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Investigation Into The Relationship Between Hurricane Storm Parameters and Damage

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INVESTIGATION INTO THE RELATIONSHIP BETWEEN HURRICANE STORM PARAMETERS AND DAMAGE

by

Jeremy S. Young

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in partial fulfillment of the requirements for the degree of

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Some of the Hurricanes presented in this paper I have personally experienced: Hurricane Frederic blew through my homeland, when I was a toddler. The other "big one" for the

Pensacola and Mobile area was Ivan and my family nicknamed it “Ivan the Terrible”, and it was terrible since it took us three weeks to remove the trees from the road, so that we could resupply on food. Of course later on in my life, I witnessed many more Hurricanes such as Erin, Dennis, Charlie, Jeanne, and Opal: each one I believe taught me something new in style and nature of destruction. I will never forget following Hurricane Katrina, how some people that moved to the Pensacola area because their homes were destroyed: many of those people have never moved back tocoastal Louisiana.

It was an honor to attend school at UNF and to work as a graduate assistant. My life has been shaped by events and people, as it is a natural way of growing into one’s character.

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ABSTRACT

"Economic damage, such as damage to property and infra-structure, from hurricane surges depends on two factors 1) the depth of coastal inundation and 2) the area covered by the surge" (Irish et. al 2007). Typically, damage estimates are developed after hurricanes have dissipated. To have the ability to predict hurricane damage in advance based upon various physical parameters would be a technical advance that could aid vulnerable coastal communities with hurricane planning. This thesis advances this goal forward by relating "Total Normalized Damage" to "Surge Scale" along with other key parameters. In this thesis Total Normalized Damages are compared to Surge Scale in three statistically significant ways: Un-separated Comparison, Separated Comparison and Separated Comparison without "micro-canes". An attempt at the surge damage function has been presented in this thesis as a cornerstone of the research work contained herein. This thesis also examines the effect of different damage components and their uncertainties on Total Normalized Damage. Such damage estimates include wind damage, surge damage, and inland flooding, which were separated into individual damage categories.

Chapter 1

INTRODUCTION

The most unpredictable and regionally destructive types of coastal storms, hurricanes, are becoming better understood thanks to technological improvements since the 1970s and beyond. In particular, Hurricane Katrina [2005], provided a large impetus for improving our understanding of hazards and risks associated with this type of storm. In spite of this progress, hurricanes and their impacts are still somewhat unpredictable. Understanding climate cycles can be realized through generations of experience and observation; however, the length of many of these cycles and the lack of good data before the middle of the last century make this difficult today. The damage costs each year due to hurricanes means, that as a nation, we should be more purposeful in our zoning, building codes, etc., to account for inevitable hurricanes since the relationship to a Coastal Construction Control Line (CCCL) (Dean et al., 2002) and damages is apparent. This thesis analyzes relationships between "Total Normalized Damage" and other key variables including population growth rates and population density, among others. This thesis analyzes the impact that population growth rates and population density have on damages. Perhaps society must prepare for higher damages with higher growth rates or otherwise restrict coastal growth rates to reduce damage liabilities. This is already being accomplished in several ways such as through government land purchasing into the United States National Park Service, or other state or local parks since many of these coastal areas are environmentally sensitive ecosystems. The CCCL is another way of allowing growth only in designated areas defined by risk.

In addition to analyzing the impact population growth rates have on damages; this thesis presents a perspective of how damage estimates accuracy is related to the methods used to estimate surges and damages available at the time of hurricane landfall through analyzing the connections of damages to Surge Scale (SS). It is not completely clear the exact survey methods that the Federal Emergency Management Agency (FEMA), Army Corps of Engineers (ACOE) and the National Oceanic and Atmospheric Association (NOAA) use to currently make damage estimates, though total damages without separation of the data is the reported source of information. Functional relationships between "Total Normalized Damages" and SS exist and are also discussed at length in this thesis.

Specifically, this thesis has been organized into five chapters. Chapter 1 presents an introduction to the thesis information. Chapter 2 presents a summary of historic literature on the subject and details the datasets required for the thesis. Chapter 3 describes Total Normalized Damages (TND) and the sample calculation to year 2010; it also describes the origins of SS. Chapter 4 describes the relationship between TND and other key variables along with the proposed damage prediction methodology. Finally, Chapter 5 gives the conclusions and recommendations that have been derived from the research conducted. Two of the chapters are considered the most important; Chapter 3 and Chapter 4.

Chapter 2

LITERATURE REVIEW

Following the very active 2004 and 2005 hurricane seasons, research into the quantification of hurricane damages has been escalating. It is not the intention of this paper to re-create the methodology for Normalized Damages formulated by Pielke (2008); rather, it will focus on developing a relationship between SS and various other key hurricane parameters to the Total Normalized Damages.

Pielke and Landsea (2008) builds on previous research complied into Pielke and Landsea (1998) and utilizes National Hurricane Center (NHC) loss estimates back to 1900. This paper presents the most comprehensive methodology to date on adjusting damages caused by Atlantic Hurricanes to a current year. Additionally, it shows areas along the Atlantic and Gulf coastlines that are particularly vulnerable to large damages due to population (See Appendix D.) In this thesis, research conducted by Malmstadt and Scheitlin (2009) were used as a resource for checking purposes for damage estimates presented in Pielke and Landsea (2008).

The Surge Scale or SS was initially developed by Irish and Resio (2007) and is a simplified approach to determining the magnitude of surges associated with hurricane events. The methodology in particular accounts for the size of a hurricane as well as bathymetry influences (a more detailed explanation can be found in Chapters 3 and 4). In tests with historical data, the SS was shown to produce the most accurate parametric means of estimating the hurricane surge response at the coastline. Resio and Westerink (2008) presents an approach to mitigating damages, such as, wetlands that can influence surge levels. On coastlines with shallow offshore and/or onshore slopes a Multiple Lines of Defense Strategy is often utilizes for mitigating damages. Figure 1 shows a graphical example of this concept.

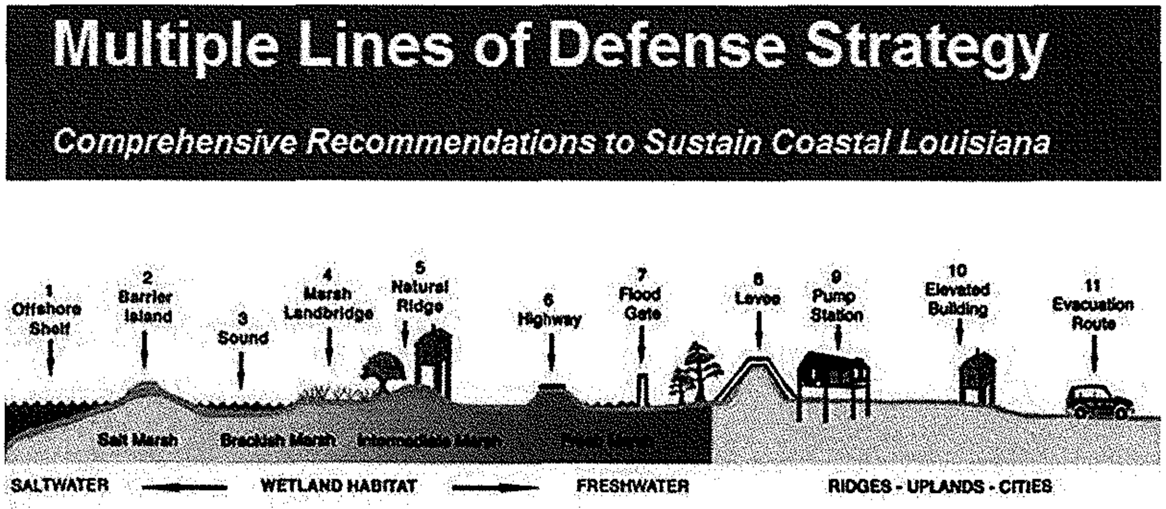

Figure 1: MSCIP 2010 Report

Based on upland topography, offshore bathymetry and the probabilities of hurricane occurrence, a "multiple lines of defense strategy" can reduce damages significantly. This strategy is similar to the Dutch approach of coastal disaster mitigation and coastal engineering issues; building surge infrastructure in multiple lines allows redundant protection from hurricane induced damages.

2.1 Introduction to the Damage Function

The Damage Function for surge (Irish and Resio, 2007) consists of several factors in which economic damage is related to storm parameters such as surge elevation, storm size, alongshore extent of surge, storm intensity, shelf and beach geometry (e.g. bathymetry, topography and shoreline orientation), forward speed, track, storm duration and population density. In order to compare the various storm parameters to damages to build the damage function for surge it is necessary to adjust the economic damage caused by hurricanes to the same year through the normalization procedure discussed in sections 2.3 and 2.4.

2.2 Classification of Damage Categories and Types

In order to understand damage derived from hurricanes, it is important to discuss Damage Survey Categories. Table 1 presents the categories of damage represented in official United States government (NOAA, 2011) estimates for damage. Table 2 presents a description of hurricane classification based on damage and SS.

Table 1: Damage Survey Categories

Category	**Description**
Wind Normalized Damage – ND_w	Damage determined to be derived from wind and not flooding.
Inland Flooding Normalized Damage – ND_f	Failures due to saturated soil or damage to upland infrastructure, misc. damage.
Surge Normalized Damage – ND_s	Damage determined to be caused by hurricane surge.

These Damage Survey Categories are a simple representation of contributing categories of normalized damage to the total normalized damage estimates such that:

$$TND = ND_w + ND_f + ND_s \qquad (1)$$

where, TND is "Total Normalized Damage" and ND_i is normalized damage category with subscripts defined in Table 1.

Table 2: Description of Hurricane Classification Based on Damage and Surge Scale

Hurricane Classification	**Qualitative Description**	**Damage (US$ Billions)**	**Surge Scale (SS)**
H_1	Low to Moderate Damage	0 – 17	0 – 0.5
H_2	Moderate to Extreme Damage	6 – 19	0.5 – 1.0
H_3	Moderate to Catastrophic Damage	5 – 80	1.0 – 3.0
H_4	Catastrophic Damage	80+	3.0 +

In addition to Damage Survey Categories, some hurricanes make multiple landfalls. In this case equation 1 would become:

$$TND_1 + TND_2 = TND_T = \Sigma TND \qquad (2)$$

where the notion used simply means that the Total Normalized Damage estimated is from multiple landfalls, making the task of classification particularly difficult since surge scale is calculated for each specific landfall and damage can be highly variable. In the specific case of Katrina [2005], the south Florida land fall was relatively benign and therefore represents a small amount of the TND. It is important to note that damage could be broken into a “per landfall” basis which would improve the correlations found later in Chapter 4.

2.3 The Effect of Storm Parameters on the Damage Function

The Damage Function was preliminarily investigated by Irish and Resio (2007). The authors assumed that the damage function could be written as:

$$D \approx \frac{\kappa(\gamma+\delta)}{m+1} \zeta_{\max} R_{33} \qquad (3)$$

where the Damage (D) is proportional to κ, γ, and δ which are all dimensionless constants. The parameter ζ_{max},is the maximum surge at the coast measured from the normal water level and R_{33} is the radius to hurricane force winds measured from the center of circulation. The power constant, m indicates that damage is non-linearly dependent on storm surge for m not equal to 1; however, it depends only linearly on storm size. From equation 3, we see that damages can be especially high for large with which generate large maximum surges.

This approach to the surge damage function suggests there is a way to relate economic damage in terms of hurricane storm surge parameters, which represents damage dissimilar to TND such that, TND is the estimated historical damage caused by a hurricane.

2.4 The Damage Normalization Methodology

A normalization methodology is used here to provide a consistent means of determining economic damage of past storms to current year levels of development and population. Otherwise, economic damage becomes highly dependent on the year of landfall, which would introduce a spurious relationship between the year of the hurricane and damages. The normalization methodology can be found in Pielke and Landsea (2008). Their equation is as follows:

$$D_{2005} = D_y * I_y * RWPC_y * P_{2005y} \qquad (4)$$

The quantity D_{2005}, refers to hurricane damage adjusted to the year 2005, where, D_y is the reported economic damage in current-year dollars, I_y is the inflation adjustment, $RWPC_y$ is the real wealth per capita adjustment and $P2005_y$is the coastal county population adjustment. This adjustment is a United States national level adjustment; whereas, some areas experience economic development faster/slower than others.

2.5 Surge Scale – A Hydrodynamics Based Surge Scale for Hurricanes

The SS is an empirical simplified approach to determining the magnitude of a surge event produced by hurricanes. Irish and Resio (2007) present SS as follows:

$$SS = (2.43 * 10E-4) * \Delta p * L_{30_m} * \phi_x(\frac{R_{33}}{L_{30m}}) \qquad (5)$$

The Δp is hurricane central pressure differential (mb), L_{30m} (km, also shown as w_{30}^{b}) is the horizontal distance between the shoreline and the 30 meter depth contour. Additionally, φ_x is a dimensionless storm size function and R_{33} is the radius to hurricane force winds from center of circulation.

The hurricanes presented in Chapter 3 reflect those that have a relatively normal to shoreline track (-60 to +45 degree strike angle). Hurricanes that make landfall near basin boundaries will tend to cause errors in the SS since Equation 5 assumes that a hurricane (forcing mechanism) has a sufficient length of coast to develop a surge. For multiple land falling hurricanes such as Donna [1960] and Gloria [1985]and even Floyd [1999] (not included in study) the tracks are such that they landed near basin boundaries, have oblique angles and are significantly more unrelated to the SS.

2.6 Chapter Summary

Hurricane related damages have been demonstrated to have a negative effect on the economic health of coastal communities that can persist for many years after landfall; however, this study will focus on the short-term damages since these are more directly quantifiable. The relationship between storm parameters and SS to damages is apparent. Classification of hurricanes in terms of damage, in particular focusing on surge specific damages will ultimately lead to a hurricane surge damage scale.

Previous studies, such as Powell and Reinhold (2006), have focused on the evaluation of hurricane surge damage potential (S_{DP}) a function of storm parameters in the form of an integrated kinetic energy; however, this study focuses on using actual historical damage data to advance the cause of finding a surge damage function that will be related to the SS. Since SS has been shown to be an improvement over previous hurricane indices for surges (Irish, et al. 2007), it is used here as a measure of surge impact for the estimation of surge damage. In Irish and Resio (2007), the authors also point out how the tide will sometimes have a measurable effect on total water elevation and thus damages. In this damage function the effects of wave action and run-up are assumed to be absorbed within other constants (i.e. produces a constant proportion of the damage) or can be neglected.

Other notable research for surge indices Kantha (2008) who presented the Hurricane Surge Index (HSI) which found a good positive relationship to surge; however, like the S_{DP} there is wider cone of uncertainty for the HSI when compared to Surge (m), particularly on the upper end of the scale.

Chapter 3

TESTING AND RESULTS

Chapter 3 presents a description of the data, data preparation, data comparisons and summarized test results. It's focus is to explore and explain correlations between various storm parameters, SS and normalized damages.

Historical hurricane storm parameters are chosen based on interest in effects on economic damage as suggested by Irish and Resio (2007) and others listed in section 2. Therefore, for this thesis only the most important parameters were considered. These include the radius to hurricanes force winds (R_{33}) to reflect hurricane size, central pressure (c_p^a) to incorporate intensity, maximum surge at the coast measured from the normal water level (ζ_{max}),offshore slope (w_{30}^b) for bathymetry effects, alongshore extent of surge (Y^2_m) and 2010 storm specific coastal population density (ρ) and other parameters that are included in Appendix A &B.

3.1 Hurricane Data

The hurricane storm parameters data obtained in this thesis were taken are from Irish and Resio (2007) and NOAA (2012). Table 3 lists the hurricanes evaluated and their respective affected coastal counties. This data represents an estimate based on radius to hurricane force winds (R_{33}) and the alongshore extent of surge greater than 2 meters (Y^2_m). Additionally only US mainland land falling hurricanes are listed.

Table 3: Introduction to Hurricane Data

Hurricane Name (Date) – Landfall State(s)	Affected Coastal Counties/Parishes
Katrina [2005] – Florida & Louisiana	Baldwin, Mobile Al. Jackson, Harrison, Hancock MS. St. Mary, Terrebonne, Lafourche, St. Charles, St. John the Baptist, Jefferson, Plaquemines, St. Bernard, Orleans, St. Tammany, Tangipahoa LA.
Andrew [1992] – Florida & Louisiana	Miami-Dade FL. Iberia, St. Mary, Terrebonne LA.
October [1944] – Florida	Monroe, Collier, Lee, Charlotte, Sarasota, Manatee, Hillsborough, Pinellas, Pasco Fl.
Donna [1960] – Multi-State	N/A – Most of East Coast
Ike [2008] – Texas	San Patricio, Aransas, Refugio, Calhoun, Victoria, Jackson, Matagorda, Brazoria, Galveston, Harris, Chambers, Jefferson, Orange TX. Cameron, Vermilion, LA.
Wilma [2005] – Florida	Sarasota, Charlotte, Lee, Collier, Monroe FL.
Betsy [1965] – Louisiana	Vermilion, Iberia, St. Mary, Terrebonne, Lafourche, St. Charles, St. John the Baptist, Jefferson, Plaquemines, St. Bernard, Orleans, St. Tammany, Tangipahoa, LA. Hancock, Harrison, MS.
Camille [1969] – Louisiana	St. Mary, Terrebonne, Lafourche, St. Charles, St. John the Baptist, Jefferson, Plaquemines, St. Bernard, Orleans, St. Tammany, Tangipahoa LA. Hancock, Harrison, Jackson, MS. Mobile, Baldwin AL.
Hugo [1989] – South Carolina	Chatham, GA. Jasper, Beaufort, Colleton, Charleston, Georgetown, Horry, SC. Brunswick, NC.
Charley [2004] – Florida	Charlotte, Lee FL.
Ivan [2004] – Florida/Alabama	Jackson, MS. Mobile, Baldwin AL. Escambia, Santa Rosa, Okaloosa FL.
Carla [1961] – Louisiana	Kenedy, Kleberg, Nueces, San Patricio, Aransas, Refugio, Calhoun, Victoria, Jackson, Matagorda, Brazoria, TX.
Rita [2005] – Louisiana/Texas	Matagorda, Brazoria, Galveston, Harris, Chambers, Jefferson, Orange, TX. Cameron, Vermilion, Iberia, St. Mary, Terrebonne LA.
Fredric [1979] – Alabama	Plaquemines, St. Bernard, Orleans, St. Tammany LA. Hancock, Harrison, Jackson, MS. Mobile, Baldwin, AL. Escambia, Santa Rosa, Okaloosa, FL.
Frances [2004] – Florida	Palm Beach, Martin, St. Lucie, Indian River, Brevard, FL.
Opal [1995] – Florida	Gulf, Bay, Walton, Okaloosa, Santa Rosa, Escambia, FL.
Celia [1970] – Texas	Calhoun, Aransas, Nueces, Kleberg, San Patricio, Refugio, TX.
Gustav [2008] – Louisiana	Vermilion, Iberia, St. Mary, Terrebonne, Lafourche, Jefferson, Plaquemines
Isabel [2003] – North Carolina	Brunswick, New Hanover, Pender, Onslow, Carteret, Pamlico, Beaufort, Hyde, Dare, Tyrrell Washington, Bertie, Chowan, Perquimans, Pasquotank, Camden, Currituck, NC.
Beulah [1967] – Texas	Cameron, Willacy, Kenedy, Kleberg TX.
Audrey [1957] – Louisiana/Texas	Brazoria, Galveston, Harris, Chambers, Jefferson,

	Orange, TX. Cameron, Vermilion, Iberia LA.
Eloise [1975] – Florida	Escambia, Santa Rosa, Okaloosa, Walton, Bay, Gulf, Franklin, FL.
Gloria [1985] – Multi-State	Carteret, Pamlico, Beaufort, Hyde, Dare, Tyrell, Washington, Bertie, Chowan, Perquimans, Pasquotank, Camden, Currituck, NC. Atlantic, Ocean, Monmouth, Middlesex, NJ. Richmond, Kings, Queens, Nassau, Suffolk, Bronx, NY.
Dennis [2005] – Florida	Baldwin, AL. Escambia, Santa Rosa, FL.
Hilda [1964] – Louisiana	Cameron, Vermilion, Iberia, St. Mary, Terrebonne LA.
October [1941] – Florida	Bay, Gulf, Franklin, Wakulla, Jefferson, Taylor, Levy, Dixie, Monroe, Miami-Dade, Broward, Palm Beach, FL.
Allen [1980] – Texas	Cameron, Willacy, Kenedy, TX.
Dolly [2008] – Texas	Cameron, TX
Lilli [2002] – Louisiana	Cameron, Vermilion, Iberia, St. Mary, LA.
September [1938] – New York	Atlantic, Ocean, Monmouth. NJ. Richmond, Kings, Queens, Nassau, Suffolk, Bronx, Westchester, NY. Fairfield, New Haven, Middlesex, New London, CT. Washington, Kent, Bristol, Newport, RI. Bristol, Dukes, MA.
Bret [1999] – Texas	Cameron, Willacy, Kenedy, Kleberg, TX.

The affected counties in Table 3 are used to calculate storm specific coastal population densities found later in this chapter. Although the Hurricane data extends over approximately 72 years, it is important to note the limitations of having a statistical sample approach used in this thesis versus a larger sample closer to statistical population of hurricane events on the order of centuries to more accurately reflect weather pattern effects on hurricane development and tracks.

3.2 Hurricane Damage Classification

Hurricane damage data was obtained from Pielke and Landsea (2008) and cross-checked against data from NOAA (2011) and Malmstadt and Scheitlin (2009).It should be noted that Malmstadt and Scheitlin (2009) was used as an additional reference for checking purposes as stated previously. Table 4 lists the hurricanes of interest and its SS/damage classification. The following paragraphs attempt to describe each hurricane event listed in this study according to Hurricane Damage Classification.

Table 4: Hurricanes Classified

Hurricane State/Category	Hurricane
H_1	September [1938], Ivan [2004], Frances [2004], Opal [1995], Isabel [2003], Beulah [1967], Eloise [1975], Gloria [1985], Dennis [2005], October [1941], Allen [1980], Dolly [2008], Bret [1999], Celia [1970]
H_2	Andrew [1992], October [1944], Donna [1960], Betsy [1965], Charley [2004], Hugo [1989], Carla [1961], Fredric [1979], Lilli [2002]
H_3	Ike [2008], Wilma [2005], Camille [1969], Rita [2005], Gustav [2008], Audrey [1957], Hilda [1964]
H_4	Katrina [2005]

As can be seen some hurricanes with moderate damages are in a lower category; however, these categories as shown in Table 2 are based on SS since damages within each category overlap. Notice, Katrina [2005] is the only H_4 hurricane in this study. The recurrence interval is almost every 300 years for a storm capable of a 3.0+ SS and is informative in respect to what could be expected; however, probabilities are no guarantee of non-occurrence. (Please see Appendix H)

3.2.1 H_1 Classification

Table 5 gives a detailed list of the hurricane parameters utilized in this study. As shown in section 4 of this thesis patterns emerge inherent in those parameters that are related to damages. (See Appendices A& B)

Table 5: Storm Parameters by Hurricane

Storm	**Year**	R_{33}**(km)**	w_{30}^{b} **(km)**	c_p^{a} **(mb)**	Y_2^{m} **(km)**	**Storm Angle (⍰)**	**Track Speed (v - kph)**	**Storm Duration over land (Ω - Hrs)**	ζ_{max} **(m)**	ζ_{mean} **(m)**
Katrina	2005	217	140	919	404	-2	20	48	8.5	8
Andrew	1992	77	4	949	32	36	20	60	2.4	2.4
October	1944	179	53	960	132	-47	20	48	3.4	2.8
September	1938	233	10	936	179	-12	44	30	3.5	2.8
Donna	1960	235	4	970	200	15	15	48	3.7	3
Ike	2008	195	92	952	303	-18	18	30	5.9	5.3
Wilma	2005	179	118	951	213	3	18	4	2.4	2.1
Camille	1969	109	120	910	189	15	24	60	6.9	6.6
Charley	2004	40	57	950	5	22	25	28	2.1	2.2
Betsy	1965	195	52	945	265	18	27	76	4.8	4.4
Hugo	1989	146	56	934	235	5	30	24	5.7	5.6
Ivan	2004	128	31	955	109	-10	20	64	3.1	3
Carla	1961	177	34	936	188	-15	11	66	3.7	3.5
Rita	2005	230	119	946	270	7	17	60	4.6	3.8
Frances	2004	139	15	960	16	-23	10	122	2.4	2.2
Frederic	1979	164	48	950	184	28	20	60	3.8	3.7
Opal	1995	169	21	940	173	-23	30	36	3.7	2.4
Celia	1970	101	30	944	68	12	25	48	2.8	2.8
Gustav	2008	110	81	957	151	58	25	96	4.5	4.4
Isabel	2003	214	25	957	20	-6	20	24	2	1.9
Beulah	1967	164	20	950	100	-45	15	48	2.9	2.6
Audrey	1957	164	118	964	181	-15	12	72	3.8	3.6
Eloise	1975	150	21	955	255	-8	25	26	3.4	2.6
Gloria	1985	229	24	951	74	-38	50	24	2.7	2.3
Dennis	2005	33	24	952	4	10	15	42	2.5	2.1
Hilda	1964	154	88	960	94	1	15	48	3	2.6
October	1941	143	40	970	136	5	20	30	3.24	3.2
Allen	1980	150	21	945	116	-30	20	34	3.7	2.8
Dolly	2008	35	21	967	20	-25	12	84	2.4	2
Lili	2002	133	84	966	136	34	27	24	3.6	3.4
Bret	1999	108	22	953	0	-20	14	48	1.5	2.1

R_{33} is the radius from center of the hurricane to hurricane force winds; w_{30}^{b} is the offshore normal distance to the 30 meter depth contour; c_p^{a} is the central pressure measured in millibars;

Y_2^m is the alongshore extent of surge greater than 2 m; θ is the storm angle measured from the shore normal; v is the forward track speed of the hurricane; Ω is the storm duration over land; ζ_{max} is the maximum water surface elevation measured vertically from the normal water level. ζ_{mean} is the observed peak mean hurricane surge which is always somewhat less the ζ_{max}.

Fourteen storms were classified as H_1. For these storms, there was little to moderate damage; however, an assessment of each hurricane is necessary to understand why these storms fall under the H_1 classification. September [1938] which was rather large at R_{33}= 233 km and Y_2^m= 179 had a w_{30}^b = 10 km which mitigated the surge; however, landed on a highly populated coastline which leads to higher damage through other forms of damage. Ivan [2004] was a small to moderately sized and moderately intense hurricane with an R_{33} of 128 km at c_p^a of 955 mb. The surge was approximately 3 meters at the highest; however, due to the size of the storm contributing to a relatively small alongshore extent of the surge, the ND_s is suspected to be relatively small in comparison to the other forms of damage. The storm had a long duration over land and spawned many tornados; therefore, much of the damage related to this storm was of the type ND_w and ND_f. Frances [2004] was a hurricane that made landfall on a narrow section of the shelf with the w_{30}^b being 13 km which attenuated the majority of the storm surge. The high coastal county population density along with long storm duration over land indicates a high amount of ND_w and ND_f damage. Opal [1995] was a low to moderately damaging storm. The storm was intense at a central pressure of approximately 940 mb, R_{33} of 169 km and an Y_2^m of 175 km; however, the population density was low to moderate in this area along with a narrow continental shelf in this region.

Isabel [2003] was a large hurricane with and R_{33} of 214 km and an Y_2^m of estimated smaller size than the R_{33}. Additionally, Isabel was an intense hurricane at 954 mb; however, the population density was relatively low in this region. Additionally, landfall was within 80 km of a shoreline angle change, which tends to allow some of the surge to escape into a "lower setup" through current bypassing Cape Hatteras, NC and thus lower damages. Beulah [1967] was a moderately intense hurricane at central pressure of 950 mb, R_{33} of 164 km and an estimated Y_2^m of over 100 km. On the day of landfall Beulah reached 160 mph wind speeds; however, had a non-normal track which would tends to reduce the surge and thus damages. Eloise [1975] was a moderately intense hurricane at 955 mb with an R_{33} of 150 indicating a moderate size. Eloise [1975] was similar to Opal [1995] in regards to track and size. Eloise at a $w_{30}^b = 21$ km indicates much of the damage was in the form of ND_w and ND_f damages. Gloria [1985] represented a minimal surge threat due to the steep beach ($w_{30}^b = 30$ km) along with an oblique angle. Gloria [1985] like Donna [1960] made landfall near a basin boundary which disperses the surge. Dennis [2005] was a "micro-cane" with an $R_{33} = 33$ km similar to Charley [2004] and Andrew [1995]. So although Mobile, AL. experienced some low to moderate wind damage, Pensacola, FL. at 50 km away, there was little to no damage.

Oct. 1941 was a moderate sized hurricane at $R_{33} = 143$ km and intensity of 970 mb; however, there were two landfalls in Florida. Important to note, the population in South Florida was not large until later in the twentieth century. Hurricane Allen [1980] was a fairly intense hurricane at landfall, briefly intensifying into a Saffir-Simpson Category 5 at approximately 180 mph with an R_{33} of 150 km; however, the population density was very low and the landfall happened to be on the Texas/Mexico border which would also tend to lower the damage estimate. Furthermore, the offshore slope in the area is steep and thereby reducing the surge and reducing damages. Similarly, Dolly [2008] made landfall near the Texas/Mexico border and had a very small R_{33} of 35 km. Same with Allen [1980], the continental shelf is narrow in this area which helps to reduce the surge and thus damages. Bret [1999] was relatively small at R33 = 108 km and also landed on a narrow section of the continental shelf, in fact the $Y_2^m = 0$ km means that Bret [1999] was a benign surge threat. Celia [1970] like Opal was a moderately intense storm at 944 mb, but was significantly smaller at an R33 of 101 km and an Y_2^m of 75 km indicating that the wider continental shelf (bathymetry), storm duration or other storm parameters may dominate in terms of damages.

3.2.2 H_2 Classification

There were nine storms classified as H_2 storms. Andrew [1992], which was small at $R_{33} = 77$ km and central pressure of 949 when land falling in southeast Florida which has a narrow $w_{30}^b = 4$ km and therefore, most of the damage derived in Florida was mostly ND_w damage and some ND_f damage. Andrew was still small and less intense at 956 mb at land fall in Louisiana; however, forward speed decreased significantly after landfall and caused mostly ND_f damage. Oct. [1944] had a highly oblique angle of $\theta = -47°$ to shore normal along with a track which is not hydrodynamically capable of producing large surges and thus the SS was very minimal at 0.7 and thus creating mostly ND_w and ND_f damage. Donna [1960] not only took a similar track to Oct [1944] in terms of angle, but also close to the basin boundary Gulf of Mexico and the Atlantic Ocean, producing mostly ND_w and ND_f damage. Additionally, October [1944] took an east coast track which involves large population densities.

Charley [2004] was a small sized hurricane with an alongshore Y_2^m of just 5 km and thus offered no major threat in terms of storm surge; however, caused heavy localized ND_w damage; whereas, rapid intensification just prior to landfall to 944 mb and an R_{33} of 40 km along with a high coastal population density along the storm track is indicative of high amounts of wind damage. Hugo [1989] R_{33} = 146 km and an intense central pressure of 934, tracked on an almost shore-normal trajectory, thus a damaging surge was released in that Y_2^m = 235 km. Carla [1961] was a large hurricane with an R_{33} of 177 km and an intensity of 936 mb. The SS = 0.6 is relatively small for this hurricane, but due to the steeper section offshore slope (w_{30}^b = 37 km) the surge was somewhat attenuated. Additionally the coastal population density was low in this area and since Carla [1961] took a track that included the Dallas/Fort Worth metropolis, the majority of damage is in ND_w and ND_f Damage Survey Categories. Land falling approximately 40 km west of Ivan, Fredric [1979] was larger at R_{33} of 164 km at 950 mb. Similar to Ivan, Fredric's track was along a moderately steep offshore slope (w_{30}^b = 56 km); therefore, the surge was partially attenuated through depth. Lilli [2002] was a moderately intense storm at 966 mb, an R_{33} of 133 km and making land fall on a relatively wide continental shelf: All of which would tend to increase damages; however, the damages remained low due to a low population density.

3.2.3 H_3 Classification

There were seven storms classified as H_3 Storms. Recently Ike [2008] made landfall near Galveston, TX. With and R_{33} = 195, an Y_2^m = 303 km and a shallow slope (w_{30}^b = 86 m) caused a significant surge, SS = 1.3. Wilma [2005] was a large hurricane with an R_{33} = 179 km at 951 mb. The offshore slope was also shallow in this area and therefore SS = 1.7 indicating relatively high damages; however, the track suggests that much of the damages was in the forms ND_w and ND_f since the landfall was in extreme southwest Florida in which there is no population along the coast. (Everglades) Gustav [2008], a small to medium sized hurricane $R_{33} = 110$ km at 957, took a track similar to Betsy [1965]; however, the w_{30}^{b} was much larger indicating more energy could be transferred to the shelf across the storm. Audrey [1957] was a moderately sized storm, R_{33} of 164 km and Y_2^{m} of 181 km, landed on a wide section of the continental shelf with a SS=1.3. The coastal population density was moderate leading to moderate damages. Hilda [1964] $R_{33} = 154$ at 960 mb tracked onto a moderately sloping offshore profile. ($w_{30}^{b} = 88$ km) The SS = 1.1 indicates the possibility of a moderate surge event and thus moderate damages. Additionally, Hilda weakened rapidly once it made landfall and thereby averting more damages, indicated by the low storm duration.

Betsy [1965] was a massive hurricane with an R_{33} of 195 km and an Y_2^{m} of 265 km and track included moderately populated areas of Louisiana; however, the track was such that much of the damage was through ND_w and ND_f damage. Interesting, is that a moderately steep beach slope and a helpful track that dissipates the surge energy to both sides of the Mississippi delta causes the surge to be less than a "Katrina like" normal to coastline track in which water piles up onto the Mississippi-Alabama Shelf. Camille [1969] was the standard New Orleans went by before Katrina [2005]. Camille [1969], a medium sized storm, took an almost identical track to Katrina thus producing a large surge. The storm had an $R_{33} = 110$ km and a low 910 mb; therefore, illustrating the point that if the w_{30}^{b} (30 meter contour) is wide then any hurricanes larger than "micro-canes" pose a serious surge risk to coastal areas. Another interesting fact is the configuration of the southeast Louisiana coastline with respect to circulating counter-clockwise winds inevitably creates a "funnel" for surge energy into Lake Pontchartrain. Rita [2005] was a massive storm at an R_{33} of 230 km (Irish and Resio, 2007) and intensity of 946 mb. The coastal population density for this storm was low and the track went through a sparsely populated Texas/Louisiana border; otherwise, the damage from this storm could have been much greater.

3.2.4 H_4 Classification

Katrina [2005] was an outlier in so many categories. (See Table 7 and Appendix B) Not only was this storm massive in size, but also the offshore profile and coastline in respect to the track collaborated to create a devastating surge (SS = 3.1), which indicates a catastrophic combination of unfavorable storm/geophysical parameters.

3.3 Storm Parameters Comparison to Damages

The data collected from HURDAT (North American Hurricane Database, 2012) consisted of track information for location, wind speed, track speed along with assisting with estimating some land falling storm parameters which are related to the SS and damages. Irish and Resio (2007) also were used to determine other storm parameters of significance to storm surge generation. Given that the storm parameters were assessable through these mentioned sources, a qualitative relationship between storm parameters and contribution of storm surge is found in Table 6.

Table 6: Qualitative Relationship between Hurricane Parameters and Surge Generation

Parameter	**Negligible to low Contribution**	**Low to Moderate Contribution**	**Moderate to High Contribution**
R_{33}		X	
$\zeta^{2}_{\max}$			X
$w_{30}{}^{b}$	X	X	
$Y_{2}{}^{m}$		X	
θ	X	X	
$c_{p}{}^{a}$		X	
V (Track Speed)	X		
Ω (Storm Duration)	X		
P (Population Density)		X	X

Since damages from hurricanes can be very case-specific in terms of storm parameterized storm characteristics, Table 6 over-simplifies the complex and dynamic nature of these storms to some extent. In fact, if a surge damage function exists it may be a dynamic equation such that the equation changes along the coastline and for each hurricane type. This table has severe limitations; however, provides a basis for developing a surge damage function found in section 4.5. In appendix A, the correlations to TND helped to develop the qualitative relationship listed in Table 6.

As equation 3 states, the damage function for storm surge generation is not well understood; however, in comparing the storm parameters found in Table 5, it becomes apparent that certain parameters are more highly correlated to storm damage than others. The most highly correlated parameters and their respective ranges and hurricane classifications are shown in Table 7.

Table 7: Approximate Range Storm Parameters for Hurricane Surge Scale Categories

Hurricane Surge Scale Category	**Surge Scale**	**ζ^{m}_{max} (m)**	**R_{33} (km)**	**Y_2^{m} (km)**	**ρ (Person/km^2)**	**w_{30}^{b} (km)**	**v (kph)**	**c_p^{a} (mb)**
H_1	0 - 0.5	0 - 3.7	30 - 233	0 - 179	40 - 810	4 - 40	10 - 50	936 - 970
H_2	0.5 - 1.0	2.1 - 5.7	40 - 195	5 - 265	20 - 200	4 - 84	11 - 30	934 - 970
H_3	1.0 - 3.0	2.4 - 6.9	77 - 230	32 - 303	23 - 236	4 - 120	12 - 30	910 - 970
H_4	3.0+	7.0+	150+	300+	83+	120+	20+/-	920-

Since storm duration (Ω – hours) and storm angle (θ – degrees) mimics a normal distribution, the ranges could be obtained in terms of z-scores instead of the above Table 6. It can be seen from Table 7, the ranges of storm parameters overlap, have wide variability and a single parameter is not necessarily representative of hurricane category; therefore, the table is mostly for summary purposes.

3.4 Total Normalized Damages

Normalized Damage as previously described in Peilke and Landsea (2008) was adjusted to the year 2010, since this is the last available year United States Census Bureau data is available.

Since SS is a measure of the magnitude of hurricane storm surge, SS was compared to TND in this thesis for the specific purpose of correlating the two. The limited duration of appropriate damage data (approximately 100 yr) relative to the estimated return periods for extreme events in specific locations (100-500 yr events) leaves the correlation between TND and SS, relatively weak when comparing the entire data set (R=0.295). Furthermore, there are weather pattern and climatic shifts that create additional uncertainty on these interrelationships.

In order to compare the SS and TND a sensitivity analysis was performed to determine the relative impact the adjusted year and coastal population growth have on the correlation of SS to TND. Please see Figures 2 and 3.

The TND is explained in detail in the following paragraphs which describe the procedures used to derive Tables 8, 9 and 10. Data for Normalized Damages to the year 2005 found in Pielke and Landsea (2008) was used along with other estimates from NOAA (2011) and Malmstad (2009); this study expands the data to 2010 and 2020 projections. The Columns in Table 8, 9 and 10 have been lettered for convenience referencing. Starting with Column A, the rank of the storms is based on the year 2010. Column B lists the hurricane name. Column C is the year of the hurricane event and Column D describes the state(s) of land fall. Column E is the simplified SS from Irish and Resio (2007) along with Donna (1960) and Eloise (1975) being estimated. Column F is from Pielke and Landsea(2008), which is the Normalized Damages to the year 2005. Column G is the TND adjusted to the year 2010.

Since Katrina is the most recent extreme event for Damages and SS (Ike [2005], Irene [2011], Sandy [2012] were also extreme events), a sample calculation explaining columns G through N can be found below within the Inflation Adjustment, Wealth Per Capita Adjustment, Affected Coastal County Population and Future Normalized Damages Adjustment sub-sections. TND as expressed in 2010 US Billion Dollars in column G is found from equation 4.

Column H is the coastal county population adjustment from the year 2005 to 2010. A list of affected counties can be found in Table 3. Column H represents a ratio of the 2010 population to the 2005 population for the affected counties, with the exception of storms occurring in year 2008. Column I represents a low growth scenario for coastal county population adjustment. Column J represents a moderate growth scenario for coastal county population adjustment. Column K represents a high growth scenario for coastal county population adjustment. Columns L through N correspond to columns I through K in that only the affected coastal county population has been adjusted; whereas, a reasonable adjustment for national population growth was used to derive the Real Wealth Per Capita.

3.4.1 Inflation Adjustment

Reported Damages are adjusted from 2005 dollars (D_{2005}). This is true for all cases except for Gustav, Ike and Dolly which were 2008 Hurricanes; therefore, the inflation adjustment was estimated from national inflation index(s): the implicit price deflator for gross domestic product (IPDGDP) and Consumer Price Index (CPI) (for 2008 hurricanes), reported by the Bureau of Economic Analysis (BEA) and the Bureau of Labor Statistics (BLS).So, the inflation adjustment can be found by the ratio of 2010 IPDGDP to 2005 IPDGDP. The IPDGDP for 2010 was approximately 111 and 100 for 2005. Therefore, $I_Y = 111/100 = 1.11$. There are obvious differences in what has been found in the BEA numbers for IPDGDP presented in Pielke, et al., 2008 vs. the IPDGPD numbers presented herein.

3.4.2 Real Wealth Per Capita Adjustment

According to the BEA (2011) real wealth for consumer durable goods for year 2005 was 40.98 trillion and for 2010, 45.82 trillion; where, real wealth for consumer durable goods is defined as "the net stock of equipment and software and of structures owned by business and government and the net stock of durable goods owned by consumers" (BEA, 2012). In other words Real

Wealth per Capita is a measure of how much stuff people currently own as compared to the past. Inflation, however, is the decrease in value of a currency over time. The ratio of 2010 and 2005 is 45.820/40.98=1.118. The inflation multiplier for 2005 was 1.11; therefore, the inflation corrected wealth adjustment is 1.118/1.11=1.007 or is called the Real Wealth Multiplier (RWM). The estimated United States population from the United States Census Bureau in 2005 was 297,777,921 and in 2010, 312,471,327 (USCB); thus, the United States population multiplier is the ratio of the 2010 estimate to the 2005: 312,471,327/297,777,921=1.049. Finally, the real wealth per capita ($RWPC_y$) is 1.007/1.049=0.960. This information is found in Table 10.

Table 8: General Information and Hurricane Damages

A	B	C	D	E	F	G
Rank	**Storm**	**Year**	**State(s)**	**Surge Scale (SS)**	**PL_{05} Damage (US$ Billions)**	**PL_{10} Damage (US$ Billions)**
1	Katrina	2005	FL, LA (Double Landfall)	3.1	81	85.4
2	Andrew	1992	FL, LA (Double Landfall)	1	57.7	64.4
3	October	1944	FL	0.7	38.7	44.9
4	September	1938	NY	0.2	39.2	42.4
5	Donna	1960	Mult. St. (Multiple Landfall)	1	29.6	33.0
6	Ike	2008	TX	1.3	-	28.5
7	Wilma	2005	FL	1.7	20.6	24.6
8	Camille	1969	LA, MS	2.7	21.2	23.2
9	Charley	2004	FL	0.6	16.3	19.9
10	Betsy	1965	LA	0.8	20.7	18.6
11	Hugo	1989	SC	1	15.3	18.2
12	Ivan	2004	FL, AL	0.4	15.5	17.2
13	Carla	1961	LA	0.6	14.2	16.0
14	Rita	2005	LA, TX	1.9	10	11.5
15	Frances	2004	FL	0.2	9.7	11.2
16	Frederic	1979	AL, MS, FL	0.7	10.3	10.9
17	Opal	1995	FL	0.4	6.1	6.8
18	Celia	1970	TX	0.5	5.6	6.1

19	Gustav	2008	LA	1.1	-	5.1
20	Isabel	2003	VA, NC	0.3	4	4.7
21	Beulah	1967	TX	0.3	4	4.6
22	Audrey	1957	LA, TX	1.3	3.8	4.4
2	Eloise	1975	FL	0.4	2.8	3.1
24	Gloria	1985	Mult. St. (Multiple Landfall)	0.3	2.4	2.6
25	Dennis	2005	FL	0.3	2.2	2.5
26	Hilda	1964	LA	1.1	2.2	2.4
27	October	1941	FL	0.4	2	2.2
28	Allen	1980	FL	0.3	1.6	1.9
2	Dolly	2008	TX	0.2	-	1.3
30	Lili	2002	LA	0.9	1.1	1.18
31	Bret	1999	TX	0.3	0.1	0.12

3.4.3 Affected Coastal County Population

The affected coastal counties variable was based upon NOAA published data along with information shown from Figure 20, Pielke and Landsea (2008). Additionally, HURDAT (North American Hurricane Database) was used for determining storm size, track, along with 2011 NOAA billion dollar estimate reports were used as a method to determining coastal counties affected. County population data is available for 2000 and 2010 from the United States Census Bureau. The ratio of affected population of 2010 to 2005 for Hurricane Katrina [2005]is 2517648/2543485=0.99: A complete list of these ratios for the data is found in Table 9 and is under column H. Notice the ratio represents stagnant growth and some lives were lost while others were displaced by the storm; this is evidenced by a drop in population in counties hardest hit by the storm; however, some population growth in storm outlier counties.

3.4.4 Future Normalized Damages

Although we cannot predict future damages deterministically, the methodology presented in this thesis provides a means to develop reasonable estimates of damage within an uncertainty range; this capability would be a step forward in estimating damage from a given storm surge. Furthermore, to adjust the future damage estimates, some basic understanding and assumptions are required in order to extrapolate reasonable estimates. Inflation indexes have averaged approximately 1.1(I_y), from year to year over the last two decades; therefore, a linear extrapolation was used to obtain the year 2020 IPDGDP of 123 and thus, giving an inflation adjustment to the year 2020 by 123/111=1.108. Due to the nature of the recent financial crisis, it will be difficult to ascertain the correct wealth; whereas, Appendix E shows the US wealth growth leveling off at 2008 and could cause errors in the 2020 predictions herein. Nevertheless, a modest wealth growth of 48.11 trillion USD for 2020 (45.82 trillion USD in 2005) was chosen. Wealth as shown in Appendix E looks hyperbolic until the years 2007-2010 are considered; it is shown that the numerator, the Real Wealth Multiplier (RWM) 2020 is 0.948 and the $RWPC_y$=0.948/1.092=0.868 is less than 1 (Table 10).

Table 9: Future Damages

B	C	H	I	J	K	L	M	N
Storm	**Year**	**$P_{2010/y}$**	**$P_{2020/y}$ (low growth)**	**$P_{2020/y}$ (moderate growth)**	**$P_{2020/y}$ (high growth)**	**$PL_{20(low)}$ Damage (US$ Billions)**	**$PL_{20(mod)}$ Damage (US$ Billions)**	**$PL_{20(high)}$ Damage (US$ Billions)**
Katrina	2005	0.99	0.79	0.99	1.19	64.9	81.3	97.8
Andrew	1992	1.05	0.85	1.05	1.25	52.6	65.0	77.4
October	1944	1.09	0.89	1.09	1.29	38.3	46.9	55.6
September	1938	1.01	0.81	1.01	1.21	33.2	41.4	49.5
Donna	1960	1.05	0.85	1.05	1.25	26.9	33.3	39.6
Ike	2008	1.09	0.89	1.09	1.29	24.5	30.0	35.5
Wilma	2005	1.12	0.92	1.12	1.32	21.8	26.6	31.3
Camille	1969	1.03	0.83	1.03	1.23	18.4	22.9	27.3
Charley	2004	1.14	0.94	1.14	1.34	18.0	21.9	25.7
Betsy	1965	0.84	0.64	0.84	1.04	11.5	15.1	18.7
Hugo	1989	1.12	0.92	1.12	1.32	16.1	19.7	23.2
Ivan	2004	1.04	0.84	1.04	1.24	13.9	17.3	20.6
Carla	1961	1.06	0.86	1.06	1.26	13.3	16.4	19.5
Rita	2005	1.08	0.88	1.08	1.28	9.8	12.0	14.2
Frances	2004	1.09	0.89	1.09	1.29	9.6	11.8	13.9
Frederic	1979	0.99	0.79	0.99	1.19	8.3	10.4	12.5
Opal	1995	1.05	0.85	1.05	1.25	5.6	6.9	8.2
Celia	1970	1.03	0.83	1.03	1.23	4.9	6.1	7.2
Gustav	2008	1.00	0.80	1.00	1.20	3.9	4.9	5.9
Isabel	2003	1.10	0.90	1.10	1.30	4.0	4.9	5.8
Beulah	1967	1.09	0.89	1.09	1.29	4.0	4.8	5.7
Audrey	1957	1.08	0.88	1.08	1.28	3.7	4.6	5.4
Eloise	1975	1.05	0.85	1.05	1.25	2.6	3.2	3.8
Gloria	1985	1.02	0.82	1.02	1.22	2.0	2.5	3.0
Dennis	2005	1.07	0.87	1.07	1.27	2.1	2.6	3.0
Hilda	1964	1.02	0.82	1.02	1.22	1.9	2.3	2.8
October	1941	1.05	0.85	1.05	1.25	1.8	2.3	2.7
Allen	1980	1.09	0.89	1.09	1.29	1.6	2.0	2.3
Dolly	2008	1.04	0.84	1.04	1.24	1.0	1.3	1.5
Lili	2002	1.01	0.81	1.01	1.21	0.9	1.1	1.4
Bret	1999	1.09	0.89	1.09	1.29	0.1	0.1	0.1

Decadal national population growth has decreased gradually from the early twentieth century value of approximately 20% to about 10% for the end of the twentieth century and early twenty-first century as can be noted in APPENDIX G, which depicts decline in the growth rate for national population. For damage parameters used in Equation 4refer to Table 10in order to adjust Pielke and Landsea 2005 to 2010 and 2020 Normalized Damages.

Table 10: Damage Calculation Adjustment (2005-2020)

I_y	R_2	R_1	R	RWM	US Pop 1	US Pop 2	Pop Ratio	$RWPC_y$	Adjust Year
1.110	45.818	40.980	1.118	1.007	297,777,921	312,471,327	1.049	0.960	2005-2010
1.037	45.820	45.670	1.003	0.967	304,094,000	312,471,327	1.028	0.976	2008-2010
1.108	48.111	45.820	1.050	0.948	312,471,327	341,114,336	1.092	0.868	2010-2020

3.5 Explanation of Surge Scale

Previously the SS (Irish and Resio, 2007) was described in equation 5 in the simplest form. Additionally the storm parameters data used to estimate this data was included into Table 5.

Some storms will naturally produce small errors in any Simplified SS. The SS work identifies the storms which have the capability to produce large surges such as Katrina [2005]. Hurricane Andrew [1992] which was very intense and created high amounts of wind damage produced a minimal surge; whereas, the hurricane size was small and current was allowed to bypass through the Florida Straits. Cases such as these have been given more consideration and analysis in Chapter 4. SS in its more complicated form is described in the following:

$$SS = \frac{\zeta}{\bar{\zeta}} = (\frac{\chi \Delta p}{\bar{\zeta}}) \frac{L_*}{h_* \phi_*} \psi_x (\frac{R}{L_*}) \psi_t (\frac{t_*}{t_{in}}) \qquad (6)$$

In this equation, ζ is the normal water surface elevation measured from normal water level and ζ (bar) is a surge of 1 meter; therefore, SS is shown to be dimensionless. χ is a dimensionless constant, Δp is the hurricane central pressure differential, $L_*$is the horizontal integration limit, h_* is the water depth at L_*, φ_* is a dimensionless integral shape function, ψ_x is a dimensionless storm size function and R is the characteristic storm size. Additionally, ψ_t is a dimensionless storm duration function, t_* is the characteristic storm duration and t_{in} is the time required to reach steady-state equilibrium surge.

Simplification comes from recognizing that the interactive storm response to the land occurs in water shallower than 30 meters. The equivalent depth argument is found in Irish and Resio (2007), which effectively replaces the term $L_*/h_*\varphi_*$ with L_{30m}.Once the equivalent depth argument is made, the storm size term in the equation (R/L_*) becomes R_{33}/L_{30m}. For Atlantic hurricanes, ψ_t can be approximated to be equal to 1 and if the proportionality constant between hurricane intensity and wind speed $\lambda = 0.325$ and wind drag coefficient $c_d = 0.0022$, the dimensionless constant, $\chi = 7.29(10)^8$ kg/m^3/s^2. With the above assumptions, and using hurricanes with θ (Storm Angle) between -60° and +45°, the simplified SS shown in equation 5 works well with little loss in accuracy.

3.6 The Surge Damage Function

As previously noted, population has a significant effect on TND consistent with its exponential form in Equation 8. Equation 7 represents a dimensionless population factor. With the exception of Gloria [1985] in the sorted data set of 17 hurricanes the population densities are all below 200 persons/km; therefore, a benchmark in K is introduced.

$$K = \rho / 200 \qquad (7)$$

A Surge-Only Damage Function (The Normalized Damage due to surge (ND_s)) is termed the Hurricane Coastal Surge Damage Scale (HCSDS) here. An approach to finding the predicted TND is presented in this section. Shown as Figure 7, a linear relationship has been listed in Table 16 between SS and TND. The primary focus of this thesis is to present a beginning non-linear relationship by introducing a mathematical damping function using the storm parameters listed herein. The non-linear relationship for TND vs. SS:

$$TND_P = \left[\left(\left((SS * 21.852) - 4.946\right) * \left(e^{-K * Hs}\right)\right) + \left({w_{30}}^{b} / 30\right)\right] \qquad (8)$$

If the Hurricane Damage Correction Factor (H_s) is allowed to vary, when multiplied by K, the equation successfully dampens the predicted damage to the actual damage. Please see section 4.5 and Appendix I; whereas, a more detailed explanation of sensitivity and boundary conditions can be found.

Chapter 4

DISCUSSION OF RESULTS

This thesis develops relationships between physical storm parameters and SS to damages in terms of hurricane state/category, as well as with the associated damages. This chapter begins with a discussion on the relationships developed for the hurricane damage events with SS and hurricane parameters. Finally, a table which incorporates all of the results from the developed relationships is presented. (Table 16)

4.1 Coefficient of Determination Measurements

The coefficient of determination, or R^2 value was obtained for each relationship. The R^2 value was used as a measure of how well each trend-line fits a given covariate data set. Trend-lines for each relationship were modeled by computing the least-squares fit regressions. R^2 can range from 0 to 1.0. An R^2 of 1.0 indicates that all points lie on the regression line, indicating that all of the variability is accounted for. As R^2 values decrease from 1.0, less of the variability is accounted for in the relationship.

Considering that the hurricane events are natural phenomena, they are inherently variable with respect to interactions with the land masses. There is sparse research which relates hurricane parameters to damage; however, the following scale will be used here to provide a qualitative assessment of the relative importance of different R^2 values. For this study, it is assumed that an R^2 below 0.2 is a poor relationship, a R^2 value between 0.2-0.7 is good, and a R^2 value higher than 0.7 excellent.

4.2 Developed Relationships

Data on physical storm parameters, surge scale, and damages for thirty-one hurricane events were available. Parameters for these storms can be found in Table 14. Relationships were developed for the hurricane damage events with surge scale and hurricane parameters.

4.2.1 Surge Scale and Damage Relationships

Data from all of the hurricanes were combined to produce relationships in five categories. The first category is evaluated TND as a function of SS without sorting. The second category is evaluated TND as a function of SS by adjusted year. The third category is evaluated TND as a function of SS for coastal growth scenarios. The fourth category is evaluated TND as a function of SS sorted for technological improvements in damage surveying (Post 1970). The final category excludes "micro-canes" from the data which tend to produce high amounts of localized wind damage and thereby causes error in the correlation.

4.2.2 Hurricane Parameter and Damage Relationships

The majority of the relationships for the hurricane parameters contained a high degree of scatter. This scatter produced poor correlations between the parameters and damages indicated by a low coefficient of determination (R^2). Although there is high scatter in the data, and resulting poor correlations, R values above 0.1 will be discussed in further detail in section 4.4. Due to the infancy of research relating these relationships, even low correlations mean there is potential for these parameters to be included into the damage function. Graphs showing these relationships have been placed into Appendix B.

4.3 Total Normalized Damage Relationship to Surge Scale

Figure 2 illustrates the relationship between the TND and SS for the complete data set. The data comparisons are presented below in this section. The comparisons herein represent a leap forward in the understanding of actual historical damage and to storm surge in terms of parametric surge.

4.3.1 Un-Sorted Data R value Results

A sensitivity analysis was conducted for the influence of adjusted year and coastal growth (Figures 2 and 3) on the correlation between TND and SS. As can be seen from the figures, both the adjusted year and coastal growth make little impact on the correlation; however, examining Figure 4, one can observe an increase in the magnitude of damages for coastal growth.

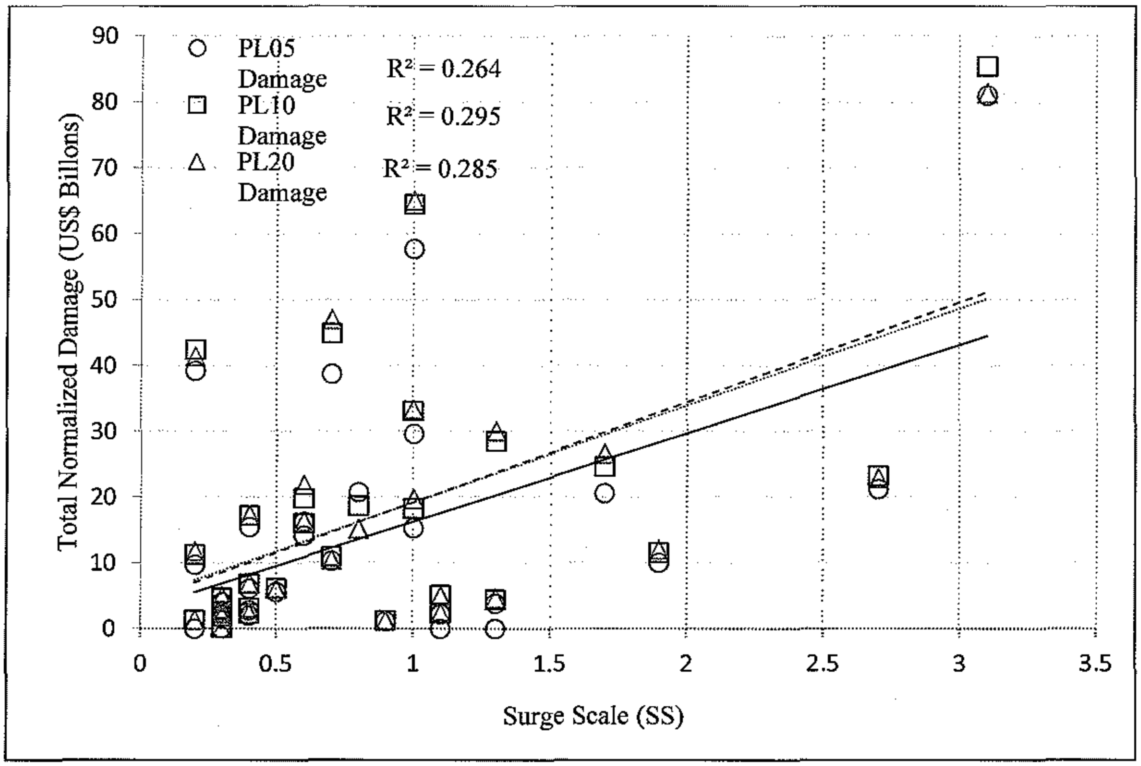

Figure 2: Total Normalized Damages versus Surge Scale for Adjusted Damage

Note that the correlation, regardless of adjusted year, remains near constant: Interestingly, the best correlation is found for year 2010; but these differences are not statistically significant. Additionally, Figure 3 shows that, for variable coastal growth rates, the correlation again remains relatively constant.

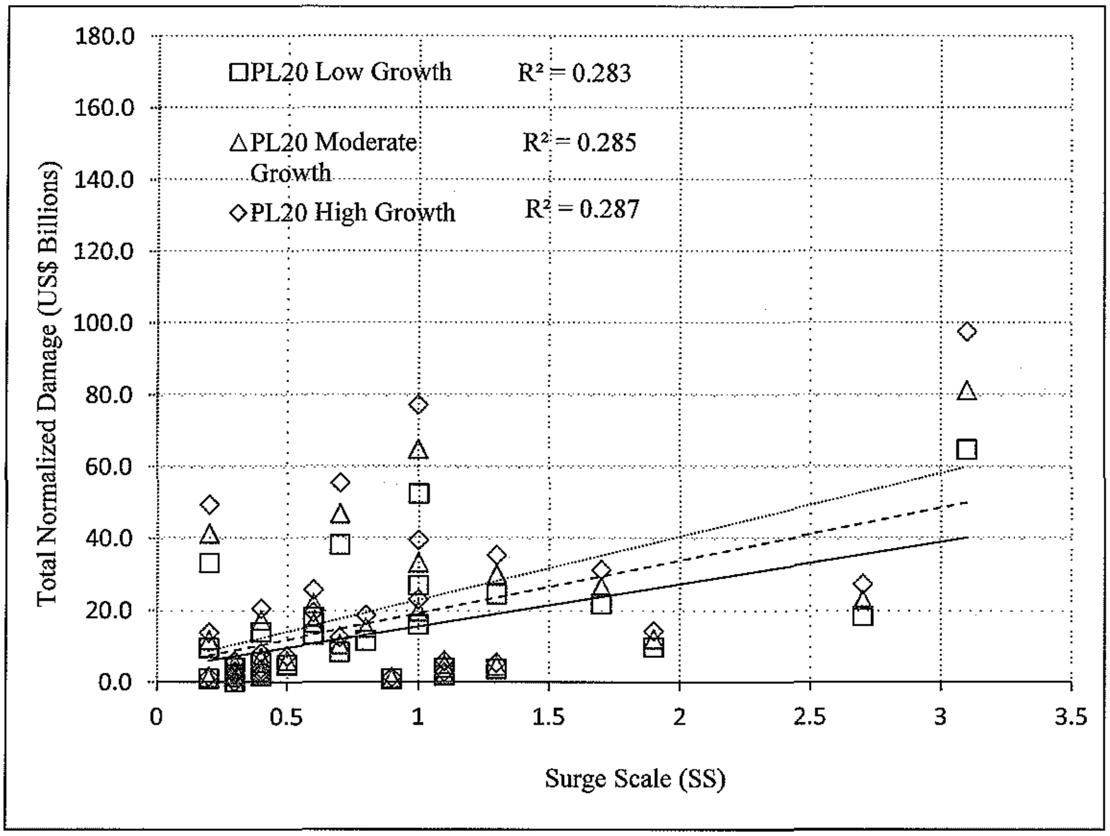

Figure 3: Total Normalized Damages versus Surge Scale for Various Coastal Growth Scenarios

As shown in these figures the R values are slightly less than 0.3; therefore, from our definition, the relationship is rated as good. Next, Figure 4 below shows the distribution of damages. It is important to realize that growth rates in population will strongly influence damages. For some hurricane events this will imply decreasing damages due to the negative growth rates in some areas along the coast.

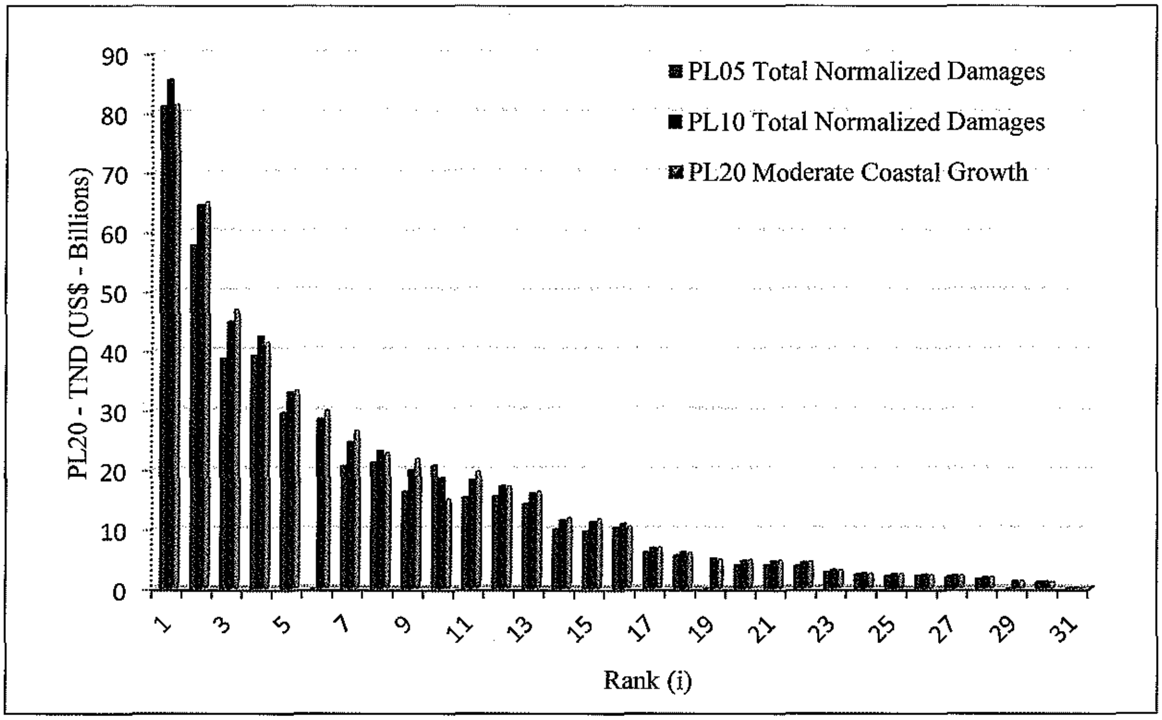

Figure 4: Coastal Growth Influence on Total Normalized Damages by Storm Rank

4.3.2 Potential Improvements in Damage Estimation Methods

The correlations between the SS and TND is somewhat weak though when considering a moderately long range (72 years) of data, which is likely due to a number of factors.For example, since 1970 many technological improvements have been made that allows for damage estimates to be more consistent and accurate. It is not the intention of this thesis to explain all the improvements that have been made; however, it is important to show the relative importance technological improvements have over the correlation between SS and TND. Table 11& 12 has been segregated into 1941-1969 and 1970-2010 intervals.

Table 11: General Information and Hurricane Damages – Sorted (1938-1969)

A	B	C	D	E	F	G	H
Rank	**Storm**	**Year**	**State(s)**	**Surge Scale (SS)**	**PL_{05} Damage (US$ Billions)**	**PL_{10} Damage (US$ Billions)**	**$P_{2010/y}$**
3	October	1944	FL	0.7	38.7	44.9	1.09
4	September	1938	NY	0.2	39.2	42.4	1.01
5	Donna	1960	Mult. St. (Multiple Landfall)	1	29.6	33.0	1.05
8	Camille	1969	LA, MS	2.7	21.2	23.2	1.03
9	Betsy	1965	LA	0.8	20.7	18.6	0.84
13	Carla	1961	LA	0.6	14.2	16.0	1.06
21	Beulah	1967	TX	0.3	4	4.6	1.09
22	Audrey	1957	LA, TX	1.3	3.8	4.4	1.08
26	Hilda	1964	LA	1.1	2.2	2.4	1.02
27	October	1941	FL	0.4	2	2.2	1.05

For the period before 1970, the relationship between TND and SS exhibits a high degree of scatter, resulting in poor correlation as indicated by a low coefficient of determination (R^2). Graphs showing these relationships have been placed into Appendix A.

Table 12: General Information and Hurricane Damages – Sorted (1970-2010)

A	B	C	D	E	F	G	H
Rank	**Storm**	**Year**	**State(s)**	**Surge Scale (SS)**	**PL_{05} Damages D_{y2005} (US$ Billions)**	**PL_{10} Damages D_{y2010} (US$ Billions)**	**$P_{2010/y}$**
1	Katrina	2005	FL, LA (Double Landfall)	3.1	81	85.4	0.99
2	Andrew	1992	FL, LA (Double Landfall)	1	57.7	64.4	1.05
6	Ike	2008	TX	1.3	-	28.5	1.09
7	Wilma	2005	FL	1.7	20.6	24.6	1.12
10	Charley	2004	FL	0.6	16.3	19.9	1.14
11	Hugo	1989	SC	1	15.3	18.2	1.12
12	Ivan	2004	FL, AL	0.4	15.5	17.2	1.04
14	Rita	2005	LA, TX	1.9	10	11.5	1.08
15	Frances	2004	FL	0.2	9.7	11.2	1.09
16	Frederic	1979	AL, MS, FL	0.7	10.3	10.9	0.99
17	Opal	1995	FL	0.4	6.1	6.8	1.05
18	Celia	1970	TX	0.5	5.6	6.1	1.03
19	Gustav	2008	LA	1.1	-	5.1	1.00
20	Isabel	2003	VA, NC	0.3	4	4.7	1.10
2	Eloise	1975	FL	0.4	2.8	3.1	1.05
24	Gloria	1985	Mult. St. (Multiple Landfall)	0.3	2.4	2.6	1.02
25	Dennis	2005	FL	0.3	2.2	2.5	1.07
28	Allen	1980	FL	0.3	1.6	1.9	1.09
2	Dolly	2008	TX	0.2	-	1.3	1.04
30	Lili	2002	LA	0.9	1.1	1.2	1.01
31	Bret	1999	TX	0.3	0.1	0.1	1.09

A comparison of Figures 5& 6 in this section show a large improvement in the correlation between SS and TND for post-1969 data as compared to the pre-1970 data. There is a "good" correlation ($R^2 = 0.554$) between the SS and TND, based on the data presented post-1969. Whereas, the correlation was poor ($R^2 = 0.001$) for the pre-1970 data, suggesting that hurricane damage estimates in the earlier era might not be sufficiently accurate to be used for quantifying this relationship. Though it is somewhat instructive to arrange data in descending order in terms of damage as Pielke and Landsea (2008) have presented, unfortunately a large portion of damage data has a questionable connection to SS because of technological improvements for damage estimates post-1969. Figure 5 indicates the pre-1970 relationship and Figure 6 shows the post-1969 relationship.

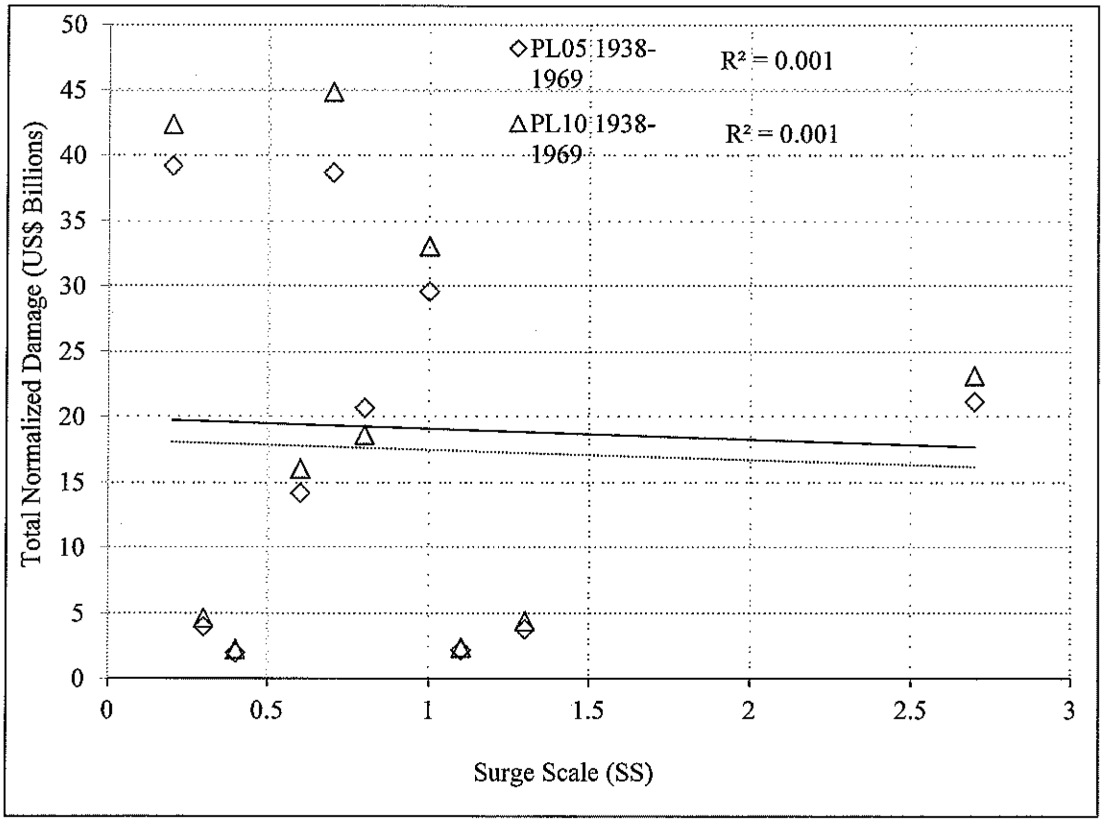

Figure 5: Total Normalized Damages versus Surge Scale (1938-1969)

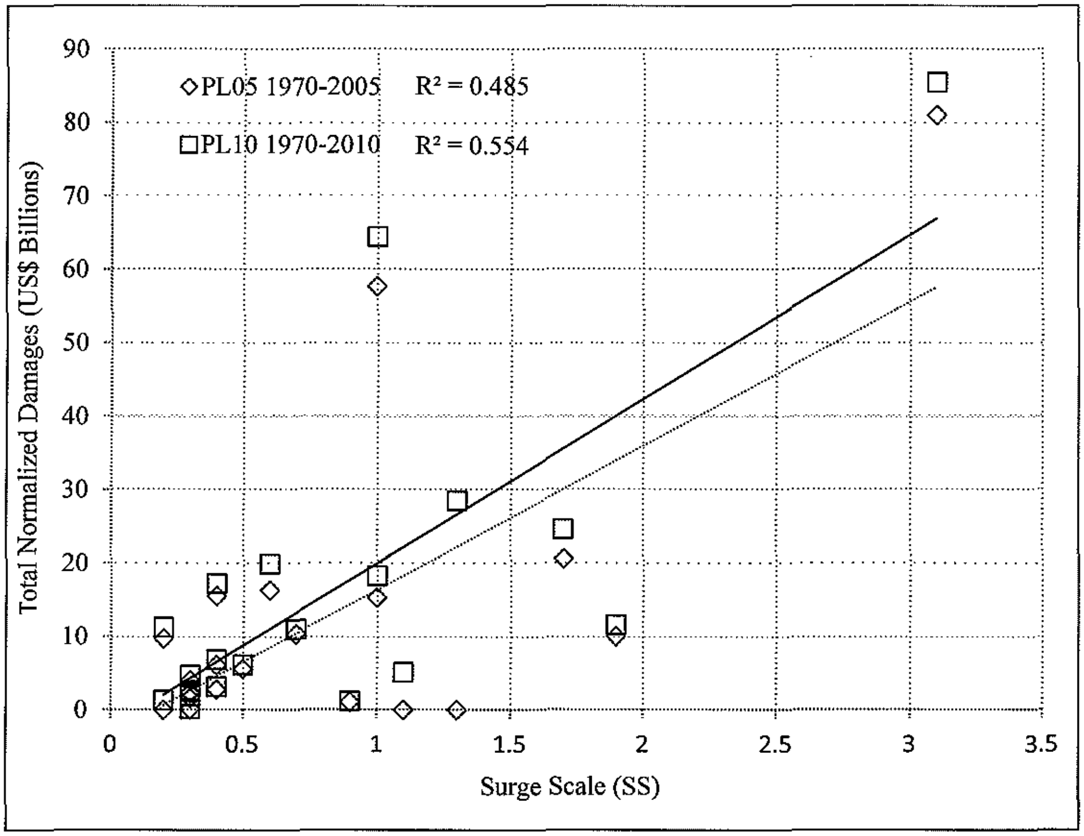

Figure 6: Total Normalized Damages versus Surge Scale (1970-1969)

4.3.3 Additional Analysis: Improvements and Exclusion of "Micro-canes"

As discussed in section 2.2, there are three types of damages included in the damage estimates. To illustrate this point further additional hurricanes have been removed from the data set. Andrew [1992], Charley [2004], Dennis [2005] and Dolly [2008] had very small R_{33}, which is the radius to hurricane force winds. As shown in section 2.3, the damage function for surge depends on R_{33}. There are many hurricane parameters that are related to the surge damage function. Very small hurricanes, sometimes termed "Micro-canes" tend to produce high amounts of wind damage (ND_w) with relatively small amount of inland flooding damage (ND_f) and small amounts of surge damage (ND_s); therefore, extracting them from the data set improves the correlation to R = 0.701 indicating a good to excellent correlation.

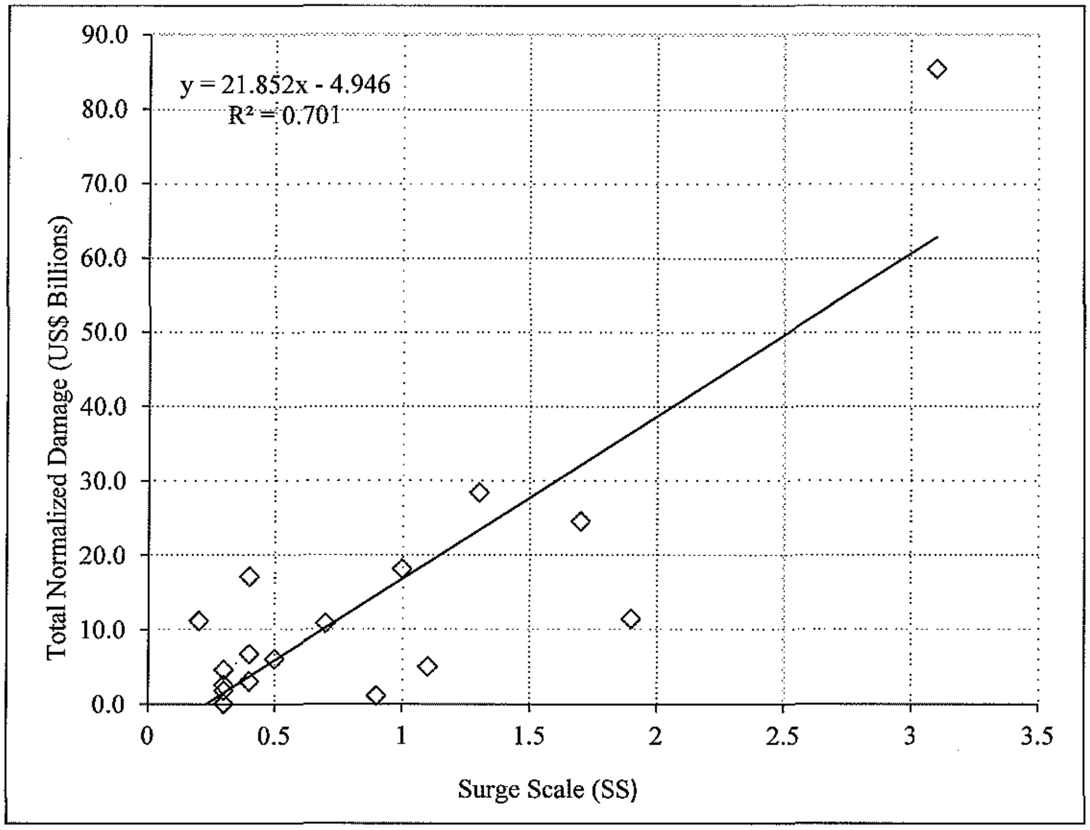

Figure 7: Total Normalized Damages versus Surge Scale (1970-1969) - Exclusion of "micro-canes"

The definition of micro-canes for the purposes in determining criteria to remove hurricanes from the data set is the following:

- RMW (radius of max winds)<20 km
- R_{33}<80 km

Hurricanes smaller than 80 km in size lack the potential to generate a significant surge, regardless of the other hurricane parameters or geophysical characteristics of a region. So, damage due to surge (ND_s) could be considered negligible in the damage estimates for these small hurricanes.

Table 13: General Information and Hurricane Damages – Sorted (1970-2010) and Micro-canes Excluded

Rank	**Storm**	**Year**	**State(s)**	**Surge Scale (SS)**	**PL_{05} Damage (US$ Billions)**	**PL_{10} Damage (US$ Billions)**	**$P_{2010/y}$**
1	Katrina	2005	FL, LA (Double Landfall)	3.1	81	85.4	0.99
6	Ike	2008	TX	1.3	-	28.5	1.09
7	Wilma	2005	FL	1.7	20.6	24.6	1.12
10	Hugo	1989	SC	1	15.3	18.2	1.12
12	Ivan	2004	FL, AL	0.4	15.5	17.2	1.04
14	Rita	2005	LA, TX	1.9	10	11.5	1.08
15	Frances	2004	FL	0.2	9.7	11.2	1.09
16	Frederic	1979	AL, MS, FL	0.7	10.3	10.9	0.99
17	Opal	1995	FL	0.4	6.1	6.8	1.05
18	Celia	1970	TX	0.5	5.6	6.1	1.03
19	Gustav	2008	LA	1.1	-	5.1	1.00
20	Isabel	2003	VA, NC	0.3	4	4.7	1.10
23	Eloise	1975	FL	0.4	2.8	3.1	1.05
24	Gloria	1985	Mult. St. (Multiple Landfall)	0.3	2.4	2.6	1.02
28	Allen	1980	FL	0.3	1.6	1.9	1.09
30	Lili	2002	LA	0.9	1.1	1.2	1.01
31	Bret	1999	TX	0.3	0.1	0.1	1.09

The above data represent the best current estimate of SS relationship to TND. With further extraction of non-surge related damages, through correction factors based on rainfall amounts or wind field hyetographs, it is suspected that the correlation between ND_s and SS could improve even over what is seen here.

4.4 Hurricane storm parameters comparison to Total Normalized Damages

In an effort to illustrate the storm parameters that cause significant surge damage, the parameters in equation 3 will be discussed in some detail. This section covers current research in describing the damage function for hurricane surge. The damage function for surge is complex and there has been considerable focus in this study on those hurricane parameters that are contributing factors to storm surge.

4.4.1 Radius to Hurricane Force Winds (R_{33}) Relationship to Damages

Some parameters also have connections to other types of damage: R_{33} is related to all three types of damage (ND_w, ND_f, ND_s). Additionally, R_{33} is found in equation 3, being one of the largest contributors to damage. As Irish and Resio (2007) describe damage "depending linearly on storm size". In the comparison of TND and R_{33} only an R-value of 0.06 was found, which is somewhat counter-intuitive.

4.4.2 Maximum Surge Elevation (ζ_{max}) Relationship to Damages

The storm parameter that was found to be most highly correlated to TND is ζ_{max} with an R-value of 0.235. Fortunately, as shown by Irish and Resio (2007) there is a fair amount of maximum surge data; since, records of maximum surge elevation have been of general interest for some time. Again, once surge specific damage data is compared to ζ_{max}, the correlation will be more representative of a parameter that cannot be connected to other types of damage.

4.4.3 Alongshore Extent of Surge Greater Than 2 meters (Y_2^m) Relationship to Damages

The alongshore extent of surge greater than 2 m exhibits the next highest correlation to surge damages. In fact, this study shows an R-value of 0.185, which suggests that the Damage Function should include this parameter. It is intuitive that this parameter is related to surge damage as it is one of the parameters in determining the approximate area of inundation (Section 4.4.6).

4.4.4 Coastal Storm Specific Population Density (ρ) Relationship to Damages

Coastal storm specific county population density is only accurate for surge, in that, the interior counties were not included in this study. Obviously, with many hurricanes the damage sustained is due to inland flooding and wind damage; therefore, it is suspected that the correlation between surge specific normalized damage will be well correlated to the coastal county population density. An R-value of 0.071 was calculated for the total data set indicating a somewhat deceptive relationship to the surge damage function: It was concluded here that a population density factor should be included. An unfortunate observation however, there is a large cone of uncertainty as illustrated by the Figure 17, Appendix B, especially on the upper end of the scale. Since there is a large cone of uncertainty, the correlation is negatively affected; however, most of the data trends are much better than the coefficient of determination indicate. The trend is positive and as shown in the section 4.3.1, growth scenarios can have large effects on future total normalized damages.

It is apparent that, even if in cases in which all other storm parameters indicated there would be large surge and thus damages, it is likely that the damages will be mitigated if the population is low. (An exception to this relationship is Katrina [2005] which was massive as to not only cover highly populated areas, but also include highly un-populated areas and thus lowering the population density significantly) Figure 7, Appendix A shows Rita [2005] as an example, was a massive hurricane capable of producing major damages, yet damages were lower than expected by the overall trend, due to the fact it made landfall along an unpopulated stretch of coastline at the Louisiana/Texas border. When analyzing Figure 17, data points (hurricanes) above the trend line indicate other forms of damage and those below have lower population densities.

Table 14: Storm Specific Coastal County Population Density Calculations

Year	Storm Name	Area (km^2)	Storm Year Population	Storm Year Specific Coastal Population Density (Person/km^2)	2010 Year Population	2010 Storm Specific Coastal Population Density (Person/km^2)	2010 Normalized Damage ($US Billions)
2005	Katrina	28,357	2,498,656	88.1	2,517,648	88.8	85.4
1992	Andrew	11,242	2,225,093	197.9	2,736,185	243.4	64.4
1944	11 (Oct.)	20,481	368,516	18.0	4,106,640	200.5	44.9
1938	Sept.	18,451	8,162,408	442.4	14,979,620	811.9	42.4
1960	Donna	-	-	-	-		
2008	Ike	33,437	5,157,529	154.2	5,303,437	158.6	28.5
2005	Wilma	13,186	1,396,114	105.9	1,208,204	91.6	24.6
1969	Camille	20,734	1,342,424	64.7	2,517,648	121.4	23.2
2004	Charley	3,878	661,002	170.5	778,732	200.8	19.9
1965	Betsy	25,264	1,529,355	60.5	1,913,962	75.8	18.6
1989	Hugo	16,732	746,485	44.6	927,910	55.5	18.2
2004	Ivan	15,981	1,298,493	81.3	1,364,738	85.4	17.2
1961	Carla	24,866	304,269	12.2	839,294	33.8	16
2005	Rita	29,567	5,250,714	177.6	5,407,430	182.9	11.5
2004	Frances	11,975	2,194,130	183.2	2,279,327	190.3	11.2
1979	Frederic	24,773	1,879,923	75.9	2,232,280	90.1	10.9
1995	Opal	10,185	719,621	70.7	869,571	85.4	6.8
1970	Celia	10,186	321,737	31.6	481,173	47.2	6.1
2008	Gustav	15,162	855,751	56.4	849,661	56.0	5.1
2003	Isabel	20,831	724,196	34.8	777,234	37.3	4.7
1967	Beulah	9,922	171,229	17.3	460,831	46.4	4.6
1957	Audrey	21,844	1,858,629	85.1	5,204,218	238.2	4.4
1975	Eloise	14,334	481,064	33.6	881,120	61.5	3.1
1985	Gloria	22,773	10,301,250	452.4	12,125,454	532.5	2.6
2005	Dennis	8,482	430,572	50.8	631,256	74.4	2.5
1964	Hilda	12,769	214,977	16.8	304,588	23.9	2.4
1941	5 (Oct.)	31,094	503,189	16.2	5,959,319	191.7	2.2
1980	Allen	7,666	455,530	59.4	428,770	55.9	1.9
2008	Dolly	2,347	392,021	167.1	406,220	173.1	1.3
2002	Lili	9,518	191,627	20.1	192,728	20.2	1.18
1999	Bret	9,922	373,472	37.6	460,831	46.4	0.12

4.4.5 Central Pressure (c_p^a) Relationship to Damages

Central Pressure is actually thought to be more related to wind damage (D_w) and somewhat to inland flooding damage (D_f), and thus less disscussion is reserved for this parameter. There is a clear connection though, as R = 0.182; however, there is a negative relationship which is intutitive: more intense storms with lower central pressures produce more damage.

4.4.6 Area of Indunation (A_{in}) Relationship to Damages

Area of Inundation represents the area of water coverage over the uplands due to a hurricane surge. Equation 27 in Irish and Resio (2007) it is as Follows:

$$A_{in} = \frac{\zeta_{\max}}{2} * [(\gamma + \delta) R_{33}] * \cot \alpha \qquad (9)$$

Defining the unknowns: γ and δ are dimensionless constants and cot α is an upland topography function. While there will be continued effort towards inserting the parameters discussed herein into the above equation, there also should be a damage survey conformation of the proposed area of inundation equation. Surge damage will be highly correlated to the area of inundation.

It may also be of some use to relate the area of inundation to damages by using approximations from parameters gathered herein, Y_2^m as well as w_{mean}, as a normal inland projection of average inundation and thus giving an approximate area of inundation.

$$A_{in} = Y_{2^m} * w_{mean} \qquad (10)$$

It would be useful to relate area of inundation to a separated surge specific normalized damages and thereby, increasing the correlation between storm surge parameters and economical damage. This assumption may only be somewhat valid for a uniform upland topography.

4.4.7 Other Parameter Relationship to Damages

There were other parameters compared as a part of this study although the R-values are less than those included here and are expected to be less important for insertion into the surge damage function. One exception may be w_{30}^{b}, which is the width of the 30 m contour, R = 0.047. It is possible for a hurricane capable of creating a large surge to land fall on a very steep shelf; thereby attenuating the surge into deeper waters. As illustrated in Appendix C, Irish and Resio equivalent depth Figures 18 and 19: examples of these coastlines are particularly not conducive to high surge generation such as off-shore profiles for Northeastern US, Cape Hatteras, NC., Southeastern Florida, the panhandle of Florida and Southern Texas.

On the opposite end of the spectrum are those coastlines that are susceptible to large hurricanes surges due to the off-shore bathymetry and upland topography. Among these coastlines are the Texas-Louisiana border, the New Orleans area and Mississippi, the "Big-Bend" of Florida to Southwestern Florida and the Georgia and South Carolina coastlines. Other parameters compared to TND in this study are the angle from shore normal (θ), track speed (v) and storm duration (Ω). Storm Duration and Storm Angle mimics a normal distribution when compared to damages. (Please see Appendix B)

4.5 The Process of Developing a Surge Damage Function

The variable H_s is the Hurricane Surge Damage Correction Factor, which is a nonlinear varying parameter that “filters” out the ND_f and ND_w damages along with other errors such as multiple landfalls. The damping exponential function shown in Equation 8 is needed to properly curve fit the predicted damages to the actual damages. As a general rule those data points that lie beneath the trend line in Figure 7 often have relatively lower population densities, and data points above the trend line often have high ND_w damages; thereby, requiring an exponential multiplier to dampen out the error from the trend line.

Table 15: Damage Prediction

Storm	Surge Scale (SS)	w_{30}^{b} (km)	Hurricane Surge Damage Correction Factor (H_S)	Pop. Factor (K)	M-1 X	M-2 X (TND_P)	Y (TND_A)	$(X-Y)^2$
Katrina	3.1	140	-0.5704	0.44	62.8	85.4	85.4	1.4E-08
Ike	1.3	92	-0.1047	0.77	23.5	28.5	28.5	2.9E-10
Wilma	1.7	118	0.8376	0.53	32.2	24.6	24.6	1.1E-10
Hugo	1	56	0.1545	0.22	16.9	18.2	18.2	7.6E-11
Ivan	0.4	31	-3.5654	0.41	3.8	17.2	17.2	1.0E-09
Rita	1.9	119	1.7792	0.89	36.6	11.5	11.5	1.4E-11
Frances	0.2	15	20.9057	0.92	-	0.5	11.2	-
Frederic	0.7	48	0.2820	0.38	10.3	10.9	10.9	2.8E-10
Opal	0.4	21	-1.3427	0.35	3.8	6.8	6.8	8.0E-12
Celia	0.5	30	1.0075	0.16	6.0	6.1	6.1	1.0E-10
Gustav	1.1	81	7.3538	0.28	19.1	5.1	5.1	6.9E-10
Isabel	0.3	25	-5.0368	0.17	1.6	4.7	4.7	1.2E-09
Eloise	0.8	21	9.8398	0.17	12.5	3.1	3.1	7.3E-10
Gloria	0.3	24	-0.0494	2.26	1.6	2.6	2.6	9.3E-12
Allen	0.3	21	0.9887	0.30	1.6	1.9	1.9	1.2E-09
Lili	0.9	84	136.2641	0.10	14.7	2.8	1.2	2.6E+00
Bret	0.3	22	55.6390	0.19	1.6	0.7	0.1	4.0E-01
							Σ =	3.0E+00

Referring to some undefined columns in the table above: M-1 (X) is damage prediction method 1, which uses only the linear relationship to damages. M-2 (X) is damage prediction method 2, which uses the full Equation 8. Y is the actual estimated 2010 damage estimates.

The H_S found in Equation 8 represents that part of the relationship that is still unknown. There is also a sensitivity problem inherent for those storms that are less that SS = 0.3; since, the exponential function is not able to predict damage due to the boundary conditions of Equation 8. The predicted damage for Frances [2004] has been left blank due to this issue. There are also some tail effects for the lower damage hurricanes but since the lower end of the SS and damage are of less concern, there is no need to correct for these boundary conditions. (Not to say that 1.0-2.0 Billion is not significant) The strike angle (θ) and Storm Duration (Ω) becomes relatively unimportant to surge damages (ND_S) if θ is between the limits expressed in section 3.5 and if a storm doesn't stall causing large amounts of ND_f. SS in general accounts for the majority of the damage in equation 8. There is a great deal of uncertainty for the variable H_s. No combination of the parameters studied in this thesis can explain H_s, which suggests the focus for future research should be to find accurate and predictable ways to extract non-related surge damage, then H_s becomes less volatile and thus less damping will be required. This also suggests that other parameters such as rainfall (R), wind speed (V) and other factors may be involved in the formulation for H_S. This thesis presents SS vs. TND for a wide spectrum of coastal areas and types of coastal development; therefore, there will inevitably be randomness in such a relationship.

For most hurricanes the TND can be predicted with the linear relationship to SS within 25 billion (which is significant): In most other cases the linear prediction is much closer to the actual TND. Additionally, w_{30}^b is shown to be a smaller part but critical in the addition term: without it the TND_P ranges from 1 to 5 billion lower than the Actual Total Normalized Damage (TND_A).

4.6 Chapter Summary

Relationships between TND were developed for hurricane parameters and SS. The economical parameter of interest was TND. The hurricane parameters of greater interest were maximum surge elevation ($\zeta^{m}{}_{max}$), radius of hurricane force winds (R_{33}), the alongshore extent of surge greater than 2 meters ($Y_2{}^{m}$),the central pressure ($c_p{}^{a}$) and the coastal storm specific population density (ρ).

The relationships for hurricane parameters and SS were displayed in terms of TND. In terms of the definitions adopted here the relationships provided poor to excellent correlations as indicated by the coefficient of determination (R^2) value. The majority of the relationships for the hurricane data contained a high degree of scatter and poor correlations between hurricane parameters as indicated by a low R^2 value. Due to the high degree of scatter in the data, and resulting poor correlations, these relationships were briefly discussed and the graphs showing these relationships can be found in Appendix B. The equations and coefficient of determination (R^2 values) for all of the relationships computed are summarized in Table 16.

Table 16: Summary of Equations and Associated Coefficient of Determination

Property		**Independent Variable**				
		R_{33}	w_{30}^{b}	c_p^{a}	Y_2^{m}	**ρ**
Dependent Variable	**TND**	TND = $0.086R_{33}$ + 3.682 $R^2 = 0.060$	TND = $0.109w_{30}^{b}$ + 11.166 $R^2 = 0.047$	TND = - $0.631c_p^{a}$ + 615.982 $R^2 = 0.182$	TND = $0.086Y_2^{m}$ + 4.419 $R^2 = 0.185$	TND = 0.033ρ + 11.476 $R^2 = 0.071$
		θ	**V**	**Ω**	ζ^{m}_{max}	**SS**
		No Trend Computed	N/A $R^2 = 0.005$	No Trend Computed	TND = $6.450\zeta^{m}_{max}$ - 6.687 $R^2 = 0.235$	TND = 21.852*SS - 4.946 $R^2 = 0.701$

The R^2values range from 0.047 to 0.701. The ‘No Trend Computed’ entries in Table 17 indicate no relationships were determined. Appendix I contains Figures depicting the hurricane damages and their predicted values.

Chapter 5

CONCLUSIONS AND RECOMMENDATIONS

Thirty-one hurricane events were obtained from the Irish and Resio (2007) and Pielke and Landsea (2008) along with other sources listed in the References section of this thesis. The hurricanes were classified in terms of hurricane states. The hurricanes listed in the study were classified as H_1 (small surge potential), H_2 (moderate surge potential), H_3 (high surge potential) and H_4 (extreme surge potential). Aside from Surge Scale, classifications and investigations into hurricane parameter comparisons provide a basis for future research into the surge damage function. Fourteen of the hurricanes had questionable connections in terms of damage and SS. These hurricanes were either determined to have errors in the damage estimates or were "micro-canes" which tend to produce somewhat anomalous surges at a coast.

The economic parameter of interest was Total Normalized Damages (TND). The hurricane/geophysical parameters of interest were the maximum surge elevation ($\zeta^{m}{}_{max}$), radius of hurricane force winds (R_{33}), the alongshore extent of surge greater than 2 meters ($Y_2{}^{m}$), the central pressure ($c_p{}^{a}$), the shore normal projection offshore to the 30 meter contour ($w_{30}{}^{b}$), and the 2010 coastal storm specific population density (ρ). Other parameters included in the study, yet were not discussed in detail were the storm angle measured from normal projection (θ), track speed (v) and the storm duration (Ω). A certain amount of scatter was present in all the data, but the best correlations were found between Surge Scale (SS) and Total Normalized Damage (TND), suggesting Surge Scale is inherently related to Damages in general and much more so to surge specific damages as suggested by elimination of "micro-canes" from the data set. Surge

Scale may provide the best chance for finding a surge damage function. Surge Scale could be additive, in that, adding the SS from multiple land falls may put data points closer to the trend line.

Future studies should include a further investigation into the area of inundation and surge specific damages (ND_s) and SS relationship to surge specific damages, perhaps leading to a Hurricane Coastal Surge Damage Scale (HCSDS) (Similar to the Dolan-Davis classification for Northeast storms (Hondula, et. al. 2010) or Beaufort Force for winds. This future research may include gathering information on an average inland extent of surge (w_{mean}) and further investigation into surge specific damage, thereby separating out the damages due to surge and increasing the correlation. The research conducted in this study and studies mentioned herein in the References section, should be a "bridge" to finding a HCSDS which could be used as a public warning system for assessing damage potential prior to landfall.

As Irish and Resio (2007) points out "While a number of hurricane indices already exist, the surge scale (SS) proposed in their paper is the first to be based specifically on simplified approximations to the hydrodynamic equations governing surge generation and has been shown to be well-correlated with observed historical maximum hurricane surges." (Please see Figure 20, Appendix C)Therefore, for practical usage, if the damage estimate errors/correction factors for other types of non-surge related damages are found (damage survey categories) and continued research between the surge specific damage and SS is accomplished, then the general damage function consisting of the several components could be analyzed in more detail. As of now, the damage function stands as an elusive equation, yet to be fully understood.

Damage Estimates for surge may be more highly correlated at the local level instead of using a macro perspective to the comparisons made herein. Surveying the damage into distinct damage survey categories will be of particular interest to separate those types of storms that have high potential for damage based on SS, which has been the focus of this thesis. Reporting of data in these categories will allow FEMA and the scientific community to better access the surge damage potential realized in devastating storms such as Katrina (2005).

There are currently ways of separating the survey damage categories forensically, even though, the best way is through historical damage survey reporting. There will always be a "grey" area into whether some damages were caused by flood, surge or wind; however, most damages should be separated without much problem by observation during damage surveying. The forensic ways could be to investigate cumulative historical wind hyetographs and NEXRAD radar cumulative rainfall in order to determine the relative amounts of each survey damage category's contribution to Total Normalized Damages. There is of course some software for these applications: HEC-FDA developed by the Army Corp. of Engineers for determining inland flooding damage and HAZUS for determining damages due to several types of natural phenomena: earth quakes, hurricanes, tsunamis, etc. This type of damage simulations require extraordinary amounts of time, money, effort and verification to historical record for model calibration, but could provide the basis of future damage assessments.

Katrina [2005] exposed some vulnerable infrastructure problems with Levees: In addition, the New Orleans proximity and susceptibility to historically devastating surges is of great interest while engineers and scientists reassess our coastal disaster risk due to hurricane surges. Coastal wetlands (Resio, et al. 2008) and other forms of coastal defense in mitigating disaster will continue to be a focus for future researches. Katrina [2005] exposed some weaknesses in the coastal planning process in Louisiana just as Andrew [1992] exposed building code weaknesses in Florida: Planning in respect to our coastal population is of paramount importance.

It is stressed that much more data will be needed in order to obtain the correct surge damage prediction equations. This study took into account only 72 years of data (40 sorted) and since climatology in respect to advanced measurement equipment has only been around 50 +/- years, we will need several centuries to have a more process-based damage relationship to surge, instead of an extrapolative approach used in this thesis. Time scales are paramount when it comes to dynamic relationships such as normalized hurricane damage prediction. Damage Prediction for hurricane surge is fertile ground for the future research described in this chapter.

It is suggested that future research conduct damage scenarios in order to simulate hurricane data across centuries, thereby, testing equation 8 and updating as necessary. Additionally, it is inferred in this thesis that H_s includes ND_f and ND_w damages and additional study will be needed for inland counties to better assess the relationship of TND to SS. Otherwise, survey categories will provide a fairly linear relationship of ND_s to SS. The historical data and information herein and in referenced work can provide a basis for calibrating a surge damage model.

Perhaps damages will be derived from "Geographic Information Systems (GIS)" as (Wheeler, et al., 2008) suggests these systems "have become an important tool for the spatial modeling and analysis of many coastal zone issues." Structural studies for wind damage (Jean-Paul Pinelli, et al., 2004) may provide a basis for separating damage estimates into the proper damage survey categories. Separating the damage data into damage survey categories should be a priority in future research and damage surveying since insurance companies and FEMA will help bear the cost of wind and flooding damage, respectively. Every extreme event will give vital information statistically for overall coastal impact in respect to economic, physical and biological processes.

There are two suggestions for future research in order to improve the relationship in terms of accuracy for Eq. 8, found herein. Amplification of surge damage often happens as a result of two factors not included in this thesis: "Hydraulic Funnels" (ie: bays and shoreline angle change) and time of landfall in relation to tidal cycle. Both of these concepts/parameters definitely affect surge damage and therefore amplification factors which could be addressed in the calculations for predicted damages.

Actual occurrence of hurricane events or event prediction; however, is beyond the scope of this thesis; whereas, this involves longer periods of record than we have data, since climate cycles vary over centuries. Nonetheless, the damage function will need continuing research in terms of historical reporting and future synthetic hurricane modeling so that investigation into physical inundation limits and analyzing the hurricane parameters mentioned in this thesis for further correlation to damages. It is thought that through these connections between actual population growth rates and damage scenarios, this will allow us to more adequately plan America's hurricane coastal disaster risk.

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APPENDIX A

Mean Surge (m) vs. Surge Scale

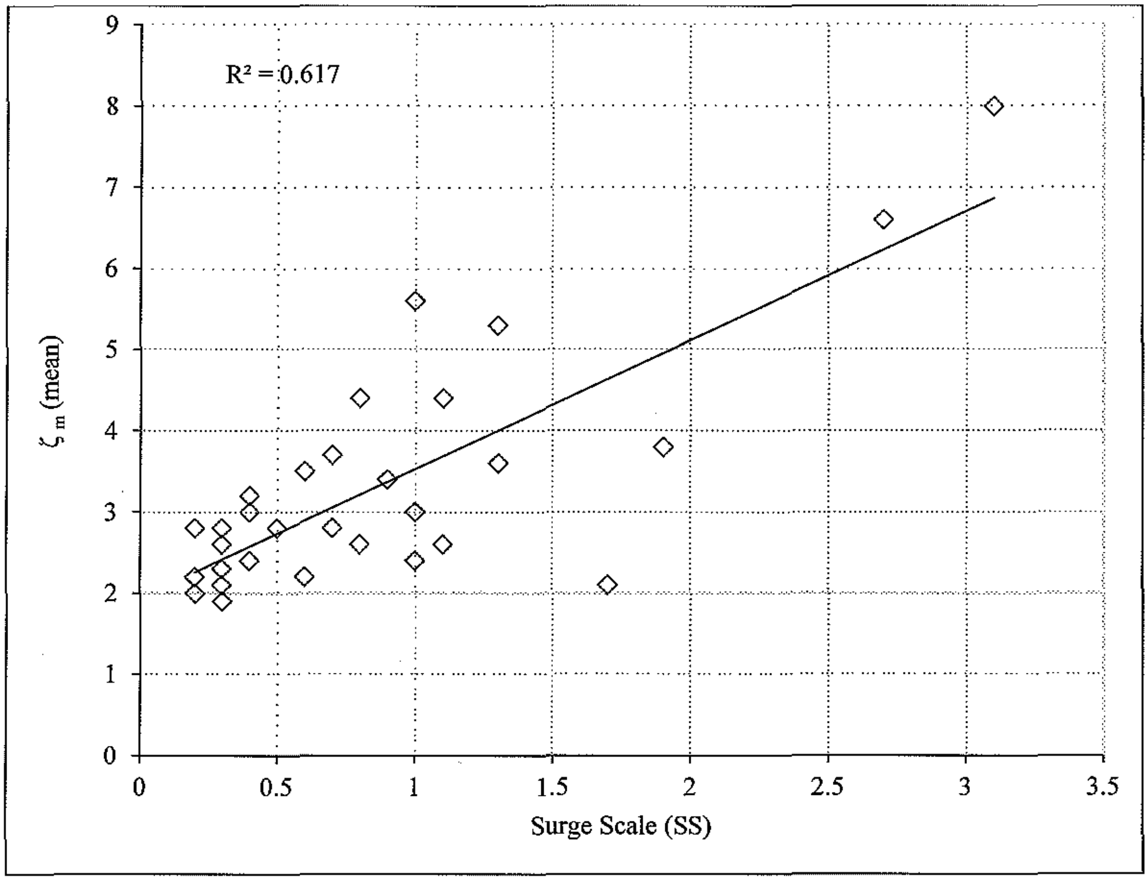


Figure 8: Mean Surge versus Surge Scale

APPENDIX B

Storm Parameters Comparison to Total Normalized Damages

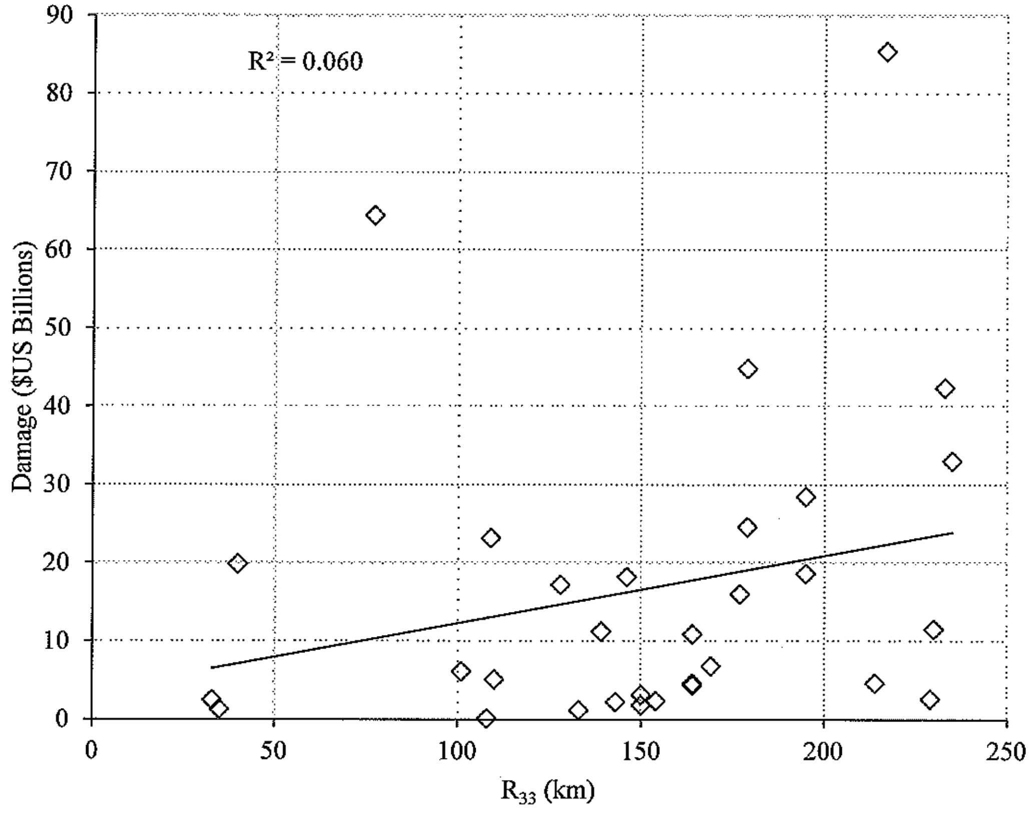


Figure 9: Total Normalized Damage vs. Radius to Hurricane Force Winds

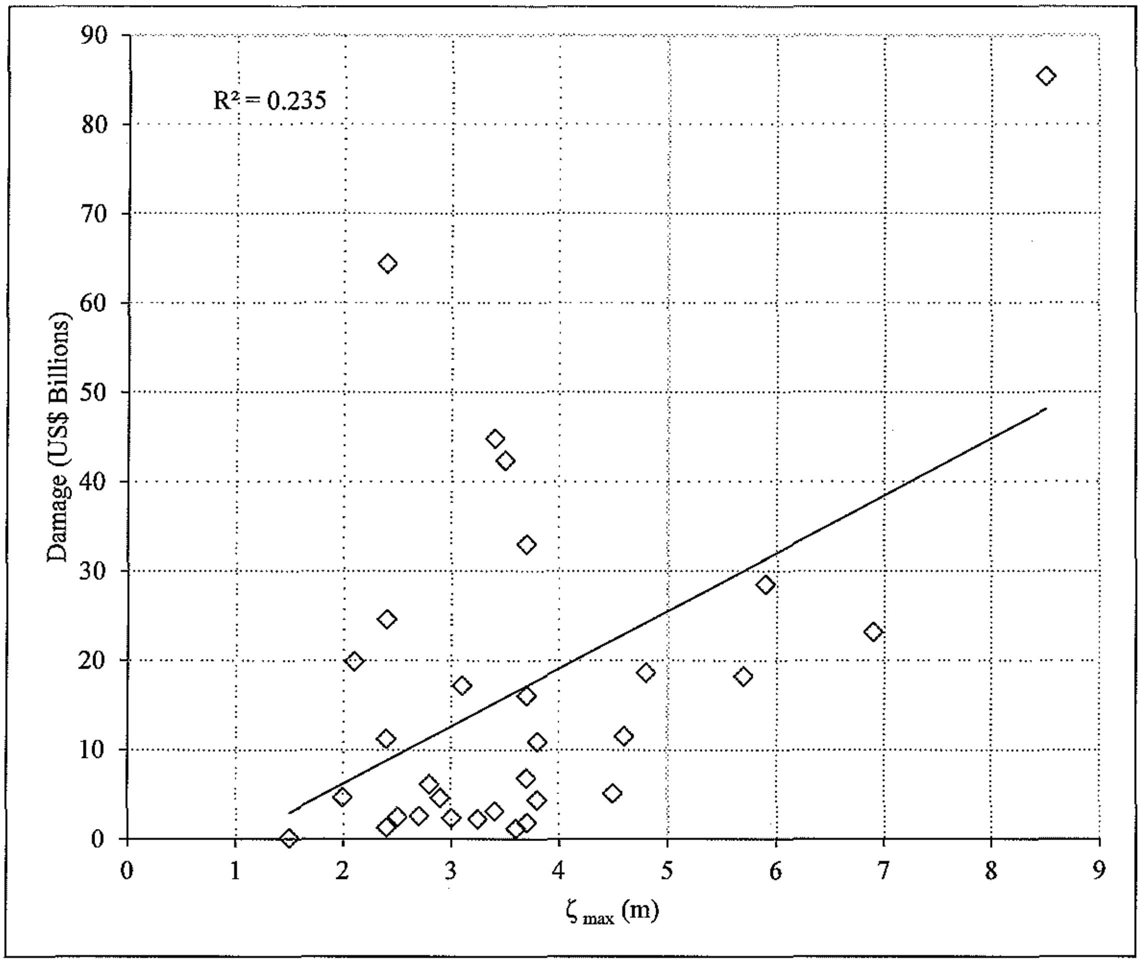


Figure 10: Total Normalized Damage vs. Maximum Surge

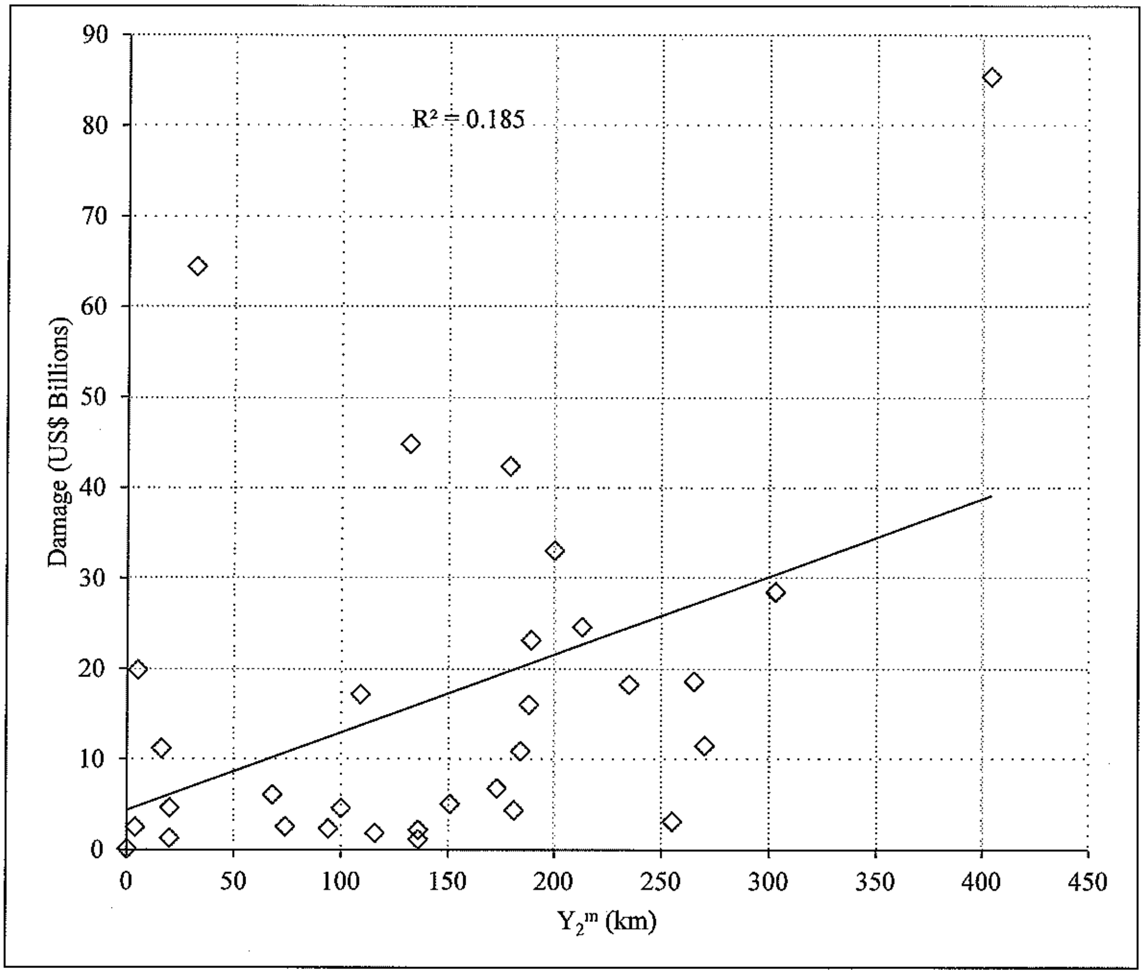


Figure 11: Total Normalized Damage vs. Alongshore Extent of Surge

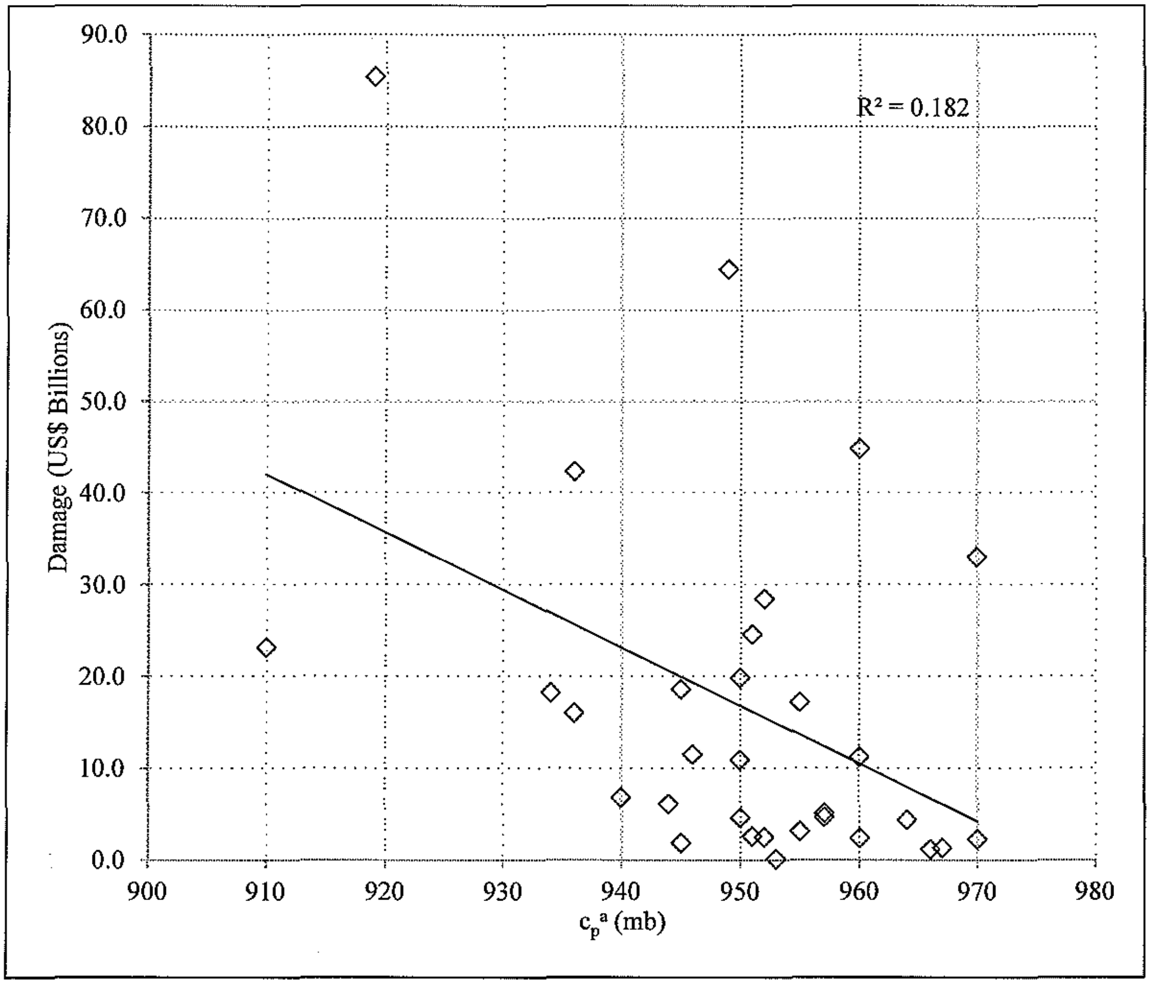


Figure 12: Total Normalized Damage vs. Central Pressure

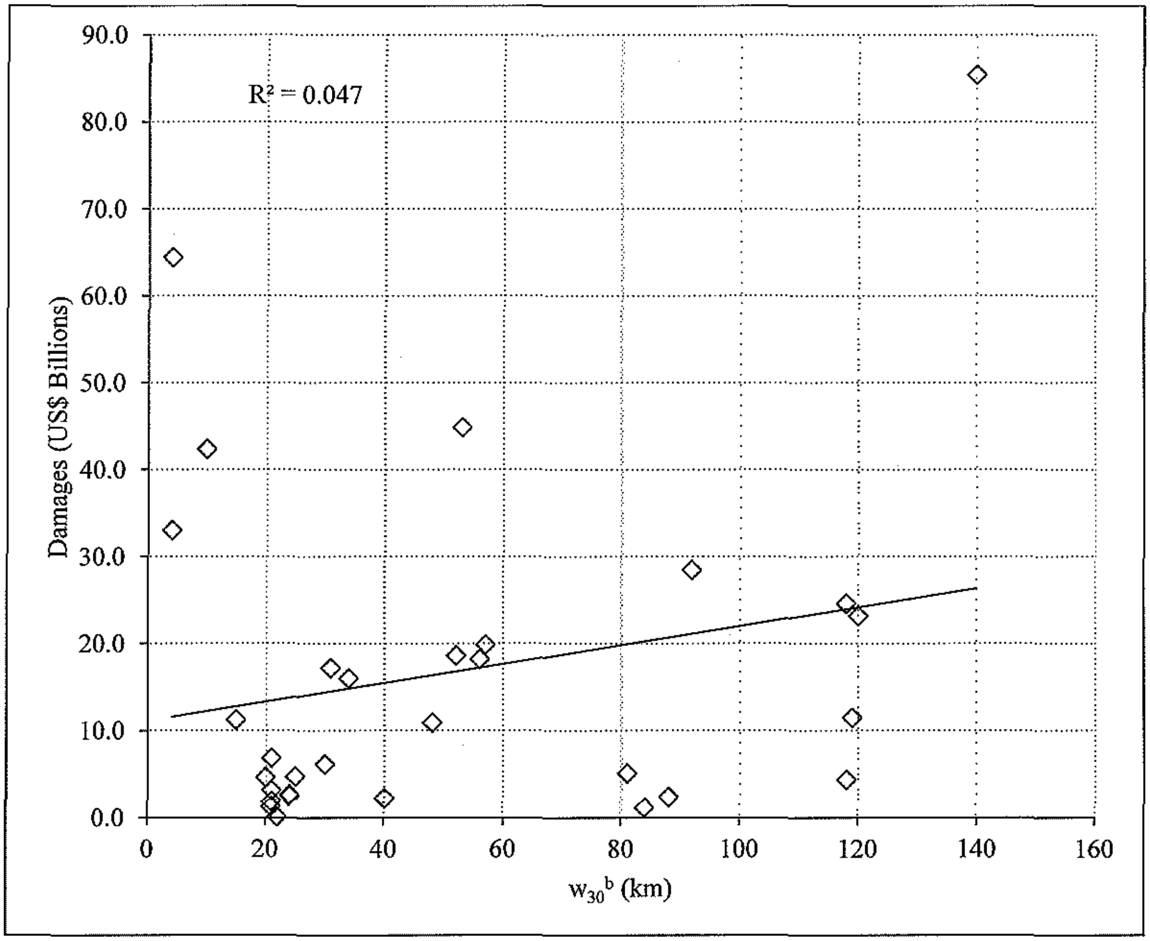


Figure 13: Total Normalized Damage vs. Offshore Normal Projection to 30 Meter Contour

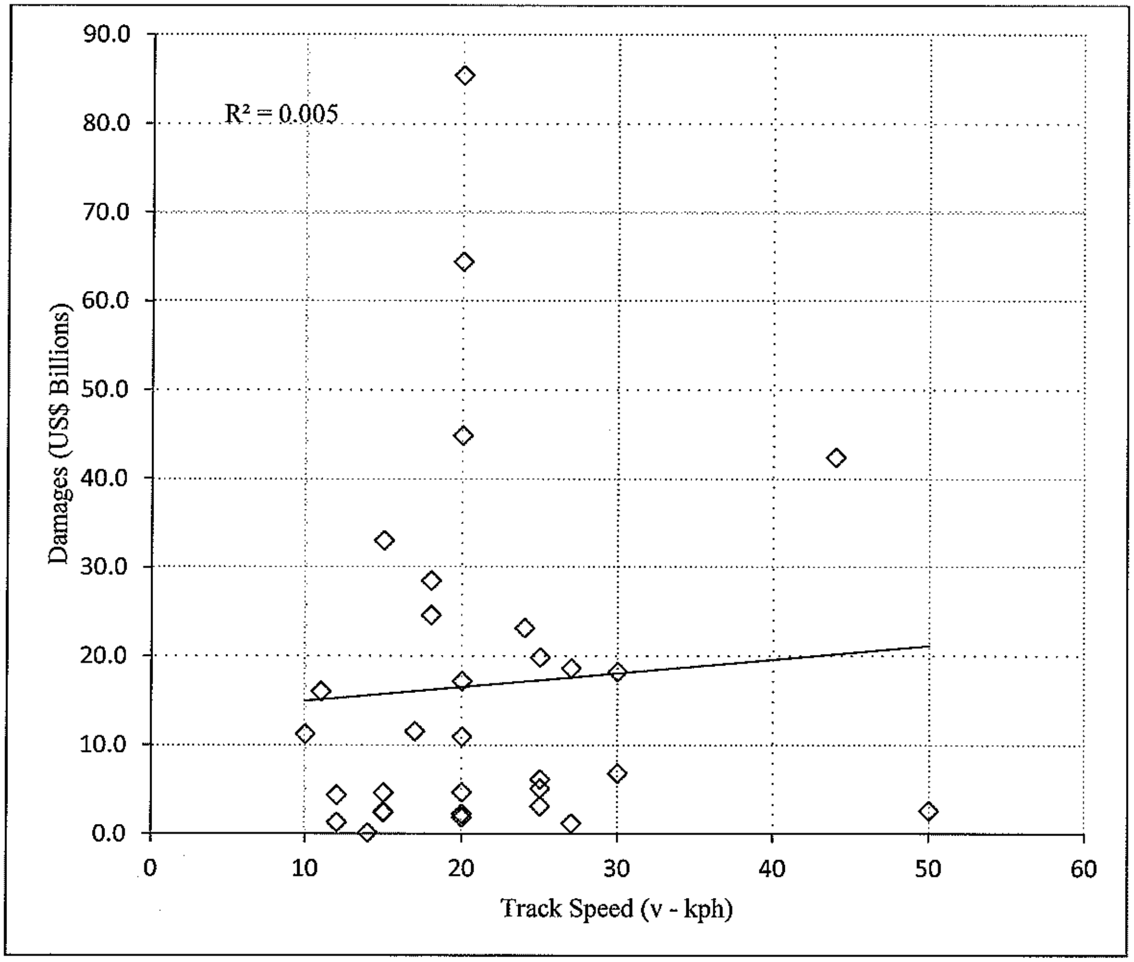


Figure 14: Total Normalized Damage vs. Track Speed

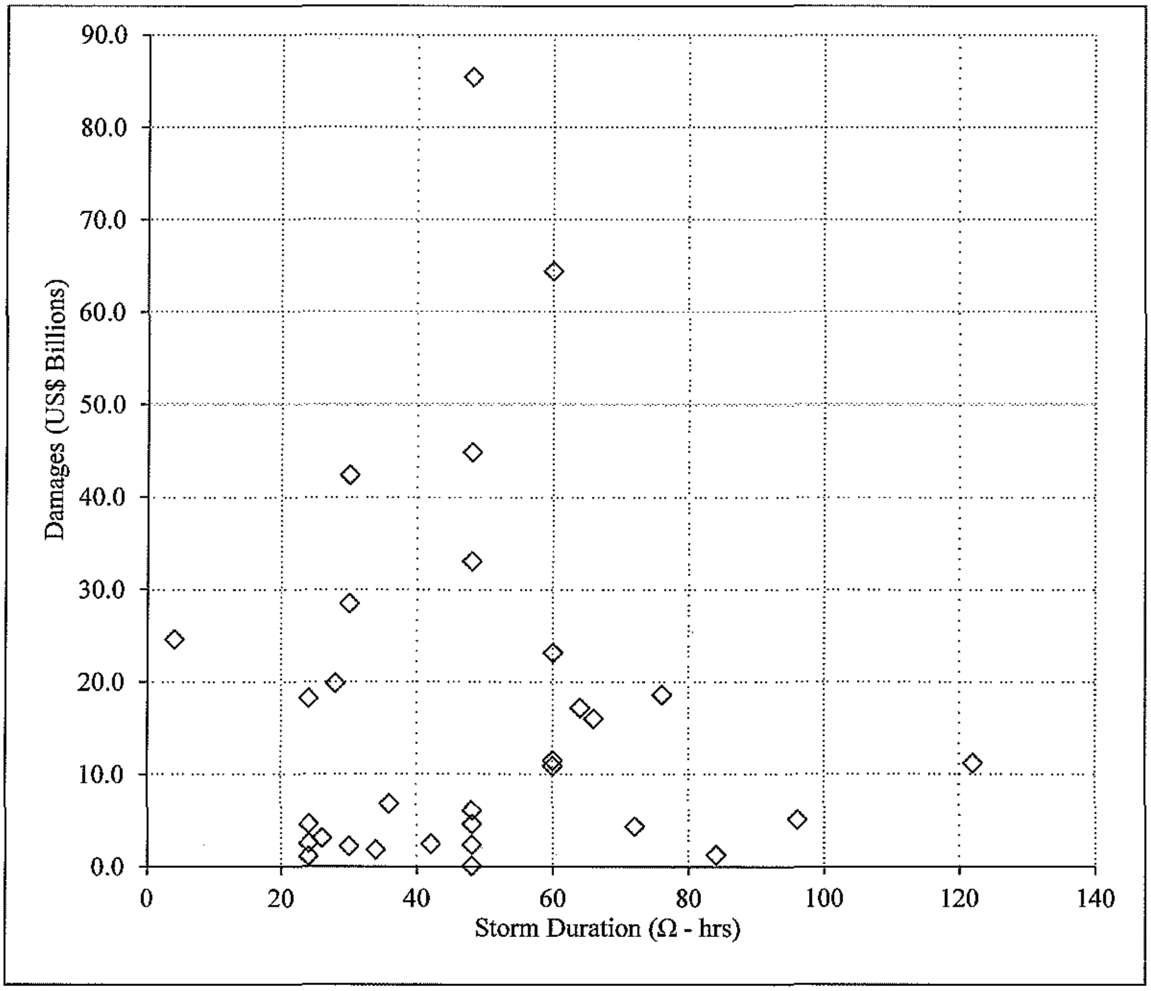


Figure 15: Total Normalized Damage vs. Storm Duration

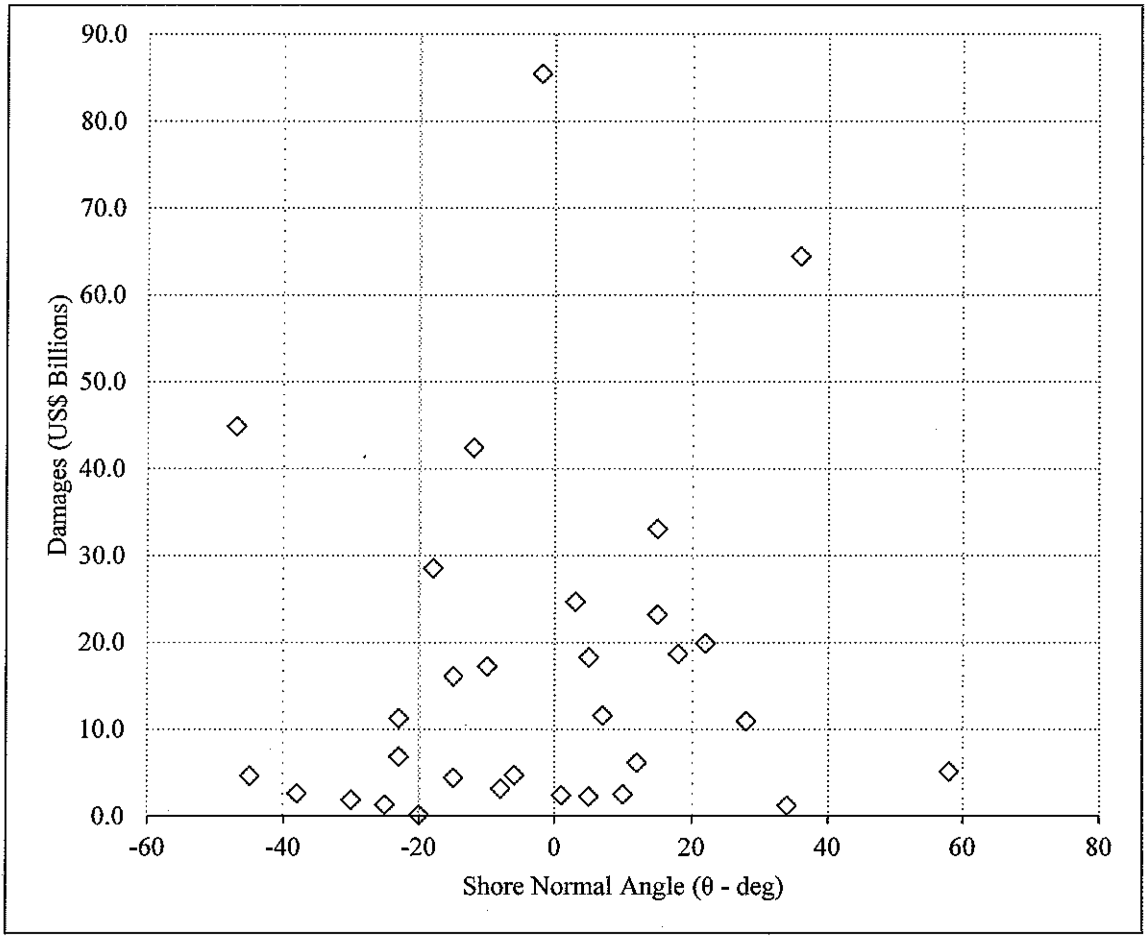


Figure 16: Total Normalized Damage vs. Storm Angle Measured from Normal Projection

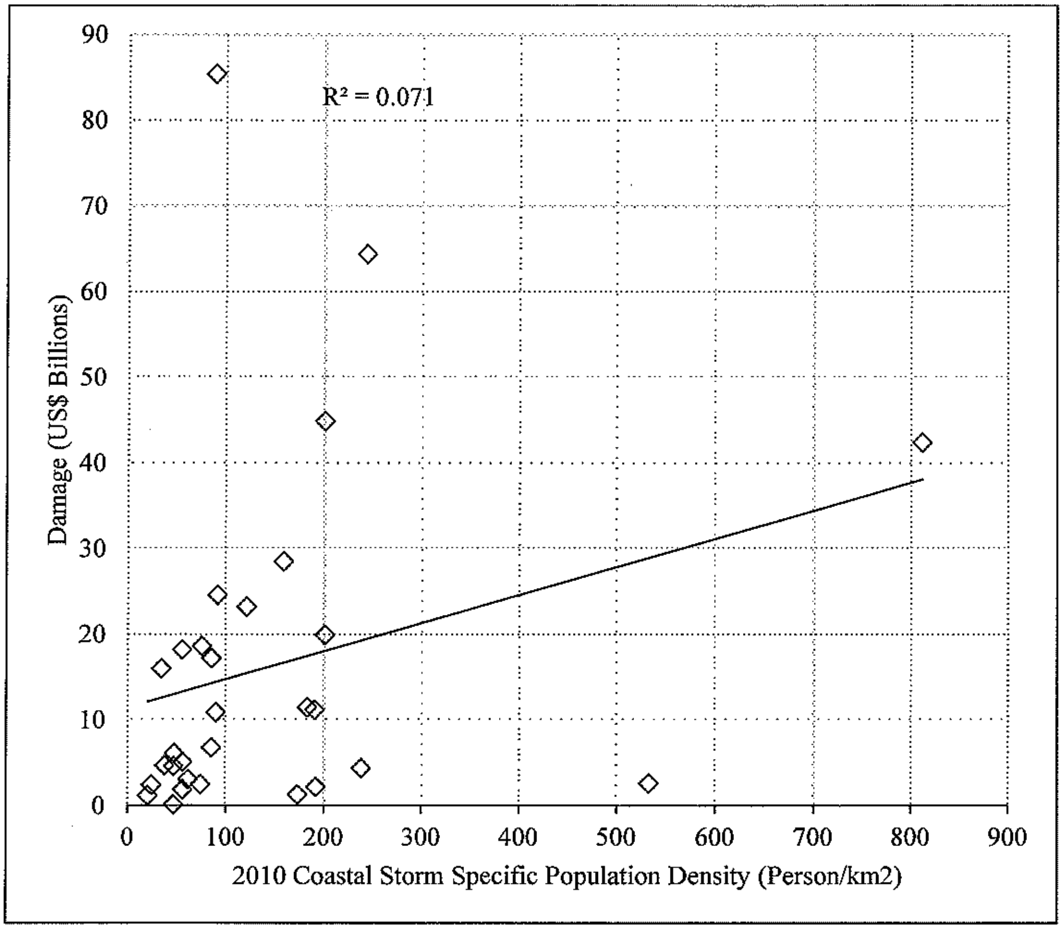


Figure 17: Total Normalized Damage vs. 2010 Coastal Storm Specific Population Density

APPENDIX C

Figures from Irish and Resio (2007)

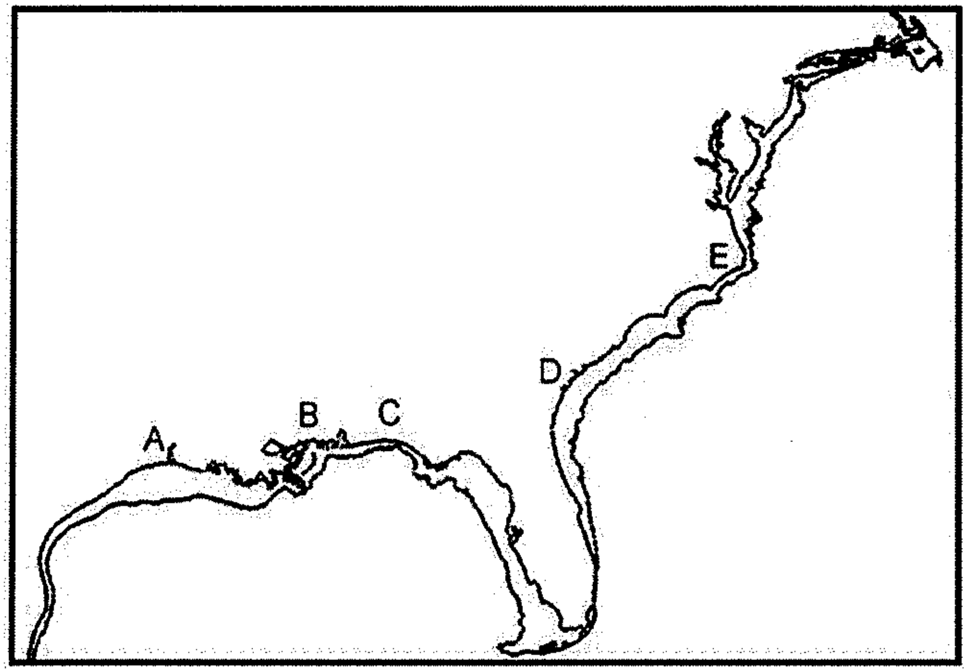


Figure 18: The 30 Meter Shelf Contour (Blue Line)

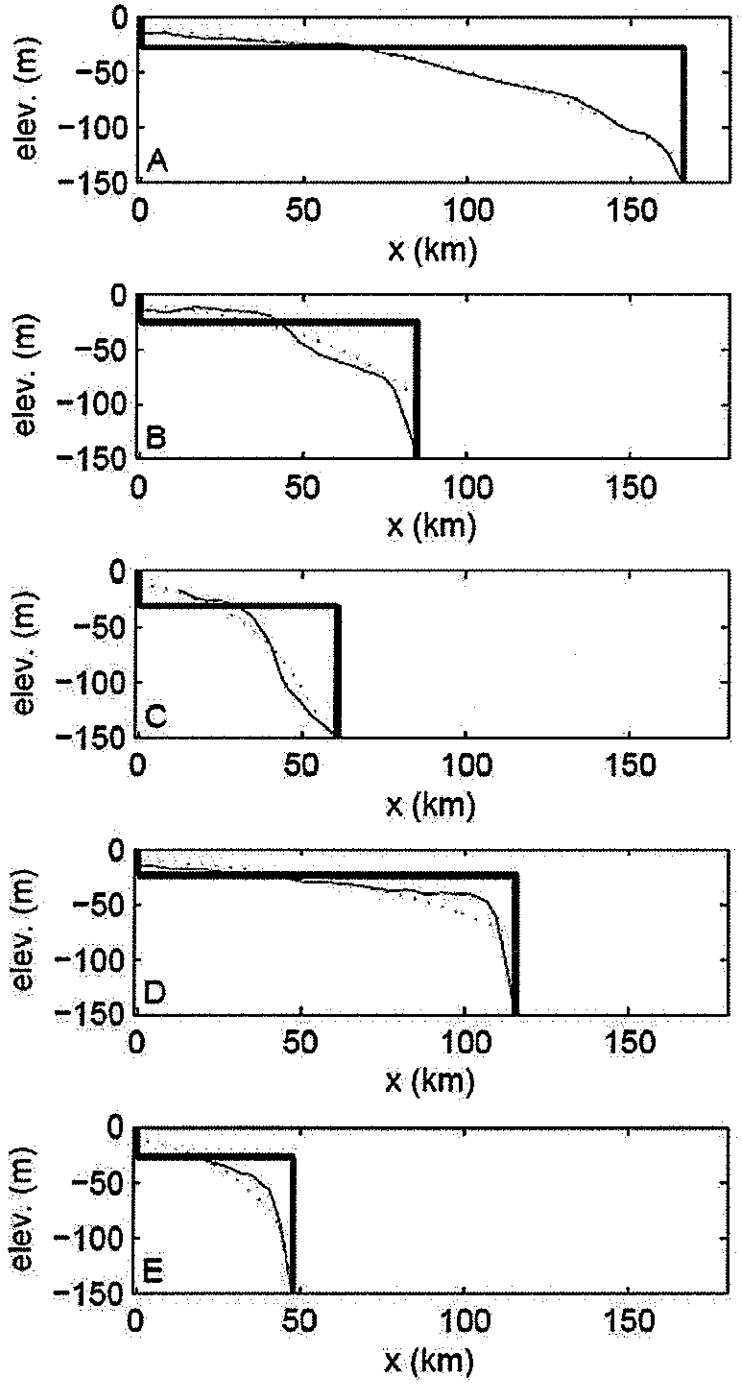


Figure 19: Offshore Profiles Corresponding to Figure 17

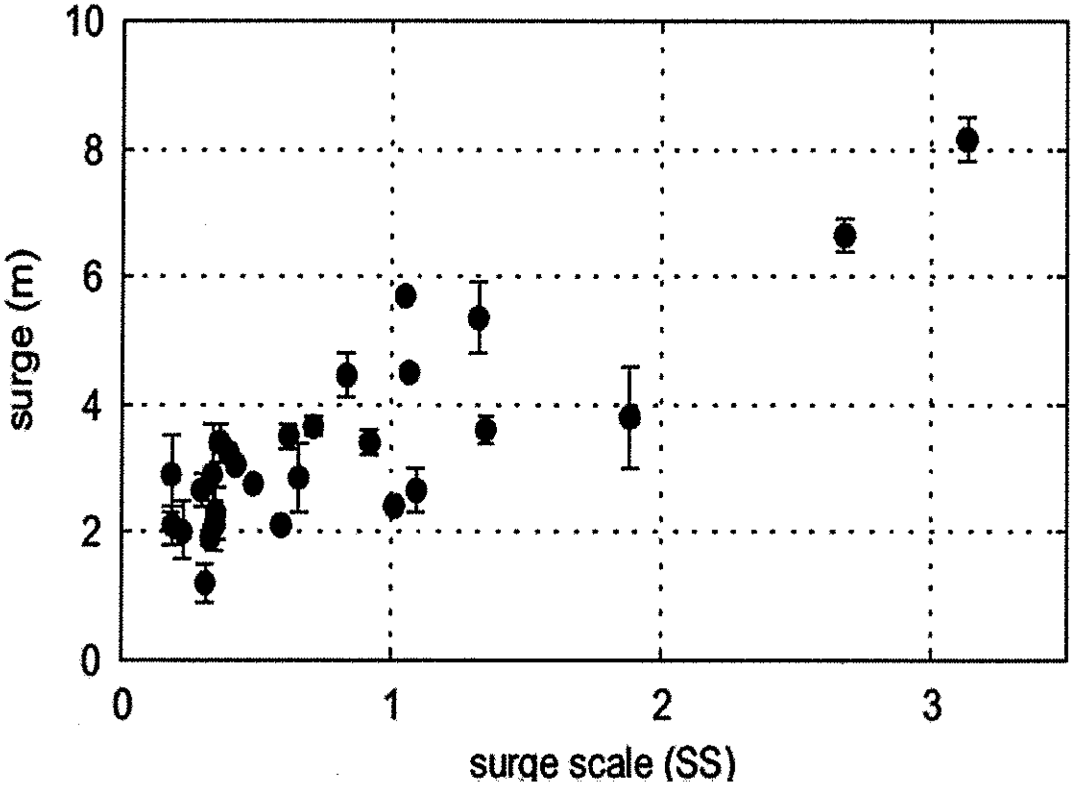


Figure 20: Surge Scale Comparison to Surge (R=0.72)

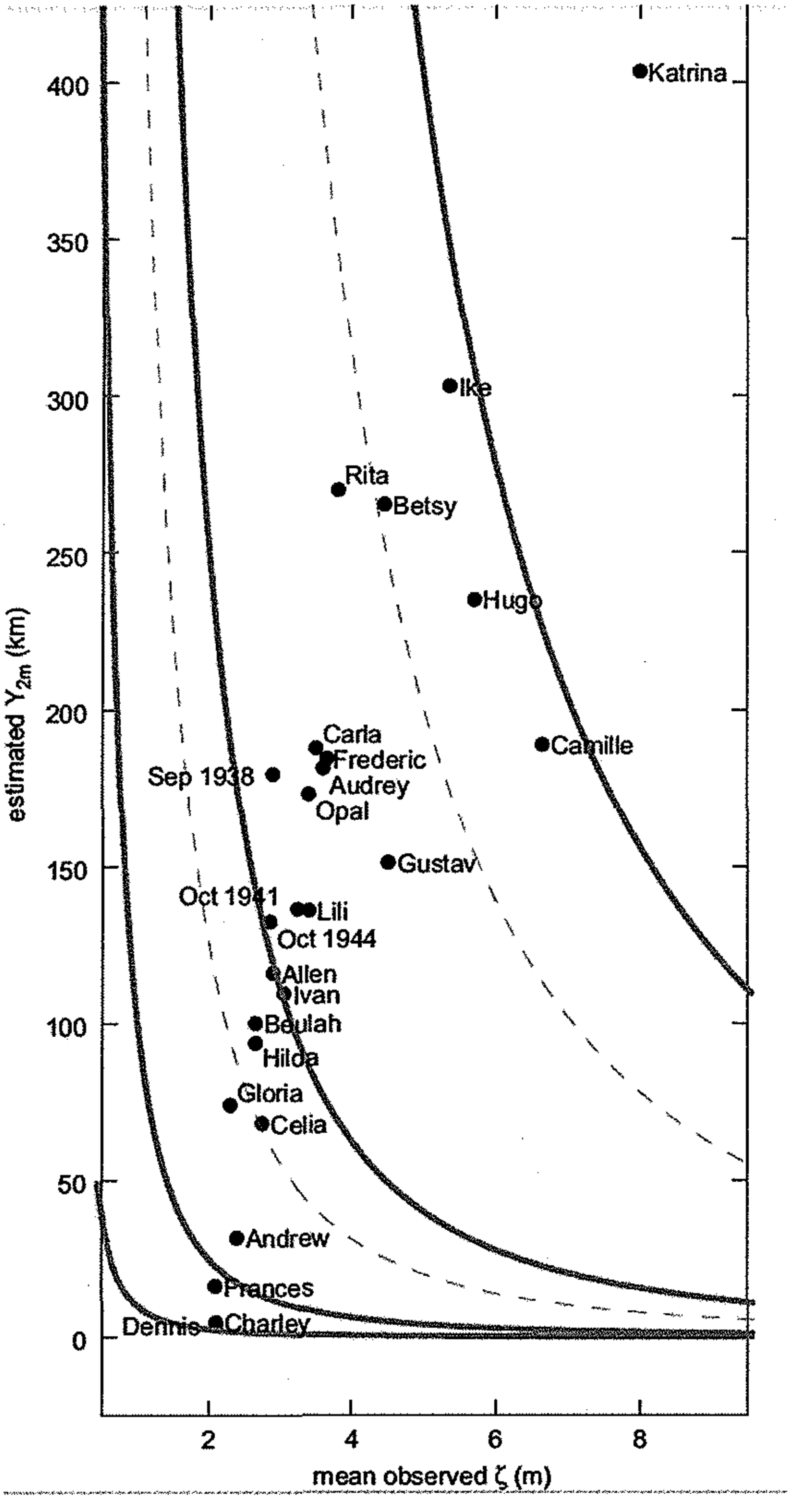


Figure 21: Alongshore Extent of Surge vs. Mean Surge

APPENDIX D

Figures from Pielke and Landsea (2008)

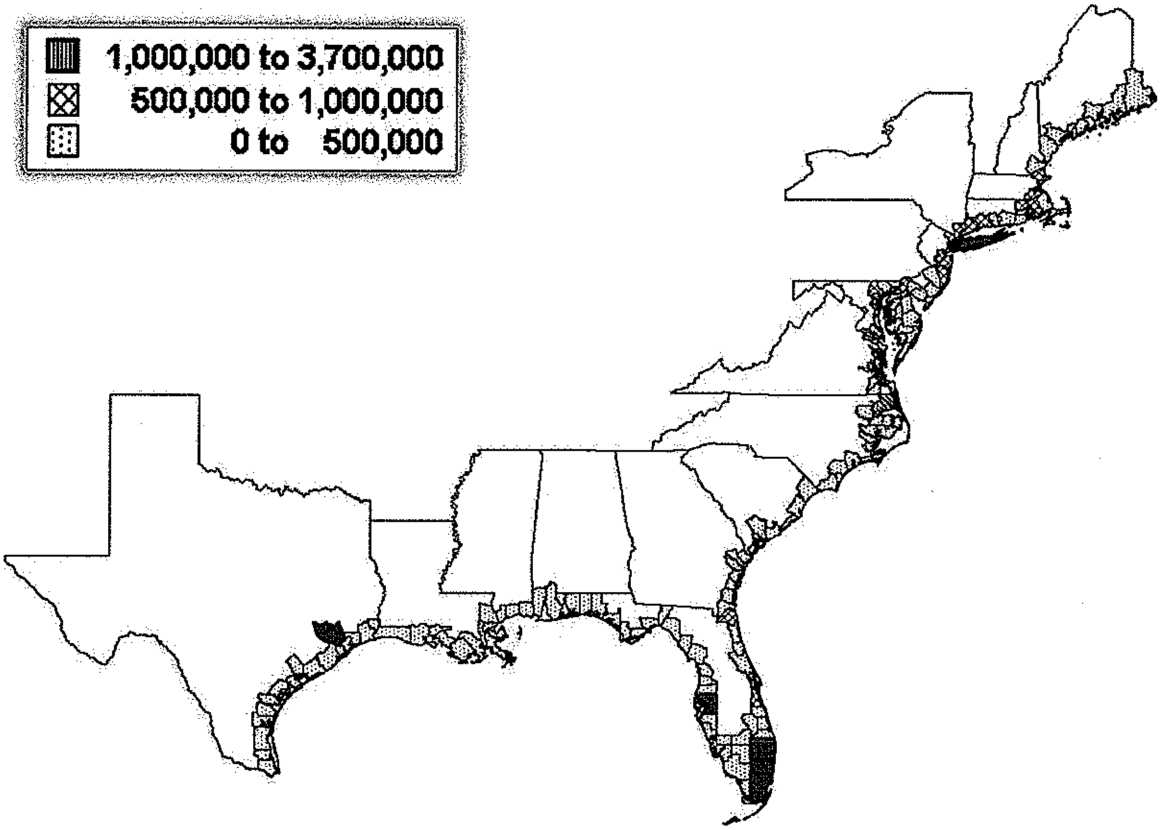


Figure 22: 2005 Population by County (Plan-view)

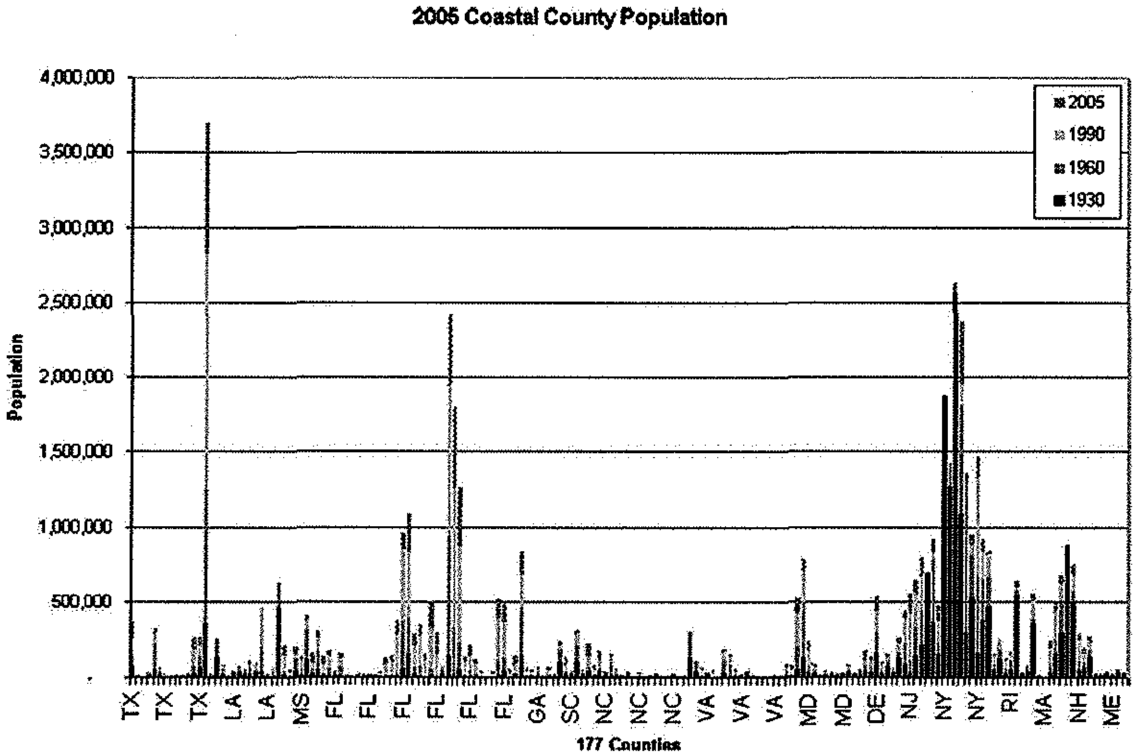


Figure 23: 2005 Population by County

APPENDIX E

US Wealth Figure

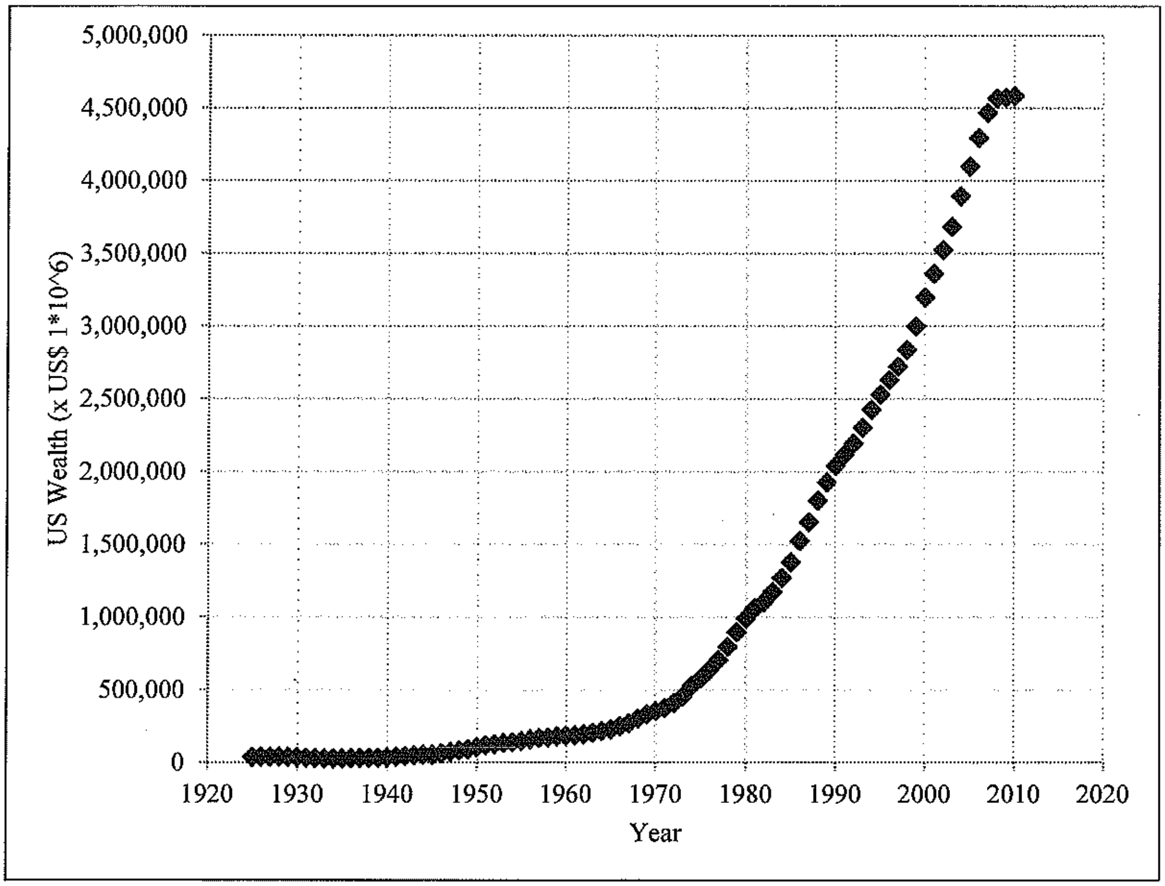
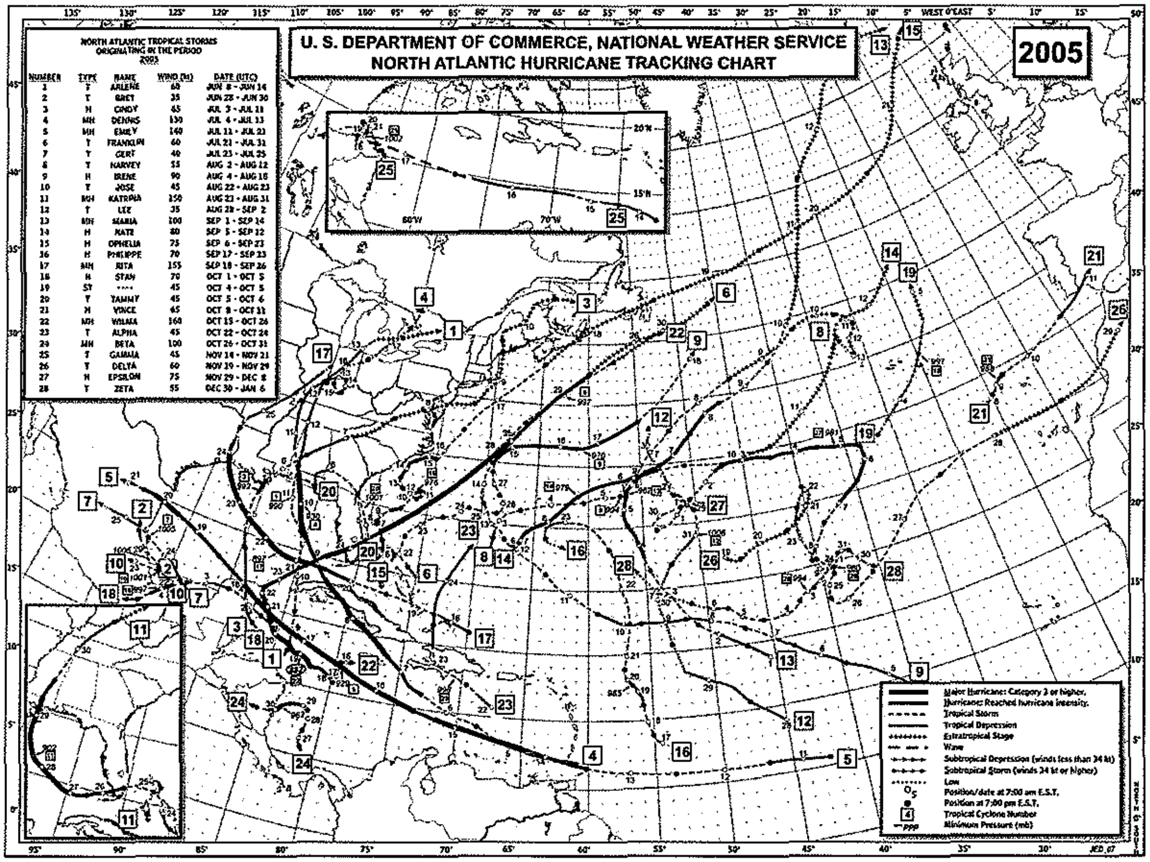


Figure 24: US Wealth vs. Year

APPENDIX F

2005 Hurricane Season



NORTH ATLANTIC TROPICAL STORMS
ORIGINATING IN THE PERIOD
2005

NUMBER	TYPE	NAME	WIND (kt)	DATE (UTC)
1	T	ARLENE	60	JUN 8 - JUN 14
2	T	BRET	35	JUN 28 - JUN 30
3	H	CINDY	65	JUL 3 - JUL 11
4	MH	DENNIS	130	JUL 4 - JUL 13
5	MH	EMILY	140	JUL 11 - JUL 21
6	T	FRANKLIN	60	JUL 21 - JUL 31
7	T	GERT	40	JUL 23 - JUL 25
8	T	HARVEY	55	AUG 2 - AUG 12
9	H	IRENE	90	AUG 4 - AUG 18
10	T	JOSE	45	AUG 22 - AUG 23
11	MH	KATRINA	150	AUG 23 - AUG 31
12	T	LEE	35	AUG 28 - SEP 2
13	MH	MARIA	100	SEP 1 - SEP 14
14	H	NATE	80	SEP 5 - SEP 12
15	H	OPHELIA	75	SEP 6 - SEP 23
16	H	PHILIPPE	70	SEP 17 - SEP 23
17	MH	RITA	155	SEP 18 - SEP 26
18	H	STAN	70	OCT 1 - OCT 5
19	ST	----	45	OCT 4 - OCT 5
20	T	TAMMY	45	OCT 5 - OCT 6
21	H	VINCE	45	OCT 8 - OCT 11
22	MH	WILMA	160	OCT 15 - OCT 26
23	T	ALPHA	45	OCT 22 - OCT 24
24	MH	BETA	100	OCT 26 - OCT 31
25	T	GAMMA	45	NOV 14 - NOV 21
26	T	DELTA	60	NOV 19 - NOV 29
27	H	EPSILON	75	NOV 29 - DEC 8
28	T	ZETA	55	DEC 30 - JAN 6

Figure 25: 2005 Hurricane Tracks

APPENDIX G

US Census Bureau Figure

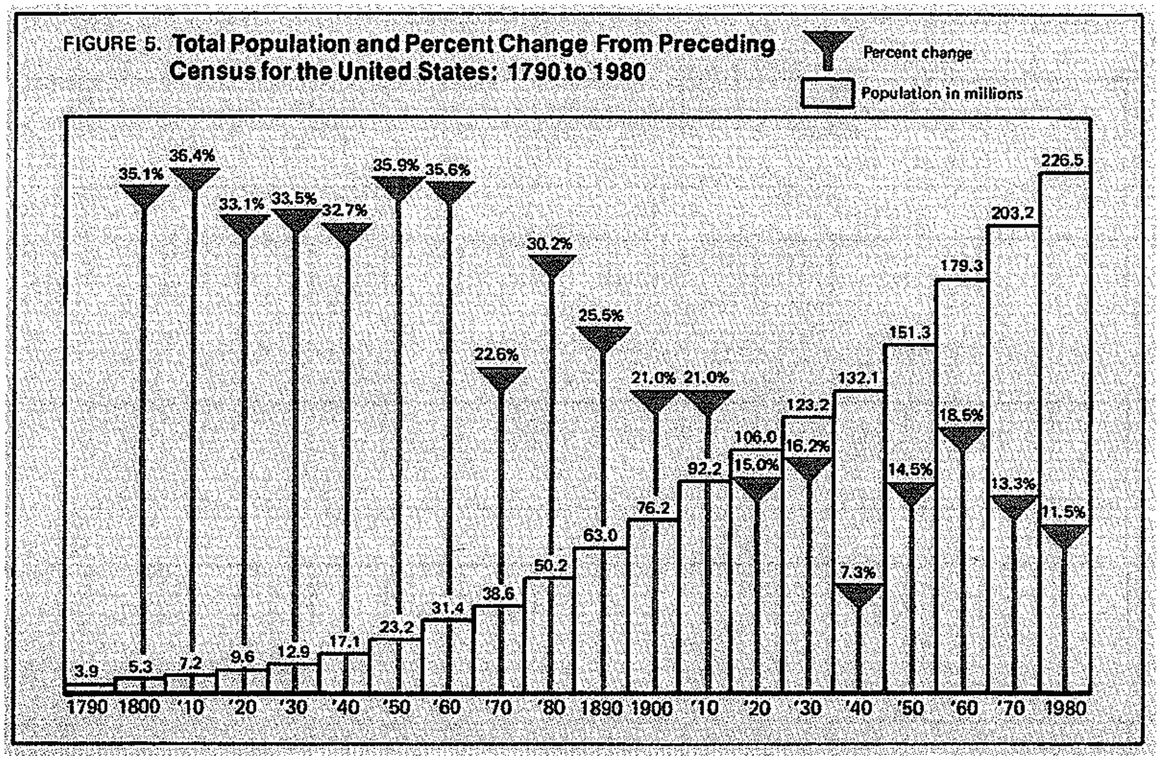


FIGURE 5. **Total Population and Percent Change From Preceding Census for the United States: 1790 to 1980**

Figure 26: US Census National Historical Percent Growth in Population

APPENDIX H

Gumbel Distribution for Damages

i (rank)	D	$D_i - \mu$	$(D_i - \mu)^2$	f(D_i)	-LN(-LN(f(x)))
1	88.7	71.0	5040.405	0.992	4.779
2	67.1	49.39581	2439.946	0.970	3.501
3	64.2	46.49581	2161.86	0.965	3.329
4	44.4	26.69581	712.6661	0.891	2.157
5	33.0	15.29581	233.9617	0.797	1.482
6	28.5	10.79581	116.5494	0.743	1.216
7	23.5	5.795806	33.59137	0.671	0.920
8	22.0	4.295806	18.45395	0.647	0.831
9	21.5	3.8	14.40815	0.639	0.802
10	19.9	2.195806	4.821566	0.611	0.707
11	19.8	2.095806	4.392405	0.609	0.701
12	17.3	-0.4	0.163372	0.563	0.553
13	16.2	-1.50419	2.262598	0.541	0.488
14	11.5	-6.20419	38.49202	0.445	0.210
15	11.3	-6.40419	41.0137	0.440	0.198
16	11.0	-6.70419	44.94621	0.434	0.180
17	6.8	-10.9042	118.9014	0.343	-0.068
18	6.2	-11.5042	132.3465	0.330	-0.104
19	5.1	-12.6042	158.8657	0.306	-0.169
20	4.6	-13.1	171.7199	0.295	-0.199
21	4.4	-13.3042	177.0016	0.291	-0.210
22	4.3	-13.4042	179.6724	0.289	-0.216
23	3.2	-14.5042	210.3716	0.266	-0.281
24	2.6	-15.1042	228.1367	0.253	-0.317
25	2.5	-15.2042	231.1675	0.251	-0.323
26	2.4	-15.3042	234.2183	0.249	-0.329
27	2.3	-15.4042	237.2892	0.247	-0.335
28	1.9	-15.8042	249.7725	0.239	-0.358
29	1.3	-16.4042	269.0976	0.227	-0.394
30	1.2	-16.5042	272.3884	0.225	-0.400
31	0.13	-17.5742	308.8523	0.204	-0.463
Σ	548.8		14087.73		

Katrina [2005]

$T_R = 1/(\lambda(1-f(D_i)))$

$\lambda =$	0.43	
$T_R =$	277.51	Years (Return Period)
$P_e =$	0.003603	Probability of Exceedance
$P_{ne} =$	0.996397	Probability of Non-Exceedance

APPENDIX I

Predicted Damage Figures

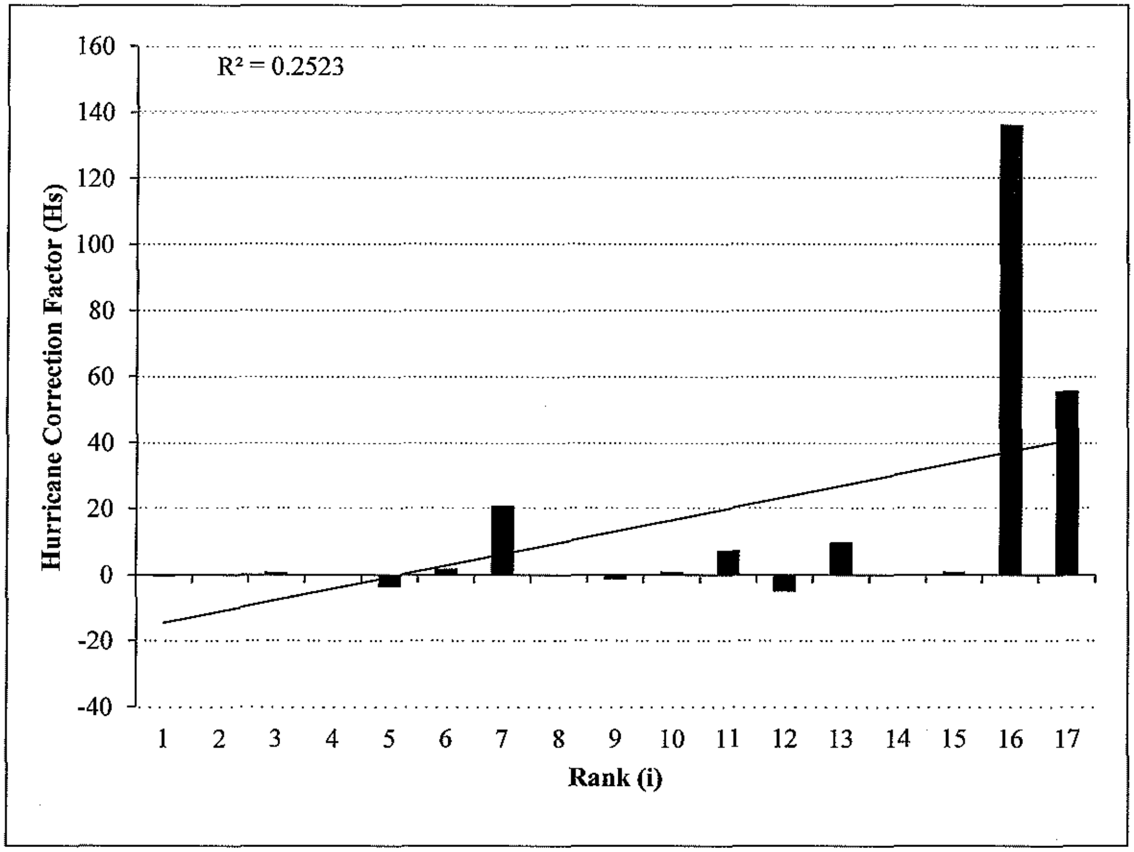


Figure 27: Hurricane Surge Damage Correction Factor

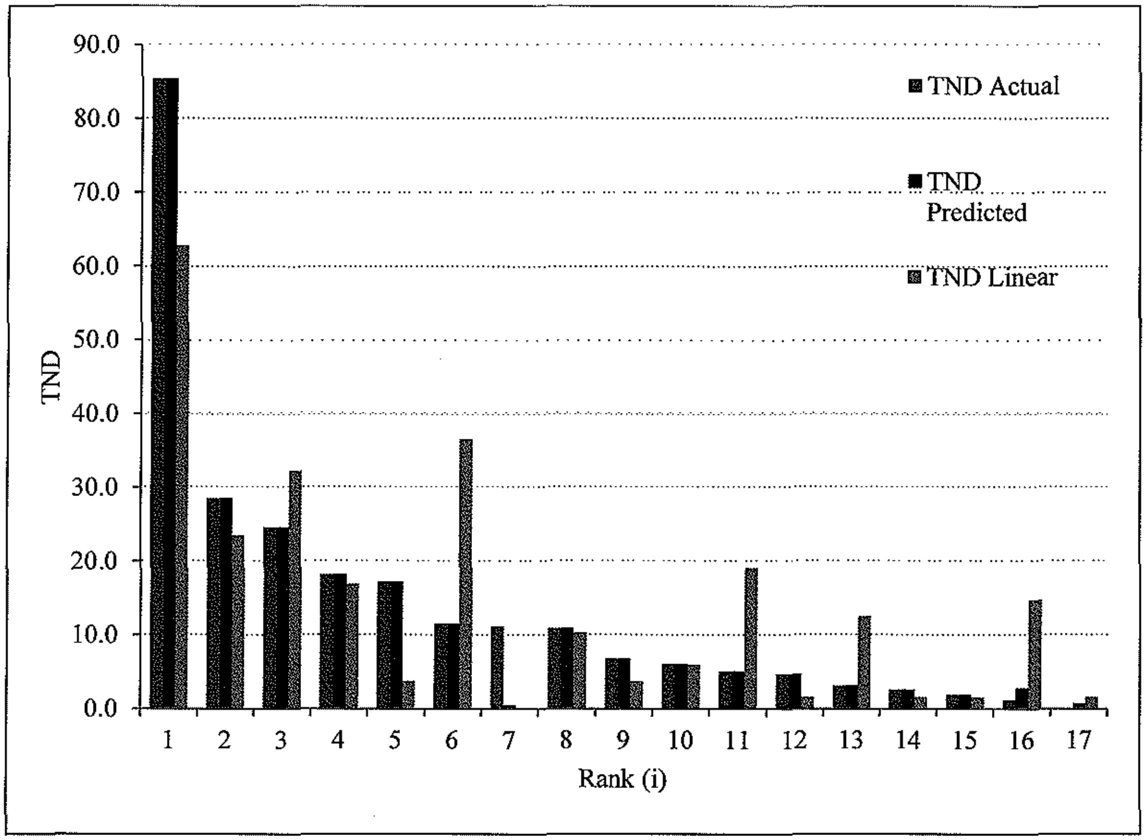


Figure 28: Total Normalized Damage Predictions

APPENDIX J

County Densities

Table 17: 2010 Population Densities by County

County Number	County/Parishes	State	Land Area (mi^2)	Land Area (km^2)	2010 Population	2010 Population Density (Person/km^2)
1	Cameron	TX	906	2347	406,220	173.1
2	Willacy	TX	597	1546	22,134	14.3
3	Kenedy	TX	1457	3774	416	0.1
4	Kleberg	TX	871	2256	32,061	14.2
5	Nueces	TX	836	2165	340,223	157.1
6	San Patricio	TX	692	1792	64,804	36.2
7	Aransas	TX	252	653	23,158	35.5
8	Refugio	TX	770	1994	7,383	3.7
9	Calhoun	TX	512	1326	21,381	16.1
10	Victoria	TX	882	2284	86,793	38.0
11	Jackson	TX	829	2147	14,075	6.6
12	Matagorda	TX	1114	2885	36,702	12.7
13	Brazoria	TX	1386	3590	313,166	87.2
14	Galveston	TX	398	1031	291,309	282.6
15	Harris	TX	1729	4478	4,092,459	913.9
16	Chambers	TX	599	1551	35,096	22.6
17	Jefferson	TX	904	2341	252,273	107.7
18	Orange	TX	356	922	81,837	88.8
19	Cameron	LA	1313	3401	6,839	2.0
20	Vermilion	LA	1174	3041	57,999	19.1
21	Iberia	LA	575	1489	73,240	49.2
22	Saint Mary	LA	613	1588	54,650	34.4
23	Terrebonne	LA	1255	3250	111,860	34.4
24	Lafourche	LA	1085	2810	96,318	34.3
25	St. Charles	LA	284	736	52,780	71.8
26	St. John the Baptist	LA	277	717	45,924	64.0
27	Jefferson	LA	307	795	96,318	121.1
28	Plaquemines	LA	845	2189	23,042	10.5
29	Saint Bernard	LA	465	1204	35,897	29.8
30	Orleans	LA	181	468	343,829	735.1
31	Saint Tammany	LA	846	2191	233,740	106.7

32	Tangipahoa	LA	790	2046	121,097	59.2
33	Hancock	MS	477	1235	43,929	35.6
34	Harrison	MS	581	1505	187,105	124.3
35	Jackson	MS	727	1883	139,668	74.2
36	Mobile	AL	1233	3194	412,992	129.3
37	Baldwin	AL	1596	4135	182,265	44.1
38	Escambia	FL	662	1715	297,619	173.5
39	Santa Rosa	FL	1016	2632	151,372	57.5
40	Okaloosa	FL	936	2423	180,822	74.6
41	Walton	FL	1058	2739	55,043	20.1
42	Bay	FL	764	1978	168,852	85.4
43	Gulf	FL	555	1436	168,852	117.6
44	Franklin	FL	544	1410	11,549	8.2
45	Wakulla	FL	607	1571	30,776	19.6
46	Jefferson	FL	598	1548	14,761	9.5
47	Taylor	FL	1042	2699	22,570	8.4
48	Dixie	FL	704	1823	16,422	9.0
49	Levy	FL	1118	2897	40,801	14.1
50	Pasco	FL	745	1929	464,697	240.9
51	Pinellas	FL	280	725	916,542	1264.2
52	Hillsborough	FL	1051	2722	1,229,226	451.6
53	Manatee	FL	741	1919	322,833	168.2
54	Sarasota	FL	572	1480	379,448	256.3
55	Charlotte	FL	694	1796	159,978	89.1
56	Lee	FL	804	2081	618,754	297.3
57	Collier	FL	2025	5246	321,520	61.3
58	Monroe	FL	997	2582	73,090	28.3
59	Miami-Dade	FL	1898	4915	2,496,435	507.9
60	Broward	FL	1,205	3122	1,748,066	559.9
61	Palm Beach	FL	1974	5113	1,320,134	258.2
62	Martin	FL	556	1439	146,318	101.7
63	St. Lucie	FL	572	1483	277,789	187.4
64	Indian River	FL	503	1303	138,028	105.9
65	Brevard	FL	1018	2637	543,376	206.1
66	Chatham	GA	438	1135	265,128	233.7
67	Jasper	SC	656	1699	24,777	14.6
68	Beaufort	SC	587	1520	162,233	106.7
69	Charleston	SC	919	2380	350,209	147.1
70	Colleton	SC	1056	2735	38,892	14.2
71	Georgetown	SC	815	2111	60,158	28.5
72	Horry	SC	1134	2937	269,291	91.7
73	Brunswick	NC	855	2214	107,431	48.5
74	New Hanover	NC	199	515	202,667	393.2
75	Pender	NC	871	2256	22,099	9.8

76	Onslow	NC	767	1987	177,772	89.5
77	Carteret	NC	520	1347	66,469	49.4
78	Bertie	NC	699	1810	21,282	11.8
79	Pamlico	NC	337	873	13,144	15.1
80	Beaufort	NC	828	2145	47,759	22.3
81	Hyde	NC	613	1588	5,810	3.7
82	Dare	NC	384	995	33,920	34.1
83	Tyrrell	NC	390	1010	4,407	4.4
84	Washington	NC	348	901	13,228	14.7
85	Chowan	NC	173	448	14,793	33.0
86	Perquimans	NC	329	852	13,453	15.8
87	Pasquotank	NC	227	588	40,661	69.2
88	Camden	NC	241	624	9,980	16.0
89	Currituck	NC	262	679	23,547	34.7
90	Atlantic	NJ	556	1439	274,549	190.8
91	Ocean	NJ	629	1629	576,567	354.0
92	Monmouth	NJ	469	1214	630,380	519.2
93	Middlesex	NJ	309	800	809,858	1012.2
94	Richmond	NY	58	151	468,730	3094.7
95	Kings	NY	71	183	2,504,700	13695.9
96	Queens	NY	109	283	2,230,722	7884.3
97	Nassau	NY	287	743	1,339,532	1802.1
98	Suffolk	NY	912	2362	1,493,350	632.2
99	Bronx	NY	42	109	1,385,108	12733.2
100	Westchester	NY	433	1121	949,113	846.3
101	Fairfield	CT	626	1621	916,829	565.7
102	New Haven	CT	606	1569	862,477	549.8
103	Middlesex	CT	369	956	165,676	173.2
104	New London	CT	666	1725	274,055	158.9
105	Washington	RI	333	862	126,979	147.2
106	Kent	RI	170	440	166,158	377.4
107	Bristol	RI	25	65	49,875	770.3
108	Newport	RI	104	269	82,888	307.7
109	Bristol	MA	556	1440	548,285	380.7
110	Dukes	MA	104	269	16,535	61.5

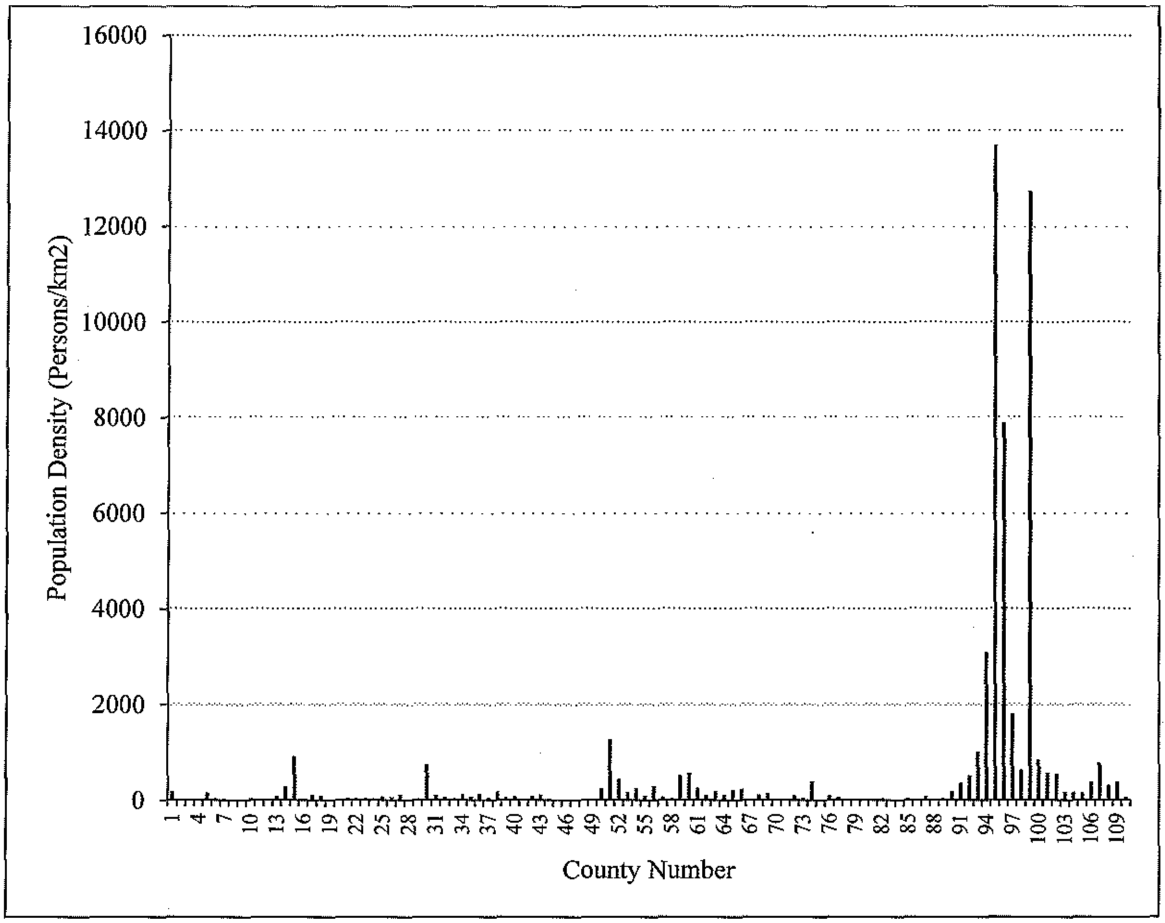


Figure 29: 2010 Population Densities by County