AEROSPACE REPORT NO.
ATR-2021-00933

GOES-R Socioeconomic Benefits Study: Phase I – Hurricane Products

May 3, 2021

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Prepared for:

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Contract No. 80GSFC19D0011

Authorized by: Civil Systems Group

PUBLIC RELEASE IS AUTHORIZED.

Acknowledgments

We especially thank two NOAA offices:

- NOAA Office of the Chief Economist, led by Monica Grasso, for their generous and expert review of, comments on and recommendations for this report, and
- NOAA/NESDIS/OPPA/Office of Technology, Planning, and Integration for Observation (TPIO) NOAA Observation Systems Integrated Analysis II (NOSIA II) Team, led by David Helms, for their sharing of data and ideas and their continuing cooperation to help understand the potential use of their NOSIA 2.1 GOES-R data in our study Phase 2.

We furthermore especially thank Renato Molina, David Letson, Brian McNoldy, Matthew Varkony of the University of Miami, and Pallab Mozumder of Florida International University for access to their draft manuscript on their valuation study and additional help on the population distribution used in their analysis.

We also thank the following people and organizations for their contributions to this pathfinder phase of our study and to this intermediate report:

- Thomas J. Cuff, Jordan J. Gerth, Brian S. Gockel, Joseph K. Zajic and Lee A. Byerle: NWS/Office of Observations (OBS) and NWS TOWER-S Lab, Silver Spring MD.
- Timothy J. Schmit, Meteorologist, NESDIS/STAR/CRPD, Advanced Satellite Products Branch (ASPB), University of Wisconsin, Madison WI
- Dan T. Lindsey, GOES-R Chief Scientist, NESDIS / NOAA Cooperative Institute for Research in the Atmosphere, Colorado State University, Fort Collins, CO
- John A. Knaff, NESDIS Center for Satellite Applications and Research, CRPD/RMMB, CIRA, Fort Collins CO
- Michael J. Brennan, Chief, Hurricane Specialist Unit Branch, NWS National Hurricane Center (NHC), Miami FL
- Daniel P. Brown, Senior Hurricane Specialist/WCM, Hurricane Specialist Unit Branch, NWS National Hurricane Center (NHC), Miami FL
- John D. Murphy, NWS Chief Operating Officer, Silver Spring MD
- NWS Satellite Applications Workshop, NWS Training Center, Kansas City MO, July 2019.
- NWS Aviation Weather Center: Amanda Terborg and Steven Silberberg.
- 2019 AMS-NOAA-EUMETSAT Joint Satellite Conference Short Course: Significant Hazards Satellite Applications, 29 Sept 2019.
- Greg Hansen, Paul Schletter and Todd Dankers: Denver-Boulder CO Weather Forecast Office
- Kathy Lantz, Meteorologist-Contractor; Steve Weygant, Meteorologist; Irina Petropavlovskiku, Scientist-Contractor; and Lori Bruhwiler, Physical Scientist: NOAA's Earth System Research Laboratory Global Monitoring Division, Boulder, Colorado
- Sue Haupt, Tim Schneider, Will Cheng, Jake Liu, Francois Vandenberghe, Cathy Kessinger, Pedro Munoz, Christopher Rozoff and Tyler McCandless and William Maloney: National Center for Atmospheric Research (NCAR/UCAR): NCAR is sponsored by the National Science Foundation (managed by the University Corporation for Atmospheric Research), Boulder CO:
- NWS Weather Forecast Offices (WFOs) and personnel including:

- Joseph DelliCarpini, John Metz, Chris Brenchley, Joshua J. Schroeder, Mike Buchanan, Jeffrey Medlin, Dave Radell, Michael Colby
- Wilmington NC; New York/Upton NY; Boston MA; Mobile AL; Brownsville TX; Honolulu HI; Corpus Christi TX
- NOAA Pacific Region/Honolulu WFO/Central Pacific Hurricane Center (CPHC), Honolulu HI – Ray Tanabe – Regional Director
- Pam Sullivan, Alexander Krimchansky, Ed Grigsby, Craig Keeler, Richard Rivera, Matthew Seybold, and members of the GOES-R Program Office and GOES-R System Engineering team

Preface

As this analysis and report was nearing completion, Hurricane Laura made landfall as a Category 4 hurricane near Cameron, Louisiana. We include a brief discussion of Laura as it shows the importance of GOES-R data and information in the hurricane forecast and warning process. Although it is impossible to know what the impacts of Laura would have been without the information provided by GOES-R, it seems certain that the overall high quality of hurricane warning system in the US and throughout the Caribbean provided significant benefits as people prepared for, endured, and continued to recover from the hurricane's devastation.

Based in part on GOES-R observations (Figure 1 and Figure 2), the NWS National Hurricane Center track and intensity forecasts showed the potential vulnerability to Laura across large portions of the south, central, and eastern United States (Figure 3).

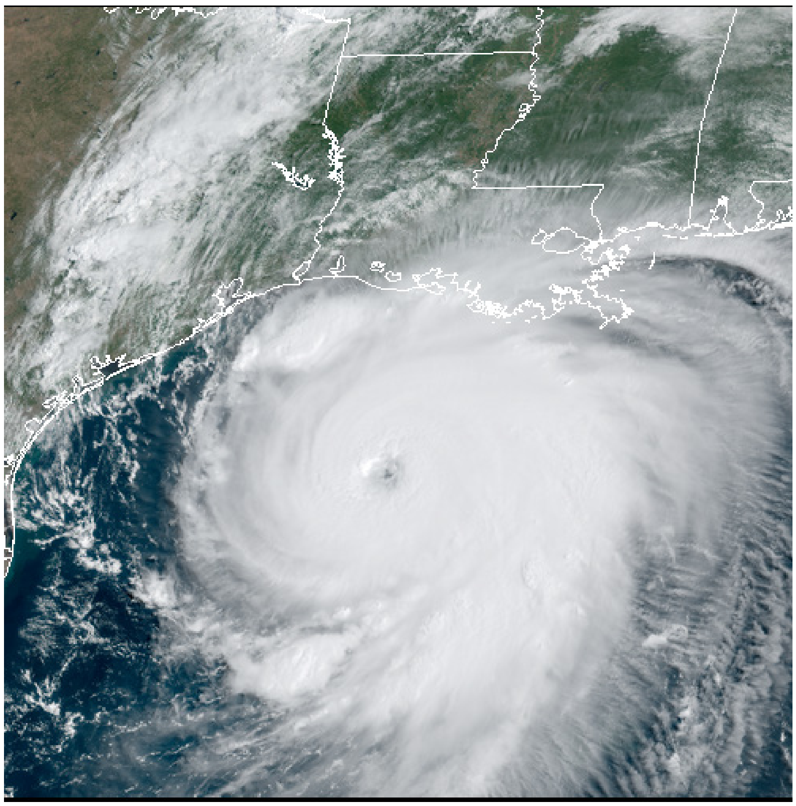

Figure 1. Hurricane Laura – Prior to U.S. landfall.
(August 2020, GOES-16 (NOAA/CIRA.)

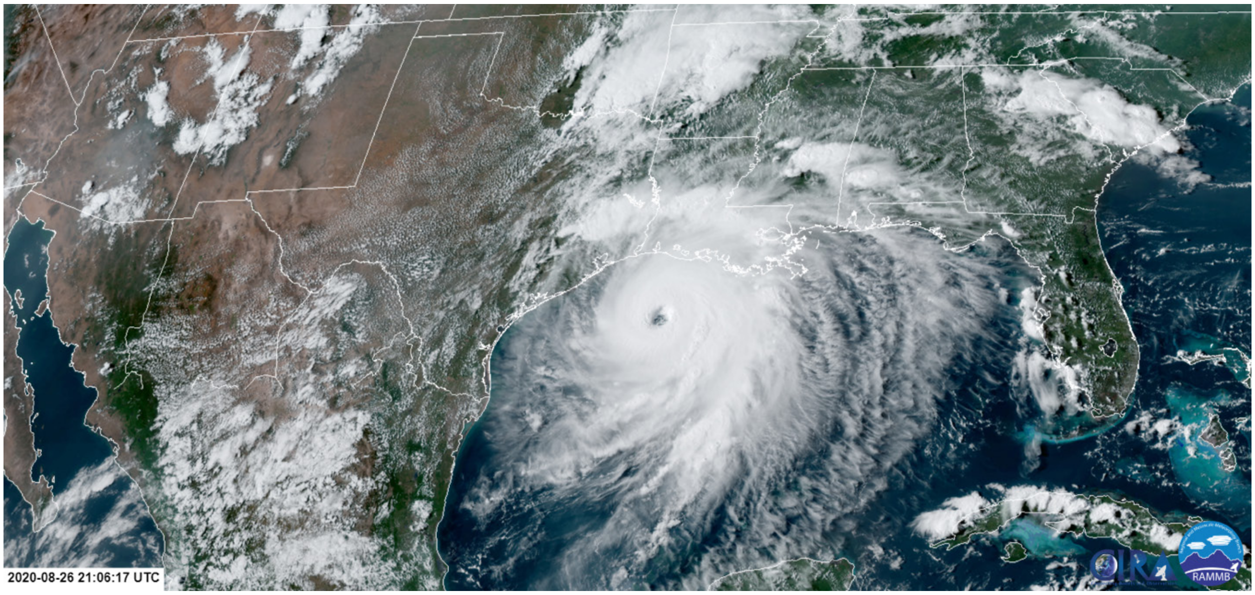

Figure 2. GOES-R imagery of Hurricane Laura before landfall.
(Source: https://rammb-slider.cira.colostate.edu/. GOES-16 CONUS with GeoColor (CIRA) 2020-08-26 21:26:17 UTC. From the Satellite Loop Interactive Data Explorer in realtime (SLIDER).)

As the forecast graphic from August 26, 2020 shows (Figure 3), Hurricane Impacts can extend far inland (and even re-emerge into other coastal areas!).

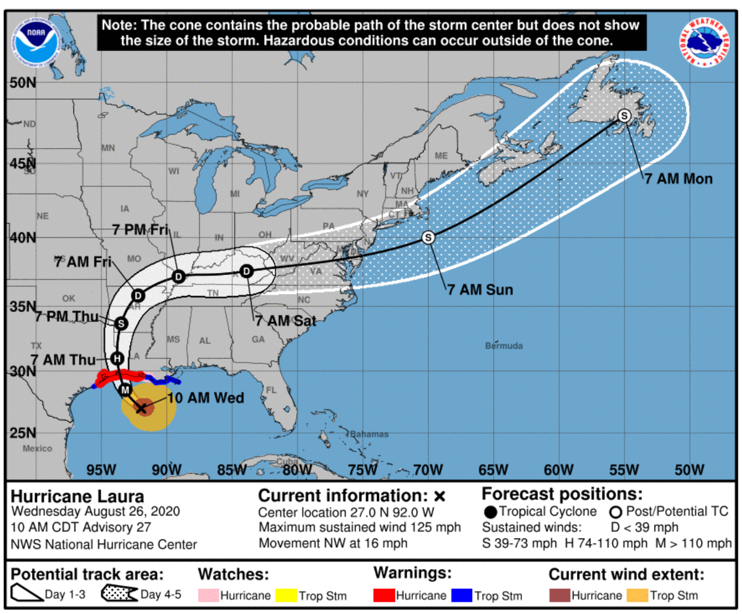

Figure 3. Hurricane Laura – forecast from August 26, 2020 – Coastal Watches/Warnings and Forecast Cone for Storm Center.
(Source: https://www.nhc.noaa.gov/refresh/graphics_at3+shtml/091953.shtml?cone - contents. Accessed August 26, 2020.)

Hurricane Laura made landfall on Thursday August 27 in southwestern Louisiana, near Cameron, as a high-end Category 4 hurricane with maximum winds of 150-mph. Peak wind gusts of 133 and 130-mph were reported in southern Louisiana, with winds from the northern portion of the eyewall destroying the NWS weather radar[1] in Lake Charles, LA.[2] Laura then moved across Louisiana and Arkansas with significant impacts from heavy rains and strong winds. As Laura continued inland, it weakened to a tropical storm and then eventually a tropical depression as it moved north and east. Maximum sustained winds (at 2100 UTC 27 August) were still at 50 mph.[3] As a tropical depression, Laura moved across Kentucky and Tennessee, and across the Virginias as it moved to the Mid-Atlantic region. Laura triggered Flash Flood Watches in northeast Arkansas, southeast Missouri, western Kentucky and Tennessee, northern Mississippi, and northwest Alabama[4]. Hurricane Laura rapidly intensified as it traversed the Gulf of Mexico, moving from Category 1 to Category 4 within twenty-four hours, with a 65-mph wind speed increase. On Friday August 28, the tropical depression, with maximum sustained winds of 30 mph, still triggered Flash Flood Watches in portions of the Tennessee Valley and Mid-Atlantic States.[5] Laura continued eastward toward the coast before becoming a remnant low with diminished heavy rainfall and flash flood threats before emerging into the northwest Atlantic.[6]

Laura after-effects are examples of hurricane and post-tropical impacts that move beyond coastal counties in the U.S. to cover a wide swath of states before dissipation or moving out to sea. The preliminary impacts from Laura include at least 71 fatalities and over $8.9 billion in damages across the Lesser and Greater Antilles, The Bahamas, and Gulf Coast, Midwestern, and Eastern areas of the United States.[7] This includes one fatality in Florida, 27 in Louisiana, and 8 in Texas. The U.S. experienced over $8.7 billion in insured damages that do "not include National Flood Insurance Program (NFIP) losses, or any losses suffered to offshore assets." (Evans 2020).

Observations of Hurricane Laura included "satellite imagery, weather observations, radar and meteorological analysis." (Konarik 2020). Satellite observations not only supplement ground-based observations but are even more critical in situations where ground-based instruments may fail or be damaged as during Hurricane Laura when "the weather radar in both Lake Charles and Fort Polk failed." (Stewart 2020). GOES-R imagery captured the complete cycle of formation, landfall, and dissipation of Hurricane Laura. (Line 2020).

In this Phase 1 report we examine the benefits to hurricane vulnerable populations of improved hurricane forecasts and information attributable to data and information from the GOES-R satellite series. As Hurricane Laura shows, this is not simply a matter of monetary impacts but the importance of such information (as stated in the Mission Statement of the National Weather Service) for "the protection of life and property and enhancement of the national economy."[8]

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1 https://twitter.com/rivera_ariel/status/1299054249322483715.

2 https://cimss.ssec.wisc.edu/satellite-blog/archives/38100.

3 All historical files on Hurricane Laura may be found on the Internet at https://www.nhc.noaa.gov/archive/2020/LAURA.shtml. This 50-mph reference from Wind Speed Probabilities Report 32, National Hurricane Center 27 Aug 2020.

4 Tropical Depression Advisory 35, Friday August 28, 2020 Weather Prediction Center.

5 Tropical Depression Advisory 37, Friday August 28, 2020 Weather Prediction Center.

6 Post-Tropical Cyclone Laura, Advisory 38, Saturday August 29, 2020, Weather Prediction Center.

7 https://en.wikipedia.org/wiki/Hurricane_Laura Accessed September 11, 2020).

8 https://www.weather.gov/about/ Accessed September 11, 2020.

Executive Summary

The Aerospace Corporation Civil Systems Group (CSG) Civil Spectrum Management branch[9], was requested by the GOES-R (Geostationary Operational Environmental Satellite – R Series) Systems Program Office, to undertake the task of performing a socioeconomic benefits study of the GOES-R Series system using the previous system, GOES N-O-P, as the counter factual. Under this task, an Aerospace Corporation team (consisting of an engineer, a meteorologist, and an economist) was to determine the socioeconomic public and private benefits of the GOES-R Series system in both unquantifiable and quantifiable terms for a limited number of National Weather Service (NWS) products whose percentage of contributions from GOES-R data could be readily determined.

In the first phase of this study, the team selected an NWS forecast product area as a Pathfinder for which there was significant monetary and human value from the GOES-R data contribution. The primary purpose of this Pathfinder phase was to identify and demonstrate a credible process and methodology for determining additional GOES-R benefit values.

The team undertook a number of visits to various NOAA and non-NOAA agencies and participated in several forecaster satellite-use workshops to narrow down the Pathfinder product area and to learn which GOES-R data and products were most important/valuable to the NWS forecasters. The area of Hurricane products was then chosen for this Pathfinder effort.

The Aerospace Corporation engaged Dr. Jeffrey Lazo, an environmental economist as an outside consultant for the team. Besides his many publications and studies, Dr. Lazo brought previous work in valuation of Hurricane forecasting which allowed us to build on relevant existing economic assessment surveys and data.

Primary economic methods and concepts used for this Pathfinder phase were the (1) Weather Information Value Chain (WIVC), (2) Willingness-To-Pay (WTP), (3) benefits transfer, and (4) a modified expert elicitation interview protocol.

1. Weather Information Value Chain: The WIVC is a conceptual model of the creation, communication, use, and value of hydrometeorological information used in the current analysis to articulate the process from GOES-R observations through to end-user benefits. This model is used to frame and discuss value creation across project participants to ensure consistency and enhance the validity and reliability of economic benefit estimation.
2. Willingness-to-pay (WTP) is the maximum amount an individual is willing to pay to ensure that a welfare-increasing activity takes place. WTP is not a measure for advocating charging for weather information. Rather, it is the theoretically correct economic valuation measure for a non-market commodity such as weather information.
3. Benefits transfer is the process of adjusting benefit estimates from a prior WTP study to the current context to avoid having to undertake a new primary benefits study. We relied on three existing studies of the economic value of improved hurricane forecasts to members of the general public to adjust and transfer to the current analysis.
4. The modified expert elicitation interview protocol undertook data collection from Federal research and operational hurricane forecast experts to determine what percent of the improvements in hurricane forecasts could be attributed to GOES-R information.

The team authored questions and received NWS inputs and approvals on the interview protocol content and subsequently sent out the protocol to U.S. coastal NWS Weather Forecast Office (WFO) forecasters

[9] Under NSEETS Contract # 80GSC19D0011.

for their voluntary participation. Nine respondents provided input which was compiled and then distributed to the respondents to elicit whether they wanted to update or revise their initial estimates based on the group responses. All nine respondents provided follow-up responses although some did not change their initial estimates. From the follow-up nine responses, the team derived an estimate of the percentage of GOES-R contributions to specific Hurricane products: Landfall timing, Landfall location, Landfall Wind Strength and Storm Surge Magnitude. The team used an average of estimates from three existing economic studies to derive a baseline estimate of per household willingness-to-pay (WTP) value for improved hurricane forecast products. This average was multiplied by the percent attributable to GOES-R derived from the WFO interview protocol to derive a WTP for improved forecasts attributable to GOES-R. Using this per household GOES-R attributable WTP an aggregate Present Value Benefits was then derived taking into account:

- coastal and inland counties population.
- number of households.
- rate of coastal and inland population increases.
- rate of increase of per capita GDP.
- real prices (accounting for inflation implicitly).
- real rate of discount.
- and a GOES-R mission lifetime (in accordance with published NOAA Satellite Fly-Out Charts).

As a baseline estimate, over its lifetime, GOES-R will generate **$9.27B** in benefits from improved hurricane forecasting to the US hurricane-prone public (with a 90% confidence interval of **$5.39B** to **$13.14B** related to uncertainty in attribution of benefits to GOES-R from the interview protocol results). Table 1 shows the benefit estimates using the baseline parameters as well as a range of sensitivity analysis.

Table 1. GOES-R Hurricane Products Benefits Uncertainty and Sensitivity

Analysis Scenario (baseline parameters as indicated in Table 17)	**Present Value**	**Lower bound small sample 90% confidence interval**	**Upper bound small sample 90% confidence interval**
Baseline – Discount Rate - 0.300%	**$9.27B**	**$5.39B**	**$13.14B**
Discount Rate - 1.185%	**$8.36B**	**$4.86B**	**$11.85B**
Discount Rate – 3.000%	**$6.85B**	**$3.98B**	**$9.71B**
Discount Rate – 7.000%	**$4.68B**	**$2.72B**	**$6.64B**
No population increases (DR – 0.3%)	**$8.18B**	Not Calculated	Not Calculated
No wealth increase (DR – 0.3%)	**$7.82B**	Not Calculated	Not Calculated

It is noteworthy to mention that: (1) the interview protocol results do not represent a large number of forecaster responses and therefore entails a large degree of uncertainty, and (2) since these results are a strong indicator of GOES-R economic benefits value for only one weather focal area of NWS products and services ($9.27B present value for hurricane forecast improvements applied to less than half of the U.S. population), it seems reasonable to expect that the total present value of GOES-R economic benefits for all forecasts and products (e.g., for tornadoes, winter storms, droughts, flooding, fire weather, lightning, and even “normal weather”) to which it contributes data would possibly be significantly more.

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1. Introduction and Background

1.1 Objectives

1.1.1 Overall

The overall objective of this study is to perform a socioeconomic benefits study of the Geostationary Operational Environmental Satellite– R Series (GOES-R) satellite to determine public benefits and economic impacts on selected user sectors.[10]

1.1.2 This Phase

The objective of this first phase of the study is to undertake a "Pathfinder" initial effort to demonstrate methods for quantifying public benefits of GOES-R-related improvements in hurricane forecasts.

1.1.2.1 Goals of the Pathfinder Process

- Develop and refine a set of interview protocol questions through interviews and elicited feedback from GOES-R researchers, forecasting experts, and other stakeholders.
- Explore a given product area with GOES-R contributions: Hurricanes.
- Solicit data from Federal forecasters.
- Use pre-existing economic data to scale up to the GOES-R contribution percentage across the relevant population segment.
- Aggregate the present value benefits.
- Demonstrate a credible and cogent process for quantifying public benefits of GOES-R-related improvements in (hurricane) products and forecasts.

1.2 GOES-R Background Information

1.2.1 GOES-R Background and History

These statements are overall descriptions of the GOES systems and the current GOES-R series of satellites:

> "Since 1975, Geostationary Operational Environmental Satellites (GOES) have "provided continuous imagery and data on atmospheric conditions and solar activity (space weather)."[11]
> "The Geostationary Operational Environmental Satellite (GOES) – R Series is the nation's most advanced fleet of geostationary weather satellites."[12]

Figure 4 provides a timeline of GOES from 1975–2016.

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[10] Throughout this report we refer to GOES-R as the GOES-R Series which is a four-satellite program including GOES-R, GOES-S, GOES-T and GOES-U. See https://www.goes-r.gov/mission/mission.html. Accessed April 14, 2020.

[11] https://www.goes-r.gov/mission/history.html. Accessed April 14, 2020.

[12] https://www.goes-r.gov/. Accessed April 14, 2020.

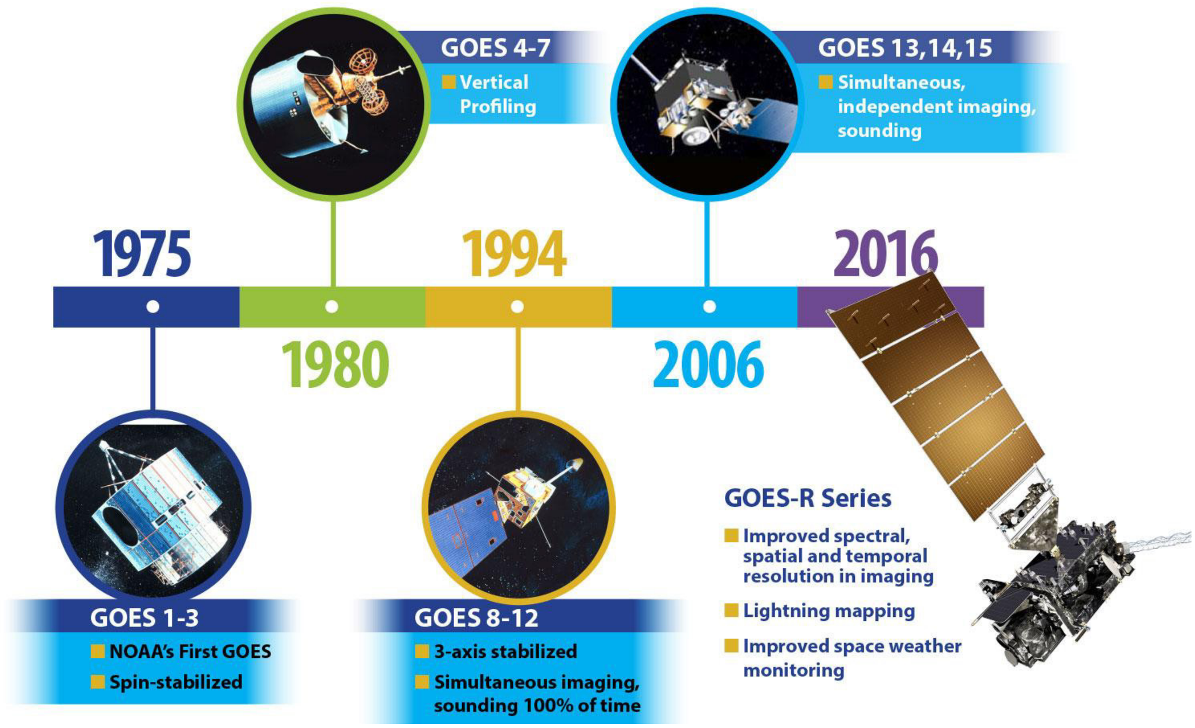

Figure 4. GOES-R history 1995–2016.
(Figure from https://www.goes-r.gov/mission/history.html. Accessed April 14, 2020.)

1.2.2 GOES-R Series Description and Functions

1.2.2.1 GOES-R Series Spacecraft Launched to Date

Table 2 provides the designators, positions, and operational dates of the two GOES-R series spacecraft launched to this date, GOES 16 and GOES 17.

Table 2. GOES-R Series Spacecraft Launched to Date: Designators, Positions, and Operational Dates.

Pre-Launch Spacecraft Designator	Post-Launch Spacecraft Designator	Operational Position:	Operational Date:
GOES-R	GOES 16	East	12/18/2017
GOES-S	GOES 17	West	2/12/2019
GOES-T	Assumed GOES 18	TBD	Planned 2022
GOES-U	Assumed GOES 19	TBD	Planned 2025

Table 3 provides the Pre and Post launch designators for NOAA's Geostationary satellites. Prior to launch, satellites are assigned an alphabet letter. Once they arrive at geostationary orbit, they are re-designated with a number. Table 19 contains the information on all GOES satellite designations and status including those that are decommissioned from NOAA satellite service. GOES-13 has been transferred to another US government agency. Yellow-shaded satellites in the second column are used for backup operations for on-orbit storage as of the date of this writing. Current information may be found at https://www.ospo.noaa.gov/Operations/GOES/status.html

Table 3. GOES-R Series Pre- and Post-Launch Designators

Pre-Launch Spacecraft Designator	Post-Launch Spacecraft Designator	Pre-Launch Spacecraft Designator	Post-Launch Spacecraft Designator
GOES-I	GOES-8	GOES-O	GOES-14
GOES-J	GOES-9	GOES-P	GOES-15
GOES-K	GOES-10	GOES-R	GOES-16
GOES-L	GOES-11	GOES-S	GOES-17
GOES-M	GOES-12	GOES-T	To Be Assigned
GOES-N	GOES-13	GOES-U	To Be Assigned

See Table 29 for a complete list of all GOES satellite designations and status.

1.2.2.2 GOES-R Instruments

GOES-R has an impressive array of advanced-technology instruments including the Advanced Baseline Imager (ABI), Geostationary Lightning Mapper (GLM), and a suite of space environment sensors. For a more detailed description of these instruments, see Appendix 8.1: New GOES-R Products and Services. The GOES-R System provides both atmospheric, terrestrial and space environment products. See Appendix 8.6 New GOES-R Products and Services for a complete list.

- Level 1b Products: The GOES-R ABI provides over 20 products, the three GLM products, and the nine Space Environment Suite products. See Appendix 8.6.1, Table 24 for a complete list.
- Level 2+ Products: The GOES-R ABI provides 25 products and the GLM three. See Appendix 8.6.2, Table 25 for a complete list.
- Transition from GVAR to GRB: The transition from the GOES Variable (GVAR) data broadcast system in the previous GOES series to the GOES Rebroadcast (GRB) data broadcast system in the GOES-R series has provided significant improvements to the amount, timeliness and volume of the data for users. See Appendix 8.6.3, Table 26 for specific details.

1.2.3 GOES-R Improvements Over Previous GOES Series

Overall, the improvements in GOES-R over the previous series of GOES Satellite Systems are significant, many and of great importance to the user community. As shown in Figure 5 (from Holmlund and Goldberg 2019), the imager improvements are: three times more channels, four times better resolution and five times faster scans (NASA 2019). For a more-detailed description of all these improvements, see the figures in Appendix 8.7.

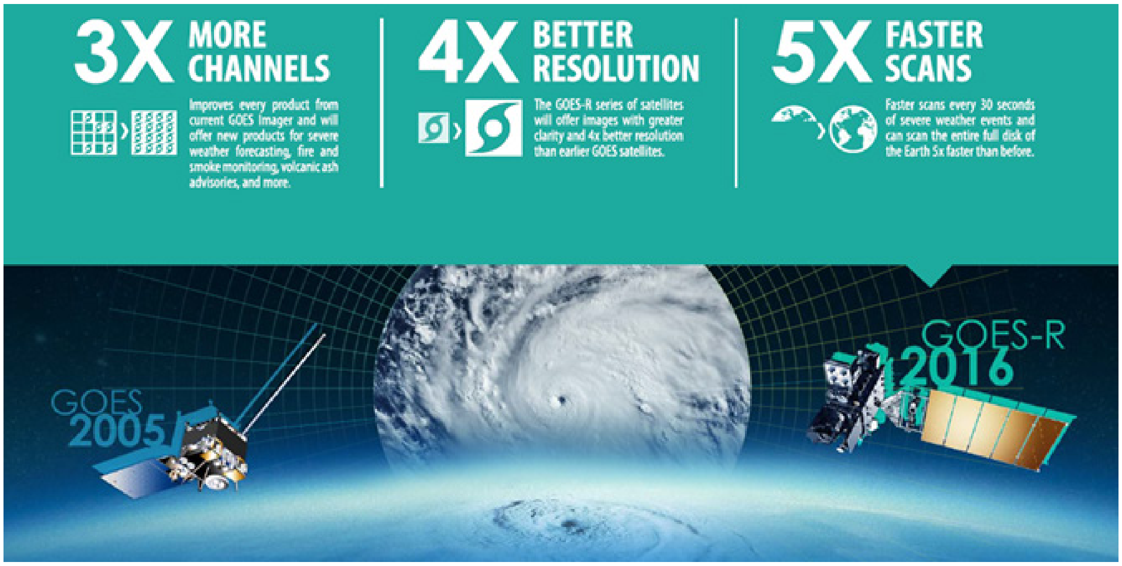

Figure 5. GOES-R primary improvements over GOES N-O-P.
(Source: Holmlund and Goldberg, 2019.)

1.2.3.1 GOES I-M, GOES N-O-P and GOES-R Performance Capabilities

The areas of GOES performance capabilities have seen an evolution of improvements since the GOES I-M series: Imaging (Visible & IR resolutions, full-disk coverage rates, and numbers of channels), Solar Monitoring, Lightning detection, and Raw data volume per spacecraft. Appendix 8.7.1, Table 27 shows Table 27: GOES Satellite Designations and Status. For a full list and side-by side comparison of the latest three GOES series, see Appendix 8.7.2, Table 28. The differences between the GOES N-O-P and GOES-R series instruments have been significant improvements and upgrades (Imagers, INR[13], Lightning Mapping, and Space Environment). For a full list and side-by side comparison of these instrument improvements, See Appendix 8.7.3, Table 29.

1.2.4 GOES-R Hurricane Tracking and Forecasting Improvements Over GOES N-O-P

GOES-R provides input information to hurricane nowcasting and forecasting over GOES N-O-P as bulleted below.[14]

- **Better data quality and faster scan speeds:** Higher-resolution GOES-R ABI visible and IR data, advanced Image Navigation and Registration (INR) and up to six times faster scan speeds improve tropical storms and hurricanes nowcasting and forecasting.
- **Improved tropical cyclone track and intensity forecasts:** The GOES-R ABI provides twice the image resolution in the visible and four times the resolution in the IR and up to six times the number of scans per hour for greater spatial and temporal resolution which contributes significantly to tropical cyclone track and intensity forecasts.
- **Increased warning lead times for severe storms:** For tropical storm- or hurricane-spawned Tornadoes, for example, the GOES-R ABI provides the greater (visible and IR) image resolution,

[13] INR is the Image Navigation and Registration. See https://www.ospo.noaa.gov/Operations/GOES/goes-inrstats.html. Accessed April 14, 2020. See also Kamel 1996.

[14] Much of the information in this comparison was provided to the research team by Dr. Daniel Lindsey, GOES-R Chief Scientist.

more-frequent number of scans per hour and Geostationary Lightning Monitor (GLM) data needed to help considerably increase warning lead times (nowcasting).

- **ABI and GLM provide weather-radar-like capabilities:** In combination, the GOES-R ABI higher-resolution visible and IR imagery and the GLM in cloud (IC) and cloud-to-cloud (CC) lightning data provide a virtual weather-radar-like capability for areas not reached by land-locked weather radars such as inter mountain and off-shore and open ocean areas (e.g. oil platforms).
- **ABI data[15] helps the National Hurricane Center (NHC) to significantly reduce the "Cone of Uncertainty":** The GOES-R ABI higher-accuracy, higher-resolution and more frequent data translates to enhanced NHC model inputs therefore reducing the width of the uncertainty cone in a probable track of the center of the hurricane and hence saves more lives, evacuation costs and resources.
- **Improved Atmospheric Wind Vectors (AMVs) or Derived Motion Winds (DMWs):** The main product communicator and model inputs are the Atmospheric Wind Vectors (AMVs) or Derived Motion Winds (DMWs) from the GOES-R ABI. "These high spatiotemporal AMVs represent estimates of the wind field around the storm and can provide critical dynamical information on the targeted storm and its near environment."[16] The GOES-R-derived DMW product provides key wind observations to operational numerical weather prediction (NWP) data assimilation systems where their use has been demonstrated to improved NWP forecasts including tropical cyclones.[17]
- **Dust in the Air:** Airborne dust (e.g., from Western Africa) actually tamps down Tropical Cyclones, especially over the South Atlantic Ocean, a primary development area for Gulf of Mexico and East-Coast U.S. tropical storms and hurricanes. The GOES-R ABI can see, display, and track that dust and substantially aid forecasters and models in predicting tropical storm and hurricane development.

1.2.5 GOES-R and GOES N-O-P Measures from NOSIA II and TPIO

The NOAA/NESDIS/OPPA/Office of Technology, Planning and Integration for Observation (TPIO) released the NOAA Observations Systems Integrated Analysis II (NOSIA II) in 2016 which, among many other things, provided a detailed analysis of how much the GOES N-O-P data contributed to the many NWS products. It was this analysis that aided our team in determining which set of products we would use in this Pathfinder phase of our study. In late 2019 through early 2020, TPIO initiated a refresh of NOSIA II (2.1) to account for the improvements provided by the GOES-R Series. At the time of writing this report, those results for GOES-R were not yet available nor releasable.

[15] Other space sensors/systems and inputs also support Hurricane models. This report focuses only on the contribution from ABI data.

[16] Li, J., Li, J., Velden, C., Wang, P., Schmit, T. J., & Sippel, J. (2020). Impact of rapid-scan-based dynamical information from GOES-16 on HWRF hurricane forecasts. Journal of Geophysical Research: Atmospheres, 125, e2019JD031647. https://doi.org/10.1029/2019JD031647.

[17] https://www.goes-r.gov/products/baseline-derived-motion-winds.html. Accessed April 22, 2020.

2. Value Chain Approach

A "value chain approach" is used in this analysis for characterizing the creation, communication, use, and value of weather (hurricane) information, forecasts, and warnings. The purpose of articulating the value chain is so the researchers and project participants understand conceptually the value creation process and can use this tool to discuss and articulate socio-economic values. Further, the value chain is useful to ensure that valuation studies reflect an accurate understanding of the connections between NOAA activities, products and services, end-user decisions, societal outcomes, and economic measures. In the following sections, to develop the value chain approach we 1) started with a conceptual framework previously used to present weather information value chains[18]; 2) discuss how this is also related to approaches used in other NOAA information value studies; and 3) discuss how this was operationalized in this study with respect to hurricane information products related to GOES-R data sources.

2.1 The Weather Information Value Chain

Figure 6 presents a conceptual model of a "Weather Information Value Chain" (WIVC) (Lazo 2018b). Dr. Lazo has been developing and advocating the value chain approach to assessing and understanding the weather information process for several years along with others working with the World Meteorological Organization (WMO), the U.S. National Weather Service (NWS), and others (Haupt et al., 2018; WMO 2015). As shown in Figure 6, in this process, hydrological, climatological, and meteorological systems (called "hydromet" forthwith) are observed and modeled and forecasting and warnings created – generally by national meteorological and hydrological services (NMHS) such as NOAA's National Weather Service (NWS) in the United States. This information is then disseminated through multiple channels and potentially enhanced or formatted for specialized applications by secondary information providers (e.g., private weather services, media channels such as television, internet and radio) and communicated to end-users. Different information processes may also include other intermediaries such as emergency managers, specific Federal, state, or local agencies (e.g., public health services), or specific sectoral stakeholders (e.g., energy, transportation or energy companies). End-users may (or may not) then use this information to make decisions about uncertain future hydrometeorological events. It is within the context of information improving or changing the decisions of end-users, that economists would argue there is actual or potential economic value to this information.

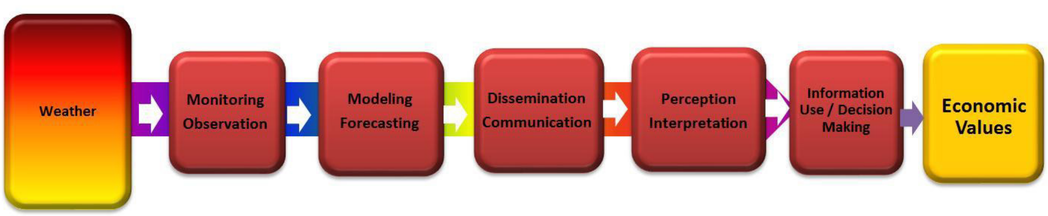

Figure 6. Weather Information Value Chain.
(Source: Lazo 2018b.)

The economic **impacts** of weather are "outcomes" that occur with the actualization of weather events (which is not causally related to weather information) and the decisions made by end-users. The **value of weather information** is in informing end-user decisions to change outcomes potentially for the better in light of uncertainty (e.g., improve benefits or reduce damages or costs). Weather information has *ex ante*

18 See for instance https://www.7thverificationworkshop.de/Presentation/tutorial_topic2_assessing_value_of_forecasts.pdf.

value, and the economic impacts of weather are *ex post* measures of weather occurrences – not of information.

By *ex ante* we mean "before" the actualization of the weather event and *ex post* means "after." Information thus has value to assist in decision making before the event occurs. Economic impacts of weather are a result of the weather event that actually occurs and are thus after, or *ex post*, event measures. Weather information or data may also have value ex post for instance in analyzing causes of traffic accidents, but this is not "value-of-information" in the sense of information ex ante decision making. (Perrels et al., 2015)

To ensure that value estimates of hydromet information from economic studies are valid and reliable, it is essential to appropriately characterize study-relevant links along the information value chain process and apply meaningful information quality measurements (Stvilia et al., 2007). Connecting measures of information quality to end-user decisions ensures that benefit estimates are indicative of actual socio-economic welfare improvement. The degree of rigor necessary in developing, characterizing, and quantifying the process depends ultimately on the purpose of the economic study and the use of the resulting value estimates.

2.2 NOAA Fleet Study Approach Example

In undertaking the current project, we built our approach on the weather information value chain concept as well as work undertaken by Abt Associates and Corona Environmental Consulting in their 2018 report on the societal benefits of the NOAA fleet (Abt and Corona, 2018). In the NOAA "Fleet Study," Abt characterized each benefit assessed with a value chain and then quantified a benefit based on methods consistent with the specific information process. Figure 7 shows Abt's general value chain framework for the Fleet Study.

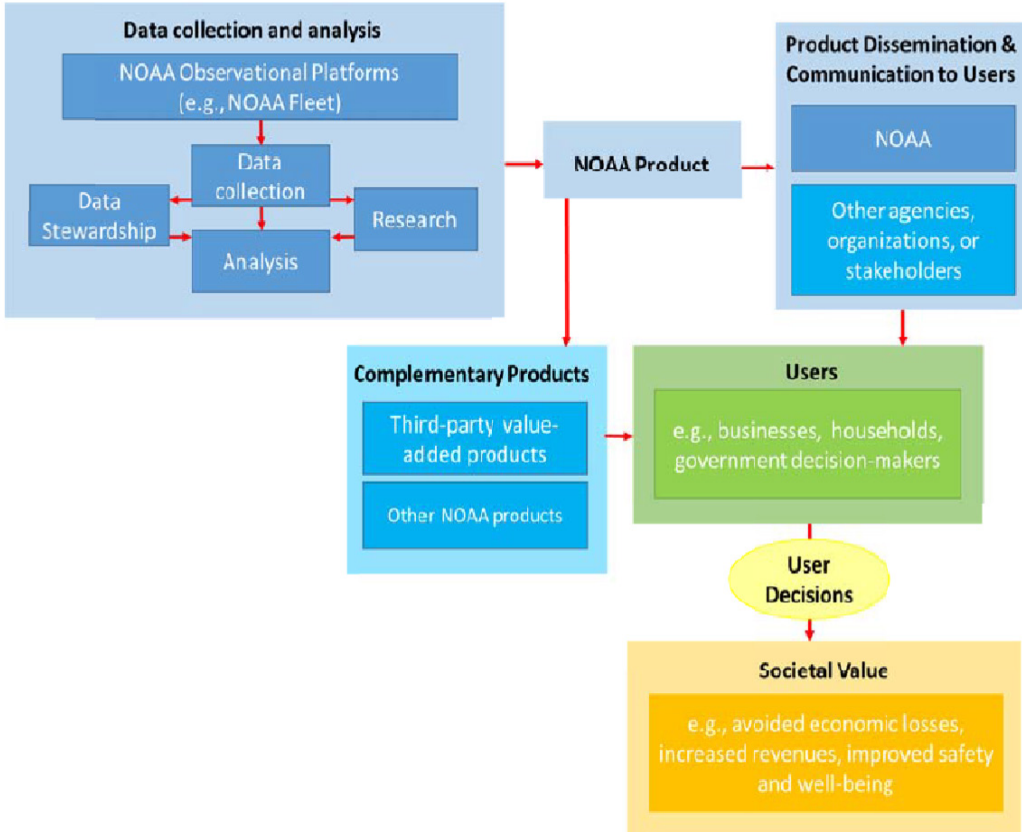

Figure 7. NOAA fleet products and services benefits study value chain model.
(Source: Figure 2 from Abt and Corona 2018, p.4.)

2.3 GOES-R Related Hurricane Information Value Chain

Building on the prior Lazo 2018b work and the Abt NOAA Fleet study framework we developed a general schematic of the value of GOES-R products and services. Preliminary versions were reviewed by GOES experts and adapted to include in the interview protocol with the forecasters (see Section 8.8). This was further adapted to indicate the hurricane information process as shown in Figure 8. The hurricane information model includes more specificity with respect to processes outside of NOAA than were indicated in the Abt models for the Fleet Study (Figure 7). Developing a better understanding of information intermediaries including emergency managers, broadcast meteorologists, and private sector meteorologists is critical to enhancing societal value as the vast majority of the public does not obtain their information directly from NOAA but rather through some sort of intermediary who may enhance or supplement that information (Bostrom et al., 2016; Morss et al., 2016; Lazo et al., 2015; Demuth et al., 2012; Lazo et al., 2009).

It is important to note as well as shown in Figure 8 that there are numerous potential endpoints for assessing the socio-economic value of any weather information process. For the current study we focus on members of the general public. Other endpoints such as energy, transportation, or environmental impacts could also be assessed and may require different benefit assessment methods and different characterizations of the types of information use. If evaluating multiple end points, it is also important to avoid double counting of benefits (see Brent 1994).

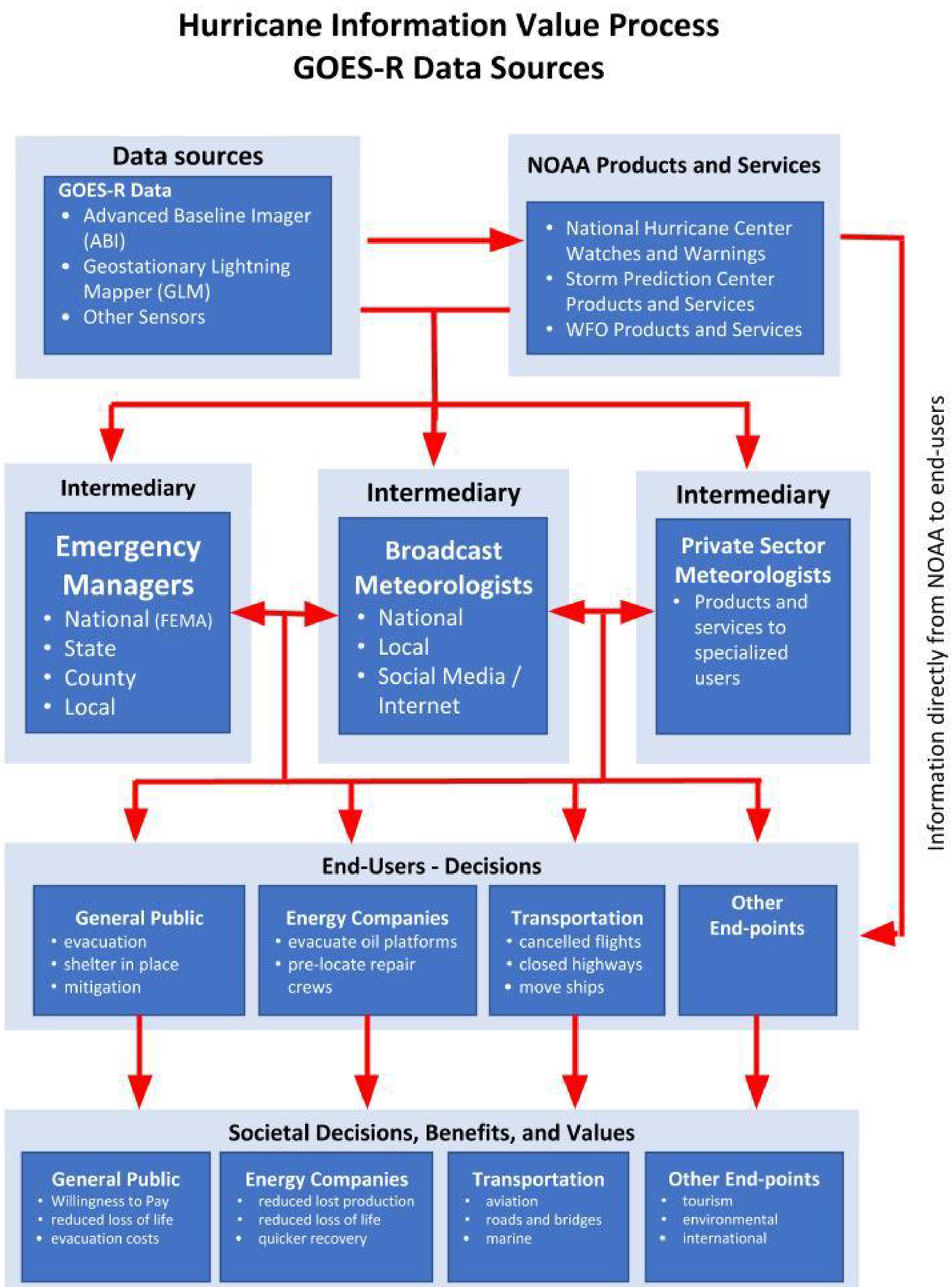

Figure 8. GOES-R hurricane information value chain model.

3. Methods

This analysis primarily combines two approaches supported by extensive meetings, interviews, and input from GOES experts, weather forecasters, existing literature, and researchers. The primary efforts are (1) a modified "expert elicitation" from forecasters on the percent of improvements in hurricane forecasting attributable to GOES and (2) transferring benefit (i.e., benefits transfer) estimates from prior economic analysis of household's willingness-to-pay for improvements in hurricane forecasts. These methods were chosen and implemented to demonstrate the feasibility of such benefit estimation while also constraining the research to available resources in terms of time for data collection. We chose the benefits transfer approach as this allows us to use existing benefit information rather than undertaking a new benefits study which would be more expensive and take considerably more time.[19] A primary study using a survey approach would have required OMB approval under the Paperwork Reduction Act and there is no certainty that this would even have been feasible considering the lead-time needed for approval, and potential complexity of the approval process.[20]

3.1 Expert Elicitation

A key aspect of the current study is to provide evidence attributing improvements in hurricane forecasts and warnings to contributions from GOES information and data. We are unaware of any specific study or models that identified this contribution that would be compatible with the valuation approach used and thus we undertook an "expert elicitation" to characterize and quantify this. As stated by Knol et al., 2010, "Formal expert elicitation is a structured approach to systematically consult experts on uncertain issues. It is most often used to quantify ranges for poorly known parameters but may also be useful to further develop qualitative issues such as definitions, assumptions or conceptual (causal) models." (Knol et al., 2010. p.1). As shown in Figure 9 (copied from Knol et al., 2010) the expert elicitation approach is a multi-step process to gather information from subject matter experts on the parameters of interest. Expert elicitation is related to the Delphi Method[21] which generally involves a follow-up step of re-elicitation of input from respondents to further refine the parameter estimates. We did implement a follow-up round of interviews as described below.

We implemented a modified expert elicitation using an "interview protocol" emailed to respondents rather than undertaking in-depth in-person interviews. This modification is based in part on prior work with national hydrometeorological services to assess the value of improvements (e.g., Lazo 2017; Lazo and Quiroga 2018). This approach also built on existing literature on GOES-R, interviews and discussions with GOES-R experts, and meetings with researchers at NOAA-ESRL and NCAR, and operational forecasters at the NWS Weather Forecast Office (WFO) in Boulder, Colorado. Section 4.3 describes this process step-by-step using the Knol et al., framework.

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[19] OMB notes that "Although benefit-transfer can provide a quick, low-cost approach for obtaining desired monetary values, the methods are often associated with uncertainties and potential biases of unknown magnitude. It should therefore be treated as a last-resort option and not used without explicit justification." OMB 2019. p.24. Although this suggests a limited role for benefits transfer, in reality it is extremely common to use some form of benefits transfer as much more rarely is primary research necessary or even funded given the more lengthy and expensive process of primary research.

[20] Under the PRA Federally funded survey efforts are required to undergo review by the Office of Management and Budget (OMB). Recent experience suggests that this process may take months if it is approved at all by OMB. See https://www.opm.gov/about-us/open-government/digital-government-strategy/fitara/paperwork-reduction-act-guide.pdf accessed April 20, 2020.

[21] As stated on the RAND website regarding the Delphi Method "The method entails a group of experts who anonymously reply to questionnaires and subsequently receive feedback in the form of a statistical representation of the "group response," after which the process repeats itself. The goal is to reduce the range of responses and arrive at something closer to expert consensus." https://www.rand.org/topics/delphi-method.html. Accessed April 7, 2020.

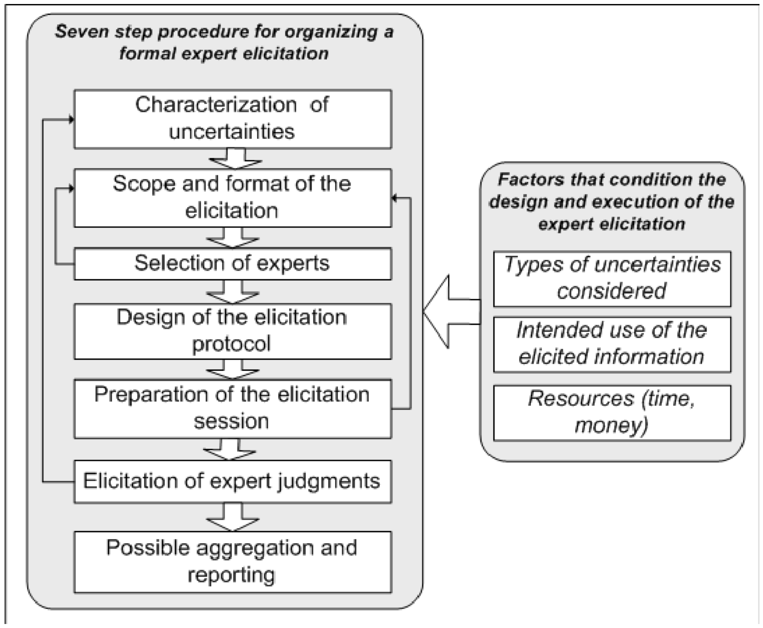

Figure 9. Seven step procedure for a formal expert elicitation.
(From Knol et al., 2010.)

3.2 Benefits Transfer

Benefit transfer is used to estimate economic values or benefits by "transferring" or applying available information from existing or prior studies conducted in one context to another similar context or valuation question (e.g., Rosenberger and Loomis 2003; Wilson and Hoehn. 2006).[22] The goal is to estimate benefits for a policy context by adapting an estimate of benefits from some other context. The method can be used if appropriate when it is too expensive, there is too little time, or it is too complex (e.g., other restrictions such as uncertainty of completion of a study under the Paperwork Reduction Act[23] (PRA)) to conduct an original or primary study. The accuracy will only be as good and no better than the original study depending on how closely matched the valuation contexts and the quality of the application of the "transfer." Benefit transfer is especially useful where a first order approximations of economic benefits are adequate for policy decisions. It may then be used to indicate the need for a primary study and help guide design and implementation of a primary study.

There is an extensive literature on benefits transfer methods that includes discussions of how to transfer benefit estimates accounting for differences in cultural and socioeconomic context (Dumas et al., 2005; Johnston et al., 2018; Johnston et al., 2015; Rosenberger and Loomis 2003). Adjusting values estimates often includes accounting for differences in the change of economic impact or policy context; different socioeconomic characteristics of the household; or differing characteristics or the valued goods and services. This includes transferring estimates between countries and across different populations. In the current study we are applying the benefit estimates in essentially the same policy context; to essentially the same population as the original studies (residents of coastal hurricane vulnerable areas of the United States); and the same goods and services (improving hurricane forecast and warning information). Therefore, the application of benefits from the three WTP studies used in this analysis (Lazo et al., 2010, Molina et al., 2020, and the WDEWE analysis (n.d.)) to the current context is relatively straightforward

[22] See http://www.ecosystemvaluation.org/benefit_transfer.htm for more information and an example of benefits transfer. The current text is based in part on information from this website (accessed April 7, 2020).

[23] See https://pra.digital.gov/.

and does not require extensive adjustments for differing contexts. In fact, the design of the expert interview protocol as discussed below was based specifically on the context of this valuation study to facilitate the transfer of benefit estimates. We note that the authors have used benefits transfer extensively to evaluate improvements in hydro-meteorological programs for the World Bank (Lazo 2015; Lazo 2017; Lazo and Quiroga 2018; Lazo 2018a)

3.3 Implementation

As discussed above and shown in Knol et al., 2010 we followed the seven steps for the expert elicitation as described below step by step.

- ***Step 1: Characterization of uncertainties***[24]

After determining to use the Lazo et al., Molina et al., and WDEWE studies for the initial benefits component of the valuation exercise, the primary uncertainty for the analysis is how much GOES information contributes to potential improvements in hurricane forecasts and warnings as described in Lazo et al., Other efforts in research, modeling, human forecasters, etc., also make contributions to the quality of hurricane forecasts (e.g., Zhang et al., 2019; Gall et al., 2013; Emanuel and Zhang 2016) and determining the contribution of each to forecast improvements is not readily obvious. Based on prior research using expert elicitation, it was determined that expert elicitation was a valid approach for the current study given available resources.

- ***Step 2: Scope and format of the elicitation***

Initial work on the project focused on potentially eliciting information from emergency managers and broadcast meteorologists. Interview protocols were developed and pre-tested but, due to limited response, little usable feedback was obtained. Alternatively, given that we were able to relate the benefits from improvements in forecasts as described in Lazo et al., directly to information from hurricane forecasters it was determined to interview only Federal weather forecast personnel. In terms of scope and format of the elicitation, it was determined to use an interview protocol in a written format to facilitate access to these key personnel who often work irregular shifts.

- ***Step 3: Selection of experts***

The scope of the elicitation was thus focused on lead personnel from National Weather Service (NWS) Weather Forecast Offices (WFOs) in hurricane vulnerable areas – primarily coastal US areas. The interview protocol recipient in each office were chosen as the Meteorologist in Charge (MIC), the Science and Operations Officer (SOO), and the Warning Coordination Meteorologist (WCM). Experts were given the option to respond as a group or elicit input from other experts in their office as well. Most responses received were from individuals, but one forecast office did respond as a group from the MIC, SOO, and WCM. While the MIC, SOO, and WCM are often some of the most likely hurricane- experienced personnel in a WFO, respondents were also able to access input from any other personnel in their WFO who may have specific experience in the use and communication of hurricane information.

- ***Step 4: Design of the elicitation protocol***

The interview protocol was based in part on expert elicitation protocols used in Nicaragua and Honduras (Lazo 2017 and Lazo and Quiroga 2018) and in part on Lazo's prior survey work on hurricane communication and decision making (Bostrom et al., 2018; Demuth et al., 2016; Bostrom et al., 2016; Morss et al., 2016 ; Morrow and Lazo 2015; Lazo et al., 2015; Morrow et al., 2015; Morrow and Lazo

[24] We retain the spelling of "Characterisation" from Knol et al.

2014; Lazrus et al.; Demuth et al., 2012;). The primary elicitation information is based on the willingness-to-pay study reported in Lazo et al., 2010 and Lazo and Waldman 2011 and the forecast attributes described in that study. An initial pre-test of the protocol with GOES scientific experts led to some revisions and rewording of the final product. Indeed, the primary attribution question was reformatted based on input from NOAA personnel during the pre-testing phase.

- ***Step 5: Preparation of the elicitation session***

Permission for contacting NWS staff was obtained from John D. Murphy, Chief Operating Officer of the NWS. Mr. Murphy emphasized that respondents were to be informed that their participation was voluntary and that this was not a required NWS activity. This information was included in the contact emails and interview protocol. The invitation emails and interview protocol codebook are shown in Section 8.8.

- ***Step 6: Elicitation of expert judgements***

The interview protocol was emailed to all potential respondents on December 19, 2019. A reminder email was sent to non-respondents on January 30, 2020. A total of 9 useable responses were received including one from the pre-test group who would be better characterized as a hurricane researcher than as a member of a WFO. Data entry was undertaken manually in an Excel spreadsheet with some limited spot checking for quality assurance (QA/QC) on non-critical questions and complete cross checking and confirmation of the key empirical data for the benefits transfer. Appendix 8.8 contains the Codebook which is the interview protocol with qualitative responses inserted and quantitative responses indicated along with summary data. Although delayed until Nov 19, 2020 (after much of the hurricane season), using the Delphi method, we implemented the follow-up interview by sending each respondent the results of the initial interview and asked if they wanted to update or revise their initial estimates. Section 8.9 shows the follow-up email and protocol, Table 12 shows the first-round responses, and Table 13 shows the follow-up responses.

- ***Step 7: Possible aggregation and reporting***

The following sections provide information on the aggregation and reporting of responses to derive quantitative benefit estimates.

3.4 Economic Measurement of Socio-economic Benefits[25]

The socio-economic value of information from GOES-R can be understood using the economics terminology "Value of Information" (or VOI). The concept of willingness-to-pay (WTP) is the metric used to quantify individual's benefits from improved information. We provide a brief explanation of these concepts to show these are the correct theoretical measure of the value of information in the context and methods used in this study.

Weather forecast and warning information, such as a hurricane forecast, provides end-users a decision aid to reduce uncertainty. Framing uncertainty as individuals' subjective probability distributions over possible states of the world, the availability of potentially improved environmental information changes those subjective probability distributions used in making decisions in response to such information (Hirschleifer, 1973). In other words, individuals have perceptions of the possible future states of the world (e.g., probability that a hurricane makes landfall near them) and make decisions based on these probability perceptions. Information can change those perceptions (hopefully making them more

[25] This section is adapted largely from Letson, D., D. Sutter, J.K. Lazo. 2007. "The Economic Value of Hurricane Forecasts: An Overview and Research Needs." *Natural Hazards Review*. 8(3):78-86.

"accurate" or "correct") and thus influence (or "improve") decision-making. We provide a simplified decision model to illustrate the central concepts of the economic theory of the Value of Information or VOI. We further define the concept of "willingness-to-pay" or WTP as the correct valuation measure for a non-market commodity such as weather information.

Economists assume that an individual's utility, labeled ***U***, is a function of commodities the individual consumes, labeled ***X*** (with consumption broadly defined to include concepts such as altruism and existence value; Lazo et al., 1997; Nguyen and Robinson 2015). For purposes of this description, utility is modeled a function of consumption of commodities, ***X***. The level of utility is also dependent or contingent on the quality of hurricane forecast information that the individual uses to make decisions, ***FQ***:

$$U = U(x|FQ)$$

The individual is taken to have a certain level of income, ***Y*** and to face a vector of commodity prices, ***P***. We assume constant ***P*** and therefore suppress ***P*** in our notation although the impact of a hurricane on prices can be accounted for in this framework as well. The individual starts with a given level of forecast quality, FQ_1. The person will choose the level and composition of ***X*** that maximizes utility – that is she will choose how much of each commodity or activity to undertake to maximize her well-being. The "optimal" or maximum level of utility that she can achieve given these constraints, ***U****, can thus be written as a function of income and the initial forecast quality:

$$U^* = V(Y|FQ_1)$$

V indicates that utility is now measured as a function of income and forecast quality using what economists call an "indirect utility function." We use this rather than a direct utility function, ***U***, which is a function of the consumption of commodities, ***X***, to more easily evaluate changes in well-being using a monetary metric.

Given the choice between different levels of forecast quality, FQ_1 and FQ_2, where we assume FQ_2 to be a "better forecast," we can define willingness-to-pay (labeled ***WTP***) as the maximum amount an individual is willing to have income reduced to ensure that a welfare-increasing activity (i.e., improved forecast) takes place:

$$U^* = V(FQ_1) = V(Y - WTP|FQ_2)$$

WTP is thus the amount of money that can be taken away from income, Y, while keeping the individual at the same level of utility, U*, that she had before forecast quality was improved. WTP is the value to the "ultimate" end users of information – members of the general public – who are also essential measures and foci of the concept of societal well-being.

We further note that weather information can generally be considered a public good. A public good is one that is both non-excludable and non-rivalrous (Samuelson 1954). Non-excludable means that once it is provided, we cannot prevent others from using the good (i.e., once a forecast is broadcast anyone and everyone can use that forecast). Non-rivalrous means that one person's use of that good does not consume the good and thus it is still useable by anyone else (i.e., your use of a forecast does not diminish that information in a manner that keeps me from using the information). While there are conditions under which weather information may be "excludable" or "rivalrous" for the most part for the general public much weather information is freely provided, and should be freely provided, as a public good. In a related manner, when the marginal cost of adding another user is at or near zero then it is in the interest of society to let that user access the good – that is societal welfare is increased at little or no cost.

An important result of something being a public good – or at least being non-excludable – is that the provider can generally not charge a price for that good (e.g., if anyone can get it freely then you cannot get them to pay for it) and thus markets will not form for that good. In this case we will not have market information on what “buyers” are willing to pay. In addition, as we are evaluating future forecast improvements, we cannot directly use past market responses (e.g., changes in evacuation behavior and, thus, reduced costs with past forecast improvements) to assess benefits from future forecast improvements. Thus, we will not have market-based information on values (which is one type of “revealed preferences”) but need to use non-market methods to assess the value of the commodity (Champ et al., 2003).

It is also possible that individuals hold values for improved information not directly related to their use (e.g., altruistic, bequest, or existence values). While this seems less likely with something like a hurricane forecast compared to something such as species preservation where non-use values are important, prior work on weather information has indicated the possibility of non-use values (Nguyen et al., 2013, Nguyen and Robinson. 2015). The use of stated preference approaches in such cases is supported by OMB guidance: “Stated Preference Methods (SPM) have been developed and used in the peer-reviewed literature to estimate both “use” and “non-use” values of goods and services. They have also been widely used in regulatory analyses by Federal agencies, in part, because these methods can be creatively employed to address a wide variety of goods and services that are not easy to study through revealed preference methods.” (OMB 2019. p.22).

Next, we describe the non-market valuation studies used to evaluate the benefits of improved hurricane information.

3.5 Existing Benefit Studies Used for GOES-R Analysis

A critical aspect of the current research is linking changes in forecast quality related to GOES-R to an existing estimate of benefits of weather information. To do this we evaluate existing benefit estimates (WTP estimates) from three studies to choose a value or values to use in the current analysis. Publications or documents related to these three studies include:

- ***Lazo et al., 2010***
  - Lazo, J. K., and D. M. Waldman. 2011. “Valuing Improved Hurricane Forecasts.” Economics Letters. 111(1): 43-46. doi:10.1016/j.econlet.2010.12.01
  - Lazo, J. K., D. M. Waldman, B.H. Morrow, and J. A. Thacher. 2010. “Assessment of Household Evacuation Decision Making and the Benefits of Improved Hurricane Forecasting.” *Weather and Forecasting*. 25(1):207-219. DOI:10.1175/2009WAF2222310.1
- ***Molina et al., 2020***
  - Molina, R., D. Letson, B. McNoldy, P. Mozumder and M. Varkony. 2020. A Contingent Valuation of Hurricane Forecast Improvement. Preliminary Draft March 2020.
  - Molina, R., D. Letson, B. McNoldy, P. Mozumder and M. Varkony. 2020a. Striving for Improvement: The Perceived Value of Improving Hurricane Forecast Accuracy. Working paper. Submitted to the *Bulletin of the American Meteorological Society* for publication. 11 pages.
  - Molina, R., D. Letson, B. McNoldy, P. Mozumder and M. Varkony. 2020b. Supplementary Material for Striving for Improvement: The Perceived Value of Improving Hurricane Forecast Accuracy. Working paper. Submitted to the *Bulletin of the American Meteorological Society* for publication. 43 pages.
- ***WDEWE n.d.*** – Warning Decisions: Extreme Weather Events: This project resulted in several publications including the following as well as several relevant items on the analysis of the valuation portion of the survey that are not published but are in the possession of the project team.

- Bostrom, A., R. E. Morss, J. Demuth and H. Lazrus, and J. K. Lazo. 2018. Eyeing the Storm: How Residents of Coastal Florida See Hurricane Forecasts and Warnings. *International Journal of Disaster Risk Reduction*. 30(A):105-119. https://doi.org/10.1016/j.ijdrr.2018.02.027
- Bostrom, A., R. E. Morss, Lazo, J. K., J.L. Demuth, H. Lazrus, and R. Hudson. 2016. "A mental model's study of hurricane forecast and warning production, communication, and decision making." *Weather, Climate, and Society*. 8(2):111-129. DOI: 10.1175/WCAS-D-15-0033.1
- Demuth, J. L., R. E. Morss, J. K. Lazo, and C. Trumbo. 2016. "Examining Different Past Hurricane Experiences and How They Affect Future Evacuation Intentions" *Weather, Climate, and Society*. 8:327-344. DOI: 10.1175/WCAS-D-15-0074.1
- Lazo, J. K., A. Bostrom, R. E. Morss, J. L. Demuth, and H. Lazrus. 2015. Communicating Hurricane Warnings: Factors Affecting Protective Behavior. *Risk Analysis*. 35(10):1837-1857. DOI: 10.1111/risa.12407.

All three studies implemented stated preference valuation methods[26] to analyze choices between potential forecast-improvement programs and the accuracy of existing forecasts and to derive the willingness-to-pay (WTP) for improved forecasts from survey respondents.

In stated choice (SC) studies, a type of stated preference (SP) method, respondents are presented with sets of alternatives and asked to choose their preferred alternatives thus revealing information about the underlying values for the goods and services included in those alternatives. This method evolved from approaches used extensively in marketing and transportation research that are now widely used in non-market valuation studies in environmental and health economics (Adamowicz et al., 1998; Ben-Akiva and Lerman 1994; Louviere et al., 2001; Champ et al., 2003). In the contingent valuation method (CVM), respondents generally either indicate a specific amount they are WTP for a commodity (open-ended or payment card method) or indicate a Yes / No response to an offered commodity at a specific price (referendum method). A variation on the CVM is implemented in the Molina et al., work. While the Molina et al., and WDEWE studies are somewhat different, the theoretical modeling approach for deriving WTP estimates is, in general, the same thus we only provide details on this in the following section on the Lazo et al., study.

In a stated choice survey, a commodity (i.e., a good or service) is presented as a set of attributes where commodities vary in the level or quality of each attribute. Choices between offered commodities reveals information about respondents' preferences for those attributes. Including cost as an attribute provides information about the individual's marginal utility of money and allows for the conversion of marginal utilities for non-monetary attributes into marginal values for those attributes.

A limited number of studies have implemented non-market methods to evaluate the benefits of hurricane (tropical cyclone) forecasts or impacts from these events. As discussed in more detail below as one of the studies used in the benefits transfer for the current analysis, Lazo et al., 2010, and Lazo and Waldman 2011, estimate the value to U.S. households of improved hurricane forecasts in a pilot survey using discrete choice econometric methods. In those studies, it was found that each household had WTP approximately $14 (2007$) for the intermediate improvements and $24 for maximal improvements in forecast attributes such as landfall time and position, wind speed, and storm surge (discussed further below and shown in Table 3). They further explore several issues on evacuation decision making and

[26] These methods are sometimes called the "contingent valuation method" (CVM) as well but the fine distinctions between terminology here are not relevant to our analysis. For instance, see Brown 2003 or Armstrong et al. 2012 for more information on stated preference methods.

perceptions of hurricane vulnerability. Building in part on the Lazo et al., work, Nguyen et al., 2013 and Nguyen et al., 2015, undertook a choice experiment with 1014 respondents in Vietnam to estimate benefits to households of an improved cyclone warning service determining that the value of maximal improvements in cyclone warning services are approximately USD7.1–8.1 per household per year[27]. In a related paper, Nguyen et al., 2015 undertook a WTP study of values for an improved cyclone warning service in Vietnam looking specifically at individual's motivations for values such as use, altruistic, or bequest values (see Lazo et al., 1992; Lazo et al., 1997; Schulze et al., 1998). Of interest here is that individuals may have positive WTP for improved hurricane information beyond their own use of that information for their own decision-making. They may hold values for the information knowing that others in their family or in their community or even future generations could benefit from improved information. This potentially suggests positive WTP for improved information far outside populations directly exposed to hurricane risks. While not a value-of-information (VOI) study, Landry et al., 2015 describe a stated-choice study of WTP for post-Katrina rebuilding of New Orleans' man-made storm defenses, restoring natural storm protection, and improving evacuation options. Similarly, Shaw and Baker 2010 sampled individuals displaced by Hurricane Katrina or Rita in Gulf-coast areas and a comparison group to explore respondents' perceptions of the risks of hurricanes and relocation decisions as well as WTP to obtain protection from risks.

3.5.1 Lazo et al., 2010 "Assessment of Household Evacuation Decision Making and the Benefits of Improved Hurricane Forecasting"

As noted above, we discuss the implementation and analysis of the Lazo et al., 2010 work in more detail than the other studies as they are substantively similar in methods. In Lazo et al., 2010 the commodity evaluated was improvements in hurricane forecasting programs at that time related to the Hurricane Forecast Improvement Program (HFIP). The attribute levels indicated in the survey were based on the goals of the HFIP program and at that time current levels of forecast accuracy based on input from HFIP and NHC personnel. [28]

In the survey, respondents chose between two hurricane forecasting programs in each of eight scenarios where each program was described by different levels of quality for four hurricane forecast attributes: time of expected landfall, maximum windspeed, projected location of landfall, and expected storm surge, as well as increased annual cost to the household as shown in Table 4.

[27] Assuming a unitary income elasticity of WTP, and with World Bank data indicating median per capita GDP of $2,058.10 and $56,803.50 in Vietnam and the United States respectively (measure in 2015 US dollars) the USD7.1-8.1 from Nguyen et al. would translate to $193.42-$220.60 per household per year in the United States.

[28] See http://www.hfip.org/. According to the first HFIP strategic plan the goals of the HFIP was "…to achieve a 20% overall improvement in hurricane numerical forecast guidance provided by the National Centers for Environmental Prediction (NCEP) to the National Hurricane Center (NHC). This improvement in guidance is for both track and intensity. HFIP also includes goals for predicting rapid intensification and for extending forecast guidance out to seven days. In addition, this plan sets in place development to achieve a 50% improvement in both track and intensity within 10 years." Toepfer et al. 2010.

Table 4. Attributes and Levels (Lazo et al., 2010 Survey.)

Attributes	Levels		
	Baseline	**Intermediate Improvement**	**Maximum Improvement**
Time of expected landfall	8 hours 48 hours in advance	6 hours	4 hours
Maximum wind speed	20 miles per hour 48 hours in advance	15 miles per hour	10 miles per hour
Projected location of landfall	100 miles 48 hours in advance	80 miles 48 hours in advance	65 miles 48 hours in advance
Expected storm surge	plus or minus 8 feet of height above sea level 48 hours in advance	6 feet of height above sea level	4 feet of height above sea level
Increase in Annual Cost to Your Household	No Additional Cost if all attributes at baseline	\$12, \$24, \$48 – If any attribute improved then an increase in cost included in scenario	\$12, \$24, \$48 – If any attribute improved then an increase in cost included in scenario

Each program evaluated was a combination of different levels of the forecast attributes at some cost to the household. For each choice scenario, respondents indicated their preference between two potential improvement programs, for instance Program A and Program B, and then whether they would prefer the status quo (SQ) (i.e., keeping all levels at their baseline level) over their A-B choice. Programs were labeled A-B in the first scenario, C-D in the second, and so forth. A typical choice appeared as shown in Question 34, Figure 10 where the programs were labeled C and D. They were then asked whether they would like to stay with their indicated preference or keep forecast quality the same as now and pay no more in annual costs (Question 35, Figure 10**)**. This follow-up question has been shown to improve parameter estimates especially with respect to the marginal utility of money (e.g., annual household cost) which is critical to deriving benefit estimates (Savage and Waldman 2008).

34 **Please indicate which Program, if you had to choose, you would prefer.**

	Accuracy of Current Forecasts	Program C	Program D
Time of expected landfall	Now accurate to within 8 hours	4 hours	No change
Maximum wind speed	Now accurate to within 20 miles per hour	No change	15 hours
Projected landfall	Now accurate to within 100 miles	80 miles	65 miles
Expected storm surge	Now accurate to within 8 feet above sea level	4 feet	No change
Increase in Annual Cost to Your Household		$12 per year	$24 per year
I would prefer (please put check mark in box indicating your preferred Program)		**Program C** ☐	**Program D** ☐

35 **Would you prefer to keep forecast quality the way it is now and pay no more in taxes or stay with the Program you indicated above?**

☐	Keep forecast quality the way it is now and pay no more in taxes.
☐	Undertake the Program chosen above and pay the amount indicated.

Figure 10. Example of stated preference choice question.

After having respondents answer many different scenarios with different programs offered, Lazo et al., then use statistical methods based on a theoretical model of decision making called the Random Utility Model (RUM) to estimate respondent preferences and values for the different attributes. Based on Manski (1977) and McFadden (1976), the RUM was assumed for econometric modeling of the choice question responses. In this analysis the utility of each choice was modeled as a linear combination of the choice attributes and a random error:

$$U_{ij} = \beta' x_{ij} + \varepsilon_{ij}, \qquad i = \text{A, B}; j = 1,\ldots 8,$$

where the elements of the vector β are the marginal utilities of the attributes in the vector $\boldsymbol{x}$:

$$x = \begin{pmatrix} \text{Time of landfall accuracy} \\ \text{Maximum wind speed accuracy} \\ \text{Project location of landfall accuracy} \\ \text{Expected storm surge accuracy} \\ \text{Annual household cost} \end{pmatrix},$$

and ε is a random disturbance.

Table 5 shows the regression estimates from Lazo et al.'s Table 3, and the t-ratios indicating that all estimates were significant. This modeling also accounted for the follow-up status quo (SQ) option. As U is the total utility defined as the sum of the utility from the different attributes (x's), the ß's measure the change in total utility due to a unit change in any given forecast attribute, x. The ß's are interpreted as the marginal utility of the attributes – including the cost attribute. Thus, the ß associated with the cost attribute measures the marginal utility of money (expected to be negative as increasing costs decreases utility). Marginal willingness-to-pay (*MWTP*) for an improvement in a forecast quality attribute is calculated as the negative of the ratio of the marginal utility coefficient to the marginal disutility of cost:

$$MWTP_k = - MU_k/MU_{cost}\ ,\ k = \text{landfall time accuracy, …, surge accuracy.}$$

Table 4 also shows the estimation results and the derived marginal WTP values for the four forecast attributes. For instance, a household would be willing to pay $2.18 per year for a one-unit improvement (i.e., one-hour improvement) in the accuracy of time of expected hurricane landfall. Using the marginal WTP values, total household benefit estimate for any program is the sum of the marginal WTP values times the changes from baseline in attribute levels for that program.

As shown in Table 4 the total willingness-to-pay for a program that increased all forecast attributes to the level of the intermediate improvements (from baseline to intermediate levels on all attributes) is $14.34 per household per year. Similarly, the total willingness-to-pay for a program that increased all forecast attributes to the level of the maximum improvements (from baseline to maximum improvement levels on all attributes) is $27.53 per household per year.

As noted previously, the Molina et al., and WDEWE studies undertook substantively similar theoretical and empirical analysis of survey responses and we do not go into detail on the exact methods employed in those studies.

The key numbers from this work are the $14.34 and $27.53 (2007$) per household WTP for intermediate and maximum hurricane forecast improvement programs, respectively.

Table 5. Modeling Results Based in Part on Tables 3 and 4. (Lazo et al., 2010)

Parameter estimates and marginal WTP					**WTP for Intermediate Improvement**			**WTP for Maximum Improvement**		
Attribute	$ß_k$	t-ratio	Marginal WTP	Baseline	Intermediate	Diff.	WTP	Maximum	Diff.	WTP
Time of expected landfall	-0.07	-3.57	$2.18	8 hours 48 hours in advance	6 hours	2	$4.36	4 hours	4	$8.72
Maximum wind speed	-0.01	-1.08	$0.26	20 miles per hour 48 hours in advance	15 miles per hour	5	$1.30	10 miles per hour	10	$2.60
Projected location of landfall	-0.01	-3.22	$0.23	100 miles 48 hours in advance	80 miles 48 hours in advance	20	$4.60	65 miles 48 hours in advance	35	$8.05
Expected storm surge	-0.06	-3.5	$2.04	plus or minus 8 feet of height above sea level 48 hours in advance	6 feet of height above sea level	2	$4.08	4 feet of height above sea level	4	$8.16
Increase in Annual Cost to Household	-0.03	-11.3								
						Total WTP	**$14.34**			**$27.53**

3.5.2 Molina et al., 2020 " Striving for Improvement: The Perceived Value of Improving Hurricane Forecast Accuracy"

An early version of a manuscript on the study was provided to the GOES-R research team by David Leston of the University of Miami by email on April 6, 2020. Two revised documents were provided by the study authors (Renato Molina by email) to the GOES-R socioeconomic benefits research team on July 1, 2020 indicating this version has been submitted to the *Bulletin of the American Meteorological Society* (BAMS). A further revision was received on December 11, 2020. Dr. Molina indicated that there were no major revisions in the value estimates between the July and December versions and, therefore, our analysis retains the July value estimates. Therefore, the discussion below is based on primarily on the July manuscript versions which may be subject to change in the peer review and publication process.

- Molina, R., D. Letson, B. McNoldy, P. Mozumder and M. Varkony. 2020. Striving for Improvement: The Perceived Value of Improving Hurricane Forecast Accuracy. 11 pages.
- Molina, R., D. Letson, B. McNoldy, P. Mozumder and M. Varkony. 2020. Supplementary Material for Striving for Improvement: The Perceived Value of Improving Hurricane Forecast Accuracy. 43 pages.

Beginning in April 2020 and over the last several months we have communicated with the Molina et al., team on several questions with respect to their work as well as requested and received data sets on the population by county they used to aggregate their results. We thank Molina et al., for their willingness to share their data and analysis prior to publication.

Molina et al., present a survey-based, double-bounded, dichotomous choice contingent valuation method (CVM) study. The survey was implemented on-line in late 2019 / early 2020. Respondents were presented information about the past and potential improvements of three hurricane forecast attributes – the accuracy or error in track, wind speed, and rainfall. They were then asked if they would vote for or against a program to improve one of the randomly assigned attributes which would entail an increased tax to their household – the level of the tax was a random value on the interval \$1-\$50. If they voted 'yes', they were then asked if they would be willing to pay 1.2 x the previously assigned value and, if instead they voted 'no', they were asked if they would be willing to pay 0.8 x the previously assigned value (hence the method being labeled "double-bounded dichotomous choice"). After this question they then answered another similarly designed set of questions about one of the other two forecast attributes and, after answering that set of questions, they were asked another similarly-designed set of questions about the last of the three forecast attributes.

The respondent sample was drawn from counties exposed to either Hurricane Florence or Michael in 2018. It is not clear how the respondents were recruited, nor how many were contacted and, thus, there is no way to determine the underlying response rate. Their comparison of the socio-demographics of their sample to census track data does indicate specific differences between their sample and the general population. The authors undertake some statistical analysis presented in the supplementary material using census track data to suggest that their results are representative.

Molina et al., examined the historical improvements in forecast during the decade 2008-2018 and used estimates of error reduction during this period as the baseline for error reduction in the following decade for which they asked their respondents to evaluate (2018-2028). The 2008-2018 period could be considered as representing the GOES N-O-P era of contributions to these forecasts, and the 2018-2028 period as a projection of the contributions of the first portion of the GOES-R era considered in this analysis of GOES-R benefits. The forecast attributes evaluated in the Molina et al., survey are shown in Table 6.

Table 6. Forecast Improvement Attributes and Levels in Molina, et al.

Forecast Attribute	Description
Track error	Based on the cone of uncertainty 72 hours from landfall, they assume the average calculated trend of improvement over the decade 2008-2018 of 41.3% continues through the decade 2018-2028 plus or minus 20%, producing decadal error-reduction rates used in the survey scenarios of 49.6%, 41.3%, or 33.0%. See Figure 17 below.
Wind speed	The authors calculated a 29.4% reduction in error over the 2008-2018 period. This was then projected into the decade 2018-2028 with a 20% higher-than-the-average historical reduction, a constant continuation of the historical reduction (29.4%), or a 20% lower-than-average improvement relative to the previous decade's improvement rate producing decadal error reduction rates used in the survey scenarios of 35.3%, 29.4%, or 23.5%.
Rainfall	Using the forecast in 2018 as a benchmark, respondents were "shown a map with a shaded region indicating the area where there was at least a 20% probability of the rainfall amounts generated from the forecast storm attributes being less than the rainfall amounts generated from the observed storm attributes (an under-forecast) by at least one inch."

For empirical estimation, the authors undertook econometric analysis using a random utility model (RUM) specific to the double-bounded-CVM framework. They analyzed models for three sample groups: the combined (full) sample, and one each for just Hurricane Florence or Hurricane Michael impacted respondents (geographically distinct areas). Further, they estimate three models for each sample group: first a basic model only accounting for the order in which the attribute was presented and the level of forecast improvement; second a model including first one set of socio-demographic explanatory variables; and a third model adding additional socio-demographic explanatory variables. Some relevant regression results include:

1. The parameter on "Order" (the order in which an attribute appeared in the survey) is negative and significant in all model specifications. One possible interpretation of this may be that some respondents felt they were being asked to pay for improvements in a cumulative process and thus had either diminishing marginal utility for an improvement or perceived the attributes to be correlated and, thus, were not willing to pay separately for each improvement. The importance of this (and as noted for other reasons by the authors) is that, even though the attributes are modeled and analyzed separately, the total value of the improvements would likely not be the simple sum of the individual WTP estimates. A conservative approach would be to use the maximum value for any single attribute (in this case wind speed) and assume no additional value from other attributes (i.e., not summing across WTP for different attributes).
2. The parameter estimate on "Rate" is not significant in any of the regression models indicating respondents were not sensitive to the rate of improvement in forecasts but were still willing to pay for some improvement. In the stated preference / CVM literature this would be considered a "failure of the scope" test in that respondents do not value different levels of the improvement. The authors recognize and discuss this and cite other literature with similar findings and explanations. It is also relevant in deriving their estimated WTP values – the authors generate values for "an improvement" and not for a specific level of improvement. This level of improved forecast presumably could be for anywhere in the range of percent improvements indicated by the authors for each attribute (i.e., historical decadal improvements plus or minus 20%).
3. In the extended model analysis, an attribute for "Coast Distance" is included which can be used to evaluate if the distance from the coast as measured by the county centroid in which the respondent lives affects WTP. In the full models for all attributes, "Coast Distance" is not significant for any attribute. In the models for the Hurricane Michael sample, it is negative but not significantly different from zero. In the Hurricane Florence sample, it is positive and significant at the 5% level in the "Precipitation Forecast" model but not for track or wind speed. This result may provide some support for aggregating the WTP

values across populations further from the coast and even possibly indicating increased values for improved precipitation forecasts further from the coast where inland flooding is likely a larger problem than wind speed or landfall location.

Molina et al., provide derived WTP estimates based on their empirical model estimates and average respondent socio-demographics. They provide WTP estimates for each of the three forecast attributes independently as shown in Figure 11 and Figure 12 copied from their manuscripts. The bars in Figure 11 denote the 95% confidence interval for each derived WTP estimate with the overlap in the error bars thus showing that there is not a statistical difference in WTP for the three attributes although WTP is higher on average for improved wind speed forecasts. Across the three attributes (as shown in Table 6 above), the minimum of the 95% confidence interval is slightly above $15 (for precipitation) and the maximum is slightly above $35 (for wind speed).

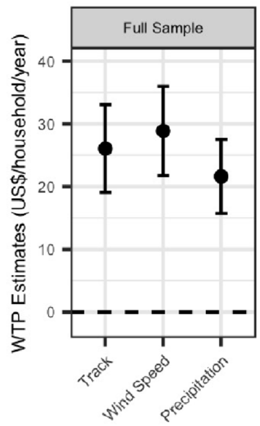

Figure 11. Average willingness to pay full sample with 95% confidence intervals for hurricane forecast improvement.[29]

	Full Sample		
WTP (Storm track)	32.88***	25.69***	26.07***
	(1.80)	(3.48)	(3.57)
WTP (Wind speed)	30.01***	27.80***	28.89***
	(1.86)	(3.51)	(3.62)
WTP (Precipitation)	28.87***	21.83***	21.63***
	(2.01)	(2.90)	(3.00)
Observations	4650	4644	4581
Control Set 1		X	X
Control Set 2			X

Standard errors in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Figure 12. Average willingness to pay for hurricane forecast improvement for the full sample using sample means.[30]

The authors aggregate their WTP estimates over "all counties having experienced wind speeds of at least 30 miles per hour due to a hurricane between 2006-2018 in the continental US." They call this "extrapolating these results to out-of-sample individuals" which is the first step before aggregating over the 10-year period covered in their survey (2018-2028). Their choice of WTP values to use is based on taking "the fully specified WTP for an attribute in the full sample and assume the average respondent is representative of households in the sampled regions." This means they are taking their most complete model (the last column in Figure 12) with all variables included and the full sample and fitting a WTP for each respondent using his or her socio-demographic information and then taking the

[29] Copied from Molina et al. 2020a Figure 2.
[30] Copied from Molina et al. 2020b Table 8.

average of these fitted WTP values.[31] "Respondents are, on average, willing to pay US$26.07, US$28.89, and US$21.63 in additional household taxes per year for the next ten years for improvements in track, wind speed and precipitation forecasts, respectively."

Figure 13 below is Figure 6 from Molina et al., supplemental material. Panel A shows their fitted aggregated county WTP values for wind speed forecast improvement for the counties included in their sample. Panel B shows their extrapolation to all counties having experienced winds of at least 30 miles per hour due to a hurricane between 2006-2018. The figure indicates a Log(WTP) scale ranging presumably from 1.0 to over 17.5 as labeled. It is not clear what this means as the inverse of Log(WTP)=17.5 is several orders magnitude greater than US National GDP. Further they note that "WTP is log-adjusted to reduce contrast for counties with disproportionally large number of occupied households." It is not clear what this means, but we reasonably assume their analysis is correct, but their terminology is unclear.

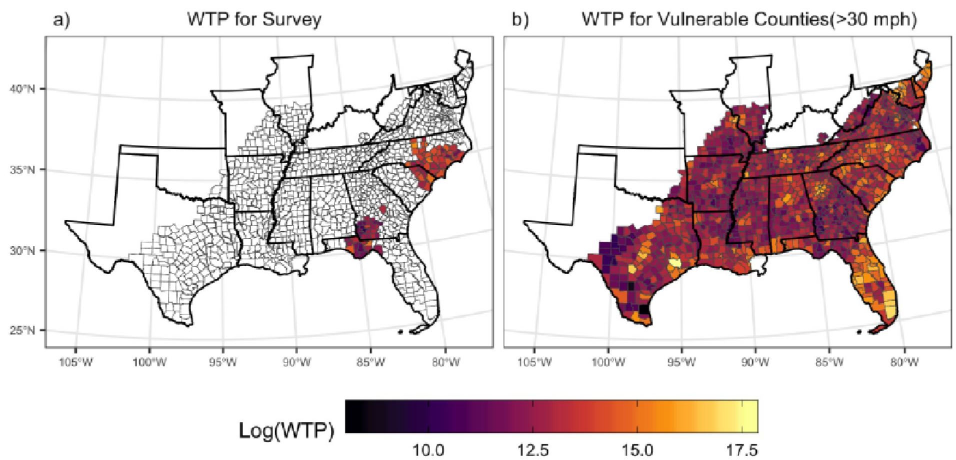

Figure 13. Spatial aggregation of WTP values from Molina et al.

Subsequently they "report these calculations for thresholds at 20, 30, 40 and 50 miles per hour, respectively." Figure 14 below shows their map of the extrapolation to 20 MPH affected areas.

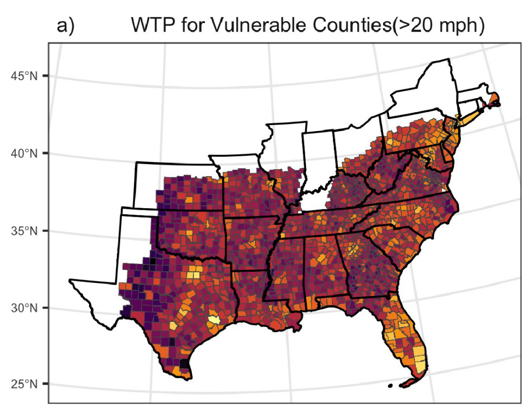

Figure 14. Spatial aggregation of WTP to counties experiencing winds greater than 20 mph.

31 It not immediately clear if this is correct or if instead all WTP values are fitted based on average county socio-demographics. In their supplementary material the authors appear to test both approaches (using individual respondent values and average county values) and do not find a significant difference in average derived (fitted) WTP values.

3.5.3 Warning Decisions in Extreme Weather Events (WDEWE)

The NSF funded project "Warning Decisions in Extreme Weather Events: An Integrated Multi-Method Approach" (labeled "WDEWE" by the project team and the acronym used here) in which Jeffrey Lazo was a co-principal investigator while at the National Center for Atmospheric Research (NCAR), used "a multidisciplinary approach to understanding weather warning systems, system components, and their interactions. Integrating information and research methods from meteorology, sociology, economics, decision science, and public policy analysis, the project … analyze[d] how extreme weather warnings
are communicated, obtained, interpreted, and used in decision making, as well as stakeholder perceptions of warning characteristics needed for sound decision making." (from project abstract https://www.nsf.gov/awardsearch/showAward?AWD_ID=0729302 , accessed August 12, 2020).[32]
The project implementation occurred April 1, 2008 through March 31, 2012.

The WDEWE project built on 1) a prior NSF project "Examining the Hurricane Warning System: Content, Channels, and Comprehension"[33] (Demuth et al., 2012; Lazrus et al., 2012; Morss et al., 2015), 2) NOAA funded work on improving hurricane forecasts (Gladwin et al., 2007; Gladwin et al., 2009; Lazo and Peacock. 2007; Letson et al., 2007) and developing a storm surge warning (Morrow and Lazo 2014; Morrow et al., 2015), as well as 3) World Meteorological Organization (WMO) efforts related to improving weather forecasting globally (Morss et al., 2008). Besides looking at the public value of improved hurricane forecasts, the WDEWE project examined different mental models of hurricanes held by forecasters, broadcasters, emergency managers, and the public (Bostrom et al., 2016), the impacts of experience on decision making (Demuth et al., 2016), perceptions of hurricane risks (Bostrom et al., 2018), and factors influencing evacuation decision making (Lazo et al., 2015).

The WDEWE project work relates closely to the weather information value chain concept in that all phases of the information process were explored in depth using multiple methods from the social sciences including risk communication, factor analysis, mental modeling, cultural theory of risk, content analysis, focus groups, in-depth interviews, surveys, observational sessions, and economics. Figure 15 provides one example of the WDEWE work to characterize the creation, communication, and use of hurricane information that fed into the valuation exercised discussed here.

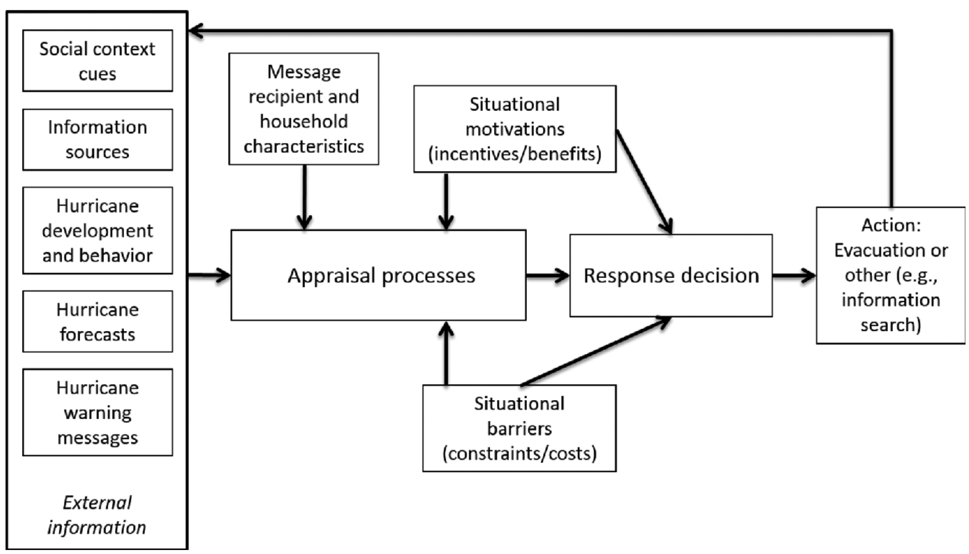

Figure 15. Conceptual model of hurricane information and decision-making process developed by the WDEWE project.[34]

[32] WDEWE examined flash floods and hurricanes. We focus only on the work on hurricanes in this analysis.
[33] https://www.nsf.gov/awardsearch/showAward?AWD_ID=0838702&HistoricalAwards=false.
[34] From Lazo et al., 2015 Fig. 1. "Hurricane information appraisal and response model investigated in this article."

The final component of the WDEWE project was a stated preference survey of the general public in Florida and Texas for improved hurricane forecasts building largely on the prior Lazo et al., 2010 work. The design of the survey instrument drew extensively on prior literature and on related prior and concurrent research by the project team, including work on the sources, communication, perceptions, uses, and value of hurricane information using stated-preference valuation and interview methods; hurricane mental modeling work in Miami; and work on a related project on communicating hurricane information. The survey was implemented online by Knowledge Networks (KN). The target population consisted of 18-year-old and older residents of Broward, Miami-Dade, and Palm Beach counties in Florida and Brazoria, Galveston, Harris, and Matagorda counties in Texas. For the sample KN invited 1,311 of its "KnowledgePanel" participants in these 7 counties. Since a significant portion of the sample is primarily Spanish speaking, the survey was translated into Spanish by KN and offered in English and Spanish to all respondents. The survey was implemented in May 2012 and resulted in 808 respondents with a survey completion rate of 61.6%.

There were 804 complete responses to the choice sets (n=804). There were five forecast attributes (including a cost attribute) as shown in Table 7. Different than the Lazo et al., 2010 work (see Table 4), the WDEWE survey presented only a baseline level and a single-improved level of each attribute (other than cost for which 4 levels were included). Table 7 shows the attributes and levels used in the WDEWE valuation scenarios. Subsequently, WTP values derived from this survey only focus on the overall improvement in all four attributes rather than an intermediate program and a maximum program (as shown for Lazo et al., in Table 5).

Each respondent first answered one "referendum" choice set and then five choice set comparisons each with a follow-up "do nothing" alternative. So, for each respondent (n=804) there were 11 responses. Respondents were also asked a follow-up after all choice questions of "When completing the previous questions where you indicated your preference between the two programs, how confident are you that you understood these questions?" with a 1-5 response scale of "Not At All Confident" to "Extremely Confident." This response can be used in the econometric analysis to weight each individual's responses based on their confidence that they represent their true preferences.

Table 7. Attributes and Levels from the WDEWE Survey

Attribute	Current	Improved
Landfall location	within 50 miles	25 miles
Maximum wind speed	within 15 miles per hour	7 mph
Inland flooding from rainfall	detected 50% of the time	75%
Storm surge information	no separate storm surge information	Yes
Increase in annual cost to your household	no increase in cost	$6, $12, $24, $36

Figure 16 shows a typical choice question from the WDEWE survey. This is comparable to Figure 10 from the Lazo et al., 2010 study. Building on that prior work, the data analysis completed at this time from the WDEWE project followed a similar method as that described for the Lazo et al., 2010 analysis.

[CHOICE SET 2]
[prompt "Please select the program you prefer."]

Q27 Please indicate which Program you would prefer if you had to choose.

	Accuracy of Current Forecasts	Program F	Program G
Landfall location	within 50 miles	**25 miles**	No change
Maximum wind speed	within 15 miles per hour	No change	**7 mph**
Flooding from rainfall	detected 50% of the time	No change	No change
Storm surge information	no separate storm surge information	**Separate storm surge information**	**Separate storm surge information**
Increase in Annual Cost to Your Household		**$24 per year**	**$24 per year**
I would prefer (check one box)		**Program F** ☐	**Program G** ☐

Q28 Would you prefer to keep forecast accuracy the way it is now (current levels of accuracy) with no increased costs to your household or the Program (F or G) you chose above at the cost indicated?

☐ Keep forecast accuracy the way it is now with no increased costs to my household.

☐ Undertake the program (F or G) chosen above at the cost indicated.

Figure 16. Typical full choice question with "no change from current accuracy" follow-up.

Table 8 shows a select set of results from the preliminary data analysis conducted by Donald Waldman for the WDEWE data. This work has not been developed into a manuscript or peer reviewed and there are a wide range of models and WTP estimates that were developed to explore the information in the survey results.[35] In Table 8 we show only three models that were derived from the full sample (n=784 complete responses usable in data analysis) for three variations on a model only looking at responses as a function of the attributes (i.e., no interacting socio-demographic variables). The "AB-SQ+constant" model included responses to the A-B choice as well as the follow-up status quo (or SQ) question that helps refine the marginal utility of income and included a constant (that seemed to help refine model parameter estimates considerably compared to models without a constant). The other two models shown were identical in terms of specifications, but responses were weighted with by a "population" weight provided by KN indicating each respondent's representativeness relative to the entire population for the survey counties or weighted by the respondent's indication of how certain they were there responses were accurate (this variable is discussed above). As can be seen, the WTP derived from these three models falls into a relatively tight range from $36.36 to $40.25 per household per year for improving all forecast attributes from current level to "improved" as shown in Table 8 above.

[35] At this time, a final version of the data analysis has not been completed for potential publication although several preliminary models have been estimated some of which are discussed here.

Table 8. Multinomial Logit (MNL) Models for Hurricane Data
(Full Sample, n = 784)

		AB-SQ+constant			Weighted by population			Weighted by certainty		
Expected Sign	**Attribute**	**Beta**	**t**	**WTP**	**Beta**	**t**	**WTP**	**Beta**	**t**	**WTP**
-	Location	-0.028	-11.01	*$15.69*	-0.024	-9.55	*$13.80*	-0.031	-12.05	*$18.18*
-	Speed	-0.019	-2.26	*$ 3.33*	0.010	1.18	*$(1.76)*	-0.023	-2.74	*$ 4.26*
+	Flooding	0.013	4.85	*$14.91*	0.020	7.15	*$22.60*	0.013	4.64	*$15.05*
-	Surge Info	-0.109	-1.78	*$ 2.43*	-0.168	-2.76	*$ 3.85*	-0.119	-1.93	*$ 2.76*
-	Cost	-0.045	-14.59	---	-0.044	-14.41	---	-0.043	-13.98	---
+	Constant	1.067	12.30	---	0.978	11.50	---	1.194	13.56	---
Total WTP				**$ 36.36**			**$ 38.48**			**$ 40.25**
The "Beta"s are the parameter estimates, and the "t" values are the t-statics for those parameter estimates.										

To explore some respondent heterogeneity (i.e., how individual differences in socio-demographic characteristics relate to WTP), Table 9 shows some WTP estimates for select sub-samples of the WDEWE responses. For each sub-sample, the entire sample was split into two groups (e.g., youngest half of the sample and oldest half of the sample or male and female sub-samples), the models re-estimated, and WTP values derived for each sub-sample group. As can be seen, there are some differences in WTP between sub-samples – the most prominent being that between respondents who own their house (WTP=$28.67) compared to those who rent their dwelling (WTP=$7.99). It is not clear why WTP estimates for all these subsamples are lower than those shown in Table 8 for the complete sample.

Table 9. Demographic Subsample Comparisons from WDEWE Choice Analysis
all Models Estimated AB-SQ with SQ Constant

Subsample		**WTP**		**WTP**
Age	Youngest half	$22.76	Oldest half	$18.99
Gender	Men	$22.62	Women	$20.14
Education	Less educated	$25.64	More educated	$17.09
Income	Higher income (>$40K)	$24.40	Lower income	$16.45
Home ownership	Dwelling owner	$28.67	Renter	$7.99
Marital Status	Married	$20.78	Single	$21.02

3.5.4 WTP Values for GOES-R Benefit Analysis

As with any applied studies, each of the three studies on WTP for improved hurricane forecasts and warnings have specific strength and weaknesses. Overall, we feel the studies reinforce each other to indicate that members of the general public in hurricane vulnerable locations have significant willingness to pay for and motivation to use improved hurricane information. Some notes and perspectives on the strengths and weaknesses of each of the studies with respect to use for benefits transfer for the current analysis are presented in Table 10.

Table 10. Strengths and Weakness of the Studies

	Strengths	Weaknesses
Lazo et al., 2010	Published and peer reviewed. Included valuation for different levels of attributes (passes scope test)	Small sample (n=80) Older data (2007) Covers only one geographical location (Miami-Dade, Florida)
Molina et al., 2020	Most recent of the studies evaluated reviewed (data from 2019) Independent of current researchers (Lazo) prior work Large sample (n=4,650) WTP values extrapolated to large population Covers two geographical locations	Does not and cannot sum values across attributes. Some inconsistencies and lack of clarity on the survey and analysis Cannot directly determine sample representativeness. Would not pass scope test
WDEWE n.d.	Large sample (n=804) Comprehensive project across entire information value chain Covers two geographical locations	Unpublished and incomplete analysis Some inconsistencies in model estimates for certain attributes. Cannot perform scope test based on attribute levels included

Across these studies we summarize that there are:

- reasonable consistencies across the different studies in terms of respondents' experience with, attitudes towards, and preferences for hurricane information
- the derived benefit estimates are comparable with each other based on degree of forecast improvement and consistent with theory and expectations about the value of such information
- the sampling of different populations in different geographical locations suggests that these values are applicable across a much wider geographical area than just those surveyed
- the analysis across different time periods indicates continuing public demand for and benefits from improving hurricane forecast and warning information.

While implementing the same basic valuation approach, the studies cover a range of time periods, population samples, and derivation of WTP. A summary of the WTP estimates from the three studies is provided in Table 11.

Table 11. WTP Estimates, Year of Estimate, and Time Period of WTP

Study	Model / estimate	WTP Estimate	Year of Dollar Estimate
Lazo et al., 2010	Intermediate Improvement	$14.34	2007 $HH^{-1}YR^{-1}$ perpetual
	Maximum Improvement	$27.53	2007 $HH^{-1}YR^{-1}$ perpetual
Molina et al., 2020	Track forecasts	$26.07	2020 $HH^{-1}YR^{-1}$ for 10 yrs.
	Wind speed forecasts	$28.89	2020 $HH^{-1}YR^{-1}$ for 10 yrs.
	Precipitation forecasts	$21.63	2020 $HH^{-1}YR^{-1}$ for 10 yrs.
WDEWE, n.d.	AB-SQ+constant	$36.36	2012 $HH^{-1}YR^{-1}$ perpetual
	Weighted by population	$38.48	2012 $HH^{-1}YR^{-1}$ perpetual
	Weighted by certainty	$40.25	2012 $HH^{-1}YR^{-1}$ perpetual

Figure 17 copied from Molina et al., (their Figure 4 from the main manuscript) shows the historical reduction in track error and that projected into the decade evaluated in their survey. Essentially, the Lazo et al., 2010 work covers the period from 2008 through 2018 with the survey implemented in 2007 and the HFIP program projected to run about 10 years. The reduction in track error during that time period is 41.3% as per Molina et al.'s calculations. As indicated in Table 5 (page) on the Lazo et al., 2010 work, the track error was initially indicated to be "100 miles 48 hours in advance" (note that Molina et al., consider the error for 72 hours in advance) and a 41.3% reduction would have led to a track error of 58.7 miles which is less than the "65 miles 48 hours in advance" offered in the maximum improvement scenario.

The error reduction for windspeed, calculated by Molina et al., of 29.4% reduction in error over the 2008-2018 period applied to the Lazo et al.'s "maximum wind speed" attribute of "20 miles per hour 48 hours in advance," translates to about 14.1 MPH error. This is closer to the intermediate improvement suggested in the Lazo et al., study (15 MPH) rather than the "10 miles per hour" of the maximum improvement.

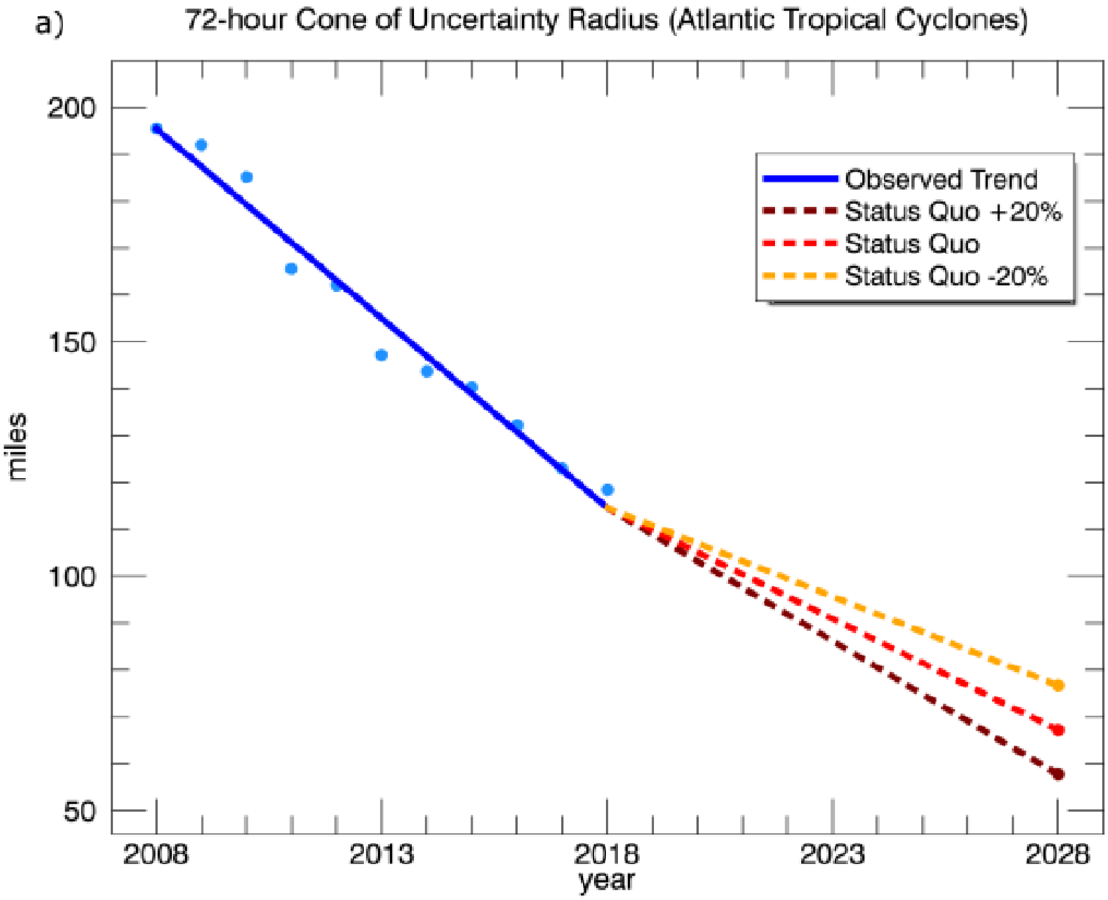

Figure 17. Historical and hypothetical hurricane track (cone of uncertainty) forecast errors.[36]

Based on this perspective on the various timing of the studies and reductions in forecast errors, to derive a WTP value to use in the GOES-R analysis we have:

- Averaged WTP estimates for the intermediate and maximum improvement programs from Lazo et al., 2010.
- Averaged the three WTP values for the different attributes from Molina et al.
- Averaged the three WTP values based on different models from the WDEWE data.

As shown in Table 12, we then use the consumer price index (CPI) to convert these three estimates into 2020$ and then averaged these three values to derive our baseline WTP value for the GOES-R analysis. The baseline WTP used is **$31.78** per household per year in 2020$.

[36] Copied from Molina et al., Figure 4.

Table 12. Summary of WTP Estimates

Study	Averaged WTP Estimate	Year of Dollar Estimate	Year	CPI[1]	2020$
Lazo et al., 2010	$20.94	2007 $HH^{-1}YR^{-1}$perpetual	2007	207.300	$26.17
Molina et al., 2020	$25.53	2020 $HH^{-1}YR^{-1}$ for 10 yrs.	2020	255.657	$25.87
WDEWE n.d.	$38.36	2012 $HH^{-1}YR^{-1}$ perpetual	2012	229.594	$43.29
				Average from three study averages (2020$)	**$31.78**
[1]Average annual All Urban Consumers CPI from: https://www.usinflationcalculator.com/inflation/consumer-price-index-and-annual-percent-changes-from-1913-to-2008/					

While the Molina et al., WTP values are estimated over a limited time-period rather than for perpetuity as in the Lazo et al., and WDEWE studies, we could convert Molina et al.'s estimate to a continuous stream in perpetuity by finding the value of that perpetuity that would generate the same total present value. For instance, $25.53 per year for 10 years discounted at 7% yields the same total present value at $13.40 a year in perpetuity also discounted at 7%. This is highly dependent on the discount rate (DR) as using a 3% DR would require only $7.09 in perpetuity and using a 0.3% DR would require only $1.17 in perpetuity to generate the same total present value as the $24.53 per year for ten years. If we convert the Molina et al., WTP values into a 23-year stream of payments (which is the lifetime of GOES-R for this analysis), rather than the 10 years indicated in their results, to maintain the same total present value the stream of payments would be 12.43, 14.37, or 16.98 at 0.3%, 3.0%, and 7.0% discount rates, respectively. As a compromise between using the lower payment streams over 23 years versus adding up the WTP values for the three different forecast attributes, we retain the average $25.53 of the 10-year payment stream for the individual attributes.

3.6 Application of the Lazo et al., Study in the GOES-R Phase 1 Interview Protocol

To connect the Lazo et al., study with the current benefit analysis for GOES-R, the interview protocol asked respondents how much they felt the improvement in forecast attributes as described in Lazo et al., could be attributed to GOES-R. Given the need to connect improvements attributable to GOES-R to an existing benefits study, we took this approach rather than asking the forecasters what the improvements were and then having to find an existing study to match those – a study which may not exist in a form usable for benefits transfer. In the interview protocol, WFO forecasters and GOES-R experts were asked a series of questions about the potential uses and impacts of GOES-R information. The Lazo et al., study was then described and the forecast attributes and levels, as presented in Lazo et al., were presented to the protocol respondents. They were then asked what percent of the improvements in each attribute could be attributed to information provided from GOES-R. Table 13 shows each individual response and summary statistics. Columns labeled 2 through 10 indicate respondent number and their percent response.[37] Also shown are the average and median responses and the standard deviation of the 9 responses. The bottom row shows their response indicating overall how much of the improvements could be attributed to GOES-R (Question 9 in the interview protocol; see Appendix 10.6).

As can be seen in Table 13, respondents felt that anywhere from 0% to 75% of improvements in forecast accuracy for individual attributes could be attributable to GOES-R. Overall, they felt that between 2% and 70% of improvements could be attributable to GOES-R as indicated in the last row. We note that Respondent 6 may have misinterpreted the question slightly when he indicated an overall improvement of 20% but then had distributed this across the four attributes rather than considering each attribute separately. We feel that his overall estimate is as intended but his allocation across the four attributes may understate the perceived improvements for those individually.

[37] Respondent #1 did not receive the same value attribution question and is not included in this data analysis.

Table 13. Interview Responses

Question in Protocol: "For each of the four attributes please indicate in the right-hand column what percentage of the potential improvement you feel could be attributed to information from GOES-R compared to information without GOES-R." (***Percent response shown***)[38]												
Respondent	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**Mean**	**Median**	**StdDev**
Forecasters can estimate when the hurricane will reach land.	75	25	15	60	10	10	75	15	5	32.22	15	29.17
Forecasters can estimate how strong winds will be when the hurricane reaches land.	75	25	15	30	8	5	50	10	1	24.33	15	24.33
48 hours in advance of landfall, forecasters can project within 100 miles where a hurricane will make landfall.	45	25	15	70	1	20	25	10	2	23.67	20	21.98
Forecasters can determine how much storm surge will be caused by the hurricane in terms of how high the water will rise above sea level.	25	10	5	70	1	5	10	5	0	14.56	5	22.06
Average of individual attributes	44.40	17.60	10.80	47.00	5.20	9.40	33.60	9.80	3.60			
Overall, what percentage of improvement in hurricane forecasting and warnings do you think is attributable to information from GOES-R?	70	25	10	60	20	10	60	10	2	29.67	20	26.24

Following the Delphi Method process and following a recommendation from the external reviewers, in November 2020 we undertook a follow-up elicitation with the same respondents to see if they wanted to update or revise the estimates from the December 2020 elicitation. Appendix 10.7 (Follow-Up Forecaster Interview Invitation Emails and Protocol) provides the email elicitation and the protocol sent in November 2020. Respondents were presented with their initial responses as well as the responses from the other 8 respondents and asked to indicate "I do not want to revise my estimate." If they did want to change it, they were asked to enter "Your revised estimate". Table 14 shows either their retained estimate or their revised estimate—in other words their final estimate.

[38] We note that an external reviewer questions whether respondents in the original WTP studies could understand and evaluate the forecast attributes as presented. While we assert that the WTP studies were all well designed, pre-tested, and contained internal consistency checks, we leave it to the reader to review the original reports and peer reviewed papers on those studies to further assess those details rather than replicate the content of those documents here.

Table 14. Interview Follow-Up Responses

Question in Protocol: "For each of the four attributes please indicate in the right-hand column what percentage of the potential improvement you feel could be attributed to information from GOES-R compared to information without GOES-R." (***Percent response shown***).									
Respondent	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Forecasters can estimate when the hurricane will reach land.	75	30	15	60	20	20	60	15	10
Forecasters can estimate how strong winds will be when the hurricane reaches land.	75	30	15	30	20	10	50	10	5
48 hours in advance of landfall, forecasters can project within 100 miles where a hurricane will make landfall.	45	30	15	50	10	5	25	10	2
Forecasters can determine how much storm surge will be caused by the hurricane in terms of how high the water will rise above sea level.	25	10	5	40	5	0	10	10	0
Average of the four attributes	**55**	**25**	**12.5**	**45**	**13.75**	**8.75**	**36.25**	**11.25**	**4.25**
Average (of the averages)								**23.53%**	
Standard Deviation (of the averages)								**17.94%**	

For each respondent we took the average of their responses for each attribute and then took the average and standard deviation of these nine estimates. The key number from the interview protocol is the average response from the 9 respondents for the overall improvements in hurricane forecasts. This is shown in the second to last row of Table 14 as the average of **23.53%**. As explained later, we also use the 17.94% standard deviation for the sensitivity analysis to derive a 90% confidence interval on our aggregated benefit estimates.

4. Aggregation of Benefits

4.1 Overview

The aggregation of benefits to a present value of benefits involved several adjustments based on past and likely future conditions of the hurricane vulnerable regions and populations. These were implemented to provide a reasonable estimate of the total benefits from improved hurricane information to U.S. Atlantic and Gulf Coast populations over the planned lifetime of the GOES-R series.

4.2 Adjustment of WTP for Inflation from 2007 to 2020

As noted in Table 12 above, the key WTP benefit estimates were adjusted for inflation from the year in which the surveys were conducted or the estimates were derived. These have all been converted to 2020$ and, thus, all analysis reported here is based in 2020$. This is held constant (e.g., constant dollars) and future inflation is not considered as all aggregation is in "real terms" (not current dollars).[39]

4.3 Duration of GOES-R Benefits

Based on guidance from the NOAA GOES-R program office, we assume capability for the GOES-R series starting in 2018 and continuing until 2040. This timeline is supported by the graphic "NOAA Geostationary Satellite Programs Continuity of Weather Observations"[40] that shows the GOES-R (GOES-16/GOES-East) became operational in late 2017 and will continue at least through 2032 and that other GOES satellites will continue seamless operations at least through 2040. The benefit analysis thus aggregates over 23 years (2018–2040 inclusive).

4.4 Income Growth

Results from Lazo et al., 2010 indicate that those households with higher income had larger WTP (specifically from Table 5, those with income less than $60,000 had a fitted WTP of $14.74 and those with income greater than $60,000 had a fitted WTP of $18.79). To estimate average annual increase in income over time, we use historical data from the Bureau of Economic Analysis interactive data tables.[41] Table SAGDP10N was accessed for "Per capita real GDP by state (Percent change from preceding period)" for the years 1997 through 2019 (22 years) and a simple average indicates 1.469% of annual real increased in per capita GDP. We use this to increase annual household WTP assuming a unit income elasticity of WTP.[42]

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[39] See https://www.census.gov/topics/income-poverty/income/guidance/current-vs-constant-dollars.html#:~:text=Constant%20or%20real%20dollars%20are,dollars%20adjusted%20for%20purchasing%20power. for a discussion of real versus constant dollars).

[40] See graphic: "NOAA Geostationary Satellite Programs Continuity of Weather Observations" https://www.nesdis.noaa.gov/s3/2022-01/GEO-Flyout-December-2021_signed.pdf. accessed March 25, 2020.

[41] https://apps.bea.gov/itable/iTable.cfm?ReqID=70&step=1#reqid=70&step=1&isuri=1 Accessed August 31, 2020 for Table SAGDP10N Per capita real GDP by state. Data downloaded for Annual GDP by State / Per capita real GDP / NAICS / All United States (Per capita real GDP (chained 2012 dollars) / All Years (1997-2019). From the raw data we calculated percent change year to year and then took a simple average of these 21-year percent changes. Percent changes ranged from -3.39% to 3.56% with an average of 1.469%, median 1.75%, and std dev of 1.53%.

[42] There is an ongoing literature on the income elasticity of WTP for environmental commodities derived from WTP studies and applicable to benefits transfer. The following four quotes are representative of these findings and indicate two studies finding income elasticities only less than unity and two finding income elasticities at or above unity. In part due to uncertainty with respect to the magnitude of the income elasticity of WTP (which may well vary from commodity to commodity) we also undertake sensitivity analysis using zero income elasticity (i.e., assuming no income growth in this analysis. "Meta-regression analyses show that income is statistically significant, explains a substantial proportion of WTP variability and its elasticity is considerable in magnitude ranging from 0.6 to almost 1.7." (Tyllianakis and Skuras. 2016). "…our empirical results suggest that the elasticity is not constant but is always less than one." (Barbier et al. 2017). "The study finds that income and willingness to pay vary directly and significantly. The elasticity estimates, in general, are

4.5 Choice of Population Areas and Size

The three studies assessed for WTP values are all based on survey samples relatively near coastal areas of the Atlantic Ocean and Gulf of Mexico. The choice of samples in each study was based on the fact that coastal or near-coastal residents are more likely to have hurricane experience or experience with receiving or responding to hurricane information. As pointed out in Molina et al.'s work though, those affected by hurricanes or weather patterns following hurricanes may extend far inland and, thus, the population having WTP for improved hurricane information likely extends to inland states and counties.

The most conservative population we could define would be only for those counties actually surveyed in one of the three studies:

- Miami-Dade counties in Florida in the Lazo et al., 2010.
- Counties exposed to either Hurricane Florence or Michael in 2018 in the Molina et al., project.
- Broward, Miami-Dade, and Palm Beach counties in Florida and Brazoria, Galveston, Harris, and Matagorda counties in Texas in the WDEWE project.

As discussed with respect to our initial population assumption, we feel that at a minimum we could define the study population as all hurricane-vulnerable coastal counties along the United States Atlantic Ocean, Gulf of Mexico, and Hawaiian Islands.[43] If we exclude the west coast of the U.S. and Alaska due the very low level of experience with hurricanes (cyclones) and generally low return rates of hurricanes in these areas, these states include: Alabama, Connecticut, Delaware, Florida, Georgia, Hawaii, Louisiana, Maine, Maryland, Massachusetts, Mississippi, New Hampshire, New Jersey, New York, North Carolina, Rhode Island, South Carolina, and Texas. For this minimum population count we use information from the US Bureau of the Census for the coastal population at risk from hurricanes as indicated in Darryl T. Cohen's 2018 "60 Million Live in the Path of Hurricanes"[44]. A link in this article[45] provides an Excel spreadsheet listing all coastal US counties and their 2016 populations. The population indicated for only the Atlantic Ocean, Gulf of Mexico and Hawaiian counties is 61,046,254. We then use Table HH4 from the US Census Historical Households Tables (November 2019 data)[46] to derive an average 2018 household size of 2.53 persons per household. This indicates 24,128,954 households in the Atlantic Ocean, Gulf of New Mexico, and Hawaiian hurricane-prone coastal counties. This is something of a mix of 2016 and 2018 population and household size data, but also is a conservative approach to identifying the number of relevant households in 2020 which likely have increased due to population growth and a slight ongoing decrease in household size.

As suggested in Figure 3 at the front of this report of the Hurricane Laura track forecast and warnings, there are significant potential impacts from hurricanes across a significant portion of the Eastern United States, including inland areas as far north as Illinois.

Alternatively, as discussed above, Renato Molina and Matt Varkony kindly provided a data set used in the Molina et al., work on the populations in counties experiencing winds related to hurricanes. This included 1,724 counties affected by Hurricanes Florence, Harvey, Ike, Irma, and Michael. Wind speeds varied from 4.2 mph to 79.9 mph and distance from shore ranged from 65.5 to 1,100,698 meters (this is the distance from the centroid of the county to the nearest shoreline (up to 684 miles)). Molina et al., extrapolated their WTP estimates based on all counties impacted by winds of 20, 30, 40 and 50 miles per hour related to a hurricane between 2006-2018. In their data set

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greater than zero, but less than unity." (Kahn 2014). Our results indicate that even when goods are demand luxuries they may or may not have income elasticities of willingness to pay which are greater than one." (Flores and Carson. 1997).

43 Hurricane forecasts and warnings from the NWS are provided to several other countries, especially in the Caribbean and Central America. The economic value of GOES-R-related hurricane forecasts improvements to end-users in these areas is not included in the current analysis but may also be substantial.

44 https://www.census.gov/library/stories/2018/08/coastal-county-population-rises.html. Accessed March 24, 2020.

45 https://www2.census.gov/library/stories/2018/08/coastline-counties-list.xlsx?#. Accessed March 24, 2020.

46 https://www.census.gov/data/tables/time-series/demo/families/households.html880025 Fr8800. Accessed March 24, 2020.

this covers Hurricanes Florence, Harvey, Ike, Irma, and Michael. From the data provided by Molina et al., Table 15 shows the cumulative county populations subject to hurricane-related winds during this period. This represents 1,724 counties (or parishes) in 28 states and the District of Columbia. The total population subject to any wind is 138,861,964 which represents 42.44% of the 327,167,439 U.S. population in 2018.[47] We note that increasing the period under consideration could only increase the population numbers as it would include counties not affected by the four hurricanes included by Molina, et al.

Table 15. County Population Subject to Hurricane Related Winds (2016-2018)

Max Wind Speed (mph)	Cumulative Population
>00	138,861,964
>10	138,317,700
>20	120,030,134
>30	50,778,220
>40	16,828,916
>50	5,551,323

To further characterize the portion of the U.S. population subject to hurricane impacts we obtained data from the SHELDUS database (https://cemhs.asu.edu/sheldus) for all impacts associated with tropical storms / hurricanes. SHELDUS™ "is a county-level hazard data set for the U.S. and covers natural hazards such thunderstorms, hurricanes, floods, wildfires, and tornadoes as well as perils such as flash floods, heavy rainfall, etc." We obtained records on all tropical storm / hurricane events between 1969 and 2019. This information was downloaded in csv format and converted into an Excel .xlxs format file. This yielded 6,290 records of events at the county level for crop and property damage in aggregate and on a per capita basis as well as injuries and fatalities. These records also include information on duration of events, but this information has not been used in the current analysis. Property and crop damages were provided in current and in 2018 dollars. We have used the 2018 dollar estimates here.

Using the total damages and per capita damages, we then backed out the county populations and determined the maximum population for each county.[48] (There may be some counties with reduced population, so this may overestimate population somewhat). For each record, we created a new variable called Total Impact (Total_Impact) which is the sum of the total crop and property damages and the number of fatalities multiplied by $10M.[49] We then derived the per capita total damage (TotImpPerCap).[50] As shown in Table 16, these monetized impacts range from less than 3/10ths of a penny to almost $150,000 in different counties with an average maximum per capita impact of $4,264.01.

Table 16. Summary Statistics from SHELDUS Tropical Cyclone Impacts

Variable	Mean	Std Dev	Minimum	Maximum	N
Population_Max	109,378.5	253,815	164	3,064,888	1,035
TotalImpPerCap_Sum	$4,264.01	$12,299.92	$0.00311	$149,750.5	1,035

47 Source: US Census: https://data.census.gov/cedsci/table?q=United%20States%202018%20total&g=0100000US&tid=ACSDT1Y2018.B01003&hidePreview=false. Accessed August 24, 2020.

48 Subsequent data analysis and manipulation was conducted in SAS enterprise Guide Version 7.1.

49 Current U.S. Department of Transportation (DOT) guidance on the appropriate value of statistical life (VSL) to use in policy analysis is $10,636,600 https://www.transportation.gov/sites/dot.gov/files/2020-01/benefit-cost-analysis-guidance-2020_0.pdf accessed July 1, 2020.

50 Based on this approach, over the 49 years (1969 to 2019) the total economic impacts are $177,472,689,736 and average annual impacts $3,621,891,627 (in 2018$).

The sum of the "population maximums" is 113,206,735 across 1,035 counties. This compares with the population of 61,046,254 across 190 coastal counties and 138,861,964 across 1,724 counties in Molina et al.[51]

While we feel it is appropriate to apply the full WTP estimate to coastal county populations, it seems likely that those further inland would have a reduced WTP for hurricane information due to their lower vulnerability and lower prior experience with hurricanes. The existing literature on the relationship between WTP and distance is usually with respect to a specific geographic location where a commodity is being valued (e.g., Pate and Loomis 1997; Hanley et al., 2003; Parker 2014). For instance, a lake with improved water quality or a recreational site for fishing or sight-seeing are examples of specific geographic locations. In the case of hurricane information, the relevant geographic location at least of "use value" would seem to be anywhere an individual could be affected by hurricane-related weather (including inland flooding and tornadoes) and would be able to use that information to improve decision making. Ideally, we would have a distance function or other weighting based on empirical results from a WTP study indicating WTP as a function of distance from coast, prior hurricane experience, or some other relevant weight variable. Currently, we do not have such a variable. We, therefore, explore a couple of empirically subjective approaches.

Using the SHELDUS data, one approach to determining an appropriate population to use in the benefit analysis is to weight each county population by the total per capita impacts relative to total per capita impacts in Miami-Dade county (i.e., setting the weight for Miami-Dade = 1 and weighting all other counties relative to this). The TotalImpPerCap_Sum for Miami-Dade is $7,878.46. Using this approach significantly reduces the effective weighted population as the average weight is only 0.54 across all counties. The weighted population using this approach is 26,426,323—considerably lower than the coastal-only population used in the initial (March 2020) baseline benefit analysis. We feel this would underestimate the relevant population as the Molina et al., study found higher WTPs in counties other than Miami-Dade that are weighted much lower than 1 using this approach. An alternative approach, again using the SHELDUS data, is to order the counties based on TotalImpPerCap_Sum and gives weights based on quartiles where the lowest one fourth TotalImpPerCap_Sum get a weight of 0.25, the second lowest quartile get a weight of 0.50, the next quartile a weight of 0.75 and the top quartile a weight of 1.00. This yields as weighted population of 61,188,858—almost the same as that used in the baseline analysis.

While we feel the above methods are justifiable, they represent a lower-bound evaluation of the potential population with a WTP for improved hurricane information. Our preferred approach is to use the Molina, et al., county population data and create quintiles based on the county center distance from a coastline. (The choice of quintiles versus quartiles or some other breakdown is subjective and would benefit from empirical studies on the relationship between distance to coast and WTP). We then weight the population as 1 for the closet quintile, 0.8 for the next closest quintile, down to a population weight of 0.2 for the fifth of the counties furthest from the coastline. This generates a distance-weighted population of 105,204,927. As we assume coastal residents have full WTP, for purposes of splitting this distance-weighted population total into coastal and non-coastal populations, we assume the 61,046,254 from are "coastal population" and the remainder (44,158,673) are "non-coastal population."

4.6 Population Growth

Neumann et al., 2015 used five scenarios to project coastal populations in several regions around the world. Using data for the United States from Table 7 (Top 25 countries with highest LECZ[52] population and people in the 100-year flood plain in 2030/2060, ranked by LECZ Scenario C 2060.) for the 2000-2030 projections, we calculate rates of population increase ranging from 0.43% to 1.35% annually with an average projected rate of 0.83%. Noting that Texas and Florida represent a significant part of this coastal population and that Texas' population grew 15.31%

[51] An external reviewer raised several issues with respect to the accuracy and reliability of the SHELDUS estimates. Note that we agree there are issues with extant damage databases, but we only use this information to derive a measure of the population vulnerable to hurricane impacts. Whether or not there was any impact is likely quite accurate in the SHELDUS database and thus we feel this is a valid approach for identifying historically hurricane vulnerable counties and population.

[52] LECZ is "Low Elevation Coastal Zone."

and Florida's grew 14.22% since April 2010[53], we feel the upper-bound growth rate can be applied to coastal U.S. populations. We thus use the 1.35% rate to project increases in coastal populations who would be willing to pay for improved hurricane information.

For non-coastal counties, we apply an average annual growth rate of the US population for the decade 2010-2019 according to the U.S. Census. This "average annual growth between July 2010 and July 2019 was 0.66% compared to an average of 0.97% for the previous decade."[54] We thus use the 0.66% rate to project annual increases in non-coastal populations who would be willing to pay for improved hurricane information.

4.7 Choice of Discount Rates

We use the real rate of discount of 0.3% for a 20-year "Real Interest Rates on Treasury Notes and Bonds of Specified Maturities (in percent)" as indicated in the December 17, 2019 OMB circular "2020 Discount Rates for 0MB Circular No. A-94" (https://www.whitehouse.gov/wp-content/uploads/2019/12/M-20-07.pdf, accessed March 24, 2020). Appendix 10.1 provides a more complete discussion of our choice of discount rate as well as an analysis real Treasury Bond rates to identify a rate of 1.185% to include in the analysis. As concluded in Appendix 10.1, "Based on this literature and professional judgement we have undertaken the baseline analysis using the 0.3% rate recommended in OMB Circular M-20-07 for an analysis period of 20 years (i.e., we did not extrapolate to 23 years which would have minimally increased the rate)."

4.8 Present Value of Benefits

Table 17 shows the values of the primary variables for the benefit aggregation as discussed above.

Table 17. Analysis Parameters

Line	Parameter	Level	Value
1	Time period	Beginning	2018
2		Ending	2040
3		total years (inclusive)	23
4	WTP	Baseline – Table 12	$31.78
7	Percent Attributable to GOES-R	Baseline	23.53%
8		Lower Bound 95% *	13.69%
9		Upper Bound 95% *	33.36%
10	WTP Attributable to GOES-R	Baseline – Line 4 x Line 7	$7.48
11		Lower 95% – Line 4 x Line 8	$4.35
12		Upper 95% – Line 4 x Line 9	$10.60
13	Population	Coastal	61,046,254
14		Inland	44,158,673
15	Pop Growth	Coastal	1.35%
16		Inland	0.66%
17	Household Size	Average	2.52

[53] Growth change pulled from interactive online map at: https://www.census.gov/library/stories/2020/04/nations-population-growth-slowed-this-decade.html?#:~:text=Growth%20has%20slowed%20every%20year,by%2019.5%20million%20or%206.3%25. Accessed August 24, 2020.

[54] U.S. Census: https://www.census.gov/library/stories/2020/04/nations-population-growth-slowed-this-decade.html?#:~:text=Growth%20has%20slowed%20every%20year,by%2019.5%20million%20or%206.3%25. Accessed August 24, 2020.

Line	Parameter	Level	Value
18	Discount Rate	Baseline	0.30%
19		T-Bill Decadal Average	1.185%
		Medium	3.00%
20		Highest	7.00%
21	Rate of Income Growth	Average	1.469%
* Lower and upper bound values derived based on standard deviation of attribution estimates from WFO respondents.			

Table 18 shows the baseline benefit calculation aggregating over the 23-year period where the WTP is increased annually; coastal and inland populations are increased annually and summed to total population and then converted to the number of households; and the discount factor is how much the annually aggregated WTP is reduced due to discounting. The last column indicates the present value (PV) of that year's WTP – that is the WTP for that year discounted back to the year 2018.

Table 18. Benefit Aggregation
Baseline Parameters

Year	WTP	Coastal Population	Inland Population	Total Pop	Households	Discount Factor	PV Year Benefit
2018	$7.48	61,046,254	44,158,673	105,204,927	41,747,987	1.0000	$312,155,032.55
2019	$7.59	61,870,378	44,450,120	106,320,499	42,190,674	0.9970	$319,141,817.39
2020	$7.70	62,705,629	44,743,491	107,449,120	42,638,540	0.9940	$326,288,687.93
2021	$7.81	63,552,155	45,038,798	108,590,953	43,091,648	0.9911	$333,599,388.97
2022	$7.93	64,410,109	45,336,054	109,746,163	43,550,065	0.9881	$341,077,754.44
2023	$8.04	65,279,645	45,635,272	110,914,917	44,013,856	0.9851	$348,727,709.61
2024	$8.16	66,160,920	45,936,465	112,097,385	44,483,089	0.9822	$356,553,273.22
2025	$8.28	67,054,093	46,239,646	113,293,738	44,957,833	0.9792	$364,558,559.83
2026	$8.40	67,959,323	46,544,827	114,504,150	45,438,155	0.9763	$372,747,782.07
2027	$8.53	68,876,774	46,852,023	115,728,797	45,924,126	0.9734	$381,125,253.02
2028	$8.65	69,806,610	47,161,246	116,967,857	46,415,816	0.9705	$389,695,388.68
2029	$8.78	70,749,000	47,472,511	118,221,510	46,913,298	0.9676	$398,462,710.39
2030	$8.91	71,704,111	47,785,829	119,489,940	47,416,643	0.9647	$407,431,847.46
2031	$9.04	72,672,116	48,101,216	120,773,332	47,925,925	0.9618	$416,607,539.73
2032	$9.17	73,653,190	48,418,684	122,071,874	48,441,220	0.9589	$425,994,640.24
2033	$9.31	74,647,508	48,738,247	123,385,755	48,962,601	0.9561	$435,598,118.02
2034	$9.44	75,655,249	49,059,919	124,715,169	49,490,146	0.9532	$445,423,060.86
2035	$9.58	76,676,595	49,383,715	126,060,310	50,023,933	0.9504	$455,474,678.19
2036	$9.72	77,711,729	49,709,647	127,421,377	50,564,038	0.9475	$465,758,304.05
2037	$9.86	78,760,838	50,037,731	128,798,569	51,110,543	0.9447	$476,279,400.08
2038	$10.01	79,824,109	50,367,980	130,192,089	51,663,527	0.9418	$487,043,558.66
2039	$10.16	80,901,735	50,700,409	131,602,143	52,223,073	0.9390	$498,056,506.03
2040	$10.31	81,993,908	51,035,032	133,028,939	52,789,262	0.9362	$509,324,105.57
						Aggregate Present Value	$9,267,125,117

Summing over the 23 years, the estimated Aggregate Present Value as shown in the last row is **$9,267,125,117**. Recognizing that there are multiple areas of uncertainty, we restate this as **$9.27B** rather than indicate too many significant digits which would suggest more precision than is realistic. We thus take **$9.27B** as our baseline derived estimate of the value of GOES satellites in improving hurricane forecasting and warning to the US hurricane vulnerable coastal populations.

4.9 Uncertainty and Error Bounds

There are numerous areas of uncertainty in the analysis that could lead to different benefit estimates. We address several of them in this section.

One of the primary sources of uncertainty or variation is the estimates provided in response to the interview protocol. Since this is a small sample (n<30), to calculate a confidence interval for the percent attribution we use a t-stat and a small sample correction. The 90% confidence interval on the percent of hurricane forecast improvements attributable to GOES is [13.69, 33.36] which when applied to the WTP for hurricane improvements yields a 90% confidence interval for WTP attributable to GOES of [$4.35-$10.60]. Using these values as the GOES WTP value, and keeping all other analysis parameters the same, yields a 90% confidence interval for the present value benefit estimate of **[$5.39B-$13.14B]**.

The rate of discount used (0.3%) is based on guidance from December 17, 2019 OMB circular "2020 Discount Rates for 0MB Circular No. A-94." This is an historically low rate of discount compared to rates often used in prior years, generally ranging from 3% to 7%. Undertaking the same analysis and varying only the rate of discount to 3% or 7% lowers the present value of benefits to **$6.85B** and **$4.68B**, respectively.

As noted in Appendix 10.1, we also identified a discount rate of 1.185% as a more recent real rate of discount based on an analysis of real 30-year Treasury Bond rates. Using a 1.185% rate of discount generates a present value estimate of **$8.36B** and a 90% confidence interval of $4.86B to $11.85B.

We further undertook a sensitivity analysis (a) holding both coastal and inland population constant and (b) holding wealth constant, and derived present value estimates of **$8.18B** and **$7.82B**, respectively.

Table 19 shows the aggregated Present Value Benefit Estimates from the baseline analysis and the various sensitivity analysis.

Table 19. GOES-R Benefits Uncertainty and Sensitivity

Analysis Scenario (baseline parameters as indicated in Table 17)	Present Value	Lower bound small sample 90% confidence interval	Upper bound small sample 90% confidence interval
Baseline benefit estimate – DR 0.3%	**$9.27B**	**$5.39B**	**$13.14B**
Discount Rate - 1.185%	**$8.36B**	**$4.86B**	**$11.85B**
Higher rate of discount – 3%	**$6.85B**	**$3.98B**	**$9.71B**
Higher rate of discount – 7%	**$4.68B**	**$2.72B**	**$6.64B**
No adjustment for population increases	**$8.18B**	**Not Calculated**	**Not Calculated**
No adjustment for wealth increase	**$7.82B**	**Not Calculated**	**Not Calculated**

In addition to the sensitivity analysis as describe above we undertook a "synthetic" Monte Carlo to 1) investigate the feasibility of undertaking such an analysis to support the benefits assessment and 2) examine which variables impacted the analysis the most. This analysis is reported in Section 10.2.

5. Summary, Connections with NESDIS/TPIO NOSIA 2.1, and Discussion

5.1 Summary

In this analysis we combined input from weather forecast experts (NWS employees at coastal Weather Forecast Offices) who identified the percent contribution of GOES-R to improved hurricane forecasts with results from three willingness-to-pay studies of the value of improved hurricane forecasts. Accounting for increased coastal population and increasing wealth, a central estimate of the present value of GOES-R over a 23-life span is **$9.27** billion US dollars (2020$) ($6.85B and $4.68B use discount rates of 3 percent and 7 percent respectively). We emphasize that these are benefits to the general public for improved hurricane information only and do not count other potential and likely sources of benefits from GOES-R. Examining factors leading to uncertainty in the benefit estimates, there is little variation if we assume population and wealth remain constant. The greatest source of uncertainty lays in the variation of the forecasters estimates of the percent attributable to GOES-R. This variation generates a 90% confidence interval of **$5.39B** to **$13.14B**. Further research may reduce these uncertainty bounds by better focusing the attribution estimates either with a larger sample of forecasters or with follow-up on the current sample to refine estimates. At this time, we have not accounted for uncertainty in the modeling estimates from three WTP studies (i.e., uncertainty in the regression estimates generating the baseline WTP values) but suspect they may be on a slightly smaller magnitude compared to the uncertainty from the forecasters' inputs.

5.2 NESDIS/TPIO NOSIA 2.1

For the duration of this work, our study team closely communicated with the NOAA/NESDIS Office of Technology Planning for the Integration of Observations (TPIO) which was responsible for producing the NOAA Observing Systems Integrated Analysis II (NOSIA-II), released in December 2015. In NOSIA-II, they created a very comprehensive database of NOAA observing systems, derived products and a survey of National Weather Service (NWS) forecaster's opinions/estimations of the contribution of those observing systems to the various NWS products and services: "The NOAA Observing System Integrated Analysis (NOSIA-II) is a capability used to document the relationship between available observing systems and their impact on NOAA's diverse services and scientific objectives. Understanding the relationship between the cost of available data sources and their impact on mission outcomes is fundamental to informing current and future observing system investments and managing NOAA's observing system architecture." (https://nosc.noaa.gov/tpio/main/nosia_main.html)

NOSIA-II was completed before the launch of the GOES-R series and employed the previous GOES N-O-P series observation data. The TPIO NOSIA Team has recently completed a refresh (referred to as 'NOSIA-2.1') which includes data and surveys for the GOES-R series satellites launched to date. Our GOES-R Socioeconomic Benefits Study Team has strong indications that TPIO's NOSIA-2.1 survey questions, and thus, their GOES-R contribution estimates, closely align with our study Phase 1 Hurricane products elicitation questions and resulting GOES-R contribution estimates. A December 31, 2020 memo from the NESDIS/OSAAP/TPIO Analysis Team to our study team (Appendix 10.8) definitively shows a moderate-to strong alignment between our Phase 1 Hurricane products survey questions to the parallel NOSIA Hurricane products.

It is due to this close alignment that our study team is very encouraged at the potential to use the NOSIA-2.1 survey data in our upcoming Phase 2 of this study for the GOES-R capabilities contributions (percentages) for the various NWS products and services in lieu of performing our own forecaster surveys. These NOSIA-2.1 data may significantly reduce the work needed to produce valuation/monetization numbers for other NWS products and services to which GOES-R contributes, especially where socioeconomic benefits study data already exists (e.g., Willingness-to-Pay, etc.).

5.3 Discussion

The overall objective of this effort is to perform a study of the socio-economic benefits of Geostationary Operational Environmental Satellite – R Series (GOES-R) satellites to the general public and selected market sectors. The objective of this first phase of the study is to undertake a "Pathfinder" initial effort to demonstrate one approach for quantifying the public benefits of GOES-R-related improvements in hurricane forecasts. In part the focus of this study was chosen based on available information (i.e., existing benefits studies we could apply benefits transfer to). Initial work was undertaken as well to generate a broad understanding of the GOES-R value chain that can support in future benefits assessments.

It is noteworthy to emphasize that the interview protocol results from this phase do not represent a large number of forecaster responses – the Pathfinder purpose was to demonstrate a credible process for determining the value of GOES-R economic benefits for one area of NWS forecasters' products.

Furthermore, since these results are a strong indicator of GOES-R economic benefits value for only one weather focal area of NWS products and services ($9.27B present value for hurricane forecast improvements applied to less than one half of the U.S. population), it seems reasonable to predict that the present value of GOES-R economic benefits value for all forecasts and products (e.g., for tornadoes, winter storms, droughts, flooding, fire weather, lightning, and even "normal weather") to which the GOES-R series contributes data would possibly be significantly larger.

An effort to assess all GOES-R-related product values would be a considerably larger task (in time, manpower and funding), than the current effort. As with any economic analysis, the resources to be applied to the analysis should be based on the desired use of the information.[55]

One important benefit from continuing to undertake this and similar analyses is to build the capacity for ongoing and future economic analysis for the next-generation satellite program (i.e., the Geostationary and Extended Orbits satellite system or GEO-XO[56]).

This effort has increased socio-economic literacy of the participants on the GOES-R technical side and the understanding of the GOES-R program and products on the economics side that can better support future studies. Such capacity is critical if NOAA is to not reinvent the wheel with every new socio-economic benefits study.

Finally, while this project was initiated as a "Pathfinder" project, we feel it is worth pursuing a broader critique and evaluation of the study and consider submitting its results to peer review. This would permit the project sponsors to obtain external input on the reliability and validity of the study process – the methods and results. It would also put this information "in the literature" which can provide a stronger foundation for other studies of the socio-economic benefits of observational systems.

5.4 Lessons Learned

Finally, we list a number of "lessons learned" from our work on this Pathfinder project as guidance to ongoing and future work:

- The value chain concept was very useful to: 1) improve and integrate communication across research disciplines, 2) inform research subjects about the topic and relevance of different participants in the project, and 3) ensure the validity and reliability of the economic assessment by demonstrating the connection of GOES-R observations to outcomes and economic values held by members of the general public.

[55] As noted by a reviewer "Practically speaking, there may never be a need to attempt a full assessment of GOES-R benefits. Once the lower bound estimates for several benefit classes exceeds the cost by a sufficient margin, the economic case for this investment will be solid. Except, of course, that this analysis looks at investments in GOES-R in isolation from alternative investments that could generate additional net benefits (e.g., other satellite investments that could achieve similar levels of performance or even investments in risk communication, which could potentially have a greater effect on societal outcomes than improved forecasting)." We agree that the appropriate use of benefit analysis should evaluate all alternatives and the choice made between all viable options.

[56] "NOAA's Geostationary and Extended Orbits (GEO-XO) satellite system is the ground-breaking mission that will advance Earth observations from geostationary orbit. GEO-XO will supply vital information to address major environmental challenges of the future in support of U.S. weather, ocean and climate operations. The GEO-XO mission will continue and expand observations provided by the GOES-R Series." https://www.nesdis.noaa.gov/GEO-XO. Accessed February 11, 2021.

- The combination of team members (a meteorologist, an engineer, and an economist) allowed us to characterize the information process throughout the value chain.
- Things we thought would be straight forward were not; and we better appreciate the value of some of the information resources, whether they be at the front end or back end of the value chain.
- The approach requires both identifying where GOES-R makes the greatest contributions, identifying available end-user economic benefit information, and filling in the process between these as there were neither the time nor resources to gather extensive primary data.
- A lack of primary economic studies in certain areas of interest to use for benefits transfer would limit the implementation of this Pathfinder approach, thus indicating the need for well-chosen primary studies to support future benefits assessments.
- Asking meteorologists to assign economic values to products does not work but they can characterize improvements in forecast information.
- Asking economists to assign information improvements to weather forecasts does not work but they can characterize the value of improvements in forecast information.
- The methods implemented in this Pathfinder – a combination of the value chain approach, modified expert elicitation, and benefits transfer – can be judiciously applied to focus on additional information processes affecting larger population segments with significantly larger aggregated economic benefits.

6. Acronyms List

ABI	Advanced Baseline Imager
AFD	Area Forecast Discussion
AMS	American Meteorological Society
AMV	Atmospheric Motion Vector
AOD	Aerosol Optic Depth
APV	Aggregate Present Value
AWIPS	Advanced Weather Interactive Processing System
BEA	Bureau of Economic Analysis
BLS	Bureau of Labor Statistics
CCD	Charged Coupled Diode
CG	Cloud-to-Ground (Lightning)
CIRA	Cooperative Institute for Research in the Atmosphere
CONUS	Continental United States
CPHC	Central Pacific Hurricane Center
CPI	Consumer Price Index
CSG	(The Aerospace Corporation) Civil Systems Group
CVM	Contingent Valuation Method
CWA	County Warning Area
DMW	Derived Motion Winds
EM	Emergency Management
ENTLN	Earth Networks Total Lightning Network
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
EUV	Extreme Ultraviolet
EXIS	Extreme Ultraviolet and X-ray Irradiance Sensors
FAA	Federal Aviation Administration
FEMA	Federal Emergency Management Agency
FQ	Forecast Quality
GEO-XO	Geostationary and Extended Orbits (future follow on to GOES-R)
GDP	Gross Domestic Product
GFDRR	Global Facility for Disaster Recovery
GLM	Geostationary Lightning Mapper
GOES	Geostationary Operational Environmental Satellite
GOES 16	Geostationary Operational Environmental Satellite 16 (launched/operational)
GOES-R	Geostationary Operational Environmental Satellite – R Series
GOES 17	Geostationary Operational Environmental Satellite 17 (launched/operational [currently serving as GOES West])
GOES-S	Geostationary Operational Environmental Satellite – R Series, 2nd in series
GOES-T	Geostationary Operational Environmental Satellite – R Series, 3rd in Series
GOES-U	Geostationary Operational Environmental Satellite – R Series, 4th in Series
GVAR	GOES Variable Report (GOES N-O-P) (Rebroadcast)
GOES East	Geostationary Operational Environmental Satellite – Launched and operated for the Eastern US over the Atlantic Ocean; currently is GOES 16
GOES I-M	Geostationary Operational Environmental Satellite – I Series; GOES I, L and M
GOES N-O-P	Geostationary Operational Environmental Satellite – N Series; GOES N, O and P
GOES West	Geostationary Operational Environmental Satellite – Launched and operated for the Western US over the Pacific Ocean; currently is GOES 17
GRB	Geostationary Operational Environmental Satellite (GOES) (Rebroadcast)
GVAR	GOES Variable Report (GOES N-O-P) (Rebroadcast)
HFIP	Hurricane Forecast Improvement Program
HWO	Hazardous Weather Outlook
IC	In-Cloud (Lightning)
IDSS	Integrated Decision Support System/ Intelligent Decision Support Systems
IFR	Instrument Flight Rules

INR	Image Navigation and Registration
IR	Infrared
ISBN	International Standard Book Number
JFK	John F Kennedy International Airport (3-Letter Identifier)
KM	Kilometer
KN	Knowledge Networks
KPP	Key Performance Parameter
L1RD	Level-1 Requirements Document
LECZ –	Low Elevation Coastal Zone
LGA	LaGuardia Airport (3-Letter Identifier)
LIFR	Limited Instrument Flight Rules
LLC	Limited Liability Corporation
MAG	Magnetometer
Mbps	megabits per second (10E6 bits)
MHz	Megahertz
MIC	(NWS) Meteorologist In Charge
MIT	Massachusetts Institute of Technology
MVFR	Marginal Visual Flight Rules
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NESDIS	National Environmental Satellite, Data, and Information Service
NHC	National Hurricane Center
NM or NMI	Nautical Mile
NMHS	National Meteorological and Hydrological Services
NOAA	National Oceanic and Atmospheric Administration
NOSIA II	NOAA Observations Systems Integrated Analysis II
NSEETS	NASA-wide Specialized Engineering, Evaluation and Test Services (contract)
NWP	Numerical Weather Prediction
NWS	National Weather Service
OMB	Office of Management and Budget
PRA	Preliminary Risk Assessment
PV	Present Value
QA/QC	Quality Assurance/Quality Check
QPE	Qualitative Precipitation Estimate
RGB	Red-Green-Blue
RUM	Random Utility Model
SC	Stated Choice
SEISS	Space Environment In-Situ Suite
SIGMET	Significant Meteorological Advisory
SOO	(NWS) Science Operations Officer
SP	Stated Preference
SQ	Status Quo
SST	Sea Surface Temperature
STAR	(NOAA/NESDIS) Center for Satellite Applications and Research
SUVI	Solar Ultraviolet Imager
SXI	Solar X-Ray Imager
TAF	Terminal Aviation Forecast
TCDAT	Tropical Cyclone Discussion Atlantic
TCPAT	Tropical Cyclone Public Advisory Atlantic
TOA	Top of the Atmosphere
TOR	Tornado Warning
TPC	Tropical Prediction Center
TPIO	(NOAA/NESDIS/OPPA) Office of Technology, Planning and Integration for Observation
TS	Tropical Storm

TWDAT	Tropical Weather Discussion Atlantic
TWO	Tropical Weather Outlook
UCAR	University Center for Atmospheric Research
UK	United Kingdom
USAID	United States Agency for International Development
UV	Ultraviolet
VIS	Visual
VOI	Value of Information
WBG	World Bank Group
WCM	(NWS) Warning Coordination Meteorologist
WFO	(NWS) Weather Forecast Office
WIVC	Weather Information Value Chain
WMO	World Meteorological Organization
WTP	Willingness To Pay
XRS	X-Ray Spectrometer

6.1 Sources for Acronyms

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- Geostationary Operational Environmental Satellite – R Series Acronyms – https://www.goes-r.gov/resources/acronyms

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8. Glossary of Technical Terms

Every discipline has its own language. This Appendix provides a glossary of key technical terminology to assist readers in understanding the language of economics, other related social sciences, space, and meteorology. These definitions have been compiled from the resources listed either with the term or footnoted at the end of this glossary.

Advanced Weather Interactive Processing System (AWIPS). This system replaced the Automation of Field Operations and Services (AFOS) in all NWS WFOs, WSFOs and Centers and allows the operator to overlay meteorological data from a variety of sources[1].

Atmospheric Wind Vectors (AMVs): Wind observations derived by tracking cloud or water-vapor features in consecutive satellite images. These observations are incorporated into numerical weather prediction (NWP) through data assimilation. In the assimilation algorithm, the weighting given to an observation is determined by the uncertainty associated with its measurement and representation (https://rmets.onlinelibrary.wiley.com/doi/full/10.1002/qj.2925).

Avoided Cost Method: A valuation method that assesses actual or imputed costs for preventing environmental deterioration by alternative production and consumption processes, or by the reduction of or abstention from economic activities (OECD, 2008); for example, measuring the benefits of reduced air pollution by assessing the cost of installing indoor air purifiers[2].

Aggregation: Summation of a benefit stream to a single (aggregated measure) of benefit. "… the aggregation of individuals' benefits in order to compare these with the total costs of a project or policy" (Bateman et al., 2006. p.450).

Basic Services: Those services provided by National Meteorological and Hydrological Services in discharging their governments' sovereign responsibility to protect the life and property of their citizens, to contribute to their general welfare and the quality of their environment and to meet their international obligations under the Convention of the World Meteorological Organization and other relevant international agreements (WMO, 1990)[2].

Baseline: A reference case, assuming no changes in historical trends, that can be compared to actual outcomes or impacts to measure changes due to both project outputs and confounding factors[1]. AS may be called a "counterfactual."

Benchmarking: A process in which a business evaluates its own operations (often specific procedures) by detailed comparison with those of another business (especially a competitor), in order to establish best practices and improve performance; the examination and emulation of other organizations' strengths (Oxford English Dictionary)[2]. "…the benchmarking method assesses the losses caused by earlier events and estimates the reduction in losses that could be achieved with improved services. However, the benchmarking method provides a way to address limited sector-level data and expertise on weather-related losses. This method relies on expert opinion and readily available data to assess the vulnerability of the country's overall economy to weather-related events and obtain results about direct damages caused by weather impacts." (WMO 2015. p.72.) (See also Tsirkunov et al., 2007)

Benefit: A quantified gain of an action (Tietenberg and Lewis, 2009; from benefit–cost analysis)[2].

Benefit–Cost Analysis: The quantification of the total social costs and social benefits of a policy or a project, usually in money terms. The costs and benefits concerned include not only direct pecuniary costs and benefits, but also externalities, meaning external effects not traded in markets. These include external costs, for example, pollution, noise and disturbance to wildlife, and external benefits such as reductions in travelling time or traffic accidents. Benefit–cost analysis is often used to compare alternative proposals. If the total social benefits of an activity exceed total social costs, this can justify subsidizing projects that are not privately profitable. If the total social costs exceed total social benefits, this can justify preventing projects even when these would be privately profitable (Black et al., 2012; from cost–benefit analysis)[2].

Benefit Transfer: Transferring benefit estimates developed in one context to another context as a substitute for developing entirely new estimates (Tietenberg and Lewis, 2009)[2]. (See also Rosenberger and Loomis 2003.)

Blended Satellite Products: NWS products derived from 'blending', combining, merging, or overlaying retrievals from various satellites, sensors, sensors, wavelengths and algorithms to create a superior product of great use to forecasters (This publication).

Coordination Group for Meteorological Satellites (CGMS): Group that globally coordinates meteorological satellite systems. This includes protection of in-orbit assets, contingency planning, improvement in quality of data, support to users, facilitation of shared data access and development of the use of satellite products in key application areas. (https://www.cgms-info.org/index_.php/cgms/page?cat=ABOUT&page=INDEX) accessed September 1, 2020.

Cone of Uncertainty: The cone of uncertainty represents the probable track of the center of the hurricane, based on the models used to make the forecast. The cone represents the uncertainty in the forecast of the storm's center, not necessarily the areas that will experience impacts (http://wxguys.ssec.wisc.edu/2019/09/17/hurricane-cone/). "The cone represents the probable track of the center of a tropical cyclone and is formed by enclosing the area swept out by a set of circles … along the forecast track (at 12, 24, 36 hours, etc.). The size of each circle is set so that two-thirds of historical official forecast errors over a 5-year sample fall within the circle." (https://www.nhc.noaa.gov/aboutcone.shtml accessed April 23, 2020.)

Confidence Interval: A type of estimate computed from the statistics of the observed data. This proposes a range of plausible values for an unknown parameter (for example, the mean). The interval has an associated confidence level that the true parameter is in the proposed range. (https://en.wikipedia.org/wiki/Confidence_interval).

Consumer Price Index (CPI): A measure that examines the weighted average of prices of a basket of consumer goods and services, such as transportation, food, and medical care. It is calculated by taking price changes for each item in the predetermined basket of goods and averaging them. Changes in the CPI are used to assess price changes associated with the cost of living. The CPI is one of the most frequently used statistics for identifying periods of inflation or deflation (https://www.investopedia.com/terms/c/consumerpriceindex.asp).

Consumer Surplus: Consumer surplus is the difference between what a consumer pays for a unit of a good and the maximum amount the consumer would be willing to pay for that unit. It is measured by the area between the price and the demand curve for that unit. Producer surplus is the difference between the amount a producer is paid for a unit of a good and the minimum amount the producer would accept to supply that unit. It is measured by the area between the price and the supply curve for that unit[4].

Contingent Valuation: A survey method used to ascertain WTP for services or environmental amenities (Tietenberg and Lewis, 2009)[2]. "Contingent Valuation is a method of estimating the value that a person places on a good. The approach asks people to directly report their willingness to pay (WTP) to obtain a specified good, or willingness to accept (WTA) to give up a good, rather than inferring them from observed behaviors in regular market places." http://www.fao.org/3/X8955E/x8955e03.htm Accessed April 23, 2020.

Cost: The value of the inputs needed to produce any good or service, measured in some units or numeraire, generally money (Black et al., 2012)[2].

Cost-Effectiveness: The achievement of results in the most economical way. This approach assesses efficiency by checking whether resources are being used to produce any given results at the lowest possible cost. Cost-effectiveness is most relevant as a concept of efficiency in cases such as the provision of defense, education, health care, policing or environmental protection, where it is sometimes difficult to measure the monetary value of the results achieved (Black et al., 2012)[2]. Cost-effectiveness analysis can provide a rigorous way to identify options that achieve the most effective use of the resources available without requiring monetization of all relevant benefits or costs. Generally, cost-effectiveness analysis is designed to compare a set of regulatory actions with the same primary outcome (e.g., an increase in the acres of wetlands protected) or multiple outcomes that can be integrated into a single numerical index (e.g., units of health improvement)[4].

Current Dollars: Inflation-included dollars (This publication). "The value of a dollar at the time at which it is measured. This varies from year to year …" https://financial-dictionary.thefreedictionary.com/ Accessed April 23, 2020.

Customer (of meteorological or hydrological services): In the context of a cost-basis hydromet service provision, this is the person or organization which pays for products and services and agrees on the specifications for delivery through a customer–supplier agreement or service-level agreement. The customer may or may not be the end-user (WMO, 2014b)[2].

Data Stewardship: The most common label to describe accountability and responsibility for data and processes that ensure effective control and use of data assets. Stewardship can be formalized through job titles and descriptions, or it can be a less formal function driven by people trying to help an organization get value from its data (https://www.dataversity.net/what-is-data-stewardship/).

Delphi Method: A method of eliciting information from subject matter experts on the value of a parameter of interest when measurement of the parameter is infeasible, too costly, or would take too long given the need to understand or use that parameter value. Generally, involves a follow-up step of re-elicitation of input from respondents to further refine the parameter estimates (This publication). "The method entails a group of experts who anonymously reply to questionnaires and subsequently receive feedback in the form of a statistical representation of the "group response," after which the process repeats itself." https://www.rand.org/topics/delphi-method.html Accessed April 23, 2020. (See also Landeta, 2006).

Demand: The desire and ability to acquire a good or service, or the quantity of a good or service that economic agents are willing to buy at a given price (Black et al., 2012).[2]

Derived Motion Winds (DMWs): The derived motion winds product is derived from using a sequence of visible or infrared spectral bands to track the motion of cloud features and water vapor gradients. The resulting estimates of atmospheric motion are assigned heights by using the cloud height product (https://www.goes-r.gov/products/baseline-derived-motion-winds.html).

Discounting: Placing a lower value on future receipts than on the present receipt of an equal sum. The fundamental reason for discounting the future is impatience: immediate consumption is preferred to delayed consumption (Black et al., 2012; from "discounting the future")[2].

Discount Rate: The interest rate at which future benefits or costs are discounted to find their present value (Black et al., 2012). See also discounting[2].

Dvorak Technique: Developed between 1969 and 1984 by Vernon Dvorak, it is a widely-used system to estimate tropical cyclone intensity (which includes tropical depression, tropical storm, and hurricane/typhoon/intense tropical cyclone intensities) based solely on visible and infrared satellite images. Within the Dvorak satellite strength estimate for tropical cyclones, there are several visual patterns that a cyclone may take on which define the upper and lower bounds on its intensity (https://en.wikipedia.org/wiki/Dvorak_technique).

Economic Efficiency: A general term that expresses the notion that all available resources are allocated optimally. Economic efficiency in this sense is purely descriptive and does not provide a precise definition or test. Pareto efficiency is a formalization of the concept of economic efficiency that provides a method of testing for efficiency (Black et al., 2012)[2].

Economies of Scale: The factors which make it possible for larger organizations or countries to produce goods or services more cheaply than smaller ones. Economies of scale that are internal to firms are due to indivisibilities and the division of labor. Economies of scale that are external to firms, but operate at the national level, arise from similar causes; there is scope for more specialist services in a larger economy than in a small one (Black et al., 2012)[2].

Economies of Scope: The benefits arising from engaging in related activities. These are similar to economies of scale, but whereas with economics of scale cost savings arise from carrying out more of the same activity, with economics of scope cost savings arise from engaging in related activities (Black et al., 2012)[2].

Efficiency: Obtaining the maximum output for given inputs. Efficiency in consumption means allocating goods or services between consumers so that it would not be possible by any reallocation to make some people better off without making anybody else worse off. Efficiency in production means allocating the available resources between industries so that it would not be possible to produce more of some goods or services without producing less of any other (Black et al., 2012).

Ex Ante: "Before" the actualization of the weather event (This publication).

Ex Post: "After" the actualization of the weather event (This publication).

Expenditures: Spending, by consumers, investors or the government. Consumer expenditure is restricted to purchasing real goods and services; acquiring assets of making transfers to others by individuals does not count as expenditure. Government expenditure is treated differently; some government expenditure is on real goods and services, but government interest payments and transfer payments to individuals, such as pensions, are counted as government expenditure, and government spending is not clearly divided between current and capital account items, possibly because these are hard to distinguish. National expenditure is what a country spends (Black et al., 2012)[2].

Expert Elicitation: In science, engineering, and research, expert elicitation is the synthesis of opinions of authorities of a subject where there is uncertainty due to insufficient data or when such data is unattainable because of physical constraints or lack of resources (https://en.wikipedia.org/wiki/Expert_elicitation).

Exposure: The presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected (IPCC, 2014)[2].

External Cost: A cost arising from any activity which does not accrue to the person or organization carrying out the activity. Negative externalities (external costs) cause damage to other people or the environment, for example by radiation, river or air pollution, or noise, which does not have to be paid for by those carrying out the activity (Black et al., 2012; from "externality"). See also externality[2].

Externality: A cost or benefit arising from any activity which does not accrue to the person or organization carrying out the activity. Negative externalities (external costs) cause damage to other people or the environment, for example by radiation, river or air pollution, or noise, which does not have to be paid for by those carrying out the activity. Positive externalities (external benefits) are effects of an activity which are pleasant or profitable for other people who cannot be charged for them, for example fertilization of fruit trees by bees, or the public's enjoyment of views of private buildings or gardens (Black et al., 2012)[2].

Forecast: A statement of expected meteorological (or hydrological) conditions for a specific period and for a specific area or portion of air space (WMO, 1992)[2].

Full-Disk Coverage: From a GOES-R Advanced Baseline Imager, it is an image of the full disk of the earth. Hemispheric Coverage of 83° local zenith angle, temporal resolution of 5-15 minutes, and spatial resolution of 0.5 to 2km Mesoscale. In mode 4, or continuous full disk mode, the ABI produces a full disk (Western Hemisphere) image every five minutes (https://www.goes-r.gov/spacesegment/abi.html).

Geostationary Orbit Satellite: A satellite that rotates at the same rate as the earth, remaining over the same spot above the equator[1]. For GOES-R, approximately 22,300 miles above the Earth (https://www.goes-r.gov/mission/mission.html).

Hazard: The potential occurrence of a natural or human-induced physical event or trend, or physical impact, that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, and environmental resources (IPCC, 2014)[2].

Hurricane Forecast Improvement Program (HFIP): A NOAA effort begun in 2010 whose goals are: "to reduce the average errors of hurricane track and intensity forecasts by 20% within five years and 50% in ten years with a forecast period out to seven days." (http://www.hfip.org/).

Hydrology: Science that deals with the waters above and below the land surfaces of the Earth, their occurrence, circulation and distribution, both in time and space, their biological, chemical and physical properties, and their interactions with their environment including their relation to living beings (WMO, 2012a). Hydrology is often subdivided into "scientific" and "operational" hydrology[2].

Hydrological Services: The provision of information and advice on the past, present and future state of rivers, groundwater and other inland waters, including but not limited to streamflow, river and lake levels, and water quality (this publication).

Hydrometeorology (a.k.a. Hydromet): Study of the atmospheric and land phases of the hydrological cycle, with emphasis on the interrelationships involved (WMO, 2012a). Joint costs: Costs which are shared by two or more products. It may be possible for a firm to measure the marginal cost of each product separately, but joint costs make it impossible to measure the average cost of each product (Black et al., 2012)[2].

Image Navigation and Registration: GOES Image Navigation and Registration (INR) Statistics (https://www.ospo.noaa.gov/Operations/GOES/goes-inrstats.html).

Information Intermediaries: Includes emergency managers, broadcast meteorologists, and private sector meteorologists which are critical to enhancing societal value (This publication).

Impact: A positive or negative benefit[3].

Intangible Impact: An impact that is difficult to quantify directly. Example: Attractiveness of a national park due to lower old-growth forest destruction from wildfires[3].

Interview Protocol: A researcher's instrument of inquiry—asking questions for specific information related to the aims of a study as well as an instrument for conversation about a particular topic (i.e., someone's life or certain ideas and experiences) (https://nsuworks.nova.edu/cgi/viewcontent.cgi?article=2337&context=tqr).

Loss: The result of a business operation where expenditures exceed receipts. Business losses may arise internally, through failure to produce enough of anything the market will buy to cover production expenses, or externally, through failure of others to pay bills due, or to repay debts. (Black et al., 2012)[2].

Marginal Benefit: The additional benefit from an increase in an activity. This is the addition to total benefit resulting from a unit increase if it varies discretely, or the addition to total benefit per unit of the increase, if it varies continuously. Marginal private benefit is marginal benefit accruing to the person or firm deciding on the scale of the activity, excluding any external benefits; marginal social benefit includes external benefits as well as private benefits accruing to the decision taker (Black et al., 2012)[2].

Marginal Cost: The additional cost from an increase in an activity. This is the addition to total cost resulting from a unit increase in output if it varies discretely, or the addition to total cost per unit of the increase, if it varies continuously. Marginal cost may be short run, when only some inputs can be changed, or long run, when all inputs can be adjusted. Marginal private cost is marginal cost falling on the person or firm deciding on the scale of the activity, excluding any external costs; marginal social cost includes external costs as well as private cost falling on the decisionmaker (Black et al., 2012)[2].

Marginal Utility: A concept from economics that describes the change in utility from consuming more or less of a good or service. Economists sometimes speak of a law of diminishing marginal utility, meaning that consuming the first unit usually has a higher utility than every other unit (https://simple.wikipedia.org/wiki/Marginal_utility).

Market: A market is any medium that allows providers and consumers for the exchange of goods and services to interact to facilitate an exchange. A market can be physical or virtual. The cost applied to the exchange may be defined or goods/services may be exchanged for free. Markets may be regulated with price established by a government entity or "free" wherein price is determined by supply and demand[3].

Mesoscale: Size scale referring to weather systems smaller than synoptic-scale systems but larger than storm-scale systems. Horizontal dimensions generally range from around 50 miles to several hundred miles. Squall lines, Mesoscale Convective Complexes (MCCs), and Mesoscale Convective Systems (MCSs) are examples of mesoscale weather systems[1].

METAR: An international code (Aviation Routine Weather Report) used for reporting, recording and transmitting weather observations[1].

Meteorology: The science of the atmosphere dealing, in particular, with its structure and composition, interactions with the oceans and land, movements (including weather-forming processes), weather forecasting, climate variability and climate change (WMO, 1996)[2].

Meteorological Services: The provision of information and advice on the past, present and future state of the atmosphere including information on temperature, rainfall, wind, cloudiness, air quality and other atmospheric variables and on the occurrence and impacts of significant weather and climate phenomena such as storms, floods, droughts, heatwaves and cold waves (this publication).

Met/Hydro Services: The provision of weather, climate, and hydrological information and products. See also climate services[2].

Monetized Impact: An impact that has been converted into the equivalent amount of money. This usually represents the maximum amount of money that a person or group would be willing to pay to obtain or avoid the impact[3].

Monte Carlo Method: A method of investigating the behavior of economic models which are too complicated for analytical solutions to be possible. A system is started off at a large number of initial positions chosen at random and followed through a numerical simulation to see how it evolves. Monte Carlo methods can be used to check whether a system has an equilibrium, and whether this is stable for any starting point, or some limited region of possible starting points (Black et al., 2012)2.

National Hydrological Service: An organization with national responsibility for river, lake and other hydrological observation, data management, research, modelling and streamflow forecasting and warning responsibilities (WMO, 1992, 2000, 2001, 2012b)[2]. The functions of the NHS are similar to those of the National Meteorological Service but focused mainly on the surface phase of the hydrological cycle; NHSs are often located with water supply or river management ministries[3].

National Meteorological and Hydrological Service (NMHS): Refers to an NMS or NHS, or an organization which combines the functions of both (WMO, 1992, 2000, 2012b). The plural, NMHSs, refers to multiple organizations (NMHS, NMS, and NHS)[2].

National Meteorological Service: An organization established and operated primarily at public expense to carry out those national meteorological and related functions which governments accept as a responsibility of the state in support of the safety, security and general welfare of their citizens and in fulfilment of their international obligations under the Convention of the World Meteorological Organization (WMO, 1992, 2000, 2012b; Zillman, 1999). The primary functions of an NMS are usually identified as observation, data archival, research, service provision and international cooperation.

Net benefits: The excess of benefits over costs resulting from some allocation (Tietenberg and Lewis, 2009)[2]. The size of net benefits, the absolute difference between the projected benefits and costs, indicates whether one policy is more efficient than another. The ratio of benefits to costs is not a meaningful indicator of net benefits and should not be used for that purpose. It is well known that considering such ratios alone can yield misleading results[4].

Net Present Value: The present value of a security or an investment project, found by discounting all present and future receipts and outgoings at an appropriate rate of discount (see discount rate). If the NPV calculated is positive, it is worthwhile investing in a project (Black et al., 2012)[2].

Non-Excludability: A property of a good or service that exists when no individual or group can be excluded from enjoying the benefits that good or service may confer, whether they contribute to its provision or not (Tietenberg and Lewis, 2009)[2]. It also means that once it is provided, we cannot prevent others from using the good (i.e., once a forecast is broadcast anyone and everyone can use that forecast) (this publication) (This publication).

Non-Market Goods and Services (or Commodity): Goods and services not distributed through markets (Black et al., 2012, from "non-marketed economic activities"), for example, clean air and water, scenic vistas and beach visits[2].

Non-Market Valuation: The economic valuation of goods and services not distributed through markets (Black et al., 2012; from "non-marketed economic activities"). Methods can be based on either revealed-preference or stated-preference methods and assessed either directly or indirectly[2].

Non-Rivalry: A property of a good or service that exists when consumption by one consumer does not reduce the quantity available for consumption by any other (Black et al., 2012; from "public good")[2]. In other words, it means that one person's use of that good doesn't consume the good and thus it is still useable by anyone else (i.e., your using a forecast does not diminish that information in a manner that keeps me from using the information) (this publication).

Nowcast: A description of current weather and a short-period (one to two hours) forecast (WMO, 1992)[2].

Numerical Weather Prediction: The forecasting of the behavior of atmospheric disturbances by the numerical solution of the governing fundamental equations of hydrodynamics, subject to observed initial conditions. Electronic computers and sophisticated computational models are required (Geer, 1996)[2].

Oceanography: The science of the ocean, including its composition, circulation and behavior, and the observation, description and forecasting of characteristic ocean phenomena on various time and space scales. It is often subdivided into physical, chemical and biological oceanography (Holland and Pugh, 2010)[2].

Operational Hydrology: (a) Measurements of basic hydrological elements from networks of meteorological and hydrological stations: collection, transmission processing, storage, retrieval and publication of basic hydrological data; (b) hydrological forecasting; (c) development and improvement of relevant methods, procedures and techniques in those areas of activity (WMO, 1996)[2].

Opportunity Cost: The cost of something in terms of an opportunity forgone. Opportunity cost is given by the benefits that could have been obtained by choosing the best alternative opportunity. For example, for a farmer the opportunity cost of growing wheat is given by what they would have earned if they had grown barley, assuming barley is the best alternative (Black et al., 2012)[2].

Pareto Efficiency: A form of efficiency for an economic allocation. An allocation is Pareto efficient if there is no feasible reallocation that can raise the welfare of one economic agent without lowering the welfare of any other economic agent. The concept of Pareto efficiency can be applied to any economic allocation whether it emerges from trade, bargaining, strategic interaction, or government imposition (Black et al., 2012)[2].

Pathfinder: An experimental plan or forecast to Guide, Lead, Trailblaze, Scout, Vanguard, Pioneer, Groundbreak and/or Experiment. https://www.google.com/search?q=pathfinder+definition&rlz=1C1GCEA_enUS828US828&oq=Pathfinder&aqs=chrome.2.69i59j69i57j0l6.5764j0j8&sourceid=chrome&ie=UTF-8 Accessed September 11, 2020.

Polarization: The action of restricting the vibrations of a transverse wave, especially light, wholly or partially to one direction (https://www.dictionary.com/browse/polarization).

Prediction: The act of making a forecast of a future occurrence, such as a weather event, or the forecast itself (Geer, 1996). In established meteorological usage, "prediction" is essentially interchangeable with "forecast", although some preferred usages exist for some timescales[2].

Preliminary Risk Analysis/Assessment (PRA): A preliminary risk analysis is an assessment of the level of the qualitative and quantitative risk involved in a clearly defined situation that involves a potential hazard. The risk analysis is carried out prior to the activity in order to specify all potential problem areas and put in place a plan to meet any challenges that may arise (https://www.safeopedia.com/definition/3676/preliminary-risk-analysis-pra).

Present Value: The value today of a future payment, or stream of payments, discounted at some appropriate compound interest – or discount – rate (Downes and Goodman, 2010). See also discount rate[2].

Probabilistic: Based on or adapted to a theory of probability; subject to or involving chance variation (https://www.google.com/search?q=Probabilistic&rlz=1C1GCEA_enUS828US828&oq=Probabilistic&aqs=chrome..69i57j0l7.5946j1j8&sourceid=chrome&ie=UTF-8).

ProbSevere: An NWS product or tool providing the forecaster with great situational awareness of the probability of severe convective weather using GOESR ABI and GLM data to monitor probabilistic trends in individual convective cells (This publication).

Proxy: A tangible quantity used to infer information about a related intangible impact. Example: Contributions to charities that work for species preservation might be a proxy for happiness due to biodiversity[3].

Public Good: A good that no consumer can be excluded from using if it is supplied and for which consumption by one consumer does not reduce the quantity available for consumption by any other. The first property is referred to as non-excludability, whereas the latter is termed non-rivalry. As a consequence of these properties, public goods cause market failure (Black et al., 2012)[2]. A public good is one that is both non-excludable and non-rivalrous (Samuelson 1954)[3]. "Public goods," such as defense or basic scientific research, are goods where provision of the good to some individuals cannot occur without providing the same level of benefits free of charge to other individuals.[4]

Public Weather Services: Those basic weather and related services provided, usually by the NMS, for the benefit of the public (WMO, 1999)[2].

Rainband: A cloud and precipitation structure associated with an area of rainfall which is significantly elongated. Rainbands can be stratiform or convective and are generated by differences in temperature. When noted on weather radar imagery, this precipitation elongation is referred to as banded structure. Rainbands within tropical cyclones are curved in orientation. Tropical cyclone rainbands contain showers and thunderstorms that, together with the eyewall and the eye, constitute a hurricane or tropical storm. The extent of rainbands around a tropical cyclone can help determine the cyclone's intensity (https://en.wikipedia.org/wiki/Rainband).

Random Disturbance or noise: In a dynamical system is a result of the error in the modelling of the system or the error due to sensor… (https://math.stackexchange.com/questions/1212429/what-exactly-is-a-random-disturbance-in-control-theory).

Random Utility Model (RUM): A theoretical model of decision making providing statistical methods to estimate respondent preferences and values for the different attributes (This publication).

Real Dollars: Inflation-removed dollars (This publication).

Resilience: The capacity of a social-ecological system to cope with a hazardous event or disturbance, responding or reorganizing in ways that maintain its essential function, identity, and structure, while also maintaining the capacity for adaptation, learning, and transformation (IPCC, 2014)[2].

Revealed-Preference Methods: Methods for valuating non-market goods and services based on actual observable choices and from which actual resource values can be directly inferred. These methods can be direct (such as market prices or simulated markets) or indirect (such as travel costs and hedonic pricing) (Tietenberg and Lewis, 2009, p. 39)[2].

Risk: The potential for consequences where something of value is at stake and where the outcome is uncertain, recognizing the diversity of values. Risk is often represented as probability of occurrence of hazardous events or trends multiplied by the consequences if the events occur. Risk results from the interaction of vulnerability, exposure, and hazard (IPCC, 2014)[2].

Scarcity: The property of being in excess demand at a zero price. This means that in equilibrium the price of a scarce good or factor must be positive (Black et al., 2012). Scarce goods or services are limited in availability[2].

Sensitivity Analysis: The study of how the uncertainty in the output of a model (such as a BCA) can be apportioned to different sources of uncertainty in the model input (Saltelli, 2002)[2].

Social Benefit: The total benefit from any activity. This includes benefits accruing directly to the person or firm conducting the activity, as well as external benefits outside the price system accruing to other people or firms (Black et al., 2012)[2].

Social Cost: The total cost of any activity. This includes private costs which fall directly on the person or firm conducting the activity, as well as external costs outside the price system which fall on other people or firms (Black et al., 2012)[2].

Social Welfare: The well-being of society. This can be measured by a social welfare function (Black et al., 2012)[2].

Social Welfare Function: (a) The level of welfare in an economy or society expressed as a function of economic variables. Social welfare is expressed as a function of the aggregate consumption levels of goods. Alternatively, an individualistic social welfare function is a function of individual utility levels. (b) A process for aggregating individual preferences into social preferences (Black et al., 2012)[2].

Socioeconomic: Concerning the use of resources belonging to a group of people[3].

(Solar) Energetic Particles (SEP): High-energy particles coming from the Sun. They consist of protons, electrons and HZE ions with energy ranging from a few tens of keV to many GeV (the fastest particles can approach the speed of light, as in a "ground-level event"). They are of particular interest and importance because they can endanger life in outer space (especially particles above 40 MeV) (https://en.wikipedia.org/wiki/Solar_energetic_particles).

Special Weather Services: Those services beyond the basic service aimed at meeting the needs of specific users and user groups, and which may include provision of specialized data and publications, their interpretation, distribution and dissemination (WMO, 1990)[2].

Stated-Preference Methods: Methods for valuating non-market goods and services in which respondents are directly asked about their WTP for a good or service, such as the preservation of a species. These methods can be direct (such as contingent valuation surveys) or indirect (such as contingent ranking or conjoint analysis) (Tietenberg and Lewis, 2009, p. 39)[2].

Statistically-Significant: Statistical significance is a determination by an analyst that the results in the data are not explainable by chance alone (https://www.investopedia.com/terms/s/statistically_significant.asp).

Storm Surge: An abnormal rise in sea level accompanying a hurricane or other intense storm, whose height is the difference between the observed level of the sea surface and the level that would have occurred in the absence of the cyclone. Storm surge is usually estimated by subtracting the normal or astronomic tide from the observed storm tide[1].

Supply: The amount of a good or service offered for sale. The supply function relates supply to the factors which determine its level. These include the price of the good, the prices of factor services and intermediate products employed in producing it, the number of firms engaged in producing it, and their levels of capital equipment (Black et al., 2012)[2].

Survey Codebook: Complete copy of a survey with all question and information as presented and asked with responses and summary entered as well as indicating the manner in which data is coded or entered into a data set.

Synoptic Scale: The spatial scale of the migratory high- and low-pressure systems of the lower troposphere, with wavelengths of 1000 to 2500 km[1].

Tangible Impact: A directly quantifiable impact. Example: Reduced timber losses due to more timely detection of wildfires[3].

Terminal Aerodrome Forecast (TAF): This NWS aviation product is a concise statement of the expected meteorological conditions at an airport (i.e., terminal aerodrome) during a specified period (usually 24 hours). Each country is allowed to make modifications or exceptions to the code for use in each particular country. TAFs use the same weather code found in METAR weather reports[1].

Trade-Off: The requirement that some of one good or one objective has to be given up obtaining more of another. The need to trade off goods or objectives against one another is a sign of economic efficiency; if it is possible to get more of one good without accepting less of another, or to achieve one objective without sacrificing another, the economy is not Pareto efficient (Black et al., 2012)[2].

Transaction Costs: The costs incurred in undertaking an economic exchange. Practical examples of transaction costs include the commission paid to a stockbroker for completing a share deal, and the booking fee charged when purchasing concert tickets. The costs of travel and time to complete an exchange are also examples of transaction costs. The existence of transaction costs has been proposed as the explanation for many of the economic institutions that are observed. For example, it has been argued that production occurs in firms rather than through contracting via the market because this minimizes transaction costs. Transactions costs have also been used to explain why the market does not solve externality problems (Black et al., 2012)[2].

Travel Cost Method: A pricing method that seeks to estimate a money value on the basis of the amount that people actually pay (in money and time) to gain access to beautiful sites, wilder-ness and so on, or to avoid various forms of damage and degradation. The costs incurred by visitors to a site are used to determine a demand curve for the recreational value they place upon that site. This can be the basis for estimates of the value of the site, and hence of the significance in monetary terms of benefit or damage to or loss of availability of the site (OECD, 2008)[2].

Uncertainty: A consciousness of limited knowledge about present facts or future events. There is a formal distinction between risk and uncertainty: risk applies when probabilities can be assigned to the likely occurrence of future outcomes; uncertainty applies when probabilities cannot be assigned (Black et al., 2012)[2].

User (of meteorological or hydrological services): The individual, organization or intermediary who receives the product and services and bases his or her decisions on them. For the delivery of public weather services, members of the public will ideally have their needs considered by an organization or representative body, although in reality, this is often done in an ad-hoc manner based on different information-gathering methods such as surveys or focus groups, involving little direct contact with individual members of the public (WMO, 2014b)[2].

Value Added: The amount by which the value of information, services or goods is increased at each stage of its production (Oxford English Dictionary)[2].

Value Chain: The process or activities by which value is added to information, services or goods, from production to final use or consumption (Stevenson and Waite, 2011)[2].

Value of Information: The value of the outcome of action taken with the information less its value without the information (West and Courtney, 1993, p. 230)[2].

Verification: A process for determining the accuracy of a weather or climate forecast or prediction) by comparing the predicted weather with the actual observed weather or climate for the forecast period (Glickman, 2000)[2].

Vulnerability: The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts including sensitivity or susceptibility to harm and lack of capacity to cope and adapt (IPCC, 2014)[2].

Weather: State of the atmosphere at a particular time, as defined by the various meteorological elements (WMO, 1992)[2].

Weather Forecast: A statement of expected meteorological conditions for a specific time period and for a specific area (Geer, 1996). A weather forecast usually specifies the various meteorological elements and phenomenon on a day-by-day basis out to the predictability limit of a few weeks[2].

Weather Information Value Chain (WIVC): Employing the value chain approach to assessing and understanding the weather information process (This publication).

Weather Service: The provision of weather forecasts and warnings about hazardous conditions, and the collection, quality control, verification, archiving and dissemination of meteorological data and products (WMO, 1992)[2].

Whole-of-Service Assessment: A comprehensive assessment of all the services provided by a given entity, as opposed to an assessment of one or more specific services[2].

Willingness To Pay: The maximum amount that an economic agent is willing to pay to acquire a specific good or service. The WTP is private information but may be obtained using revealed-preference methods or stated-preference methods (Black et al., 2012)[2]. The correct valuation measure for a non-market commodity such as weather information (This publication). "Opportunity cost" is the appropriate concept for valuing both benefits and costs. The principle of "willingness-to-pay" (WTP) captures the notion of opportunity cost by measuring what individuals are willing to forgo to enjoy a particular benefit. In general, economists tend to view WTP as the most appropriate measure of opportunity cost, but an individual's "willingness-to-accept" (WTA) compensation for not receiving the improvement can also provide a valid measure of opportunity cost[4].

World Weather Watch: The coordinated international system for the collection, analysis and distribution of weather information under the auspices of WMO (Geer, 1996)[2].

World Meteorological Organization: A specialized agency of the United Nations established for the meteorological and related purposes set down in Article 2 of the 1950 Convention of the World Meteorological Organization as subsequently amended (WMO, 2012b; Geer, 1996). Through a 1975 amendment, it was given United Nations system responsibility for operational hydrology. Its membership consists of national governments who carry out its responsibilities through a World Meteorological Congress and a number of other subsidiary constituent bodies, including an elected Executive Council[2].

8.1 Sources for Glossary

1. National Weather Service (NWS) Glossary: https://w1.weather.gov/glossary/
2. WMO-No. 1153 WMO-WBG-GFDRR, "Valuing Weather and Climate: Economic Assessment of Meteorological and Hydrological Services," May 2015
3. Coordination Group for Meteorological Satellites, Socioeconomic Benefits Tiger Team (SETT) Report: Valuing Meteorological Satellite Programs: Guidelines for Socioeconomic Benefit Studies, Appendix A: Key Terminology, March 2016
4. OMB Circular A-4. Issued September 17, 2003.

9. Appendices

9.1 Notes on Choice of Discount Rate

A critical parameter in the economic analysis is the choice of a discount rate. The NOAA Office of the Chief Economist recommended the use of a 3% or 7% discount rate rather than the 0.3% used in the baseline analysis.[57] We have reviewed primary guidance from the Office of Management and Budget as well as related literature to determine the baseline discount rate. There is a large body of theoretical and applied literature on this topic and some of the decisions on discount rate take on an ethical perspective which we cannot address in this analysis[58]. We recognize that the choice of discount rate is critical to the final benefit estimates with a lower value generating larger present value of benefits. We also recognize that this discussion is much broader and more complex than we can present here and, therefore, this appendix attempts to support our choice of discount rate while also noting we undertook a sensitivity analysis using the higher discount rates suggested.

OMB 2003. Circular A-4. (Regulatory Analysis) Issued: September 17, 2003 Section 8b states:

> Public Investment and Regulatory Analyses. The guidance in this section applies to benefit-cost analyses of public investments and regulatory programs that provide benefits and costs to the general public. Guidance related to cost-effectiveness analysis of internal planning decisions of the Federal Government is provided in Section 8.c.
>
> In general, public investments and regulations displace both private investment and consumption. To account for this displacement and to promote efficient investment and regulatory policies, the following guidance should be observed.
>
> Base-Case Analysis. Constant-dollar benefit-cost analyses of proposed investments and regulations should report net present value and other outcomes determined using a real discount rate of 7 percent. This rate approximates the marginal pretax rate of return on an average investment in the private sector in recent years. Significant changes in this rate will be reflected in future updates of this Circular.

It appears that NOAA's review recommendation to use a 7% or 3% rate is based historically on this guidance. As noted in OMB Circular M-20-07 dated December 17, 2019: "Real Discount Rates. A forecast of real interest rates from which the inflation premium has been removed and based on the economic assumptions from the 2021 Budget is presented below. These real rates are to be used for discounting constant-dollar flows, as is often required in cost-effectiveness analysis." Table 20 is copied from OMB Circular M-20-07 showing real rates of treasury bonds in 2019. These rates are recommended for analysis of "lease-purchase and cost-effectiveness analysis." This resource was the basis of our choice of 0.3% as our baseline discount rate.

Table 20. Real Interest Rates on Treasury Notes and Bonds of Specified Maturities (Percentages)

3-Year	5-Year	7-Year	10-Year	20-Year	30-Year
-0.4	-0.3	-0.2	0.0	0.3	0.4

57 Specifically, the NOAA review memo stated: "The rates presented in Appendix C do not apply to regulatory analysis or benefit-cost analysis of public investment. They are to be used for lease-purchase and cost-effectiveness analysis, as specified in the Circular. " OMB Circular A-4 says we should use a 7 percent discount rate for investment decisions (e.g., the costs and benefits of satellite sensors, IDSS, data collection by the NOAA fleet and most of the other things we deal with in our office), but Circular A-94 recommends sensitivity analysis using other discount rates. Circular A-4 says we should use both a 7 percent and a 3 percent discount rate to evaluate the benefits and costs of regulatory actions. OMB and NOAA's preference is that we show discounted benefits and costs for investments using 7 percent, 3 percent, and undiscounted values. -- See earlier comment. The 0.3 percent rate (updated annually) is for use only in lease-purchase and cost-effectiveness analysis. I don't think this analysis should show figures representing the use of that discount rate. OMB and NOAA prefer that benefits and costs be discounted using a 3 percent and 7 percent discount rate, along with the undiscounted values."

58 For instance, Kazlauskienė states "The works of the authors who analyze SDR problems present four alternative SDR determination approaches: social rate of time preference (SRTP); social opportunity cost of capital (SOC); weighted average approach; shadow price of capital (SPC) approach. In essence, these different approaches reflect differing views on how public projects affect domestic consumption, private investment, and cost of international borrowing (Harrison, 2010). The SRTP approach is based on the idea that the fundamental goal in welfare economics is to maximize the utility of society." (Kazlauskienė, 2015, p.462).

While OMB Circular M-20-07 states “The rates presented in Appendix C do not apply to regulatory analysis or benefit-cost analysis of public investment. They are to be used for lease-purchase and cost-effectiveness analysis, as specified in the Circular,” we feel the current guidance on appropriate discount rates is outdated (e.g., OMB Memo M-20-07 appears to use 2003 data) given current economic data that suggest a much lower average annual rate on 30-year Treasury bonds that supported the guidance to use 3% or 7%. To explore this, we derived an estimate of real current Treasury rates as shown in Table 21. We derived real rates of return on average 30 Year treasury bonds as show in Table 21.

Table 21. Derivation of Real 30-Year Treasury Rate

Year	Annual Average 30 Yr. Treasury	Inflation	Real Rate	Decadal Average
1981	13.446	8.912	4.534	
1982	12.763	3.826	8.937	
1983	11.175	3.787	7.388	
1984	12.420	4.043	8.377	
1985	10.795	3.791	7.004	
1986	7.785	1.187	6.597	
1987	8.588	4.332	4.256	
1988	8.961	4.412	4.550	
1989	8.446	4.640	3.806	
1990	8.610	6.255	2.355	5.780
1991	8.139	2.981	5.159	
1992	7.666	2.967	4.699	
1993	6.592	2.811	3.781	
1994	7.373	2.597	4.775	
1995	6.880	2.532	4.349	
1996	6.712	3.379	3.333	
1997	6.607	1.697	4.910	
1998	5.577	1.607	3.970	
1999	5.872	2.676	3.196	
2000	5.941	3.436	2.505	4.068
2001	5.495	1.604	3.891	
2002	5.430	2.480	2.950	
2006	4.913	2.524	2.389	
2007	4.838	4.109	0.729	
2008	4.278	-0.022	4.300	
2009	4.077	2.814	1.263	
2010	4.251	1.438	2.813	2.619
2011	3.911	3.062	0.849	
2012	2.922	1.760	1.162	
2013	3.446	1.513	1.933	
2014	3.338	0.653	2.685	
2015	2.841	0.639	2.202	

Year	Annual Average 30 Yr. Treasury	Inflation	Real Rate	Decadal Average
2016	2.597	2.082	0.515	
2017	2.893	2.116	0.777	
2018	3.111	1.939	1.172	
2019	2.580	2.292	0.288	
2020	1.556	1.289	0.267	1.185

The annual average 30-year Treasury rate was derived from daily averages taking the simple average across all reported days for each year. The data were downloaded from Macrotrends 30 Year Treasury Rate – 39 Year Historical Chart. Data are missing as the U.S Treasury suspended issuance of the 30-year bond between February 15, 2002 and February 9, 2006. The inflation rate was calculated from Census Bureau data from 1981 through 2020 (CPI for All Urban Consumers (CPI-U), All items in U.S. city average, all urban consumers, seasonally adjusted, Series ID CUSR0000SA0 Seasonally Adjusted). The real rate is taken as the difference between the annual yield and the inflation rate. Table 22 repeats Table 21 showing the decadal averages. As can be seen these have been declining steadily over the last four decades and were 1.185% on average between 2011 and 2020.

Table 22. Average Decadal Real 30-Year Treasury Rate

Decade	Decadal Average 30 Yr. Treasury
1981–1990	5.780
1991–2000	4.068
2001–2010	2.619
2011–2020	1.185

Based on this literature and professional judgement, we have undertaken the baseline analysis using the 0.3% rate recommended in OMB Circular M-20-07 for an analysis period of 20 years (i.e., we did not extrapolate to 23 years which would have minimally increased the rate). We further undertook analysis using the 1.185% rate we derived in our analysis of decadal real 30-year treasury rates and then also undertook a sensitivity analysis using 3% and 7% discount rates.

9.2 GOES-R Benefits “Synthetic” Monte Carlo Analysis

As part of the sensitivity analysis, we attempted to perform a Monte Carlo analysis using available data but felt there was insufficient information to perform this adequately. Here we present a “synthesized” Monte Carlo analysis using assumptions about the distributions of key parameters in part to guide future benefits analyses. That guidance includes obtaining additional information on the distribution of key parameters as well as expanding the size of the expert elicitation or intensifying the iterations and consensus values to reduce the standard deviation of those estimates. The standard deviations of the WTP estimates are likely in the literature but we did not extract that information given the approach we used of taking the simple average across the three extant studies. Future work could more rigorously evaluate the extant studies to generate more information on the distribution of reliable WTP estimates.

Table 23 shows the parameters that we allowed to vary in the Monte Carlo analysis, their baseline values, an estimated standard deviation, if available, and the assumptions or manipulations made for generating a feasible distribution for the analysis.

Table 23. Parameters for GOES-R Hurricane Benefits Synthetic Monte Carlo Analysis

Parameter	Level	Value
WTP	baseline	$31.78
From 3 extant studies	std dev	9.97
Divided by 2 to constrain variation	constrained std dev	4.99
Percent Attributable to GOES-R	baseline	23.53%
From Expert Elicitation	std dev	17.94
Divided by 3 to constrain variation	constrained std dev	5.98
Pop Growth		
Generated uniform distribution ±50% of baseline	coastal – baseline value	1.35%
Generated uniform distribution ±50% of baseline	inland – baseline value	0.66%
Rate of Income Growth		
Generated uniform distribution ±100% of baseline	average – baseline value	1.469%

We used statistical functions in Microsoft Excel to generate random variables from the baseline variables to use in the Monte Carlo analysis as follows:

- We used the NORMINV function in Excel and the mean WTP value and derived standard deviation to generate random WTP values. These are further constrained to be positive (>0).
- We used the NORMINV function in Excel and the mean "Percent attributable to GOES-R" value and derived standard deviation to generate random WTP values. These are further constrained to be positive (>0).
- For population (coastal and inland) and income growth we used the RAND() function in Excel to generate a uniformly distributed random number between 0 and 1 and then adjusted that to multiply by the baseline value to produce a random variable to use in the Monte Carlo analysis.

The analysis was set up in Excel using the baseline values for WTP, population, etc. as the primary baseline analysis. We used a 0.3% discount rate for the Monte Carlo analysis, but this is easily changed to other feasible values. We did not randomize the discount rate for the Monte Carlo analysis as the prior sensitivity analysis indicated how significant outcomes are dependents on the choice of discount rate and varying that in this synthetic analysis would likely have dominated the variability being evaluated in the other parameters.

We generated 10,000 total benefit estimates (in Billions 2020$) and undertook statistical analysis of that total benefit estimate as shown in Table 24 (below). The average total benefit (average across these 10,000 trials) is $9.35B as generated in the baseline analysis. This is comparable to the $9.27B generated in the baseline analysis.

The median estimate is slightly lower at $9.08B which is a result of having constrained certain variables to be non-negative (without that constraint the mean would also have been lower and likely identical to the median).

As across 10,000 trials, there are likely to be individual trials that incorporate multiple extreme values from the randomly distributed parameters, some actualizations will generate extreme benefit estimates. This is seen in that the minimum and maximum total benefit estimates are $1.27B and $22.80B respectively. Rather than using such values as indicative of the range we use a 90% confidence interval by sorting the results by magnitude and selecting the 500th lowest and 9500th highest estimates indicating the lowest 5% and highest 5%, respectively. This sorting generates a 90% confidence interval of $4.90B to $14.68B (i.e., 9,000 of the 10,000 trials or 90% lie in this range). This is comparable to the confidence interval from the baseline analysis of $5.39B-$13.14B which only considered the variation in the WFO forecasters expert attribution of benefits to GOES-R. The similarity in ranges between the baseline analysis and the Monte Carlo analysis is because of the constraints put on the variation of parameters in the Monte Carlo analysis were purposefully chosen to generate a reasonable similar range. In this way we can determine what the actual variation would need to be to generate the 90% confidence interval derived in the baseline analysis and to guide us about the quality of information needed on parameters in future research.

Table 24. Estimated Total Benefits (Billions 2020$)

Average	9.35
Median	9.08
Min	1.27
Max	22.80
Lower 5%	4.90
Upper 95%	14.68

Note that each iteration of the Monte Carlo analysis will generate slightly different results, so results shown here are the actualization of only one of these possible outcomes. In general, with 10,000 trials in each Monte Carlo analysis, the changes in the resulting output variables of interest (the mean and range of total benefits) will only change slightly.

The purpose of the "synthetic" Monte Carlo analysis was to investigate the feasibility of undertaking such an analysis to support the benefits assessment and examine which variables impacted the analysis the most. This was determined by evaluating which standard deviations must be better estimated to constrain the final benefit estimates to a reasonable range. It was found that more accurate representation of the variance of WTP is critical (we divided the standard deviation estimate from the 3 studies by 2). It may be possible to derive better understanding of the uncertainty of the WTP estimates from a more in-depth analysis of the studies available with closer examination of the statistical results in those studies or potentially reanalysis of those data with a focus on generating better information on the variability of the derived WTP values. It was also found that more accurate representation of the variance of the estimated percent attributable to GOES-R as derived from the expert elicitation is critical (we divided the standard deviation estimate from the N=9 respondents by 3). A larger sample of experts could narrow the standard deviation. As the sample standard deviation is a function of the square root of the inverse of (N-1), even with the same set of expert estimates, a larger sample would decrease the standard deviation. An even better approach would be a more rigorous implementation of the expert elicitation including more interaction between experts and further iterations to help them converge on a consensus value that would also have lower individual variation across respondents. The population growth and income growth parameters were derived from a literature search of extant estimates. Further review of the literature may provide a range of estimates or the confidence interval for these parameters. For this Monte Carlo analysis, we simply assumed a uniform distribution around the baseline value constrained to be non-negative. In future work, for any parameters found to be truly critical, it would be feasible to undertake an expert elicitation of the relevant experts (e.g., on population growth and future economic growth) to derive estimates and variation for such parameters.

As this Phase 1 effort was a pathfinder analysis to develop and demonstrate the approach as cogent and appropriate, we pursued the expert elicitation approach with only 9 subjects as this is acceptable practice for such elicitation. We leave a more-detailed analysis for Phase 2. Based on this exploratory "synthetic" Monte Carlo analysis, we feel that:

- "Beginning with the end in mind," future work could benefit from preliminary "synthetic" Monte Carlo analysis to understand and identify which parameters are most critical to the analysis and possibly guide choices of sample sizes or level of effort used to reduce uncertainty;
- In the current analysis, it may have been possible to reduce the uncertainty (e.g., magnitude of the standard deviation) of the WTP values by more extensive analysis of the underlying studies used in the benefits transfer or obtaining the primary data from those studies and undertaking econometric analysis specifically to characterize that uncertainty;

- In the current analysis, it may have been possible to reduce the uncertainty (e.g., magnitude of the standard deviation) of the estimates from the forecast experts of the percent of forecast improvement attributable to GOES-R by increasing the sample size or undertaking more in-depth elicitation with the experts to better converge on a consensus value; and
- Future analysis should include Monte Carlo analysis as a method of sensitivity analysis to better characterize the confidence interval on benefit estimates when many of the critical parameters have a degree of uncertainty.

9.3 GOES-R Instruments:

As previously stated, GOES-R has an impressive array of advanced-technology instruments to include the Advanced Baseline Imager (ABI), Geostationary Lightning Mapper (GLM), and a suite of space environment sensors. For images and a more-detailed description of these instruments, see Figure 18 and the following sub-sections.

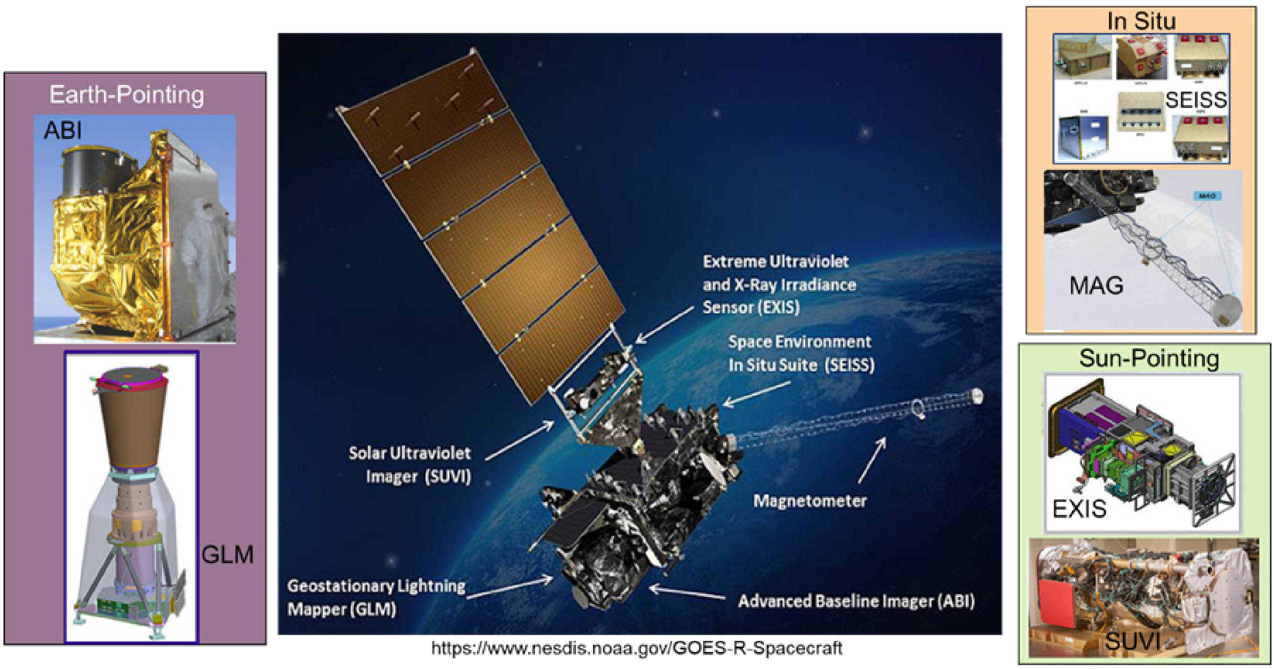

Figure 18. GOES-R instruments.

9.3.1 The Advanced Baseline Imager (ABI)

The ABI is the primary instrument on the GOES-R series spacecraft for imaging Earth's weather, oceans and environment. ABI views Earth with 16 spectral bands (compared to five on previous GOES), including two visible channels, four near-infrared channels, and ten infrared channels. It provides three times more spectral information, four times the spatial resolution, and five times faster coverage than previous GOES.

9.3.2 The Geostationary Lightning Mapper (GLM)

The GLM on board GOES-R series spacecraft, is the first operational lightning mapper flown in geostationary orbit. GLM detects the light emitted by lightning at the tops of clouds day and night and collects information such as the frequency, location and extent of lightning discharges. The instrument measures total lightning, both in-cloud and cloud-to-ground, to aid in forecasting developing severe storms and a wide range of high-impact environmental phenomena including hailstorms, microburst winds, tornadoes, hurricanes, flash floods, snowstorms, and fires.

9.3.3 Space Weather Instruments

The GOES-R Series hosts a suite of instruments that provide significantly improved detection of approaching space weather hazards. Two sun-pointing instruments measure solar ultraviolet light and X-rays. The **Solar Ultraviolet Imager (SUVI)** observes and characterizes complex active regions of the sun, solar flares, and eruptions of solar filaments which may give rise to coronal mass ejections. The **Extreme Ultraviolet and X-ray Irradiance Sensors (EXIS)** detects solar flares and monitors solar irradiance that impacts the upper atmosphere. The satellites also carry two instruments that measure their space environment. The **Space Environment In-Situ Suite (SEISS)** monitors proton, electron and heavy ion fluxes in the magnetosphere. The **Magnetometer (MAG)** measures the magnetic field in the outer portion of the magnetosphere.

9.3.4 Compact Coronagraph (CCOR)

The Compact Coronagraph (CCOR) is planned only to be flown on the GOES-U satellite. CCOR, developed by the Naval Research Laboratory, is an additional space weather instrument to be mounted on the solar pointing platform of the GOES-U satellite. The CCOR will image the solar corona (the outer layer of the sun's atmosphere) and help detect and characterize coronal mass ejections (CMEs). CCOR is designed to capture white light imagery of the upper solar corona. [For further explanation about CME's see **https://www.swpc.noaa.gov/phenomena/coronal-mass-ejections** on the Internet.] CCOR will capture at least two images of each CME and will be capable of operating during intense solar storms and flares.

CCOR will provide an enhanced capability over the Large Angle and Spectrometric Coronagraph (LASCO) instrument that is currently flown on the NASA Solar and Heliospheric Observatory (SOHO) satellite to characterize CMEs.

9.4 New GOES-R Products and Services

The GOES-R System provides a remarkable array of both atmospheric, terrestrial and space- environment products and services providing significant improvements over the previous GOES Series (N-O-P). The following sub-sections and tables provide details on these GOES-R products and services.

9.4.1 Level 1b Products

All Level 1b products represent calibrated measurements expressed in terms of physical units that are generated from L0 observation data during ground processing (Ref: GOES-R Series Product Definition And Users' Guide (PUG), Vol. 1, December 17, 2019: https://www.goes-r.gov/users/docs/PUG-L1b-vol3.pdf). For example, the Advanced Baseline Imager (ABI) instrument samples the radiance of the Earth in sixteen spectral bands using several arrays of detectors in the instrument's focal plane. Single reflective band ABI Level 1b Radiance Products (channels 1 - 6 with approximate center wavelengths 0.47, 0.64, 0.865, 1.378, 1.61, 2.25 microns, respectively) are digital maps of outgoing radiance values at the top of the atmosphere for visible and near-infrared (IR) bands. Single emissive band ABI L1b Radiance Products (channels 7 - 16 with approximate center wavelengths 3.9, 6.185, 6.95, 7.34, 8.5, 9.61, 10.35, 11.2, 12.3, 13.3 microns, respectively) are digital maps of outgoing radiance values at the top of the atmosphere for IR bands. Detector samples are compressed, packetized and down-linked to the ground station as Level 0 data for conversion to calibrated, geo-located pixels (Level 1b Radiance data). The detector samples are decompressed, radiometrically corrected, navigated and resampled onto an invariant output grid, referred to as the ABI fixed grid.(Ref: https://data.nodc.noaa.gov/cgi-bin/iso?id=gov.noaa.ncdc:C01501) The full list of GOES-R Level 1b products is contained in Table 25.

Table 25. GOES-R Level 1b Products

Advanced Baseline Imager (ABI)	Geostationary Lightning Mapper (GLM)
Aerosol Detection (Including Smoke & Dust)	Lightning Detection: Events, Groups & Flashes

Advanced Baseline Imager (ABI)	Geostationary Lightning Mapper (GLM)
Aerosol Optical Depth (AOD)	
Clear Sky Masks	**Space Environment In-Situ Suite (SEISS)**
Cloud & Moisture Imagery	Energetic Heavy Ions
Cloud Optical Depth	Magnetospheric Electrons & Protons: Low Energy
Cloud Particle Size Distribution	Magnetospheric Electrons & Protons: Med & High Energy
Cloud Top Height	Solar & Galactic Protons
Cloud Top Phase	
Cloud Top Pressure	**Magnetometer (MAG)**
Cloud Top Temperature	Geomagnetic Field
Derived Motion Winds	
Derived Stability Indices	**Extreme Ultraviolet & X-Ray Irradiance Sensors (EXIS)**
Downward Shortwave Radiation: Surface	Solar Flux: EUV
Fire/Hot Spot Characterization	Solar Flux: X-Ray
Hurricane Intensity Estimation	
Land Surface Temperature (Skin)	**Solar Ultraviolet Imager (SUVI)**
Legacy Vertical Moisture Profile	Solar EUV Imagery
Legacy Vertical Temperature Profile	
Radiances	
Rainfall Rate / QPE	
Reflected Shortwave Radiation: TOA	
Sea Surface Temperature (Skin)	
Snow Cover	
Total Precipitable Water	
Volcanic Ash: Detection & Height	
Reference: GOES-R Level-1 Requirements Document (L1RD)	

9.4.2 Level 2+ Products

GOES-R Series Advanced Baseline Imager (ABI) Level 2 Cloud and Moisture Imagery Products (CMIP) contains one or more Earth-view images with pixel values identifying brightness values that are scaled to support visual analysis. The product includes data quality information that provides an assessment of the cloud and moisture imagery data values for on-earth pixels. Cloud and Moisture Imagery product files are generated for each of the sixteen Advanced Baseline Imager (ABI) reflective bands (channels 1 - 6 with approximate central wavelengths 0.47, 0.64, 0.865, 1.378, 1.61, 2.25 microns respectively) and emissive bands (channels 7–16 with approximate central wavelengths 3.9, 6.185, 6.95, 7.34, 8.5, 9.61, 10.35, 11.2, 12.3, 13.3 microns respectively). In addition, there is a multiband product file where the imagery at all bands is included. The imagery value for the reflective bands, ABI bands 1 through 6, is a dimensionless reflectance factor quantity that is normalized by the solar zenith angle. These bands support the characterization of clouds, vegetation, snow/ice, and aerosols. The imagery value for the emissive bands, ABI bands 7 through 16, is the brightness temperature at the Top-Of-Atmosphere (TOA) in Kelvin. These bands support the characterization of the surface, clouds, water vapor, ozone, volcanic ash and dust based on emissive properties. (Ref: https://catalog.data.gov/dataset/noaa-goes-r-series-advanced-baseline-imager-abi-level-2-cloud-and-moisture-imagery-products-cmi). The full list of GOES-R Level 2+ products is contained in Table 26 below.

Table 26. GOES-R Level 2+ Products

Advanced Baseline Imager	
Aerosol Detection (Including Smoke & Dust)	Downward Shortwave Radiation: Surface
Aerosol Optical Depth (AOD)	Fire/Hot Spot Characterization
Clear Sky Masks	Hurricane Intensity Estimation
Cloud & Moisture Imagery* (KPP)	Land Surface Temperature (Skin)
Cloud Optical Depth	Legacy Vertical Moisture Profile
Cloud Particle Size Distribution	Legacy Vertical Temperature Profile
Cloud Top Height	Rainfall Rate / QPE
Cloud Top Phase	Reflected Shortwave Radiation: TOA
Cloud Top Pressure	Sea Surface Temperature (Skin)
Cloud Top Temperature	Snow Cover
Derived Motion Winds	Total Precipitable Water
Derived Stability Indices	Volcanic Ash: Detection & Height
Geostationary Lightning Mapper (GLM)	
Lightning Detection: Events, Groups & Flashes	
Reference: https://www.goes-r.gov/resources/docs/Latest_Program_Brieing.pdf	

9.4.3 Further Product Information

Multiple sources have developed operational, non-operational products as derived from GOES-R instruments. Other materials listed may be tutorial in nature, especially for new capabilities from the GOES-R series of satellites.

This section is not a comprehensive list and readers are directed to web pages of relevant NOAA Cooperative Institutes or other agencies as noted in the table[59]. Some entries in this section contain short reference documents at the Virtual Institute for Satellite Integration Training (VISIT) at the Regional and Mesoscale Meteorology Branch of the Cooperative Institute for Research in the Atmosphere (CIRA) at Colorado State University. [See https://rammb2.cira.colostate.edu/training/visit/quick_reference/#tab17 on the Internet for further information.]

This section should not be used as a primary source by meteorologists and scientists for operational and non-operational products derived from GOES-R series data. Instead, it is an incomplete list of such products which may be useful in support of socioeconomic studies.

[59] CIMSS: www.cimss.ssec.wisc.edu; CIRA: www.cira.colostate.edu; CISESS: https://cisess.umd.edu/; NWS Columbia SC: www.weather.gov/cae; SPC: www.spc.noaa.gov; SPoRT: www.weather.msfc.nasa.gov; STAR: www.star.nesdis.noaa.gov.

Table 27. Selected Operational and Non-Operational Products

Product	Description	Information Source
Aerosol Detection	Qualitative Aerosol product to detect presence of dust and smoke in atmosphere.	CIMSS
Aerosol Optical Depth	Aerosols released into the atmosphere from cars, industry, fires, dust storms that may affect human health, reduce visibility and alter Earth's radiation budget.	CIMMS
Air Mass RGB	Used to diagnose the environment surrounding synoptic systems by enhancing temperature and moisture characteristics of air masses	SPoRT
Ash RGB	Day and Night detection of volcanic ash and sulfur dioxide, both hazards to public health and aviation	SPoRT
Baseline Cloud Top Pressure	Estimates cloud top pressure	CIMSS
Baseline Cloud Top Temperature	Estimates temperature of cloud tops	CIMSS
CIMSS Natural True Color	Product Created to simulate true color	CIMSS
Clear Sky Mask	Establishes the presence or lack of clouds	CIMSS
Cloud Optical Depth	Provides information on radiative properties of clouds	CIMSS
Cloud Particle Size Distribution	Provides valuable information regarding radiative properties of clouds	CIMSS
Cloud Phase Baseline Product	Describes cloud top composition	CIMSS
Cloud Top Height	Estimates the top of the cloud in feet, useful for aviation	CIMSS
Day Cloud Convection RGB	Helps to distinguish high and low clouds and can help reveal wind sheer	CIRA

Product	Description	Information Source
Day Cloud Phase Distinction RGB	Evaluate the phase of cooling cloud tops to monitor convective initiation, storm growth and decay and for snow identification on ground	CIRA, CIMMS, SPC
Day Convection RGB	Helps to increase nowcasting capabilities of severe storms by identifying early stage of strong convection	SPoRT
Day Land Cloud Fire RGB	Highlights fire hotspots with red color but changes interpretation of the water vs ice clouds	SPoRT
Day Land cloud RGB	Used for discriminating water/ice clouds to identify low/high clouds	SPoRT
Day Snow/Cloud Layers	Daytime only multi band product to help distinguish clouds from snow and ice	CIRA
Day Snow/Fog RGB	Provides greater contrast between snow, water and ice clouds using ABI Imagery	CIRA
DEBRA-Dust Product	Dust identification product through 2 band difference products from ABI	CIRA
Derived Motion Winds	Sequential ABI images can provide wind vectors. Areas of wind shear and jet maxima can be identified	CIMMS
Derived Stability Indices	Different stability indices to diagnose where convection might occur	CIMMS
Differential Water Vapor RGB	Analysis of water vapor upper-level distribution. Used for high-impact wind events and for predicting changes in hurricane intensity and extratropical transition	SPoRT
Dust RGB	Contrasts airborne dust from clouds	SPoRT

Product	Description	Information Source
Fire / Hot Spot Characterization	Fire Area, Fire Power and Fire Temperature products to aide in better monitoring of wildfires and their rapid changes	CIMSS
Fire Temperature RGB	Allows a user to identify where most intense fires are occurring	SPoRT
Geo Color	Close approximation to True Color Imagery	CIRA
GLM and Ground-Based Networks	Intercomparison of GLM and Ground-based Lightning Networks	SPoRT
GLM Applications	Descriptive application guide for GLM	SPoRT, STAR
GLM Average Flash Area & Total Optical Energy	Detect/Monitor Thunderstorm Growth, monitor convective mode and storm evolution and identify and strengthening and weakening storms. See data sheet	CICS, STAR
GLM Data Quality	Maximizes GLM detection efficiency while minimizes false alarm rate	CICS, CIMMS, SPoRT, STAR
GLM Full Disk Gridded Products	GLM Full Disk products for lightning in the Western Hemisphere	CISESS, STAR
GLM Gridded Products	Portrays the quantity/extent of GLM flashes/events in a single Gridded product	CIMMS, SPoRT, STAR
GLM Minimum Flash Area (MFA)	Minimum size of any GLM flash during a specified time period	CISESS, STAR
GOES-R Cloud Thickness	Estimates the depth of lowest deck of clouds made up of water droplets used to estimate when radiation fog might dissipate	CIMSS
GOES-R IFR Probability	Combination of GOES cloud information with low-level saturation from RRM to determine probability of IFR conditions for aviation	CIMSS

Product	Description	Information Source
Legacy Vertical Profiles	CONUS products used to monitor the evolution of the atmosphere.	CIMSS
Night Fog Difference	Brightness Temperature Difference used to identify clouds made up of water droplets	CIMSS
Nighttime Microphysics RGB	Aids in the distinction between low clouds and fog in GOES imagery	SPoRT
Sea Surface Temperature Product	Useful in analyzing oceanic SST for Hurricane Intensity Applications	CIRA
Simple Water Vapor RGB	Allows a forecaster to distinguish where moisture return is occurring in the absence of clouds	NWS Columbia SC
Split Cloud Phase Brightness Temperature	This product can differentiate between thick and thin cirrus and between clouds made of ice and those of water.	CIMSS
Split Ozone	Split Ozone Brightness Temperature Difference can reveal the influence of ozone absorption	CIMSS
Split Snow Reflectance Difference	Highlights regions where ice is present as either glaciated cloud or snow/ice on ground	CIMSS
Split Water Vapor Difference	Band difference gives an approximation of the concentration and distribution of water vapor	CIMSS
Split Window Difference	Brightness Temperature Difference highlights low-level moisture and dust	CIMSS
Sulfur Dioxide RGB	SO2 gas created by volcanic eruptions or from power plants may be detected	CIRA
Total Precipitable Water Product	Used to monitor moisture gradients and time trends in clear sky conditions. Used for convective and flood events, atmospheric rivers and mesoscale analysis. See data sheet.	CIRA

Product	Description	Information Source
Turbulence Probability Product	Machine learning algorithm to detect turbulence for aviation applications	CIMSS

9.4.4 Transition from GVAR to GRB

The transition from the previous GOES Variable (GVAR) Rebroadcast service to the GOES Rebroadcast (GRB) service on GOES-R series spacecraft has provided considerable upgrades to the system's modes and capabilities, especially in the areas of more and better imager modes, added polarization and data compression, higher data rate, more data sources and added space weather and lightning data. Table 28 below provides comparisons of specific GVAR versus GRB modes and capabilities values.

Table 28. GOES-R Transition from GVAR to GRB

Modes & Capabilities	GOES Variable (GVAR)	GOES Rebroadcast (GRB)
Full Disk Image	30 minutes	5 minutes (Mode 4)
		15 minutes (Mode 3)
Other Modes	Rapid Scan, Super Rapid Scan	3000 km x 5000 km CONUS: 5 Mins
		1000 km x 1000 km Mesoscale: 30 Sec
Polarization	None	Dual circular polarized
Data Compression	None	Lossless compression
Receive Center Frequency	1685.7 MHz (L-Band)	1686.6 MHz (L-Band)
Data Rate	2.11 Mbps	~30 Mbps
Antenna Coverage	Earth coverage to 5o	Earth coverage to 5o
Data Sources	Imager & Sounder	ABI (16 Bands), GLM, SEISS, EXIS, SUVI, MAG
Space Weather	None	~2 Mbps
Lightning Data	None	~0.5 Mbps
Reference: https://www.goes-r.gov/resources/docs/Latest_Program_Briefing.pdf		

9.5 GOES-R Improvements over previous GOES series (GOES N-O-P and I-M)

GOES-R was designed to make some epic improvements in the capabilities of the previous GOES series, GOES N-O-P and I-M.

9.5.1 GOES Satellite Designations and Status

Table 29 is GOES Satellite Designations and Status (as of September 14, 2020). For most of this report we refer to the launch designation of satellites. The GOES-R series is comprised of GOES-R, -S, -T, and -U.

Table 29. GOES Satellite Designations and Status

Launch Designation	Operational Designation	Launch	Status
GOES-A	GOES-1	16-Oct-75	Decommissioned 1985
GOES-B	GOES-2	16-Jun-77	Decommissioned 1993, reactivated 1995, deactivated 2001
GOES-C	GOES-3	16-Jun-78	Decommissioned 2016
GOES-D	GOES-4	9-Sep-80	Decommissioned 1988
GOES-E	GOES-5	22-May-81	Decommissioned 1990
GOES-F	GOES-6	28-Apr-83	Decommissioned 1992
GOES-G	N/A	3-May-86	Failed to orbit

Launch Designation	Operational Designation	Launch	Status
GOES-G	N/A	3-May-86	Failed to orbit
GOES-H	GOES-7	26-Feb-87	Decommissioned 2012
GOES-I	GOES-8	13-Apr-94	Decommissioned 2004
GOES-J	GOES-9	23-May-95	Decommissioned 2007
GOES-K	GOES-10	25-Apr-97	Decommissioned 2009
GOES-L	GOES-11	3-May-00	Decommissioned 2011
GOES-M	GOES-12	23-Jul-01	Decommissioned 2013
GOES-N	GOES-13	24-May-06	Inactive
GOES-O	GOES-14	27-Jun-09	On-orbit spare
GOES-P	GOES-15	4-Mar-10	Operational GOES West backup
GOES-R	GOES-16	19-Nov-16	In operation as GOES East
GOES-S	GOES-17	1-Mar-18	In operation as GOES West
GOES-T			Scheduled for launch in December 2021
GOES-U			Launch commitment date 1Q FY 2025
Source: https://www.goes-r.gov/mission/history.html. Accessed September 14, 2020.			

9.5.2 GOES I-M, GOES N-O-P and GOES-R Performance Capabilities

A side-by-side comparison of GOES-R performance capabilities with those of the two previous GOES series of satellites shows important GOES-R improvements in almost every major area. For example, GOES-R imaging has half the visible resolution, one quarter the IR resolution, six times the coverage rate and over three times the number of channels compare to the previous GOES series. Table 30 vividly provides side-by-side comparisons of specific performance capability values between GOES I-M, N-O-P and GOES-R.

Table 30. Improvements from GOES I-M and N-O-P to GOES-R

	GOES I-M	GOES N-P	GOES R
Performance Capability			
Imaging			
Visible Resolution	1 km	1 km	0.5 km
IR Resolution	4-8 km	4-8 km N 4 km O/P	1-2 km
Full-Disk Coverage Rate	30 min	30 min	5 min
Number of Channels	5	5	16
Solar Monitoring	GOES-M only	Yes	Yes
Lightning Detection	No	No	Yes
Operate through Eclipse	No	Yes	Yes
Ground System Backup	Limited	Limited	Enhanced
Archive and Access	Limited	Limited	Yes
Reference: https://www.goes-r.gov/resources/docs/Latest_Program_Briefing.pdf			

9.5.3 GOES N-O-P vs GOES-R Instruments Differences

When one focuses in on the GOES instruments, great improvements in GOES-R over GOES N-O-P are evident. Table 31 shows a dramatic side-by-side comparison of instrument features and capabilities between GOES-R and GOES N-O-P differences.

Table 31. GOES N-O-P vs GOES-R Instruments Differences

GOES N-O-P	GOES-R
Imager:	ABI:
5 Channels	16 Channels
1.6 Mbs raw instrument data rate	120 Mbs raw instrument data rate
1.0 km spatial resolution	0.5 km spatial resolution
26 minute full disk	5 min full disk
Frame-by-frame commanding required via multiple daily schedules	Autonomous sequences; no daily commanding
INR: Accomplished by precise image acquisition (control)	INR: Accomplished by post-image processing (knowledge)
Requires multiple INR uploads daily	Single ABI Target Star List uploaded daily
Lightning Mapper: None	GLM: Provides continuous full disk total lightning measurements
SXI (Solar X-Ray Imager): X-Ray/EUV CCD 512x512 pixels, 5 arcsec/pixel resolution	SUVI (Solar Ultraviolet Imager): UV CCD 1280x1280 pixels, 0.28 arcsec/ pixel resolution
XRS (X-Ray Spectrometer): Ionization chamber design	EXIS (Extreme Ultraviolet and X-ray Irradiance Sensors): Solid state detector design, higher dynamic range, adds flare location capability
Reference: https://www.goes-r.gov/resources/docs/Latest_Program_Briefing.pdf	

9.6 Forecaster Interview Invitation Emails, Protocol and Codebook

Email sent from Mike Jamilkowski on Dec 19, 2019.

Dear Weather Forecast Office Members:

My name is Michael ("Jammer") Jamilkowski and I am a project engineer/meteorologist for Aerospace Corporation. I am working with David Lubar, also of Aerospace, and Dr. Jeffrey Lazo (economics consultant) under contract to the GOES Program Office to perform an economic assessment of the benefits of GOES-R information. We request that you take our short, voluntary interview protocol (attached), which should not take more than 45 minutes to 1 hour of your time and ask that you return the completed protocol to us by early January 2020, if possible. Your inputs will be critical to our next assessment update to the GOES-R Program Director during the American Meteorological Society Annual Meeting, 13–17 January 2020.

At this time, we are focusing on the benefit of GOES-R related hurricane forecast and warning information to the general public. A key aspect of this analysis is forecasters' perceptions of improvements in hurricane information from GOES-R over the previous series, GOES N-O-P. To obtain this, we are asking NHC and WFO forecasters to complete this interview protocol.

We are sending the interview protocol to the MIC, SOO, and WCM of 25 coastal WFOs. We ask that you consider completing this individually. If your WFO would prefer, you can complete this as a group exercise but please indicate that you have done so and let us know who was involved so we know how to analyze and report the results.

Please note that this interview protocol is completely voluntary. But we ask that you complete the protocol at your earliest convenience as a hurricane expert because your input is vital to our analysis.

If you can complete this, please return it to us at the cited email addresses. If not, please let us know and, if possible, identify an alternate person who could help us on this. If you have any questions or concerns, please include them with your responses or contact any of us by email.

We sincerely appreciate your feedback and input!

Thank You,
Michael

Mike "Jammer" Jamilkowski
Sr. Project Engineer – Spectrum
GOES-R Program Office
Civil Systems Group
The Aerospace Corporation
michael.l.jamilkowski@aero.org

Second Email sent from Mike Jamilkowski on January 30, 2020

We have an opportunity for you to provide your thoughts and inputs on the value of GOES satellite data to select NWS products. Your input will help us determine the socioeconomic benefit of this type of weather satellites and may influence the funding of future missions.

This research, which is a simple survey that should take a small amount of your time, is for the GOES-R Program Office and your completely voluntary participation is encouraged by the NWS Chief of Operations.

As per the email attached below from me that you should have received before the Holidays, we are asking MICs, SOOS, and WCMs from coastal WFOs to complete an interview protocol (survey) on
this topic.

We are making one last attempt to elicit your input before we complete this evaluation of hurricane product contributions from GOES-R, and we sincerely request your input.

Please review the attached interview protocol and return it to me at this email address {and Cc: Dr. Jeffrey Lazo, (jeffrey.k.lazo@gmail.com), our team economist} by Wednesday February 7th, 2020.

If you are unable to or do not want to complete the survey, or do not feel qualified, we ask that you please email us with a quick short sentence indicating so, as that feedback would be useful as well.

If you have any questions, please email me or, if you prefer, we can arrange a call.

Thanks in advance!

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GOES-R Benefit Study – Interview Protocol

Version: February 19, 2020
Notes: Respondent 10: only answered percent question (Q10) and is not included unless otherwise noted
N/R = No response (e.g., question asked but left empty)
N/A – Not applicable (e.g., question not asked of this respondent)
DK responses not included for statistical analysis of min, max, median, average, or count

CONFIDENTIALITY STATEMENT

The study team members are available for any questions or issues you may have regarding this survey.

- Dr. Jeffrey K. Lazo, economist – Jeffrey K Lazo Consulting, LLC – Jeffrey.K.Lazo@gmail.com
- Mr. David G. Lubar – The Aerospace Corporation – David.G.Lubar@aero.org
- Mr. Michael L. Jamilkowski (AMS Fellow) – The Aerospace Corporation – Michael.L.Jamilkowski@aero.org

We are working on a NOAA (GOES-R Program Office)-funded project on the value of potential improvements in hurricane forecast and warning processes based on information from the GOES-R satellites. You are being asked to volunteer for this research study. You were selected as a possible participant because of your experience and expertise in either hurricane forecasting and meteorology. Participation in this research is voluntary. You are free to stop the survey at ***any*** time and you are free to refuse to answer any questions as you see fit.

We stand by a strong ethical obligation to maintain confidentiality of our participants. Therefore, unless you waive your right to confidentiality and allow us to identify your responses with your name, we will maintain your confidentiality to the extent possible by reporting our results in the aggregate or identified only by a respondent number and not be name. However, given the small nature of your community, we cannot guarantee your confidentiality.

Q1. Do you voluntarily agree to participate in this study?

	Frequency
□ Yes	10
□ No ***– if "No" a sincere Thank You – end interview***.	0
□ Don't Know	0
N/R – No Response or N/A – Not applicable	1

Q2. May we quote or cite your responses verbatim in our report? (If not, we will only consider your responses in the aggregate and not identify you in the report).

	Frequency
□ Yes	9
□ No	1
□ Don't Know	0
N/R – No Response or N/A – Not applicable	1

Q3. May we credit your responses with your name and affiliation in the report?

	Frequency
□ Yes	9
□ No	1
□ Don't Know	0
N/R – No Response or N/A – Not applicable	1

Q4. If yes, please confirm the name, affiliation, and job title or position you would like us to use.

Name
Affiliation
Job Title or Position

Thank you very much for your participation. We know your time is valuable and for many of you, there has been considerable need recently to warn your audiences from hazards of hurricanes, tropical storms, flooding or severe weather.

GOES-R SATELLITE IMAGERY PRODUCT OVERVIEW AND IMPROVEMENTS

The newest NOAA geostationary weather satellites, strategically located over the eastern and western United States, are the source of imagery for broadcast meteorologists that are seen on television broadcasts and on the Internet. The imagery is used by forecasters for situational awareness, and some GOES-R data are used in numerical weather prediction models. The Geostationary Operational Environmental Satellites, Series-R (GOES-R) now has two operational satellites in place, providing imagery and data that are essential for the creation of meteorological forecasts and situational awareness.

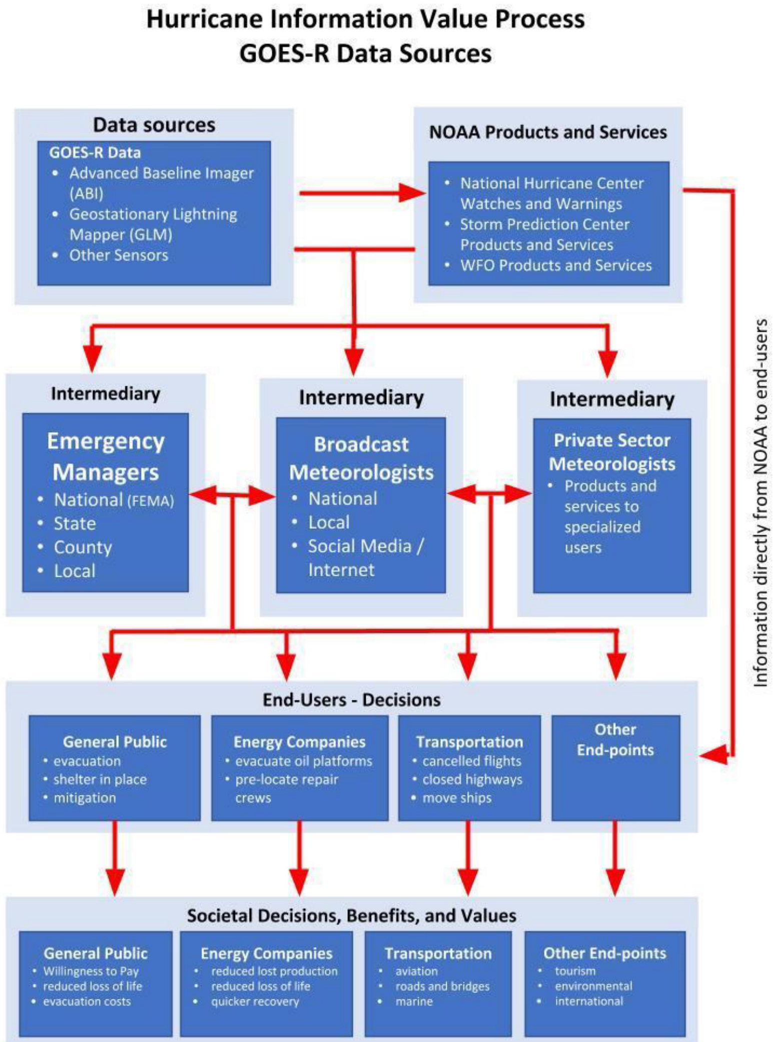
A recent imagery example (***click on this link for: Hurricane Dorian GOES-R Imagery***) is the visible and infrared images of Hurricane Dorian, when it was just east of Great Abaco Island in the Bahamas on September 1, 2019.

An overview of the GOES-R satellite may be found on the GOES-R website at ***What is GOES-R?*** or on YouTube at ***What is GOES-R (YouTube)?***

- Improvements or enhancements of the GOES-R satellite series as compared to the recently retired satellites include (but are not limited to): Improved hurricane track and intensity forecasts
- Increased thunderstorm and tornado warning lead time
- Earlier warning of ground lightning strike hazards
- More accurate detection of heavy rainfall and flash flooding risks
- Improved transportation safety and aviation route planning
- Improved detection of low clouds/fog
- Improved air quality warnings and alerts
- Earlier fire detection and improved fire intensity estimation
- Improved solar flare warnings for communications and navigation disruptions
- More accurate monitoring of energetic particles responsible for radiation hazards to humans and spacecraft
- Better monitoring of space weather to improve geomagnetic storm forecasting

A. YOUR PERSPECTIVE ON THE "HURRICANE INFORMATION VALUE PROCESS"

The following picture is an initial representation of the "Hurricane Information Value Chain" with an emphasis on data inputs from the GOES-R satellites. For now, we are focusing on the end value to the general public called "willingness to pay." This is an economic concept of value for something that is not actually bought or sold in markets (such as hurricane forecasts) but indicates what it would be worth to them if they did have to pay for this information. **Rest assured there are no plans to charge for any public meteorological information.**



Note: the diagram as shown here was updated and revised based on input from Respondent 1.

Q1. Do you believe this is a reasonably correct characterization of the creation, communication, and use of hurricane information?

	Frequency
□ Yes	8
□ No	2
□ Don't Know	0
N/R – No Response or N/A – Not applicable	1

Q2. Please indicate below any specific GOES-R data sources, instruments or information streams that are used specifically for hurricane research, modeling, forecasting, or warnings.

Respondent 1: I would add a new box between the first 2 called Numerical Weather Prediction models. That then feeds into NOAA products and services. A direct line should still go from GOES-R info into NOAA products and services. Also - the intermediary users also use the GOES-R data directly, and the NWP data directly, in addition to the NOAA products and services. So, you may want to add more arrows to make it more accurate. Insurance companies are another important end user.

Respondent 2: We utilize everything that is available to our office: visible / infrared / mature (?) imagery / GLM / especially with mesoscale domain requests.

Respondent 3: GOES-R data feeds directly into NWS AWIPS systems for monitoring and forecasting hurricanes at the local forecast office level. Forecasters also access GOES-R data is also obtained from https://www.nhc.noaa.gov/satellite.php.

Respondent 4: ABI, GLM

Respondent 5: ABI and GLM

Respondent 6: I am assuming the entire product stream from both GOES-East and GOES-West are used. By the way, they are not called GOES-R any more.

Respondent 7: Several thoughts: 1) as far as data stream, very helpful when a mesoscale sector (i.e., data stream) is employed for increased temporal resolution; 2) Clean IR - a) looking at cold cloud top warming\cooling and also integrate with radar to aid warning decision making process for flash flooding; b) use of same in #1 for detached outer rainband tornado potential formation areas (via updraft stretching); c)potential intensity changes at landfall from correlating cloud-top cooling to latent heat release; 3) using low- and mid-level WV to assess dry air entrainment \ mixing for large scale circulation and along back edge of outer rainbands for enhancing deep convective potential; 4) VIS – speaks for itself (invaluable to locate circulation center, individual updraft bursts (both around core and in bands); 5) RGB Airmass (can be helpful with extratropical transition).

Respondent 8: ABI and GLM are used at our WFO in real time for tropical cyclone monitoring, forecasts and warnings via NWS AWIPS system. Latency is small, temporal and spatial resolution are much improved compared to legacy geo satellite. Do not have much experience with AMVs yet but seems promising.

Respondent 9: I can't think of any used specifically for hurricanes because each of the products have many uses beyond just tropical cyclones.

Respondent 11: GOES-R derived SST values.
– 1-minute meso-sector imagery Red Visible Channel 2.

Q3. You will note we do not have details in the top right box indicating specific NOAA products and services. Please indicate below any specific NWS/NHC/WFO related hurricane products and services relying on GOES-R data.

Respondent 1: N/A

Respondent 2: hurricane local statements / all watches and warnings / area forecast discussions / decision support briefings.

Respondent 3: GOES-R data is used specifically in the NHC TWO Product, NWS Briefings to Emergency Management Partners, and Graphicasts that appear on our web pages and posted to social media for the public. During landfall, GOES lightning and satellite data also directly supplements 88D radar data when issuing extreme wind warnings and tornado warnings. GOES-R data is also used for outreach purposes, to educate decision makers, and the public about the dangers associated with hurricanes.

Respondent 4: Dvorak fixes, Tropical Weather Outlook (TWO), graphical display of TWO, tropical cyclone forecast initialization, and subsequent tropical cyclone forecast package.

Respondent 5: NHC center fixes, NHC discussions, WFO AFD's, TPC discussions, IDSS briefings to EM partners.

Respondent 6: Graphical TWO, email briefings, video briefings, graphicasts (used in Southern Region).

Respondent 7: Primarily for a WFO, short-fused watch and warning products.

Respondent 8: We have only had one recent experience thus far during tropical season-- Dorian. The 1-minute, or 30s data from the imager is invaluable from the meso windows. Monitoring the motion, center, and convection within the system with the increased spatial and temporal resolution is the biggest benefit we've seen.

Respondent 9: N/R

Respondent 11: TCDAT#, where # is hurricane number, relies on GOS-R imagery as the basis of the tropical/hurricane discussion.
– WFO tornado warning (TOR) relies on trends in rapid-update imagery during feeder and outer-band passages, when tornado frequency is heightened.

Q4. What are the key products or services based on your research or operational activities that come from or are based on GOES-R satellite information or are improved based upon the inclusion of GOES-R information?

<u>**Respondent 1:**</u>
NHC is tasked with tropical cyclone intensity estimates, and they use GOES-R information to accomplish this. Both subjective and objective algorithms exist to assist with this, including the Dvorak Technique. They also must provide center fixes for the storms, and they use a combination of GOES-R and polar orbiting satellite info for this. Center fixing is made easier by the better temporal and spatial resolution improvements provided by GOES-R, particularly for weaker storms whose centers may be partially cloud covered.

<u>**Respondent 2:**</u> Improved local forecasts & decision support briefings.

<u>**Respondent 3:**</u> The NHC TWO is a product that is directly derived from GOES-R satellite data. NHC relies on GOES-R satellite data for monitoring a storms location and intensity for minute by minute changes. GOES-R data is supplemented by reconnaissance aircraft data. This information is then made available in all of the NHC forecast products which are used directly by our forecast office during events to keep our partners and the public informed.

<u>**Respondent 4:**</u> Flash Flood products, Aviation turbulence SIGMETs, Tropical cyclone analysis, warning and forecast/outlook products, thunderstorm detection, situational awareness for fire monitoring and fire weather warnings.

<u>**Respondent 5:**</u> WFO AFD's, HWO's, IDSS partner e-mails and webinars.

<u>**Respondent 6:**</u> RGB satellite products which can help short-fuse warnings for convective and fire weather situational awareness.

<u>**Respondent 7:**</u> See #2.

<u>**Respondent 8:**</u> Tropical cyclone motion and investigating the convection within the cyclone as well.

<u>**Respondent 9:**</u> Social media and briefings to partners are improved upon based on GOES-R information.

<u>**Respondent 11:**</u> TWDAT# , the hurricane discussions and reasonings of the NHC rely heavily on GOES-data interpretation.
TCPAT# , hurricane product issuances for the public, forecast track and intensity.

B. YOUR PERSPECTIVE ON GOES-R RELATED IMPROVEMENTS IN HURRICANE INFORMATION

The GOES-R series has three times the number of channels as compared to the older NOAA geostationary satellites they replaced (e.g., 16 channels of visible, near infra-red and infra-red versus 5 channels). This allows optimization of the imagery for observation of clouds, aerosols, smoke, dust, haze, fog at night, vegetation, snow, water vapor, and the measurement of total ozone, turbulence, atmospheric temperatures and winds.

The new satellites also have 4 times better resolution than the old ones and they scan five times faster than the previous system. Current operation performs: a full-disk scan every 10 minutes, a continental United States scan every 5 minutes, and a smaller 1000 x 1000 km pair of sectors updated every 60 seconds, allowing for viewing of motion and changes in these smaller mesoscale sectors.

Q5. Compared to GOES-N-O-P how important are the following changes provided by GOES-R in hurricane forecasts and warnings?						
	Not at all important				**Extremely Important**	**Don't Know**
Three times the number of channels	1	2	3	4	5	9
Four times the spatial resolution	1	2	3	4	5	9
Five times the temporal coverage	1	2	3	4	5	9
Ability to obtain mesoscale domains (resolution 1000 km by 1000 km at the satellite sub-point)	1	2	3	4	5	9

Response Statistics					
Q5. Compared to GOES-N-O-P how important are the following changes provided by GOES-R in hurricane forecasts and warnings?	**Min**	**Max**	**Med**	**Avg**	**Count**
Three times the number of channels	4	5	5	4.67	9
Four times the spatial resolution	3	5	5	4.78	9
Five times the temporal coverage	5	5	5	5.00	9
Ability to obtain mesoscale domains (resolution 1000 km by 1000 km at the satellite sub-point)	4	5	5	4.89	9

Q6 How much has hurricane information changed due to the information provided by GOES-R?					
Significantly Worse	**Somewhat Worse**	**No change**	**Somewhat Better**	**Significantly Better**	**Don't Know**
1	2	3	4	5	9

Response Statistics					
	Min	**Max**	**Med**	**Avg**	**Count**
Q6. How much has hurricane information changed due to the information provided by GOES-R?	4	5	5	4.75	8

Respondent 1 only answered the following question: Q5. To what extent and how has the communication of hurricane information changed due to the information provided by GOES-R?
Respondent 1: A side benefit of better temporal sampling is lower latency, meaning forecasters view the imagery more quickly after the satellite scans a storm. This may allow them to provide slightly more timely information.

Respondent 1 only answered the following question: Q6. To what extent and how have decisions changed or improved due to the information provided by GOES-R?
Respondent 1: This is partially answered by my reply to Q4 above. Besides that, I think you'll need to get this info from NHC directly.

Q7. Please describe any societal or economic benefits you are aware of related to information provided by GOES-R.

Respondent 1:
GOES-R info helps improve the initialization of NWP models, which should in turn improve their accuracy. Better models mean better forecasts, which has societal and economic benefits. I don't know that we know how much better the model initialization has become since the launch of GOES-R, nor how that maps into an improvement in the forecast.

Respondent 2: Improved analysis & forecasts of tropical systems.

Respondent 3: Data from GOES-R was paramount during Hurricane Harvey's landfall in our warning area in August 2017. Our forecasters were able to accurately observe Harvey's rapid intensification to a category 4 storm and provide enough advanced warning for citizens to get to safety. During landfall, GOES-R data supplemented radar data to time the arrival of the eye of the hurricane over Rockport Texas. Emergency managers were able to safely rescue dozens of citizens in the eye of the storm. Miraculously, there were no direct fatalities in our warning area where Harvey made a direct landfall.

Respondent 4: Early detection of high-level clear air turbulence, giving pilots a heads up about turbulence areas. Early detection of wildfire starts, allowing fire managers to position resources more efficiently. More rapid updates to position and intensity of a tropical cyclone assists with emergency managers in response timing and location.

Respondent 5: Sorry, I have no direct information on this one.

Respondent 6: N/R

Respondent 7: N\A

Respondent 8: N/R

Respondent 9: N/R

Respondent 11: The public often shows fascination and responsiveness on social media when we post interesting, or insightful GOES-R imagery. Words like 'amazing' and 'beautiful' are sometimes used to describe the GOES-R photographs and time lapse data.

Q8. Please describe who you believe are the key users or recipients of information you develop on hurricanes that may be related to information provided by GOES-R.

Respondent 2: Emergency management, other federal, state, and local partners / pubic / media.

Respondent 3: Emergency Managers, other federal, state, and local officials, media partners and the public.

Respondent 4: Federal, State and County emergency managers and responders, media, general public.

Respondent 5: Emergency managers and the general public.

Respondent 6: The public, emergency managers, and other core partners.

Respondent 7: The entire hydrometeorological community.

Respondent 8: Emergency management community and media are probably our two biggest partners who directly benefit from the information we provide during tropical systems.

Respondent 9: Emergency managers and the general public.

Respondent 11: Emergency Managers, as they are required to issue evacuation orders if a significant hurricane hazard is deemed as probable, or highly possible.

Q9. The following statements are adapted from input received from other experts in GOES-R Data uses mainly with respect to hurricane forecasting. Some have been changed from positive to negative statements, or vice versa, so they do not replicate the exact input. For each statement please circle the number indicating your level of agreement or disagreement with the statement.

	Strongly Disagree		Neither Agree nor Disagree		Strongly Agree	Don't Know
GOES-R's biggest contribution has been improved latency, navigation and Atmospheric Motion Vectors (AMVs).	1	2	3	4	5	9
By design, GOES-R programs did not address surface wind estimates beyond the intensity and thus these have been very little affected by the new imagery.	1	2	3	4	5	9
GOES-R provides more rapid updates and better resolution (order 2 n.mi.) that improves hurricane forecast information.	1	2	3	4	5	9
Forecasts of storm surge or time of arrival (landfall) are largely unchanged with GOES-R data.	1	2	3	4	5	9
Forecasters are using most of the GOES-R channels.	1	2	3	4	5	9
Geostationary Lightning Mapper (GLM) data has been especially useful in the tropics.	1	2	3	4	5	9
GLM has not been as useful where threshold updrafts associated with lightning are very close to the maximums observed over the ocean.	1	2	3	4	5	9
Not all storms have lightning near the eyewall and thus there is missing information about thunderstorm structure, microphysics, and distribution of charged regions.	1	2	3	4	5	9
GLM has not yet provided homogeneous data to conduct comprehensive studies and thus GLM's impact is very low.	1	2	3	4	5	9
GOES-R capabilities have helped a lot with public awareness by providing multi- colored high temporal resolution images resulting in better press engagement and public awareness.	1	2	3	4	5	9

Response Statistics					
	Min	Max	Med	Avg	Count
Q9. The following statements are adapted from input received from other experts in GOES-R Data uses mainly with respect to hurricane forecasting. Some have been changed from positive to negative statements, or vice versa, so they do not replicate the exact input. For each statement please circle the number indicating your level of agreement or disagreement with the statement.					
1. GOES-R's biggest contribution has been improved latency, navigation and Atmospheric Motion Vectors (AMVs).	2	4	4	3.43	7
2. By design, GOES-R programs did not address surface wind estimates beyond the intensity and thus these have been very little affected by the new imagery.	2	4	3	3.00	4
3. GOES-R provides more rapid updates and better resolution (order 2 n.mi.) that improves hurricane forecast information.	4	5	5	4.89	9
4. Forecasts of storm surge or time of arrival (landfall) are largely unchanged with GOES-R data.	2	5	4	3.57	7
5. Forecasters are using most of the GOES-R channels.	1	5	3	2.88	8
6. Geostationary Lightning Mapper (GLM) data has been especially useful in the tropics.	4	5	4	4.29	7
7. GLM has not been as useful where threshold updrafts associated with lightning are very close to the maximums observed over the ocean.	3	3	3	3.00	2
8. Not all storms have lightning near the eyewall and thus there is missing information about thunderstorm structure, microphysics, and distribution of charged regions.	3	4	4	3.83	6
9. GLM has not yet provided homogeneous data to conduct comprehensive studies and thus GLM's impact is very low.	2	4	3	2.88	8
10. GOES-R capabilities have helped a lot with public awareness by providing multi- colored high temporal resolution images resulting in better press engagement and public awareness.	2	6	5	4.56	9

C. BENEFIT ESTIMATION

In the prior sections we asked you how GOES-R data has changed or improved hurricane forecasting and warning information. In answering the questions in this section please consider all ways in which GOES-R has improved information whether from models, nowcasting, imaging direct to users, or any other information pathways.

In part, we are basing our benefit estimates on a survey done of the general public in Miami and Houston in September 2008*. In this survey respondents were told about a set of possible improvements to hurricane forecasts and warnings described as accuracy of four different attributes of hurricane forecasts.

Please keep in mind that the descriptions of the attributes were developed through focus groups and survey pre-testing so that members of the general public could understand and respond to the questionnaire and may not closely reflect the way that forecasters would define the attributes. The degree of current and potentially improved accuracy as based on information provided by forecasters at the National Hurricane Center at the time of the survey.

The table below shows the four attributes, their definitions as provided in the survey, and the current level of accuracy (at the time of the survey) and the maximum potential improvement discussed in the survey. For each of the four attributes please indicate in the right-hand column what percentage of the potential improvement you feel could be attributed to information from GOES-R compared to information without GOES-R.

	48 hours in advance **currently** accurate to within	Maximum **Improvement**	Percent of potential improvement attributable to GOES-R
Forecasters can estimate when the hurricane will reach land.	plus or minus 8 hours	4 hours	___ %
Forecasters can estimate how strong winds will be when the hurricane reaches land.	plus or minus 20 miles per hour	10 miles per hour	___ %
48 hours in advance of landfall, forecasters can project within 100 miles where a hurricane will make landfall.	plus or minus 100 miles	65 miles 48 hours in advance	___ %
Forecasters can determine how much storm surge will be caused by the hurricane in terms of how high the water will rise above sea level.	plus or minus 8 feet of height above sea level	4 feet of height above sea level	___ %
Q10. Overall, what percentage of improvement in hurricane forecasting and warnings do you think is attributable to information from GOES-R? ___ %			

Response Statistics					
	Min	**Max**	**Med**	**Avg**	**Count**
C. BENEFIT ESTIMATION: For each of the four attributes please indicate in the right-hand column what percentage of the potential improvement you feel could be attributed to information from GOES-R compared to information without GOES-R.					
Forecasters can estimate when the hurricane will reach land.	5	75	15	32.22	9
Forecasters can estimate how strong winds will be when the hurricane reaches land.	1	75	15	24.33	9
48 hours in advance of landfall, forecasters can project within 100 miles where a hurricane will make landfall.	1	70	20	23.67	9
Forecasters can determine how much storm surge will be caused by the hurricane in terms of how high the water will rise above sea level.	0	70	5	14.56	9
Q10. Overall, what percentage of improvement in hurricane forecasting and warnings do you think is attributable to information from GOES-R?	2	70	20	29.67	9

Q11. How significant are future improvements hurricane forecasts and warnings if all available data from GOES-R was fully incorporated in modes, nowcasting, imaging, and other products and services and communicated to decision makers?					
No future improvements		**Some future improvements**		**Significant future improvements**	**Don't Know**
1	2	3	4	5	9

Response Statistics					
	Min	**Max**	**Med**	**Avg**	**Count**
Q11. How significant are future improvements hurricane forecasts and warnings if all available data from GOES-R was fully incorporated in modes, nowcasting, imaging, and other products and services and communicated to decision makers?	3	5	4	3.86	7

*** References:** Lazo, J.K., D.M. Waldman, B.H. Morrow, and J.A. Thacher. 2010. "Assessment of Household Evacuation Decision Making and the Benefits of Improved Hurricane Forecasting." *Weather and Forecasting*. 25(1):207–219. and Lazo, J.K. and D.M. Waldman. 2011. "Valuing Improved Hurricane Forecasts." *Economics Letters*. 111(1): 43–46.

D. FOCUS ON BENEFITS OF IMPROVED INFORMATION ON HURRICANE INTENSIFICATION

One of the instruments on GOES-R is the Advanced Baseline Imager (ABI) which "...is the primary instrument on the GOES-R Series for imaging Earth's weather, oceans and environment. ABI views the Earth with 16 different spectral bands (compared to five on the previous generation of GOES), including two visible channels, four near-infrared channels, and ten infrared channels."
(https://www.goes-r.gov/spacesegment/abi.html).

Q12. One a scale of 1= "Not at all familiar" to 5= "Extremely familiar", how familiar are you with the ABI?					
Not at all familiar		**Moderately familiar**		**Extremely familiar**	**Don't Know**
1	2	3	4	5	9

Response Statistics					
	Min	**Max**	**Med**	**Avg**	**Count**
Q12. One a scale of 1= "Not at all familiar" to 5= "Extremely familiar", how familiar are you with the ABI?	3	5	4.5	4.38	8

One use of ABI information is input into the "hurricane intensity algorithm" which "...makes use of the ABI longwave infrared window band to monitor changes in the cloud top temperature near the tropical cyclone center. An analysis of the cloud top temperature field over the tropical cyclone center, together with a cloud pattern recognition analysis, enables the retrieval of an intensity estimate for the tropical cyclone valid at the time of the ABI image."
(https://www.goes-r.gov/products/baseline-hurricane-intensity.html)

Q13. One a scale of 1="Not at all important" to 5="Extremely important", how important is ABI information to understanding and determining hurricane intensification?					
Not at all important		**Moderately important**		**Extremely important**	**Don't Know**
1	2	3	4	5	9

Response Statistics					
	Min	**Max**	**Med**	**Avg**	**Count**
Q13. One a scale of 1="Not at all important" to 5="Extremely important", how important is ABI information to understanding and determining hurricane intensification?	4	5	4	4.13	8

Q14. One of the attributes from the willingness to pay economics study is defined as "how strong winds will be when the hurricane reaches land." The information in this attribute relates to how strong winds will be and not specifically to hurricane intensification. How closely related is understanding how strong winds will be to understanding hurricane intensification?					
Not at all related		**Moderately related**		**Extremely related**	**Don't Know**
1	2	3	4	5	9

Response Statistics					
	Min	**Max**	**Med**	**Avg**	**Count**
Q14. One of the attributes from the willingness to pay economics study is defined as "how strong winds will be when the hurricane reaches land." The information in this attribute relates to how strong winds will be and not specifically to hurricane intensification. How closely related is understanding how strong winds will be to understanding hurricane intensification?	3	5	4	4.14	7

Q15. The goals of NOAA's Hurricane Forecast Improvement Program (HFIP), which began in 2010, are "to reduce the average errors of hurricane track and intensity forecasts by 20% within five years and 50% in ten years with a forecast period out to 7 days." (http://www.hfip.org/) To what extent do you think forecasts of hurricane winds and intensity have improved over the last ten years?					
Not at all improved		**Moderately improved**		**Extremely improved**	**Don't Know**
1	2	3	4	5	9

Response Statistics					
	Min	**Max**	**Med**	**Avg**	**Count**
Q15. The goals of NOAA's Hurricane Forecast Improvement Program (HFIP), which began in 2010, are "to reduce the average errors of hurricane track and intensity forecasts by 20% within five years and 50% in ten years with a forecast period out to 7 days." (http://www.hfip.org/) To what extent do you think forecasts of hurricane winds and intensity have improved over the last ten years?	2	4	3.5	3.38	8

Q16. Of the improvements in predicting or forecasting hurricane wind speeds at landfall, what percent can be attributed to information from GOES-R (compared to information previously available perhaps from GOES-N-O-P)? ______ %

Response Statistics	Min	Max	Med	Avg	Count
STATISTICS FOR ALL	2	65	17.5	25.33	6

Q17. Of the improvements in predicting or forecasting intensification of hurricane wind speeds at landfall, what percent can be attributed to information from GOES-R (compared to information previously available perhaps from GOES-N-O-P)? ______ %

Response Statistics	Min	Max	Med	Avg	Count
STATISTICS FOR ALL	2	65	20	27.86	7

E. OTHER GOES-R RELATED PRODUCTS, SERVICES, USERS OR VALUE?

In addition to the current study on benefits to the general public from improved hurricane forecasts and warnings, we are planning on additional studies of the societal and economic benefits of GOES-R. The following 11 areas have been identified as potential benefits and applications from information provided by the GOES-R program website (https://www.goes-r.gov/mission/mission.html):

1. Improved hurricane track and intensity forecasts
2. Increased thunderstorm and tornado warning lead time
3. Earlier warning of lightning ground strike hazards
4. More accurate detection of heavy rainfall and flash flood risks
5. Better monitoring of smoke and dust
6. Improved air quality warnings and alerts
7. Earlier fire detection and improved fire intensity estimation
8. Improved detection of low cloud/fog
9. Improved transportation safety and aviation route planning
10. Improved warning for communications and navigation disruptions and power blackouts
11. More accurate monitoring of energetic particles responsible for radiation hazards

Applications from information provided by GOES-R: https://www.goes-r.gov/mission/mission.html.

Q18. Other than hurricane information, for any one of these benefit areas please provide any information on specific improvements from GOES-R that would lead to end-users making improved decisions.

<u>Respondent 1 answered the following slightly different question:</u> Q13. Are there other products or services that have changed due the inclusion of GOES-R related information?
<u>Respondent 1:</u> There's an experimental flood monitoring product that has been improved by the inclusion of GOES-R related info. After a storm dumps inland rain and after the clouds sufficiently clear, the product can be used to assess the extent of the flood waters.

<u>Respondent 1 then answered the follow-on question:</u> Q14. Please explain how this has changed or what societal values are from this change.
<u>Respondent 1:</u> I'm not sure. FEMA gets the flood extent info and may use it for rescues, etc., but that's speculation on my part.

<u>Respondent 2:</u> H – aviation forecasts (TAFs) would be significantly improved, leading to better air traffic control management & a reduction in flight delays.

<u>Respondent 3:</u> GOES-R is being used for monitoring and forecast Fog within the Port of Corpus Christi. Port closures due to fog cost the Port of Corpus Christi an estimated $100 Million per day. They average 20 port closures per year due to fog (based on last 4-year average).

<u>Respondent 4:</u> Improved transportation safety and aviation route planning. Early detection of areas of clear air turbulence would greatly assist with route planning across the vast Pacific Ocean, where lack of other observations makes satellite detection capability an important piece of information to avoid unexpected severe turbulence.

<u>Respondent 5:</u> C. Earlier warning of lightning ground strike hazards: This is a fascinating topic, but the amount of improvement possible (even with the GLM) seems to vary greatly by climatological regime. I am in the early stages of some local research on lead times from IC (using ENTLN) to CG lightning strikes in our CWA during the warm season/sea-breeze regime. Early results suggest only a few minutes is typical, with a relatively large number of CG strikes with no prior IC activity for a given storm. GLM might finally make it plausible to sort out some of these differences for various regions across North America.

<u>Respondent 6:</u> N/R

<u>Respondent 7:</u> Basically, this bolsters NWS short-fused warnings and watches. It is amazing, for the first time, that we can time-match radar to satellite due to increased temporal frequency. This is 24/7/365 and is extremely difficult to precisely quantify - but many improvements are had on a daily basis across local NWS offices and NCEP Centers. Fire detection is also greatly improved.

<u>Respondent 8:</u> "Blended" satellite products, rather than individual channels, are the way to go, and we've been advocating for this for quite some time for use at NWS Weather Forecast offices. Forecasters have lots of different data at their fingertips, almost too much, and so we prefer satellite information to be integrated with other data sets when possible.

#H and I above...we utilize the GOES-16 Fog/Low Stratus and Probabilistic Flight Categories (IFR, LIFR, MVFR) products to monitor for these conditions in our data sparse areas, over the ocean, etc. Very beneficial to the onset of low ceilings which can be better timed with the increased temporal resolution. Also, monitoring the summer sea breeze with the 1 minute visible...helps us to time wind shifts at JFK and LGA a bit better with the increased temporal resolution. This feeds back directly to better airspace traffic management (if, say, a runway configuration change is needed due to the wind shift) and can impact the entire national air space.

#B above. The derived ProbSevere product, which utilizes new GOES16 data (and eventually GLM I believe) has been a great situational awareness tool for convective activity, for monitoring probabilistic trends in individual cells.

<u>Respondent 9:</u> Increased thunderstorm and tornado lead time because the forecaster can now see storms beginning to gain intensity on GOES-R before they can see the same on radar. This allows the forecaster to be more situationally aware prior to putting out warnings and ultimately leads to better lead time.

<u>Respondent 11:</u> N/R

Q19. For that specific benefit area, can you provide any information on end-users of GOES-R related information we could contact to elicit their perspective on benefits?

Respondent 2: Meteorologists at the NWS Aviation Weather Center, civil (?) weather service (?) units, & the ATESEC (?) in Herndon, VA.

Respondent 3: Lead Forecaster Waylon Collins from our office here at WFO Corpus Christi.

Respondent 4: Aviation industry, FAA

Respondent 5: Not at this time; don't know of any end-users who routinely utilize GLM data.

Respondent 6: N/R

Respondent 7: N\A

Respondent 8: N/R

Respondent 9: N/R

Respondent 11: N/R

Q20. Once we have enough responses, we will calculate the range of percentages from Section C for perceived improvements in hurricane forecasts and warnings from GOES-R. Once we have this information would you be willing to see these aggregated responses and tell us if you would feel your responses are accurate or if you want to revise your responses?

	Frequency
□ Yes	8
□ No	0
N/R – No Response or N/A – Not applicable	3

If "Yes," please provide your contact information in case we have follow-up questions.

Email
Phone

F. PLEASE PROVIDE ANY OTHER THOUGHTS OR COMMENTS

Respondent 1: GOES-R imagery is used very widely throughout the NWS in a very qualitative way, making a quantitative and/or economic assessment extremely difficult.

Respondent 2: At our office, we routinely use GOES-16 data for all of our forecast programs: public, aviation, marine, hydrology, fire weather/ convective & winter weather.

Respondent 3: N/R

Respondent 4: N/R

Respondent 5: I have been a SOO at a coastal Texas office for approximately four years, but my only direct experience with an approaching hurricane in the GOES-R era was Harvey in 2017.
Q15.: I understand that this is how the HFIP goals may have been stated, but it's difficult to lump improvements in both track and intensity together. Quite sure that track forecasts have improved significantly more vs. intensity forecasts during the past ten years.

Respondent 6: N/R

Respondent 7: This was mutually completed by the MIC, SOO and WCM.

Respondent 8: N/R

Respondent 9: N/R

Respondent 11: N/R

Thank you sincerely for your time and input!
Please return this when completed to Jeffrey.K.Lazo@gmail.com

9.7 Follow-Up Forecaster Interview Invitation Emails and Protocol

Example email sent by Mr. Jamilkowski on Nov 19, 2020

Dear Respondent:

You responded about 11 months ago to our "GOES-R Benefit Study – Interview Protocol" and indicated you would be willing to answer a brief follow-up question. This should only take 10 – 15 minutes of your time. Now that you have additional experience using GOES-R products, perhaps you would like to review or revise your responses.

We would now like to present you with a summary of all responses to the most critical question from the survey, indicate how you responded, and ask if you would like to change your response based on how the other experts also responded. This is a normal practice in this method of socioeconomic interview.

We received 9 responses to our protocol. The first page of the attached document shows a table with the question numbers and with columns indicating each response – including yours. Your responses are shown in the column labeled **6**. The responses are shown for "Question B. Benefit Estimation" on each of the four forecast attributes and for "Question 10" on overall improvements attributable to GOES-R.

The average percent indicated across all nine responses is shown in the column labeled "average." As you can see there was a wide range of responses.

Please review all the responses, including yours, and in the same table please indicate either "**I do not want to revise my estimate"** or enter "**Your revised estimate**" as a percent between 0% and 100%.

The original questions about the percent improvement in four hurricane forecast attributes that you felt could be attributed to GOES-R information are listed on the second page the attachment for your reference. You were then asked to indicate how much of the improvement in overall could be attributed to GOES-R.

Once you have entered your response or revisions please save the file and email it back to us (Michael.Jamilkowski@noaa.gov and Jeffrey.K.Lazo@gmail.com) by December 1st if possible.

Thank you for your time and input!

The study team members are available for any questions or issues you may have regarding this survey.

- Dr. Jeffrey K. Lazo, economist – Jeffrey K Lazo Consulting, LLC -Jeffrey.K.Lazo@gmail.com
- Mr. David G. Lubar – The Aerospace Corporation - David.Lubar@noaa.gov
- Mr. Michael L. Jamilkowski– The Aerospace Corporation -Michael.Jamilkowski@noaa.gov

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SUMMARY OF ALL RESPONSES TO THIS KEY QUESTION
YOUR ANSWERS ARE INDICATED IN COLUMN BY RESPONDENT NUMBER

BENEFIT ESTIMATION: For each of the four attributes please indicate in the right-hand column what percentage of the potential improvement you feel could be attributed to information from GOES-R compared to information without GOES-R.

Respondent	1	2	3	4	5	6	7	8	9	Average	I do not want to revise my estimate	Your revised estimate
Forecasters can estimate when the hurricane will reach land.	75	25	15	60	10	10	75	15	5	32.22%	____	____ %
Forecasters can estimate how strong winds will be when the hurricane reaches land.	75	25	15	30	8	5	50	10	1	24.33%	____	____ %
48 hours in advance of landfall, forecasters can project within 100 miles where a hurricane will make landfall.	45	25	15	70	1	20	25	10	2	23.67%	____	____ %
Forecasters can determine how much storm surge will be caused by the hurricane in terms of how high the water will rise above sea level.	25	10	5	70	1	5	10	5	0	14.56%	____	____ %

COPY OF KEY QUESTION FROM SURVEY YOU ANSWERED PREVIOUSLY BENEFIT ESTIMATION

In the prior sections we asked you how GOES-R data has changed or improved hurricane forecasting and warning information. In answering the questions in this section please consider all ways in which GOES-R has improved information whether from models, nowcasting, imaging direct to users, or any other information pathways.

In part, we are basing our benefit estimates on a survey done of the general public in Miami and Houston in September 2008*. In this survey respondents were told about a set of possible improvements to hurricane forecasts and warnings described as accuracy of four different attributes of hurricane forecasts.

Please keep in mind that the descriptions of the attributes were developed through focus groups and survey pre-testing so that members of the general public could understand and respond to the questionnaire and may not closely reflect the way that forecasters would define the attributes. The degree of current and potentially improved accuracy as based on information provided by forecasters at the National Hurricane Center at the time of the survey.

The table below shows the four attributes, their definitions as provided in the survey, and the current level of accuracy (at the time of the survey) and the maximum potential improvement discussed in the survey. For each of the four attributes please indicate in the right-hand column what percentage of the potential improvement you feel could be attributed to information from GOES-R compared to information without GOES-R.

	48 hours in advance **currently** accurate to within	Maximum **Improvement**	Percent of potential improvement attributable to GOES-R
Forecasters can estimate when the hurricane will reach land.	plus or minus 8 hours	4 hours	_____ %
Forecasters can estimate how strong winds will be when the hurricane reaches land.	plus or minus 20 miles per hour	10 miles per hour	_____ %
48 hours in advance of landfall, forecasters can project within 100 miles where a hurricane will make landfall.	plus or minus 100 miles	65 miles 48 hours in advance	_____ %
Forecasters can determine how much storm surge will be caused by the hurricane in terms of how high the water will rise above sea level.	plus or minus 8 feet of height above sea level	4 feet of height above sea level	_____ %
Q10. Overall, what percentage of improvement in hurricane forecasting and warnings do you think is attributable to information from GOES-R? _____ %			

* **References:** Lazo, J.K., D.M. Waldman, B.H. Morrow, and J.A. Thacher. 2010. "Assessment of Household Evacuation Decision Making and the Benefits of Improved Hurricane Forecasting." *Weather and Forecasting*. 25(1):207-219. and Lazo, J.K. and D.M. Waldman. 2011. "Valuing Improved Hurricane Forecasts." *Economics Letters*. 111(1): 43–46.

9.8 December 31, 2020 memo from the NESDIS/OSAAP/TPIO Analysis Team

Memorandum: Aligning NOSIA and Socio-Economic Benefits Studies 31 Dec 2020
From: Analysis Team, NESDIS/OSAAP/TPIO
To: GOES-R Socio-Economic Benefits Team

TPIO compared the questions asked by the GOES-R Socio-Economic Benefits Team of their Weather Forecast Office (WFO) survey participants--hereafter socioeconomic benefits (SEB) questions--to those questions asked during the NOAA Observing System Integrated Analysis (NOSIA) surveys. Since each of the surveys differ in their intent and the data's interpretation, TPIO instead compared the SEB questions to related products surveyed in NOSIA. The table below summarizes.

SEB Question	NOSIA Product	Strength of Alignment
Forecasters can estimate when the hurricane will reach land.	Hurricane Track	Strong
Forecasters can estimate how strong winds will be when the hurricane reaches land.	Hurricane Track Hurricane Intensity Hurricane Structure	Moderate Strong Moderate
48 hours in advance of landfall, forecasters can project, within 100 miles, where a hurricane will make landfall.	Hurricane Track Hurricane Structure	Strong Moderate
Forecasters can determine how much storm surge will be caused by the hurricane in terms of how high the water will rise above sea level.	Hurricane Storm Surge Hurricane Track Hurricane Intensity	Strong Moderate Moderate
What percentage of improvement in hurricane forecasting and warnings do you think is attributable to information from GOES-R?	All tropical cyclone products	Strong

The figure on the following page illustrates the changes in utility between GOES-NOP and GOES-RS for tropical cyclone products. The split-bar chart shows GOES-NOP utility on top, and GOES-RS utility on bottom, with the surveyed products on the x-axis and the impact score on the y-axis. The plot provides the formula used for the impact score in the subtitle. The color scheme describes whether or not the SME stated they used GOES imagery directly in the creation of the surveyed product: Red means the satellite imagery indirectly provides value to the product, while green means the product directly uses the imagery.

The plot also provides a couple key caveats. First, the data should not be interpreted as a direct, one-to-one comparison of the changes in utility between the two satellite imagery systems. The analysis cannot account for any changes in requirements, personnel, and procedures that may have affected their respective usage and utility. Second: Through the course of the NOSIA refresh, TPIO has not surveyed any products from CPHC (last surveyed in 2016) and will be unable to assess the indirect utility of GOES-RS in the NHC's storm surge product, as well as the full utility of GOES-RS in the other products, until the NOSIA refresh data integrates with the Value Tree Model.

Generally, utility and usage increased from GOES-NOP to GOES-RS. Five products show increased utility for GOES-RS compared to GOES-NOP, ranging from 5 to 65 percentage points. Two products began using geosynchronous satellite imagery directly, with the advent of GOES-RS. This does not indicate, however, that those two products did *not* use *any* satellite imagery in their development. For example, the NHC's Dvorak estimates of hurricane intensity relied most heavily on microwave imagery from polar orbiting satellites, and indirectly gained modest value from GOES-NOP.