The Florida Catastrophic Storm Risk Management Center

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Florida Hurricanes and Damage Costs

THE FLORIDA STATE UNIVERSITY
COLLEGE OF BUSINESS
The Florida Catastrophic Storm Risk Management Center

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JILL MALMSTADT
Florida State University

KELSEY SCHEITLIN
Florida State University

JAMES ELSNER
Florida State University

Florida has been visited by some of the most destructive and devastating hurricanes on record in the United States causing well over $450 billion in damage since the early 20th century. The value of insured property in Florida against windstorm damage is the highest in the nation and on the rise. The frequency and severity of hurricanes affecting Florida are examined from the best set of available data and the damages are related to characteristics of the storms at landfall. Results show that normalized losses are increasing over time consistent with small increases in hurricane intensity and hurricane size. The best predictor of potential losses is minimum central pressure. Hurricane size alone or in combination with hurricane intensity does not improve on the simpler relationship. An estimate of potential losses from hurricanes can be obtained using a formula involving only a forecast of the minimum pressure at landfall. The ability to estimate potential losses in Florida will increase the ability to estimate losses in other areas of the United States, and will also allow policy makers and insurance companies to provide relevant information to the concerned public.

KEY WORDS: Florida, hurricanes, landfall, insurance, losses, trends, correlation

INTRODUCTION

The hurricane is an awesome, yet deadly and destructive natural phenomenon of the Earth's occasionally tumultuous atmosphere. A hurricane is powered by the heat and moisture of the tropical oceans rather than thermal contrasts across latitudes as is the case for the more common extratropical cyclone. The result is a powerful storm, causing unprecedented amounts of deaths and economic loss. Dollar losses from hurricanes are at the top of the list of catastrophic events ahead of tornadoes and terrorism. Not surprisingly, because of its location relative to the warm waters of the North Atlantic (including the Gulf of Mexico and the Caribbean Sea), Florida is more likely to get hit by a hurricane than any other state in the union. On average at least one hurricane strikes Florida every two years and a strong hurricane hits Florida on average once every four years (averages come from available data during 1900–2007). Eight of the 10 most expensive hurricanes ever to make landfall in U.S. history have had at least some affect on Florida, causing in excess of $60 billion (constant 2005 dollars) in insured losses

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(hurricanes Andrew 1992, Charley, Frances, Ivan and Jeanne in 2004, and Katrina, Rita, and Wilma in 2005). For this reason, as well as the devastating impact these storms have on human lives, scientists have been tackling the issue of hurricanes in order to further understand their characteristics and better predict their impending impact on the coastline ahead. This paper will focus on economic loss in the state of Florida, as Florida represents a unique case study for hurricane science.

Interest in economic loss from hurricanes is not new, as it was discussed throughout the 1960s (Demsetz 1962; Sugg 1967), but interest has become elevated in recent times due to the destructive Atlantic hurricane seasons of 2004 and 2005.

The most damage-causing characteristics of a hurricane are the high winds, storm surge and large waves, as they each have potential for total destruction of property and livelihoods (Williams and Duedall 1997). This potential for damage has recently increased due, in part, to a notable rise in global atmospheric temperatures.

The issue of climate change brings along a challenge to hurricane researchers, as attempts are made to try to quantify the impact of climate change on the future of hurricanes. While many other factors play a role in hurricane development and intensity, the increasing sea surface temperatures associated with climate change provide an obvious increase of fuel for these storms and a heightened cause for alarm. Elsner et al. (2008) found an increasing trend in the strength of the strongest hurricanes, especially the 90th percentile, meaning, in short, the strongest storms are getting stronger. Emanuel (2005) uses the observed increase in sea surface temperature to explain the increase in power dissipation within the average North Atlantic hurricane and found that tropical cyclones have become more destructive within the last 30 years. The combination of increasing storm strength and coastal develop ment should yield increasing economic loss due to hurricanes. Changnon (2003) believes that coastal development is the main reason for recent increasing economic loss, as the increase in losses throughout the 1990s occurred when hurricane frequencies decreased; the data showing no shift due to global warming. That is not to say that weather extremes do not cause notable increases in economic loss, as the active weather of 1991–1994 and associated hurricanes, severe storms, floods, tornadoes, etc. caused more economic loss due to weather events than any other four-year period. Yet still, the largest increases occurred in areas with the greatest population growth (Changnon 1997).

Florida, like most of the coastal United States, has seen a building boom, and the increasing population and wealth is forcing insurers and re-insurers to rethink their exposures. According to the U.S. Census Bureau, Florida has the highest population growth among states affected by hurricanes and is expected to gain about 13 million residents between 2000 and 2030. The *Citizens Property Insurance Corporation* in Florida (aka, *Citizens*), set up by the State of Florida in 2002 to be the property insurer of last resort, is now the largest provider of property insurance in the state. Florida homeowners can buy coverage from *Citizens* if the rates for a comparable policy from a private insurer exceed by 15 percent *Citizens*' rates.

According to the Insurance Information Institute (Hartwig 2008), the value of insured coastal property in Florida ranks first in the nation and, as of 2007, exceeds $2 trillion with about 60 percent in commercial exposure and the rest in residential exposure (AIR 2005). Florida homeowner insurers' underwriting losses in 2004 ($9.3 billion) and 2005 ($3.8 billion) resulted in a four-year cumulative loss of $6.7 billion, even after including the profitable years of 2006 ($3 billion) and 2007 ($3.4 billion), when there were no hurricanes (Hartwig 2008). Since 1992, Florida insurers have experienced a net loss of $6.2 billion (Hartwig 2008).

Citizens' total exposure to loss is high and growing, increasing from $154.6 billion in 2002 to $434.3 billion during the first quarter of 2007 (Insurance Information Institute 2007). The number of policies written by *Citizens* is also on the rise with the total reaching 1.35 million as of July 31, 2007. If losses by *Citizens* exceed its claim-paying capacity in a single season, the state is required to impose an assessment on other lines of insurance, including policies not written by *Citizens*. Loss assessments (collected from all insured property owners from the entire state), general revenue appropriations, and the reinsurance market can be augmented with the issuance of catastrophe bonds. Catastrophe bonds help alleviate the risk of a catastrophic event by transferring some of that risk to investors. In July of 2007, *Citizens* floated a catastrophe bond worth nearly $1 billion, and in July of 2008, Berkshire Hathaway, Inc. agreed to buy $4 billion in bonds if *Citizens* incurs at least $25 billion in losses. The state has estimated the probability of this level of damage occurring annually in the state of Florida to be about 3.1 percent per year. In 2008, in exchange for taking on this risk, Florida will pay Berkshire Hathaway, Inc. $224 million for a guarantee that the state will receive up to $4 billion if the damage threshold is reached (Kaczor 2008). Large investors are becoming increasingly interested in catastrophe bonds and other insurance-linked securities because of their low correlation to traditional financial market performance providing a better diversification of investment portfolios.

This paper provides a climatology of hurricanes and hurricane losses in Florida. It is hypothesized that hurricane intensity is a predictor of total economic loss due to hurricane landfalls. The purpose is to build a foundation for assessing the likelihood of future hurricane losses. The strategy is to graph and tabulate the historical record of hurricane strikes and their associated damage costs, and examine how the statistics of occurrence, intensity, and size are related to losses. Although others have examined damage losses from hurricanes (Katz 2002; Pielke et al. 2008; Jagger et al. 2008), this work is the first to look at the problem focusing exclusively on Florida.

The paper begins with a brief description of the data sets followed by an examination of Florida's hurricane statistics from the period 1900–2007. Inter-annual, seasonal, and intra-seasonal variability of various hurricane characteristics are examined first. Then the distributions and temporal variations of the direct damage costs associated with Florida hurricanes are considered. To bring together geophysical and economic issues, relationships between losses and hurricane characteristics are examined. It is found that historical losses correlate best with minimum central pressure alone.

FLORIDA HURRICANE AND LOSS DATA

This study relies on two principal sources of data. For hurricanes affecting Florida, we use the list of historical hurricanes employed to evaluate a risk model developed by the Florida Commission on Hurricane Loss Projection Methodology (FCHLPM) and supported by a research grant from the Florida Office of Insurance Regulation (FOIR). A hurricane is a tropical cyclone with maximum sustained wind speeds of at least 33 m/s (64 kt/74 mph). The data set largely conforms to the U.S. National Hurricane Center's HURDAT storm archive (Ho et al. 1987; Landsea et al. 2004), but includes storms only for the state of Florida. This dataset is available online at http://www.aoml.noaa.gov/hrd/lossmodel/AllFL.html.

The focus here is on hurricanes that directly strike Florida. A direct strike (or hit) is one in which all or part of the hurricane's eye wall reaches the coast. For this work, the Florida coast is defined as the boundary of the sea with the mainland, including all barrier islands surrounding Florida. For the purposes of this study, hurricanes that approach Florida, but where the eye wall remains out at sea (e.g., Hurricane Elena in 1985) are not considered directly striking Florida. A direct strike includes landfalling hurricanes and those that hit the islands making up the Florida Keys.

A hurricane can make more than one direct hit on the state. This occurs for instance when it first strikes the peninsula then moves out over the eastern Gulf of Mexico before striking the panhandle region (e.g., Storm #3 in 1903). Since a hurricane weakens over land, the intensity of the hurricane at second landfall is typically less than at first landfall. That said, most of the descriptive statistics presented in this study are based on characteristics at the time of first landfall, which for our purposes, is defined as the first direct strike to the mainland or a direct hit to the Florida Keys only if the hurricane makes no other landfall in the state. If the hurricane makes landfall in the state more than once, the landfall characteristics at maximum intensity are used because this comparison is between loss data and hurricane characteristics, and the majority of losses come from the strike of greatest intensity.

For losses incurred by hurricanes that directly strike Florida, normalized damage data are taken from the work of Pielke et al. (2008). There are two normalization procedures presented in Pielke et al. (2008), both of which are estimates of the damage that would have occurred if historic hurricanes struck in the year 2005. One procedure allows for changes in inflation, wealth, and population, and the other procedure allows for inflation, wealth, and an additional factor that represents a change in the number of housing units that exceed population growth between the year of the loss and 2005. The methodology produces a longitudinally consistent estimate of economic damage from past tropical cyclones. Losses caused by each storm event are aggregated from around the entire state and do not necessarily cluster around the location of landfall. However, it is well known that the amount of damage experienced is highly dependent upon where the storm makes landfall in terms of buildings, infrastructure, population, and so forth. Although this research focuses on aggregated loss values, it is useful because it provides a general understanding of the

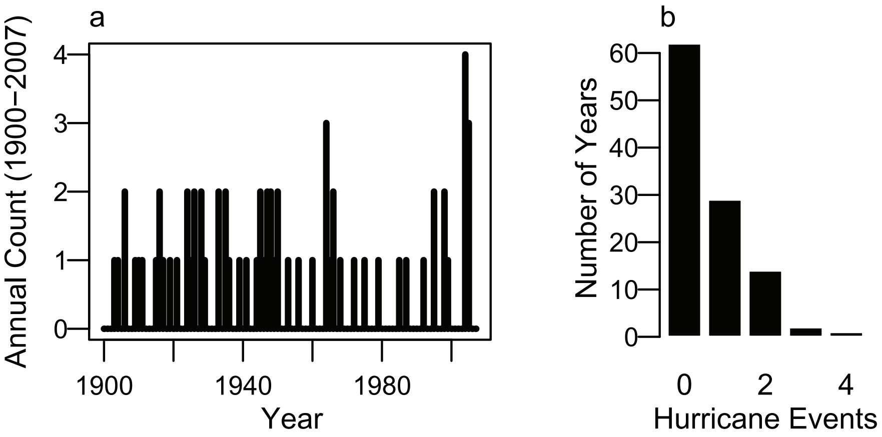

Figure 1. Florida's annual hurricane occurrence (1900–2007). (a) Time series of annual Florida hurricane counts. Only storms that made a direct strike on Florida with hurricane-force winds and that have available economic loss values are included. (b) Distribution of annual Florida counts. There are a total of 67 known Florida hurricanes in the 108-year period.

economic losses experienced throughout Florida from 1900 to 2007.

HURRICANE STATISTICS

The analysis begins with an examination of the frequency of Florida hurricanes. Here the record starts with the 1900 season and ends after the 2007 season. Note that these economic loss data are referred to as losses and damage costs interchangeably throughout this study. A Florida hurricane is a tropical cyclone that makes at least one direct strike on the state as a hurricane. A hurricane that makes more than one landfall in the state of Florida (e.g. Storm #3 in 1903) is considered and counted as one, single Florida hurricane.

Figure 1 shows the time series and distribution of annual Florida hurricanes over the 108-year period. There are a total of 67 Florida hurricanes. There are 62 years without a Florida hurricane and one year (2004) with 4 different hurricanes affecting the state. There are more years without Florida hurricanes during the second half of the 20th century (Elsner et al. 2004). Approximately 16 percent of the years have more than one hurricane event. The average annual number of Florida hurricanes is 0.62 hur/yr with a variance of 0.72 (hur/yr)^2. Assuming that hurricane occurrence in Florida follows a Poisson distribution similar to the climatological record for the rest of the United States affected by hurricanes (Elsner and Jagger 2006), this translates into a 46 percent chance that Florida will be hit by at least one hurricane each year.

Florida's hurricane season runs from the beginning of June through the end of November (even though storms occasionally occur outside this season), but the most active months are September followed by October (Figure 2). In fact, twice as many hurricanes have hit Florida in October than in August. Collectively the months of June, July, and November ac-

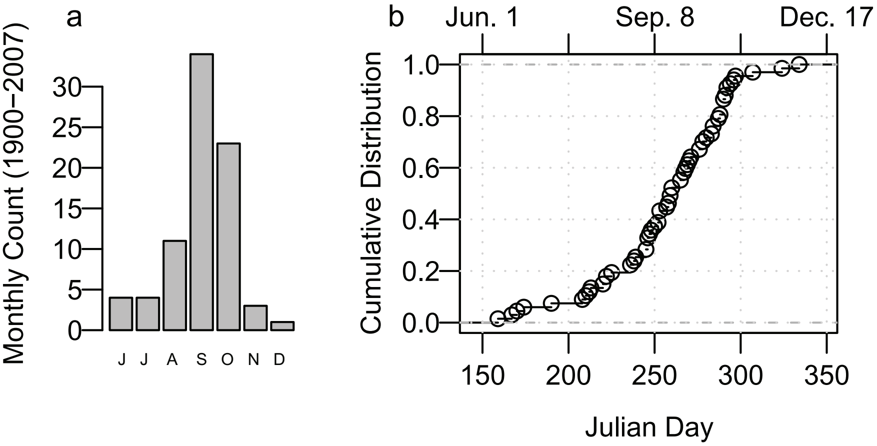

Figure 2. Florida's intra-seasonal hurricane occurrence. (a) Monthly counts and (b) cumulative distribution function (CDF) of Florida hurricanes.

count for about 16 percent of all Florida hurricanes while August, September, and October account for the remaining 84 percent. Yet the monthly distribution does not tell the entire story; another way to look at intra-seasonal activity is with the cumulative distribution function (CDF). The CDF suggests a division of the season into four distinct periods. The periods are marked by a nearly straight line on the CDF indicating a constant probability of observing a hurricane during the period, but the periods do not have equal lengths. The early period runs from 1 June through 31 July. The early mid period (with a steeper slope on the CDF) runs from 1 August through about 5 September. The mid-season period, featuring the highest probability of observing a Florida hurricane, runs from 6 September through 25 October, although there is a slight break in activity during late September and October (represented by a small line just prior to Julian Day 300 in Figure 2). The late period runs from 26 October through the end of November.

The 1st quartile, median, and 3rd quartile dates are 242, 260, and 284, respectively. This implies that only 25 percent of the Florida hurricane season is typically complete by 31 August, half the season is complete by 18 September, and 75 percent of the season is over by 12 October. The 1st quartile date, 31 August, falls into the second period (early-mid) established by the CDF. As expected, the median date, 18 September, falls during the mid-season period established by the CDF, which is slightly more than a week after the median date for all Atlantic hurricanes (Elsner and Kara 1999). The 3rd quartile date, 12 October, also falls into this mid-season period. None of these dates fall into the late period established by the CDF showing that, for this sample of Florida hurricanes, the majority of the season is over by 12 October.

When comparing this seasonality of Florida hurricanes to the remainder of the United States coastline, Florida stands as unique. Coasts that are affected by Atlantic hurricanes extend from Texas to Maine,

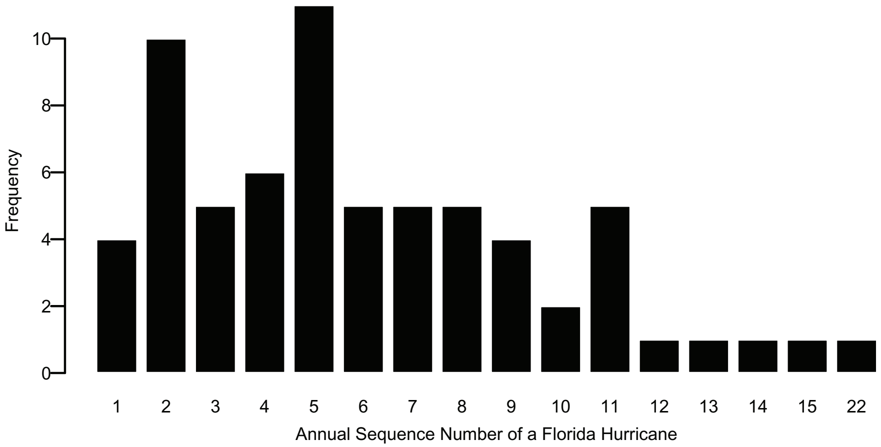

Figure 3. Florida's occurrence of hurricanes by sequence number. The number refers to the sequence of tropical storms and hurricanes within a season, where 1 is the first named tropical cyclone of the season.

and have been regionalized into four areas for comparison purposes. The first region extends from Texas to Alabama, and the second region consists of only Florida. The third and fourth regions consist of the entire eastern coast beginning with Georgia and ending at Maine, and are separated at the state of Virginia. It is found that for all regions, the month of highest hurricane occurrence is September. The main difference between Florida and the other regions is that Florida experiences hurricanes during the entire span of the Atlantic hurricane season with a median date of 18 September, while the other regions experience hurricane seasonality of a different scale. Region 1 experiences hurricanes from June through October with a median date of 30 August. Region 3 is affected by storms from July through November and has a median date of 4 September, and the northern most region, region 4, experiences storms during the shortest amount of time than any other region, July through September with a median date of 11 September. Florida, therefore, is unique in its susceptibility to hurricanes because it experiences a much longer season than other regions, and it experiences more storms later in the year than any other region as its median landfall date is later than anywhere else.

It is interesting also to consider which tropical storm of the season is most likely to strike Florida. Figure 3 shows the distribution of storm numbers associated with Florida hurricanes. Storm number refers to the sequence of tropical storms and hurricanes within a season, with the first named tropical cyclone being storm one. The plot shows that historically the most likely hurricane to affect Florida is the 5th tropical cyclone of the season followed, in likelihood, by the 2nd tropical cyclone. Florida has seen every sequence number through 15. The highest sequence number (22) was Hurricane Wilma in 2005. There were a record 27 tropical storms and hurricanes during this remarkable season.

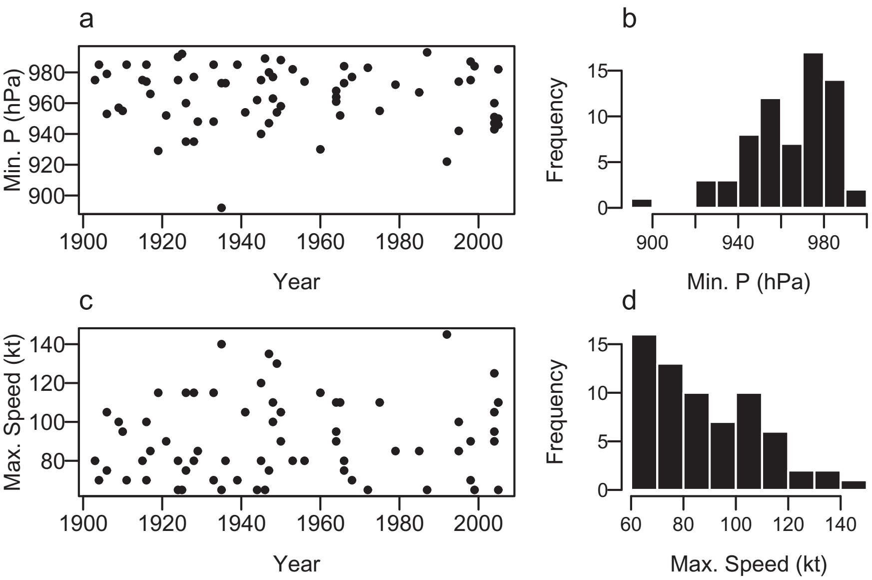

Figure 4. Florida's hurricane intensity at time of landfall (1900–2007). (a) Time series of minimum central pressure (hPa) and (b) distribution of minimum central pressure. (c) Time series of maximum wind speed (kt) and (d) distribution of maximum wind speed.

The average intensity (as measured by the minimum central pressure) of Florida hurricanes at the time of first landfall is 966 hPa (millibars), and 90 kts as measured by the maximum wind speed. The average intensity of Florida hurricanes at second landfall is 981 hPa (75 kt). All five of the second landfalls (for storms striking Florida more than once) occurred over the northwestern part of the state. These five events have a mean central pressure at first landfall of 970 hPa showing that, for these five storms, the average difference between first and second landfall is +11 hPa. This increase in air pressure from first to second landfall indicates a decrease in intensity for these storms. The lowest pressure of any Florida hurricane is 892 hPa, which occurred with the Labor Day hurricane of 1935 that demolished the middle Florida Keys.

Figure 4 shows the time series and histogram of minimum central pressures and wind speeds at landfall. If the hurricane made more than one landfall (or Keys crossing), the highest intensity (lowest pressure and highest wind speeds) is used. There appears to be no obvious long-term trend in these variables for this sample of Florida hurricanes. The distributions are skewed (negatively for pressure and positively for wind speed) as expected from a set of data representing a threshold process (only cyclones at hurricane intensity are considered).

Locations of hurricane landfalls are shown in Figure 5. The points delineate where the eye crossed the shore (or crossed the Keys). Symbols signify intensity as determined by the maximum wind speeds and grouped by the Saffir/Simpson cate-

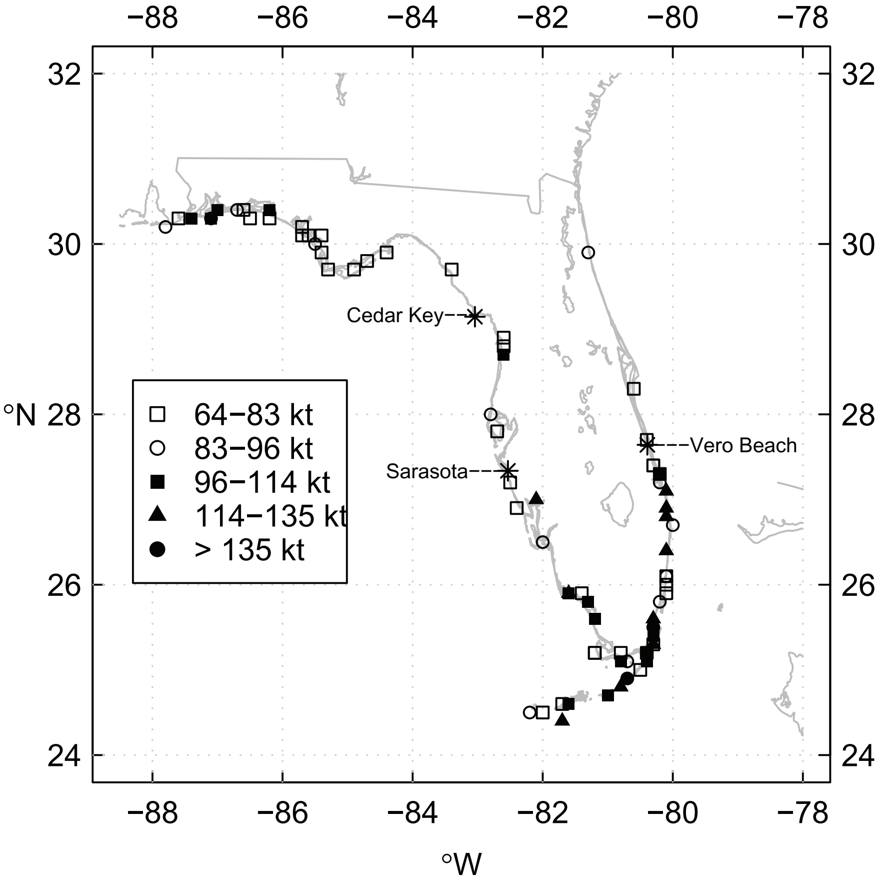

Figure 5. Florida hurricane landfalls 1900–2007. The locations indicate the landfall (or Key crossing) locations, including second landfalls. The symbols denote hurricane intensity as measured by the maximum wind speed and categorized by the Saffir-Simpson hurricane damage potential scale. A notable lack of hurricane strikes have occurred along the peninsula north of Cedar Key. All of the strongest hurricanes (Category 4 & 5) have occurred south of a line from Sarasota to Vero Beach.

gories. Landfalls are more common over the southern half of the peninsula including the Keys and along the panhandle. There is a notable lack of hurricane strikes along the northeast coast and around the western peninsula north of Cedar Key. All of the strongest hurricanes (categories 4 and 5, having wind speeds of 114 kt or greater) have occurred south of a line from Sarasota to Vero Beach.

The size of hurricanes directly affecting Florida varies from storm to storm. Figure 6 shows the time series and distribution of the radius of maximum wind (RMW) at landfall as an indication of hurricane size. Five of the 67 Florida hurricanes do not

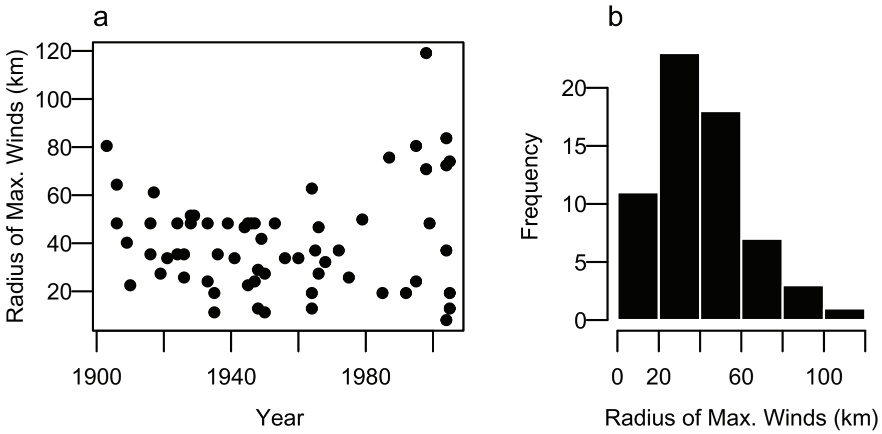

Figure 6. Florida's hurricane size at time of landfall (1900–2007). (a) Time series of radius of maximum wind (km) and (b) distribution of the radius.

have a value for RMW. The variation in size is quite large but there appears to be a modest trend toward larger hurricanes. The average size is 41 km (radius) with a variance of 434 km^2. The distribution is positively skewed with most hurricanes having an RMW between 20 and 60 km, and only a few greater than 80 km. Historically, the smallest storm was Hurricane Charley (2004) at 8 km and the largest was Hurricane Earl (1998) at 119 km.

DAMAGE STATISTICS

The data on damage losses from hurricanes are taken from Pielke et al. (2008). The values represent the total estimated economic damage amounts normalized to 2005 dollars. The values are based on total damage estimates as opposed to insured loss figures. Economic damage is the direct loss associated with a hurricane's impact. It does not include losses due to business interruption or other macroeconomic effects including increases in demand for construction materials and other household items. Total damage costs are twice the estimated insured damage costs. Details and caveats of the normalization procedure are provided in Pielke et al. (2008). The complete set of data used in this study is provided as an Appendix. It should be noted that prior to 1940, 32 storms made landfall somewhere on the United States' coastline with no reported damages, where only 8 such storms have occurred since 1940 (Pielke et al. 2008). Some damage likely occurred during all early 20th century storms but the lack of data probably results in an undercount of the overall economic loss from the storms affecting the United States prior to 1940, and, if at least one hurricane strikes Florida every two years, there is an undercount of overall damage in Florida prior to 1940 as well.

There are two sets of damage estimates based on slightly different normalization procedures provided in Pielke et al. (2008). The two approaches are the methodology used by Pielke and Landsea (1998), which adjusts for inflation, wealth, and population updated to 2005, and the methodology used by Collins and Lowe (2001), which adjusts for inflation, wealth, and housing units updated to 2005 (Pielke et al. 2008). Pielke et al. (2008) have taken the methodologies given by Pielke and Landsea (1998) and Collins and Lowe (2001) and have slightly adjusted their methodologies to be appropriate for 2005 dollars. Here we focus on the data set from the Collins and Lowe methodology, but note that both data sets are quite similar. In both cases, researchers have estimated total dollar value of damage that historic storms *would have caused* had they occurred in 2005—given all the growth and development that has taken place since these historical storms occurred. The Collins and Lowe methodology produces a temporally consistent estimate of economic damage from past tropical cyclones affecting the U.S. Gulf and Atlantic coasts. Results presented in this study are not sensitive to the choice of data set. The Collins and Lowe methodology is used for this study, as opposed to that of Pielke and Landsea, because the housing unit variable included in Collins and Lowe is more relevant when dealing with economic loss than population statistics. The Collins and Lowe (2001) values, adjusted to 2005 dollars in Pielke et al. (2008), are presented in our Appendix under the Damage column.

Table 1 lists the top ten all-time hurricane loss events in Florida since 1900. The damage amount (loss) is in billions of U.S. dollars. Fourteen of the 67 Florida hurricanes do not have an estimated loss value for unknown reasons. Topping the list is the Great Miami Hurricane of 1926 with an estimated total damage to Florida of $129 billion. Again, this dollar figure represents an estimate of the total damage if the same cyclone were to have hit in 2005. Hurricane Andrew, which hit southeast Florida in 1992, comes in second with a damage tag of $52.3 billion if it would have hit in 2005. Note that 3 of the top ten costliest Florida hurricanes occurred in 2004 and 2005.

Table 1. Top ten loss events from Florida hurricanes (1900–2007). Damage amount is in billions of U.S. dollars, normalized to the dollar value of 2005. Loss values come from the adjustments made to Collins/Lowe (2001) presented in Pielke et al. (2008).

Rank	Storm	Year	Region	Loss ($bn)
1	Great Miami	1926	SE	129.0
2	Andrew	1992	SE	52.3
3	Storm # 11	1944	SW	35.6
4	Lake Okeechobee	1928	SE	31.8
5	Donna	1960	SW	28.9
6	Wilma	2005	SW	20.6
7	Charlie	2004	SW	16.3
8	Ivan	2004	NW	15.5
9	Storm # 2	1949	SE	13.5
10	Storm # 4	1947	SE	11.6

The total normalized losses for the 53 Florida hurricanes (for which contemporary damage estimates are available) would be $459 billion if these storms occurred in 2005. Eighty percent of this total is from the top 11 (21 percent) storm event losses. The median loss amount is $2.21 billion, but the 95th percentile value is $33.3 billion. Figure 7 shows the time series and histogram of hurricane damage losses in the state of Florida since 1900. The distribution is highly skewed with many relatively small losses and few very large losses. The Great Miami Hurricane of 1926 is clearly the worst loss event (normalized) in Florida since 1900. There are two years with total losses of less

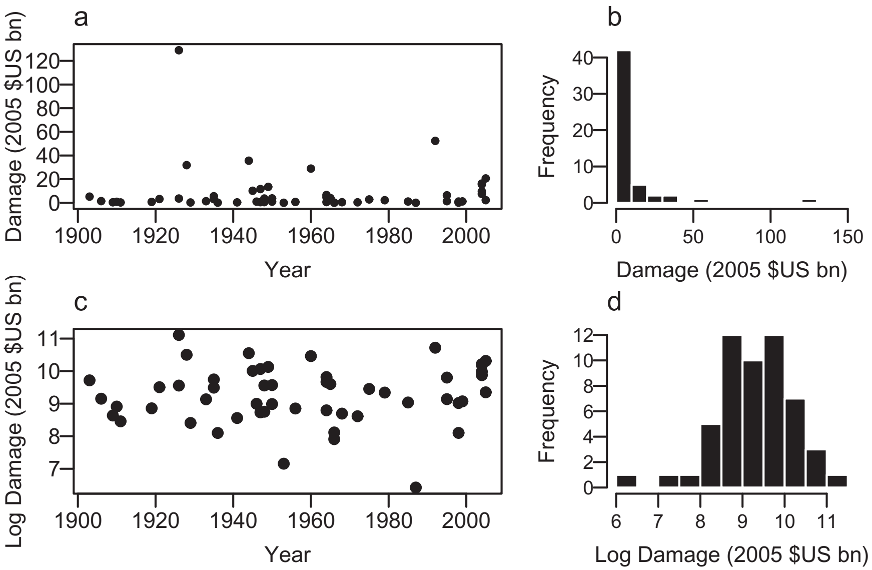

Figure 7. Florida's hurricane damage losses (1900–2007). (a) Time series and (b) distribution of losses by event and (c) time series and (d) distribution of the logarithm (base 10) of losses. Some years are without loss events.

than $15 million. The *Insurance Service Office* (ISO), a private corporation that provides information about risk assessment, defines a catastrophe as an event that causes more than $25 million in insured ($50 million total) losses and causes a major disruption (Insurance Information Institute 2008). Of the Florida hurricanes that have available economic loss values, 96 percent of the events were above this $50 million threshold. There are only two storms of the 53 in this sample that do not have losses exceeding this amount, and they are Florence (1953) and Floyd (1987).

A good way to examine skewed distributions is to use logarithms. Figure 7c shows the time series and histogram after taking the logarithm (base 10) of each annual loss amount. In this figure, a value of nine indicates a billion dollar loss, a value of 10 indicates a $10 billion loss, and a value of 11 indicates a $100 billion loss. Consistent with the modest increase in size for hurricanes affecting Florida seen in the previous section, there appears to be a slightly increasing trend in the upper and lower quartile amounts of normalized damage since 1900, although these slightly increasing trends are not statistically significant.

To estimate the annual probability of yearly losses exceeding specified amounts the normalized data are fit to a model. The model consists of the generalized Pareto distribution (GPD) to describe the behavior of extreme losses and the Poisson distribution to specify the rate of loss years above a given threshold level (Jagger and Elsner 2006). Here the threshold value is set at $250 million as a compromise be-

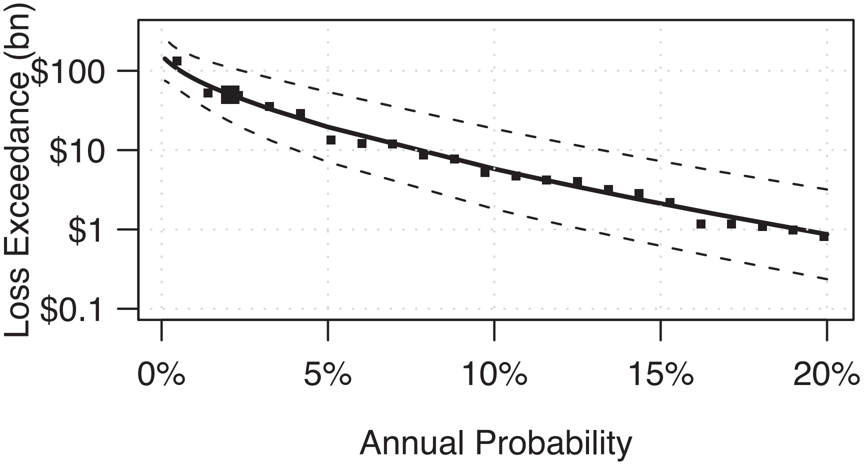

Figure 8. A model for Florida's hurricane damage losses. The solid curve is based on using a generalized Pareto distribution for describing the magnitude of yearly total loss amount and a Poisson distribution for the number of years exceeding a threshold loss amount of $250K. The dashed lines are the upper and lower 95 percent confidence limits on the loss model. The small boxes are empirical estimates of the loss amount and the large box corresponds to a total loss of $25 bn. The empirical estimates are based on $1\text{-}e^{[-\alpha*(\mathrm{rank}-0.5)/M]}$*, where* α *is the number of years with losses* (M) *divided by the total number of years (N), and* rank *is the order of losses, with a rank of 1 being the greatest loss.*

tween being low enough to retain enough years to estimate the parameters of the GPD, but high enough so that the yearly loss amount (exceedance) follows a GPD (Jagger and Elsner 2006). The model specifies exceedance loss levels as a function of annual probabilities.

Figure 8 shows the model as a curve on a semi-log plot; the higher the annual loss, the lower the probability of occurrence. The model indicates a 5 percent chance of losses exceeding about $19.6 billion on an annual basis and a 10 percent chance of losses exceeding $5.8 billion. Finally, Florida can expect a storm to produce at least $1 billion in damage once every five years (a probability of 20 percent in any given year). According to the model, a loss of at least $25 billion occurs with an annual probability of about 2.1 percent, which is a percentage point below the state's estimate of 3.1 percent mentioned in the Introduction. Although this difference is not statistically significant it shows that the state of Florida estimates their catastrophic losses ($25 billion +) to occur a bit more often than this model suggests.

TRENDS AND ASSOCIATIONS

As seen in the previous section, there appears to be increasing trends in the size and intensity of Florida hurricanes and in normalized damage costs. To examine these observations in more detail, trends are computed and examined using ordinary least squares regression and quantile regression (Elsner et al. 2008). Ordinary regression is a

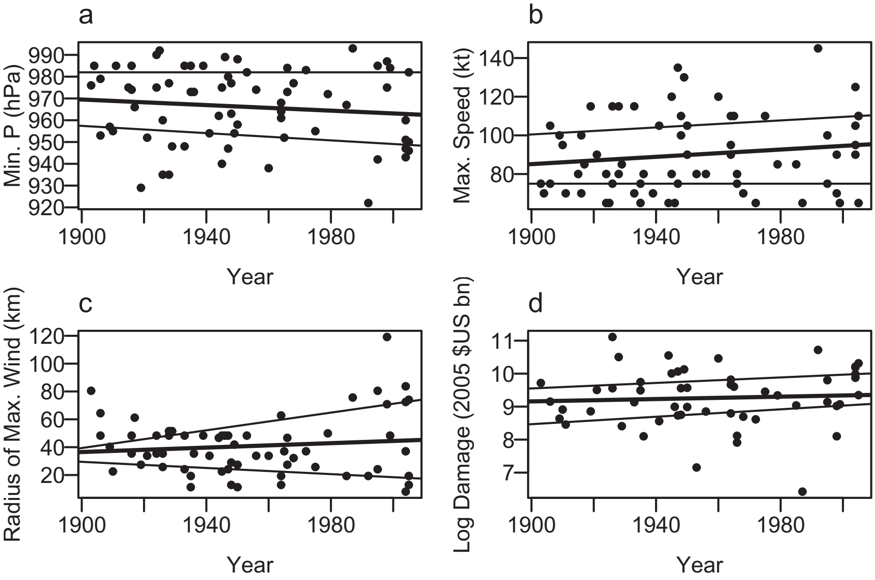

Figure 9. Florida's hurricane trends (1900–2007). (a) minimum central pressure, (b) maximum wind speed, (c) radius of maximum wind, and (d) logarithm of damage costs (losses). The thick line is the trend in mean value. The upper, thin line is the trend in the upper quartile values for wind speed, RMW, and damage cost and the lower quartile for central pressure. The lower, thin line is the trend in lower quartile values for wind speed, RMW, and damage cost, and the upper quartile for central pressure. The trend values and standard errors are given in Table 2.

model for the conditional mean, where the mean is conditional on the value of the explanatory variable. Quantile regression extends ordinary least-squares regression to quantiles of the response variable. Quantiles are points taken at regular intervals from the cumulative distribution function of a random variable. The quantiles mark a set of ordered data into equal-sized data subsets. Thus, quantile regression is a model for the conditional quantiles. For trend analysis the explanatory variable is year. Relationships between hurricane characteristics and losses are also examined.

Figure 9 shows the median and upper and lower quartile trends in hurricane intensity and size at landfall, and the corresponding damage costs. Downward trends are found in the mean and lower quartile of minimum central pressures, and upward trends are found in the mean and upper quartile of maximum wind speeds, both showing an increase in the strongest storms over time. An upward trend is found in the upper quartile of the size of Florida hurricanes. This indicates that on average and for the strongest cyclones, Florida hurricanes are getting more powerful over time. Trend values along with their associated standard errors are given in Table 2. The relatively large standard errors on the trends indicate the increases in trend values shown in Table 2 are not statistically significant against the null hy-

Table 2. Trend statistics and standard error (1900–2007). The lower quartile of the pressure trend corresponds to the upper quartile of damage cost trend.

Minimum Central Pressure (hPa/yr)		
	Trend	S.E.
upper quartile	0.000	0.0367
mean	−0.064	0.0687
lower quartile	−0.083	0.0918
Maximum Wind Speed (hPa/yr)		
	Trend	S.E.
upper quartile	+0.091	0.1403
mean	+0.094	0.0787
lower quartile	0.000	0.1225
Radius to Maximum Wind (km/yr)		
	Trend	S.E.
upper quartile	+0.318	0.1038
mean	+0.093	0.0865
lower quartile	−0.204	0.0614
Log Damage Costs (/yr)		
	Trend	S.E.
upper quartile	+0.0042	0.00398
mean	+0.0018	0.00408
lower quartile	+0.0056	0.00356

pothesis of no trend. However, the upward trends in the 25th and 75th percentiles of damage costs might be associated with the upward trends in the power characteristics of hurricanes as seen in the previous section.

Figure 10 shows a scatter plot matrix along with regression lines of damage costs as a function of hurricane characteristics. It is clear that there is a statistically significant relationship between the intensity of the hurricane at landfall and the amount of damage. This strong relationship is seen using either minimum central pressure or maximum wind speed as the indicator of hurricane intensity. However, the relationship between damage amount and hurricane size is much less clear. In fact, the weak negative relationship is counterintuitive as the larger hurricanes are associated with somewhat less damage. This somewhat puzzling observation can be explained by the fact that hurricane intensity is inversely related to hurricane size for this set of hurricanes. Thus the larger hurricanes tend to be weaker and thus cause less damage.

It has been suggested that estimations of potential losses from hurricanes combine intensity and size characteristics (Kantha 2006). The Carvill Hurricane Index (CHI), discussed in Kantha (2006), determines a numerical measure of the potential for damage from a particular hurricane event. On the Chicago Mercantile Exchange, the CHI is used as the basis for trading hurricane futures and for trading options about how best to mitigate the storms, and captures this idea using the following equation:

$$CHI = (v/v_o)^3 + 1.5\,(r/r_o)\,(v/v_o)^2 \quad (1)$$

where v is the maximum wind speed (kt), v_o is the threshold hurricane-wind speed (64 kt), r is the radius of threshold hurricane-wind speed or greater (km), and r_o is the threshold radius (97 km). To obtain r, a form of the Rankine vortex equation is used to obtain the radial decay of the winds from their maximum value (Holland 1980). The equation is given by:

$$r = r_{max}\,(v/v_o)^{1.5} \qquad (2)$$

The CHI is computed from the set of Florida landfalling characteristics. As expected, the relationship between damage

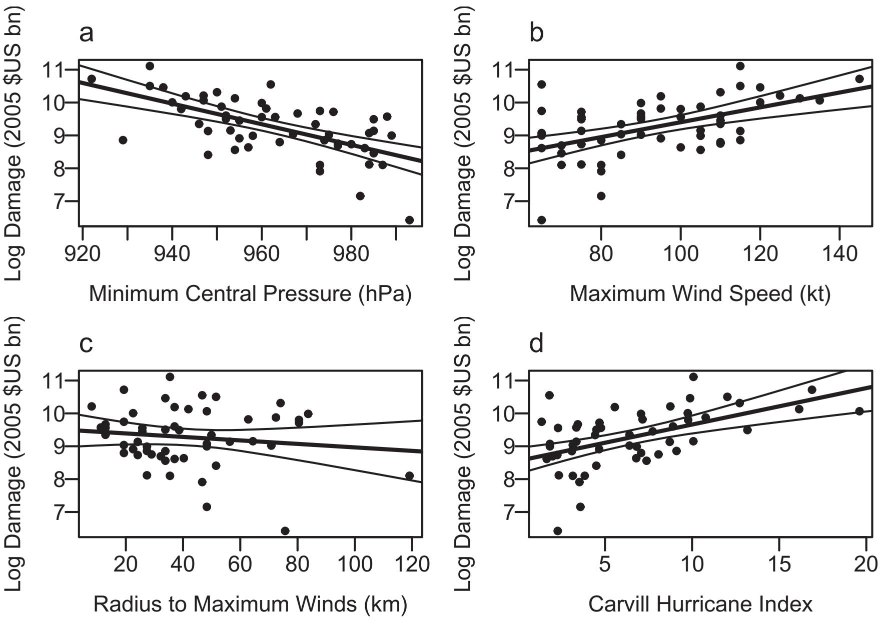

Figure 10. Scatterplot matrix of damage costs and hurricane characteristics. Logarithm of damage cost as a function of (a) minimum central pressure, (b) maximum wind speed, (c) radius to maximum wind, and (d) Carvill Hurricane Index. The thick line is the trend in mean value, the thin lines are the 95 percent confidence limits on the trend.

losses and the CHI is positive and significant. However the relationship does not appear to be stronger than either of the intensity estimates alone. The strong link between hurricane intensity and damage cost coupled with the rather weak link with hurricane size indicates that the Saffir-Simpson hurricane scale, which is based solely on wind speed, is, in large measure, an adequate measure of potential damage amount, at least in Florida. Yet based on the somewhat better correlation of losses with minimum central pressure (see Table 3), we argue that central pressure be used as a single variable for potential loss estimation.

For instance, regressing the logarithm (base 10) of losses onto the minimum central pressure, an equation representing a loss index for Florida, called the Florida hurricane loss index (FHLI), is defined by the following equation:

$$FHLI = 10^{40.912-0.0329pmin} \qquad (3)$$

where p_{min} is the minimum central pressure in units of hPa forecast at landfall. Values of FHLI are damage estimates expressed in dollar amounts. For multiple landfalls the lowest minimum pressure is used. This model (which is not applicable for hurricanes that hit only the Florida Keys) explains only 40 percent of the variability in the logarithm of Florida loss amounts but compares favorably with the CHI, which explains less than 28 percent of the losses. Table 4 shows resulting ex-

Table 3. Correlation of hurricane characteristics at landfall with damage costs (losses) based on 53 Florida hurricanes. Correlation coefficient r *and the associated 95 percent confidence interval on that correlation under the null hypothesis of zero correlation.*

	r	95% Confidence Interval
P min	−0.59	(−0.74, −0.38)
W max	+0.52	(+0.29, +0.70)
RMW	−0.13	(−0.39, +0.14)
CHI	+0.53	(+0.30, +0.70)

pected economic loss from the FHLI based on the pressure categorization associated with the Saffir-Simpson Scale (Kantha 2006). The expected losses do not reflect future changes in wealth and inflation, nor the expected increases in coastal development. It is important to note that these loss index values will be highly dependent upon where the storm makes landfall and the amount of development and population in the affected area.

Of course, the actual amount of damage a hurricane inflicts will also depend to some extent on its forward speed and the rate at which the wind subsides over land. Neither of these characteristics are considered here, but have been analyzed elsewhere. Huang et al. (2001) considers economic loss as a function of the wind decay rate, and Watson and Johnson (2004) look at forward speed as one of the parameters of their hurricane loss estimation models. These characteristics could be included in this model in a future study to try and increase its ability to explain the variability in the logarithm of Florida loss amounts.

SUMMARY

More hurricanes strike Florida than anywhere else in the United States. Records of Florida hurricanes have recently been updated and are reliable back to 1900. This study examines various statistics of hurricanes affecting the state over the period 1900–2007 and their associated damage costs.

It is shown that the annual count of Florida hurricanes is consistent with a random Poisson process with a mean of 0.62 hurricanes per year that translates to an annual probability of 46 percent for at least one hurricane. Florida differs from other regions of the United States in terms of hurricane seasonality because it is affected by storms throughout the entire Atlantic hurricane season, and it experiences storms later into the year than any other area of the United States' coastline.

Although the variability in the amount of damage is quite large from one hurricane to the next, normalized losses are increasing over time, which is consistent with the slight increases in hurricane intensity and hurricane size. The model provided shows that on an annual basis, we can expect a 10 percent chance of losses exceeding $5.8 billion and a 5 percent chance of losses exceeding $19.6 billion. In addition, each year Florida has a 20 percent chance of experiencing at least $1 billion in hurricane related losses; in other words, the State can plan on at least $1 billion in losses once every five years.

Of the hurricane landfall characteristics examined here, the best predictor of potential losses is minimum central pressure. Hurricane size by itself or in combination with hurricane intensity does not

Table 4. Expected loss computed using the Florida Hurricane Loss Index based on categorical pressure values presented by Kantha (2006). Approximate exponent values are x *where* FLHI = 10^x. *Expected loss is given in US dollars, normalized to 2005 dollar amounts. These approximate losses do not reflect future changes in wealth, inflation, and property, and are highly reliant on where the storm actually makes landfall in terms of development and population.*

Category	Pmin Values	Approximate Exponent Values (x)	Approximate Expected Loss (Normalized 2005 $US)
1	989–980	8.40–8.69	$250 million–$499 million
2	979–965	8.70–9.17	$500 million–$1.49 billion
3	964–945	9.18–9.90	$1.50 billion–$7.99 billion
4	944–920	9.91–10.69	$8.00 billion–$49.99 billion
5	<920	≥10.70	≥$50.00 billion

improve on the simpler relationship. An estimate of potential losses from hurricanes can be obtained by a formula involving only an estimate of the minimum pressure at landfall. Expected economic damage costs are computed using the FHLI and categorized to provide a scale similar to the Saffir-Simpson for economic loss based on minimum central pressure.

In one sense Florida has been rather fortunate. Although the 2004 and 2005 seasons featured 7 Florida hurricanes, there are more years during the second half of the record without a Florida hurricane. Moreover, despite some large losses since 1950, Florida has not seen a repeat, in terms of losses, of the Great Miami Hurricane (of 1926).

Florida, along with other coastal states, is in a race to retrofit and harden its infrastructure before another major storm occurs. Over the past 20 years alone, Hurricane Andrew (1992) almost made a direct hit on downtown Miami, Hurricane Floyd (1987) made a last minute turn away from the state, and Hurricane Charley (2004) veered east and away from the Tampa Bay area just hours before landfall. Had any of these storms made direct strikes on urban areas, they could have caused losses larger than anything Florida has experienced to date.

Recently, researchers have made improvements in understanding and predicting hurricane intensity (Jones et. al 2006, Davis et. al 2008), hurricane tracks (Barret et al. 2006), and seasonal hurricane activity (Elsner and Jagger 2006). In combination with this paper, better understanding of hurricane activity and resulting damage can better prepare coastal communities with what to expect with each approaching season, allowing for informed decisions by their citizens, policy makers and insurance agencies about the future of Florida's hurricane seasons and the proper way to mitigate.

APPENDIX

Year	Region	Seq	Name	Mo	Da	Lat	Lon	Wmax	Pmin	RMW	Time	SNBR	Damage	Code
1903	FLSE	3	Storm3	9	11	26.1	80.1	75	976	80	2300	397	5.2 billion	1
1903	FLNW	3	Storm3	9	13	30.1	85.6	80	975	NA	2100	397	NA	2
1904	FLSE	3	Storm3	10	17	25.3	80.3	70	985	NA	700	407	NA	1
1906	FLSW	2	Storm2	6	17	25.2	80.8	75	979	48	700	416	NA	1
1906	FLNW	6	Storm6	9	27	30.4	88.7	95	958	80	1200	420	NA	0
1906	FLSW	8	Storm8	10	18	25.1	80.8	105	953	64	1100	422	142 million	1
1909	FLSW	10	Storm10	10	11	24.7	81	100	957	40	1800	450	433 million	1
1910	FLSW	5	Storm5	10	18	26.5	82	95	955	23	600	456	814 million	1
1911	FLNW	2	Storm2	8	11	30.3	87.6	70	985	NA	2200	458	286 million	1
1912	FLNW	4	Storm4	9	14	30.4	88.4	65	990	48	800	466	NA	0
1915	FLNW	4	Storm4	9	4	30.1	85.4	80	975	NA	1000	480	NA	1
1916	FLNW	13	Storm13	10	18	30.3	87.4	100	974	35	1400	494	NA	1
1916	FLSW	14	Storm14	11	15	24.5	82	70	985	48	1800	495	NA	1
1917	FLNW	3	Storm3	9	29	30.4	86.7	85	966	61	300	498	NA	1
1919	FLSW	2	Storm2	9	10	24.4	81.7	115	929	27	400	505	720 million	1
1921	FLSW	6	TampaBay	10	25	28	82.8	90	952	34	1900	516	3.2 billion	1
1924	FLNW	4	Storm4	9	15	30.2	85.7	65	990	48	1500	531	NA	1
1924	FLSW	7	Storm7	10	21	25.9	81.4	80	975	35	300	534	NA	1
1925	FLSW	2	Storm2	12	1	27.2	82.5	65	992	NA	430	537	NA	1
1926	FLNE	1	Storm1	7	28	28.3	80.6	75	960	26	600	538	3.6 billion	1
1926	FLSE	6	GrtMiami	9	18	25.6	80.3	115	935	35	1200	543	129 billion	1
1928	FLSE	1	Storm1	8	8	27.4	80.3	80	977	48	600	556	NA	1
1928	FLSE	4	Lake	9	17	27.1	80.1	115	935	51	600	559	31.8 billion	1
1929	FLSE	2	Storm2	9	28	25.1	80.7	85	948	51	1800	563	256 million	1
1929	FLNW	2	Storm2	9	30	29.7	85.3	65	988	NA	1700	563	NA	2

1933	FLSE	5	Storm5	7	30	27.4	80.3	70	985	48	2000	591	NA	1
1933	FLSE	12	Storm12	9	4	26.9	80.1	115	948	24	400	598	1.4 billion	1
1935	FLSW	2	LaborDay	9	3	24.9	80.7	140	892	11	130	620	NA	3
1935	FLNW	2	LaborDay	9	4	29.7	83.4	75	985	39	1900	620	3.1 billion	1
1935	FLSE	6	Storm6	11	4	25.9	80.1	65	973	19	1500	624	5.6 billion	1
1936	FLNW	5	Storm5	7	31	30.4	86.6	80	973	35	1500	629	126 million	1
1939	FLSE	2	Storm2	8	11	27.3	80.2	70	985	48	1900	659	NA	1
1939	FLNW	2	Storm2	8	13	29.7	84.9	70	985	NA	0	659	NA	2
1941	FLSE	5	Storm5	10	6	25.4	80.3	105	954	34	1030	675	362 million	1
1941	FLNW	5	Storm5	10	7	29.8	84.7	75	981	34	900	675	NA	2
1944	FLSW	11	Storm11	10	19	26.9	82.4	65	962	47	630	707	35.6 billion	1
1945	FLNW	1	Storm1	6	24	28.9	82.6	80	975	48	1100	708	NA	1
1945	FLSE	9	Storm9	9	15	25.3	80.3	120	940	23	2200	716	10.1 billion	1
1946	FLSW	5	Storm5	10	8	27.8	82.7	65	989	48	300	723	991 million	1
1947	FLSE	4	Storm4	9	17	26.4	80.1	135	947	48	1500	728	11.6 billion	1
1947	FLSW	8	Storm8	10	12	25.2	81.2	75	980	24	200	732	540 million	1
1948	FLSW	7	Storm7	9	21	24.6	81.6	105	NA	NA	1400	740	NA	3
1948	FLSW	7	Storm7	9	22	25.6	81.2	100	963	13	0	740	3.6 billion	1
1948	FLSW	8	Storm8	10	5	24.7	81	110	NA	24	2000	741	NA	3
1948	FLSE	8	Storm8	10	5	25.2	80.4	110	977	29	2200	741	565 million	1
1949	FLSE	2	Storm2	8	27	26.8	80.1	130	954	42	0	744	13.5 billion	1
1950	FLNW	5	Easy	9	5	28.7	82.6	105	958	27	1200	760	973 million	1
1950	FLSE	11	King	10	18	25.8	80.2	90	988	11	600	766	3.7 billion	1
1953	FLNW	8	Florence	9	26	30.3	86.2	80	982	48	1700	793	14.3 million	1
1956	FLNW	7	Flossy	9	24	30.3	86.5	80	974	34	2300	829	711 million	1
1960	FLSW	5	Donna	9	10	24.8	80.8	115	930	34	700	864	NA	3

APPENDIX (continued)

Year	Region	Seq	Name	Mo	Da	Lat	Lon	Wmax	Pmin	RMW	Time	SNBR	Damage	Code
1960	FLSW	5	Donna	9	10	25.9	81.6	120	938	34	1600	864	28.9 billion	1
1964	FLSE	5	Cleo	8	27	26.1	80.1	90	968	13	1000	896	4.7 billion	1
1964	FLNE	6	Dora	9	10	29.9	81.3	95	961	63	500	897	6.6 billion	1
1964	FLSW	11	Isbell	10	14	25.8	81.3	110	964	19	2100	902	624 million	1
1965	FLSE	3	Betsy	9	8	25.1	80.4	110	952	37	1100	906	4.0 billion	1
1966	FLNW	1	Alma	6	9	29.9	84.4	80	973	47	2000	910	81.3 million	1
1966	FLSW	9	Inez	10	4	25	80.5	75	984	27	1800	918	131 million	1
1968	FLNW	8	Gladys	10	19	28.8	82.6	70	977	32	500	936	495 million	1
1972	FLNW	2	Agnes	6	19	29.9	85.4	65	983	37	2100	979	411 million	1
1975	FLNW	5	Eloise	9	23	30.4	86.2	110	955	26	1230	1008	2.8 billion	1
1979	FLSE	4	David	9	3	26.7	80	85	972	50	1500	1044	2.2 billion	1
1985	FLNW	5	Elena	9	2	30.4	89.1	100	959	27	1300	1100	3.8 billion	0
1985	FLNW	11	Kate	11	21	30	85.5	85	967	19	2230	1106	1.1 billion	1
1987	FLSW	7	Floyd	10	12	25.2	80.4	65	993	76	2200	1119	2.6 million	1
1992	FLSE	2	Andrew	8	24	25.5	80.3	145	922	19	905	1166	52.3 billion	1
1995	FLNW	5	Erin	8	2	27.7	80.4	75	985	56	600	1191	1.4 billion	1
1995	FLNW	5	Erin	8	3	30.3	87.1	85	974	24	1500	1191	NA	2
1995	FLNW	15	Opal	10	4	30.3	87.1	100	942	80	2200	1201	6.3 billion	1
1998	FLNW	5	Earl	9	3	30.1	85.7	70	987	119	600	1231	126 million	1
1998	FLSW	7	Georges	9	25	24.5	82.2	90	975	17	1630	1233	1.1 billion	1
1999	FLSW	9	Irene	10	15	24.6	81.7	65	987	56	1300	1249	NA	3
1999	FLSW	9	Irene	10	15	25.2	81.2	65	984	48	1900	1249	1.2 billion	1
2004	FLSW	3	Charley	8	13	27	82.1	125	947	8	2100	1313	16.3 billion	1
2004	FLSE	6	Frances	9	5	27.2	80.2	90	960	84	600	1316	9.7 billion	1

2004	FLNW	9	Ivan	9	16	30.2	87.8	95	943	37	730	1319	15.5 billion	1
2004	FLSE	10	Jeanne	9	26	27.3	80.2	105	951	72	400	1320	7.5 billion	1
2005	FLNW	4	Dennis	7	10	30.4	87	110	946	13	1930	1329	2.2 billion	1
2005	FLSE	11	Katrina	8	25	26	80.1	65	982	19	2230	1336	NA	1
2005	FLSW	22	Wilma	10	24	25.9	81.6	110	950	74	1030	1347	20.6 billion	1

Notes
1906 Storm 2 P min taken from the hurricane earlier in the day
1906 Storm 8 P min taken from the hurricane earlier in the day
1911 Storm 2 Landfall point in Alabama
1916 Storm 4 P min and wind speed from hurricane 3 hours later
1926 Storm 6 Additional losses from FLSW & AL 1.08E+10
1941 Storm 5RMW taken from 2nd landfall
1948 Storm 7 P min taken from earlier along track
1960 Storm 5 RMW taken from island pass
1985 Storm 5 Losses from AL & MS are included
2004 Storm 6 RMW taken from when it was over the Bahamas
2004 Storm 9 Landfall point in Alabama

Damage = Collins/Lowe (2001) data adjusted to 2005 dollars presented in Pielke et al. (2008) rounded to 1 significant decimal point
SNBR= Storm sequence number as catalogued in HURDAT dataset
Code=
0: Not direct landfall, hurricane force winds may have been felt somewhere in the state
1: First direct landfall, Keys hit if this is the only direct hit in the state
2: Second direct landfall
3: Keys hit if the hurricane made landfall elsewhere in the state

Units
Wind speeds (kt); Pressure (hPa); RMW (statute miles)

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JILL MALMSTADT is a Master's student in the Department of Geography at the Florida State University, Tallahassee, FL 32306. Email: jmalmstadt@fsu.edu.

KELSEY SCHEITLIN is a Ph.D. student in the Department of Geography at the Florida State University. Email: kscheitlin@fsu.edu.

DR. JAMES ELSNER is a Professor in the Department of Geography at the Florida State University. Email: jelsner@fsu.edu. His research interests include hurricanes, climate, and spatial statistics.