WRITTEN STATEMENT OF
DR. KELVIN K. DROEGEMEIER
VICE PRESIDENT FOR RESEARCH, REGENTS' PROFESSOR OF METEOROLOGY, PRESIDENTIAL PROFESSOR, WEATHERNEWS CHAIR EMERITUS, DIRECTOR EMERITUS OF THE CENTER FOR ANALYSIS AND PREDICTION OF STORMS
UNIVERSITY OF OKLAHOMA

ON
"RESTORING US LEADERSHIP IN WEATHER FORECASTING, PART 2"

BEFORE THE
SUBCOMMITTEE ON ENVIRONMENT
U.S. HOUSE OF REPRESENTATIVES COMMITTEE ON SCIENCE, SPACE AND TECHNOLOGY

26 JUNE 2013

I wish to thank Chairman Stewart, Ranking Member Bonamici, and other Members of the Committee for the privilege of testifying on the important topic of US leadership in weather forecasting. I especially applaud your efforts to improve our ability to protect citizens from the destructive forces of nature, and I thank you for considering my earlier suggestions regarding the Weather Forecasting Improvement Act of 2013.

As a professor of meteorology and researcher at the University of Oklahoma's National Weather Center, I have, for nearly 30 years, both lived in and worked at the global epicenter of severe weather. My research involves using computer models, initialized with fine scale data such as those provided by Doppler radars, to explicitly predict intense local weather such as thunderstorms and, hopefully one day, tornadoes.

We have been reminded this spring, as in many years past, that high impact weather can cause heartbreaking loss of life, extraordinary property damage, and long-term economic and societal disruption extending far beyond the areas directly affected. As I witnessed firsthand last month, hundreds and perhaps thousands of people in Moore, Oklahoma are alive today because of our nation's forecast and warning system. The same is true for Joplin, Missouri, Tuscaloosa, Alabama, and countless other places that have been ravaged by severe weather. To the many exceptional public servants within NOAA, including its outstanding leader, Dr. Katherine Sullivan, we owe a tremendous debt of gratitude. We also must acknowledge academic, government and private sector researchers, along with the media and private weather companies, the latter of which play a vital role in developing products and delivering services to the public.

Yet more can and needs to be done. Even one death from hazardous weather is intolerable and should be prevented.

We have in place a foundation of unprecedented capability upon which to build. Our understanding of the atmosphere, our technologies and tools, our research facilities and capabilities, and our recognition of the most important roadblocks and challenges equip us not for incremental change, but rather for a bold transformation that will lead us to achieve the ultimate goal: ZERO DEATHS. With that focus, we are led naturally to look at all aspects of this enormously complex problem, and all metrics for assessing progress, in a comprehensive, interdisciplinary fashion – to include observations, computer models, human behavior, communication of threat information, sheltering, building codes, and response and recovery, to name but a few. We achieved the goal of zero deaths for airline crashes resulting from wind shear, and we should be no less bold here.

1. STATE OF WEATHER FORECASTING CAPABILITIES AND HOW THE US COMPARES WITH OTHER COUNTRIES

Although the United States is not unique in facing high impact weather, including thunderstorms, hurricanes and tornadoes, the incidence of such weather in the US is higher than any other location on the planet. During the past three decades, due principally to the use of numerical simulation models and theoretical analyses of their output, and more recently as a result of the nationwide NEXRAD Doppler radar network as well as experimental observing systems such as mobile Doppler radars, our understanding of, and ability to predict, high impact weather have increased dramatically.

For example, vertical changes in wind, temperature and humidity, measured by balloons and vertical profiling radars and also predicted by global and regional models, now allow for the accurate determination of general storm features – such as type (supercell, squall line, cluster, isolated weak cells) and likely motion – many days in advance. US models continue to improve relative to their counterparts in other countries, and with planned computer upgrades at NOAA along with other enhancements, the US should soon claim the global lead.

New finer-scale models in the US, such as the Weather Research and Forecast (WRF) and High Resolution Rapid Refresh (HRRR), are being run at spatial resolutions capable of capturing important storm details, thereby allowing forecasters to state with reasonable certainty, up to a few days in advance, that particular events, such as supercells or squall lines, are likely to occur in a given area during a specified period of time. The assimilation of fine-scale observations, especially from the NEXRAD radar network but also from satellites and wind profilers, is a key step toward providing even greater fidelity in the forecasts, and is receiving considerable attention within the research community. Other nations, especially China, Japan, and Korea, are investing in new radar and modeling capabilities to achieve similar goals.

A notable example of the impact of capabilities just described occurred in central Oklahoma on April 13, 2012. For only the second time in its history, a day-two outlook of “high risk” for severe weather was issued by the NOAA Storm Prediction Center, suggesting a major tornado outbreak in the southern Plains. A rare high probability for tornadoes was issued on the 13th, and experimental models, run at the NOAA Hazardous Weather Test Bed in Norman, Oklahoma, accurately predicted the location, type and timing of the storms. On another occasion, so far in advance was the information available that many State offices, businesses and schools in central Oklahoma closed early, as frequently happens in anticipation of winter storms. This suggests consideration be given, especially by schools, to declaring “Tornado Days” in a manner analogous to “Snow Days.”

Our inability to measure all key atmospheric variables at fine scales, and limitations in models and our understanding of the atmosphere, lead to uncertainty or error in the starting conditions and other parameters of any computer model forecast. Because of the fundamental nature of the atmosphere, such uncertainty can cause forecasts, started from nearly the same conditions, to diverge with time. To account for the many facets of uncertainty, the so-called ensemble approach is used, in which dozens of forecasts, rather than only one, are produced, each starting with slightly different initial conditions. This allows for the creation of probabilities and the quantification of uncertainty in any given forecast – a critical element and the subject of the NRC report entitled *Completing the Forecast*.[i] Ensembles are now foundational to the US forecasting portfolio at global and regional scales, and are being tested experimentally at the scale of individual storms. They represent the only meaningful strategy for numerically predicting high impact weather.

At the highly tactical level of detecting and characterizing severe storm threats, and providing associated warnings, the principal tool of choice is the Doppler weather radar. Formally commissioned in 1994, the more than 150 Doppler radars operated within the tri-agency (Commerce, Transportation, Defense) NEXRAD program have saved countless lives. In concert with other tools, described below, NEXRAD has dramatically improved tornado warning lead time from an average of approximately 6 minutes in 1994 to approximately 14 minutes today, though with a false alarm ratio that has remained disturbingly high – at around 75% – for nearly 20 years.

The recently completed upgrade of NEXRAD to dual polarization capability, which provides for characterizing precipitation type (such as rain, snow, and hail), will be of immense benefit in flood forecasting, aviation safety and efficiency, and computer model prediction. The multi-function phased array radar (MPAR), which is under development as a NEXRAD replacement and offers a ten-fold improvement in storm scanning time with simultaneous tracking of aircraft, may lead to additional improvements in warning lead time, possibly on the order of several minutes. However, as described below, extending the average warning lead time to an hour or more, which is a goal of the bill under consideration, can only be achieved using numerical prediction models (reflecting NOAA's Warn on Forecast concept), and must be pursued carefully lest it create unintended negative consequences.

Other important advances contribute to notable capability in the US forecasting enterprise. NOAA's Advanced Weather Information Processing System (AWIPS), and outstanding training, including that provided by the NOAA Warning Decision Training Branch (WDTB) in Norman, Oklahoma, allow forecasters to deal with vast amounts of information in a highly structured, efficient manner. National Weather Service Test Beds, operated by the National Centers for Environmental Prediction (NCEP) in collaboration with OAR laboratories, NOAA Cooperative Institutes, and universities, are a vital mechanism by which research outcomes and translated into operational practice. The aforementioned Hazardous Weather Test Bed, the Aviation Weather Test Bed in Kansas City, Missouri, and the Hydrologic Test Bed in College Park, Maryland, are but three examples, and all are poised to play a critical role in future activities, as described below.

2. IMPORTANCE OF TIMELY AND ACCURATE WEATHER FORECASTS AND OPPORTUNITIES FOR WEATHER RESEARCH AND TECHNOLOGY DEVELOPMENT TO IMPROVE FORECASTING OF SEVERE WEATHER EVENTS

Our society is increasingly vulnerable to the impacts of severe weather for many reasons. For example, urbanization, and significant development in coastal zones, have dramatically increased our nation's exposure to high impact weather and, in especially dense population areas, have substantially decreased the ability to efficiently move citizens out of harm's way. These points are underscored in the 2007 National Science Board (NSB) report titled *Hurricane Warning: The Critical Need for a Hurricane Research Initiative*[ii]:

> To place the Nation's vulnerability in perspective, 50 percent of the U.S. population lives within 50 miles of a coastline.[6] The physical infrastructure in coastal regions has grown dramatically over the past few decades and in the late 1990's was worth about $3 trillion in the Gulf and Atlantic regions alone.[7] Trillions of dollars in new seaboard infrastructure investment are expected over the next several decades. As our economy grows and the value of built-infrastructure continues to increase, the economic and

> societal impacts of hurricanes also can be expected to escalate. Although not all coastal regions are directly vulnerable to hurricanes, impacts from those regions that are affected can have national consequences, for example, via increased fuel prices and displaced citizens. Additionally, even though decaying tropical storms are an important source of fresh water for inland regions, associated flooding – occurring hundreds of miles from the coast and days after storm landfall – can be astonishingly destructive. Historically, flooding has claimed more lives in the U.S. than any other weather phenomenon[10] and destructive tornadoes frequently accompany hurricanes.

Sensitive electronics systems, including the power grid, cellular towers, microwave links, surveillance cameras, and high-capacity communications infrastructure, are vulnerable to high impact weather and, ironically, represent essential elements for both communicating information prior to, during, and following major disasters. Likewise, energy production and storage facilities, and the entire national airspace system, are subject to tremendous disruption owing to severe weather. Finally, the entire supply chain, especially with regard to the delivery of perishable goods, is highly vulnerable.

The notion of a timely and accurate forecast, as a means for reducing exposure and mitigating loss, is very complex and highly dependent upon the needs of the recipient and even the particular weather situation at hand. In assessing opportunities for forecast improvement via research and development, this point must receive careful consideration.

For example, with regard to timeliness, an industrial chemical plant may require an entire day to secure for a hurricane, whereas an airline may need three to four hours to plan for a significant weather event that will last only 30 minutes over a hub airport. The time needed for a school to react to a significant tornado threat likely depends upon the grade levels involved, the location of the school, access to major roadways, and sheltering options. A different time and procedure no doubt would be utilized for a possible blizzard.

With regard to accuracy, conventional statistical measures of skill are quite limited in their applicability to phenomena such as thunderstorms, which have a high degree of spatial and temporal intermittency. For example, a thunderstorm perfectly predicted by a computer model, but with a position error of 20 miles such that no overlap exists with the real storm, would have zero skill by most conventional metrics. Yet, the forecast may have significant practical value, especially if made in a probabilistic framework. Research is needed to develop measures of accuracy, skill and value for high impact weather, and strategies developed to convey this information, in appropriate ways, to end users, especially the general public.

Another important consideration in the context of research and development leading to forecast improvements – and arguably THE most important consideration – stems from the fact that although high impact weather is the destructive force of concern, loss of life is related to our ability to understand, prepare, predict, warn and respond. This is an enormously complex, multi-faceted challenge that fundamentally involves human behavior and thus transcends physical science and technology.

To underscore this point, in 1953, 519 people died in tornadoes in the US – when only one in four US households had a television set, when telephones were bulky and wired, when no national radar network was in place, when centralized operational weather prediction was in its infancy, and when our principal mobile information device was the transistor radio. In 2011, 550 people in the US died in tornadoes. Although the population was significantly higher and denser than in 1953, the nation had at its disposal sophisticated computer models, a world-leading national Doppler radar network, the Internet, cell phones, social media, 24-hour television with multiple sets in nearly every home and streaming broadcasts on mobile devices, and a national weather radio network. Considering the population caveat noted above, why was the death toll so high two years ago and nearly six decades after enormous advances had been made in physical science, technology and operations?

I believe the answer relates, in part, to ineffective understanding and incorporation into our operational enterprise of the human dimensions of high impact weather. We need to understand how the public perceives weather risk and the factors influencing that perception. We need to understand how to formulate and convey threat information and uncertainty to the public and understand its comprehension and response, as noted in *Completing the Forecast*. And we must address issues of trust and source verification, and study whether the current watch/warning system needs to be re-thought from the ground up, starting with the human dimension.

A preliminary study[iii], conducted at the University of Oklahoma, regarding public perception of tornado warning accuracy underscores the importance of social sciences research. Of the more than 3000 people surveyed, roughly 25% of respondents noted they would take *no protective action* for a hypothetical tornado warning in the "light" intensity category. Once the warning level rises to "significant," 7% said they would take no action. For "severe," devastating and incredible events," roughly 7% continue to report they would take no action in any of the categories. Also for these categories, up to 18% of respondents reported they would *drive way from the warned area*. These early results clearly suggest a correlation between the level of threat communicated in a tornado warning and resulting human behavior, though perhaps not in the intended direction.

Related to the above, improving tornado warning lead time to more than an hour, as noted specifically in the bill, is a necessary and very important goal. However, it is not sufficient. Too great an emphasis on this metric will lead to missing the real point. The ultimate question to be addressed concerns how people will use that hour, and the answer resides in domain of the human and behavioral sciences. Indeed, achieving a one hour lead time via physical science and technological advances may actually worsen the situation, as noted in the preliminary study described above, if the human dimension is not considered throughout.

I witnessed precisely this circumstance on May 31, 2013, when in the presence of long-lived and slowly moving tornadic storms over Oklahoma City, thousands of residents of south Oklahoma City, Norman, and surrounding communities fled their homes, heading south. City streets, highways and Interstates became parking lots, placing individuals in great peril (an automobile is the worst possible refuge from tornadoes, especially violent ones). The substantial advance notice available during that evening, coupled with fresh memories of tornadoes just 11 days earlier, led to a reaction in the citizenry unlike any seen to date. It is difficult to imagine an example that provides a more compelling argument for making social sciences research foundational to a high impact weather initiative.

In light of the above, I suggest that the overall goal of improving forecasts of high impact weather be one of ZERO DEATHS, not solely improvement of metrics such as warning lead time. Our nation achieved zero deaths for airline crashes resulting from wind shear, and we should be no less bold here.

Turning to opportunities, by definition, an opportunity is a convergence of favorable circumstances that provides a likelihood of advancement or progress. The opportunities before us for improving the forecasting of high impact weather are profound because of the tremendous Federal and private sector investments made to date, which have produced a world class foundation upon which to undertake a transformative program. For example, as shown in the video during my oral testimony, we have demonstrated the ability of a cloud-resolving numerical model to predict the location and timing of intense vertical rotation consistent with tornadoes actually observed on a given date. Although representing important progress, an enormous amount of work remains before this sort of forecast might be provided operationally with requisite accuracy, reliability and value.

Specific opportunities before us include using unmanned aerial systems, and special radars[iv] such as those developed by the NSF-funded Center for Collaborative Adaptive Sensing of the Atmosphere (CASA), to gather data on temperature, moisture, wind, and precipitation from the ground to 4-5 kilometers in altitude. This region of the atmosphere plays an extremely important role in severe weather and in fact is where most severe weather actually occurs; however, as noted in the NRC study *Observing Weather and Climate from the Ground Up*[v], this region also is among the most poorly sampled.

Although other observations are needed, especially from satellites for improving global and regional models, those which focus on the lower parts of the atmosphere are likely to have the greatest impact on the performance of cloud-resolving models. Tools and techniques such as adjoint sensitivity models, Observing System Experiments (OSEs), and Observing System Simulation Experiments (OSSEs) can be deployed to authoritatively address this issue. Note that such studies are needed because placing observational systems where none exist can, in some cases, actually degrade a forecast, and because data assimilation systems sometimes are able to provide retrieved information of sufficient quality in gap areas so as to preclude the need for additional observing resources. In the context of the bill under consideration, I therefore suggest avoiding narrow prescription of approach (for example, using OSSEs), thus allowing the community of researchers to define observational needs and forecast goals and determine which specific tools and approaches are best suited for meeting them.

Cloud resolving models, which are the foundation of high impact weather prediction, have become quite sophisticated during the past several years. Advances in computational techniques, grid structures, physics, and in particular, the assimilation of observations from a vast array of sensors, have opened new horizons for fine scale forecasting. One of the most important challenges, related not only to effectively capturing storm dynamics but also to precipitation forecasting and storm electrification, involves the assimilation of hydrometeor data from dual polarization Doppler radars, and concomitant improvements in how models represent both liquid and frozen water species. Because the entire NEXRAD network is now producing dual polarization data, the utilization of it in forecast models is not only an opportunity but an imperative.

The final important opportunity concerns the exploration of new strategies for utilizing high performance computing systems, with particular emphasis on elastic/cloud computing rather than static, centralized resources. In this manner, the prediction system is operated not in a fixed mode using the same configuration each day, independent of the weather, but rather is adjustable so as to optimally address the particular weather situation at hand. This concept, known as dynamically adaptive numerical prediction, was prototyped in the $11.5 million NSF project titled Linked Environments for Atmospheric Discovery (LEAD)[vi] and evaluated in the NOAA Hazardous Weather Test Bed.

Continuing to test this strategy, and others, would benefit substantially from involvement by private technology companies such as Google, Microsoft, Yahoo, and others. Making progress toward bold goals in high impact weather prediction requires a true partnership among academia, the government and private sector, bringing to bear unique resources (e.g., the Blue Waters supercomputer, funded by NSF, at the University of Illinois) and strategies provided by them.

3. SPECIFIC RECOMMENDATIONS INCLUDING RESEARCH AND R2O

Vitally important to a high impact weather initiative is a thoughtfully formulated, effective program structure and execution strategy, including a pathway to operations. The complexity of the multi-faceted challenges involving transforming the prediction of high impact weather must not be underestimated, and critically important is true integration of multiple perspectives and strategies from the physical, social, and behavioral science research communities with those of operational practitioners and end users.

In that regard, the highly successful Hurricane Forecast Improvement Project (HFIP)[vii] would serve as a superb role model as HFIP rapidly brought science-based changes to operational hurricane forecasting. The identification of key challenges, and early delineation of prioritized goals and approaches for meeting them, are essential elements of such a successful program. These tasks can best be accomplished by researchers, with NOAA leading the overall program and Congress providing the mandate, funding, and oversight.

Consideration also should be given in the high impact weather initiative to creating an analog of the National Hurricane Research Test Bed, which was suggested by the National Science Board in the aforementioned report. It represents a framework for optimally coordinating research and operational collaboration. Quoting from the NSB report:

> The proposed NHRTB will involve linking relevant theoretical, physical and computational models from atmospheric, oceanic, economic, sociological, engineered infrastructure, and ecologic fields, conducting experimental research to understand the complexities of hurricanes, and obtaining measurable results in a comprehensive framework suitable for testing end-to-end integrative systems. Test Bed results can be applied experimentally to real situations and provide simulations of important transfer linkages to operational entities and decision makers. NHRTB could be a single facility or a physically distributed environment; regardless of its structure, NHRTB should be operated an interdisciplinary working laboratory where much of the basic research from NHRI can be experimentally substantiated using suitable quantitative metrics, and where a culture of interaction and collaboration can be promoted.

Supporting the concept just described, the National Weather Service operates a number of exceptional test beds ideally, cited previously, that are ideally suited to composing a physically distributed collaborative environment. Indeed, they should even be expanded, though going beyond the traditional linear model of research to operations (R2O) and into a new research plus operations (R+O) concept involving government, academia and the private sector.

Other specific recommendations presented below build upon many of the opportunities described in the previous section.

1. Develop strategies to assess the skill, accuracy and value of high impact weather predictions, taking into account the temporal and spatial intermittency of associated phenomena and using this information as a foundation for developing appropriate message content and communication strategies.
2. The human and behavioral sciences must be a foundational component of a high impact weather initiative from the very beginning, and efforts therefore must be directed toward identifying social science scholars who can contribute and operate in a highly multidisciplinary environment. Additionally, key social science questions need to be identified early and

approaches determined for addressing them – not in isolation, but as an integrated component of the initiative.

3. Use appropriate tools to determine which new observations will lead to the greatest improvements in high impact weather forecasts, particularly emphasizing low cost and rapidly, adaptively deployable technologies such as unmanned aerial systems.
4. Continue making improvements in forecasting models and data assimilation techniques, with particular emphasis on the assimilation of dual polarization Doppler radar data and new data platforms from item 3 above. Test such methods in real time utilizing NWS test beds.
5. Use test beds to evaluate dynamically adaptive prediction strategies built upon new computational modalities (e.g., cloud computing). Further, seek to understand the operational (technological as well as behavioral) consequences of their potential implementation.
6. Architect, in a practical conceptual framework, a completely new threat communication/warning system that starts with the human dimension and proceeds upstream toward operational capabilities enabled by physical science and technology.

Finally, I strongly suggest that studies be undertaken to understand the fundamental predictability of high impact weather. We know, for example, that experimental cloud-resolving models are able to predict certain types of thunderstorms for periods of time much longer – up to 24 hours – than theory suggests should be possible. But unlike for larger-scale weather, which has a predictability limit of about two weeks, we have no idea of the predictability limits for thunderstorms and larger storm systems. Such knowledge is needed for many reasons, but would be especially useful to policy makers in guiding financial investments.

For example, suppose predictability theory indicates that numerical models have achieved 90% of the theoretical limit in forecasting storms capable of producing tornadoes, and that achieving the final 10% will provide little added benefit yet cost $500 million. Such information might lead the required funds to be directed toward addressing other challenges.

4. COMMENTS ON THE ACT ITSELF

I applaud the efforts of the Committee, and those of Mr. Bridenstine via the bill he introduced, to improve our ability to protect citizens from the destructive forces of high impact weather. The challenges before us are immense, and the need for more than incremental progress is unquestionable. I recognize that a single bill, and the funding recommended within it, will not solve every problem or satisfy every constituent. Yet, it is an appropriate down payment on the future if it considers the important recommendations made herein regarding less prescription and greater flexibility, wherein NOAA and the relevant other agencies and communities involved define specific goals and decide which tools and approaches are needed to achieve them.

My final comment concerns climate and weather in a mutually reinforcing context. All of us recognize the importance of balance between weather and climate investments in our nation's research and operations portfolio. Yet, the traditional "line" dividing weather and climate is increasingly blurred as climate models are now run at resolutions approaching those of weather models. Consequently, we would do well to consider weather and climate not as two distinct elements at the extreme ends of a spectrum, but rather as inseparable parts of the Earth system.

To illustrate, recent dramatic improvements in severe weather forecasts are due, in part, to two important factors: a greater understanding of complex relationships between storm type/severity and the environments in which storms form, and the ability of our global and regional models to accurately predict those environments. Climate models have proven capable of reproducing environments hundreds of years in the past and thus can be useful for determining future environments and hence the types of storms that might be expected to form within them. Conversely, our understanding of, and ability to predict, high impact weather will improve climate model representations of storms, precipitation, the radiation budget, and even chemical processes. We are moving toward the day when we will no longer use separate models for weather and climate, and our investments likewise should reflect that trajectory.

ENDNOTES

[i] National Research Council, 2006: Completing the Forecast: Characterizing and Communicating Uncertainty for Better Decisions Using Weather and Climate Forecasts, 112 pp. http://www.nap.edu/catalog.php?record_id=11699

[ii] National Science Board, 2007: HURRICANE WARNING: The Critical Need for a National Hurricane Research Initiative, 36 pp. http://www.nsf.gov/nsb/publications/landing/nsb06115.jsp?org=NSF

[iii] Silva, C.L., H. J-Smith, J. Ripberger, K. Herron, D. Carlson, and M. James, 2013: Attention to, Perceptions of, Responses to Severe Weather Warnings: Preliminary Findings. Unpublished manuscript, 6 pp. Corresponding author address is clsilva@ou.edu.

[iv] National Research Council, 2001: Weather Radar Technologies Beyond NEXRAD, 83 pp. http://www.nap.edu/catalog.php?record_id=10394

[v] National Research Council, 2009: Observing Weather and Climate from the Ground Up: A Nationwide Network of Networks. 234 pp. http://www.nap.edu/catalog.php?record_id=12540

[vi] Droegemeier, K.K., 2009: Transforming the Sensing and Numerical Prediction of High-Impact Local Weather Through Dynamic Adaptation. *Phil. Trans. R. Soc. A*, 367, 885-904. http://rsta.royalsocietypublishing.org/content/367/1890/885.full

[vii] Gall, R, J. Franklin, F. Marks, E. N. Rappaport, and F. Toepfer, 2013: The Hurricane Forecast Improvement Project. *Bull. Amer. Meteor. Soc.*, **94**, 329–343. http://dx.doi.org/10.1175/BAMS-D-12-00071.1

OTHER RELEVANT MATERIALS

National Research Council, 2010: When Weather Matters: Science and Services to Meet Critical Societal Needs, 181 pp. http://www.nap.edu/catalog.php?record_id=12888

National Research Council, 2012: Weather Services for the Nation: Becoming Second to None, 98 pp. http://www.nap.edu/catalog.php?record_id=13429

National Research Council, 2012: The National Weather Service Modernization and Associated Restructuring: A Retrospective Assessment, 108 pp. http://www.nap.edu/catalog.php?record_id=13216

National Weather Service, 2013: Weather-Ready Nation Roadmap, 75 pp. http://www.nws.noaa.gov/com/weatherreadynation/files/nws_wrn_roadmap_final_april17.pdf

National Academy of Public Administration, 2013: Forecast for the Future: Assuring the Capacity of the National Weather Service, 137 pp. http://www.napawash.org/publications/forecast-for-the-future-assuring-the-capacity-of-the-national-weather-service/