ABSTRACT

HILDERBRAND, DOUGLAS CLARENCE. Risk assessment of North Carolina tropical cyclones (1925-2000). (Under the direction of Dr. Lian Xie)

Previous tropical cyclone risk assessment studies have been national in scope. This study demonstrates the need for regional risk assessments, using the tropical cyclone history of North Carolina as an example. The standard normalization procedure for historical damage data was reevaluated. A housing factor was used instead of the more conventional population factor to go along with inflation and changes in wealth. For coastal counties in North Carolina, housing figures from 1940-2000 increased 780% while population figures increased only 370%. It is believed that use of housing data in lieu of population data in the normalization procedure provides a more realistic measure of impact. Using the new normalization method, 1954-55 tropical cyclone storm totals in North Carolina added together would have caused over $18 billion in damage (expressed in 2000 dollars). By comparison, the destructive period from 1996 to 1999 in North Carolina added up to $13 billion.

Storm damage totals were separated into damages caused by wind, flooding, and storm surge. For all 36 direct landfalling tropical cyclones in North Carolina from 1925-2000, flooding caused approximately 40% of all damages, while wind and storm surge caused an estimated 35% and 25%, respectively. From these results, it is clear that flooding produced relatively greater damage in North Carolina compared to the United States in general.

Rainfall was correlated to meteorological parameters of tropical cyclones making landfall in North Carolina. There was a weak relationship between intensity of the tropical cyclone and maximum rainfall totals. There was a stronger relationship between

rainfall and translation speed. For those tropical cyclones that did not directly interact with synoptic-scale features such as upper-level troughs, lows, or surface fronts, the relationship between rainfall and translation speed can be expressed by the equation $Y=29.529X^{-0.6134}$ where Y is the average of the five highest recorded rainfall totals and X is the translation speed (expressed in knots). Rain volume calculations quantified the magnitude of the September 1999 flood event in eastern North Carolina. Hurricane Floyd yielded an estimated 4.14 cubic miles of water on North Carolina only 10 days after Tropical Storm Dennis brought North Carolina out of drought conditions with 3.67 cubic miles of water. The next-highest value from previous tropical cyclones was Hurricane Fran (1996) with 3.14 cubic miles of water.

While major hurricanes accounted for 83% of the overall damage due to hurricanes nationally, this percentage changes regionally. Using the total normalized damage numbers for North Carolina, 70 % of all tropical cyclone damage was caused by major hurricanes, while category-2 hurricanes added a significant percentage (21.4%). The results of this study suggest a stronger consideration for weaker tropical cyclones, especially category-2 hurricanes, in risk management decisions.

RISK ASSESSMENT OF NORTH CAROLINA

TROPICAL CYCLONES (1925-2000)

by

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BIOGRAPHY

Douglas C. Hilderbrand was born on May 19, 1973 in Washington, D.C. and is the son of Robert H. Hilderbrand (deceased) and Sally H. Hilderbrand. After spending his childhood in Collegeville, PA and graduating from Methacton High School, Douglas attended Bucknell University in Lewisburg, PA. In 1995, he earned his Bachelor of Arts degree in geology and was accepted to the geology masters program at the University of South Florida in Tampa, FL. Douglas received his Master of Science degree in 1998. His thesis was titled "*Elemental Ratio Determination via ICP-MS and DCP-AES: Methodology to Extract Climate Records from Coral Aragonite*".

Douglas entered the Graduate School at North Carolina State University in August of 1999 to pursue a Master of Science in meteorology. During his time at North Carolina State, he interned at the Blue Sky Foundation, working on hazard mitigation projects and building a comprehensive North Carolina tropical cyclone database. In February 2002, Douglas moved to Alexandria, VA and started working for the National Weather Service at the Hydrometeorological Prediction Center in Camp Springs, MD.

ACKNOWLEDGEMENTS

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Sincere appreciation is extended to those who assisted in providing me with data used in this thesis. The United States Geological Survey provided flood data. Employees of the North Carolina Department of Emergency Management helped collect and direct me to North Carolina damage data. Thanks to Don Markle from the Blue Sky Foundation for the opportunity to work at the Blue Sky Foundation, Keith Brill of the Hydrometeorological Prediction Center (HPC) for statistical assistance and other co-workers who helped review my thesis, especially Pete Manousos, Mike Eckert, and Dave Roth. Thanks also to the HPC management for the time needed to finish this thesis.

I want to specially thank those closest to me-my mother, my family, my friends, and my dog. To succeed, you need to surround yourself with the best. In this case, I succeeded. I would like to dedicate this thesis to my father who was killed in an airplane crash on a rainy, foggy night. This was when my passion for weather started.

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I. Introduction

A. Statement of Problem

Risk assessments based on past tropical cyclone damage records are crucial for prudent decision-making regarding hazard mitigation of property and reduction of fatalities by government policy makers and emergency management officials. Previous tropical cyclone damage studies (Pielke and Landsea, 1998; Pielke and Landsea, 1999) have focused on the United States in general. These studies, based on normalized historical damage data, indicated that over 80% of the total hurricane damage in the United States was caused by major (Saffir/Simpson categories 3, 4, 5; Simpson, 1974) hurricanes. As a result of this, some recent hurricane-related climate change studies have focused only on major hurricanes. However, this approach may not be appropriate for regional applications (i.e. individual states). More detailed risk assessments focusing on smaller regions of the country may better quantify risks associated with tropical systems, identify local trends, and predict future impacts.

B. Purpose/Objectives

The objectives of this study are to 1) reevaluate and improve upon the normalization procedure for historical damage data, 2) separate storm damage totals of North Carolina tropical cyclones into categories of wind, flooding, and storm surge damage, 3) correlate meteorological characteristics to recorded rainfall totals, and 4) explain quantitatively and qualitatively the property risk from wind, rain, and storm surge damage based on the historical record from 1925-2000.

This study focuses on the state of North Carolina. Since 1996, Hurricanes Bertha (1996), Fran (1996), Bonnie (1998), and Floyd (1999), along with Tropical Depression

Danny (1997) and Tropical Storm Dennis (1999) have severely impacted the state with damage totaling over $12 billion. The inland flooding attributed to Floyd in September 1999 has been regarded as the worst flooding in the state's history, while in September 1996 Fran's winds blew at hurricane strength well into the central part of the state. North Carolina was chosen for other reasons. North Carolina ranks only behind Florida and Texas in tropical cyclone direct hits and receives more activity proportional to its amount of coastline due to its geographic orientation (extends into the Atlantic Ocean close to the Gulf Stream). Furthermore, the Outer Banks region is extremely vulnerable and has seen a large increase in coastal development over the past 50 years.

C. Definition of Terms

In this study, a tropical cyclone is defined as a cyclone that originates over the tropical oceans (water temperatures >79°F) and includes hurricanes, tropical storms, and tropical depressions (Glossary of Meteorology, 2000). Only tropical cyclones that impacted North Carolina were included in the dataset. Impacting tropical cyclones are those storms that have struck North Carolina directly, made landfall in another state and later moved through North Carolina, or remained over water but passed close enough to the state to have caused coastal damage. Impacts include damages directly attributable to the storm, as defined by Changnon (1996) and include rainfall-induced flooding, high winds, tornadoes embedded within the storm, coastal storm surge and beach erosion. Although fatality statistics were included in the overall summary of tropical cyclones, fatalities were not included in the damage assessment.

D. Data Collection

Damage data from 82 tropical cyclones that have impacted North Carolina between 1925-2000 were collected. Storm track data were based on National Oceanic and Atmospheric Administration's (NOAA) hurricane database[1]. Damage data prior to 1925 were deemed unreliable and too incomplete to be useful in this study. Final damage totals were taken from many different sources and included yearly summaries in the Monthly Weather Review, local newspapers (Wilmington News; News & Observer), historical accounts summarized by Barnes (1998), and data from the National Climate Data Center (NCDC). Where there were conflicting damage totals, government sources and the higher total took precedence.

II. Damage Assessment

A. North Carolina Tropical Cyclone History

A total of 82 tropical cyclones impacted North Carolina from 1925-2000 (an average of 1.1 impacting tropical cyclones per year). Of the 82 tropical cyclones, 36 made direct landfall along the coast, 12 remained offshore, 16 made landfall along the Gulf Coast and tracked into North Carolina, and 18 made landfall along the East Coast (mostly South Carolina) and moved into North Carolina. Of the 36 tropical cyclones that made direct landfall, 25 were hurricanes (11 major hurricanes), 9 tropical storms, and 2 tropical depressions. The classification distribution included 37 hurricanes, 29 tropical storms, and 16 tropical depressions.

[1]HURDAT project is described in http://www.aoml.noaa.gov/hrd/hurdat/index.html

Figure 1 shows the frequency of tropical cyclones impacting North Carolina from 1925-2000. Active individual years (>2 tropical cyclones) were 1944, 1954, 1955, 1964, 1985, 1995, 1996, and 1999. Periods of low tropical cyclone activity (<2 tropical cyclones annually) were 1929-1932, 1934-1943, 1977-1983 and 1986-1993.

Owing to inflation, economic growth, and changing development patterns, unadjusted damage totals are not useful when assessing climatological trends. In North Carolina since 1989, there have been four hurricanes that have caused more than $1 billion in damages. Prior to 1989, the greatest annual loss was $255 million in 1954 due mostly to Hurricane Hazel. A time series of annual tropical cyclone damage shows a large increase since 1989 (Figure 2a). In figure 2b, the unadjusted damage totals are shown using a logarithmic scale to illustrate better the magnitude change over the past 76 years. In fact, it appears from the unadjusted values of North Carolina tropical cyclone damage that the period of 1996-1999 has been unprecedented. However, to accurately compare damage totals from year-to-year, the data must be normalized to reflect changes in inflation, land-use, wealth and population of areas vulnerable to tropical cyclones.

B. Normalization Methodology

Normalization of the damage data in previous studies involved three factors: inflation, population growth, and wealth changes (Pielke and Landsea, 1998). This study claims that population growth may not always be an accurate normalization factor. The population along the North Carolina coast has increased throughout the 20^{th} century, especially since 1970. From 1940-2000, the coastal population has increased by 370%. Population growth implies that there is a proportional increase in property. However, one cannot assume that population and property are directly correlated. In the case of North

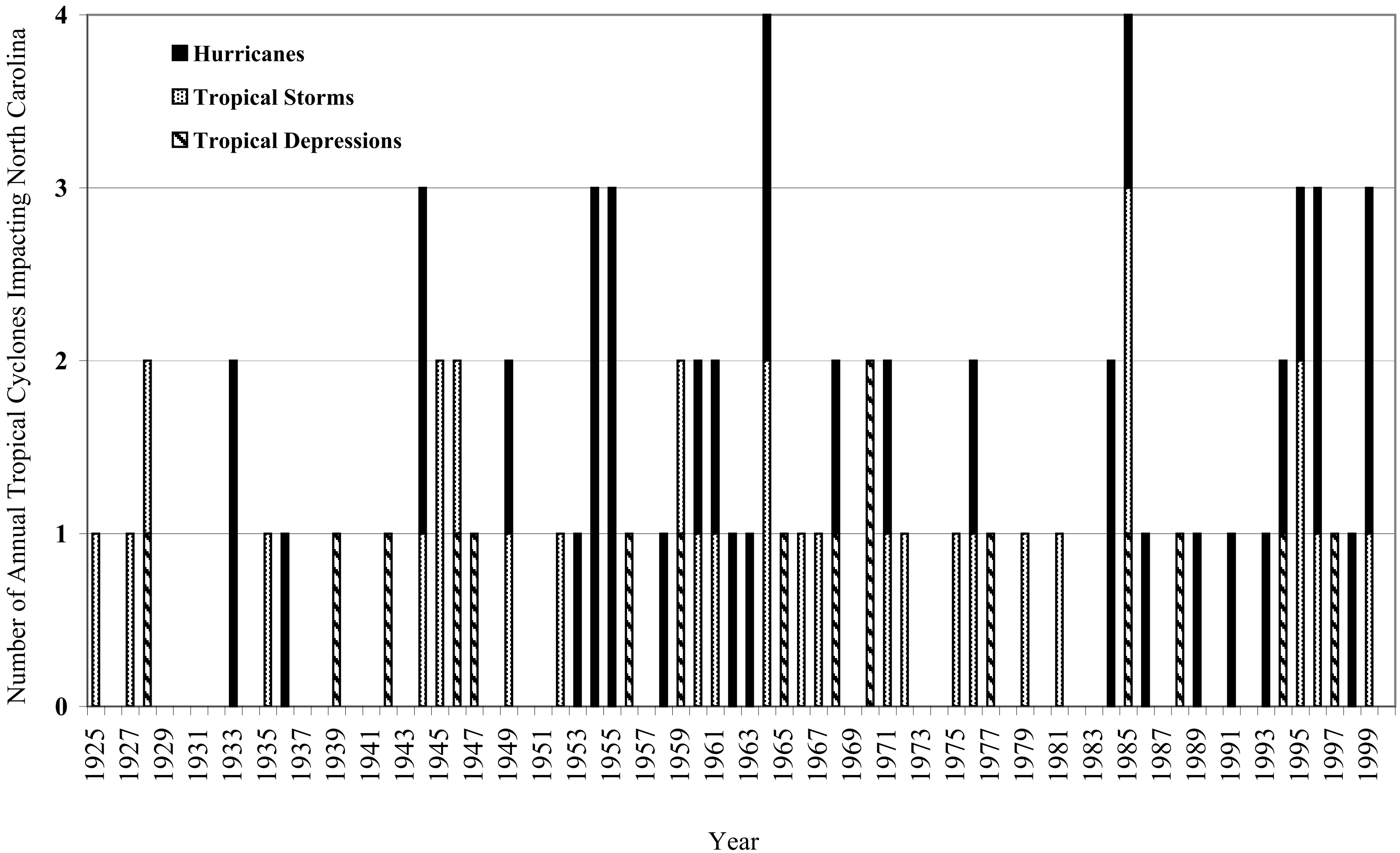


Figure 1. Annual number of tropical cyclones impacting North Carolina from 1925-2000.

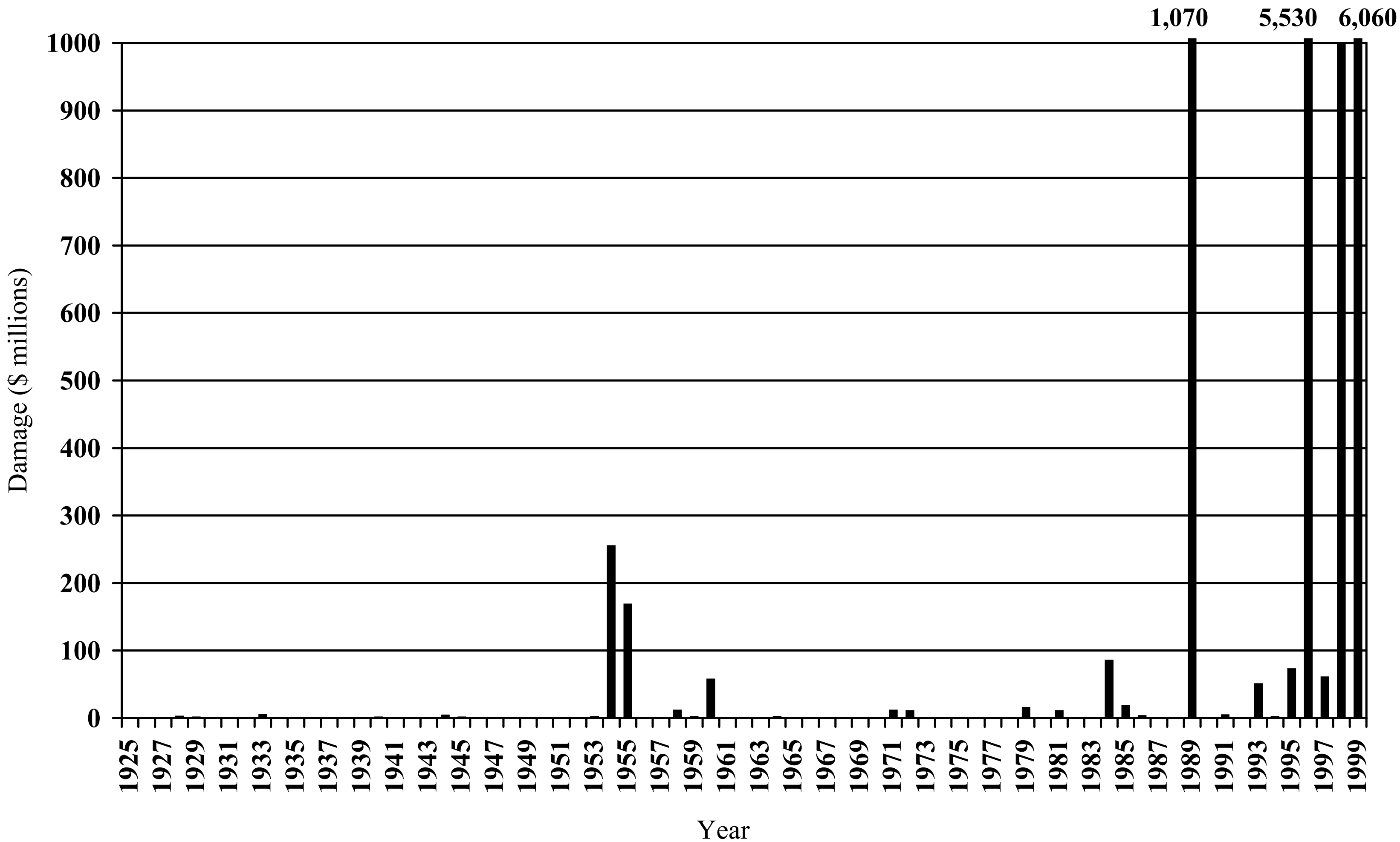


Figure 2a. Annual North Carolina tropical cyclone unadjusted damage totals from 1925-2000. Prior to 1925, damage estimates were deemed incomplete and unreliable. Damage totals are not normalized and therefore represent the values at the time the damage occurred.

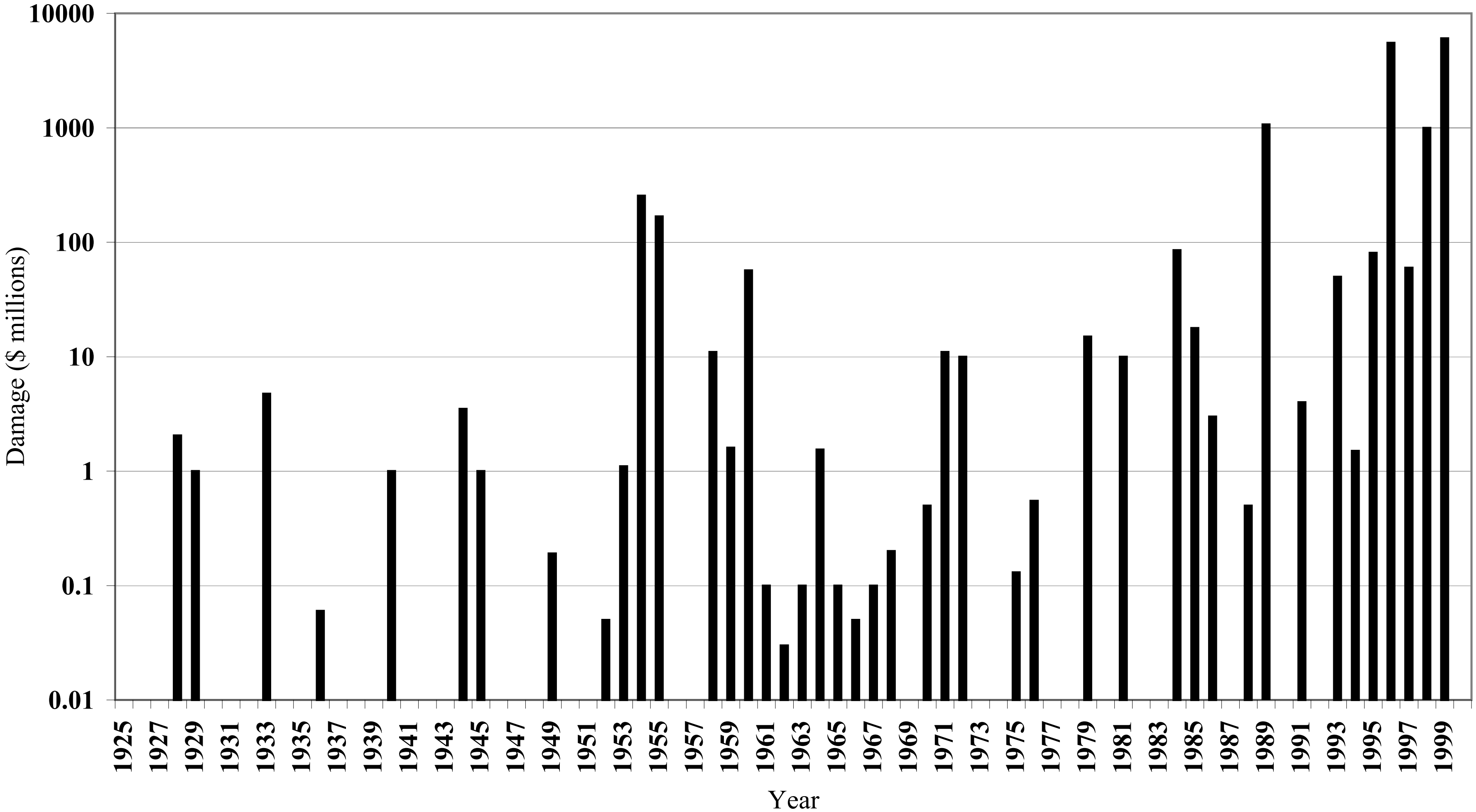


Figure 2b. Annual North Carolina tropical cyclone unadjusted damage totals from 1925-2000 using a logarithmic scale. Damage totals are not normalized and therefore represent the values at the time the damage occurred. Notice how weighted the most recent years appear compared to the destructive decade of the 1950's.

Carolina, from 1940-2000, housing totals throughout the coastal counties have increased 780%. Figure 3 illustrates the population and housing increases in the coastal counties of North Carolina. An explanation of the dichotomy might be that North Carolina depends heavily on tourism along most of the coastline. Many owners of vacation homes, rental homes, etc. are not counted in the population figures for each county. By using a housing factor instead of population factor, storm damage totals are twice as high in some cases.

The inflation factor is well represented by two economic statistics. Either the implicit price deflator or the consumer price index (CPI) can be used. This study used the CPI as it is the standard measure of inflation[2]. The wealth factor was determined by the "fixed reproducible tangible wealth". This economic statistic, kept by the Bureau of Economic Analysis (1993), accounts for the trend that Americans have more wealth today than in the past (bigger houses, more expensive cars, etc.).

Table 1 summarizes the normalization values for each impacting tropical cyclone that caused significant damage. Those storms that only caused minor or no damage were not normalized. Table 1 includes the housing factor recommended by this study. A comparison of the storm damage totals can be made with Table 2 that uses the population factor. Deviation between the storm damage totals is greatest for storms from 1940-1960. For example, in 1955, housing factor values are 2.96 while population values are lower at 2.2.

[2] Bloomberg News (2001) is quoted as stating "CPI is one of the most widely recognized price measures for tracking the price of a market basket of goods and services purchased by individuals. The weights of the components are based on consumer spending patterns."

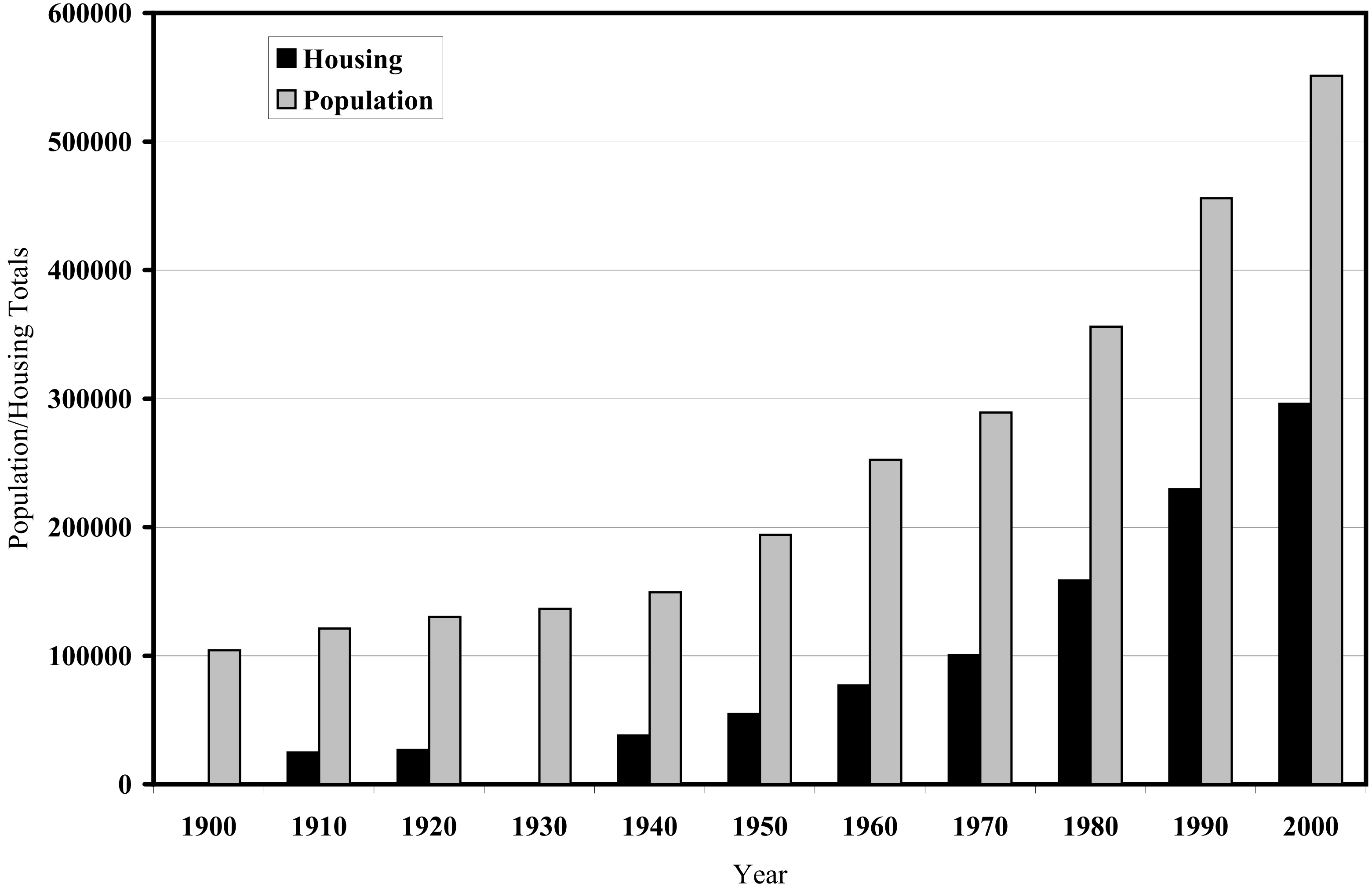


Figure 3. North Carolina coastal population and housing trends from 1900-2000 based on U.S. Census data. Housing data for 1900 and 1930 were not available. Coastal counties included in the study are Brunswick, Carteret, Currituck, Dare, Hyde, New Hanover, Onslow, Pamlico, and Pender.

Table 1: List of North Carolina Tropical Cyclones with unadjusted and normalized damage totals in 2000 dollars. inflation, wealth, and housing factors for each storm are also listed. Housing factor replaced the population factor that was used in Pielke and Landsea (1998).

Tropical Cyclone	Date of Landfall	Unadjusted damage	Inflation	Wealth	Housing	Normalized Damage
Hurricane Irene	10/17/1999	minor	---	---	---	minor
Hurricane Floyd	9/16/1999	$6 billion	1.03	1.02	1.02	$6.36 billion
T.S. Dennis	9/4/1999	$60 million	1.03	1.02	1.02	$64.3 million
Hurricane Bonnie	8/26/1998	$1 billion	1.05	1.02	1.04	$1.125 billion
T.D. Danny	7/24/1997	$60 million	1.07	1.03	1.04	$72 million
T.S. Arthur	6/19/1996	no damage	---	---	---	none
Hurricane Bertha	7/12/1996	$330 million	1.1	1.04	1.09	$411 million
Hurricane Fran	9/6/1996	$5.2 billion	1.09	1.04	1.08	$6.36 billion
T.S. Jerry	8/28/1995	$9 million	1.12	1.08	1.1	$12 million
Hurricane Felix	8/17/1995	$2 million	1.12	1.08	1.1	$3 million
T.S. Opal	10/5/1995	$70 million	1.12	1.08	1.1	$93 million
T.D. Beryl	8/17/1994	$1 million	1.15	1.09	1.2	$2 million
H. Gordon	11/18/1994	$0.5 million	1.15	1.09	1.2	$1 million
Hurricane Emily	8/31/1993	$50 million	1.19	1.1	1.2	$78 million
Hurricane Bob	8/19/1991	$4 million	1.22	1.11	1.25	$7 mllion
Hurricane Hugo	9/22/1989	$1.07 billion	1.38	1.12	1.28	$2.12 billion
T.D. Chris	8/29/1988	$0.5 million	1.4	1.14	1.3	$1 million
Hurricane Charley	8/17/1986	$3 million	1.5	1.16	1.4	$7 million
T.S. Bob	7/25/1985	$1.5 million	1.55	1.16	1.4	$4 million
T.D. Danny	8/17/1985	$2.5 million	1.55	1.16	1.4	$6 million
Hurricane Gloria	9/27/1985	$14 million	1.59	1.17	1.49	$38 million
T.S. Kate	11/23/1985	minor	---	---	---	minor
Hurricane Diana	9/13/1984	$79 million	1.64	1.18	1.63	$249 million
Hurricane Josephine	10/12/1984	minor	---	---	---	minor
T.S. Dennis	8/20/1981	$10 million	2.07	1.26	1.69	$44 million
T.S. David	9/5/1979	$15 million	2.31	1.3	1.95	$88 million
T.D. Babe	9/9/1977	no damage	---	---	---	none
Hurricane Belle	8/9/1976	minor	---	---	---	minor
T.S. Dottie	8/21/1976	$0.5 million	2.9	1.4	2.2	$4 million
T.S. Eloise	9/24/1975	minor	---	---	---	minor
T.S. Agnes	6/21/1972	$10 million	4.13	1.4	1.99	$115 million
T.S. Doria	8/27/1971	$1 million	4.22	1.43	2.78	$17 million
Hurricane Ginger	9/30/1971	$10 million	4.22	1.43	2.78	$168 million
T.D. Alma	5/26/1970	no damage	---	---	---	none
T.S. #4	8/17/1970	$0.5 million	4.25	1.44	2.8	$9 million
T.D. Abby	6/8/1968	minor	---	---	---	minor
Hurricane Gladys	10/20/1968	minor	---	---	---	none
T.S. Doria	9/17/1967	minor	---	---	---	minor
T.S. Alma	6/11/1966	minor	---	---	---	minor
T.D. #1	6/16/1965	minor	---	---	---	minor
T.S. Cleo	8/31/1964	$0.5 million	5.55	1.65	4.5	$21 million
T.S. Dora	9/13/1964	$0.1 million	5.55	1.65	5	$5 million
Hurricane Gladys	9/21/1964	$0.1 million	5.55	1.65	5	$5 million
Hurricane Isbell	10/16/1964	$1 million	5.55	1.65	5.93	$54 million

Table 1: continued.

Tropical Cyclone	Date of Landfall	Unadjusted damage	Inflation	Wealth	Housing	Normalized Damage
Hurricane Ginny	10/21/1963	$0.1 million	5.6	1.68	5.5	$5 million
Hurricane Alma	8/28/1962	minor	---	---	---	minor
T.S. #6	9/14/1961	no damage	---	---	---	none
Hurricane Esther	9/20/1961	$0.1 million	5.8	1.78	3.7	$4 million
T.S. Brenda	7/30/1960	$0.25 million	5.82	1.8	3.9	$10 million
Hurricane Donna	9/12/1960	$56.5 million	5.82	1.8	3.95	$2.34 billion
T.D. Cindy	7/10/1959	$1.1 million	5.87	1.8	4	$46 million
T.S. Gracie	9/30/1959	$0.5 million	5.87	1.8	4	$21 million
Hurricane Helene	9/27/1958	$11 million	5.96	1.9	4.2	$523 million
T.D. Flossy	9/26/1956	no damage	---	---	---	none
Hurricane Connie	8/12/1955	$40 million	6.4	2.06	2.96	$1.56 billion
Hurricane Diane	8/17/1955	$80 million	6.4	2.06	2.96	$2.54 billion
Hurricane Ione	9/19/1955	$88 million	6.4	2.06	2.96	$3.44 billion
Hurricane Carol	8/31/1954	$0.25 million	6.42	2.06	3.4	$11 million
Hurricane Edna	9/11/1954	$0.1 million	6.42	2.06	3.4	$4 million
Hurricane Hazel	10/15/1954	$254 million	6.42	2.06	3.4/3.0	$10.52 billion
Hurricane Barbara	8/14/1953	$1.1 million	6.5	2.08	3.65	$54 million
T.S. Able	8/31/1952	minor	---	---	---	minor
Hurricane #1	8/24/1949	$0.2 million	7	2.2	4	$12 million
Hurricane #2 (T.S.)	8/29/1949	minor	---	---	---	minor
T.S. #6 (T.D)	9/24/1947	minor	---	---	---	minor
Hurricane #2 (T.S.)	7/6/1946	minor	---	---	---	minor
Hurricane #5 (T.D.)	10/9/1946	no damage	---	---	---	none
Hurricane #1 (TS)	6/26/1945	minor	---	---	---	minor
Hurricane #9 (T.S.)	9/18/1945	$2 million	9.7	2.4	4.5	$209 million
Hurricane #3	8/1/1944	$2 million	9.75	2.4	5	$234 million
Hurricane #7	9/14/1944	$1.5 million	9.75	2.4	4.8	$168 million
Hurricane #11 (T.S.)	10/20/1944	minor	---	---	---	minor
T.S. #8 (T.D.)	10/12/1942	minor	---	---	---	minor
Hurricane #2 (T.D.)	8/18/1939	$1 million	12.5	2.5	5	$156 million
Hurricane #13	9/18/1936	$0.1 million	12.3	2.5	5	$15 million
Hurricane #2 (T.S.)	9/5/1935	minor	---	---	---	minor
Hurricane #8	8/23/1933	$0.25 million	13	2.5	5	$40 million
Hurricane #13	9/16/1933	$4.5 million	13	2.5	5	$731 million
Hurricane #1 (T.D.)	8/11/1928	$0.05 million	10.1	2.5	5	$6 million
Hurricane #4 (T.S.)	9/19/1928	$2 million	10.1	2.5	5	$252 million
T.S. #5	10/3/1927	no damage	---	---	---	none
Hurricane #2 (T.S.)	12/2/1925	no damage	---	---	---	none

Table 2: List of North Carolina tropical cyclones with unadjusted and normalized damage totals in 2000 dollars. The normalized totals dollars. The normalized totals are based on the Pielke and Landsea (1998) normalization method, including the use of the population factor.

Tropical Cyclone	Date of Landfall	Unadjusted damage	Inflation	Wealth	Population	Normalized Damage
Hurricane Irene	10/17/1999	minor	---	---	---	minor
Hurricane Floyd	9/16/1999	$6 billion	1.03	1.02	1.01	$6.36 billion
T.S. Dennis	9/4/1999	$60 million	1.03	1.02	1.01	$64 million
Hurricane Bonnie	8/26/1998	$1 billion	1.05	1.02	1.02	$1.092 billion
T.D. Danny	7/24/1997	$60 million	1.07	1.03	1.02	$67 million
T.S. Arthur	6/19/1996	no damage	---	---	---	none
Hurricane Bertha	7/12/1996	$330 million	1.1	1.04	1.06	$400 million
Hurricane Fran	9/6/1996	$5.2 billion	1.09	1.04	1.06	$6.25 billion
T.S. Jerry	8/28/1995	$9 million	1.12	1.08	1.07	$12 million
Hurricane Felix	8/17/1995	$2 million	1.12	1.08	1.1	$3 million
T.S. Opal	10/5/1995	$70 million	1.12	1.08	1.08	$91 million
T.D. Beryl	8/17/1994	$1 million	1.15	1.09	1.1	$2 million
H. Gordon	11/18/1994	$0.5 million	1.15	1.09	1.1	$1 million
Hurricane Emily	8/31/1993	$50 million	1.19	1.1	1.12	$76 million
Hurricane Bob	8/19/1991	$4 million	1.22	1.11	1.16	$6 mllion
Hurricane Hugo	9/22/1989	$1.07 billion	1.38	1.12	1.18	$1.836 billion
T.D. Chris	8/29/1988	$0.5 million	1.4	1.14	1.19	$1 million
Hurricane Charley	8/17/1986	$3 million	1.5	1.16	1.2	$6 million
T.S. Bob	7/25/1985	$1.5 million	1.55	1.16	1.22	$3 million
T.D. Danny	8/17/1985	$2.5 million	1.55	1.16	1.22	$5 million
Hurricane Gloria	9/27/1985	$14 million	1.59	1.17	1.25	$33 million
T.S. Kate	11/23/1985	minor	---	---	---	minor
Hurricane Diana	9/13/1984	$79 million	1.64	1.18	1.22	$187 million
Hurricane Josephine	10/12/1984	minor	---	---	---	minor
T.S. Dennis	8/20/1981	$10 million	2.07	1.26	1.25	$33 million
T.S. David	9/5/1979	$15 million	2.31	1.3	1.3	$59 million
T.D. Babe	9/9/1977	no damage	---	---	---	none
Hurricane Belle	8/9/1976	minor	---	---	---	minor
T.S. Dottie	8/21/1976	$0.5 million	2.9	1.4	1.25	$3 million
T.S. Eloise	9/24/1975	minor	---	---	---	minor
T.S. Agnes	6/21/1972	$10 million	4.13	1.4	1.37	$79 million
T.S. Doria	8/27/1971	$1 million	4.22	1.43	1.75	$11 million
Hurricane Ginger	9/30/1971	$10 million	4.22	1.43	1.75	$105 million
T.D. Alma	5/26/1970	no damage	---	---	---	none
T.S. #4	8/17/1970	$0.5 million	4.25	1.44	2.2	$7 million
T.D. Abby	6/8/1968	minor	---	---	---	minor
Hurricane Gladys	10/20/1968	minor	---	---	---	none
T.S. Doria	9/17/1967	minor	---	---	---	minor
T.S. Alma	6/11/1966	minor	---	---	---	minor
T.D. #1	6/16/1965	minor	---	---	---	minor
T.S. Cleo	8/31/1964	$0.5 million	5.55	1.65	2.2	$10 million
T.S. Dora	9/13/1964	$0.1 million	5.55	1.65	2	$2 million
Hurricane Gladys	9/21/1964	$0.1 million	5.55	1.65	3.3	$3 million
Hurricane Isbell	10/16/1964	$1 million	5.55	1.65	4.1	$38 million

Table 2: continued.

Tropical Cyclone	Date of Landfall	Unadjusted damage	Inflation	Wealth	Population	Normalized Damage
Hurricane Alma	8/28/1962	minor	---	---	---	minor
T.S. #6	9/14/1961	no damage	---	---	---	none
Hurricane Esther	9/20/1961	$0.1 million	5.8	1.78	3.5	$4 million
T.S. Brenda	7/30/1960	$0.25 million	5.82	1.8	2.2	$6 million
Hurricane Donna	9/12/1960	$56.5 million	5.82	1.8	2.2	$1.302 billion
T.D. Cindy	7/10/1959	$1.1 million	5.87	1.8	2.3	$27 million
T.S. Gracie	9/30/1959	$0.5 million	5.87	1.8	2.3	$12 million
Hurricane Helene	9/27/1958	$11 million	5.96	1.9	2.4	$299 million
T.D. Flossy	9/26/1956	no damage	---	---	---	none
Hurricane Connie	8/12/1955	$40 million	6.4	2.06	2.2	$1.16 billion
Hurricane Diane	8/17/1955	$80 million	6.4	2.06	2.2	$2.32 billion
Hurricane Ione	9/19/1955	$88 million	6.4	2.06	2.2	$2.552 billion
Hurricane Carol	8/31/1954	$0.25 million	6.42	2.06	2.2	$7 million
Hurricane Edna	9/11/1954	$0.1 million	6.42	2.06	2.2	$3 million
Hurricane Hazel	10/15/1954	$254 million	6.42	2.06	2.2	$7.39 billion
Hurricane Barbara	8/14/1953	$1.1 million	6.5	2.08	3.5	$52 million
T.S. Able	8/31/1952	minor	---	---	---	minor
Hurricane #1	8/24/1949	$0.2 million	7	2.2	2.4	$7 million
Hurricane #2 (T.S.)	8/29/1949	minor	---	---	---	minor
T.S. #6 (T.D)	9/24/1947	minor	---	---	---	minor
Hurricane #2 (T.S.)	7/6/1946	minor	---	---	---	minor
Hurricane #5 (T.D.)	10/9/1946	no damage	---	---	---	none
Hurricane #1 (TS)	6/26/1945	minor	---	---	---	minor
Hurricane #9 (T.S.)	9/18/1945	$2 million	9.7	2.4	2.6	$121 million
Hurricane #3	8/1/1944	$2 million	9.75	2.4	2.6	$122 million
Hurricane #7	9/14/1944	$1.5 million	9.75	2.4	2.6	$91 million
Hurricane #11 (T.S.)	10/20/1944	minor	---	---	---	minor
T.S. #8 (T.D.)	10/12/1942	minor	---	---	---	minor
Hurricane #2 (T.D.)	8/18/1939	$1 million	12.5	2.5	2.9	$91 million
Hurricane #13	9/18/1936	$0.1 million	12.3	2.5	3.1	$10 million
Hurricane #2 (T.S.)	9/5/1935	minor	---	---	---	minor
Hurricane #8	8/23/1933	$0.25 million	13	2.5	4	$33 million
Hurricane #13	9/16/1933	$4.5 million	13	2.5	4	$585 million
Hurricane #1 (T.D.)	8/11/1928	$0.05 million	10.1	2.5	4.5	$6 million
Hurricane #4 (T.S.)	9/19/1928	$2 million	10.1	2.5	4.5	$227 million
T.S. #5	10/3/1927	no damage	---	---	---	none
Hurricane #2 (T.S.)	12/2/1925	no damage	---	---	---	none

Although the normalization procedure is highly simplified, it does give a fair comparison of tropical cyclones throughout the past 75 years. The normalization method used in this study is:

$$NL_{2000} = L_y \times I_y \times W_y \times H_{y,c} \qquad (1)$$

where:

NL_{2000} = normalized loss to 2000 value

y = year of storm's impact

c = all counties affected by storm including inland counties

L_y = storm's damage (unadjusted)

I_y = inflation factor based on 2000 Consumer Price Index to that of year y.

W_y = wealth factor based 2000 fixed reproducible tangible wealth expressed as per capita (state) to that of year y.

$H_{y,c}$ = housing factor, based on the change in the number of houses from year y to 2000. Data includes only counties most affected by storm, including inland counties.

For example, application of (1) to Hurricane Hazel yields the following:

L_{1954} = $254,000,000 ($72M along coast/$182M inland)

I_{1954} = 5.86

W_{1954} = 1.96

H_{1954} =3.4/3.03 (3.4 used for the coastal damage/3.03 used for inland damage)

Coastal counties represented include: New Hanover, Brunswick, Columbus, Pender, Onslow, Bladen, Duplin, Sampson, and Carteret.

Normalized Total Damage: NL_{2000} = $10,520,000,000.

The time series of normalized annual North Carolina tropical cyclone damage totals (figure 4a) reveals a different trend compared to the unadjusted trend (figure 2). Figure 4a indicates that the damage totals of the 1990's are not unprecedented although over $13 billion in damage occurred from 1996-1999, the active hurricane period of the mid 1950's would have caused over $18 billion in damage had these storms taken place in 2000. In between these active periods in the 1950's and 1990's, there was relative calm. Only four storms provided significant damages to North Carolina during the period of 1956-1995. In those forty years, only hurricanes Helene (1958), Donna (1960), and Diana (1984), and Hugo (1989) caused greater than $200 million damage. Not coincidentally, greater trends in coastal construction and population growth occurred during the 1960's through the early 1990's. The North Carolina tropical cyclones included in this study are listed in Appendix A along with the date of landfall, intensity at landfall, area of landfall, unadjusted and normalized damage totals.

Figure 4b shows a comparison graphically of the normalized damage totals based on the housing vs. population factor. There is less divergence in damage totals of more recent tropical cyclones as compared to earlier tropical cyclones. The coastal construction boom of the 1960's and 1970's is a reason for the greater divergence between the housing and the population factor prior to 1961.

C. Interpretation of Damage Data

Pielke and Landsea (1998) concluded that the majority of tropical cyclone damage (over 83%) in the United States was caused by major hurricanes (Saffir-Simpson categories-3,4, and 5). However, on a regional scale, the percentage attributed to major hurricanes can be different than the 83% for the U.S. in general. Table 3a summarizes

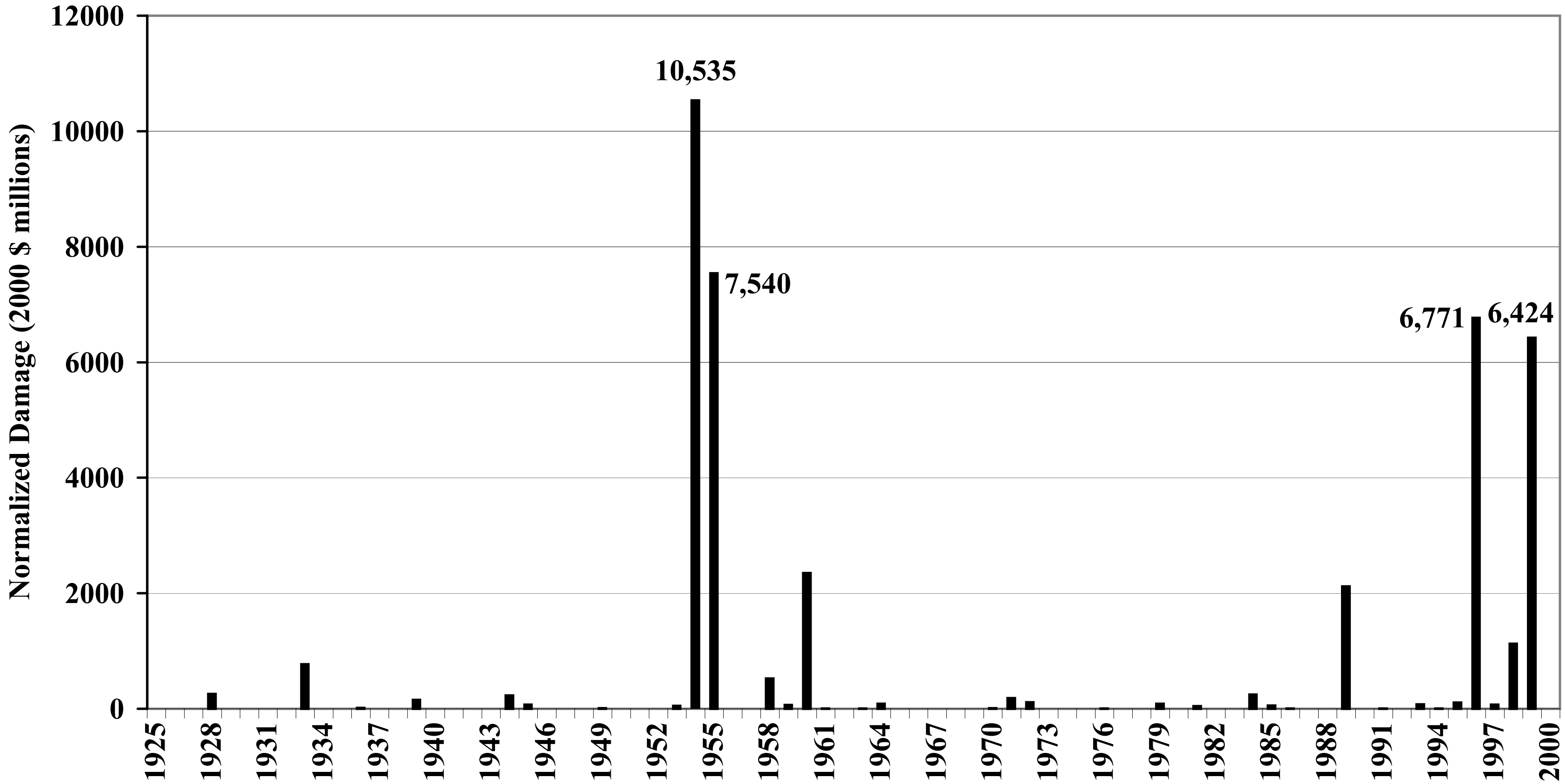


Figure 4a. Annual North Carolina tropical cyclone damage totals from 1925-2000 normalized to 2000 values. Normalization takes into account inflation, changes in wealth and housing trends.

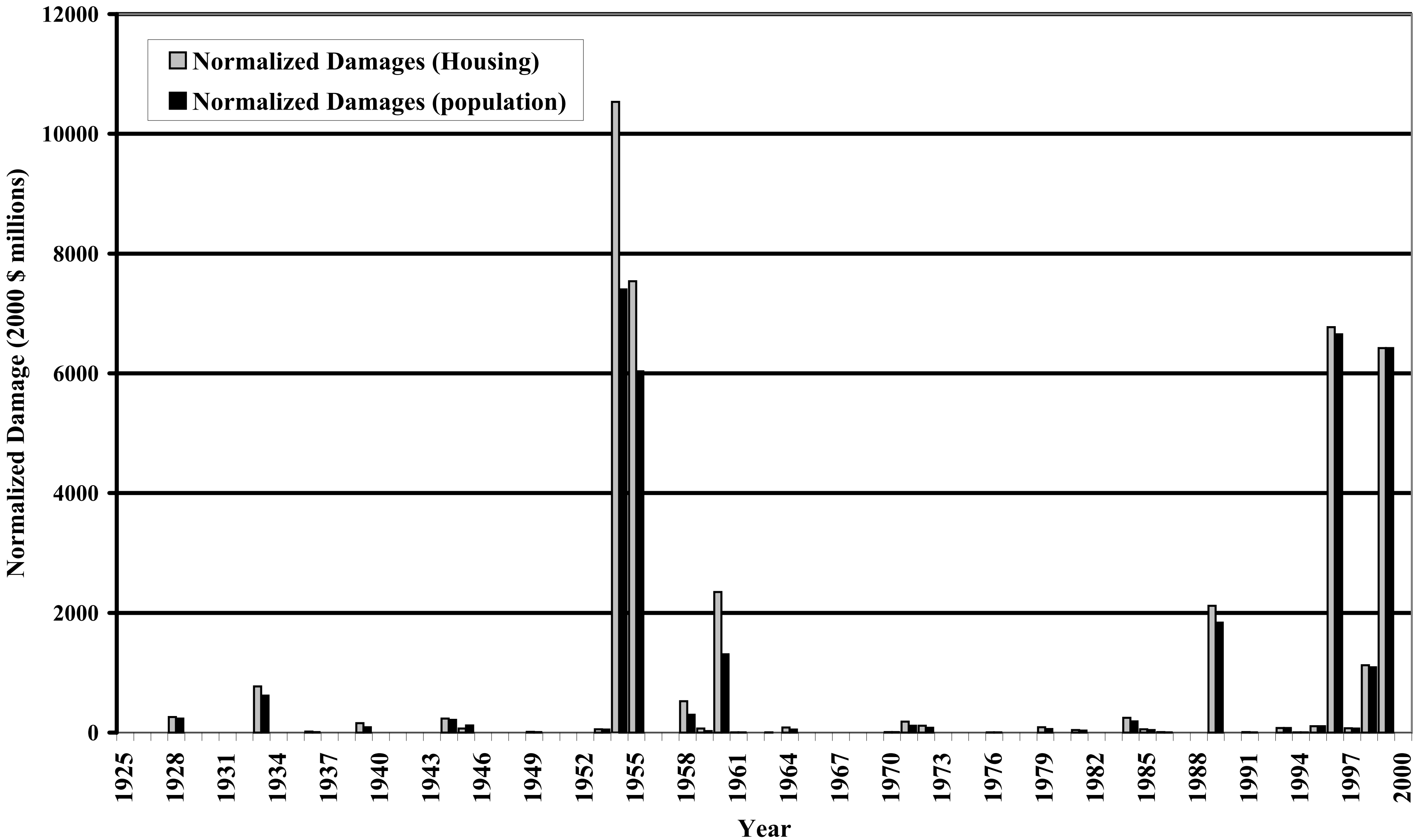


Figure 4b. Comparison of annual North Carolina tropical cyclone normalized damage totals from 1925-2000 based on housing vs. population factor. Damage totals are normalized to 2000 values.

the mean damage, total damage and percentage of total damage for each tropical cyclone category (normalized to 2000 values using the housing factor). For comparison, table 3b summarizes the same damage statistics but is based on the population factor instead of the housing factor. The tropical cyclones are separated into categories based on the intensity at landfall from tropical depression up to category-5 hurricane. The number of total storms per category is in parentheses. The mean damage for each category is just the total damage per storm. The percentage of total damage is the total damage for each category per the total amount of damage of all categories together. The major hurricane contribution of total damage in North Carolina is only 70%. This is lower than the 83% for the U.S. (Pielke and Landsea, 1998). Although category-3 hurricanes account for 41.7% of the total, the mean damage is relatively close for category-2 and 3 hurricanes. Category-2 hurricanes added a significant 21.4% to the total. A large part of North Carolina damages is due to coastal and inland flooding from weaker hurricanes and tropical storms, especially Hurricane Floyd (1999). Although the dataset is small (only 36 tropical cyclones included), it is an inherent problem in tropical cyclone studies that use a similar time frame. Just as Hurricane Floyd weighs heavily on category-2 storms, Hurricane Hazel was the only category-4 hurricane to hit North Carolina over the past 100 years. The risk assessment for North Carolina indicates a clear fact--North Carolina has a significant damage risk from category-2 hurricanes. This can be explained by the fact that category-2 hurricanes are destructive both by wind and flooding potential. It should be noted, however, that major hurricanes still cause the greatest damage per storm and should not be understated.

Table 3a. Damage statistics from direct landfalling North Carolina tropical cyclones (1925-2000) based on housing data.

Category of Storm	Mean Damage*	Total Damage*	Total Damage (%)
Tropical Depressions (2)	4.5	9	0.02
Tropical Storms (9)	14	125	0.34
Hurricane Cat. 1 (8)	383	3062	8.2
Hurricane Cat. 2 (6)	1327	7962	21.4
Hurricane Cat. 3 (10)	1549	15,487	41.7
Hurricane Cat. 4 (1)	10,520	10,520	28.3
Hurricane Cat. 5 (0)	0	0	0

Total Damage (36) $37.165 billion

Percentage of damage due to major hurricanes: 70%.

Parentheses indicate the number of storms for each category.

*Damage figures (in $ millions) are normalized to 2000 values.

Housing factor was used in normalization of the data to 2000 dollar values.

Table 3b. Damage statistics from direct landfalling North Carolina tropical cyclones (1925-2000) based on population data.

Category of Storm	Mean Damage*	Total Damage*	Total Damage (%)
Tropical Depressions (2)	3.5	7	0.02
Tropical Storms (9)	12	108	0.35
Hurricane Cat. 1 (8)	330	2643	8.7
Hurricane Cat. 2 (6)	1317	7902	26
Hurricane Cat. 3 (10)	1235	12,348	40.6
Hurricane Cat. 4 (1)	7,390	7,390	24.3
Hurricane Cat. 5 (0)	0	0	0

Total Damage (36) $30,398 billion

Percentage of damage due to major hurricanes: 64.9%.

Population factor was used in normalization of the data to 2000 dollar values.

Damage assessment studies can also focus on the characteristics of individual storms and how hurricanes of different intensity, flooding potential, and coastal impacts can cause different types of damage. Figures 5a,b illustrate the damage to specific sectors for Hurricane Andrew in South Florida and Hurricane Floyd in eastern North Carolina. The statistics are the result of a compilation of sources including Pielke and Pielke (1997), The *Miami Herald*, *News & Observer*, National Climate Data Center, National Hurricane Center, and the Hurricane Floyd Economic Impact Report (FEMA, 1999). Both hurricanes caused record unadjusted damage to each region. However, two different aspects caused the damages-high winds and 500-year flood levels. The majority of the damages from both storms were to private property. However, there was a significant difference in the business/jobs and agriculture sectors. Andrew caused a devastating blow to Dade County businesses totaling almost $6 billion (23%), but because Andrew was so localized, agricultural losses only contributed to 4% of the total losses. Contrarily, 17% of Floyd's impacts were to agriculture. Animal farms and crops over much of the eastern third of the state were flooded. By focusing on the mechanisms that cause damage, a better risk assessment can be made.

D. Separation of damages

Separating tropical cyclone damage totals into three categories based on the three most damaging aspects-wind, flooding, and storm surge was attempted. Wind damage includes the combination of the central circulation, straight-line winds from associated squall lines, and tornadoes directly related to the tropical cyclone. Flood damage, highly influenced by secondary factors such as previous rainfall and flood susceptibility, includes freshwater flooding unassociated with storm surge. This includes inland

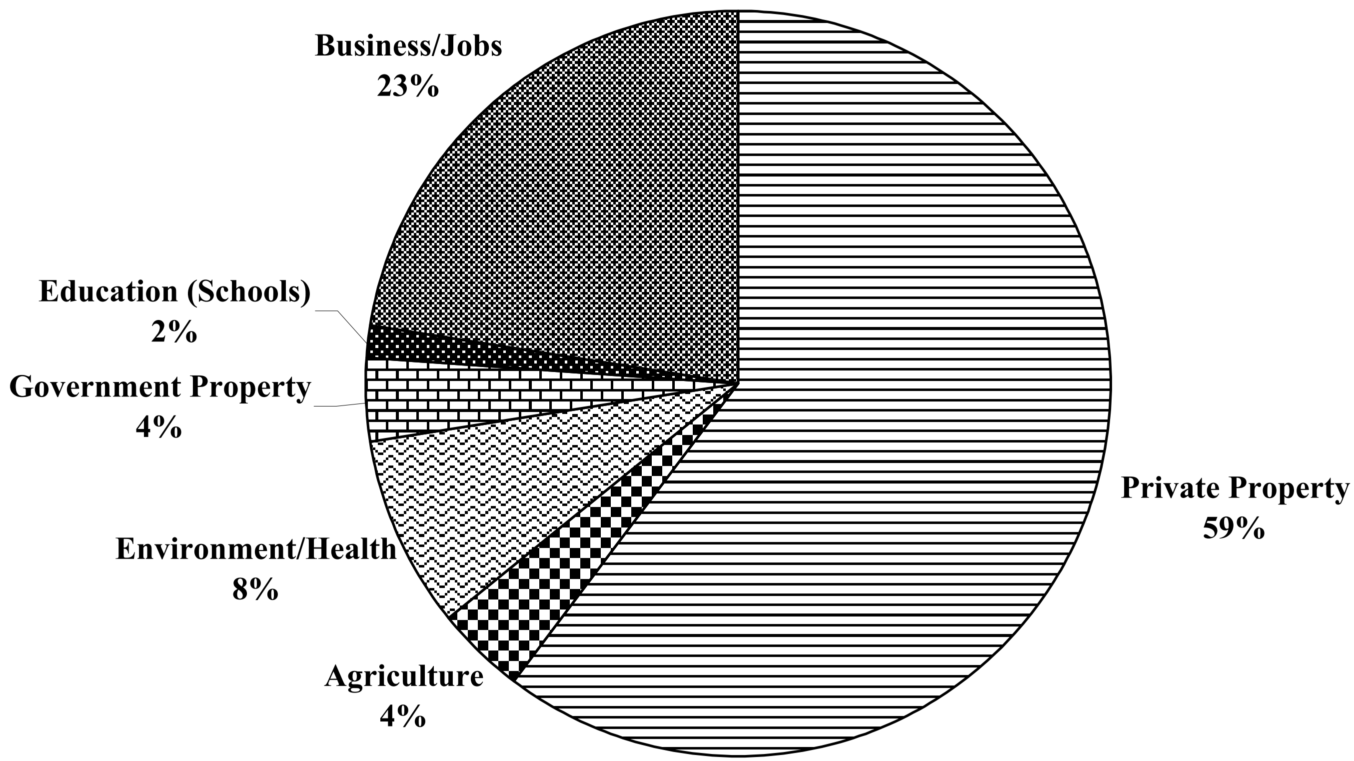


Figure 5a. Hurricane Andrew (1992) damage (%) distribution for individual sectors.

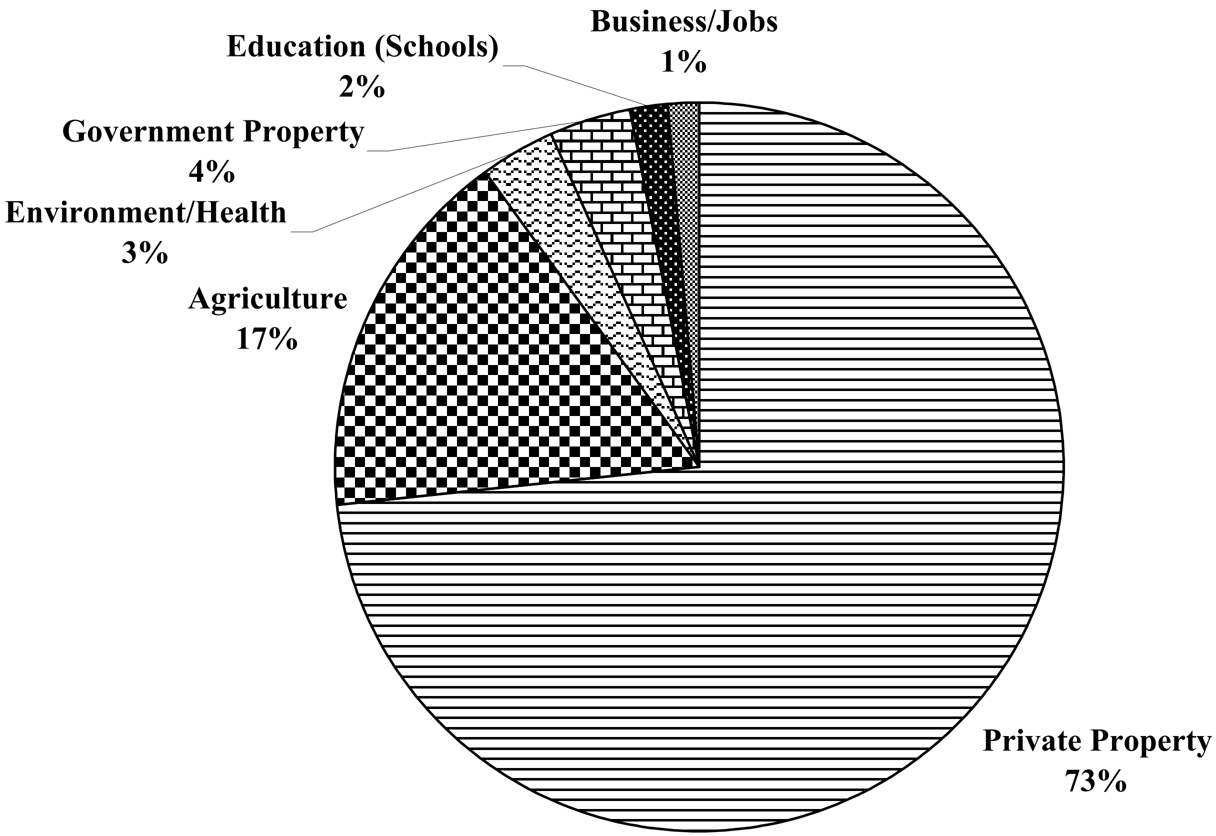


Figure 5b. Hurricane Floyd (1999) damage (%) distribution for individual sectors.

counties as well as coastal counties. Storm surge damage is caused by wave action and includes beach erosion and the costs of replenishment.

Separating damage totals, however, is extremely difficult. There are many uncertainties and often times an accurate damage assessment is near impossible. One big reason for this difficulty is the fact that all three categories-wind, flooding, and storm surge ultimately influence each other. For example, storm surge can weaken a house foundation. High winds can then penetrate the structure. Any structure would then be vulnerable to water damage from wind-swept rain. The difficulty in determining the cause of the damage is obvious and the decision-making process is subjective in nature.

In this section, damage totals of North Carolina tropical cyclones from 1925-2000 were separated into wind, flooding, and storm surge damage and a percentage (rounded to multiples of five) was given to each of the three major categories. The percentages given were rounded to a multiple of five to offset the subjectivity and inherent difficulty of the methodology. Table 4 summarizes the results. The sum of the three categories each adds up to 100% for each storm. Although a percentage was given to each tropical cyclone, the objective of this study is qualitative-not quantitative. The percentages given should be used only to define broader trends instead of absolute quantifications of damage. Due to the high degree of uncertainty (+/- 5%), only general conclusions were made.

The methodology in the separation of the damages, although subjective in nature, was based on three sources of information. First, where available, actual damage statistics were collected (all damage figures and storm totals collected were unadjusted values). From 1959 to 2000, the publication Storm Data, published by NCDC, was used.

Table 4. Causation of Damage: wind/flood/storm surge from North Carolina impacting tropical cyclones (1925-2000).

Tropical Cyclone	Date of Landfall	Unadjusted Damage	Normalized Damage	Wind (%)	Flood(%)	Storm Surge (%)
Hurricane Irene	10/17/1999	minor	minor	0	100	0
Hurricane Floyd	9/16/1999	$6 billion	$6.36 billion	5	90	5
T.S. Dennis	9/4/1999	$60 million	$64.3 million	10	30	60
Hurricane Bonnie	8/26/1998	$1 billion	$1.125 billion	70	20	10
T.D. Danny	7/24/1997	$60 million	$72 million	0	100	0
T.S. Arthur	6/19/1996	no damage	none	0	0	0
Hurricane Bertha	7/12/1996	$330 million	$411 million	40	30	30
Hurricane Fran	9/6/1996	$5.2 billion	$6.36 billion	50	30	20
T.S. Jerry	8/28/1995	$9 million	$12 million	0	100	0
Hurricane Felix	8/17/1995	$2 million	$3 million	10	0	90
T.S. Opal	10/5/1995	$70 million	$93 million	0	100	0
T.D. Beryl	8/17/1994	$1 million	$2 million	0	100	0
Hurricane Gordon	11/18/1994	$0.5 million	$1 million	0	0	100
Hurricane Emily	8/31/1993	$50 million	$78 million	30	0	70
Hurricane Bob	8/19/1991	$4 million	$7 mllion	90	10	0
Hurricane Hugo	9/22/1989	$1.07 billion	$2.12 billion	80	0	20
T.D. Chris	8/29/1988	$0.5 million	$1 million	100	0	0
Hurricane Charley	8/17/1986	$3 million	$7 million	75	20	5
T.S. Bob	7/25/1985	$1.5 million	$4 million	80	10	10
T.D. Danny	8/17/1985	$2.5 million	$6 million	10	90	0
Hurricane Gloria	9/27/1985	$14 million	$38 million	50	0	50
T.S. Kate	11/23/1985	minor	minor	0	100	0
Hurricane Diana	9/13/1984	$79 million	$249 million	40	40	20
Hurricane Josephine	10/12/1984	minor	minor	0	0	100
T.S. Dennis	8/20/1981	$10 million	$44 million	0	100	0
T.S. David	9/5/1979	$15 million	$88 million	40	50	10
T.D. Babe	9/9/1977	no damage	none	0	0	0
Hurricane Belle	8/9/1976	minor	minor	10	10	80
T.S. Dottie	8/21/1976	$0.5 million	$4 million	0	100	0
T.S. Eloise	9/24/1975	minor	minor	50	50	0
T.S. Agnes	6/21/1972	$10 million	$115 million	10	90	0
T.S. Doria	8/27/1971	$1 million	$17 million	50	25	25
Hurricane Ginger	9/30/1971	$10 million	$168 million	50	30	20
T.D. Alma	5/26/1970	no damage	none	0	0	0
T.S. #4	8/17/1970	$0.5 million	$9 million	0	0	100
T.D. Abby	6/8/1968	minor	minor	10	90	0
Hurricane Gladys	10/20/1968	minor	none	0	0	0
T.S. Doria	9/17/1967	minor	minor	0	100	0
T.S. Alma	6/11/1966	minor	minor	50	50	0
T.D. #1	6/16/1965	minor	minor	0	100	0
T.S. Cleo	8/31/1964	$0.5 million	$21 million	50	50	0
T.S. Dora	9/13/1964	$0.1 million	$5 million	80	20	0
Hurricane Gladys	9/21/1964	$0.1 million	$5 million	0	0	100
Hurricane Isbell	10/16/1964	$1 million	$54 million	90	0	10

Table 4. continued.

Tropical Cyclone	Date of Landfall	Unadjusted Damage	Normalized Damage	Wind (%)	Flood(%)	Storm Surge (%)
Hurricane Ginny	10/21/1963	$0.1 million	$5 million	10	10	80
Hurricane Alma	8/28/1962	minor	minor	20	80	0
T.S. #6	9/14/1961	no damage	none	0	0	0
Hurricane Esther	9/20/1961	$0.1 million	$4 million	0	0	100
T.S. Brenda	7/30/1960	$0.25 million	$10 million	40	60	0
Hurricane Donna	9/12/1960	$56.5 million	$2.34 billion	60	0	40
T.D. Cindy	7/10/1959	$1.1 million	$46 million	90	10	0
T.S. Gracie	9/30/1959	$0.5 million	$21 million	80	20	0
Hurricane Helene	9/27/1958	$11 million	$523 million	100	0	0
T.D. Flossy	9/26/1956	no damage	none	0	0	0
Hurricane Connie	8/12/1955	$40 million	$1.56 billion	30	20	50
Hurricane Diane	8/17/1955	$80 million	$2.54 billion	10	60	30
Hurricane Ione	9/19/1955	$88 million	$3.44 billion	10	70	20
Hurricane Carol	8/31/1954	$0.25 million	$11 million	60	0	40
Hurricane Edna	9/11/1954	$0.1 million	$4 million	30	20	50
Hurricane Hazel	10/15/1954	$254 million	$10.52 billion	40	30	30
Hurricane Barbara	8/14/1953	$1.1 million	$54 million	90	10	0
T.S. Able	8/31/1952	minor	minor	0	100	0
Hurricane #1	8/24/1949	$0.2 million	$12 million	100	0	0
Hurricane #2 (T.S.)	8/29/1949	minor	minor	0	0	0
T.S. #6 (T.D.)	9/24/1947	minor	minor	0	0	0
Hurricane #2 (T.S.)	7/6/1946	minor	minor	0	0	0
Hurricane #5 (T.D.)	10/9/1946	no damage	none	0	0	0
Hurricane #1 (T.S.)	6/26/1945	minor	minor	0	0	0
Hurricane #9 (T.S.)	9/18/1945	$2 million	$209 million	0	100	0
Hurricane #3	8/1/1944	$2 million	$234 million	30	0	70
Hurricane #7	9/14/1944	$1.5 million	$168 million	50	0	50
Hurricane #11 (T.S.	10/20/1944	minor	minor	0	100	0
T.S. #8 (T.D.)	10/12/1942	minor	minor	0	0	0
Hurricane #2 (T.D.)	8/18/1939	$1 million	$156 million	80	20	0
Hurricane #13	9/18/1936	$0.1 million	$15 million	20	0	80
Hurricane #2 (T.S.)	9/5/1935	minor	minor	0	0	0
Hurricane #8	8/23/1933	$0.25 million	$40 million	30	20	50
Hurricane #13	9/16/1933	$4.5 million	$731 million	50	0	50
Hurricane #1 (T.D.)	8/11/1928	$0.05 million	$6 million	100	0	0
Hurricane #4 (T.S.)	9/19/1928	$2 million	$252 million	0	100	0
T.S. #5	10/3/1927	no damage	none	0	0	0
Hurricane #2 (T.S.)	12/2/1925	no damage	none	0	0	0

Sources: Storm Data published by the NCDC (1959-1997)
Monthly Weather Review Summaries (1925-1999)
Wilmington News Archives, 2001: New Hanover Library
Meteorological Data (rainfall, wind) provided by the NCDC; (storm surge) data by NOS.

Prior to 1959, storm summaries published in the Monthly Weather Review were used but lacked specific details. The second source of information used to determine the percentage of damage from wind, flooding, and storm surge was meteorological data provided by NCDC and coastal tidal data provided by the United States Geological Survey. By evaluating the maximum wind gusts, the levels of storm surge and flood levels, a better idea of what caused the damages can be made. Third, historical reports, newspaper articles, and specific reports on individual tropical cyclones (example includes USGS, 2000) were collected and used. Based on all three types of information, the separated percentages were determined.

The following descriptions of each significant tropical cyclone event in North Carolina include some of the damage reports along with maximum wind gusts, rainfall totals, and storm surge measurements. All the different types of information were analyzed and a best-guess percentage of damage caused by wind, flooding, and storm surge was made. It should be stressed that only a detailed study of each particular storm could give more precise percentages and that the percentages are based on information that themselves are estimates collected from many different sources.

Starting with the most recent tropical cyclone to significantly impact North Carolina, Hurricane Floyd in September 1999, caused an estimated $6 billion (unadjusted value). Hurricane Floyd was a weakening category-2 hurricane with recorded wind gusts of 100-120 knots along the Wrightsville Beach and Wilmington area. Although Floyd made landfall with 100-knot winds and a 5-10 foot storm surge, flooding was the major event as a large part of central and eastern North Carolina received over 15” with a maximum over southeastern counties (the rainfall distribution is shown in figure 6).

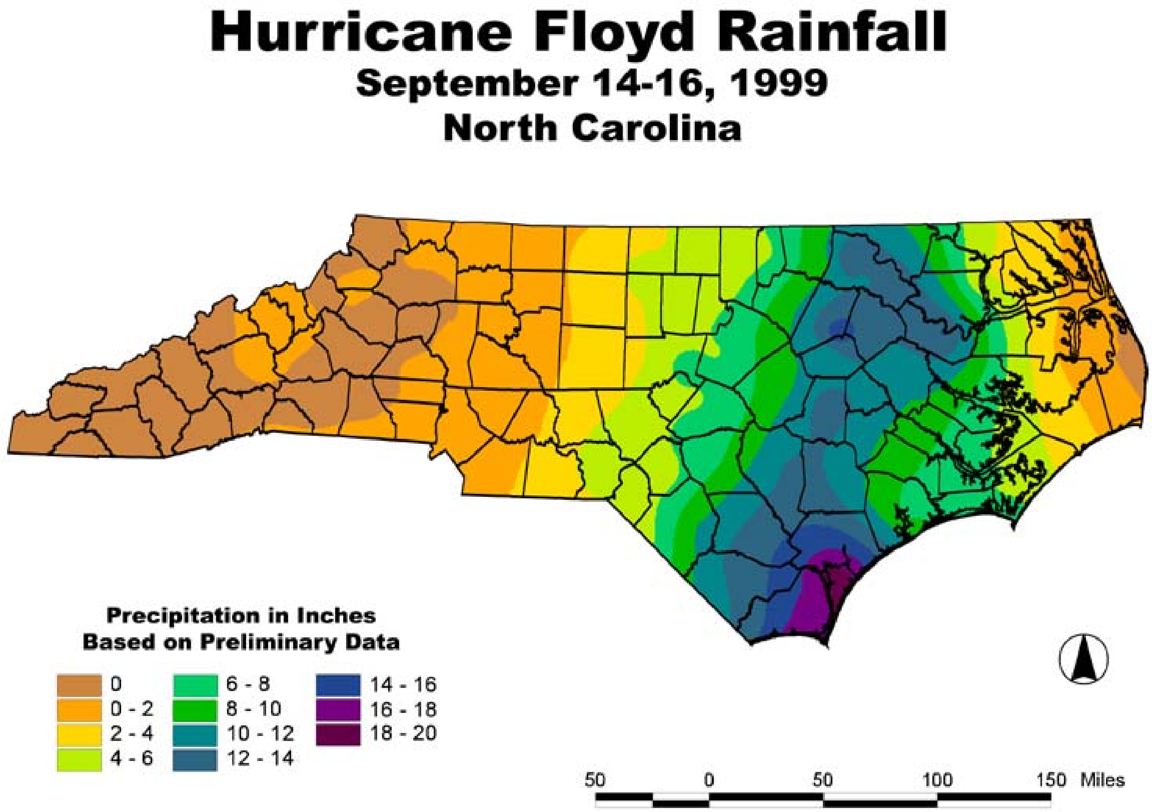


Figure 6. Hurricane Floyd (1999) rainfall distribution. (Source: State Climate Office of North Carolina)

Southport recorded the highest storm total with 24” of rainfall. Maximum rainfall amounts were also located in east-central regions along Interstate-95.

Only a week earlier, Tropical Storm Dennis broke a season-long drought in eastern North Carolina saturating the ground and filling up the rivers to near flood levels. After Floyd hit, some stream gauge stations measured flood levels that broke 100-500 year records. Due to the estimated $1 billion total damage to agriculture, the 7,000 houses destroyed, 17,000 houses with severe damage, and the reports of flood damage to schools, roads, bridges, airports, water and sewage treatment plants, and losses of small businesses, it was estimated that 90% of the total damage from Floyd was caused by flooding. Storm surge costs included $76 million for beach renourishment and $39 million damage to Oak Island, Holden Beach, Ocean Isle, and Sunset Beach due to ocean overwash. Wind damage was significant at the coast along the track of the storm but was limited in scope. Tornadoes were numerous but were weak in nature, causing an estimated $2 million. Of the $80 million in forestry losses, $40 million was caused by wind. Storm surge and wind split the remaining 10% of the total damage from Hurricane Floyd.

As previously mentioned, Tropical Storm Dennis (1999) broke the persistent drought in eastern North Carolina by dumping 14-19” of rain on the Outer Banks and 6-10” over most of eastern North Carolina. Although river flooding was not significant due to drought conditions prior to Tropical Storm Dennis, of the $60 million in total damage, $21 million was caused by flooded crop damage. Minor wind damage to crops was reported. The majority of damage was caused by storm surge. For days, Dennis meandered off the coast of North Carolina strengthening into a hurricane and weakening back to a tropical storm. While doing this, Dennis caused severe erosion to the Outer Banks region near Cape Hatteras. A 3000-foot section of Highway-12 was destroyed north of Buxton, while dunes valued at $16.5 million were lost at Nags Head. The sea undermined six houses in Rodanthe. Storm tides were 6-10 feet in limited areas including the Wichards Beach area but the length of time that Dennis remained just offshore was the main reason for the severity of the damage.

In August 1998, Hurricane Bonnie hit the Wilmington area as a category-2 hurricane. Significant wind damage was caused by localized downbursts in precursor rain bands. Winds topped 85 knots along Topsail Beach. There was moderate flooding after 7-10" of rain fell but was eased by the below normal rainfall conditions prior to Bonnie making landfall. Crop damage was severe due to a combination of rain and wind. Moderate beach erosion was also a significant impact. From all this, 70% was wind related, 20% flooding, and 10% storm surge.

Tropical Depression Danny was a significant rainfall event causing $60 million in damage to the Charlotte metropolitan area. Rainfall totals in the area ranged from 8-11". Danny made landfall along the Gulf coast and moved slowly to the northeast. The circulation center was over North Carolina for 24 hours.

Hurricanes Bertha and Fran both made landfall in the Wilmington area during the summer of 1996. Bertha was a category-2 hurricane. Its winds damaged 1500 homes and 250 businesses. Wind gusts of 94 knots were measured at the New River Marine Corp Air Field and 87 knots at Southport. Crop flooding was significant as 6-11" of wind-driven rain fell on immature plants in early July. Storm surge was also significant as 4 piers were damaged and 40 houses in Pender County were undermined by erosion.

Due to the broad scope of damage, 40% was attributed to wind and 30% each to storm surge and field flooding. Almost 2 months later Hurricane Fran made landfall again near Wilmington, but this time as a category-3 major hurricane. Long Beach measured 95-knot winds. The timber industry reported losses of $1 billion due to wind damage along the coast and inland. A 69-knot wind was measured at the Raleigh-Durham International airport. Downed trees damaged buildings and power lines far inland including Wake County. In all, Hurricane Fran caused $5.2 billion in total damage, $2.3 billion in damage to housing, $1.1 billion for cleanup costs, $700 thousand for crop lost shared between wind and flooding. Inland damages totaled almost $2 billion. Storm surge was measured up to 10 feet in many areas of the coastline and within the sounds of North Carolina. Wilmington Beach was hit with a 12-16 foot surge. Topsail Island, left exposed after Hurricane Bertha hit, lost 40 feet of beach from Hurricane Fran. Pender County reported $112 million in beach damage. Flooding was severe as a few stream stations broke 100-year records. Southport received 12.65" of rain while Raleigh totaled 8.59". During Fran wind, flooding, and storm surge all caused tremendous amounts of damage. As a category-3 hurricane, most damage was attributed to wind (50%) while a 100-year flood event in certain areas caused 30% of the total damage. The 20 % left for storm surge can also be attributed to Hurricane Bertha as the beaches were vulnerable before Fran made landfall.

The first half of the 1990's was much less destructive than the years 1996-1999. Tropical Storm Jerry (1995), Tropical Storm Opal (1995), and T.D. Beryl (1994) each caused flood damage alone. The remnants of Jerry stalled over central North Carolina, where 15" of rain fell locally. The Charlotte area was hit hard in a similar way as Danny did in 1997. Opal caused $70 million in flood damage to the western regions of the state as up to 12” of rain fell. Asheville even recorded a wind gust of 50 knots. Beryl dropped 13” of rain at Lake Toxaway in western North Carolina.

Also of note in the 1990’s was Hurricane Bob (1991), which caused mostly wind damage from 5 confirmed tornadoes. Hurricane Emily (1993) was a category-3 hurricane that brushed the Outer Banks, significantly reducing the amount of damage. Nonetheless, significant winds (90 knot at Buxton) and storm surge (up to 10.5 feet) destroyed 553 houses. Hurricane Felix (1995) never made landfall but caused significant erosion problems along the coast.

During the 1980’s, only three storms caused significant damage to North Carolina. Although making landfall near Charleston, South Carolina, Hurricane Hugo (1989) caused $1.07 billion to North Carolina. Most of this damage was confined to the far southern portions of the coast and to the Charlotte metropolitan area. Charlotte reported hurricane force winds with blown-out skyscraper windows. At Lake Norman, 1000 boats were damaged. Downed trees damaged buildings and power lines. Along the coast, 100 houses were condemned due to erosion. Sunset Beach reported a 9-foot storm surge. In all, Hugo caused minor damage to 2638 buildings, major damage to 1149 buildings, and destroyed 205 buildings. Wind damage was the cause of 80% of the total damage with 20% attributed to storm surge west of the Cape Fear region.

Hurricane Gloria (1985) was a category-3 major hurricane as it brushed Cape Hatteras. High winds and storm surge caused all of the damage as the rains were not a factor due to previously dry conditions. At Hatteras, winds were measured at 76 knots. Damages were attributed equally between high winds and storm surge.

Hurricane Diana (1984), another category-3 hurricane, caused significant wind, rain, and storm surge damage. The storm stalled for three days off the coast, adding to erosion problems and increasing rainfall totals. As it made landfall, Oak Island recorded a 115-knot wind. Carolina Beach recorded a 7-foot storm surge, but the erosion problem was due mostly because of the amount of time the storm stalled off the coast. Rainfall amounts were extremely high, with almost 19” at Southport and 11.3” at Morehead City. Due to such high wind gusts and rainfall totals, wind and rain damage accounted for 40% each and 20% for storm surge.

Similar to the 1980’s, tropical cyclone activity in North Carolina during the 1970’s was very quiet. Three storms of much consequence struck North Carolina. In 1979, Tropical Storm David caused $15 million in damage. Crop damage totaled almost half of all the reported damage mostly due to flooded fields. The other half was damage to beach property by high winds and minor damage from storm surge. Rain totals included 10.73” at Hatteras and 8.83” at Elizabeth City. A modest 52-knot wind gust was measured at Wrightsville Beach but the intensity of Tropical Storm David did not decrease as it made landfall, causing extensive tree damage inland as well. Flooding of crop fields added up to 50% of the total damage with 40% due to wind. The remaining 10% was caused by beach erosion.

In 1972, Tropical Storm Agnes wreaked havoc throughout the Northeast. North Carolina did not get the worst of the flooding. The storm total of $10 million pales in comparison to the damage in Pennsylvania and New York (Bosart and Dean, 1991). Although mostly due to freshwater flooding (6-8” rainfall totals were common in western and central North Carolina), some damage to several houses and mobile homes was caused by wind gusts. In all, flooding caused 90% of the total damage.

Hurricane Ginger (1971) used a wind and rain combination to destroy most of the corn and soybean crop. In Morehead City, moderate wind damage occurred to mobile homes, roofs, piers, and boats. Tidal surges of 6 feet were reported along with some inland flooding from 9-11” of rainfall. Although wind caused the most damage (50%), this category-1 hurricane caused significant flooding (30%) and coastal damage (20%).

Only two tropical cyclones of real significance struck North Carolina during the 1960’s. Hurricane Isbell (1964) was a category-1 hurricane that made landfall in Morehead City. Winds caused only moderate damage. Elizabeth City reported a wind gust of 65 knots. In total, Isbell caused $1 million in damage but also was responsible for the loss of a ship near Morehead City.

A very powerful hurricane struck Topsail Island in 1960. Hurricane Donna was a category-3 major hurricane with 95-knot gusts at Morehead City, 7” rainfall totals, and 6-8 foot storm surge. Damage was estimated at $56.5 million in 1960. Severe crop damage was reported due to high winds. Severe beach erosion and tornado damage was also reported. Due to dry conditions prior to the arrival of Donna, there was no serious flooding. With the significant crop damage, total damage was 60% wind and 40% storm surge damage.

The 1950’s was a devastating decade in North Carolina tropical cyclone history. Six hurricanes made landfall in North Carolina, four of which were major hurricanes. Unadjusted damage totals throughout the 1950’s were almost $500 million. However, if those totals were adjusted to the year 2000, damage totals would be over $18 billion.

In 1958, North Carolina narrowly avoided further destruction with Hurricane Helene. Although Helene technically made landfall along the Outer Banks, its strong category-3 winds stayed mostly offshore. The storm only briefly brushed North Carolina before heading off to the Northeast and out to sea. Helene caused \$11 million in damage which would have been much worse had it tracked further inland. Regardless, the Cape Fear area recorded 130-knot wind gusts. All damage was caused by the high winds.

Hurricanes Connie and Diane struck North Carolina in 1955 only 5 days apart from each other. It was estimated that Connie (category-3 hurricane) caused \$40 million, while Diane (category-1) hurricane caused \$80 million. Separating the damages from each storm was nearly impossible and many sources group the damages from the two storms together. However, it can be stated that Diane was much more a flood event and Connie was more a storm surge event. Connie dumped 13” of rain on New Bern while the sounds of North Carolina were inundated with an 8-foot storm surge. The highest wind gust was 79 knots at Cherry Point. Crop damage was severe from storm surge, wind, and flooding. Diane produced only 64-knot wind gusts and rain totals were only 5-7”. However, due to the vulnerability of the region after Connie, record flooding occurred in many areas. Half of Connie’s damage total was caused by storm surge while 60% of Diane’s damage was due to flooding. Combining the two storms would give a more equal percentage for storm surge and flooding.

Only a month after Diane hit North Carolina, the third hurricane of the year, Ione, struck Salter Path as a category-3 hurricane. Flooding from Ione was an historical event. Before Ione hit, the area of eastern North Carolina was swamped with over 30” the month before from Hurricanes Connie and Diane. Ione produced storm totals of 10-13”. Half of the damage totals were crop losses due to flooding of fields. Storm surge was also significant with reports of up to 10 feet. Wind damage was only moderate even with a wind gust of 93 knots at Cherry Point. Total damage for Hurricane Ione was $88 million.

If 1955 was the worst hurricane season in North Carolina, 1954 produced the worst storm in modern North Carolina history. As the only category-4 storm to hit the state in the 1900's, Hurricane Hazel blew through the southern regions of the coast causing tremendous wind, storm surge, and flood damages adding up to $254 million. Rainfall totals in many locations broke 24-hour records of over 10" as flash floods added to the destruction. Storm surge was estimated at 17 feet. Entire beach communities were swept away by the wind and tide. Along the coast with such powerful storms, it is very difficult to separate wind and storm surge damage. Most destruction was probably caused by a combination of both. Because there was such extensive damage from flooding, wind and storm surge, damage was split between the three with wind a little more weighted.

Hurricane Barbara in 1953 was mostly an agricultural event. Almost all of the damage was caused by wind on the corn crop. Minor wind damage to coastal homes was also reported. Minor flood damage was caused by storm rain totals of 5-7".

Separating damages back in the 1940's was a difficult task to perform. Fewer statistics on storms were replaced by general storm descriptions and eyewitness accounts of damage. Three storms in the 1940's caused significant damage, again occurring in the middle of the decade similar to the 1950's. In 1945, Hurricane #9 (prior to 1950 tropical cyclones were identified by number instead of by name) made landfall in South Carolina.

In North Carolina, as a tropical storm, Hurricane #9 caused $2 million in flood damage, mostly in Asheboro, where 10.71” of rain fell.

Hurricane #3 was the first of two storms to make landfall in North Carolina. As a minimal category-1 storm, Hurricane #3 caused heavy beach damage from storm surge along Carolina and Wrightsville Beach. Minor wind damage to roofs and power lines were reported. Oak Island recorded a wind gust of 65 knots. Rain totals were generally light. An estimated 15% of the total crops in New Hanover, Pender, and Onslow counties were destroyed. The majority of coastal damage was caused by storm surge while the crop damage was mostly due to high winds.

The following month in September 1944, Hurricane #7 made landfall along the Outer Banks as a category-3 major hurricane. Wind gusts of 95 knots at Hatteras and a 7-foot storm surge destroyed 108 buildings, mostly by undermining of the structure from erosion. Crop losses from wind and saltwater intrusion were near $1 million of the $1.5 million total. Winds and storm surge were equal causes of the total damage.

The 1930’s and last half of the 1920’s were relatively quiet. Storms in 1939, 1933, and 1928 caused significant damages. The 1939 storm, Hurricane #2, was only a tropical depression once it reached North Carolina from the Gulf coast. The high damage was caused by secondary tornadoes from the main remnant circulation. Further inland, 5” of rain at Winston-Salem caused some minor crop damage. Total damage was $1 million mostly from tornadoes.

In 1933, Hurricane #13 hit Ocracoke Island as a category-3 hurricane. Storm surge was severe, killing 21 people. New Bern recorded a wind gust of 109 knots, and the Outer Banks received 13" of rain adding to the coastal flooding from the storm surge. The damage was split between storm surge and high winds.

Finishing off the tropical cyclones that caused significant damage from 1925-2000 was Hurricane #4 in 1928. After making landfall in South Carolina, the weakening hurricane became a tropical storm once in North Carolina. Central North Carolina recorded 6-9" from Lumberton to Goldsboro to Salisbury. Severe flooding occurred due to heavy rains and rainfall the previous month. Records were broken in Elizabethtown. Half of the damage was to flooded crops. Damage totals reached $2 million all due to flooding.

This study has attempted to separate the causes of damage from tropical cyclones that have impacted North Carolina. From this data, the percentage of damage expected from specific intensity storms was calculated by adding up the separated damages caused by each category of tropical cyclone. Figure 7a illustrates the damage assessment based on all tropical cyclones that impacted North Carolina from 1925-2000. The separated percentages of wind, flood, and storm surge damage from individual storms were multiplied by the normalized total storm damage. It was important to use normalized data to eliminate time biases. To get the total damage assessment, all the wind, flood, and storm surge damage was added up separately to get the separated damage from all the tropical cyclones. These totals were then divided by the total of all damage to North Carolina from 1925-2000 to get a percentage of wind, flood, and storm surge from all tropical cyclones. As shown in figure 7a, for North Carolina tropical cyclones, flooding has caused the most damage with an estimated 40%, followed by wind and storm surge with 35% and 25%, respectively.

In figure 7b, the same method was used except only category-1 and 2 hurricanes along with tropical storms and tropical depressions were included (hereby called weaker tropical cyclones). For weaker tropical cyclones, flooding was responsible for 60% of the total damage. Wind and storm surge damage dropped to 25% and 15%, respectively. For figure 7c, major hurricane damage was only included and wind now was responsible for 40% with flooding and storm surge both at 30%. Figure 7d included only category-1 to 3 hurricanes, with the resulting percentages very similar to figure 7a (all North Carolina tropical cyclones). Clearly and reasonably, the more intense hurricanes caused more wind and storm surge damage than flooding damage as compared to weaker tropical cyclones. The importance from the statistics is not absolute percentages per se but the overall trends. For all tropical cyclones, flooding was the cause of a large percentage of the damage. For stronger hurricanes, flooding was still significant with 30% of all damages. For the weaker tropical cyclones, the flooding percentage rose significantly to 60%.

The +/- 5% uncertainty in the separation of damage statistics was based on the change in the statistics after changing the normalization procedure from housing back to the population factor used in previous studies. Statistical differences in the outcomes were usually only 1-3% with maximum values in the most distant tropical cyclones of 5%. Adding this error to the rounding error of 5% for each category gave an uncertainty of +/-5% for the final statistics.

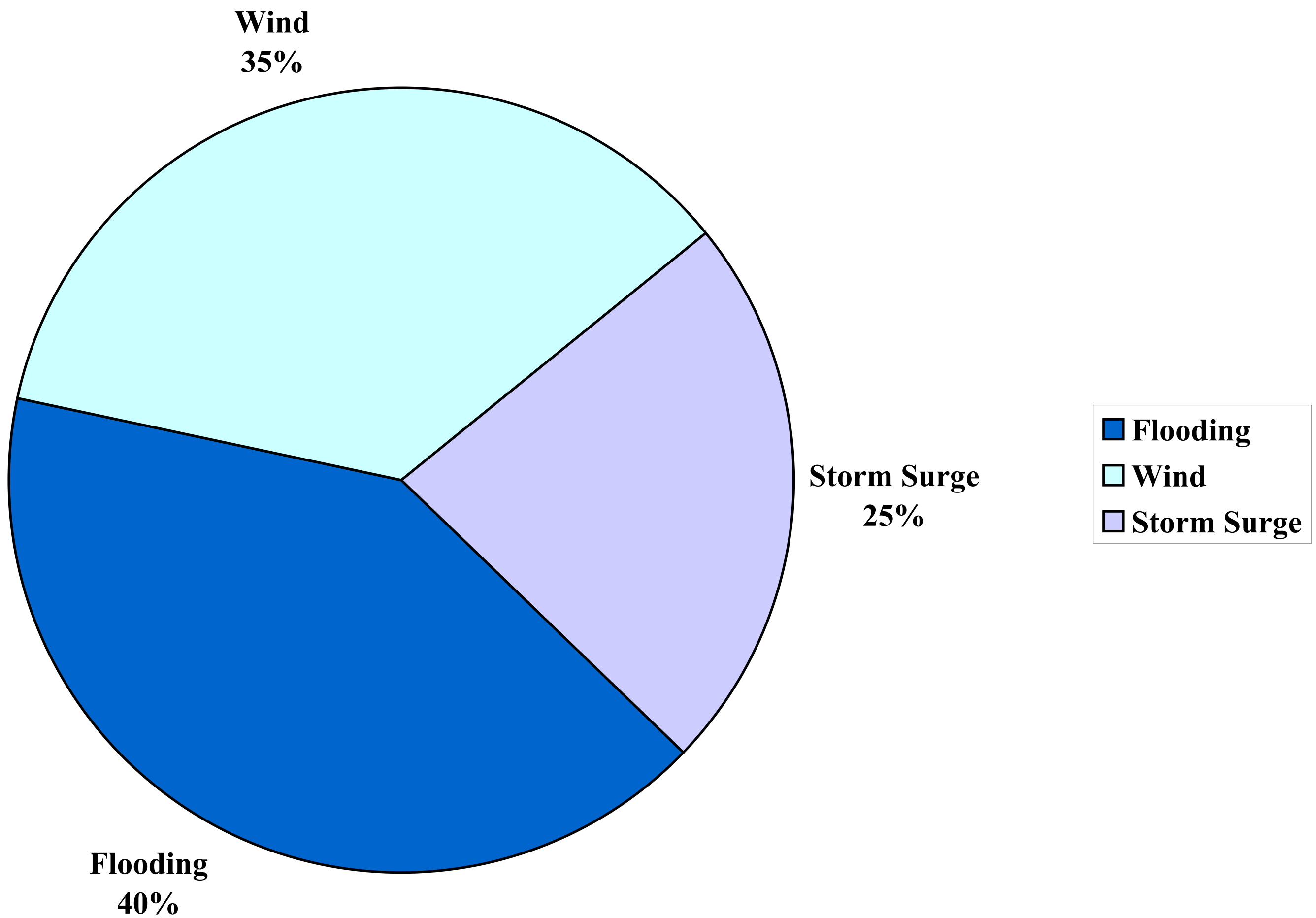


Figure 7a. Total North Carolina Tropical Cyclone Damage Assessment (1925-2000).

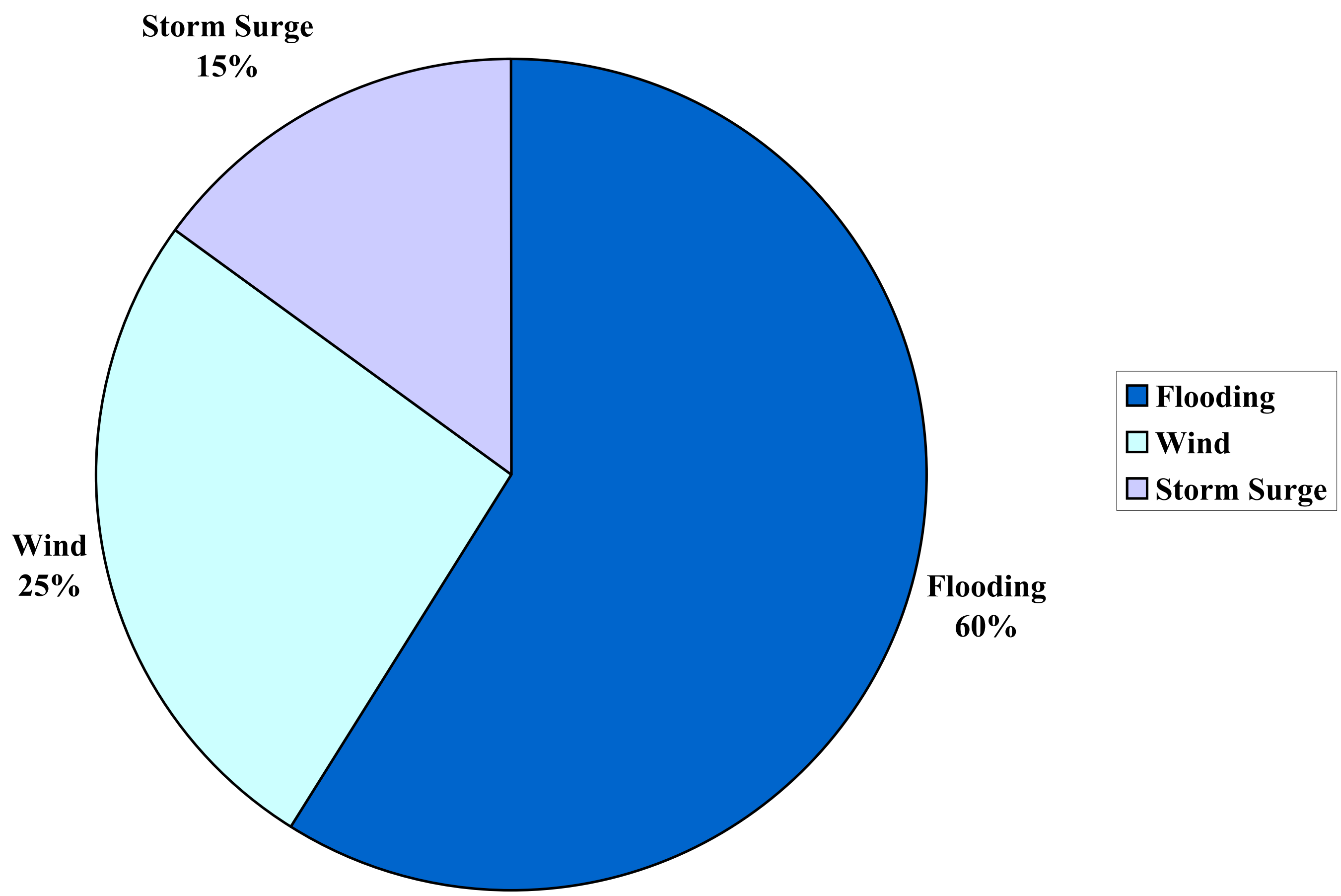


Figure 7b. North Carolina Category-1,2 Hurricanes, T.S., T.D. Damage Assessment (1925-2000).

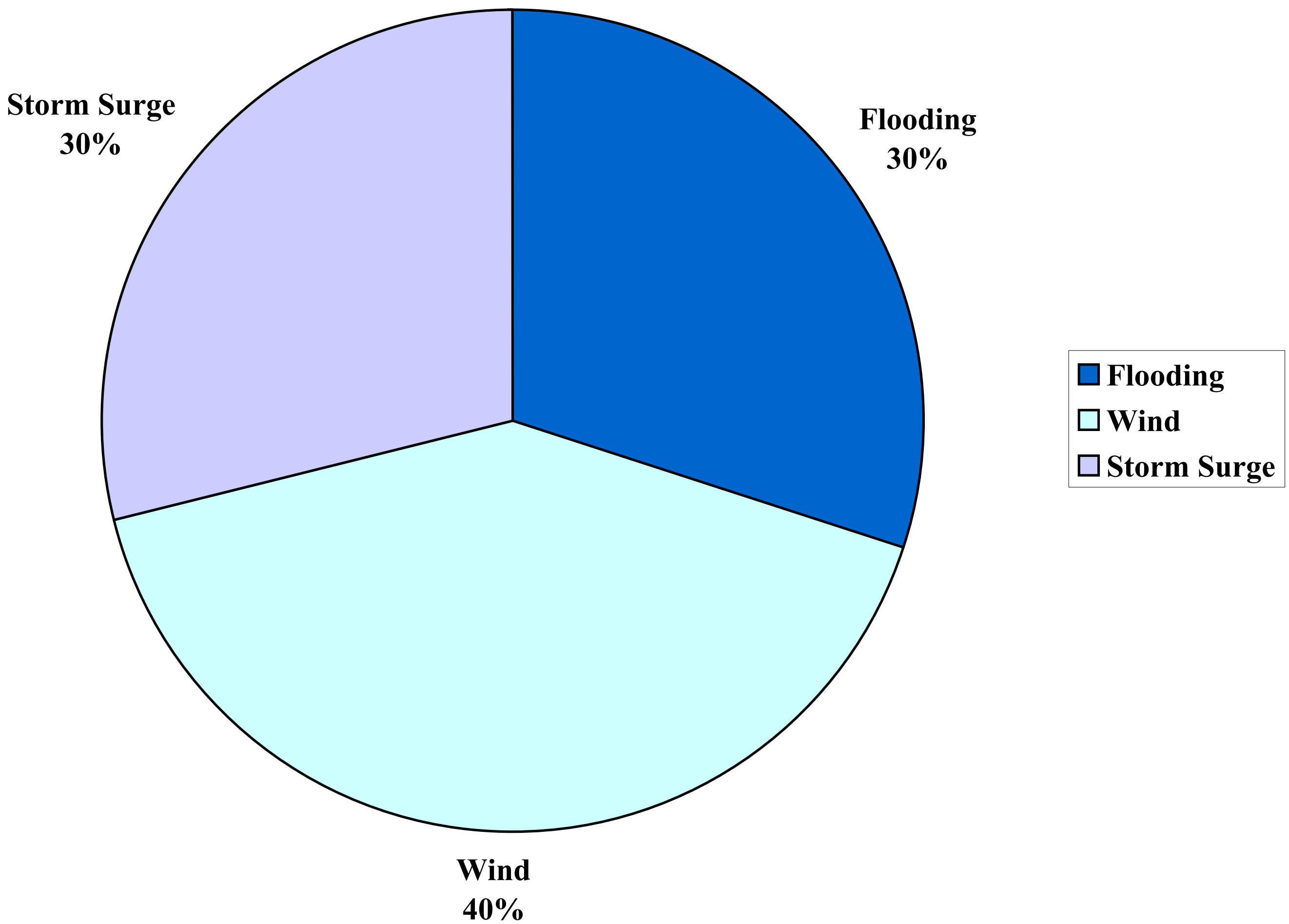


Figure 7c. North Carolina Major Hurricane (Category-3,4) Damage Assessment (1925-2000).

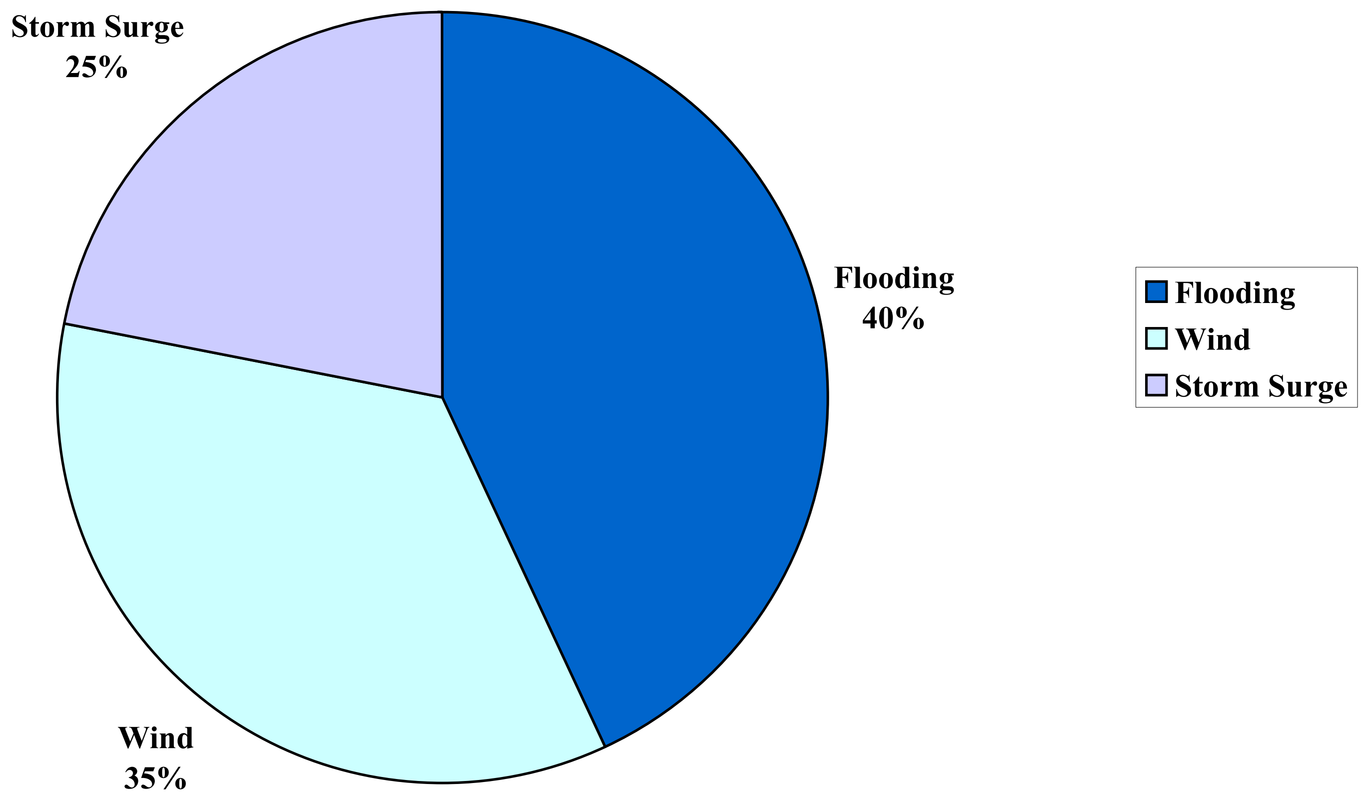


Figure 7d. North Carolina Category 1-3 Hurricane Damage Assessment (1925-2000).

III. Flooding Assessment

A. Introduction

It was estimated that 40% of tropical cyclone damage from 1925-2000 in North Carolina was caused by inland flooding. Recently, inland flooding has become a very hot topic both in the press and in the scientific community. Hurricane Floyd (1999) was one of the deadliest hurricanes in North Carolina history with a death toll of 56, 50 of which can be attributed to inland flooding. Hurricane Fran (1996), primarily thought of as just an intense wind event, caused nineteen deaths with eleven attributed to inland flooding. Inland flooding, however, has been a serious problem throughout the past century, not just since 1996. Inland flooding is a dangerous feature of a tropical cyclone, yet one of the least understood and most underestimated by the general public. Since the 1970's, inland flooding has caused more fatalities in North Carolina than wind and storm surge combined (Joel Cline, personal communication, 2001). This chapter addresses the issue of tropical cyclone rainfall and subsequent flooding in North Carolina. First, a review of the mechanisms of tropical cyclone precipitation and the major parameters that determine rainfall amounts are described. Second, rainfall data are analyzed to better determine apparent relationships between maximum rainfall distributions, intensity, and translation speed of the tropical cyclone. The goal is to identify why extreme rainfall and flood events occurred in the past by quantitatively and qualitatively linking rainfall to tropical cyclone parameters. Analyzing past rainfall and flood events can better inform forecasters of the possible outcomes from future tropical cyclones and can lead to better parameterizations in quantitative precipitation forecast (QPF) models. Better rainfall forecasts can ultimately save lives and reduce property losses.

B. Tropical Cyclone Rainfall Characteristics

There are four general mechanisms associated with tropical cyclone precipitation. Classified by Bao (1980), the four mechanisms are:

1) spiral bands around the tropical cyclone
2) central convective region, including the eyewall where extremely heavy rain persists
3) interaction between a tropical cyclone and the mid-latitude environment
4) interaction between a tropical cyclone and other tropical systems.

Within a tropical cyclone itself, Bao (1980) found that for the majority of the tropical cyclones, rainfall occurs in the front quadrants. As a tropical cyclone makes landfall, rainfall patterns generally shift to the left front quadrant as the circulation becomes impeded by friction, the warm-core structure dissipates, and the extratropical transition begins (see previous work section for references). The effect of increased friction is to increase the low-level convergence and hence the rate of lift. Rainfall totals from landfalling tropical cyclones depend on many processes that are often complex. Currently, forecasting tropical cyclone rainfall totals is extremely difficult, especially prior to landfall. The parameters that determine rainfall include:

1) intensity or stage of development (surface winds, warm/cold core structure)
2) forward movement of the storm (translation speed)
3) rate of ascent of air (low-level convergence)
4) topography
5) moisture supply

6) temperature and lapse rate in the storm's environment

7) mid-latitude interactions (surface frontal zones; jet streaks; etc.)

Often the result of heavy rainfall is flooding. Forecasting flood levels and the areal extent of flooding is also challenging and extremely dependent on accurate rainfall and TC track forecasting. The factors that determine flooding include:

1) amount of rainfall

2) duration of rainfall

3) areal extent of rainfall

4) previous rainfall before tropical cyclone influence (pre-storm river and reservoir levels; soil moisture/saturation)

5) local topography

6) geomorphology of the land (soil character; slope)

7) human interaction (dams/flood-control structures; urbanization).

The uncertainties of track and intensity forecasting can be added to the inaccuracies of precipitation measurements. Rain gauges are limited as point sources of data and are inaccurate in high wind environments. Ayoade (1983) performed wind tunnel experiments showing that with winds of only 23 knots, 50% of the rainfall amount in a gauge can be lost due to wind and turbulence effects. This makes forecasting empirically very difficult and is a limiting factor in the verification of models. An alternative to rain gauge data is the estimation of precipitation based on radar reflectivity. Radar is now used to estimate storm precipitation totals using a reflectivity-rainfall relationship. Unfortunately, there is no unique linear relationship. The WSR-88D usually underestimates tropical cyclone rainfall, even with a special tropical version of the reflectivity-rainfall relationship (Rinehart, 1997). Reasons for the underestimation of rainfall totals include:

1) tropical raindrops have a larger size distribution than mid-latitude storms (Rinehart, 1997),
2) attenuation of the radar beam due to the large areal extent of precipitation (the WSR-88D produces better estimates in smaller watersheds),
3) clutter cancellation filters underestimate at close ranges,
4) radar beam overshoots the rainfall at longer ranges (Serafin and Wilson, 2000),
5) the radar must be calibrated correctly.

C. Previous Work

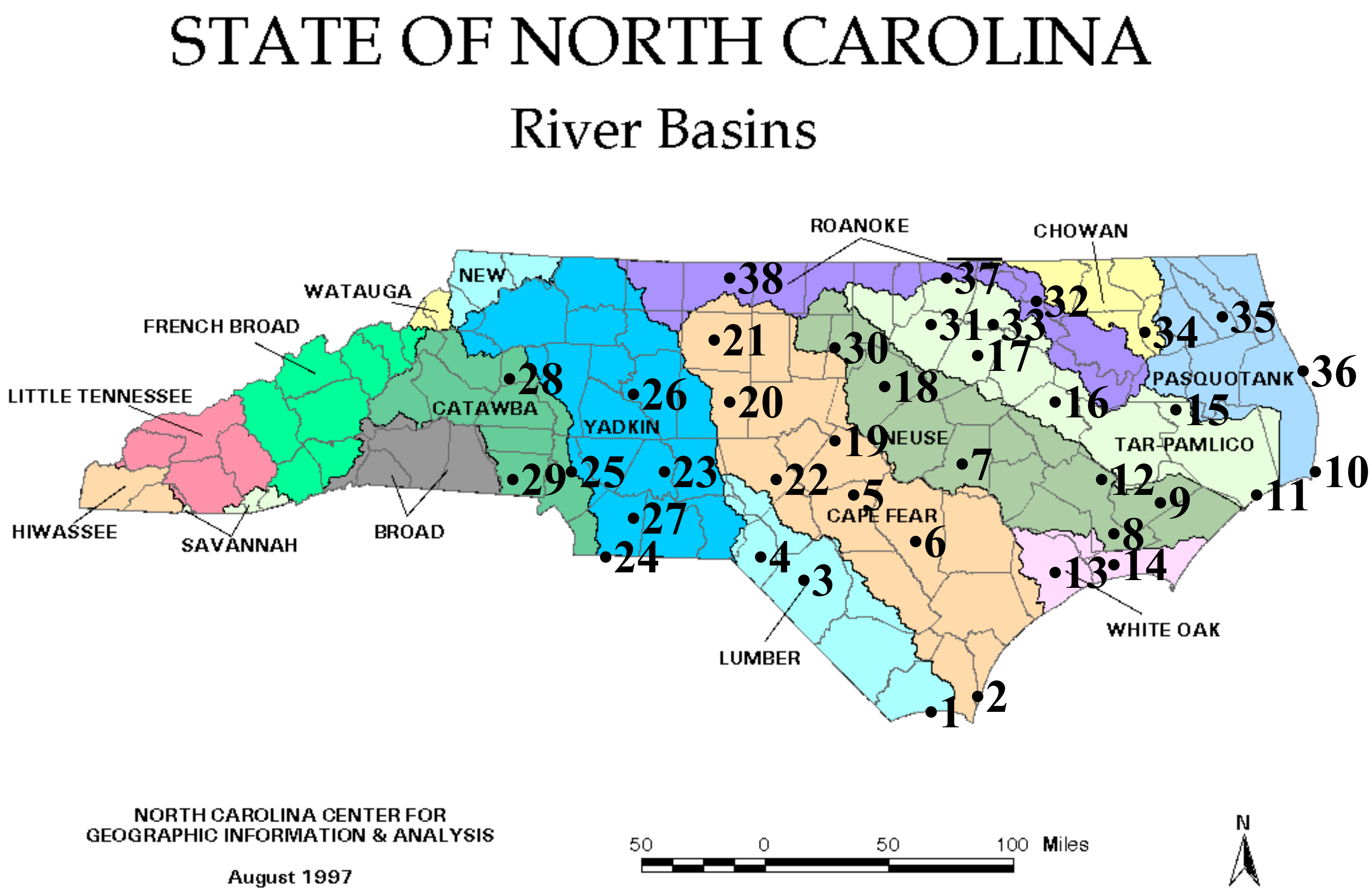
Tropical cyclone forecasting is an active research area. Wood and Frank (2000) have attempted to model the rainfall distribution of Hurricane Floyd using the non-hydrostatic Penn State/NCAR Mesoscale Model (MM5). The accuracy of the model is limited to the track forecast accuracy and has been underestimating rainfall values. Cerveny and Newman (2000) have performed a climatological study using satellite-derived oceanic precipitation records from non-landfalling tropical cyclones. Tibbetts and Krishnamurti (1999) have developed hurricane forecasts using three different Special Sensor Microwave Imager (SSM/I) rain rate algorithms on the Florida State University Global Spectral Model (FSU GSM). Algorithm validation points toward an underestimation of rainfall.

Numerous previous studies have focused on rainfall patterns as tropical cyclones become extratropical. Palmen (1958) emphasized the contributions of preexisting cyclonic vorticity and latent heat release to increased precipitation during the extratropical redevelopment stage of Hurricane Hazel in 1954. Klein et al. (2000) defined a conceptual model of extratropical transitions as a two-stage process. First, the tropical cyclone changes from a warm-core to a cold-core structure. Second, reintensification occurs as an extratropical cyclone. Cerveny and Newman (2000) found evidence for an increase in rainfall rates between 40°-45°N latitude due to mid-latitude interactions and/or any general recurvature toward the northeast as the tropical cyclone penetrates into a high pressure ridge's subsidence. Harr and Elsberry (2000) concluded that increased warm frontogenesis occurs during the initial stage of the extratropical transition. During the extratropical transition, complex processes that are not fully understood occur as the tropical cyclone loses its heat and moisture source after landfall. Dissipation and the eventual decrease in rainfall occur after landfall unless other influences interact with the tropical cyclone. Orographic lifting and moisture flux convergence during the transition of Agnes (1972) as described in Bosart and Carr (1978) and frontal zone interactions (Floyd, 1999) are mechanisms that can increase rainfall rates after landfall. Other studies of extratropical transitions and precipitation distribution include Atallah (2000) description of increased precipitation north and west of the circulation due to the interaction of the tropical cyclone with a mid-latitude trough which causes an enhancement of the potential vorticity gradients and increase in the intensity of the jet streak. Bosart and Atallah (2000) describe the process of low-level warm advection poleward of the tropical cyclone and the downstream jet streak release of baroclinic energy during the transition to an extratropical cyclone. Bosart and Lackmann (1995) studied Tropical Storm David (1979) and its reintensification 27 hours after making landfall. Drury and Evans (1998) discussed tropical cyclone interaction with mid-latitude troughs, while Bosart and Dean (1991) analyzed surface features of Agnes (1972). These studies attempted to explain how tropical cyclones interact with mid-latitude systems to produce extreme rainfall and flood events.

D. Methodology of Rainfall Database

Rainfall storm totals were calculated for each North Carolina tropical cyclone from 1925-2000 for 38 weather stations across eastern and central North Carolina. Data consisted of 24-hour rainfall totals. Storm totals were calculated based on the estimation of storm arrival and departure from North Carolina. It was difficult to exactly separate tropical cyclone rainfall totals from other systems that may have added additional rainfall. The 38 weather stations were individually chosen based on geographical location and total period of available data. Those stations with under twenty years of data were not selected for this database. A very limited amount of rainfall data was available for storms prior to 1925. Additional historical rainfall reports were added to the database.

The names and geographical location of the 38 weather stations are shown in figure 8. Also provided is the areal extent of North Carolina river basins. Weather stations were chosen to achieve an even distribution of stations across the eastern and central regions of North Carolina. Table 5 lists the ten river basins of eastern and central North Carolina. The attempt was made to include one weather station for each 1,000 square miles. For example, the Tar-Pamlico river basin has six weather stations covering 5,440 square miles. The total area for each river basin is listed in Table 6.



1.	Southport	8.	Cherry Point	15.	Belhaven	22.	Carthage	29.	Gastonia	36.	Manteo
2.	Wilmington	9.	Bayboro	16.	Greenville	23.	Albemarle	30.	Durham	37.	Henderson
3.	Lumberton	10.	Hatteras	17.	Nashville	24.	Catawba	31.	Louisburg	38.	Reidsville
4.	Laurinburg	11.	Ocracoke	18.	Raleigh	25.	Charlotte	32.	Jackson		
5.	Fayetteville	12.	New Bern	19.	Sanford	26.	Salisbury	33.	Enfield		
6.	Clinton	13.	New River MCAF	20.	Asheboro	27.	Monroe	34.	Edenton		
7.	Goldsboro	14.	Morehead City	21.	Greensboro	28.	Conover	35.	Elizabeth City		

Figure 8. Map of North Carolina river basins and location of the 38 weather stations.

Table 5. List of weather stations attributed to each river basin.

Tar-Pamlico (6)	Cape Fear (7)	Neuse (6)	Pasquotank (4)	Lumber (3)
Ocracoke	Wilmington	Goldsboro	Elizabeth City	Southport
Belhaven	Fayetteville	Cherry Pt.	Manteo	Lumberton
Greenville	Clinton	Bayboro	Hatteras	Laurinburg
Louisburg	Sanford	New Bern	Edenton	
Enfield	Carthage	Raleigh		
	Asheboro	Durham		
	Greensboro			

White Oak (2)	Catawba (4)	Yadkin (4)	Roanoke (3)	Chowan (1)
New River MCAF	Conover	Salisbury	Jackson	Edenton
Morehead City	Gastonia	Albemarle	Henderson	
	Charlotte	Monroe	Reidsville	
	Catawba	Catawba		

Table 6. List of river basin areas.

River Basin	River Basin Area (sq. miles)
Tar-Pamlico	5,440
Neuse	6,192
Cape Fear	9,149
Lumber	3,336
White Oak	1,233
Pasquotank	3,697
Yadkin	7,213
Catawba	3,274
Roanoke	3,600
Chowan	1,315

E. Results of Rainfall Analyses

1. Relationship Between Intensity and Rainfall

A total of 31 tropical cyclones were chosen out of 36 that made direct landfall along the North Carolina coast from 1925-2000. Five storms were not used because they brushed the coast and briefly made landfall but the heaviest rainfall remained offshore. A list of the 36 tropical cyclones that made direct landfall in North Carolina is found in appendix B along with recorded maximum rainfall for each storm. The five discarded tropical cyclones have an asterisk. Based on the 38 weather stations chosen for this study, the recorded maximum rainfall for each storm was determined. Figure 9 is a bar graph of the 31 tropical cyclones separated based on intensity and their corresponding recorded maximum rainfall. The average maximum rainfall from all the tropical cyclones for each intensity category was calculated and identified by a horizontal bar. From figure 9, it can be concluded that the intensity of a tropical cyclone at landfall has a weak correlation with maximum rainfall in North Carolina. Furthermore, extreme rainfall events from weaker tropical cyclones are possible Tropical Storm Dennis (1999) produced over 19" of rain along the Outer Banks, while Hurricane Floyd (1999) broke rainfall records by dumping two feet of rain on Southport. More intense hurricanes (category-3 and 4) produced over 7" of rain consistently.

Tropical cyclones that made landfall outside of North Carolina were not included in this study. As a tropical cyclone makes landfall, de-intensification occurs rapidly and the true relationship between intensity and rainfall is lost and other factors become predominant. The number of tropical cyclones is again a problem in this particular

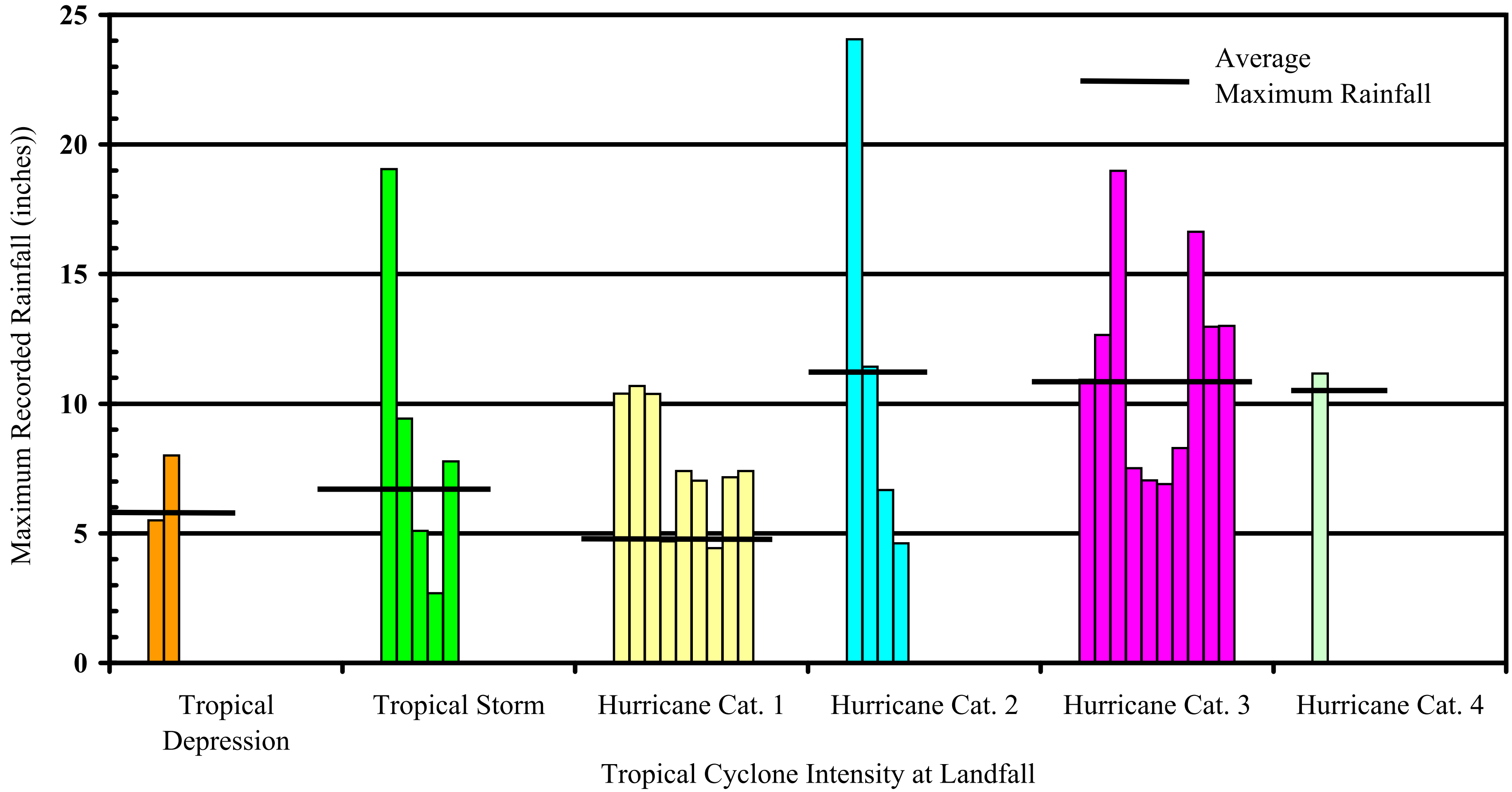


Figure 9. Maximum recorded rainfall from 31 direct landfalling tropical cyclones along the North Carolina coast (1925-2000). Rainfall data were provided by NCDC and included 38 official weather stations. Names and locations of each station are shown in figure 7 and the archived rainfall data is provided in appendix B. The list of tropical cyclones used in this analysis is provided in appendix C. Five tropical cyclones were omitted because they only briefly brushed the coast.

analysis. Only one category-4 hurricane and only two tropical depressions were included.

2. Maximum Rainfall Distribution

Based on the 36 direct landfalling tropical cyclones, a maximum rainfall distribution was made. Figure 10 illustrates the number of tropical cyclones that have their recorded maximum rainfall within the shown 3-inch maximum rainfall interval. From figure 10, it is clear that the most common rainfall total interval is 6-9”, followed by 9-12”. Over 50% of the 36 direct landfalling tropical cyclones in North Carolina produced a maximum of 6-12” of rainfall. Larger rainfall amounts occurred 20% of the time.

Using only the 24 direct landfalling hurricanes, the results are nearly identical (figure 11). Over 50% of the hurricanes produced 6-12” of maximum rainfall while 25% produced more than 12”. These results again support the conclusion that intensity and maximum rainfall are only weakly correlated to each other.

3. Rainfall Relationship to Translation Speed

The widely accepted “Kraft rule of thumb” rainfall forecast (Pfost, 2000) for landfalling tropical cyclones is the formula:

$$Y=100/X \tag{2}$$

where: Y=maximum storm total (in inches)

X=translation speed at landfall.

This formula is overly simplified and does not take into account other important factors such as intensity, size of the tropical cyclone, topographic effects, or mid-latitude

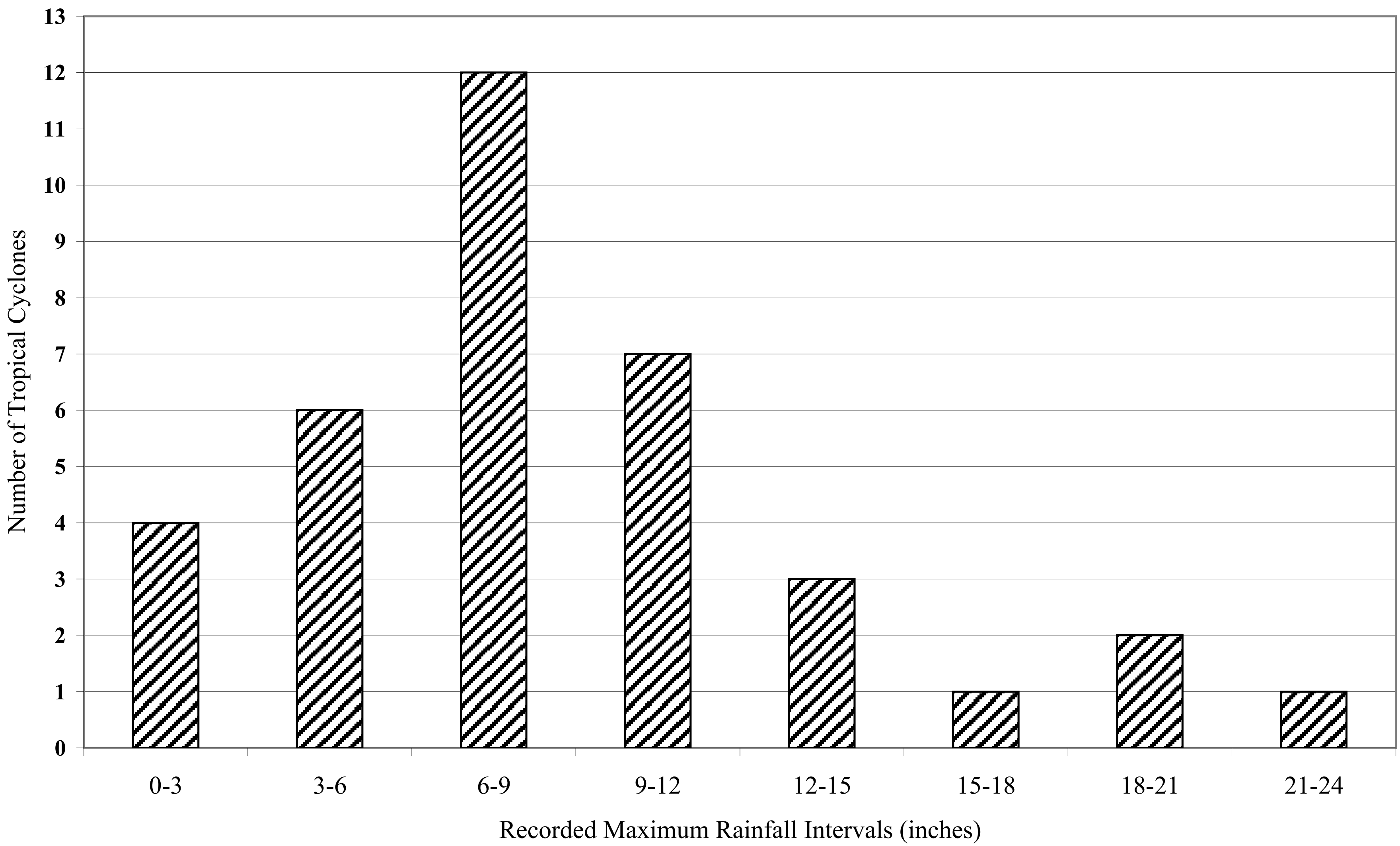


Figure 10. Maximum rainfall distribution of direct landfalling North Carolina tropical cyclones (1925-2000).

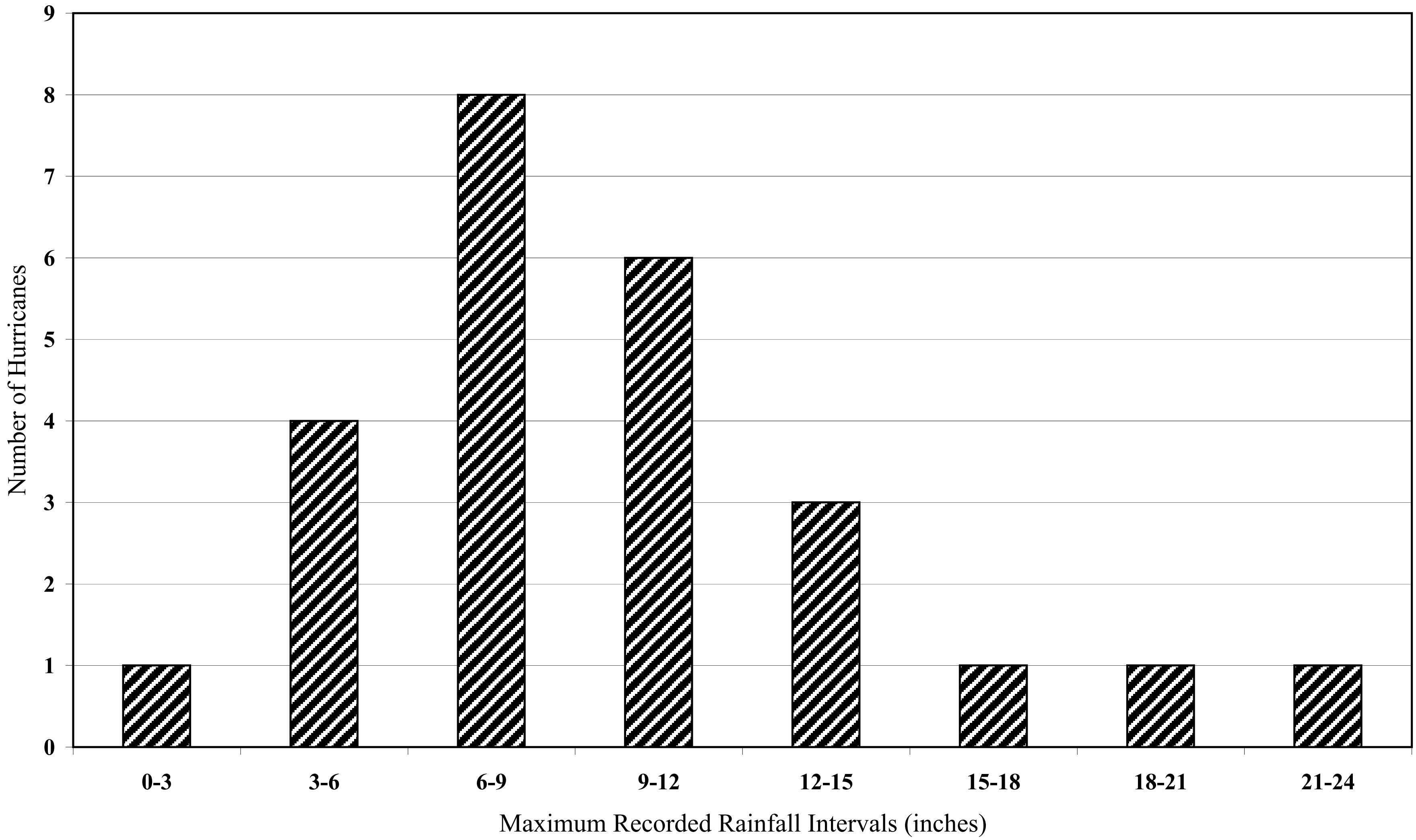


Figure 11. Maximum rainfall distribution of direct landfalling North Carolina hurricanes (1925-2000).

interactions. However, at the very least, this relationship between translation speed and rainfall is a good starting point in precipitation forecasts.

Using nineteen tropical cyclones (see appendix C for the list of included tropical cyclones) with similar tracks and over five rainfall measurements (from the 38 weather stations available), the average of the top five rainfall totals were plotted against the average translation speed over North Carolina. Figure 12 illustrates the resultant scatter plot. Average translation speed was determined using best-track analysis latitude/longitude data points on N-AWIPS graphing software to determine the 6-hourly distance. The best-guess estimate of average translation speed over North Carolina tried to take into account storms that drifted just off the coast before eventually making landfall (examples include Dennis, 1999, Charley, 1986, Diana, 1984).

Two of the nineteen points were classified as outliers. Hurricanes Floyd (1999) and Hazel (1954) were not included in the statistical analysis. Hurricane Floyd was extremely rare since it was moving relatively fast yet produced over 15" of rain mostly due to upper-level trough and coastal front interactions. Hurricane Hazel was extremely fast moving (40 knots) and very powerful (category-4 hurricane).

A statistical analysis was performed on the scatter plot. The power function best-fit curve resulted in an equation:

$$Y=29.529X^{-0.6134} \tag{3}$$

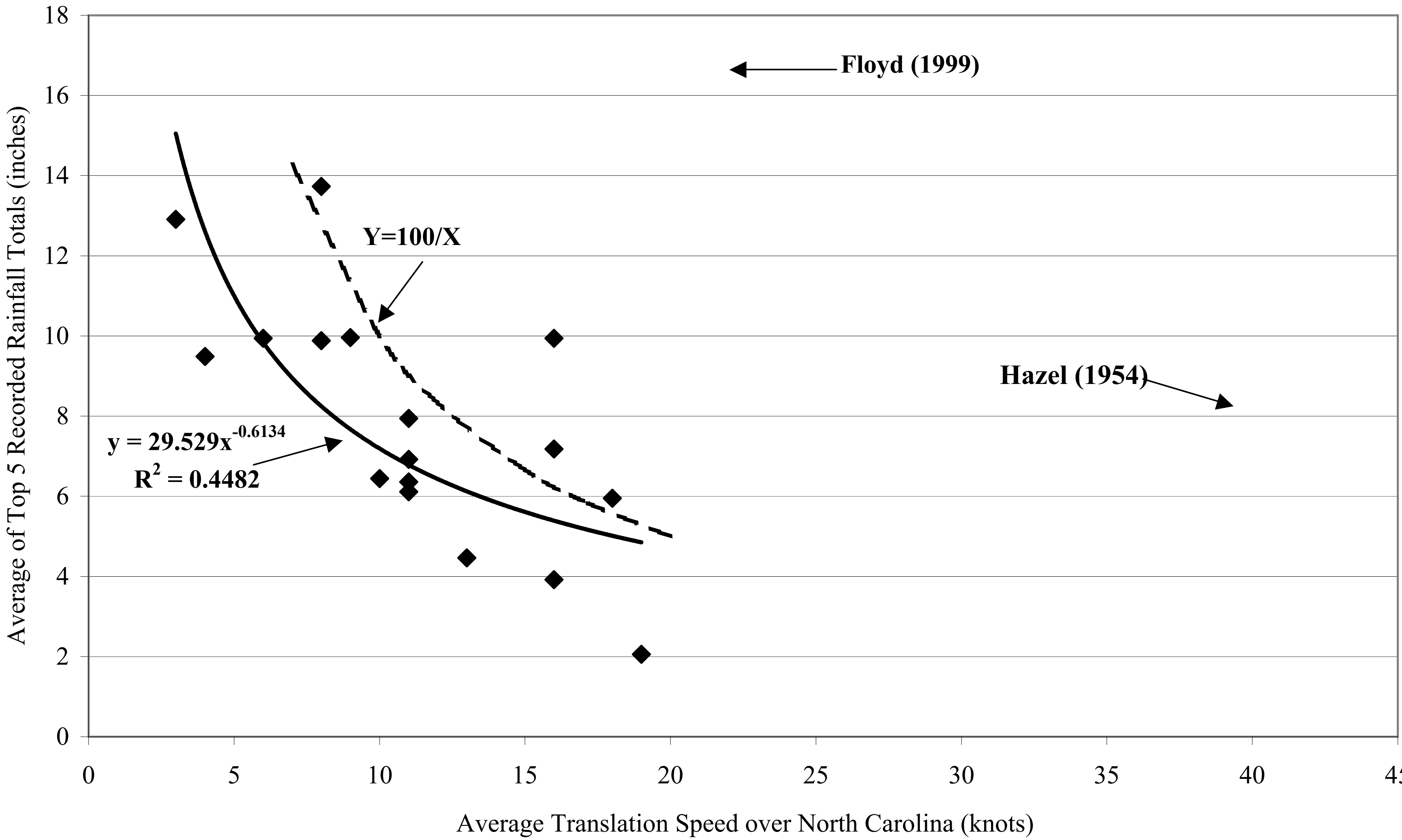


Figure 12. Tropical cyclone rainfall versus translation speed over North Carolina. Hurricanes Floyd(1999) and Hazel (1954) were determined to be outliers and were not included in the statistical analysis.

with an R-squared value of 0.4482. This new curve based on equation (3) indicates that in North Carolina without significant influence from other factors tropical cyclones must move 2-5 knots slower to achieve an equal rainfall total compared to equation (2).

4. Rainfall Volume Determination

The total volume of rain over North Carolina watersheds was estimated for eleven tropical cyclones with similar tracks through North Carolina. The purpose of this exercise was to better quantify the relationship between rainfall totals and flooding. Rainfall data was integrated over entire watersheds. Volume estimation calculations allow for historical flood events to be evaluated by isolating one factor of flooding-water volume added to the land (product of rainfall amount and areal extent of rainfall). The other factors previously mentioned in section III.B. do not influence the rainfall volume calculation. The similar track requirement is necessary to eliminate those tropical cyclones that brushed the coast and entails an approach angle into the North Carolina coastline of between the 270 and 10-degree clockwise angle.

The total rain volume was calculated using simple methods. First, rainfall storm totals were gathered for each of the 38 weather stations. Then the average rainfall was calculated for each river basin (refer to table 5 for the list of weather stations for each river basin). The average rainfall (in inches) was multiplied by the river basin area (in square miles). To make the final calculation expressed in cubic miles, a conversion of the rainfall average to feet (1/12 feet per inch) and then to miles (1/5280 feet per mile) was performed. The calculated total rain volume for the eleven tropical cyclones is given in table 7. The name of the tropical cyclone, the date of landfall, the maximum recorded rainfall, intensity, average translation speed, and any notable mid-latitude interactions are

Table 7. Rain volume from 11 similar-tracking North Carolina landfalling tropical cyclones and the factors involved.

Tropical Cyclone:	Date of Landfall:	Total Rain Volume (cubic miles):	Maximum Recorded Rainfall:	Intensity:	Ave. speed over NC (kt)	Mid-latitude Interactions:
Floyd	9/16/1999	4.14	24.06"	Cat. 2	22	jet/trough; coastal front
Dennis	9/4/1999	3.67	19.05"	T.S.	8 (drifted off coast)	weak steering current
Bonnie	8/26/1998	1.62	11.0"	Cat. 2	6	weak steering current
Fran	9/6/1996	3.14	12.65"	Cat. 3	16	-
Bertha	7/12/1996	1.69	11.43"	Cat.2	16	-
Diana	9/13/1984	2.76	18.98"	Cat. 1	3 (drifted off coast)	embedded cool environment
Ginger	9/30/1971	2.7	10.69"	Cat. 1	4	-
Doria	8/27/1971	1.33	9.43"	T.S.	18	-
T.S. #6	9/14/1961	0.47	2.49"	T.D.	19	-
Diane	8/17/1955	2.12	7.4"	Cat. 1	11	-
Hazel	10/15/1954	2.57	11.25"	Cat. 4	40	intensifying trough to west

Each of the eleven storms selected had similar tracks* as it approached, entered, and moved through North Carolina.
*Similar Track: requirement of an approach angle into NC coastline be between the 270 and 10 clockwise angle.
Total rain volume: rainfall measured from 38 weather stations throughout the 10 easternmost river basins.
Maximum Recorded Rainfall: storm total based on highest rainfall measured by 38 weather stations throughout eastern and central North Carolina.
Intensity: classification at landfall based on HURRDAT data.
Average speed over North Carolina: estimated average storm translation speed expressed in knots based on HURRDAT best-track analysis.
Midlatitude interactions: influence of synoptic-scale systems on the tropical cyclone while over North Carolina.

also given in table 7. The rain volume for the individual river basins is given in table 8. Notice the very high rain volume for Hurricane Floyd (1999) in the Cape Fear, Neuse, and Tar-Pamlico river basins. It is not surprising that Hurricane Floyd dropped the largest volume of rain (4.14 cubic miles) since the flooding associated with Floyd was the worst in eastern North Carolina history. Just as impressive, however, is the volume of rain that Tropical Storm Dennis (1999) dropped on North Carolina (3.67 cubic miles) just one week before Hurricane Floyd made landfall. Combining the two rainfall events, 7.81 cubic miles of water fell over eastern and central North Carolina in late August and early September of 1999. By comparison, Hurricane Fran (1996) caused 100-year flooding in some areas and the rain volume from Fran was only 3.14 cubic miles and the average of the eleven tropical cyclones is 2.38 cubic miles. The claim can be made that Tropical Storm Dennis brought eastern North Carolina out of a drought and into a vulnerable flood state with any additional rainfall.

E. North Carolina Flood Events

There have been 22 significant flood events in North Carolina caused in part by tropical cyclones since 1925. Table 9 lists the 22 tropical cyclones along with the factors that explain why the flooding occurred. The location in North Carolina of the heaviest rainfall, intensity at landfall, average translation speed, maximum rainfall, previous rainfall, and mid-latitude interactions for each of the 22 tropical cyclones are also listed.

Except for a high translation speed, Hurricane Floyd (1999) had all the ingredients for a major flood event. Hurricane Floyd made landfall in extreme southeastern North Carolina on September 16, 1999 as a large category-2 hurricane. The intensity of the storm was decreasing before it made landfall and weakened to a category-

Table 8. Volume of rainfall on North Carolina river basins (cubic miles).

Tropical Cyclone	Date of Landfall	Tar-Pamlico	Neuse	Cape Fear	Yadkin	Catawba	Roanoke	Chowan	Lumber	White Oak	Pasquotank	Total:
H. Floyd	9/16/1999	0.67	0.64	1.14	0.13	0.012	0.45	0.13	0.68	0.13	0.16	4.14
T.S. Dennis	9/6/1999	0.86	0.78	0.63	0.17	0.03	0.31	0.1	0.12	0.1	0.57	3.67
H. Bonnie	8/26/1998	0.35	0.42	0.36	0	0	0.03	0.03	0.23	0.11	0.09	1.62
T.D. Danny	7/24/1997	0.09	0.1	0.72	0.61	0.27	0.24	0.02	0.08	0.03	0.05	2.04
H. Fran	9/6/1996	0.47	0.7	0.78	0.23	0.04	0.24	0.05	0.38	0.2	0.05	3.14
H. Bertha	7/12/1996	0.26	0.37	0.31	0.03	0.02	0.08	0.06	0.25	0.1	0.21	1.69
H. Hugo	9/22/1989	0.03	0.04	0.23	0.32	0.18	0.02	0.01	0.09	0	0.06	0.98
H. Diana	9/13/1984	0.33	0.6	0.64	0.01	0.28	0.04	0.07	0.46	0.14	0.19	2.76
H. Ginger	9/30/1971	0.44	0.56	0.39	0.25	0.08	0.19	0.16	0.16	0.08	0.39	2.7
T.S. Doria	8/27/1971	0.21	0.29	0.21	0.08	0.02	0.05	0.05	0.05	0.1	0.27	1.33
H. Donna	9/12/1960	0.33	0.43	0.44	0.07	0.03	0.16	0.12	0.2	0.06	0.21	2.05
H. Ione	9/19/1955	0.44	0.56	0.32	0	0	0.08	0.14	0.22	0.21	0.35	2.32
H. Diane	8/17/1955	0.3	0.58	0.52	0.14	0	0.22	0.05	0.16	0.06	0.09	2.12
H. Connie	8/12/1955	0.48	0.56	0.26	0.22	0	0.19	0.15	0.13	0.24	0.33	2.56
H. Hazel	10/15/1954	0.15	0.27	0.8	0.63	0.08	0.25	0.02	0.3	0.02	0.05	2.57

Totals (cubic miles) = (average rainfall in inches) * (1/12 ft. per inch) * (1/5280 ft. per mile) * (river basin area)   average: 2.38

Table 9. North Carolina flood-producing tropical cyclones (1925-2000).

Tropical Cyclone	Location of Max. Rainfall	Ave. speed over NC (kt)	Intensity	Previous Rainfall	Max. Rainfall	Mid-Latitude Interaction
H. Floyd (9/16/99)	eastern, central	22	Cat. 2	9/4/99 T.S. Dennis (>8")	10-24" over eastern NC	Jet/trough, coastal frontogenesis
T.D. Danny (7/24/97)	central	17	T.D.	5"on 7/11	8" @Charlotte 13" max	none
H. Fran (9/6/96)	eastern, central	16	Cat. 3	9/3/96 T-storms > 11"	11" along coast	none
T.D. Danny (8/17/85)	south-central (Charlotte)	11	T.D.	6" from 7/25/85 T.S. Bob	5.4" @Shelby	merged with frontal system
H. Diana (9/16/84)	southeast	3	Cat. 3	drought	19" @Southport	none
T.S. Dennis (8/20/81)	eastern, central	10	T.S.	5" @Wilmington on 17th	7.8" @Bayboro	none
T.S. David (9/5/79)	eastern, north-central	13	T.S.	2.8"@Greenville on 1st	10.7"@Hatteras	tropopause lifting
T.S. Agnes (6/21/72)	southwest-central	16	T.S.	scattered showers=1"	8" @Asheboro	joined low-pressure system
H. Ginger (9/30/71)	eastern, central	4	Cat. 1	9" @Elizabeth City T.S. Doria	10.7" @Belhaven	none
T.D. Abby (6/8/68)	Charlotte	8	T.D.	average rainfall	5.8" @Charlotte	none
T.D.#1 (6/16/65)	eastern, central	25	T.D.	4.7"on 12-13th	6.3" @Ocracoke	none
T.S. Dora (9/13/64)	extreme eastern	40	T.S.	7" @Elizabeth City T.S. Cleo	8.7" @New Bern	none
T.S. Cleo (8/31/64)	central	9	T.S.	2.8" @ Hatteras on 28th	7" @ Elizabeth City	none
T.S. Brenda (7/30/60)	southeast	28	T.S.	1.4" @Goldsboro on 14th	7.5" @Wilson	none
H. Ione (9/19/55)	extreme northeast	9	Cat. 3	up to 30" fell in past month	16" in Maysville	none
H. Connie (8/12/55)	widespread	8	Cat. 3	8.7" @Goldsboro on 2-5th	12" in Morehead City	none
H. Diane (8/17/55)	widespread	11	Cat. 1	13" @New Bern H. Connie	7.4" @ New Bern	none
H. Hazel (10/15/54)	central	40	Cat. 4	below average rainfall	4.93" @ RDU, up to 11.25"	intensifying trough to west
T.S. Able (8/31/52)	central	15	T.S.	2" @Monroe on 27th	6.3" @Fort Bragg	none
H. #9 (9/18/45)	eastern, central	13	T.S.	3-5" Charlotte area on 15th	10.7 @ Asheboro	none
H.#2 (8/18/39)	eastern, central	14	T.D.	1.8" @Winston-Salem on 15th	5" @Winston-Salem	none
H. #4 (9/19/28)	eastern	11	T.S.	above average rainfall	9" @ Lumberton	none

1 hurricane as it tracked to the north-northeast. Figure 13 is an SSM/I color composite of Hurricane Floyd at 23Z on September 15, 1999. The lack of deep convection in the southeast quadrant of the inner core signifies weakening of the hurricane before landfall. The center of circulation was located over North Carolina for about ten hours averaging 22 knots in speed but precipitation fell 24 hours prior to landfall (notice the expansive area of convection over the eastern half of North Carolina in figure 13). Rainfall patterns based on radar loops after landfall show a transition to very heavy precipitation in both the front right and left quadrants with a defined eyewall. An abrupt transition took place a few hours after landfall as the heavy rain shield shifted to the western half of the circulation. Atallah (2000) along with Bosart and Atallah (2000) suggested this was caused by the development of a surface coastal front over the eastern part of North Carolina and the interaction with a jet/trough aloft. Figure 14 shows the Eta 500 mb heights and height changes on September 16 at 12Z. Hurricane Floyd is positioned over eastern North Carolina. Notice the upper-level 500 mb trough located over Ohio. The upper-level trough added to the dynamics of Hurricane Floyd as Floyd by increasing the outflow from the hurricane (Schneider, 1998). Floyd subsequently tracked along the coastal front from North Carolina up into eastern Virginia. Figures 15 and 16 are surface analysis maps (produced by the National Weather Service at the Hydrometeorological Prediction Center) of the eastern United States at 3Z on both September 15th and 16th, respectively. As the hurricane tracked toward the north-northwest, the surface trough (coastal front) moved inland and as the hurricane tracked more toward the north-northeast the surface trough reversed back toward the Atlantic Ocean. From figures 15 and 16, notice also the baroclinicity associated with the arrival of the hurricane. On September

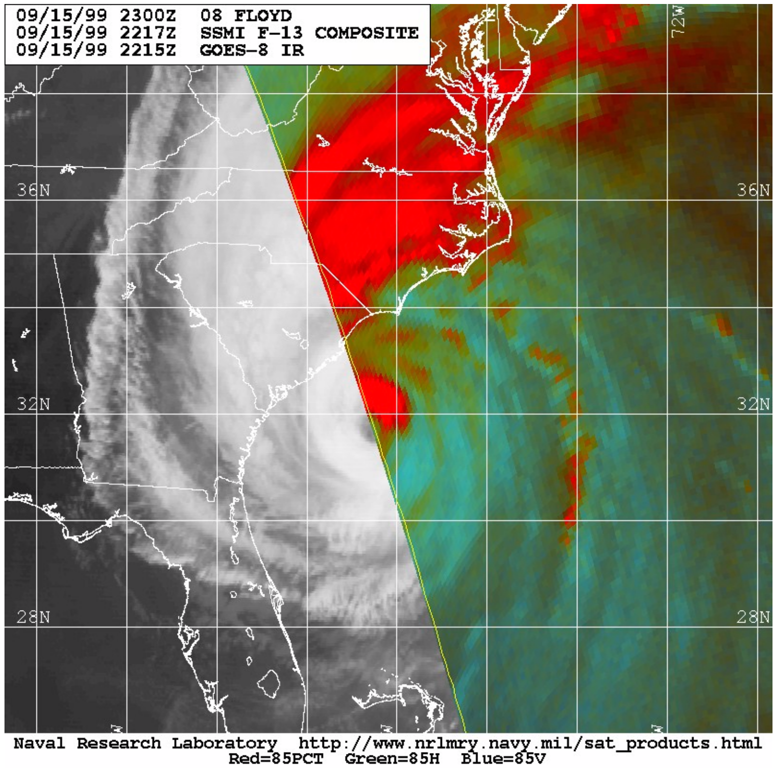


Figure 13. SSM/I color composite (passive microwave imagery) of Hurricane Floyd at 23Z on September 15, 1999. The GOES-8 IR image is underlain. The red areas represent the deepest convection. There is a lack of convection in the southeast quadrant of the eyewall (inner core) that signifies weakening is occurring at the time of the satellite photo. Also notice the extensive convection over eastern North Carolina well in advance of the inner core.

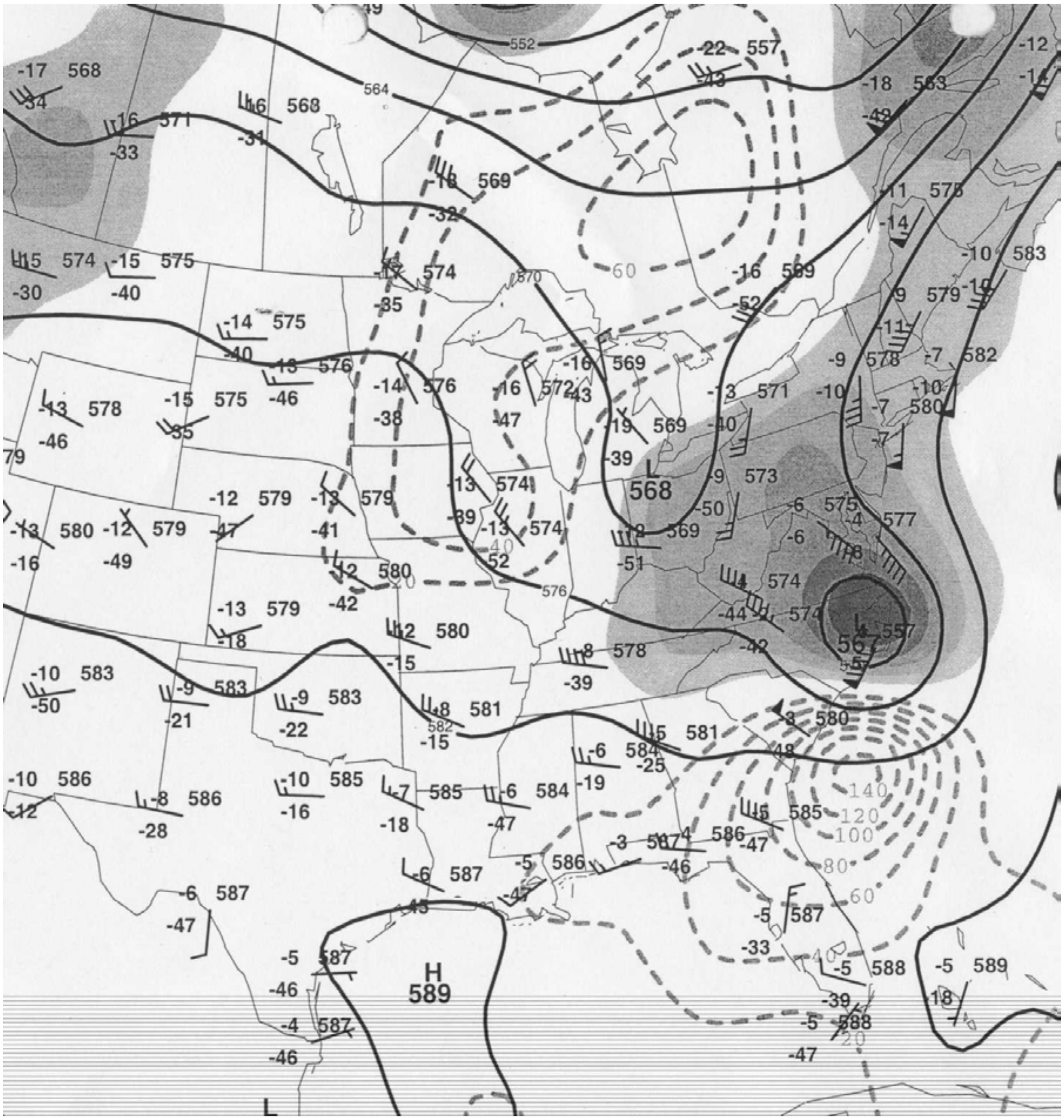


Figure 14. Eta 500 mb heights and height changes on September 16th, 1999 at 12Z. Hurricane Floyd is located over eastern North Carolina (dark spot). Notice the strong upper-level trough propogating over the Great Lakes region. Courtesy of the Hydrometeorological Prediction Center.

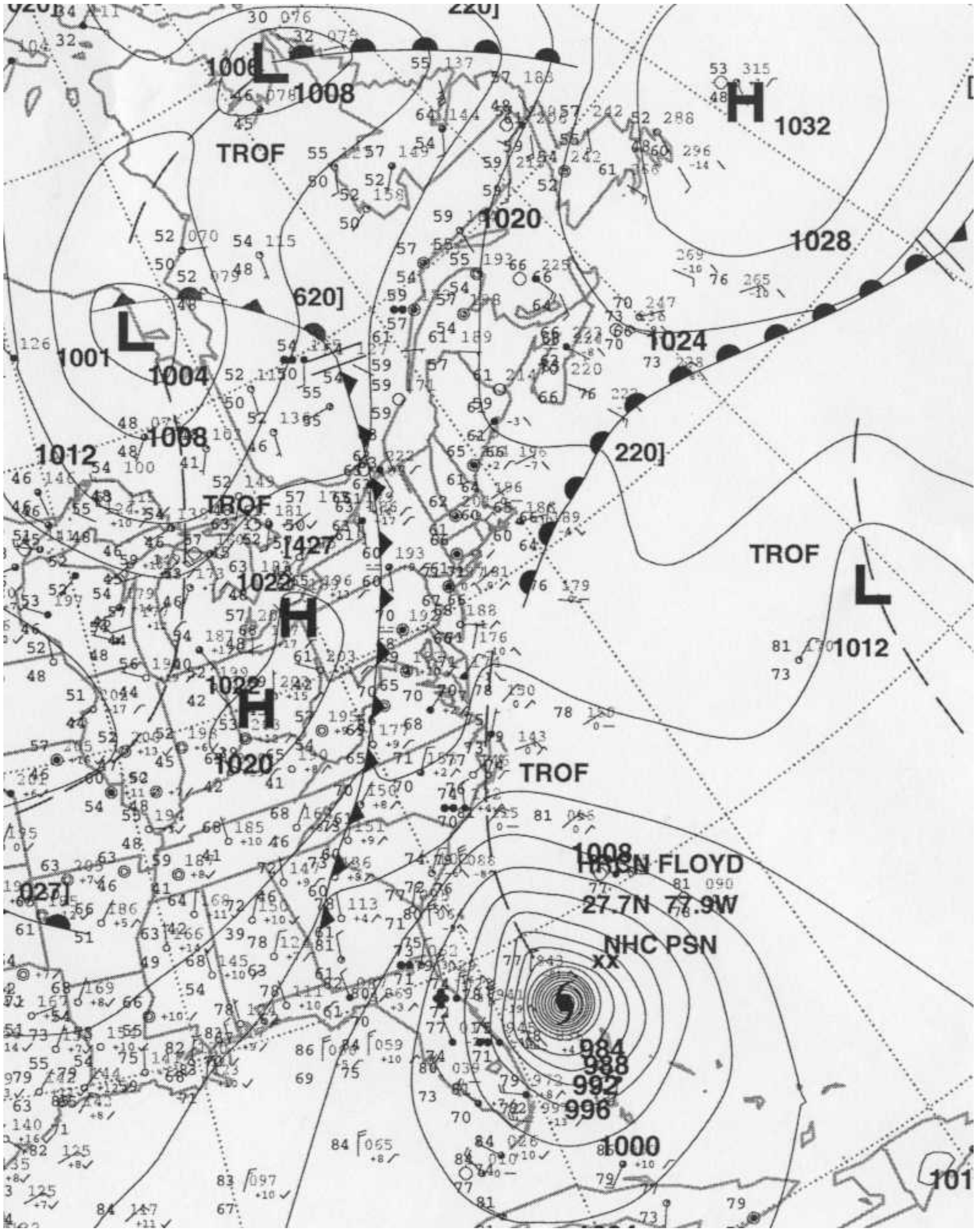


Figure 15. Surface analysis map of the eastern United States at 3Z on September 15th, 1999. Surface trough is oriented along a north-south axis just over extreme eastern North Carolina.

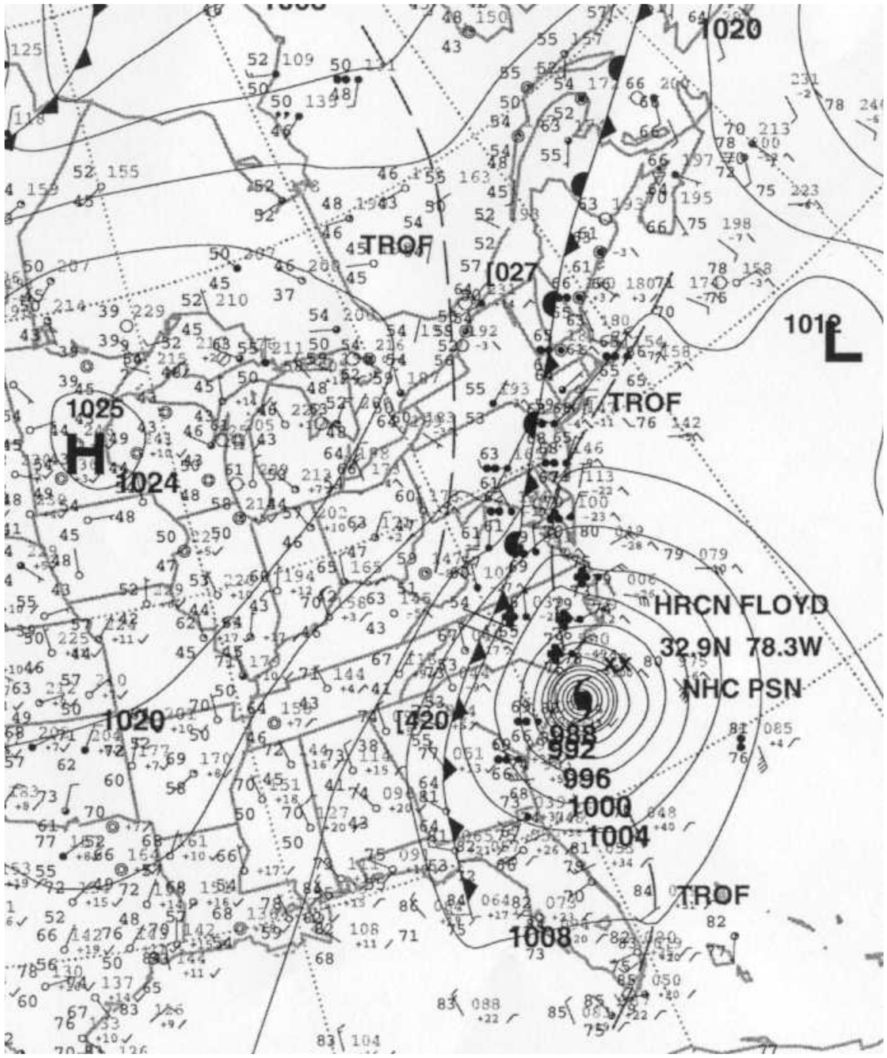


Figure 16. Surface analysis map of the eastern United States at 3Z on September 16th, 1999. Surface trough moved farther to the west over the areas of maximum rainfall (refer to figure 6).

16th, dew points behind the cold front in Alabama and Georgia were in the 40's and 30's °F.

The floods that ensued were historic in nature. Many stream monitoring stations recorded 500-year flows, sometimes over twenty feet above flood stage. Figure 17 identifies the locations and flood levels within the Neuse and Tar-Pamlico watersheds. The worst flood damages were found in towns along the Neuse and Tar Rivers.

Only twelve days before Hurricane Floyd made landfall, the eastern half of North Carolina was hit by Tropical Storm Dennis. Rainfall totals from Dennis were greater than 8" in many locations. The ground became saturated and the rivers were almost at flood level. Rainfall totals from Floyd were astounding with 10-24" recorded over much of the eastern half of North Carolina. The areas hardest hit by Dennis in early September were hit again by Floyd in mid-September. A list of rainfall totals includes: Wilmington at 19.06", Clinton at 11.5", Goldsboro at 12.7", Clayton at 9.8", and Rocky Mount between 14-18" (USGS, 2000). Flooding was not only severe but also widespread and lasted many weeks.

For Hurricane Floyd, the strength, size, previous rainfall from Dennis, and interaction with a coastal front at low levels and a jet/trough at upper levels all added up to record flooding, $6 billion in damage, and 56 lives lost, 50 of which were attributed to inland flooding.

Before Hurricane Floyd, Hurricane Fran (1996) dominated the memories of North Carolinians. After making landfall as a category-3 hurricane, Fran held its structure together until well inland (approximately until Garner where the circulation finally collapsed). In Carteret and Onslow counties, 7.5" of rain fell from these showers.

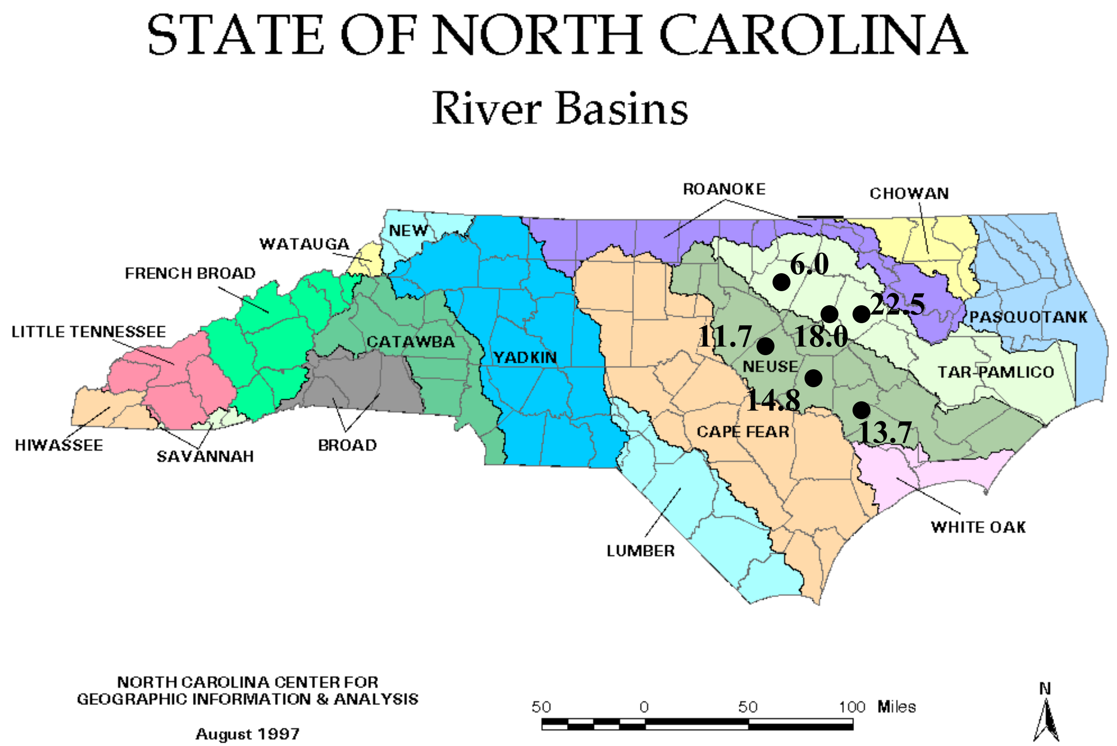


Figure 17. Hurricane Floyd (1999) location and flood levels (expressed in feet above flood stage) along the Neuse and Tar-Pamlico watersheds-areas of worst flood damage.

Hurricane Fran rapidly de-intensified once its center of circulation collapsed. Before this event, intense winds reached deep into the state. As Fran was downgraded to a tropical storm over Wake County, heavy rainfall dropped as the warm-core structure developed extratropical characteristics. Rainfall totals included 8.8" at RDU, 6.72" at Pope AFB, 7.05" in Jacksonville, and up to 12" in Brunswick and Pender counties. Some stream gauges recorded Fran as a 100-year flood event.

Other tropical cyclones of note were the three hurricanes that struck eastern North Carolina in 1955. Hurricanes Connie, Diane, and Ione inundated eastern North Carolina with over 45” of rain over a two-month period. Tropical Storm Agnes (1972) caused significant flooding in North Carolina but nothing compared to the flooding it caused in Pennsylvania and New York.

The most intense hurricane to make landfall in North Carolina was Hurricane Hazel in 1954. A category-4 major hurricane, Hazel destroyed almost everything in its path. Fortunately, the center of circulation was over North Carolina for only 4 hours as it rapidly progressed northward. Four hours was enough to produce 4.93" RDU and up to 11.25" in some areas. Most of the rainfall was to the left of the storm track as Hazel quickly interacted with an intensifying trough to its west shortly after landfall.

IV. Wind Assessment

The amount of wind data available for North Carolina tropical cyclones is much less than for rainfall data. Only twelve weather stations provided enough wind data to be included in this study. Along with the twelve weather stations, other “unofficial” wind reports were added to the database.

Intensity determination was made based on HURDAT and best-track data from the National Hurricane Center. Intensity at landfall was not always determined by fixed wind observations but by estimations based on other means (minimum central pressure, satellite data, aircraft data). From 1925-2000, 36 tropical cyclones made direct landfall in North Carolina, while 82 total tropical cyclones impacted North Carolina. Of the 36 direct landfalling tropical cyclones, 25 (70%) were of hurricane strength. This high percentage can possibly be explained by the proximity of warm Gulf Stream waters just off the coast of North Carolina. Direct landfalling tropical cyclones must track over the warmer waters and often intensify or maintain intensity before making landfall.

From 1925-2000, there have been eleven major hurricanes (category-3 and stronger) that have made landfall in North Carolina, a frequency of one every seven years. Hurricane Hazel (1954) was the only category-4 hurricane and there have been no category-5 hurricanes to make landfall in North Carolina. This may be explained by the inherent low frequency of such intense hurricanes in the Atlantic Basin and the 76-year period chosen for this study. However, the lack of category-4 and category-5 hurricanes may be explained by geographical and meteorological reasons. North Carolina is located in the mid-latitudes (33.8°N-36.6°N) and is subject to stronger shear from westerlies that decrease tropical cyclone intensities.

The most serious threat of wind damage comes from category-3 hurricanes. A total of ten category-3 hurricanes (maximum sustained winds 96-113 knots) have made landfall in North Carolina from 1925-2000. In fact, category-3 hurricanes are the most frequent tropical cyclones to have made landfall in North Carolina. Figure 18 shows the number of storms from each tropical cyclone category. Note that these are only direct

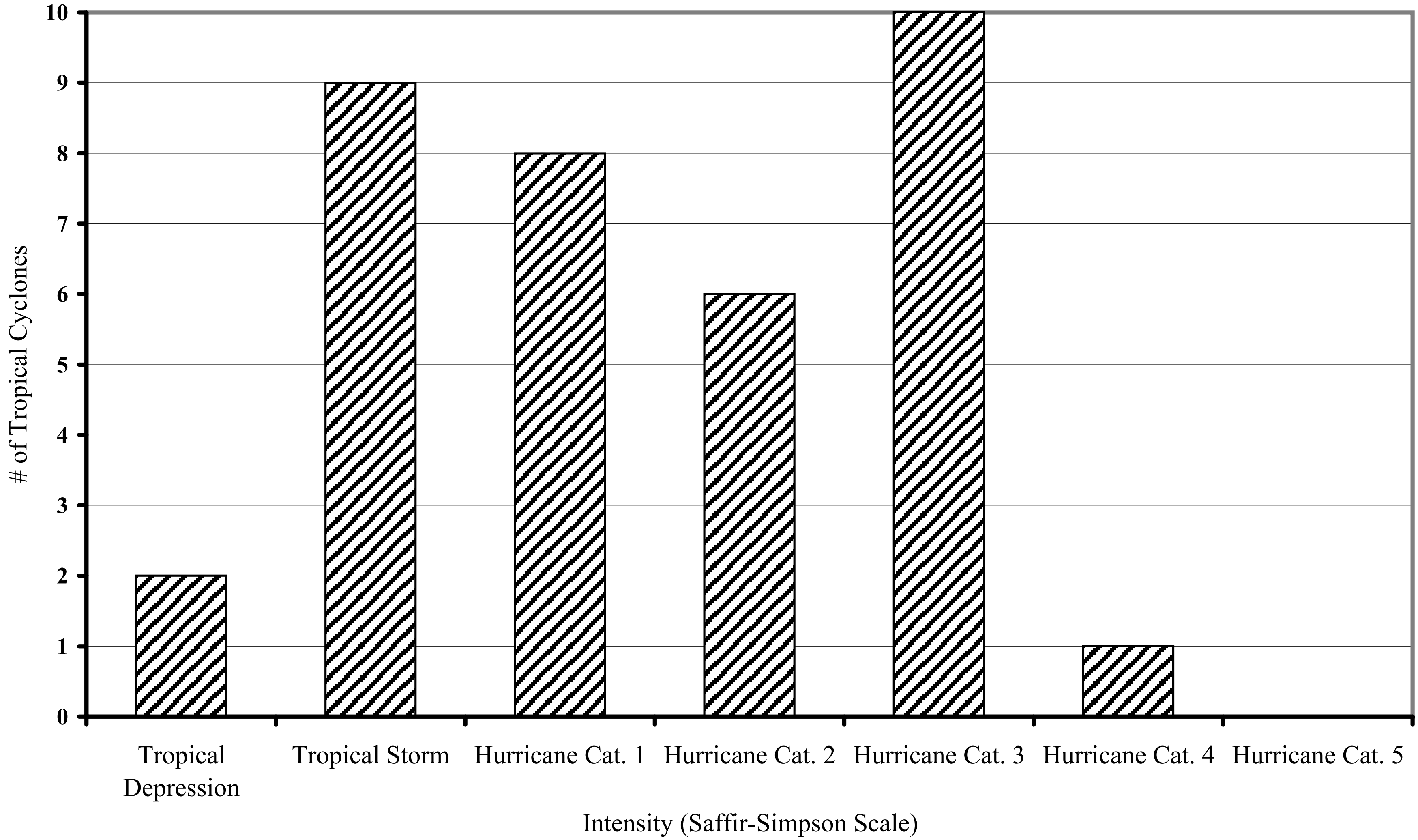


Figure 18. North Carolina tropical cyclone intensity distribution from 1925-2000. Intensity is based on the Saffir-Simpson scale. There were a total of 36 tropical cyclones that made direct landfall in North Carolina from 1925-2000.

landfalling tropical cyclones. Many more tropical cyclones made landfall elsewhere and de-intensified as they tracked into North Carolina.

V. Storm Surge Assessment

Similar to the wind database, the storm surge data collected were minimal in scope. Only 9 tidal gauge stations provided sufficient data (data provided by the National Ocean Service (NOS) Center for Operational Oceanographic Products and Services (CO-OPS)). Table 10 summarizes the significant storm surge events in North Carolina since 1950. Prior to 1950, storm surge data is too incomplete to be included. The major factors that determine storm surge are intensity (strength of winds), storm track in relationship to the coastline during landfall, translation speed at landfall, and other factors including astronomical tides and erosion due to stalled systems.

The highest storm surge values are created when a powerful storm with its strongest winds in the front right quadrant makes landfall perpendicular to the coastline while moving ashore rapidly. Hurricane Hazel (1954) made landfall with category-4 winds, perpendicular to the extreme southern coast of North Carolina while moving at 40 knots. Storm surge levels were estimated at 10-17 feet. The storm surge created by Hazel destroyed entire beach communities.

Vulnerable areas of North Carolina to storm surge are the sounds located between the mainland and the Outer Banks. Hurricanes Fran (1996) and Hurricane Connie (1955) caused widespread damage within the sounds as waters dammed up against the coastline with no place to go. Coastal flooding and beach erosion have caused an estimated 24% of all damage to North Carolina from 1925-2000. Coastal erosion has been a significant problem to the Outer Banks region. Tropical Storm Dennis (1999) and Hurricane Diana

Table 10. Significant North Carolina tropical cyclone storm surge/coastal erosion events (1950-2000).

Tropical Cyclone:	Landfall Date:	Maximum Recorded Storm Surge:	Intensity	Storm Path at Coastline:	Ave. Speed over NC (kt)	Other Factors:
H. Floyd	9/16/1999	10 ft. @ Masonboro/Long B.	Cat. 2	angled	22	extremely large storm
T.S. Dennis	9/4/1999	5-6 ft. @Hatteras/Duck	T.S.	perpendicular	8 (drifted off coast)	storm stalled off coast causing severe erosion
H. Bonnie	8/26/1998	9 ft. @ Manteo	Cat. 2	near perpendicular	6	
H. Fran	9/6/1996	12-16 ft. @ Wrightsville B.	Cat. 3	near perpendicular	16	dune system previously destroyed by Bertha
H. Bertha	7/12/1996	6 ft. @ Elizabeth City	Cat. 2	angled	16	
H. Hugo	9/22/1989	8-10 ft. @ Brunswick County	Cat. 4	perp. to South Carolina	26	
H. Gloria	9/27/1985	6-8ft. @ Cherry Point	Cat. 3	brushed coast	22	
H. Josephine	10/12/1984	na	Cat. 2	offshore	-	hit at astronomical high tide; strong high to north
H. Diana	9/13/1984	7 ft. @ Carolina B.	Cat. 3	perpendicular	3 (drifted off coast)	storm off coast for 3 days
H. Donna	9/12/1960	6-8 ft. reported unknown	Cat. 3	angled	11	
H. Connie	8/12/1955	7-8ft. @ Southport to Nags Head	Cat. 3	brushed coast	8	
H. Hazel	10/15/1954	10-17 ft. reported unknown	Cat. 4	perpendicular	40	

Storm Surge data provided by the USGS and/or historical reports.
Storm path at coastline was determined by angle between path and coastline located along the northeast quadrant of circulation.
Speed at landfall was determined using N-AWIPS based on HURRDAT best track analysis.
Data prior to 1950 was deemed too incomplete to be included.

(1984) lingered off the coast for days causing extreme erosion by the incessant pounding of the surf. During Tropical Storm Dennis (1999), sections of highway were destroyed and swept out to sea near Buxton. Beach replenishment and dune reconstruction have occurred regularly to protect communities from further events. In 1996, Hurricane Bertha wiped out the protective dunes of Topsail Island leaving it vulnerable to the storm surge from Hurricane Fran just two months later.

VI. Tropical Cyclone Database

A. Database Methodology

The complete spreadsheet summarizing 82 North Carolina tropical cyclones is found in appendix D. The date of landfall was precisely taken from best-track data at the time the center of circulation passed into North Carolina. The intensity of each storm was determined also by best-track data provided by the National Hurricane Center. The storm track for each tropical cyclone describes where the system made landfall. All tropical cyclones that made landfall in another state were designated as indirect hits. Those tropical cyclones whose center of circulation remained over water were designated as off coast. For those tropical cyclones that did make direct landfall in North Carolina, the location along the coast where landfall occurred was specified. The methods in determining the average speed over North Carolina was discussed previously in section III.

Previous rainfall data set up conditions prior to the tropical cyclone impacting North Carolina and the vulnerability to flooding. If there was insignificant previous rainfall, the climatological conditions at the time were given (drought, dry, normal). Maximum rainfall, wind speed, and storm surge were all previously discussed. Wind speeds are given as maximum 1-minute sustained winds while those in parentheses are wind gusts. The degree of beach erosion was determined in general terms, from none to severe. Any interaction between mid-latitude synoptic processes and tropical cyclones was briefly described. The most common interactions were between the tropical cyclone and upper-level troughs and surface frontal systems.

Although not discussed previously, confirmed tornado and death statistics were included in the database. Accuracy problems occurred with older storms. Back in the first half of the century, the reduced number of trained observers and lack of radar data caused false observations and missed observations, compromising the accuracy of exact numbers. Finally, the unadjusted and normalized damage values were listed as were discussed in section II.

B. Tropical Cyclone Data Inaccuracies and Difficulties

This section lists and discusses data collection inaccuracies and difficulties found while compiling the North Carolina tropical cyclone database. Determining storm damage totals is a very difficult task. A lack of clear definitions of what is and is not damage directly attributable to the tropical cyclone causes inconsistencies in the damage record. For example, in the National Hurricane Center Preliminary Report on Hurricane Fran (1996), total damage was listed as $3.2 billion. However, a NCDC Special Report on Hurricane Fran stated damages of $5.2 billion. Similar inconsistent reports of total damage can be found for Hurricane Hazel (1954) where total damage ranged from $136 million to $254 million. On top of these inconsistencies is the accepted practice of taking the total insured damage and doubling it to determine storm totals. This procedure is clearly meant for general estimates and cannot be taken as accurate.

Damage estimates are not the only data with consistent inaccuracies. An inherent problem with tropical cyclones is that meteorological data are difficult to collect accurately. Previously mentioned in this study, rainfall data can be highly inaccurate due to wind effects. Radar estimates, wind speeds, confirmed tornadoes, and storm surge data can be inaccurate. The scarcity of wind and storm surge data makes risk assessments challenging.

Another major problem while collecting data was the exact classification of tropical cyclones at landfall. There were many inconsistencies found on landfall intensities from many different sources. Hurricane Diana (1984) has been classified as either a category-1 or category-3 hurricane when it made landfall in North Carolina. Hurricanes Connie (1955), Ione (1955), and Donna (1960) have all been reported with intensities of category-1 to category-3. In this study, NHC best-track reports were used when there were discrepancies.

Risk assessments of tropical cyclones are only as accurate as the data involved in the studies. This particular study focuses on general trends based on 76 years of tropical cyclone activity. Improved techniques must be done to increase the accuracy of tropical cyclone data. Further, specific protocol must be made in the determination of storm damage totals.

VII. Conclusions

The purposes of this study were four-fold. First, the standard normalization procedure for historical damage data was re-evaluated and changes were made. A housing factor was used instead of the population factor. For coastal counties in North Carolina, housing figures from 1940-2000 increased 780% while population figures increased only 370%. Using the housing data, it was believed that a more accurate result was achieved. Using the new normalization method, the mid-1950's storm totals in North Carolina added together would have caused over $18 billion in damage (expressed in 2000 dollars). By comparison, the destructive period from 1996 to 1999 in North Carolina added up to $13 billion. Clearly, the late 1990's were not unprecedented.

The second objective was to separate the storm damage totals into damages caused by wind, flooding, and storm surge. For all 36 direct landfalling tropical cyclones in North Carolina from 1925-2000, 40% of all damage was caused by flooding, while wind and storm surge caused 35% and 25%, respectively. For weaker hurricanes (category-1 and 2), tropical storms, and tropical depressions, 60% of all damage was caused by flooding, 25% by wind, and 15% by storm surge. The trend reversed for major hurricanes (category-3 and 4). Wind caused 40% of all damage while flooding and storm surge both caused 30%. From these results, it is clear that flooding is a major cause of damage in North Carolina and is not strongly correlated with the intensity of the tropical cyclone.

The third objective was to correlate tropical cyclone rainfall to meteorological parameters. The results from this study include:

- There is a weak relationship between intensity of the tropical cyclone and rainfall totals.
- Over 50% of all direct landfalling North Carolina tropical cyclones from 1925-2000 produced maximum rainfall amounts between 6-12".

- There is a relationship between rainfall and translation speed. When not influenced by other factors such as mid-latitude interactions, the relationship between rainfall and translation speed can be expressed by the equation:

  $$Y=29.529X^{-0.6134} \tag{1}$$

  where Y is the average top 5 recorded rainfall totals and X is the translation speed expressed in knots. The R-squared value was 0.4482.
- Rain volume calculations quantified the magnitude of the September 1999 flood event in eastern North Carolina. Hurricane Floyd dropped an estimated 4.14 cubic miles of water on North Carolina only 10 days after Tropical Storm Dennis brought North Carolina out of drought conditions with 3.67 cubic miles of water. The next-highest value from previous tropical cyclones was Hurricane Fran (1996) with 3.14 cubic miles of water.

Last, property risk from tropical cyclone damage was quantified based on the historical record from 1925-2000. Using the total normalized damage numbers, 70 % of all tropical cyclone damage was caused by major hurricanes. Category-2 hurricanes added a significant percentage (21.4%). Category-3 hurricanes, the most frequent intensity tropical cyclone to make direct landfall in North Carolina, has a recurrence interval of 7.7 years.

Risk assessments are important tools for decision-making regarding hazard mitigation and the protection of property and lives. By focusing on smaller regions, more detailed assessments can be made leading to more accurate conclusions. Based on this study, the dangers of flooding from any type of tropical cyclone cannot be over stressed.

Wind and storm surge damage from tropical cyclones often overshadow the damage potential and danger of inland flooding.

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APPENDICES

Appendix A. North Carolina Impacting Tropical Cyclones (1925-2000).

Tropical Cyclone	Date of Landfall	Intensity	Area of Landfall	Unadjusted Damage	Normalized Damage
Hurricane Irene	10/17/1999	Cat. 1	off coast	minor	minor
Hurricane Floyd	9/16/1999	Cat. 2	Topsail Island	$6 billion	$6.36 billion
T.S. Dennis	9/4/1999	T.S.	Core Banks	$60 million	$64.3 million
Hurricane Bonnie	8/26/1998	Cat. 2	Wilmington	$1 billion	$1.125 billion
T.D. Danny	7/24/1997	T.D.	Gulf Coast indirect	$60 million	$72 million
T.S. Arthur	6/19/1996	T.S.	Cape Lookout	no damage	none
Hurricane Bertha	7/12/1996	Cat. 2	Wrightsville Beach	$330 million	$411 million
Hurricane Fran	9/6/1996	Cat. 3	Wilmington	$5.2 billion	$6.36 billion
T.S. Jerry	8/28/1995	T.S.	FL indirect	$9 million	$12 million
Hurricane Felix	8/17/1995	Cat. 1	off coast	$2 million	$3 million
T.S. Opal	10/5/1995	T.S.	Gulf Coast indirect	$70 million	$93 million
T.D. Beryl	8/17/1994	T.D.	Gulf Coast indirect	$1 million	$2 million
Hurricane Gordon	11/18/1994	Cat. 1	off coast	$0.5 million	$1 million
Hurricane Emily	8/31/1993	Cat. 3	Hatteras	$50 million	$78 million
Hurricane Bob	8/19/1991	Cat. 2	off coast	$4 million	$7 mllion
Hurricane Hugo	9/22/1989	Cat. 1	SC indirect	$1.07 billion	$2.12 billion
T.D. Chris	8/29/1988	T.D.	SC indirect	$0.5 million	$1 million
Hurricane Charley	8/17/1986	Cat. 1	Morehead City	$3 million	$7 million
T.S. Bob	7/25/1985	T.S.	SC indirect	$1.5 million	$4 million
T.D. Danny	8/17/1985	T.D.	Gulf Coast indirect	$2.5 million	$6 million
Hurricane Gloria	9/27/1985	Cat. 3	Hatteras	$14 million	$38 million
T.S. Kate	11/23/1985	T.S.	Gulf Coast indirect	minor	minor
Hurricane Diana	9/13/1984	Cat. 3	Long Beach	$79 million	$249 million
Hurricane Josephine	10/12/1984	Cat. 2	off coast	minor	minor
T.S. Dennis	8/20/1981	T.S.	Wilmington	$10 million	$44 million
T.S. David	9/5/1979	T.S.	SC indirect	$15 million	$88 million
T.D. Babe	9/9/1977	T.D.	Gulf Coast indirect	no damage	none
Hurricane Belle	8/9/1976	Cat. 3	off coast	minor	minor
T.S. Dottie	8/21/1976	T.S.	SC indirect	$0.5 million	$4 million
T.S. Eloise	9/24/1975	T.S.	Gulf Coast indirect	minor	minor
T.S. Agnes	6/21/1972	T.S.	Gulf Coast indirect	$10 million	$115 million
T.S. Doria	8/27/1971	T.S.	Atlantic Beach	$1 million	$17 million
Hurricane Ginger	9/30/1971	Cat. 1	Atlantic Beach	$10 million	$168 million

Appendix A. continued.

Tropical Cyclone	Date of Landfall	Intensity	Area of Landfall	Unadjusted Damage	Normalized Damage
T.D. Alma	5/26/1970	T.D.	Gulf Coast indirect	no damage	none
T.S. #4	8/17/1970	T.D.	Outer Banks	$0.5 million	$9 million
T.D. Abby	6/8/1968	T.D.	SC indirect	minor	minor
Hurricane Gladys	10/20/1968	Cat. 1	Outer Banks	minor	none
T.S. Doria	9/17/1967	T.S.	VA border	minor	minor
T.S. Alma	6/11/1966	T.S.	off coast	minor	minor
T.D. #1	6/16/1965	T.D.	Gulf Coast (indirect)	minor	minor
T.S. Cleo	8/31/1964	T.S.	SC indirect	$0.5 million	$21 million
T.S. Dora	9/13/1964	T.S.	SC indirect	$0.1 million	$5 million
Hurricane Gladys	9/21/1964	Cat. 1	off coast	$0.1 million	$5 million
Hurricane Isbell	10/16/1964	Cat. 1	Morehead City	$1 million	$54 million
Hurricane Ginny	10/21/1963	Cat. 1	off coast	$0.1 million	$5 million
Hurricane Alma	8/28/1962	Cat. 1	Hatteras	minor	minor
T.S. #6	9/14/1961	T.S.	Cape Fear	no damage	none
Hurricane Esther	9/20/1961	Cat. 4	off coast	$0.1 million	$4 million
T.S. Brenda	7/30/1960	T.S.	SC indirect	$0.25 million	$10 million
Hurricane Donna	9/12/1960	Cat. 3	Topsail Island	$56.5 million	$2.34 billion
T.D. Cindy	7/10/1959	T.D.	SC indirect	$1.1 million	$46 million
T.S. Gracie	9/30/1959	T.S.	SC indirect	$0.5 million	$21 million
Hurricane Helene	9/27/1958	Cat. 3	Outer Banks	$11 million	$523 million
T.D. Flossy	9/26/1956	T.D.	Gulf Coast indirect	no damage	none
Hurricane Connie	8/12/1955	Cat. 3	Cape Lookout	$40 million	$1.56 billion
Hurricane Diane	8/17/1955	Cat. 1	Carolina Beach	$80 million	$2.54 billion
Hurricane Ione	9/19/1955	Cat. 3	Salter Path	$88 million	$3.44 billion
Hurricane Carol	8/31/1954	Cat. 2	Hatteras	$0.25 million	$11 million
Hurricane Edna	9/11/1954	Cat. 3	off coast	$0.1 million	$4 million
Hurricane Hazel	10/15/1954	Cat. 4	NC/SC border	$254 million	$10.52 billion
Hurricane Barbara	8/14/1953	Cat. 1	Cape Lookout	$1.1 million	$54 million
T.S. Able	8/31/1952	T.S.	SC indirect	minor	minor
Hurricane #1	8/24/1949	Cat. 1	off coast	$0.2 million	$12 million
Hurricane #2 (T.S.)	8/29/1949	T.S.	SC indirect	minor	minor
T.S. #6 (T.D.)	9/24/1947	T.D.	Gulf Coast indirect	minor	minor
Hurricane #2 (T.S.)	7/6/1946	T.S.	Wilmington	minor	minor
Hurricane #5 (T.D.)	10/9/1946	T.D.	Gulf Coast indirect	no damage	none

Appendix A. continued.

Tropical Cyclone	Date of Landfall	Intensity	Area of Landfall	Unadjusted Damage	Normalized Damage
Hurricane #1 (T.S.)	6/26/1945	T.S.	Hatteras	minor	minor
Hurricane #9 (T.S.)	9/18/1945	T.S.	SC indirect	$2 million	$209 million
Hurricane #3	8/1/1944	Cat. 1	Southport	$2 million	$234 million
Hurricane #7	9/14/1944	Cat. 3	Outer Banks	$1.5 million	$168 million
Hurricane #11 (T.S.)	10/20/1944	T.S.	Gulf Coast indirect	minor	minor
T.S. #8 (T.D.)	10/12/1942	T.D.	Ocracoke	minor	minor
Hurricane #2 (T.D.)	8/18/1939	T.D.	Gulf Coast indirect	$1 million	$156 million
Hurricane #13	9/18/1936	Cat. 2	Hatteras	$0.1 million	$15 million
Hurricane #2 (T.S.)	9/5/1935	T.S.	Gulf Coast indirect	minor	minor
Hurricane #8	8/23/1933	Cat. 2	Hatteras	$0.25 million	$40 million
Hurricane #13	9/16/1933	Cat. 3	Ocracoke	$4.5 million	$731 million
Hurricane #1 (T.D.)	8/11/1928	T.D.	SC indirect	$0.05 million	$6 million
Hurricane #4 (T.S.)	9/19/1928	T.S.	SC indirect	$2 million	$252 million
T.S. #5	10/3/1927	T.S.	SC indirect	no damage	none
Hurricane #2 (T.S.)	12/2/1925	T.S.	Cape Lookout	no damage	none

Sources: "Atlantic Hurricanes" by GE Dunn and BI Miller, LSU Press, 1964, 377 pp.
ftp.nhc.noaa.gov/pub/tracks/tracks1851to2000.atl

Statistics of North Carolina Tropical Cyclone History (1925-1999)

Total # Tropical Cyclones:	82
Total # Direct TC:	36
# Direct TD:	2
# Direct TS:	9
# Direct Hurricanes	25
# Direct Major Hurricanes:	11
% Major Hurricane Damage:	70%
Total Damage from direct TCs (normalized):	$40.444B*

*using housing normalization factor

44% of all direct hurricanes are major hurricanes

31% of all direct tropical cyclones are major hurricanes

Appendix B: List of 36 direct landfalling North Carolina tropical cyclones.

Tropical Cyclone	Date of Landfall	Max. Recorded Rainfall (inches)
Hurricane Floyd	9/16/1999	24.06
T.S. Dennis	9/4/1999	19.05
Hurricane Bonnie	8/26/1998	11
T.S. Arthur*	6/19/1996	1.35
Hurricane Bertha	7/12/1996	11.43
Hurricane Fran	9/6/1996	12.65
Hurricane Emily	8/31/1993	7.51
Hurricane Charley	8/17/1986	10.39
Hurricane Gloria	9/27/1985	7.04
Hurricane Diana	9/13/1984	18.98
T.S. Dennis	8/20/1981	7.78
Hurricane Ginger	9/30/1971	10.69
T.S. Doria	8/27/1971	9.43
T.S. #4	8/17/1970	5.5
Hurricane Gladys	10/20/1968	7.03
T.S. Doria	9/17/1967	5.1
Hurricane Isbell	10/16/1964	4.69
Hurricane Alma	8/28/1962	10.38
T.S. #6*	9/14/1961	2.49
Hurricane Donna	9/12/1960	6.9
Hurricane Helene	9/27/1958	8.29
Hurricane Connie	8/12/1955	12.97
Hurricane Diane	8/17/1955	7.4
Hurricane Ione	9/19/1955	16.63
Hurricane Carol	8/31/1954	6.67
Hurricane Hazel	10/15/1954	11.25
Hurricane Barbara	8/14/1953	7.16
Hurricane #2 (T.S.)	7/6/1946	7.84
Hurricane #1 (T.S.)	6/26/1945	8.24
Hurricane #3	8/1/1944	4.43
Hurricane #7*	9/14/1944	3.85
T.S. #8 (T.D.)	10/12/1942	7.99
Hurricane #13	9/18/1936	4.61
Hurricane #8*	8/23/1933	2.15
Hurricane #13	9/16/1933	13
Hurricane #2 (T.S.)*	12/2/1925	1.89

* Tropical cyclones not included in rainfall study.

Appendix C: List of 19 tropical cyclones used in the rainfall vs. translation speed analysis.

Tropical Cyclone	Date of Landfall	Average Translation Speed (knots)	Ave. of Top 5 Rainfall Amounts (inches)
Hurricane Floyd*	9/16/1999	22	16.79
T.S. Dennis	9/4/1999	8	13.73
Hurricane Bonnie	8/26/1998	6	9.94
Hurricane Bertha	7/12/1996	16	9.94
Hurricane Fran	9/6/1996	16	7.18
Hurricane Charley	8/17/1986	11	7.94
Hurricane Diana	9/13/1984	3	12.91
T.S. Dennis	8/20/1981	10	6.44
Hurricane Ginger	9/30/1971	4	9.49
T.S. Doria	8/27/1971	18	5.95
T.S. #4	8/17/1970	16	3.92
Hurricane Isbell	10/16/1964	13	4.46
T.S. #6	9/14/1961	19	2.06
Hurricane Donna	9/12/1960	11	6.36
Hurricane Ione	9/19/1955	9	9.96
Hurricane Diane	8/17/1955	11	6.11
Hurricane Connie	8/12/1955	8	9.88
Hurricane Hazel*	10/15/1954	40	8.17
Hurricane Barbara	8/14/1953	11	6.92

* Outlier points removed from statistical analysis.

Appendix D. Complete North Carolina Tropical Cyclone Summary.

Landfall in NC	T.C. Name	Intensity @ Landfall	Storm Track	Area of Landfall	Ave. Speed over NC (kt)	Previous Rainfall
10/17/1999	Irene	Category 1	off coast	---	---	H. Floyd/Dennis; 4.3" on 11th @Albemarle
9/16/1999	Floyd	Category 2	direct hit	Topsail Island	22	9/4/99 T.S. Dennis (>8")
9/4/1999	Dennis	tropical storm	direct hit	Core Banks	8 (drifted off coast)	drought
8/26/1998	Bonnie	Category 2	direct hit	Wilmington	6	below normal; 2.62" on 30th @ Manteo
7/24/1997	Danny	tropical depression	indirect (Gulf Coast)	---	17	4.72" on 11th @ Bayboro
9/6/1996	Fran	Category 3	direct hit	Wilmington	16	9/3/96 T-storms>11"; 5.52" @ Greensboro
7/12/1996	Bertha	Category 2	direct hit	Wrightsville Beach	16	2"on 10th @Cherry Pt.
6/19/1996	Arthur	tropical storm	direct hit	Cape Lookout	10 (brushed coast)	3" @ Lumberton on 10-11th
10/5/1995	Opal	tropical storm	indirect (Gulf Coast)	---	---	1.18" @ Asheboro on 1-2nd
8/28/1995	Jerry	tropical depression	indirect (Florida)	---	--- (remnants stalled over NC)	H. Felix on 8/17
8/17/1995	Felix	Category 1	off coast	---	---	2.67" @ Hatteras on 10th
11/18/1994	Gordon	Category 1	off coast	---	---	dry
8/17/1994	Beryl	tropical depression	indirect (Gulf Coast)	---	17	dry
8/31/1993	Emily	Category 3	direct hit	Hatteras	11 (brushed coast)	dry
8/19/1991	Bob	Category 2	off coast	---	---	1.62" @ Hatteras on 7th
9/22/1989	Hugo	Category 1	indirect (South Carolina)	---	26	8.25" on 16th @ Fayetteville
8/29/1988	Chris	tropical depression	indirect (South Carolina)	---	17	dry
8/17/1986	Charley	Category 1	direct hit	Morehead City	11 (drifted off coast)	9.08" on 12th@ Greenville; 5.5"@ Raleigh
11/23/1985	Kate	tropical depression	indirect (Gulf Coast)	---	27	5.21" @ Southport on 4-5th
9/27/1985	Gloria	Category 3	direct hit	Hatteras	22	1.43" @ Cherry Point on 22nd
8/17/1985	Danny	tropical depression	indirect (Gulf Coast)	---	11	7/25/85 T.S. Bob
7/25/1985	Bob	tropical storm	indirect (South Carolina)	---	9	2"on 23rd @ Belhaven
10/12/1984	Josephine	Category 2	off coast	---	---	dry
9/13/1984	Diana	Category 3	direct hit	Long Beach	3 (drifted off coast)	drought
8/20/1981	Dennis	tropical storm	direct hit	Wilmington	10	5.1" on 16-17th @ Wilmington
9/5/1979	David	tropical storm	indirect (South Carolina)	---	13	2.8" on 1st @ Greenville
9/9/1977	Babe	tropical depression	indirect (Gulf Coast)	---	---	normal

Landfall in NC	T.C. Name	Intensity @ Landfall	Storm Track	Area of Landfall	Ave. Speed over NC (kt)	Previous Rainfall
8/21/1976	Dottie	tropical storm	indirect (South Carolina)	---	---	2.41" @ Wilmington on 16th
8/9/1976	Belle	Category 3	off coast	---	---	5.3" on 3rd
9/24/1975	Eloise	tropical storm	indirect (Gulf Coast)	---	10	dry
6/21/1972	Agnes	tropical storm	indirect (Gulf Coast)	---	16	scattered showers=1"
9/30/1971	Ginger	Category 1	direct hit	Atlantic Beach	4	8/27/71 T.S. Doria
8/27/1971	Doria	tropical storm	direct hit	Atlantic Beach	18	dry
8/17/1970	T.S. #4	tropical depression	direct hit	Outer Banks	16	normal
5/26/1970	Alma	tropical depression	indirect (Gulf Coast)	---	14	normal
10/20/1968	Gladys	Category 1	direct hit	Outer Banks	21 (brushed coast)	severe drought
6/8/1968	Abby	tropical depression	indirect (South Carolina)	---	8	normal
9/17/1967	Doria	tropical storm	direct hit	NC/VA border	10	dry
6/11/1966	Alma	tropical storm	off coast	---	---	normal
6/16/1965	T.D. #1	tropical depression	indirect (Gulf Coast)	---	25	4.7" on 12-13 @
10/16/1964	Isbell	Category 1	direct hit	Morehead City	13	6.36"on 6th @ Greenville
9/21/1964	Gladys	Category 1	off coast	---	---	drought
9/13/1964	Dora	tropical storm	indirect (South Carolina)	---	40	8/31/64 T.S. Cleo
8/31/1964	Cleo	tropical storm	indirect (South Carolina)	---	9	2.81" on 28th @ Hatteras
10/21/1963	Ginny	Category 1	off coast	---	---	dry
8/28/1962	Alma	Category 1	direct hit	Hatteras	---	dry
9/20/1961	Esther	Category 4	off coast	---	---	1.57" @ Hatteras on 14-15th
9/14/1961	T.S. #6	tropical storm	direct hit	Cape Fear	19	dry
9/12/1960	Donna	Category 3	direct hit	Topsail Island	11	dry
7/30/1960	Brenda	tropical storm	indirect (South Carolina)	---	28	1.44" @ Goldsboro on 14th
9/30/1959	Gracie	tropical storm	indirect (South Carolina)	---	13	dry
7/10/1959	Cindy	tropical depression	indirect (South Carolina)	---	10	3.91" on 6-7th @ Laurinburg
9/27/1958	Helene	Category 3	direct hit	Outer Banks	16 (brushed coast)	1.55" @Wilmington on 22nd

Appendix D. continued.

Landfall in NC	T.C. Name	Intensity @ Landfall	Storm Track	Area of Landfall	Ave. Speed over NC (kt)	Previous Rainfall
9/26/1956	Flossy	tropical depression	indirect (Gulf Coast)	---	5	dry
9/19/1955	Ione	Category 2	direct hit	Salter Path	9	up to 30" fell in previous month
8/17/1955	Diane	Category 1	direct hit	Carolina Beach	11	H. Connie 5 days earlier
8/12/1955	Connie	Category 3	direct hit	Cape Lookout	8	8.72" on 2-5th @ Goldsboro
10/15/1954	Hazel	Category 4	direct hit	NC/SC border	40	dry
9/11/1954	Edna	Category 3	off coast	---	---	H. Carol; 6.56" @ Hatteras on 8/31
8/31/1954	Carol	Category 2	direct hit	Hatteras	24	2.54" on 28th @ Fayetteville
8/14/1953	Barbara	Category 1	direct hit	Cape Lookout	11	3.68" on 7-8th @ Southport
8/31/1952	Able	tropical storm	indirect (South Carolina)	---	15	2.06" on 29th @ Monroe
8/29/1949	H. #2	tropical storm	indirect (South Carolina)	---	20	2.55" on 20th @ Nashville
8/24/1949	H. #1	Category 1	off coast	---	---	5.95" on 21st @ Greensboro
9/24/1947	T.S. #6	tropical depression	indirect (Gulf Coast)	---	17	3.91" @ Greensboro on 21st
10/9/1946	H. #5	tropical depression	indirect (Gulf Coast)	---	13	dry
7/6/1946	H. #2	tropical storm	direct hit	Wilmington	10	4" on 3rd @ Elizabeth City;Raleigh
9/18/1945	H. #9	tropical storm	indirect (South Carolina)	---	13	3.5" on 13-15th @ Charlotte
6/26/1945	H. #1	tropical storm	direct hit	Hatteras	15	1.53" @ wilmington on 19-20th
10/20/1944	H. #11	tropical storm	indirect (Gulf Coast)	---	22	2.14" @ Wilmington on 12th
9/14/1944	H. #7	Category 3	direct hit	Outer Banks	28 (brushed coast)	normal
8/1/1944	H. #3	Category 1	direct hit	Southport	15	normal
10/12/1942	T.S. #8	tropical depression	direct hit	Ocracoke	9	0.91" @ Goldsboro on 6th
8/18/1939	H. #2	tropical depression	indirect (Gulf Coast)	---	14	1.83" @ Winston-Salem on 15th
9/18/1936	H. #13	Category 2	direct hit	Hatteras	10 (brushed coast)	dry
9/5/1935	H. #2	tropical storm	indirect (Gulf Coast)	---	17	1.58" on 3rd, 3.68" on 12th @Lumberton
9/16/1933	H. #13	Category 3	direct hit	Ocracoke	11	2.02" @ New Bern on 5-6th
8/23/1933	H. #8	Category 2	direct hit	Hatteras	12	0.96" @ Belhaven on 20th
9/19/1928	H. #4	tropical storm	indirect (South Carolina)	---	11	8/11/28 T.D., significant rain on 9/1-9/5
8/11/1928	H. #1	tropical depression	indirect (South Carolina)	---	14	0.91" @ Shelby on 5th
10/3/1927	T.S. #5	tropical storm	indirect (South Carolina)	---	22	dry
12/2/1925	H. #2	tropical storm	direct hit	Cape Lookout	12	dry

Appendix D. continued.

Landfall in NC	T.C. Name	Maximum Rainfall	Wind Speed (kt)	Storm Surge (ft)	Degree of Beach Erosion
10/17/1999	Irene	11" @ Ernul; 6.24 @ Elizabeth City	40 (49 gust) @ Duck	2-3@ Albemarle Sound	minor
9/16/1999	Floyd	24" in Southport; 19.06" @ Wilmington	(120 gust) @ Wrightsville B.	10 @Masonboro; Long Beach	severe
9/4/1999	Dennis	14.2" @ Hatteras; 19.05" @ Ocracoke	50 (85 gust) @ Hatteras	6-8 @ Wichard Beach	severe
8/26/1998	Bonnie	11" in Jacksonville (7-10" widespread)	(85 gust) @ Topsail B.	9 @Masonboro; Manteo	significant
7/24/1997	Danny	13.11" max.; 8.22"@ Charlotte	42(55 gust) @ Elizabeth City	---	---
9/6/1996	Fran	12.65" @ Soutport; 8.59" @ Raleigh	(95 gust) @ Long B.	12-16@Wrightsville Beach	severe
7/12/1996	Bertha	11.43" @ Soutport; 5.68" @ Bayboro	70 (94 gust) @ New River	6 @Elizabeth City	significant
6/19/1996	Arthur	1.35" @ Monroe	(23 gust) @ Cherry Point	5-7 @ Cape Lookout	none
10/5/1995	Opal	5.98 @ Sanford	(50 gust) @ Asheville	---	---
8/28/1995	Jerry	7.39 @ Hatteras; locally=15" in central NC	(29 gust) @ Wilmington	---	---
8/17/1995	Felix	1.5" @ Bayboro	(26 gust) @ Wilmington	3.56 @ Duck	significant
11/18/1994	Gordon	3.2" @ Manteo	44 (50 gust) @ Buxton	3.8 @ Duck	significant
8/17/1994	Beryl	3.97" @ Charlotte	17 (31 gust) @ Wilmington	---	---
8/31/1993	Emily	7.51" @ Hatteras; little inland	65 (90 gust) @ Buxton	10.5 @ Buxton to Avon	na
8/19/1991	Bob	5.3" on Hatteras Is.	40 (64 gust) @ Hatteras	na	na
9/22/1989	Hugo	9.1" @ Boone; 3.3" @ Charlotte	60 (76 gust) @ Charlotte	8-10 Brunswick County	severe
8/29/1988	Chris	5.31" @ Fayetteville	20 (35 gust) @ Charlotte	---	---
8/17/1986	Charley	10.39" @ New Bern	41 (56 gust) @ Hatteras	3.65@ Duck	na
11/23/1985	Kate	4.53" @ Sanford; 3.48" @ Southport	32 (42 gust) @ Hatteras	---	---
9/27/1985	Gloria	7" in New Bern; 7.04" @ Cherry Point	64 (76 gust) @ Hatteras	6-8 @Cherry Point	severe
8/17/1985	Danny	5.43" @ Shelby	(30 gust) @ Raleigh	---	---
7/25/1985	Bob	6.5" @Red Springs; 4.24 @ Carthage	(72 gust) @ Holden B.	na	na
10/12/1984	Josephine	0.77" @ Manteo	24 (35 gust) @ Hatteras	na	severe (due to astro tides)
9/13/1984	Diana	14.53"@Wilmington, 18.98" @ Southport	(100 gust) @ Oak Island	7 @Carolina Beach	severe
8/20/1981	Dennis	7.78" @ Bayboro	(39 gust) @ Cedar Island	4.4 @Duck	na
9/5/1979	David	10.73" on Hatteras; 9.84" @ Wilmington	(52 gust) @ Wrightsville B.	5@ Pender City	significant
9/9/1977	Babe	up to 9" in western NC	(34 gust) @ Hatteras	---	---

Appendix D. continued.

Landfall in NC	T.C. Name	Maximum Rainfall	Wind Speed (kt)	Storm Surge (ft)	Degree of Beach Erosion
8/21/1976	Dottie	7.78" @ Carolina Beach; 4.68 @ Wilm.	(30 gust) @ Greensboro	3.5 @Atlantic Beach	moderate
8/9/1976	Belle	5.3" @ Ocracoke	32 (55 gust) @ Hatteras	3	moderate
9/24/1975	Eloise	8.49" @ New Bern	(38 gust) @ New River	---	---
6/21/1972	Agnes	8.33" @ Asheboro	32 (54 gust) @ Hatteras	---	---
9/30/1971	Ginger	10.69" @ Belhaven; 9.68"@Hatteras	(83 gust) @ Cherry Point	4 -7 @Pamlico Sound	minor
8/27/1971	Doria	9.43" @ Elizabeth City;4.17" in Hatteras	(60 gust) @ Atlantic B.	na	na
8/17/1970	T.S. #4	5.5" @ Cherry Point	(35 gust) @ Cherry Point	---	---
5/26/1970	Alma	2.71" @ Albemarle	(25 gust) @ Cherry Point	---	---
10/20/1968	Gladys	7.03" @ Elizabeth City	(85 gust) @ Ocracoke	2-5	minor
6/8/1968	Abby	5.82" @ Charlotte	(40 gust) @ Charlotte	---	---
9/17/1967	Doria	5.1" @ Sanford	(30 gust) @ Fayetteville	2 (in sounds)	minor
6/11/1966	Alma	7.8" @ Wilmington	(56 gust) @ Hatteras	na	na
6/16/1965	T.D. #1	6.36" @ Ocracoke	(35 gust) @ New River	---	---
10/16/1964	Isbell	4.69" @ Shelby	(65 gust) @ Elizabeth City	2	na
9/21/1964	Gladys	0.18" @Elizabeth City	(41 gust) @ Hatteras	na	na
9/13/1964	Dora	8.74" @ New Bern	(37 gust) @ Goldsboro	2.5-3	na
8/31/1964	Cleo	6.95" @ Elizabeth City	(48 gust) @ Hatteras	na	na
10/21/1963	Ginny	4.54" @ Hatteras	(40 gust) @ New River	na	na
8/28/1962	Alma	10.38" @ Hatteras	(42 gust) @ Hatteras	na	na
9/20/1961	Esther	1.55" @ Hatteras	(37 gust) @ Hatteras	---	---
9/14/1961	T.S. #6	2.49" @ New Bern	(38 gust) @ Hatteras	---	---
9/12/1960	Donna	6.9" @ New Bern	(82 gust) @ Hatteras	3.8 @ Ocracoke; 6-8 locally	severe
7/30/1960	Brenda	7.5" @ Wilson	(54 gust) @ N. Topsail B.	na	na
9/30/1959	Gracie	4.89" @ Charlotte	50 (58 gust) @ Wilmington	2-5 southern coast	na
7/10/1959	Cindy	6.68" @ Albemarle	39 (45 gust) @ Wilmington	2-3 Cape Fear	---
9/27/1958	Helene	8.29" @ Wilmington	109 (130 gust) @ Cape Fear	7.5 @ Hatteras and Pamlico S.	moderate

Landfall in NC	T.C. Name	Maximum Rainfall	Wind Speed (kt)	Storm Surge (ft)	Degree of Beach Erosion
9/26/1956	Flossy	7.1" @ Wnston-Salem	(47 gust) @ Hatteras	na	na
9/19/1955	Ione	16.63" in Maysville; 13.02" @ New Bern	65 (93 gust) @ Cherry Point	3-10 @ New Bern	significant
8/17/1955	Diane	7.4" @ New Bern	58 (64 gust) @ Wilmington	5-9 @Wilmington	significant
8/12/1955	Connie	12" in Morehead City; 12.97" @ New Bern	(79 gust) @ Cherry Point	7-8 @Southport-Nags Head	significant
10/15/1954	Hazel	up to 11.25"; 9.7"@Carthage	78 (85 gust) @ Wilmington	10-17(9@Morehead City)	severe
9/11/1954	Edna	6" @ Manteo	(65 gust) @ Outer Banks	na	na
8/31/1954	Carol	6.67" @ Hatteras	(59 gust) @ Cherry Point	na	
8/14/1953	Barbara	7.16" @ Elizabeth City	(90 gust) @ Cherry Point	na	
8/31/1952	Able	6.33" @ Fort Bragg	(46 gust) @ Fayetteville	---	---
8/29/1949	H. #2	4.88" @ Lumberton	(42 gust) @ Fayetteville	---	---
8/24/1949	H. #1	3.79" @ Hatteras	(63 gust) @ Hatteras	na	na
9/24/1947	T.S. #6	7.54" @ Greensboro	na	---	---
10/9/1946	H. #5	4.53" @ Charlotte	na	---	---
7/6/1946	H. #2	7.84" @ Manteo	(57 gust) @ Elizabeth City	na	na
9/18/1945	H. #9	10.71" @ Asheboro; 8.39" @ Monroe	na	---	---
6/26/1945	H. #1	8.24" @ Wilmington	(61 gust) @ Oak Island	na	na
10/20/1944	H. #11	4.73" @ Wilmington	na	---	---
9/14/1944	H. #7	3.85" @ Elizabeth City	(78 gust) @ Hatteras	7 @Hatteras	na
8/1/1944	H. #3	4.43" @ Goldsboro	(65 gust) @ Oak Island	na	severe
10/12/1942	T.S. #8	7.99" @ Goldsboro	na	na	na
8/18/1939	H. #2	4.97" @ Winston-Salem	na	---	---
9/18/1936	H. #13	4.61" @ Elizabeth City	(78 gust) @ Manteo	6.3 @ Ocracoke	na
9/5/1935	H. #2	6.5" @ Weldon	na	---	---
9/16/1933	H. #13	13" in Outer Banks region	(109 gust) @ New Bern	7.0 @ Ocracoke	na
8/23/1933	H. #8	2.15" @ Belhaven	na	na	na
9/19/1928	H. #4	9.03" @ Lumberton	na	---	---
8/11/1928	H. #1	6.21" @ Shelby	na	---	---
10/3/1927	T.S. #5	3.55" @ Winston-Salem	na	---	---
12/2/1925	H. #2	1.89" @ Weldon	(54 gust) @ Hatteras	na	na

Appendix D. continued.

Landfall in NC	T.C. Name	Mid-latitude Interaction	Confirmed Tornadoes	Deaths	Unadjusted Damage ($)	Normalized Damage (2000$)
10/17/1999	Irene	No	2	0	minor	minor
9/16/1999	Floyd	jet/trough, coastal frontogenesis	17	35	$6 billion	$6.36 billion
9/4/1999	Dennis	No	0	0	$60 million	$64.3 million
8/26/1998	Bonnie	No	8	1	$1 billion	$1.125 billion
7/24/1997	Danny	No	0	3	$60 million	$72 million
9/6/1996	Fran	No	7	9	$5.2 billion	$6.36 billion
7/12/1996	Bertha	No	4	1	$330 million	$411 million
6/19/1996	Arthur	No	0	0	no damage	none
10/5/1995	Opal	upper trough over Miss. Valley	1	1	$70 million	$93 million
8/28/1995	Jerry	No	0	3	$9 million	$12 million
8/17/1995	Felix	No	0	3	$2 million	$3 million
11/18/1994	Gordon	No	0	0	$0.5 million	$1 million
8/17/1994	Beryl	No	5	0	$1 million	$2 million
8/31/1993	Emily	No	0	2	$50 million	$78 million
8/19/1991	Bob	No	4	1	$4 million	$7 mllion
9/22/1989	Hugo	No	1	1	$1.07 billion	$2.12 billion
8/29/1988	Chris	lifting trough over western Virginia	0	0	$0.5 million	$1 million
8/17/1986	Charley	No	2	0	$3 million	$7 million
11/23/1985	Kate	No	0	0	minor	minor
9/27/1985	Gloria	No	0	1	$14 million	$38 million
8/17/1985	Danny	merged with frontal system	3	0	$2.5 million	$6 million
7/25/1985	Bob	No	0	0	$1.5 million	$4 million
10/12/1984	Josephine	large high-pressure to north caused winds	0	0	minor	minor
9/13/1984	Diana	No	1	0	$79 million	$249 million
8/20/1981	Dennis	No	0	0	$10 million	$44 million
9/5/1979	David	tropopause lifting from disturbance	0	1	$15 million	$88 million
9/9/1977	Babe	stationary front (W-E) over S. Appalachians	0	0	no damage	none

Appendix D. continued.

Landfall in NC	T.C. Name	Mid-latitude Interaction	Confirmed Tornadoes	Deaths	Unadjusted Damage ($)	Normalized Damage (2000$)
8/21/1976	Dottie	No	0	0	$0.5 million	$4 million
8/9/1976	Belle	No	0	0	minor	minor
9/24/1975	Eloise	No	0	0	minor	minor
6/21/1972	Agnes	joined w/ low-pressure system	0	2	$10 million	$115 million
9/30/1971	Ginger	No	0	0	$10 million	$168 million
8/27/1971	Doria	No	0	0	$1 million	$17 million
8/17/1970	T.S. #4	No	1	0	$0.5 million	$9 million
5/26/1970	Alma	No	0	0	minor	minor
10/20/1968	Gladys	No	0	0	minor	none
6/8/1968	Abby	No	1	0	minor	minor
9/17/1967	Doria	No	0	0	minor	minor
6/11/1966	Alma	No	0	0	minor	minor
6/16/1965	T.D. #1	No	0	0	minor	minor
10/16/1964	Isbell	No	0	0	$1 million	$54 million
9/21/1964	Gladys	No	0	0	$0.1 million	$5 million
9/13/1964	Dora	No	2	0	$0.1 million	$5 million
8/31/1964	Cleo	No	3	0	$0.5 million	$21 million
10/21/1963	Ginny	No	0	0	$0.1 million	$5 million
8/28/1962	Alma	No	0	0	minor	minor
9/20/1961	Esther	No	0	0	$0.1 million	$4 million
9/14/1961	T.S. #6	No	0	0	no damage	none
9/12/1960	Donna	No	2	8	$56.5 million	$2.34 billion
7/30/1960	Brenda	No	0	0	$0.25 million	$10 million
9/30/1959	Gracie	No	2	0	$0.5 million	$21 million
7/10/1959	Cindy	No	3	0	$1.1 million	$46 million
9/27/1958	Helene	No	0	0	$11 million	$523 million

Appendix D. continued.

Landfall in NC	T.C. Name	Mid-latitude Interaction	Confirmed Tornadoes	Deaths	Unadjusted Damage ($)	Normalized Damage (2000$)
9/26/1956	Flossy	No	0	0	no damage	none
9/19/1955	Ione	No	0	7	$88 million	$3.44 billion
8/17/1955	Diane	No	0	0	$80 million	$2.54 billion
8/12/1955	Connie	No	1	0	$40 million	$1.56 billion
10/15/1954	Hazel	intensifying trough to west after landfall	0	19	$254 million	$10.52 billion
9/11/1954	Edna	No	0	0	$0.1 million	$4 million
8/31/1954	Carol	No	0	0	$0.25 million	$11 million
8/14/1953	Barbara	No	0	1	$1.1 million	$54 million
8/31/1952	Able	No	1	0	minor	minor
8/29/1949	H. #2	No	na	0	minor	minor
8/24/1949	H. #1	No	na	2	$0.2 million	$12 million
9/24/1947	T.S. #6	No	na	0	minor	minor
10/9/1946	H. #5	No	0	0	no damage	none
7/6/1946	H. #2	No	0	0	minor	minor
9/18/1945	H. #9	No	na	na	$2 million	$209 million
6/26/1945	H. #1	No	0	0	minor	minor
10/20/1944	H. #11	No	0	0	minor	minor
9/14/1944	H. #7	No	na	1	$1.5 million	$168 million
8/1/1944	H. #3	No	0	na	$2 million	$234 million
10/12/1942	T.S. #8	No	na	0	minor	minor
8/18/1939	H. #2	No	na	0	$1 million	$156 million
9/18/1936	H. #13	No	na	2	$0.1 million	$15 million
9/5/1935	H. #2	No	na	na	minor	minor
9/16/1933	H. #13	No	na	21	$4.5 million	$731 million
8/23/1933	H. #8	No	na	na	$0.25 million	$40 million
9/19/1928	H. #4	No	na	na	$4.5 million	$731 million
8/11/1928	H. #1	No	na	na	$0.05 million	$6 million
10/3/1927	T.S. #5	No	0	0	no damage	none
12/2/1925	H. #2	No	0	0	no damage	none