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Next Generation Weather Radar (NEXRAD) Societal Benefit Study

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Abstract

The National Weather Service (NWS) Office of Observations asked The MITRE Corporation (MITRE) to describe and monetize the societal benefits of Next Generation Weather Radar (NEXRAD). NEXRAD radars are approaching end of life, and determining the societal benefits generated by these radars can help inform the value proposition of the replacement program, Radar Next. For this report, MITRE was asked to estimate the societal benefits of NEXRAD in a single year against a baseline where there is no data from NEXRAD radars. We monetized six sources of benefit: (1) reduced injuries and fatalities from tornadoes; (2) reduced injuries and fatalities from flash floods; (3) reduced injuries and fatalities from severe winds; (4) reduced commercial aviation delays from thunderstorms; (5) reduced injuries and fatalities from avoided general aviation accidents; and (6) reduced damage to aircraft from avoided general aviation accidents. We estimate that NEXRAD provides an annual benefit of $8.9 billion across these sources of benefit, with a low estimate of $5.2 billion and a high estimate of $11.2 billion.

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Executive Summary

The National Weather Service (NWS) Office of Observations asked The MITRE Corporation (MITRE) to describe and monetize the societal benefits of Next Generation Weather Radar (NEXRAD). NEXRAD is a network of high-resolution S-band Doppler weather radars jointly operated by the NWS, the Federal Aviation Administration (FAA), and the U.S. Air Force (USAF). NEXRAD radars, which were primarily deployed in the 1990s, are approaching end of life, and determining the societal benefits that these radars continue to generate today affirms the critical value of the National Oceanic and Atmospheric Administration's (NOAA) nationwide Doppler radars. It will also inform the value proposition of the replacement program, Radar Next.

For this report, MITRE was asked to estimate the societal benefits of NEXRAD in a single year against a baseline where there is no data from NEXRAD radars. Since our results may be used in formal assessments of Radar Next alternatives in the future, such as benefit-cost analysis, we considered the applicable guidelines in Circular A-4 provided by the Office of Management and Budget [1]. Specifically, while we are only able to monetize a subset of benefits, we aim to qualitatively describe key benefits given our available resources. We discuss the uncertainty in our benefit calculations, and we focus on the United States. Throughout the report, we indicate when our benefit estimate should be further validated through additional research before use in a formal decisional context.

NEXRAD radars detect precipitation and wind, and the data is used in various weather applications. NEXRAD data can be processed to map precipitation patterns and movement [2], and it is best known as a key resource in various near-term weather products. These products include, but are not limited to, tornado and thunderstorm warnings and watches [3], and NEXRAD mosaic imagery for aviation [4]. NEXRAD is also a key source used to enhance certain forecasting models that feed into derived products. Numerical weather prediction models that incorporate NEXRAD data include, but are not limited to, the High-Resolution Rapid Refresh (HRRR) model [5] and the North American Mesoscale (NAM) Forecast System [6].

With NEXRAD data freely available online [2] and its wide range of potential applications, identifying the full spectrum of uses exceeds the scope of a single analysis. Interested parties with an understanding of radar technology have applied the data in creative ways beyond the original intention. We found examples of researchers using NEXRAD data for meteorite fall detection [7], ornithologists and hobbyists using it to track bird migration [8], and agricultural scientists using it to track pest migration [9].

In discussions with the NWS Office of Observations and NOAA's Performance, Risk and Social Science Office (PRSSO), we prioritize two sectors for analysis in this report: (1) watches, warnings, and forecasts distributed to the general public and (2) aviation. Our preliminary review indicates that the societal benefits of NEXRAD are relatively high for these two sectors, and, based on analysis from NOAA's Technology, Planning and Integration for Observation (TPIO) group, these sectors closely align with NOAA mission service areas (MSAs) that are highly dependent on NEXRAD surface radar data (e.g., Severe Weather, Integrated Water and Prediction Information, and Aviation Weather). To qualitatively describe the benefits NEXRAD provides to these two sectors, we describe value chains that explain how NEXRAD data impacts decision-making, which ultimately leads to benefits. NEXRAD data is disseminated to relevant decision makers via the many general and specialized reports and tools that leverage the information.

We monetize six sources of benefit across the two sectors. Table 1 presents our estimates of the annual benefit of NEXRAD in 2024 dollars due to the availability of key economic inputs at the time of our calculations. The estimates in rows (a) through (c) come from existing literature on NEXRAD radars and do not have corresponding low and high estimates. Estimates in row (d) come from an expert elicitation analysis, where the primary estimate represents the experts' best guess point estimates, and the low and high estimates represent the ranges they provided around these "best guesses." Given limitations in the study approach, the benefit estimate should be further validated through additional research before use in a formal decisional context, such as a benefit-cost analysis. Estimates in rows (e) and (f) arise from original statistical analysis of aviation accident data. The primary estimates in rows (e) and (f) come from our preferred model specification, and our low and high estimates represent the range of results from reasonable variants. We conduct additional analysis to confirm that there is unlikely to be double counting across the benefits arising from reduced injuries and fatalities, and, therefore, we present the summed totals.[1] The total row for the low and high estimates includes the primary estimates when the low and high estimates are not available. We estimate that NEXRAD generates $8.9 billion per year in societal benefits, with a low estimate of $5.2 billion and a high estimate of $11.2 billion per year.

Table 1. Annual Benefit of NEXRAD in 2024 Dollars

Source of Benefit	Primary Estimate (millions)	Low (millions)	High (millions)
(a) Reduced Injuries and Fatalities from Tornadoes	$619	N/A	N/A
(b) Reduced Injuries and Fatalities from Flash Floods	$377	N/A	N/A
(c) Reduced Injuries and Fatalities from Severe Winds	$225	N/A	N/A
(d) Reduced Commercial Aviation Delays from Thunderstorms	$7,515	$3,915	$9,771
(e) Reduced Injuries and Fatalities from Avoided General Aviation Accidents	$172	$86	$219
(f) Reduced Damage to Aircraft from Avoided General Aviation Accidents	$2.6	$0.4	$5.0
(g) Total	**$8,911**	**$5,222**	**$11,217**

Notes: Minor differences in formula results are attributable to rounding. Rows (a), (b), and (c) do not have low and high estimates because they are directly derived from point estimates in existing literature. Section 4.1.1 contains additional detail on this literature. The total row includes primary estimates when the "Low" and "High" estimates are not available.

To underscore the magnitude of the benefit in reduced commercial aviation delays, we compared our findings with a 1983 report by NOAA's Federal Coordinator for Meteorological Services

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[1] The statistical model, the reasonable variants, and the analysis of double counting are discussed in detail in Section 4.3.

and Supporting Research that estimated the anticipated impact of NEXRAD on aviation delays [10], and we compared our findings with three benefit studies of FAA weather products for which NEXRAD is a key sensor [11], [12], [13]. These comparisons reinforce our conclusion that NEXRAD's impact on reducing commercial aviation delays is likely to translate into an annual benefit of several billion dollars.[2]

At the end of this report, we outline the key assumptions and sources of uncertainty that should be considered when interpreting our findings. Below, we highlight a few important points:

- The decision to focus on a subset of sectors likely leads to an understatement of the societal benefits. Other sectors that may benefit from NEXRAD include, but are not limited to, agriculture, energy, ground shipping, insurance, reinsurance, and water resource management. Future research could describe value chains for these sectors and attempt to monetize the benefits.
- For the sectors we did analyze, we were only able to monetize a subset of the benefits in the time we had, and this likely leads to an understatement of the societal benefits. For example, while we qualitatively discuss the benefit that the general public gains in day-to-day aspects of their lives from NEXRAD's impact on improving various weather forecasts, we do not monetize this source of benefit. Future research could develop approaches for monetizing this benefit (and others), such as assessing NEXRAD's contribution to improving forecasts and determining societal willingness to pay for forecast improvements.[3]
- Many of the results in Table 1 depend on existing literature and thus depend on the veracity of that literature. Independent replication of applicable literature was beyond the scope of our analysis.
- One of the benefits of assessing a program that has existed for decades is that we can leverage rich historic data to estimate the impact. We take this approach to derive the estimates in all rows of Table 1 except for row (d). However, this approach will primarily identify the impact of the program relative to the state of the world as it existed during the time of the data. Thus, our approach may overstate the current impact of NEXRAD due to improvements in other NOAA sensor technology assets since NEXRAD deployment. It may also understate the current impact because of improvements to NEXRAD radar technology and improvements in dissemination capabilities such as warning systems and the proliferation of smartphones.
- Our analysis of the impact of NEXRAD on commercial aviation delays from thunderstorms relies on expert elicitation. This approach has been used by other benefit studies of NOAA programs including a study of Geostationary Extended Observations (GeoXO) [14]. Simulation models of the National Airspace System (NAS) could provide a more robust and data-driven estimate of the impact of NEXRAD on delays. Such modeling was beyond the resources available for our analysis, and we leave it for future research.

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[2] These comparisons are presented in Section 4.2.3.

[3] For example, existing research estimates that the current total value to the United States of current weather forecast information is $102.1 billion per year [67]. Future research could be conducted to try to isolate the contribution of NEXRAD to the national value.

Acknowledgments

We received valuable feedback from economists in the National Oceanic and Atmospheric Administration's (NOAA) Performance, Risk and Social Science Office (PRSSO) including the Chief Economist, Monica Grasso, and Arnab Acharya, Ravi Chittilla, Joseph Conran, George Gardner, and Austin Sandler. We are grateful for their input, guidance, and thoughtful review.

We would also like to thank the many other NOAA and federal employees who shared their knowledge with our team. We especially appreciate the helpful advice and feedback from members of the National Weather Service (NWS), National Transportation Safety Board (NTSB), and Federal Aviation Administration (FAA).

In addition, we appreciate the guidance from our colleagues at The MITRE Corporation (MITRE) who helped during different phases of this report, including Bill Bauman, Matt Fronzak, Bob Fuller, Pam Schiffleger, Elisa Turner, and Bill Zachman. We would also like to thank the anonymous subject matter experts from MITRE's Center for Advanced Aviation System Development (CAASD) who participated in the commercial aviation delay expert elicitation exercise.

Finally, we note that a preliminary version of this work was shared at the 2025 American Meteorological Society Conference in New Orleans, under the title "An Economic Analysis of the Benefits Created by NEXRAD - Study Approach" [15], and we thank all those who participated in the conversation at that event.

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1 Study Approach

The purpose of this report is to describe and estimate the primary societal benefits of the Next Generation Weather Radar (NEXRAD). A critical step in estimating the benefits is to define the baseline against which to compare the existing world. We estimate the benefits of NEXRAD in a single year against a baseline where the NEXRAD radars do not provide data. We report our results in 2024 dollars based on the availability of key economic inputs at the time of our calculations.

The study began with authors from The MITRE Corporation (MITRE) collaboratively brainstorming sectors that are likely to benefit from NEXRAD, with staff from the National Weather Service (NWS) and economists in the National Oceanic and Atmospheric Administration's (NOAA) Chief Economist Team, Performance, Risk and Social Science Office (PRSSO). Given that NEXRAD data is publicly available for free online [2] and the breadth of potential applications, the full range of sectors impacted is beyond what we could identify in a single analysis. We, therefore, performed a preliminary qualitative review of various sectors of interest; we assessed the availability of existing literature and searched for established dependence on NEXRAD data and products. Based on this review, we determined that current benefits were likely high for the impact of warnings, watches, and forecasts on the general public (henceforth "general public warnings and forecasts") and the impact on the aviation community (henceforth "aviation"), which became the focus of this report.

Our analysis starts by qualitatively describing the two sectors and describing value chains that depict how NEXRAD data leads to benefits. The value of information depends, at least in part, on how decision makers use the information [16]. Thus, benefits arise from the impact that NEXRAD data (including products that incorporate NEXRAD data) has on decisions; if people do not change their decisions based on this information, then NEXRAD has no benefits. Therefore, we prioritized finding connections between NEXRAD data, products, and, ultimately, decisions. We aimed to substantiate these connections through credible sources, including, but not limited to, articles, product descriptions, industry manuals, and industry experts. For example, the 2024 Federal Aviation Administration (FAA) Aviation Weather Handbook instructs decision makers to "[u]se data-linked weather radar (i.e., NEXRAD) mosaic imagery as the sole means for negotiating a path through a thunderstorm area (tactical maneuvering)" [4]. The resulting value chains depict the progression of NEXRAD data through these intermediate steps (e.g., products, organizations, and decision makers), ultimately leading to societal benefit.

As discovered in our qualitative analysis, each application of NEXRAD data can yield multiple sources of societal benefit. For example, when aviation decision makers use NEXRAD mosaic imagery to understand the location of adverse weather conditions,[4] this can reduce accidents (which leads to fewer injuries and fatalities, and less aircraft damage), and it can reduce weather-related delays through more efficient use of the available airspace (which reduces costs to airlines, reduces time costs to passengers, preserves perishable cargo, etc.). Each source of benefit generated by NEXRAD data warrants careful treatment to fully describe and monetize, and each has the potential to stand as a research article on its own. Thorough quantitative

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[4] A radar mosaic is, "[a] radar product that combines information from multiple radars to give a regional or national view of reflectivity or precipitation. An individual NEXRAD radar is limited to a range of about 200 miles. Typically, a mosaic product is produced for regions spanning several hundreds to several thousands of miles. Mosaic products are produced by vendors external to the NEXRAD system" [135].

analysis of all benefit sources within the two focus sectors was beyond our scope and resources for this report.

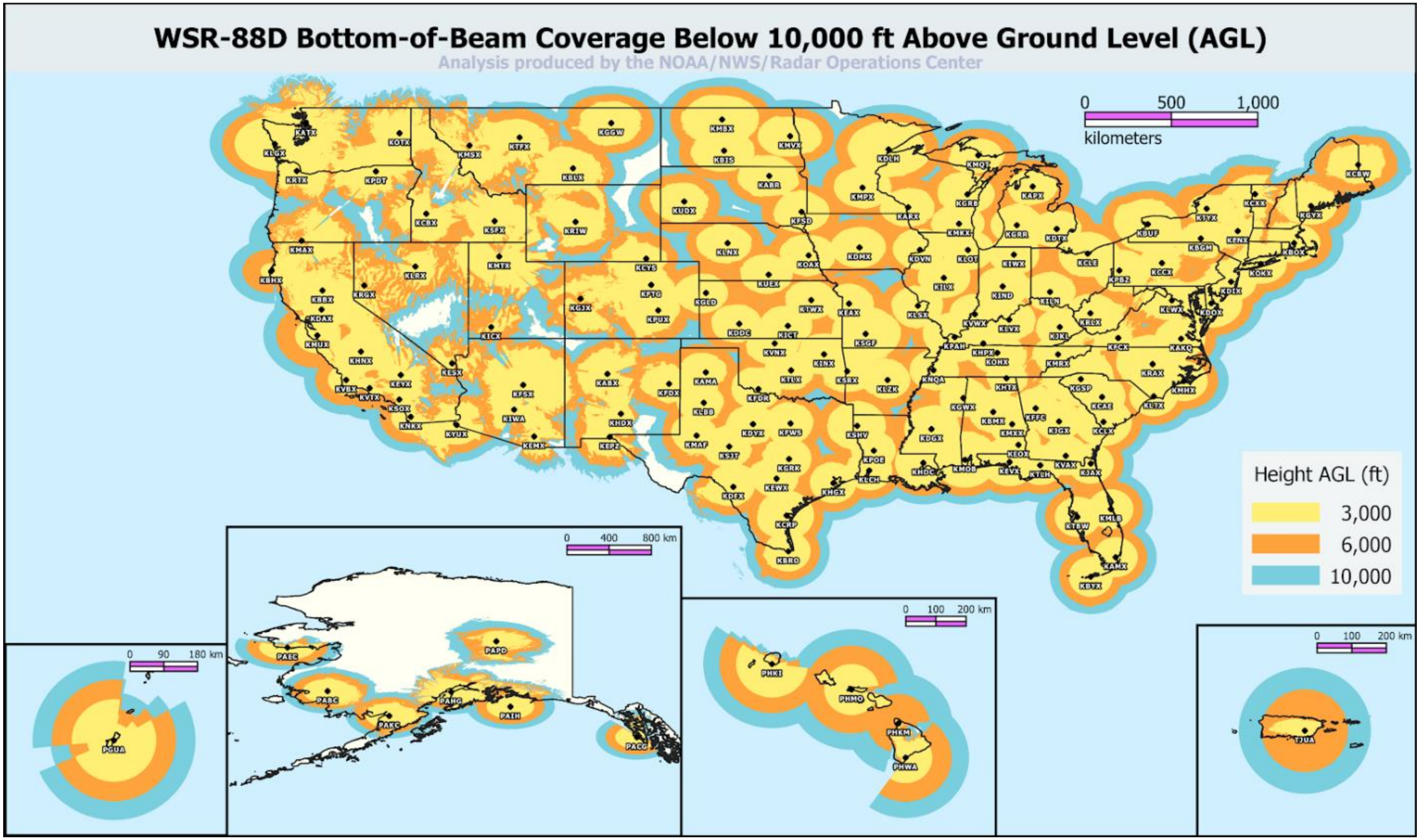
We monetized six sources of benefit across the two sectors of focus: (1) reduced injuries and fatalities from tornadoes; (2) reduced injuries and fatalities from flash floods; (3) reduced injuries and fatalities from severe winds; (4) reduced commercial aviation delays from thunderstorms; (5) reduced injuries and fatalities from avoided general aviation accidents; and (6) reduced damage to aircraft from avoided general aviation accidents. We prioritized these six sources based on the expected magnitude, the availability of existing literature, and the availability of data for original analysis. We then performed additional analysis to confirm that there is unlikely to be double counting across the benefits in reduced injuries and fatalities, and, therefore, the estimates can be summed.

This report proceeds as follows: Section 2 provides background information on NEXRAD, Section 3 describes the benefits accrued to the two sectors of focus, Section 4 presents our methodology and calculations, and Section 5 presents assumptions and sources of uncertainty in our analysis.

2 NEXRAD Background

NEXRAD is a network of 159 high-resolution S-band Doppler weather radars jointly operated by the NWS, the FAA, and the U.S. Air Force (USAF) [2], [17]. The individual radars in the network are known as Weather Surveillance Radars, 1988 Doppler (WSR-88D), consistent with the naming conventions for earlier generations of U.S. weather radars. Deployment of WSR-88D primarily occurred in the 1990s, with most sites deployed between 1991 and 1998. The first WSR-88D was deployed in Norman, Oklahoma on June 5, 1991, and the last of the initial radars was deployed in Kohala, Hawaii on July 23, 1998. Since this initial deployment, a small number of sites across the network have been added, decommissioned, and/or moved. Figure 1 depicts the WSR-88D sites in the United States as of January 2024. While there are a few WSR-88D sites operated by the USAF on American military bases in foreign countries, this report focuses on the United States.

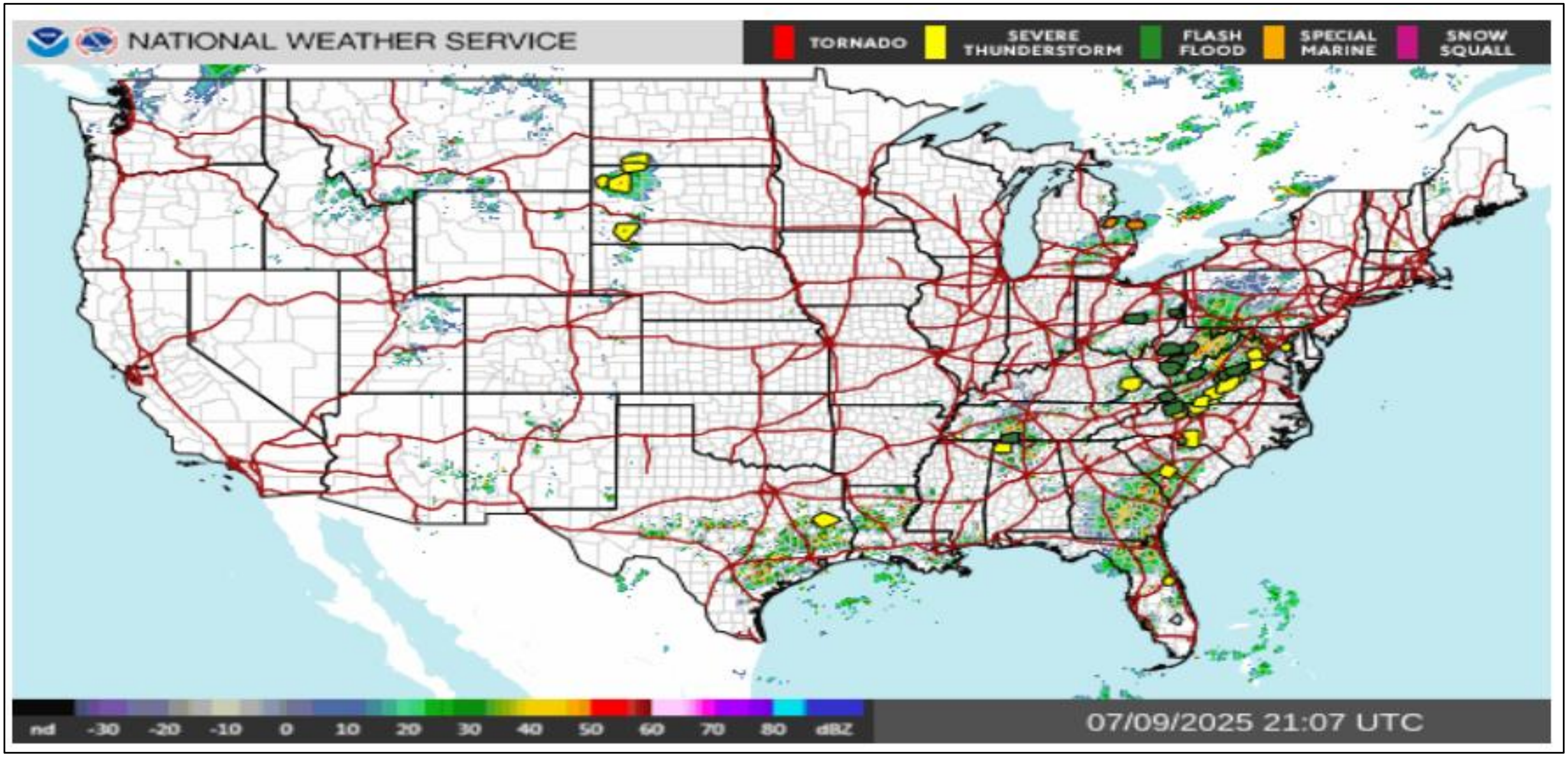
Figure 1. NEXRAD Sites in the United States



Source: The National Weather Service.

NEXRAD radars detect precipitation and wind, and the data can be processed and displayed in maps that show precipitation patterns and movement [18]. Doppler processing allows the WSR-88D to provide wind speed and direction information. The predecessors to the WSR-88D, the Weather Surveillance Radar, 1954 (WSR-54) and the Weather Surveillance Radar, 1977 (WSR-77), did not have Doppler capabilities. Between 2010 and 2013, the WSR-88D were upgraded from single polarization to dual polarization operation, allowing for the identification of precipitation type, such as rain, hail, and snow. Figure 2 depicts a static image of the U.S. NWS Doppler radar mosaic map animation from July 9, 2025. The mosaic map is an example of "nowcasting"—describing current weather conditions or those expected in the immediate future—for which NEXRAD data is primarily known.

Figure 2. U.S. NWS Doppler Radar Mosaic Map, July 9, 2025



Source: The National Weather Service [19].

NEXRAD data is also used as one source of information in data assimilation models, such as the Multi-Radar, Multi-Sensor (MRMS) system [20], and numerical weather prediction (NWP) models, such as the High-Resolution Rapid Refresh (HRRR)[5] [5], [21], [22], and the North American Mesoscale (NAM) Forecast System [6], [23], [24]. The HRRR model provides hourly forecasts for the continental United States, Canada, and Mexico up to 48 hours in the future [21]. The NAM Forecast System produces forecasts out to 3.5 days, four times per day [25]. The output from these NWP models feeds into publicly accessible forecasts. According to the Windy App, and with respect to the HRRR model and the NAM Forecast System, "…if right now you're looking at the weather forecast for the US, Canada, or Mexico, it's probably from one of these two models" [26]. NEXRAD data also continues to be leveraged in promising, new weather models, such as the experimental Warn-on-Forecast System (WoFS) [27].

In addition to routine forecasts, NEXRAD plays a role in severe weather prediction either directly (i.e., visual cues) or through NWP models, and that role is continuously evolving through new research. For example, NOAA's National Severe Storms Laboratory (NSSL) "…is developing techniques to use dual-polarized radar data [i.e., NEXRAD data] in short-term computer forecast models to improve forecasts of hail and large hail" [28]. While not intended to be exhaustive, Table 2 lists NWS severe weather warnings and watches that depend, at least in part, on NEXRAD data. This list was obtained from NOAA's Technology, Planning, and Integration for Observation (TPIO) program, which maintains the Consolidated Observational User Requirements List (COURL). COURL is a database that contains, among other things, a list of meteorological data products generated in support of NOAA mission service areas (MSAs) [29]. In Table 2, we included the corresponding lead time for each product, indicating the amount of time one may have to act.[6]

Table 2. Examples of NWS Severe Weather Products that Depend on NEXRAD Data

Product	Typical Lead Time
(a) Severe Thunderstorm Watch	1 – 2 hours
(b) Severe Thunderstorm Warning	30 minutes
(c) Tornado Watch	1 – 2 hours
(d) Tornado Warning	13 minutes
(e) Flash Flood Watch	Several hours to days
(f) Flash Flood Warning	Minutes to hours
(g) Fire Watch	Up to 72 hours
(h) Red Flag Warning[7]	Less than 24 hours

Note: Not intended to be an exhaustive list.

Sources: Lead times come from various NOAA and NWS webpages [30], [31], [32], [33].

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[5] The HRRR model leverages radar-reflexivity information from MRMS, and MRMS intakes NEXRAD data.

[6] Lead time is typically how long it takes for the event to begin after the watch or warning is issued.

[7] "A Red Flag Warning means warm temperatures, very low humidities, and stronger winds are expected to combine to produce an increased risk of fire danger" [132].

NWS also has an Aviation Weather Center (AWC), and our conversations with TPIO indicate that NWS creates various aviation-specific weather products that depend, at least in part, on NEXRAD data. These include, but are not limited to, products listed in Table 3.

Table 3. Examples of NWS Aviation Weather Products that Depend on NEXRAD Data

Product	Description
Airman's Meteorological Information (AIRMET)	An AIRMET advises of weather that may be hazardous, other than convective activity,[8] to single-engine aircraft, other light aircraft, and visual flight rules pilots [34].
Airport Weather Warnings (AWWs)	AWWs are notification text products that highlight when adverse weather conditions are expected at an individual airport. The NWS works with local airport management to establish local thresholds when impacts are likely to affect the airport ground operations area [35].
Various Significant Meteorological Information (SIGMET) including the following: 1. Convective 2. Dust, Sand 3. Icing 4. Tropical Cyclone 5. Turbulence 6. Volcanic Ash	A SIGMET is a type of in-flight weather advisory specific to meteorological hazards. "A SIGMET is 'widespread' in that it covers an area of at least 3,000 square miles. Note that the particular hazard may be present in only a small portion of the area at any particular time" [36]. Further, a convective SIGMET is issued for severe convective activity, which implies phenomena such as certain types of thunderstorms, tornadoes, severe turbulence, severe icing, and low-level wind shear (LLWS) [36].

Note: Not intended to be an exhaustive list.

Because NEXRAD data is free and publicly available, non-NWS entities can make products using NEXRAD data, including other government organizations, researchers, media, and private citizens. Many of these groups use NEXRAD data for weather products. However, scientists who understand radar technology have applied NEXRAD data to detect other phenomena beyond precipitation and wind. During our preliminary qualitative review of NEXRAD applications, we identified many examples of NEXRAD being used by non-NWS entities. These examples are depicted in Table 4. We recognize that some of the listed organizations and products/applications may no longer be active, but we include them to demonstrate the diverse use of NEXRAD data since deployment.

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[8] "In meteorology, the term [convection] is used specifically to describe vertical transport of heat and moisture in the atmosphere, especially by updrafts and downdrafts in an unstable atmosphere. The terms 'convection' and 'thunderstorms' often are used interchangeably, although thunderstorms are only one form of convection" [136].

Table 4. Examples of Non-NWS Products and Applications that Depend on NEXRAD Data

Organization	Product/Application	NEXRAD Dependence
FAA	Integrated Terminal Weather System (ITWS)	ITWS provides improved integration of weather data into timely, accurate aviation weather information. This is an essential component in reducing delays and improving National Airspace System (NAS) capacity utilization while enhancing aviation safety [37]. According to members of the FAA, NEXRAD is one of two key sensors used in ITWS.
FAA	Weather and Radar Processor (WARP)	WARP is an operational system that provides weather products and tools for the FAA's en route and oceanic environments. Part of its main function is to provide weather for controllers' situation displays, provide operationally significant weather information to air traffic supervisors and traffic flow managers, and distribute weather products to other NAS customers [38]. WARP is a visual depiction of NEXRAD data [39].
FAA	Corridor Integrated Weather System (CIWS)	CIWS is a fully automated weather analysis and forecasting system designed to support the development and execution of convective weather impact mitigation plans for congested en route airspace [40]. According to members of the FAA, nearly all of CIWS's value is attributable to NEXRAD.
FAA	Aviation Weather Display (AWD)	AWD consolidates WARP and CIWS information [41]. The dependence on NEXRAD is implied by WARP and CIWS.
U.S. Department of Agriculture (USDA)	Crop Explorer	Per its user guide, "The Crop Explorer Web Site features near-real-time global crop condition information based on satellite imagery and weather data" [42]. NEXRAD data was introduced in Crop Explorer in 2008, and analysts noticed it had "…superior data quality compared to the other global precipitation data sets that cover the United States" [43].
USDA	Pest migration	Scientists have shown that signals routinely collected by NEXRAD could serve as an early-warning system to track nighttime traveling pests that can cause considerable damage to corn and other crops [9].
Birders and Ornithologists	Birdcasting	NEXRAD is used by avid birders and professional ornithologists to track migratory birds [8].
USAF	Bird movement	The USAF Safety Center Bird/wildlife Aircraft Strike Hazard Team uses NEXRAD data to track the movement of birds to increase flight crew awareness and planning capabilities [44].
National Aeronautics and Space Administration (NASA)	Meteorite falls	NASA has funded work to use NEXRAD radars to detect and analyze meteorite falls [45].

Organization	Product/Application	NEXRAD Dependence
AccuWeather	Various products	AccuWeather is a private company that provides commercial weather forecasting services. AccuWeather has multiple NEXRAD products. In 2019, it claimed to have 20 basic NEXRAD products plus StormTimer™ and numerous other value-added products, including mosaics [46].
The Weather Company	Various products	The Weather Company is a private company that provides a variety of weather products specialized for various applications including aviation, media, and defense [47]. It claims to make use of public and proprietary data to develop forecasts [48], and a 2019 poster describes in part its use of NEXRAD data in a global radar mosaic tool, NOWrad [49].
DTN	Various products	DTN is a global data and technology company with a specialization in weather-driven sectors [50]. One of DTN's weather products is RadarScope®, an app that offers mosaic and single site radar information, which leverages NEXRAD in US coverage [51], [52].
Garmin	Aviation weather products	Garmin creates a variety of devices for navigation, communications and information [53]. Garmin's D2™ Charlie, D2™ Delta, and MARQ® Aviator watches can display NEXRAD radar for certain coverage regions [54].
ForeFlight	Aviation weather products	ForeFlight creates flight planning software. One feature of its products is reporting weather information, including composite reflectivity and lowest tilt radar layers from NEXRAD [55].
Advanced Ag Solutions LLC	Optimizer 2.0	Advanced Ag Solutions specializes, in part, in precision agronomic and economic data collection, and the company developed the Optimizer 2.0 smartphone app [56]. The product includes a feature that accumulates NEXRAD rainfall data for unique fields [57].
Insurers and Reinsurers	Retrospective confirmation of weather events	NEXRAD data is capable of verifying whether hail events occurred, the size of the hail, and the location in which the event took place. This data can help insurance companies verify whether the hail event that took place was capable of producing the damage claimed, and reinsurers can become aware of losses prior to reporting by insurers [58].

Note: Not intended to be an exhaustive list.

It is important to note that not all weather phenomena are addressable by NEXRAD (e.g., it is currently unhelpful for predicting temperature), and NEXRAD is typically not the only source of data used in generating the forecasts and products discussed in this section. Determining the precise contribution (i.e., the degree to which quality would degrade for each forecast and product without NEXRAD data) is beyond the scope of this work and would likely be impossible for us to determine for proprietary products created by commercial companies. When we qualitatively describe the benefits of NEXRAD in Section 3, we consider all forecasts and products discussed in this section, while recognizing that NEXRAD is likely only partially responsible for these benefits. Nonetheless, the quantitative analyses in Section 4 were developed to estimate the specific impact on societal outcomes should there be no data from NEXRAD radars.

3 Description of Benefits Accrued to Select Sectors

3.1 General Public Warnings and Forecasts

Background: Adverse weather events pose a substantial risk to the general public.[9] The weather events that NEXRAD assists in forecasting can be deadly and cause significant damage. The following list provides a few examples of how various weather events can impact the general public.

1. There are approximately 1,000 tornadoes reported annually in the United States, which result in an average of 80 deaths and over 1,500 injuries [59].
2. Flash floods can occur when rainfall exceeds the rate at which the ground can absorb it, or when precipitation causes bodies of water to swell beyond their typical boundaries [60]. Flash floods can occur anywhere in the country, and, in 2024, floods were responsible for 145 deaths in the United States [61].
3. The unsafe driving conditions caused by winter storms can lead to traffic accidents, vehicle damage, and casualties; vehicle crashes on snowy, slushy or icy pavement result in more than 1,300 fatalities and over 116,800 injured people each year [62].
4. Hail can cause injuries and damage on impact with people, buildings, or vehicles, especially when hailstones are large [63].
5. Wildfires, which can be exacerbated by windy conditions and suppressed by precipitation, can cause casualties (e.g., from burns and smoke inhalation), destroy property, and damage natural environments [64], [65].

Individuals and organizations in the United States, including federal, state, and local governments and emergency managers, depend on forecasts for advance notice of weather conditions. A study based on 2022 survey data estimated that the U.S. public accessed weather forecasts roughly 317 billion times per year, which represents an increase in aggregate use compared to 2006 [66], [67]. According to a 2023 poll from YouGov, "60% of Americans say they read, watch, or listen to the weather forecast for their local area at least daily…" [68]. Specifically, these forecasts may be accessed through weather apps, television news and weather reports, weather websites, radio stations, and social media [68]. Additional sources for severe weather information include outdoor warning sirens, Wireless Emergency Alerts (WEAs),[10] the Emergency Alert System (EAS), and NOAA Weather Radio (NWR) [69].

Dependence on NEXRAD: Many of the forecasts received by these individuals and organizations rely on NEXRAD and the NEXRAD-dependent products and models discussed in Section 2, such as tornado warnings and watches, thunderstorm warnings and watches, flash flood warnings and watches, fire watches, red flag warnings, the HRRR model, and the NAM Forecast System. DTN reiterated the importance of NEXRAD when it stated that NWS, "…produces a wealth of weather information, including surface observations, radar, and satellite data, and atmospheric model runs" [70]. It goes on to state that NOAA freely sharing its data and forecasts "…provides the backbone of the American weather enterprise" [70].

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[9] In our context we opt to define the general public as, "ordinary people, especially all the people who are not members of a particular organization or who do not have any special type of knowledge" [130].

[10] The NWS is an authorized alerting authority for WEAs [131].

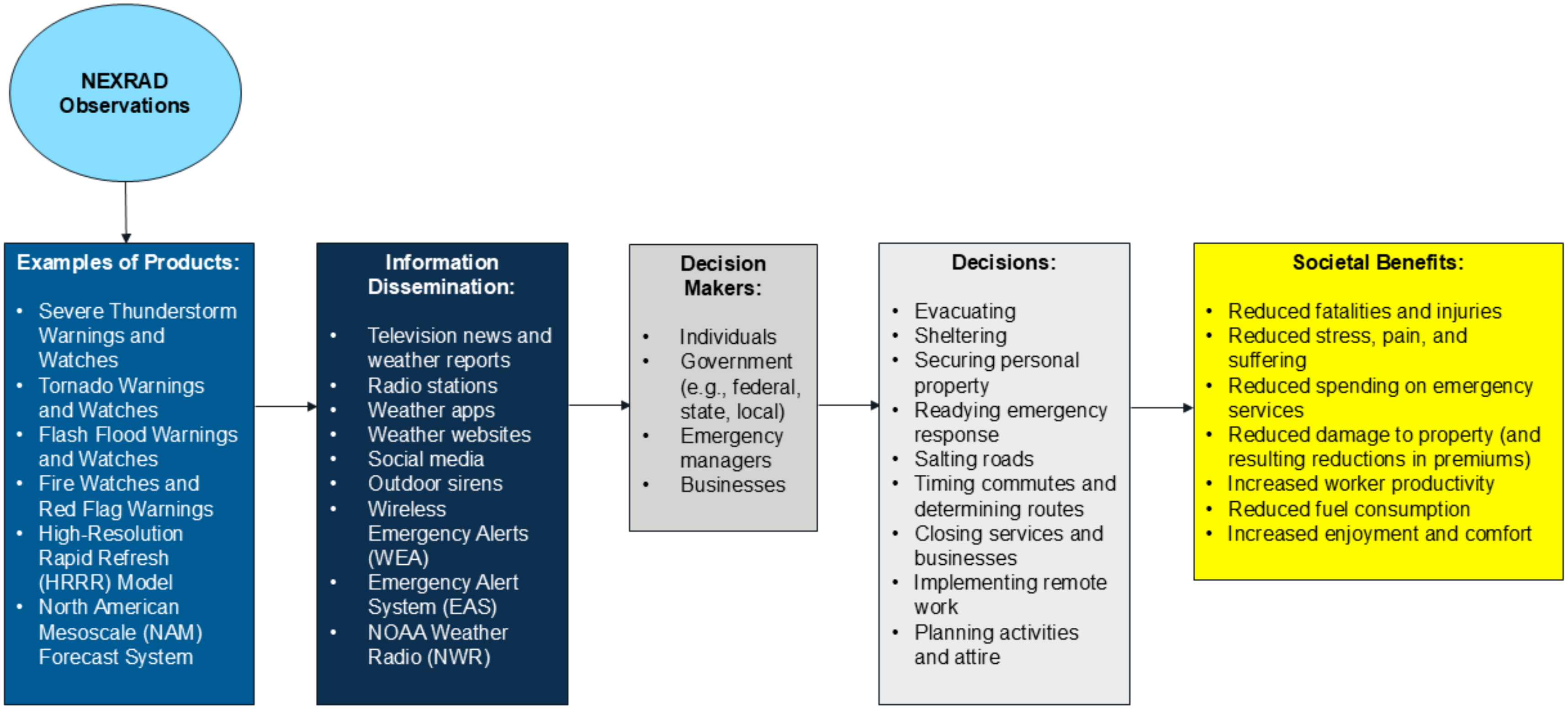
Societal Impact: Individuals, when aware of dangerous weather, can take various direct protective actions to prevent bodily harm. As depicted in Table 2, lead times for NEXRAD-dependent severe weather warnings and watches can range from minutes to multiple days. Some immediate actions may include finding appropriate shelter or evacuating. NEXRAD does not eliminate injuries and fatalities from these severe weather events, as is evident by the fact that tornado fatalities continue today. However, the impact of NEXRAD on *reducing* these casualties has been empirically established; casualties are lower today than they would be without NEXRAD. We discuss this empirical work in more detail in Section 4.1. Being prepared during an extreme weather event can not only reduce casualties, but it can also alleviate stress, pain, and suffering. Appropriate protective actions can also minimize additional associated costs, such as emergency rescue or medical treatment following an extreme weather event, especially if affected individuals do not appropriately shelter, evacuate, or prepare.

While safeguarding lives remains the primary benefit of NEXRAD for the general public, its contribution to advanced weather insights—both routine and severe—empowers Americans to make more informed and efficient decisions in their daily lives. For example, precipitation often affects road conditions and increases traffic. When an individual is aware of forecasted rain, snow, sleet, or other precipitation, they can make travel and/or commuting decisions accordingly. Adjustments to these decisions can directly decrease traffic accidents, reduce casualties, reduce damage to vehicles, and save time. Indirect benefits of improved driving decisions include reduced auto insurance premiums, increased worker productivity for commuters, and reduced fuel consumption, which can lessen both fuel costs and environmental impacts. Additional benefits to the general public due to weather reports and forecasts include, but are not limited to, protecting property with sufficient notice, such as moving their vehicles into garages to avoid hail damage, and reducing stress or inconvenience by allowing individuals the opportunity to make informed decisions about clothing and activities, especially when planning to be outdoors.

In addition, organizations, including federal, state, and local governments, and emergency managers, can take actions to support the general public during weather events. For example, cities may salt roads to improve driving conditions in winter storms; companies may close or mandate remote work to avoid unnecessary travel; public services, like schools and transportation, may close; or a state of emergency could be declared to protect residents. These actions ultimately impact the individual by enhancing benefits such as reduced injuries, fatalities, and traffic accidents.

Value Chain: The value chain depicted in the Figure 3 summarizes this discussion of how NEXRAD supports the general public through warnings and forecasts and ultimately results in societal benefits. While we intend to depict the primary sources of benefit, this value chain is not exhaustive.

Figure 3. Value Chain for General Public Warnings and Forecasts



Value Chain in Action: Localized examples of this value chain in action include the following:

1. In May 2019, the local emergency siren system in Cole County, Missouri, successfully warned residents of an impending tornado. No fatalities were reported in the county despite the tornado reaching an Enhanced Fujita 3 classification [71].
2. In July 2013, a WEA alerted a summer camp director of an approaching tornado in East Windsor, Connecticut, and as a result, 34 people (29 children and 5 adults) were able to seek shelter and remain safe. The tornado destroyed a dome that covered the soccer field where occupants were located prior to the alert [72], [73].

3.2 Aviation

Background: Aviation is broadly defined as the flying or operating of aircraft, and it can be subcategorized to capture different types of aircraft and purposes for flight. Aircraft include, but are not limited to, large airplanes designed for hundreds of passengers, small airplanes designed for few passengers, helicopters, and unmanned aircraft. Reasons for flying include, but are not limited to, commercial passenger travel, cargo operations, chartered travel, recreation, medical transport, and delivery of humanitarian aid.

At the highest level, aviation can be categorized as aircraft operations for military purposes (military aviation) and aircraft operations for non-military purposes (civil aviation). Civil aviation accounted for 4.0 percent of U.S. gross domestic product (GDP) in 2022 [74]. Civil aviation can be further categorized into commercial aviation and general aviation. Commercial aviation includes both passenger transport by airlines (e.g., Delta Air Lines and United Airlines) and cargo transport, including logistics companies (e.g., FedEx and DHL). The National Air and Space Museum states, “[g]eneral aviation is civilian, non-commercial flight” [75]. Some examples of general aviation include flying for recreation, agriculture, or humanitarian aid. Both commercial aviation and general aviation generate large volumes of flight activity. There were 10 million scheduled U.S. commercial aviation flights in 2023 [76]. In 2024, more than 90% of the 220,000 civil aircraft registered in the United States were general aviation aircraft [77]. U.S. general aviation had about 23 million flight hours in 2022 [78].

All aircraft, regardless of their purpose—whether passenger transport, cargo operations, general aviation, or military—are exposed to potential risks and damage when flying through adverse weather conditions. For example, thunderstorms are associated with various hazards that impact the flying and operation of aircraft, including, but not limited to, heavy precipitation, tornadoes, downbursts, icing, and lightning [79]. The following list provides a few examples of how various hazards can impact aviation.

1. Heavy precipitation (e.g., rain, snow, and hail) can limit visibility and damage aircraft [80], [81].
2. Tornadoes and downbursts are both threats to aircraft safety, since the violent winds can limit pilots’ ability to maintain control, increasing the potential risk for accidents and associated damage [81].
3. Turbulence is “[i]rregular motion of an aircraft in flight, especially when characterized by rapid up-and-down motion, caused by a rapid variation of atmospheric wind velocities” [82]. Convective weather and different types of wind can cause turbulence [82]. Severe turbulence can cause people and equipment to be violently displaced within an aircraft, and in turn can cause injury or death to passengers and damage to aircraft interiors [83].

4. Airborne particles, like ash and smoke, can be spread by winds and may pose threats to safe and efficient aviation operations. For example, volcanic ash is extremely dangerous for aircraft, since the small particles of rock and glass are not only abrasive, which can have various negative impacts on aircraft functionality, but also melt at operating temperatures of modern jet engines, which can result in engine failure [84]. Additionally, wildfire smoke can cause poor visibility, limiting pilots' ability to safely navigate by sight [85].

Given the consequences of adverse weather on aviation safety, the Federal Aviation Regulations (FARs) mandate that aviation decision makers take weather conditions into consideration when flying or operating aircraft. Certain regulations specifically address weather conditions.[11] Other regulations do not specifically address weather conditions but defer to the judgment of the pilot and/or aircraft dispatcher in determining unsafe flying conditions.[12] Taken in their totality, the FARs provide a concrete basis for aircraft pilots, dispatchers, and operators to repeatedly consider weather conditions and forecasts along the entire flight path (from pre-flight planning through arrival) in the decision-making process. Examples of when aviation decision makers must consider weather conditions include the following:

1. Prior to takeoff, the flight plan must consider weather conditions and forecasts at the origin airport, destination airport at the estimated time of arrival, alternate airport (as applicable), and along the entirety of the flight path to ensure safe travel conditions and to meet minimum fuel requirements.
2. An airport cannot be designated as an alternate airport unless weather conditions at the airport are forecasted to meet minimum standards at the estimated time of arrival.
3. The pilot cannot begin an approach procedure to an airport unless weather conditions at the airport meet minimum standards.

The FARs also address the responsibility for operational control of aircraft. There are some instances in which multiple decision makers bear responsibility. For example, the pilot in command and the aircraft dispatcher are jointly responsible for preflight planning, delay, and dispatch release in domestic operations of Part 121 aircraft [86]. However, the pilot in command of an aircraft is ultimately responsible for, and is the final authority as to, the operation of the aircraft [86], [87]. The timing of weather information received by the key decision makers can vary from as soon as possible to well in advance of the planned flight time. An outlook briefing for early flight planning is provided six or more hours before flight; a standard briefing, which is a comprehensive briefing, occurs within six hours of departure; and an abbreviated briefing updates specific information as soon as possible [88].

Dependence on NEXRAD: NEXRAD is one of the established resources for understanding weather conditions and determining unsafe flying conditions across the U.S. airspace. As discussed in Section 2, there are various aviation weather products produced by the NWS, FAA, and commercial companies that rely on NEXRAD data. All aviation subject matter experts with whom we spoke confirmed the sector's dependence on NEXRAD with some describing the dependence as "critical." This dependence is further confirmed by formal industry documents such as the FAA's Aviation Weather Handbook [4]. The handbook is designed as a technical

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[11] These include but are not limited to 14 CFR 135.219, 14 CFR 121.687, 14 CFR 135.223, 14 CFR 121.639, 14 CFR 135.225, 14 CFR 125.381, 14 CFR 121.567, 14 CFR 91.1039, 14 CFR 135.221, 14 CFR 125.369, 14 CFR 121.647, 14 CFR 121.601, and 14 CFR 121.621.

[12] These include but are not limited to 14 CFR 121.533, 14 CFR 121.627, and 14 CFR 121.663.

reference for all individuals who operate in the NAS, and it states that "[p]ilots, dispatchers, and operators will find this handbook a valuable resource for flight planning and decision making" [4]. The handbook references NEXRAD multiple times as a resource for aviation decision making under certain adverse weather conditions. Example quotes are listed below (emphasis added):

> *Use data-linked weather radar* ***(i.e., NEXRAD)*** *mosaic imagery as the sole means for negotiating a path through a thunderstorm area (tactical maneuvering) [4].*
>
> *Use data-linked weather* ***NEXRAD mosaic imagery*** *(e.g., FIS-B) for route selection to avoid thunderstorms entirely (strategic maneuvering) [4].*
>
> *If precipitation is forecasted, other products, including* ***SIGMETs and NEXRAD weather radar****, where available, can determine if hazardous convective weather will be present when the aircraft arrives [4].*

Societal Impact on Civil Aviation: Because NEXRAD data is an important observational source for predicting, locating, and avoiding adverse weather, the availability of NEXRAD data reduces the frequency of accidents across all aviation sectors. Fewer accidents lead to reductions in injuries, fatalities, and damage to aircraft.

Additional benefits that accrue to commercial aviation beyond reduced accidents include improved flight planning and coordination during adverse weather, helping to minimize flight delays and cancellations. Commercial aviation scheduling is a complex logistical exercise and disruptions in one part of the United States can impact flights across the country. While delays and cancellations from weather are inevitable, the information provided by NEXRAD-dependent weather products helps to mitigate these disruptions. For example, in interviews on the decisions impacted by information from ITWS (an FAA weather product for which NEXRAD is a key sensor, for more information see Table 4), traffic facilities discussed the ability to release additional departures each hour, plan efficient and effective reroutes, execute ground delays as opposed to in-air delays,[13] and plan runway changes in advance [11]. This benefit is corroborated through our discussions with aviation experts, who indicated that NEXRAD data allows for better utilization of the available airspace and minimizes excessive vectors, reroutes, and traffic management initiatives. In addition to improved flight planning and coordination during adverse weather, mitigation strategies can also include improved ground operations. For example, advanced notice of snow can allow for better preparation of equipment for snow removal from airports and more efficient application of deicing treatments to aircraft [89]. Mitigation of delays and cancellations results in the following:

1. Reduced lost time, stress, and inconvenience to the three million average daily commercial aviation passengers [76].
2. Reduced operating costs to airlines including reduced fuel consumption by mitigating excessive vectors and reroutes. U.S. jet fuel consumption was 1.65 million barrels per day in 2023 with commercial aviation accounting for 85 percent of this total [90].

Indirect benefits that accrue to industries that depend on the aviation sector include, but are not limited to, the following:

1. Reduced cargo damage, loss, and delay of the 10 million tons of domestic revenue cargo (freight or mail) loaded on aircraft for flight per year [91].

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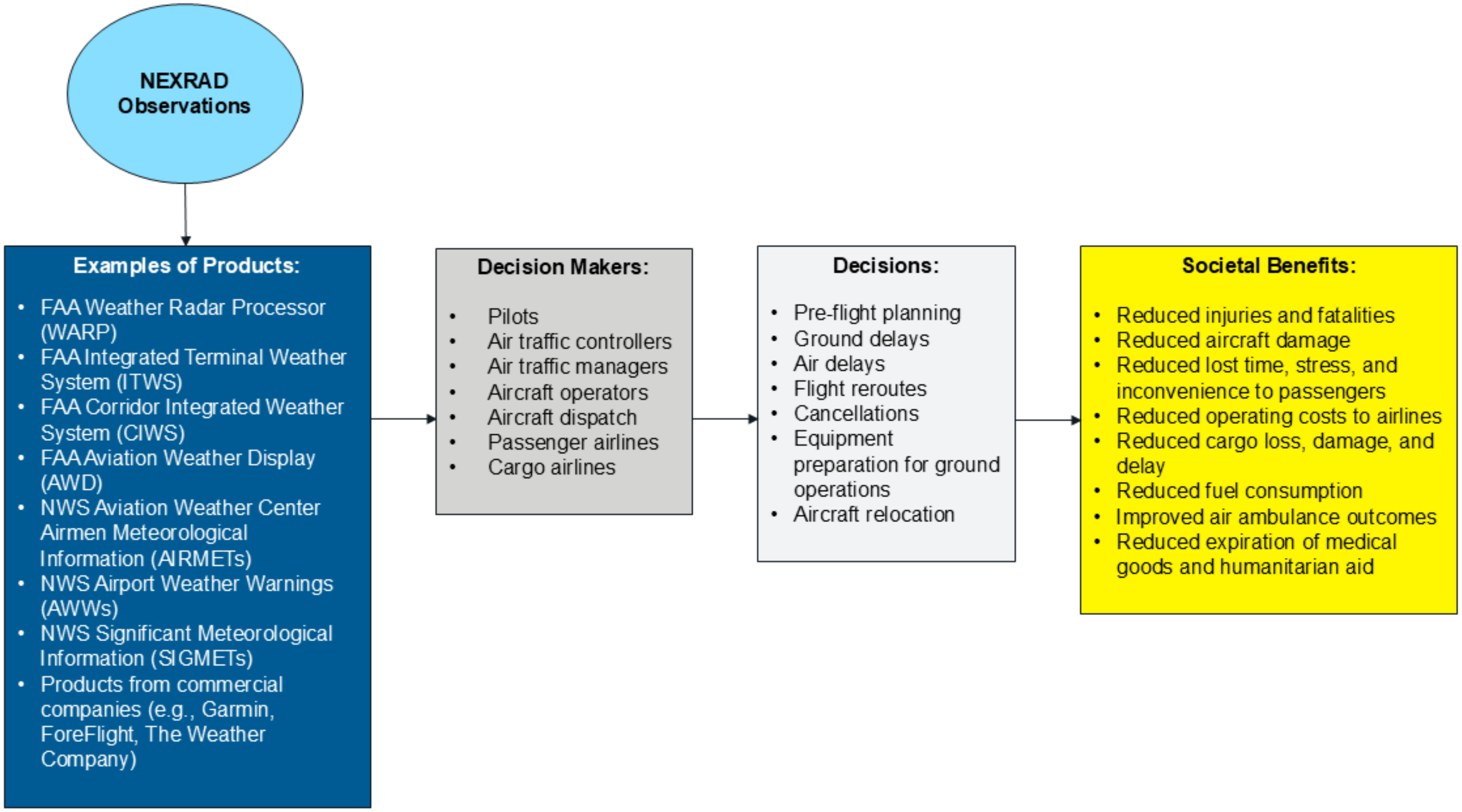
[13] Ground delays require fewer resources to manage compared to in air delays.

2. The avoidance of accidents, delays, and cancellations has additional benefits such as reducing delays in medical services and the avoidance of expiration for medical goods and humanitarian aid. Over 500 thousand Americans use air ambulances annually [92].

Societal Impact on Military Aviation: Due to the availability of information, most of this discussion focuses on civil aviation. However, NEXRAD is co-operated by the USAF, and many of the NEXRAD benefits to civil aviation are also benefits to military aviation. According to MITRE aviation subject matter experts, there are similar requirements for military aviation decision makers to take weather into consideration when flying or operating aircraft. A USAF publication on weather operations states that "[w]eather personnel routinely monitor weather along planned flight routes, alerting decision makers to the onset of hazardous weather conditions such as turbulence, icing, and thunderstorms" [93], and "[d]epending upon the type and intensity of weather conditions and the installation's mission assets, commanders may exploit decision-grade weather information by directing a series of actions to mitigate risk ranging from moving, tying down, or sheltering aircraft to a full-scale evacuation of aircraft and personnel" [93].

Value Chain: The value chain presented in Figure 4 summarizes this section's discussion of how NEXRAD supports the aviation sector and ultimately results in societal benefits. While this value chain captures the primary sources of value and how they arise, there are likely additional products, decisions, and impacts not captured in the figure given the breadth of this sector and its continuing evolution.

Figure 4. Value Chain for Aviation



NEXRAD Observations

Examples of Products:

- FAA Weather Radar Processor (WARP)
- FAA Integrated Terminal Weather System (ITWS)
- FAA Corridor Integrated Weather System (CIWS)
- FAA Aviation Weather Display (AWD)
- NWS Aviation Weather Center Airmen Meteorological Information (AIRMETs)
- NWS Airport Weather Warnings (AWWs)
- NWS Significant Meteorological Information (SIGMETs)
- Products from commercial companies (e.g., Garmin, ForeFlight, The Weather Company)

Decision Makers:

- Pilots
- Air traffic controllers
- Air traffic managers
- Aircraft operators
- Aircraft dispatch
- Passenger airlines
- Cargo airlines

Decisions:

- Pre-flight planning
- Ground delays
- Air delays
- Flight reroutes
- Cancellations
- Equipment preparation for ground operations
- Aircraft relocation

Societal Benefits:

- Reduced injuries and fatalities
- Reduced aircraft damage
- Reduced lost time, stress, and inconvenience to passengers
- Reduced operating costs to airlines
- Reduced cargo loss, damage, and delay
- Reduced fuel consumption
- Improved air ambulance outcomes
- Reduced expiration of medical goods and humanitarian aid

Value Chain in Action: Localized examples of this value chain in action include the following:

1. As discussed in Table 4, CIWS is an FAA aviation weather product that depends on NEXRAD, and our FAA contacts attribute nearly all CIWS value to NEXRAD. A 2006 study assessed the Air Traffic Control (ATC) productivity benefits attributed to CIWS using real-time observations of CIWS product usage during three multi-day thunderstorm events in 2005 at eight U.S. Air Route Traffic Control Centers (ARTCCs). The authors found that CIWS improved ATC productivity by reducing the time required to develop, coordinate, and implement weather impact mitigation plans, increasing the number of safety and capacity-enhancing plans that were executed (e.g., more efficient, proactive rerouting, and greater ability to keep routes open), and assisting with FAA staffing decisions [13].
2. As discussed in Table 4, ITWS is an FAA aviation weather product that depends on NEXRAD, and our FAA contacts note that NEXRAD is one of two key sensors used in ITWS. The authors of a 2005 study interviewed operational ITWS users at Atlanta International Airport (ATL). They found that there are times at ATL when the thunderstorms do not impact both north side and south side operations simultaneously. Prior to ITWS, traffic managers usually did not feel confident enough in the available weather information to continue partial operations with a thunderstorm in such close proximity. After ITWS, there were times when they could maintain operations on a reduced number of runways rather than shutting down all runway operations [12].

4 Monetization of Benefits

4.1 Reduced Fatalities and Injuries from Tornadoes, Flash Floods, and Severe Winds

We estimate the annual benefit of NEXRAD in reducing fatalities and injuries from tornadoes, flash floods, and severe winds to be $1.2 billion in 2024 dollars. We rely on existing empirical literature to arrive at this result. In this section, we describe the literature and our calculations.

4.1.1 Methodology for Estimating the Impact of NEXRAD on Fatalities and Injuries from Tornadoes, Flash Floods, and Severe Winds

There are multiple radar-specific statistical studies that empirically establish high benefits of the NEXRAD system for reducing fatalities and injuries from severe weather, specifically tornadoes, flash floods, and severe winds. A paper from Bieringer and Ray [94] found that the probability of detection increased by 10-15 percentage points and mean lead time improved from 8 to 13 minutes for tornadoes following NEXRAD deployment. A paper from Simmons and Sutter [95] found that expected fatalities and injuries were 45 percent and 40 percent lower, respectively, for tornadoes occurring after WSR-88D radar was installed in the NWS Weather Forecast Office.

Cho and Kurdzo built upon this literature with a series of econometric papers from 2019 to 2020 that first monetized these reductions in fatalities and injuries from tornadoes [96], and then extended their research to include flash floods [97] and severe winds [98]. In these publications, they estimated that the benefit to society from the present-day radars (i.e., both NEXRAD and Terminal Doppler Weather Radars (TDWRs)) with respect to tornadoes, flash floods, and severe winds was $1,123 million per year in 2020 dollars [98].[14] These results are derived from a robust econometric analysis leveraging temporal and geographic variation in radar coverage, looking back 30 years, primarily using the NWS Storm Events Database [99].

Cho and Kurdzo were coauthors on a related paper published in 2024 [100] that reported an updated estimate of the benefit specific to NEXRAD. This updated estimate was $1,176 million per year in 2023 dollars, with $596 million from tornado benefits, $363 million from flash flood benefits, and $217 million from severe wind benefits. We leveraged these updated, NEXRAD-specific results in our analysis.

It is important to note that Cho and Kurdzo do not provide ranges in their result tables; they only provide point estimates. Since our results are directly derived from their estimates, we also only provide point estimates. We recognize that if these figures are used in a formal analysis of benefits in the future, the uncertainty in these estimates should be considered and characterized.

4.1.2 Monetized Results

We adjusted the $1,176 million annual benefit to 2024 dollars using the Valuation of a Statistical Life (VSL), resulting in an estimate of $1,221 million in 2024 dollars. The VSL is a key multiplicative input in Cho and Kurdzo's model. Therefore, we use the percent increase between

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[14] We note that a small portion (< 2%) of their annual value attributable to NEXRAD was derived from time lost to unnecessary sheltering during tornadoes [96].

the 2023 VSL and the 2024 VSL, as reported by the U.S. Department of Transportation (DOT), to scale their results. Our calculations are presented in Table 5.

Table 5. Annual Reduction in General Public Fatalities and Injuries from Tornadoes, Flash Floods, and Severe Winds in 2024 Dollars

Input	Tornadoes (millions)	Flash Floods (millions)	Severe Winds (millions)	Total (millions)
(a) Reduced Cost of Weather-Related Fatalities and Injuries Due to NEXRAD in 2023 Dollars	$596	$363	$217	$1,176
(b) Value of a Statistical Life in 2024 Dollars	$13.7	$13.7	$13.7	$13.7
(c) Value of a Statistical Life in 2023 Dollars	$13.2	$13.2	$13.2	$13.2
(d) Benefit of Reduced Fatalities and Injuries (d) = (a)*[(b) / (c)]	**$619**	**$377**	**$225**	**$1,221**

Notes: Minor differences in formula results are attributable to rounding.
Sources:

(a) Rudlosky et al. [100]
(b) DOT 2024 VSL [101]
(c) DOT 2023 VSL [101]

A detailed list of assumptions and sources of uncertainty in our analysis of reduced injuries and fatalities from tornadoes, flash floods, and severe winds is presented at the end of this report in Table 10.

4.2 Reduced Commercial Aviation Delays

We estimate the annual benefit of NEXRAD in reducing commercial aviation delays due to convective weather to be $7.5 billion (2024 dollars), with a range from $3.9 billion to $9.8 billion. We designed and executed an expert elicitation activity to achieve this result. In this section, we describe our methodology and calculations. Given limitations in the study approach, the benefit estimate should be further validated through additional research before use in a formal decisional context, such as a benefit-cost analysis.

4.2.1 Methodology for Estimating the Impact of NEXRAD on Commercial Aviation Delays

To quantify the impact of NEXRAD on commercial aviation delays, we designed and executed an expert elicitation activity, which is the process of extracting expert knowledge about uncertain quantities and formulating that information into probability distributions [102]. Expert elicitation has been relied on in other benefit analyses of NOAA assets, such as the Geostationary Extended Observations (GeoXO) satellite constellation [14].

There are different approaches to expert elicitation, and our method is based on the Investigate, Discuss, Estimate, and Aggregate (IDEA) protocol described by Hemming et al. [103]. This protocol improves the accuracy of expert judgments and includes key steps such as four-point elicitation and a modified Delphi procedure. The key steps of the protocol are summarized in Table 6.

Table 6. Key Steps of the IDEA Protocol

Stage	Description
Pre-elicitation	Background information is compiled. Contact and brief experts on the elicitation process.
Elicitation, **Investigate**	All experts individually answer questions and provide reasons for their judgements.
Elicitation, **Discuss**	Experts are shown anonymous answers from each participant and visual summary of responses.
Elicitation, **Estimate**	All experts make a second, final, and private estimate.
Post-elicitation, **Aggregate**	The mean of experts' second-round responses is calculated. Experts may review and discuss individual and group outcomes, add commentary, and correct residual misunderstandings.

Source: Based on Figure 1 in Hemming et al. [103].

We selected the IDEA protocol for the following reasons:

1. The protocol can incorporate remote elicitation (e.g., teleconferencing and email), making it accessible with modest resources.
2. While the protocol includes a discussion, the goal is not to reach consensus, but to resolve linguistic ambiguity, promote critical thinking, and share evidence. The individual estimates are combined using mathematical aggregation. We prefer a method that does not require consensus for the following reasons:
    a. As discussed in Soares et al. [102], in situations where understanding and characterizing uncertainty is important, it may be desirable to fully capture differences in views and divergent opinions. As the first study, to our knowledge, to explore the national impact of NEXRAD on commercial aviation delays, we felt it was important to highlight the range of expert opinions.
    b. Reaching consensus can be impractical under limited resources, time constraints, and limited availability of experts.
    c. Requiring a consensus where one does not exist might result in social phenomena like groupthink, the bandwagon effect, and the halo effect, which threaten the interpretation of results [104].

While this research was conducted under MITRE's Center for Enterprise Modernization, MITRE also operates an FAA Federally Funded Research and Development Center, the Center for Advanced Aviation and Development (CAASD). We chose to source experts from CAASD for the following reasons:

1. We wanted to include perspectives from experts intimately familiar with aviation products that depend on NEXRAD through their experience with the FAA, NWS, and commercial aviation. Sponsored by the FAA, CAASD's data-driven insights enhance aviation safety, help improve the efficiency of the NAS, and strengthen both domestic and global airspace system resilience [105]. As such, CAASD employs individuals with deep knowledge of aviation weather, including former FAA, NWS, and commercial aviation employees.[15]
2. None of the authors are affiliated with CAASD, and we had not worked with any of the aviation experts prior to this research.
3. By working with experts within our organization, we believed there was a higher likelihood of access to and responsiveness by participants throughout the process, including ensuring engagement through multiple iterations of questioning.

In total, we contacted ten aviation experts, and eight agreed to participate in our research activity. After attending the required introductory meeting and reviewing the questionnaire, one participant self-excluded from the activity. This participant indicated a lack of appropriate expertise to complete the questionnaire; they explained that their expertise was primarily in military aviation and that they had very limited experience supporting commercial aviation. The combined relevant experience of the final group of seven participants included over a century of ATC, air traffic management (ATM), operations, dispatch, meteorology, and applied weather. The IDEA protocol emphasized the importance of a diverse group of expert participants, and as such, we believed the diverse aviation specialization was a positive attribute of our group of experts.

We focused the exercise on the impact of NEXRAD during thunderstorms. As described previously in Section 3.2, thunderstorms present various hazards to aviation; these hazardous conditions can cause delays to commercial aviation operations. Further, we believed focusing the scope of the activity and associated questions would help participants minimize the number of scenarios and variables to consider while developing their responses, and as a result, potentially allowed for better cohesion among respondents.

We used a slideshow presentation to provide background on NEXRAD, examples of products that use NEXRAD, information on the questionnaire, and examples of four-point elicitation. The point of providing examples of products that use NEXRAD was to clarify for the experts that not all weather products would be impacted should NEXRAD data no longer be available, only those products that depend on NEXRAD. Some of these products might no longer be available, in the case of products for which NEXRAD is a critical input, and other products might degrade in quality, in the case of products for which NEXRAD is one of multiple data inputs.

Figure 5 depicts the experts' final standardized responses as to the percent increase in commercial aviation delays due to thunderstorms should NEXRAD data no longer be available. The figure displays each expert's reasonable minimum, best guess, and reasonable maximum. We also asked each participant to indicate the level of confidence they had that the correct answer falls within their provided range of reasonable minimum to maximum. Taken together,

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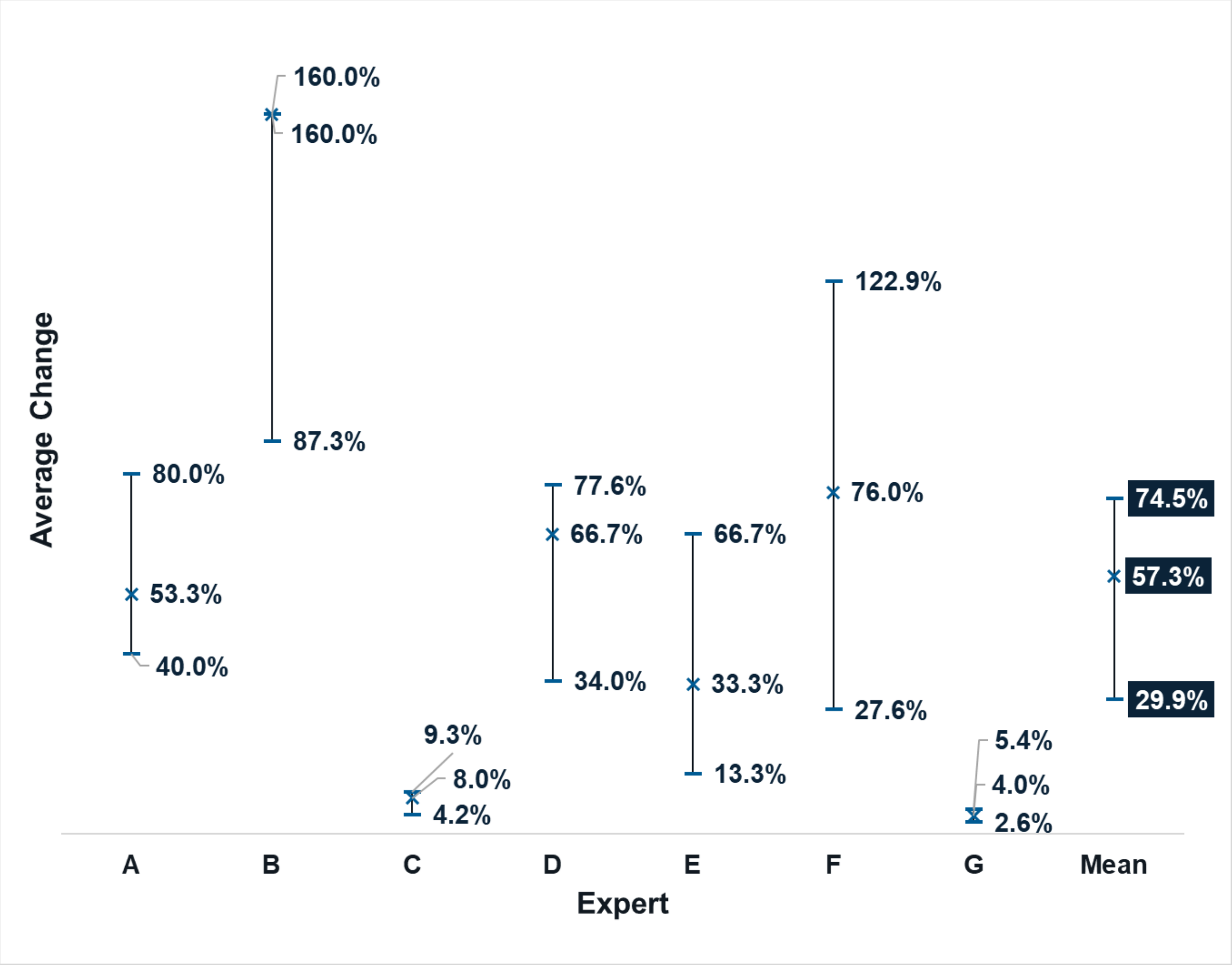
[15] Some examples of MITRE CAASD employee experience include positions at the NWS Aviation and Space Weather Services Branch, FAA Aviation Weather Division, and as commercial pilots, dispatchers, and air traffic controllers. Note, that while MITRE CAASD employs individuals with these varied experiences, we refrain from listing the specific experience of our experts to preserve anonymity.

these four values (i.e., reasonable minimum, best guess, reasonable maximum, and confidence) make up the four-point elicitation.

Figure 5. Experts' Responses of the Percent Change in Convective Weather Delays Should NEXRAD Data No Longer be Available



We used the suggested protocol formulas in Hemming et al. [103] for response aggregation, including standardizing the reasonable minimum-to-maximum range provided by each participant using linear extrapolation with respect to confidence, and combining the standardized maximum, minimum, and elicited best-guess values using the arithmetic mean of each. Further details of the expert elicitation approach, including the questionnaire and aggregation of responses, can be found in Appendix A.1. Based on the aggregated responses, we estimate that commercial aviation delays due to convective weather would increase by 57 percent, where the reasonable minimum is a 30 percent increase and the reasonable maximum is a 75 percent increase. We do not trim the outliers in our results because Hemming et al. states, "[w]e believe outliers should only be trimmed if they are clearly and uncontroversially incorrect (for example, outside of possible bounds)" [103]. Although we do not trim outliers, it is interesting to note that if we were to remove the three apparent outliers from our aggregation (Experts B, C, and G), we would arrive at the same average best guess response of 57 percent. In the following discussion we explain potential reasons for the divergence in the experts' responses.

Although the IDEA protocol does not require consensus, we do recognize the wide range of responses from the experts. There appear to be three outliers, two on the low end (responses less than 10 percent) and one on the high end (best guess response of 160 percent). We shared the anonymized results with all the experts (as well as each expert's reasoning), and these three experts chose to keep their responses unchanged. The expert with the highest best guess and maximum responses referred to a world without NEXRAD as the "dark ages" of tactical and strategic ATC and ATM.[16] One of the experts with low responses recalled the time prior to NEXRAD, when the NAS was managed with weather information from various sources and when controllers leaned heavily on pilot reports of weather. They believed the NAS could be managed like this again, with small losses in efficiency.

The other expert with a low response possibly had a limited view of all the aviation products NEXRAD supports, based on a review of their reasoning. While it was stressed that many aviation products depend on NEXRAD (like WARP, CIWS, and ITWS), we found in our conversations with aviation experts, even beyond this expert elicitation exercise, that many people may narrowly consider NEXRAD to only be mosaic imagery. In fact, this misconception may be propagated by FAA documents themselves; as discussed in Section 3.2, the FAA Weather Handbook states, "[i]f precipitation is forecasted, other products, including SIGMETs and NEXRAD weather radar, where available, can determine if hazardous convective weather will be present when the aircraft arrives" [4]. This sentence portrays SIGMETs and NEXRAD as distinct. However, as described in Table 3, many SIGMETs, including convective SIGMETs, depend on NEXRAD data. This potential misunderstanding of the full scope of NEXRAD data's use in various aviation tools could translate to an undervaluation of NEXRAD's impact on commercial aviation delays. Future analysis of this topic should work to address this potential misconception.

4.2.2 Monetized Results

To monetize the benefit of these reduced commercial aviation delays, we used the following information. Our calculations are presented in Table 7, and are derived as the product of the following values:

1. An FAA analysis [106] reported that in fiscal year (FY) 2019, the cost of U.S. commercial flight delays was $33.0 billion.[17]
2. The inflation factor between 2019 and 2024 was 1.2 [107].
3. On average, weather accounted for 55 percent of flight delays at the Core 30 airports from 2021 through 2024 [108].
4. About 60 percent of all weather delays in the NAS are attributable to convective weather [109].
5. Our expert elicitation results that commercial aviation delays due to convective weather would increase by 57 percent in the absence of NEXRAD data, where the reasonable minimum is a 30 percent increase and the reasonable maximum is a 75 percent increase.

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[16] "Tactical behaviors are generally considered to be near-term, dynamic activities while strategic behaviors are generally considered to be long-term and big-picture activities" [134].

[17] This calculated as a total of costs to passengers ($18.1 B), airlines ($8.3 B), indirect costs ($4.2 B), and lost demand ($2.4 B).

Table 7. Annual Reduction in Commercial Aviation Delays in 2024 Dollars

Input	Primary Estimate	Low	High
(a) Annual Cost of U.S. Aviation Delays in 2019 Dollars	$33 billion	$33 billion	$33 billion
(b) Inflation Factor 2019 to 2024	1.2	1.2	1.2
(c) Percent of Annual Delays Attributable to Weather	55%	55%	55%
(d) Percent of Weather Delays Attributable to Thunderstorms	60%	60%	60%
(e) Percent Increase in Thunderstorm-Related Delays without NEXRAD Data	57%	30%	75%
(f) Benefit of Reduced Delays (f) = (a)*(b)*(c)*(d)*(e)	**$7.5 billion**	**$3.9 billion**	**$9.8 billion**

Notes: Minor differences in formula results are attributable to rounding.
Sources:

(a) 2022 Air Traffic by the Numbers [106]
(b) GDP deflators [107]
(c) MITRE analysis of the Operations Network (OPSNET) Delay by Cause Report [108]
(d) Weather Forecasting Accuracy for FAA Traffic Flow Management: A Workshop Report [109]
(e) MITRE expert elicitation exercise detailed in Appendix A.1

A detailed list of assumptions and sources of uncertainty in our analysis of commercial aviation delays is presented at the end of this report in Table 10.

4.2.3 Comparison to Related Studies

To underscore the magnitude of our estimates for commercial aviation delays, we compared our findings with multiple related benefit studies [10], [11], [12], [13]. These studies used different methods of quantification compared to our expert elicitation approach, and these comparisons reinforce our conclusion that NEXRAD's impact on reducing commercial aviation delays is likely to translate into an annual benefit of several billion dollars. Below, we summarize these comparisons and provide detailed calculations in Appendix A.2.

1. After completing our expert elicitation analysis, we identified a 1983 report by NOAA’s Federal Coordinator for Meteorological Services and Supporting Research [10] that includes estimates of the anticipated annual benefit of NEXRAD to aviation.[18] The 1983 report estimates an annual NEXRAD benefit resulting from reduced commercial aviation delays of $143.6 million (1981 dollars) using data from

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[18] This NOAA report is from 1983 and not available online.

1979. We performed an analysis to adjust this estimate to 2024 to account for inflation, increased sector capacity, and other delay costs not contemplated in the 1983 report. This produced a range of \$5.2 billion - \$11.1 billion per year, which is higher but comparable to the range in Section 4.2.2 of \$3.9 billion - \$9.8 billion per year.

2. A paper from 2006 [13] estimates the annual benefit of CIWS at five ARTCCs in reducing delays to be \$295 million per year using data from 2005. CIWS is an aviation weather product for which NEXRAD is the key sensor, and FAA experts indicate that almost all CIWS value is attributable to NEXRAD. We performed an analysis to adjust the estimate from the 2006 paper to 2024 to account for inflation, increased sector capacity, other delay costs not contemplated in the 2006 report, and to scale to a national estimate. This produced a range of \$1.2 billion – \$1.7 billion per year. The benefit of CIWS alone is not expected to be comparable to the whole value of NEXRAD in reducing aviation delays. This is because CIWS is designed for en route traffic, which represented only about 18 percent of all weather-related delay minutes in 2005,[19] and there are many other aviation products that incorporate NEXRAD data (see Table 3 and Table 4). Nevertheless, this exercise demonstrates that just one of the many aviation products that depend on NEXRAD, that addresses only one component of aviation traffic, can create benefits exceeding \$1 billion per year.
3. A paper from 2001 estimates the annual benefit of ITWS [11], another aviation weather product for which NEXRAD is a key sensor, by New York FAA users in reducing delays to be \$168 million per year. Another paper from 2005 [12] estimates the annual benefit of ITWS at ATL in reducing delays to be \$23 million per year. We performed an analysis to adjust the estimates from the 2001 and 2005 papers to 2024 to account for inflation, increased sector capacity, other delay costs not contemplated, and to scale to a national estimate. The 2001 paper produced a range of \$1.8 billion - \$2.8 billion, while the 2005 paper produced a range of \$403 million - \$680 million. Together, this could be viewed as a potential range of annual benefit of ITWS as \$403 million - \$2.8 billion. The benefit of ITWS alone is not expected to capture all the benefit from NEXRAD in reducing aviation delays due to the existence of other aviation products (like CIWS, discussed previously), nor is it expected to all be attributable to NEXRAD. FAA experts indicate that TDWRs are also a key sensor for ITWS. Nevertheless, this exercise confirms again that just one of the many aviation products that depend on NEXRAD may create benefits of over \$2 billion per year.

4.3 Avoided General Aviation Accidents

We estimate the annual value of NEXRAD in reducing fatalities and injuries from weather-related general aviation accidents to be \$172 million (2024 dollars) with a range from \$86 million to \$219 million. We estimate the annual value of NEXRAD in reducing aircraft damage from avoided general aviation accidents to be \$2.6 million (2024 dollars) with a range from \$0.4 to \$5.0 million. We conducted original statistical analysis of general aviation accident data to arrive at these results. In this section, we describe our methodology and calculations.

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[19] MITRE analysis of the OPSNET Delay by Cause Report [127].

4.3.1 Methodology for Estimating the Number of Avoided General Aviation Accidents per Year

The National Transportation Safety Board (NTSB) provides publicly available data on each civil aviation accident, including date of occurrence, number of fatalities, number of injuries, and accident location, going back to 1982 (nine years prior to the deployment of the first NEXRAD site). Certain weather phenomena pose substantial risk to aircraft and are detectable by WSR-88D radars out to a threshold distance. One such phenomenon is LLWS, of which the FAA has had a long-standing concern.[20] During the development of NEXRAD, researchers from the NSSL further estimated that a weather radar of WSR-88D design would be able to detect LLWS out to a range of approximately 60 kilometers (km) [110], [111], [112].

In Figure 6, we plot the natural logarithm (log) of general aviation accidents for areas both within and beyond 60 km of a NEXRAD site in the left panel, and we plot the difference between these two lines in the right panel.[21] Because the majority of the country's land area lies outside of the 60 km range, there are more general aviation accidents occurring outside of the range compared to inside the range, as depicted by the vertical gap between the lines in the left panel.

Figure 6 reveals that the number of general aviation accidents within 60 km of NEXRAD sites decreased more quickly compared to areas farther from NEXRAD sites after deployment. The graph on the right shows there is not a clear trend upwards or downwards in the difference between the two lines prior to the deployment of the first NEXRAD site. The implication is that while the natural logarithm of the number of accidents in areas close to NEXRAD sites and farther away from NEXRAD sites are both trending down, they are essentially moving in parallel. After the deployment of the first site, the difference begins to trend down. In other words, the number of accidents in areas close to NEXRAD sites is decreasing faster than in areas farther away from NEXRAD sites *after deployment* implying an impact of NEXRAD on the number of general aviation accidents.

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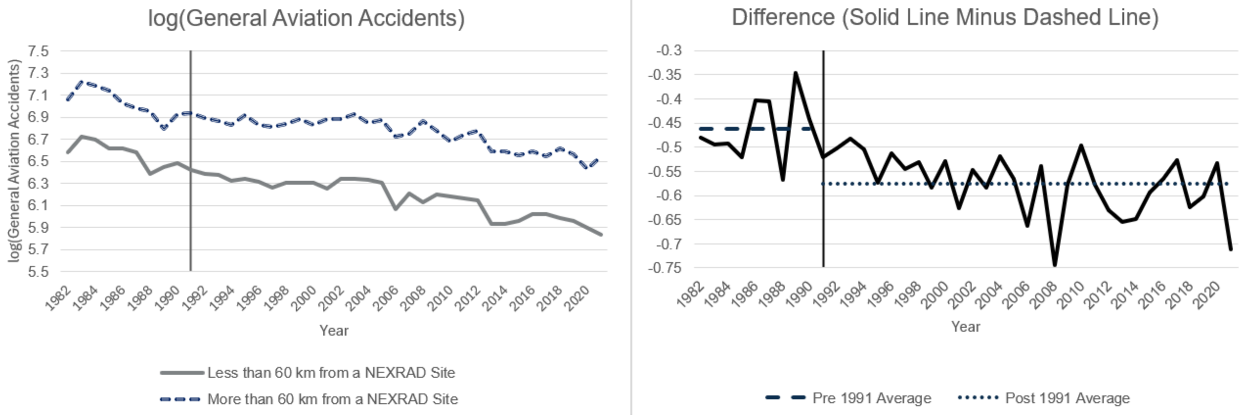
[20] The National Weather Service (NWS) defines LLWS as "[a] wind shear of 10 knots or more per 100 feet in a layer more than 200 feet thick which occurs within 2,000 feet of the surface" [137]. This atmospheric volume corresponds to a radar line-of-sight of approximately 100 km, as the curvature of the Earth precludes the radar from sensing below 2,000 ft at farther distances [137], [133].

[21] It is common to use log transformation in difference-in-differences analyses when the outcome is a count variable.

Figure 6. General Aviation Accidents Over Time by Proximity to NEXRAD Site



Source: MITRE analysis of NTSB data.

We use this finding in a staggered difference-in-differences analysis to formally estimate the impact of NEXRAD on general aviation accidents. We focus on weather-related general aviation accidents within 60 km of a NEXRAD site as the treatment group in our primary model specification. The main limitation of our approach comes from the focus on LLWS for defining the boundaries. NEXRAD likely impacts general aviation accidents outside of the 60 km range since there are certain weather phenomena that NEXRAD can be useful for, even at far distances from the radar sites. Therefore, by focusing on the impact within the 60 km range, our results are likely to underestimate the true impact, as some of the downward trend in the control group is also likely explained by NEXRAD. We recognize that future work on this topic may expand our knowledge by leveraging different approaches and statistical models. Nonetheless, we determined that a difference-in-differences design was our preferred methodology for this report for the following reasons:

1. Given that this is the first analysis, to our knowledge, of the national impact of NEXRAD on general aviation accidents, we wanted to select a methodology that convincingly demonstrated that NEXRAD had an impact on general aviation accidents. The difference-in-differences analysis shows that general aviation accidents fell in areas that are close to NEXRAD radars only after the NEXRAD radars were deployed, relative to areas far from NEXRAD radars, and this difference is statistically significant.
2. General aviation accidents have been decreasing for decades, well before the deployment of the first NEXRAD site and well after. A simple comparison of accident counts prior to and after the introduction of NEXRAD would fail to separately identify the impact of NEXRAD from the ongoing industry-wide trends, such as the certification of the first GPS unit in 1994 [113] and the introduction of more advanced terrain awareness and warning systems in 1996 [114].[22]

The details of the staggered difference-in-differences econometric analysis, including the regression equation, notation, and coefficient estimates, can be found in Appendix A.3. Our

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[22] More sophisticated statistical techniques that leverage data before and after NEXRAD deployment, like the Chow test, may not be suitable for situations when there are multiple break points or the change is gradual. Given the staggered deployment of radars and the fact that pilots and other aviation decision makers would need to learn how to use and interpret NEXRAD-dependent tools and products, we expected a gradual change.

primary model specification leverages data from 1982 through 2022 and includes state, year, and month fixed effects. This primary model estimates that 26.3 weather-related general aviation accidents are avoided annually in the United States due to the availability of NEXRAD data. This figure is used in our "Primary" estimate calculations.

We estimate the following variants of our primary model as robustness checks, confirming the impact of NEXRAD. We present the main results below, and the full results are in Appendix A.3.

1. Defining the treatment group by reducing the range to 50 km. This variant yields an estimate of 21.8 reduced weather-related general aviation aircraft accidents per year in the United States.
2. Defining the treatment group by increasing the range to 70 km. This variant yields an estimate of 29.1 reduced weather-related general aviation aircraft accidents per year in the United States, which is used in our "High" estimate benefit calculations.
3. Removing all areas within 60 nautical miles (nmi) of a TDWR, which were also deployed in the 1990s to address low level wind shear at specific locations. While the instrumented range of the TDWR is 55 nmi and velocity data is only provided to 48 nmi, a conservative 60 nmi cutoff is chosen to account for siting of TDWRs at some distance from the airports for which they provide warnings [115], [116]. This variant yields an estimate of 14.4 reduced weather-related general aviation aircraft accidents per year in the United States, which is used in our "Low" estimate benefit calculations.

4.3.2 Monetized Results

4.3.2.1 Reduced Fatalities and Injuries

We estimate the annual value of NEXRAD in reducing fatalities and injuries from weather-related general aviation accidents to be $172 million (2024 dollars) with a range from $86 million to $219 million. We use recent averages from the NTSB data to translate avoided weather-related accidents to avoided fatalities and injuries. We then use [101] the six-level Maximum Abbreviated Injury Scale (MAIS) [117] paired with the U.S. DOT VSL to monetize injuries.[23] Our calculations are presented in Table 8, and are derived as a sum of the estimated cost of avoided fatalities, avoided major injuries, and avoided minor injuries.

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[23] The MAIS has six levels (minor, moderate, serious, severe, critical, unsurvivable) and NTSB has three levels (minor, severe, fatal).

Table 8. Annual Reduction in Fatalities and Injuries from Avoided Weather-Related General Aviation Accidents in 2024 Dollars

Input	Primary Estimate	Low	High
(a) Reduced U.S. Weather-Related General Aviation Accidents per Year Due to NEXRAD	26.3	14.4	29.1
(b) Average Fatalities per Weather-Related Accident	0.42	0.42	0.42
(c) Average Serious Injuries per Weather-Related Accident	0.18	0.18	0.18
(d) Average Minor Injuries per Weather-Related Accident	0.28	0.28	0.28
(e) Value of a Statistical Life in 2024 Dollars	\$13.7 million	\$13.7 million	\$13.7 million
(f) Value of a Serious Injury in 2024 Dollars	\$3.6 million	\$1.4 million	\$8.1 million
(g) Value of a Minor Injury in 2024 Dollars	\$0.6 million	\$0.04 million	\$1.4 million
(h) Benefit of Reduced Fatalities and Injuries (h) = (a)*(b)*(e) + (a)*(c)*(f) + (a)*(d)*(g)	**\$172 million**	**\$86 million**	**\$219 million**

Notes: Minor differences in formula results are attributable to rounding.
Sources:

(a) MITRE statistical analysis of NTSB data detailed in Appendix A.3
(b) 2018-2022 average from NTSB data [118], [119]
(c) 2018-2022 average from NTSB data [118], [119]
(d) 2018-2022 average from NTSB data [118], [119]
(e) DOT 2024 VSL [101]
(f) We assume that a serious injury reported in NTSB data would map to a severe injury (level 4) in the MAIS scale and be measured as 0.266 the total VSL. For the low value we assumed a serious injury reported in NTSB data would map to a serious injury (level 3) in the MAIS scale and be measured as 0.105 the total VSL, whereas for the high value we assumed a serious injury reported in NTSB data would map to a critical injury (level 5) in the MAIS scale and be measured as 0.593 the total VSL.
(g) We assume that a minor injury reported in NTSB data would map to a moderate injury (level 2) in the MAIS scale and be measured as 0.047 the total VSL. For the low value we assumed a minor injury reported in NTSB data would map to a minor injury (level 1) in the MAIS scale and be measured as 0.003 the total VSL, whereas for the high value we assumed a minor injury reported in NTSB data would map to a serious injury (level 3) in the MAIS scale and be measured as 0.105 the total VSL.

We conducted a supplemental analysis to demonstrate that these general aviation results can be added to the monetized benefits we reported in Section 4.1. The fatalities and injuries in the NTSB data appear to be distinct from those in the NWS Storm Events Database [120] used to arrive at the results in Cho and Kurdzo's series of papers. By comparing the date of occurrence and geographic state of all weather-related general aviation accidents reported in the NTSB data to the subset of the NWS Storm Events Database leveraged by Cho and Kurdzo, it appears that very few aviation accidents are captured. We found that only two out of the over 18,000 weather-related general aviation accidents from 1982 to 2022 we used in our analysis overlapped with direct casualties reported in the NWS Storm Events Database. We note that Cho and Kurdzo [97] also leveraged the U.S. Flash Flood Observation Database compiled by the Flooded Locations and Simulated Hydrographs (FLASH) project. Given the expected limited impact of flash floods on aviation operations, we did not complete a comparison in relation to the alternate data. As such, we believe any double counting of benefits are near zero, and therefore, it is appropriate to add the annual saving attributable to NEXRAD with respect to casualties from general aviation accidents to our results from Section 4.1.

We note that while NEXRAD data improves safety for commercial aviation flights, given the low frequency of these events, the econometric approach we employ for general aviation accidents will likely be inappropriate for this application, and therefore, we do not quantify the benefit at this time. However, given the large losses associated with a commercial aviation accident, we recognize that there is likely a benefit.

4.3.2.2 Reduced Damage to General Aviation Aircraft

We estimate the annual value of NEXRAD in reducing aircraft damage from avoided general aviation accidents to be $2.6 million (2024 dollars) with a range from $0.4 to $5.0 million. Although this magnitude is relatively modest compared to other estimates in this report, we include it to emphasize that the seemingly minor benefits of NEXRAD discussed in Sections 2 and 3 (e.g., enjoyment by birders) may accumulate to a significant total when considered collectively. Our primary estimate is based on an average price of $175,000 for a used Cessna 172. This is the midpoint of the range from a 2024 article [121] which states the used price as $50,000-$300,000, depending on several factors. The Cessna 172 is the most frequent make and model of aircraft reported in the recent five-year subset of accident data used in our analysis, and overall, the Cessna 172 is an extremely popular general aviation aircraft [122].

Our calculations are presented in Table 9 and are derived as a sum of the estimated cost of avoided destruction of aircraft and avoided substantial damage to aircraft. For simplicity, we assume that destruction of the aircraft results in loss of the full value of the aircraft, and substantial damage to the aircraft results in loss of half the value of an aircraft. We omitted minor damage to aircraft from our calculations, which resulted from less than one percent of weather-related accidents in our data.[24] Furthermore, unlike the VSL, where values are equal for all lives and equivalent injuries, we recognize that the value of different aircraft can vary dramatically, especially with respect to age and condition [121], and these variables were not reported in the NTSB data. Due to the comparably small magnitude of our estimated benefit, we defer further refinement to future work.

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[24] We note that insurance payments may complicate the consideration of benefits but given the comparably small magnitude of the estimated benefits in this section, we leave this for future research.

Table 9. Annual Reduction in Aircraft Damage from Avoided Weather-Related General Aviation Accidents in 2024 Dollars

Input	Primary Estimate	Low	High
(a) Reduced U.S. Weather-Related General Aviation Accidents per Year Due to NEXRAD	26.3	14.4	29.1
(b) Value of used Cessna 172	$175 thousand	$50 thousand	$300 thousand
(c) Percent of Weather-Related Accidents that Resulted in Destruction of Aircraft	16.2%	16.2%	16.2%
(d) Percent of Weather-Related Accidents that Resulted in Substantial Damage to Aircraft	82.1%	82.1%	82.1%
(e) Benefit of Reduced Damage to General Aviation Aircraft (e) = (a)*(b)*(c) + 0.5*(a)*(b)*(d)	**$2,639 thousand**	**$413 thousand**	**$5,003 thousand**

Notes: Minor differences in formula results are attributable to rounding. For simplicity, we assume that destruction of the aircraft results in loss of the full value of the aircraft and substantial damage to the aircraft results in loss of half the value of an aircraft.
Sources:

(a) MITRE statistical analysis of NTSB data detailed in Appendix A.3
(b) Value range for used Cessna 172 [121]
(c) 2018-2022 average from NTSB data [118], [119]
(d) 2018-2022 average from NTSB data [118], [119]

A detailed list of assumptions and sources of uncertainty in our analysis of general aviation accidents is presented at the end of this report in Table 10.

5 Assumptions and Sources of Uncertainty

This report presents our estimates of the annual benefit that NEXRAD provides to the general public through watches, warnings, and forecasts, and the annual benefit that NEXRAD provides to aviation. To ensure transparency, we include a detailed list of assumptions and sources of uncertainty that could influence our findings in Table 10. These factors should be carefully considered when interpreting the results presented in this report.

Table 10. Assumptions and Sources of Uncertainty

Source of Benefit	Assumption/Source of Uncertainty	Impact on Estimate	Description
Reduced injuries and fatalities from tornadoes, flash floods, and severe winds	The benefit of NEXRAD for this application is $1.176 billion per year (2023 dollars)	Unknown	This estimate comes directly from Rudlosky et al. [100], a paper coauthored by Cho and Kurdzo, which reports this updated, NEXRAD-specific figure based on their previous series of papers [96], [97], [98]. The value is reported as a point estimate without ranges. Independent replication of applicable literature was beyond the scope of our analysis. A small amount of this value was attributed to reduced lost time due to unnecessary sheltering.
Reduced injuries and fatalities from tornadoes, flash floods, and severe winds	Focus on tornadoes, flash floods, and severe winds	Underestimate	NEXRAD data is also useful for forecasting other weather phenomena not included in this benefit calculation (e.g., winter storms and wildfires), and for reducing costs beyond casualties and some lost time (e.g., costs associated with medical care and emergency rescues). Therefore, it is likely that this valuation underestimates the full benefit of NEXRAD with respect to all severe weather warnings.
Reduced Commercial Aviation Delays	Annual cost of commercial aviation delays in the United States is $33 billion (2019 dollars)	Unknown	This estimate is from the FAA's analysis [106] and was the most recent report of this value we identified in our research. Independent replication was beyond the scope of our analysis.
Reduced Commercial Aviation Delays	Percent of aviation delays attributable to weather is 55%	Unknown	This estimate was derived from the OPSNET Delay by Cause Report [108] based on the average number of delays at Core 30 airports for the four-year period from 2021 through 2024. Reporting this metric with respect to Core 30 airports appears to be consistent with the FAA's annual approach within Air Traffic by the Numbers [76], [106], but we use a multi-year average in an attempt to account for variation that occurs year-to-year. We are unsure if this method might over- or underestimate the true percentage of delays that are attributable to weather.

Source of Benefit	Assumption/Source of Uncertainty	Impact on Estimate	Description
Reduced Commercial Aviation Delays	Percent of weather aviation delays attributable to convective weather is 60%	Unknown	This statistic was challenging to identify. While we found references to lower estimates [123], we were unable to substantiate these figures and chose to defer to the work from the 2003 National Research Council [109]. The impact of this assumption is unknown because of the uncertainty in how accurately the past reflects the future.
Reduced Commercial Aviation Delays	Focus on convective weather delays only	Underestimate	Convective weather is only one cause of commercial flight delays that NEXRAD can identify; we identified convective weather as the largest contributor to weather delays in the United States, but we also acknowledge that other types of NEXRAD-identifiable phenomena can also cause commercial flight delays. In addition, flight cancellations, as opposed to delays, can also be issued, and can result in similar societal costs. We recognize that future work should consider additional relevant weather phenomena and flight cancellations.
Reduced Commercial Aviation Delays	Use of expert elicitation	Unknown	Aviation simulation models could be used to quantify aviation delays with and without NEXRAD through thoughtful assumptions and parameterizations. However, this approach was beyond the resources and timeline for this project. We recognize that future work should consider and implement aviation simulation approaches as feasible.
Reduced Commercial Aviation Delays	Experts had adequate subject matter expertise and understood the questionnaire	Unknown	While we stressed the many aviation products that depend on NEXRAD and that other weather information would remain available, we cannot be certain how experts interpreted the world without NEXRAD data given their varied experiences in aviation. If they did not consider all the aviation products that incorporate NEXRAD data, this would understate our estimate. If they did not realize other non-NEXRAD weather information would remain available, this would overstate our estimate. Uncertainty in expert thinking is reflected in their minimum and maximum responses and self-reported confidence.

Source of Benefit	Assumption/Source of Uncertainty	Impact on Estimate	Description
Reduced Commercial Aviation Delays	Average commercial aviation delay due to thunderstorms is approximately 75 minutes in United States	Unknown	While the experts were made aware that our key interest was in a percent change in thunderstorm delays, we chose to ask for their answers in minute changes to a national average thunderstorm delay of 75 minutes because we believed that this unit would be more familiar for them to consider. This approximation of 75 minutes is supported by a 2019 paper [124] investigating weather delays focused on 10 major U.S. airports, which reported the average delay due to thunderstorms as 74.3 minutes for departure delays and 67.8 minutes for arrival delays. We viewed 75 minutes as a conservative value. The average time at a mix of all airports throughout the country may be higher or lower than this value, and newer data may differ from the timeframe investigated in the cited paper.
Avoided General Aviation Accidents	Statistical analysis of data from 1982 through 2022 is relevant today	Unknown	Using data from 1982 through 2022 will identify the impact of the NEXRAD relative to the state of the world as it existed during this period. This approach may overstate the current impact of NEXRAD due to improvements in other NOAA sensor technology assets since NEXRAD deployment. It may also understate the current impact due to improvements in NEXRAD radar technology and improvements in dissemination capabilities, such as warning systems and the proliferation of smartphones.
Avoided General Aviation Accidents	Model predictions from 2022 are relevant today	Overestimate	We use the model's predicted impact on reducing weather-related general aviation accidents in the latest year of data (2022) as our estimate of the current annual impact. However, there appears to be a downward trend in the model's predicted impacts over time, likely due to the overall reduction in general aviation accidents over time. Should this trend continue, our decision to use 2022 impacts may overstate the true impact of NEXRAD on accidents today.

Source of Benefit	Assumption/Source of Uncertainty	Impact on Estimate	Description
Avoided General Aviation Accidents	Areas close to radar sites are a valid treatment group for statistical analysis	Underestimate	Our statistical analysis leverages the fact that NEXRAD is expected to have a higher impact on reducing accidents closer to the radar sites because there are certain low-level weather phenomena that are addressable by NEXRAD only within a certain proximity to the site. However, NEXRAD likely impacts accidents in our control group as well, since there are certain weather phenomena that NEXRAD can be useful for, even at very far distances from the radar sites. In other words, part of the downward trend in the control group is likely due to NEXRAD, which means our results are likely to underestimate the true impact.
Avoided General Aviation Accidents	TDWRs deployed in the 1990s	Overestimate of "Primary" and "High" estimates	While our "Low" estimate removes the impact of TDWRs, it is possible that part of the impact in our "Primary" and "High" estimates is attributable to TDWRs.
Avoided General Aviation Accidents	State, year, and month fixed effects are adequate controls	Unknown	The econometric analysis of general aviation accidents relies on accident data and does not incorporate time-varying control variables within a state. Ideal data would have information on each flight and the accident outcome, so we could model NEXRAD's impact on the accident probability with multiple flight-specific control variables as opposed to modeling the count of accidents. The impact depends on how these unobserved variables correlate with key variables in the model.
Avoided General Aviation Accidents	Recent historical average rates of fatalities and injuries are similar to current rates	Unknown	For each avoided general aviation accident derived from our difference-in-differences model, we estimated associated casualties using the aggregate average rate of fatalities and injuries per weather-related accident from 2018 through 2022. This assumes that historical data is representative of future outcomes.
Avoided General Aviation Accidents	Translating NTSB Injury Scale to MAIS Injury Scale	Unknown	To monetize injuries reported in the NTSB data, we needed to map the levels of injuries to that of the MAIS Injury Scale used to weigh the VSL. We have limited information on the meaning of injury levels in the NTSB data. Therefore, we are unsure if the different mappings we used are over- or underestimates of the injury levels across the different scales.

Source of Benefit	Assumption/Source of Uncertainty	Impact on Estimate	Description
Avoided General Aviation Accidents	Price of aircraft damage	Unknown	Based on available information, we estimated that the average price of a used Cessna 172 is $175 thousand. We are unsure whether this is an over- or underestimate of the true average value of this style of aircraft, given the wide range of potential values and limited information in the NTSB data about involved aircraft. Moreover, we used this make and model of aircraft as a proxy for all aircraft involved in accidents, given its frequency in our data set and popularity as a general aviation aircraft in the United States, but we acknowledge that many different types of aircraft are involved in accidents reported in the NTSB data. As such, we cannot confidently determine the potential direction of impact on our estimate due to this assumption.
Avoided General Aviation Accidents	Substantial damage to aircraft involved in weather-related accident accounts for 50% of the value of an aircraft	Unknown	We have limited detail on the damage scale for aircraft in the NTSB data. Therefore, we are unsure if an assumption of 50% of an aircraft's value is an over- or underestimate of the associated cost of substantial damage.
Avoided General Aviation Accidents	Minor damage to aircraft involved in weather-related accidents was excluded from our calculations	Underestimate	Given that less than 1% of the accidents in our weather-specific data set resulted in minor damage to the aircraft, we omitted this damage from our calculations. We believe this would result in an underestimate of the benefit of reduced aircraft damage.
Aggregation of Benefits	Results can be added across sources of benefit	Overestimate	While we conducted a detailed overlap analysis to support aggregation of our results, should there be overlap between the sources of benefit, our total benefit calculation would be overestimated.

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[136] National Weather Service, "National Weather Service Glossary - Convection," [Online]. Available: https://forecast.weather.gov/glossary.php?word=CONVECTION. [Accessed 12 September 2025].

[137] National Weather Service, "Low Level Wind Shear," National Oceanic and Atmospheric Administration, [Online]. Available: https://www.weather.gov/zme/safety_llws. [Accessed 8 August 2025].

Appendix A Quantification Details

A.1 Expert Elicitation of Change in Commercial Aviation Delays from Convective Weather

A.1.1 Approach

The exercise included three main components: an introductory meeting, a questionnaire with first-round responses, and one opportunity to revise responses after seeing all anonymized responses. The meeting served as a forum to introduce participants to our research question and to allow them to discuss high-level understandings of how Next Generation Weather Radar (NEXRAD) is currently used in commercial aviation operations. We also discussed the questionnaire, demonstrated common misunderstandings regarding the types of questions we were asking (as illustrated through a fictitious example), and provided participants with the opportunity to ask questions. A slideshow presentation was used to help facilitate the hour-long meeting with participants, and it included structured information about participation, background on NEXRAD, examples of products that use NEXRAD, information on the questionnaire, four-point elicitation examples, and time for open discussion about the role of NEXRAD in managing commercial aviation delays. To maintain independence and minimize potential bias in responses, prior to and during the meeting, we emphasized that participants should not discuss their responses with one another and that their responses would be kept anonymous.

Following the meeting, participants were asked to complete a questionnaire, provided in full in Appendix A.1.2. To begin the questionnaire, we first asked participants to describe their relevant experience. The next question in the document was a multiple-choice question, asking each participant to indicate whether NEXRAD data had an impact on commercial aviation delays caused by convective weather. This multiple-choice question is provided for reference below.

> *On average, does NEXRAD data (including products that use NEXRAD data) have an impact on commercial aviation delays caused by convective weather?*
>
> *a) Yes - on average, the availability and use of NEXRAD data decreases commercial aviation delays caused by convective weather.*
>
> *b) Yes - on average, the availability and use of NEXRAD data increases commercial aviation delays caused by convective weather.*
>
> *c) No - on average, the availability and use of NEXRAD data does not impact commercial aviation delays caused by convective weather, and no longer providing the data would not have an effect on commercial aviation delays as they occur today.*
>
> *d) Unsure – I am unsure if, on average, NEXRAD data has an impact on reducing commercial flight delays caused by convective weather.*

We believed this question was important for two reasons. First, this high-level qualitative question helps us understand each expert's initial thinking about our value of interest. Second, it can indicate whether the answers to the quantitative questions reasonably match their high-level thinking. For example, it would be illogical for a respondent to answer that they believe the availability and use of NEXRAD data decreases commercial aviation delays caused by convective weather but answer in a later question that a reasonable maximum increase in a world without NEXRAD is less than zero. Because of this, it was important for us to build in this logical check to ensure that the experts were properly expressing their thoughts in the specific confines of quantitative questions to come.

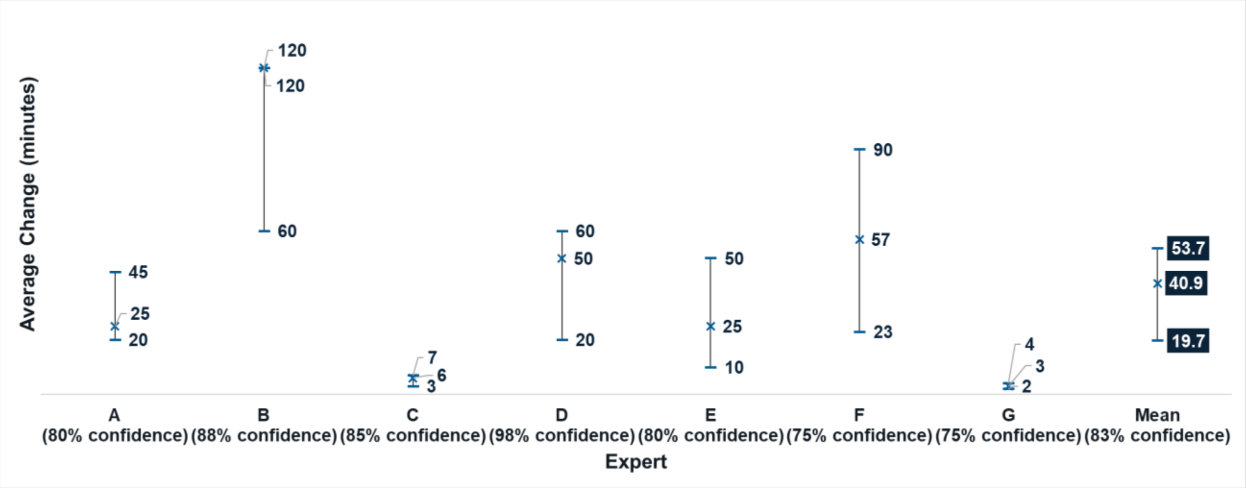
All seven experts selected the same answer to this question, option (a), and indicated that on average, the availability and use of NEXRAD data decreases commercial aviation delays caused by convective weather. We also asked participants to explain the reason behind their choice. In summary, respondents generally indicated that NEXRAD data allows for better utilization of the available airspace and minimizes excessive vectors, reroutes, and traffic management initiatives.

The next set of questions we asked participants via the questionnaire were about the expected change in delay minutes to commercial flights due to thunderstorms if NEXRAD data were no longer available and were designed according to the four-point elicitation method [103]; we asked each expert to provide (1) a reasonable minimum, (2) a reasonable maximum, (3) a best guess value, and (4) a rating of confidence. Despite our benefit calculation ultimately requiring answers to be represented in a percent change in commercial delay times during convective weather between current NEXRAD availability and no NEXRAD, we asked for the minimum, maximum, and best guess values in terms of minutes, since we suspected changes in time would be more straightforward for our participants to consider as opposed to percent changes. However, the experts were aware that their responses would be converted to percentages and how those percentages would be used to calculate the benefit. The experts were asked to explain their reasoning behind all four of the numerical values to the best of their abilities. A summary of the four-point elicitation questions asked is provided below.

> *We recognize that thunderstorms have differential impacts on airports across the country. For the following questions, we consider the impact on the national average. For reference, on average in the United States, a commercial aviation delay due to thunderstorms is approximately 75 minutes [124].*
>
> - *(Minimum) If NEXRAD data were no longer available, what is the lowest plausible number of minutes you would expect average thunderstorm delays to increase by? Please explain the reasoning for your answer to the best of your ability.*
> - *(Maximum) If NEXRAD data were no longer available, what is the highest plausible number of minutes you would expect average thunderstorm delays to increase by? Please explain the reasoning for your answer to the best of your ability.*
> - *(Best Guess) If NEXRAD data were no longer available, what is your best guess as to the average number of minutes you would expect thunderstorm delays to increase by? Please explain the reasoning for your answer to the best of your ability.*
> - *(Confidence) How confident are you that your interval, from lowest to highest, could capture the true number of minutes that the average thunderstorm delay would increase by if NEXRAD data were no longer available? Please answer with a number between 50% and 100%. Please explain the reasoning for your answer to the best of your ability.*

After reviewing the submitted Round 1 responses, we followed up with participants as needed to confirm any answers that seemed inconsistent with the opinions or information an expert provided elsewhere in their questionnaire, to ensure that responses to the four-point elicitation questions accurately reflected each expert's true thinking and intentions. We also reached out to any participants that offered answers that did not adhere to the method, for example, if a participant gave a range of values for their best guess, we asked them to revise their answer to be a single point estimate. Figure A-1 illustrates the Round 1 responses, following these quality assurance efforts.

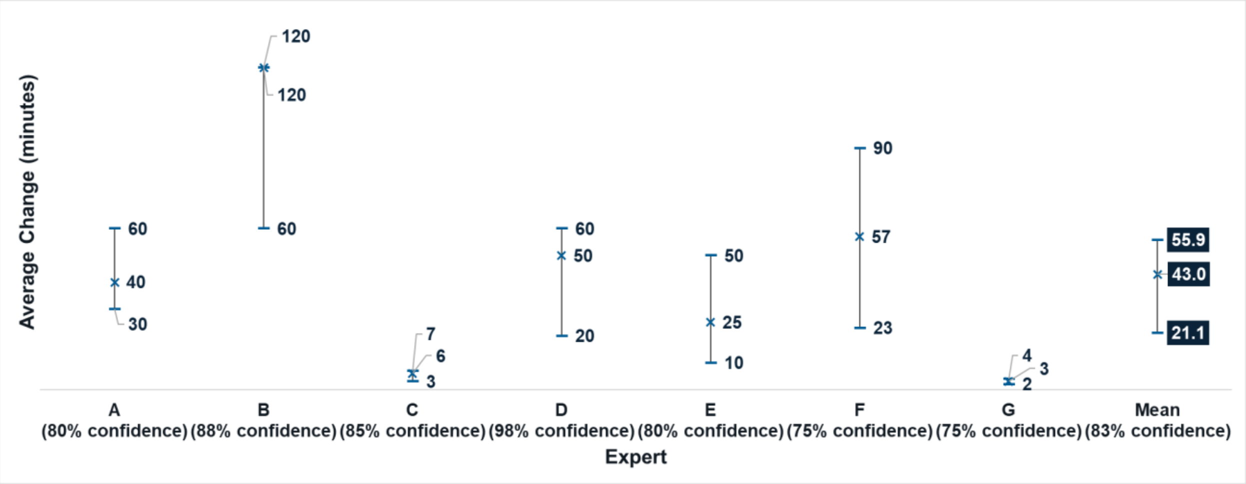
Figure A-1. Experts' Round 1 Responses to the Four-Point Elicitation Questions



We aggregated the seven participants' responses by calculating arithmetic means of the elicited values (i.e., quantile aggregation). The paper by Hemming et al. [103] suggests this method for aggregation for multiple reasons, including that it is simple to understand, does not require distributional assumptions, and has performed well in some applications. As shown on the right of Figure A-1, the average best guess across the seven participants during Round 1 was 40.9 minutes.

We then conducted the discussion phase over email, an allowable platform for the Investigate, Discuss, Estimate, Aggregate (IDEA) protocol [103]. We outlined anonymized responses from Round 1, including the reasoning provided by each participant to justify their predictions. We asked each participant to review their answers in the context of the whole group and determine if they would like to update their responses, given the information other experts provided. We further asked that even if a participant would not like to modify their responses, that they confirm their final answer. One of the seven participants in the activity, Expert A, provided an updated answer in Round 2, while all other participants indicated satisfaction with their initial, individual responses. The results from this second iteration of questioning (Round 2) are provided in Figure A-2. Note, given the update to Expert A's responses, the mean results at the right of the figure slightly increased compared to the Round 1 results, as illustrated previously in Figure A-1. Per the IDEA protocol, we considered the expert elicitation exercise complete following the receipt of Round 2 responses.

Figure A-2. Experts' Round 2 Responses to the Four-Point Elicitation Questions



To execute our benefit calculation, we converted the responses provided by the participants in minutes into percent changes as compared to the baseline value of 75 minutes (the approximate national average we provided within the questionnaire). This was done by dividing all minimum, maximum, and best guess responses by 75.

Further, formulaic adjustments to the data were applied following the methods described in Hemming et al. [103]. We standardized the reasonable minimum to maximum range provided by each participant using linear extrapolation according to the following formulas, where B is the best guess, L is the lower estimate, U is the upper estimate, S is the level of credible intervals to be standardized, and C is the level of confidence given by participants. We standardized all intervals to a confidence level of 80 percent (i.e., S = 80).

$$\text{Lower standardized interval: } B - \left((B - L) * \left(\frac{S}{C}\right)\right)$$

$$\text{Upper standardized interval: } B - \left((U - B) * \left(\frac{S}{C}\right)\right)$$

Lastly, we combined the seven responses into a single average distribution according to quantile aggregation, as discussed in this section. The final values are presented earlier, in Figure 5. Following the steps described, we concluded that the combined best guess from this group of experts is a 57 percent increase, the reasonable minimum is a 30 percent increase, and the reasonable maximum is a 75 percent increase. We refrained from providing responses to the open-ended questions in this report to protect the anonymity of the experts.

A.1.2 Questionnaire

Below is the complete questionnaire that was provided to participants for Round 1 elicitation.

Expert Elicitation of NEXRAD's Impact on Commercial Aviation Delays - Questionnaire

Note: Taking part in this research exercise is entirely voluntary, and you can decline or stop participation at any time. Our MITRE project will retain a copy of your answers to this questionnaire. We will be aggregating our findings in draft materials and a final report we provide to NOAA/NWS and the Radar Next team and will not attribute answers and comments to specific individuals, though we may describe some of your relevant experience which relates to the question we are exploring (which qualifies you as an expert for our exercise) and your affiliation with MITRE. We encourage you to share your thoughts and feelings as candidly as possible.

(1) **Name:**

(2) **Relevant Experience in Aviation and/or Meteorology:**

(3) **On average, does NEXRAD data (including products that use NEXRAD data) have an impact on commercial aviation delays caused by convective weather?** *(bold your choice)*
   a. Yes - on average, the availability and use of NEXRAD data <u>decreases</u> commercial aviation delays caused by convective weather.
   b. Yes - on average, the availability and use of NEXRAD data <u>increases</u> commercial aviation delays caused by convective weather.
   c. No - on average, the availability and use of NEXRAD data <u>does not impact</u> commercial aviation delays caused by convective weather, and no longer providing the data would not have an effect on commercial aviation delays as they occur today.
   d. Unsure – I am <u>unsure</u> if, on average, NEXRAD data has an impact on reducing commercial flight delays caused by convective weather.

(4) **Please explain the reasoning for your selection in question (3).**

We recognize that thunderstorms have differential impacts on airports across the country. For the following questions, we consider the impact on the national average. For reference, on average in the United States, a commercial aviation delay due to thunderstorms is approximately 75 minutes.[1]

(5) **(Minimum) If NEXRAD data were no longer available, what is the <u>lowest</u> plausible number of minutes you would expect average thunderstorm delays to increase by?** *Note: an answer of "1 minute" indicates you believe without NEXRAD data, the new national average for commercial aviation delays due to thunderstorms could be <u>at least</u> 76 minutes. An answer of "0 minutes" indicates, at minimum, no change.*

(6) **Please explain the reasoning for your answer to (5) to the best of your ability.**

(7) **(Maximum) If NEXRAD data were no longer available, what is the <u>highest</u> plausible number of minutes you would expect average thunderstorm delays to increase by?** *Note: an answer of "1 minute" indicates you believe without NEXRAD data, the new national average for commercial aviation delays due to thunderstorms could be <u>at most</u> 76 minutes. Negative numbers would indicate that delay times would improve without NEXRAD data.*

(8) **Please explain the reasoning for your answer to (7) to the best of your ability.**

(9) **(Best Guess) If NEXRAD data were no longer available, what is your <u>best guess</u> as to the average number of minutes you would expect thunderstorm delays to increase by?** *Note: this*

is your best estimate for a new value in place of 75 minutes, and it should reasonably fall somewhere within your range created by answering questions (5) and (7).

(10) **Please explain the reasoning for your answer to (9) to the best of your ability.**

(11) **(Confidence) How confident are you that your interval, from lowest to highest (i.e., your answers to questions (5) and (7), respectively), could capture the true number of minutes that the average thunderstorm delay would increase by if NEXRAD data were no longer available? Please answer with a number between 50% and 100%.** *Note: 95% means you are 95% confident that the true value lands between your minimum and maximum values. 50% means you are equally confident that the true value is inside the range you provided as outside (this is a reasonable minimum for this answer). An answer of 5% implies a significant level of confidence that the answer you provided is incorrect, and that you are 95% confident the true answer falls outside the range you selected.*

(12) **Please explain the reasoning for your answer to (11) to the best of your ability.**

(13) **Would you like to add anything else regarding your answers above and/or this exercise?**

[1] Goodman, C. J., & Small Griswold, J. D. (2019). Meteorological impacts on commercial aviation delays and cancellations in the continental United States. *Journal of applied meteorology and climatology, 58*(3), 479-494. https://doi.org/10.1175/JAMC-D-17-0277.1

A.2 Analysis of Related Studies on Aviation Delays

Table A-1. Adjusting Results from 1983 National Oceanic and Atmospheric Administration (NOAA) Report to 2024

Description	Low Estimate	High Estimate
(a) 1983 NOAA report estimate of national NEXRAD benefit on reducing operating costs to airlines from delays (1981 dollars)	$143.6 million	$143.6 million
(b) Inflation factor to 2024 dollars	2.91	6.21
(c) Scale factor to include all delay costs considered by the Federal Aviation Administration (FAA)	3.98	3.98
(d) Sector growth to 2024	3.14	3.14
(e) Total (e) = (a)*(b)*(c)*(d)	**$5,206 million**	**$11,121 million**

Note: Minor differences in formula results are attributable to rounding.
Sources:

(a) Report from NOAA's Federal Coordinator for Meteorological Services and Supporting Research [10]
(b) Low estimate: gross domestic product (GDP) deflators [107]; High estimate: Inflation in hourly aviation operating costs based on proportion of direct costs of delays to airlines reported in 2023 [125], adjusted to 2024 dollars according to GDP deflators [107], and compared to value described in 1983 report [10]
(c) Proportion of total delay costs compared to costs to airlines from the FAA Fiscal Year (FY) 2019 analysis [106]
(d) The MITRE Corporation (MITRE) analysis of available seat miles [126]

Table A-2. Adjusting Results from 2006 Corridor Integrated Weather System (CIWS) Paper to 2024

Description	Low Estimate	High Estimate
(a) 2006 paper estimated annual CWIS benefit in reducing operating costs to airlines and time cost to passengers from delays at five Air Route Traffic Control Centers (ARTCCs) (2005 dollars)	$295 million	$295 million
(b) Inflation factor to 2024 dollars	1.54	2.20
(c) Scale factor to include all delay costs considered by the FAA	1.25	1.25
(d) Sector growth to 2024	1.33	1.33
(e) Scale to national estimate	1.57	1.57
(f) Total (f) = (a)*(b)*(c)*(d)*(e)	**$1,178 million**	**$1,685 million**

Note: Minor differences in formula results are attributable to rounding.
Sources:

(a) Robinson et al. [13]
(b) Low estimate: GDP deflators [107]; High estimate: Weighted average of inflation in hourly aviation operating costs and hour of passenger time according based on proportion of values reported in 2023 [125], adjusted to 2024 dollars according to GDP deflators [107], and compared to value described in 2006 paper [13]
(c) Proportion of total delay costs compared to costs to airlines and passengers from the FAA FY2019 analysis [106]
(d) MITRE analysis of available seat miles [126]
(e) MITRE analysis of the Operations Network (OPSNET) Delay by Cause Report [127]

Table A-3. Adjusting Results from 2001 Integrated Terminal Weather System (ITWS) Paper to 2024

Description	Low Estimate	High Estimate
(a) 2001 paper estimated annual ITWS benefit in reducing operating costs to airlines and time cost to passengers from delays by New York FAA users (2000 dollars)	$167.6 million	$167.6 million
(b) Inflation factor to 2024 dollars	1.72	2.20
(c) Scale factor to include all delay costs considered by the FAA	1.25	1.25
(d) Sector growth to 2024	1.39	1.39
(e) Scale to national estimate	3.55	4.29
(f) Total (f) = (a)*(b)*(c)*(d)*(e)	**$1,784 million**	**$2,750 million**

Note: Minor differences in formula results are attributable to rounding.
Sources:

(a) Allan et al. [11]
(b) Low estimate: GDP deflators [107]; High estimate: Weighted average of inflation in hourly aviation operating costs and hour of passenger time according based on proportion of values reported in 2023 [125], adjusted to 2024 dollars according to GDP deflators [107], and compared to value described in 2001 paper [11]
(c) Proportion of total delay costs compared to costs to airlines and passengers from the FAA FY2019 analysis [106]
(d) MITRE analysis of available seat miles [126]
(e) Low estimate: Lower bound of MITRE analysis of the OPSNET Delay by Cause Report; High estimate: Upper bound of MITRE analysis of the OPSNET Delay by Cause Report [127]

Table A-4. Adjusting Results from 2005 ITWS Paper to 2024

Description	Low Estimate	High Estimate
(a) 2005 paper estimated annual ITWS benefit in reducing operating costs to airlines and time cost to passengers from delays in Atlanta (2003 dollars)	$23 million	$23 million
(b) Inflation factor to 2024 dollars	1.63	1.63
(c) Scale factor to include all delay costs considered by the FAA	1.25	1.25
(d) Sector growth to 2024	1.48	1.48
(e) Scale to national estimate	5.82	9.80
(f) Total (f) = (a)*(b)*(c)*(d)*(e)	**$403 million**	**$680 million**

Note: Minor differences in formula results are attributable to rounding.
Sources:

(a) Allan and Evan [12]
(b) GDP deflators [107]
(c) Proportion of total delay costs compared to costs to airlines and passengers from the FAA FY2019 analysis [106]
(d) MITRE analysis of available seat miles [126]
(e) Low estimate: Lower bound of MITRE analysis of the OPSNET Delay by Cause Report; High estimate: Upper bound of MITRE analysis of the OPSNET Delay by Cause Report [127]

A.3 Statistical Analysis of General Aviation Accidents

In this section, we explain our econometric approach for estimating the number of avoided weather-related general aviation accidents per year due to NEXRAD. We performed a staggered difference-in-differences analysis, leveraging geographic variation in the proximity of general aviation accidents to NEXRAD sites and temporal variation in the existence of NEXRAD radars.

Our primary data source is publicly available data from the National Transportation Safety Board (NTSB) on over 150,000 civil aviation accidents and incidents dating back to 1962 [118], [119]. Key variables used in our analysis include the event date, report status, accident location (longitude and latitude), number of fatalities, number of serious injuries, number of minor injuries, level of aircraft damage (destroyed, substantial, minor, or none), Federal Aviation Regulations (FARs) Part, and findings (to identify weather-related accidents). Accident location (longitude and latitude) is only available for accidents occurring in 1982 and later. Findings depend on the report being completed, which can often take up to two years [128]. Therefore, we restrict our analysis to 1982–2022. We identified general aviation accidents using the data element event type and FARs Part not equal to 121 or 135.[25] We restricted our analysis to

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[25] Based on conversation with NTSB data experts. We also excluded accidents with unknown or blank FARs Part data.

accidents within the United States using the country data element.[26] A general aviation accident was determined to be weather-related if there was a weather finding. Findings are the result of an NTSB investigation that identifies the probable cause(s) of the accident and factors that contributed to the outcome of the accident [129]. For example, the probable cause for one of the general aviation accidents in the data identified as a weather-related accident (NTSB Number ERA22FA397) states, "[t]he pilot's decision to attempt the cross-country flight in thunderstorm conditions, which resulted in controlled flight into terrain. Contributing to the accident was the pilot's failure to obtain a weather briefing" [118].

We formally estimated the impact of NEXRAD on weather-related general aviation accidents using the following regression equation and considered a coefficient to be statistically significant if the estimation yields a p-value less than one percent (i.e., $p < 0.01$). We defined the treatment group as weather-related accidents within 60 kilometers (km) of a NEXRAD site.

$$\mu_{A|T,s,y,m} = f(\beta_0 + \beta_1 * T * Post_{y,s} + \beta_2 * T + \sum_{y} \gamma_y + \sum_{m} \alpha_m + \sum_{s} \delta_s)$$

Explanations of notation are in Table A-5.

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[26] For some accidents where the country was listed as the United States, the state was empty or listed as "Pacific Ocean". These observations were also excluded from the analysis.

Table A-5. Regression Equation Notation

Notation	Definition
T	An indicator that equals 1 for weather-related accidents within 60 km of a NEXRAD site and 0 otherwise.
s	Geographic state
y	Year
m	Month
$Post_{y,s}$	An indicator variable that equals 1 starting in the year of deployment of the first NEXRAD site in state s and 0 otherwise.
γ_y	An indicator variable that equals 1 if the year equals y and 0 otherwise.
α_m	An indicator that equals 1 if the month equals m and 0 otherwise.
δ_s	An indicator that equals 1 if the state equals s and 0 otherwise.
$\mu_{A\|T,s,y,m}$	The expected value of the number of general aviation accidents occurring in treatment group T, in state s, in year y, and in month m.
β_1	The coefficient of interest is β_1. This coefficient captures the impact of NEXRAD on the treatment group compared to the control group post deployment of the first NEXRAD site.

The model was estimated on 50,184 observations, one for each year, month, state (51 including Washington, D.C.), and treatment assignment combination. We present summary statistics by year in Table A-6.

Table A-6. Accident Counts by Treatment Assignment and Time Period

Time Period	Treatment Group Accident Count (Mean)	Treatment Group Accident Count (Standard Deviation)	Control Group Accident Count (Mean)	Control Group Accident Count (Standard Deviation)
Whole Time Period (1982 – 2022)	0.21	0.55	2.35	3.18
Prior to First NEXRAD Deployment (1982 – May 1991)	0.32	0.70	2.98	3.95
After First NEXRAD Deployment (June 1991 – 2022)	0.18	0.49	2.16	2.89

Data source: NTSB data from 1982 through 2022.

Given that the count variable exhibits overdispersion, we estimated a negative binomial model.[27] The results of the primary estimation are shown below in Table A-7. The coefficient of interest is negative (implying that NEXRAD reduces general aviation accidents) and statistically significant ($p < 0.001$). We modeled the predicted reduction in weather-related accidents in the latest year of data (2022) using the estimated model parameters.

Table A-7. Results of Primary Negative Binomial Model

Covariate	Coefficient	Standard Error	p-value
NEXRAD Coefficient of Interest	-0.27	0.030	< 0.001
Treatment	-2.2	0.024	< 0.001
Number of Observations	50,184	N/A	N/A
Implied Reduction in Weather-Related Accidents in 2022	26.3	N/A	N/A

Data source: NTSB data from 1982 through 2022.
Notes: Includes month, year, and state fixed effects.

To support our methodological framework, we performed a statistical assessment to investigate the parallel trends assumption in difference-in-differences analyses. Specifically, we tested for a differential linear time trend between the treatment and control groups prior to the deployment of the first NEXRAD site. The results are displayed in Table A-8. The results confirm that there was no statistically different annual linear trend for the treatment group compared to the control group from January 1982 through May 1991 (prior to the deployment of the first NEXRAD site);

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[27] This is the same justification used by Simmons and Sutter [95]for using a negative binomial model to estimate tornado fatalities and injuries.

the p-value for the coefficient estimate on the interaction term between the treatment group and year value is 0.6.

Table A-8. Assessment of Trends between Treatment and Control Groups Prior to Deployment of the First NEXRAD Site

Covariate	Coefficient	Standard Error	p-value
Treatment*Year	-0.01	0.009	0.6
Treatment	8.6	18.6	0.6
Year	-0.04	0.003	< 0.001
Number of Observations	11,526	N/A	N/A

Data source: NTSB data from 1982 through May 1991.
Notes: Includes month and state fixed effects.

To support the validity of our results, we performed numerous robustness checks. For example, while our preferred model selection was a negative binomial to account for the frequency of zeros, we also estimated Poisson and log-linear models, which are commonly used models for count outcomes and/or difference-in-differences analysis. While we cannot display the results of every robustness check in this report (we ran more than 100 regressions), we display the results of key checks here. We repeatedly found a negative and statistically significant parameter estimate for the coefficient of interest.

We tested the robustness of our results to various distance thresholds for the treatment assignment. While our preferred specification included a threshold of 60 km, we tested robustness to shorter and longer distances. The results of these robustness checks for 50 km and 70 km are shown in Table A-9 and Table A-10, respectively. The coefficient of interest is negative and statistically significant in both robustness checks presented. The magnitude of the coefficient is smaller the larger we make the threshold, confirming that NEXRAD sites have a larger impact on areas closer to the radar. However, the implied reduction in the number of accidents grows, because this dampening in the treatment effect coefficient is outweighed by the growing number of accidents in the treatment group.

Table A-9. Robustness of Results to Distance Threshold for Treatment Assignment of 50 km

Covariate	Coefficient	Standard Error	p-value
NEXRAD Coefficient of Interest	-0.29	0.034	< 0.001
Treatment	-2.5	0.026	< 0.001
Number of Observations	50,184	N/A	N/A
Implied Reduction in Weather-Related Accidents in 2022	21.8	N/A	N/A

Data source: NTSB data from 1982 through 2022.
Notes: Includes month, year, and state fixed effects.

Table A-10. Robustness of Results to Distance Threshold for Treatment Assignment of 70 km

Covariate	Coefficient	Standard Error	p-value
NEXRAD Coefficient of Interest	-0.24	0.027	< 0.001
Treatment	-2.0	0.022	< 0.001
Number of Observations	50,184	N/A	N/A
Implied Reduction in Weather-Related Accidents in 2022	29.1	N/A	N/A

Data source: NTSB data from 1982 through 2022.
Notes: Includes month, year, and state fixed effects.

Since Terminal Doppler Weather Radars (TDWRs) were deployed in the 1990s to address low level wind shear at specific locations, we performed another robustness check by excluding areas that are within 60 nautical miles (nmi) of a TDWR. While the instrumented range of the TDWR is 55 nmi and velocity data is only provided to 48 nmi, we chose a conservative 60 nmi cutoff to account for the siting of TDWRs at some distance from the airports for which they provide warnings [115], [116]. The results of this robustness check are found in Table A-11. After excluding accidents that occurred in areas close to TDWRs, we still found a statistically significant impact of NEXRAD on weather-related general aviation accidents.

Table A-11. Results Excluding Areas within 60 nmi of a Terminal Doppler Weather Radar

Covariate	Coefficient	Standard Error	p-value
NEXRAD Coefficient of Interest	-0.25	0.038	< 0.001
Treatment	-2.4	0.029	< 0.001
Number of Observations	49,200	N/A	N/A
Implied Reduction in Weather-Related Accidents in 2022	14.4	N/A	N/A

Data source: NTSB data from 1982 through 2022.
Notes: Includes month, year, and state fixed effects.

Finally, since NEXRAD's primary application for aviation is to support navigation during adverse weather conditions, we would not expect it to impact non-weather-related general aviation accidents. Table A-12 presents the results from an additional robustness check based on our primary regression, in which we changed the treatment group to non-weather-related accidents within 60 km of a NEXRAD site. As expected, we found that there is no statistically significant impact of NEXRAD on these non-weather-related accidents ($p = 0.909$).

Table A-12. Impact of NEXRAD on Non-Weather-Related General Aviation Accidents

Covariate	Coefficient	Standard Error	p-value
NEXRAD Coefficient of Interest	-0.002	0.021	0.909
Treatment	-0.86	0.017	< 0.001
Number of Observations	50,184	N/A	N/A

Data source: NTSB data from 1982 through 2022.
Notes: Includes month, year, and state fixed effects.

Appendix B Abbreviations and Acronyms

Term	**Definition**
AIRMET	Airman's Meteorological Information
ARTCC	Air Route Traffic Control Center
ATC	Air Traffic Control
ATL	Atlanta International Airport
ATM	Air Traffic Management
AWC	Aviation Weather Center
AWD	Aviation Weather Display
AWW	Airport Weather Warning
CAASD	Center for Advanced Aviation System Development
CIWS	Corridor Integrated Weather System
COURL	Consolidated Observational User Requirements List
DOT	Department of Transportation
EAS	Emergency Alert System
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulations
FLASH	Flooded Locations and Simulated Hydrographs
FY	Fiscal Year
GDP	Gross Domestic Product
GeoXO	Geostationary Extended Observations
HRRR	High Resolution Rapid Refresh
IDEA	Investigate, Discuss, Estimate, and Aggregate
ITWS	Integrated Terminal Weather System
km	Kilometers
LLWS	Low-Level Wind Shear
log	Natural Logarithm
MAIS	Maximum Abbreviated Injury Scale
MITRE	The MITRE Corporation
MRMS	Multi-Radar, Multi-Sensor
MSA	Mission Service Area
NAM	North American Mesoscale

Term	**Definition**
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NEXRAD	Next Generation Weather Radar
nmi	Nautical Miles
NOAA	National Oceanic and Atmospheric Administration
NSSL	National Storm Systems Laboratory
NTSB	National Transportation Safety Board
NWP	Numerical Weather Prediction
NWR	NOAA Weather Radio
NWS	National Weather Service
OPSNET	Operations Network
PRSSO	Performance, Risk and Social Science Office
SIGMET	Significant Meteorological Information
TDWR	Terminal Doppler Weather Radar
TPIO	Technology, Planning, and Integration for Observation
USAF	U.S. Air Force
USDA	U.S. Department of Agriculture
VSL	Valuation of a Statistical Life
WARP	Weather and Radar Processor
WEA	Wireless Emergency Alert
WoFS	Warn-on-Forecast System
WSR-54	Weather Surveillance Radar, 1954
WSR-77	Weather Surveillance Radar, 1977
WSR-88D	Weather Surveillance Radar, 1988 Doppler