A CLIMATOLOGY OF HURRICANE-TORNADOES ASSOCIATED WITH GULF COAST-LANDFALLING HURRICANES (1950-2005)

THESIS

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CHAPTER I

INTRODUCTION

1.1 Research Problem

Hurricanes are one of Earth's most destructive natural hazards. Upon landfall, hurricanes have the potential to cause catastrophic physical and financial damage to life and property. Specific hazards associated with landfalling hurricanes include wind, storm surge, inland flooding, and tornadoes. Increasing coastal populations and development continue to expose more people and development to hurricane hazards, thus increasing the probability of fatalities and damage associated with hazards within landfalling hurricane environments.

Tornadoes produced by landfalling hurricanes are a notable hazard. An early study by Novlan and Gray (1974) stated that tornadoes associated with landfalling hurricanes contribute up to 10 % of the overall fatalities and up to 0.5 % of the overall damage caused by the hurricanes that spawn them. Hurricane Allen's (1980) associated tornadoes produced over $70 million in damage (Gentry 1983). A more recent study indicated that fatalities associated with tornadoes produced by landfalling hurricanes have decreased to 4 % of total fatalities (Rappaport 2000). The decrease in fatalities can be partly attributed to advances in detection technology and warning systems, and more effective hurricane evacuations. Fatalities will, however, persist because many people on the outer fringes of forecasted landfall locations do not evacuate. The outer fringe region, approximately 200 to 400 km from hurricane center, is also the region of maximum tornado frequency (Spratt et al. 1997), thus creating an interface between tornadoes, life, and property.

Forecasting which hurricanes will produce tornadoes upon landfall is a difficult task. Some hurricanes do not produce any tornadoes while others produce many. Tornado detection within the hurricane environment is difficult. Traditional tornadic radar signatures such as bounded weak echo regions and hook echoes may be subtle or non-existent with tornadoes associated with hurricanes (Spratt et al. 1997). Further, power outage associated with landfalling hurricanes proves a problematic situation to the successful delivery of issued tornado warnings via television, radio, internet, or other personal electronic devices.

A better understanding of tornadoes produced by landfalling hurricanes is needed to mitigate associated fatalities and damages. Tornadoes associated with landfalling hurricanes have been the focus of diverse research. Research has examined individual events, however, these do not provide a comprehensive understanding of the phenomenon, but rather provide knowledge about a specific event. Individual events may be extreme and not reflect the normal (average) nature of the phenomenon. Research has explored methods of tornado detection within hurricane environments. These studies can benefit short-term and real-time forecasting; however, long-term forecasting is needed to increase awareness and adequately issue warnings of potential tornado activity. Other research has provided climatic descriptions of tornadoes associated with landfalling hurricanes. Understanding the climatological nature of tornadoes associated with landfalling hurricanes, including their averages, variation, frequencies, and probabilities can improve general knowledge of the phenomenon and enhance long-term forecasting ability. Various groups, such as weather forecasters, emergency managers, insurance companies, and the public, can benefit from such information. Therefore, this thesis will develop climatic descriptions of tornadoes associated with Gulf Coast-landfalling hurricanes.

Tornadoes associated with landfalling hurricanes will be referred to as "hurricane-tornadoes" for the remainder of this thesis. Tornadoes independent of hurricanes will be referred to as "tornadoes."

1.2 Purpose Statement

The purpose of this thesis is to develop a fifty-five year climatology of hurricane-tornadoes associated with Gulf Coast-landfalling hurricanes from 1950 to 2005. The specific climatic descriptions included in this thesis are: (1) hurricane-tornado characteristics; (2) temporal distributions of hurricane-tornado occurrence associated with Gulf Coast landfalling hurricanes; (3) spatial distributions of hurricane-tornadoes associated with Gulf Coast-landfalling hurricanes; and (4) the relationships between hurricane-tornadoes and their associated hurricanes.

1.3 Research Questions and Hypotheses

Several questions guided the formulation and organization of this thesis. These questions were derived while reviewing previous literature pertinent to the climatology of hurricane-tornadoes. The intent of these questions is to provide a better understanding of the probability of hurricane-tornado occurrence. That is, are hurricane-tornadoes becoming more frequent? When are hurricane-tornadoes most probable, both seasonally and diurnally? Where are hurricane-tornadoes most probable, both throughout the Gulf Coast region and with respect to their associated hurricane? Are there any geophysical hurricane characteristics that influence hurricane-tornado frequency and intensity?

To address these inquiries, several research questions and hypotheses were developed. These questions can help weather forecasters, emergency managers, insurance companies, and the public to be more aware of normal hurricane-tornado characteristics and the probability of occurrence. This thesis employs a combination of Geographic Information System (GIS) technologies, statistical techniques, and subjective reasoning to address the posed questions and hypotheses. Following is a list of research questions and their associated hypotheses, if applicable.

1. What are hurricane-tornado characteristics, including the magnitude of outbreaks, their intensity, and their path lengths and widths? Magnitude of outbreaks and path lengths and widths are analyzed with descriptive statistics and frequency and probability distributions. Hurricane-tornado intensity is analyzed with frequency and probability distributions and a chi-square test. Following are the research hypotheses for the chi-square test.

   H_O: Hurricane-tornadoes are uniformly distributed with respect to hurricane-tornado intensity, as measured by the Fujita Scale.

   H_A: Hurricane-tornadoes are not uniformly distributed with respect to hurricane-tornado intensity, as measured by the Fujita Scale.

2. What are the temporal distributions of hurricane-tornadoes associated with Gulf Coast-landfalling hurricanes, including inter-annual, intra-seasonal, and diurnal distributions? The inter-annual and diurnal distributions are analyzed

with frequency and probability distributions. The intra-seasonal distribution is analyzed with frequency and probability distributions and a chi-square test. Following are the research hypotheses for the chi-square test.

H_O: Hurricane-tornadoes are uniformly distributed throughout hurricane season.

H_A: Hurricane-tornadoes are not uniformly distributed throughout hurricane season.

3. What are the spatial distributions of hurricane-tornadoes associated with Gulf Coast-landfalling hurricanes, including the small scale distribution throughout the Gulf Coast region and their distribution within their respective hurricane? The spatial distribution of hurricane-tornadoes is analyzed with GIS and with frequency and probability distributions.
4. What is the distribution of hurricane-tornadoes with respect to hurricane intensity, as measured by the Saffir-Simpson Scale? The association between hurricane-tornado frequency and hurricane intensity is analyzed with frequency and probability distributions, a chi-square test, and a correlation test. Following are the research hypotheses for the chi-square test.

   H_O: Hurricane-tornadoes are uniformly distributed with respect to hurricane intensity, as measured by the Saffir Simpson Scale.

   H_A: Hurricane-tornadoes are not uniformly distributed with respect to hurricane intensity, as measured by the Saffir Simpson Scale.
5. Is hurricane-tornado intensity, as measured by the Fujita Scale, related to hurricane intensity, as measured by the Saffir Simpson Scale? The

association between hurricane-tornado intensity and hurricane intensity is analyzed with frequency and probability distributions, a chi-square test, and correlation test. Following are the research hypotheses for the chi-square test.

H_O: Hurricane intensity, as measured by the Saffir Simpson Scale, and hurricane-tornado intensity, as measured by the Fujita Scale, are independent with respect to hurricane-tornado frequency.

H_A: Hurricane intensity, as measured by the Saffir Simpson Scale, and hurricane-tornado intensity, as measured by the Fujita Scale, are related with respect to hurricane-tornado frequency.

6. What is the distribution of hurricane-tornadoes with respect to their associated hurricane's directional heading? The association between hurricane-tornado frequency and hurricane directional heading is analyzed with GIS and with frequency and probability distributions.

1.4 Overview of Thesis

This thesis is organized into six chapters. The current chapter, chapter I, is an introduction to the research problem, purpose, questions, and general methods used to address the questions. Chapter II provides necessary information needed to develop a climatology of hurricane-tornadoes. Chapter III provides data sources and collection techniques, and introduces the specific methods used to analyze the data. Chapter IV provides results of the methods. Chapter V provides interpretations and analyses of the results. Chapter VI provides concluding remarks.

CHAPTER II

LITERATURE REVIEW

2.1 Introduction

Within this chapter pertinent literature is reviewed to gain a comprehensive understanding of current hurricane-tornado knowledge. It is imperative to first discuss the two individual climatological elements: hurricanes and tornadoes. Sections 2.2 and 2.3 provide the definitions of hurricanes and tornadoes, respectively, and will briefly discuss their climatology and intensity scales. Section 2.4 briefly discusses the dynamics involved in hurricane-tornado formation. Section 2.5 will be an analysis of previous hurricane-tornado research, with an emphasis on climatological studies. Section 2.6 defines the Gulf Coast region and briefly discusses its vulnerability to hurricane hazards. Section 2.7 discusses common methodologies found within hurricane-tornado climatology research. Section 2.8 provides a summary of significant hurricane-tornado research results and discusses the contribution of this thesis.

2.2 Hurricanes

The term "hurricane" is a regional name assigned to tropical cyclones. Tropical cyclones are warm-core, non-frontal, synoptic-scale cyclones that originate over tropical or subtropical waters. They have organized deep convection and a closed surface wind circulation about a well defined center (NOAA 2005a). Tropical cyclones are termed hurricanes when they are located over the Atlantic and Northeast Pacific Oceans, Caribbean Sea, and Gulf of Mexico. When located over the Northwest Pacific Ocean tropical cyclones are termed typhoons and as cyclones over the Indian Ocean.

The Atlantic hurricane season spans from 1 June to 30 November. Hurricanes can develop at any time within hurricane season; however, hurricane activity peaks from mid-August to late October. The East and Gulf Coasts of the United States experience an average of 1.7 landfalling, or near-landfalling hurricanes per season (Neumann et al. 1999). Landfall occurs when all or part of the hurricane eye wall crosses the coastline (Elsner and Kara 1999). Hurricanes begin to impact coastlines before actual landfall, as the radial distance between the eye wall and outer rainbands can be hundreds of kilometers. Upon landfall, hurricanes begin to lose intensity as the barometric pressure rises and rotational wind speed decreases due to mechanical friction with land. Hurricane intensity can, however, persist for 24 hours or longer post-landfall. Notable hazards associated with landfalling hurricanes include storm surge, torrential rains, coastal and inland flooding, dangerous winds, and tornadoes.

Saffir Simpson Scale

Hurricane intensity is measured using the Saffir-Simpson Hurricane Scale (S.S. Scale) (Table 2.1). Wind speed is the primary parameter used by the S.S. Scale in determining hurricane intensity. One minute sustained wind speed and hurricane intensity are directly related. The S.S. Scale ranks hurricanes on a five category scale, with one being minimum intensity and five being maximum intensity. For the purposes of this thesis, category 3, category 4, and category 5 hurricanes are considered intense.

TABLE 2.1. Saffir-Simpson Hurricane Intensity Scale (NOAA 2008a).

Category	Central Pressure (mb)	Wind Speed (mph)	Typical Damage
1	≥ 980	74 – 95	No real structural damage. Damage primarily to unanchored mobile homes, shrubbery, and trees. Some damage to poorly constructed signs. Some coastal road flooding and minor pier damage.
2	965 – 979	96 – 110	Some roof, door, and window damage to buildings. Damage to shrubs and trees with some trees blown down. Considerable damage to mobile homes, poorly constructed signs, and piers. Coastal and low-lying escape routes flood two to four hours before arrival of the hurricane center. Small craft in unprotected anchorages break moorings.
3	945 – 964	111 – 130	Some structural damage to small residences and utility buildings. Large trees blown down. Mobile homes and poorly constructed signs are destroyed. Low-lying escape routes are cut by rising water three to five hours before arrival of the hurricane center. Flooding near the coast destroys smaller structures with larger structures damaged by battering by floating debris. Terrain continuously lower than 5 ft (1.5 m) above mean sea level may be flooded inland 8 mi (13 km) or more. Evacuation of low-lying residences within several blocks of the shoreline required.
4	920 – 944	131 – 155	Complete roof structure failure on small residences. Shrubs, trees, and all signs are blown down. Complete destruction of mobile homes. Extensive damage to doors and windows. Low-lying escape routes may be cut by rising water three to five hours before arrival of the hurricane center. Major damage to lower floors of structures near the shore. Terrain lower than 10 ft (3 m) above sea level may be flooded requiring massive evacuation of residential areas as far inland as 6 mi (10 km).
5	< 920	> 155	Roof failure on many residences and industrial buildings. Some complete building failures with small utility buildings blown over or away. All shrubs, trees, and signs down. Complete destruction of mobile homes. Severe window and door damage. Low-lying escape routes cut by rising water three to five hours before arrival of the hurricane center. Major damage to lower floors of all structures located less than 15 ft (4.5 m) above sea level and within 500 yds of the shoreline. Massive evacuation of residential areas on low ground within 5 to 10 mi (8 to 16 km) of the shoreline required.

2.3 Tornadoes

A tornado is a violently rotating column of air, usually pendant to a cumulonimbus cloud, with circulation reaching the ground (NOAA 2005a). Tornadoes are not unique to a specific geographic location. They have been documented on every continent with the exception of Antarctica. Some parts of the world are, however, more prone to tornadoes than others. The middle latitudes, between 30 degrees and 50 degrees latitude, experience the most tornadoes.

Globally, the United States has the highest number of annual tornadoes, with an average of over 1,000 tornadoes per year (NOAA 2008c). Most of these tornadoes occur in the central United States in a region known as "Tornado Alley" due to the relatively high frequency of tornado occurrence (Figure 2.1). Tornado Alley is not a formal region; however, it is a vernacular region defined by tornado frequency parameters. Generally, Tornado Alley spans from northern Texas north through Oklahoma, Arkansas, Kansas, Missouri, Nebraska, Illinois, Iowa, and Wisconsin. Tornadoes in this region are commonly associated with supercell and squall line thunderstorms. Figure 2.1 also indicates that the Gulf Coast region has notable tornado activity. The relatively high frequency of tornadoes in this region has earned it the name "Dixie Alley". Unlike the tornadoes in Tornado Alley, which are associated with severely convective thunderstorms (supercells and squall lines) due to the collision of cold dry polar air and warm moist tropical air, many tornadoes in Dixie Alley are associated with landfalling hurricanes.

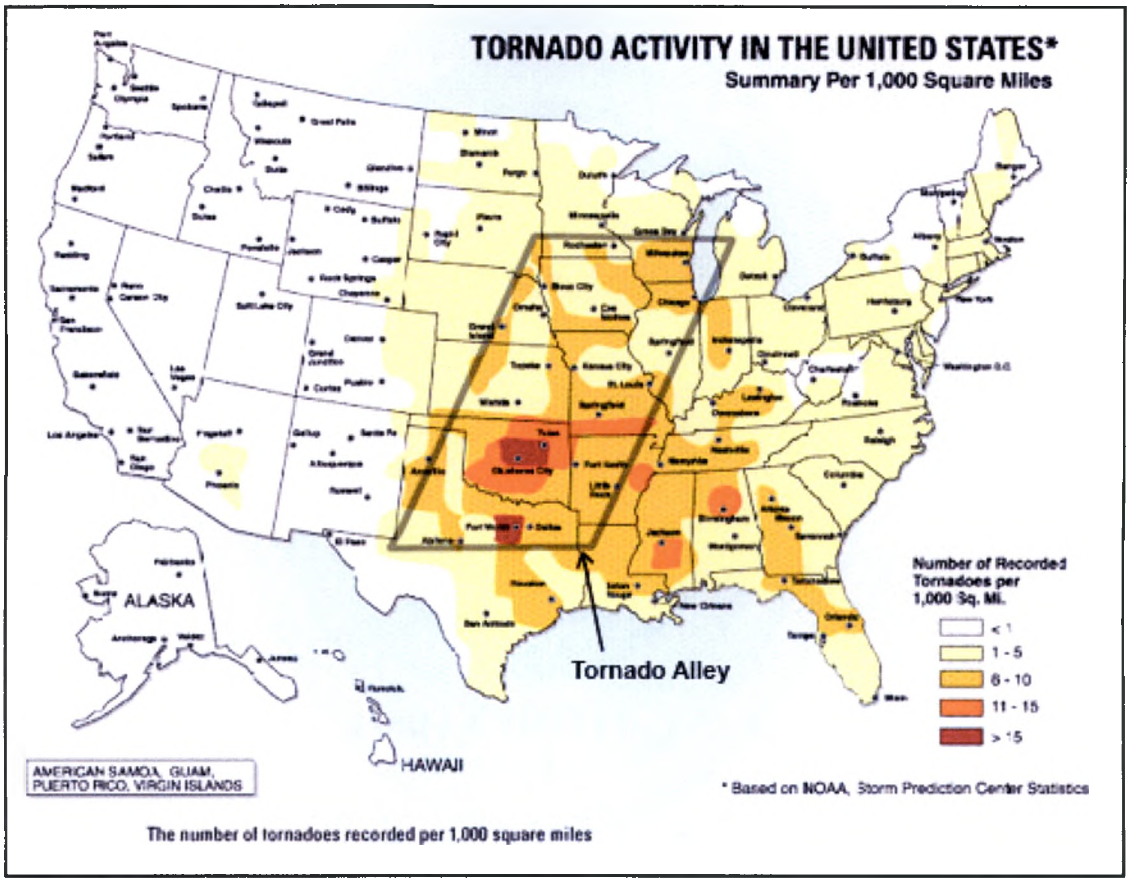


FIGURE 2.1. Tornado Alley (NOAA 2008c).

Fujita Scale

Tornado intensity is measured using the Fujita Scale (F-Scale) (Table 2.2). The F-Scale estimates wind speeds based on observed tornado damage. According to the F-Scale, tornadoes are categorized into one of six categories, zero being minimum intensity and five being maximum intensity. For the purposes of this thesis, F0 and F1 tornadoes are considered weak, F2 and F3 are considered strong, and F4 and F5 are considered violent. The F-Scale has been the focus of controversial discussion within the tornado climatology research community. Doswell and Burgess (1988) attribute much of this controversy to the difference between damage and intensity, stating that the F-Scale is more accurately described as a damage scale rather than an intensity scale, and that while a relationship exists between damage and intensity, the information needed to assign an accurate intensity rating is not limited to damage. In February 2007, the Enhanced Fujita Scale (EF-Scale) was implemented with the purpose of accounting for the limitations of the F-Scale. However, the original F-Scale will be used as the hurricane-tornado intensity rating in this thesis, as the EF-Scale was implemented after the examined time period.

TABLE 2.2. Fujita Tornado Damage Scale (NOAA 2008b).

Category	Estimated Wind Speed (mph)	Typical Damage
F0	< 73	Light damage: some damage to chimneys; branches broken off trees; shallow rooted trees pushed over; sign boards damaged
F1	73 – 112	Moderate damage: peels surface off roofs; mobile homes pushed off foundations or overturned; moving autos blown off roads
F2	113 – 157	Considerable damage: Roofs torn off frame houses; mobile homes demolished; boxcars overturned, large trees snapped or uprooted; light-object missiles generated; cars lifted off ground.
F3	158 – 206	Severe damage: Roofs and some walls torn off well-constructed houses; trains overturned; most trees in forest uprooted; heavy cars lifted off the ground and thrown.
F4	207 – 260	Devastating damage: Well-constructed houses leveled; structures with weak foundations blown away some distance; cars thrown and large missiles generated.
F5	261 – 318	Incredible damage: Strong frame houses leveled off foundations and swept away; automobile-sized missiles fly through the air in excess of 100 m (109 yds.); trees debarked; incredible phenomena will occur.

2.4 Hurricane-Tornadoes

As hurricanes approach the coastline, boundary layer wind speed immediately decreases due to mechanical friction with land, whereas the flow at higher altitudes is not impeded by mechanical friction and therefore conserves momentum (Gentry 1983). The differential effect that land has on wind speed creates vertical wind shear, which is a change in wind speed with height. Vertical wind shear is the most documented factor contributing to the development of hurricane-tornadoes (Novlan and Gray 1974; Gentry 1983; McCaul 1991; McCaul and Weisman 1996; Suzuki et al. 2000; McCaul et al.

2004; Verbout et al. 2007). Other factors that contribute to hurricane-tornado production are high storm relative helicity (McCaul 1991; Suzuki et al. 2000; McCaul et al. 2004) [helicity is the amount of rotation found in a storm's updraft air; significant helicity can contribute to tornado production], buoyancy (McCaul and Weisman 1996), convective rainband instability (Hills, Malkin and Schulz 1966; Novlan and Gray 1974; Gentry 1983), and midlevel dry intrusion by a converging airmass (Hills, Malkin and Schulz 1966; Novlan and Gray 1974; McCaul 1987; Curtis 2004).

2.5 Hurricane-Tornado Research

Hurricane-tornadoes have been the focus of diverse research. The research can be broadly organized into three categories: (1) case studies (Gray 1919; Barbour 1924; Hills 1929; Malkin and Galway 1953; Sadowski 1962; Rudd 1964; Orton 1970; McCaul 1987; Suzuki et al. 2000); (2) thematic studies (McCaul 1991; McCaul and Weisman 1996; Spratt et al. 1997; Curtis 2004; McCaul et al. 2004); and (3) climatological studies (Smith 1965; Hill, Malkin and Schulz 1966; Novlan and Gray 1974; Gentry 1983; Verbout et al. 2007).

Case studies have focused on single hurricane-tornado events. These studies provide specific details of storms such as location, number of hurricane-tornadoes, temporal hurricane-tornado occurrence, and attributed damages. For instance, Orton (1970) studied the distribution of tornadoes associated with the landfall of hurricane Beulah in 1967.

Thematic studies generally focused on tornadogenesis and/or methods used to study tornadogenesis and hurricane-tornadoes detection. For instance, McCaul (1991) analyzed the role of buoyancy and wind shear in tornadogenesis using upper air soundings. Spratt et al. (1997) assessed the formation and characteristics of tornadoes within tropical cyclones' outer rainbands using Doppler weather surveillance radar.

Climatological studies attempt to distinguish patterns and correlations within hurricane-tornado datasets aggregated from multiple storm events spanning over large spatial areas and long temporal periods. For instance, Novlan and Gray (1974) presented a climatology of United States hurricane-tornadoes using data from East Coast and Gulf Coast-landfalling hurricanes from 1948 to 1972. More recently, Verbout et al. (2007) examined hurricane-tornado outbreaks and the geophysical hurricane characteristics that supported outbreaks from 1954 to 2004.

Generally, the climatological studies examined hurricane-tornado characteristics (Smith 1965; Novlan and Gray 1974), temporal hurricane-tornado distribution (Smith 1965; Novlan and Gray 1974; Gentry 1983; McCaul 1987; McCaul 1991; Verbout et al. 2007), the spatial distribution of hurricane-tornadoes along the East and Gulf Coasts of the United States (Sadowski 1962; Smith 1965; Hill, Malkin and Schulz 1966; Novlan and Gray 1974; Gentry 1983; Weiss 1985; McCaul 1991; Hagemeyer and Hodanish 1995; Verbout et al. 2007), and the relationships between geophysical hurricane characteristics and hurricane-tornado production (Pearson and Sadowski 1965; Smith 1965; Hill, Malkin and Schulz 1966; Novlan and Gray 1974; Gentry 1983; McCaul 1991; Hagemeyer 1997; Verbout et al. 2007).

Hurricane-Tornado Characteristics

No studies have provided a detailed description of hurricane-tornado characteristics. Studies have, however, indicated that hurricane-tornadoes tend to be weaker (Smith 1965; Novlan and Gray 1974) and have half the path length and width

(Smith 1965) than that of tornadoes. For instance, during the period 1948 - 1986, the percentage of hurricane-tornadoes that reached F2 or greater was 26% (McCaul et al. 2004), whereas during the period 1950 - 1976 the corresponding percentage of all United States tornadoes was 36% (Kelly et al. 1978).

This thesis will not provide comparative analysis between hurricane-tornadoes and tornadoes, but will, however, provide detailed descriptions of hurricane-tornado intensity, path length, and path width. It will also determine a normal range of hurricane-tornado frequency per landfalling hurricane.

Temporal Distribution

Temporally, research has examined diurnal (Novlan and Gray 1974; Gentry 1983; McCaul 1987; McCaul 1991) and monthly (Smith 1965; Novlan and Gray 1974; Verbout et al. 2007) distribution of hurricane-tornadoes. These studies have, however, provided varied results. Maximum hurricane-tornado frequencies have been found at 1100 LST (Novlan and Gray 1974), 1500 LST (McCaul 1991), and from 1500 to 1800 LST (Gentry 1983). Examination of the monthly distribution of hurricane-tornadoes has also produced varied results. Smith (1965) indicated that a maximum hurricane-tornado frequency exists in September and a minimum exists in October. This finding was later supported by Novlan and Gray (1974). Conversely, Verbout et al. (2007) did not find a significant monthly pattern.

This thesis will examine both diurnal and monthly hurricane-tornado distributions. It will also examine the time difference between hurricane-tornado touchdown and the landfall time of their respective hurricane. Further, it will examine long-term (55 years) hurricane-tornado distribution for variation.

Spatial Distribution

Few studies have examined the long-term, small scale spatial distribution of hurricane-tornadoes. Novlan and Gray (1974) plotted the geographical distribution of East and Gulf Coast hurricane-tornadoes from 1948-1972. Their study indicates that the majority of hurricane-tornadoes are located within 100 nautical miles (185.2 km) of the coastline. Later, Gentry (1983) plotted hurricane-tornadoes along the East and Gulf Coasts from 1972 to 1980. Like Novlan and Gray (1974), Gentry (1983) indicated that the majority of hurricane-tornadoes are located within approximately 108 nautical miles (200 km) of the coastline. The proximity of hurricane-tornadoes to the coastline supports the hypothesis that vertical wind shear created by mechanical friction greatly contributes to the development of hurricane-tornadoes. Both studies also indicate that most hurricane-tornadoes are located along the Gulf of Mexico coastline, rather than the East coast.

Within their respective hurricane, the most favorable locations for hurricane-tornadoes are the outer rainbands (Rudd 1964; Hill, Malkin and Schulz 1966; Orton 1970; Gentry 1983; McCaul 1991) and within the right front quadrant of a hurricane relative to its directional heading (Pearson and Sadowski 1965; Smith 1965; Hill, Malkin and Schulz 1966; Orton 1970; Novlan and Gray 1974; Gentry 1983; McCaul 1991; Hagemeyer 1997; Verbout et al. 2007). This region is associated with the strongest vertical wind shear (McCaul 1991; Spratt et al. 1997; Bogner, Barnes and Franklin 2000), helicity (McCaul 1991; Bogner, Barnes and Franklin 2000), and convection (Hill, Malkin and Schulz 1966; Novlan and Gray 1974; Gentry 1983), all of which contribute to the development of hurricane-tornadoes. Hurricane-tornadoes can also occur within the strong convective inner rainbands and eyewall (Gentry 1983; Weiss 1987; McCaul 1991).

This thesis will examine the long-term, small scale spatial distribution of hurricane-tornadoes associated with Gulf Coast-landfalling hurricanes. Furthermore, it will examine the spatial distribution of hurricane-tornadoes within their respective hurricane. Specifically, it will examine the distance between hurricane-tornadoes and their respective hurricane center, and whether they are more prone to occurrence to the right or left of hurricane center.

Relationship between Geophysical Hurricane Characteristics and Hurricane-Tornadoes

Research has examined the relationship between hurricane-tornadoes and the geophysical characteristics of their associated hurricane, specifically directional heading and intensity. Hurricanes with a directional heading of north to northeast near landfall have been found to produce more hurricane-tornadoes than those with other directional headings (Smith 1965; Hill, Malkin and Schulz 1966; Novlan and Gray 1974; Verbout et al. 2007). Moreover, intense hurricanes have been found to produce more hurricane-tornadoes (Smith 1965; Hill, Malkin and Schulz 1966; Novlan and Gray 1974; McCaul 1991; Verbout et al. 2007). For instance, Verbout et al. (2007) found that landfalling hurricanes categorized as 2 or above on the S.S. Scale are most likely to be associated with an outbreak of hurricane-tornadoes.

This thesis will examine the hypothesis that hurricane directional heading and intensity are influential in hurricane-tornado production. It will also examine the relationship between hurricane intensity and hurricane-tornado intensity.

2.6 Gulf Coast Region

The Gulf Coast region of the United States consists of five states (Texas, Louisiana, Mississippi, Alabama, and Florida) that abut the Gulf of Mexico. The Gulf Coast region is vulnerable to hurricane damage. Hurricane vulnerability is a function of population size, property value, and storm risk (Dixon and Fitzsimons 2001; Herbert, Dixon and Isom 2005).

The Gulf Coast region is experiencing increases in population and property value. In 2003, the Gulf Coast region accounted for thirteen percent of the United State's coastal population, with over nineteen million residents (Crossett et al. 2004). Furthermore, the Gulf Coast region is home to the Houston-Galveston-Brazoria metropolitan area, which is one of the nation's largest. The Gulf Coast region is also experiencing an increase in development and property value as new housing and infrastructure are built to meet the needs and demands of a growing population.

Gulf Coast-landfalling hurricanes are inevitable. Increasing coastal population and development mean that more lives and property are at risk of hurricane damage, including damage from hurricane-tornadoes. Novlan and Gray (1974) and Gentry (1983) found that hurricane-tornadoes are more probable with Gulf Coast-landfalling hurricanes than with East Coast-landfalling hurricanes. Moreover, Hagemeyer and Hodanish (1995) found that 87% of tornado-producing hurricanes that make landfall in Florida approached from the Gulf of Mexico to the west, rather than from the southern Atlantic to the east. Gulf Coast-landfalling hurricanes produce more tornadoes because their right front quadrant is more prone to make initial landfall and remain over land for a longer time period (Sadowski 1962; Smith 1965; Verbout et al. 2007), thus providing more time for hurricane-tornado production. Conversely, East Coast-landfalling hurricanes often parallel the coastline. Therefore, they do not penetrate far inland before recurving northeastward towards the Atlantic Ocean. As a result, East Coast hurricanes do not have as much interaction between their right front quadrant and land surfaces (Hill, Malkin and Schulz 1966; Gentry 1983; McCaul 1991), thus producing fewer hurricane-tornadoes.

2.7 Research Methodologies

Primary goals of climatological methodologies are classification and generalization of large datasets. To achieve such goals, a primary emphasis on the use of descriptive statistics and quantitative methods exists (Carleton 1999). These techniques are often relatively simple, but can be more complex, depending on the nature of the research topic. Fundamental properties of climatological studies include normals (averages), extremes, and frequencies. Visualization of climatic data, such as histograms, bar and line graphs, time-series plots, and maps are used to evaluate data and illustrate significant trends and relationships (Robeson 2005). Spatial variations of climatological features are often visualized and subjectively analyzed with the aid of maps.

Initial classification of hurricane-tornado data is essential to conducting climatological research. Classification enables the use of frequency distributions, which have been widely used when examining the relationship between hurricane-tornado frequency and geophysical hurricane characteristics (e.g. Smith 1965; Hill, Malkin and Schulz 1966; Novlan and Gray 1974; Gentry 1983; Verbout et al. 2007) and when examining various temporal distributions of hurricane-tornadoes (e.g. Pearson and

Sadowski 1965; Smith 1965; Hill, Malkin and Schulz 1966; Novlan and Gray 1974; Gentry 1983). Other quantitative methods are often used to test for statistical significance. For instance, Verbout et al. (2007) used chi-square tests to examine the homogeneity of hurricane-tornado outbreak frequencies per S.S. Scale and per landfall location (East and Gulf Coast). Spatial distributions of hurricane-tornadoes have been represented and analyzed by plotting the latitude and longitude coordinates of touchdown locations (e.g. Smith 1965; Hill, Malkin and Schulz 1966; Novlan and Gray 1974).

2.8 Summary

Hurricane-tornadoes have been the focus of abundant literature. The literature can be broadly categorized as case studies, thematic studies, and climatological studies. This chapter primarily focused on the climatological studies, for they provide the most insight for this thesis. These studies have been termed climatological; however, most do not meet the most fundamental requirement to conducting climatological research - time period. According to the Climate Prediction Center, climate is the average weather over at least a 30 year time period (NOAA 2004). Therefore, to develop a climatology of a meteorological phenomenon, that phenomenon should be examined over at least a 30-year time period. Most of the studies that provided climatic descriptions did not examine a 30-year period. However, they have provided insight for the development of this climatology.

The climatological literature revealed many results that aided in the formulation of this thesis. First, the study area was selected based on indications that hurricanes making landfall along the Gulf Coast produce more hurricane-tornadoes than those making landfall along the East Coast. This, along with increasing coastal population, development, and property value, make the Gulf Coast region vulnerable to hurricane damage, including damage from hurricane-tornadoes. Furthermore, the Gulf and East Coast regions are likely to have different hurricane-tornado climatologies due to differences in their associated hurricane landfall characteristics, assuming that previous results are correct in their suggestions that hurricane characteristics (i.e. directional heading and intensity) influence hurricane-tornado production. It is therefore imperative to examine the hurricane-tornado climatology of these regions independently. Second, the literature provided parameters for developing a hurricane-tornado climatology. Third, the literature revealed common quantitative analysis techniques. Unique among all of the climatological studies were initial generalization and categorization to make the data easier to analyze. Other common techniques were descriptive statistics, and distribution, correlation, and trend analyses.

This thesis will be the first to develop a climatology of hurricane-tornadoes exclusively associated with Gulf Coast-landfalling hurricanes. It will also examine a longer time period than previous research. The updated hurricane-tornado climatology is necessary to reveal temporal and spatial patterns and pattern variation of hurricane-tornado occurrence that smaller datasets conceal. Moreover, the larger dataset will provide results that more precisely represent actual hurricane-tornado climatology, as defined by this thesis.

CHAPTER III

DATA AND METHODS

3.1 Introduction

All data collected in this thesis were obtained from governmental databases. This approach was taken to minimize subjectivity with regard to data collection. Statistical techniques and GIS were used to analyze the data. The following sections will provide a detailed description of the data sources and collection processes, statistical analysis techniques, and GIS techniques used in this thesis.

3.2 Hurricane Data

Hurricane data were obtained from the National Oceanic and Atmospheric Administration (NOAA), National Weather Service (NWS), National Hurricane Center (NHC) and NOAA's Coastal Services Center (CSC). Specific hurricane variables collected for this thesis were landfall date, approximated landfall time, landfall intensity, and hurricane track coordinates. Landfall date, approximated time, and intensity were obtained from the NHC's Atlantic, Caribbean, and Gulf of Mexico Hurricane Seasons Tropical Cyclone Reports (http://www.nhc.noaa.gov/pastall.shtml). Atlantic Basin hurricane track shapefiles were obtained from the CSC's Historical Hurricane Tracks (http://maps.csc.noaa.gov/hurricanes/download.jsp).

Data were collected for Atlantic Basin hurricanes that made landfall along the Gulf Coast of the United States from 1950 to 2005. This includes the coastlines of

Texas, Louisiana, Mississippi, Alabama, west coastline of Florida, and the northeast coastline of Mexico (at or within 400 km of the Texas-Mexico border). All hurricanes making landfall along the Texas, Louisiana, Mississippi, and Alabama coastlines were included. Only those hurricanes making landfall along the west coast of Florida were included because they approached from the Gulf of Mexico. Those making landfall along the east coast of Florida approach from the Atlantic. Hurricanes making landfall along the northeast coast of Mexico were included because their outer rainbands can impact south Texas. Overall, data were compiled for 60 hurricanes. Appendix A provides a list of hurricane names, landfall dates, landfall intensities, and associated hurricane-tornadoes.

3.3 Hurricane-Tornado Data

Hurricane-tornado data were obtained from NOAA's National Environmental Satellite, Data, and Information Service (NESDIS), National Climatic Data Center (NCDC), Storm Events database (http://www4.ncdc.noaa.gov/cgi-win/wwcgi.dll?wwEvent~Storms). The Storm Event database is comprised of data from the NWS. Specific hurricane-tornado variables collected for this thesis were date, time, touchdown latitude and longitude coordinates, F-scale, and path length and width.

Data were collected for hurricane-tornadoes that were associated with the 60 Gulf Coast-landfalling hurricanes from 1950 to 2005. Hurricane-tornadoes were considered to be associated with their respective landfalling hurricane if they occurred the day before, the day of, or the day after landfall and were located at or within 400 km of the hurricane center. The three day period (day before, day of, and day after landfall) was chosen because hurricanes begin to impact the coastline long before landfall and can conserve hurricane intensity for 24 hours or longer post landfall. The distance (400 km from hurricane center) is consistent with Spratt et al.'s (1997) definition of maximum tornado frequency within a hurricane. This distance parameter was used by Verbout et al. (2007) when examining tornado outbreaks associated with landfalling hurricanes in the North Atlantic basin.

Collecting hurricane-tornado data was a two step process. The initial step involved collecting data for tornadoes that occurred the day before, the day of, or the day after their associated hurricane's landfall in all states surrounding the hurricane's track. This process resulted in the collection of data for 858 hurricane-tornadoes. Next, with the aid of GIS technologies, the hurricane-tornadoes were narrowed to only those that fell at or within 400 km of their associated hurricane track. More specifically, they had to be at or within 400 km of their associated hurricane track's segment that corresponded with the date of hurricane-tornado occurrence. This process is further discussed in section 3.5. The final database consisted of 734 hurricane-tornadoes.

Several statements should be made about potential errors regarding tornado data that can impact research concerning tornado climatology. Perhaps no issue creates more controversy than the F-scale rating assigned to particular events (Doswell and Burgess 1988). Doswell and Burgess (1988) and Grazulis (2001) state that the accuracy and temporal consistency of tornado reports are limited with respect to basic errors in the recording of time and location, and the assignment of F-scale ratings. Many of the reporting errors can be attributed to untrained witnesses producing tornado information (Doswell and Burgess 1988), and to the dependency of assigned F-scale ratings on individual qualifications of the person reporting the damage (Marshall 2002). Hurricane-tornado detection and F-scale errors have the potential to be amplified when reporting hurricane-tornadoes. Fewer people are present to witness and report hurricane-tornado occurrence due to evacuations. Furthermore, the ambient meteorological conditions and damage associated with hurricanes impede the detection of tornado damage during and after landfall. Another issue concerns the increase in tornado frequency since the 1950s. This increase can be partially attributed to population sprawl, which increases reporting and documentation, and to advances in detection technologies (Bluestein 1999; Golden and Adams 2000; Grazulis 2001).

3.4 Datasets

Prior to analysis, the collected data were organized into datasets. Two datasets were created for this thesis. One dataset includes the following variable for each of the 60 hurricanes: hurricane name, landfall date, landfall intensity, directional heading near landfall, and hurricane-tornado frequency (Table 3.1). The other dataset includes the following variables for each of the 734 hurricane-tornadoes: associated hurricane's name, landfall intensity, and landfall date and time; and hurricane-tornado's touchdown state, date, time, intensity, latitude and longitude coordinates, and path length and width (Table 3.2).

TABLE 3.1. Example of dataset categorized by hurricanes.

Hurricane	Landfall Date	Landfall Intensity	Directional Heading	F0	F1	F2	F3	F4	Total Tornadoes
Baker	8/31/1950	1	NE	1	1	0	0	0	2
Easy	9/5/1950	3	NE	0	0	0	0	0	0
Florence	9/26/1953	1	NE	0	0	0	0	0	0
Alice	6/25/1954	1	NW	0	0	0	0	0	0
Audrey	6/27/1957	4	NE	3	5	6	1	0	15
Debra	7/24/1959	1	NE	1	0	0	0	0	1
Donna	9/10/1960	4	NW	0	2	1	1	0	4
Ethel	9/15/1960	1	N	1	2	2	0	0	5
Carla	9/11/1961	4	NW	0	0	1	5	1	7
Cindy	9/17/1963	1	NW	0	0	0	0	0	0
Hilda	10/3/1964	3	N	0	4	6	0	1	11
Isbell	10/14/1964	2	NE	1	4	4	0	0	9
Betsy	9/9/1965	3	NW	1	2	0	0	0	3
Alma	6/9/1966	2	N	2	2	0	0	0	4

TABLE 3.2. Example of dataset categorized by hurricane-tornadoes.

Hurricane	Saffir-Simpson	Landfall Date	Landfall Time (UTC)	State	Date	Time (UTC)	Fujita Scale	Begin Lat. (N)	Begin Long. (W)	Path Length (km)	Path Width (m)
Katrina	3	8/29/2005	1110	Alabama	8/28/2005	2404	0	30.2333333	-88.0166666	1.6	27.4
Katrina	3	8/29/2005	1110	Alabama	8/28/2005	2422	0	30.3666666	-88.1166666	1.6	27.4
Katrina	3	8/29/2005	1110	Florida	8/29/2005	1342	0	30.7166666	-86.7666666	1.6	27.4
Katrina	3	8/29/2005	1110	Florida	8/29/2005	1205	0	30.85	-86.9333333	4.8	27.4
Katrina	3	8/29/2005	1110	Florida	8/29/2005	1347	0	30.85	-86.8666666	1.6	27.4
Katrina	3	8/29/2005	1110	Florida	8/29/2005	1207	0	30.9666666	-87.2666666	1.6	27.4
Katrina	3	8/29/2005	1110	Alabama	8/29/2005	1230	0	31.1166666	-87.4666666	3.2	27.4
Katrina	3	8/29/2005	1110	Mississippi	8/29/2005	1625	1	31.3166666	-89.2833333	1.6	45.7
Katrina	3	8/29/2005	1110	Alabama	8/29/2005	2030	0	32.15	-85.7666666	0.0	22.9
Katrina	3	8/29/2005	1110	Alabama	8/29/2005	2016	0	32.25	-85.95	3.2	274.3
Katrina	3	8/29/2005	1110	Alabama	8/29/2005	2019	0	32.2666666	-85.9666666	4.8	274.3
Katrina	3	8/29/2005	1110	Mississippi	8/29/2005	1700	1	32.3833333	-88.9333333	20.9	91.4
Katrina	3	8/29/2005	1110	Mississippi	8/29/2005	1714	1	32.45	-88.6166666	4.8	68.6
Katrina	3	8/29/2005	1110	Alabama	8/29/2005	2241	0	32.4666666	-85.2833333	0.0	22.9
Katrina	3	8/29/2005	1110	Mississippi	8/29/2005	1706	2	32.4833333	-89.0833333	1.6	68.6
Katrina	3	8/29/2005	1110	Alabama	8/29/2005	2119	0	32.4833333	-85.7666666	4.8	365.8
Katrina	3	8/29/2005	1110	Mississippi	8/29/2005	1724	1	32.5666666	-88.7666666	1.6	45.7
Katrina	3	8/29/2005	1110	Mississippi	8/29/2005	1727	2	32.5833333	-89	4.8	91.4
Katrina	3	8/29/2005	1110	Alabama	8/29/2005	1855	1	32.5833333	-85.8166666	4.8	274.3
Katrina	3	8/29/2005	1110	Mississippi	8/29/2005	1722	1	32.5833333	-88.7333333	3.2	45.7
Katrina	3	8/29/2005	1110	Mississippi	8/29/2005	1741	1	32.65	-88.9333333	3.2	45.7
Katrina	3	8/29/2005	1110	Mississippi	8/29/2005	1739	1	32.6666666	-88.9	3.2	45.7
Katrina	3	8/29/2005	1110	Mississippi	8/29/2005	1736	1	32.6833333	-89.1166666	4.8	68.6
Katrina	3	8/29/2005	1110	Mississippi	8/29/2005	1748	1	32.7	-88.95	6.4	137.2

Note: End latitude and longitude coordinates are available in an extended dataset for use in future studies.

3.5 Statistical Analysis

Several statistical techniques, specifically descriptive statistics, correlation, and chi-square tests, were used to analyze the data. The purposes of these techniques were to explore and generalize the data, to examine frequency distributions, and to examine correlation between variables. Statistical analysis was performed with SPSS Graduate Package 16.0 for Windows or by manual computation using formulas and tables from Ebdon (1985). Data tables and figures were produced with SPSS 16.0 and Microsoft Excel 2007. Bar graphs and histograms are primarily used to illustrate frequency and probability distributions because they enable easy visualization. Following is a discussion of the statistical techniques used and how they were applied in this thesis.

Descriptive Statistics

Descriptive statistics were used to generalize and describe basic characteristics of datasets. Together with graphical analysis, they formed the foundation of the analysis performed in this thesis. Specific descriptive statistical techniques used in this thesis were measures of central tendency (mean, median, and mode), variability (range and standard deviation), and frequency and probability distributions. Hurricane-tornado characteristics were examined using central tendency, dispersion analysis, and frequency distributions. Frequency distributions were also used to examine the temporal and spatial distribution of hurricane-tornadoes, and the relationship between hurricane intensity and hurricane-tornadoes.

Correlation

Correlation examines the strength and direction of a relationship between two variables (Meyers, Gamst and Guarino 2006). Correlation implies concomitant variation between variables; however it does not imply causation. The specific correlation coefficient used in this thesis is the Kendall's tau-b. Kendall's tau-b correlation is a nonparametric measure of association between two sets of ordinal, ranked values (Meyers, Gamst and Guarino 2006). Kendall's tau-b was chosen over the more popular Spearman's Rank Correlation because it accounts for tied ranks, which are abundant in the current data. The ties arose because all 60 hurricanes and 734 hurricane-tornadoes had to be classified using S.S. scale and F-scale ratings, which have only five and six categories, respectively.

Kendall's tau-b correlation coefficient ranges from -1 to +1. A value of -1 indicates a perfect inverse association (negative correlation). A value of 0 indicates no association (no correlation). A value of +1 indicates a perfect direct association (positive correlation). Kendall's tau-b correlation was performed using SPSS. Kendall's tau-b correlation was used to test for a correlation between hurricane intensity and hurricane-tornado frequency and between hurricane intensity and hurricane-tornado intensity. An α of 0.05 was used to determine statistical significance in the correlation analysis.

Chi-Square Test

Chi-square tests examine the difference between an observed frequency distribution of variables and a theoretical expected frequency distribution. Several types of chi-square tests exist. This thesis will use the chi-square tests for homogeneity and independence. Chi-square test for homogeneity tests whether variables are uniformly distributed with respect to some characteristic. Chi-square test for independence tests whether variables are related or independent with respect to some characteristic. The null hypothesis (H_O) for the chi-square test for homogeneity asserts that the variables are uniformly distributed. The alternative hypothesis (H_A) asserts that the variables are not uniformly distributed. H_O for the chi-square test for independence asserts that the variables are independent. H_A asserts that the variables are related. Chi-square tests were manually performed. The chi-square tests for homogeneity were used to examine the homogeneity of hurricane-tornado distribution with respect to hurricane-tornado intensity, month of occurrence, and hurricane intensity. A chi-square test for independence was used to test the independence of hurricane-tornado intensity and hurricane intensity with respect to hurricane-tornado frequency.

Chi-square tests for independence require the development of a contingency table, which organizes the frequency of a characteristic shared by two or more variables. The two variables used in this test were S.S. scale and F-scale. The characteristic shared by the variables was hurricane-tornado frequency. The contingency table used to test the independence between S.S. scale and F-scale was four by four. Category 4 and 5 hurricanes and F3, F4, and F5 hurricane-tornadoes had to be combined to meet criteria needed to perform chi-square analysis; specifically, since the number of categories is greater than two, no more than 1/5 of the expected frequencies can have a value less than five (Ebdon 1985).

After developing the observed contingency table, an expected contingency table must be developed. The expected frequencies of each cell are calculated by multiplying the column total and the row total, then dividing by the grand total. The chi-square value (x^2), for homogeneity and independence tests, is then calculated using the following equation:

$$x^2 = \sum \frac{d^2}{e},$$

Where d is the difference between the observed and expected frequency for each cell and e is the expected frequency for the corresponding cell (Ebdon 1985). If x^2 is greater than a critical value, then H_O is rejected.

The critical value is based on degrees of freedom (df) and significance level (α). Degrees of freedom is determined by the contingency table (number of rows minus one multiplied by the number of columns minus one). The chi-square test used to examine S.S. scale and F-scale had 9 df. The chi-square test used to examine hurricane-tornado frequency per month had 4 df. The chi-square tests used to examine hurricane-tornado frequency distribution per F-scale and per S.S. scale had 3 df. The significance level is picked at the researchers discretions. An α of 0.01 was used for all chi-square tests.

3.6 Geographic Information Systems

Climatological phenomena are spatially variable. The advent of GIS in the early 1960s enabled spatial data to be simplified and visualized as electronic maps (Chapman and Thornes 2003). In this thesis, GIS was used to create maps in order to visualize and subjectively analyze the spatial distribution of hurricane-tornadoes. All maps, unless otherwise cited, were created with ArcGIS 9, ArcMAP version 9.2 by ESRI, copyright 2006.

In order to examine the spatial distribution of hurricane-tornadoes, hurricane track shapefiles and hurricane-tornado touchdown latitude and longitude coordinates were imported into ArcMAP. Hurricane tracks were separated into line segments, with one segment representing one day of the hurricane track. The day before, the day of, and the day after landfall were the only days of each hurricane track to be plotted. Hurricane-tornado touchdown latitude and longitude coordinates were also plotted.

ArcMAP was used for several spatial analyses. First, ArcMAP was used to determine which hurricane-tornadoes were located at or within 400 km of their associated hurricane track. To do so, a 400 km buffer was placed around each daily segment of each hurricane track. Then hurricane-tornadoes were selected by their location with the *select by location* option in ArcMAP. Only those hurricane-tornadoes that were located on or within the buffer placed around their associated hurricane's track, on the same date as hurricane-tornado occurrence, were selected. Second, ArcMAP was used to examine the directional heading of the landfalling hurricanes. After the hurricane paths were plotted, they were assigned a general directional heading of south of west (S of W), west (W), west of north (W of N), north (N), east of north (E of N), or east (E). Third, ArcMAP was used to examine the distance of hurricane-tornadoes from their associated hurricane center. To do so, hurricane-tornadoes were selected and organized by distance from their associated hurricane track, on the same date as hurricane-tornado occurrence, with the *select by location* option in ArcMAP. Hurricane-tornadoes were organized into distance intervals of 0 - 100 km, 101 - 200 km, 201 - 300 km, and 301 - 400 km from hurricane center.

CHAPTER IV

RESULTS

4.1 Introduction

The purpose of this chapter is to present initial results from the statistical and GIS analyses. Results will primarily take the form of measures of central tendency, variability, and frequency distributions. Descriptive statistics (central tendency and variability) and specific statistical test (chi-square and correlation) results and summaries will be provided in tables. Frequency distributions will be illustrated in figures to enable easy visualization. Chapter V will provide an in-depth analysis of the results presented in this chapter.

4.2 Hurricane-Tornado Characteristics

Hurricane-Tornado Frequency per Hurricane

According to the methodology used in this thesis, 60 Gulf Coast-landfalling hurricanes produced a total of 734 hurricane-tornadoes from 1950 - 2005. Hurricane-tornado outbreaks ranged from 0.00 - 101.00 tornadoes per hurricane, with a mean of 12.23, median of 5.00, and standard deviation of 18.81. Within this chapter and chapter V the term outbreak will be often used to denote a single event (i.e. a hurricane landfall that produced hurricane-tornadoes). Table 4.1 provides descriptive statistics for hurricane-tornado frequency per landfalling hurricane.

TABLE 4.1. Descriptive statistics: hurricane-tornado frequency per hurricane.

Hurricane-Tornado Frequency			
N = 60.00			
Central Tendency:		Variance:	
Mean	12.23	Range	101.00 (min = 0.00, max = 101.00)
Median	5.00	Standard Deviation	18.81
Mode	0.00	Skewness	3.00
		Kurtosis	10.51

Figure 4.1 illustrates the frequency distribution of hurricane landfalls categorized by hurricane-tornado frequency. Maximum frequency occurred with hurricanes producing 0 - 5 hurricane-tornadoes. Minimum frequency occurred with hurricanes producing 36 - 45 hurricane-tornadoes.

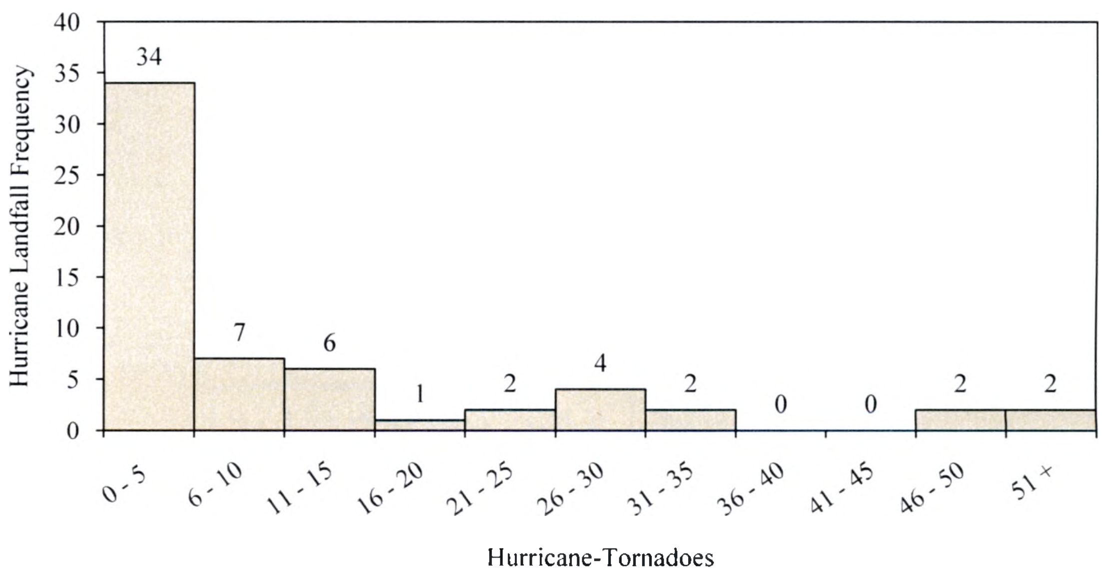


FIGURE 4.1. Frequency distribution: hurricane-tornado frequency per hurricane.

Hurricane-Tornado Intensity

Out of the 734 observed hurricane-tornadoes, 667 had F-scale ratings. Figure 4.2 illustrates hurricane-tornado frequency distribution per F-scale. Hurricane-tornado intensity ranged from F0 - F4. Maximum frequency occurred with F0 rating. Minimum frequency occurred with F4 rating. No F5 hurricane-tornadoes were reported.

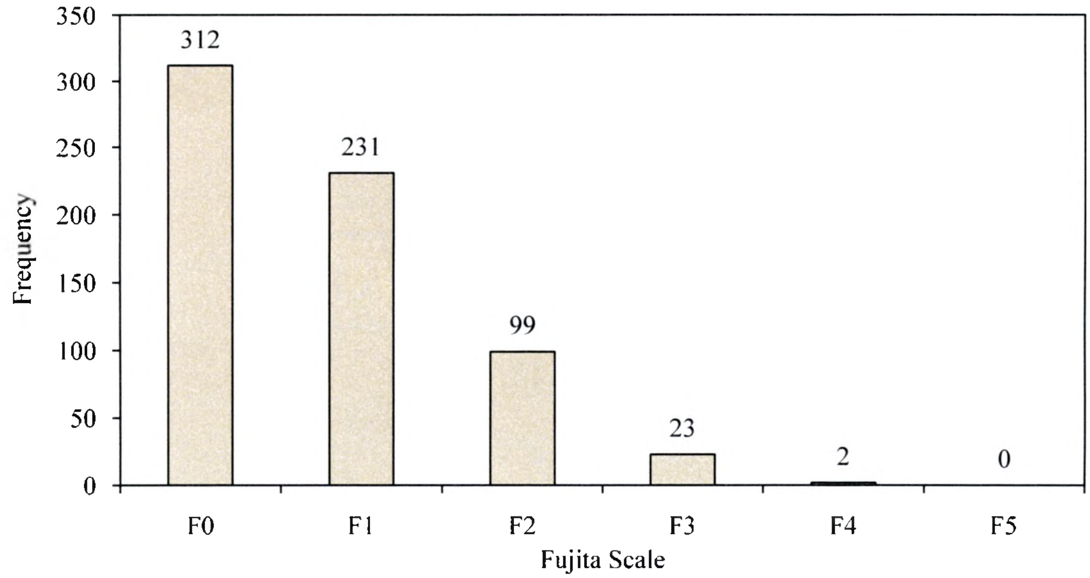


FIGURE 4.2. Frequency distribution: hurricane-tornado intensity.

A chi-square test for homogeneity was used to statistically test the uniformity of hurricane-tornado intensity distribution. Table 4.2 provides a summary of the test.

TABLE 4.2. Chi-square test for homogeneity: hurricane-tornado intensity distribution.

Chi-Square Test for Homogeneity

Observed Distribution:

	F0	F1	F2	F3, F4, F5	∑
Hurricane-Tornadoes	312	231	99	25	667

Expected Distribution:

	F0	F1	F2	F3, F4, F5	∑
Hurricane-Tornadoes	166.75	166.75	166.75	166.75	667

Degrees of Freedom (df): 3
Significance Level (α): 0.01
Critical Value at $\alpha = 0.01$ and 3 df: 11.34
Calculated Chi-Square: 299.30

H_O: Hurricane-tornadoes are uniformly distributed with respect to F-scale.

H_A: Hurricane-tornadoes are not uniformly distributed with respect to F-scale.

Result:
Calculated Chi-Square > Critical Value; Reject H_O at $\alpha = 0.01$.

Hurricane-Tornado Path Length and Width

Out of the 734 observed hurricane-tornadoes, 631 provided path lengths and 630 provided path widths. Prior to statistical analysis, all hurricane-tornadoes with a path length of zero were filtered out. This process narrowed the path length total to 463. Table 4.3 provides descriptive statistics of hurricane-tornado path length and width. Path length ranged from 1.6 - 67.6 km, with a mean of 5.9 km, median of 3.2 km, and standard deviation of 7.0 km. Path width ranged from 2.7 - 804.7 m, with a mean of 68.5 m, median of 45.7 m, and standard deviation of 82.6 m. Figures 4.3 and 4.4 illustrate path lengths and widths frequency distributions, respectively.

TABLE 4.3. Descriptive statistics: hurricane-tornado path length and width.

Hurricane-Tornado Path Length (km) and Path Width (m)			
Path Length:			
N = 463			
Central Tendency:		Variance:	
Mean	5.9	Range	66.0 (min = 1.6, max = 67.6)
Median	3.2	Standard Deviation	7.0
Mode	1.6	Skewness	3.3
		Kurtosis	17.5
Path Width:			
N = 630			
Central Tendency:		Variance:	
Mean	68.5	Range	802.0 (min = 2.7, max = 804.7)
Median	45.7	Standard Deviation	82.6
Mode	45.7	Skewness	4.1
		Kurtosis	23.4

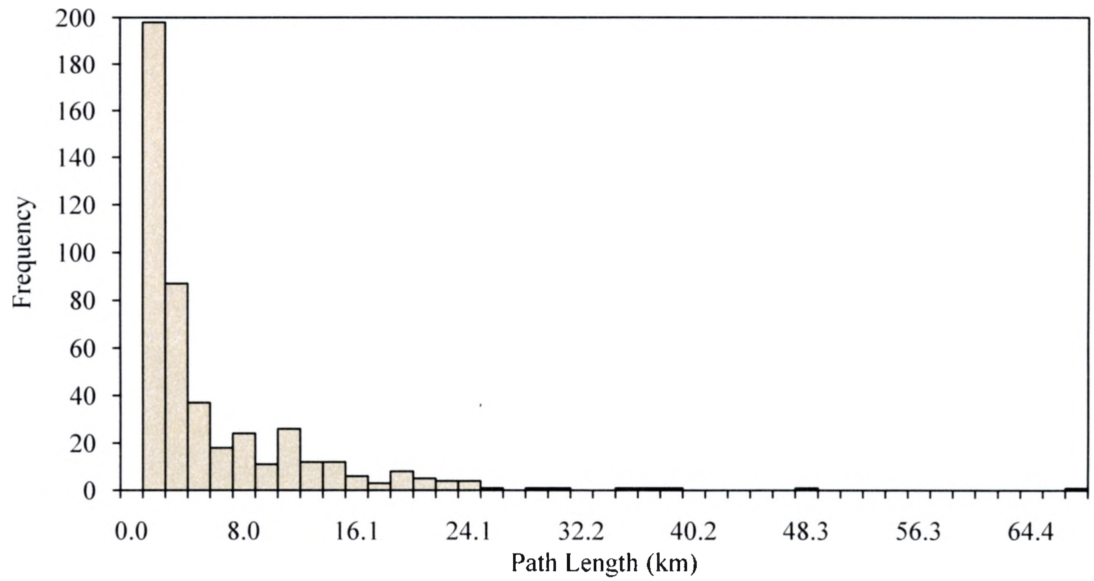


FIGURE 4.3. Frequency distribution: hurricane-tornado path length.

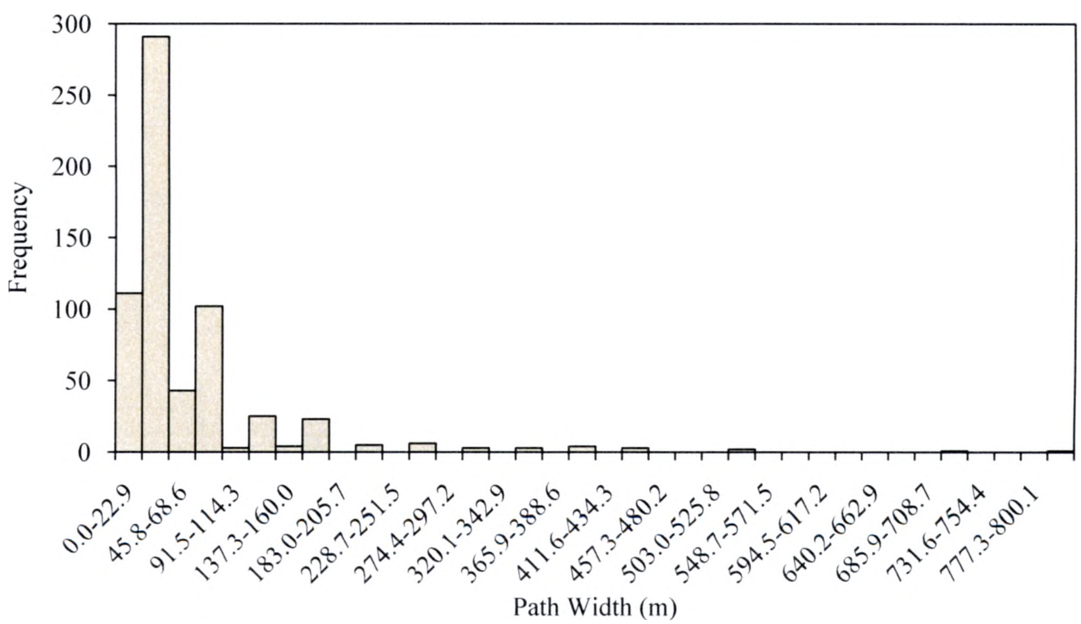


FIGURE 4.4. Frequency distribution: hurricane-tornado path width.

4.3 Temporal Distribution

Inter-Annual Distribution

Figure 4.5 illustrates the frequency distribution of hurricane-tornadoes per annum from 1950 - 2005. Annual hurricane-tornado frequency ranged from 0 - 125. Maximum frequencies occurred in 2004 and 2005. Minimum frequencies occurred in 23 years, which reported zero hurricane-tornadoes.

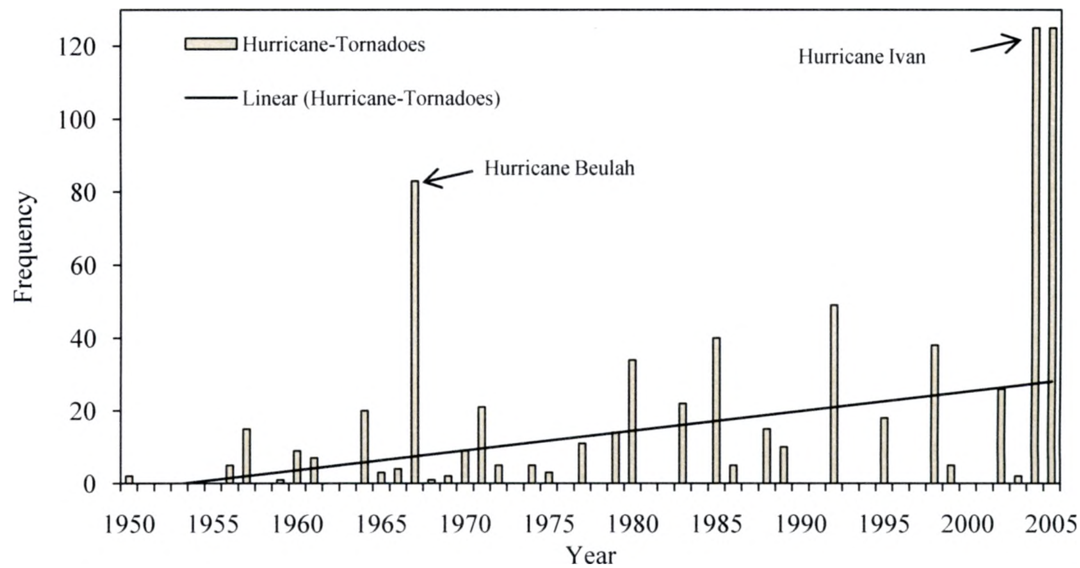


FIGURE 4.5. Frequency distribution: hurricane-tornadoes per annum.

Intra-Seasonal Distribution

All 734 observed hurricane-tornadoes were included in the seasonal and monthly distribution analyses. The intra-seasonal distribution of hurricane-tornadoes was examined in two ways. First, hurricane-tornado season was divided into early (June and July), middle (August and September), and late (October and November) season (Figure 4.6). The intra-seasonal frequency of hurricane-tornadoes ranged from 76 - 554. Maximum frequency occurred in middle season. Minimum frequency occurred in late season. Second, individual monthly frequencies were examined (Figure 4.7). The monthly frequency of hurricane-tornadoes ranged from 0 - 342. Maximum frequency occurred in September. Minimum frequency occurred in November.

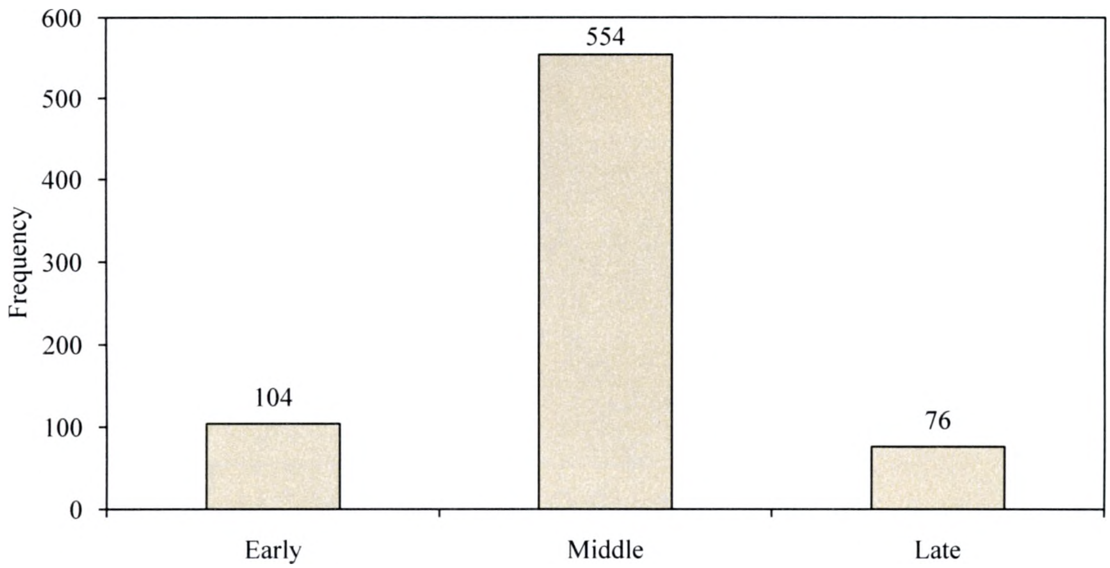


FIGURE 4.6. Frequency distribution: hurricane-tornado intra-seasonal distribution.

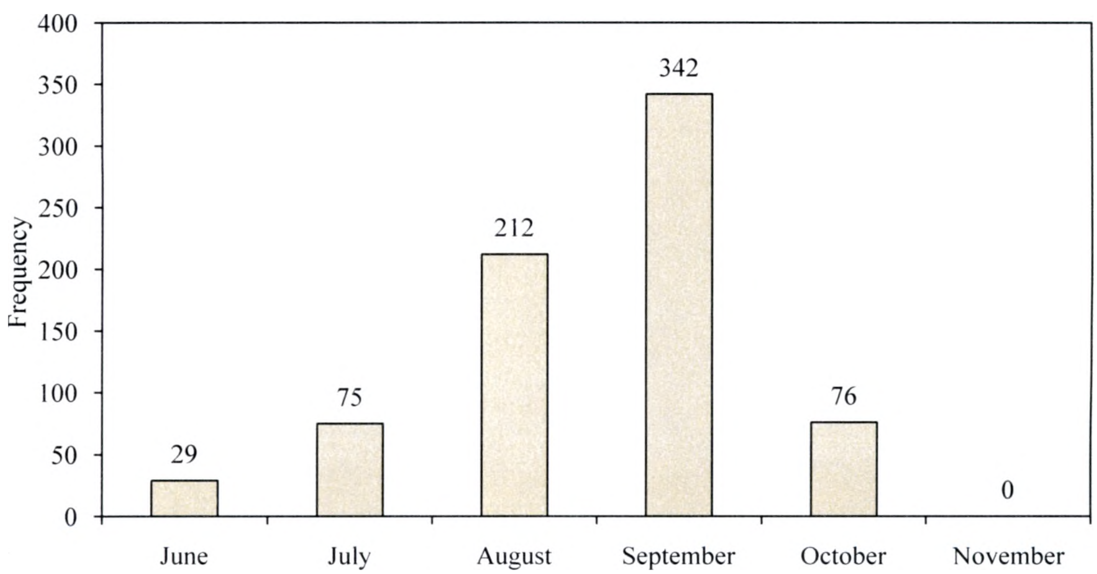


FIGURE 4.7. Frequency distribution: hurricane-tornado monthly distribution.

A chi-square test for homogeneity was used to statistically test the uniformity of hurricane-tornado distribution throughout hurricane-tornado season. Table 4.4 provides a summary of the test.

TABLE 4.4. Chi-square test for homogeneity: hurricane-tornado monthly distribution.

Chi-Square Test for Homogeneity

Observed Distribution:

	Jun	Jul	Aug	Sep	Oct	Σ
Hurricane-Tornadoes	29	75	212	342	76	734

Expected Distribution:

	Jun	Jul	Aug	Sep	Oct	Σ
Hurricane-Tornadoes	146.8	146.8	146.8	146.8	146.8	734

Degrees of Freedom (df): 4
Significance Level (α): 0.01
Critical Value at $\alpha = 0.01$ and 4 df: 13.28
Calculated Chi-Square: 339.44
H_O: Hurricane-tornadoes are uniformly distributed throughout hurricane season months.
H_A: Hurricane-tornadoes are not uniformly distributed throughout hurricane season months.

Results:
Calculated Chi-Square value > Critical Value; Reject H_O at $\alpha = 0.01$

Diurnal Distribution

Out of the 734 observed hurricane-tornadoes, 692 were used in the analysis of the diurnal distribution and 687 for the time difference between hurricane-tornado touchdown and associated hurricane landfall. Figure 4.8 illustrates the diurnal distribution of hurricane-tornadoes. Hurricane-tornado frequencies were determined for two hour intervals. The bi-hourly frequency ranged from 14 - 118. Maximum frequency occurred between 2000 and 2159 UTC (2:00 - 3:59 PM CST and 3:00 - 4:59 PM EST). Minimum frequency occurred between 0400 and 0559 UTC (10:00 - 11:59 PM CST and 11:00 PM - 12:59 AM EST).

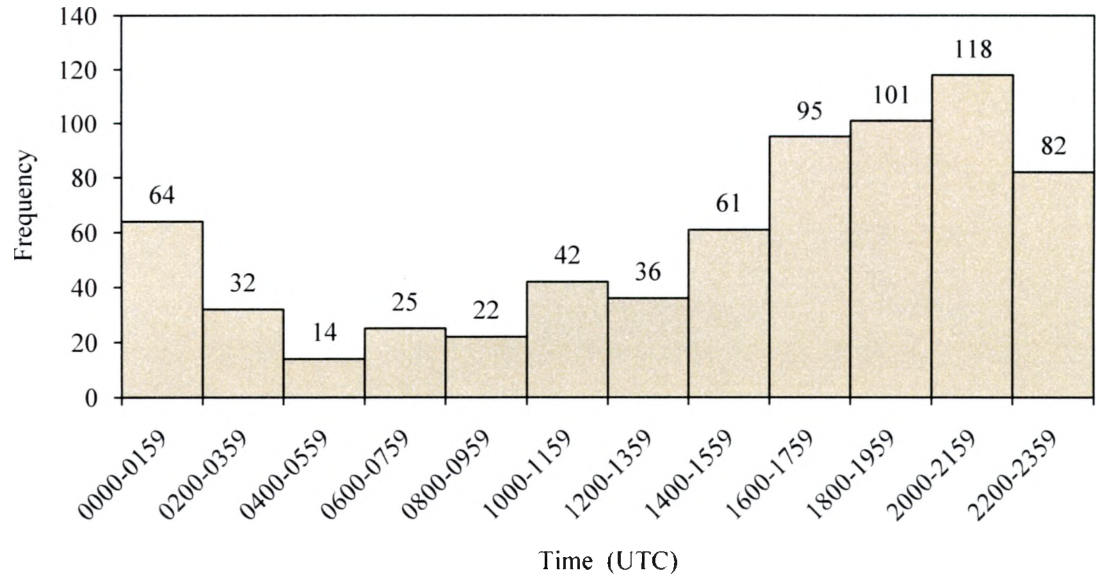


FIGURE 4.8. Frequency distribution: hurricane-tornado diurnal distribution.

Figure 4.9 illustrates the time difference between hurricane-tornado touchdown and associated hurricane landfall. Hurricane-tornado occurrence ranged from 41 hours pre-landfall to 42 hours post-landfall. Hourly frequency, relative to hurricane landfall time, ranged from 0 - 37. Maximum frequency occurred 1.0 - 1.9 hours post-landfall. Minimum frequencies occurred approximately 39 - 34, 32 - 30, and 20 - 19 hours pre-landfall. Several clusters can be observed in Figure 4.9. The clusters are located at approximately 9.9 - 0 hours pre-landfall, with a peak at 3.9 - 3.0 hours; 0 - 10.9 hours post-landfall, with a peak at 1.0 - 1.9 hours; 12.0 - 18.9 hours post-landfall, with a peak at 15.0 - 15.9 hours; and 36.0 - 39.9 hours post-landfall, with a peak at 38.0 - 38.9 hours.

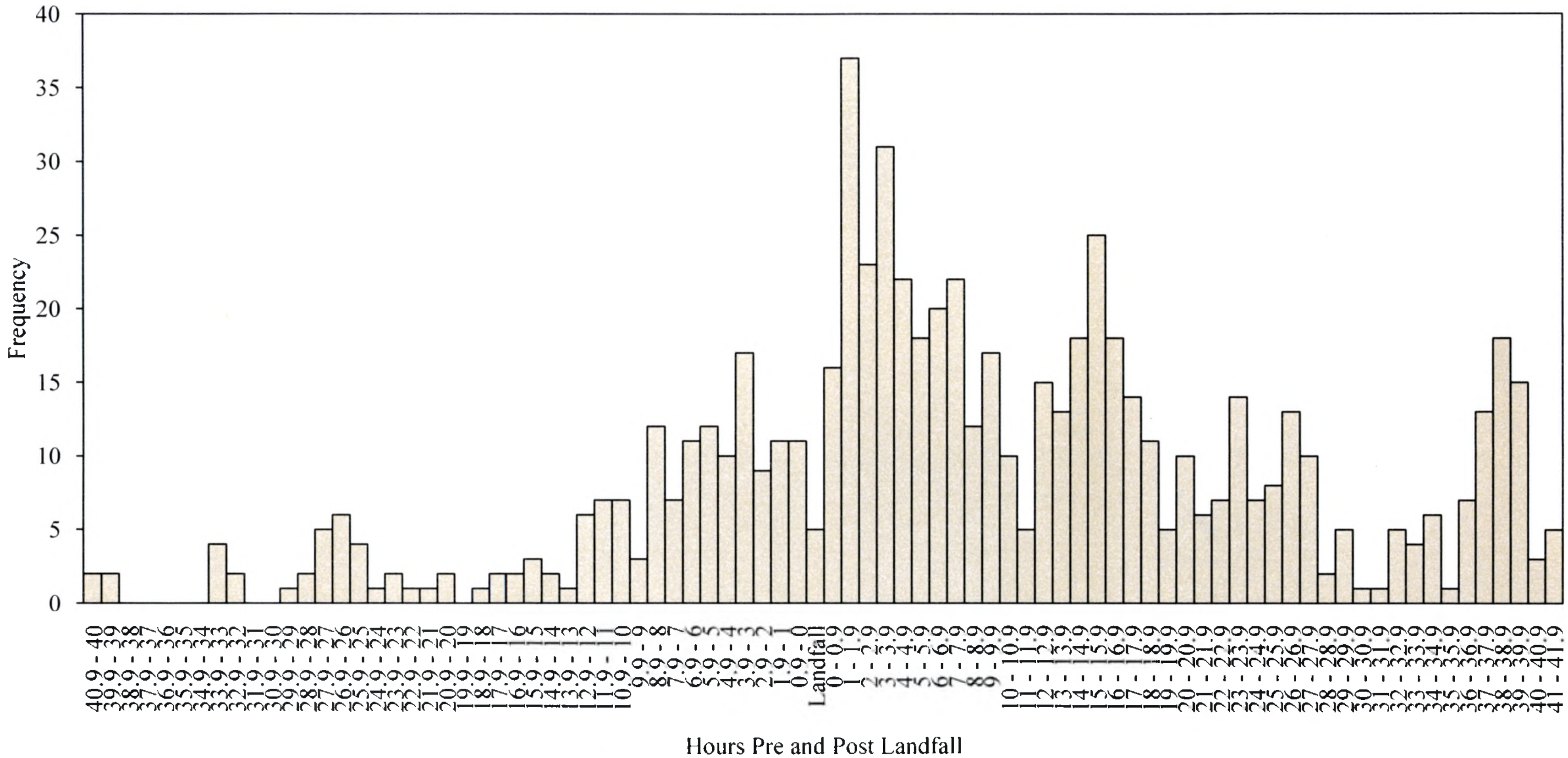


FIGURE 4.9. Frequency distribution: time difference between hurricane-tornado touchdown and associated hurricane landfall.

4.4 Spatial Distribution

Distribution by State

All 734 observed hurricane-tornadoes provided touchdown latitude and longitude coordinates. Hurricane-tornadoes occurred in the following states: Texas, Louisiana, Arkansas, Mississippi, Alabama, Florida, Georgia, Tennessee, South Carolina, North Carolina, Indiana, Kentucky, Virginia, West Virginia, and Maryland. Table 4.5 lists the states and associated hurricane-tornado frequency. Hurricane-tornado frequency per state ranged from 1 - 199. Maximum frequency occurred in Texas. Minimum frequency occurred in Indiana and Kentucky. Figure 4.10 illustrates the small scale spatial distribution of hurricane-tornadoes.

TABLE 4.5. Hurricane-tornado frequency distribution by state.

State	Hurricane Landfall Frequency	Hurricane-Tornado Frequency	F0	F1	F2	F3	F4
Alabama	3	120	62	37	16	5	0
Arkansas	-	18	4	11	3	0	0
Florida	15	115	58	34	19	0	0
Georgia	-	30	12	13	5	0	0
Indiana	-	1	0	1	0	0	0
Kentucky	-	1	0	1	0	0	0
Louisiana	17	73	26	35	8	3	1
Maryland	-	7	3	3	1	0	0
Mississippi	4	70	34	28	7	1	0
N Carolina	-	23	12	8	3	0	0
S Carolina	-	17	9	5	2	1	0
Tennessee	-	7	3	1	2	1	0
Texas	13	199	76	27	21	11	1
Virginia	-	50	12	26	11	1	0
W. Virginia	-	3	1	1	1	0	0

Note: Eight hurricanes made landfall along northeast coast of Mexico.

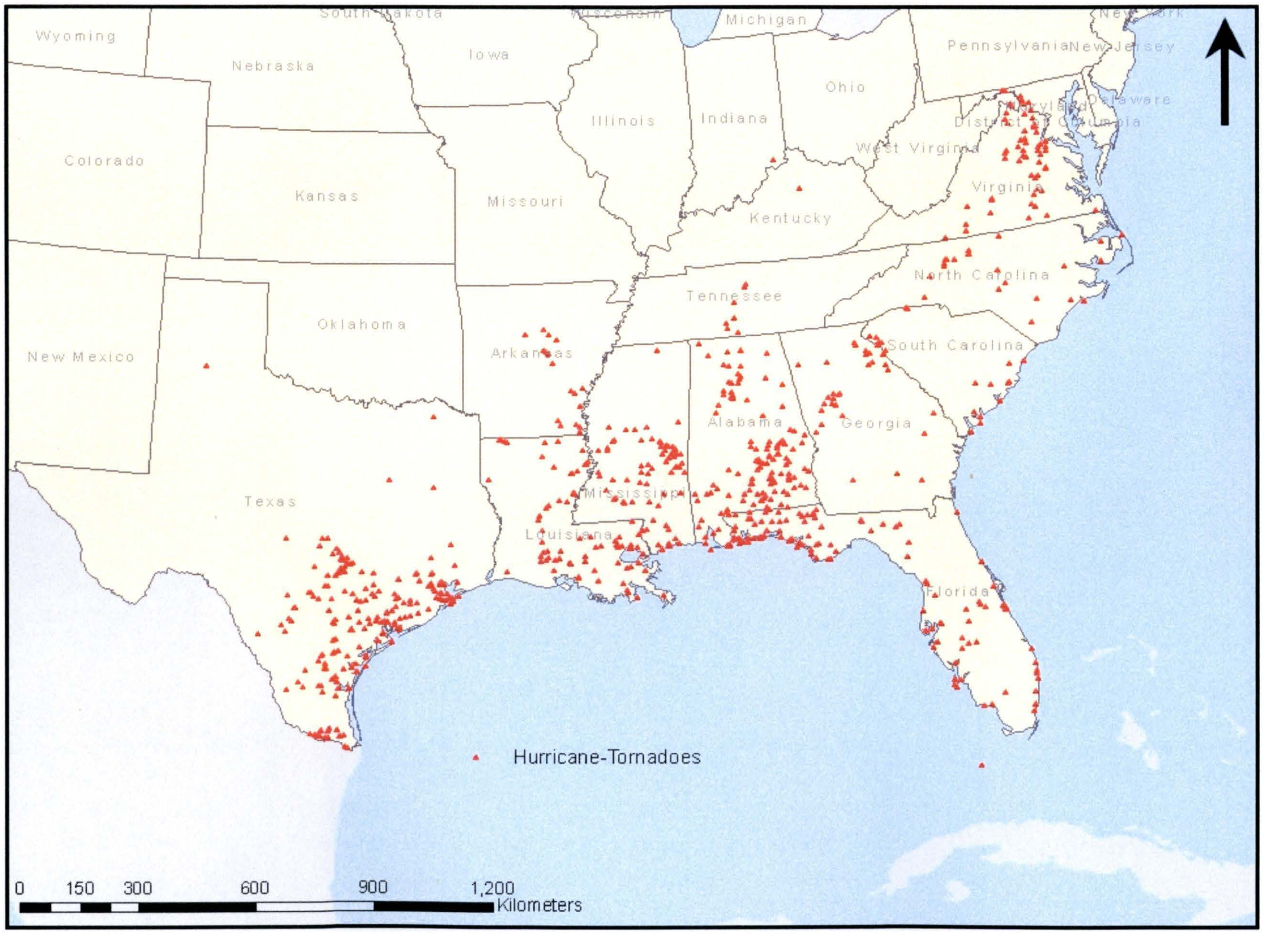


FIGURE 4.10. Spatial distribution of hurricane-tornadoes associated with Gulf Coast-landfalling hurricanes (1950-2005).

Distribution with Respect to Hurricane Center

Figure 4.11 illustrates the distance intervals from hurricane center and associated hurricane-tornado frequency. Hurricane-tornado frequency ranged from 160 - 214. Maximum frequency occurred 201 - 300 km from hurricane center. Minimum frequency occurred 301 - 400 km from hurricane center.

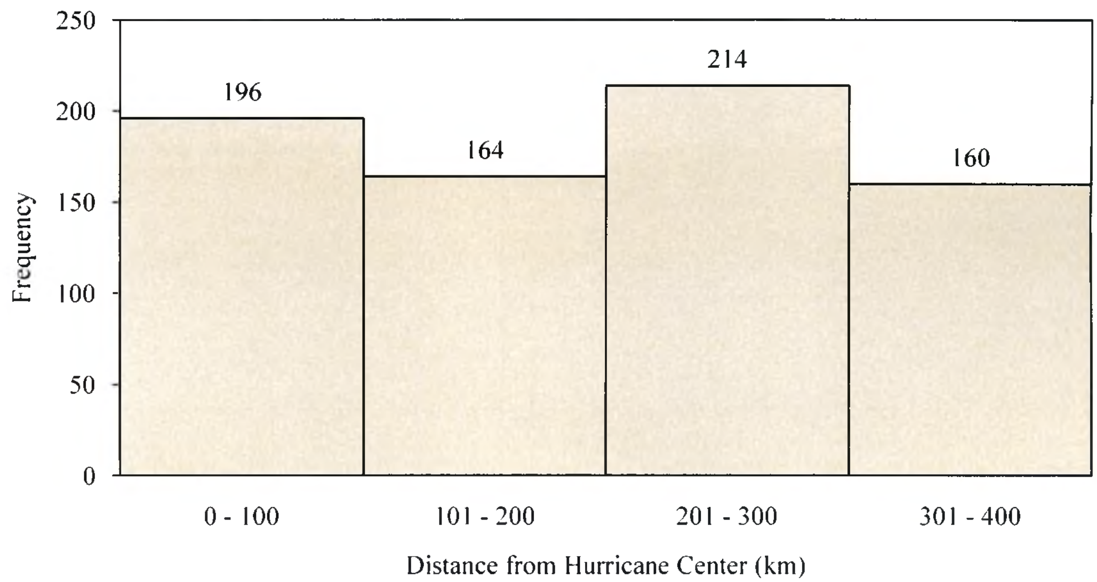


FIGURE 4.11. Frequency distribution: hurricane-tornado distance from hurricane center.

Maps of individual hurricanes and their associated hurricane-tornadoes can be found in Appendix B. These maps were used to examine hurricane-tornado location relative to their associated hurricane's center. The maps clearly illustrate that hurricane-tornadoes were most often located to the right of hurricane center, relative to the hurricane's directional heading. Further observational discussion of the maps is in chapter V.

4.5 Relationship between Hurricane-Tornadoes and Associated Hurricanes

Hurricane Intensity and Hurricane-Tornado Frequency

Figure 4.12 illustrates hurricane-tornado frequency with respect to S.S. scale. The frequency of hurricane-tornadoes, relative to S.S. scale, ranged from 2 - 443.

Maximum frequency occurred in association with category 3 hurricanes. Minimum frequency occurred in association with category 5 hurricanes.

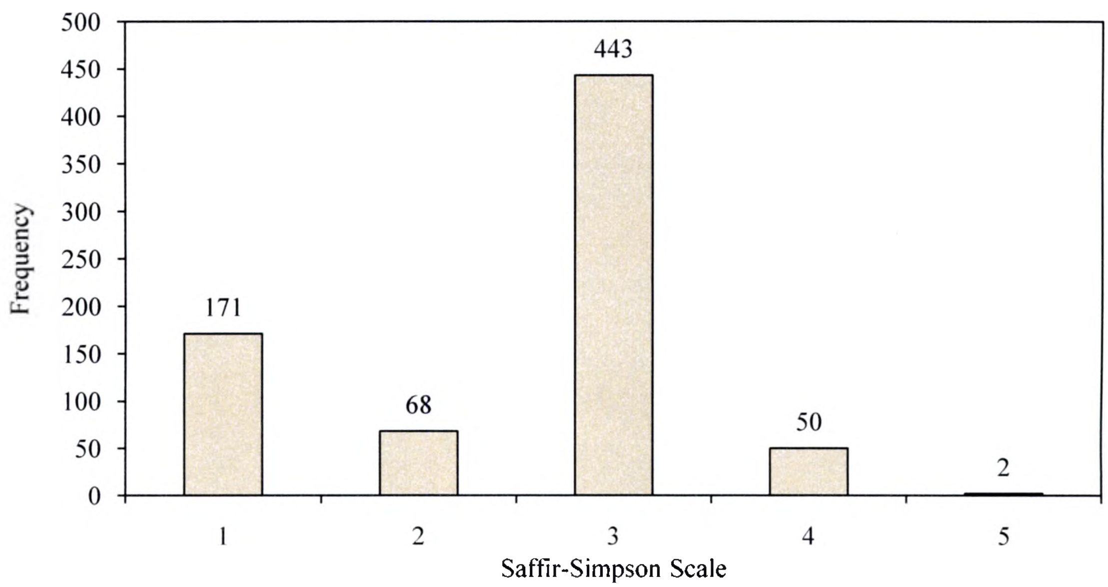


FIGURE 4.12. Frequency distribution: hurricane-tornado frequency per S.S. scale.

A chi-square test for homogeneity was used to statistically test the uniformity of hurricane-tornado distribution per S.S. scale. Further, Kendall's tau-b correlation (2-tailed) was performed to test for a possible correlation and, if a correlation exists, to determine the strength of the correlation between hurricane-tornado frequency and S.S. scale. Table 4.6 provides a summary of the tests.

TABLE 4.6. (A) Chi-square test for homogeneity and (B) Kendall's tau-b correlation: hurricane-tornado frequency and S.S. scale.

(A)

Observed Distribution:

	Cat 1	Cat 2	Cat 3	Cat 4, 5	∑
Hurricane-Tornadoes	171	68	443	52	734

Expected Distribution:

	Cat 1	Cat 2	Cat 3	Cat 4, 5	∑
Hurricane-Tornadoes	183.5	183.5	183.5	183.5	734

Degrees of Freedom (df): 3

Significance Level (α): 0.01

Critical Value at $\alpha = 0.01$ and 3 df: 11.34

Calculated Chi-Square: 534.73

H_O: Hurricane-tornadoes are uniformly distributed with respect to S.S. scale.

H_A: Hurricane-tornadoes are not uniformly distributed with respect to S.S. scale.

Results:

Calculated Chi-Square > Critical Value; Reject Ho at $\alpha = 0.01$.

(B)

Correlation Coefficient: 0.201

p value: 0.049

*statistically significant at $\alpha = 0.05$

Hurricane Intensity and Hurricane-Tornado Intensity

Table 4.7 provides a cross-tabulation of hurricane-tornadoes categorized by F-scale and S.S. scale. No apparent relationship exists based on the observed distribution.

TABLE 4.7. Hurricane-tornado frequency cross-tabulated by F-scale and S.S. scale.

Saffir-Simpson Scale (rows) and Fujita Scale (columns)

	0	1	2	3	4	∑
1	78	60	27	5	0	170
2	22	29	13	2	0	66
3	191	129	50	9	1	380
4	20	13	9	7	1	50
5	1	0	0	0	0	1
∑	312	231	99	23	2	667

A chi-square test for independence was performed to statistically test for an association between S.S. scale and F-scale. Further, Kendall's tau-b correlation (2-tailed) was performed to examine the possible correlation and, and if one exists, to determine the strength of the association between S.S. scale and F-scale. Table 4.8 provides a summary of the tests.

TABLE 4.8. (A) Chi-square test for independence and (B) Kendall's tau-b correlation: F-scale and S.S. scale.

(A)

Observed Distribution:

	F0	F1	F2	F3,4, 5	Σ
Cat 1	78	60	27	5	170
Cat 2	22	29	13	2	66
Cat 3	191	129	50	10	380
Cat 4, 5	21	13	9	8	51
Σ	312	231	99	25	667

Expected Distribution:

	F0	F1	F2	F3, 4, 5	Σ
Cat 1	80	59.2	25.4	6.4	171
Cat 2	30.9	22.9	9.8	2.5	66.1
Cat 3	177.8	131.6	56.4	14.2	380
Cat4, 5	23.9	17.7	7.6	1.9	51.1
Σ	312.6	231.4	99.2	25	668.2

Degrees of Freedom (df): 9
Significance Level (α): 0.01
Critical Value at $\alpha = 0.01$ and 9 df: 14.68
Calculated Chi-Square: 30.26

H_O: S.S. scale and F-scale are independent with respect to hurricane-tornado frequency.

H_A: S.S. scale and F-scale are related with respect to hurricane-tornado frequency.

Result:

Calculated Chi-Square value > Critical Value; Reject H_O at $\alpha = 0.01$

(B)

Correlation Coefficient: -0.012
p value: 0.734

Hurricane Directional Heading and Hurricane-Tornado Frequency

Figure 4.13 illustrates hurricane-tornado frequency per hurricane directional heading. The frequency ranged from 0 - 406. Maximum frequency occurred in association with hurricanes heading W of N near landfall. Minimum frequency occurred in association with hurricanes heading W of S, or E near landfall.

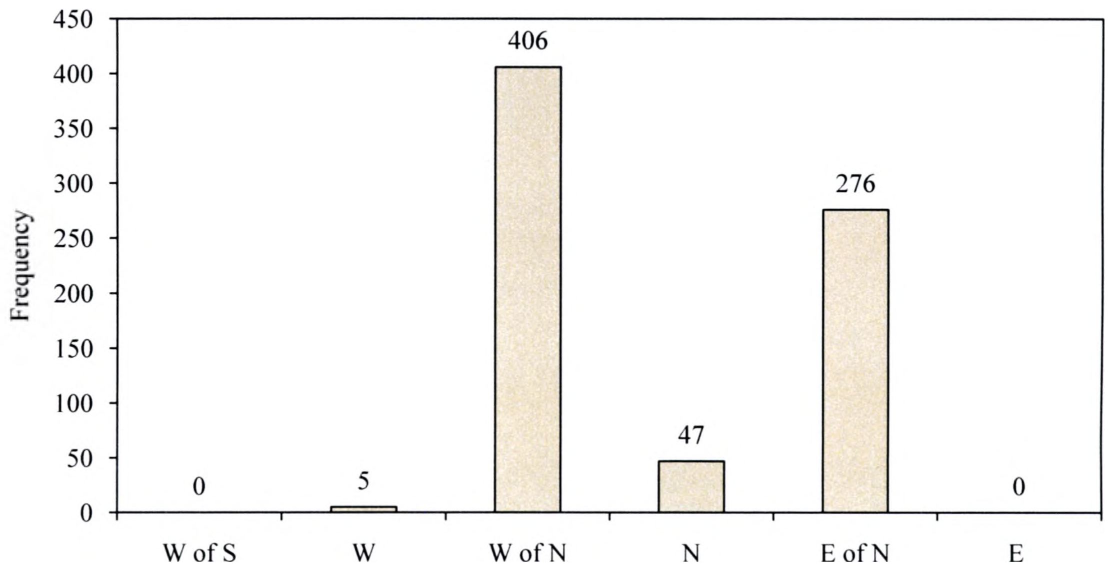


FIGURE 4.13. Frequency distribution: hurricane-tornadoes with respect to directional heading of associated hurricane near landfall.

4.6 Summary

Statistical and GIS technologies were used to analyze the data. Initial analysis consisted of frequency distributions to examine distributions and search for patterns within the data. When warranted, statistical tests were used to further examine patterns and relationships. Specific tests used were chi-square tests for homogeneity and independence and Kendall's tau-b correlation. GIS was used to visualize and examine the spatial distribution of the data. The following chapter will provide interpretation, discussion, and contextualization of the results presented in this chapter. Further, when appropriate, descriptive statistics and statistical tests will be repeated to provide results with extreme values excluded.

CHAPTER V

ANALYSIS OF RESULTS

5.1 Introduction

The purpose of this chapter is to interpret, analyze, and contextualize the results presented in chapter IV. Descriptive statistics, Kendall's tau-b, and chi-square tests will be interpreted and contextualized. When appropriate, descriptive statistics and statistical tests will be repeated to provide results with extreme values excluded. Hurricane-tornado probability distributions will be provided based on the observed frequency distributions. Results will be linked to previous hurricane-tornado research. It is not in the purpose of this chapter to provide causality; however, when appropriate, causality will be deduced from links within the data and information attained from previous research. The organization of this chapter will follow chapter IV.

5.2 Hurricane-Tornado Characteristics

Hurricane-Tornado Frequency

The magnitude of hurricane-tornado outbreaks varied. Ten hurricanes produced 0 hurricane-tornadoes, while two hurricanes produced more than 50. On average, Gulf Coast-landfalling hurricanes produced 12 hurricane-tornadoes. Fifty-four hurricanes fell within one standard deviation of the mean. The six hurricanes that fell outside of one standard deviation are Danny (1985), Allen (1980), Cindy (2005), Andrew (1992), Beulah (1967), and Ivan (2004). Hurricanes Ivan and Beulah were the most extreme, with 101 and 83 hurricane-tornadoes respectively. These two values fell outside of three standard deviations from the mean.

For this thesis, those values outside three standard deviations are considered extreme. Descriptive statistics were repeated on hurricane-tornado frequency with hurricanes Beulah and Ivan excluded due to their extreme values (Table 5.1). This is not to say that hurricanes Beulah and Ivan were errors in the data that should be excluded from analysis; on the contrary, they should be noted as extreme meteorological events in the context of hurricane-tornadoes. However, the extremities of their values skew the results, especially the mean, range, and standard deviation. As a result, the initial descriptive statistics may not reflect normal hurricane-tornado frequency.

With hurricanes Beulah and Ivan excluded, the range of hurricane-tornado outbreaks decreased from 0 - 101 to 0 - 49 tornadoes per hurricane, the mean decreased from 12.23 to 9.48 tornadoes per hurricane, and standard deviation decreased from 18.81 to 11.52. These values more accurately reflect normal hurricane-tornado frequency. Therefore, assuming that hurricanes Beulah and Ivan were extreme events that do not reflect normal hurricane-tornado frequency, Gulf Coast-landfalling hurricanes will produce, on average, nine hurricane-tornadoes. Furthermore, normal hurricane-tornado outbreaks, based on one standard deviation, have a range of 0 - 21. In other words, an outbreak of 0 - 21 hurricane-tornadoes with a Gulf Coast-landfalling hurricane can be considered within normal range. However, it is speculated that the maximum extent of this range may be too low. Advances in tornado detection due to technology and human observations are likely to create an increase in the number of hurricane-tornadoes reported, thus increasing the number of reported hurricane-tornadoes.

TABLE 5.1. Descriptive statistics: hurricane-tornado frequency per hurricane, excluding hurricanes Beulah and Ivan.

Hurricane-Tornado Frequency			
N = 58.00			
Central Tendency:		Variance:	
Mean	9.48	Range	49.00 (min = 0.00, max = 49.00)
Median	5.00	Standard Deviation	11.52
Mode	0.00	Skewness	1.79
		Kurtosis	2.87

Figure 5.1 illustrates the skewed nature of hurricane-tornado outbreaks. The positive skewness indicates that hurricanes are more likely to produce relatively few hurricane-tornadoes, rather than large outbreaks. As discussed, hurricane-tornado outbreaks between 0 - 21 can be considered normal. Eighty percent of the observed hurricanes produced 0 - 21 hurricane-tornadoes. Further, 57 % produced 0 - 5 hurricane-tornadoes. Outbreaks with greater than 21 hurricane-tornadoes become increasingly rare as their extremity increases. Only 20 % produced 21 + hurricane-tornadoes, with 13 % producing 21 - 35 and only 7 % producing more than 46.

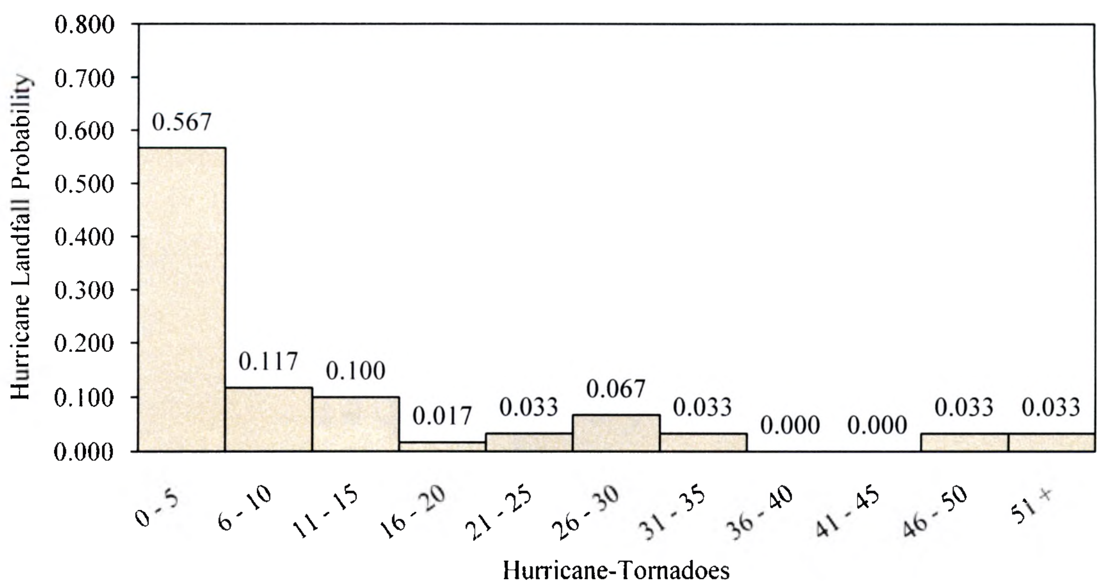


FIGURE 5.1. Probability distribution: hurricane-tornado outbreaks.

As seen, most hurricanes produce relatively few hurricane-tornadoes. However, hurricanes are capable of producing significant hurricane-tornado outbreaks. Table 5.2 provides a list of the ten maximum outbreaks. These hurricanes account for only 17 % of the observed hurricanes, but produced 62 % of the observed hurricane-tornadoes.

TABLE 5.2. Ten maximum hurricane-tornado outbreaks (1950-2005).

Name	Landfall Date	Landfall State	Landfall Intensity	Total Tornadoes	F0	F1	F2	F3
Ivan	9/16/2004	Alabama	3	101	44	39	17	1
Beulah	9/20/1967	Texas	3	83	66	8	3	6
Andrew	8/26/1992	Louisiana	3	49	29	19	0	1
Cindy	7/6/2005	Louisiana	1	46	28	15	3	0
Allen	8/10/1980	Texas	3	34	12	11	11	0
Danny	8/15/1985	Louisiana	1	33	6	14	8	5
Georges	9/28/1998	Mississippi	2	28	16	11	1	0
Katrina	8/29/2005	Louisiana	3	27	12	13	2	0
Lili	10/3/2002	Louisiana	1	26	20	6	0	0
Rita	9/24/2005	Louisiana	3	26	10	12	3	1

Hurricane-Tornado Intensity

Observed hurricane-tornadoes were not uniformly distributed with respect to F-scale (Figure 5.2). Rather, the distribution was positively skewed, indicating that weak hurricane-tornadoes occur most often. Hurricane-tornadoes rated F0 have the greatest probability of occurrence - 47 % of the observed hurricane-tornadoes examined were F0. Furthermore, 81 % were rated weak, 18% were rated strong, and only 0.3 % were rated violent. There were zero F5 hurricane-tornadoes reported and only two F4 hurricane-tornadoes. The two F4 hurricane-tornadoes were associated with hurricanes Carla (1961) and Hilda (1964).

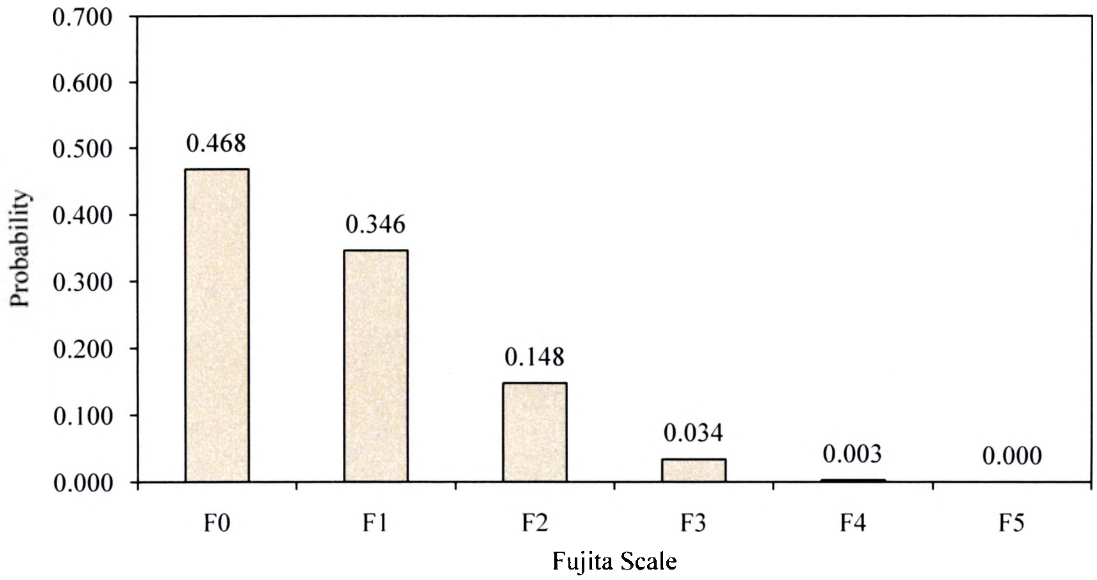


FIGURE 5.2. Probability distribution: hurricane-tornado intensity.

A chi-square test for homogeneity was performed to statistically test the distribution. The purpose was to test whether the non-uniform distribution was tangible or due to chance in the sampling process. The x^2 was 299.30 and the critical value at 3 df and $\alpha = 0.01$ was 11.34. The x^2 was greater than the critical value, therefore H_O was rejected. The rejection of H_O indicates that there is a tangible non-uniformity within the distribution of hurricane-tornadoes with respect to F-scale. Thus, according to this chi-square test, it can be concluded that weak hurricane-tornadoes are more probable than strong or violent hurricane-tornadoes. This result concurs with previous research (Smith 1965; Novlan and Gray 1974), which reported that hurricane-tornadoes are relatively weak. The relative weakness of hurricane-tornadoes can be partly attributed to the relative weakness and low altitude location of mesocyclones within landfalling hurricanes (McCaul 1987, 1991; McCaul and Weisman 1996; Spratt et al. 1997; McCaul et al. 2004).

Hurricane-Tornado Path Length and Width

Hurricane-tornado path length and width had large ranges (1.6 - 67.6 km and 2.7 - 804.7 m, respectively). Average path length was 5.9 km, with a 7.0 km standard deviation. Four-hundred and thirteen path length values fell within one standard deviation of the mean. There were seven extreme values (those outside three standard deviations), which were greater than 26.9 km. The maximum path length (67.6 km), which was an F2, was associated with hurricane Charley (2004), which was a category 4. Average path width was 68.5 m, with an 82.6 m standard deviation. Five-hundred and seventy-five path width values fell within one standard deviation of mean. There were 16 extreme values (those outside three standard deviations), which were greater than 316.3 m. The maximum path width (804.7 m), which was also an F2, was associated with hurricane Cindy (2005), which was a category 1. The presences of such extreme values skew the data. Thus, the descriptive statistics may not accurately reflect actual hurricane-tornado path lengths and widths.

Descriptive statistics were repeated on path length and width without the extreme values (Table 5.3). Similar to hurricane-tornado frequency, it is not thought that these values were data errors, but were, however, extreme events that do not reflect normal path lengths and widths. With the extreme values excluded, path length range decreased from 1.6 - 67.6 km to 1.6 - 25.7 km, mean decreased from 5.9 km to 5.3 km, and standard deviation decreased from 7.0 km to 5.4 km; path width range decreased from 2.7 - 804.7 m to 2.7 - 304.5 m, mean decreased from 68.5 m to 58.3 m, and standard deviation decreased from 82.6 m to 49.4 m. Therefore, assuming that path lengths greater than 26.9 km are extreme events, hurricane-tornadoes have an average path length of 5.3 km, rather than 5.9 km. Path lengths can be considered normal (within one standard deviation) when falling within a range of 1.6 - 10.7 km. Likewise, assuming that path widths greater than 316.3 m are extreme events, hurricane-tornadoes have an average path width of 58.3 m, rather than 68.5 m. Path widths can be considered normal (within one standard deviation) when falling within a range of 2.7 - 107.7 m.

TABLE 5.3. Descriptive statistics: hurricane-tornado path length and width, excluding extreme values.

Hurricane-Tornado Path Length (km) and Path Width (m)			
Path Length:			
N = 456			
Central Tendency:		Variance:	
Mean	5.3	Range	24.1 (min = 1.6, max = 25.7)
Median	3.2	Standard Deviation	5.4
Mode	1.6	Skewness	1.7
		Kurtosis	2.3
Path Width:			
N = 614			
Central Tendency:		Variance:	
Mean	58.3	Range	301.8 (min = 2.7, max = 304.5)
Median	45.7	Standard Deviation	49.4
Mode	45.7	Skewness	2.0
		Kurtosis	4.8

Observed hurricane-tornadoes were not uniformly or normally distributed with respect to their path lengths and widths (Figure 5.3 and 5.4, respectively). Both, path length and width, distributions were positively skewed. This indicates that hurricane-tornadoes with relatively small path lengths and widths occur more frequently than those with larger path lengths and widths. Hurricane-tornadoes with a path length of one mile have the greatest probability of occurrence - 43 % of the observed hurricane-tornadoes had a path length of one mile. The probability of occurrence generally decreases as hurricane-tornado path length increases. Hurricane-tornadoes with a path width of 26 - 50 yards have the greatest probability of occurrence - 46 % of the observed hurricane-tornadoes had a path width of 26 - 50 yards. Similar to path length, the probability of occurrence generally decreases as path width increases.

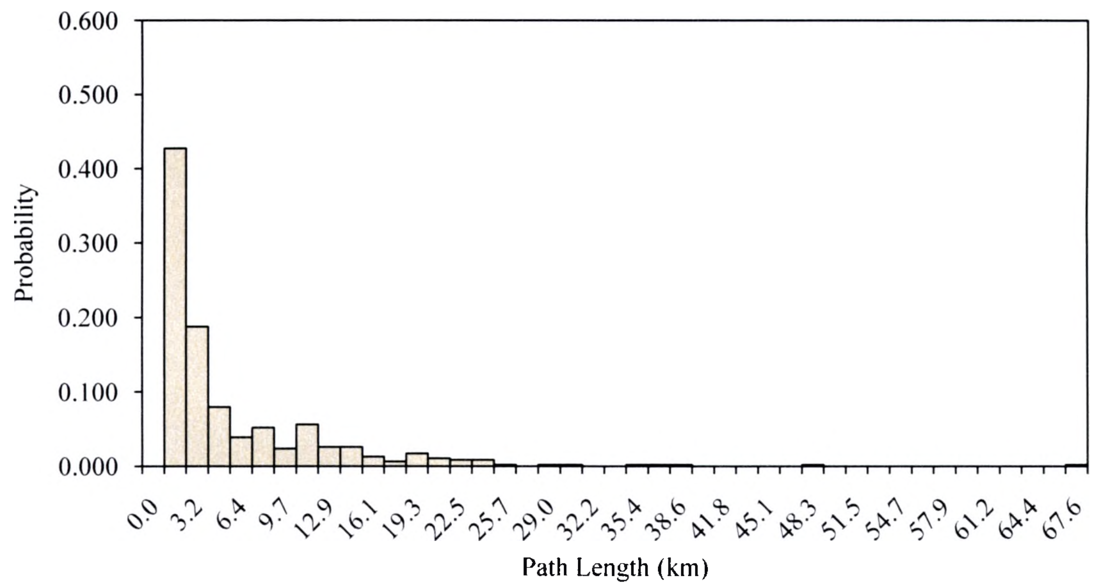


FIGURE 5.3. Probability distribution: hurricane-tornado path length.

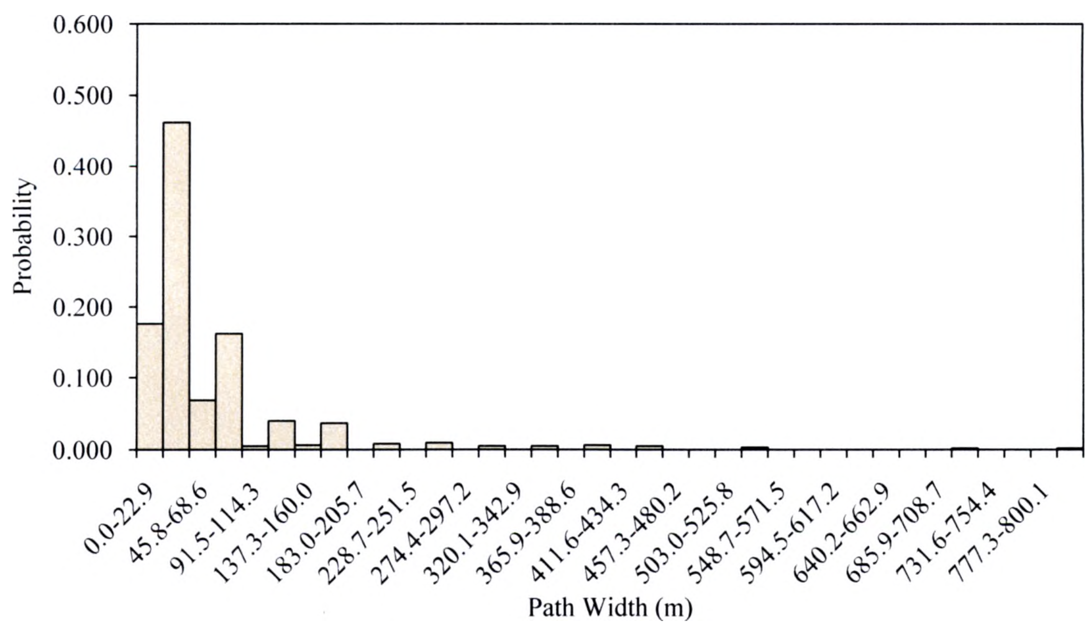


FIGURE 5.4. Probability distribution: hurricane-tornado path width.

5.3 Temporal Distribution

Inter-Annual Distribution

Inter-annual hurricane-tornado frequency varied, but indicated a general increasing trend throughout the study period. Further, events that can be considered more extreme than normal (recall from section 5.2 that outbreaks within a range of 0 - 21 are considered normal) appear to occur more frequently from 1980 – 2005, with only one occurring before 1980 (Figure 5.5). In fact, only one outbreak (hurricane Beulah) that produced more than 21 hurricane-tornadoes occurred before 1980. Moreover, all of the top ten maximum outbreaks (Table 5.2), except hurricane Beulah, have occurred after 1980. This is not, however, to say that hurricane-tornado outbreaks are becoming more frequent or extreme. Some of the increase may be due to climatological variation, but it more likely results from increased public awareness and advancements in tornado detection technology, especially the deployment of Doppler Weather Surveillance Radar.

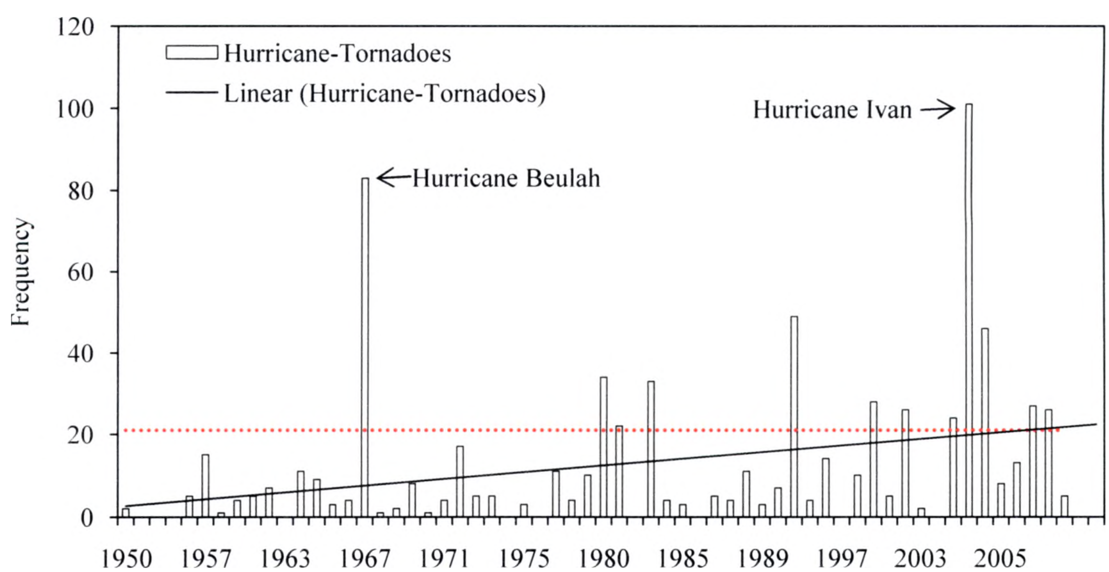


FIGURE 5.5. Hurricane-tornadoes per annum. Red dotted line indicates the maximum extent of normal hurricane-tornado frequency.

The inter-annual distribution of hurricane-tornadoes depends on hurricane landfall frequency. Generally, more hurricane landfalls provide more opportunity for hurricane-tornado production. Twenty-three of the observed years had zero hurricane-tornadoes. Nineteen of these years had zero hurricane landfalls, hence zero opportunity for hurricane-tornadoes. The remaining four years had only one hurricane landfall, which were associated with zero hurricane-tornadoes. Oppositely, 11 of the observed years had 20 or more hurricane-tornadoes, and most of these years had two or more hurricane landfalls. For instance, there were six hurricane landfalls in 2005. Subsequently, that year had the highest frequency of hurricane-tornadoes, along with 2004. Other years, such as 1967 and 2004, were anomalous. These years had hurricanes that produced many hurricane-tornadoes. Hurricane Beulah in 1967 produced 82 hurricane-tornadoes and hurricane Ivan in 2004 produced 101 hurricane-tornadoes. Besides anomalous years, such as 1967 and 2004, the annual frequency of hurricane-tornadoes is dependent on hurricane landfall frequency. Therefore, it can be concluded that hurricane-tornadoes are more probable in those years with multiple hurricane landfalls.

Intra-Seasonal Distribution

Observed hurricane-tornadoes were not uniformly distributed throughout the season (Figures 5.6 and 5.7). Hurricane-tornadoes have the greatest probability of occurrence in middle season, specifically September - 76 % of observed hurricane-tornadoes occurred in middle season, 47 % occurred in September. The probability of hurricane-tornadoes in early and late season was substantially less - 14 % and 10 %, respectively. A general pattern emerges when examining the monthly distribution of hurricane-tornadoes - the probability of hurricane-tornado occurrence increases from June to a maximum in September, and then sharply declines to November, when zero hurricane-tornadoes were reported.

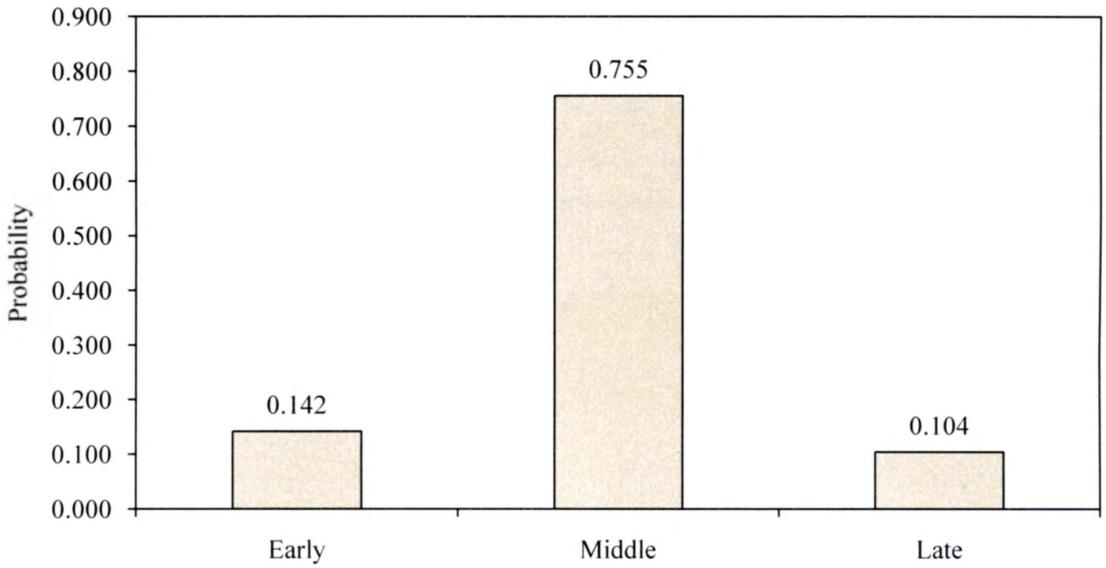


FIGURE 5.6. Probability distribution: hurricane-tornado intra-seasonal distribution.

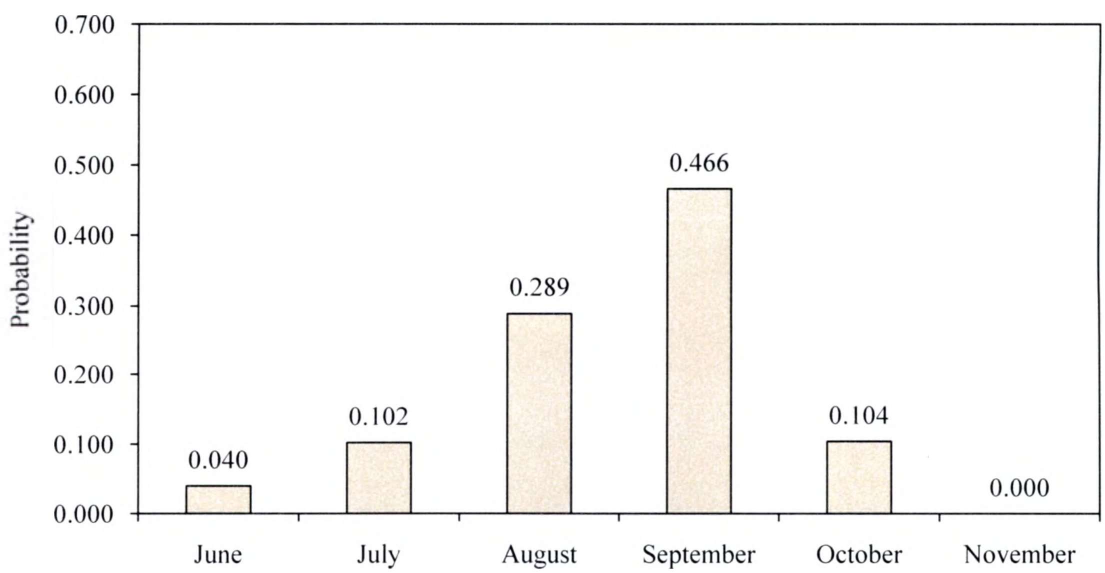


FIGURE 5.7. Probability distribution: hurricane-tornado monthly distribution.

A chi-square test for homogeneity was performed to statistically test the distribution. The purpose was to test whether the non-uniform distribution was tangible or due to chance in the sampling process. The x^2 was 339.44 and the critical value at 4 df and α = 0.01 was 13.28. The x^2 was greater than the critical value, therefore H_O was rejected. The rejection of H_O indicates that there is a tangible non-uniformity in the distribution of hurricane-tornadoes throughout the season. Thus, according to this chi-square test, the probability of hurricane-tornado occurrence is greatest in middle season, specifically September. Table 5.4 provides a detailed description of monthly hurricane-tornado distribution. Note that all hurricane-tornadoes, regardless of their F-scale rating, are most probable in middle season.

TABLE 5.4. Hurricane-tornado monthly distribution categorized by F-scale. The top number is the frequency, middle number is the monthly probability, and the bottom number is the F-scale probability.

Hurricane-Tornadoes per Month						
	Hurricane-Tornadoes	F0	F1	F2	F3	F4
		4	12	11	1	0
June	28	0.143	0.429	0.393	0.036	0.000
		0.013	0.052	0.111	0.043	0.000
		51	20	4	0	0
July	75	0.680	0.267	0.053	0.000	0.000
		0.163	0.087	0.040	0.000	0.000
		108	66	28	6	0
August	208	0.519	0.317	0.135	0.029	0.000
		0.346	0.286	0.283	0.261	0.000
		108	114	42	16	1
September	281	0.384	0.406	0.149	0.057	0.004
		0.346	0.494	0.424	0.696	0.500
		41	19	14	0	1
October	75	0.547	0.253	0.187	0.000	0.013
		0.131	0.082	0.141	0.000	0.500

This result concurs with previous research (Smith 1965; Novlan and Gray 1974) reporting a maximum frequency in September. An important note to make is that hurricanes Beulah and Ivan occurred in September. They contribute significantly to September's hurricane-tornado frequency. September might not have been the monthly maximum if these values were less extreme; however, middle season would remain the maximum regardless of these two values.

The intra-seasonal distributions of hurricane landfalls and hurricane-tornadoes are nearly identical, indicating that the monthly distribution of hurricane-tornadoes is, at least partially, controlled by hurricane landfall frequency (Figure 5.8). Generally, more hurricane landfalls provide more opportunities for hurricane-tornado production.

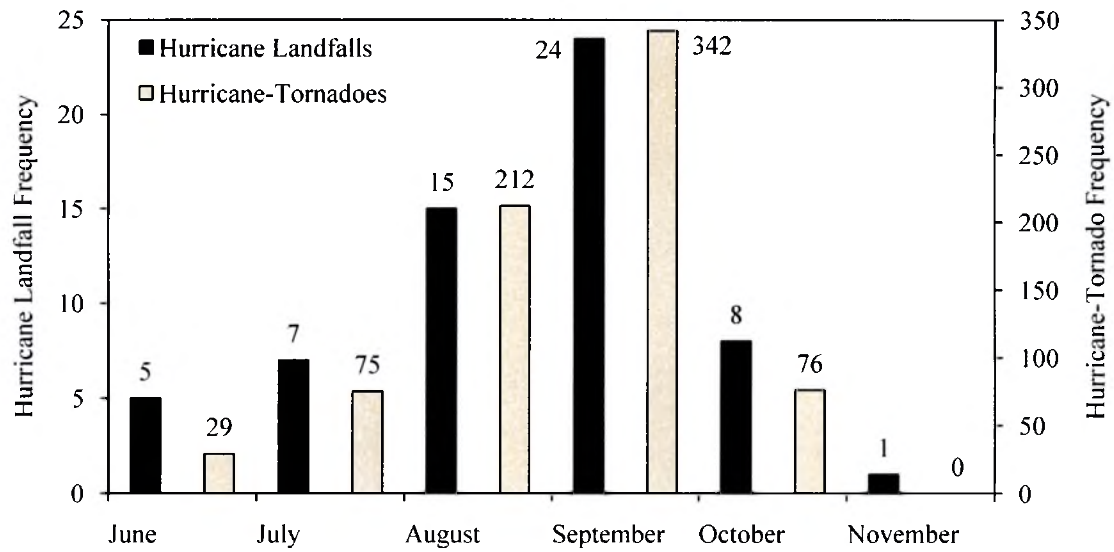


FIGURE 5.8. Monthly hurricane landfall and hurricane-tornado frequency.

Furthermore, the frequency of intense hurricane landfalls was greatest in middle season (Table 5.5). Hurricane intensity is a factor that can influence hurricane-tornado frequency. Specifically, intense hurricanes are more likely to produce a greater number of hurricane-tornadoes (Smith 1965; Hill, Malkin and Schulz 1966; Novlan and Gray 1974; McCaul 1991; Verbout et al. 2007). The relationship between S.S. scale and hurricane-tornado frequency is discussed in section 5.5. For this section, note that 79 % of the observed intense hurricanes made landfall in middle season, with 48 % occurring in September.

TABLE 5.5. Monthly hurricane landfall distribution categorized by S.S. scale.

Hurricane Landfalls per Month	Category 1	Category 2	Category 3	Category 4	Category 5
June	3	1	0	1	0
July	5	0	2	0	0
August	5	1	7	1	1
September	8	2	11	2	1
October	3	2	3	0	0
November	0	1	0	0	0

Observed hurricanes making landfall in middle season produced, on average, more hurricane-tornadoes than those in early and late season (Figure 5.9). Further, eight of the top 10 hurricane-tornado producing hurricanes, including Beulah and Ivan, occurred in middle season (Table 5.2). Therefore, hurricane-tornado outbreaks that occur in middle season (i.e. landfalling hurricanes) are likely to be greater than those in early and late season. This can be partly attributed to the greater frequency of intense hurricane landfalls in middle season, which as seen above are more likely to produce greater numbers of hurricane-tornadoes. Another possible attribution could be interaction with synoptic weather systems present at the time of landfall, which can induce hurricane-tornado production.

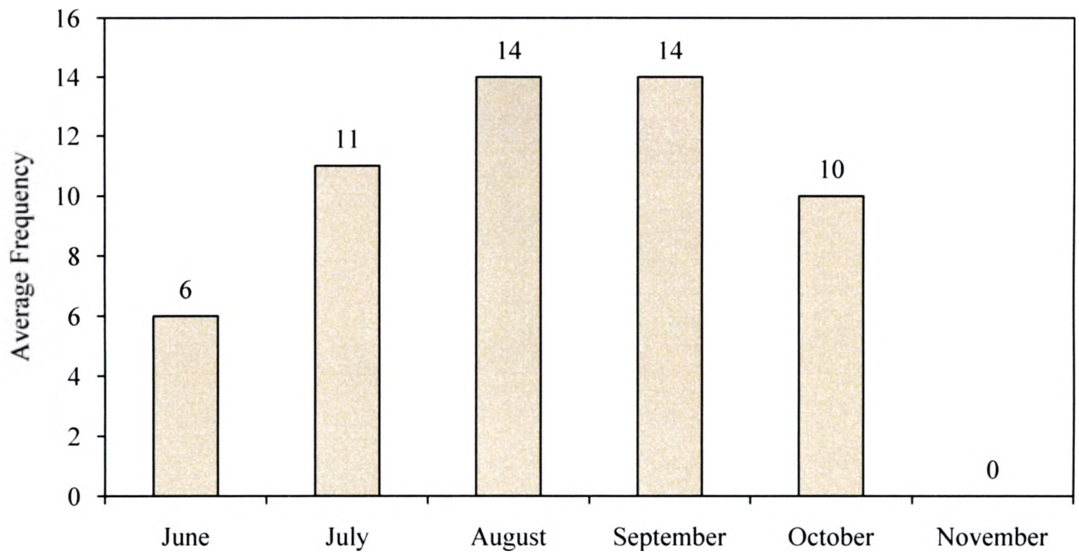


FIGURE 5.9. Average hurricane-tornado frequency per hurricane per month.

In summation, hurricane-tornadoes are most probable in middle season, specifically September. Much of the observed distribution can be attributed to the relatively high frequency of hurricane landfalls, especially intense hurricanes, in middle season. The relatively high frequency of total hurricane landfalls in middle season provides more opportunities for hurricane-tornado production. The relatively high frequency of intense hurricane landfalls in middle season increases the potential for significant hurricane-tornado outbreaks.

Diurnal Distribution

Figure 5.10 illustrates hurricane-tornado bi-hourly probability distribution. The probability of hurricane-tornado occurrence is greatest between 2000 and 2159 UTC (2:00 - 3:59 PM CST and 3:00 - 4:59 PM EST) - 17 % of the observed hurricane-tornadoes occurred during this time interval. More importantly, nearly half (44 %) of hurricane-tornadoes occur between 1800 - 2359 UTC (12:00 - 6:00 PM CST and 1:00 - 7:00 PM EST), indicating a preference for afternoon hours. Hurricane-tornadoes are least probable between 0400 and 0559 UTC (10:00 - 11:59 PM CST and 11:00 PM -

12:59 AM EST) - 2 % of the observed hurricane-tornadoes occurred during this time interval.

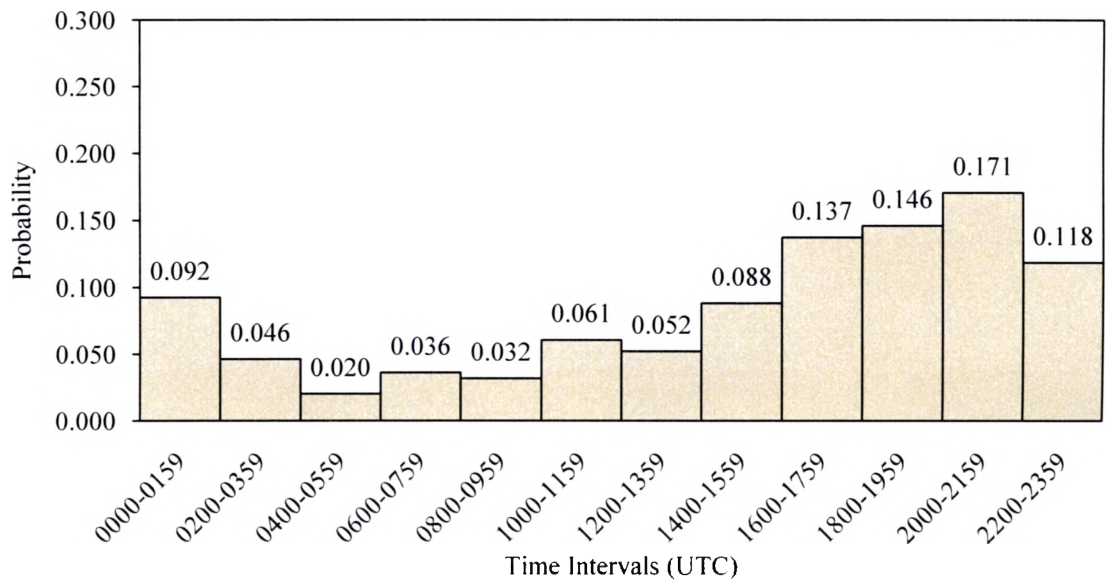


FIGURE 5.10. Probability distribution: hurricane-tornado diurnal distribution.

The bi-hourly distribution of hurricane-tornadoes is variable. However, a general diurnal pattern is observable. This pattern is better illustrated by expanding the bi-hourly distribution over a three day period (Figure 5.11). A four-hour moving mean was applied to the distribution to smooth the variations to more clearly show the general trend. Generally, the probability of hurricane-tornado occurrence increased from midnight to a maximum in mid-afternoon, and then decreased towards a minimum near midnight. This pattern supports the bias of hurricane-tornado occurrence to afternoon hours.

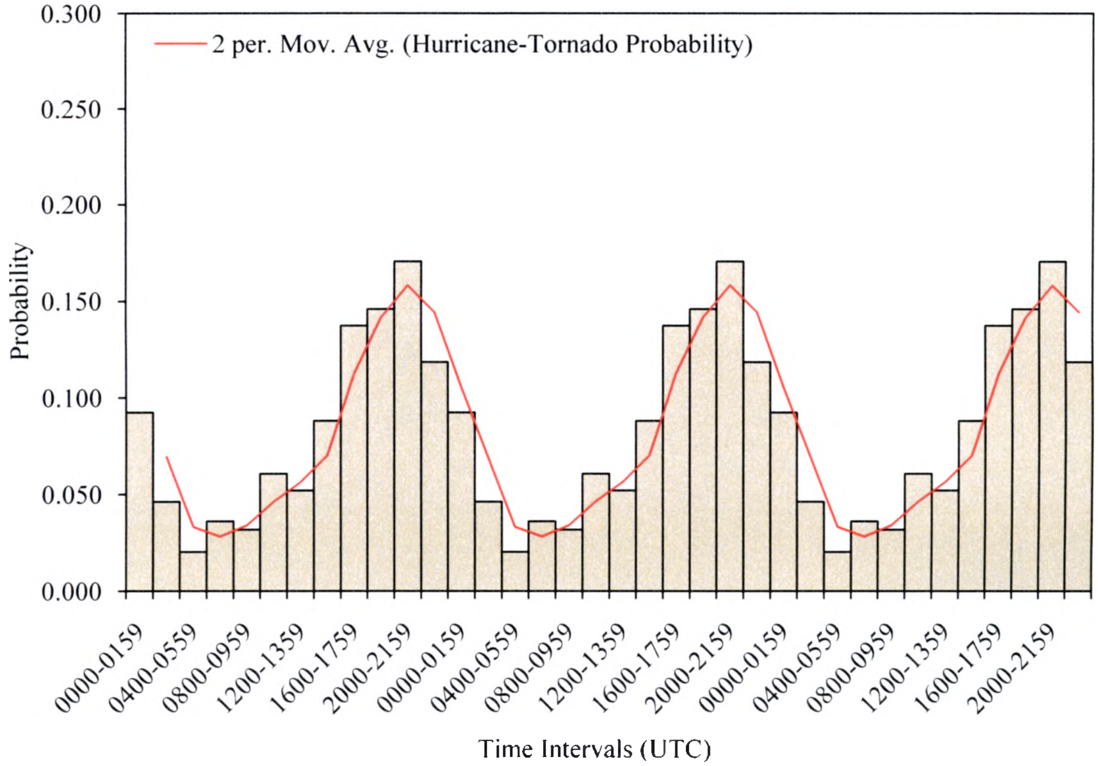


FIGURE 5.11. Probability distribution: hurricane-tornado bi-hourly distribution extended over a three day period.

The preference for hurricane-tornado occurrence in afternoon hours, between 1800 - 2359 UTC, determined by this thesis concurs with previous research (Gentry 1983). Part of this preference can be explained by assuming that more hurricane-tornadoes will be detected in afternoon hours. However, there are likely to be other physical mechanisms. One such mechanism could be the accumulation of solar radiation by the land surface in the afternoon, which in turn heats the boundary layer enough to induce convective instability (Gentry 1983; McCaul 1991), thereby increasing the potential for hurricane-tornado production.

In relation to hurricane landfall time, observed hurricane-tornado occurrence ranged from 41 hours pre-landfall to 42 hours post-landfall. The hourly distribution pre and post-landfall was variable, however a general pattern can be seen by applying a two-hour moving mean to the distribution (Figure 5.12). Generally, hurricane-tornado frequency increases from 41 hours pre-landfall to a maximum frequency 1 - 1.9 hours post-landfall, where it then begins to decline with clustered activity peaking approximately every 13 - 15 hours. The primary clusters are located at 0 - 11 hours post-landfall, with a peak at 1.0 - 1.9 hours; 11.0 - 19.9 hours post-landfall, with a peak at 15.0 - 15.9 hours; and 35.0 - 40.9 hours post-landfall, with a peak at 38.0 - 38.9 hours. Two less peaked clusters are located at 8.9 - 0 hours pre-landfall and 22.0 - 27.9 hours post-landfall. The probability of hurricane-tornado occurrence was greatest in the first cluster (0 - 11 hours post-landfall) - 33 % of the observed hurricane-tornadoes occurred in this time interval. Following, hurricane-tornadoes are likely to occur from 12.0 - 18.9 hours post-landfall, when 17 % of the observed hurricane-tornadoes occurred, and from 8.9 - 0 hours pre-landfall, when 15 % of the observed hurricane-tornadoes occurred.

The primary cluster, from 0 - 11 hours post-landfall, likely results from vertical wind shear brought upon by mechanical friction between land surface and boundary layer winds. In essence, as hurricanes make landfall their boundary layer winds decelerate due to mechanical friction with the underlying land surface, thereby creating vertical wind shear. This mechanism likely plays a part in hurricane-tornado production before landfall as outer rainbands begin to interact with land surface and during landfall as inner rainbands begin to move over land. Other mechanisms, such as convective rainband instability, dry air intrusion, or a converging air mass, likely contribute to post-landfall hurricane-tornado clustering (e.g. 35.0 - 40.9 hours post-landfall). One such example is hurricane Ivan (2004). Ivan merged with a frontal system approximately 36 hours post-landfall after tracking NE through the eastern United States (NOAA 2005b).

Consequentially, Ivan produced 67 % of the observed hurricane-tornadoes that occurred 28 hours or after post-landfall.

In summation, hurricane-tornadoes are most probable in the afternoon hours, with a small probability peak between 2000 and 2159 UTC. Further, they are most probable within the first 24 hours post-landfall, with a significant peak of activity 1 - 1.9 hours post-landfall.

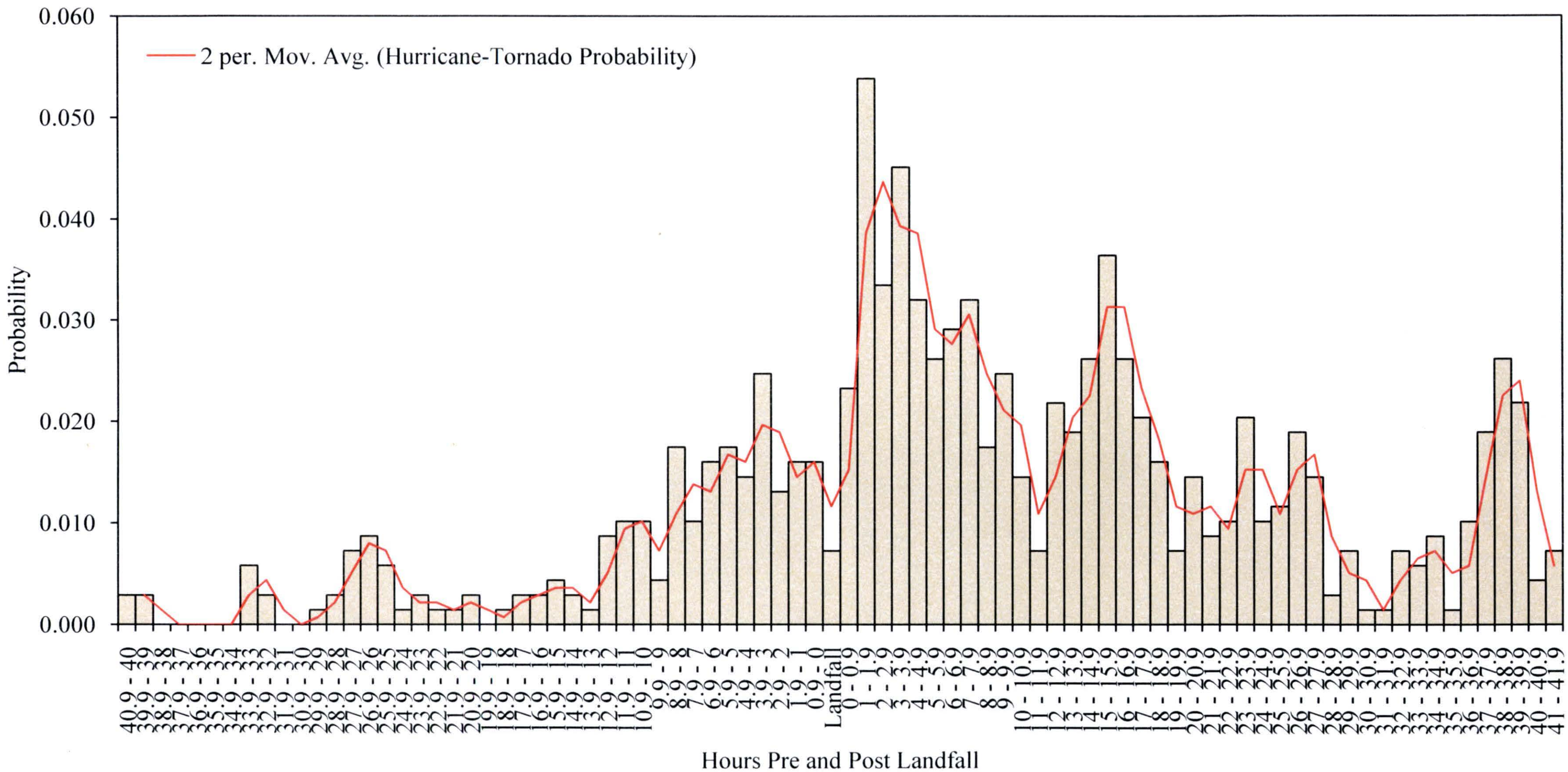


FIGURE 5.12. Probability distribution: time difference between hurricane-tornado touchdown and associated hurricane landfall.

5.4 Spatial Distribution

Distribution by State

Hurricane-tornadoes associated with Gulf Coast-landfalling hurricanes are most likely to occur in the states proximate to the Gulf of Mexico. Seventy-nine percent of the observed hurricane-tornadoes occurred in Gulf Coast states. In respect to the Gulf Coast states, Texas had the greatest frequency with 199 observed hurricane-tornadoes and Mississippi had the lowest frequency with 70. Further, a large portion of the observed hurricane-tornadoes were located within 200 km of the Gulf Coastline. The remaining 21 % were distributed throughout Non-Gulf Coast States, mainly along the East Coast. The observed spatial distribution concurs with previous research (Hill, Malkin and Schulz 1966; Novlan and Gray 1974) which found that the majority of hurricane-tornadoes occur within 100 nautical miles (185.2 km) of the coastline.

Distribution with Respect to Hurricane Center

Observed hurricane-tornado distribution with respect to distance from hurricane center is rather uniformly distributed (Figure 5.13), thus indicating that hurricane-tornadoes are not biased to a certain distance from hurricane center. They are, however, slightly more probable between 0 - 100 km and 201 - 300 km from hurricane center, where 27 % and 29 % of the observed hurricane-tornadoes occurred, respectively. These two distance intervals are likely associated with inner and outer rainbands. Hurricane-tornado production is more probable within rainbands due to their increased vertical wind shear and convective potential (Hill, Malkin and Schulz 1966; Novlan and Gray 1974; Gentry 1983; Weiss 1987; McCaul 1991; Spratt et al. 1997; Bogner, Barnes and Franklin 2000).

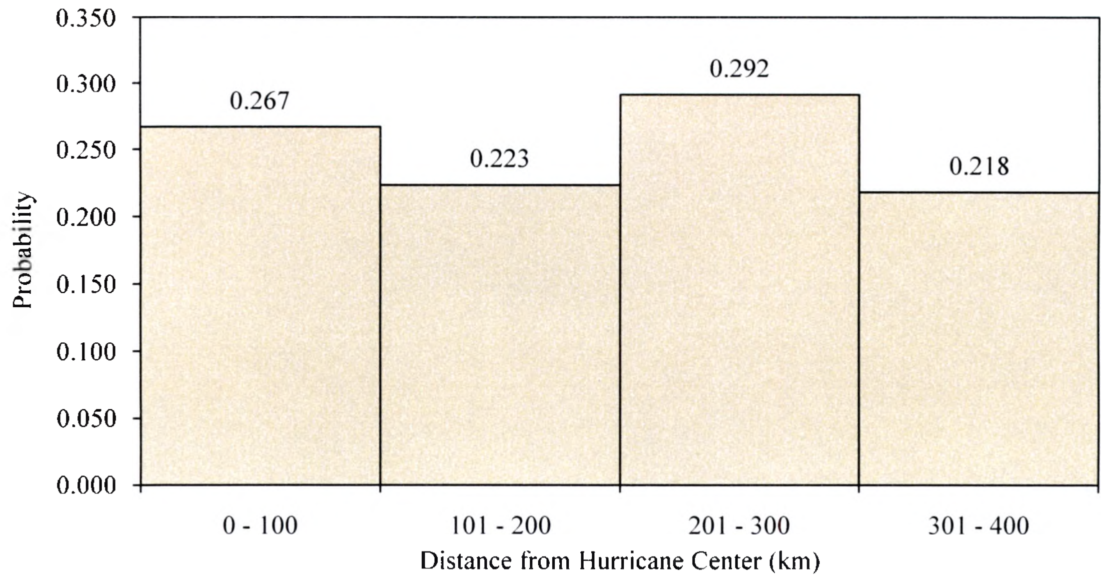


FIGURE 5.13. Probability distribution: hurricane-tornado distance from hurricane center.

Hurricane-tornadoes are more probable to the right of their associated hurricane center rather than left, relative to directional heading. Appendix B provides maps of each hurricane track and their associated hurricane-tornadoes. The maps clearly illustrate the bias of hurricane-tornadoes to be located to the right of hurricane center. Two distinct examples are hurricanes Ivan (2004) and Cindy (2005). All of Cindy's hurricane-tornadoes were located to the right of center and nearly all of Ivan's were located to the right of center, with some occurring to the left on the day after landfall. One notable exception was hurricane Andrew (1992), in which hurricane-tornadoes were moderately evenly distributed to the right and left of hurricane center. Further, the maps illustrate the preference for hurricane-tornado occurrence in the right-front quadrant of hurricanes, relative to directional heading, as determined by previous research (Pearson and Sadowski 1965; Smith 1965; Hill, Malkin and Schulz 1966; Orton 1970; Novlan and Gray 1974; Gentry 1983; McCaul 1991; Hagemeyer 1997; Verbout et al. 2007). For examples see hurricanes Babe (1977), Danny (1985), Earl (1998), Ivan (2004), and

Cindy (2005). This observation was derived from the tendency for the hurricane-tornadoes to lead their associated hurricane track.

Two other observations were derived from the maps in Appendix B. One, hurricane-tornadoes that occurred to the left of hurricane center were primarily located near the hurricane center, usually within 100 km. Hurricane-tornadoes that were right of center, on the other hand, were rather uniformly distributed throughout a range of 0 - 400 km from center. Two, only one of the hurricane-tornadoes that occurred to the left of hurricane center occurred on the day before landfall. This hurricane-tornado was associated with hurricane Allen (1980). All other hurricane-tornadoes that were left of center occurred on the day of or after landfall.

Therefore, based on these observations, several conclusions can be made. One, hurricane-tornadoes are most probable in coastal states, specifically within 200 km. Two, hurricane-tornadoes are most likely to be located to the right of hurricane center, relative to hurricane directional heading. Three, hurricane-tornadoes located right of center occur throughout a distance of 0 - 400 km from hurricane center and occur the day before, the day of, and the day after landfall. Four, hurricane-tornadoes located left of center are primarily located within 100 km of hurricane center and are highly unlikely to occur before landfall.

5.5 Relationship between Hurricane-Tornadoes and Associated Hurricanes

Hurricane Intensity and Hurricane-Tornado Frequency

Observed hurricane-tornadoes were not uniformly distributed with respect to S.S. scale (Figure 5.14). Rather, they were erratically distributed. Hurricane-tornadoes are most probable with category 3 hurricanes - 60 % of the observed hurricane-tornadoes were associated with category 3 hurricanes. Furthermore, 68 % of the observed hurricane-tornadoes were associated with intense hurricanes.

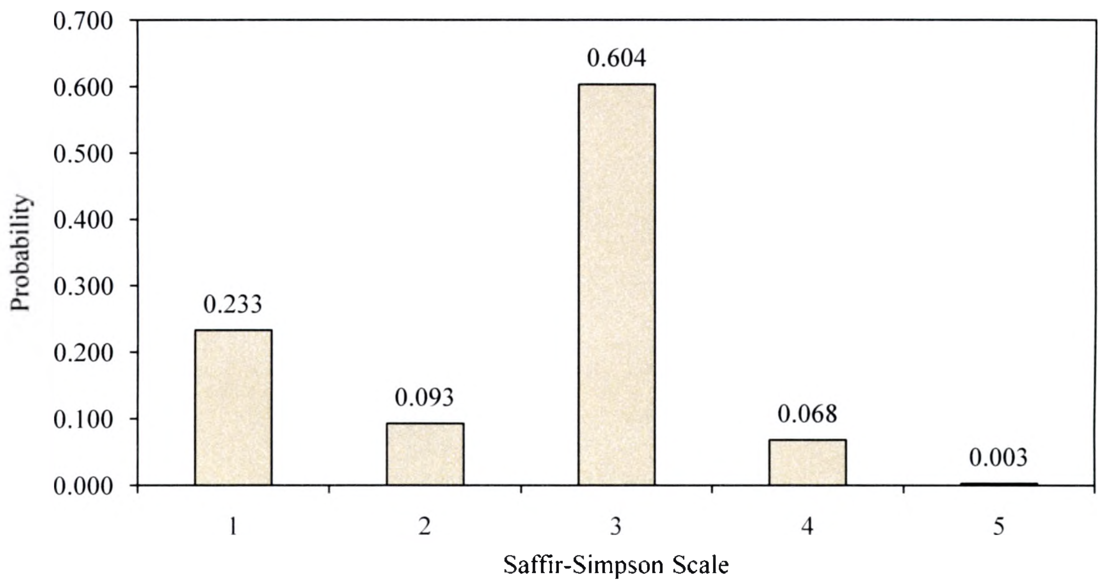


FIGURE 5.14. Probability distribution: hurricane-tornado probability per S.S. scale.

A chi-square test for homogeneity was performed to statistically test the distribution. The purpose was to test whether the non-uniform distribution was tangible or due to chance in the sampling process. The x^2 was 534.73 and the critical value at 3 df and $\alpha = 0.01$ was 11.36. The x^2 was greater than the critical value, therefore H_O was rejected. The rejection of H_O indicates that there is a tangible non-uniformity in the distribution of hurricane-tornadoes with respect to S.S. scale. Thus, according to this chi-square test, the probability of hurricane-tornado occurrence is greatest with category 3 hurricanes. This result concurs with previous research (Smith 1965; Hill, Malkin and Schulz 1966; Novlan and Gray 1974; McCaul 1991; Verbout et al. 2007) that has reported greater hurricane-tornado probability with intense hurricanes.

To further examine the association between hurricane-tornado frequency and S.S. scale, a two-tailed Kendall's tau-b correlation test was performed. The purpose was to test the association and determine the strength of the association between hurricane-tornado frequency and S.S. scale. The test resulted in a correlation coefficient of 0.201 and a p value of 0.049, which is statistically significant at $\alpha = 0.05$. This indicates that there is a weak positive correlation between hurricane-tornado frequency and S.S. scale. However, it is important to note that the extreme values associated with hurricanes Beulah and Ivan contribute to the significance and correlation coefficient (Table 5.6). With Beulah and Ivan excluded, the correlation coefficient decreases to 0.178, which is not statistically significant at $\alpha = 0.05$. Therefore, without the influence of the two most extreme values, a statistically significant association does not exist between hurricane-tornado frequency and S.S. scale. However, based on the observed distribution and a weak positive association, it can be concluded that hurricane-tornadoes are most probable with intense hurricanes, specifically category 3.

TABLE 5.6. Kendall's tau-b test results with and without hurricanes Beulah and Ivan.

	Including Beulah and Ivan	Excluding Beulah and Ivan
N	60	58
Correlation Coefficient	0.201	0.178
Significance	0.049	0.088

Category 3 hurricanes accounted for only 38 % of the observed hurricanes, but were associated with 60 % of the observed hurricane-tornadoes (Figure 5.15). An important note to make is that hurricanes Beulah and Ivan were both rated category 3. Their extreme values contribute significantly to the abundance of hurricane-tornadoes associated with category 3. However, when these values are excluded, category 3 hurricanes still accounted for nearly half (47 %) of the observed hurricane-tornadoes.

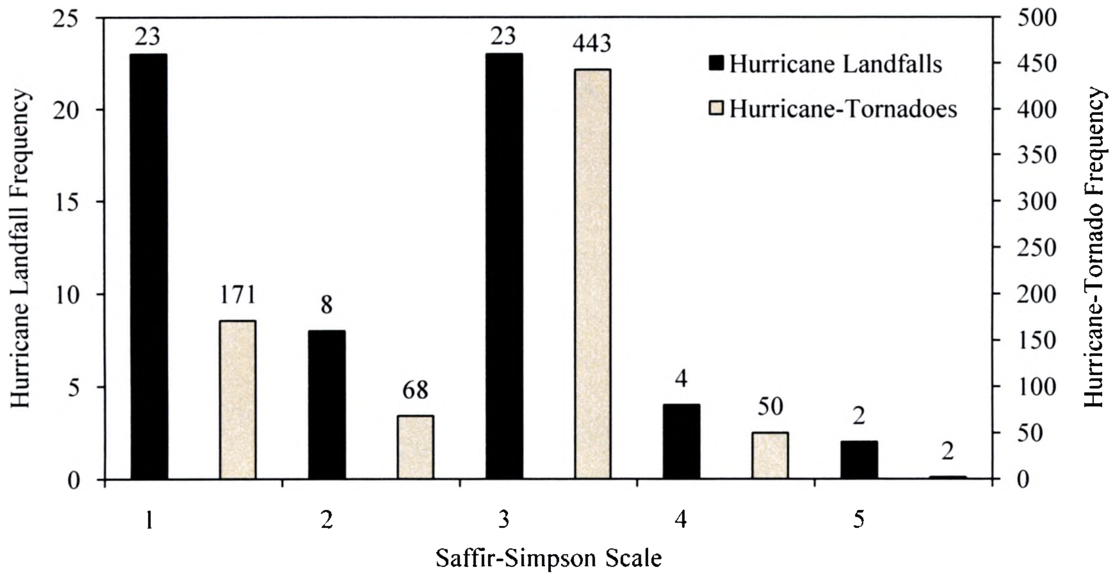


FIGURE 5.15. Hurricane landfalls and hurricane-tornadoes per S.S. scale.

Category 3 hurricanes produce, on average, more hurricane-tornadoes than other categories (Table 5.7). Moreover, six of the top 10 hurricane-tornado producing hurricanes were rated category 3 (Table 5.2). Hurricanes Beulah and Ivan skew the category 3 average. Excluding hurricanes Beulah and Ivan, category 3 and 4 are the maxima, which further supports the conclusion that hurricane-tornadoes are most probable with intense hurricanes.

TABLE 5.7. Average hurricane-tornado frequency per S.S. scale. The number in parentheses associated with category 3 is the value with hurricanes Beulah and Ivan excluded.

Saffir-Simpson Scale	Average Hurricane-Tornado Frequency
1	7
2	9
3	19 (13)
4	13
5	1

In summation, hurricane-tornadoes are most probable with intense hurricanes, specifically category 3. Further, large outbreaks are most probable with intense hurricanes.

Hurricane Intensity and Hurricane-Tornado Intensity

Weak hurricane-tornadoes are the most likely F-scale ratings to occur in all hurricanes, regardless of their S.S. scale ratings. However, there appears to be an association between strong and violent hurricane-tornadoes and intense hurricanes (Table 5.8). Sixty percent of the observed strong hurricane-tornadoes were associated with intense hurricanes. Further, the two observed violent hurricane-tornadoes were associated with intense hurricanes. A chi-square test for independence was performed to test for a statistically significant association between S.S. scale and F-scale. The x^2 was 30.26 and the critical value at 9 df and α = 0.01 was 14.68. The x^2 was greater than the critical value, therefore H_O was rejected. The rejection of H_O indicates that S.S. scale and F-scale are associated.

TABLE 5.8. Hurricane-tornado frequency cross-tabulated by S.S. scale and F-scale. Top number is the frequency, middle number is the S.S. scale probability, and the bottom number is the F-scale probability.

Saffir Simpson Scale and Fujita Scale Matrix						
	Hurricane-Tornadoes	F0	F1	F2	F3	F4
		78	60	27	5	0
Category 1	170	0.459	0.352	0.159	0.029	0.000
		0.250	0.260	0.273	0.217	0.000
		22	29	13	2	0
Category 2	66	0.333	0.439	0.197	0.030	0.000
		0.071	0.126	0.131	0.087	0.000
		191	129	50	9	1
Category 3	380	0.503	0.339	0.132	0.024	0.003
		0.612	0.558	0.505	0.391	0.500
		20	13	9	7	1
Category 4	50	0.400	0.260	0.180	0.140	0.020
		0.064	0.056	0.091	0.304	0.500
		1	0	0	0	0
Category 5	1	1.000	0.000	0.000	0.000	0.000
		0.003	0.000	0.000	0.000	0.000

Once again, a two-tailed Kendall's tau-b correlation test was performed to test the association and strength of the association between S.S. scale and F-scale. The test resulted in a correlation coefficient of -0.012, which was not statistically significant. This indicates that there is not a statistically significant association between S.S. scale and F-scale.

Therefore, based on the chi-square and correlation tests, it is concluded that S.S. scale and F-scale are not associated. However, it should be noted that with the relatively high frequency of hurricane-tornadoes associated with intense hurricanes there is greater opportunity for the production of strong and violent hurricane-tornadoes.

Hurricane Directional Heading and Hurricane-Tornado Frequency

Observed hurricane-tornadoes were not uniformly distributed with respect to hurricane directional heading (Figure 5.16). Hurricane-tornadoes are most probable with hurricanes heading W of N near landfall - 55 % of the observed hurricane-tornadoes occurred with hurricanes heading W of N.

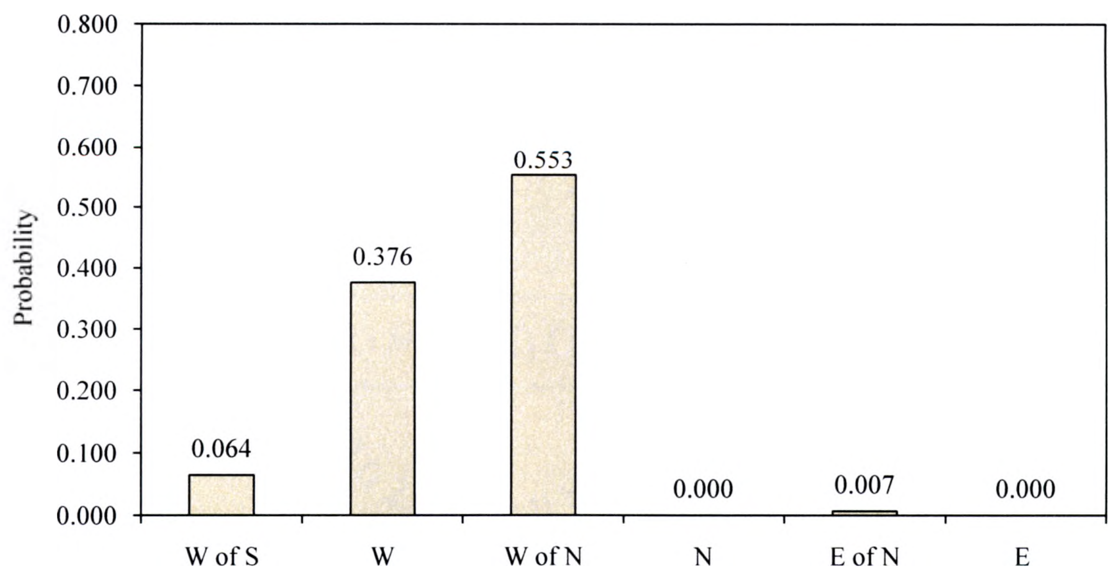


FIGURE 5.16. Probability distribution: hurricane-tornadoes with respect to directional heading of associated hurricane near landfall.

Hurricanes with a directional heading of W of N, N, and E of N produced, on average, comparable hurricane-tornado frequencies - 12, 13, and 14 respectively (Table 5.9). Furthermore, the frequency of hurricane landfalls is greatest in association with a directional heading W of N near landfall, thus providing more opportunity for hurricane-tornado production (Table 5.9). Therefore, hurricane-tornadoes are not necessarily more probable with hurricanes heading W of N. However, the slight maximum in average hurricane-tornado frequency associated with hurricanes heading W of N can be attributed to the duration of interaction between a hurricane's right-front quadrant and land surface. Hurricane-tornadoes are most likely to occur in the right-front quadrant due to increased vertical wind shear, helicity, and convection. Hurricanes heading W of N near landfall along the Gulf Coastline (especially the central section that runs approximately parallel to lines of latitude) have more interaction between their right-front quadrant, relative to directional heading, and land surface, thus increasing the potential for hurricane-tornado production. This result differs from previous research (Smith 1965; Hill, Malkin and Schulz 1966; Novlan and Gray 1974; Verbout et al. 2007) that reported maximum frequency with hurricanes heading N to NE near landfall.

TABLE 5.9. Hurricane frequency, hurricane-tornado frequency, and average hurricane-tornado frequency per hurricane with respect to hurricane directional heading near landfall.

Directional Heading	Hurricanes Landfalls	Hurricane-Tornadoes	Average Hurricane-Tornadoes per Hurricane
W of S	3	0	0
W	2	5	3
W of N	29	406	14
N	4	47	12
E of N	22	276	13

5.6 Summary

This chapter interpreted, analyzed, and contextualized the results presented in chapter IV. Links within the data were examined, specifically the links between hurricane landfall frequency and hurricane-tornado frequency. It was found that many of the observed distributions could be, at least partially, attributed to hurricane-landfall frequency (i.e. more hurricane landfalls provide more opportunities for hurricane-tornado production) and the presence of mechanisms reported to increase potential for hurricane-tornado production (i.e. vertical wind shear, helicity, and convection). Chapter VI will reiterate this information specifically addressed to the research questions.

CHAPTER VI

CONCLUSION

The purpose of this thesis was to develop a climatology of hurricane-tornadoes associated with Gulf Coast-landfalling hurricanes from 1950 - 2005. A combination of statistical and GIS analysis was used to address the research questions posed by this thesis. Following is a list of concluding remarks specifically addressed to the research questions posed in this thesis. The conclusions are generalized, reference previous chapters for details.

1. What are hurricane-tornado characteristics, including the magnitude of outbreaks, their intensity, and their path lengths and widths?

   The magnitude of hurricane-tornado outbreaks and hurricane-tornado path lengths and widths were analyzed with descriptive statistics. Hurricane-tornado intensity was analyzed with descriptive statistics and a chi-square test. It was found that the majority of landfalling hurricanes produce fewer than 10 hurricane-tornadoes, with an average of 9. However, reports of 80 + hurricane-tornadoes have been documented in association with Gulf Coast-landfalling hurricanes. Hurricane-tornadoes associated with Gulf Coast-landfalling hurricanes are relatively weak, with the probability of weak hurricane-tornadoes much greater than that of strong and violent hurricane-tornadoes. Hurricane-tornadoes in association with Gulf Coast-landfalling hurricanes have relatively small path lengths and widths -

average path length is approximately 5.3 km and average path width is approximately 58.3 m.

2. What are the temporal distributions of hurricane-tornadoes associated with Gulf Coast-landfalling hurricanes, including inter-annual, intra-seasonal, and diurnal distributions?

   The temporal distributions of hurricane-tornadoes associated with Gulf Coast-landfalling hurricanes were primarily analyzed with the use of frequency distributions. A chi-square test was used to further analyze the intra-seasonal distribution. The inter-annual distribution of hurricane-tornadoes varies greatly. Annual hurricane-tornado frequency ranged from 0 - 125. Since 1950, annual hurricane-tornado frequency analysis indicates a general increasing trend. Furthermore, extreme outbreaks have occurred more frequently since 1980. However, the climatological record of hurricane-tornadoes is not long enough to conclude with certainty that hurricane-tornadoes are occurring more frequently, or that extreme outbreaks are becoming more frequent. The intra-seasonal hurricane-tornado distribution also varies. Hurricane-tornadoes associated with Gulf Coast-landfalling hurricanes are most probable in middle season, specifically September. Also, extreme events, both significant outbreaks and strong and violent hurricane-tornadoes, are most probable in middle season. Diurnally, hurricane-tornadoes are most probable in afternoon hours. With respect to respective hurricane landfall, hurricane-tornadoes are most probable post-landfall, especially in the first 24 hours post-landfall.

3. What is the spatial distribution of hurricane-tornadoes associated with Gulf Coast-landfalling hurricanes, including the small scale distribution throughout the Gulf Coast region and the distribution within their respective hurricane?

   The spatial distributions of hurricane-tornadoes associated with Gulf Coast-landfalling hurricanes were analyzed using GIS. Hurricane-tornadoes associated with Gulf Coast-landfalling hurricanes are most probable in Gulf Coast states, especially within 200 km of the coastline. With respect to hurricane center, hurricane-tornadoes are most likely to be located to the right of hurricane center. Those located to the right of center do not show a preference for certain distances from hurricane center. They are fairly uniformly distributed throughout 400 km radius from hurricane center. On the other hand, those that occur to the left of hurricane center are usually located within 100 km of center.

4. What is the distribution of hurricane-tornadoes with respect to hurricane intensity, as measured by the Saffir-Simpson Scale?

   The distribution of hurricane-tornadoes associated with Gulf Coast-landfalling hurricanes with respect to hurricane intensity was analyzed using chi-square and Kendall's tau-b tests. It was found that there is not a significant linear correlation between hurricane-tornado frequency and hurricane-intensity; however, there is an association between intense hurricanes and hurricane-tornado frequency. That is, intense hurricanes, specifically category 3, have the greatest probability to produce hurricane-tornadoes. Further, intense hurricanes are most probable to produce significant hurricane-tornado outbreaks.

5. Is hurricane-tornado intensity, as measured by the Fujita Scale, related to hurricane intensity, as measured by the Saffir Simpson Scale?
   The relationship between hurricane-tornado intensity and hurricane intensity was analyzed with chi-square and Kendall's tau-b tests. It was found that there is not a significant linear correlation between hurricane-tornado intensity and hurricane intensity. However, it is hypothesized that strong and violent hurricane-tornadoes are most probable with intense hurricanes because intense hurricanes produce more hurricane-tornadoes, thus providing more opportunities for the development of strong and violent hurricane-tornadoes.
6. What is the distribution of hurricane-tornadoes with respect to their associated hurricane's directional heading?
   The distribution of hurricane-tornadoes with respect to the directional heading of their associated Gulf Coast-landfalling hurricane was analyzed with the use of frequency distributions. It was found that hurricane-tornadoes occur with hurricanes heading W of N, N, and E of N near landfall, however they are slightly more probable with hurricanes heading W of N as they approach the Gulf Coastline.

These findings can benefit weather forecasters, emergency managers, insurance companies, and the public to be more aware of, and better prepared for, hurricane-tornadoes. Primarily, the provided temporal and spatial probabilities can increase awareness of when and where hurricane-tornadoes are most likely to occur, which will aid preparation. For instance, when an intense hurricane is expected to make landfall along the Gulf Coast in middle season, the public, within an area of 100 km left, 400 km right, and 200 km inland of the anticipated hurricane center landfall location, should be alerted for the possibility of hurricane-tornadoes.

Future research should continue to update hurricane-tornado climatologies, for the East and Gulf Coasts. The longer climatological records will provide results that better reflect normal hurricane-tornado activity. As such, the datasets created for this thesis are to be a continuing project, with the intent to continually update the climatological record of hurricane-tornadoes associated with Gulf Coast-landfalling hurricanes. Further, it is warranted to develop a climatology of hurricane-tornadoes associated with East Coast-landfalling hurricanes to determine if hurricanes making landfall along different coastlines have different hurricane-tornado climatologies.

Upon completion of this thesis, four topics of future study came to mind. One, the examination of intra-seasonal synoptic weather patterns in the Gulf Coast region and what, if any, impact these have on hurricane-tornado activity. Two, the effect that atmospheric teleconnections have on hurricane-tornado activity. Three, to further analyze the time difference between hurricane-tornado touchdown and associated hurricane landfall. Four, the examination of hurricane-tornado path direction using a methodology similar to that employed by Suckling and Ashley (2006).

APPENDIX A

Name	Landfall Date	Landfall Intensity	Total Tornadoes	F0	F1	F2	F3	F4
Baker	8/31/1950	1	2	1	1	0	0	0
Easy	9/5/1950	3	0	0	0	0	0	0
Florence	9/26/1953	1	0	0	0	0	0	0
**Alice	6/25/1954	1	0	0	0	0	0	0
*Flossy	9/24/1956	2	5	1	1	3	0	0
Audrey	6/27/1957	4	15	3	5	6	1	0
Debra	7/24/1959	1	1	1	0	0	0	0
Donna	9/10/1960	4	4	0	2	1	1	0
Ethel	9/15/1960	1	5	1	2	2	0	0
Carla	9/11/1961	4	7	0	0	1	5	1
Cindy	9/17/1963	1	0	0	0	0	0	0
Hilda	10/3/1964	3	11	0	4	6	0	1
Isbell	10/14/1964	2	9	1	4	4	0	0
Betsy	9/9/1965	3	3	1	2	0	0	0
Alma	6/9/1966	2	4	2	2	0	0	0
Beulah	9/20/1967	3	83	66	8	3	6	0
Gladys	10/19/1968	2	1	0	0	1	0	0
Camille	8/17/1969	5	2	2	0	0	0	0
Celia	8/3/1970	3	8	3	0	5	0	0
**Ella	9/12/1970	3	1	0	1	0	0	0
Fern	9/10/1971	1	4	2	2	0	0	0
Edith	9/16/1971	2	17	1	10	4	2	0
Agnes	6/19/1972	1	5	0	1	4	0	0
Carmen	9/8/1974	3	5	2	3	0	0	0
**Caroline	8/31/1975	3	0	0	0	0	0	0
Eloise	9/23/1975	3	3	1	2	0	0	0
**Anita	9/2/1977	5	0	0	0	0	0	0
Babe	9/5/1977	1	11	1	7	3	0	0
Bob	7/11/1979	1	4	1	2	1	0	0
Frederic	9/13/1979	3	10	6	4	0	0	0
Allen	8/10/1980	3	34	12	11	11	0	0
Alicia	8/18/1983	3	22	20	1	1	0	0
**Barry	8/28/1983	1	0	0	0	0	0	0
Danny	8/15/1985	1	33	6	14	8	5	0
Elena	9/2/1985	3	4	1	3	0	0	0
Juan	10/29/1985	1	3	1	2	0	0	0
Kate	11/21/1985	2	0	0	0	0	0	0
Bonnie	6/26/1986	1	5	0	4	1	0	0
Florence	9/10/1988	1	4	4	0	0	0	0

**Gilbert	9/16/1988	3	11	9	2	0	0	0
Chantal	8/1/1989	1	3	3	0	0	0	0
Jerry	10/16/1989	1	7	6	0	1	0	0
Andrew	8/26/1992	3	49	29	19	0	1	0
Erin	8/3/1995	2	4	3	1	0	0	0
Opal	10/4/1995	3	14	12	1	1	0	0
*Danny	7/18/1997	1	0	0	0	0	0	0
Earl	9/3/1998	1	10	3	3	4	0	0
Georges	9/28/1998	2	28	16	11	1	0	0
Bret	8/23/1999	3	5	5	0	0	0	0
Lili	10/3/2002	1	26	20	6	0	0	0
Claudette	7/15/2003	1	2	1	1	0	0	0
**Erika	8/16/2003	1	0	0	0	0	0	0
Charley	8/13/2004	4	24	18	5	1	0	0
Ivan	9/16/2004	3	101	44	39	17	1	0
Cindy	7/6/2005	1	46	28	15	3	0	0
Dennis	7/10/2005	3	8	7	1	0	0	0
**Emily	7/20/2005	3	13	12	1	0	0	0
Katrina	8/29/2005	3	27	12	13	2	0	0
Rita	9/24/2005	3	26	10	12	3	1	0
Wilma	10/24/2005	3	5	2	2	1	0	0

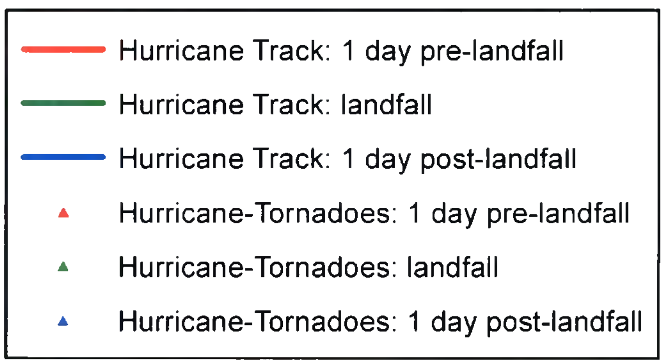
Note:

* indicates two landfall locations. Landfall date and intensity used in this thesis are those of the first landfall.

** indicates landfall location along northeast coastline of Mexico.

APPENDIX B

Maps portray individual Gulf Coast-landfalling hurricane tracks the day before, the day of, and the day after landfall, and associated hurricane-tornadoes from 1950 - 2005. Red line represents the hurricane track the day before landfall. Green line represents the hurricane track the day of landfall. Blue line represents the hurricane track the day after landfall. Triangles represent hurricane-tornadoes. Hurricane-tornado occurrence, categorized as the day before, the day of, or the day after hurricane landfall, is color coordinated with the hurricane track. Below is a generic legend.



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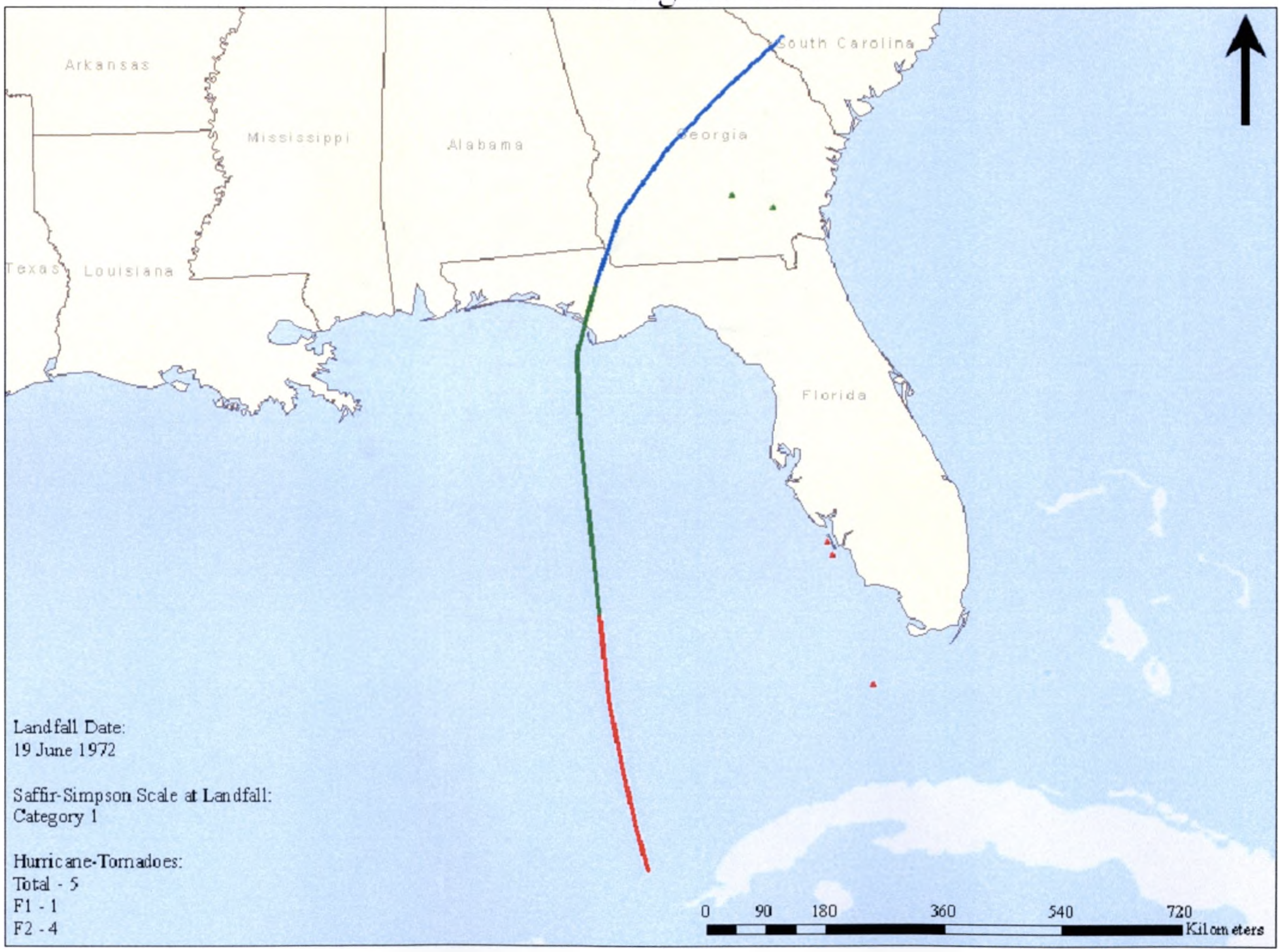

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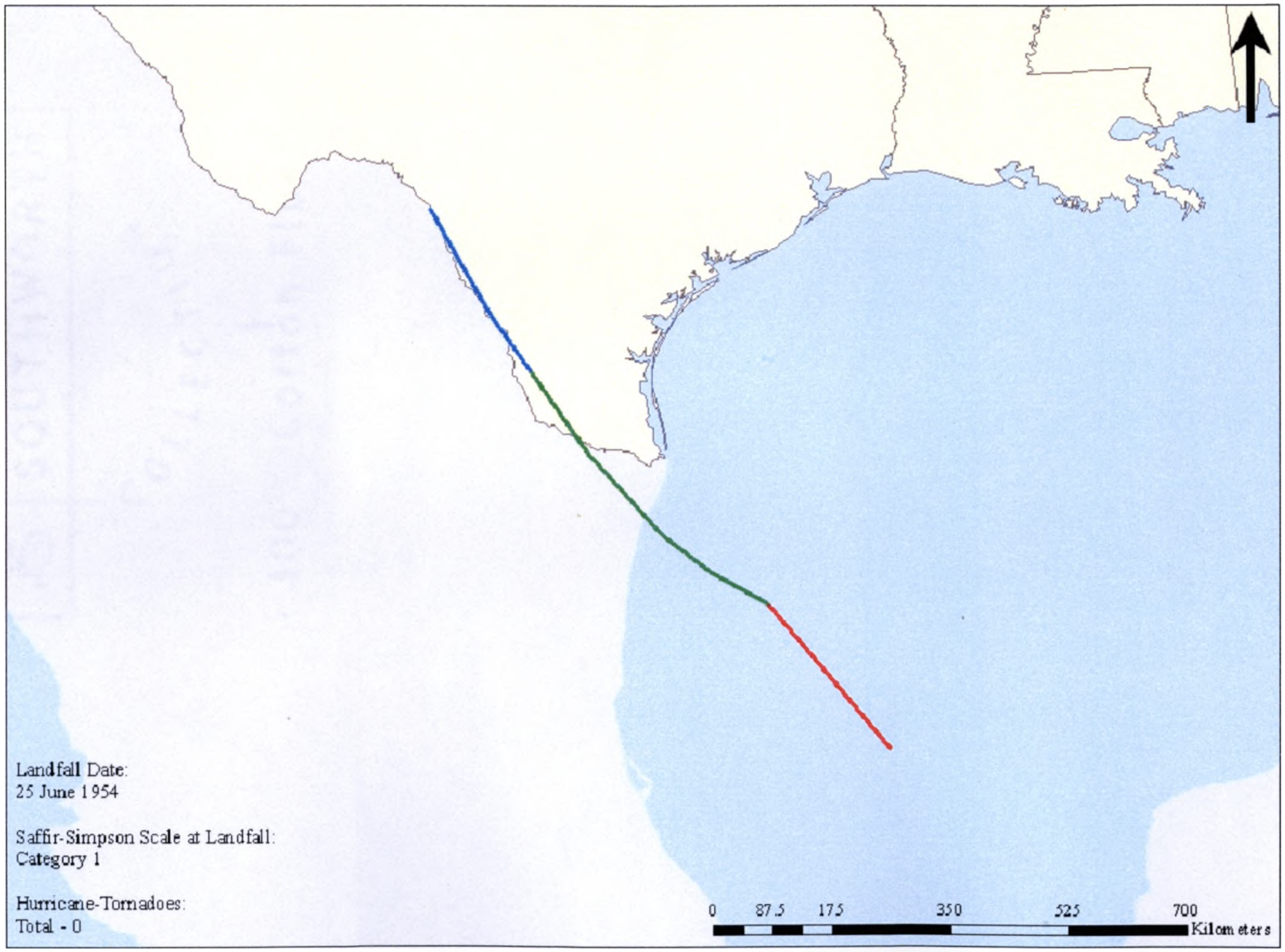

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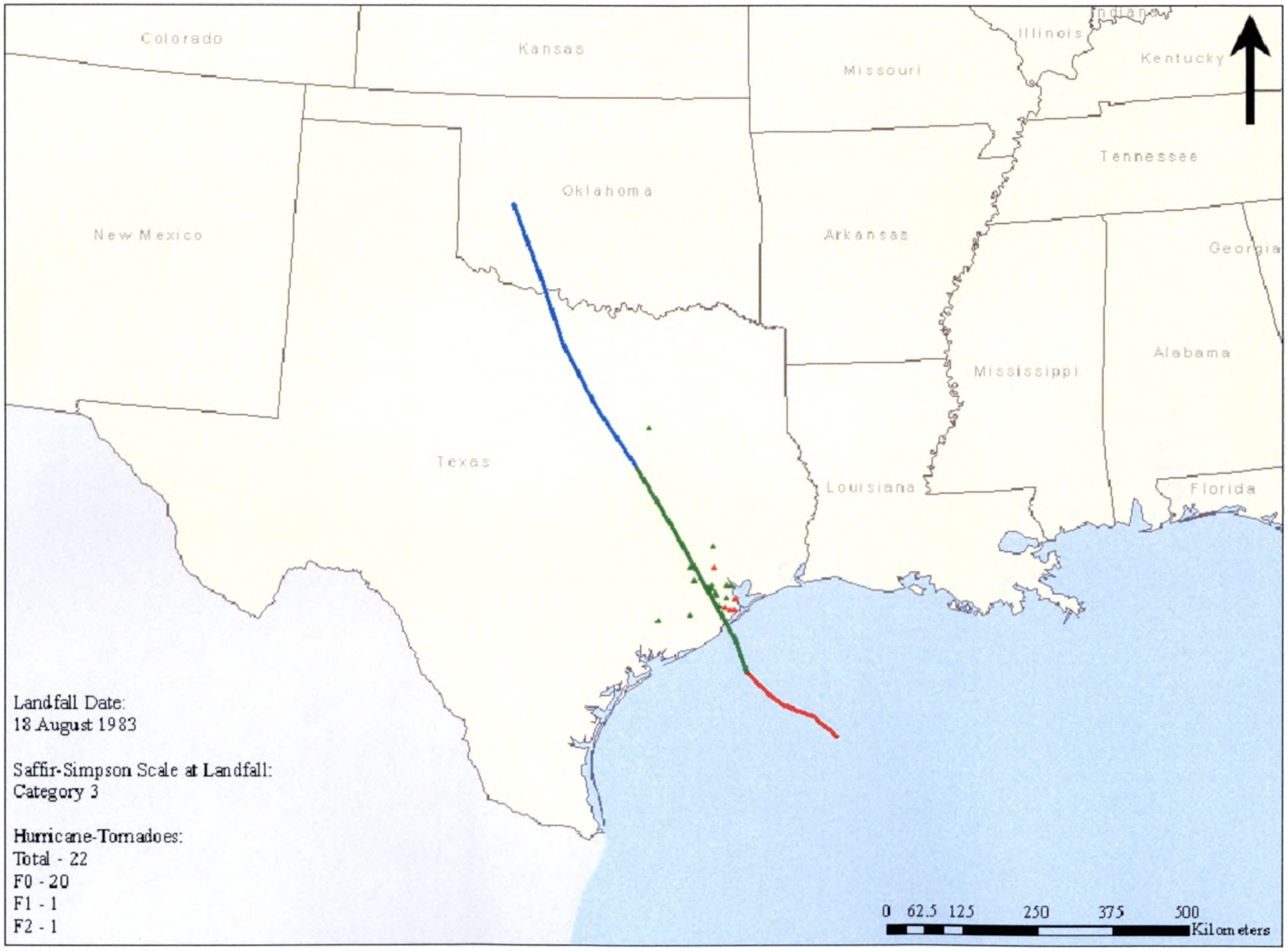

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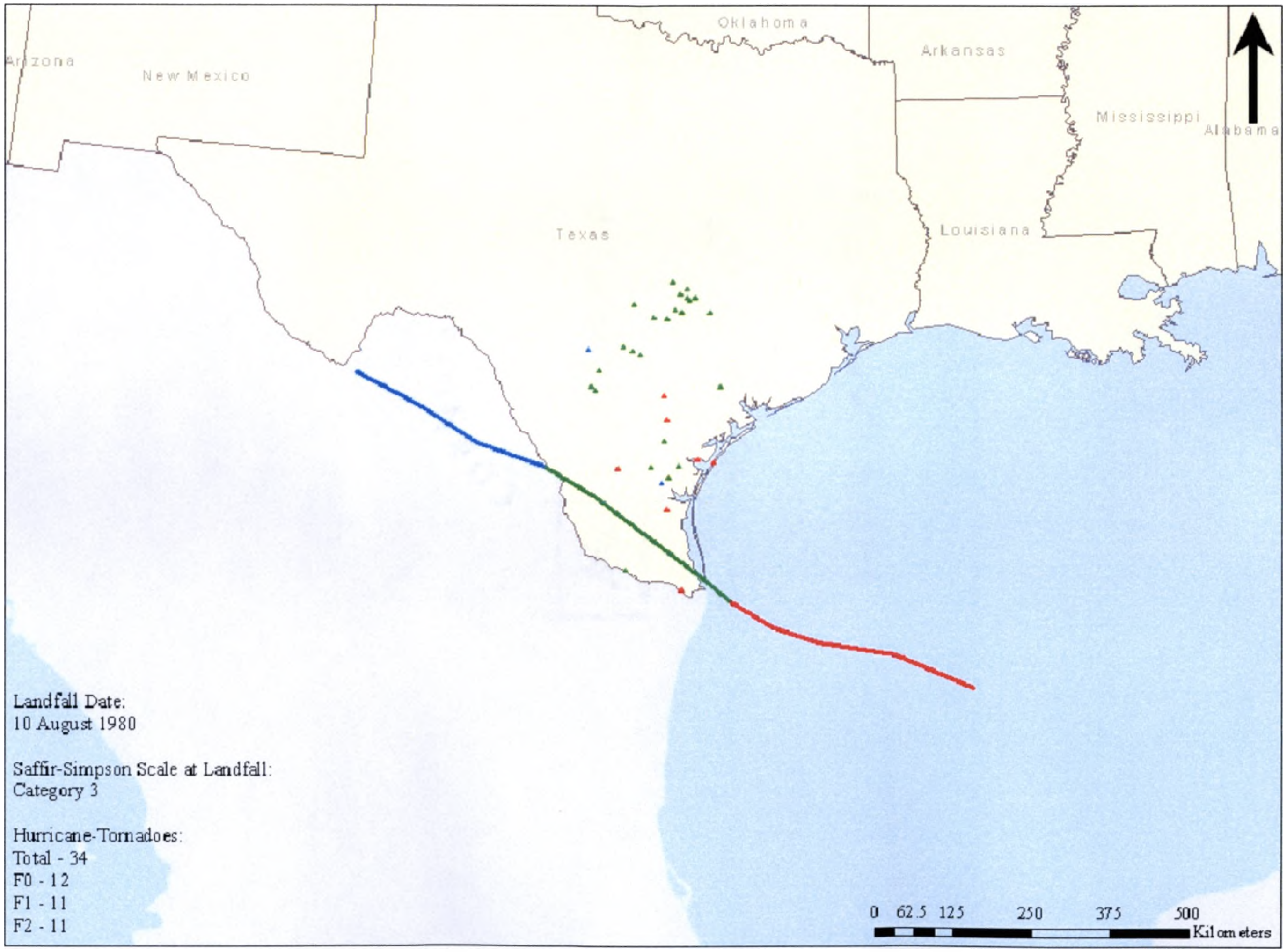

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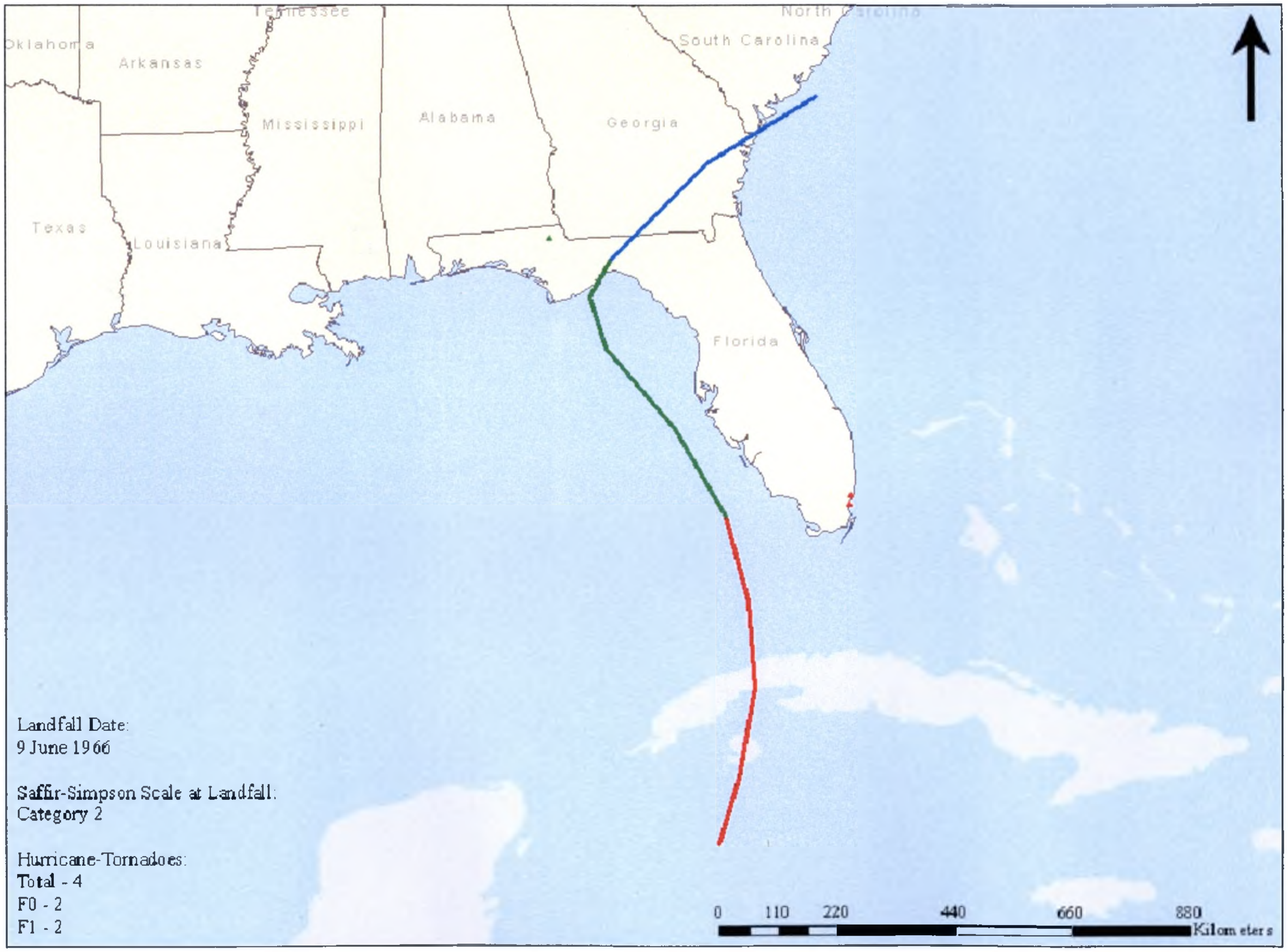

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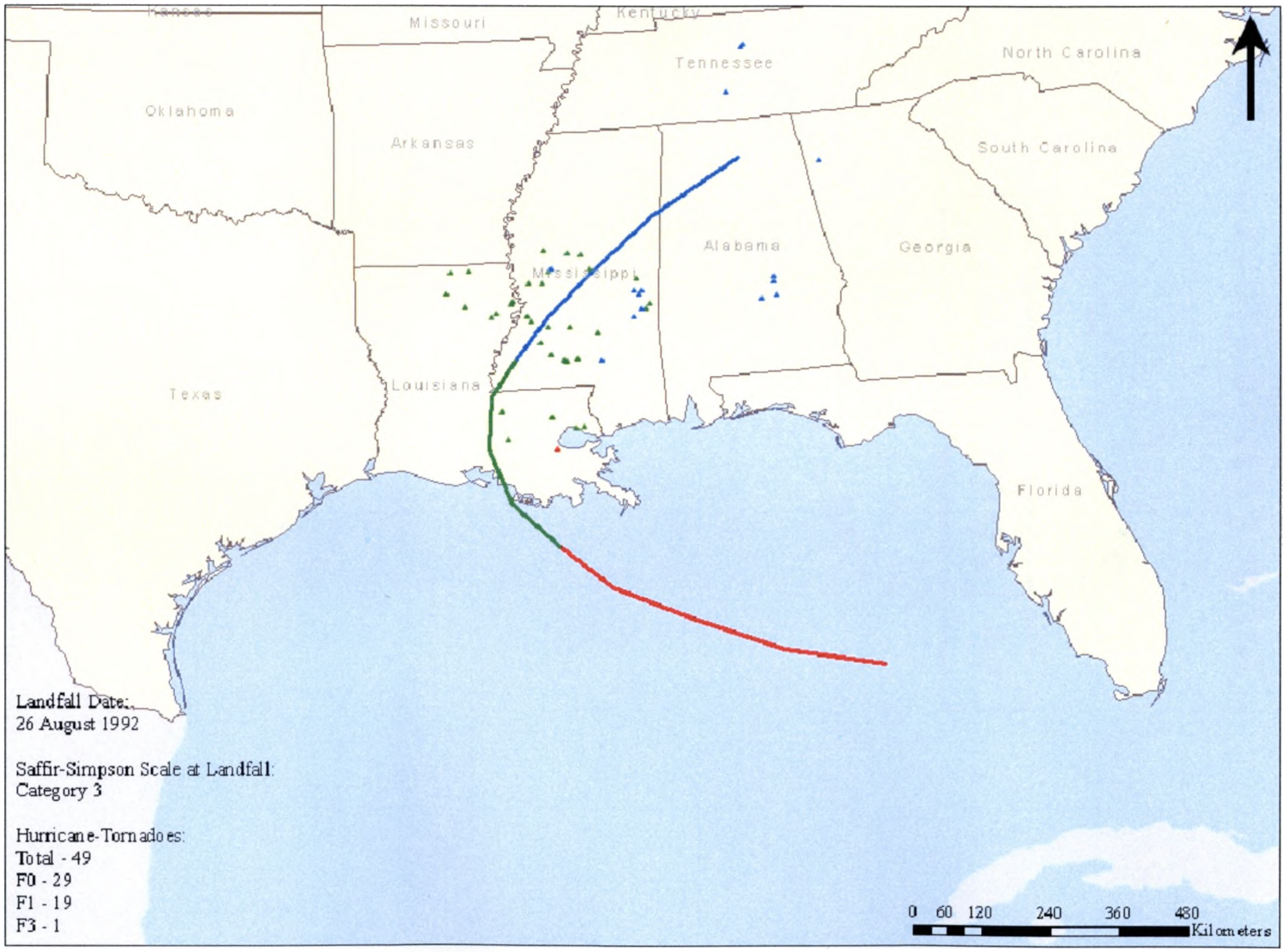

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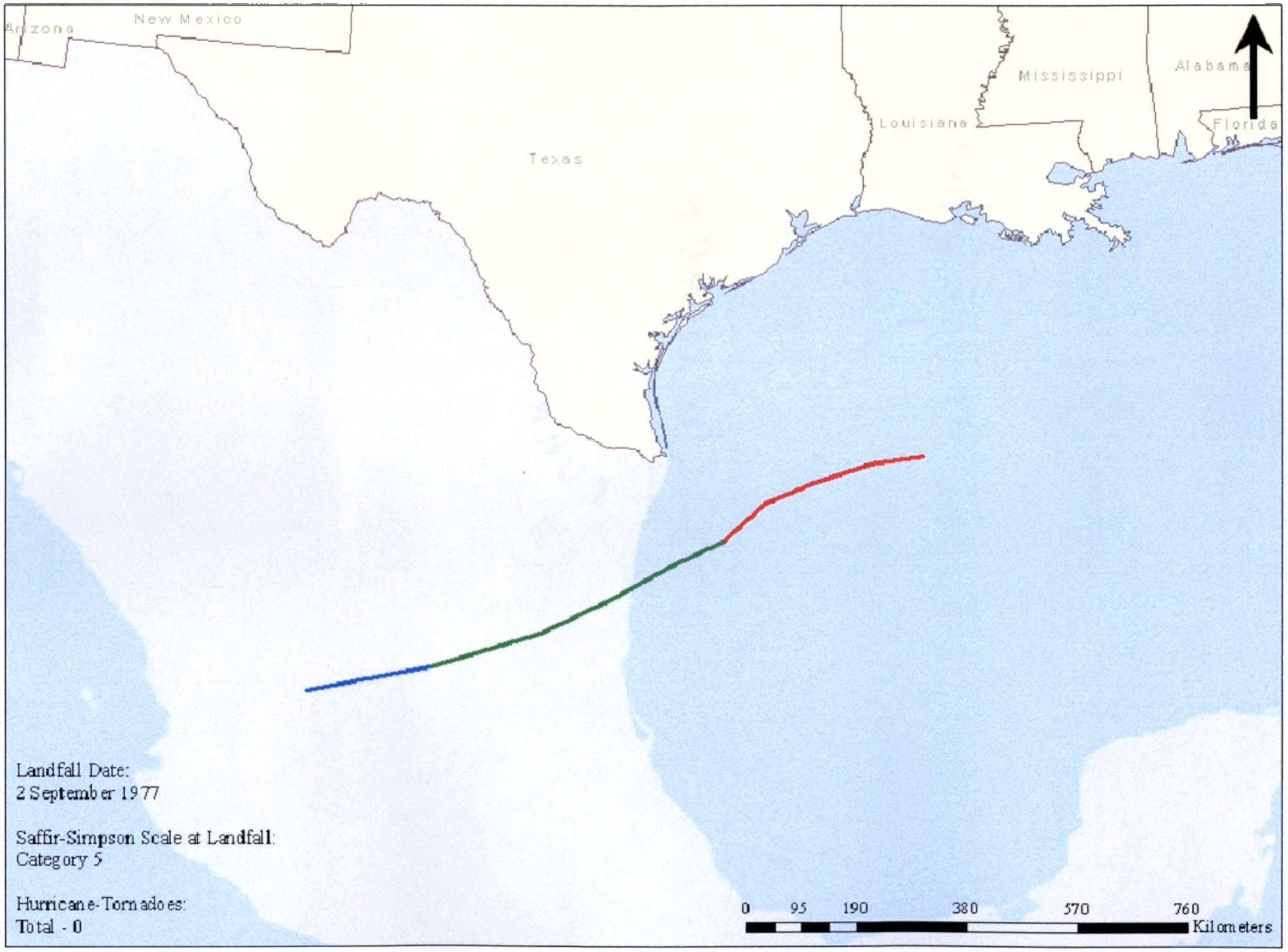
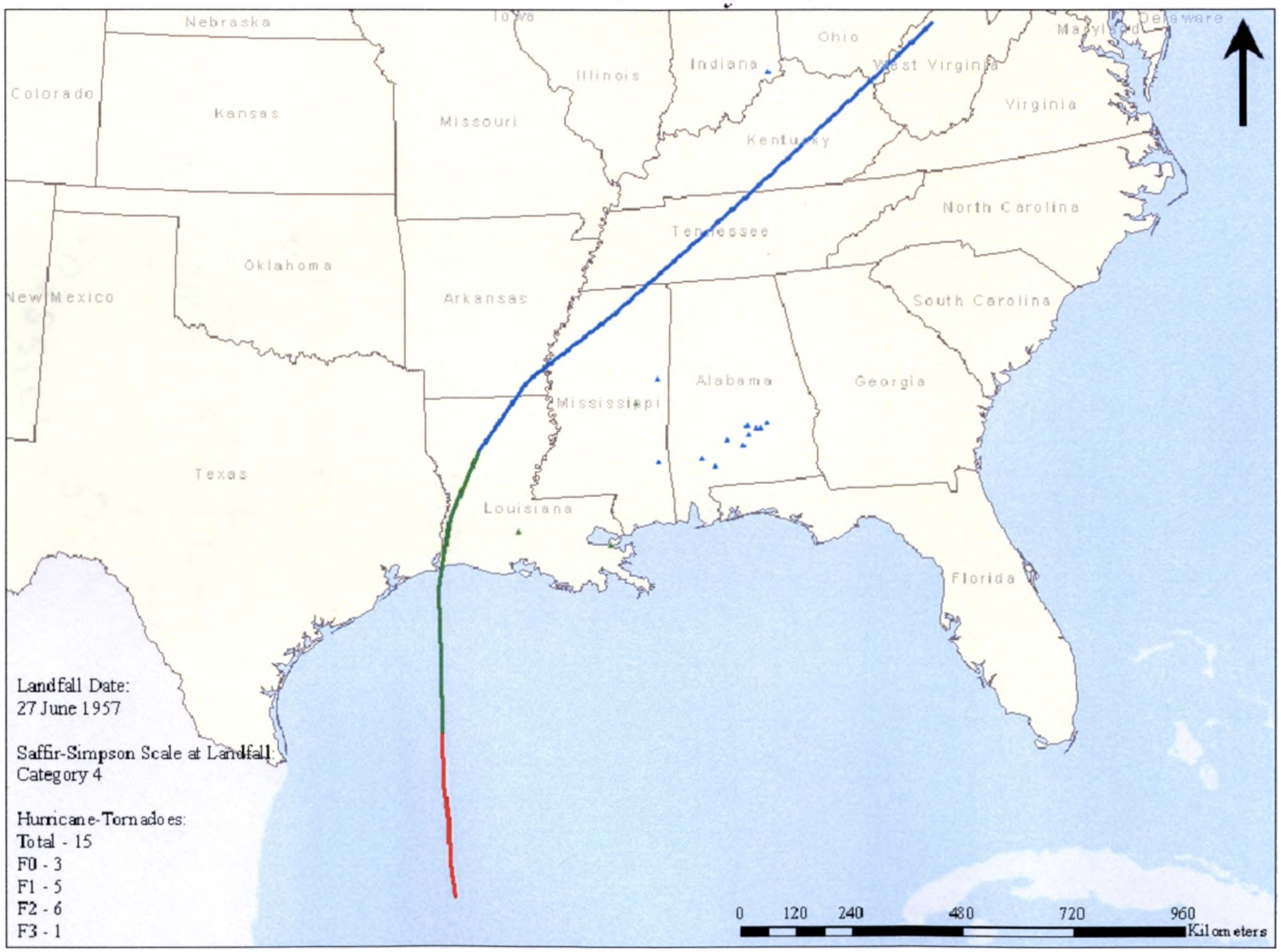


Hurricane Audrey 1957



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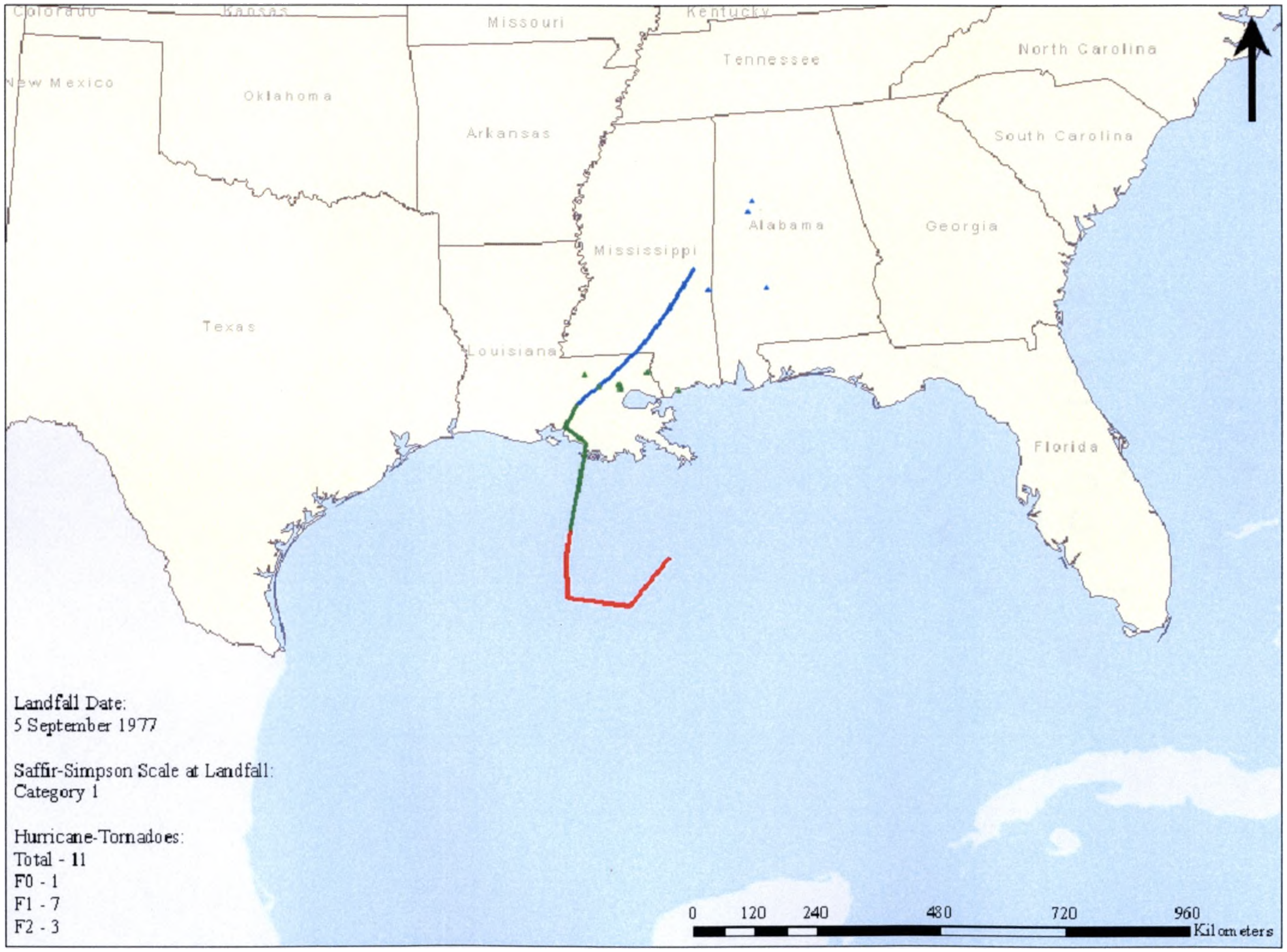

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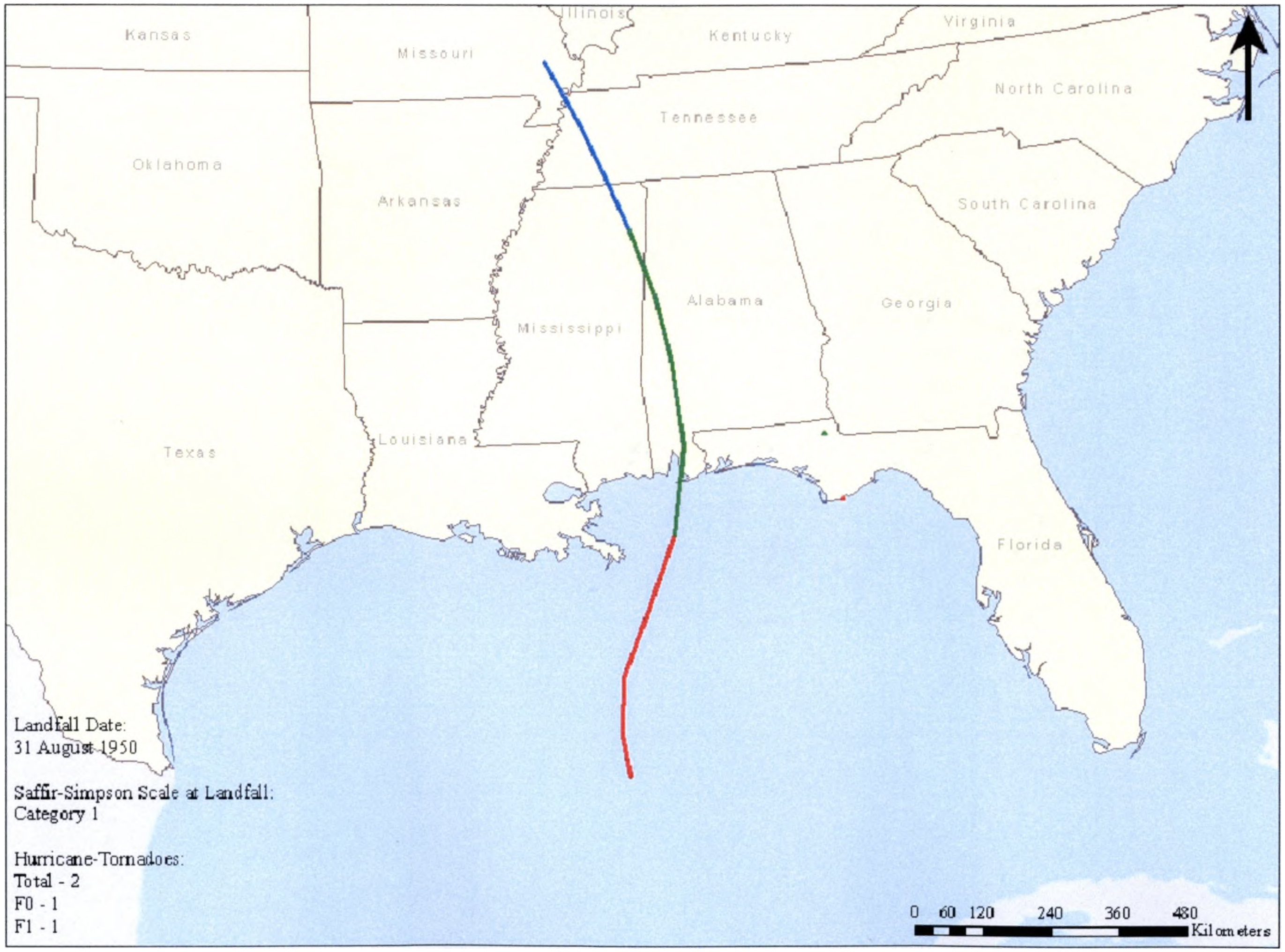

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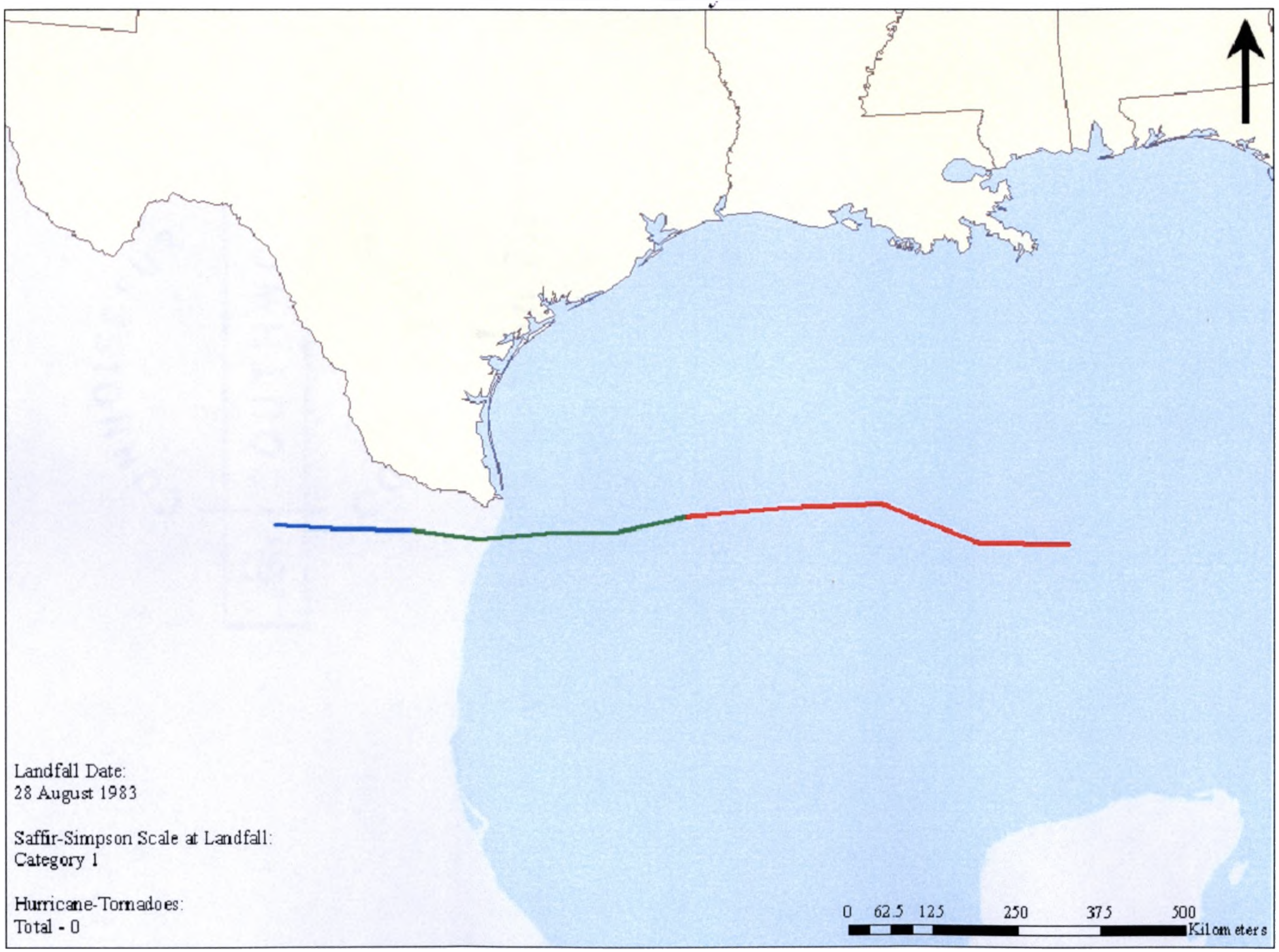

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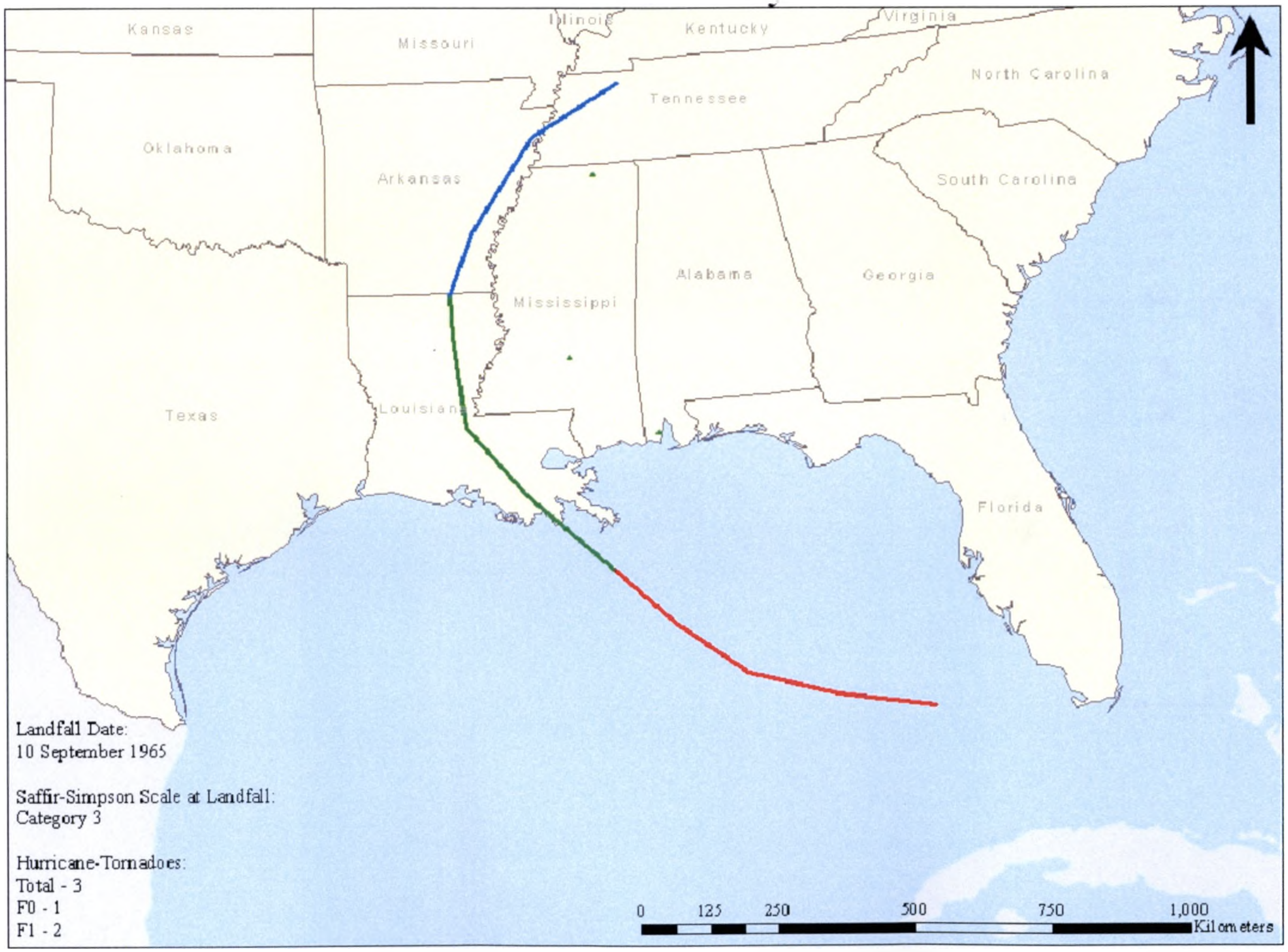

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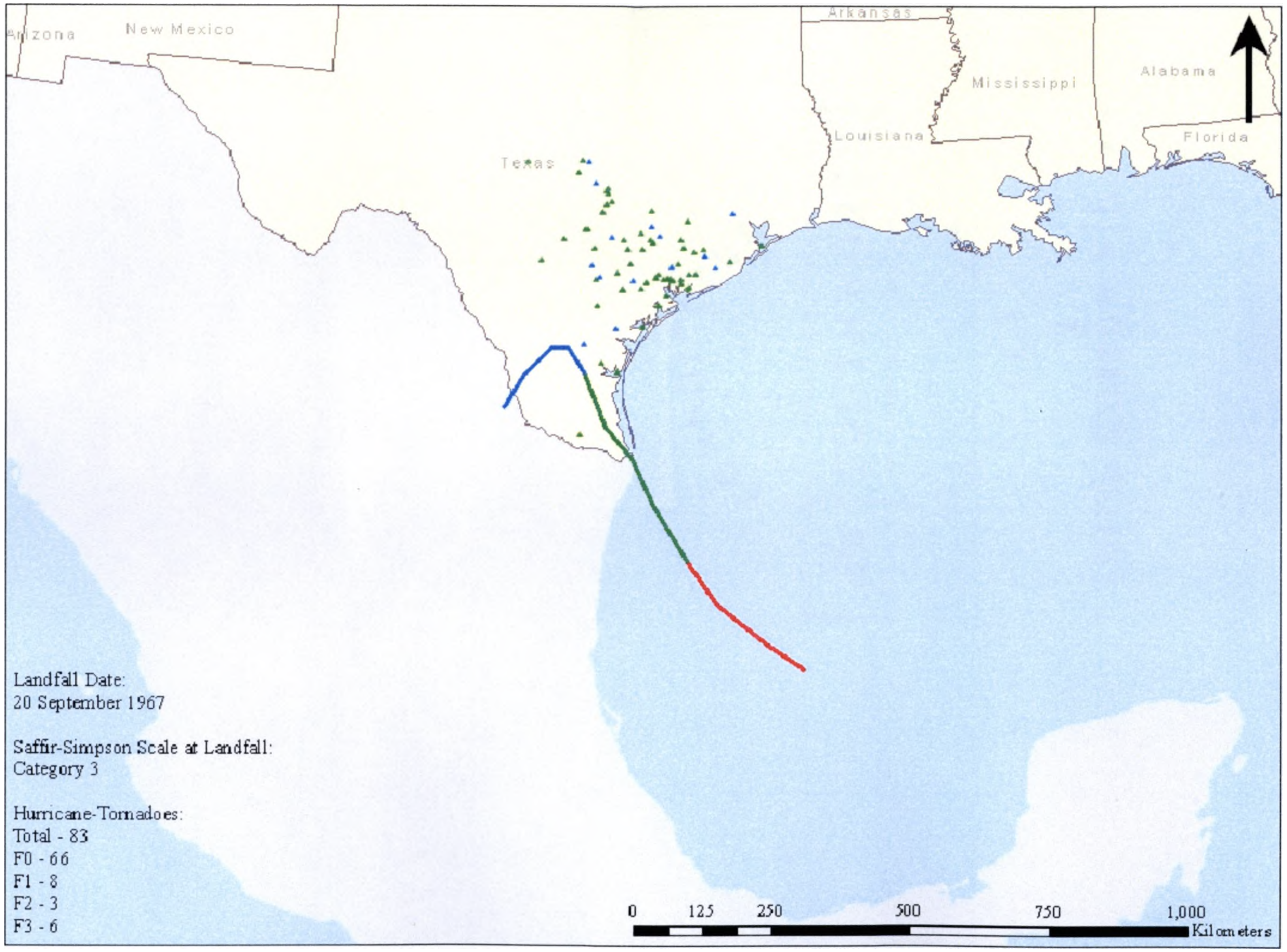

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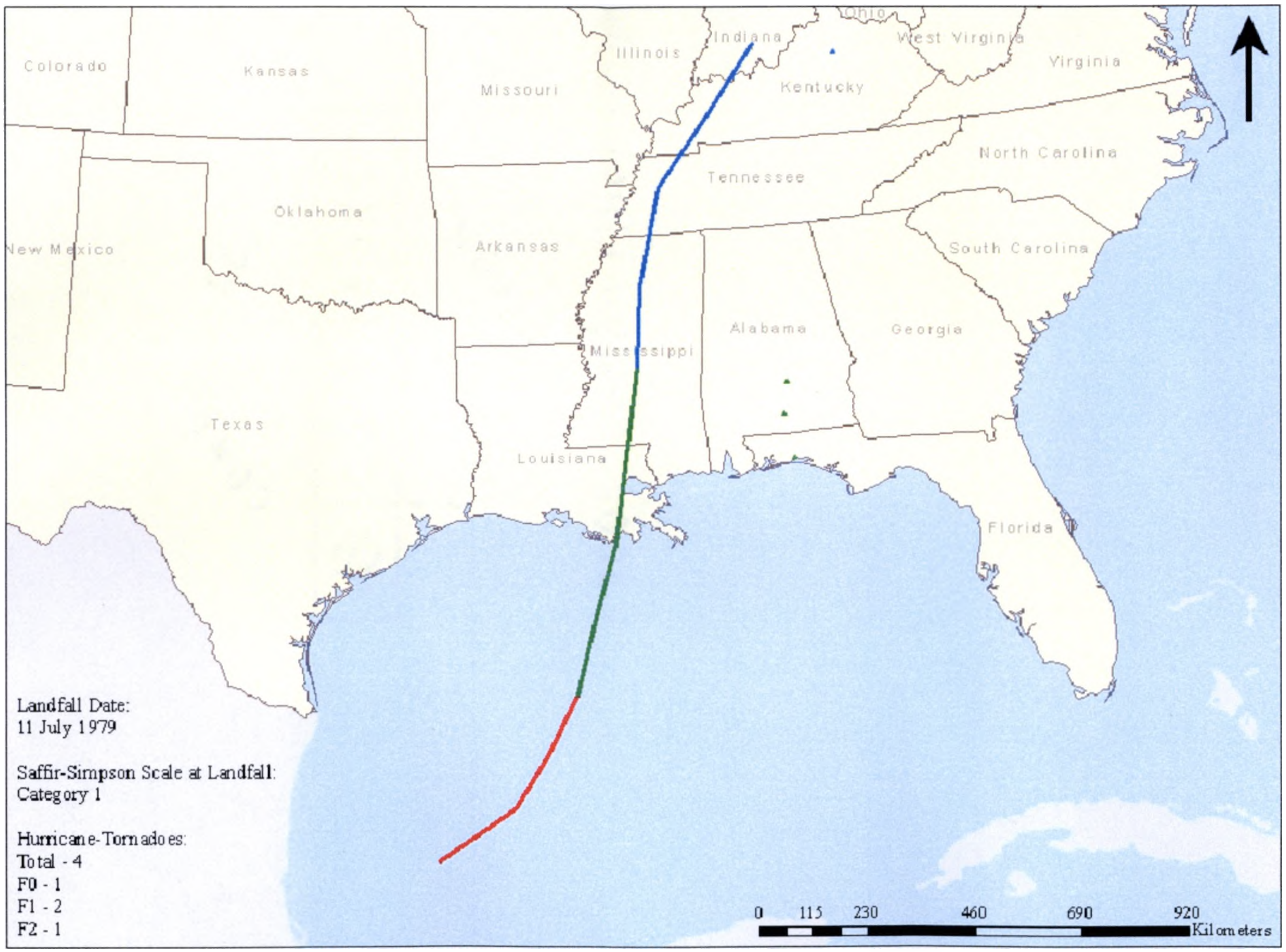

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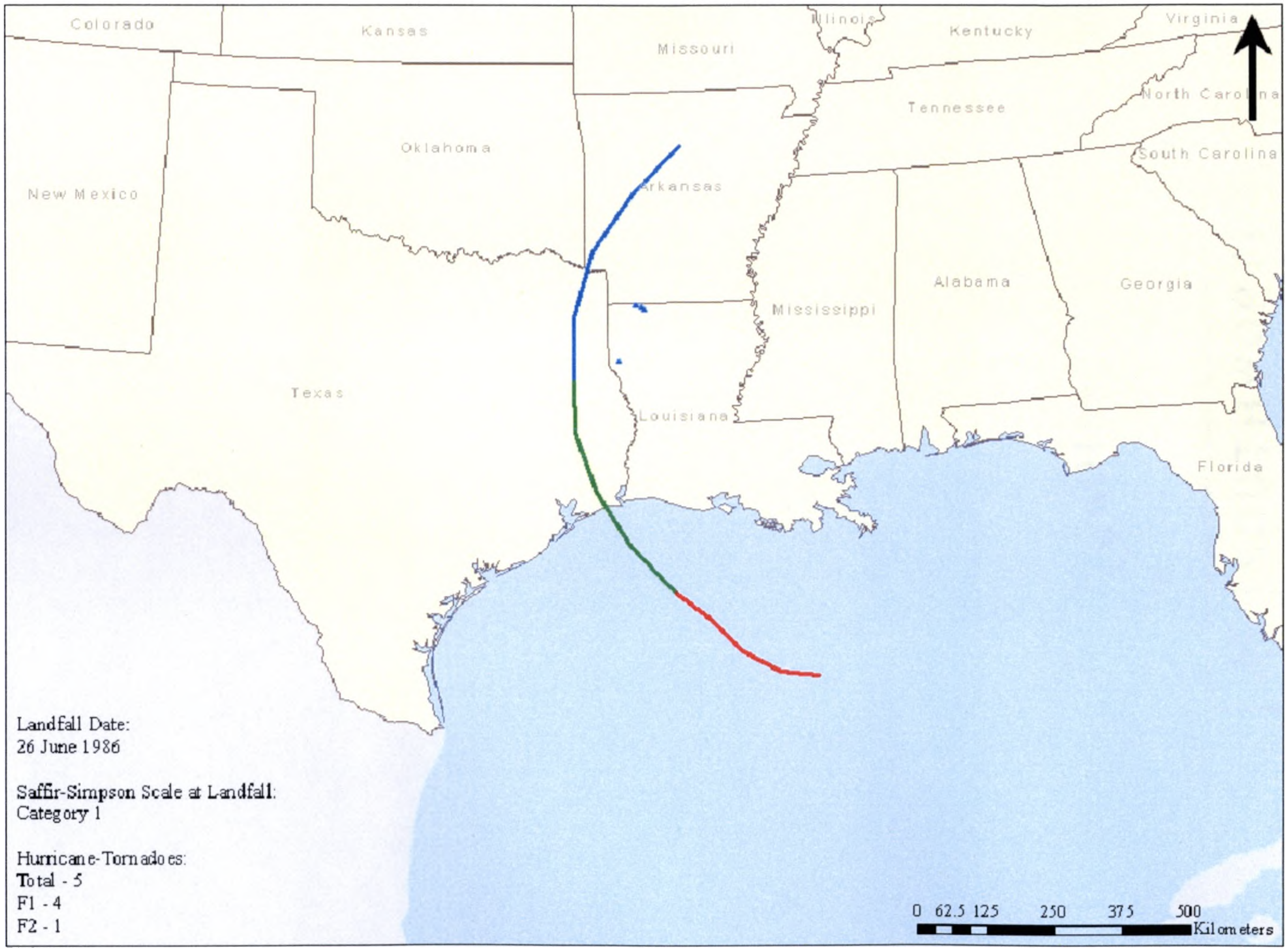
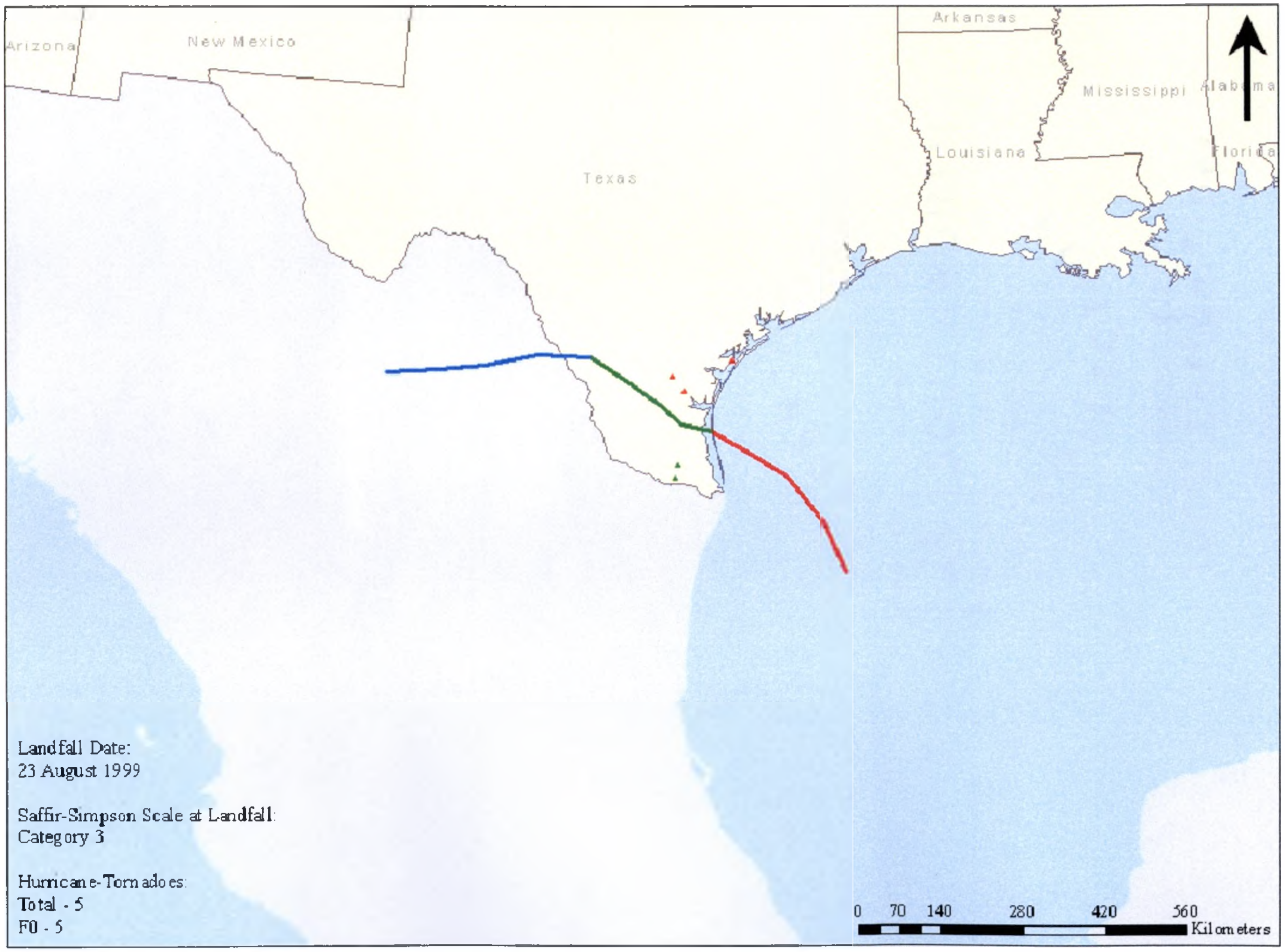
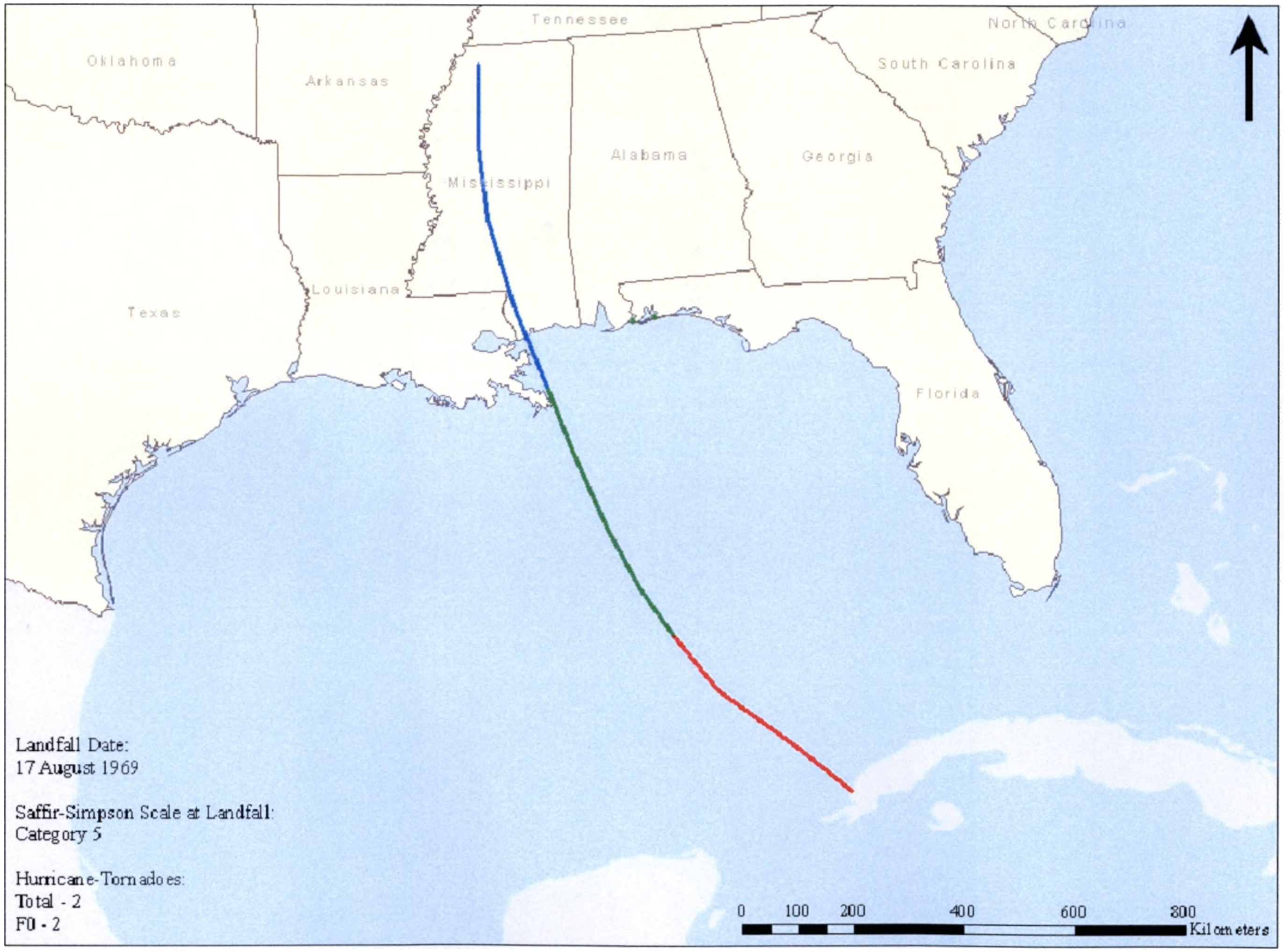


Hurricane Bret 1999



Hurricane Camille 1969



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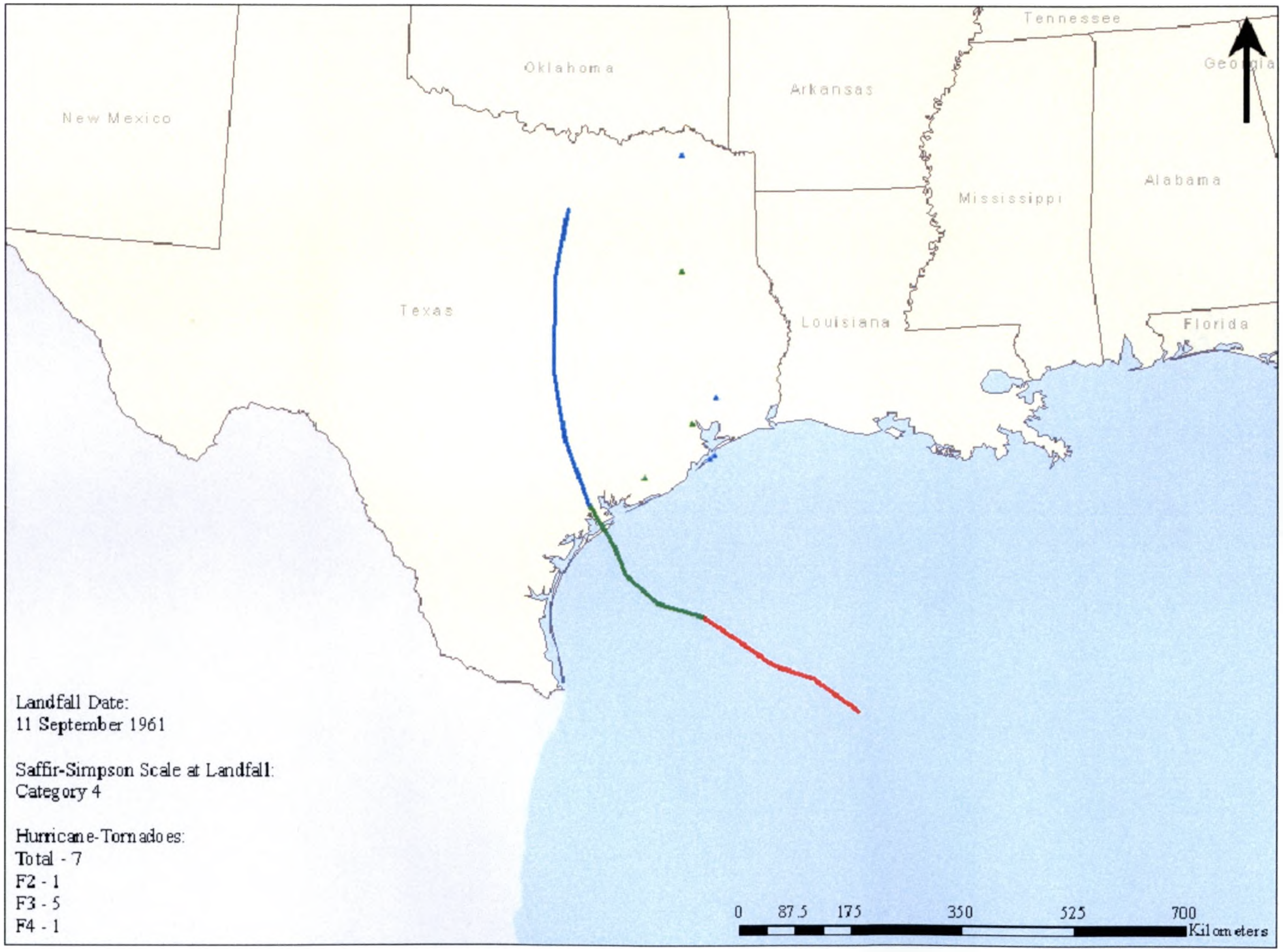

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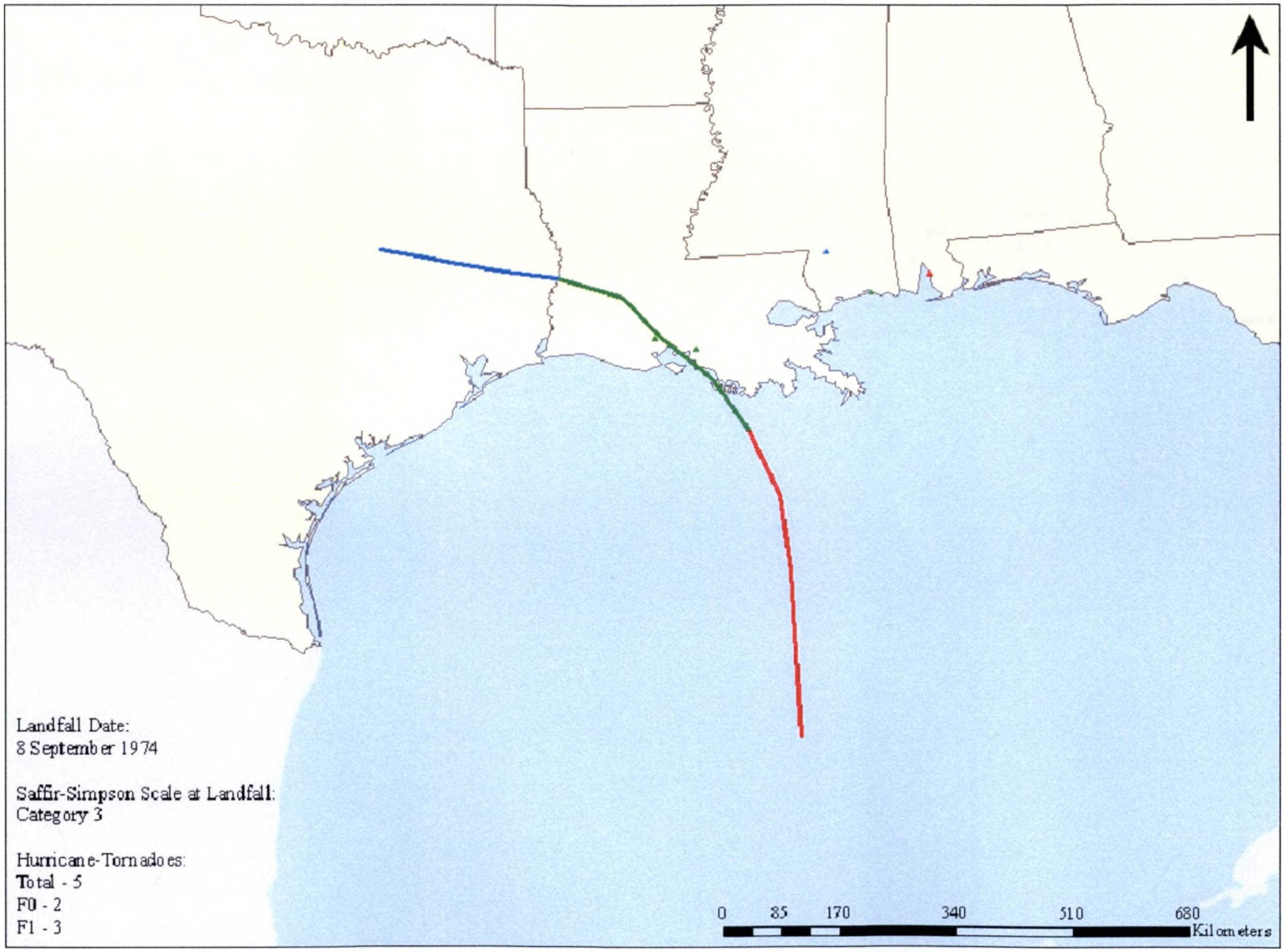

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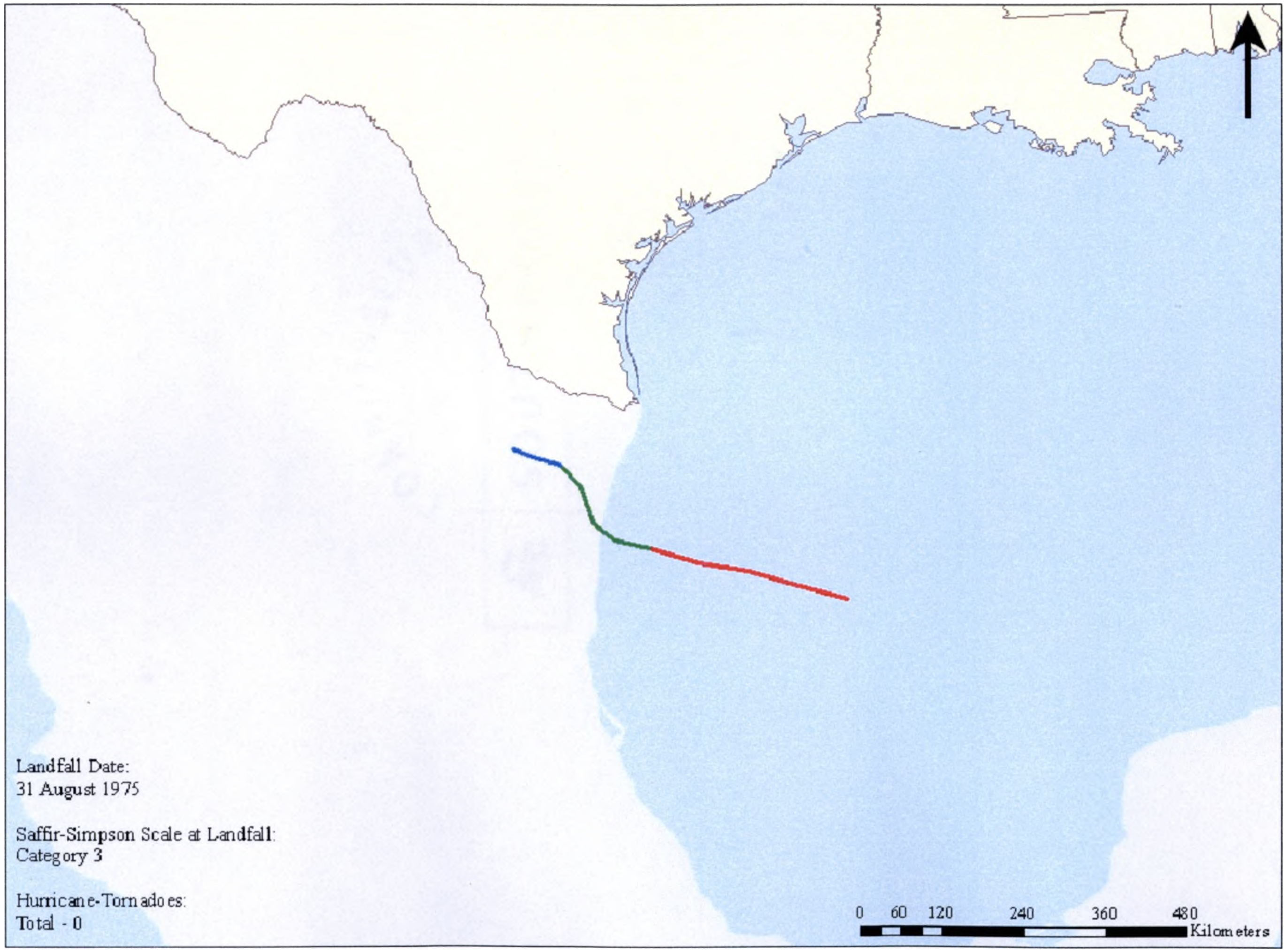

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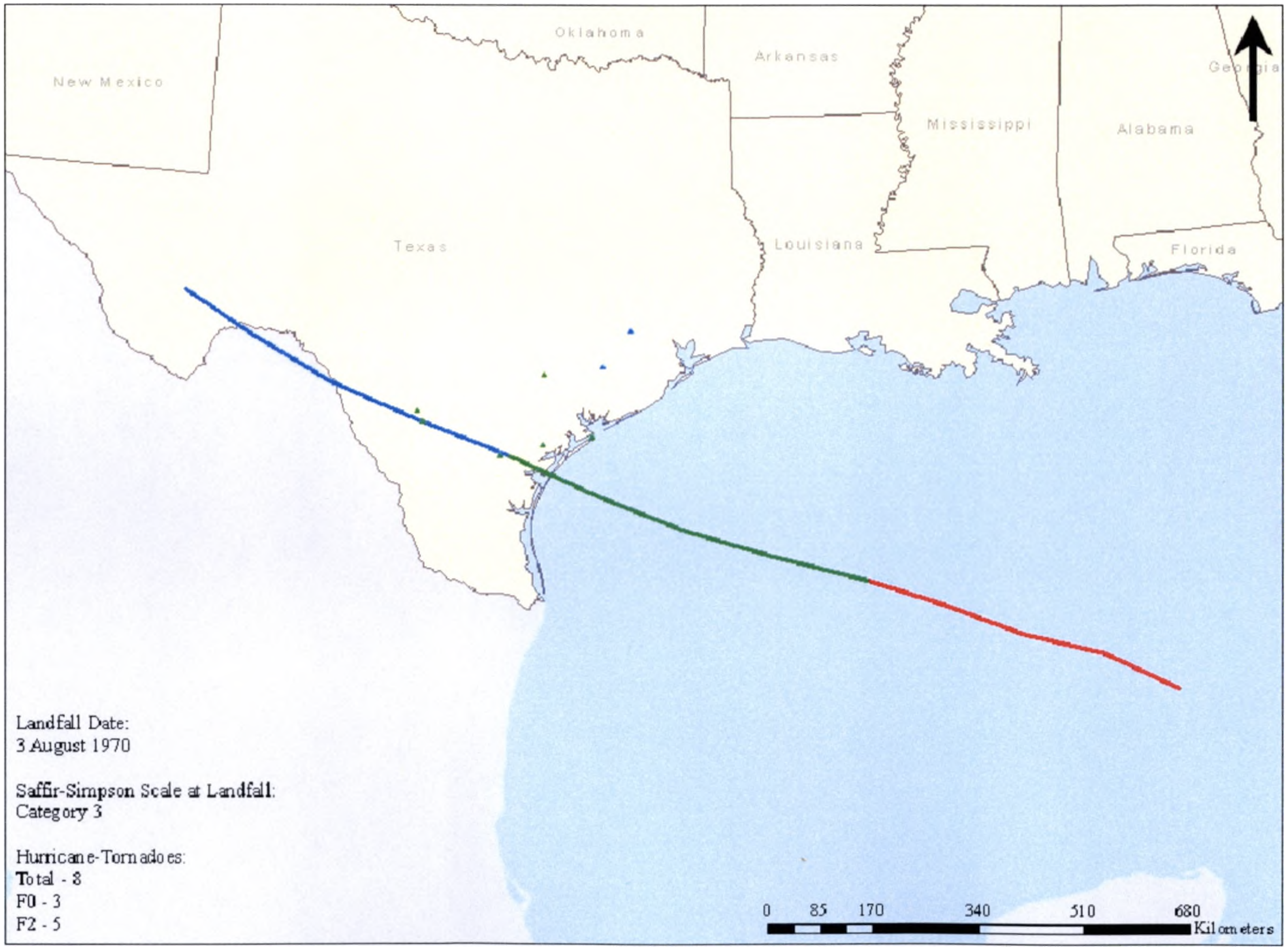

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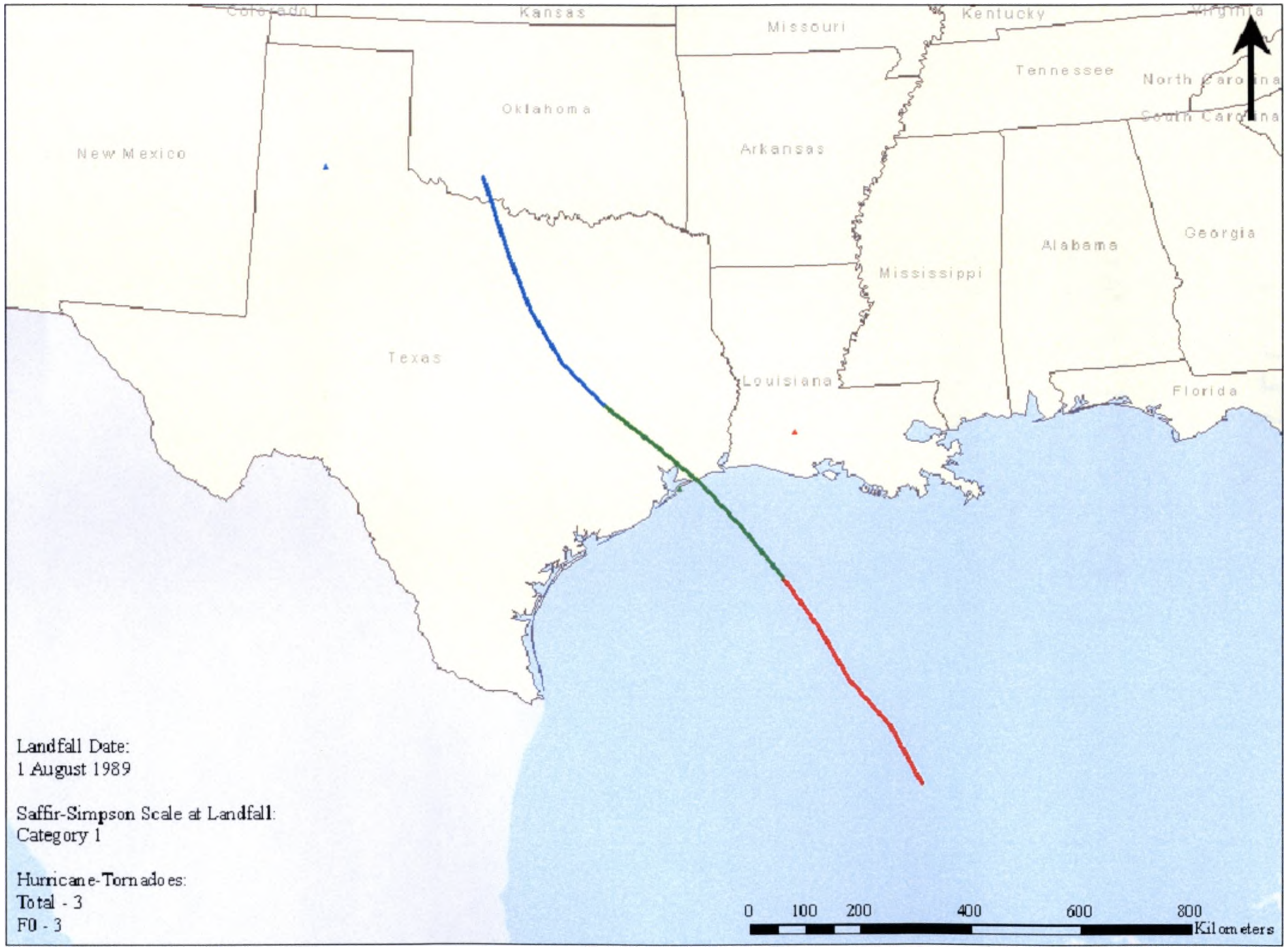

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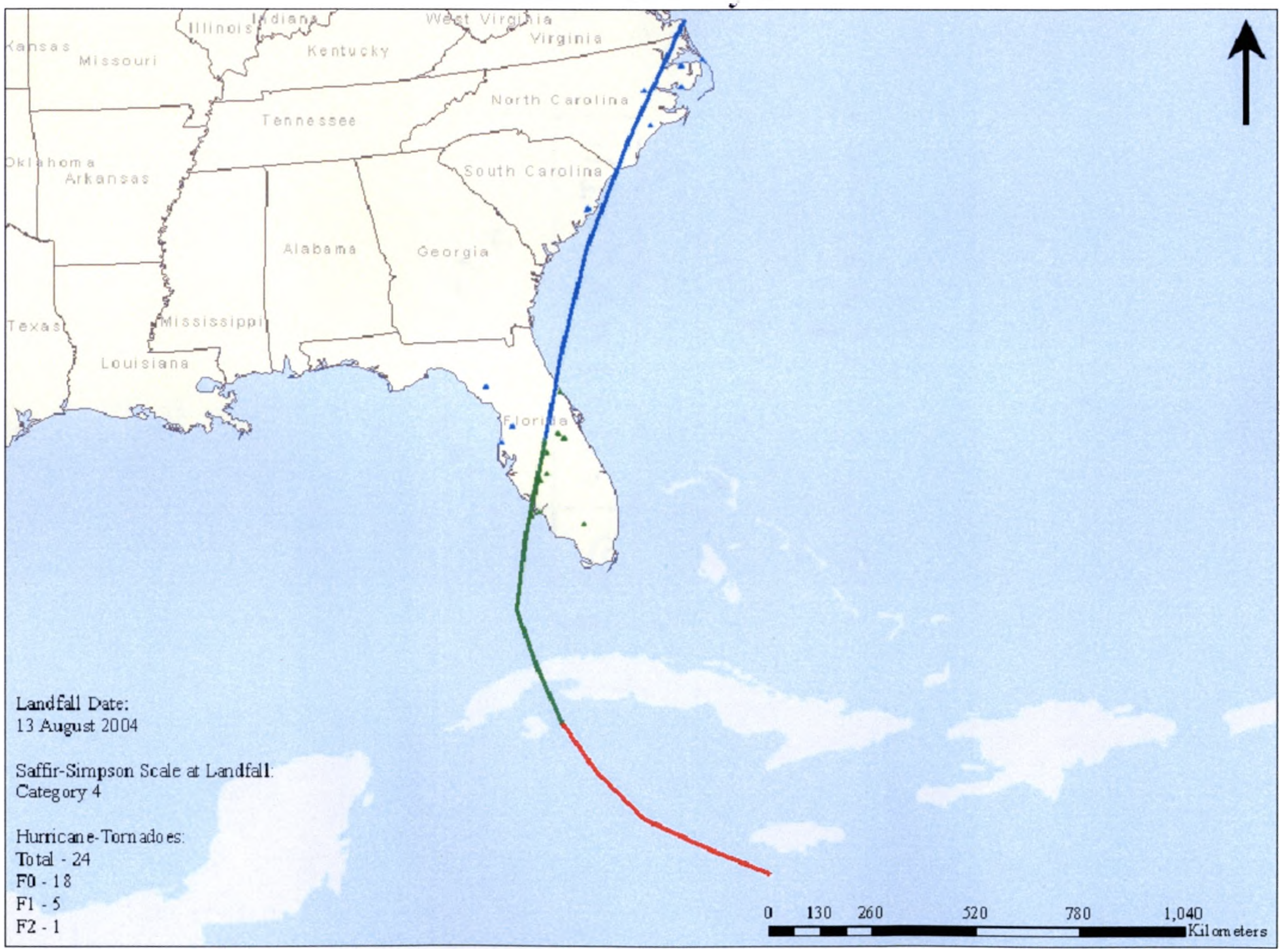
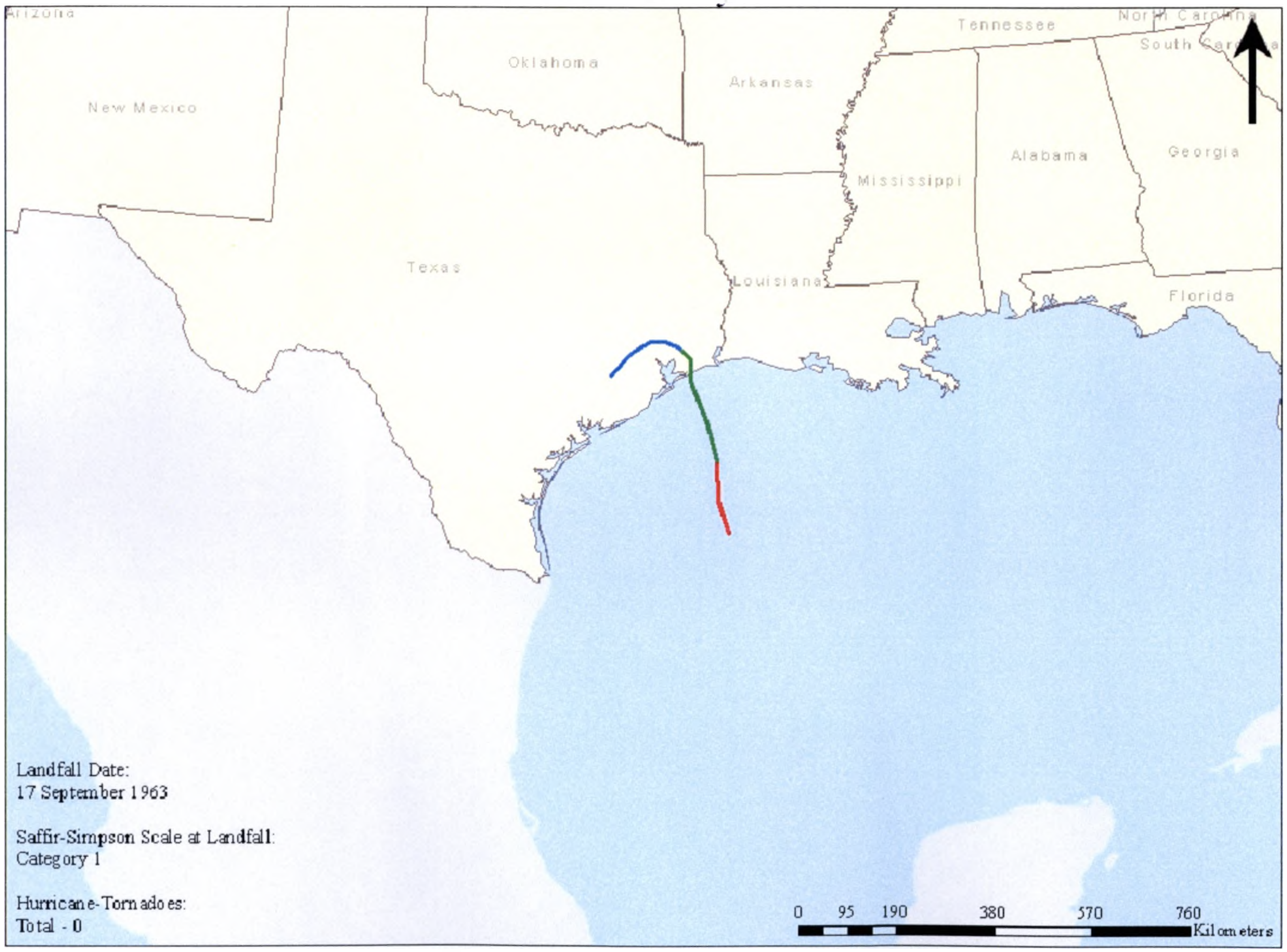
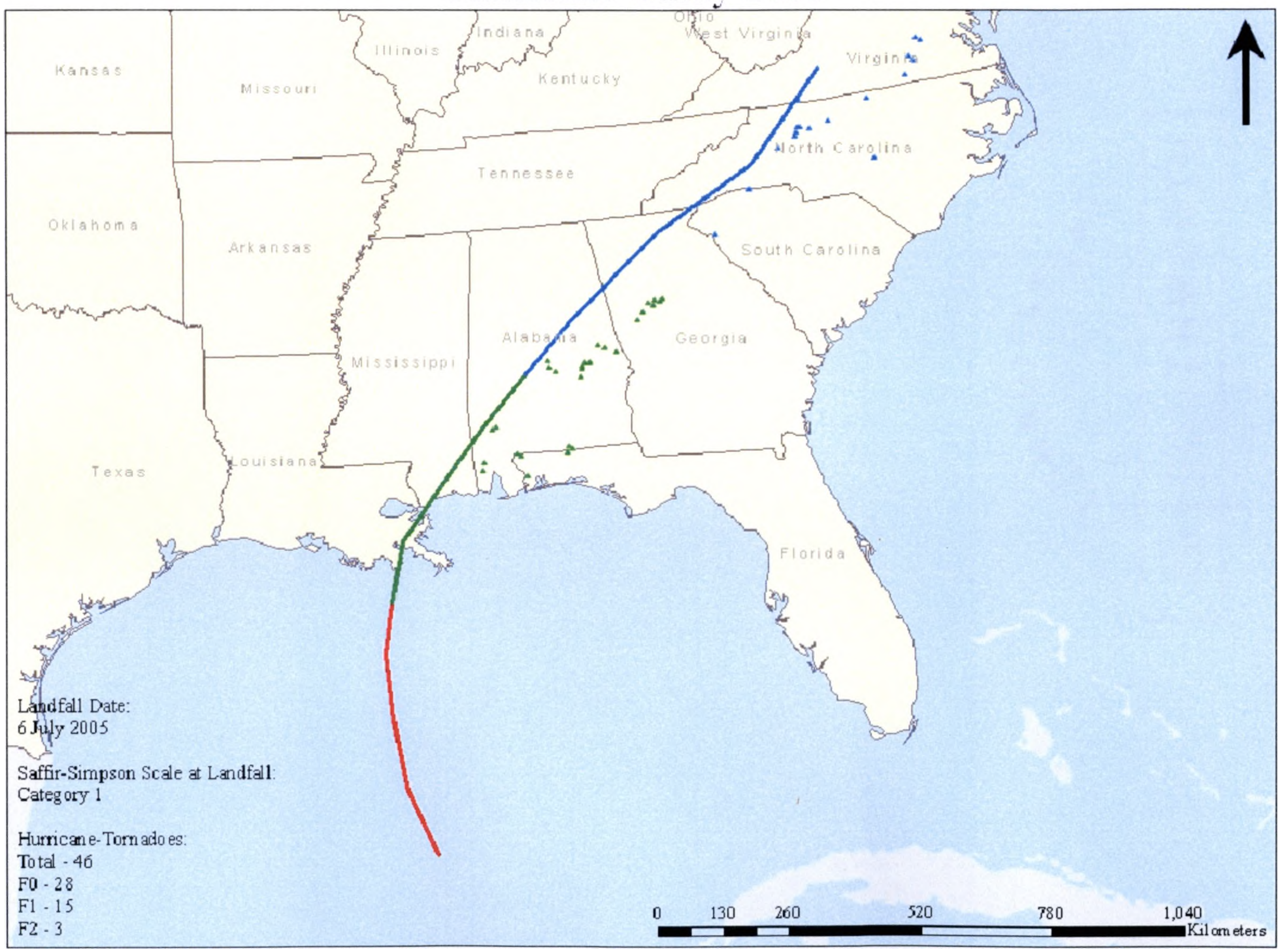


Hurricane Cindy 1963



Hurricane Cindy 2005



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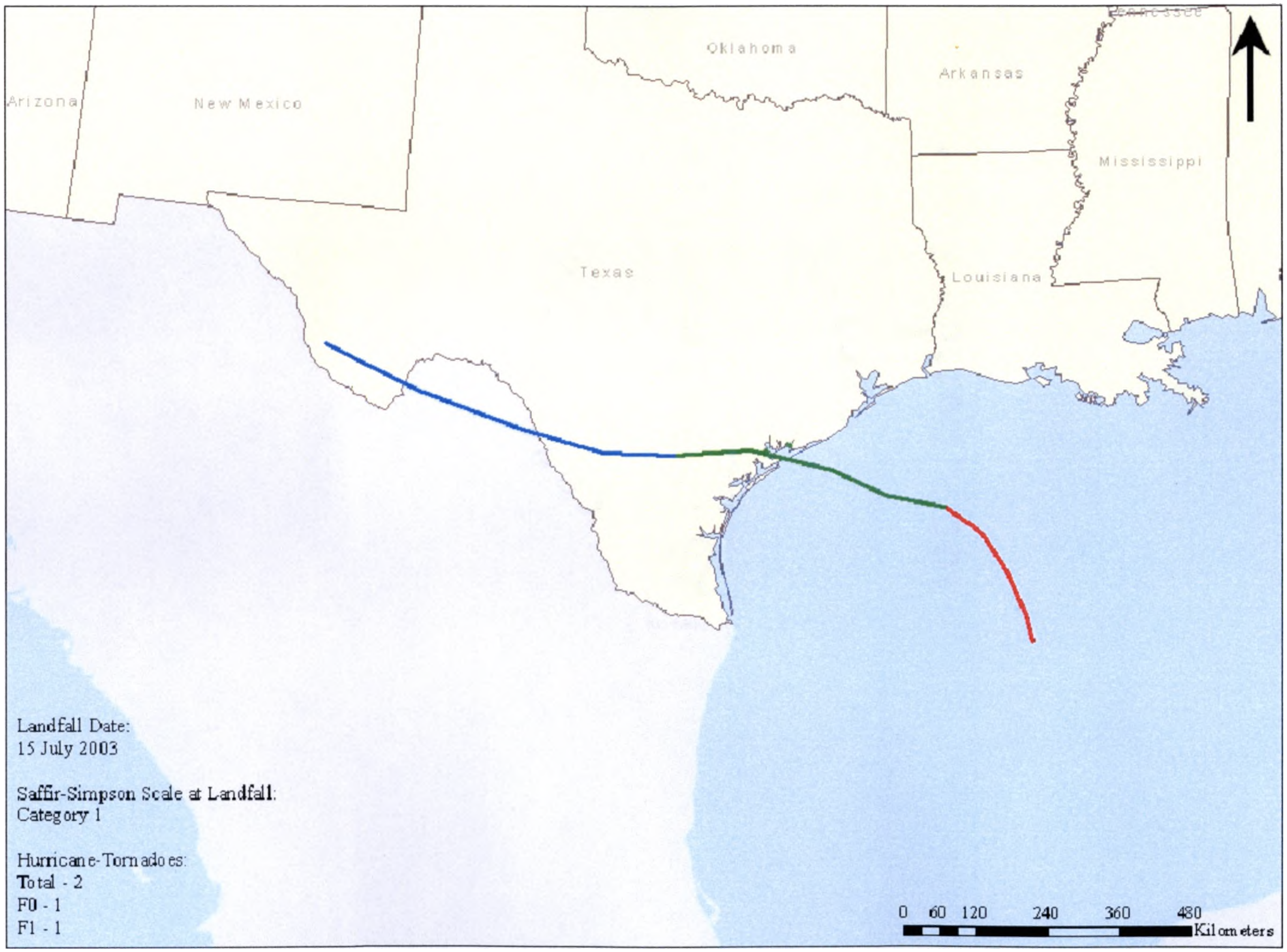

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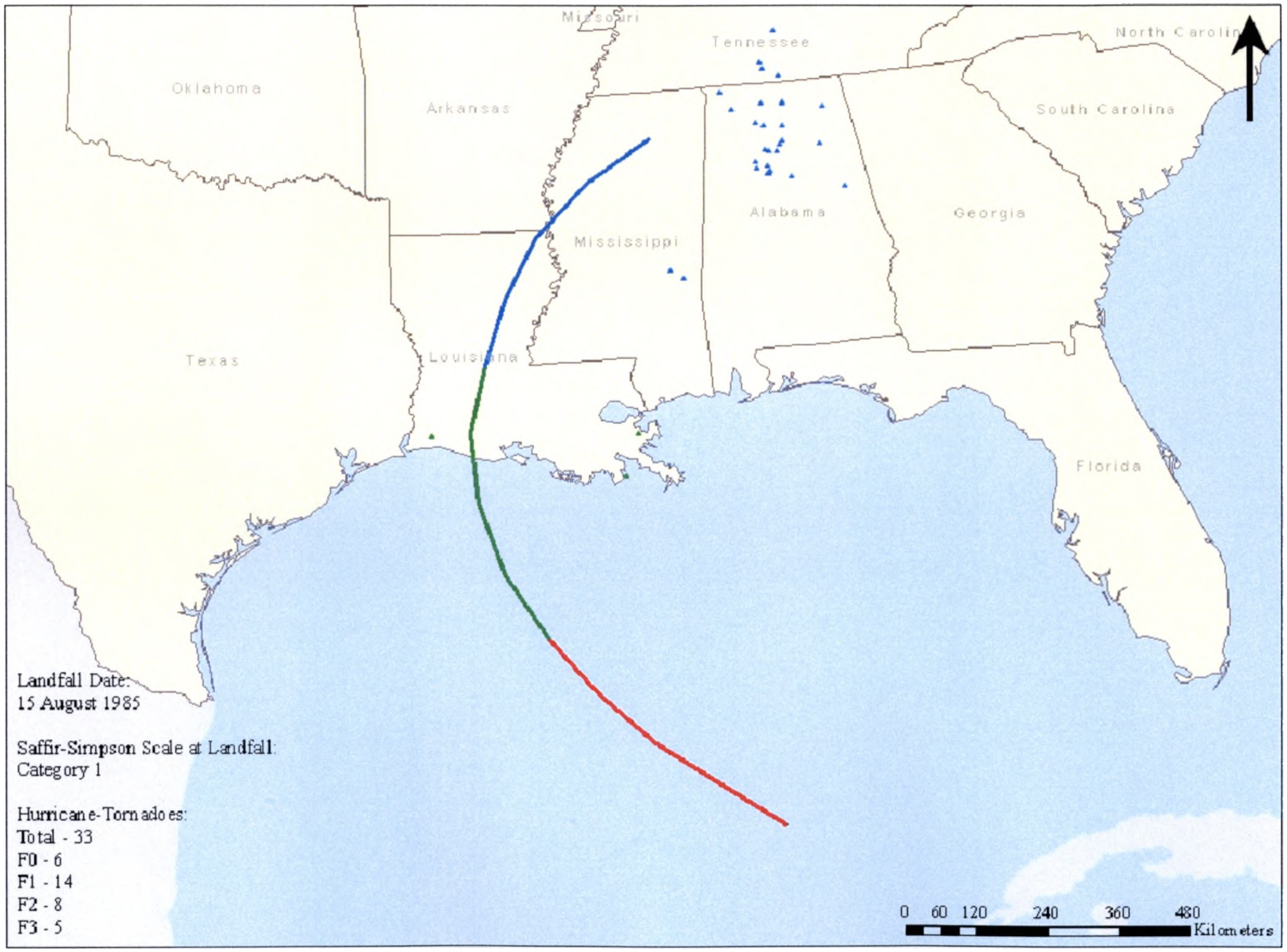

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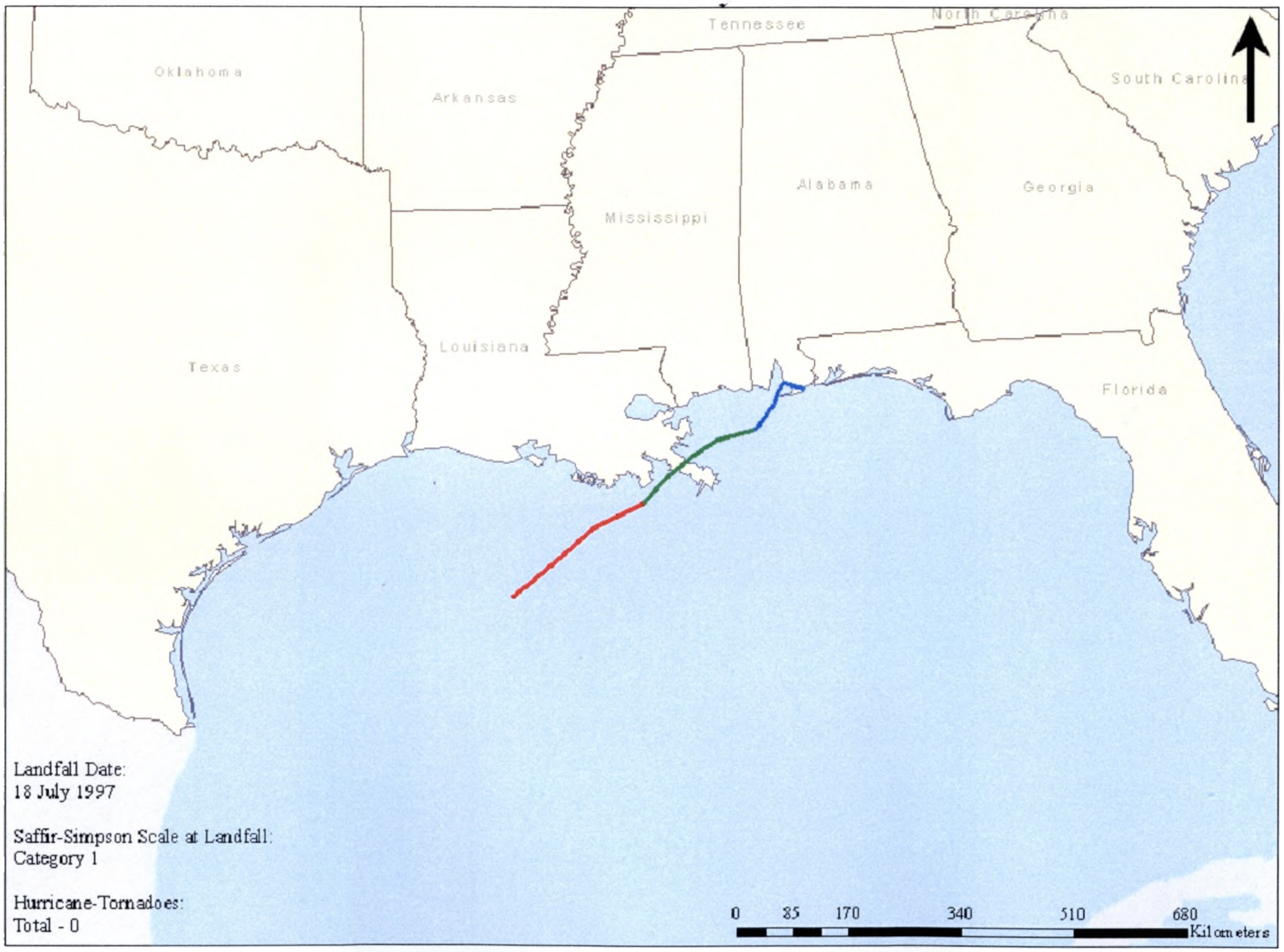

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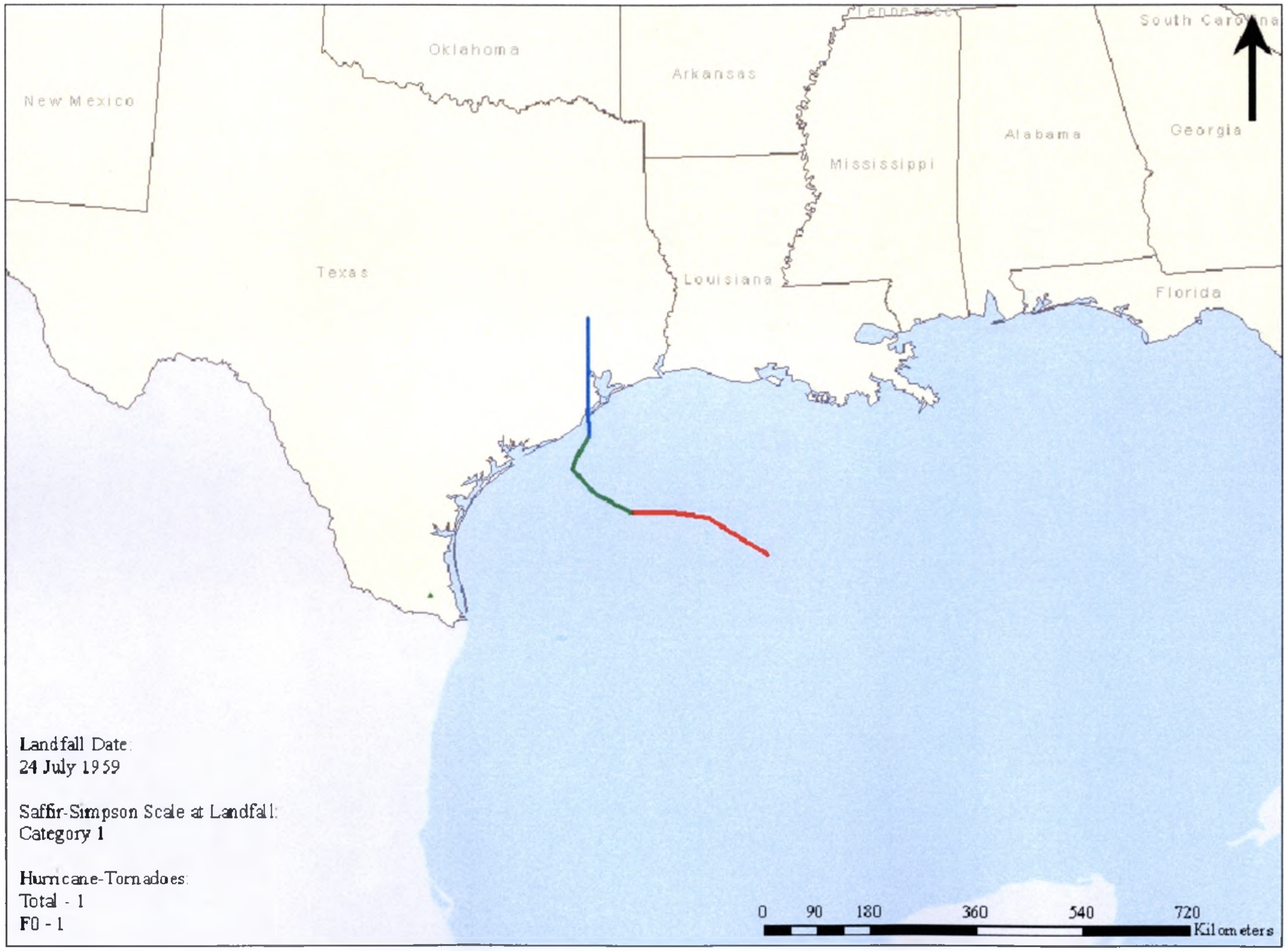

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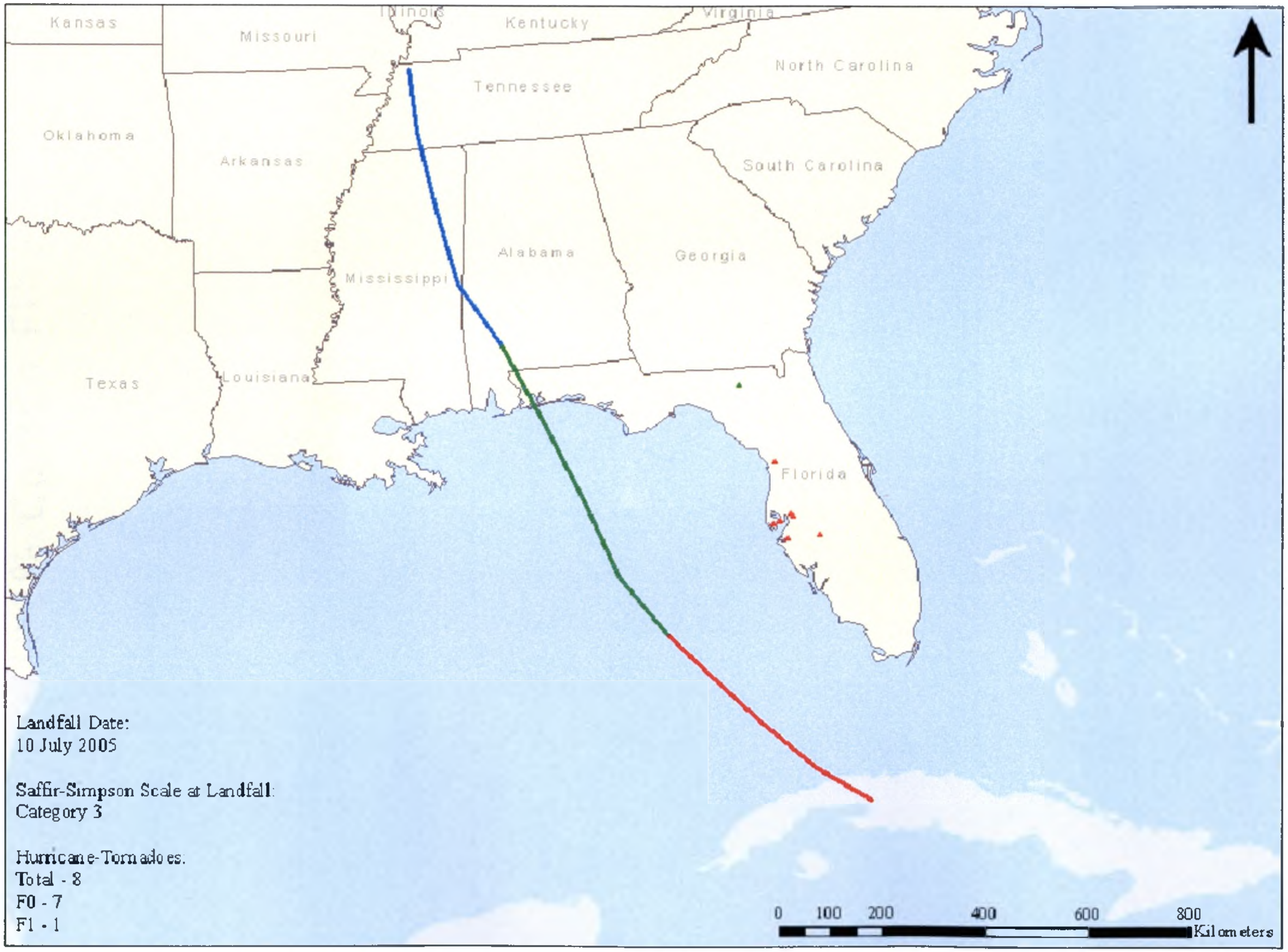
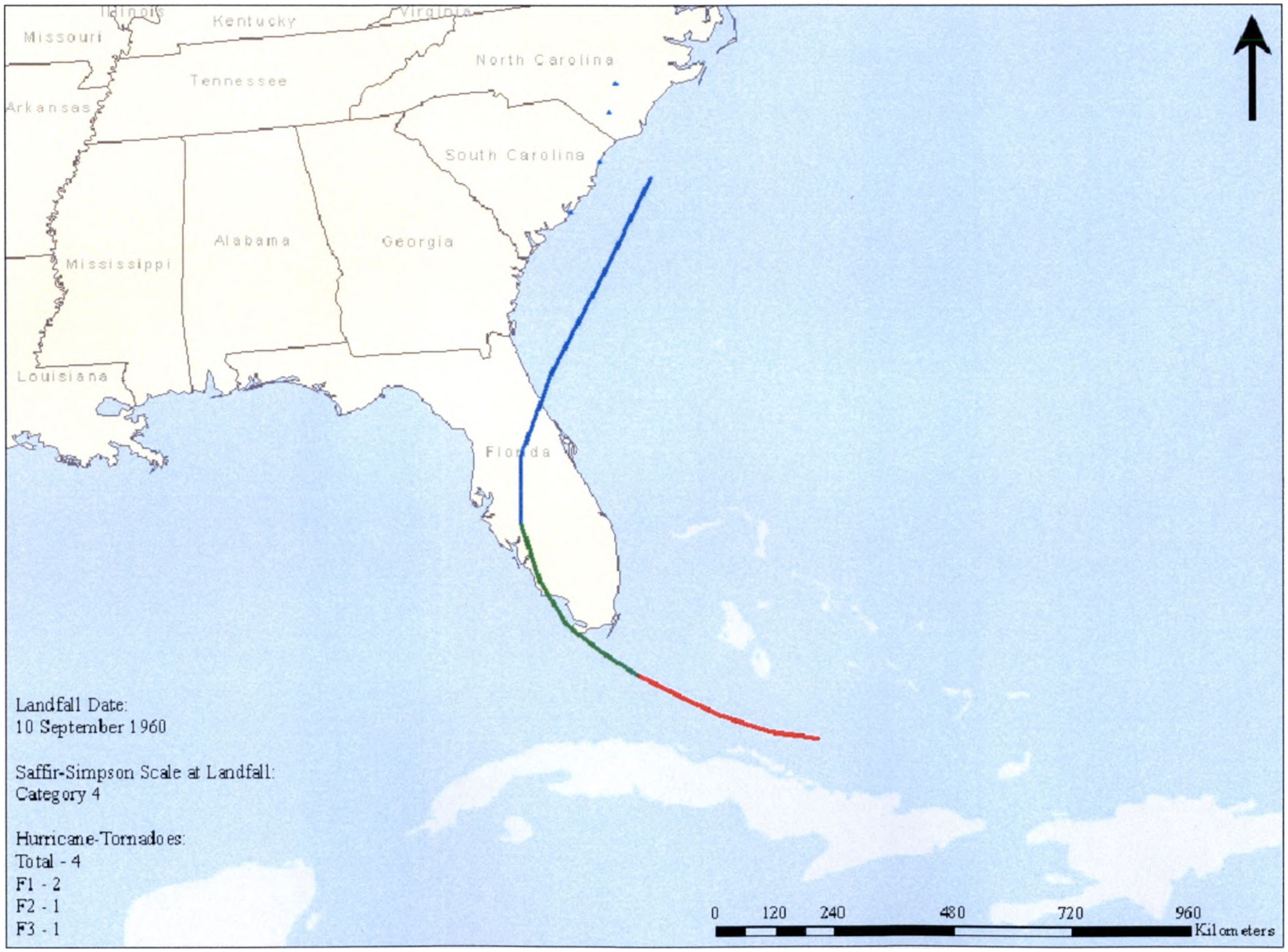


Hurricane Donna 1960



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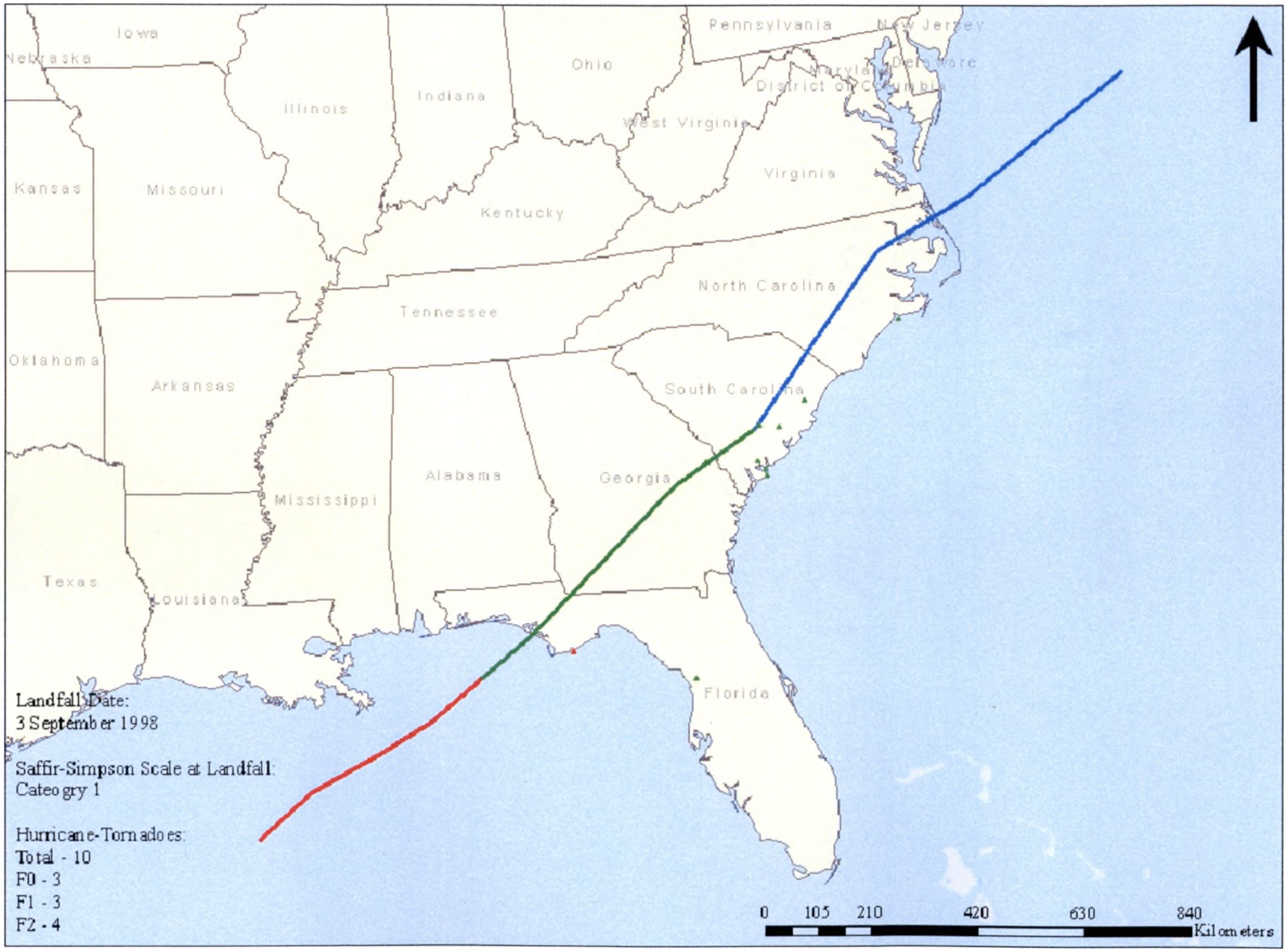

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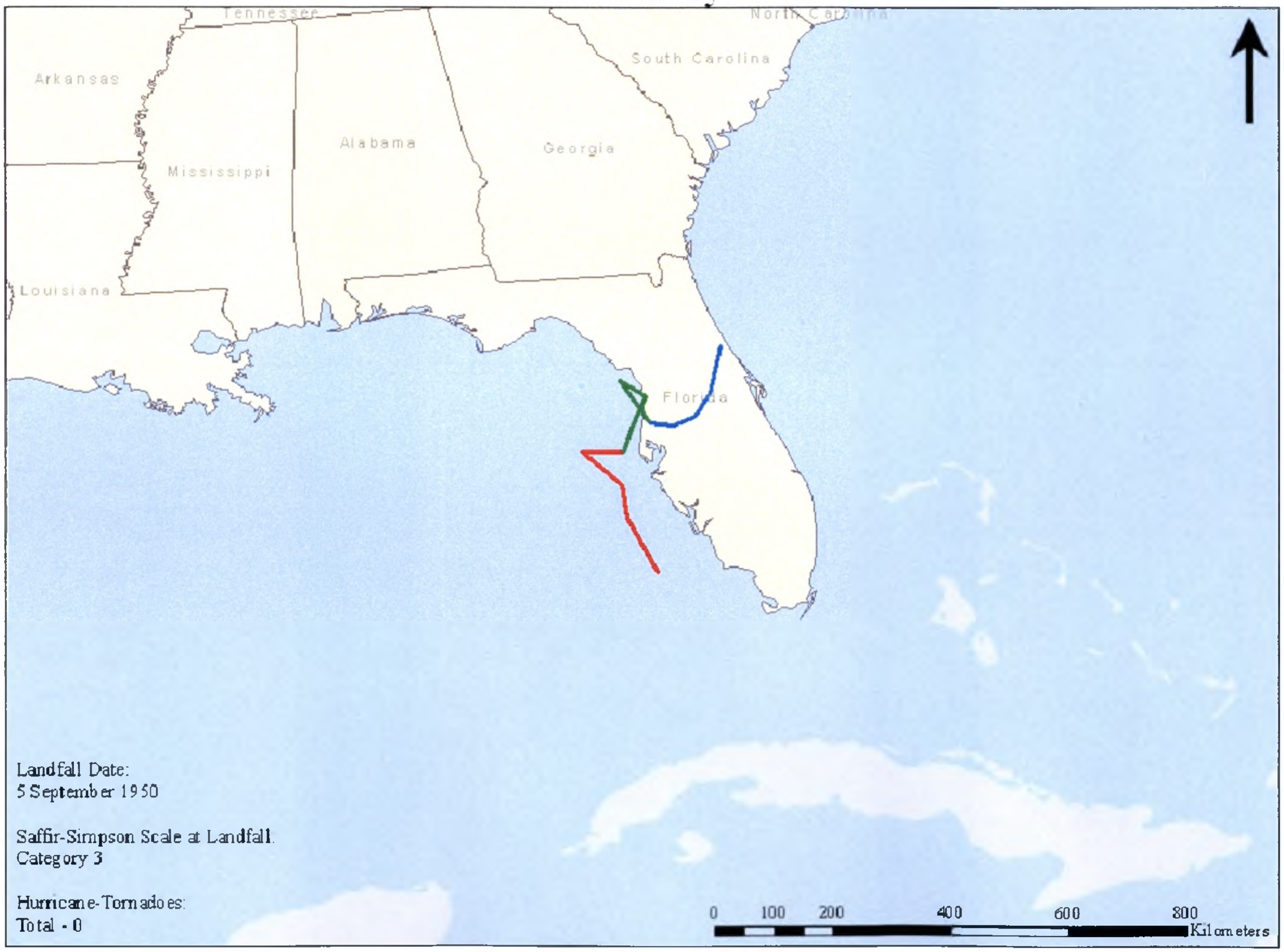
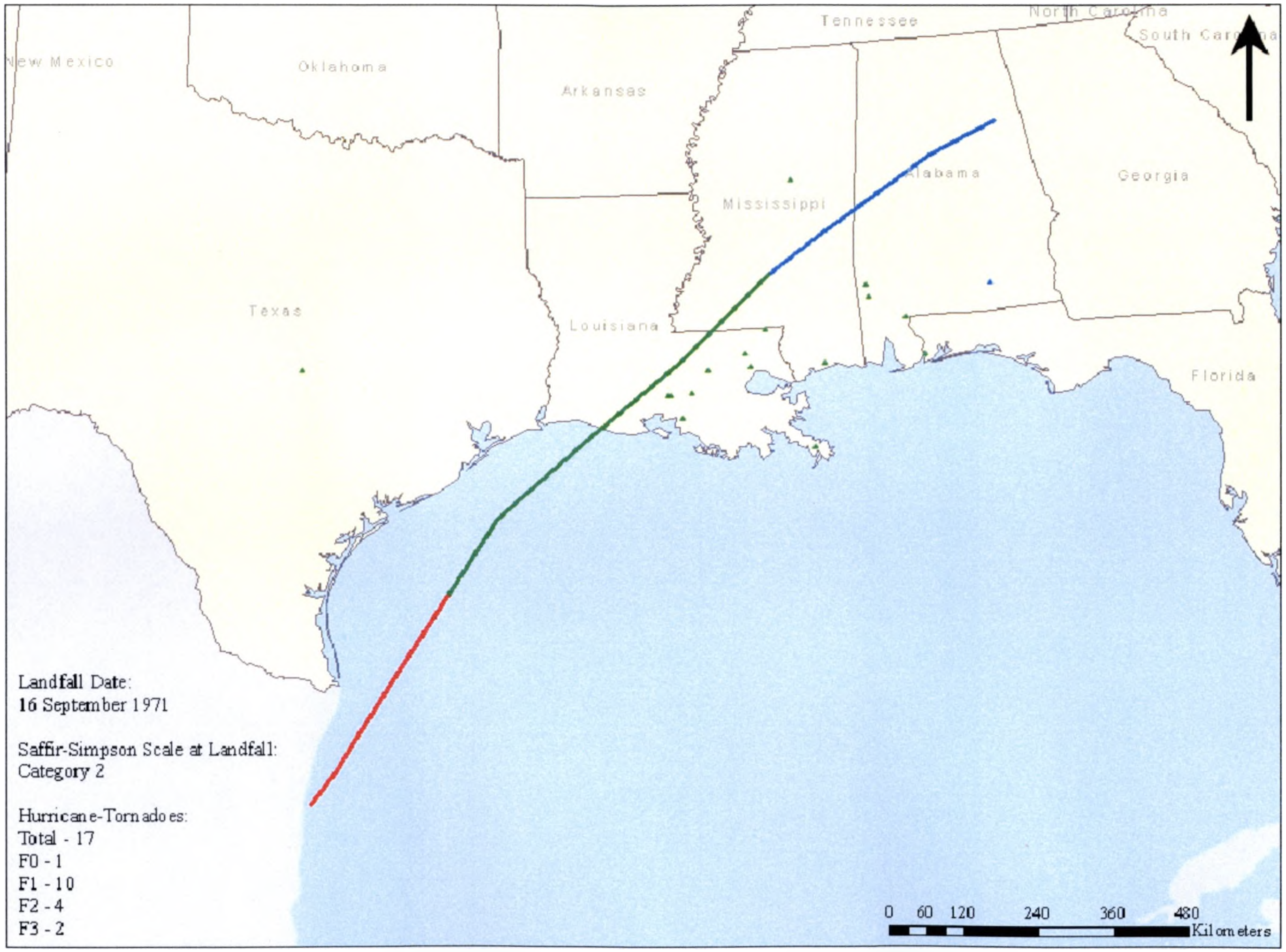
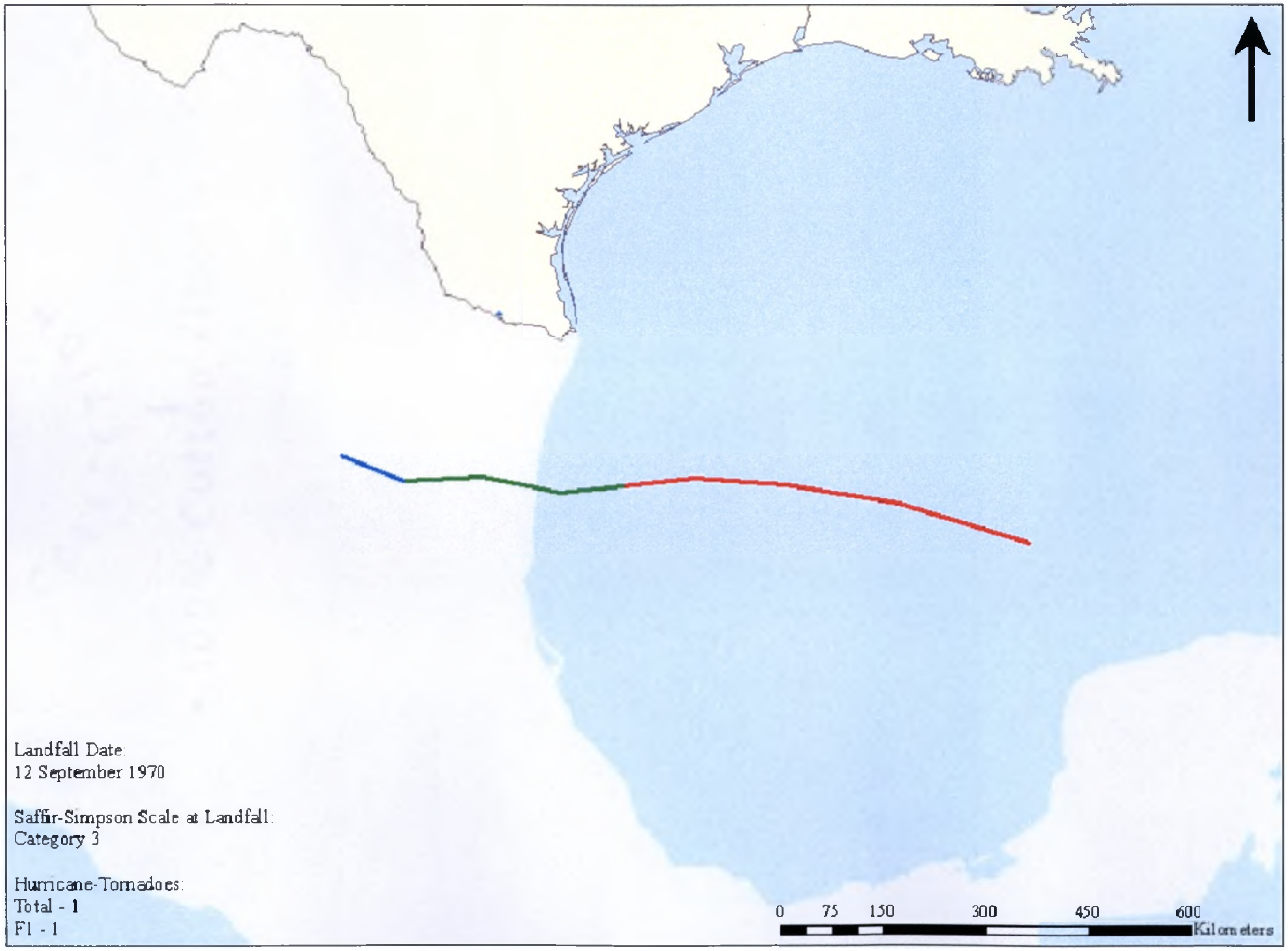


Hurricane Edith 1971

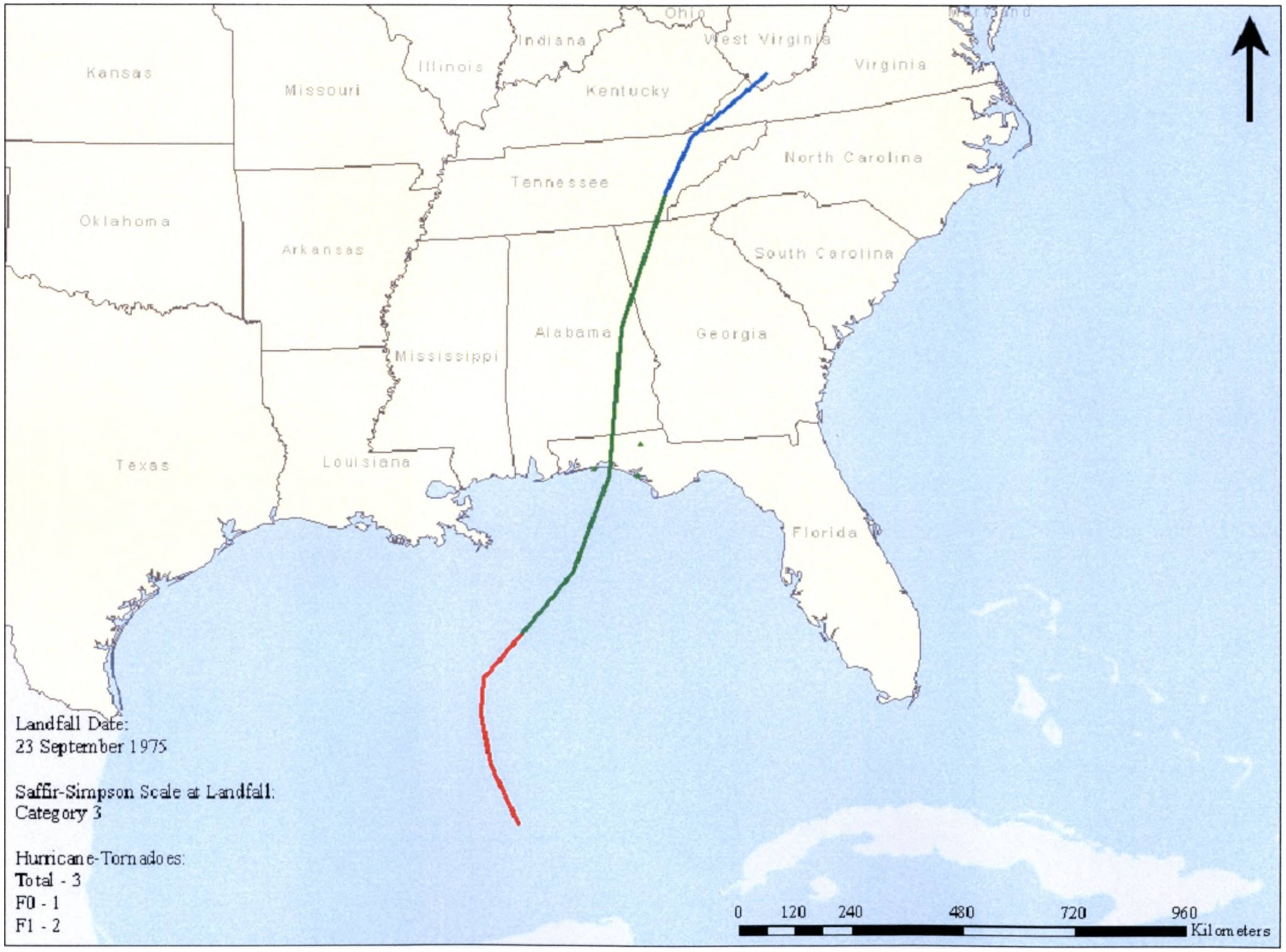


Hurricane Elena 1985

Hurricane Ella 1970



Hurricane Eloise 1975



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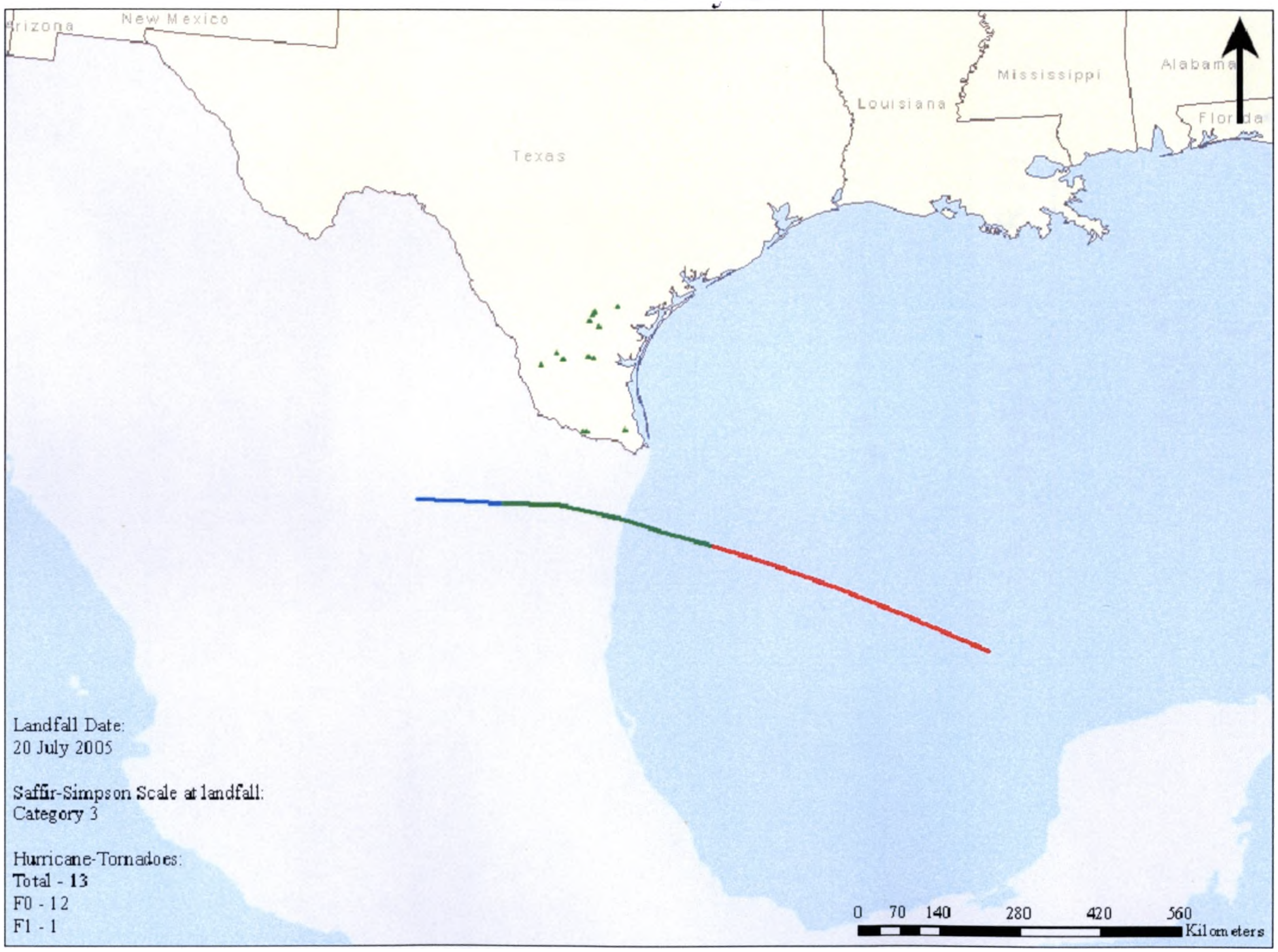
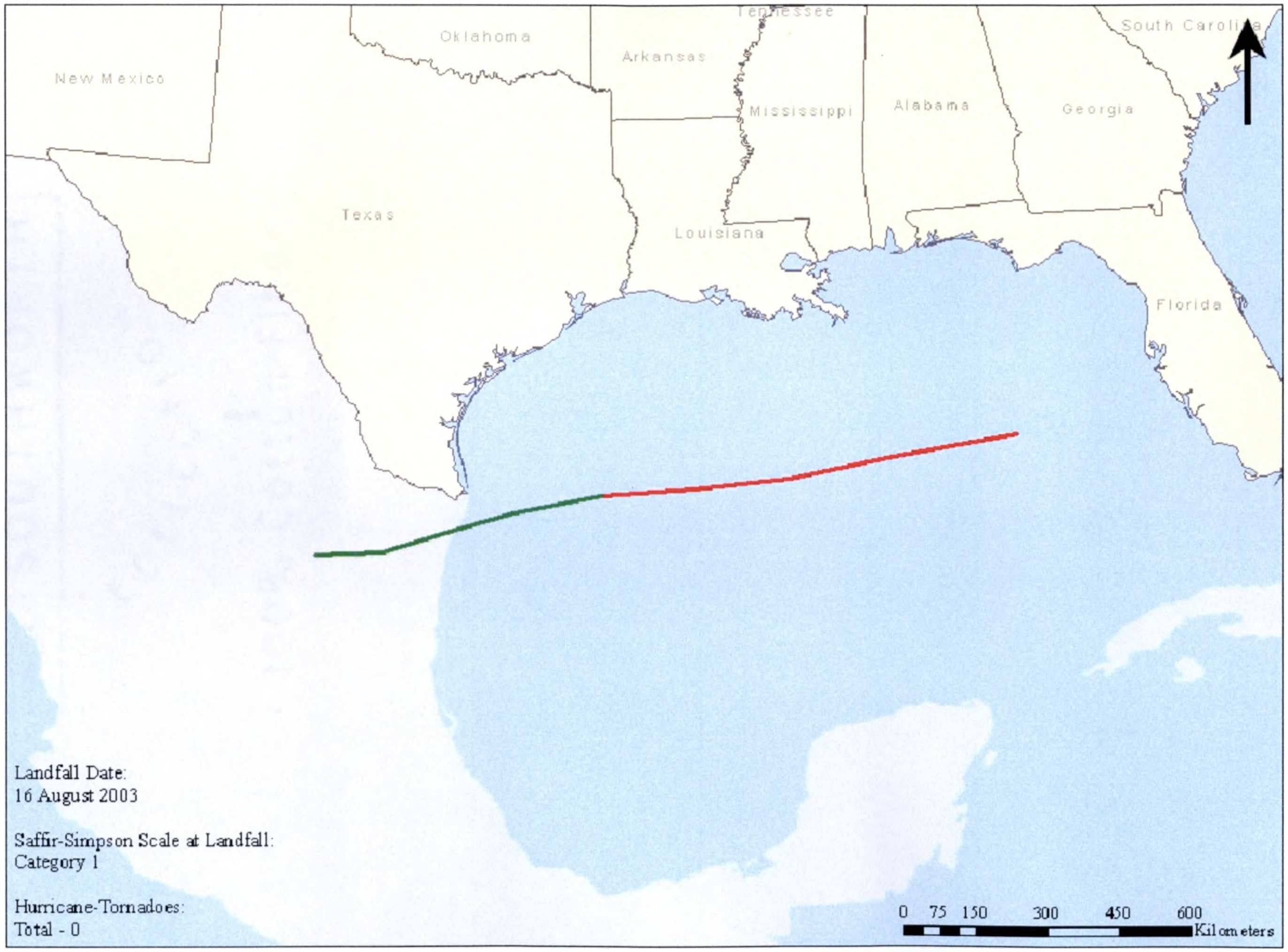
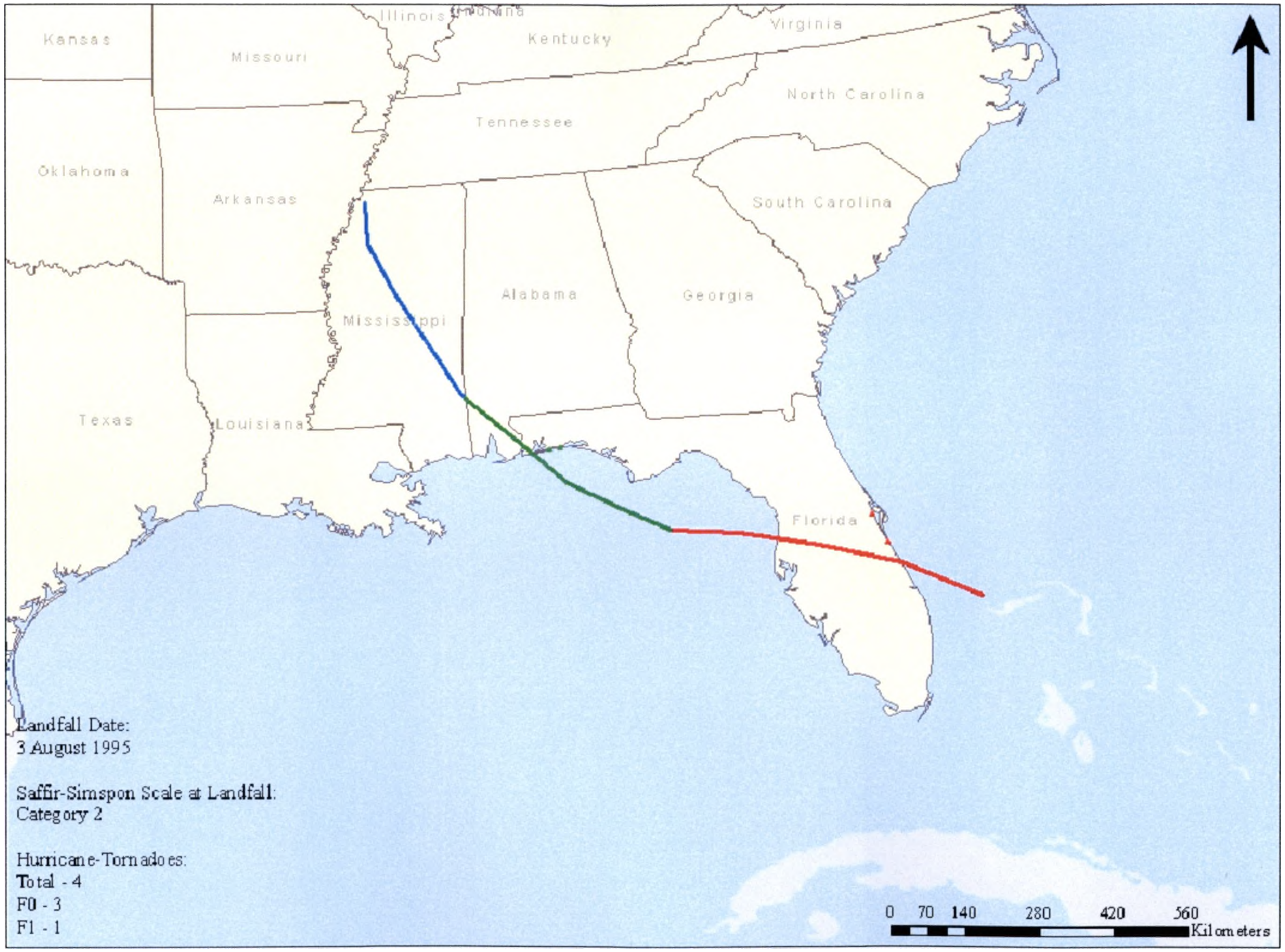


Hurricane Erika 2003



Hurricane Erin 1995



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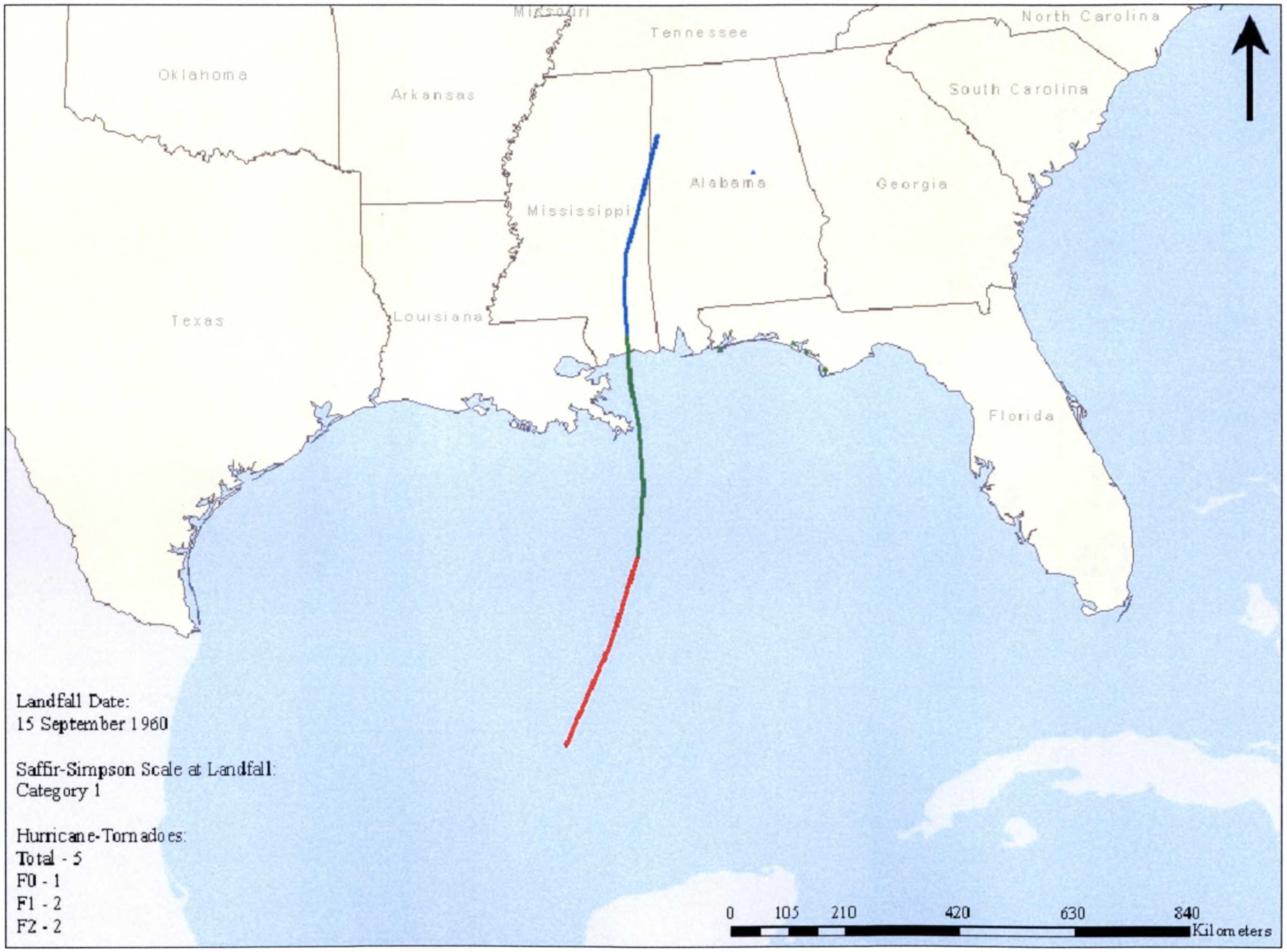
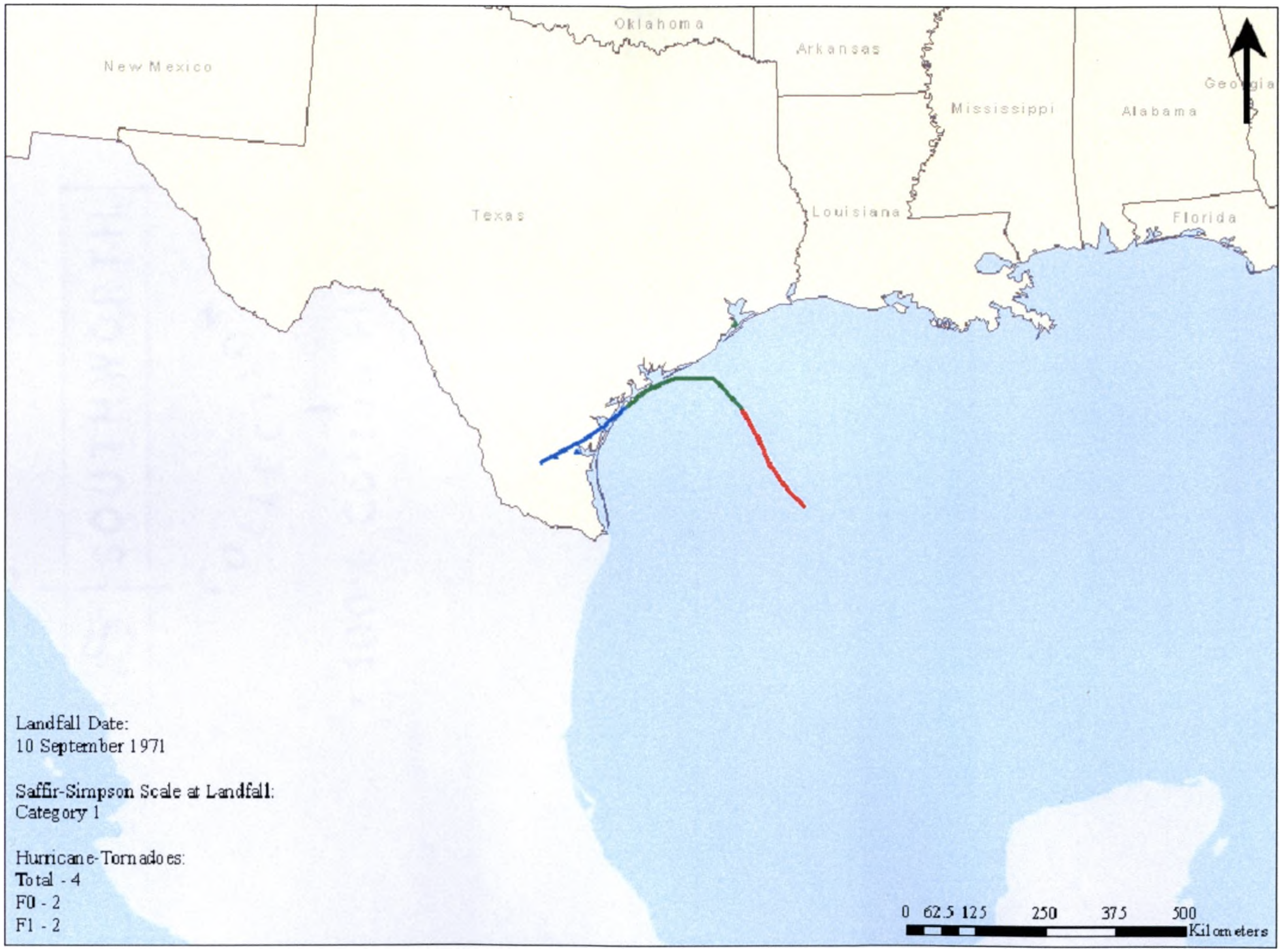


Hurricane Fern 1971

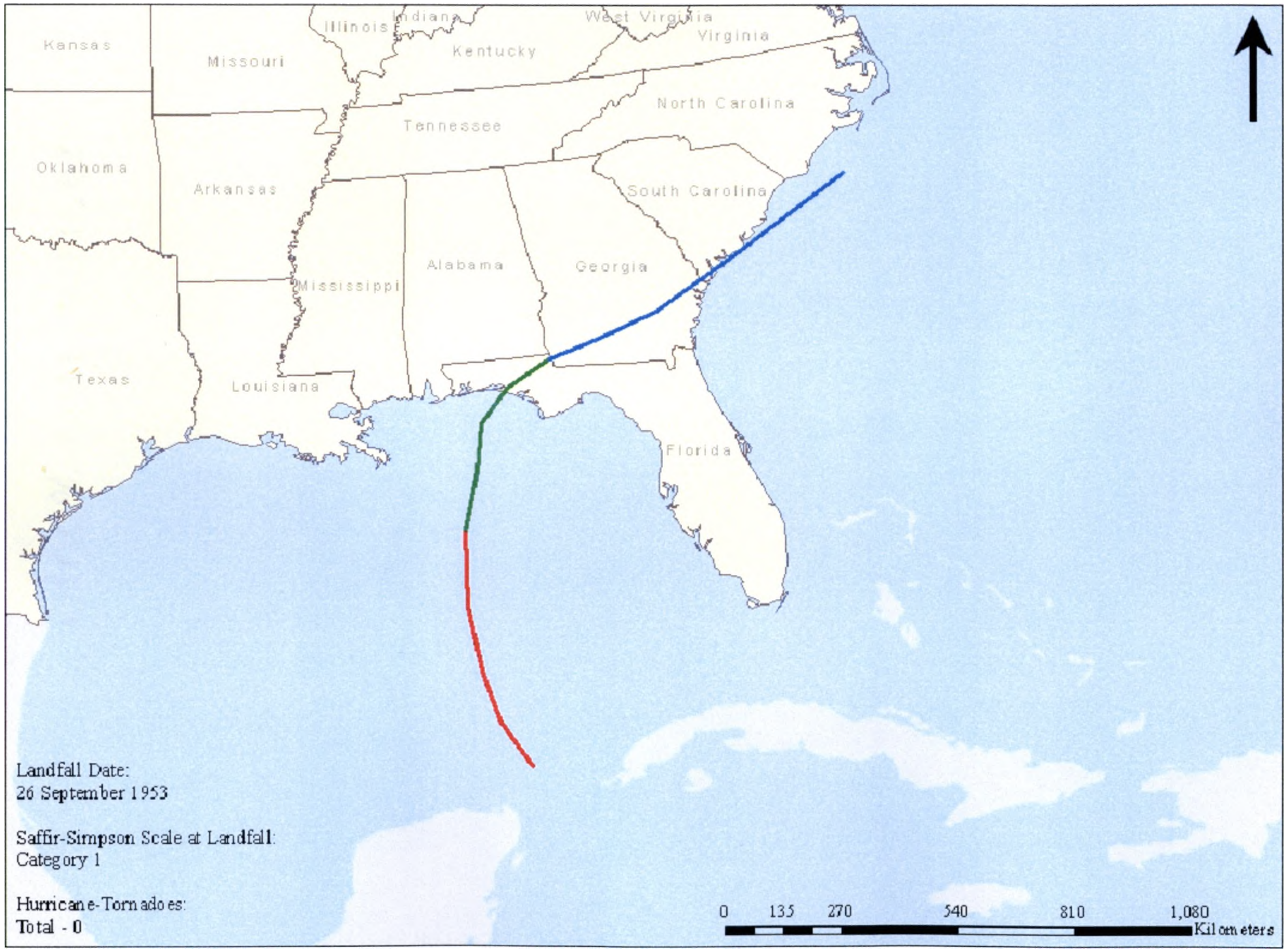


Landfall Date:
10 September 1971

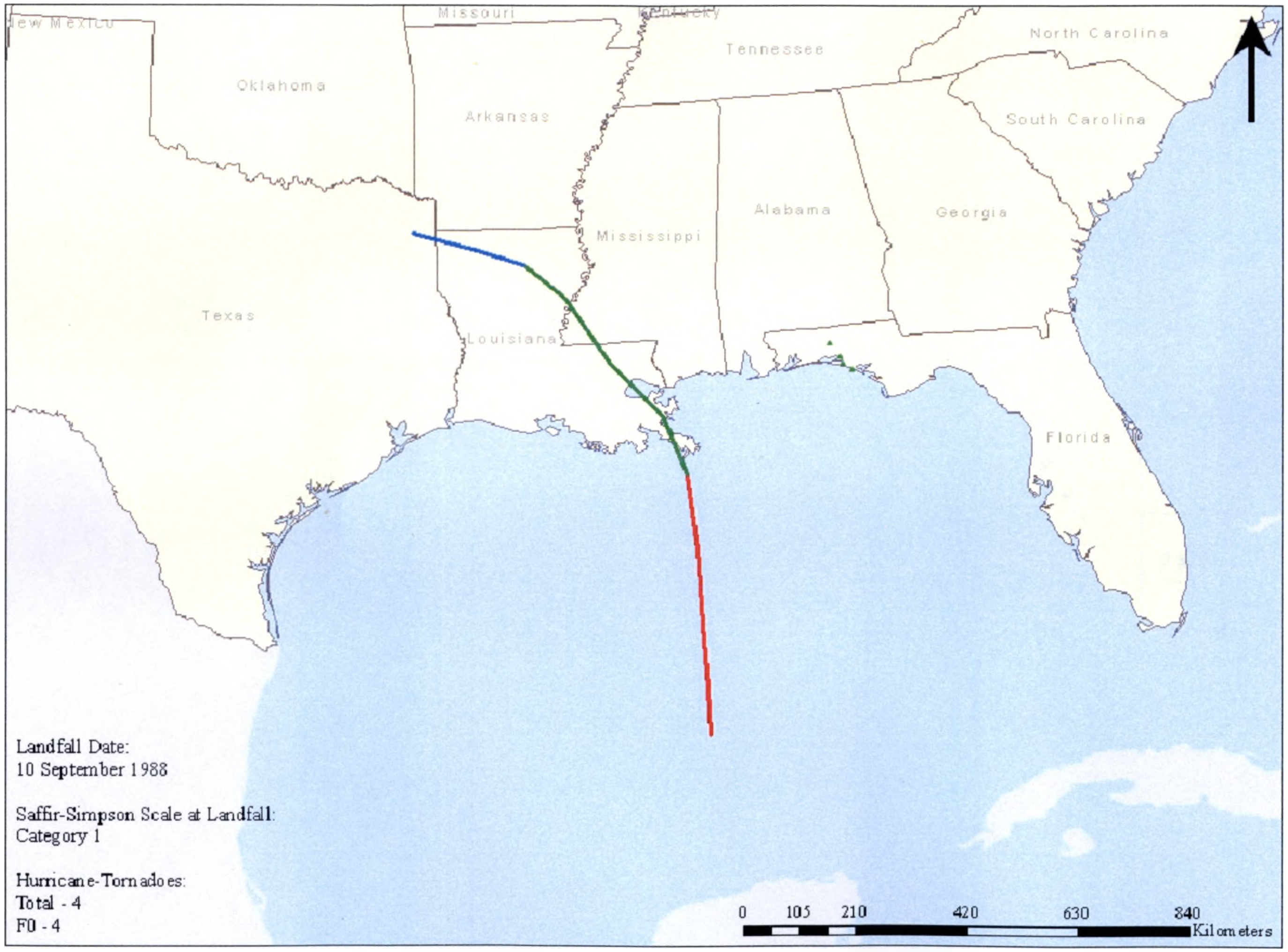
Saffir-Simpson Scale at Landfall:
Category 1

Hurricane-Tornadoes:
Total - 4
F0 - 2
F1 - 2

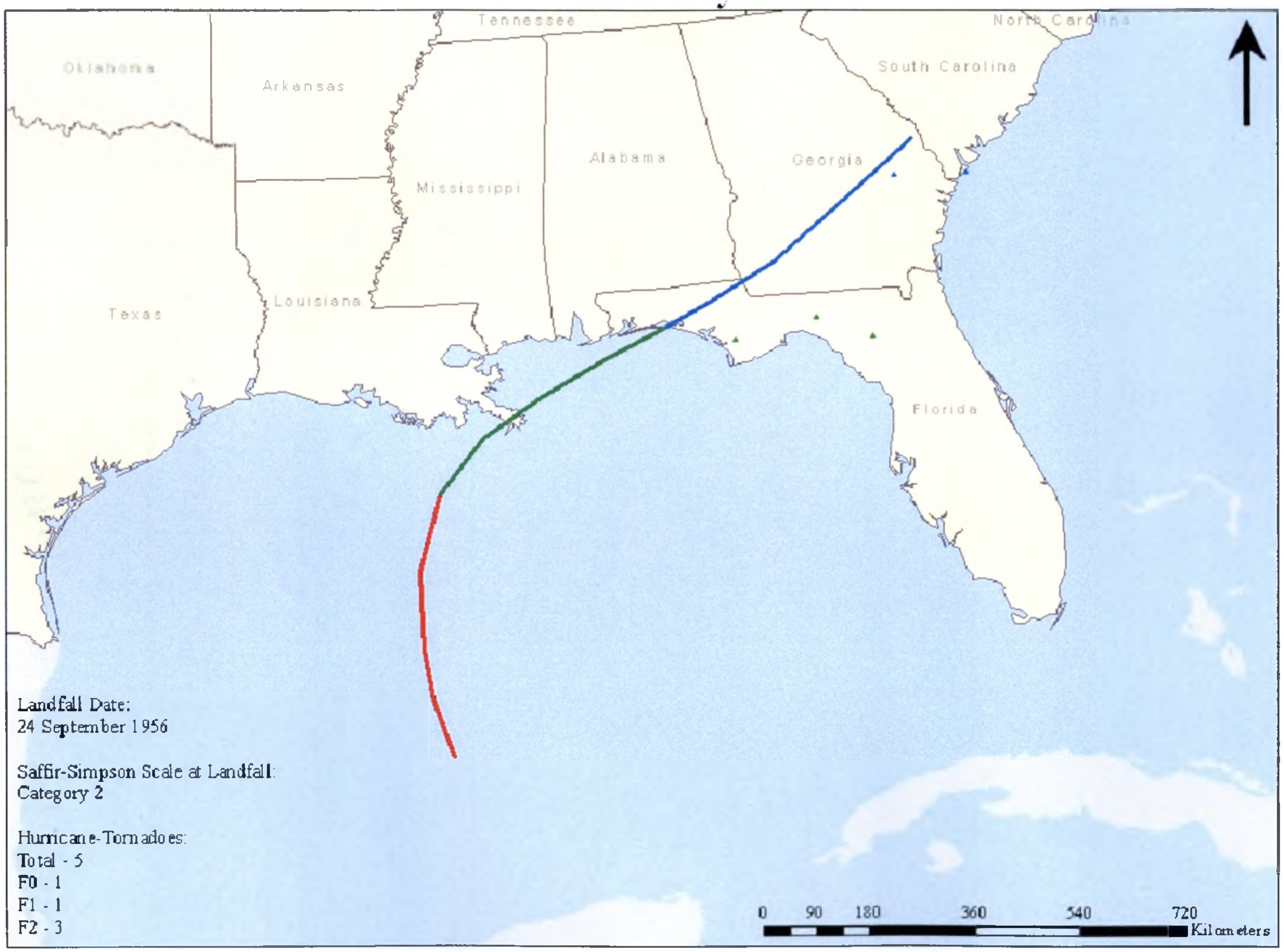
Hurricane Florence 1953



Hurricane Florence 1988

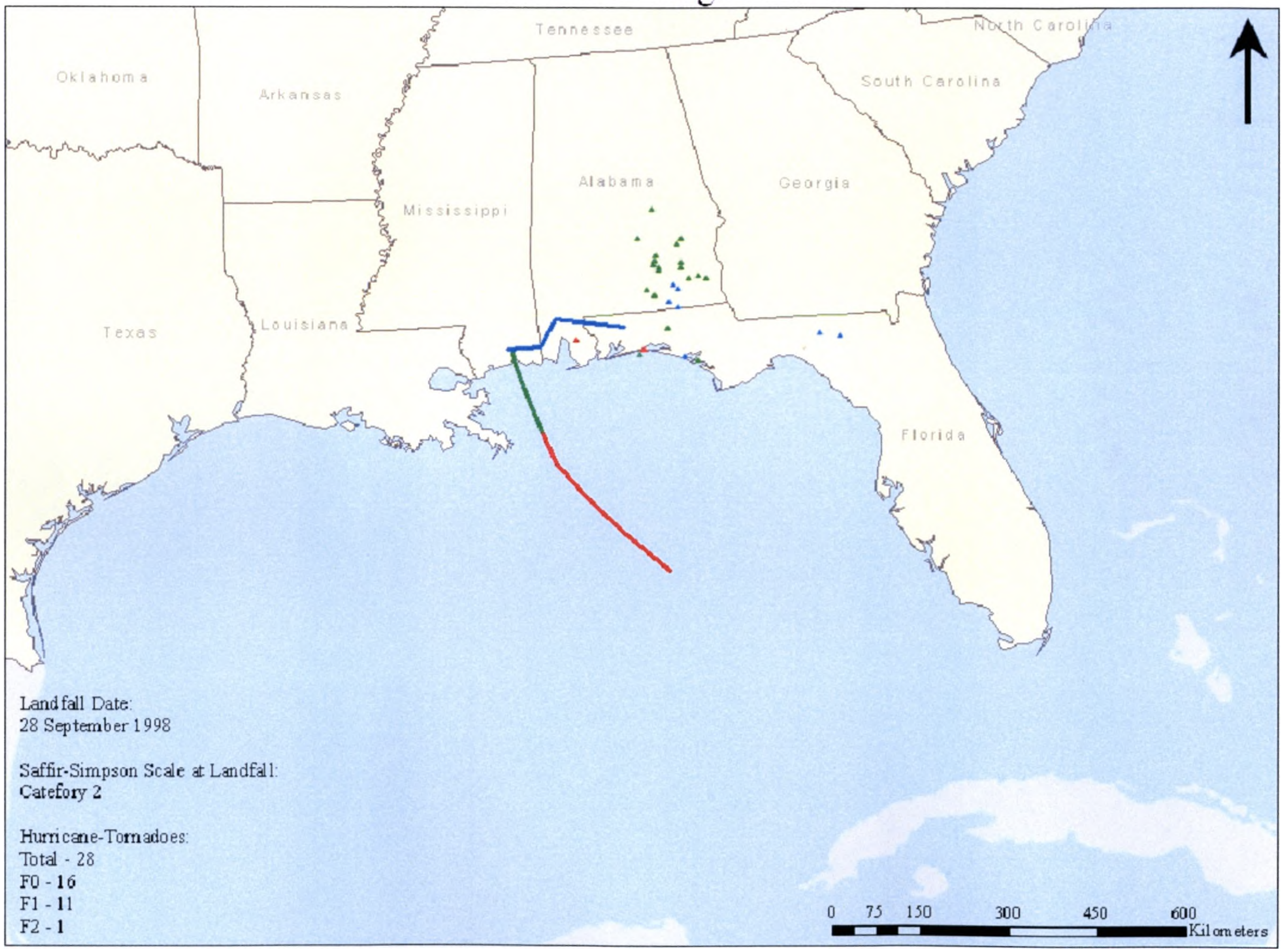


Hurricane Flossy 1956



Hurricane Frederic 1979

Hurricane Georges 1998



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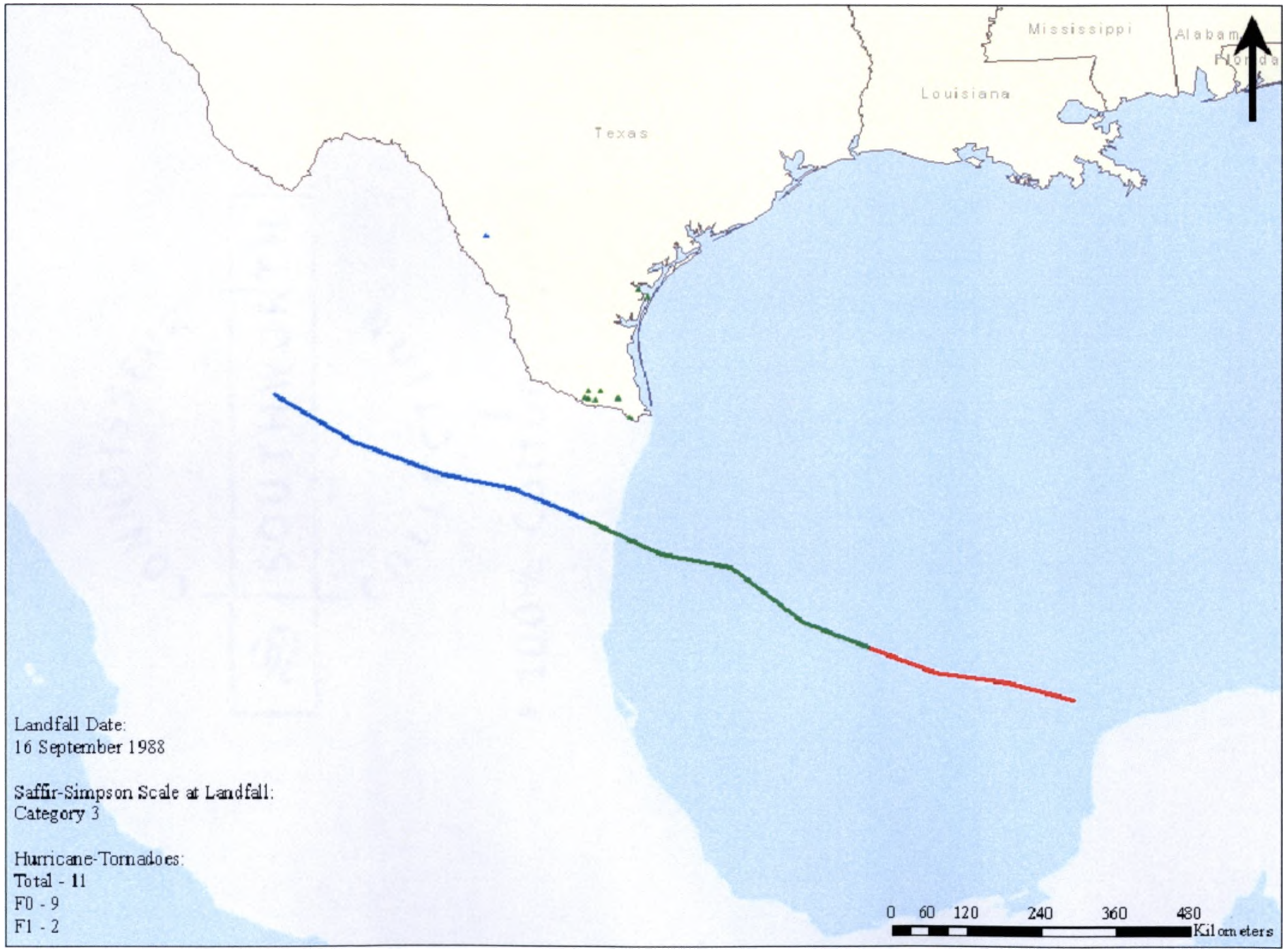
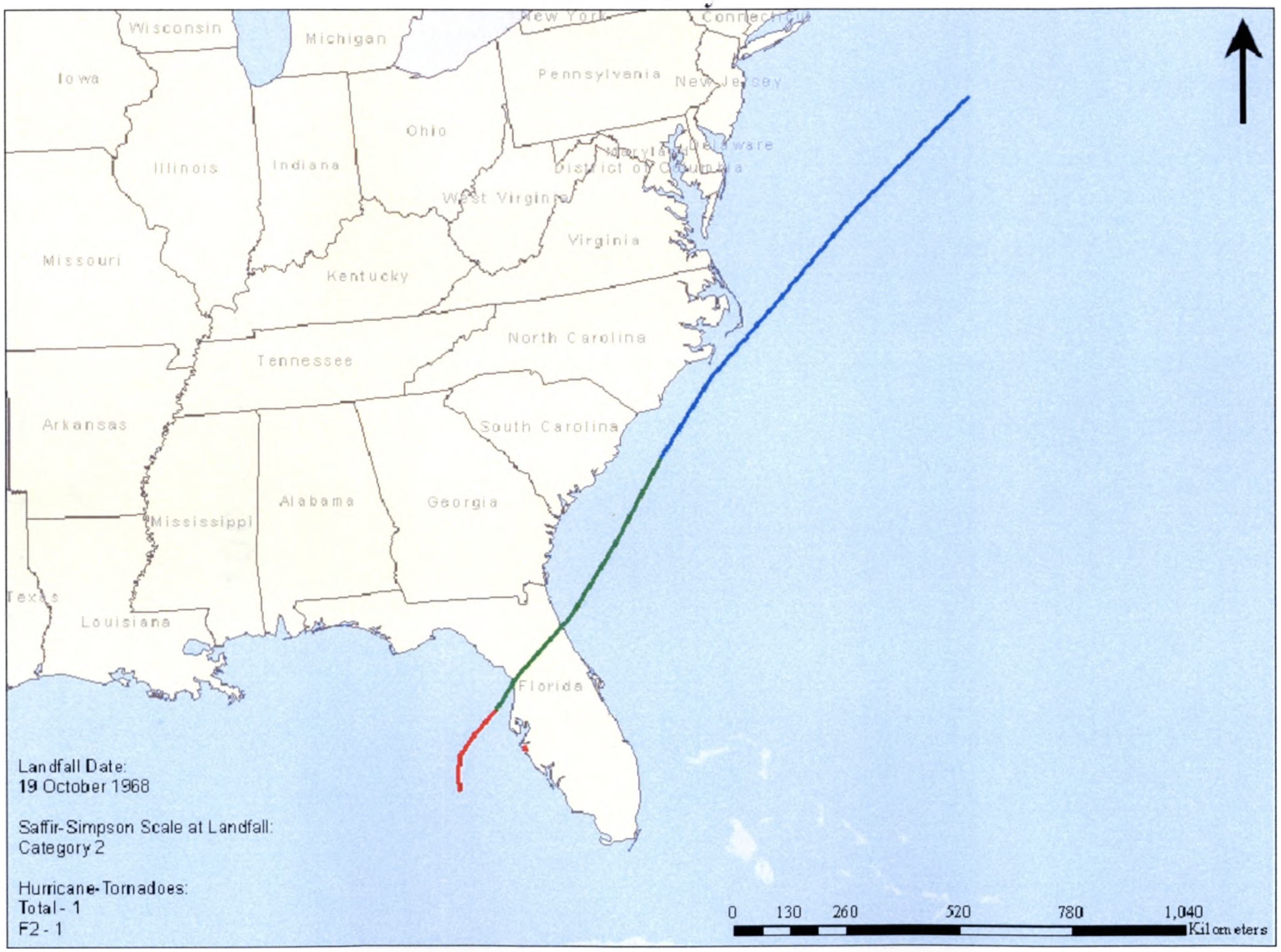
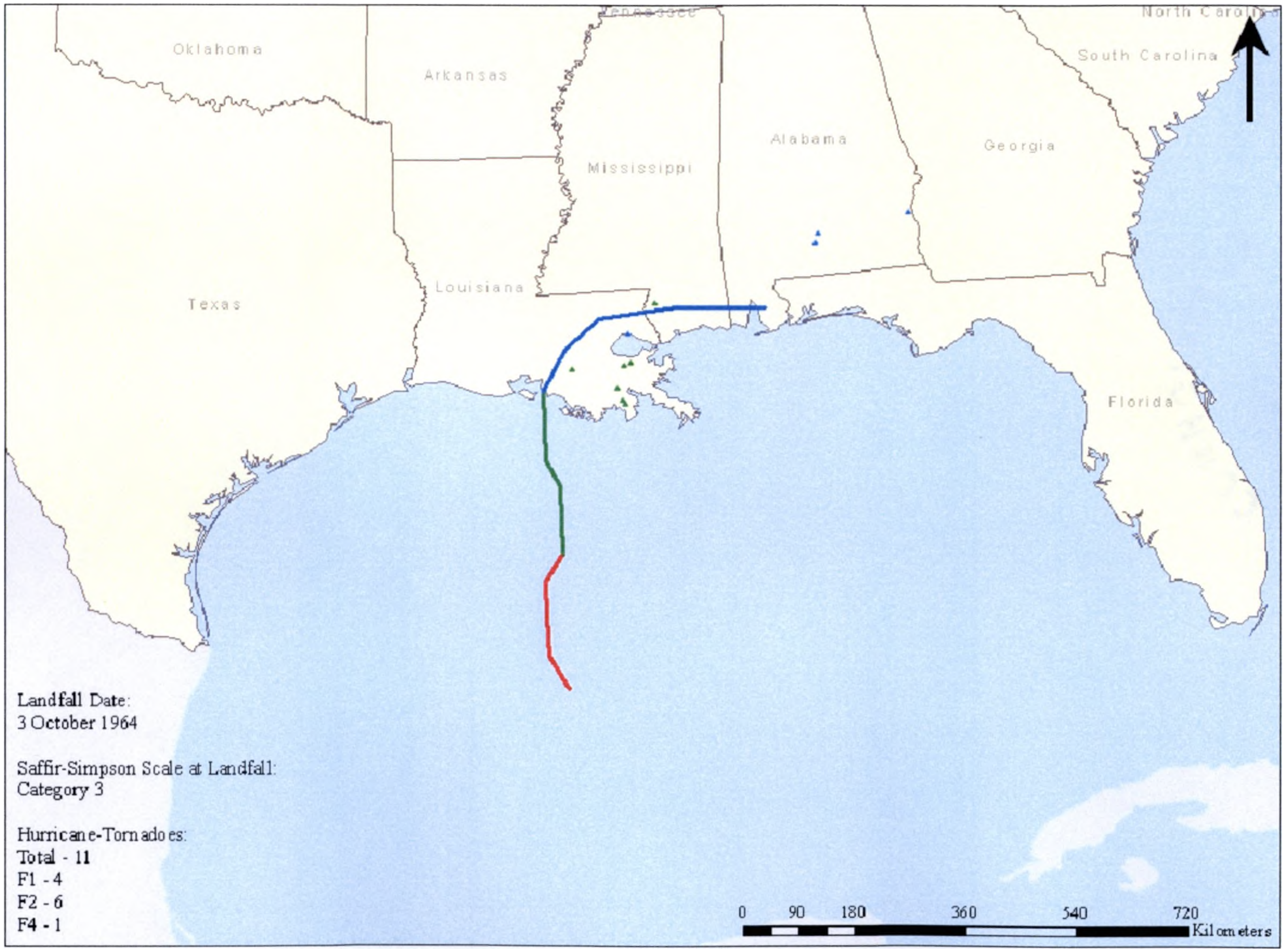


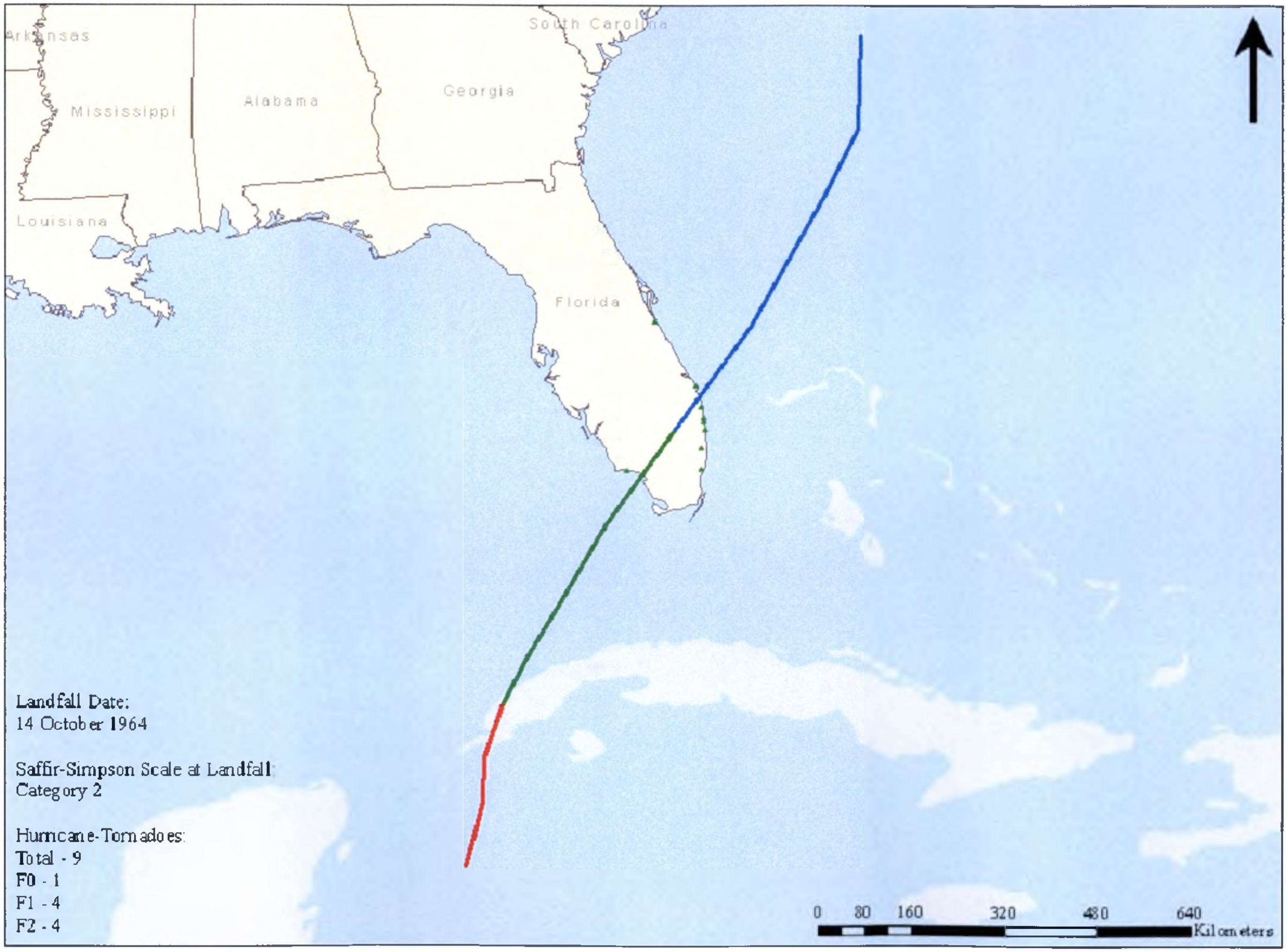
Hurricane Gladys 1968



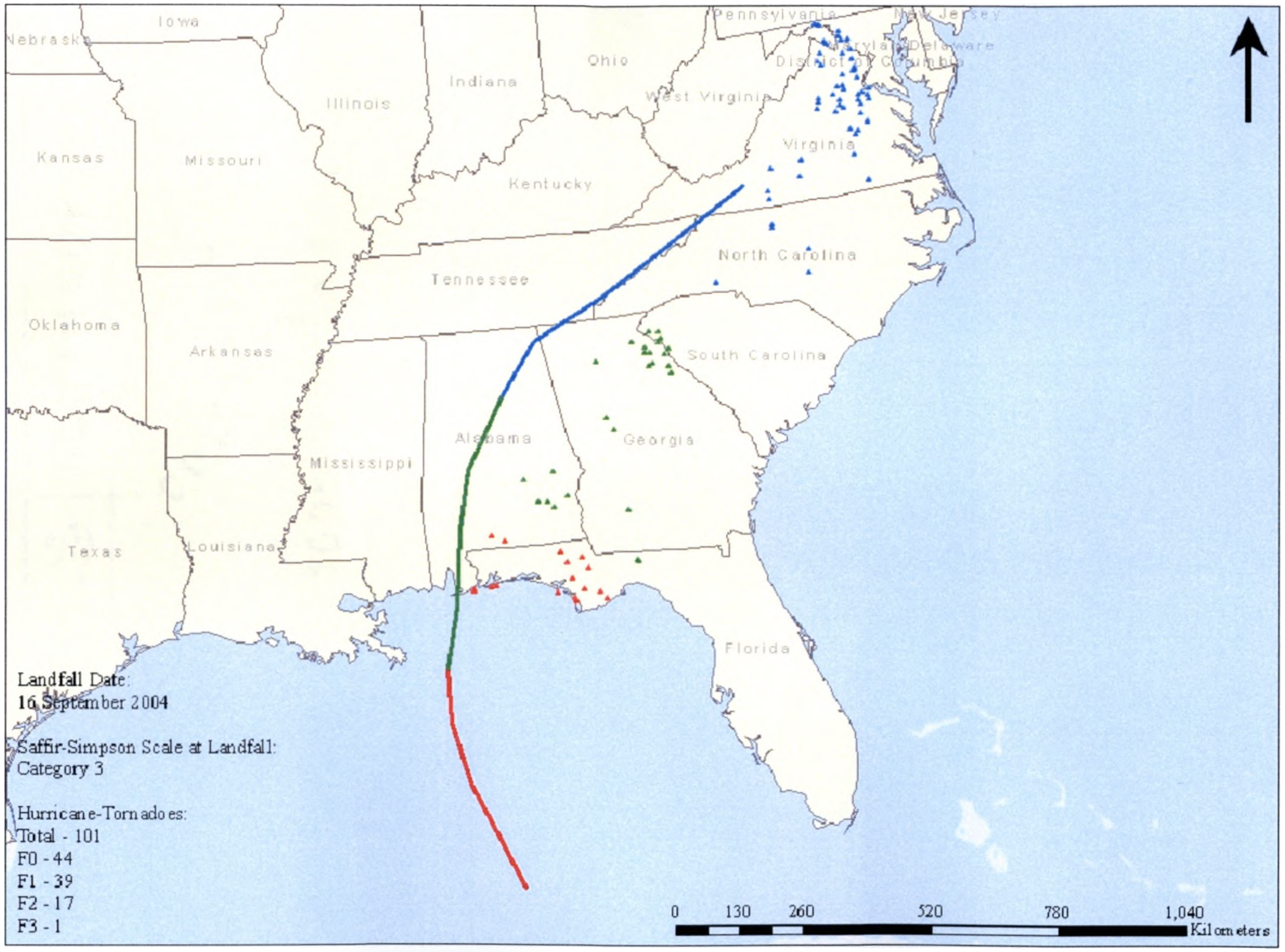
Hurricane Hilda 1964



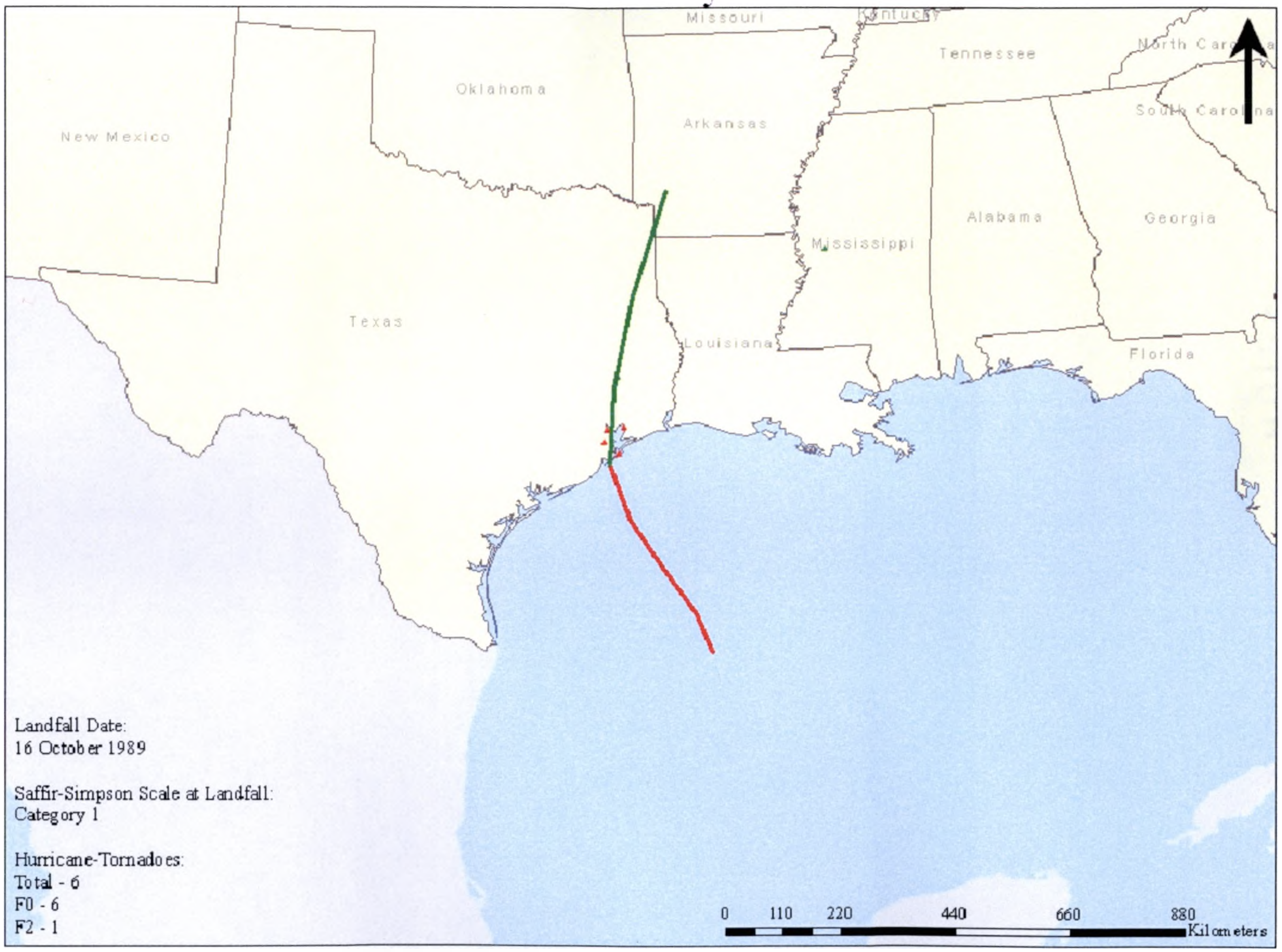
Hurricane Isbell 1964



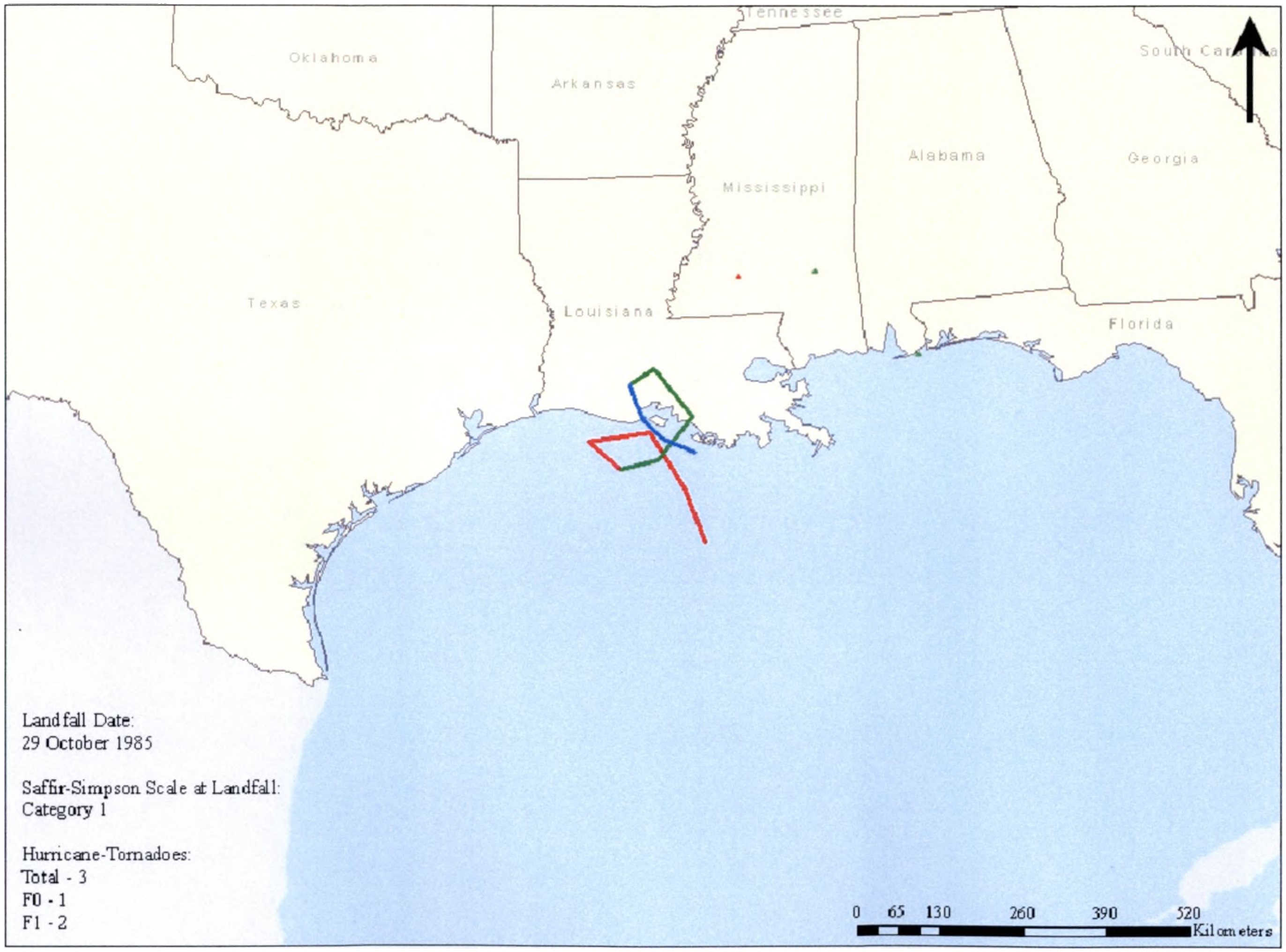
Hurricane Ivan 2004



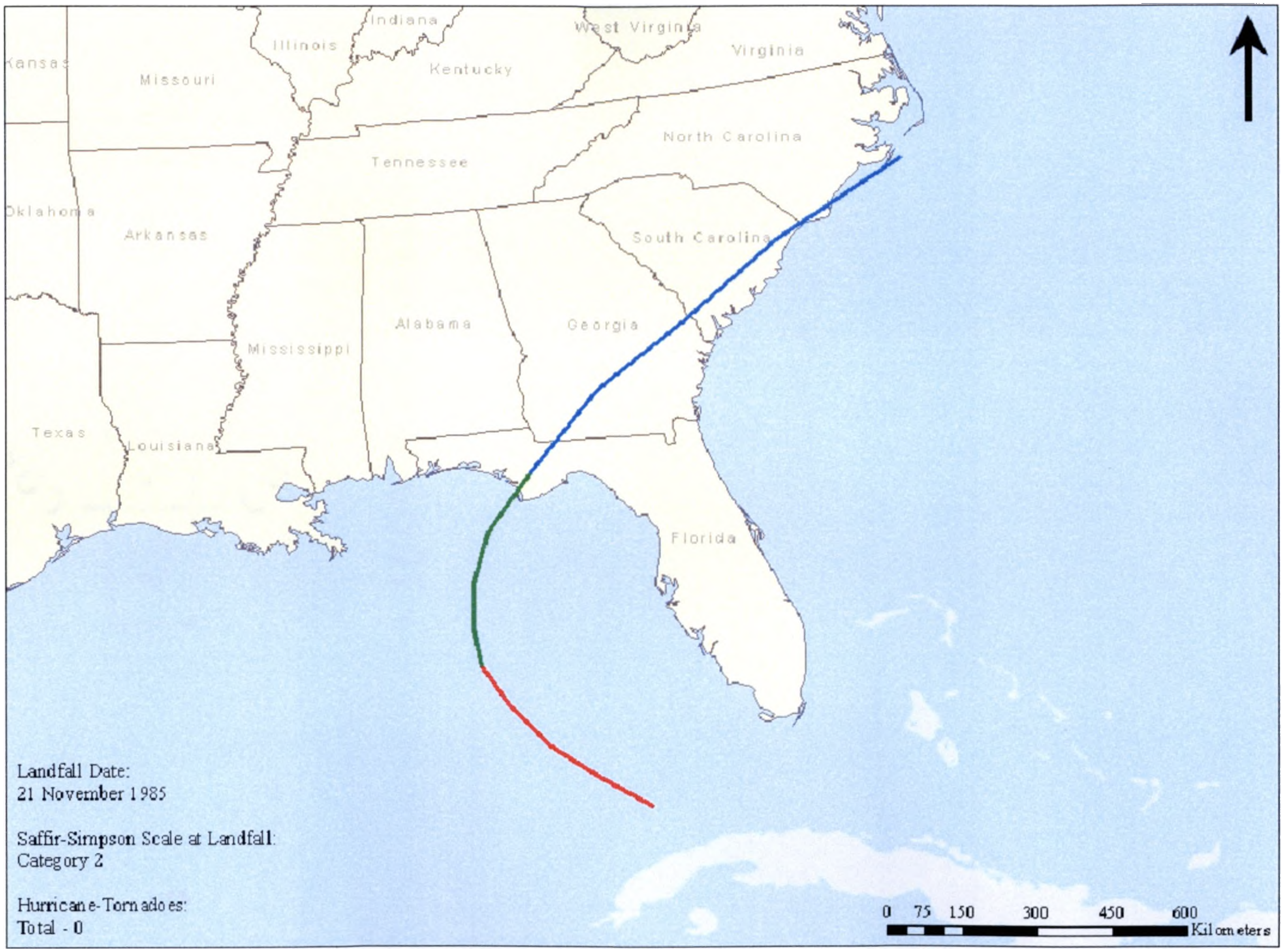
Hurricane Jerry 1989



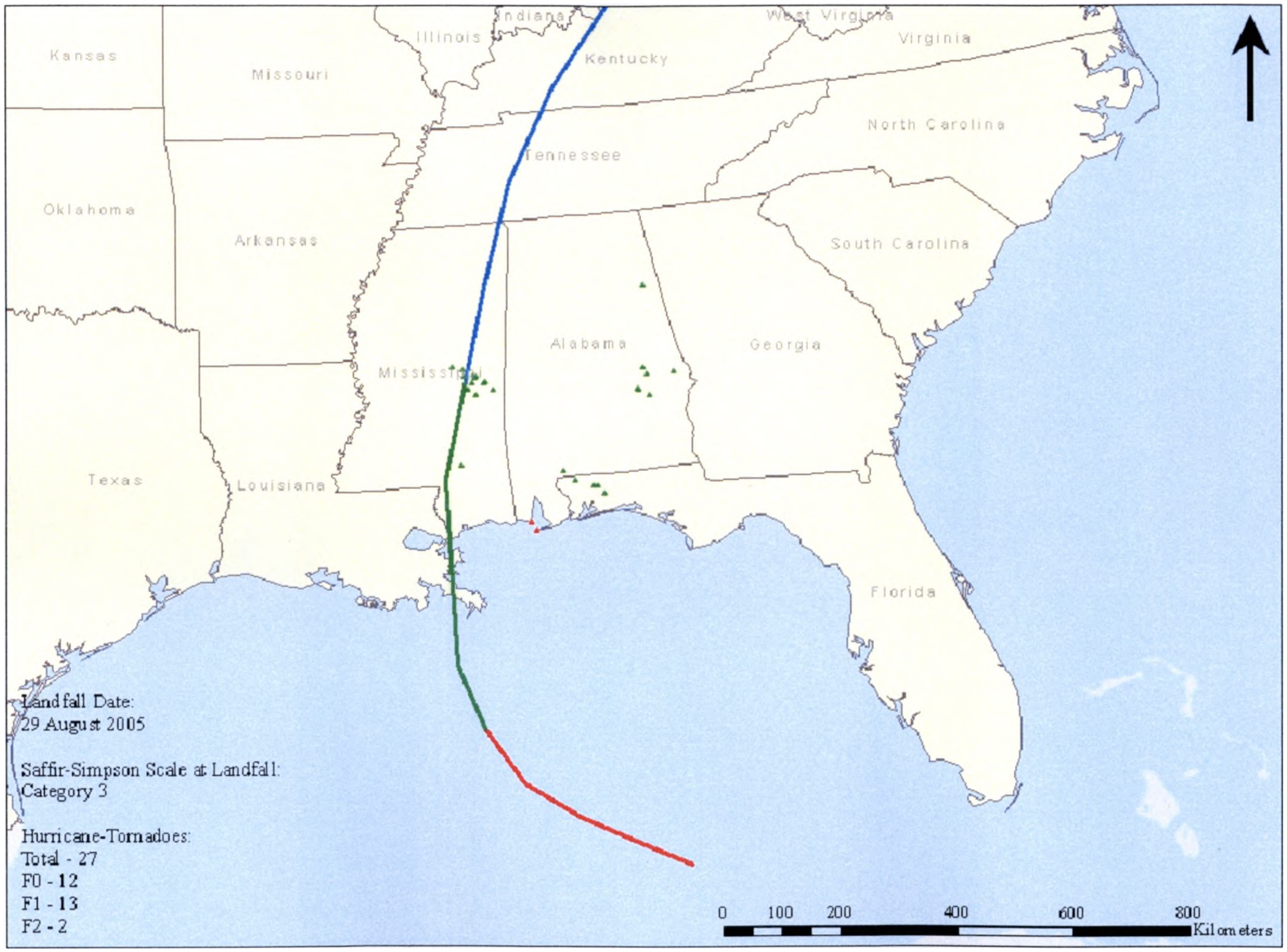
Hurricane Juan 1985



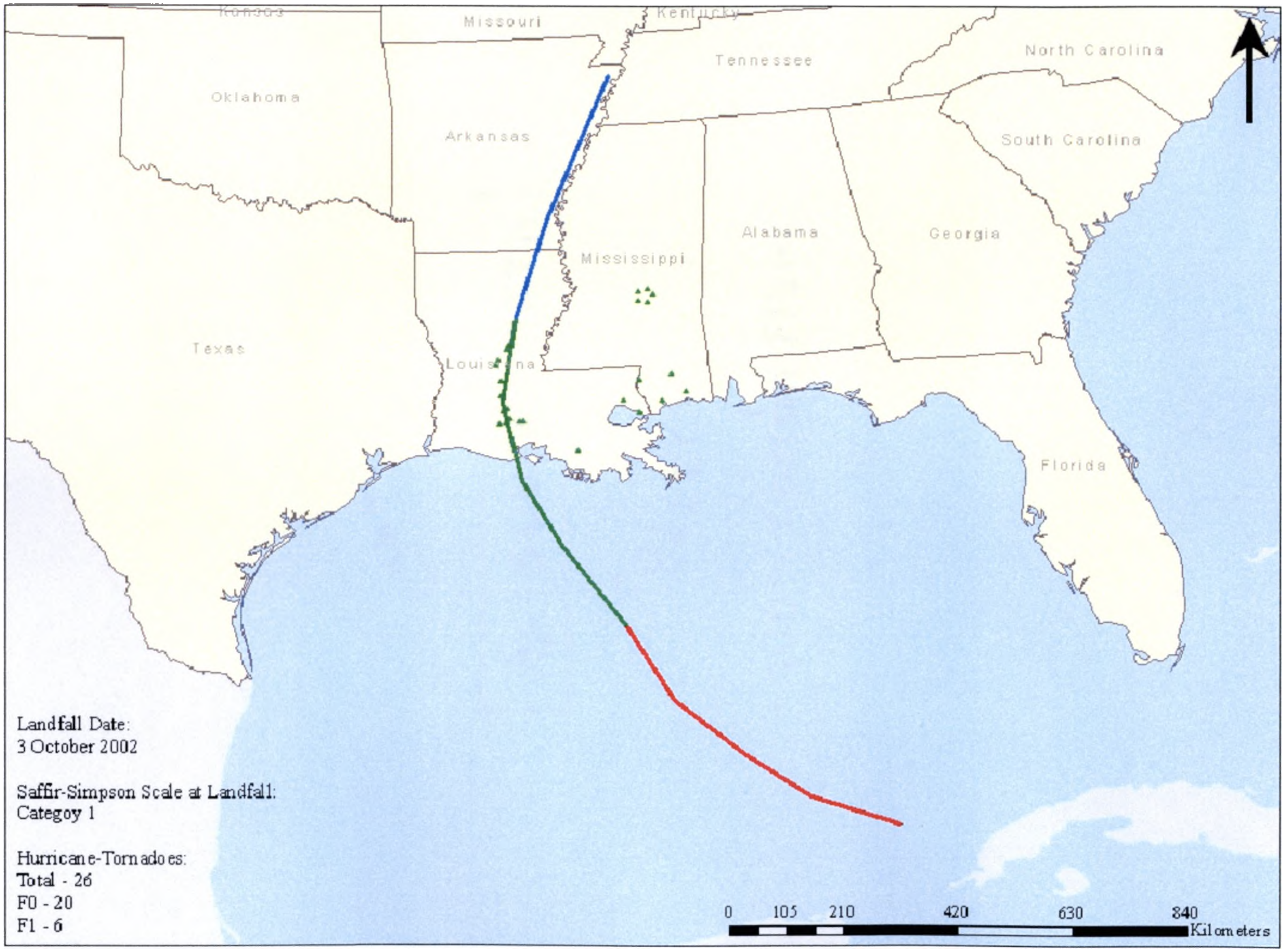
Hurricane Kate 1985



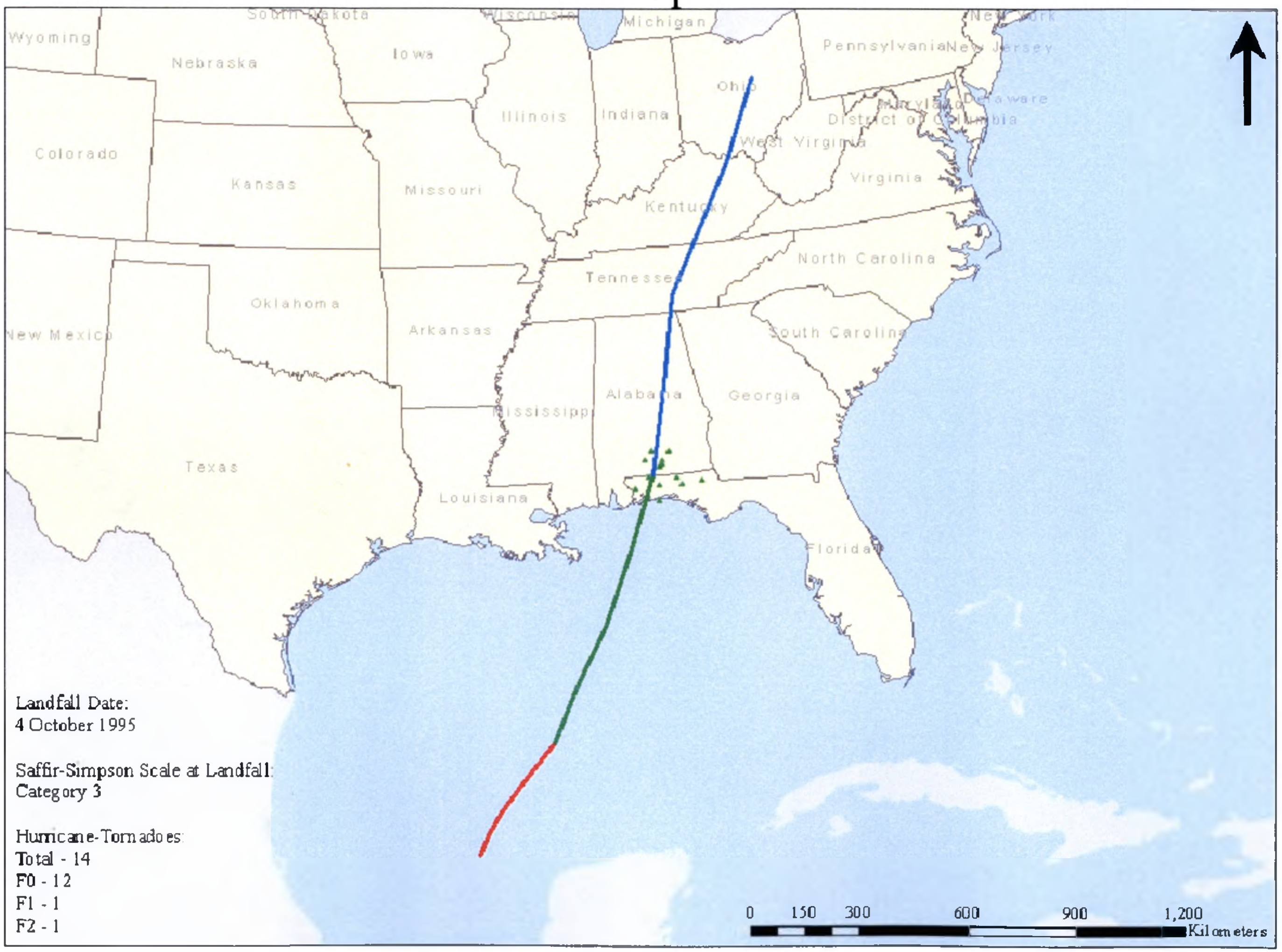
Hurricane Katrina 2005



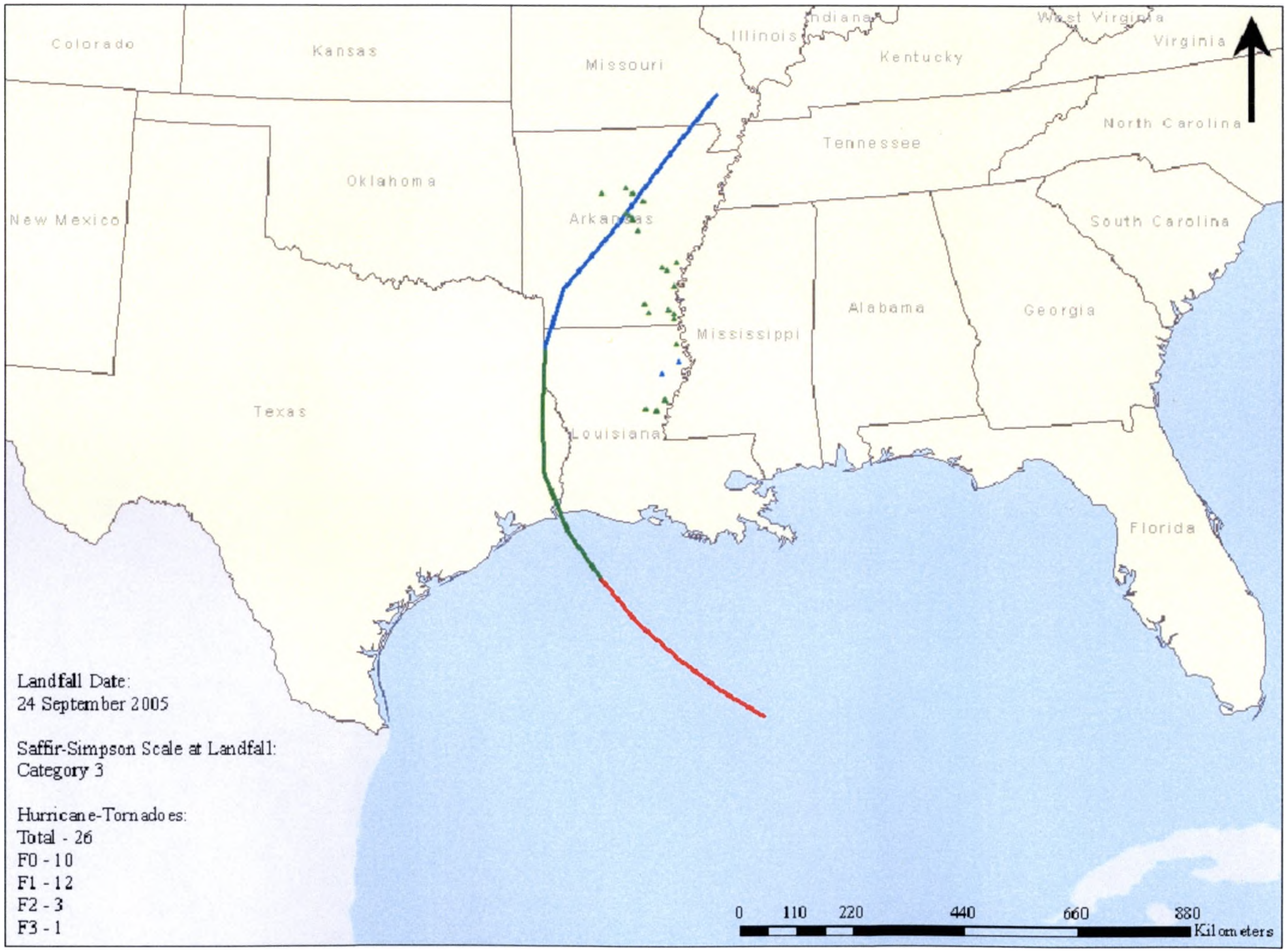
Hurricane Lili 2002



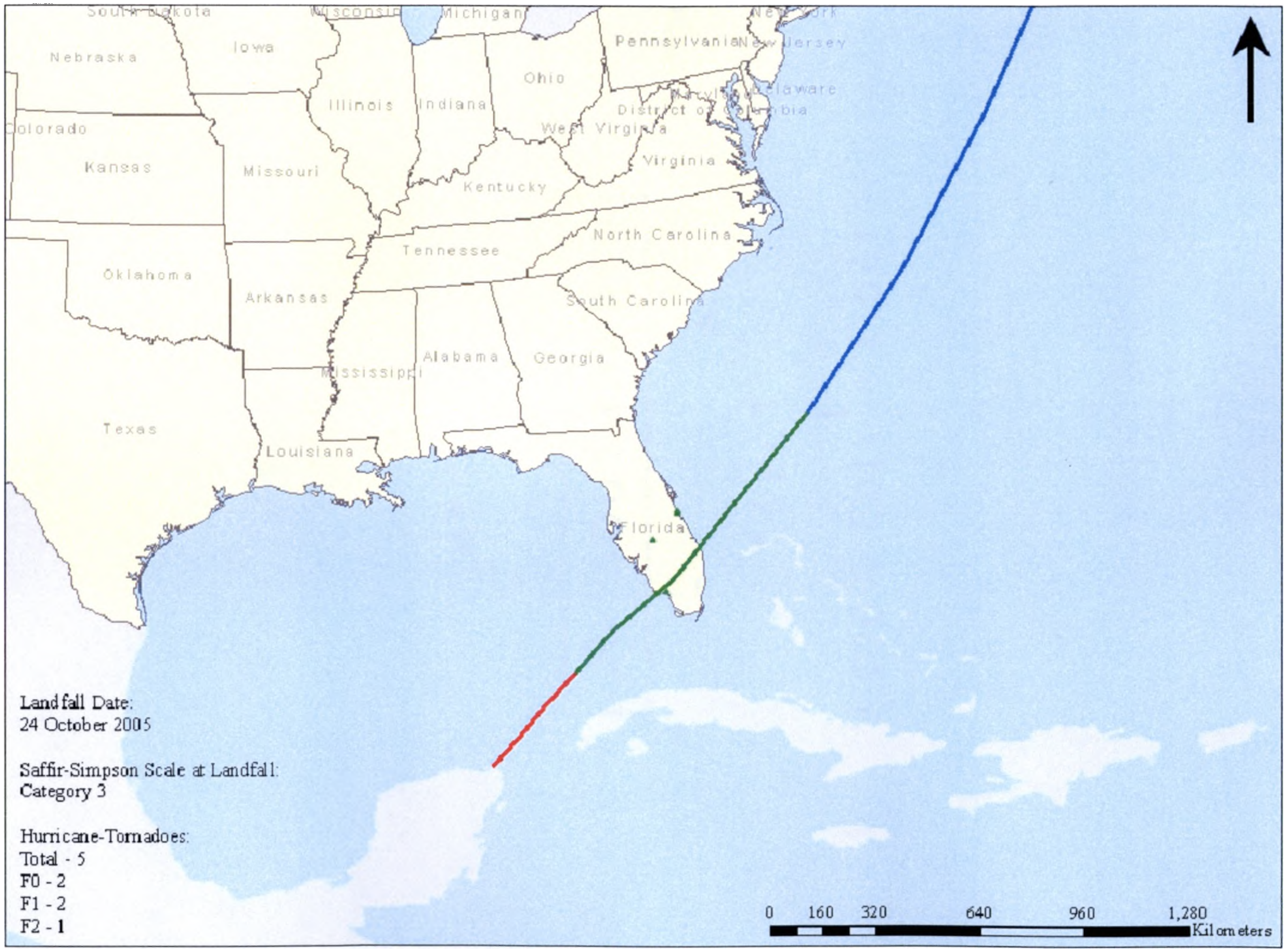
Hurricane Opal 1995



Hurricane Rita 2005



Hurricane Wilma 2005



LITERATURE CITED

Barbour, George B. 1924. Waterspouts and tornado within a typhoon area. *Monthly Weather Review*: 106 - 107.

Bluestein, H. B. 1999. *Tornado Alley: monster storms of the Great Plains*. New York: Oxford University Press.

Bogner, P. B., G. M. Barnes and J. L. Franklin. 2000. Conditional instability and shear for six hurricanes over the Atlantic Ocean. *Weather Forecast* 15: 192 - 207.

Carleton, Andrew M. 1999. Methodology in climatology. *Annals of the Association of American Geographers* 89: 713 - 735.

Chapman, Lee and John E. Thornes. 2003. The use of geographic information systems in climatology and meteorology. *Progress in Physical Geography* 27: 313 - 330.

Crossett, Kristen M., Thomas J. Culliton, Peter C. Wiley and Timothy R. Goodspeed. 2004. Population trends along the coastal United States: 1980-2008. *Coastal Trend Report Series*. National Oceanic and Atmospheric Administration/National Ocean Service Management and Budget Office Special Project.

Curtis, Lon. 2004. Midlevel dry intrusion as a factor in tornado outbreaks associated with landfalling tropical cyclones from the Atlantic and Gulf of Mexico. *Weather and Forecasting* 19: 411 - 427.

Dixon, Richard W. and Dennis E. Fitzsimons. 2001. Toward a quantified hurricane vulnerability assessment for Texas coastal counties. *Texas Journal of Science* 53: 345 - 352.

Doswell III, Charles A. and Donald W. Burgess. 1988. On some issues of the United States tornado climatology. *Monthly Weather Review* 116: 495 - 501.

Ebdon, David. 1985. *Statistics In Geography second edition*. Malden, MA: Blackwell Publishers Inc.

Elsner, James B. and A. Birol Kara. 1999. *Hurricanes of the North Atlantic*. New York: Oxford University Press.

Gentry, R. Cecil. 1983. Genesis of tornadoes associated with hurricanes. *Monthly Weather Review* 111: 1793 - 1805.

Golden, J. H. and C. R. Adams. 2000. The tornado problem: forecast, warning, and response. *Natural Hazards Review* 1: 107 - 118.

Gray, Richard W. 1919. A tornado within a hurricane area. *Monthly Weather Review*: 639.

Grazulis, Thomas P. 2001. *The Tornado*. Norman, OK: University of Oklahoma Press. Hagemeyer, Bartlett C. 1997. Peninsular Florida tornado outbreaks. *Weather and Forecasting* 12: 399 - 427.

______ and S. J. Hodanish. 1995. Florida tornado outbreaks associated with tropical cyclones. Preprints, *Twenty-First Conference on Hurricanes and Tropical Meteorology*, Miami, FL. American Meteorological Society: 312 - 314.

Herbert, Jonathan M., Richard W. Dixon and Jeffrey L. Isom. 2005. A tropical weather vulnerability assessment for Texas coastal counties. *Texas Journal of Science* 57: 187 - 196.

Hill, E. L., William Malkin and W. A. Schulz, Jr. 1966. Tornadoes associated with cyclones of tropical origin-practical features. *Journal of Applied Meteorology* 5, no. 6: 745 - 763.

Hills, G. B. 1929. The September 28, 1929, tornado in Fort Lauderdale, FL. *Monthly Weather Review* 57: 420 - 421.

Kelly, D. L., J. T. Schaefer, R. P. McNulty and C. A. Doswell III. 1978. An augmented tornado climatology. *Monthly Weather Review* 106: 1172 - 1183.

Malkin, W. and J. G. Galway. 1953. Tornadoes associated with hurricanes as illustrated by Franconia, Va., tornado, September 1, 1952. *Monthly Weather Review*: 299 - 303.

Marshall, Timothy P. 2002. Tornado damage survey at Moore, Oklahoma. *Weather and Forecasting* 17: 582 - 598.

McCaul, Eugene W., Jr. 1987. Observations of the hurricane “Danny” tornado outbreak of 16 August 1985. *Monthly Weather Review* 115: 1206 - 1223.

______ E. W., Jr. 1991. Buoyancy and shear characteristics of hurricane-tornado environments. *Monthly Weather Review* 119: 1954 - 1978.

______ Eugene W., Jr. and Morris L. Weisman. 1996. Simulations of shallow supercell storms in landfalling hurricane environments. *Monthly Weather Review* 124: 408 - 429.

______ Eugene W., Jr., Dennis E. Buechler, Steven J. Goodman and Michael Cammarata. 2004. Doppler radar and lightening network observation of a severe outbreak of tropical cyclone tornadoes. *Monthly Weather Review* 132: 1747 - 1763.

Meyers, Lawrence S., Glenn Gamst and A. J. Guarino. 2006. *Applied Multivariate Research Design and Interpretation*. London: Sage Publications.

NOAA. 2004. National Oceanic and Atmospheric Administration/National Weather Service/Climate Prediction Center. Climate Glossary. http://www.cpc.noaa.gov/products/outreach/glossary.shtml#C. last accessed 18 November 2008.

______ 2005a. National Oceanic and Atmospheric Administration/National Weather Service. National Weather Service Glossary. http://www.nws.noaa.gov/glossary/. last accessed 05 March, 2008.

______ 2005b. National Oceanic and Atmospheric Administration/National Weather Service/National Hurricane Center. Tropical Cyclone Report: Hurricane Ivan 2-24 September 2004. http://www.nhc.noaa.gov/2004ivan.shtml?. last accessed 12 January 2009.

______ 2008a. National Oceanic and Atmospheric Administration/National Weather Service/National Hurricane Center. The Saffir-Simpson Hurricane Scale. http://www.nhc.noaa.gov/aboutsshs.shtml. last accessed 05 March 2008.

______ 2008b. National Oceanic and Atmospheric Administration/Storm Prediction Center. Fujita Tornado Damage Scale. http://www.spc.noaa.gov/faq/tornado/f-scale.html. last accessed 05 March 2008.

______ 2008c. National Oceanic and Atmospheric Administration/National Environmental Satellite, Data, and Information Services/National Climatic Data Center. U.S. Tornado Climatology. http://www.ncdc.noaa.gov/oa/climate/severeweather/tornadoes.html. last accessed 05 March 2008.

Neumann C. J., B. R. Jarvinen, C. J. McAdie and G. R. Hammer. 1999. Tropical Cyclones of the North Atlantic Ocean, 1871-1998. *Historical Climatology Series 6-2.* National Climatic Data Center 32 Asheville, NC in cooperation with the Tropical Prediction Center/National Hurricane Center Miami, FL.

Novlan, David J. and William M. Gray. 1974. Hurricane-spawned tornadoes. *Monthly Weather Review* 102: 476 - 488.

Orton, Robert. 1970. Tornadoes associated with hurricane Beulah on September 19-23, 1967. *Monthly Weather Review* 98, no. 7: 541 - 547.

Pearson, A. D. and A. F. Sadowski. 1965. Hurricane-induced tornadoes and their distribution. *Monthly Weather Review* 93, no. 7: 461 - 464.

Rappaport, Edward N. 2000. Loss of life in the United States associated with recent Atlantic tropical cyclones. *Bulletin of the American Meteorological Society* 81, no. 9: 2065 - 2073.

Robeson, Scott M. 2005. Statistical climatology. In *Encyclopedia of World Climatology*, ed. John E. Oliver, 687 - 694. Dordrecht: Springer.

Rudd, Milton I. 1964. Tornadoes during hurricane Carla at Galveston. *Monthly Weather Review* 92, no. 5: 251 - 254.

Sadowski, A. F. 1962. Tornadoes associated with hurricane Carla, 1961. *Monthly Weather Review* 90: 514 - 516.

Smith, John S. 1965. The hurricane-tornado. *Monthly Weather Review* 93, no. 7: 453 - 459.

Spratt, Scott M., David W. Sharp, Pat Welsh, Al Sandrik, Frank Alsheimer and Charlie Paxton. 1997. A WSR-88D assessment of tropical cyclone outer rainband tornadoes. *Weather and Forecasting* 12: 479 - 501.

Suckling, Philip W. and Walker S. Ashley. 2006. Spatial and temporal characteristics of tornado path direction. *The Professional Geographer* 58, no. 1: 20 - 38.

Suzuki, Osamu, Hiroshi Nino, Hisao Ohno and Hiroshi Nirasawa. 2000. Tornado-producing mini supercells associated with typhoon 9019. *Monthly Weather Review* 128: 1868 - 1882.

Verbout, S. M., D. M. Schulz, L. M. Leslie, H. E. Brooks, D. J. Karoly and K. L. Elmore. 2007. Tornado outbreaks associated with landfalling hurricanes in the north Atlantic basin: 1954-2004. *Meteorology and Atmospheric Physics* 97: 255 - 271.

Weiss, S. J. 1985. On the operational forecasting of tornadoes associated with tropical cyclones. Preprints, *Fourteenth Conference on Severe Local Storms*, Indianapolis, IN. American Meteorological Society: 293 - 296.

______ 1987. Some climatological aspects of forecasting tornadoes associated with tropical cyclone. Preprints, *Seventeenth Conference on Hurricanes and Tropical Meteorology*, Miami, FL. American Meteorological Society: 160 - 163.

VITA

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