



# Severe Thunderstorms and Tornadoes in the United States

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## Summary

Severe thunderstorms and tornadoes affect communities across the United States every year, causing fatalities, destroying property and crops, and disrupting businesses. Tornadoes are the most destructive products of severe thunderstorms, and second only to flash flooding as the cause for most thunderstorm-related fatalities. Damages from violent tornadoes seem to be increasing, similar to the trend for other natural hazards—in part due to changing population, demographics, and more weather-sensitive infrastructure—and some analysts indicate that losses of \$1 billion or more from single tornado events are becoming more frequent.

Policies that could reduce U.S. vulnerability to severe thunderstorms and tornadoes include improvements in the capability to accurately detect storms and to effectively warn those in harm's way. The National Weather Service (NWS) has the statutory authority to forecast weather and issue warnings. Some researchers suggest that there are limits to the effectiveness of improvements in forecasting ability and warning systems for reducing losses and saving lives from severe weather. The research suggests that, for example, social, behavioral, and demographic factors now play an increasingly important role in tornado-related fatalities.

One issue for Congress is its role in mitigating damages, injuries, and fatalities from severe thunderstorms and tornadoes. The National Science and Technology Council has recommended the implementation of hazard mitigation strategies and technologies, including some—such as conducting weather-related research and development and disseminating results—that Congress has supported through annual appropriations for the National Oceanic and Atmospheric Administration, the National Science Foundation, the Federal Emergency Management Agency, the National Aeronautics and Space Administration, and other federal agencies. Other recommended strategies include land use and zoning changes, which are typically not in the purview of Congress.

Congress attempted to clarify the federal role in mitigating damages from windstorms (including tornadoes and thunderstorms) by passing the National Windstorm Impact Reduction Act of 2004 (P.L. 108-360). It is not evident whether the program made progress toward its objective: achievement of major measurable reductions in the losses of life and property from windstorms. Authorization for the program expired at the end of FY2008. In the 113<sup>th</sup> Congress, legislation introduced in the House (H.R. 1786) would reauthorize the wind hazards program through FY2016. Similar legislation was introduced in the House and Senate in the 112<sup>th</sup> Congress, but no action was taken.

It is not clear whether changes to climate over the past half-century have increased the frequency or intensity of thunderstorms and tornadoes, or whether climate changes were responsible for the intense and destructive tornado activity in 2011, or for the extremely destructive EF-5 tornado that struck Moore, Oklahoma, on May 20, 2013. An issue for Congress is whether future climate change linked to increases in greenhouse gas emissions will lead to more frequent and more intense thunderstorms and tornadoes, and whether efforts by Congress to mitigate long-term climate change will reduce potential future losses from thunderstorms and tornadoes.

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## Overview

Severe thunderstorms and tornadoes affect communities across the United States every year, causing fatalities, destroying property and crops, and disrupting businesses. State and local governments are typically the first to respond to the consequences of extreme weather events, but the federal government has responsibilities for forecasting and issuing warnings to citizens and communities lying in harm's way. When severe weather catastrophes overwhelm the resources of state and local governments, the Stafford Act authorizes the President to issue major disaster or emergency declarations, resulting in the distribution of a wide range of federal aid to those affected.<sup>1</sup> Also, U.S. Department of Agriculture programs, such as federal crop insurance and emergency disaster loans, can help farmers recover financially from severe weather disasters even without a presidential disaster declaration.<sup>2</sup>

Many observers note that although the number of lives lost each year to natural hazards in the United States has decreased, the costs of major disasters continues to rise.<sup>3</sup> According to the National Science and Technology Council: "Due to changes in population demographics and more complex weather-sensitive infrastructure, Americans today are more vulnerable than ever to severe weather events caused by tornadoes, hurricanes, severe storms, heat waves, and winter weather."<sup>4</sup> Whether this assertion is accurate, and whether a trend of increasing costs due to extreme thunderstorms and tornadoes exists, are matters of debate (see discussion below, for example, on "normalizing" costs of tornadoes). However, despite well-documented improvements in severe thunderstorm and tornado detection and warning systems over the past 100 years, outbreaks of these types of storms still have the capability of causing enormous damage and loss of life in the United States in the 21<sup>st</sup> century.

For example, in 2011 a series of tornado and severe weather outbreaks caused over 550 fatalities in the United States, and approximately \$28 billion in total property damage.<sup>5</sup> The total fatalities in 2011 were the most since modern record-keeping began in 1950, and 2011 ties with 1936 as the second-deadliest year for tornado deaths (in 1925, 794 tornado-related deaths were reported).<sup>6</sup> Nearly 1,700 tornadoes were reported in 2011,<sup>7</sup> including 59 "killer tornadoes," according to the Storm Prediction Center of the National Oceanic and Atmospheric Administration, making 2011 one of the top three most active tornado years since 1950.<sup>8</sup> The active 2011 year was followed,

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<sup>1</sup> For more information about the Robert T. Stafford Disaster Relief and Emergency Assistance Act (P.L. 100-707, which amended and renamed the Disaster and Relief Act of 1974), see CRS Report RL33053, *Federal Stafford Act Disaster Assistance: Presidential Declarations, Eligible Activities, and Funding*, by (name redacted).

<sup>2</sup> For more information on federal agricultural assistance, see CRS Report RS21212, *Agricultural Disaster Assistance*, by (name redacted).

<sup>3</sup> National Science and Technology Council, Committee on Environment and Natural Resources, Subcommittee on Disaster Reduction, "Grand Challenges for Disaster Reduction" (Washington, DC, June 2005), p. 1. Hereafter referred to as Grand Challenges for Disaster Reduction (2005).

<sup>4</sup> *Ibid.*, p. 4.

<sup>5</sup> National Oceanic and Atmospheric Administration, National Climatic Data Center, *Tornadoes – Annual 2011*, <http://www.ncdc.noaa.gov/sotc/tornadoes/2011/13>.

<sup>6</sup> *Ibid.*

<sup>7</sup> NOAA, National Weather Service, Storm Prediction Center, *Latest U.S. Tornado Statistics*, <http://www.spc.noaa.gov/climo/online/monthly/newm.html#2011>.

<sup>8</sup> National Oceanic and Atmospheric Administration, National Climatic Data Center, *Tornadoes – Annual 2011*.

however, by a year with far fewer reported tornadoes (939). In fact, 2012 and 2010 had 22 and 21 “killer tornadoes,” respectively, resulting in 70 deaths in 2012 and 45 deaths in 2010.

In 2013, the January through April number of reported tornadoes (114 reported, 101 reports still pending) was running well below the 1991-2010 average tornado count for that four-month period (300 tornadoes).<sup>9</sup> However, on May 20, 2013, the town of Moore, Oklahoma, was struck by a large and extremely destructive tornado (ranked EF-5, the most destructive on a scale of 0-5; EF rankings, or intensity scale, for tornadoes are discussed in **Appendix**). Preliminary reports indicate dozens of fatalities due to this single tornado.<sup>10</sup> Although it is too early in 2013 to tell whether the May 20 tornado is an anomaly, or represents the beginning of an active and deadly tornado season, it does confirm that the bulk of damage and fatalities are caused by the largest and most powerful tornadoes (EF-4 and EF-5), even though the large majority of tornadoes that are reported each year are EF-0 through EF-3. This report discusses issues that may be of interest to Congress in three general categories: (1) forecasting and issuing warnings for severe thunderstorms and tornadoes; (2) the role of mitigation; and (3) the effect of climate change. It also describes the role of the National Weather Service in forecasting severe weather and communicating the risk to communities and individuals. The **Appendix** describes in more detail the risk these hazards pose to communities and individuals; where, when, how, and why they occur in the United States; and what damage they may cause.

## Issues for Congress

This report focuses on the risk from severe thunderstorms and tornadoes to the public and infrastructure, the federally sponsored forecast and warning systems, federally backed efforts to improve the scientific understanding of severe weather phenomena, and efforts to mitigate the risk of catastrophe. Congress has oversight and funding responsibilities for the federal agencies charged with these tasks. At issue is whether those programs are effective at reducing damage, injuries, and loss of life from severe thunderstorms and tornadoes.

Also at issue is the concept of disaster resilience; namely, those precautions and strategies—such as improved building materials and structural systems—that decrease the vulnerability of communities and individuals to severe thunderstorms and tornadoes. The federal role in supporting programs of hazard mitigation, such as those included in the National Windstorm Impact Reduction Act of 2004 (P.L. 108-360), has been a concern for Congress. Authorization for the Windstorm Impact Reduction Program expired at the end of FY2008, and it is not clear whether the program achieved any of the goals specified in the legislation. Legislation to reauthorize appropriations and make changes to the statute was introduced on April 26, 2013 (H.R. 1786). The House has not taken action on the bill.

Projections of a changing climate for the United States and the possibility of a more intense hydrologic cycle (e.g., more intense storms, rainfall, heat waves, and other phenomena) have raised questions about whether the costs of severe weather disasters will continue to rise in the future. Observers note that extreme events, more than shifts in average climate conditions, drive

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<sup>9</sup> NOAA National Climatic Data Center, *State of the Climate: Tornadoes for April 2013*, published online May 2013, retrieved on May 21, 2013, from <http://www.ncdc.noaa.gov/sotc/tornadoes/2013/4>.

<sup>10</sup> John Eligon et al., “Crews Search for Survivors in Oklahoma After Tornado,” *New York Times*, May 21, 2013, [http://www.nytimes.com/2013/05/22/us/oklahoma-tornado.html?hp&\\_r=0](http://www.nytimes.com/2013/05/22/us/oklahoma-tornado.html?hp&_r=0).

changes in natural and human systems.<sup>11</sup> According to the U.S. Global Change Research Program:

In the future, with continued global warming, heat waves and heavy downpours are very likely to further increase in frequency and intensity. Substantial areas of North America are likely to have more frequent droughts of greater severity. Hurricane wind speeds, rainfall intensity, and storm surge levels are likely to increase. The strongest cold season storms are likely to become more frequent, with stronger winds and more extreme wave heights.<sup>12</sup>

Another issue for Congress may be distinguishing how much of the higher costs of severe weather-related disasters may be due to changing demographics in hazard-prone areas from the effects of any increased frequency and intensity of extreme weather events due to climate change.<sup>13</sup>

## A Focus on Local Warnings and Forecasts for the National Weather Service

The National Weather Service (NWS) receives the most funding of any agency or program within NOAA's budget, and the local warnings and forecasts (LW&F) program receives approximately 70% of the NWS funding each year. **Table 1** shows appropriations for the LW&F program, NWS, and overall NOAA appropriations since FY2009.<sup>14</sup> As **Table 1** shows, spending on LW&F has increased at a slightly higher percentage than total NWS spending over the five-year period, but has increased at a lower percentage than the overall NOAA budget over the same time frame.

The LW&F program averages nearly three-quarters of the NWS budget each year, indicating that short-term weather prediction and warning is a high priority for NWS and for NOAA, in accord with its statutory authority.<sup>15</sup> Reports from RAND and other research organizations suggest, however, that reorienting research and development funding toward longer-term loss reduction efforts—particularly for weather-related hazards—might provide the nation with more long-lasting solutions to reducing natural disaster losses.<sup>16</sup> These recommendations favor increased

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<sup>11</sup> C. S. Parmesan et al., "Impacts of extreme weather and climate on terrestrial biota," *Bulletin of the American Meteorological Society*, vol. 83 (2000), pp. 443-450.

<sup>12</sup> U.S. Climate Change Science Program, Synthesis and Assessment Product 3.3, "Weather and Climate Extremes in a Changing Climate" (Washington, DC, June 2008), p. VII. Hereafter referred to as CCSP, *Weather and Climate Extremes in a Changing Climate* (2008).

<sup>13</sup> For example, see the paper by Kevin M. Simmons et al., "Normalized Tornado Damages in the United States: 1950-2011," *Environmental Hazards*, vol. 12, no. 2 (2013). Published online December 5, 2012, [http://sciencepolicy.colorado.edu/admin/publication\\_files/2012.31.pdf](http://sciencepolicy.colorado.edu/admin/publication_files/2012.31.pdf).

<sup>14</sup> These values do not reflect spending on NOAA programs included in P.L. 111-5, the American Recovery and Reinvestment Act. The act provided \$230 million for activities under the Operations, Research, and Facilities account; and \$600 million under the Procurement, Acquisitions, and Construction account. For more information on FY2010 NOAA funding, see CRS Report R40644, *Commerce, Justice, Science, and Related Agencies: FY2010 Appropriations*, coordinated by (name redacted), (name redacted), and (name redacted).

<sup>15</sup> 15 U.S.C. §313. A more detailed description of the forecasting and warning activities at the NWS is provided below.

<sup>16</sup> Charles Meade and Megan Abbott, "Assessing federal research and development for hazard loss reduction," prepared for the Office of Science and Technology Policy (RAND, Arlington, VA.), 2003, 65 p. See also "Advice to the New Administration and Congress: Actions to Make our Nation Resilient to Severe Weather and Climate Change," a document produced by the University Corporation for Atmospheric Research and seven other stakeholder organizations; at <http://www.ucar.edu/td/>.

focus on mitigation techniques and R&D to reduce loss of life and property from severe weather hazards.

**Table I. LW&F, NWS and Total NOAA Funding from FY2009 to FY2014**  
(millions of dollars, not adjusted for inflation)

	FY2009	FY2010	FY2011	FY2012	FY2013 <sup>a</sup>	FY2014 Request	Change FY09-FY13
LW&F	\$682.3	\$710.6	\$698.3	\$720.4	\$734.5	\$736.3	7.7%
NWS	\$958.9	\$999.8	\$976.5	\$991.9	\$1,002	\$1,050	4.5%
NOAA <sup>a</sup>	\$4,373.9	\$4,748.4	\$4,596.9	\$4,906.6	\$4,936.6	\$5,447.7	12.9%

**Source:** NOAA, Blue Book (Budget Summary) for FY2009 through FY2014.

**Notes:** LW&F is the local warnings and forecasts program within NWS. Funding values used as reported in the Control Tables chapter of the budget summaries (not adjusted for inflation) for FY2009-FY2014. Table does not include \$830 million provided to NOAA in P.L. 111-5, the American Recovery and Reinvestment Act (ARRA).

a. Values represent annualized CR for FY2013.

b. FY2009-FY2013 values reflect the total enacted amounts, as reported in the Control Tables chapter of the budget summaries in the NOAA Blue Book.

## A Shift in Direction?

Language in the most recent NWS strategic plan appears to reflect some shift in direction as recommended by RAND and others. In the draft plan, the NWS states, “We must go beyond producing accurate forecasts and timely warnings to better understanding and anticipating the likely human and economic impacts of such events.”<sup>17</sup> The strategic plan describes an overarching paradigm for the NWS as “impact-based decision support services,” a concept that appears to take into consideration how the information provided in NWS local warnings and forecasts could be best utilized by public safety officials.

In addition to the shift to “impact-based decision support services,” the NWS strategic plan identifies the need for scientific and technical advancements to support such services.<sup>18</sup> This could include advances in observation platforms, computing systems, and other facilities and instruments, although the draft plan focuses on “advanced information management approaches” that would be necessary to ingest and interpret all of the real-time information from instruments and systems that collect severe weather data. According to the plan, “These measures will extend the window America has to prepare for weather-dependent events that impact society.”<sup>19</sup> The current emphasis at the NWS on short-term local forecasting and warnings contrasts with a longer-term, anticipatory outlook that would focus on mitigation, although the two approaches are not mutually exclusive. The language of the strategic plan seems to suggest a longer-term approach in complement with the current short-term forecast and warning emphasis. Each approach could provide benefits in an overall strategy of increasing resilience to extreme weather events such as severe thunderstorms and tornadoes.

<sup>17</sup> NOAA, “Weather-Ready Nation,” NOAA’s National Weather Service Strategic Plan 2011, p. 7, [http://www.nws.noaa.gov/com/weatherreadynation/files/strategic\\_plan.pdf](http://www.nws.noaa.gov/com/weatherreadynation/files/strategic_plan.pdf).

<sup>18</sup> Ibid., p. 8.

<sup>19</sup> Ibid.

## Mitigation

The National Science and Technology Council (NSTC) noted that the nation’s primary focus on disaster response and recovery is “an impractical and inefficient strategy for dealing with these ongoing threats. Instead, communities must break the cycle of destruction and recovery by enhancing their *disaster resilience*” (italics added).<sup>20</sup> Among the six “Grand Challenges” identified in its report, the NSTC recommended that communities implement hazard mitigation strategies and technologies, such as development of advanced construction materials and structural systems that allow facilities to “remain robust in the face of all potential hazards.”<sup>21</sup> The report also recommended nonstructural mitigation measures, such as land use and zoning regulations that recognize the risk of natural hazards. Land use measures, such as zoning laws and building codes, are typically prerogatives of state and local governments, and thus the federal role in that aspect of hazard mitigation is limited.<sup>22</sup>

### The National Windstorm Impact Reduction Program

The federal role in developing disaster-resilient materials and structures, and evaluating their relative effectiveness in mitigating damages from severe thunderstorms and tornadoes, has been unclear. Congress attempted to clarify the federal role in mitigating damages from windstorms (including tornadoes and thunderstorms) by passing the National Windstorm Impact Reduction Act of 2004 (P.L. 108-360). The legislation identified three primary mitigation components: (1) improved understanding of windstorms; (2) windstorm impact assessment; and (3) windstorm impact reduction. Authorization of appropriations under P.L. 108-360 for the National Windstorm Impact Reduction Program expired on September 30, 2008.

It is not clear whether the program made progress toward its objective: achievement of major measurable reductions in the losses of life and property from windstorms. It is difficult to determine what levels of funding were allocated to the program because Congress has never enacted a specific appropriation for the National Windstorm program. In addition, the four agencies responsible for implementing the program—the National Science Foundation (NSF), the National Institute of Standards and Technology (NIST), NOAA, and the Federal Emergency Management Agency (FEMA)—have not identified a line item for the program in their annual budget justifications.

### Reauthorizing the National Windstorm Impact Reduction Program: H.R. 1786

On April 26, 2013, H.R. 1786 was introduced to reauthorize appropriations and make several changes to the National Windstorm Impact Reduction Program, first authorized in 2004 by P.L. 108-360. The bill states that the purpose of the program is

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<sup>20</sup> Grand Challenges for Disaster Reduction (2005), p. 1.

<sup>21</sup> *Ibid.*, p. 8. For example, the report observes that the cumulative impacts on the hydrology of flooding, including flash floods, must be incorporated into land use measures.

<sup>22</sup> See also testimony given by Sharon Hays, Associate Director and Deputy Director for Science, Office of Science and Technology Policy, to the Subcommittee on Technology and Innovation, House Science and Technology Committee, Hearing: *The National Windstorm Impact Reduction Program: Strengthening Windstorm Hazard Mitigation* (July 24, 2008).



to achieve major measurable reductions in the losses of life and property from windstorms through a coordinated Federal effort, in cooperation with other levels of government, academia, and the private sector, aimed at improving the understanding of windstorms and their impacts and developing and encouraging the implementation of cost-effective mitigation measures to reduce those impacts.

In the legislation, the Director of NIST would be responsible for planning and coordinating the program and NIST would be the lead agency in the four-agency program.<sup>23</sup> The other three agencies given responsibilities for the program would be FEMA, NOAA, and NSF. In addition to acting as lead agency, NIST would carry out research and development to improve model codes, standards, design guidance, and construction and retrofit practices for buildings, other structures, and lifelines.<sup>24</sup> FEMA would support the development of risk assessment tools and mitigation techniques, data collection and analysis, and dissemination information and implementation of mitigation measurements by households, businesses, and communities. NOAA would support atmospheric sciences research and data collection to help understand how windstorms behave and how they affect buildings, other structures, and lifelines. Lastly, NSF would fund engineering and atmospheric sciences research to better understand windstorms and their impact on buildings, structures, and lifelines.

H.R. 1786 would authorize appropriations for the four program agencies over a three-year period through FY2016 for the following amounts:

- NIST—\$16.5 million;
- NSF—\$34.2 million;
- FEMA—\$6.0 million;
- NOAA—\$7.5 million.

The total authorized amount for the program agencies from FY2014 through FY2016 would be \$64.2 million.

In addition, the legislation would establish an advisory committee to include representatives of academic and research institutions, industry standards development organizations, emergency management agencies, state and local government, and business communities. None of the members of the advisory committee would be employees of the federal government.

## **Other Legislation**

Many Members of Congress have recognized increased vulnerability to tornadoes of people living in manufactured housing. In the 112<sup>th</sup> Congress, H.R. 320, CJ's Home Protection Act of 2009, was introduced and referred to the House Financial Services Committee. The bill would have amended § 604 of the National Manufactured Housing Construction and Safety Standards Act of 2004 (42 U.S.C. 5403) to require that all manufactured homes be equipped with a NOAA Weather Radio.<sup>25</sup> NOAA Weather Radios would presumably give the residents of manufactured

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<sup>23</sup> Under the P.L. 108-360, the Director of the Office of Science and Technology Policy was responsible for establishing an interagency working group and for selecting which agency would serve as chair of the working group.

<sup>24</sup> Lifelines are essential utility and transportation systems.

<sup>25</sup> NOAA Weather Radio broadcasts official NWS warnings, watches, forecasts, and other hazard information 24 hours (continued...)

homes a better chance of receiving tornado warnings and allow them to take precautionary measures. In the 111<sup>th</sup> Congress, the House passed similar legislation, H.R. 320, but the Senate did not act on the bill.<sup>26</sup> As of May 22, 2013, similar legislation has not been introduced in the House or Senate.

In 2003, the 108<sup>th</sup> Congress passed the Tornado Shelters Act (P.L. 108-146), which amended the Housing and Community Development Act of 1974 (42 U.S.C. 5305(a)) to authorize communities to use Community Development Block Grant (CDBG) funds for construction of tornado-safe shelters in manufactured home parks. The law was aimed at communities of at least 20 manufactured homes that consist predominately of low- and moderate-income residents. To be eligible, the community has to be located in a state that was struck by a tornado during the fiscal year when funds were made available or during the previous three fiscal years.<sup>27</sup>

## Climate Change and Severe Weather

According to several reports that synthesize recent findings in the scientific literature, it is forecast that there are likely to be changes in the intensity, duration, frequency, and geographic extent of weather and climate extremes as the Earth continues to warm.<sup>28</sup> These changes may result in continuing the upward trends that have already been observed, such as the frequency of unusually warm nights, frequency and intensity of extreme precipitation events, and the length of the frost-free season.<sup>29</sup> However, the evidence is unclear as to whether the frequency and intensity of severe thunderstorms and tornadoes has increased or will increase in the future due to climate change. For example, the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment report stated that there was insufficient evidence to determine whether trends existed in small-scale phenomena such as tornadoes.<sup>30</sup> A 2012 IPCC report which focused on extreme events due to climate change made a similar observation: “There is *low confidence* in observed trends in small spatial-scale phenomena such as tornadoes and hail because of data inhomogeneities and inadequacies in monitoring systems” (emphasis in the original).<sup>31</sup>

Part of the difficulty in sorting out trends in frequency and intensity of severe thunderstorms and tornadoes lies in the way they have been observed and reported. For example, the number of annual reported tornado occurrences has doubled between 1954 and 2003.<sup>32</sup> Some studies indicate

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(...continued)

a day, seven days a week, to all 50 states, adjacent coastal waters, Puerto Rico, the U.S. Virgin Islands, and the U.S. Pacific Territories. See <http://www.nws.noaa.gov/nwr/>.

<sup>26</sup> Similar legislation, H.R. 2787, was also passed by the House in the 110<sup>th</sup> Congress, but the Senate did not act on its version of the bill, S. 2724.

<sup>27</sup> For more information on the CDBG program, see CRS Report RL33330, *Community Development Block Grant Funds in Disaster Relief and Recovery*, by (name redacted).

<sup>28</sup> CCSP, *Weather and Climate Extremes in a Changing Climate* (2008); IPCC, *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II, and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Geneva, Switzerland), 2007.

<sup>29</sup> CCSP, *Weather and Climate Extremes in a Changing Climate* (2008), p. 35.

<sup>30</sup> IPCC, *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II, and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Geneva, Switzerland), 2007.

<sup>31</sup> IPCC, 2012, Summary for Policy Makers, *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*, A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK, and New York, USA, p. 6.

<sup>32</sup> CCSP, *Weather and Climate Extremes in a Changing Climate* (2008), p. 76.

that the doubling reflects changes in observing and reporting. When the apparent trend produced by these changes is removed, the adjusted data show little or no trend in the number of reported tornadoes since the 1950s.<sup>33</sup>

Reports of severe thunderstorms without associated tornadoes increased by a factor of 20 between 1955 and 2004.<sup>34</sup> However, researchers indicate that the increase is mainly in reports of marginally severe thunderstorms, and suggest that the evidence for a change in the long-term trend of severe thunderstorms is lacking.<sup>35</sup> In studies that re-analyze environmental conditions that could have produced severe thunderstorms, changes in the frequency of those environmental conditions are observed. However, the record of observations may not be long enough to determine the range of natural variability.<sup>36</sup> Given the uncertainty, it is not yet possible to determine if these changes are due to natural variability or changing climatic conditions from greenhouse warming.

Excessive rainfall from severe thunderstorms may trigger flash floods, which are typically responsible for most flood-related deaths in the United States each year. According to researchers, one of the clearest trends over the last 30 years has been an increase in the frequency and intensity of heavy precipitation events.<sup>37</sup> Despite this clear trend, the relationship between these heavy precipitation events and the frequency and intensity of severe thunderstorms is not clear, nor do scientists agree on the relationship between increased precipitation and streamflow extremes, such as flooding.<sup>38</sup> As a further complication, studies of trends in streamflow using similar data have produced different results.<sup>39</sup> Also, some human activities that alter the landscape, such as building dams and creating large reservoirs, may mask the influence of climatic changes on streamflow.<sup>40</sup>

Climate models suggest that with continued global warming due to increasing concentrations of atmospheric greenhouse gases, precipitation intensity is projected to increase.<sup>41</sup> One set of research findings, for example, indicates that global precipitation increased by 7.4% per degree Celsius rise during 1987-2006 (plus or minus 2.6%).<sup>42</sup> Other researchers suggest that a 20-year period is too short to infer any long-term changes, but that the relationship between warming and more precipitation likely holds true.<sup>43</sup> It is unclear whether any intensification of precipitation is or will be linked in the future to more severe thunderstorms, and to more severe or more frequent

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<sup>33</sup> Ibid., Figure 2.25.

<sup>34</sup> Ibid., p. 77.

<sup>35</sup> Ibid.

<sup>36</sup> Ibid.

<sup>37</sup> Ibid., pp. 46-47.

<sup>38</sup> Personal communication, Kenneth Kunkel, Executive Director of the Division of Atmospheric Science, Desert Research Institute, Reno, NV, Sept. 22, 2009.

<sup>39</sup> See, for example, H. F. Lins and J. R. Slack, "Streamflow trends in the United States," *Geophysical Research Letters*, vol. 26 (1999), pp. 227-230; and P. Ya. Groisman et al., "Heavy precipitation and high streamflow in the contiguous United States: trends in the 20<sup>th</sup> century," *Bulletin of the American Meteorological Society*, vol. 82 (2001), pp. 219-246.

<sup>40</sup> CCSP, *Weather and Climate Extremes in a Changing Climate* (2008), p. 53.

<sup>41</sup> Ibid., p. 102.

<sup>42</sup> F. J. Wentz et al., "How much more rain will global warming bring?," *Science*, vol. 317, no. 5835 (2007), pp. 233-235.

<sup>43</sup> Michael Previdi and Beate G. Liepert, "Interdecadal variability of rainfall on a warming planet," *Eos*, vol. 89, no. 21 (May 20, 2008), pp. 193-195.

flash floods. However, precipitation is, and will likely continue to be, unevenly distributed across different regions of the country. Researchers generally expect that currently wet regions of the country may get wetter, and dry regions may get drier.

### **Are Damage Costs Increasing Due to Tornadoes and Severe Thunderstorms?**

The National Climatic Data Center (NCDC) of NOAA bills itself as the “nation’s scorekeeper” for addressing severe weather and climate events in their historical perspective.<sup>44</sup> It keeps a tally of the weather and climate events that have had the greatest economic impact since 1980, and uses \$1 billion of damage as a threshold to count whether events are significant or not. The NCDC adjusts its dollar values using the Consumer Price Index (CPI).<sup>45</sup>

It is unclear what the \$1 billion threshold means in terms of its explanatory power for a given weather or climate-related disaster (for example, would a \$0.9 billion or a \$1.1 billion threshold indicate something significantly different than a \$1.0 billion disaster?). However, it is a convenient, albeit somewhat arbitrary, number that can serve as a proxy for counting disasters responsible for damage of a certain magnitude over time. The billion dollar disaster meme has also been used by some advocacy groups as an indicator of the influence of greenhouse gas-driven climate change on increasing the destructive magnitude of weather and climate related disasters.<sup>46</sup>

Although the NCDC adjusts its disaster loss estimates for inflation using the CPI, others have called into question whether the CPI is sufficient to account for the many factors that contribute to changes in the costs of disaster damage over time. For example, one 2013 report examined tornado damage from 1950 to 2011 and adjusted, or “normalized,” the cost estimates by including changes in inflation and wealth at the national level, and changes in population, income, and housing units at the county level.<sup>47</sup> The study found that, using several different methods, tornado damages have declined since 1950, even considering the extremely damaging tornado outbreaks of 2011. However, the study also noted that the 2011 season is a reminder that maximum damage levels have the potential to increase if societal change leads to increased exposure of wealth and property.

Another study concludes that there is an increasing trend in aggregate annual losses indicated in the \$1 billion disaster dataset used by NCDC of about 5% per year.<sup>48</sup> The study notes that distribution of damage and frequency of disasters over the 1980-2011 period is dominated by tropical cyclone damage. Trends in damage due to tropical cyclones appear to be linked, in part, to variations in insurance participation rates. The study observes that increasing trends in crop

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<sup>44</sup> National Climatic Data Center, NOAA, *Billion Dollar Weather/Climate Disasters*, <http://www.ncdc.noaa.gov/billions/overview>.

<sup>45</sup> The NCDC states that it is working on examining possible inaccuracies and biases and methodologies used to develop its loss assessments from 1980 to 2012.

<sup>46</sup> See, for example, Daniel J. Weiss and Jackie Weidman, Center for American Progress, *Going to Extremes: The \$188 Billion Price Tag From Climate-Related Extreme Weather*, February 12, 2013, <http://www.americanprogress.org/issues/green/news/2013/02/12/52881/going-to-extremes-the-188-billion-price-tag-from-climate-related-extreme-weather/>; and Julia Whitty, Grist, *The New Normal: Billion Dollar Disasters*, August 3, 2011, <http://grist.org/climate-change/2011-08-03-the-new-normal-billion-dollar-disasters/>.

<sup>47</sup> Simmons et al., 2013, “Normalized Tornado Damage in the United States: 1950-2011.”

<sup>48</sup> Adam B. Smith and Richard W. Katz, “U.S. Billion-dollar Weather and Climate Disasters: Data Sources, Trends, Accuracy and Biases,” *Natural Hazards*, vol. 67, no. 2, June 2013, pp. 387-410.

losses are complicated by a major expansion of the federally subsidized crop insurance program. The report also concludes that the net effect of uncertainties and biases in the billion dollar dataset has been an overall underestimation of the average loss due to weather and climate events of approximately 10%-15%.

### **The 2011 Tornadoes: A Link to Climate Change?**

Are 2011 tornado outbreaks linked to changes in climate that may be the result of greenhouse gases emitted to the atmosphere from human activities? Some commentators stated that there was such a link, and that human-induced climate change affects all climatic events today, in some growing but unquantified degree: “More extreme and violent climate is a direct consequence of human-caused climate change (whether or not we can determine if *these* particular tornado outbreaks were caused or worsened by climate change)” (emphasis in the original).<sup>49</sup>

Other sources point to the difficulties in attributing the recent tornado outbreaks to climatic factors distinguishable from the other factors discussed above, such as changed instrumentation (e.g., implementation of WSR-88D Doppler radar after 1990), increases in population, and public awareness via spotter networks, all which tend to lead to increased tornado counts particularly for weak tornadoes.<sup>50</sup> In a preliminary analysis of the April 2011 tornado outbreak, NOAA described ways to diagnose whether other factors, other than simply counting tornadoes, could reveal changes to large-scale time-averaged climate variables for April.<sup>51</sup> The preliminary analysis attempted to discern whether large-scale conditions may have become more favorable for violent storms to occur over the lower Mississippi Valley since 1979. NOAA’s preliminary analysis concluded that a discernible trend was not present over the past 30 years, and that unless new findings suggested otherwise, “... a claim of attribution (to human impacts) is thus problematic, although it does not exclude that a future change in such environmental conditions may occur as anthropogenic greenhouse gas forcing increases.”<sup>52</sup>

### **Other Factors Contributing to Risk From Tornadoes**

Most tornado fatalities occur within housing structures, unlike fatalities from floods, which occur in vehicles. This indicates that people are more likely to seek shelter during tornadic events; however, the risk of injury or death seems to depend on what type of housing stock they choose for shelter. For example, one study indicated that manufactured houses, such as mobile homes, are particularly vulnerable to tornadoes. Mobile home deaths accounted for an average of 44% of all deaths caused by tornadoes between 1985 and 2005, and showed an increasing trend over the 20-year period.<sup>53</sup> During the same time period, tornado-related deaths within permanent homes fluctuated between 20% and 30%, and deaths in vehicles decreased to 9.9% of all tornado-related

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<sup>49</sup> Peter H. Gleick, “A Cost of Denying Climate Change: Accelerating Climate Disruptions, Death, and Destruction,” *The Huffington Post, Huffpost Green*, April 28, 2011, [http://www.huffingtonpost.com/peter-h-gleick/tornadoes-2011\\_b\\_855032.html](http://www.huffingtonpost.com/peter-h-gleick/tornadoes-2011_b_855032.html).

<sup>50</sup> NOAA, Earth System Research Laboratory, Physical Sciences Division, Preliminary Assessment of Climate Factors Contributing to the Extreme 2011 Tornadoes, updated July 8, 2011, <http://www.esrl.noaa.gov/psd/csi/events/2011/tornadoes/climatechange.html>.

<sup>51</sup> NOAA, Preliminary Assessment of Climate Factors Contributing to the Extreme 2011 Tornadoes, July 8, 2011.

<sup>52</sup> Ibid.

<sup>53</sup> Walker S. Ashley, “Spatial and Temporal Analysis of Tornado Fatalities in the United States: 1880 - 2005,” *Weather and Forecasting*, vol. 22 (December 2007), p. 1224.

deaths, on average.<sup>54</sup> The study concluded that the high percentage of mobile homes in the Southeast may be the key factor explaining why most tornado-related deaths occur in lower Arkansas, Tennessee, and lower Mississippi River valleys.

The Super Tuesday Tornado Outbreak of 2008 seems to support research results indicating that demographics and other socioeconomic and behavioral factors combine to make the mid-South regions particularly vulnerable to tornado fatalities. NOAA observed several factors consistent with research pointing to the importance of social and demographic factors in determining risk from tornadoes.<sup>55</sup> These were:

- 63% of the fatalities were in manufactured houses;
- most fatalities occurred at night;
- most areas affected by the tornadoes were heavily forested;
- many reported that February was not a month in what they perceived as “tornado season.”

## Forecasting and Warning: The Role of the National Weather Service

The NWS, at the discretion of the Secretary of Commerce, has statutory authority for weather forecasting and for issuing storm warnings (15 U.S.C. §313). The NWS provides weather, water, and climate forecasts and warnings for the United States, its territories, adjacent waters, and ocean areas.<sup>56</sup>

Each of the weather forecast offices in the NWS is equipped with technologies for observing, forecasting, and warning of severe thunderstorms and tornadoes.<sup>57</sup> These technologies include Weather Surveillance Radar (WSR-88D, also known as NEXRAD, a network of 161 radars), Automated Surface Observing Systems (ASOS)<sup>58</sup> at over 1,200 sites, access to data from two Geostationary Operational Environmental Satellites (GOES 8 and 10), and the Automated Weather Interactive Processing System (AWIPS).<sup>59</sup>

### Forecasting

Severe thunderstorm and tornado forecasts are made by the Storm Prediction Center (SPC) and local weather forecast offices. Forecasters at the SPC use numerical weather prediction models to determine if atmospheric conditions, temperature, and wind flow patterns may lead to formation

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<sup>54</sup> Ibid.

<sup>55</sup> U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Weather Service, *Super Tuesday Tornado Outbreak of February 5-6, 2008*, March 2009, p. 20.

<sup>56</sup> For more details on the organization of the NWS, <http://www.weather.gov/organization#support>.

<sup>57</sup> Joseph H. Golden and Christopher R. Adams, “The Tornado Problem: Forecast, Warning, and Response,” *Natural Hazards Review* (May 2000), p. 107.

<sup>58</sup> ASOS is a climatological observing network that generates weather reports at hourly intervals, except when weather conditions are changing rapidly.

<sup>59</sup> AWIPS is an interactive computer system that integrates meteorological and hydrological data from an array of meteorological sensors—radar, satellites, surface instruments—and enables the forecaster to prepare and issue more accurate and timely forecasts and warnings.

of severe weather. The SPC uses its suite of products to relay forecasts of organized severe weather as much as three days ahead of time, and continually refines the forecast up until the event has concluded.<sup>60</sup> The severe weather forecast process typically follows the following pattern: (1) convective outlook; (2) mesoscale discussion; (3) watch; and (4) warning.

### *Convective Outlook*

The severe weather forecast process typically begins with a forecast issued one to two days in advance of where both severe and non-severe thunderstorms are expected to occur around the country.<sup>61</sup> This is known as a convective outlook. Areas of possible severe thunderstorms are labeled slight risk, moderate risk, or high risk, depending upon the coverage and intensity of expected severe thunderstorms in a region. The outlooks are the first severe weather threat notifications that the local NWS offices and local emergency officials receive.

### *Mesoscale Discussion*

As a convective outlook area becomes more defined, a next step in the forecast process is often needed to describe an evolving severe weather threat. This is known as a mesoscale discussion.<sup>62</sup> Mesoscale discussions contain information that helps forecasters at local NWS offices understand the causes and prepare for the types of severe weather expected.

### *Watch*

If development of severe thunderstorms or tornadoes is imminent, or likely to occur in the next several hours, the next step is a severe storm watch. Such watches alert the public, aviators, and local NWS offices that environmental conditions have become favorable for the development of severe storms or tornadoes. Following the issuance of a severe storm watch, local networks of storm spotters<sup>63</sup> are activated, and forecasters in the threat area closely monitor radar imagery and spotter reports to issue the appropriate severe thunderstorm and tornado warnings.<sup>64</sup>

### *Warning*

As the severe weather threat continues to develop, the local NWS offices and the storm spotters try to detect severe thunderstorms and tornadoes using radar or other detection technology and visual evidence. When severe hail, damaging winds, or a tornado appears imminent from radar or visual evidence, local NWS offices will issue a severe thunderstorm or tornado warning as

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<sup>60</sup> The SPC suite of products includes satellite imagery, radars, surface weather stations, weather balloon soundings, wind profilers, lightning detection network, and information from local NWS offices. See <http://www.spc.noaa.gov/misc/aboutus.html>.

<sup>61</sup> NOAA Storm Prediction Center, the Severe Storms Forecast Process: Outlook to Mesoscale Discussion to Watch to Warning, at <http://www.spc.noaa.gov/misc/aboutus.html>.

<sup>62</sup> Ibid.

<sup>63</sup> Storm spotters report critical weather information in real time to the NWS from a specific location.

<sup>64</sup> NOAA Storm Prediction Center, the Severe Storms Forecast Process: Outlook to Mesoscale Discussion to Watch to Warning, at <http://www.spc.noaa.gov/misc/aboutus.html>.

appropriate. The warning contains specific language about areas at risk, time frames, specific hazards, recommended protective behavior for those at risk, and the office issuing the warning.<sup>65</sup>

## **Communicating the Severe Weather Risk**

Several methods exist to communicate alerts and warnings to the public. The NWS maintains and operates NOAA Weather Radio (NWR). NWR is a nationwide network of radio stations broadcasting continuous weather information directly from the nearest NWS office. The NWR works with the Emergency Alert System (EAS). The EAS is an automated simultaneous retransmission system that allows NWS warnings to be disseminated over most radio and television networks, and over cable and satellite TV systems.<sup>66</sup> NOAA Weather Radio broadcasts official NWS warnings, watches, forecasts, and other hazard information 24 hours a day, 7 days a week, to all 50 states and the District of Columbia, adjacent coastal waters, Puerto Rico, the U.S. Virgin Islands, and the U.S. Pacific Territories.<sup>67</sup>

Issuing severe weather warnings to the public has evolved into what some observers term a weather warning partnership: a roughly triangular exchange of information between the NWS, private forecasters and the news media, and local emergency managers. The objective of the weather warning partnership is to provide a consistent warning message to the public at risk.<sup>68</sup>

The NWS depends on weather warning partnerships with the electronic news media and local and state emergency management officials to ensure that communities are prepared for severe weather outbreaks and to further communicate the outlooks, watches, and warnings to the public.<sup>69</sup> Many emergency management officials and news media monitor NWS outlooks so that they have enough lead time for activating preparedness capabilities such as storm spotters, increasing response levels, and preparing to activate the warning communication systems. The partnership is essential in guaranteeing that there is a shared understanding of the weather threats and that accurate warning information is communicated to the public at risk. Observers have noted that this shared understanding helps prevent conflicting warnings—which could lead to delays in seeking shelter—from being communicated to the public.<sup>70</sup>

## **Summary and Conclusions**

Congress may consider several options for potentially reducing the costs from the impacts of severe thunderstorms and tornadoes: improving detection and warning systems; fostering efforts to build more resilient buildings and infrastructure; and supporting research and development to better understand why and where severe thunderstorms and tornadoes occur, as well as other

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<sup>65</sup> Joseph H. Golden and Christopher R. Adams, “The Tornado Problem: Forecast, Warning, and Response,” *Natural Hazards Review* (May 2000), p. 111-112.

<sup>66</sup> EAS is administered by FEMA, in cooperation with the Federal Communication Commission and NWS. For more information on EAS, see CRS Report RL32527, *The Emergency Alert System (EAS) and All-Hazard Warnings*, by (name redacted).

<sup>67</sup> NOAA Weather Radio, at <http://www.nws.noaa.gov/nwr/>.

<sup>68</sup> R.A. Maddux, “The Weather Warning Partnership,” *Proceedings from the Hazards Research and Applications Workshop*, Natural Hazards Research and Applications Information Center, University of Colorado, Boulder (1991).

<sup>69</sup> Golden and Adams (2000), p. 112.

<sup>70</sup> Golden and Adams (2000).



measures. Whether and how climate change is influencing or could affect the frequency and intensity of thunderstorms and tornadoes is not yet evident, although some commentators ascribe a more extreme and violent climate to the influence of human-induced climate change. Thus it is not clear whether long-term efforts to mitigate greenhouse gas-induced global warming—such as by reducing emissions of carbon dioxide and other gases—could also mitigate damage to property and reduce injuries and losses of life from severe thunderstorms and tornadoes.

Enhancing the scientific understanding of how and why severe thunderstorms and tornadoes form, and improving the accuracy and timeliness of forecasting and warning systems, will likely provide individuals and communities in the United States better information to help them avoid damage and injury from severe weather events. The role of the federal government in weather and climate research, thunderstorm and tornado forecasting, and issuing warnings is substantial. Spending on weather forecasts and warnings comprises the bulk of the NWS budget, which is itself the largest component of NOAA's annual budget. Several other federal agencies contribute to the weather and climate enterprise, including NSF, NASA, the U.S. Geological Survey, and others. The federal investment in weather-related response and recovery, including programs at the Department of Agriculture and FEMA, is also substantial.

Many observers and stakeholders call for increased funding for improving the understanding of physical processes that produce extreme events, such as severe thunderstorms and tornadoes, and how these processes change with climate.<sup>71</sup> Observers and stakeholders are broadly in agreement about the types of R&D needed, such as integrated data and observation systems, improved remote sensing capabilities, better modeling capability, and others.<sup>72</sup> Even if funding increased substantially, however, it may not necessarily lead to significant decreases in damages, injuries, or deaths from severe thunderstorms and tornadoes. Shifting populations, changes in wealth density, and construction of dense infrastructure in areas prone to severe weather could offset improvements in forecasting and warning systems:

...the potential for considerable loss of life and property due to tornadoes continues to exist, especially in highly vulnerable regions of the country. Further, the increasing population and migration patterns of this population suggest that the overall vulnerability and risk to humans and their property may amplify in the future despite improvements in forecasting, detection, and warning dissemination.<sup>73</sup> (References omitted.)

In addition, implementing hazard mitigation strategies may include developing and enforcing land-use planning and zoning laws, which are traditionally state and local issues and not congressional concerns per se.<sup>74</sup> How federal agencies disseminate the results of federally

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<sup>71</sup> CCSP, *Weather and Climate Extremes in a Changing Climate* (2008), p. 122. See, for example, "Advice to the New Administration and Congress: Actions to Make our Nation Resilient to Severe Weather and Climate Change," a document produced by the University Corporation for Atmospheric Research and seven other stakeholder organizations; at <http://www.ucar.edu/td/>.

<sup>72</sup> *Grand Challenges for Disaster Reduction* (2005), p. 14.

<sup>73</sup> Walker S. Ashley, "Spatial and Temporal Analysis of Tornado Fatalities in the United States: 1880 - 2005," *Weather and Forecasting*, vol. 22 (December 2007), p. 1226.

<sup>74</sup> See, for example, Grand Challenge #3—develop hazard mitigation strategies and technologies; one of six grand challenges developed by the National Science and Technology Council, *Grand Challenges for Disaster Reduction* (2005). Arguably, the National Flood Insurance Program (NFIP)—administered by FEMA—is an example of federal involvement in local community development. The NFIP makes flood insurance available to communities that agree to adopt and enforce floodplain management ordinances. For more information on the NFIP, see CRS Report RL34610, *Midwest Flooding Disaster: Rethinking Federal Flood Insurance?*, by (name redacted).

sponsored R&D, from activities such as those originally authorized in the National Windstorm Impact Reduction Program, to states and local communities, may be more squarely in the purview of Congress, and more directly addressed through oversight of the programs and annual appropriations for the participating agencies.

## **Appendix. Risk from Severe Thunderstorms and Tornadoes**

This appendix discusses why severe thunderstorms and tornadoes are threats to some areas of the country and not others, and why they occur during some parts of the year and not others. It also describes the role of the National Weather Service (NWS) in forecasting and issuing warnings, and its relationship to private forecasters and the news media in providing clear and consistent messages to the public at risk.

Thunderstorms and tornadoes affect U.S. citizens and communities every year, albeit rarely with the same level of widespread destruction as a major hurricane or flood. Although floods are one consequence of severe thunderstorms, floods that cause widespread and prolonged destruction are typically not annual events in the United States. Major floods, such as those that affected parts of the Mississippi River region in the Midwest in 2008 and in 1993, are the result of many factors and are not solely caused by heavy rains from severe thunderstorms.<sup>75</sup>

### **Severe Thunderstorms**

Compared to tropical storms such as hurricanes, thunderstorms are small and short-lived, but can still be dangerous. An average thunderstorm is 15 miles in diameter and lasts an average of 30 minutes. Thunderstorms occur much more frequently than large tropical storms. There are an estimated 100,000 thunderstorms in the world each year, of which 10% are severe.<sup>76</sup> A severe thunderstorm is defined by the NWS as one that produces hail at least three-quarters of an inch in diameter, has winds of 58 miles per hour or higher, or produces a tornado.<sup>77</sup>

Severe thunderstorms may produce lightning, high winds, hail, flash floods, and tornadoes, any of which may be a hazard to people and property. Strong, straight-line winds can knock down trees and power lines, and can sometimes cause damage equal to that caused by many tornadoes.<sup>78</sup> Downbursts—outward bursts of damaging winds on or near the ground—can cause wind shear and lead to aircraft accidents. Tornadoes (discussed separately below), the most destructive phenomenon associated with thunderstorms, can destroy structures and cause fatalities.<sup>79</sup>

### **Risks from Severe Thunderstorms**

Severe thunderstorms can produce lightning, high winds, hail, and heavy rainfall that may lead to flash flooding. All of these phenomena may pose a risk to people and property depending on their location and the storm's intensity.

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<sup>75</sup> For a list of CRS experts on the Midwest flooding of 2008, see <http://www.crs.gov/experts/WE04010.shtml>.

<sup>76</sup> National Severe Storms Laboratory, "Severe Weather Primer: Thunderstorms," at [http://www.nssl.noaa.gov/primer/tstorm/tst\\_basics.html](http://www.nssl.noaa.gov/primer/tstorm/tst_basics.html).

<sup>77</sup> NWS, "A Comprehensive Glossary of Weather Terms for Storm Spotters," at <http://www.srh.noaa.gov/oun/severewx/glossary4.php>.

<sup>78</sup> Straight-line winds are strong winds produced by a thunderstorm that are not associated with rotation, as distinguished from tornadoes, which are narrow, violently rotating columns of air extending from the base of a thunderstorm to the ground.

<sup>79</sup> National Severe Storms Laboratory, "Severe Weather Primer: Thunderstorms," at [http://www.nssl.noaa.gov/primer/tstorm/tst\\_damage.html](http://www.nssl.noaa.gov/primer/tstorm/tst_damage.html).

## Lightning

Lightning is commonly considered the most dangerous and most frequently encountered weather hazard. Between 1977 and 2006, an average of 62 people were killed each year by lightning in the United States. Lightning-caused fatalities are often highest each year in Florida.<sup>80</sup> Lightning is also the primary cause of wildfires, which threaten natural resources, homes, businesses, and lives, particularly in the West. NOAA's National Severe Storms Laboratory estimates that lightning causes approximately \$4 billion-\$5 billion in damage each year, affecting buildings, communications systems, power lines, and electrical systems.<sup>81</sup>

## High Winds

Damage caused by severe straight-line winds during thunderstorms is more common than damage caused from tornadoes.<sup>82</sup> During severe thunderstorms, straight-line wind speeds may reach up to 100 miles per hour (damaging winds are classified as those exceeding 50-60 mph).<sup>83</sup> Estimates of the annual amount of damage caused by high winds are not provided in this report because wind damage from tropical storms, thunderstorms, and tornadoes are often reported together.

Damaging winds can develop with little or no advanced warning. Microbursts—one category of damaging winds—are dangerous to aviation and can occur in an isolated rain shower or thunderstorm.<sup>84</sup> Downbursts or microbursts may produce wind shear—a variation in wind speed and/or direction over a short distance—which can slow airspeed and cause an aircraft to lose altitude when a plane is taking off or landing and is near the ground.

## Hail

Although Florida typically experiences the most thunderstorms in the United States each year, Nebraska, Colorado, and Wyoming normally experience the most hail storms.<sup>85</sup> Crops are particularly vulnerable to hail damage; even relatively small hail can severely damage plants in minutes. Hail greater than three-quarters of an inch in diameter is considered severe and potentially damaging to aircraft. Hail also damages vehicles, roofs of buildings and homes, and landscaping. Damage from hail approaches \$1 billion in the United States each year.<sup>86</sup> Hail has been known to cause injury to humans, and occasionally has been fatal.

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<sup>80</sup> Florida has more lightning strikes than any other state and has the fourth-highest population in the United States. On average, 10 people die each year in Florida from lightning. National Weather Service, "Natural Hazard Statistics," at <http://www.weather.gov/os/hazstats.shtml#>.

<sup>81</sup> National Severe Storms Laboratory, "Severe Weather Primer: Lightning," at [http://www.nssl.noaa.gov/primer/lightning/ltg\\_damage.html](http://www.nssl.noaa.gov/primer/lightning/ltg_damage.html). The National Lightning Safety Institute indicates that losses from lightning may be \$5-\$6 billion per year. See [http://www.lightningsafety.com/nlsi\\_lls/nlsi\\_annual\\_usa\\_losses.htm](http://www.lightningsafety.com/nlsi_lls/nlsi_annual_usa_losses.htm).

<sup>82</sup> National Severe Storms Laboratory, "Severe Weather Primer: Damaging Winds," at [http://www.nssl.noaa.gov/primer/wind/wind\\_basics.html](http://www.nssl.noaa.gov/primer/wind/wind_basics.html).

<sup>83</sup> Ibid.

<sup>84</sup> Microbursts are small, concentrated *downbursts* from a thunderstorm, usually less than 4 kilometers across, that produce an outward burst of damaging winds at the ground surface. Downbursts are similar to microbursts but larger, usually greater than 4 kilometers across. See [http://www.nssl.noaa.gov/primer/wind/wind\\_basics.html](http://www.nssl.noaa.gov/primer/wind/wind_basics.html).

<sup>85</sup> In the high plains of these three states the freezing levels are much closer to the ground than at sea level. At sea level the hail has more time to melt before reaching the ground. See National Severe Storms Laboratory, "Severe Weather Primer: Hail," at [http://www.nssl.noaa.gov/primer/hail/hail\\_damage.html](http://www.nssl.noaa.gov/primer/hail/hail_damage.html).

<sup>86</sup> Ibid.

## Flash Floods

Floods are a common and widespread natural hazard in the United States.<sup>87</sup> As discussed in this report, flash floods can cause significant damage and fatalities, but they result from short-lived thunderstorms, and not from a prolonged weather pattern that produces higher than normal amounts of precipitation over several days or weeks.<sup>88</sup>

Flash floods are short in duration.<sup>89</sup> They are most commonly associated with thunderstorms, severe weather, and melting snow or ice. Flash floods can occur within minutes or a few hours of excessive rainfall, such as that from a severe thunderstorm or a series of thunderstorms occurring over the same location. Because flash floods can occur suddenly and with little warning, they are the most dangerous types of floods; typically most flood-related deaths each year in the United States are caused by flash floods.<sup>90</sup> It is difficult to assess the costs of actual damage from flash floods each year; cost estimates may vary widely, and the actual costs may not consistently correlate to preliminary estimates.<sup>91</sup>

## Where and When Severe Thunderstorms Form

Thunderstorms occur most frequently over the Florida peninsula and in other parts of the Southeast, although the most severe weather threat from thunderstorms extends from Texas to southern Minnesota along the Great Plains and midwestern United States.<sup>92</sup> Thunderstorms are most likely to occur in the spring and summer and during the afternoon and evening. In the Great Plains, most thunderstorms occur in the afternoon and at night; and along the Gulf Coast, southeastern United States, and western states they occur most frequently in the afternoon.<sup>93</sup>

The greatest potential for severe weather develops in geographical regions that are subject to warm, humid air at low levels, while dry, conditionally unstable air prevails aloft. Thunderstorms form during the summer in the southern Great Plains when a southerly flow of warm, very moist air from the Gulf of Mexico meets with a dry, westerly current aloft. The thunderstorms that form in Colorado, Arizona, and New Mexico are due to orographic lifting—ascending airflow caused by the Rocky Mountains. Few thunderstorms occur along the west coast of the United States because this region is frequently influenced by cooler, maritime air masses that suppress convective uplift over land.<sup>94</sup>

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<sup>87</sup> Slowly developing and widespread floods, such as the 2008 and 1993 floods along the Mississippi River, can cause billions of dollars in flood-related damages, although the number of deaths from floods is small in the United States relative to some other countries. For example, in 1998 floods resulting from Hurricane Mitch resulted in over 9,000 deaths in Central America, although some sources estimate as many as 18,000 deaths from Hurricane Mitch. See Roger A. Pielke, Jr. and Mary W. Downton, “Precipitation and damaging floods: Trends in the United States, 1932-97,” *Journal of Climate*, vol. 13 (Oct. 15, 2000), pp. 3625-3637.

<sup>88</sup> Significant flooding along the main stems of large river basins, such as the Mississippi River, results from excessive precipitation over weeks or months. See CCSP, *Weather and Climate Extremes in a Changing Climate* (2008), p. 50.

<sup>89</sup> A National Weather Service definition of flash flood is a flood caused by heavy or excessive rainfall in a short period of time, generally less than six hours.

<sup>90</sup> Deaths due to flooding created by Hurricane Katrina in 2005 far exceeded the annual average number of flash flood-related deaths; however, many complicating factors make comparison between hurricane-induced flooding and flash floods difficult, such as the role of levees, storm surge, tides, and other factors.

<sup>91</sup> Mary W. Downton and Roger A. Pielke, Jr., “How accurate are disaster loss data? The case of U.S. flood damage,” *Natural Hazards*, vol. 35 (2005), pp. 211-228.

<sup>92</sup> NOAA National Severe Storms Laboratory, at [http://www.nssl.noaa.gov/primer/tstorm/tst\\_climatology.html](http://www.nssl.noaa.gov/primer/tstorm/tst_climatology.html).

<sup>93</sup> *Ibid.*

<sup>94</sup> PhysicalGeography.net, “Thunderstorms and Tornadoes,” at <http://www.physicalgeography.net/fundamentals/> (continued...)

## How and Why Thunderstorms Form

A thunderstorm forms when moist, unstable air is vertically lifted in the area by unequal warming of the Earth's surface, orographic lifting due to a topographic obstruction (such as a mountain or mountain range), or the presence of a weather front. Three types of thunderstorms can produce severe weather: a squall line, a multicell storm, and a supercell storm.<sup>95</sup>

### *Squall Line*

A squall line is a line of storms with a continuous, well developed *gust front*—a boundary that separates a cold downdraft of a thunderstorm from warm, humid surface air—at the leading edge of the line. Severe weather frequently occurs near the updraft/downdraft interface at the storm's leading edge. Downburst winds are the main threat. Hail as large as golf balls along with *gustnadoes*—weak and short lived tornadoes—can occur. Flash flooding can occur when the squall line slows down or even becomes stationary, with thunderstorms forming parallel to the line and repeatedly moving across the same area.

### *Multicell Storm*

A multicell storm consists of a group of cells moving as a single unit, with each cell in a different stage of the thunderstorm life cycle.<sup>96</sup> As the multicell storm evolves, individual cells take turns at being the most dominant. New cells tend to form along the upwind (typically western or southwestern) edge of the cluster, with mature cells located at the center and dissipating cells found along the downwind (eastern or northeastern) portion of the cluster. Multicell storms come in a variety of shapes, sizes, and intensities.<sup>97</sup> They are stronger than single cell thunderstorms, but less severe than supercell storms. Each cell in a multicell storm lasts about 20 minutes; however, the multicell cluster may persist for several hours. Most flash floods occur during multicell storm events.<sup>98</sup>

### *Supercell Storm*

A supercell storm is defined as a storm with a persistent rotating updraft in which the entire storm behaves as a single entity, rather than as a group of cells.<sup>99</sup> These supercell storms are the most dangerous and rarest of the thunderstorms; they produce strong downbursts of 80 mph or more and damaging hail, and they can last for hours. Some are very prolific precipitation producers, whereas others produce very little precipitation that reaches the ground. The leading edge of the

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(...continued)

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<sup>95</sup> John M. Wallace and Peter V. Hobbs, *Atmospheric Science: An Introductory Survey* (San Diego, CA: Academic Press, 1977), p. 240.

<sup>96</sup> A *cell* in meteorology refers to an updraft or downdraft or combination of both. Updrafts and downdrafts, or their combination represent types of convection in an unstable atmosphere. The terms convection and thunderstorm are often used interchangeably, although thunderstorms are only one form of convection. For more information on meteorological terminology, see <http://www.srh.noaa.gov/oun/severewx/glossary.php>.

<sup>97</sup> Wallace and Hobbs, pp. 244 - 245.

<sup>98</sup> The Weather World 2010 Project, University of Illinois, Multicell Cluster Storms, at [http://ww2010.atmos.uiuc.edu/\(Gh\)/guides/mtr/svr/type/clstr/home.rxml](http://ww2010.atmos.uiuc.edu/(Gh)/guides/mtr/svr/type/clstr/home.rxml).

<sup>99</sup> Wallace and Hobbs, pp. 245-248.

precipitation from a supercell is usually light rain. Heavier rain falls closer to the updraft with torrential rain and/or large hail immediately north and east of the main updraft. Severe weather tends to form near the main updraft, typically towards the rear of the storm.<sup>100</sup> Most large and violent tornadoes come from supercell storms.

## **Tornadoes**

Tornadoes—the most violent storms on Earth—can sometimes produce winds that exceed 300 mph. They are the destructive products of severe thunderstorms, and second only to flash flooding as the cause for convective storm related fatalities.

### **Risks from Tornadoes**

Damages from violent tornadoes seem to be increasing, similar to the trend for other natural hazards. According to some insurance industry analysts, losses of \$1 billion or more from single tornado events are becoming more frequent.<sup>101</sup> Insurance industry analysts indicate that tornadoes, severe thunderstorms, and related weather events (such as hailstorms, but not hurricanes or earthquakes) have caused nearly 57%, on average, of all insured catastrophe losses in the United States in any given year since 1953.<sup>102</sup>

Fatalities caused by tornadoes have declined significantly since the 1930s, generally because of improved forecasting, warning systems, and increased public awareness of the tornado risk. However, some researchers suggest that the decline is unlikely to continue and may have already stopped.<sup>103</sup> These findings attribute the stalled decline to increasing vulnerability due to demographic factors, rather than shortcomings in tornado forecasts and warnings.<sup>104</sup> The results would suggest that there are limits to the number of potential lives saved by improvements in forecasting ability and warning systems, and that social, behavioral, and demographic factors may play an increasingly important role in tornado-related fatalities.<sup>105</sup> Other stakeholders, however, emphasize the need for increased investment in observations, computing power, research, and weather modeling to improve the nation's resilience to severe weather.<sup>106</sup>

Since 1950, violent tornadoes were responsible for 67.5% of all tornado deaths in the United States, yet comprise only 2.1% of all tornadoes.<sup>107</sup> The number of fatalities caused by less violent tornadoes is also significant, and some studies suggest that the percentage of fatalities caused by

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<sup>100</sup> NOAA National Severe Storms Laboratory, at [http://www.nssl.noaa.gov/primer/tstorm/tst\\_basics.html](http://www.nssl.noaa.gov/primer/tstorm/tst_basics.html).

<sup>101</sup> A. M. Best Company, Inc., *Tornado Losses Approach Those of Hurricanes* (Oldwick, NJ: A. M. Best Company, 2008), p. 1.

<sup>102</sup> A. M. Best Company, Inc., *Tornado Losses Approach Those of Hurricanes*, p. 7.

<sup>103</sup> Walker S. Ashley, "Spatial and Temporal Analysis of Tornado Fatalities in the United States: 1880 - 2005," *Weather and Forecasting*, vol. 22 (December 2007), p. 1216.

<sup>104</sup> *Ibid.*

<sup>105</sup> See, for example, Dennis S. Mileti, *Disasters by Design: A Reassessment of Natural Hazards in the United States* (Washington, DC: Joseph Henry Press, 1999), p. 226.

<sup>106</sup> See, for example, "Advice to the New Administration and Congress: Actions to Make our Nation Resilient to Severe Weather and Climate Change," a document produced by the University Corporation for Atmospheric Research and seven other stakeholder organizations; at <http://www.ucar.edu/td/>.

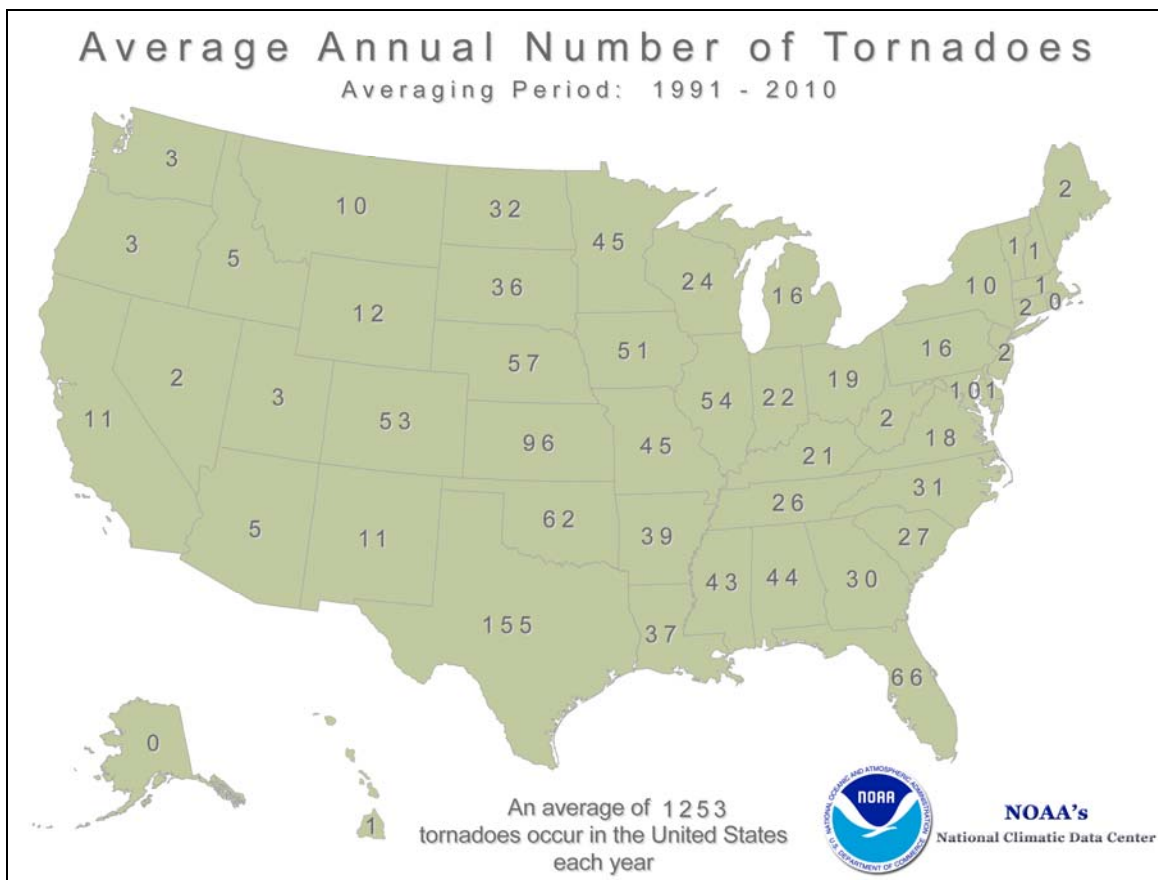
<sup>107</sup> Ashley (2007), p. 1217.

less violent tornadoes has increased since the 1970s.<sup>108</sup> (See below for an explanation of how violent tornadoes and less destructive tornadoes are classified: the F-Scale and enhanced F-scale.)

### Where and When Tornadoes Form

Tornadoes have been reported on all continents except Antarctica; however, they occur most commonly in North America and particularly in the United States.<sup>109</sup> They can occur in all 50 states but they form most commonly in three regions: (1) a swath of the Midwest extending from the Texas Gulf Coastal Plain northward through eastern South Dakota (known as “Tornado Alley”); (2) an area that extends across the Gulf Coastal Plain from south Texas eastward to Florida (known as “Dixie Alley”); and (3) an area located in eastern Iowa, south-central Indiana, western Pennsylvania, and central Arkansas (a smaller “tornado alley”). See **Figure A-1**.

**Figure A-1. Map Showing the Average Annual Number of Tornadoes in Each State**



**Source:** NOAA, National Climatic Data Center, U.S. Tornado Climatology, <http://www.ncdc.noaa.gov/oa/climate/severeweather/tornadoes.html>.

<sup>108</sup> Ibid., p. 1218.

<sup>109</sup> National Severe Storms Laboratory, at [http://www.nssl.noaa.gov/primer/tornado/tor\\_faq.shtml](http://www.nssl.noaa.gov/primer/tornado/tor_faq.shtml).



Tornadoes occur mostly during spring and summer, and usually during the late afternoon and early evening. However, they can occur on any day of the year, at any hour.<sup>110</sup> The United States averages approximately 1,200 tornadoes per year—the highest average annual number in the world.<sup>111</sup> (The actual number of recorded tornadoes per year varies, depending on the source of information.)

## **How and Why Tornadoes Form**

A tornado is a narrow, violently rotating column of air that extends from the base of a thunderstorm to the ground. Tornadoes develop from severe thunderstorms in warm, moist, unstable air along and ahead of cold fronts. There are two types of tornadoes, those that come from a supercell thunderstorm and those that do not.<sup>112</sup>

Tornadoes that form from supercell thunderstorms are the most common, usually the largest, and the most dangerous. In supercell thunderstorms, a rotating updraft is essential to development of a tornado. Rotation of the updraft can be caused by wind shear, which occurs when winds at two different levels above the ground blow at different speeds or in different directions. An invisible tube of air begins to rotate horizontally, and rising air within the thunderstorm tilts the rotating air from horizontal to vertical, resulting in rotation that extends through much of the storm. Once the updraft is rotating and being fed by warm, moist air flowing in from the ground level, a tornado can form. The mechanisms that cause tornadoes to form from supercell storms are not known precisely, and it is not currently possible to predict which supercell thunderstorms will produce tornadoes and which will not. Based on observations, approximately 20% of supercell thunderstorms produce tornadoes.<sup>113</sup>

A non-supercell tornado forms from a vertically spinning parcel of air near the ground, about 1-10 kilometers in diameter, that is caused by wind shear from a warm, cold, or sea breeze front, or from a *dryline*—the interface between warm, moist air and hot, dry air. When an updraft moves over the spinning parcel of air and stretches it, a tornado can form. This type of tornado formation commonly occurs in eastern Colorado, where cool air descending from the Rocky Mountains toward the west collides with hot dry air from the Great Plains.<sup>114</sup> Land-falling tropical storms and hurricanes can also generate non-supercell tornadoes.

## **Classifying Tornadoes: The F-Scale**

The Fujita or F-scale was developed to provide a method for estimating the intensity of tornadoes, and was intended to relate the degree of damage to the intensity of wind.<sup>115</sup> The original F-scale was used for over three decades, but its limitations prompted the development of a new scale, called the enhanced F-scale, or EF-scale. The EF-scale is intended to be a more robust and precise method of assessing tornado damage than the original F-scale. The EF-scale calibrates tornado

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<sup>110</sup> National Severe Storms Laboratory, at [http://www.nssl.noaa.gov/primer/tornado/tor\\_climatology.html#](http://www.nssl.noaa.gov/primer/tornado/tor_climatology.html#).

<sup>111</sup> NOAA, National Climatic Data Center, U.S. Tornado Climatology, <http://www.ncdc.noaa.gov/oa/climate/severeweather/tornadoes.html>.

<sup>112</sup> NOAA National Severe Storms Laboratory, “A Severe Weather Primer: Questions and Answers about Tornadoes,” at [http://www.nssl.noaa.gov/primer/tornado/tor\\_basics.html](http://www.nssl.noaa.gov/primer/tornado/tor_basics.html).

<sup>113</sup> *Ibid.*

<sup>114</sup> NOAA National Severe Storms Laboratory, “A Severe Weather Primer: Questions and Answers about Tornadoes.”

<sup>115</sup> Dr. Ted Fujita developed the scale in 1971.

damage using 28 different types of damage indicators, such as the type of construction (e.g., anchored versus unanchored houses, mobile homes, schools, garages, barns, skyscrapers, transmission towers, and others).<sup>116</sup> Even with the improvements over the original F-scale, the EF-scale represents only *estimates* of wind speed, based on damage, and not measurements of actual wind speeds in tornadoes.<sup>117</sup> Actual tornado wind speeds are still largely unknown. **Table A-1** compares the original F-scale with the EF-scale currently used by meteorologists and wind engineers.

**Table A-1. F-Scale and Enhanced F-Scale for Tornado Damage**

Original F-scale	Wind Speed (mph)	Enhanced F-scale	Wind Speed (mph)
F-0	45-78	EF-0	65-85
F-1	79-117	EF-1	86-110
F-2	118-161	EF-2	111-135
F-3	162-209	EF-3	136-165
F-4	210-261	EF-4	166-200
F-5	262-317	EF-5	Over 200

**Source:** NOAA Storm Prediction Center, at <http://www.spc.noaa.gov/faq/tornado/ef-scale.html>.

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<sup>116</sup> NOAA Storm Prediction Center, at <http://www.spc.noaa.gov/faq/tornado/index.html#f-scale3>.

<sup>117</sup> NOAA Storm Prediction Center, at <http://www.spc.noaa.gov/faq/tornado/ef-scale.html>.

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