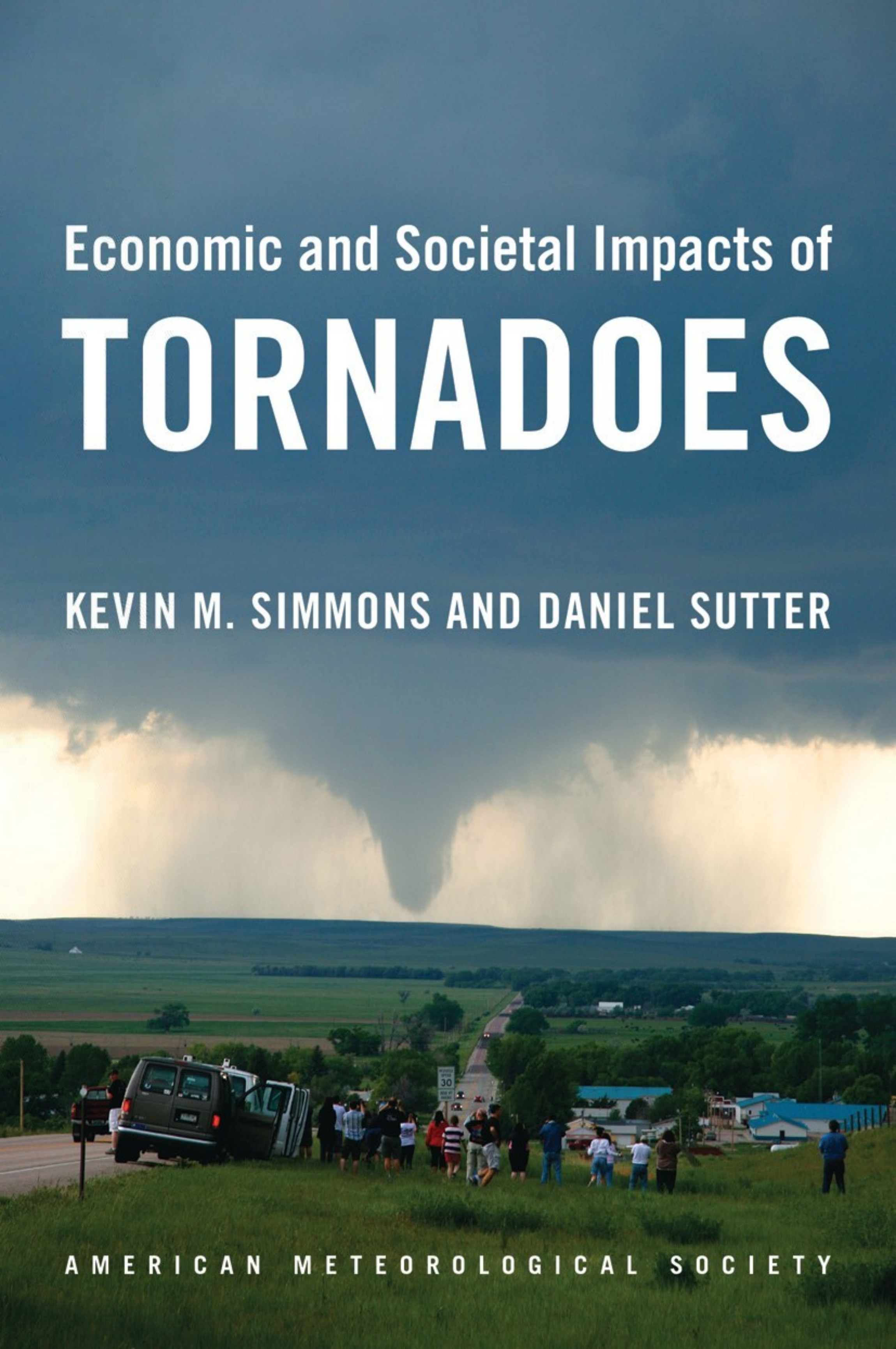
Economic and Societal Impacts of

TORNADOES

KEVIN M. SIMMONS AND DANIEL SUTTER



AMERICAN METEOROLOGICAL SOCIETY

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All photos courtesy Texas Tech University unless otherwise noted. The authors wish to thank Texas Tech University's Wind Science and Engineering (WISE) Research Center and their Wind Damage Documentation Library for the use of photos throughout the book. Many thanks to WISE Ph.D. students Ian Giammanco and Patrick Skinner for their storm chase photos; many thanks to WISE Ph.D. student Richard Krupar and Kelsey Seger for help sorting through 40 years' worth of tornado damage photographs.

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CONTENTS

DEDICATION

Kevin

To Susan, who is still as lovely to me today as when we attended our high school prom together.

Dan

To my parents, who always thought that professors should be writing books.

Special Thanks

We would like to thank NOAA's National Severe Storms Laboratory and the Institute for Catastrophic Loss Reduction for funding provided throughout our work on this research agenda. We also give a special thanks to Jeff Kimpel, Bill Hooke, Harold Brooks, Jamie Kruse, Paul Kovacs, and Kishor Mehta for encouraging our work on this topic. The project would not have been possible without the generous sharing of data from Joe Schaefer, Brent Macaloney, and Tim Crum. Finally, Dan wants to thank Natalie for her support and encouragement of his research, and his dogs Norm and Cliff for their patience in having their walks and playtime disrupted during his work on the project.

FOREWORD

The economics of natural disasters is an area of rising importance for the economics profession and also for the world more generally. For decades, economists considered this area to stand outside the normal interests of the science. But in these days of global warming, the earthquake in Haiti, flooding in Pakistan, Hurricane Katrina, and rampaging forest fires in Russia, it has become clear that natural disasters are at the very center of the problem of economic and social development.

In fact, economic disasters bring together many of the central features of economics. Disasters, including tornadoes, test the flexibility and resilience of economic and political institutions. They pose the question of how an area or a neighborhood will recover, how it will recover its ability to mobilize resources, and how it will move from a situation of lesser wealth to greater wealth. It is, sadly, a perfect controlled natural experiment to see both how wealth is destroyed and how wealth is created again.

Tornadoes are also a proxy for the larger idea that economic development is not a smooth process. Economic development involves some large and discrete steps backwards, often followed by some significant leaps forward. Tornadoes, and the recovery from tornadoes, show these same processes.

Natural disasters are important for other reasons as well. How we prepare for these disasters indicates our tolerance for risk and our ability to insure and self-insure. It shows in which ways we value human lives, and in which ways we are willing to lose some lives to minimize protective expenditures. How we treat and compensate victims reflects our sense of justice and fairness. How we rebuild demonstrates our sense of the future and how much optimism we will throw at solving a problem. It reflects some fundamental truths about how politics works and, sometimes, how politics fails.

A study of natural disasters should be of interest to all economists. It is also the case that this area is badly understudied and thus there is much low-hanging fruit to be had. It is this low-hanging fruit that you will find in the new book by Kevin M. Simmons and Daniel Sutter.

Simmons and Sutter already have staked out their ground in this area with numerous academic journal publications over the last ten years. It is now time for their work to be turned into comprehensive book form. Each year, about 1,200 tornadoes touch down across the United States, but to date we have not seen a book of this detail and analytical fortitude.

It is appropriate that this book is sponsored by the American Meteorological Society and distributed by the University of Chicago Press. This combination represents the integration of theory and practice that the authors develop so successfully.

Tyler Cowen
Professor of Economics,
George Mason University

1 WHAT WE CAN LEARN FROM SOCIETAL IMPACTS ANALYSIS

What does supply and demand teach us about whether rotating wall clouds will spin out a tornado? Nothing, really. Can we use the stock market to understand why tornadoes can be so capricious, flattening one house and leaving the one next door untouched? Well, no. So why would a couple of economists who have never even seen a tornado except on TV, and who know nothing about cloud dynamics, write a book about tornadoes? And why would anyone want to read it?

In fact, we have not written a book about tornadoes. Our subject is the economic and societal impact of tornadoes. As the geographer Gilbert White taught generations of students and scholars, societal impacts arise from the interaction of nature and humans. Tornadoes are natural events, but a tornado disaster has a human component.

1.1. Our Approach

This book is economic in its methods: We apply models and statistical methods from economics. Readers with a narrow view of economics—who think of economic topics as having to do exclusively with money and business—

may find the impacts we examine not to be economic at all, and will probably characterize this book as about societal impacts only.

Our primary focus will be on casualties, not property damage or business impacts. We seek to analyze and understand the various impacts of tornadoes on society. We also analyze the effects of efforts to reduce impacts, such as tornado warnings and watches, and tornado shelters and safe rooms. Our analysis is primarily positive, in that we seek to identify patterns and evaluate mitigative efforts. But our positive analysis is conducted with an eye toward eventually being able to offer suggestions about how impacts, and again primarily casualties, can be reduced in a cost-effective manner.

1.2. Research, Tornadoes, and Societal Impacts: A Short History

Atmospheric scientists have learned a great deal about tornadoes in recent decades, much of it through several large research projects that were cooperative ventures between the government and leading universities. One of the more famous projects is VORTEX (Verification of the Origins of Rotation in Tornadoes Experiment), conducted in the spring seasons of 1994 and 1995. The project was led by Dr. Eric Rasmussen and coordinated by the National Severe Storms Laboratory in Norman, Oklahoma, and included as partners the University of Oklahoma, Texas A&M University, the University of Illinois, Texas Tech University, New Mexico Tech, West Virginia University, the University of Alabama at Huntsville, and the University of California at Los Angeles. Funding came from the National Science Foundation (NSF), the National Center for Atmospheric Research (NCAR), the National Oceanic and Atmospheric Administration/National Weather Service (NOAA/NWS), and the Atmospheric Environment Service, Canada (AES). The objective of VORTEX was to chase tornadoes in the southern Plains between April and June 15 of each year, in the hopes of intercepting about 30 supercell thunderstorms in the process of spawning tornadoes. VORTEX specifically sought to study factors in the environment that contribute to the spawning of a tornado (tornado genesis), tornado dynamics, and the distribution of debris from a formed tornado.

While 1994 produced few tornadoes, in 1995 the team collected data on 13 days, including June 2, when a tornado hit Dimmitt, Texas. Researchers used vehicles, aircraft, and weather balloons to effectively create a mobile mesonet to capture data from the event, including temperature, humidity, wind speed, and barometric pressure observations, as well as dramatic photography. The data and photography allowed researchers to attempt a numerical simulation of the event. VORTEX also represented the first use of a mobile Doppler radar, or "Doppler on Wheels," designed by Josh Wurman of the University of Oklahoma and constructed by the National Severe Storms Laboratory (NSSL) with support from the National Center for Atmospheric Research (NCAR).

VORTEX II was a second attempt of the same type of project, funded for $10 million in 2009/2010 by the National Science Foundation and NOAA, and equipped with 40 vehicles and 10 mobile radars. One notable accomplishment from the first year of VORTEX II was the intercept of a tornado in Wyoming on June 5, 2009. For the first time, the team was able to closely track the entire life cycle of a tornado. Researchers were even able to capture video of the inside of the tornado funnel, making it the most documented tornado in history.[1]

The data and observations generated by VORTEX and VORTEX II allow scientists to better understand how tornadoes form. Meteorologists may find such research projects of immense intrinsic value, and certainly tornadoes hold a certain fascination for many members of the public, including the authors of this book. However, while scientists may be content with academic knowledge, the average taxpayer is likely to look at a project like VORTEX II and want to know what the return on this investment will be. They want to see progress toward reducing the impacts of tornadoes on society, making it less likely that lives will be lost and communities devastated by tornadoes. In short, people want to know how these large research projects improve the well-being of individuals and communities. Societal impacts research attempts to answer this question, by examining how "academic" knowledge leads to practical knowledge that allows us to reduce the impact of tornadoes on society.

1.2.1. Doppler Radar

In the 1990s, the Department of Commerce embarked on a thoroughgoing modernization of the National Weather Service (NWS). The modernization included a professionalization of personnel (a shift to university-trained meteorologists), a reduction in the number of local weather forecast offices across the country, the implementation of a new Advanced Weather Information Processing System (AWIPS), and the construction of a nationwide system of new weather radars (WSR-88D) based on Doppler technology that

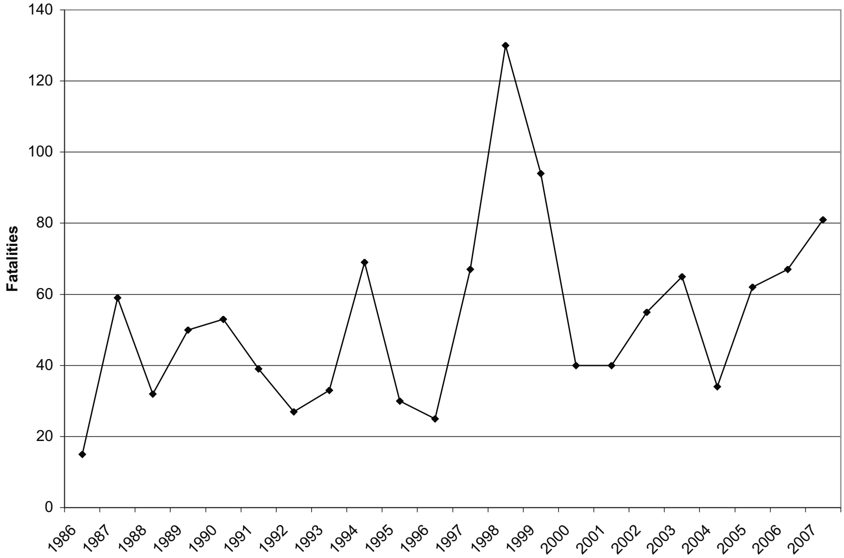

FIGURE 1.1. The modernization of the NWS and tornado fatalities

would be joined together for the first time in a true network, the NEXRAD network (Friday 1994). The NEXRAD system consists of 166 radars operated by the Departments of Commerce, Transportation, and Defense at a cost of $1.2 billion. The modernization was expected to yield a wide array of valuable new forecast products and weather services (Chapman 1992). One of the most visible expected benefits of the new Doppler radars was improved warnings, which would hopefully reduce the tornado death toll (Crum, Saffle, and Wilson 1998; Friday 1994).

Figure 1.1 displays the annual tornado fatality count for the years 1986–2007, and inspection of the time series suggests that the nation may not have purchased any reduction in tornado fatalities with the new Doppler radars. The WSR-88D radars were installed between 1992 and 1997, and if we consider fatalities in the six years immediately prior to and after the installation, we see that the two deadliest years in the sample were 1998 and 1999, immediately after the NEXRAD network was completed. Total fatalities *increased* by 70% from 248 in 1986–1991 to 424 in 1998–2003.

Did the new radars actually *cause* an increase in tornado fatalities, in contrast to the expected decline? Societal impacts research can answer this question. Doppler radar would only be expected to reduce the lethality of tornadoes when everything else is held constant: the famous *ceteris paribus* assumption from economics. A detailed analysis at the level of the individual tornado can attempt to hold these "other things" constant and estimate the effect of Doppler radar. In so doing, we can simulate an experiment with randomized trials with and without radar.

We have undertaken such an analysis (Simmons and Sutter 2005) and present updated results on this issue in Chapter 4. The analysis at the tornado level, controlling for a wide range of tornado and tornado-path characteristics, tells a very different story from the annual fatality totals in Figure 1.1.

1.2.2. Safe Rooms

For decades, residents of the Plains states have dug storm cellars for protection against tornadoes. Tornado protection has come a long way, however. In the 1980s and 1990s, engineers at Texas Tech University developed designs for "safe rooms" that can withstand the strongest tornado winds. Anyone who has visited the wind engineering lab at Tech and seen first-hand the contrast of a 2 × 4 fired from their wind cannon first at a traditional home wall and then at a safe-room wall has witnessed the amazing life-saving potential of these rooms. During the 1990s, safe-room principles were extended to a new generation of modern, underground tornado shelters. In principle, the safe-room design could be amplified to apply to entire homes. And yet as engineers were able to design shelters capable of protecting against tornadoes, homeowners in Tornado Alley stopped digging storm cellars. But shelters gained unprecedented attention when a family survived the May 3, 1999, tornado in Oklahoma City inside the only structure left standing from the destroyed home, their safe room. A total of 36 people perished and damages exceeded $1 billion, becoming the first tornado to have damages that high.

1.3. A Twister Gets Our Attention

The May 3 tornado attracted our professional interest as economists; we were both teaching at Oklahoma City–area universities that day. We were aware of and impressed with the new safe-room technology, but what was missing at the time was any hard analysis of the benefits versus costs of safe rooms or shelters. We knew that economics offered a set of research tools that would allow us to answer this valuation question. Our first collaborative research on tornadoes was to examine the benefits of shelters and safe rooms, and in the months after May 3, our efforts focused on figuring out how to assemble the data needed to perform a benefit-cost analysis, laying the groundwork for this now decade-long research project.

During the overnight hours of February 2, 2007, a fast-moving supercell tornado produced two F3 tornadoes in Lake County, Florida. The tornadoes struck The Villages retirement community and the rural Lake Mack area in the eastern part of the county. Lake County is also a popular destination for "snowbirds," who winter in Florida to escape the snow and cold of the north. News reports the next morning conveyed an all-too-familiar message: The tornadoes were killers, causing the deaths of 21 people, all in mobile homes.

Our research trip to Lake County a few weeks after the storm emphasized the vulnerability of these homes, as we saw relatively undamaged site-built homes adjacent to destroyed manufactured homes, and sites where the manufactured home had been blown away but the wooden stairs that led to the home were intact. We also met residents who were caught by surprise because they assumed tornado sirens would sound in advance of a tornado, but Lake County—like most Florida communities—does not have a siren system. The Lake County tornadoes embody what our research has identified as the four major vulnerabilities for casualties:

- Overnight (3 AM)
- Fall or winter months (February)
- Mobile homes (42% of the homes in Lake County)
- Southeast United States

Nonetheless, the event did have a silver lining: No fatalities occurred in any manufactured homes installed after the Department of Housing and Urban Development added the 1994 wind-load provisions to the HUD code for manufactured housing.

1.4. Mixing Meteorology and Economics

This study is an exercise in academic disciplinary trespassing. Our analysis is firmly grounded in the methods of economics, but the subject is outside of the traditional domain of topics studied by economists. Nobel Prize–winning economists Gary Becker and James Buchanan are famous for their interdisciplinary trespassing, using economic methods to study such topics as crime, the family, politics, and morality. This book fits into this broad tradition, and also can be thought of as an extension of environmental economics to weather and climate.

Interdisciplinary research must speak to (at least) two academic audiences. We hope we have written a book that will be of interest to atmospheric scientists and climatologists as well as to economists and social scientists interested in extreme weather. However, the message for these two audiences regarding tornado impacts will be different.

Meteorologists will be much more knowledgeable about tornadoes than the authors. Economists learn early about comparative advantage, and we will not pretend to be able to speak authoritatively on tornado genesis, multiple vortices, or the technical properties of weather radars. Any reader who doesn't already know about the physics of tornadoes isn't going to learn it here. But we believe that atmospheric scientists who study severe storms will find themselves drawn to the content of our impacts analysis and curious to learn about the determinants of tornado casualties, whether damage is increasing, and if tornado-warning false alarms create a "cry wolf" effect. In other words, meteorologists will be interested in this book as an example of societal impacts research. Many meteorologists and other physical scientists often consider societal impacts to be an "add on" to their research, but those who study cloud dynamics, for example, might be aware that in a world where funding for research is in shrinking supply, they must offer evidence of the value to society of their research. In this book, we will be studying the impacts side of the equation first and foremost. We will offer some innovative ways to attempt to estimate the value of meteorological research and the tornado-warning products of the National Weather Service. Through our analysis, meteorologists might discover some ways to think systematically about the value of their research to society, even if their areas of research are far afield from tornadoes.

Our book also attempts to reverse the standard direction of scientific research. Scientists focus on scientific advances first (which of course they see as tremendously valuable), with discussions of societal impacts a very distant second. We try to suggest some ways in which impacts can guide or direct research: We will start with information that we might need to reduce tornado impacts, and offer this as a target for research.

Economists would characterize our work as *applied*, meaning that we are using existing theoretical models and statistical techniques in our work. They will find this book interesting for very different reasons than meteorologists. Social scientists and the handful of economists who study natural hazards, and specifically extreme weather, will be interested in the substance of our study, the patterns we find, and how we address some recurring research challenges, as much of the data or many of the econometric problems that arise in studying tornado impacts also plague research on floods or hurricanes or forest fires. Others might simply find the book to be an interesting application of economics: Economists generally enjoy using their tools to study and understand the world, and applications of these tools to a new or different subject are often particularly interesting to them.

Finally, some economists might find our book interesting because it provides another piece of evidence on a few contentious and pervasive issues. For example, one area of current controversy is whether people adequately perceive and prepare for low-probability, high-consequence events. Natural disasters (and arguably financial and housing market disasters) are low-probability events, and many observers look at the impacts of the 2004 Indian Ocean tsunami and Hurricane Katrina in 2005 and conclude that as individuals and collectively, we fail to adequately prepare for disasters. Individual tornadoes do not have the regional or society-wide impacts of hurricanes, earthquakes, or other disasters, but they are clearly a high-consequence event for individual households. Thus, evidence on whether people seem to ignore tornado risk is relevant, but hardly decisive, in evaluating the prevalence of what is called low-probability event bias.

Another issue is the relationship between income inequality and risk. Economists generally find that safety is a luxury good, and that similar to other luxuries, safety is something we tend to consume much more of as we become wealthier. Recent research has looked at natural disasters to see if richer societies can afford more safety. The relationship between income and tornado impacts would be additional evidence on this question.

To conclude, we have tried to write a book that serves as a bridge between the pure science of tornadoes and the social implications these events have on the communities and people affected by them. No one discipline can adequately explain such a mysterious and often capricious phenomenon as a tornado; it is our hope that our research adds a significant element to this exciting field.

2

TORNADO CLIMATOLOGY AND SOCIETY'S TORNADO RISK

2.1. Introduction

Tornado climatology refers to the *frequency* of tornadoes. Climatology is not social science, so it may seem odd for economists to begin a book on the economic and societal impacts of tornadoes with climatology. But many of the decisions people can make to reduce their vulnerability to tornadoes depend on an understanding of the likelihood of tornadoes, or climatology. Consider the following:

- Manufactured housing exhibits vulnerability to tornadoes, which the data will validate. Yet manufactured housing represents an affordable and increasingly comfortable housing option for many Americans (Beamish et al. 2001). How is a family concerned about tornado risk to decide whether to live in a mobile home? Are residents of tornado-prone states who nonetheless choose to live in a manufactured home simply ignoring or failing to perceive and appreciate weather risk, or balancing other important life goals against safety?
- Wind engineers have developed new shelters capable of protecting against even the most powerful tornadoes. The Federal Emergency Management Agency (FEMA) issued performance standards for new tornado shelters

in 1998 and included safe rooms in its (now-abandoned) National Mitigation Strategy. Tornado shelters and safe rooms are not cheap, and their benefits are tied to the risk of tornadoes. Are shelters worth the cost? An informed decision about shelter purchase requires data on tornado risk and how this risk varies across the nation.

- The nation also invests in tornado research and technology, with the ultimate goal of helping the National Weather Service (NWS) forecast and warn for tornadoes. For example, in the 1990s, the United States invested $1.2 billion on a nationwide network of Doppler weather radars (the WSR-88D, or NEXRAD network). One of the expected benefits of Doppler radars was improved tornado warnings. In 2009, NOAA undertook a research study on tornadoes called VORTEX II (Verification of the Origins of Rotation in Tornadoes Experiment; see page 3). At a cost of $10 million, the project equipped 40 vehicles to intercept and observe the entire life cycle of a tornadic thunderstorm. Ultimately, the nation's return on these investments depends on the rate of tornado activity. The greater the threat, the greater the number of lives that can be saved by investments in research and technology to reduce the lethality of tornadoes.

Our examination of tornado climatology in this chapter focuses on the estimation of tornado frequency and differences in frequency across the United States. We do not plan to reinvent the wheel or refine previous spatial measures of tornado risk. Instead, we will consider the elements and limitations of these measures (and the tornado archives) that are relevant for the evaluation of tornado impacts. For example, measures of tornado frequency have been previously calculated (Schaefer et al. 2002, 1986) and used in analysis (Multihazard Mitigation Council 2005). Dividing the average annual damage area of tornadoes by land area of a region provides an estimate of the annual probability of tornado damage. Since not all tornadoes have equal destructive potential, F-scale adjusted frequency measures (F-scale is discussed in detail on the next page) have also been constructed, and limitations of the F-scale and existing tornado records have been discussed. This chapter will pull together prior observations by others and add several additional concerns arising from our analysis that affect the ability to assess the societal impact of tornadoes. We will address the following specific issues:

- Like all analysis of extreme weather, tornado research depends on the quality of available records. It often employs a reasonably complete archive of U.S. tornadoes maintained by the Storm Prediction Center

(SPC), which includes records of tornadoes since 1950. The improved ability to document and record tornadoes and the challenge of climate change both raise the possibility that tornado frequency may be changing over time. If the underlying frequency of tornadoes is changing, the value of historical records for estimating risk today diminishes. Thus, we will see if we can identify a trend in tornado activity that is not an artifact of our changing ability to document tornadoes.

- Sixty years of records is a very short window of observation for events with a return period (for any given location) of thousands of years. Even if tornado frequency has not changed since 1950, the observed frequency of tornadoes based on available records may differ from the true frequency. In other words, we have no guarantee that the past 60 years reflect a "normal" rate of tornado activity. We must consider rates of tornado activity consistent with the observed record and consequently construct confidence intervals, as opposed to simply calculating 60-year averages. This chapter will also address the potential for a few more years of observation to affect our estimates of tornado frequency.
- Protective investments depend on the local tornado risk: For example, tornado risk is clearly greater in "Tornado Alley" than in New England. Although 60 years is a particularly short window in which to estimate differences in tornado risk across the United States, we will construct confidence intervals for state-specific measures of tornado frequency. The overall pattern of tornado incidence also differs across the nation, and these differences can substantially affect the risk to humans posed by tornadoes. In addition, the frequency of tornadoes, the pattern of activity throughout the day, the distribution of tornadoes by F-scale rating, and the concentration of risk across the year all affect the level of threat to people and property.
- The Fujita Scale (F-scale) was adopted by the NWS in the 1970s, and like any scale of damage for natural hazards, it has limitations. Although some of its weaknesses were addressed by the adoption of the Enhanced Fujita Scale (EF-scale) in 2005, some important limitations remain. First, the NWS did not begin using the F-scale until the 1970s, so ratings needed to be constructed retrospectively for earlier tornadoes. A potentially more serious limitation is that the F-scale is a damage measure, as opposed to an intensity measure. In sparsely populated areas, the potential to cause damage to sturdy buildings is limited. Strong and violent tornadoes (i.e., those rated F2 and stronger) in rural areas tend to be undercounted, and consequently, measures of tornado frequency based on archival records understate the threat to people and property.[1]

2.2. Tornado Incidence

The likelihood of a tornado occurring affects the value of investments made by households, businesses, and government to try to reduce the impact of tornadoes by protecting persons and property. Tornado frequency can be measured in one of two ways, the first based on the number of tornadoes occurring in a given area and timeframe, and the second based on the area of the tornado damage paths (not the amount of damage to property) during the time of the event. A damage area measure allows the estimation of a probability of tornado damage; if 10 square miles (mi^2) of tornado damage occurred over 50 years in 1,000 mi^2 of land area, then the probability of damage over the same period is approximately .01 = 10/1,000. Damage areas provide a better measure of incidence because tornado paths vary tremendously in length, width, and area. They can be smaller than a football field or large enough to cover 100 miles in length. The number of tornadoes depends on the area over which the count is made: The convention is to express the rate as tornadoes per 10,000 mi^2 land area per year. We will not report measures based on societal impacts here: for example, casualties or property damage per year. Impacts depend on the interaction of tornadoes and society, including the population of the area struck by tornadoes and the actions residents take to protect themselves. Impact-based measures do not convey a pure measure of risk due to nature alone, and may misrepresent the risk for persons who choose to live in the area. For example, imagine that a tornado slams through a desolate corner of West Texas every year. Nobody lives in the area, so the only impacts are damage to sagebrush and mesquite. We may accurately state that nobody ever died in a tornado in these parts. However, inferring from this observation that tornado risk is low could lead to the building of a mobile-home park on the site, with tragic consequences: The fatality count would mount quickly. Therefore, when we make decisions in locating vulnerable facilities or investing in protection, we should use risk measures based only on the frequency of tornadoes, not human interactions.

Tornadoes differ in intensity as well as in damage area. The F-scale measures tornado damage, not intensity, but damage correlates with intensity well enough that in the absence of any alternative the F-scale can be used as a measure of tornado strength. Tornado impacts derive mainly from stronger tornadoes. For example, the 977 tornadoes rated F0 or F1 in 2007 accounted for 4 deaths, while the 125 tornadoes rated F2 or stronger resulted in 77 fa-

TABLE 2.1. Summary Statistics of Annual Tornadoes

Variable	Total Tornadoes	Strong and Violent Tornadoes	Total Area (in Sq. Mi.)	Area of Strong and Violent Tornadoes (in Sq. Mi.)
Mean	874.0	188.3	334.3	273.3
Median	861.5	186	313.9	259.1
Standard Deviation	314.8	73.36	137.3	125.0
Minimum	202	80	91.06	58.33
Maximum	1823	389	768.3	644.5

talities, a difference of more than two orders of magnitude. A large number of weak tornadoes can inflate the likelihood of a tornado, but represents a relatively modest contribution to the true tornado threat. Thus, we tabulate a damage rate for all tornadoes, and then annual damage area for F2 and stronger tornadoes only.

We examine tornado climatology in order to assess the threat to life and property. Table 2.1 reports summary totals for the annual number of tornadoes in the United States over the period from 1950 to 2007. The source for these totals, as with most of the tornado figures reported in this analysis, is the tornado archive maintained by the SPC in Norman, Oklahoma.[2] The SPC archive reports one entry for each tornado that strikes a state, along with summary totals for tornadoes striking more than one state. We construct our analysis around the state tornado entry, because this represents the most disaggregated storm-level information available. Consequently, our analysis throughout the book reports state tornado segments, but we refer to them simply as tornadoes throughout the text; we use the term *state tornado* only when necessary to avoid confusion.[3]

Table 2.1 reports four measures of tornado frequency: the tornado rate per 10,000 mi^2 for all tornadoes and for strong and violent (F2 and stronger) tornadoes; and the damage area (in mi^2) per year for all tornadoes and for F2 and stronger tornadoes. A total of 50,691 tornadoes occurred in the contiguous United States since 1950,[4] with 10,291 rated F2 and stronger, or averages of 874 and 188 per year, respectively. The land area of the contiguous United States is just under 3 million mi^2, so the national annual tornado rate and the strong and violent tornado rate are 2.95 and 0.63 per 10,000 mi^2, respectively. The damage areas of all tornadoes and of F2 and stronger tornadoes since 1950 are 19,057 and 15,580 mi^2, respectively, with annual averages of 334 and

TABLE 2.2. Tornadoes by F-Scale Category, 1950–2007

F-Scale Category	Number of Tornadoes	Percentage of Tornadoes	Mean Length (in Miles)	Mean Width (in Yards)	Mean Area (in Mi^2)
Unknown	1,843	3.63	1.36	8.98	0.06
0	21,417	42.24	1.03	9.84	0.03
1	16,522	32.59	3.00	22.57	0.17
2	8,119	16.01	6.54	43.95	0.67
3	2,199	4.34	13.70	94.39	2.62
4	540	1.07	23.41	150.5	6.88
5	64	0.13	30.27	219.8	9.86

273 mi^2, respectively. For the nation as a whole, tornado damage as a proportion of U.S. land area is .00011, and the annual proportion for F2 and stronger tornadoes is .000092. The return periods for tornado damage for the nation as a whole are 8,800 years for all tornadoes and 10,800 years for strong and violent tornadoes. The median of the annual totals is very near to the mean for each measure, indicating a symmetric distribution of annual totals. The reported totals exhibit considerable variation, with the number of tornadoes ranging from 202 to 1823, a difference of a factor of nine. The annual totals of strong and violent tornadoes range from 80 to 389. The damage areas of all tornadoes range from 91 to 768 mi^2, while the damage areas of strong and violent tornadoes range from 58 to 645 mi^2.

Table 2.2 reports the distribution of tornadoes by F-scale category. The F-scale was developed by Professor Theodore Fujita in 1972 and adopted by the NWS in 1973. The scale rates tornado damage on a six-point scale from 0 to 5, with 0 representing minimal damage and 5 "inconceivable" damage. Although Fujita proposed wind speed range estimates for the type of damage observed in a category, tornadoes are not rated based on measurement of their actual wind speed, but instead on an evaluation of the damage from the tornado. In 2005 the NWS switched to the EF-scale for rating tornado damage. The EF-scale maintains the 0 to 5 rating for tornadoes, and the numerical categories are intended to be consistent with the earlier F-scale ratings, so for simplicity we refer to all of the ratings as F-scale ratings. (We will return to the details of the F-scale and its enhancements later in this chapter.) Note that F-scale ratings were assigned retrospectively to tornadoes prior to 1975. Since the adoption of the F-scale, tornado ratings have been assigned by the NWS based on inspection of the damage paths; prior to 1975, ratings were based on available descriptions of the damage. Table 2.2 includes a category of unknown F-scale that accounts for 3.6% of tornadoes. In these cases (almost all from before the mid-1970s), the available description of damage was insufficient to assign the tornado an F-scale rating. However, given the lack of damage description, these tornadoes would appear to be weak.

Based on their F-scale ratings, tornadoes are characterized as "weak," "strong," or "violent," with F0 and F1 tornadoes in the weak category, F2 and F3 in the strong category, and F4 and F5 in the violent category. The majority of tornadoes are weak, with 42% rated F0 and 33% rated F1. The frequency of more powerful tornadoes drops rapidly, as 16% were rated F2, 4% rated F3, 1% rated F4, and 0.13% rated F5. The nation averages about one F5 tornado and ten F4 tornadoes per year. Table 2.2 reveals the variations in tornado damage paths across F-scale categories. The average damage path for F0 tornadoes was just over 1 mile in length, compared with an average path of 30 miles for F5 tornadoes. The average width of an F0 tornado damage path was 10 yards, compared with 220 yards, or 1/8 of a mile, for F5 tornadoes. This variation in both length and width of damage paths leads to an even more pronounced variation in area, from .03 mi^2 for F0 tornadoes to almost 7 mi^2 for F4 tornadoes and nearly 10 mi^2 for F5 tornadoes. Note that the mean characteristics of tornadoes with unknown F-scale values are very close to those of F0 tornadoes, suggesting that most of the tornadoes missing F-scale ratings were likely F0, with a few F1 tornadoes included in the SPC data as well.

The substantially greater damage areas of stronger tornadoes in Table 2.2 suggest that the distributions of tornadoes and damage areas by F-scale category differ substantially. Figure 2.1 displays both distributions. F0 tornadoes are most common, but F2 tornadoes cause the most damage, accounting for almost 1/3 of tornado damage. Less than 6% of tornadoes are rated F3 or stronger, and yet these tornadoes account for almost half of the damage area. It is important to remember that the NWS rates tornadoes based on the worst damage along the storm path and that tornadoes strengthen and weaken along their paths, so the proportion of area actually experiencing F4 or F5 damage will be less than the proportion reported in Figure 2.1. Comparison of the distributions of numbers of tornadoes and damage areas indicates the value of measures of frequency based on each. A state might experience a large number of weak tornadoes and appear to face great tornado risk based on the tornado rate, but have a much lower frequency based on damage areas. We will see that Florida fits this description.

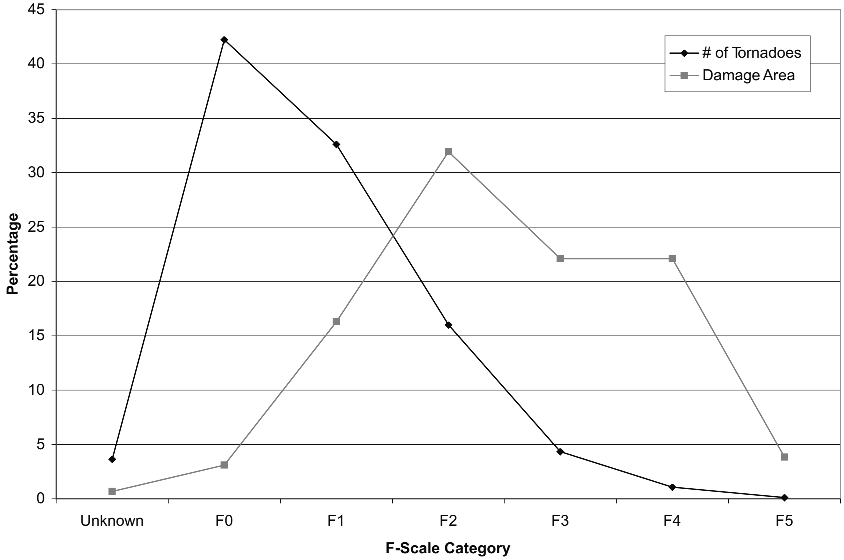

FIGURE 2.1. Distribution of tornadoes and damage area by F-scale

Concern over global warming has raised awareness of the potential for changing climatological normals. Tornadoes are one type of extreme weather that may increase with climate change, so we must be aware of and test for a change in the incidence of tornadoes over time, either nationally or regionally. Tornadoes are infrequent events; Schaefer et al. (2002) report that the highest estimated annual probability of tornado damage in the United States is 6×10^{-4} in central Oklahoma, which yields a return time of over 1,600 years. Estimation of tornado probabilities and particularly regional differences in these probabilities across the United States requires as many years of complete records as possible. At the same time, the changing climatology of tornadoes reduces the value of records from the past, since the frequency of tornadoes will begin to differ more and more. We consequently test for a change in the incidence of tornadoes since 1950.

Figure 2.2 displays the annual number of state tornadoes since 1950, and an increase over time is readily apparent. Fewer than 600 tornadoes were reported each year between 1950 and 1955, with a steady upward trend since then. New records for tornadoes were set in 1957, 1973, and 2004, with the record rising from 861 in 1957 to 1,104 in 1973 and 1,823 in 2004. Fitting a linear regression to the annual totals, as reported in Table 2.3, confirms the increase over time, with the total increasing by almost 16 state tornadoes per year, from an estimated 430 in 1950 to 1,300 in 2007, or a tripling of the annual total.

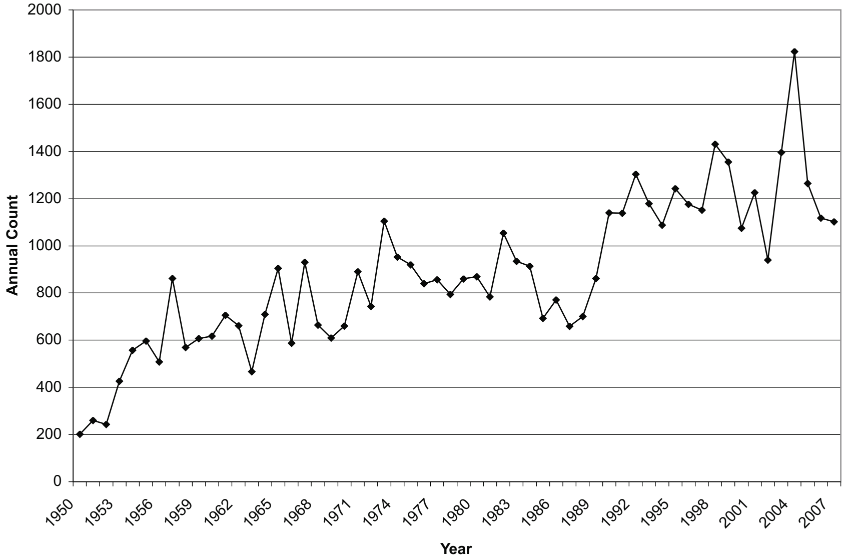

FIGURE 2.2. Tornadoes by year, 1950–2007

The total number of tornadoes is just one measure of tornado frequency, and we need to examine the other frequency measures before drawing any conclusions about climatology. It's possible that the total number of tornadoes appear to be increasing due to more effective reporting and documenting of tornadoes now than in the past. America has changed in many ways since the 1950s; today there are many more storm chasers, and video cameras and cell phones allow more effective documenting and reporting of tornadoes. The proportion of tornadoes reported and eventually entered into the SPC archive might be much greater now than in the 1950s; due to

TABLE 2.3. Time Trends in Annual Tornadoes, Damage Area

Measure of Tornado Activity	Time Trend	Constant
All Tornadoes	15.6 (11.39)	430 (9.51)
F2+ Tornadoes	−2.06 (4.04)	247 (14.64)
F4+ Tornadoes	−.159 (2.80)	14.9 (7.96)
Damage Area	−.963 (0.87)	361 (10.04)
F2+ Damage Area	−1.62 (1.63)	319 (9.90)

The table reports the results of a linear regression of each measure of annual tornado activity on a time trend term (equal to 0 in 1950) and a constant. Point estimates with absolute t-statistics based on robust standard errors in parentheses.

the increase in storm chasers and spotters, we may even be approaching 100% reporting, at least in tornado-prone states during the tornado season. In short, Figure 2.2 may simply reflect a change in the reporting, as opposed to the incidence, of tornadoes.

In reality, the improved efficiency of reporting has probably had the greatest impact on the reporting of short, weak tornadoes. A brief tornado in a rural area in the 1950s might have been seen only by a local farmer who was too busy working to report the tornado to the NWS; today, the same kind of storm could easily be broadcast live on local TV by storm chasers. On the other hand, longer-track, more powerful tornadoes causing damage to property would likely have been reported both in the 1950s and today. Figure 2.3 graphs the annual count of F2 and stronger tornadoes since 1950, and this count reveals no increase in tornado activity. The annual total of strong and violent tornadoes was between 100 and 150 in the early 1950s and in each year of the first decade of the twenty-first century. Interestingly, the total number of strong and violent tornadoes was greater between 1954 and 1976 than in the years since, with the annual total exceeding 200 eighteen times in the 23 years between 1954 and 1976, but only 4 times in the 31 years since. In fact, a time trend fitted to the count of F2 and stronger tornadoes reported in Table 2.3 indicates a statistically significant *negative* decline of about two strong and violent tornadoes per year, from around 250 in 1950 to around 130 in 2007; thus, the number of powerful tornadoes has declined by half, while total tornado reports have tripled. However, the high number of strong and violent tornadoes prior to 1976 may be an artifact of retrospective assignment of F-scale ratings to tornadoes by the NWS based on newspaper reports and other available evidence as opposed to damage surveys by NWS personnel. Researchers may have assigned higher retrospective ratings to tornadoes than they would have based on a contemporary damage-path survey. Still, even if we dismiss the decline in F2 and stronger tornadoes as a consequence of the retrospective assignment of early F-scale ratings, we still have no evidence of an *increase* in the frequency of strong and violent tornadoes over time.

Annual tornado damage provides additional evidence on trends in tornado frequency. Figure 2.4 graphs the annual damage area of all tornadoes and of tornadoes rated F2 and stronger. Neither series displays any evidence of an increase in tornado frequency; damage area in the 1950s averaged 325 mi^2 a year, with F2 and stronger tornadoes accounting for 280 mi^2, and the annual totals remain relatively steady over the period. Damage area fluctuates significantly from year to year, with extremes for all tornadoes of 768 mi^2

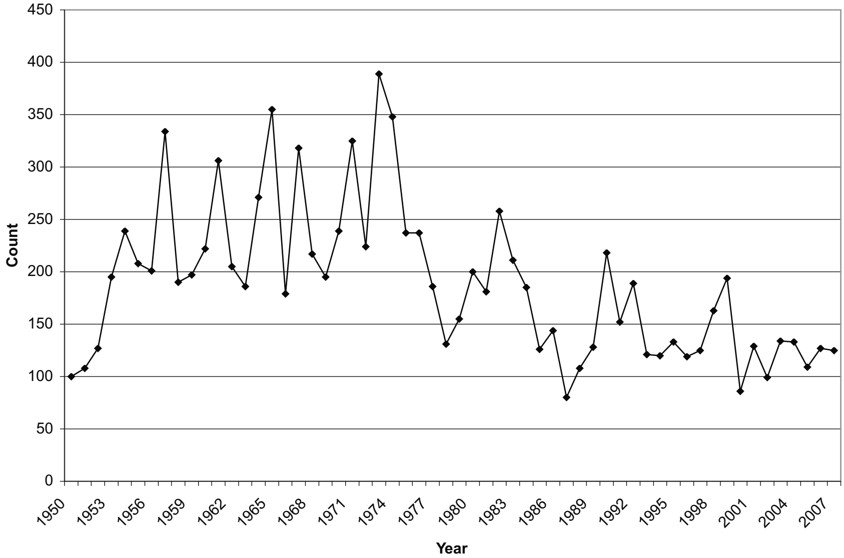

FIGURE 2.3. Strong and violent tornadoes by year, 1950–2007. Strong tornadoes are rated F2 or F3 on the F-scale of tornado damage, and violent tornadoes are rated F4 or F5.

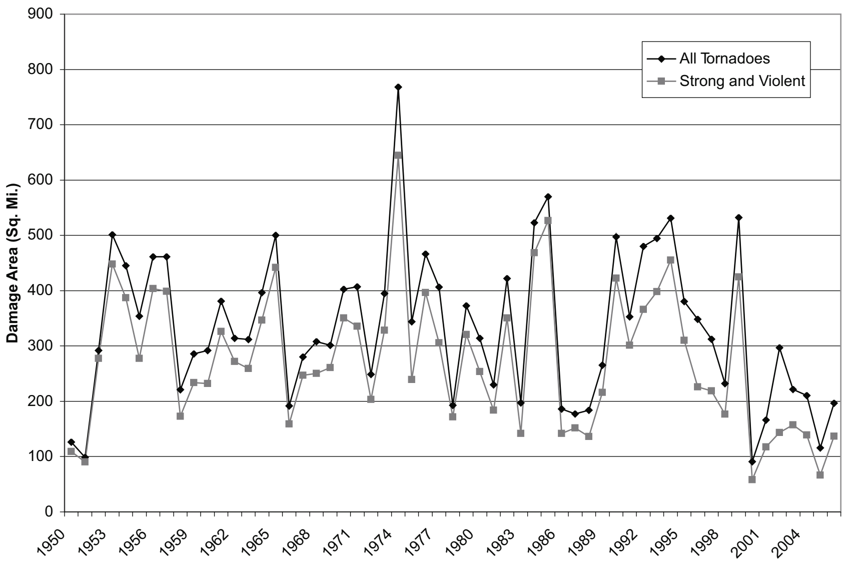

FIGURE 2.4. Tornado damage area by year, 1950–2007

TABLE 2.4. Distribution of Tornadoes by F-Scale, Pre- and Post-1976

F-Scale Category	Proportion, 1950–1975	Proportion 1976–2007
Unknown	.0806	.0141
0	.1973	.5354
1	.3615	.3080
2	.2701	.1049
3	.0698	.0301
4	.0181	.0069
5	.0027	.0006

Proportions of tornadoes occurring in each time period rated in each F-scale category

in 1974 and 91 mi^2 in 2000, and 645 mi^2 and 58 mi^2 for strong and violent tornadoes, respectively, in these same years. The correlation between the total damage area and the F2 and stronger damage area is +.98. Regression analysis in Table 2.3 confirms the lack of a trend in damage, with both total damage area and F2 and stronger damage area exhibiting a downward but statistically insignificant trend.

What does this analysis in total suggest about the trend in tornado frequency? While the annual number of tornadoes has significantly increased by about 900 state tornadoes per year since 1950, this is almost certainly a consequence of more complete reporting. Short-path, weak tornadoes that previously went undocumented are now reported and entered into official records with greater efficiency. If the increase in the total number of tornadoes were part of an increase in tornado activity, we should see increases in the other measures of frequency. But reported tornado damage area and F2+ damage area show no time trend, and a significant downward trend in the count of F2 and stronger tornadoes has been observed. This downward trend is likely due to the retrospective application of the F-scale to tornadoes from the 1950s and 1960s, compared with contemporary rating based on damage surveys since the mid-1970s.

Table 2.4 reports the distribution of tornadoes by F-scale category in the time periods of 1950–1975 and 1976–2007. Comparison of the distributions over these periods allows us to evaluate the overall impact of retrospective application of the F-scale ratings and changes in the reporting of tornadoes on apparent tornado risk. The proportions over the two periods differ considerably. Since 1976, F0 ratings have been most common, with over 53% of tornadoes receiving that rating. Prior to 1976, F0 was the third most common rating at 20% of tornadoes, trailing F1 at 36% and F2 at 27%. The proportion of tornadoes rated in each of the F3 through F5 categories before 1976 was more than double the proportion since 1976, so damage may have been overrated retrospectively. When rating tornadoes retrospectively, experts have less information to guide them and may not be able to observe weaknesses in construction of buildings, for example, which may lead to a tornado being rated F3 instead of F2.

Because we believe that tornado frequency is unchanged since 1950, we can use the entire available archive to estimate tornado risk. Table 2.1 reported averages for annual measures of tornado activity. The United States has averaged 874 tornadoes per year, including 178 strong (F2 and F3) and 10 violent (F4 and F5) tornadoes. The annual probability of a tornado is the relevant measure of frequency we use to value investments to reduce societal vulnerability. The true probability, however, is not observed. The averages in Table 2.1 merely represent an estimate of the true rates based on 58 years of data. The "normal" number of tornadoes does not occur each year, and we observe active years for tornadoes (e.g., 2004) and years with less activity (e.g., 2002). With almost 60 years of data, we can hope that the above- and below-normal years will balance out, but we have no guarantee that the average of any of our measures of frequency over the period of 1950 to 2007 equals the true, unobserved frequency. It's possible that the last 60 years have been an unusually active (or inactive) period for tornadoes. The averages in the absence of a trend represent our best guess of the true tornado frequencies, but the potential exists for even a 60-year average to deviate from the true frequency, and we must account for the potential variation.

We can approach this problem by considering the 58 years of data as a sample drawn from the true distribution of tornado activity, and construct confidence intervals for the various measures of tornado rate. The exercise is simple but assumes significant practical importance. An investment that yields expected benefits in excess of costs based on the mean tornado rate may have greater costs than benefits for lower rates consistent with the 58-year averages, and an investment that is not worthwhile at the mean rate may be worthwhile at higher rates within the confidence interval. Confidence intervals for tornado activity are thus important in assessing the value to society of protective investments. A protective measure that yields benefits in excess of costs at the lowest tornado rates in the confidence interval is probably a wise investment.

Table 2.5 reports the 99% confidence intervals for our four measures of tornado activity using the mean and standard deviation of the annual totals for 1950 through 2007. The 99% confidence interval for the true, unobserved

TABLE 2.5. Confidence Intervals for Tornado Frequency, 1950–2007

Frequency Measure	C. I. Lower Bound	Mean	C.I. Upper Bound
Tornado Count	767.5	874.0	980.4
F2+ Tornado Count	163.5	188.3	213.1
Damage Area	287.5	334.3	381.2
F2+ Damage Area	230.7	273.3	305.8

TABLE 2.6. Confidence Intervals for Tornado Frequency, 1978–2007

Frequency Measure	C. I. Lower Bound	Mean	C.I. Upper Bound
Tornado Count	937.2	1068	1199
F2+ Tornado Count	109.2	146.1	183.0
Damage Area	243.4	313.6	383.9
F2+ Damage Area	183.7	247.7	311.7

number of tornadoes per year is 768 to 980, so the upper and lower bounds are within about 12% of the mean value. The confidence intervals for the other measures are slightly larger as a percentage of the mean. Tornado probability is inversely proportional to the damage area, so the ratio of damage areas indicates the ratio of the probabilities. Thus we see that the 99% confidence interval indicates that the overall tornado probability might differ by 14% from the mean level, and the probability of F2 and stronger damage might differ by almost 16% from the mean value. Overall, we can conclude that the true national tornado rates are likely to be within about 15% of the averages.

Although the lack of a trend suggests we can use all six decades of records to estimate confidence intervals, climatology normals are usually calculated using 30 years of data, so Table 2.6 reports confidence intervals constructed using annual totals from 1978 to 2007. As we reduce the number of years of observations used to construct the mean, the sample standard deviation tends to increase, and this will widen the confidence interval. The means of each measure of tornado frequency calculated over the last 30 years also differ from the 58-year means: Tornadoes per year are over 20% higher, F2+ tornadoes are 20% lower, and the mean damage areas are about 10% lower. We are particularly interested in the combined effect of these two factors on the upper bound of the confidence intervals. But as we see in comparing Tables 2.5 and 2.6, the upper bounds of the intervals for the damage area frequencies over the two periods are within 2% of each other. Therefore, using only recent data provides no indication that the maximum tornado probabilities consistent with observed means are significantly higher than for the entire 58-year sample. The lower bounds of the confidence intervals using 30 years of data are notably smaller than for the full period: 15% lower for the damage areas of all tornadoes and 20% lower for the damage areas of F2 and stronger tornadoes. Thus, an investment that is on the margin of cost effectiveness using tornado probabilities estimated over the entire period may not be worth undertaking if we consider only more recent data.

2.3. Tornado Risk Across States

Tornado risk is not equal across the nation: "Tornado Alley"[5] is much more at risk than New England or west of the Rocky Mountains. Due to the differences in tornado risk, some protective investments, regulatory responses, or actions by the NWS might be worthwhile only in high-risk parts of the country. To explore the variation in tornado risk, Table 2.7 reports our four measures of tornado frequency calculated for each of the contiguous 48 states. Since 1950, Texas has experienced the most tornadoes at 7,539, followed by Kansas and Oklahoma; all states have experienced tornadoes, but 8 have had fewer than 100 tornadoes, led by Rhode Island at 9, or about one every six years. Florida has the highest state tornado rate at 9.4 per 10,000 mi^2, followed by Oklahoma (at 7.7), Kansas (6.9), Iowa (6.3), and Illinois (6.0). The states with the lowest tornado rates are Arizona (.32), Washington (.24), Utah (.24), Oregon (.17), and Nevada (.11). The tornado rate in Florida is 85 times greater than the rate in Nevada, a difference of almost two orders of magnitude between the highest- and lowest-rate states.

Florida is not popularly viewed as the most tornado-prone state despite its top rank in tornado rate. The perception of Florida as a modest-risk state is borne out by the other measures of frequency. Florida ranks 29th in the probability of damage, 12th in the rate of F2 and stronger tornadoes, and 26th in the probability of F2 and stronger damage. Many Florida tornadoes are short and weak. The state with the highest annual probability of tornado damage is Mississippi at .000415; to place this number in perspective, the return period for tornado damage in Mississippi is about 2,400 years, so tornadoes are very infrequent events. In comparison, the annual probability of hurricane landfall in South Florida is greater than .1, or less than 10 years on average between hurricane landfalls, while the standard for flood risk is the 100-year flood plain, or a .01 annual probability event. Of course, the 2,400-year return period for Mississippi does not mean that a residence