricane Katrina would have been very significant in southern Mississippi, the area hit with the heaviest rainfall during Katrina. In Figures 18a[22] and 18b[21] below, I show how a 20% increase in rainfall would have affected rainfall during Hurricane Katrina in Alabama and Mississippi respectively. As you can see, many areas would have been hit with much heavier rainfall.

---

[22] Data for Figures 18a and 18b were taken from the National Hurricane Center's tropical cyclone report on Hurricane Katrina. The model-projected 20% increase in hurricane rainfall is derived from Knutson (2008).

Figure 18a

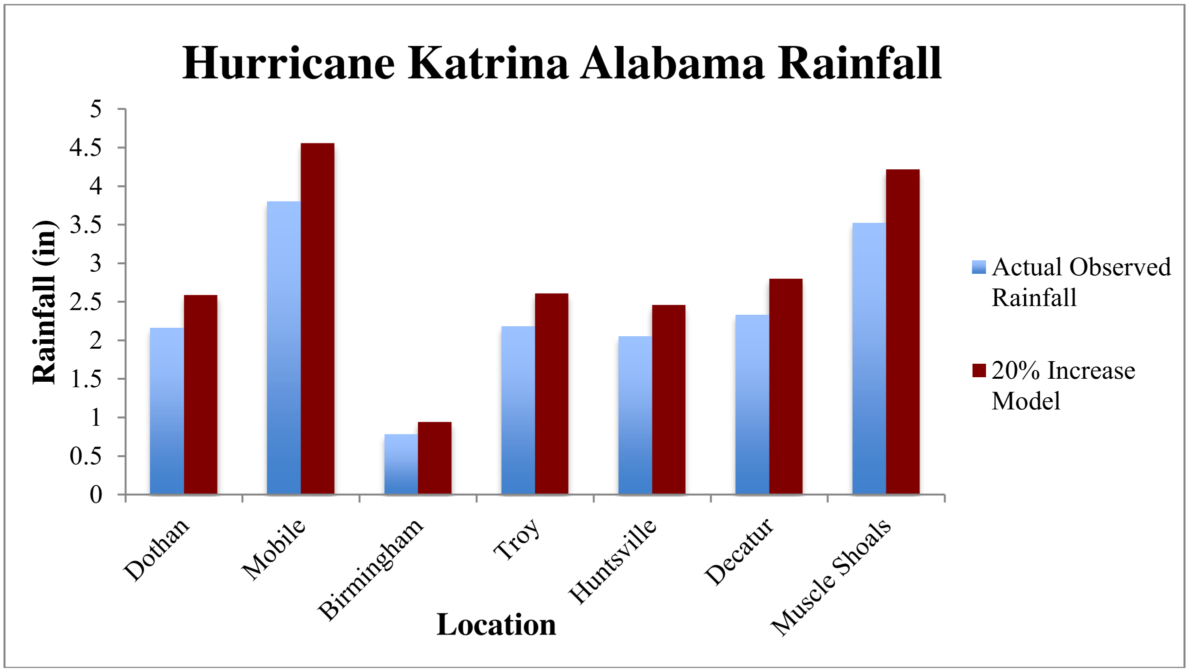

Figure 18a: Rainfall (in) during Hurricane Katrina at select locations in Alabama. The blue bars mark observed rainfall amounts while the red bars mark a model-projected 20% increase in rainfall at the same locations.

Figure 18b

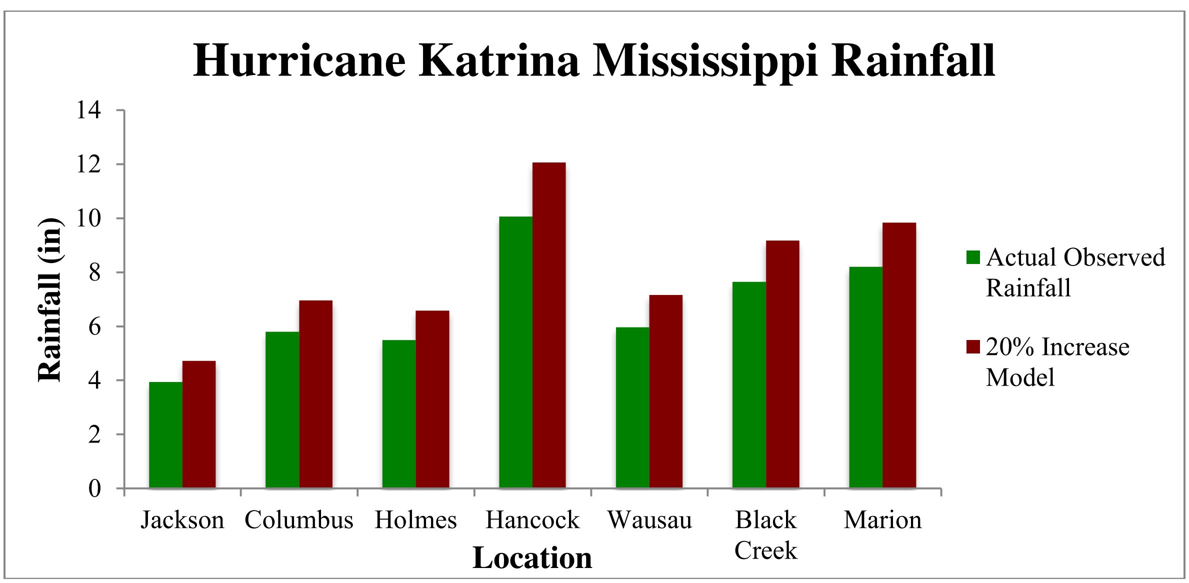

Figure 18b: Rainfall (in) during Hurricane Katrina at select locations in Mississippi. The green bars mark observed rainfall amounts while the red bars mark a model-projected 20% increase in rainfall at the same locations.

The Effect of Climate Change on Hurricane Winds:

According to the 2007 Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC-AR4), climate change by the end of the 21st century will likely cause hurricanes globally to be more intense on average by 2 to 11% according to model projections for an IPCC A1B scenario (Knutson, 2008). The most significant increases in hurricane intensity will occur in the Indian and Atlantic Oceans. Knutson (2008) predicts that average hurricane wind speeds could increase by 10% by 2100. A model-projected 10% increase in hurricane wind speeds could potentially significantly increase cyclonic deforestation caused by a category 3, 4 or 5 hurricane. Figure 19[23] below shows how the model-projected 10% increase in wind speed would affect the wind speeds of Hurricane Katrina. This 10% increase would increase wind speed at the time of landfall from 127 kt to 140 kt, an increase of 15 mph.

Figure 19

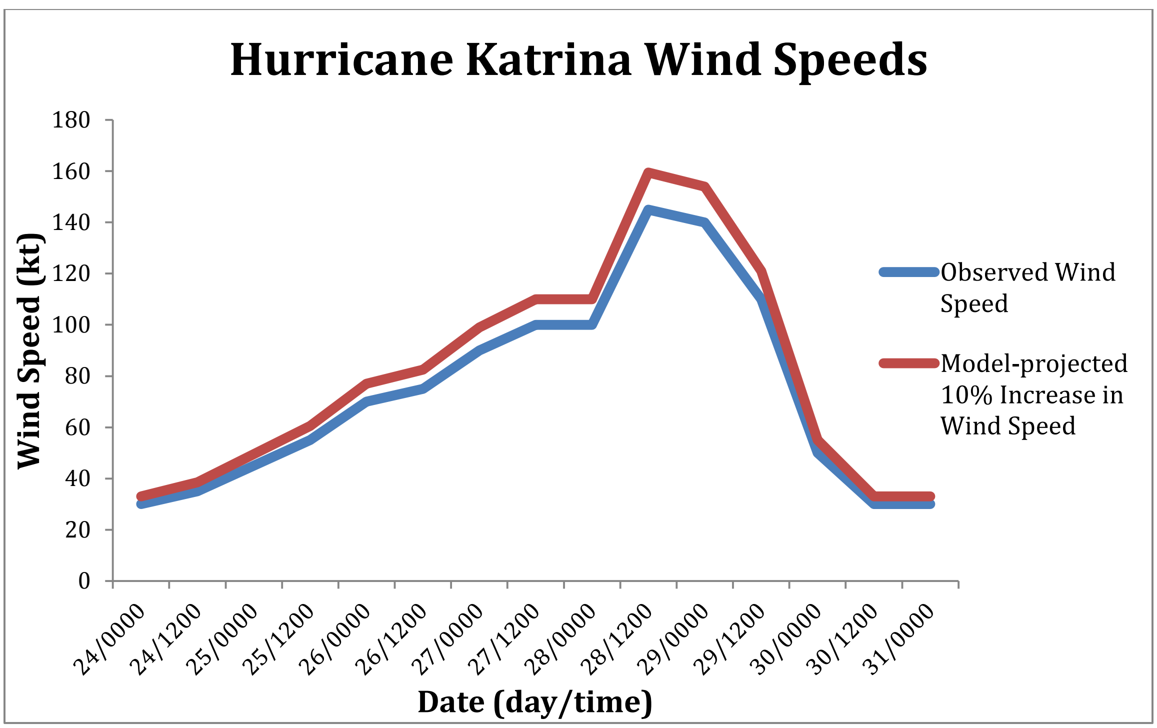

Figure 19: Observed Hurricane Katrina wind speeds vs. model-projected 10% increased wind speeds for Hurricane Katrina.

[23] Wind speed data for Figure 19 were taken from the National Hurricane Center's tropical cyclone report on Hurricane Katrina. The model-projected 10% increase in wind speed is derived from an IPCC A1B scenario taken from Knutson (2008).

Part V: Future Economic Ramifications of Cyclonic Deforestation in Light of an IPCC A1B Scenario.

In part IV, we saw that observed records of Atlantic hurricane activity show a strong correlation, on multi-year time-scales, between local Atlantic SSTs and the PDI (Emanuel, 2007). We then saw that the large increases in tropical Atlantic SSTs projected for the late 21st century by an IPCC A1B scenario would imply very substantial increases in hurricane intensity; roughly a 300% increase in the PDI by 2100 (Vecchi et al. 2008). I then analyzed how [20%] increases in hurricane rainfall rates and [10%] increases in hurricane wind speeds would affect hurricane intensity. Changes this substantial in hurricane intensity will likely cause significantly more cyclonic deforestation in the future. In part V, I will analyze how these model-projected changes may increase the average amount of cyclonic deforestation caused by a category 3, 4 or 5 hurricane.

In Figure 20 below, I took Figure 11 from part III, and plotted symbols (stars) along the trend line at every 10 mph increase in wind speed. As Figure 20 shows, timber damage increases by about $200 million for every 10 mph increase in wind speed.

Figure 20

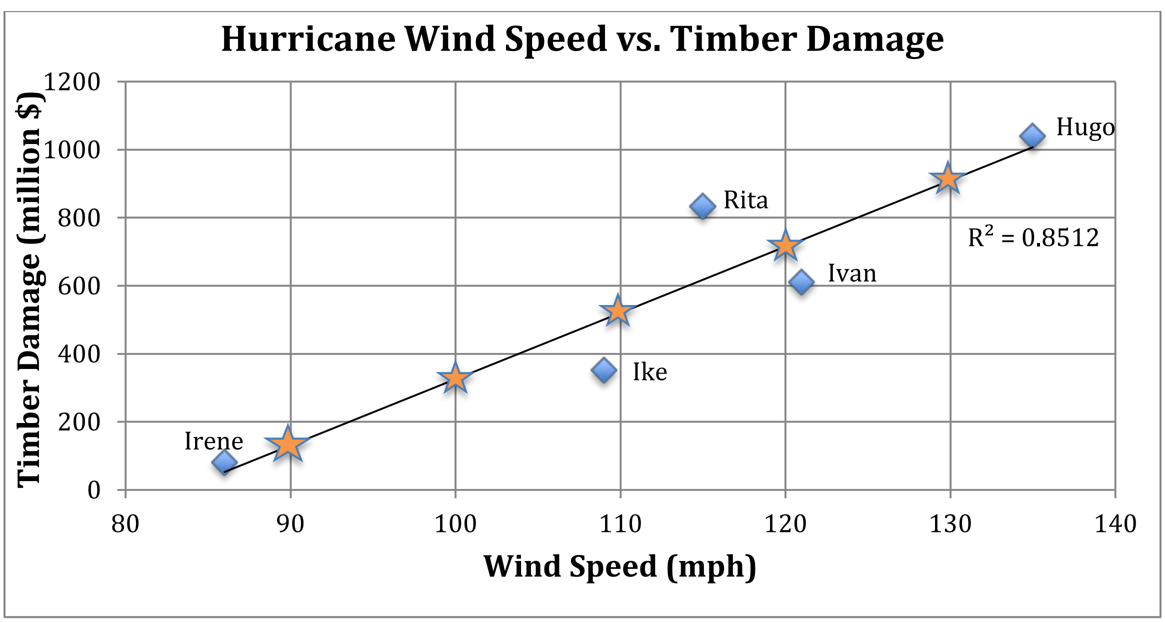

Figure 20: Hurricane wind speed vs. timber damage for 5 Atlantic basin hurricanes.

Therefore, if average hurricane wind speeds are increased by 10 mph in the future, average timber damage caused by a category 3, 4 or 5 hurricane could increase by $200 million. As mentioned in part IV, Knutson (2008) projects that under an IPCC A1B scenario, maximum sustained wind speeds could increase by as much as 10% by 2100. An increase this large would surpass 10 mph for a category 3, 4 or 5 hurricane. As Figure 19 showed, wind speed at the time of landfall for Hurricane Katrina would increase by 15 mph given a 10% increase. Therefore, average timber damage caused by a category 3, 4 or 5 hurricane could increase by at least $200 million by 2100, and perhaps even more.

Figure 20 does not take into account rainfall because rainfall is not as well correlated with average timber damage as wind speed is. However, the model-projected 20% increase in rainfall rates by 2100 (Knutson, 2008) will likely increase average timber damage per category 3, 4 or 5 hurricane. Thus, average timber damage caused by a large hurricane could increase by even more than $200 million by 2100 if rainfall is increased as well. However, I have chosen not to include increased rainfall in my model because of how loosely correlated rainfall is with average timber damage.

Part V: The Resiliency of the Timber Industry of the Southeastern United States to Increasing Cyclonic Deforestation

The main point of this paper is to analyze how resilient the timber industry of the southeastern United States is to changes in hurricane activity due to climate change. In part III, I examined the economic ramifications of cyclonic deforestation, and found the results to be quite significant. As table 2 showed, category 3, 4 and 5 hurricanes can cause millions, and even billions of dollars in timber damage. In Part IV, I examined how climate change under an IPCC A1B scenario may alter hurricane activity. Given a model-projected 10% increase in wind speed and a model-projected 20% increase in rainfall by

2100, average timber damage caused by a hurricane can be expected to greatly increase. I found that if maximum sustained wind speeds at landfall were to increase by 10 mph, the average amount of timber damaged caused by a category 3, 4, or 5 hurricane could increase by $200 million.

So, how resilient is the timber industry of the southeastern United States to the predicted average increase of $200 million in damaged timber per category 3, 4 or 5 hurricane? There are four main elements that increase the resiliency of the timber industry of the southeastern United States to future increases in cyclonic deforestation: salvage logging, government assistance, casualty loss deductions, and insurance. Together, these four elements help to make the timber industry more resilient against increased cyclonic deforestation.

Salvage Logging:

As mentioned in part II, salvage logging is one of the numerous ways forest owners can decrease the amount of timber damaged in a hurricane. After a hurricane strikes a forested area, the forestland is littered with downed and damaged trees. These trees will shortly die and will eventually rot and decay. However, if the timber is salvaged soon enough after it is damaged, some of the value of the damaged timber can be saved. Salvaging hurricane-damaged timber can also decrease the chances of losing more forestland in the future, because damaged timber becomes subject to many negative forces over time, including decay, insect infestations and wildfires, which can spread to undamaged trees.

The Decay of Damaged Timber

When timber is killed or damaged, it begins to rot and decay. As timber begins to decay, the value of timber decreases significantly with time. Thus, salvage harvests should focus on the highest value timber first, which may only be useful for pulpwood, mulch, energy wood or particleboard once stain and decay set in (Long et al. 2012). Several factors influence the amount of time that it takes for wood to degrade from a solid wood product to a less valuable product such as pulpwood. Some factors include weather conditions, type of damage, and whether the timber is immediately dead or perhaps still initially alive after the storm event (Long et al. 2012).

Insect Infestations

Hurricane damaged timber is at risk of insect infestations. The more severely the timber is damaged, the more likely it is that the timber will be attacked by insects such as bark beetles. The southern pine beetle is the most serious threat to storm-weakened pine timber (Long et al. 2012). Weakened pines emit a scent that is attractive to beetles, and once the beetles settle in, an infestation may engulf large areas of pine timber, the dominant timber of the southeastern United States. An uncontrolled southern pine beetle infestation can kill hundreds of acres of pine timber in a relatively short time span. Other species of bark beetles also attack weakened, injured and stressed pines (Long et al. 2012). Thus, damaged timber should be salvaged as soon as possible to prevent insect infestations.

Wildfire Risk

Whether the standing timber is heavily damaged or not, branches, leaves and broken tops litter the forest floor after a storm and become potential fuel for a wildfire the following spring and summer. If damaged timber is not salvaged and cleaned up, there is an increased risk of losing more timber to wildfire. Thus, damaged forests should be cleaned up following a hurricane to help mitigate wildfire risk as well.

Therefore, salvage logging not only cuts losses on hurricane-damaged timber, but also helps prevent future damage to more forestland. In order to avoid timber decay, insect infestations and wildfire risk, hurricane damaged timber should be salvaged as soon as possible. However, if damaged timber is salvaged immediately following a hurricane, prices may be significantly lower than usual. This is because as mentioned in part II, timber prices usually experience a significant price decrease following a hurricane because of the significant supply increase to the market. This increase in supply is simply due to the large influx of timber into the market because everyone is trying to salvage damaged timber simultaneously.

The longer forest owners can wait for supply to decrease and prices to increase, the more profit they can make on salvage logging. Forest owners may also be incentivized to wait to salvage log because logging costs are usually increased following a hurricane given the increased demand for logging. However, the longer damaged timber is not salvaged, the more its value will decrease due to rotting, decay and insect infestations. Therefore, many forest owners choose to salvage damaged timber too soon or too late, causing a loss in economic surplus. Deciding when to salvage damaged timber can be a very difficult decision. Overall, salvage logging is an important element in making the timber industry more resilient to future changes in hurricane activity.

Government Assistance:

Until recently, none of the disaster recovery programs administered by the federal government included forestry or timberland. Timberlands under the Conservation Reserve Program may qualify for replanting cost-share assistance according to contract stipulations. Since timber is not an annual crop, landowners that grow trees have not been eligible for federal crop insurance like many agricultural commodities. Similarly, past emergency relief funds from the federal government did not include allocations to help timber owners. However, the emergency disaster relief-funding package signed in October 2004 included $25 million for assistance to family forest owners in the Southeastern United States (Long et al. 2012). Therefore, some damaged timber may be reimbursed by the federal government.

Timber Casualty Loss Deductions

When a timber stand is storm-damaged, landowners may be able to recover the loss as a casualty loss on their federal income tax return as outlined in the Internal Revenue Code. To be allowed as a casualty deduction, a loss to one's timber must be caused by natural or other external factors acting in a sudden, unexpected and unusual manner. Hurricanes typically fit this qualification. Unfortunately, most timber casualty losses are limited to the adjusted basis of the timber. Generally, the amount of deductible loss is the lesser of the decrease in the fair market value of the timber or the adjusted basis (minus any income received from a salvage operation and/or any insurance proceeds). Basis is the cost of the timber on the property. It is either the cost allocated to the timber when the tract was purchased, or the fair market value of the timber when the property was inherited, or the cost of reforestation when the current owner planted the tract. In order to qualify for casualty loss deductions, salvaging the damaged timber must be attempted and documented (Long et al. 2012).

Insurance:

Some timber losses can be recovered through government assistance and casualty loss deductions, and some damaged timber can be salvaged. However, not all damaged timber can be salvaged or be claimed as a casualty loss deduction. Thus, insuring timber is the best way for private landowners to protect their timber against increasing cyclonic deforestation. While all the major timber companies of the southeastern United States have insurance on their timber, the same cannot be said about individual land owners. Much of the forestland in the southeastern United States is privately owned by individual land owners that hire logging companies to cut down their timber. Many of these individual land owners do not have insurance on their timber, and may be at serious risk to increased cyclonic deforestation.

Conclusion:

Global climate change will likely have a large impact on the planet over the coming century. As seasonal weather patterns are altered, entire ecosystems may change. Species will be forced to adapt to the transformations of the planet brought on by climate change. Likewise, society will also have to adapt to these transformations. Many industries around the world will be affected by climate change, and without adaptation and proper preparedness, these industries may collapse. Thus, it is crucial that society prepares for the effects of global climate change.

Over the coming century, global climate change may have a profound effect on hurricane activity. By 2100, average hurricane wind speeds may increase by up to 10%, while average hurricane rainfall rates may increase by 20%. Increases this large may significantly increase cyclonic deforestation. Average timber damage caused by a category 3, 4 or 5 hurricane could increase by $200 million, and perhaps beyond. Through salvage logging, government assistance, casualty loss deductions and insurance, it appears that the timber industry of the southeastern United States as a whole is resilient to future increases in cyclonic deforestation. However, individual landowners without insurance may be at serious risk, because insurance is the only sure way to protect timber. Therefore, it is crucial that industries consider insurance to mitigate future transformations brought about by global climate change. While a number of other methods to mitigate adverse effects caused by climate change may be used, the best and perhaps only way to protect any asset is to insure it.

Acknowledgements

I would like to acknowledge all who have helped me the past four years. I would first like to thank Lewis and Clark College for all the wonderful resources they have presented me with over the course of my college career. Specifically, I would like to thank the entire Environmental Studies department for offering a wonderful and fulfilling degree. I would like to thank Environmental Studies professors Jessica Kleiss and Jim Proctor for advising me in ENVS 499 independent studies aimed at developing my thesis. I would also like to greatly thank Environmental Studies director and Professor Liz Safran for numerous hours of dedication and help with my thesis. I would also like to thank the International Affairs, Economics and Biology departments for helpful classes and insight. Finally, I would like to acknowledge my entire senior thesis class. The help and guidance of my peers has truly helped cultivate interests within me that eventually resulted in this senior thesis.

References and Further Readings

Alan Long, Jarek Nowak. "Assessment and Management of Hurricane Damaged Timberland", November 16, 2012. http://edis.ifas.ufl.edu/fr154.

Ambinakudige, Shrinidhi, and Sami Khanal. "Assessment of Impacts of Hurricane Katrina on Net Primary Productivity in Mississippi." *Earth Interactions* 14, no. 14 (December 15, 2010): 1–12.

Bister, Marja. "Low Frequency Variability of Tropical Cyclone Potential Intensity 1. Interannual to Interdecadal Variability." *Journal of Geophysical Research* 107, no. D24 (2002). http://doi.wiley.com/10.1029/2001JD000776.

Black, Peter G., Eric A. D'Asaro, Thomas B. Sanford, William M. Drennan, Jun A. Zhang, Jeffrey R. French, Pearn P. Niiler, Eric J. Terrill, and Edward J. Walsh. "Air–Sea Exchange in Hurricanes: Synthesis of Observations from the Coupled Boundary Layer Air–Sea Transfer Experiment." *Bulletin of the American Meteorological Society* 88, no. 3 (March 2007): 357–374.

Bove, Mark C., James J. O'Brien, James B. Eisner, Chris W. Landsea, and Xufeng Niu. "Effect of El Niño on U.S. Landfalling Hurricanes, Revisited." *Bulletin of the American Meteorological Society* 79, no. 11 (November 1998): 2477–2482.

Bragg, Don C, Michael G Shelton, and Boris Zeide. "Impacts and Management Implications of Ice Storms on Forests in the Southern United States." *Forest Ecology and Management* 186, no. 1–3 (December 2003): 99–123.

Chambers, Jeffrey Q., Jeremy I. Fisher, Hongcheng Zeng, Elise L. Chapman, David B. Baker, and George C. Hurtt. "Hurricane Katrina's Carbon Footprint on U.S. Gulf Coast Forests." *Science* 318, no. 5853 (November 16, 2007): 1107–1107.

Comita, Liza S., Maria Uriarte, Jill Thompson, Inge Jonckheere, Charles D. Canham, and Jess K. Zimmerman. "Abiotic and Biotic Drivers of Seedling Survival in a Hurricane-impacted Tropical Forest." *Journal of Ecology* 97, no. 6 (November 2009): 1346–1359.

Emanuel, Kerry. *Divine Wind: The History and Science of Hurricanes*. Oxford University Press, USA, 2005.

Emanuel, Kerry. "Environmental Factors Affecting Tropical Cyclone Power Dissipation." *Journal of Climate* 20, no. 22 (November 2007): 5497–5509.

Fierro, Alexandre O., Xuan-Min Shao, Timothy Hamlin, Jon M. Reisner, and Jeremiah Harlin. "Evolution of Eyewall Convective Events as Indicated by Intracloud and Cloud-to-Ground Lightning Activity During the Rapid Intensification of Hurricanes Rita and Katrina." *Monthly Weather Review* 139, no. 5 (May 2011): 1492–1504.

Garden, Donald S. *Droughts, Floods & Cyclones: El Niños That Shaped Our Colonial Past*. North Melbourne, Vic: Australian Scholarly Pub, 2009.

Gillis, Justin. "In Weather Chaos, a Case for Global Warming." *The New York Times*, August 14, 2010, sec. Science / Environment. http://www.nytimes.com/2010/08/15/science/earth/15climate.html?ref=temperaturerising.

Gillis, Justin. "With Deaths of Forests, a Loss of Crucial Climate Protectors." *The New York Times*, October 1, 2011, sec. Science / Environment. http://www.nytimes.com/2011/10/01/science/earth/01forest.html?ref=earth.

Gray, William M. "Atlantic Seasonal Hurricane Frequency. Part I: El Niño and 30 Mb Quasi-Biennial Oscillation Influences." *Monthly Weather Review* 112, no. 9 (September 1984): 1649–1668.

Hagen, Andrew B., and Christopher W. Landsea. "On the Classification of Extreme Atlantic Hurricanes Utilizing Mid-Twentieth-Century Monitoring Capabilities*." *Journal of Climate* 25, no. 13 (July 2012): 4461–4475.

Hilti, Niklaus, Mark Saunders, and Benjamin Lloyd-Hughes. "Forecasting Stronger Profits." *Global Reinsurance* (August 2004).

Holmes, Thomas P., Jeffrey P. Prestemon, and Karen Lee Abt. *The Economics of Forest Disturbances: Wildfires, Storms, and Invasive Species*. Springer, 2008.

Howard, J. J. "Hurricane Katrina Impact on a Leveed Bottomland Hardwood Forest in Louisiana." *The American Midland Naturalist* 168, no. 1 (2012): 56–69.

Kidson, John W., and James A. Renwick. "The Southern Hemisphere Evolution of ENSO During 1981–99." *Journal of Climate* 15, no. 8 (April 15, 2002): 847.

Knabb, Richard, Jamie Rhome, and Daniel P. Beard. "Tropical Cyclone Report- Hurricane Katrina", n.d. http://www.nhc.noaa.gov/pdf/TCR-AL122005_Katrina.pdf.

Knutson, Thomas R., John L. McBride, Johnny Chan, Kerry Emanuel, Greg Holland, Chris Landsea, Isaac Held, James P. Kossin, A. K. Srivastava, and Masato Sugi. "Tropical Cyclones and Climate Change." *Nature Geoscience* 3, no. 3 (March 2010): 157–163.

Knutson, Thomas R., Joseph J. Sirutis, Stephen T. Garner, Gabriel A. Vecchi, and Isaac M. Held. "Simulated Reduction in Atlantic Hurricane Frequency Under Twenty-first-century Warming Conditions." *Nature Geoscience* 1, no. 6 (May 18, 2008): 359–364.

Kossin, J. P., K. R. Knapp, D. J. Vimont, R. J. Murnane, and B. A. Harper. "A Globally Consistent Reanalysis of Hurricane Variability and Trends." *Geophysical Research Letters* 34, no. 4 (February 28, 2007). http://doi.wiley.com/10.1029/2006GL028836.

Malmstadt, Jill, Kelsey Scheitlin, and James Elsner. "Florida Hurricanes and Damage Costs." *Southeastern Geographer* 49, no. 2 (August 2009): 108–131.

Mills, Evan. "Weighing the Risks of Climate Change Mitigation Strategies." *Bulletin of the Atomic Scientists* 68, no. 6 (November 2012): 67–78.

Moan, Jason. *Hurricane Irene Timber Damage Summary*. North Carolina Forest Service, 2011. http://ncforestservice.gov/managing_your_forest/pdf/NCFSHurricaneIreneTimberDamage%20Report.pdf.

Oswalt, Sonja N., and Tony G. Johnson. *Louisiana, 2010 Forest Inventory and Analysis Factsheet*, 2012. http://www.treesearch.fs.fed.us/pubs/40582.

Oswalt, Sonja N. *Mississippi, 2011 Forest Inventory and Analysis Factsheet*, 2013. http://www.treesearch.fs.fed.us/pubs/42530.

Oswalt, Sonja N., Christopher Oswalt, and Jeffery Turner. “Hurricane Katrina Impacts on Mississippi Forests.” *South J. Appl. For., Vol* 32, no. 3 (2008): 139–141.

Prestemon, Jeffrey, and Thomas Holmes. *Economic Impacts of Hurricanes on Forest Owners*. USDA Forest Service, 2006. http://www.fs.fed.us/pnw/pubs/gtr802/Vol1/pnw_gtr802vol1_prestemon01.pdf.

Prestemon, Jeffrey P, and Thomas P Holmes. “Market Dynamics and Optimal Timber Salvage After a Natural Catastrophe.” *For. Sci* 50, no. 4 (2004): 495–511.

Prestemon, Jeffrey P, and Thomas P Holmes. “Timber Price Dynamics Following a Natural Catastrophe.” *American Journal of Agricultural Economics* 82 (2000): 145–160.

Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller. *IPCC Fourth Assessment Report (AR4)*. Climate Change 2007: The Physical Science Basis, 2007. http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_wg1_report_the_physical_science_basis.htm.

Swanson, Kyle L. “Nonlocality of Atlantic Tropical Cyclone Intensities.” *Geochemistry, Geophysics, Geosystems* 9, no. 4 (2008): n/a–n/a.

Tanner, E. V. J., and P. J. Bellingham. “Less Diverse Forest Is More Resistant to Hurricane Disturbance: Evidence from Montane Rain Forests in Jamaica.” *Journal of Ecology* 94, no. 5 (September 2006): 1003–1010.

Vecchi, Gabriel A., and Thomas R. Knutson. “On Estimates of Historical North Atlantic Tropical Cyclone Activity.” *Journal of Climate* 21, no. 14 (July 15, 2008): 3580–3600.

Vecchi, Gabriel A., and Brian J. Soden. “Increased Tropical Atlantic Wind Shear in Model Projections of Global Warming.” *Geophysical Research Letters* 34, no. 8 (2007): n/a–n/a.

Vecchi, Gabriel A., Kyle L. Swanson, and Brian J. Soden. “Whither Hurricane Activity?” *Science* 322, no. 5902 (October 31, 2008): 687–689.

Wear, David N. *Forest Management and Timber Production in the U.S. South [Document Prepared for Canada/United States Lumber Consultations]*, 1996. http://www.treesearch.fs.fed.us/pubs/566.

Zeng, Hongcheng, Jeffrey Q. Chambers, Robinson I. Negrón-Juárez, George C. Hurtt, David B. Baker, and Mark D. Powell. “Impacts of Tropical Cyclones on U.S. Forest Tree Mortality and Carbon Flux from 1851 to 2000.” *Proceedings of the National Academy of Sciences* 106, no. 19 (May 12, 2009): 7888–7892.

Zhao, Ming, and Isaac M. Held. “TC-Permitting GCM Simulations of Hurricane Frequency Response to Sea Surface Temperature Anomalies Projected for the Late-Twenty-First Century.” *Journal of Climate* 25, no. 8 (April 15, 2012): 2995–3009.