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Introduction

Mr. Chairman and Members of the Committee, I am Dennis McCarthy, Director of the National Weather Service Office of Climate, Water, and Weather Services, of the National Oceanic and Atmospheric Administration (NOAA) within the Department of Commerce. Thank you for the opportunity to appear before you today to discuss NOAA's severe weather programs, specifically tornadoes.

In an average year, there are 1,300 tornadoes resulting in 58 deaths, 1,500 injuries, and $1.1 billion in property damage. Floods account for $5.2 billion in damage annually and average over 80 deaths per year; lightning accounts for an additional 53 fatalities each year. Thunderstorm complexes can generate tornadoes, lightning, flash floods, extreme wind, and hail. The challenge to forecasting severe weather and any associated warnings is to determine which thunderstorm complexes will produce which combination of threats.

The highest frequency of tornado occurrence in the world is in the Central Plains of the United States, east of the Rocky Mountains and west of the Appalachian Mountains. While tornadoes typically occur during the spring and summer in late afternoon and early evening, they have been known to occur at any hour, on any day of the year, in every state in the United States.

Brief History of Tornado Forecasting

The National Weather Service (NWS) Tornado and Severe Thunderstorm Watch and Warning program can be traced back to two tornadoes that struck Tinker Air Force Base, Oklahoma, in March of 1948. The first tornado (March 20) was not forecasted. At the strong urging of Major General Fred Borum, who was in charge of the base, two Air Force meteorologists, Major Ernest Fawbush and Captain Robert Miller, studied weather charts from previous tornado outbreaks looking for similarities that could indicate tornado potential. On the morning of March 25, 1948, the weather charts were very similar to those that occurred with the first tornado. This similarity was reported back to Major General Borum, and a tornado forecast was issued. That evening, the second tornado within one week struck Tinker Air Force Base. After this success, weather forecasters, both civilian and military, started to seriously explore tornado forecasting. The first tornado forecast was issued by the then Weather Bureau in 1952. During this same period, other research scientists were actively exploring the use of radar to identify on-going storms that could potentially produce tornadoes, and pioneering work was being done by the Illinois Water Survey and Texas A&M University.

In 1956, Congress appropriated funds to develop radar for meteorological purposes. A network of radars was installed to provide coverage for most of tornado alley and the hurricane prone Southeastern United States in early 1959 and 1960. The National Severe Storms Research Project, in Norman, Oklahoma, expanded its mission to include radar techniques related to severe thunderstorm warnings. In 1964, a merger of the radar and tornado research programs created the National Severe Storms Laboratory.

Because of its dependence on rapid communication of weather data from all over the country, the forecasting of tornado potential remained with the National Severe Storms Forecast Center in Kansas City. Similarly, because providing alerts for existing storms required immediate access to radar data, local radar offices issued these products.

The 1965 Palm Sunday Tornado Outbreak took 266 lives, even though tornado forecasts and alerts had been issued. The National Weather Service conducted an assessment of its products and services following the outbreak and made several significant recommendations including:

- The National Weather Service began to differentiate tornado forecasts from typical weather forecasts by using the names Tornado Watch and Tornado Warning.

- The National Weather Service started to hold preparedness meetings in collaboration with federal, state, and local government officials and news disseminators. Discussions at these meetings included the development of simple tornado safety rules.

- The National Weather Service committed itself to completing radar coverage east of the Rocky Mountains.

With these changes, the present watch and warning system was completed. However, tornado and severe thunderstorm meteorology was still in its infancy and we have made significant progress since then.

Key Research Leads to Significant Improvements in Operations

In a three-year period from 1976 to 1979, statistics indicated less than one out of three tornadoes occurred in a tornado watch area, and only one out of five tornadoes occurred in a tornado warning area. Also during that time, over 80 percent of tornado warnings were based on human spotter reports, meaning that there was virtually no lead time between when the warning was issued and when the tornado struck.

In 1976, a small group at the National Severe Storms Forecast Center (NSSFC) began developing new analyses and display techniques for meteorological data. These researchers worked with the National Aeronautics and Space Administration (NASA) and NOAA's National Environmental Satellite, Data, and Information Service to develop a computer system that allowed forecasters to collect data directly from the weather satellites to make short-range forecasts. In addition, the NSSFC research forecasters collaborated with scientists at the National Severe Storms Laboratory to develop new methods of interpreting conventional radar data and use it to issue warnings ahead of storms.

These efforts led to immediate improvements in our ability to issue accurate tornado watches and warnings. By the late 1980s, lead time for tornado warnings had increased from zero to over 5 minutes. Tornado warnings were issued for about one third of all tornadoes (compared to only one fifth in the late 1970s), and tornado watches were issued before about half of the tornadoes. Most importantly, the public was becoming more aware of tornado warnings, and the sentiment "the tornado struck without warning" was being uttered less and less.

While our scientific advances in the 1980s resulted in a marked improvement in tornado forecasting, the American public deserved more. In the late 1970s, a collaborative program had been established among NOAA, the U.S. Air Force (USAF), and the Federal Aviation Administration (FAA) to begin evaluating the value of Doppler radar for tornado detection. Tests were conducted in the Oklahoma City Weather Service Forecast Office. These tests proved Doppler radar could significantly improve tornado lead times and the detection of other measures essential for forecasting tornado warnings. A program to replace the 30-year-old weather radars with NEXRAD Doppler weather radars (the WSR-88D) was incorporated into NOAA's plan for National Weather Service Modernization. These radars, coupled with specially trained meteorologists in local National Weather Service Forecast Offices, had an immediate, dramatic impact on tornado warning skill. Following the nationwide installation of the NEXRAD network in the 1990s, tornado lead times almost doubled from 5.3 to 9.5 minutes. In addition, the probability of detecting a tornado increased from 35 to 60 percent. By 2004, tornado lead times averaged just over 13 minutes, and the probability of detection rose to 75 percent. More importantly, expected tornado deaths and personal injuries were reduced by 45 percent and 40 percent, respectively.

Similar research advances have improved long-range forecasts of tornadoes. In 1995, a National Science Foundation sponsored research project involving NOAA and several universities explored the causes of rotation in thunderstorms. This was a collaborative effort between research and operations with tornado forecasters from the Storm

Prediction Center (formerly the National Severe Storms Forecast Center) and local warning forecasters from several NWS Weather Forecast Offices participating. This collaboration led to significant improvements in forecasting strong and violent tornadoes. While only 15 percent of all tornadoes are rated F2 or stronger on the six category Fujita Intensity Scale, they produce more than 92 percent of U.S. tornado fatalities.

Underlying these improved performance measures is the added benefit of increased data and expertise sharing by the National Weather Service with its partners in the media and private sectors. The Doppler radar data sets and improved computer and communication technologies have allowed broadcast meteorologists and others to better understand and communicate severe weather threats to citizens. In addition, the expansion of NOAA Weather Radio/All-Hazards remains a vital component of the National Weather Service's ability to communicate weather and non-weather hazard information. There are currently over 900 radio transmitters across the U.S., and weather radio is now a key vehicle for federal, state and local public safety agencies to disseminate critical safety information on a variety of hazards, including man-made and natural disasters.

The success of the close collaboration between operational forecasters and research scientists, coupled with advent of new communication systems, led to a move of the Storm Prediction Center from Kansas City to Norman, Oklahoma, in 1996 to collocate with the National Severe Storms Laboratory. This move spurred NOAA to establish the Hazardous Weather Testbed, in which NWS forecasters and NOAA research scientists collaboratively test, develop, and operationally implement new forecast and warning techniques and technology on a regular basis.

Research conducted at the Hazardous Weather Testbed has led to dramatic improvements in the quality of severe thunderstorm services provided by the Storm Prediction Center. The length of severe thunderstorm forecasts has been extended from 2-3 days, and forecasts now provide specific probabilities for the occurrence of tornadoes, large hail, and damaging thunderstorm winds. Experimental products currently being tested at the Storm Prediction Center include severe weather forecasts out to eight days, and additional forecast details in tornado and severe storm watches such as probabilities for each type of severe weather and the anticipated degree of severity. In addition, trials are being conducted that break down the daily outlooks into shorter time intervals that are of great interest to the aviation community.

The 122 NWS Forecast Offices located throughout the U.S. are experimenting with improvements to the tornado and severe thunderstorm warning process. The county currently issues these warnings, however, a real threat often exists for only a portion of a given county. A number of NWS Forecast Offices are experimenting with a "warning-by-polygon" method. In this method, the polygons are derived by assessing the threat from the latest radar observation and modeling a projected path for the most threatening portion of the storm. The polygons can easily be incorporated into geospatial display technology for satellite-based or other systems. This method would allow local emergency managers to sound sirens in the high threat areas of the county only.

Strategies for the Future

The NOAA Office of Oceanic and Atmospheric Research works in partnership with the National Weather Service to substantially improve the lead times and accuracy of tornado and severe storm watches and warnings. These efforts can be classified as short (0 to 5 years) and long term (5 plus years).

<u>Short Term Efforts:</u>
The three agencies involved in NEXRAD – NOAA, the FAA, and the USAF – plan to add dual polarization capability to the radar system in the FY 2008 to FY 2012 timeframe. Dual polarization will provide information on the size and shape of the precipitation particles in clouds. Snow can be distinguished from rain, hail size can be estimated, and most importantly, rainfall amounts can be accurately obtained. This will lead to improvements in flash flood warnings and forecasts, as well as enhanced warnings for hail. The dual polarization radar data will be "cleaner," which should better identify precursors to tornadoes and the tornadoes themselves even before they descend to the ground. Dual polarization data also will allow for unique detection of debris lofted by tornadoes, giving additional valuable information on likely tornado intensity. Other improvements to the current network of weather radars include more rapid and enhanced sampling of the storm environment, and inclusion of FAA weather radars. NOAA's Warning Decision Support System - Integrated Information (WDSS-II) is the second generation of a suite of algorithms and displays for severe weather analysis, warnings and forecasting incorporating observational data from multiple sources. WDSS-II uses sophisticated artificial intelligence-based science to analyze storms for hail, wind, and tornado potential. The idea behind WDSS-II is to provide the forecaster with critical information that is easy to understand, resulting in a timely decision in the tornado and severe storm warning process. Tests in NWS Forecast Offices indicate WDSS-II will increase lead times for tornadoes and severe thunderstorms by 2 to 3 minutes and reduce the false alarm rate.

This past spring, NOAA's Storm Prediction Center and National Severe Storms Laboratory worked closely with the Norman Forecast Office, and partnered with three external organizations to generate a unique collection of three daily experimental very high-resolution numerical weather prediction models. The predictions are made from several different versions of the Weather Research and Forecasting (WRF) model, an advanced weather prediction system being designed for use by research scientists and forecasters in the United States. One of the purposes of this Hazardous Weather Testbed exercise is to extend the lead time and accuracy of tornado and severe thunderstorm watches issued by the Storm Prediction Center. Preliminary indications are that these very high-resolution numerical weather prediction models are quite useful in predicting rotating, severe thunderstorm complexes.

<u>Long Term Efforts:</u>
NEXRAD Doppler radar is the key observation tool used by forecasters to warn the public of tornadoes and severe thunderstorms. The NEXRAD network is near the mid-point in its designed lifecycle and NOAA is already exploring new technologies for a

major upgrade or eventual replacement. One likely candidate technology is phased array radar (PAR) with its electronically scanning antenna. Phased arrays work by forming and steering radar beams electronically, and they are very fast and agile compared to the mechanical, rotating dish antenna radars such as NEXRAD. The military has employed phased array radars for over 30 years in tactical systems.

NOAA is partnering with the U.S. Navy, the FAA, the University of Oklahoma, and several private companies to explore the capability of PAR for weather surveillance. The Navy has loaned NOAA a battle spare PAR antenna for testing at NSSL in Norman, Oklahoma. Properly configured, a PAR system can complete a volume scan of the surrounding atmosphere in less than one minute. It currently takes a NEXRAD 4.1 to 6 minutes to perform a similar scan. This faster scan rate can improve average tornado lead times by approximately 4 minutes. Other features of PAR could lead to improved detection of tornado and severe weather precursors and provide high-quality data for assimilation into numerical weather prediction models.

In the past, PAR systems have been deemed too costly for civilian use. Advances in parallel technologies, such as cellular telephones and wireless technologies, as well as breakthroughs in materials science, may reduce the cost of a PAR system to levels comparable with mechanical, rotating dish antenna radar. In addition, a PAR system can be designed with four fixed antennae resulting in a radar with no moving parts, which is therefore less expensive to operate. Such a PAR system may be able to perform multiple functions, thus satisfying the needs of several agencies. For example, a PAR could be designed to track aircraft (FAA), perform weather surveillance (NOAA, FAA), and scan for non-cooperative aircraft (Department of Homeland Security), all at the same time. Several agencies (NOAA, FAA, DHS, NASA, and the Department of Defense) are working together under the auspices of the Office of the Federal Coordinator for Meteorology to assess PAR capability, develop a multi-agency research and development plan, and to examine costs.

The potential exists to make significant long-term improvements to tornado and severe storm performance metrics. Presently, warnings are based on detecting certain precursors to tornado formation. Tornado watches and forecasts from several hours to several days are based, in large part, on numerical weather prediction models run at NOAA's National Centers for Environmental Prediction in Camp Springs, Maryland. The current upper limit on tornado lead times (based solely on detection) is about 20 minutes, perhaps 30 minutes for very strong tornadoes. Crossing this threshold will require reliance on forecasts from very high-resolution, detailed numerical weather prediction models capable of predicting the level of cloud formation. The warning paradigm must shift from "warn on detection" to include "warn on forecast."

Very high resolution, cloud resolving numerical models exist in the research community to better understand storm science and cloud processes. Some limited experimentation with forecasting applications has produced mixed results. One approach being explored is to run many different models and combine them into an "ensemble" forecast that yields probabilities of high consequence events occurring. Other improvements will come from more detailed observations in space and time (dual polarization, PAR, surface networks, and next generation satellite data), new science, faster and higher capacity computing, and improved numerical techniques. Improvements in forecast skill in the 0.5 to 12-hour range has the potential to improve tornado and severe storm watches and warnings, improve forecasts of heavy precipitation, contribute to better routing of aircraft enroute and at airports, and to assist local emergency managers in protecting life and property in their area of responsibility.

Over the past 50 years, NOAA has made tremendous gains in providing warnings to help protect the lives of U.S. citizens – from being able to detect and warn for most tornadoes, now with an average lead time of 13 minutes, to getting the word to people about what to do when they hear a tornado warning, either from the media or directly from NOAA via Internet or NOAA Weather Radio/All-Hazards. We can continue to improve by taking advantage of improved scientific understanding and emerging technologies to upgrade and refresh tornado and severe weather forecast products and information. The trend is clearly toward providing more detail in location and time coupled with probabilistic information allowing customers to better assess their particular risk prior to taking appropriate action. Ongoing NOAA-led efforts in radar enhancement (dual polarization and phased array) and improvements in the numerical prediction of storm scale weather events hold particular promise.

We envision a future in which the National Weather Service issues warnings at least 30 to 45 minutes before tornadic thunderstorms develop. Storm Prediction Center Watches will run from about an hour in the future out to 12 hours, and extended range forecasts are valid out to several weeks. These forecasts will allow Emergency Managers and Homeland Security to plan for severe thunderstorms and tornadoes far enough in advance to pre-position resources before a storm. Even more dramatic will be the economic impact of improved severe thunderstorm forecasts. For example, energy companies can configure their grids to ensure continuous power flow in regions impacted by storms, the transportation sector can reroute trains, trucks and airplanes away from areas that will experience significant thunderstorms, and local emergency managers can better alert the public, saving lives and mitigating property damage.