REPORT TO CONGRESS

TORNADO WARNING IMPROVEMENT AND EXTENSION PROGRAM PLAN

Developed pursuant to Title I, Section 103 of the Weather Research and Forecasting Innovation Act, 2017 (P.L. 115-25)

Craig McLean, Assistant Administrator
Office of Oceanic and Atmospheric Research
National Oceanic and Atmospheric Administration

Louis Uccellini, Ph.D., Assistant Administrator for Weather Services and
Director of the National Weather Service
National Oceanic and Atmospheric Administration

Stephen Volz, Ph.D., Assistant Administrator
Satellite and Information Services
National Oceanic and Atmospheric Administration

Neil A. Jacobs, Ph.D.,
Assistant Secretary of Commerce for Environmental Observation and Prediction
Performing the Duties of Under Secretary of Commerce for Oceans and Atmosphere /
NOAA Administrator

TITLE I, SECTION 103 OF THE WEATHER RESEARCH AND FORECASTING INNOVATION ACT, 2017 (P.L. 115-25) INCLUDED THE FOLLOWING LANGUAGE

(a) IN GENERAL. – The Under Secretary, in collaboration with the United States weather industry and academic partners, shall establish a tornado warning improvement and extension program.

(b) GOAL. – The goal of such program shall be to reduce the loss of life and economic losses from tornadoes through the development and extension of accurate, effective, and timely tornado forecasts, predictions, and warnings, including the prediction of tornadoes beyond one hour in advance.

(c) PROGRAM PLAN. – Not later than 180 days after the date of the enactment of this Act, the Assistant Administrator for Oceanic and Atmospheric Research (OAR), in coordination with the Director of the National Weather Service (NWS), shall develop a program plan that details the specific research, development, and technology transfer activities, as well as corresponding resources and timelines, necessary to achieve the program goal."

(d) ANNUAL BUDGET FOR PLAN SUBMITTAL.—Following completion of the plan, the Under Secretary, acting through the Assistant Administrator for Oceanic and Atmospheric Research and in coordination with the Director of the National Weather Service, shall, not less frequently than once each year, submit to Congress a proposed budget corresponding with the activities identified in the plan.

THIS REPORT RESPONDS TO THE CONGRESSIONAL REQUIREMENT.

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Executive Summary

This plan describes the short-term and long-term efforts of the National Oceanic and Atmospheric Administration (NOAA) to achieve the Weather Act's goal of tornado prediction beyond one hour. There are three interconnected science and technology components being developed within NOAA to achieve this goal: improved observations, including conventional and advanced radar technology; high-resolution computer prediction models; and a modern, optimized approach to communicate risk that is informed by social sciences. The plan details the observations and science necessary to develop and support these goals, including data from NOAA's new geostationary satellites, advanced radar technologies, and detailed sensing of the lowest few thousand feet of the atmosphere. Such observations are integrated into improved, high-resolution models that will be able to accurately predict thunderstorm formation and evolution. The goal is to use social science to develop more effective ways to communicate this detailed information to the public and emergency management community, and to empower society to make protective action decisions and maximize the effectiveness of these forecast improvements.

I. Introduction

This plan is in response to the Title I, Section 103(c) of the Weather Research and Forecasting Innovation Act of 2017 (Public Law 115-25, hereafter referred to as the "Weather Act"), signed into law on April 18, 2017.

Title I, Section 103 of the Weather Act includes the following language:

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II. The Reality and the Challenge

A large, violent tornado moves toward a community – a scenario that occurs all-too-often across many areas of the country. The magnitude of the tragedy about to unfold will be directly proportional to the timeliness and quality of millions of individual and collective decisions made in the minutes, hours, and days prior to the event; decisions made by forecasters and end-users alike. The challenge continuously faced by our society and its servicing partners (e.g., emergency managers, broadcasters, America's Weather Enterprise) will be developing the ability to maximize the effectiveness of these decisions so as to minimize the loss of life and property from these storms. NOAA has the opportunity and responsibility to lead the nation in meeting this challenge by fostering an information infrastructure spanning both public and private capacities, supplying a continuous flow of high-quality, critical information to make the most informed decisions in every available moment. The flow and content of information must be: 1) designed and realized by employing the talents of our entire *weather enterprise* (i.e., academia, government, and the weather industry), working together to build a Weather-Ready Nation; and 2) tailored for a diverse, mobile society to support individuals, government, and businesses in their decision-making processes.

III. Purpose and Concept

Currently used performance metrics such as average lead time, Probability of Detection, and False Alarm Ratio scores for tornado warnings improved steadily after the introduction of NEXRAD WSR-88D (Next-Generation Radar: Weather Surveillance Radar-1988 Doppler) technology in the 1990s and subsequent numerical weather prediction and WSR-88D improvements. Since 2007, however, warning performance of National Weather Service (NWS) meteorologists, as tracked by the Government Performance and Results Act metrics, has largely plateaued.   In addition, social science[1] research and stakeholder engagement revealed that NWS stakeholder groups rely on several days of NWS forecasts to best understand their risk and necessary actions. Further, stakeholder decision-making risk thresholds vary, which requires forecasters to convey a variety of information about storm characteristics (e.g., timing, location, severity, uncertainty, etc.) prior to the onset of a severe weather event.

In response to stakeholder needs, transformational improvements in warning lead times and reductions in false alarms for tornadoes, damaging winds, flash floods, and other convective hazards (as called for in P.L. 115-25) will require technologies and capabilities that ***predict*** the occurrence of these hazards at least as reliably and accurately as current technologies ***detect*** them. It will also require the capability to deliver the resulting information in ways most appropriate to specialized users (e.g., emergency managers and private enterprise meteorologists) and the general public. Such technologies and science are being developed within NOAA to accomplish this, and include three major, interconnected components:

1. Improved observation systems;
2. High-resolution, convection-allowing (thunderstorm scale) computer prediction models; and
3. A modern, optimized approach to risk communication, informed by social sciences, and delivered to decision makers, the public, and weather enterprise stakeholders before, during, and after tornado events.

IV. High-Level View of the Approach

The heart of this approach consists of a probabilistic tornado forecast and warning program, which is a forecast and warning program that considers the likelihood that an event will occur.

[1] The NOAA Science Advisory Board report defines social science as "the process of describing, explaining and predicting human behavior and institutional structure in interaction with their environments." It includes diverse disciplines, such as communication, economics, psychology, geography, political science, etc.

Compared to deterministic (e.g., binary, yes/no) forecast types, this approach is more responsive to end user requirements for information over time, with lead times sufficient to accommodate a user's unique, situation-specific needs and levels of risk tolerance. By providing a continuous flow (e.g., every two minutes) of high-resolution probabilistic information (e.g., data every half mile), end users are empowered to make decisions when the severity of the circumstances meets their respective risk thresholds. This approach also offers more lead time prior to a storm event, allowing end users to prepare in advance of the official warning statements, which typically have shorter lead times. Moving to this paradigm will require equipping forecasters with new tools, training, and techniques, and employing lessons learned from the social, behavioral and economic sciences. Work with social scientists is currently underway to understand how people will interpret and use uncertainty information in their decision-making process. The Weather Act goal of one-hour lead time requires a nearly continuous stream of information to the users and decision makers that can capture and express uncertainty in a clear and concise manner, sometimes even before the storm may be formed. This will require an evolution of the current NWS warning paradigm to attain an effective response across all segments of society.

The overarching goal of developing a Tornado Warning Improvement and Extension Program (TWIEP) will be to reduce the loss of life and economic losses from tornadoes through the development and extension of accurate, effective, and timely tornado forecasts, predictions, and warnings, including the prediction of tornadoes beyond one hour in advance. Key goals to achieve the proposed research, development, and technology transfer objectives of the (TWIEP) Plan are shown in Table 1:

Table 1: TWIEP Plan - Goals

Short-Term Goals (5 years)	Long-Term Goals (10 years)
1. **Conduct research** aimed at (a.) developing a streamlined national observational database suitable for advanced data assimilation, and (b.) reducing model error. 2. **Further develop, test, and implement a Warn-on-Forecast (WoF) prototype system,** to effectively integrate into the NWS's modeling framework by 2023. 3. **Implement a next-generation NWS warning paradigm** to include probabilistic hazard information with extended lead times that empower effective decision-making. 4. **Implement a prototype Convection Allowing Model (CAM) ensemble system** as an enabling technology for WoF infrastructure.	1. **Develop and test optimal approaches for enhancing observations (including beyond radars)** to substantively improve short-range forecasts of thunderstorm initiation and evolution. These approaches will include (a.) Observing System Simulation Experiments (OSSEs) and observing system testbed facilities to inform optimal design of existing and future networks, and (b.) development of new surface, unmanned aircraft, ground-based remote sensing systems, and other instruments. 2. **Define, develop and implement more effective dissemination strategies** (in partnership with the private sector) that enable delivery of predictions to a mobile society, including value-added content, with

forecast and warning information for core partner[2] decision makers.

3. **Triple the current skill and effectiveness of tornado forecasts and warnings** to empower society to make protective action decisions, such that:
    a. Current performance at 20 minutes is extended to greater than 60 minutes;
    b. Current performance at 4 hours is extended to 12 hours; and
    c. Current performance at 1 day is extended to 3 days.

4. **Achieve NOAA's Weather-Ready Nation goals**, by fully engaging America's Weather Industry partners in evolving all aspects of the tornado warning paradigm.

5. **Define and implement optimal predictive information content and lead time** for decision makers tailored to diverse user groups, with an overall focus on effective communication and response using social and behavioral science studies.

6. **Establish physical and societal performance metrics** to accurately assess effectiveness of current and future forecasts and warning paradigms in support of societal needs.

As an integral part of TWIEP, NOAA is moving toward a paradigm that will convey weather hazard (un)certainty in a clear and concise manner to end users and decision makers. One such effort within NOAA is the Forecasting a Continuum of Environmental Threats (FACETs) paradigm, a modern and flexible next-generation severe weather watch and warning framework Through FACETs, a nearly-continuous stream of high-resolution *probabilistic hazard information* (a network of rapidly-updating grids) extending from days before to within minutes of an event, is driven and guided by cutting-edge scientific tools optimized for user-specific decision-making through the integrated application of social sciences.

Use of the FACETs framework will address, and in some cases may exceed, the Weather Act goal by:

1. Establishing a fully-integrated continuum of accurate weather threat information to refine and improve the protective decision-making of communities, organizations, and individuals with one-hour lead times;
2. Reducing warning area sizes by a minimum of 30 percent, thereby decreasing over-warning notifications;
3. Providing new opportunities for America's Weather Enterprise to develop client-serving applications;
4. Defining more useful, actionable, and end user-specific hazardous weather information, as informed by social sciences; and
5. Reducing costs for society and improving economic opportunities.

[2] Government and non-government entities which are directly involved in the preparation, dissemination and discussion of any weather-, water-, or climate-related National Weather Service information, in support of making decisions for (routine or episodic) high impact events.

By meeting these expectations, FACETs will also address recommendations in other Congressionally-mandated (e.g., National Institute of Standards and Technology [NIST; 2014[3]]) and scientific community reports (e.g., National Academy of Sciences' National Research Council [NRC; 2006[4], 2012a[5], 2012b[6]]) for NOAA to institute an integrated, consistent approach to the provision of probabilistic hazardous weather information. NOAA's Hurricane Forecast Improvement Program (HFIP)[7] is also utilizing the FACETs approach, engaging involvement of key stakeholders from the media, America's Weather Enterprise, and emergency management in all relevant aspects of development and evaluation. The NIST-led National Windstorm Impact Reduction Program (NWIRP)[8] is also adopting the FACETs approach with both agencies leveraging the new paradigm.

V. Program Details

A. Research to Improve Observations

The Nation's current tornado warning system is dependent on the temporal and spatial capabilities of NOAA's observational and remote sensing systems and the inherent limitations of each. To address this, the TWIEP will explore improvements in three key observation systems (i.e., radar, satellite, and boundary layer sensors) and evaluate the impacts of these systems on tornado forecasting using science-based results from: (a.) Observation System Experiments (OSEs), which evaluate the effect of adding or removing individual components of the observing system on numerical weather prediction analysis and forecast quality; (b.) Observation System Simulation Experiments (OSSEs) for the study of possible future observing systems in comparison to OSEs; and (c.) next-generation mesoscale observational systems and networks evaluated in joint research/operational testbeds. (See Short- and Long-Term Goals #1 in Table 1).

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[3] "*Final Report, National Institute of Standards and Technology (NIST) Technical Investigation of the May 22, 2011, Tornado in Joplin, Missouri.*" Final Report, National Construction Safety Team Act Reports (NIST NCSTAR) - 3

[4] "*Completing the Forecast: Characterizing and Communicating Uncertainty for Better Decisions Using Weather and Climate Forecast*" Committee on Estimating and Communicating Uncertainty in Weather and Climate Forecasts

[5] "*The National Weather Service Modernization and Associated Restructuring: A Retrospective Assessment.*" Committee on the Assessment of the National Weather Service's Modernization Program, Board on Atmospheric Sciences and Climate; Division on Earth and Life Studies

[6] "*Weather Services for the Nation: Becoming Second to None*." Committee on the Assessment of the National Weather Service's Modernization Program; Board on Atmospheric Sciences and Climate; Division on Earth and Life Studies

[7] HFIP, as defined in Section 104 of the Weather Act, requires NOAA to plan and maintain a project to improve hurricane forecasting, including: 1) the prediction of rapid intensification and track of hurricanes; 2) the forecast and communication of storm surges from hurricanes; and 3) risk communication research to create more effective watch and warning products. (P.L. 115-25)

[8] NWIRP is a multi-agency program established by Congress, "…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." (P.L. 114-52)

1. *Advanced Weather Radar Technologies*

Advanced radar technology, such as Phased-Array Radar (PAR) technology, presents an opportunity to improve the cadence of full-volume scans of storms, from the current rate of every five minutes provided by the current WSR-88D radars, to approximately every one minute with PAR. Recent experiments with PAR at the National Severe Storms Laboratory (NSSL) have demonstrated the potential to improve detection, and in some cases improve warning lead times to 20 minutes. NSSL will also continue research and development on dual-polarization technology recently added to existing WSR-88D systems in order to fully exploit those enhancements for tornado detection and prediction. Future work within the TWIEP will determine the optimal update rate of radars; how forecasters best use the existing and/or new radar data, including the use of social sciences; and how best to assimilate these data into numerical weather prediction models (e.g., Warn-on-Forecasts) to extend tornado forecast lead times to 60 minutes. NOAA will consider other radar technologies, as they become available, as we move forward to improve tornado warnings.

2. *Satellites*

The next-generation geostationary operational environmental satellite data (from the most recently launched GOES East and GOES West satellites) are updated every 60-seconds for small scale sectors focusing on thunderstorm development. Likewise, current and planned hyperspectral satellites (e.g., the Joint Polar Satellite System series) are providing unprecedented views of our planet. Data from these systems are ideal for infusion into small scale, high resolution numerical weather prediction models. Through collaboration with the National Environmental Satellite, Data and Information Service, the use of these data will be instrumental in providing unique "weather-as-it-happens" information in pre- and near-storm environments to improve modeling and real-time forecasting of tornadoes.

3. *Boundary Layer*

The TWIEP will also include research on non-radar, rapidly-updated, fine-scale sensing of the boundary layer[9] and lower troposphere prior to and during storm occurrence. Observation platforms employing ground-based LIDAR (Light Detection and Ranging) instruments, thermodynamic and wind profilers, unmanned aircraft systems equipped with sensors, and Automated Surface Observing System boundary layer measurements will be evaluated for their application in helping to improve the accuracy of tornado forecasting.

B. Research to Improve Tornado Forecasting Guidance

The TWIEP will leverage ongoing research and development efforts with CAM ensembles (i.e., models that can replicate complex processes within thunderstorms), including WoF and an ensemble version of the operational High-Resolution Rapid Refresh (HRRR) model. The fundamental concept of these models is to provide a frequently-updated, regional-scale, on-demand, convection-resolving analysis and prediction system utilized in the operational framework of the national centers and NWS Weather Forecast Offices (WFOs). The TWIEP will explore continued research with WoF, HRRR, and NOAA's new Finite-Volume Cube-Sphere (FV3) Dynamical Core model, and will enhance collaboration between the NWS and

[9] The boundary layer is the mixed layer of the atmosphere closest to the Earth's surface, encompassing all interactions between the underlying land and water surfaces and the atmosphere.

NOAA's research laboratories. (See Short-Term Goals #2, #4 and Long-Term Goal #3 in Table 1).

The TWIEP will also develop guidance tools, which will be used to expand and enhance tornado prediction methods. One such tool, the Multi-Year Reanalysis of Remotely-Sensed Storms, reconstructs and statistically evaluates years of radar data to provide real-time predictions of a thunderstorm's longevity, intensity and related phenomena.

C. Research to Improve Tornado Forecast Effectiveness (Social Science)

Associated with FACETs, preliminary research in NOAA's Hazardous Weather Testbed has shown promising new concepts for increasing tornado forecast lead times, reducing false alarm rates, and improving threat communication – all of which can enhance public safety, economic productivity and serve as the foundation for expanding into other NWS threat forecasting areas (e.g., winter weather, tropical storms, fire weather, etc.). To achieve these outcomes, NOAA will advance two areas of long-term social sciences study. The first will focus on the forecaster operational decision environment to optimize usability of new tools and technologies by evaluating and understanding the cognitive demands on the human forecaster. The second area of study will focus on assessing societal information reception, interpretation, risk perception, and response, to understand how to blend forecast advancements with societal response. Specifically, evaluating all aspects of a warning recipient's response (or nonresponse), including understanding, belief, confirmation, personalization of risk, action, education, preparedness, situational awareness, and recovery, is necessary to empower society to make protective action decisions and maximize the effectiveness of forecast improvements. (See Short-Term Goals #5 and #6 in Table 1).

D. Development of the Next-Generation Warning System

The TWIEP will create a more accurate and user-adaptable warning system to facilitate improved public response under FACETs. With this in mind, OAR and NWS will collaborate on developing systems to create and disseminate probabilistic hazardous information using existing NWS systems such as the Advanced Weather Interactive Processing Systems. The TWIEP will assess probabilistic hazardous information, as well as the format, content, systems, and media platforms by which it is communicated. Social scientists will collaborate in the design and development of the systems to ensure effectiveness of forecast tools for creating and issuing this information. Probabilistic hazardous information will also effectively integrate with planned enhancements to the national broadcast media infrastructure and other modern data output formats. (See Short-Term Goal #3 and Long-Term Goals #2 and #3 in Table 1).

E. Connections with VORTEX-SE and NWIRP

Verification of the Origins of Rotation in Tornadoes EXperiment-Southeast (VORTEX-SE) is a research program mandated by Congress to understand how environmental factors in the Southeastern U.S. affect the formation, intensity, structure and path characteristics of tornadoes for this region. In addition, the program is tasked with determining the best methods for communicating to the public the forecast uncertainty of these events, and evaluating public response. All VORTEX-SE research will be applied to the TWIEP. Research and recommendations from the NWIRP will also be leveraged in support of the TWIEP's activities, and vice versa.

F. Technology Transfer and Implementation

The TWIEP will use the following tools to ensure transition of research to operations (see Long-Term Goals #2 and #4 in Table 1):

a. *Transition Plans* - developed to transition new observing systems, modeling improvements, and advancements in communicating warning information into NWS operations and America's Weather Enterprise.
b. *Concept of Operations* - developed to define NWS processes for generating and communicating probabilistic hazard information (including social and behavioral science research), to align with existing and future warning communication systems.
c. *Coordination/Collaboration with America's Weather Enterprise* – close involvement between OAR, NWS and weather enterprise partners to ensure seamless implementation and enhanced chances of success.
d. *Operational Testing and Evaluation* - to define rigorous testing and evaluation plans for introducing new technologies into operations via a phased approach of Hazardous Weather Testbed and Operational Proving Ground evaluations, and regional/national demonstrations.
e. *Formal Training* - for NWS forecasters, core partners, decision makers, the weather enterprise, and the general public on utilizing probabilistic hazard information in their decision-making processes.

VI. Program Milestones for FY 2019 – FY 2023

- **Observations**
    - **Complete installation and calibration of the PAR Advanced Technology Demonstrator**, and evaluate impacts of rapidly updated dual-polarization radar data on severe weather warning performance.
    - **Conduct Observing System Simulation Experiments (OSSEs)** to inform optimal design of existing and future observational networks.
    - **Establish a Mesoscale Observational Testbed** to inform optimal design of existing and future observational networks.
    - **Design a streamlined National observational system** suitable for advanced data assimilation and reduced model error.

- **Prediction**
    - **Validate all components of the experimental 2-km WoF system prototype at the NOAA Hazardous Weather Testbed**, including data quality control, ties to developing parent CAM-based ensembles, products and tools.
    - **Implement a WoF prototype system** into the NWS's modeling framework by 2023.
    - **Develop, test, and deliver a prototype HRRR-based 3-kilometer CAM ensemble** with particular focus on data assimilation components that can be ported to any modeling framework. This will include parallel testing and development of FV3 applications in a CAM framework and development of advanced physics packages for the FV3 framework.

- **Risk and Uncertainty Communication**
    - **Establish performance metrics** to accurately assess effectiveness of current and future forecasts and warning paradigms in support of societal needs.
    - **Define and implement optimal predictive information content and lead time** for decision makers tailored to diverse user groups, with an overall focus on effective communication and response using social and behavioral science studies.
    - **Through applied social and physical science research in Testbeds, the Operational Proving Ground, and other studies, develop a prototype FACETs concept** to optimize the forecast decision environment and understand public risk perception and response.
    - **Conduct risk reduction exercises with prototype FACETs/Probabilistic Hazard Information tools** in NWS Weather Forecast Offices.
    - **Implement a next-generation NWS warning paradigm** to include probabilistic hazard information with extended lead times that empower effective decision-making.

VII. Resources

NOAA is dedicated to meeting the requirements of the TWIEP, as laid out in the Weather Act. Resources applied to execution of the TWIEP will coordinate and enhance these efforts, leverage and integrate their results, and address identified gaps so as to achieve the overall objectives. In order to meet the goals outlined above, NOAA will require sustained funding to support the activities described in this plan. Resource requirements are still being considered within the agency and will be reflected in NOAA's future year budget requests, as well as in the annual budget plan required by Section 103 of the Weather Act. Applying a philosophy that the whole is greater than the sum of the parts, the TWIEP's comprehensive, unified approach will maximize the scientific results and societal benefits for the Nation.

VIII. Summary

Dramatically improving NOAA's tornado warning lead times to 1 hour or more, as directed by Section 103 of the Weather Act, will require the collective and enhanced contributions of observations, prediction, forecaster skill, communication, and public response. In the spirit of attacking the challenge holistically instead of through individual, disparate projects, the TWIEP will unite cutting-edge science, research, development, and operational activities of NOAA to achieve stated objectives within the Weather Act. Specifically, the TWIEP's components of research programs (e.g., VORTEX-SE, WoF, PAR, FACETs, NWIRP, etc.) and their underlying social and physical sciences, technologies, and new methodologies, will be collectively focused on improving operational capabilities to enhance the accuracy, effectiveness, and timeliness of tornado forecasts, predictions, and warnings. Emphasis will be placed on directing new and next-generation remote-sensing technologies (e.g., GOES satellites and PAR), improved understanding of boundary layer processes, and 1-hour (or longer) predictive numerical model output toward a new paradigm for more effectively communicating risk and uncertainty in hazardous weather such as tornadoes. NOAA will partner with academia, America's Weather

Enterprise, local media, and the emergency response community to achieve this and, ultimately, contribute to the objectives of the Weather Act.

This plan for the TWIEP describes the overarching goals and strategy for achieving the Weather Act objectives of Section 103. More detailed, specific, and tactical steps necessary to achieve the sub-components of the TWIEP, beyond those already described, will be developed in coordination with NOAA and DOC.

List of Acronyms

CAM	Convection Allowing Model
FACETs	Forecasting a Continuum of Environmental Threats
FV3	Finite-Volume Cube-Sphere Dynamical Core Model
GOES	Geostationary Operational Environmental Satellite
HFIP	Hurricane Forecast Improvement Program
HRRR	High-Resolution Rapid Refresh Model
LIDAR	Light Detection and Radar
NAS	National Academy of Sciences
NESDIS	National Environmental Satellite, Data, and Information Service
NEXRAD	Next-Generation Radar
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NWIRP	National Windstorm Impact Reduction Program
NWS	National Weather Service
OAR	Oceanic and Atmospheric Research
OSE	Observing System Experiments
OSSE	Observing System Simulation Experiments
PAR	Phased-Array Radar
VORTEX-SE	Verifications of the Origins of Rotation in Tornadoes Experiment-Southeast
WoF	Warn on Forecast
WSR-88D	Weather Surveillance Radar - 1988 Doppler

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