GeoXO Benefit Analysis

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August 2022

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Acknowledgements

The GeoXO satellite constellation is a complex observational system that will generate benefits within complex environmental and human systems. Thus, the analysis of GeoXO benefits occurs at the intersection of many disparate scientific and technical disciplines. This study has been made possible by the contribution of a large number of experts with specialized knowledge of:

- the physical, chemical, biological, and other environmental properties and systems that will be observed by GeoXO;
- the capabilities of the GeoXO instruments that will be used to observe these environmental properties and systems;
- the products and services that will be enhanced by GeoXO observations;
- the societal decisions to which those products and services will be applied; and
- the social and economic consequences of improving those decisions.

Key contributors to this study include:

- the GeoXO leadership team,
- GeoXO instrument and user science teams,
- GeoXO user engagement team,
- leaders and stakeholders in the GeoXO Pathfinder efforts,
- technical and scientific experts and analysts from across NOAA, NASA, and other federal agencies, and
- university-based researchers.

The NOAA chief economist and her staff provided crucial support in the design and execution of this study's economic analyses and ensuring the quality of the analysis and the report. The NOAA Chief Financial Officer (CFO) and the director of the CFO's Performance, Risk, and Social Science Office provided crucial guidance, especially with regard to ensuring the consistency of this work with guidance from the White House Office of Management and Budget.

Each group listed above represents multiple individuals who provided support that was vital to the success and improved the quality of this effort. Individual contributors are not identified because it is beyond the capabilities of this author to name all those without whose support this project would have been impossible.

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Executive Summary

This report describes many of the societal benefits that are expected to be generated through the use of observations from NOAA's future Geostationary Extended Observations (GeoXO) satellite constellation and the manner in which those benefits are produced. The report focuses on areas of substantial benefit, or novel and interesting applications. The report also provides estimates of the magnitude of a subset of the anticipated societal benefits for comparison with the anticipated cost of the constellation during its development and throughout its operational life. This information has been developed for use by the GeoXO team and the Department of Commerce in future budget discussions and in a manner that is consistent with guidance from the Office of Management and Budget.

The analysis of benefits and costs is consistent with OMB Circular A-94: "Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs" and OMB Circular A-4: "Regulatory Analysis." Specifically:

- analysis is limited to benefits and costs "accruing to citizens of the United States" and
- future benefits and costs have been discounted to show their present value using discount rates of 3 percent and 7 percent (more on discounting is provided in Appendix A)

GeoXO will provide two broad classes of benefits:

- continuation of current geospatial observing capabilities beyond the termination of the GOES-series satellites in the 2030s
- enhanced observational capabilities

Thus, the loss of current GOES-series capabilities is the baseline against which GeoXO benefits are measured. It is important to note that, in many cases, data were not available to estimate benefits at the national scale. In such cases, the benefit estimates developed for and used in this analysis represent regionally-specific subsets of the full national benefit.

The benefits analysis presented in this report focuses on the use of GeoXO observations to support NOAA products and services. Two important classes of benefits from GeoXO fall beyond this scope and were not considered in this analysis: communication and inter-satellite services that are provided by the constellation, and GeoXO's contribution to national defense.

GeoXO includes five distinct instruments but is designed as a system. Although each instrument provides unique and economically valuable observations, the codependencies, parallel uses, and enhancements of these instruments means the full value of GeoXO depends on the constellation working as a system. Even where benefits can be traced primarily to a single instrument, the magnitude of benefits is frequently increased by information provided by other instruments on GeoXO. The five instruments[1] included in the recommended GeoXO constellation are:

- Vis/IR Imager
- Geostationary Lightning Mapper
- Ocean Color
- Atmospheric Composition
- IR Sounder

The figure below shows the location of instruments on the GeoXO East, GeoXO Central, and GeoXO West satellites.

Studies completed by the GeoXO team in 2021 and the current study identified 175 pathways, called "value chains," by which GeoXO observations are expected to improve various societal outcomes. Each pathway represents a discrete set of linkages between GeoXO observations, the NOAA products that will be improved through the use of GeoXO observations, the manner in which those products are improved, and the specific manner in which society will benefit from these improvements.

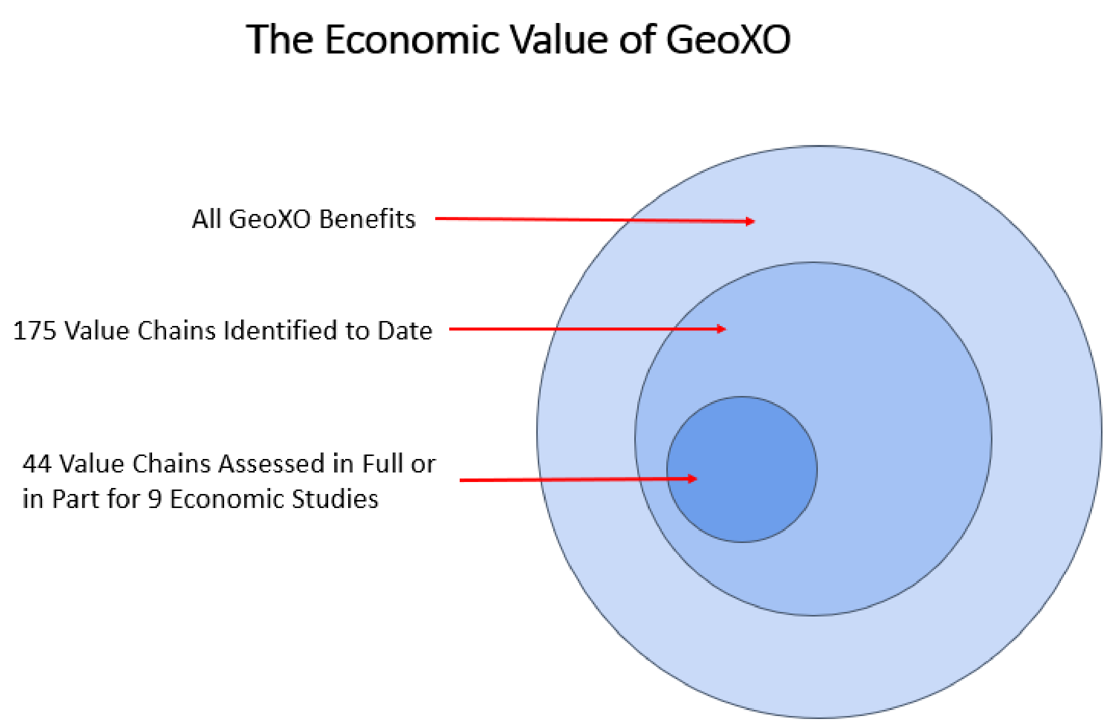
[1] The GeoXO team is currently investigating the feasibility of adding day/night observational capacity to GeoXO. However, these investigations are not sufficiently advanced to support economic analysis and, thus, benefits of the day/night band have not been included in this analysis.

The expected benefits of GeoXO include but are not limited to:

- reducing economic losses associated with natural hazards,
- increasing effectiveness and efficiency in responses to natural and man-made hazards,
- improving human health and safety,
- reducing mortality (e.g., from lightning strikes and exposure to poor air quality).
- increasing economic productivity, and
- increasing the effectiveness and efficiency of the federal government in addressing the terms of legal mandates and international treaties.

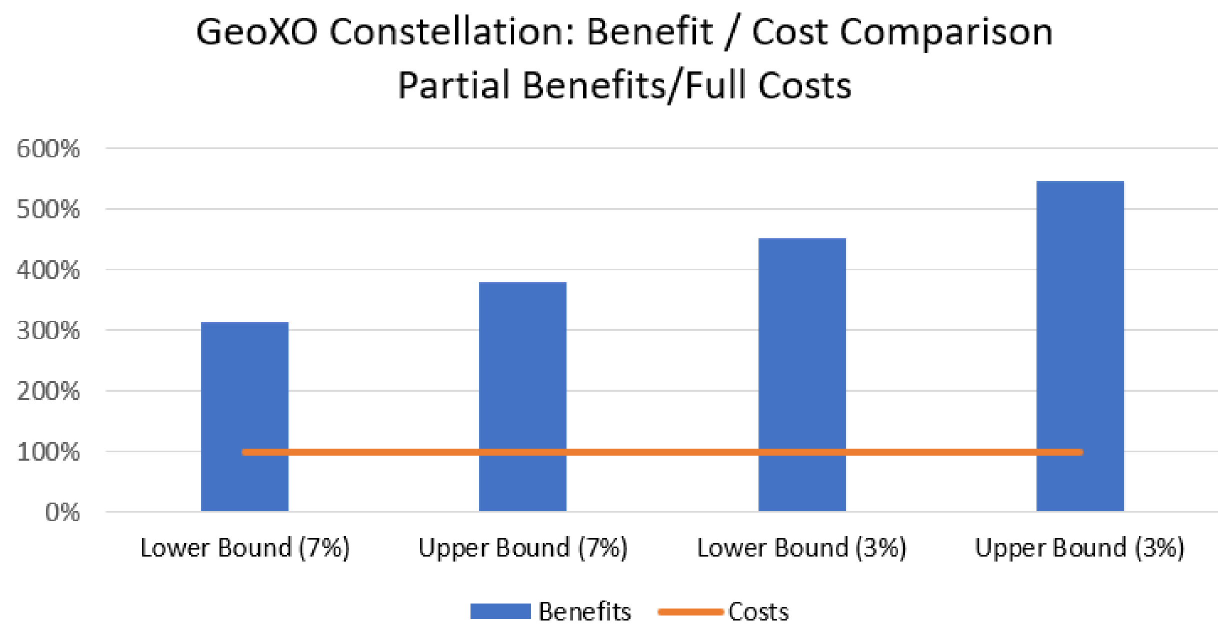
A total of 9 economic studies were performed during the present effort, addressing 44 of the 175 value chains that have been identified to date. It is important to note that:

- GeoXO will provide new types of observations that are likely to lead to discoveries and unanticipated applications (thus, the full number of GeoXO value chains almost certainly exceeds 175) and
- in most cases, the economic studies account for only part of the value indicated by the value chains



GeoXO Constellation: Benefit/Cost Summary
(Full Summary on Page 34)

The nine studies conducted in this exercise compare the benefits associated with the limited range of use cases that have been analyzed to the full cost of GeoXO. Lower bound estimates of benefits are equal to 314 percent to 452 percent of GeoXO costs. Upper bound estimates equate to 380 percent to 547 percent of costs. For comparability, the figure below shows benefits and costs of the GeoXO constellation indexed so that costs are equal to 100 percent.

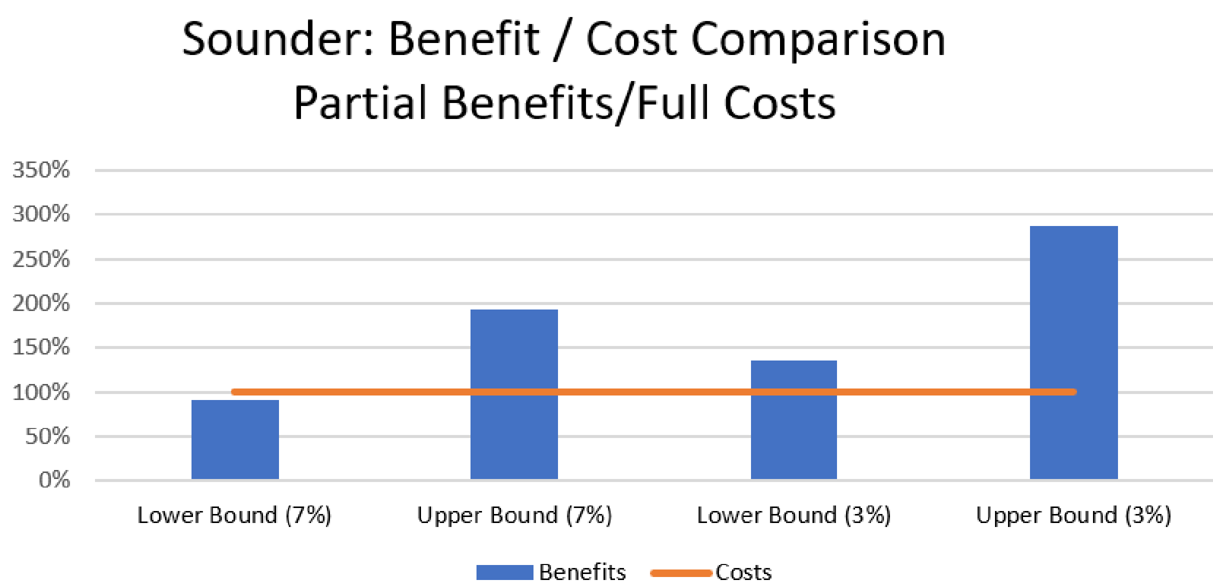


Value Study	Annual Value, Millions of 2019 $		Present Value, 2033 to 2052, Millions of 2019 $			
			7 Percent Discount Rate		3 Percent Discount Rate	
	Low	High	Low	High	Low	High
Aviation	$ 101.2	$ 151.8	$ 476.0	$ 714.0	$ 1,055.9	$ 1,583.8
Electric power	$ 40.7	$ 137.4	$ 178.9	$ 603.9	$ 412.3	$ 1,391.7
Air Quality	$ 3,695.1	$ 4,120.2	$ 16,244.2	$ 18,113.0	$ 37,434.4	$ 41,741.0
Harmful algal blooms	$ 5.3	$ 50.0	$ 23.1	$ 219.8	$ 53.3	$ 506.5
Wildfire destruction	$ 34.6	$ 173.1	$ 152.2	$ 760.9	$ 350.7	$ 1,753.5
Wildfire suppression costs	$ 18.7	$ 56.1	$ 82.2	$ 246.5	$ 189.3	$ 568.0
Hurricane evacuation	$ 11.7	$ 35.2	$ 55.3	$ 165.8	$ 122.6	$ 367.7
Smoke taint	$ 0.8	$ 1.6	$ 3.6	$ 7.1	$ 8.2	$ 16.4
Radar outage	$ 13.0	$ 18.0	$ 57.1	$ 79.2	$ 131.6	$ 182.4
Total Benefits	$ 3,921.1	$ 4,743.4	$ 17,272.6	$ 20,910.2	$ 39,758.3	$ 48,111.0
Total GeoXO Cost			$ 5,498.4	$ 5,498.4	$ 8,801.2	$ 8,801.2
Benefits/Costs			314%	380%	452%	547%

GeoXO Sounder: Benefit/Cost Summary
(Full Summary on Page 64)

Attribution of benefits for the GeoXO constellation to the sounder is based on input from the GeoXO team that indicates the degree to which each instrument contributes to the benefits measured in the nine economic studies that were conducted. A total of 33 value chains were identified for the sounder, for 8 of which full or partial benefits were quantified. The figure below compares benefits and costs attributed to the sounder using the index of costs being equal to 100 percent for comparability.

Cost estimates for GeoXO Central generation of satellites start with a sounder-only "base" configuration, wherein the sounder is the only instrument flown. Costs for the atmospheric composition instrument are the incremental cost of adding that instrument to the sounder-only configuration. For this reason, the cost of the sounder reflects a disproportionate share of the total cost of the platform, communication systems, and launch. This approach is used as it would not be logical to launch a satellite platform without any instrumentation.

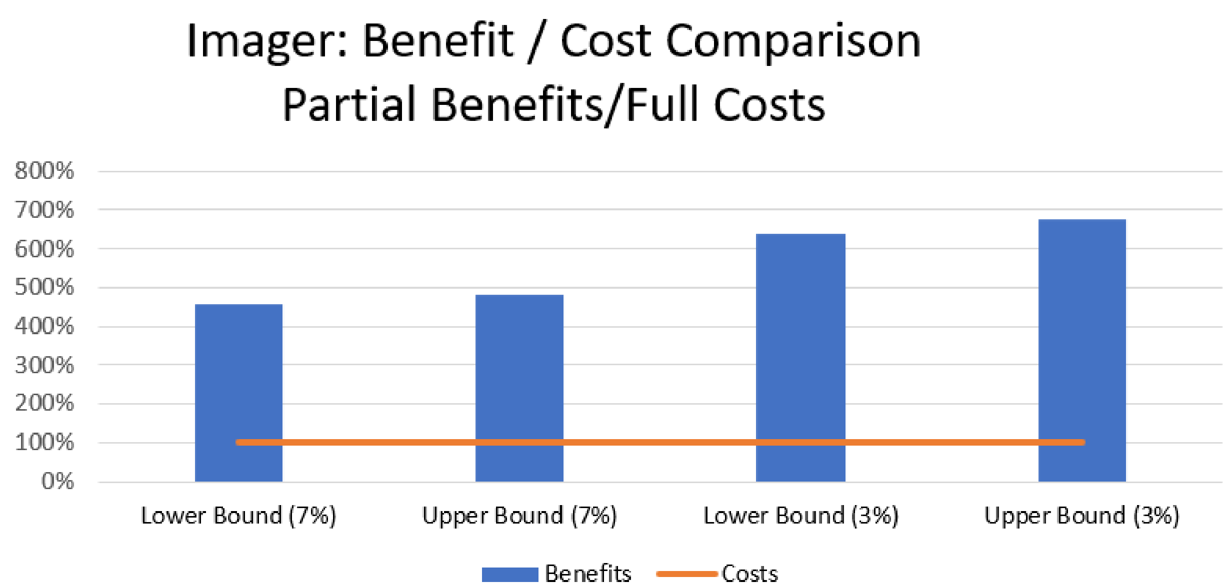


Sounder	Annual Value, Millions of 2019 $		Present Value, 2033 to 2052, Millions of 2019 $			
			7 Percent Discount Rate		3 Percent Discount Rate	
	Low	High	Low	High	Low	High
Quantified Benefits (8 of 33 value chains)	$177.59	$379.11	$790.20	$1,681.40	$1,802.90	$3,845.20
Total Costs			$871.60	$871.60	$1,335.90	$1,335.90
Benefits / Costs			91%	193%	135%	288%

GeoXO Imager: Benefit/Cost Summary
(Full Summary on Page 34)

A total of 43 value chains were identified for the imager, for 12 of which full or partial benefits were quantified. The figure below compares benefits and costs attributed to the imager using the index of costs being equal to 100 percent for comparability.

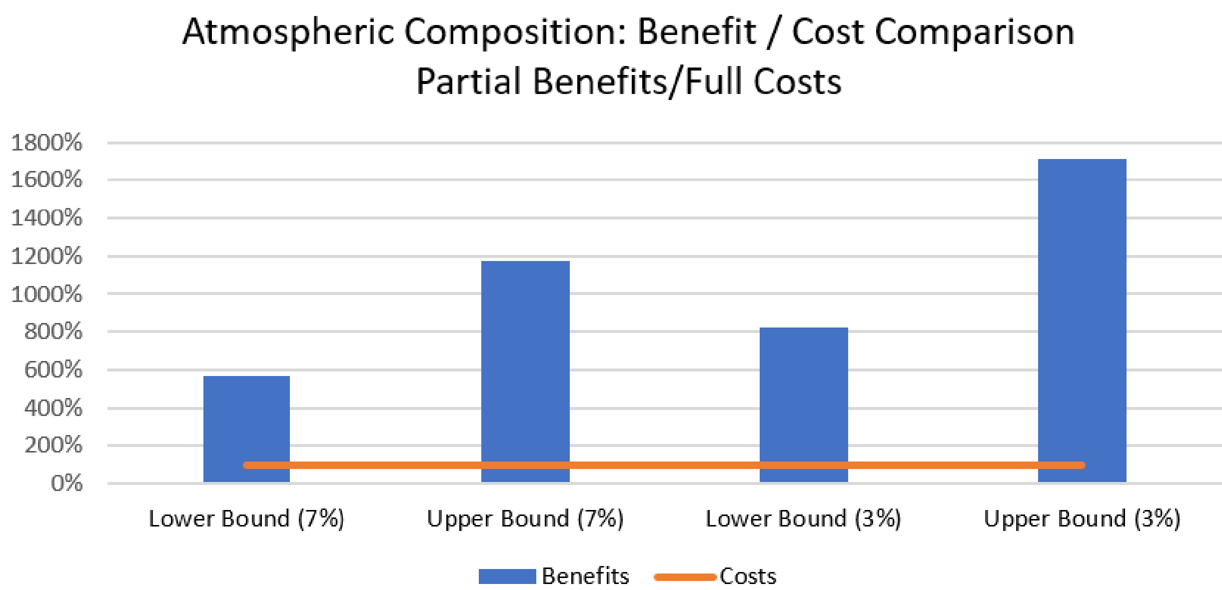
Cost estimates for the GeoXO East and West generation of satellites start with an imager-only “base” configuration. Costs for the lightning mapper and ocean color instruments are the incremental cost of adding those instruments to the imager-only configuration. For this reason, the cost of the imager reflects a disproportionate share of the total cost of the platform, communication systems, and launch. This approach is used as it would not be logical to launch a satellite platform without any instrumentation.



Imager	Annual Value, Millions of 2019 $		Present Value, 2033 to 2052, Millions of 2019 $			
			7 Percent Discount Rate		3 Percent Discount Rate	
	Low	High	Low	High	Low	High
Quantified Benefits (12 of 43 value chains)	$3,383.99	$3,576.82	$14,882.62	$15,736.19	$34,275.65	$36,228.74
Total Costs			$3,259.60	$3,259.60	$5,360.80	$5,360.80
Benefits / Costs			457%	483%	639%	676%

GeoXO Atmospheric Composition Instrument: Benefit/Cost Summary
(Full Summary on Page 57)

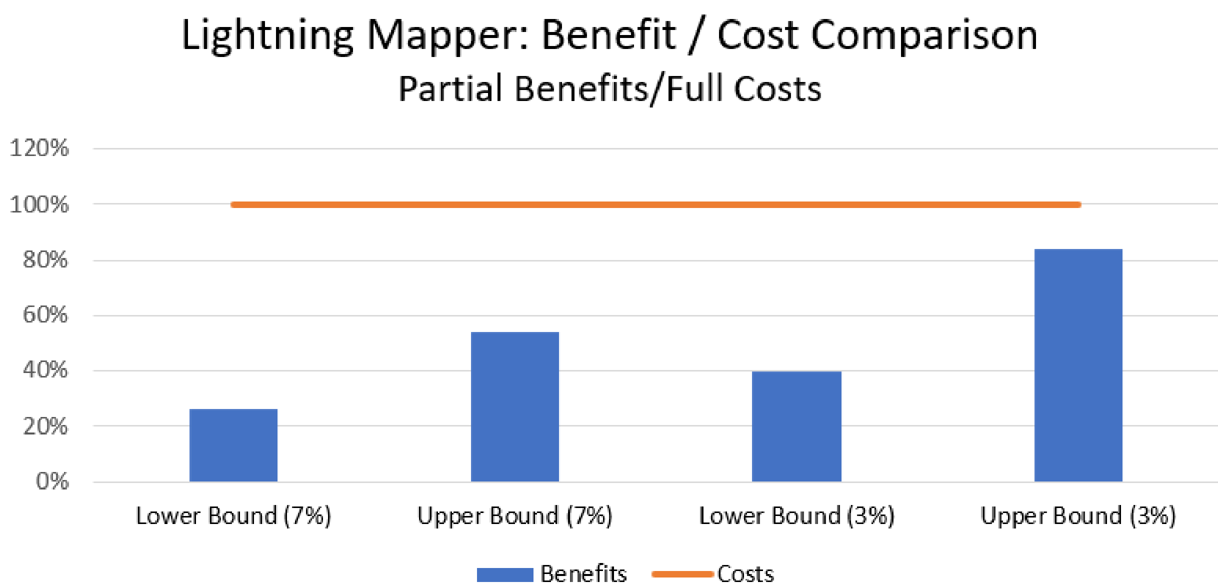
A total of 35 value chains were identified for the atmospheric composition instrument, for 5 of which full or partial benefits were quantified. The figure below compares benefits and costs attributed to the atmospheric composition instrument using the index of costs being equal to 100 percent for comparability. It is important to note that the costs attributed to the atmospheric composition instrument represent the incremental cost of adding this instrument to the sounder-alone configuration of the GeoXO Central satellite series.



Atmospheric Composition	Annual Value, Millions of 2019 $		Present Value, 2033 to 2052, Millions of 2019 $			
			7 Percent Discount Rate		3 Percent Discount Rate	
	Low	High	Low	High	Low	High
Quantified Benefits (5 of 35 value chains)	$326.31	$679.65	$1,452.00	$3,014.40	$3,345.70	$6,945.90
Total Costs			$256.10	$256.10	$405.50	$405.50
Benefits / Costs			567%	1177%	825%	1713%

GeoXO Lightning Mapper: Benefit/Cost Summary
(Full Summary on Page 40)

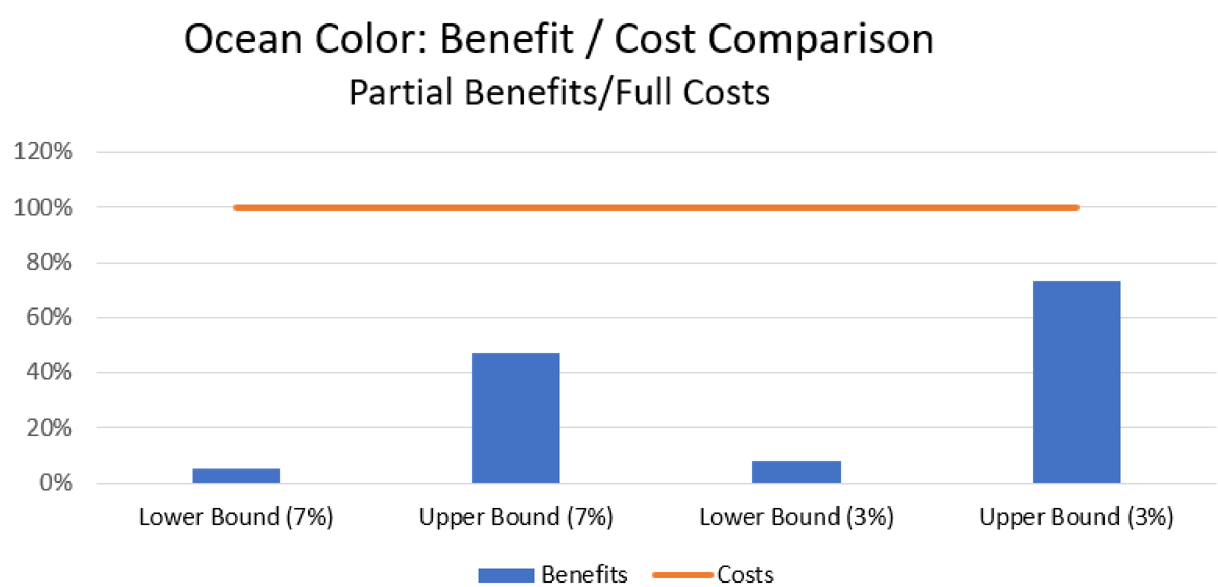
A total of 42 value chains were identified for the lightning mapper, for 11 of which full or partial benefits were quantified. The figure below compares benefits and costs attributed to the lightning mapper using the index of costs being equal to 100 percent for comparability. It is important to note that the costs attributed to the lightning mapper represent the incremental cost of adding this instrument to the imager-alone configuration of the GeoXO East and West satellite series



Lightning Mapper	Annual Value, Millions of 2019 $		Present Value, 2033 to 2052, Millions of 2019 $			
			7 Percent Discount Rate		3 Percent Discount Rate	
	Low	High	Low	High	Low	High
Quantified Benefits (11 of 42 value chains)	$28.03	$58.26	$124.70	$258.40	$280.70	$584.70
Total Costs			$474.70	$474.70	$693.70	$693.70
Benefits / Costs			26%	54%	40%	84%

GeoXO Ocean Color Instrument: Benefit/Cost Summary
(Full Summary on Page 49)

A total of 22 value chains were identified for the ocean color instrument, for 8 of which full or partial benefits were quantified. The 8 quantified value chains are all associated with reducing the effects of harmful algal blooms (HABs). The remaining value chains are associated with improving the management of marine fisheries, which is the responsibility of NOAA Fisheries fisheries management councils, and state agencies. A more comprehensive assessment of the benefits of the ocean color instrument will require support from NOAA Fisheries to ensure consistency with the extensive body of their work. The figure below compares the HAB-related benefits and the full incremental cost of the ocean color instrument using the index of costs being equal to 100 percent for comparability. It is important to note that the costs attributed to the ocean color instrument represent the incremental cost of adding this instrument to the imager-alone configuration of the GeoXO East and West satellite series



Ocean Color	Annual Value, Millions of 2019 $		Present Value, 2033 to 2052, Millions of 2019 $			
			7 Percent Discount Rate		3 Percent Discount Rate	
	Low	High	Low	High	Low	High
Quantified Benefits (8 of 22 value chains)	$5.19	$49.56	$23.10	$219.80	$53.30	$506.50
Total Costs			$465.40	$465.40	$689.70	$689.70
Benefits / Costs			5%	47%	8%	73%

Key Assumptions, Limitations, and Background Information

- The cost estimates developed for GeoXO treat the imager as the base instrument for GeoXO East and GeoXO West satellites and the sounder as the base instrument for GeoXO Central satellites. This means that cost estimates start with an imager-only configuration for GeoXO East and West and a sounder-only configuration for GeoXO Central, with most of the costs of the satellite platform, communication systems, and launch attributed to these two instruments. Costs for other instruments are the incremental costs of adding another instrument to an imager-only satellite or a sounder-only satellite. This should be considered when interpreting the benefit-cost comparisons for the imager and sounder which have the cost disadvantages associated with being the base instrument.

- The 175 value chains that have been identified do not fully account for all the beneficial uses of GeoXO observations. In fact, it is likely that new data will result in discoveries leading to beneficial uses that cannot at this time be imagined. Further, the benefit estimates in this report address only 44 of the 175 value chains that have been identified and, in the majority of those cases, the estimates represent only part of the value associated with each value chain. In most cases, studies focused on value chains that are expected to have the large benefits but, even so, the totals presented in this report do not account for the full value of GeoXO.

- Some instruments are significantly underrepresented in the value studies. Values for the ocean color instrument are based on only one study focused on this instrument's ability to reduce the impacts of harmful algal blooms. Future studies are needed to address other benefits of this instrument, many of which are associated with improved management of marine fisheries. For this reason, these studies should be conducted by or in close cooperation with NOAA Fisheries.

- Similarly, the lightning mapper should also be a focus of future benefit studies. A number of known value chains have yet to be quantified. In many cases, this is due to a lack of national scale, time-series data needed for the analysis, but it is likely that additional benefits could be quantified with an acceptable level of confidence.

- This analysis is based entirely on existing data and research. National-scale, time-series data provide the best basis for quantifying benefits but, in many cases, such data were not available. In these instances, the best available data were used. Existing research needed to support the analysis is relatively scarce. In some cases, key variables are estimated based on a single study; in a few cases, research upon which analyses are based are up to ten years old. A sustained program of research that is relevant to key benefit cases would greatly improve the quality of future benefit studies. Since the data from GeoXO primarily support products and services provided by other NOAA Line Offices, there is a shared interest in such research and, therefore, an opportunity for jointly funded and mutually beneficial studies.

- Despite the varying levels of confidence or justification provided by the differing approaches, benefits are summarized similarly and accrued in assessing total benefits. Each valuation study in "Section 3, Quantification of Benefits" identifies additional research that is needed to address limitations of the studies that have been performed and other studies that are needed to more fully account for the beneficial use of GeoXO observations.

- The United States population and economy are dynamic and generally increasing in size. However, the benefit studies described in this report do not reflect forecasts of future growth in population, wealth, the total volume of economic activity, or industry-specific trends that would affect benefit estimates. Relevant industry-specific trends that are not reflected in these studies include, for example, growth in total electricity usage, total levels of air traffic, the value of real estate in areas affected by wildfires, and the volume and value of coastal recreation. Including forecasts of future trends would in most cases increase estimates of GeoXO benefits.

- It is important to note that this study builds on a substantial body of recent and ongoing research and analysis by the GeoXO team and reflects substantial collaboration with and direct input from the broader GeoXO team. For example, user engagement workshops conducted in the summer of 2020 focused on specific areas where GeoXO observations are expected to yield substantial benefits: human health, agriculture, wildfires, ocean applications, and weather forecasting. More than 200 participants from industry, academic institutions, U.S. federal government agencies, international governments and institutions, and state, local, tribal, and territorial governments participated in these workshops to identify capability gaps to be considered in the design of the GeoXO constellation.

- The user engagement workshops conducted in the summer of 2020 cast a broad net, gathering information on the needs of the constituents of the five high-priority application areas listed immediately above. A series of instrument-specific benefit studies that were completed in late 2020 narrowed the focus, addressing the potential of GeoXO observations to address the information needs identified in the User Engagement workshops.

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Overview of Study

The purpose of this report is to describe the societal benefits of NOAA's future Geostationary Extended Observations (GeoXO) satellite system, the manner in which they are produced, and their magnitude. The societal benefits from the GeoXO instruments are expected to be large and widespread, providing continuity of service to the many products and services currently supported by the GOES-series satellites, improving a wide range of existing NOAA products and services, and providing a basis for discovery and the creation of new, economically valuable products and services. The benefits of GeoXO will extend across the economy, reducing economic losses and increasing economic productivity in the public and private sectors; benefits will be realized in the form of increased effectiveness and efficiency in addressing the terms of enforcing legal mandates and international treaties, in increased effectiveness and efficiency in responses to natural and man-made hazards, improved human health and safety, and reduced mortality.

This report builds on a series of user engagement workshops, benefit studies, and the ongoing NOAA Pathfinder efforts, as described below. The user engagement workshops focused on specific areas where GeoXO observations are expected to yield substantial benefits: human health, agriculture, wildfires, ocean applications, and weather forecasting. More than 200 participants from industry, academic institutions, U.S. federal government agencies, international governments and institutions, and state, local, tribal, and territorial governments participated in each workshop to identify capability gaps to be considered in the design of the GeoXO constellation.

In the fall of 2020, teams of scientists with subject matter expertise in the capabilities of the instruments that are included in the current GeoXO constellation and those with subject matter expertise in NOAA's use of satellite observations, produced a series of value studies describing the GeoXO's potential for addressing needs identified in the user engagement workshops and in improving NOAA's existing suite of products and services.

Ongoing NOAA Pathfinder efforts focus on a small subset of potential early adopters to expedite the beneficial use of GeoXO observations when the satellites become operational. The intensive interaction with these stakeholders provides additional information on how they can use GeoXO observations and how and to what extent the societal outcomes that are the focus of their work (e.g., wildfire losses or aviation delays) can be improved by GeoXO.

These efforts provided a foundation for the economic studies that are the subject of this report, which consists of three main sections. Section 1 summarizes the findings of the user needs workshops, the benefit studies that followed the workshops, and ongoing Pathfinder efforts with the goal of describing as comprehensively as possible the full scope of benefits that are expected to result from the GeoXO mission. The content of Section 1 reflects analysis of information in NOAA's NOSIA-II database and NOAA's Big Data Project with Amazon Web Services (AWS) that show the dependency of NOAA products and services on satellite observations; this section of the report also reflects findings from a review of other documents produced by NOAA, academic research, and research conducted by NASA and Earth observation agencies of partner nations.

Section 2 of this report describes selected "value chains" that explain how the use of data from GeoXO will benefit society. Value chains show the pathways by which different types of data from GeoXO create value to society through the creation of new and improved products or the direct use of the data. Each value chain focuses on a single use case, identifying specific end-users who apply GeoXO data or products that rely on GeoXO data to reduce losses, increase productivity, save lives, or improve other societal outcomes. The desire to focus on benefit classes that were expected to be large, the need to provide information for all five instruments, and the need to provide information for each of the applications that are the focus of the Pathfinder effort (weather forecasting, wildfires, agriculture, human health, and ocean applications) guided the selection of use cases and the corresponding value chains. The availability of data and methods to support benefit analysis also constrained the selection of value chains.

Section 3 describes methods, data, findings, and limitations of benefit estimation studies that were conducted between April 2021 and May 2022. Some of these studies are refinements of benefit estimates conducted in previous studies (e.g., through the incorporation of more complete or current data). Additional benefit estimates were developed based on the benefit studies conducted by instrument teams in the fall of 2020; additional value estimates are based on the value chains described in Section 2 of this report.

NOAA Pathfinder Projects

Concurrent with the economic studies, NOAA initiated Pathfinder efforts that further narrowed the focus, identifying a small number of potential early adopters who will work with NOAA over the next several years to expedite the beneficial use of GeoXO observations when the satellites become operational. Information gathered during the Pathfinder efforts provided rich details on the users and uses of NOAA products and services whose improvement will be enabled by GeoXO. The following Pathfinder exercises are still underway.

- Agriculture: E & J Gallo Winery, a family run winery and distributor headquartered in Modesto, California, is the largest exporter of California wines. Gallo is active in agricultural research and is also a researcher and a commercial user of satellite data. During the 2020 California fires, Gallo, like hundreds of other California vineyards, suffered from smoke damage on grapes (known as smoke taint). As users of GOES ABI aerosol data, Gallo will help develop a value chain to understand how improvements in the atmospheric composition products from GeoXO will impact future viticulture challenges and early warning scenarios in California.

- Wildfires: The WIFIRE Lab is an all-hazards knowledge cyberinfrastructure, forming a data management layer between the data collection and modeling efforts. They operate as a neutral data resource/partner to any proposed fire related activity by adding value to the raw data, preparing real-time data for fire monitoring and fire modeling for research and operational use. To develop a wildfire value chain, GeoXO engaged with WIFIRE as a future Pathfinder to demonstrate current and future uses of GEO data. As a Pathfinder, WIFIRE provides their operational decision making use case that explicitly outlines how future GeoXO data will improve the impacts of WIFIRE products and the firefighting responses of Ventura County Fire Department.

- Human Health. The NYC Mayor's Office of Climate Resiliency and the US Environmental Protection Agency will provide a detailed description of how information is scaled to fit the needs of NYC air quality warnings, addressing tourism, recreation and quality of life in NYC.

- Oceans: The Nature Conservancy and Conservation International will provide their policy experience and system knowledge for combining climate science, ecological models and economic data from the Pacific region on tuna migration. Through their decisions and actions, we will learn how GeoXO data will help communicate the impacts of climate on tuna and, in turn, on the economies of Small Island Developing States (SIDS) in the Pacific and on the U.S. economy.

- Weather and Climate: The National Hurricane Center (NHC with the Virginia Emergency Operations Center, the Federal Aviation Administration and Southwest airlines will explain how weather data impact decisions and warnings that go out to the public for safety and travel. Southwest Airlines will help translate how improvements in data and warnings from the FAA will affect the costs and benefits of flight delays. The NHC and the Virginia Emergency Operations Center will explain how small changes in model data can translate to priceless decisions in evacuation warnings.

GeoXO Capability Overview

Proposed Constellation

NOAA operates a suite of Earth observation satellites that collect data that are needed to accomplish its mission:

1. To understand and predict changes in climate, weather, oceans and coasts;
2. To share that knowledge and information with others; and
3. To conserve and manage coastal and marine ecosystems and resources.

NOAA satellites are of two general types. Geostationary (GEO) satellites orbit the Earth at altitudes of about 35,000 kilometers, which allows their orbits to be synchronized with the rotation of the Earth. This in primary comparison to NOAA's Low Earth Orbit (LEO) satellites, such as NOAA's polar-orbiting satellites which circle the Earth from pole-to-pole at altitudes of about 800 kilometers, crossing the equator 14 times daily[2] and providing full global coverage twice a day. A geostationary orbit allows continuous coverage of an area while low-Earth orbiting satellites collect data over a specific area with an update cycle of around 8-12 hours. There are also deep space satellites such as NOAA's DSCOVR which conduct specialty missions.

A geostationary orbit provides a fixed field of view, allowing nearly continuous observation. Data from geostationary satellites are particularly useful for monitoring and forecasting rapidly changing phenomena including, for example, tornadic storms, hurricanes (which often intensify rapidly just before landfall), thunderstorms, wildfires and associated smoke plumes, volcanic eruptions and the associated ash plumes, and lightning. The high temporal resolution of GEO satellites also provides unique insights into phenomena with pronounced diurnal cycles including air quality and concentrations of the marine algae that cause harmful algal blooms (HABs) and hypoxia. The high frequency of observation supports modeling and analyses that require data with high temporal resolution (of an hour or less) and greatly reduces the effects of cloud cover because portions of the field of view that are obstructed by clouds can be observed as the clouds move. The combination of high frequency and low latency can also address the quickly changing needs of first responders, the emergency operations community, and others who need near real time (NRT) data to address dynamic on-the-ground conditions.

Satellite observations are critical to the success of the NOAA mission, requiring dedicated observational capabilities. Data from satellites operated by NASA, the Department of Defense, other U.S. government agencies, partner nations, and the private sector are important complements to NOAA data but, since the uninterrupted availability of data from sources outside of NOAA is not assured, they are not substitutes for the dedicated operational observing capabilities of GeoXO.

Satellites in NOAA's current GEO program (GOES-R series) will reach the end of their operational lives in the mid-2030s. NOAA's Geostationary Extended Observations (GeoXO) satellite system will continue and expand observations provided by the current GOES-R series

[2] NASA Scientific Visualization Studio. NOAA-20 Satellite Orbit with Suomi NPP and JPSS-2. Available at https://svs.gsfc.nasa.gov/4820. Accessed May 4, 2022.

satellites. NOAA is working to ensure these critical observations are in place by the early 2030s. Since the GOES-R satellites currently operated by NOAA will be approaching the end of their operational lives as GeoXO becomes operational, observations from NOAA's existing satellites cannot be considered as substitutes for those collected by GeoXO[3]. It is, however, likely that there will be operational overlap between the two generations of satellites to ensure the continuity of NOAA's mission and other programs that rely on data provided by this series of satellites. Benefit estimates do not take this redundancy into consideration.

The current recommended constellation for GeoXO consists of a series of three satellites orbiting over the eastern, central, and western United States that will provide dedicated observational capabilities from the launch of the first satellites in 2032 until 2055. These satellites are referred to as GEO-East, GEO-Central, and GEO-West, indicating the central locations of their fields of view. The GEO-East and GEO-West satellites will each include three Earth observation instruments: a visible/infrared imager, a lightning mapper, and an ocean color instrument. GEO-Central satellites will include two Earth observation instruments: a hyperspectral infrared sounder and an atmospheric composition instrument. The recommended GeoXO constellation is depicted in the image below[4].

[3] eoPortal. 2022. Suomi NPP. Available at https://directory.eoportal.org/web/eoportal/satellite-missions/s/suomi-npp. Accessed May 4, 2022.
[4] NOAA National Environmental Satellite Data and Information Service. Geostationary Extended Observations (GeoXO). Available at https://www.nesdis.noaa.gov/next-generation/geostationary-extended-observations-geoxo. Accessed May 4, 2022.

Defining and Measuring the Value of GeoXO

Investments are considered to be in the interest of the federal government when the resulting benefit that accrues to society exceeds the cost of the investment. GeoXO observations will improve a wide range of NOAA's products and services and have the potential to lead to discoveries that, in turn, lead to new products and services that benefit society.

Since, as noted above, neither the satellites operated by other entities nor the satellites currently operated by NOAA can serve as substitutes for GeoXO capabilities, the benefits associated with GeoXO are measured as the full societal benefit associated with the use of GeoXO data to support existing products that rely on GOES-series observations and to create new NOAA products and services.

The societal benefits from the GeoXO satellites are expected to be large and widespread. For example, valuation studies conducted by NOAA in 2020 for the geostationary infrared (IR) sounder identified two use cases, commercial aviation optimization and electric power forecasting, whose benefits each independently exceeded the cost of that instrument. Earlier studies documented even greater benefits from a high-spectral resolution infrared sounder, several times the instrument cost[5]. This study focused on tropical cyclones, aviation, energy, agriculture, recreational boating, and air quality. Across all instruments in the recommended GeoXO constellation, these studies and the current study have identified 175 use cases that show the beneficial application of GeoXO data to agriculture, wildfire response, commercial and recreational fishing, aviation, outdoor recreation, drinking water suppliers, coral reef management, federal, state and local governments, and the general public.

Examples from the 175 use cases of NOAA-generated products that will be supported and improved by GeoXO data include, but are not limited to:

- weather and climate forecasts ranging from daily forecasts of temperature and precipitation to fire weather forecasts, aviation forecasts, lightning threats[6], and forecasts of hurricanes, tornadoes, thunderstorms, and other extreme events;
- fish stock assessments, and other products that are critical to the sustainable management of our nation's marine fisheries;
- marine and freshwater hypoxia forecasts used by fisheries managers, commercial and recreational fishermen and, in the Great Lakes, drinking water managers;
- monitoring and forecasting harmful algal blooms that threaten human health;
- air quality data and forecasts that reduce human exposure to poor air quality conditions and the resulting health impacts and premature mortality;
- aviation forecasts and volcanic ash advisories that help to ensure the safety and efficiency of air transportation;
- Whale Watch, which provides real-time information on the locations of whales so they can be protected from threats such as ship strikes, entanglements, and disorienting underwater sounds; and
- dispersion forecasts for chemical fires, radiological accidents and other emergency events that release hazardous pollution into the atmosphere.

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[5] Centrec Consulting Group, LLC, 2007. An investigation of the economic and social value of selected NOAA data and products for geostationary operational environmental satellites (GOES).

[6] See, for example, https://www.weather.gov/mlb/lightning.

Benefits will be realized in the form of loss reductions, increased productivity, improved human health, reduced human fatalities, and the conservation and protection of the natural environment when compared to scenarios where the GeoXO observations are not available.

The quantification of all of the 175 value chains would require dozens of economic studies, since the benefits and the manner in which they are produced differs with each use case. Further, it is not feasible to estimate the full benefit of GeoXO because many benefits are likely to result from discoveries and new insights gleaned from the data and new applications that are not yet known. It is possible that some of the currently unknown benefits of GeoXO could be very large. Further complicating the analysis is the large and diverse number of end-users who are the ultimate beneficiaries of improvements to NOAA's products and services, ranging from farmers to electric power distribution operators and individuals engaging in outdoor recreation. The benefits associated with each use case are realized in different forms and in different decision-making contexts, requiring massive efforts to identify users and the decision-making contexts within which benefits are realized. Thus, any study of the benefits of GeoXO that requires a rigorous microeconomic foundation is likely to understate its full value, perhaps to a great degree. Therefore, the case studies presented in this analysis represent only a partial accounting of the benefits of GeoXO and have been selected to illustrate the magnitude and pervasiveness of the societal benefits of GeoXO.

GeoXO is designed as a system. Although each of the five instruments provides unique and economically valuable observations, realizing the full value of GeoXO depends on multiple instruments working in combination. Even where benefits can be traced primarily to a single instrument, the magnitude of benefits is frequently increased by information provided by other instruments on the GeoXO. For example, the lightning mapper observations can be used to detect convection and growth in a hurricane cloud band observed by the imager. In many instances, the beneficial effects that are reported for one instrument have been enhanced by the use of data from other instruments. Methods used to quantify benefits that result from the use of observations from two or more instruments (Section 3) have been designed to avoid double-counting.

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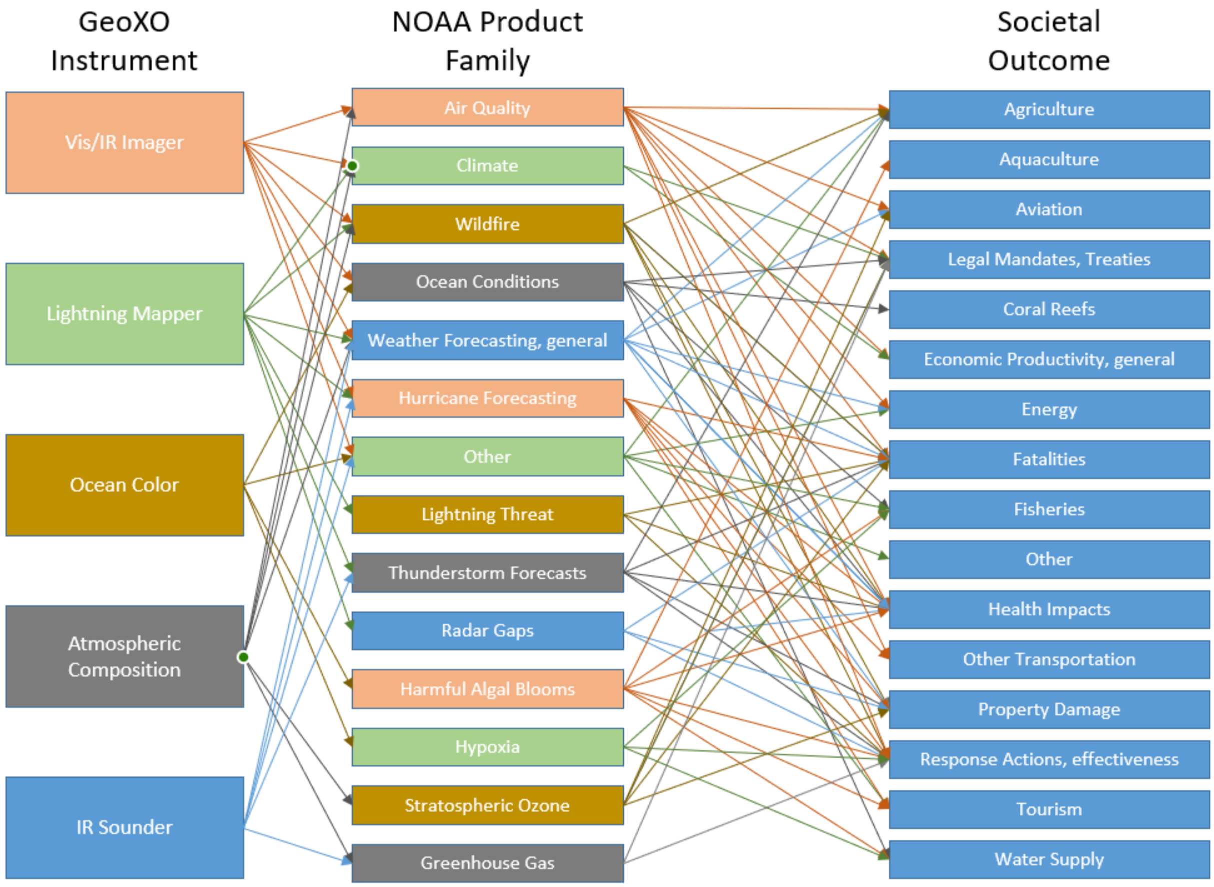
Section 1: Survey of Benefits

Identifying GeoXO Benefits

The User Engagement workshops conducted in the summer of 2020 cast a broad net, gathering information on the needs of the constituents of five high-priority application areas: human health, agriculture, wildfires, ocean applications, and weather forecasting. The benefit studies that were conducted in the fall of 2020 narrowed the focus, addressing the potential of GeoXO observations to address the information needs identified in the User Engagement workshops. These studies, together with this study and the NOAA Pathfinder efforts described below, identified 175 separate pathways, or “value chains,” by which GeoXO will generate value to society. The diagram below is a simplified representation of the 175 value chains, combining similar NOAA products that will be improved by GeoXO into “product families” and combining similar types of GeoXO-enable improvements to societal outcomes into broad classes. The Air Quality product family, for example, combines products focused on air quality monitoring and forecasting, monitoring of specific hazardous particulate emissions as from wildfires and chemical spills, and air quality modeling performed by NOAA and used to develop local air quality forecasts. The societal outcome group labeled as “Agriculture” includes the potential of GeoXO-enabled improvements to NOAA products to increase agricultural productivity, reduce economic losses associated with wildfire and the associated impairments to air quality, reduce irrigation and fertilization costs, and to reduce the impacts of damage by extreme weather.

The diagram is provided to illustrate:

- the large number of pathways by which GeoXO observations are expected to yield societal benefits,
- the complementary nature of observations in improving NOAA products and services and expanding their scope (depicted in the arrows from “GeoXO Capacity” to “NOAA Product Family”), and
- the complementary nature of product improvements used to improve societal outcomes (depicted by the arrows from “NOAA Product Family” to “Societal Outcome”).



The Pathfinder efforts further narrows the focus, identifying a small number of early adopters who will work with NOAA over the next several years to expedite the beneficial use of GeoXO observations when the satellites become operational.

The term early adopter refers to individuals, businesses, and organizations who use new products or technology before others. Companies rely on early adopters of information to provide feedback about product deficiencies and challenges and to have topical samples for how the information is applied in different areas of society. The NOAA Pathfinder Initiative is a community of front line data users; they are the community of early adopters of satellite information. NOAA Pathfinders have a key role in connecting concepts behind NOAA data and products, adopting said data and product(s), and validating the uses, applications and decisions supported in their thematic area of society for the broader community of beneficiaries.

NOAA Pathfinders help develop economic value studies for the future applications of mission data products before launch,utilizing proxy data up until mission data and products are operationally available. GeoXO is the first NOAA mission to host the Pathfinder Initiative. NOAA's Space Weather and NOAA's Low Earth's Orbit mission will soon follow with their development of value studies. The Pathfinders sponsoring GeoXO will communicate the benefits of GeoXO's instrument science to societal decisions and operations in their specific areas of society. Value chains evolve with the Pathfinders participation and input throughout the mission's life cycle and are validated during the post launch operations. GeoXO selected 6

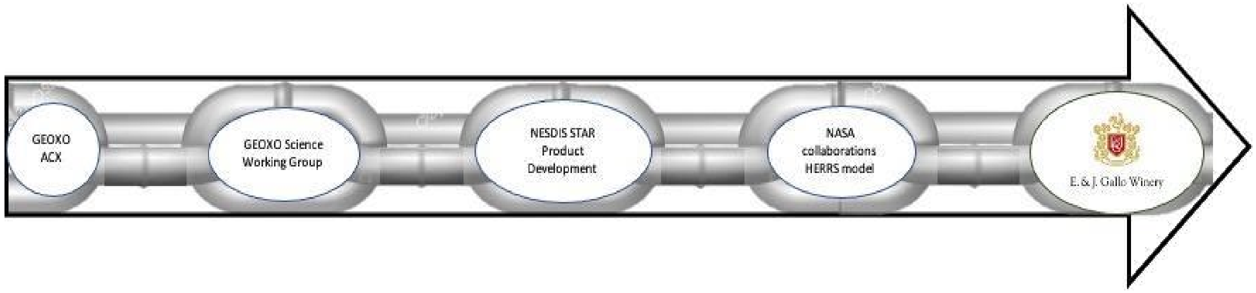
Pathfinders to help tell the story of GeoXO's future impact in wildfire, human health agriculture, weather forecasting and ocean dynamics.

This part of the report will briefly describe the Pathfinders selected for the GeoXO Value studies. Pathfinders working with GeoXO are currently using GOES 16/17 data and will continue to adopt future GEO satellites, 18, and 19 data as well other data from NASA missions such as PACE, TEMPO, GLIMR, MAIA and TROPICS. Shortly after GeoXO's launch, the Pathfinders will be among the first line of users of GeoXO data-providing demonstrable impacts to the uses of GeoXO data in society. The Pathfinder value chains will be used to trace societal benefits to GeoXO's instruments. Each value chain uses the Pathfinder's unique decision making and operations feedback specific to implementing GeoXO data. Pathfinder Value chain develops at their own individual pace and are sensitive to the operational needs and tempo of the selected Pathfinder. GeoXO will continue to utilize the NOAA Pathfinder Initiative to build and expand on known use cases to understand the impact of future data. Use cases will be validated after launch when GeoXO observations are available and applied to the Pathfinder decision making scenarios.

Below is a brief explanation of each GeoXO Pathfinder value chain.

- **Agriculture Community Overview**: Environmental data informs critical decisions across the agriculture cycle, from when to seed a crop to when to harvest and whether to plant cover crops between seasons. This information also underpins the research community's evolving understanding of the implications of a changing climate for the success and security of American agriculture. Remote sensing data has applications in both crop-based and animal agriculture and is a useful tool for growers, insurance companies, and economists alike to understand factors including livestock forage availability, soil moisture, and damage from weather events. Members of the agriculture community are both technical and non-technical end-users. This places a premium on easily accessible data designed for non-research audiences. The agriculture stakeholders engaged by GeoXO user engagement team emphasized the need for metrics such as confidence metrics to be included in forecasts to help inform decision making and highlighted that improvements in spatial resolution and soil moisture detection would be of particular use to the community. Chemical composition of smoke and soil would also be a high value also.

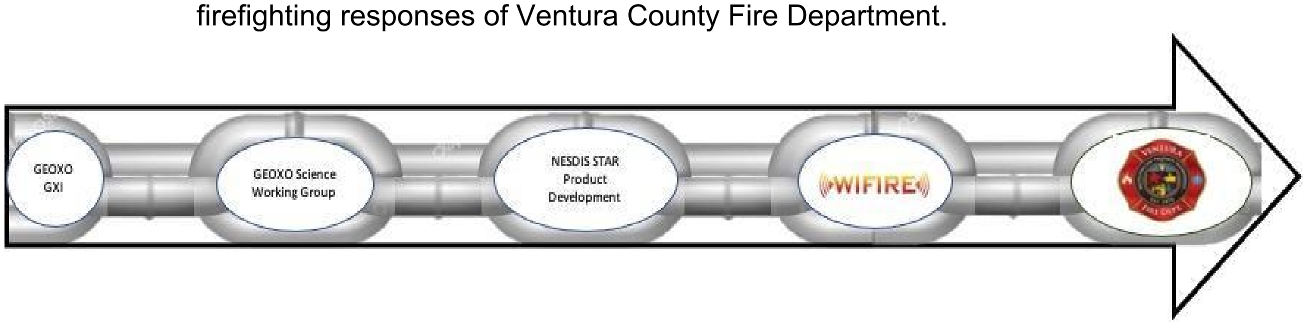
  E & J Gallo Winery, a family run winery and distributor headquartered in Modesto, California, is the largest exporter of California wines. Gallo is active in agricultural research and is a commercial user of satellite data. During the 2020 California fires, Gallo, like hundreds of other California vineyards, suffered from smoke damage on grapes (known as smoke taint). As users of GOES ABI will data, Gallo will help develop a value chain to understand how improvements in the atmospheric composition products from GeoXO will impact future viticulture challenges and early warning scenarios in California.



- **Wildfires Community Overview:** The wildfire sector represents a wide range of stakeholders, from those who work in emergency operations during wildfire events to researchers who assess wildfire risk to critical infrastructure during the pre-season. GeoXO engaged across topical areas such as fire preparedness, fire response, damage assessments, and the protection of critical infrastructure (protection?). Throughout the user engagement effort, GeoXO assessed the perspectives and challenges of state and local officials, of members of the USDA Forest Service, NASA, NOAA Fire Initiative, NWS and a series of academic, commercial, and local stakeholders researchers working to improve modeling capabilities, and of international partners who rely on NOAA data to inform their own response operations.

  The wildfire community places a high priority on data which is easily compatible with GIS-based software platforms providing low latency and high temporal resolution, due to the truncated nature of many critical decision timelines. The engaged community also stressed the challenges they face with measuring key variables such as lightning strike locations, fuel bed characteristics, and fire emissions. There was a particular emphasis throughout discussions on the unique difficulties posed by small- and low-intensity fires, which are challenging to track but can rapidly intensify to affect large, heavily populated areas.

  As a Pathfinder, the WIFIRE Lab is an all-hazards knowledge cyberinfrastructure, forming a data management layer between the data collection and modeling. They operate as a neutral data resource/partner to any proposed fire related activity by adding value to the raw data, preparing real-time data for fire monitoring and fire modeling for research and operational use. To develop a wildfire value chain, GeoXO engaged with WIFIRE as a future Pathfinder to demonstrate current and future uses of GEO data. As a Pathfinder, WIFIRE provides their operational decision making use case that explicitly outlines how future GeoXO data will improve the impacts of WIFIRE products and the firefighting responses of Ventura County Fire Department.

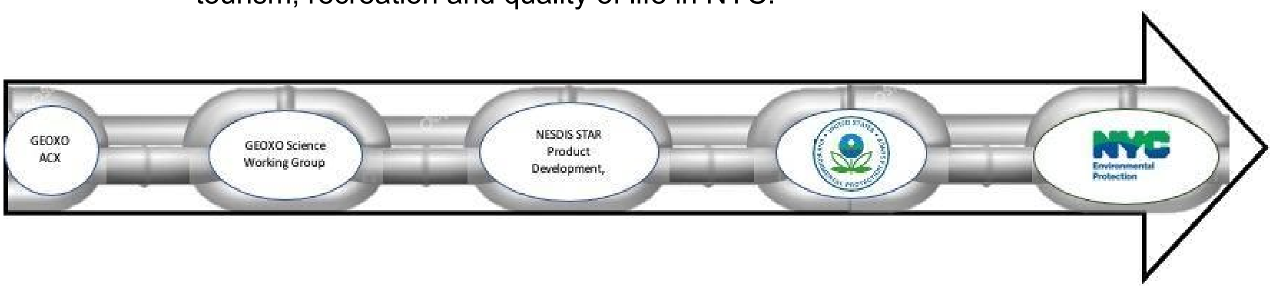


- **Human Health Community Overview:** Applications of remote sensing data in the Human Health sector span from air quality to harmful algal blooms (HABs). These data are used by public health experts to monitor extreme temperatures and urban heat island impacts. City officials use earth observations to inform the deployment of resources for heat stress mitigation within their communities.

  Public health officials also use satellite data to monitor air quality, both in day-to-day settings and in response to environmental weather events with air quality implications such as fire or a volcanic eruption. Researchers are using this data to develop a deeper understanding of the relationship between weather, climate, and waterborne diseases, as well as early detection mechanisms for HABs.

  There is widespread cooperation across the public and private sector to monitor, forecast, and model the spread of HABs using remotely sensed data. The Human Health community prioritizes data access and accessibility and improved spatial resolution so data may be more easily leveraged in a wide range of events.

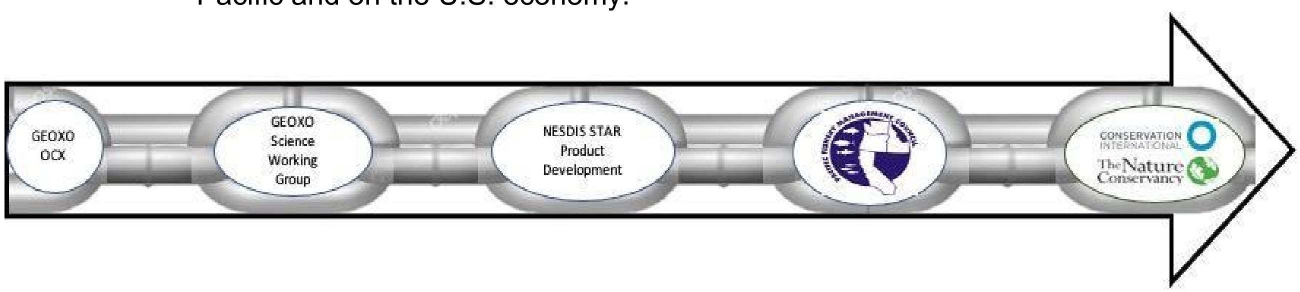
  As a Pathfinder, the NYC Mayor's Office of Climate Resiliency and the US Environmental Protection Agency will provide a detailed description of how information is scaled to fit the needs of NYC air quality warnings, addressing tourism, recreation and quality of life in NYC.



- **Oceans Community Overview:**

  The oceans community covered various topics of user needs spanning ocean life, water quality, and physical ocean properties in coastal water and deep ocean. Specific data needs and tools were addressed for the future planning and applications in these ocean areas. Across all topics discussed, the oceans community addressed a common need to have ocean data centralized and easily accessible to stakeholders, available in GIS-friendly formats for existing systems. This not only includes the future GeoXO data but also ocean specific observations coming from NASA missions such as PACE, GLIMR, and other research satellites that will provide ocean specific data. The need for higher spatial resolution in coastal zones will help users measure the land-water interface and the increased challenges posed by sea level rise. Improved temporal resolution (hourly) will allow users to detect changes driven by the tides and sporadic events. Additionally, data is needed on physical ocean properties, from wind patterns and circulation models to heat flux and atmospheric exchange. All of these needs support studies in ocean dynamics. This report will specifically look at how the future geostationary ocean color sensor will help inform tuna migration.

Small Island Developing States (SIDS) in the Pacific region depend on their commercial fisheries for food supplies and economic health. Research shows climate change will dramatically alter tuna stocks in the tropical Pacific, with potentially severe consequences for the people who depend on them. The Nature Conservancy has become one of the most effective and wide-reaching environmental organizations in the world. Conservation International is an American nonprofit environmental organization that spotlights and secures the critical benefits that nature provides to humanity, such as food, fresh water, livelihoods and a stable climate. As Pathfinders, they will provide their policy experience and system knowledge for combining climate science, ecological models, and economic data from the Pacific region on tuna migration. Through their decisions and actions, we will learn how GeoXO data will help communicate the impacts of climate on tuna and, in turn, on the economies of SIDS in the Pacific and on the U.S. economy.

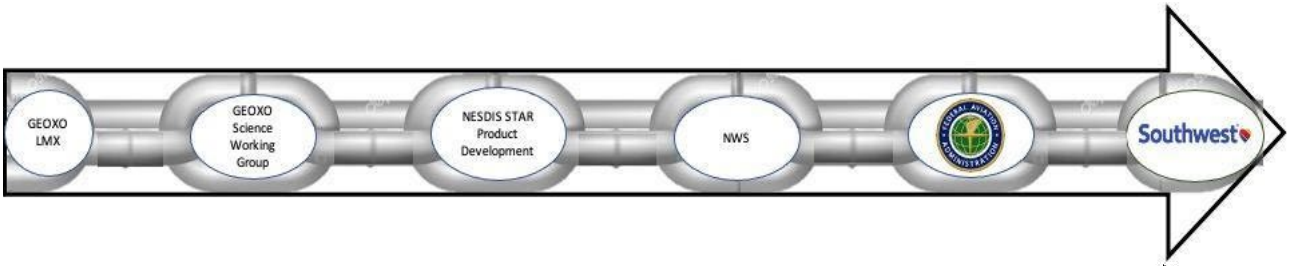


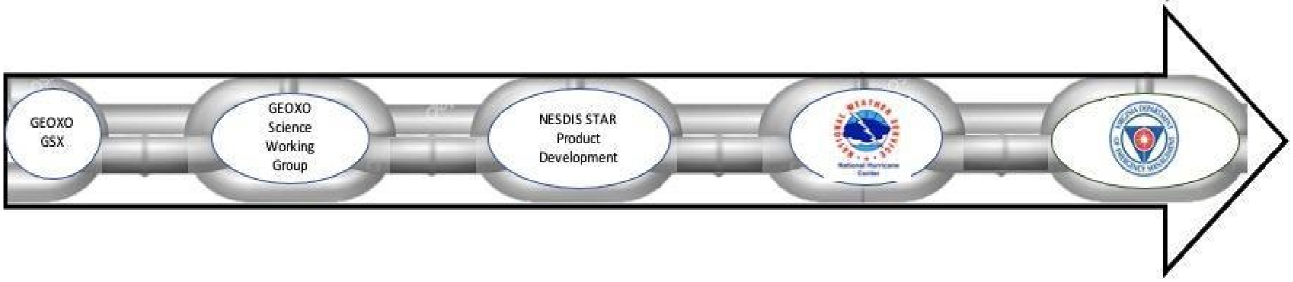
- **Weather and Climate Community Overview:** Remote sensing is vital to effective weather forecasting and success across National Weather Service (NWS) operations. Satellite data support a wide variety of weather applications from routine weather forecasting to severe storms and climate modeling. Meteorologists, public officials, and first responders alike rely on this information to prepare and warn the public of weather-related threats and ensure national security. Researchers use remotely sensed data to validate and improve models for weather events. The Weather Forecasting community highlighted the need for improvements in the measurement of specific variables such as different atmospheric layers to enhance forecasting and modeling.

  As Pathfinders, the National Hurricane Center (NHC) and the Virginia Emergency Operations Center, the Federal Aviation Administration, and Southwest Airlines will explain how weather data impact decisions and warnings that go out to the public for safety and travel.

  Southwest Airlines will help translate how improvements in data and warnings from the FAA will reduce the costs of flight delays, thus benefiting airlines and travelers.

  The NHC and the Virginia Emergency Operations Center will explain how small changes in model data can translate to priceless decisions in evacuation warnings.





Instrument-Specific Review of Societal Benefits

General Overview

The following paragraphs describe the scope of benefits associated with each GeoXO instrument. Although not comprehensive, these descriptions demonstrate that the benefits of GeoXO extend widely across the economy and society. Content is drawn largely from instrument-specific benefit studies completed in 2020[7].

The proposed GeoXO instruments complement one another in many ways. Thus, many of the benefits of GeoXO will be fully realized through the use of data from two or more instruments in combination. In the following review, benefits are organized in groups that correspond to instruments that play a key role in generating that benefit. Generally, benefits are classified by instrument according to the instrument-specific report that identified that particular application of the GeoXO observations. It should be noted that, in many instances, the beneficial effects that are reported for one instrument have been enhanced by the use of data from other instruments. Methods used to quantify benefits that result from the use of observations from two or more instruments (Section 3) have been designed to avoid double-counting.

Visible/Infrared (Vis/IR) Imager

The benefit description that follows is taken primarily from the 2007 study titled “An Investigation of the Economic and Social Value of Selected NOAA Data and Products for Geostationary

[7] The capabilities and societal benefits have been thoroughly documented in prior studies, such as the one cited below by Centrec Consulting Group. This NOAA-developed study provided much of the information used to describe the benefits of the imager. Instrument-specific value studies completed by the GeoXO team in 2020 (some of which were not published until 2021) provided much of the information used to describe the benefits of the remaining four instruments planned for GeoXO. It should be noted that this study is not verified by independent or peer review.

Operational Environmental Satellites (GOES)[8].” The current GOES-R instrument series includes a visible/infrared imager. Although GeoXO will include an improved version of this instrument, with four times the spatial resolution in several spectral bands and other improvements, the nature of the benefits is similar although the instrument improvements will increase their magnitude in some cases. Three groups of scientists supported the benefit studies for each instrument: one focused on the function and capabilities of the instrument itself, one focused on the data provided by the instrument, and one focused on the products that use those data. The science team supporting the benefit study for the imager agreed that the nature of benefits described in the 2007 report is correct[9] and accurately reflects the nature of benefits associated with the improved instrument that will be included in the GeoXO constellation. The current magnitude of those benefits is likely to have increased beyond levels reported in 2007, corresponding to increases in the population and the affluence of the U.S. (more people and wealth are exposed to the hazards whose impacts are reduced by the use of data from the GOES-R Vis/IR imager); the magnitude of benefits from GeoXO’s imager are expected to be even greater, corresponding to continued increases in population and affluence, the increased spatial resolution offered by the GeoXO imager, and complementary observations provided by other instruments on GeoXO.

Imager benefits fall into seven broad but sometimes overlapping classes, supporting products that provide information on air quality, climate, wildfires and other environmental hazards, freshwater resources, ocean conditions, vegetation, and weather.

1. Air Quality. The imager provides data at high temporal and spatial resolution that aid state and local government agencies in their compliance with EPA mandates to monitor and improve air quality. Compliance with EPA mandates reduces the health impacts of poor air quality, but also imposes costs on electric power generation and other local industries. Thus, uncertainty in measures of air quality can impose unnecessary costs on communities that restrict industrial activity more than is needed to achieve compliance; the high spatial and temporal resolution of data provided by the imager will reduce uncertainty and unnecessary costs[10].

   More than 100,000 Americans die prematurely each year from heart attacks, strokes, and other illnesses caused by exposure to poor air quality[11]. Accurate air quality forecasts help people limit their exposure to harmful air pollutants by, for example, staying indoors. This is especially important for those who are more sensitive to poor air quality (e.g., the aging and those with medical conditions that make them more vulnerable to the negative health impacts of exposure to poor air quality). The high temporal resolution of data from geostationary satellites provides a more complete understanding of air quality which has a significant degree of variability by location and over the course of the day.

[8] Centrec Consulting Group, LLC, 2007. An investigation of the economic and social value of selected NOAA data and products for geostationary operational environmental satellites (GOES).
[9] Personal communication.
[10] Ibid.
[11] Fann, N., Lamson, A.D., Anenberg, S.C., Wesson, K., Risley, D. and Hubbell, B.J., 2012. Estimating the national public health burden associated with exposure to ambient PM2. 5 and ozone. Risk Analysis: An International Journal, 32(1), pp.81-95.

Poor air quality imposes direct costs on industrial and commercial enterprises that require "cleanroom" conditions for operations[12]. Cleanrooms are designed to maintain extremely low levels of airborne particulate matter such as dust, microorganisms, and vaporized particles. Examples of enterprises requiring cleanroom conditions include manufacturers of pharmaceuticals, solar panels, rechargeable batteries, semiconductors, certain medical devices, and nanotechnology[13] (applications of nanotechnology include materials used to manufacture lightweight body armor, scratch-resistant and anti-fogging eyeglass lenses, ethanol, rechargeable batteries for automobiles[14]. GeoXO's high temporal and spatial resolution air quality data can improve the effectiveness and efficiency of cleanroom operations by providing users with information on local conditions, increasing the productivity and profitability of these enterprises.

2. Climate. Data from the imager will provide information that supports improved climate modeling. Its measurements will assist in resolving climate-relevant changes in the atmosphere, ocean, land, and cryosphere with high temporal resolution that reveals diurnal variability of conditions. The cryosphere--frozen portions of Earth's water--includes the continental ice sheets in Greenland and Antarctica, smaller ice caps, glaciers, and areas of snow and permafrost. Although most of these features are outside the field of view of the imager, it will provide observations for glaciers in North America with, at least, local relevance for climate monitoring and forecasting. The high temporal resolution of the geostationary imager will also support development of diurnal signatures for fires, clouds, lightning, and other climate-relevant factors. Improved accuracy in seasonal climate forecasts will provide benefits to the businesses, from retailers to agriculture, who rely on them. Improved accuracy in long-term climate forecasts can support the development of cost-effective climate policy that provide higher levels of environmental protection at a lower cost. Finally, the imager provides quantitative information about clouds which are a key component of the climate system.

3. Wildfire and Other Environmental Hazards. Effective response to the dynamic conditions associated with wildfire, oil spills, volcanic eruptions, and search and rescue activities require the high temporal resolution of information provided by geostationary satellites. The information generated by the Vis/IR can be used to reduce adverse health impacts, loss of life, and the cost of response activities.

4. Freshwater Resources. Many of the defining attributes of freshwater resources including rivers and lakes are dynamic in nature including, for example flows, turbidity, and sediment transport. The high temporal resolution of observations from the geostationary Vis/IR will aid in the protection, management, and use of freshwater resources, reducing costs and adverse environmental impacts. The use of this information will also improve reservoir management actions, enhancing the benefits from the reservoirs, which vary in nature according to the function of the reservoir (e.g., irrigation, flood control, hydropower generation, and recreation).

5. Ocean Conditions. The imager provides important components of data needed to characterize ocean conditions, including sea surface temperature, ocean currents, and low-

[12] Centrec 2007, op. cit.
[13] Mecart Cleanrooms, 2022. What is a Cleanroom? Available at https://www.mecart-cleanrooms.com/learning-center/what-is-a-cleanroom/. Accessed May 3, 2022.
[14] National Nanotechnology Initiative. 2022. Nanotechnology Benefits. Available at https://www.nano.gov/you/nanotechnology-benefits. Accessed May 3, 2022.

level winds. These data are key inputs to the ecological assessments that government agencies use to guide and manage the use and protection of ocean resources and the ecological systems that support, for example, fisheries productivity and the health of coral reefs. In addition to the direct benefits of improving the efficiency and effectiveness of government management and policy actions, Vis/IR data will lead to downstream benefits that reflect the goals of ocean management and policy including, for example, increased and sustainable fish harvesting, enhanced recreational and other use of coral reefs, and reduced impacts from harmful algal blooms.

6. Vegetation. The Vis/IR will provide high temporal resolution information on vegetation and conditions that affect vegetation, like moisture and thermal fields. The high resolution of the data will support monitoring of attributes that vary diurnally, which is especially important to agriculture. The data will also improve the quality of agriculture and forestry forecasting products. Vis/IR data will provide timely information on burn scars left in the wake of wildfires. The damage to biological structure in burn scar areas creates the potential for destructive mud slides that destroy property, threaten human life, and disrupt transportation. In remote areas where wildfire damage is often the most severe and extensive, restoration of normal transportation after a mudslide can take months, often isolating small communities and limiting their access to vital services such as emergency health care[15].

7. Weather. Imager observations contribute to a wide range of weather products, generating a wide range of often very large benefits. For example, enhancements to weather forecasts made possible by Vis/IR data provide a basis for more efficient crop irrigation, with savings of $61 million annually in 2015[16]. A recent report documented the benefits from an imager to be on the order of billions of dollars for hurricane forecasting alone[17].

   Enhanced aviation forecasting reduces the incidence of avoidable delays; statistics from the Federal Aviation Administration show that the cost of weather-related aviation delays average more than $20 billion annually[18], including costs to airlines, passengers, and businesses that depend on air travel. These costs have been increasing steadily over the past decade. Improved forecasts can reduce the incidence of false alarms for flight-limiting weather and allow air transportation to continue longer and resume more rapidly when weather conditions are deemed safe for air travel[19]. Reducing these costs even by a small fraction would lead to large annual benefits to airlines, passengers, and the businesses that depend on air travel (e.g., a 1 percent reduction in airline delay costs would equate to $2 billion annually).

   Electric power and gas utilities use weather forecast information in predicting next-day demands for energy. Improved forecasts reduce energy costs. When energy demand

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[15] Honolulu Civil Beat. 2022. Repeat Disasters Prompt Kauai to Build Rural Emergency Response Center. Available at https://www.civilbeat.org/2022/05/repeat-disasters-prompt-kauai-to-build-rural-emergency-response-center/. Accessed August 4, 2022.
[16] Centrec 2007, op. cit.
[17] Centrec 2007, op. cit.
[18] Federal Aviation Administration. 2020. FAA Administrator's Factbook. Available at https://www.faa.gov/sites/faa.gov/files/2021-09/2020_Administrators_Fact_Book.pdf. Accessed July 26, 2022.
[19] Federal Aviation Administration. 2021. Air Traffic by the Numbers. Available at https://www.faa.gov/air_traffic/by_the_numbers/media/Air_Traffic_by_the_Numbers_2021.pdf. Accessed May 3, 2022.

exceeds demand forecasts, utilities must resort to higher-cost measures to meet the additional demand. When energy demand falls short of demand forecasts, utilities incur the cost of producing energy that isn't needed and for which no revenues will be received. Benefits to electric and gas utilities associated with enhanced weather forecasting have been estimated to exceed $500 million annually[20]. Additional benefits to the energy sector include improved data for siting solar energy facilities (data from the GOES-16/17R imagers are a vital component of the National Renewable Energy Laboratory's Solar Radiation database, which was used to determine optimal sites for solar facilities with a total construction cost of $78 billion[21]. To promote the adoption of renewable energy, solar power has a higher dispatch priority than energy produced by fossil fuels. For this reason, forecasts of the demand for electricity from non-renewable sources must account for next-day production forecasts for solar power; forecast enhancements made possible by Imager data can improve solar production forecasts, further reducing inefficiencies in non-renewable energy production.

Imager-enabled enhancements to forecasts of hurricanes and other major storms can improve the safety of marine transportation and reduce the cost to coastal residents of avoiding hazardous conditions. This is one of the most important societal benefits of GeoXO; imagers show the location of hurricanes and improve forecasts of their tracks, which are used to protect people and property that are in harm's way. Reduced uncertainty in hurricane forecasts, for example, increases the precision of evacuation orders and provides more accurate information for reducing damages to recreational boating vessels[22].

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[20] Centrec Consulting Group, LLC, 2007. An investigation of the economic and social value of selected NOAA data and products for geostationary operational environmental satellites (GOES).
[21] Personal communication, Dr. Manajit Sengupta, Chief Scientist,Sensing and Predictive Analytics, NREL.
[22] Centrec Consulting Group, LLC, 2007. An investigation of the economic and social value of selected NOAA data and products for geostationary operational environmental satellites (GOES).

Key attributes of imager benefits are shown in the table below.

NOAA Product Improvement	Societal Outcome Improved
Air Quality monitoring/forecasting	Complying with mandates, increased effectiveness
Air Quality monitoring/forecasting	Complying with mandates, increased efficiency
Air Quality monitoring/forecasting	*Fatalities, reduced
Air Quality monitoring/forecasting	Economic productivity, reduced impacts
Air Quality monitoring/forecasting	Complying with mandates, increased effectiveness
Air Quality monitoring/forecasting	Complying with mandates, increased efficiency
Air Quality monitoring/forecasting	Fatalities, reduced
Air Quality monitoring/forecasting	Economic productivity, reduced impacts
Seasonal Climate Forecasts	Economic productivity, reduced impacts
Long-term Climate Forecasts	Complying with mandates, increased efficiency
Wildfire detection	Health impacts, reduced
Wildfire detection	Fatalities, reduced
Wildfire detection	*Response actions, increased efficiency
Wildfire detection	**Response actions, increased effectiveness
Information on freshwater resources	Protection, management, and use of freshwater resources, reduced cost
Information on freshwater resources	Protection, management, and use of freshwater resources, reduced environmental impacts
Information for reservoir management	Irrigation, improved effectiveness
Information for reservoir management	Flood control, improved effectiveness
Information for reservoir management	Hydropower generation, increased productivity
Information for reservoir management	Recreation, reduced impacts
Information on ocean conditions	Fisheries, increased long-term productivity
Information on ocean conditions	Coral reefs, increased recreational use
Information on ocean conditions	Coral reefs, health
Information on ocean conditions	Disease, reduced
Information on ocean conditions	Water Supply Operations, increased efficiency
Information on conditions that effect vegetation	Agriculture, increased productivity
Information on conditions that effect vegetation	Industry-specific forecasts, increased quality
Information on conditions that effect vegetation	Burn scars, reduced impacts (e.g., mud slides)
Weather forecasting	Agriculture, reduced costs
Weather forecasting	**Aviation, reduced costs
Weather forecasting	**Electric power and natural gas distribution, reduced costs
Weather forecasting	Solar power siting, increased productivity
Hurricane forecasting	Marine transportation, increased safety
Hurricane forecasting	Marine transportation, increased reduced costs
Hurricane forecasting	**Response actions, increased efficiency
Hurricane forecasting	Recreational boating, reduced losses
Agriculture	**Reduced Losses
Thunderstorm and tornado forecasts	Fatalities, reduced
Filling radar gaps	**Response actions, increased efficiency
Filling radar gaps	**Personal property losses, reduced
Filling radar gaps	**Property damage, reduced
Filling radar gaps	**Fatalities, reduced
Filling radar gaps	**Injuries, reduced

** Quantified in full in this study.*
*** Quantified in part in this study.*

Geostationary Lightning Mapper

The benefit description that follows is taken primarily from NOAA's 2020 "Geostationary Lightning Mapper Value Assessment[23]." NOAA's GOES-R satellites have been providing geostationary lightning mapper (GLM) observations since the first satellite in the series became operational after its launch in 2016. Since then, the GLM has established a legacy of applications likely to become ubiquitous across a wide variety of meteorological domains. GeoXO will extend GLM observations beyond the life of the GOES-R mission, improving the quality of the information by providing higher spatial resolution and continuing to provide a freely available public source of lightning data that is becoming more widely used as it is integrated into additional operational systems and web-based weather applications.

GLM observations are already providing significant economic benefits. Operational users have eagerly embraced this new source of lightning information and incorporated it into their workflow. Over the contiguous United States (CONUS), forecasters use GLM data as a complement to ground-based radar to:

- make severe weather warning decisions earlier and more confidently;
- provide a basis for generating rapidly-updating 2-D maps that accurately portray temporal trends and the full spatial extent of the storm threat; this is a significant improvement over the current single latitude/longitude point source lightning information;
- fill spatial and temporal radar coverage gaps; and
- provide observations during scheduled and unscheduled radar outages.

Outside CONUS, GLM serves as a radar proxy. By extending observations into the Atlantic Ocean, far beyond the range of radar, GLM observations aid in the assessment of tropical cyclones as they develop and approach the U.S.

The GLM is uniquely able to monitor vast areas to identify the sustained "continuing current" lightning that is most likely to ignite wildfires. This enables emergency personnel to find small and even smoldering fires before they grow, reducing forest and property loss, lowering firefighting costs, increasing the safety of firefighters and the public, and improving air quality. Many of these wildfires occur in remote, mountainous areas with limited to no radar coverage, making GLM observations especially valuable.

Radar outages are common due to both regularly scheduled maintenance and outages caused by lightning or severe wind. GLM provided observations when the radar in Puerto Rico was offline for months following damage from Hurricane Maria.

GLM observes the complete spatial footprint of total lightning flashes, improving the characterization of lightning risk and increasing confidence and certainty for airline flight and ramp operations, leading to enhanced safety, improved airline efficiency, and cost savings.

The continuity of GLM observations provided by GeoXO will allow the development of additional applications of these data, further increasing their economic value which is realized in the form of loss reductions, increased productivity, and increased public health and safety.

[23] National Oceanic and Atmospheric Administration, 2020. Geostationary Lightning Mapper Value Assessment.

1. Lightning Safety. Since 1989, an average of 43 persons annually die from lightning strikes. This figure fell to 27 annual fatalities for years since 2009[24]. The decline is attributable, in part, to improved access to weather forecasts and increased public awareness of lightning hazards[25]. Most deaths from lightning strikes are directly linked to immediate cardiac arrest and respiratory arrest in persons struck by lightning[26]. Non-fatal conditions affecting those who survive lightning strikes include skin lesions, muscle injury, central nervous system abnormalities, and impacts on vision and hearing[27].

   The continuous observational capabilities of the GLM will increase the success of weather forecasts and awareness campaigns informed by weather information in reducing lightning-related death and injury. Coupled with outreach and training, the GLM helps to better inform the public of their local lightning threat by supporting improved climatologies describing long-term risks and actionable real-time information.

   Between 2006 and 2019, almost two-thirds of lightning deaths occurred during outdoor leisure activities and another 18 percent were work-related[28], with farming and construction occupations at the highest risk[29]. The GLM is broadening access to lightning information beyond those who can afford to purchase data by providing more accurate and comprehensive information on lightning for use in outreach to help at-risk workers and those who organize, lead, and participate in outdoor leisure activities take action to reduce the threat of lightning-related death and injury.

   Estimates of the number of persons now living in the United States who will be struck by lightning during their lifetime range from 20,000[30] to more than 100,000[31]. Thus, the benefits associated with improved lightning safety are likely to be significant and will be realized in the form of reduced loss of life and injury and the associated medical costs, disabilities, productivity losses, and pain and suffering.

   Improved information on lightning hazards also reduces false alarms. For example, an outdoor concert with 30,000 attendees held in June 2018 was nearly canceled due to the threat of severe weather. Local forecasters used real-time GLM data to determine that the storm was weakening and would not be a threat to the concert, which was held as planned, avoiding the financial losses associated with canceling a large concert.

[24] National Weather Service. 2022. How Dangerous is Lightning? Available at https://www.weather.gov/safety/lightning-odds. Accessed May 3, 2022.
[25] The Washington Post. June 8, 2021. The United States has yet to see a lightning fatality this year, a record to date. Available at https://www.washingtonpost.com/weather/2021/06/08/us-weather-lightning-fataiilities/. Accessed May 4, 2023.
[26] Ritenour, A.E., Morton, M.J., McManus, J.G., Barillo, D.J. and Cancio, L.C., 2008. Lightning injury: a review. Burns, 34(5), pp.585-594.
[27] Ibid.
[28] Jensenius, J. S., 2020: A Detailed Analysis of Lightning Deaths in the United States from 2006 through 2019. Available at https://www.weather.gov/media/safety/Analysis06-19.pdf. Accessed May 4, 2022.
[29] Ritenour, A.E., Morton, M.J., McManus, J.G., Barillo, D.J. and Cancio, L.C., 2008. Lightning injury: a review. Burns, 34(5), pp.585-594.
[30] National Weather Service. 2022. How Dangerous is Lightning? Available at https://www.weather.gov/safety/lightning-odds. Accessed May 3, 2022.
[31] Ritenour, A.E., Morton, M.J., McManus, J.G., Barillo, D.J. and Cancio, L.C., 2008. Lightning injury: a review. Burns, 34(5), pp.585-594.

2. Severe Thunderstorm and Tornado Warnings. In the U.S., there are about 100,000 thunderstorms each year. About 10 percent of these reach severe levels, meaning it contains one or more of the following: hail one inch or more in diameter, winds gusting in excess of 50 knots (57.5 mph), or a tornado[32]. Many hazardous weather events are associated with thunderstorms:
    - Rainfall from thunderstorms causes flash flooding, which kills more people each year than hurricanes, tornadoes, or lightning.
    - Lightning is responsible for many fires around the world each year, causing fatalities, injuries, fatalities, property damage, and expense of firefighting efforts.
    - Hail, sometimes the size of softballs, damages cars and windows, and kills livestock.
    - Strong straight-line winds associated with thunderstorms that can exceed 120 miles per hour damage trees, power lines, homes, and other property.
    - Tornadoes with winds up to 300 mph can destroy all but the best-built man-made structures[33].

    Since the year 2000, damages from more than 100 thunderstorms have exceeded $1 billion each, with the total losses associated with these storms exceeding $250 billion and more than 1,200 fatalities[34]. These extremely destructive storms represent a tiny fraction of the thunderstorms that have occurred over that time; the combined losses from less-destructive but far more frequent storms are also significant.

    GLM data update every 20 seconds with NWS operations using 1-minute updates. Since radar scans update at an average of every 5 minutes, GLM observations greatly improve the ability of forecasters to see the rapid intensification of thunderstorms early in their development and to better understand internal storm dynamics at critical decision points. This unique, rapidly updating system provides invaluable information that forecasters have already integrated into their warning decision processes to better understand internal storm dynamics[35, 36], allowing them to:
    - make warning decisions earlier and with higher confidence;
    - improve determinations of the areal extent of warnings; and
    - end warning sooner as storms decrease in intensity[37].

    Benefits from the continued provision of GLM observations in the GeoXO constellation will be realized in the form of increased safety, reduced loss of life and injury, and reduced

[32] NOAA National Severe Storms Laboratory. 2022. Severe Weather 101-Thunderstorms. Available at https://www.nssl.noaa.gov/education/svrwx101/thunderstorms/. Accessed May 4, 2022.
[33] Ibid.
[34] NOAA National Centers for Environmental Information (NCEI) U.S. Billion-Dollar Weather and Climate Disasters (2022). Available at https://www.ncei.noaa.gov/access/monitoring/billions/. Accessed May 4, 2022.
[35] NASA SPORT, 2019: Geostationary Lightning Mapper (GLM) Data Used to Aid in Warning Decision. Available at https://nasasport.wordpress.com/2019/07/17/geostationary-lightning-data-glm-dataused-to-aid-in-warning-decision/. Accessed May 4, 2022.
[36] Goss, H. 2020: Lightning research flashes forward. Available at https://eos.org/features/lightning-research-flashes-forward. Accessed May 4, 2022.
[37] Sutter, D. and Erickson, S., 2010. The time cost of tornado warnings and the savings with storm-based warnings. *Weather, Climate, and Society*, *2*(2), pp.103-112.

property losses. Although GLM observations are already providing significant societal benefits, these benefits will increase as the observations are increasingly integrated into NWS operations.

3. Wildfire Response. Since the year 2000, 16 wildfires have resulted in damages exceeding $1 billion each, with the total losses of these 16 wildfires reaching nearly $100 billion and causing more than 350 fatalities. The United States Forest Service (USFS) reports that their firefighters have a success rate of 97 percent in suppressing the more than 5,000 wildfires occurring each year on NFS lands before they reach 300 acres in size. This implies that tremendous damages are caused by a small percentage of the wildfires that occur.

   Although human-caused wildfires are more frequent, accounting for 84 percent of the total, lightning-ignited wildfires account for more than half of the total acreage burned[38]. Wildfires caused by lightning often smolder for days without emitting enough heat or smoke to be visible by human or satellite observation; two-thirds of lightning-ignited fires are detected within 24 hours but 15 percent smolder for three or more days before being detected[39]. GLM data can be used to improve early detection of wildfires; although the observations do not distinguish between cloud-to-cloud and cloud-to-Earth lightning, algorithms applied to the data are increasingly able to do so, reducing the number of lightning flashes to be investigated for fire ignition potential[40].

   Earlier detection of wildfires can increase the efficiency and effectiveness of response and reduce damages and loss of life. The largest and most destructive wildfires occur when there is a lot of fuel (high vegetation growth in a wet spring followed by a dry summer) and high winds[41]. However, preventing only a fraction of these fires from reaching disastrous sizes through early detection using GLM observations will yield significant benefits.

   Wildfire-related benefits of GLM are realized in the following ways: fewer unnecessary evacuations, reduced loss of life and adverse health effects for firefighters and residents of areas affected by wildfires, reduced cost of wildfire suppression, and reduced property losses.

4. Short-Term Model Forecasts. Assimilation of GLM data into short-term model forecasts is emerging but early results indicate many benefits. GLM's image-based datasets differ fundamentally from the data produced by ground-based lightning detection systems, presenting both advantages and challenges. GLM observations provide insights into the development of thunderstorms that cannot be gleaned from ground-based systems by providing information on both the incidence and attributes (e.g., flash extent density[42]) of lightning. This kind of information will improve the quality of forecasts; however, the ability to

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[38] Balch, J.K., Bradley, B.A., Abatzoglou, J.T., Nagy, R.C., Fusco, E.J. and Mahood, A.L., 2017. Human-started wildfires expand the fire niche across the United States. Proceedings of the National Academy of Sciences, 114(11), pp.2946-2951.

[39] Stano, G.T., Smith, M.R. and Schultz, C.J., 2019. Development and Evaluation of the GLM Stoplight Product for Lightning Safety. Journal of Operational Meteorology, 7(7).

[40] Personal communication with Scott Rudloski, Physical Scientist, NOAA/NESDIS/STAR.

[41] Personal communication with Robyn Heffernan, National Fire Weather Science and Dissemination Meteorologist, National Weather Service.

[42] Bruning, E.C., Tillier, C.E., Edgington, S.F., Rudlosky, S.D., Zajic, J., Gravelle, C., Foster, M., Calhoun, K.M., Campbell, P.A., Stano, G.T. and Schultz, C.J., 2019. Meteorological imagery for the geostationary lightning mapper. Journal of Geophysical Research: Atmospheres, 124(24), pp.14285-14309.

assimilate GLM data into models is still developing. Model improvements expected with the full assimilation of GLM data include:

- Increased lead time and improved accuracy of NWS severe weather watches (flooding, tornadoes, wind, and hail), leading to better receptiveness of warnings and improved public safety.
- Improvements in the transition to warn-on-forecast, leading to enhanced accuracy of NWS-issued severe weather warnings, including lower false alarm rates.
- Reducing losses from hail (e.g., automobiles can be moved to avoid large losses, agricultural losses can be mitigated on small scales in response to weather forecasts).
- Predicting weather favorable to the onset or spread of wildfires, including a Fire Weather Index product in development for use in the NOAA SPC's Fire Weather Outlook.

The full range of benefits of incorporating GLM data into short-term forecasts will be realized in many ways that reduce damages and other costs, increase productivity, and increase human safety. These benefits are the result of reducing the number of false alarms, reducing the size of warning areas and the duration of warnings, and increasing the precision and timeliness of information on hazards.

5. Precipitation Estimation. Some parts of the United States lack adequate radar coverage needed for rainfall forecasts and predictions of floods and, in particular, flash floods. Areas lacking adequate radar coverage include Hawaii, Puerto Rico, large portions of the western United States and the Rio Grande Valley (the portion of the watershed lying in Mexico lacks radar coverage and rainfall there affects flooding on both sides of the river). High temporal resolution observations are especially important for predicting flash floods because there is so little time available for public response.

   In areas lacking adequate radar coverage, forecasters are still able to forecast heavy rainfall associated with deep convection (cloud height above 9 km, sometimes organized into mid-sized, or mesoscale, convective systems that are smaller than the scale of a tropical cyclone but larger than localized, short-lived thunderstorms). However, it is not possible to detect other significant contributors to rainfall and flooding in instances where rainfall is the product of low-level clouds and terrain (e.g., clouds forced upward by mountains and seeder-feeder impacts that occur when rainfall originating in higher altitudes pass through and is increased by mountaintop cloud cover).

   The annual cost of flash flooding is high in areas with poor radar coverage, even though populations and development in those areas tend to be relatively sparse. Between 2010 and 2020, flash floods in these areas caused $22 billion in property damage (not counting agricultural losses) and 142 deaths[43]. By far the largest of these events is Hurricane Maria, whose impacts in Puerto Rico account for 84 percent of total property damage. Omitting Hurricane Maria from this account reduces these figures to $340 million in annual damages and 12 deaths per year--still significant losses.

[43] NOAA National Centers for Environmental Information. 2022. Storm Events Database. Available at https://www.ncdc.noaa.gov/stormevents/. Accessed May 4, 2022.

Improvements in precipitation forecasts enabled by the use of GLM observations will reduce damage to personal property (e.g., automobiles) and loss of life associated with flash floods.

6. Tropical Cyclone Diagnosis and Warning. The GLM identifies updrafts and downdrafts below the cloud tops in hurricanes which improves forecasters' ability to diagnose their structure and evolution; it also improves forecasts of changes in the intensity of hurricanes, including the rapid intensification that often occurs just prior to making landfall. Currently, observations are limited to continuous observations of cloud top patterns provided by the GOES-R imager and twice-daily insights into the structure of the storm below cloud tops provided by NOAA's polar satellites. Lightning detection by GLM provides continuous information on the strength and behavior of the storm below cloud tops.

   As hurricanes approach the U.S. coast, they pass over warmer water and gain intensity just prior to landfall, increasing their destructive power; sustained winds have increased by more than 40 miles per hour during the 24 hours prior to landfall. Because the incidence and strength of lightning activity increases with the storm intensity, the GLM's high temporal resolution observations allow continuous monitoring of hurricane intensity. Although ground-based lightning-detection networks are able to capture lightning over the oceans, these observations are biased toward detecting cloud-to-ground lightning; during the analysis of the rapid intensification of Hurricane Maria in 2017, ground-based observations detected only 3 percent of the flashes detected by the GLM[44].

   GLM improves other aspects of hurricane analysis, providing unique insights into secondary eyewall formation, eyewall replacement cycles, center location, and storm dissipation. Much of the information needed for this analysis is obscured by clouds and therefore not observable by the geostationary imager. The low temporal resolution of data provided by polar satellites is not adequate for monitoring and forecasting these rapidly-changing attributes of hurricanes.

   The increasing integration of GLM observations into hurricane forecasts and analysis will improve the information used to guide evacuation and preparedness, reducing losses to human life and property.

7. Climate Applications. The continuation of GLM observations will extend the time series of lightning observations for another two decades, allowing the analysis of decadal trends in lightning activity, which serves as an indicator of thunderstorm activity. The time-series will provide insight into the connection between climate change and extreme storms, whose distribution differs from that indicated by rainfall patterns.

   The number and tracks of Mesoscale Convective Systems (MCS) are influenced by and serve as indicators of the strength of El Nino/Southern Oscillation (ENSO) cycles. An MCS is a collection of thunderstorms that act as a system, spreading across entire states, lasting more than 12 hours[45], and generating more than 1,000 lightning strikes per hour; as much as 25 percent of the annual lightning strikes at a single location may be caused by a single

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[44] National Oceanic and Atmospheric Administration, 2020. Geostationary Lightning Mapper Value Assessment.

[45] NOAA National Severe Storms Laboratory. 2022. Severe Weather 101-Thunderstorms. Available at https://www.nssl.noaa.gov/education/svrwx101/thunderstorms/. Accessed May 4, 2022.

MSC. Space-based optical instruments like the GLM are the only tools currently available that are able to fully characterize the spatial extent of lightning within these massive systems throughout their lifetime.

Lightning directly affects the global climate, serving as a major natural source of nitrogen oxides (NOx), which are important greenhouse gases[46]. The GLM offers a new capability for understanding the interrelationships between climate and lightning, using GLM observations to estimate the production of nitrogen oxides by lightning; a model estimating nitrogen oxide production based on measures of lightning flash energy is already in use. These measures show seasonal variability that will inform climate models.

8. Filling Data Gaps. Radar improves weather forecasting, saving lives, preventing injuries, protecting property, and reducing the cost of false alarms. However, the current ground-based radar network does not provide full coverage of the U.S.; some areas lie beyond the range of radar and the view of others is blocked by mountainous terrain. The GLM provides observations for these areas, and provides observations during scheduled and unscheduled radar outages. Some radar measurements require multiple scans, increasing the time between observations; the high temporal resolution of GLM has been shown to marginally increase warning time. The benefits associated with GLM's use to fill radar gaps are the same as those provided by radar: saving lives, preventing injuries, protecting property, and reducing the cost of false alarms.

   Since radar units are located on land and their coverage quickly diminishes offshore, GLM observations provide tremendous value in forecasting storms in near-shore waters. Many of these storms move to coastal areas where more than one-third of the U.S. population lives and where nearly half of the nation's gross domestic product originates[47]. Storms remaining offshore threaten marine transportation, commercial and recreational fishing, and offshore oil and gas production. GLM observations improve weather forecasts that protect our coastal populations, our national economy, and those working offshore.

9. Aviation. Thunderstorms and the associated threat of lightning imposes substantial costs on the aviation industry, as airport ramps are closed and flights are delayed and rerouted to ensure the safety of passengers and crews. The lightning mapper provides a complete spatial footprint of total lightning flashes, bringing increased precision and certainty of lightning risk to airport officials who control the operation of ramps where aircraft are fueled, passengers board, and cargo is loaded and unloaded. Delays associated with ramp closures vary significantly by location; a 2016 study[48] showed the associated costs to range from $1 million annually to $8 million annually for the nation's 35 major airports.

[46] Price, C. and Rind, D., 1994. Possible implications of global climate change on global lightning distributions and frequencies. Journal of Geophysical Research: Atmospheres, 99(D5), pp.10823-10831.
[47] NOAA Office for Coastal Management. 2019. Socioeconomic Data Summary. Available at https://coast.noaa.gov/data/digitalcoast/pdf/socioecon-pocket-guide.pdf. Accessed May 4, 2022.
[48] Steiner, M., Deierling, W., Ikeda, K., Robinson, M., Klein, A., Bewley, J. and Bass, R., 2016. Air traffic impacts caused by lightning safety procedures. In 16th AIAA Aviation Technology, Integration, and Operations Conference (p. 4213).

The lightning mapper's broad, uninterrupted coverage and rapid updates provide tremendous cost-savings to the aviation industry, allowing more efficient transit when it's necessary to reroute aircraft to avoid convective storm hazards; these hazards include turbulence, icing, heavy precipitation, hail, and lightning. Additional benefits result from reducing injury from encounters with turbulence. The role of the lightning mapper is especially important over the ocean where current sensor data are limited[49].

Improvements to forecasts of convective storms that are enabled by the lightning mapper reduce unnecessary flight delays. On average, weather-related flight delays cost airlines, passengers, and businesses that rely on air travel more than $20 billion annually, with $2.5 billion of those losses attributable to error in weather forecasts[50]. The lightning mapper makes significant contributions to weather forecasts that reduce those unnecessary costs.

[49] Weber, M.E., Williams, E.R., Wolfson, M.M. and Goodman, S.J., 1998. An Assessment of the Operational Utility of a GOES Lightning Map Sensor. Project report NOAA-18, Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, MA.
[50] Federal Aviation Administration. 2020. FAA Administrator's Factbook.

Key attributes of lightning mapper benefits are shown in the table below.

NOAA Product Improved	Societal Outcome Improved
Lightning threat	Fatalities, reduced
Lightning threat	Injuries, reduced
Lightning threat	Response actions, increased efficiency
Thunderstorm and tornado forecasts	Personal property losses, reduced
Thunderstorm and tornado forecasts	Fatalities, reduced
Thunderstorm and tornado forecasts	Response actions, increased efficiency
Wildfire detection	*Response actions, increased efficiency
Wildfire detection	**Personal property losses, reduced
Wildfire detection	**Property damage, reduced
Wildfire detection	Fatalities, reduced
Wildfire detection	**Agriculture
Accumulated precipitation	Personal property losses, reduced
Accumulated precipitation	Fatalities, reduced
Accumulated precipitation	Injuries, reduced
Lightning threat	Fatalities, reduced
Lightning threat	Injuries, reduced
Thunderstorm and tornado forecasts	Fatalities, reduced
Thunderstorm and tornado forecasts	Injuries, reduced
Thunderstorm and tornado forecasts	Response actions, increased efficiency
Thunderstorm and tornado forecasts	Agriculture, reduced losses
Fire Weather forecasts	Response actions, increased efficiency
Fire Weather forecasts	Personal property losses, reduced
Fire Weather forecasts	Property damage, reduced
Fire Weather forecasts	Fatalities, reduced
Fire Weather forecasts	Injuries, reduced
Flood forecasts	Personal property losses, reduced
Flood forecasts	Fatalities, reduced
Flood forecasts	Injuries, reduced
Hurricane forecasting	**Response actions, increased efficiency
Hurricane forecasting	Personal property losses, reduced
Hurricane forecasting	Property damage, reduced
Hurricane forecasting	Fatalities, reduced
Hurricane forecasting	Injuries, reduced
Long-term Climate Forecasts	Complying with mandates, increased efficiency
Filling radar gaps	**Response actions, increased efficiency
Filling radar gaps	**Personal property losses, reduced
Filling radar gaps	**Property damage, reduced
Filling radar gaps	**Fatalities, reduced
Filling radar gaps	**Injuries, reduced
Weather forecasting	**Aviation, reduced costs
Weather forecasting	Aviation, safety
Wildfire detection	Agriculture

* Quantified in full in this study.
*** Quantified in part in this study.*

Ocean Color

The benefit description that follows is taken primarily from NOAA's 2020 study (published in 2021) of the anticipated benefits of the ocean color instrument.[51] NOAA currently obtains much of its ocean color data from polar satellites operated by NASA and the European Science Agency, some of which are beyond their design life, and none of which are operationally dedicated to the NOAA mission. NOAA also obtains ocean color data from its own polar satellites, whose primary mission is meteorology and which view each location on Earth every 12 hours. The GeoXO OC ocean color (OC) instrument will refresh observations in less than two hours, with a target of hourly refresh rates.

The value of OC observations has been demonstrated in applications ranging from sustainable fishing, protected resources, ecosystem-based fisheries management, tourism, and human health and safety. GeoXO OC's observations will provide NOAA with dedicated, operational, high temporal and spatial resolution data that will provide many economically valuable improvements over the existing sources of OC observations. Many of these improvements are linked to the GeoXO OC's ability to:

- observe the significant diurnal changes associated with algae and other features being observed;
- increase the accuracy of predicted trajectories of change;
- fill gaps in data caused by cloud cover (as clouds move, the geostationary instrument can observe areas obstructed by clouds);
- provide a more data-rich basis for modeling;
- provide additional details that allow the identification of specific species of algae (of interest, those that are harmful);
- support analyses in coastal areas where higher spatial resolution is required because of the irregularity of the land/water interface.

The sections below describe the benefits associated with GeoXO OC contributions to three classes of NOAA products; benefits associated with a few additional applications of particular importance are also described in less detail.

1. Primary Production for Fisheries Models. U.S. fisheries are big business, providing jobs and recreation and keeping our coastal communities vibrant. In fact, the United States is a global leader in responsibly managed fisheries and sustainable seafood production. Working closely with commercial, recreational, and small-scale tribal fishermen, we have rebuilt numerous overfished stocks and managed to create some of the most sustainably managed fisheries in the world[52].

   U.S. fisheries are scientifically monitored and regionally managed, with 10 legally enforced national standards of sustainability. Managing sustainable fisheries is a dynamic process that requires constant and routine attention to new scientific information that can guide management actions[53].

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[51] National Oceanic and Atmospheric Administration, 2021. The Value of Geostationary Ocean Color.
[52] NOAA National Marine Fisheries Service. Sustainable Fisheries. Available at https://www.fisheries.noaa.gov/topic/sustainable-fisheries. Undated. Sustainable Fisheries. Accessed May 4, 2022.
[53] Ibid.

GeoXO OC observations of marine algae, including phytoplankton, single-celled photosynthetic algae, and cyanobacteria, will improve ecological forecast models that predict fish species distributions to ensure the sustainable use of the nation's fisheries. These marine organisms form the foundation (i.e., they are "primary producers") of the food chains that support the nation's fisheries[54]. Data from polar satellites currently used to inform these models have two shortcomings. First, many species of phytoplankton can swim and several species of cyanobacteria have gas vacuoles that allow them to sink and float. These algae move in response to changes in light, temperature, and nutrient level and their position within the water column changes throughout the day. Satellite observations are able to resolve only those features at the surface of the water column. Polar observations can understate the total biomass of algae when cells are below the surface[55]. Second, observations are frequently obstructed by clouds. The hourly resolution of observations provided by the GeoXO OC will greatly improve measurements of algae (currently based on data with 12-hour temporal resolution), the model-based predictions of fish species distribution that rely on measurements of algae, and the sustainability and productivity of our nation's fisheries.

Direct economic benefits resulting from improvements in fishery-model operations include preventing overfishing that reduces the future productivity of fisheries or, conversely, reducing unnecessarily restrictive catch limits. In either case, the long-term economic value of fish harvests is increased with the addition of the ocean color observations. Beneficiaries include commercial and recreational fishermen, the communities and businesses that depend upon commercial and recreational fishing as a basic economic activity, and consumers of domestically harvested seafood.

These NOAA activities are mandated by the Magnuson-Stevens Sustainable Fisheries Act.

2. Harmful Algal Blooms. In a balanced ecosystem, algae form the foundation of food chains that support the nation's fisheries and other uses of coastal waters. When too many nutrients are available, phytoplankton may grow out of control and form harmful algal blooms (HABs). These blooms can produce extremely toxic compounds that have harmful effects on fish, shellfish, mammals, birds, and humans.

   GeoXO OC observations will improve monitoring and forecasts of HABs. Monitoring and forecasting HABs will benefit from the higher temporal resolution of GeoXO OC observations, which provide better measures of the diurnal variation of surface-level algae and reduce the impact of cloud cover. It is important to note that several of the species of cyanobacteria that are most likely to be underrepresented in observations by polar satellites (those that move up and down in the water column by means of

[54] NOAA National Marine Fisheries Service. Multispecies and Ecosystem Modeling for the Northeast Shelf Ecosystem. Available at https://www.fisheries.noaa.gov/new-england-mid-atlantic/ecosystems/multispecies-and-ecosystem-modeling-northeast-shelf-ecosystem. Accessed May 4, 2022.

[55] Since many types of algae move up and down in the water column over the course of the day and satellites observe only what is at the surface of the water, twice-daily observations from polar satellites may occur when a significant portion of the algae is too low in the water column to be observed.

vacuoles) produce toxins that, in sufficient concentrations in air and water, are harmful to humans, marine life, and the environment.

By providing up to twelve observations daily, the GeoXO OC instrument will provide a means to refine estimates of HAB bloom extent and total bloom biomass. Information on HABs is used to guide public health officials, water plant operators, fishing and aquaculture activities and coastal managers in protecting public health.

HABs can adversely affect the health of people who swallow contaminated water, eat seafood contaminated with toxins, inhale aerosolized toxins, or come into direct contact with contaminated water when swimming or boating[56]. Symptoms range from the relatively mild (gastrointestinal distress, sinus infections, earaches, and conjunctivitis) to the more severe (atypical pneumonia)[57].

Red tides, for example, are a type of HAB caused by the algal species *Karenia brevis*, often abbreviated as *K. brevis*. Inhaling red tide toxins can produce harmful respiratory effects in humans, including coughing, sneezing, tearing and an itchy throat. For people with severe or chronic respiratory conditions, such as emphysema or asthma, red tide can cause serious illness. Depending on the winds, the effects of airborne K. brevis toxins can extend up to one mile inland[58].

The red tide toxins can also accumulate in molluscan filter-feeders such as oysters and clams, which can lead to shellfish poisoning in people who consume contaminated shellfish. Most common along Florida's west coast and elsewhere in the Gulf of Mexico, red tides have been carried by the Gulf Stream current into the Atlantic Ocean as far north as Delaware. K. brevis kills fish by producing a potent toxin called brevetoxin that affects the central nervous system of the fish. The toxin can also affect birds, sea turtles, mammals and other marine animals[59],[60].

Although HABs in certain geographies like Lake Erie and the Gulf of Mexico receive more attention from the news media, HABs occur throughout the United States. The figure below shows recent HABs in the United States (as of 2017)[61]. NOAA produces various types of HAB forecasts for the Gulf of Maine, the Puget Sound, Lake Erie, and the Gulf of Mexico. These forecasts address specific risks to shellfish harvest, drinking water management, aquaculture, tourism, and public health.

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[56] Centers for Disease Control. Facts about Cyanobacterial Blooms for Poison Center Professionals. Available at https://www.cdc.gov/habs/materials/factsheet-cyanobacterial-habs.html. Accessed May 4, 2022.

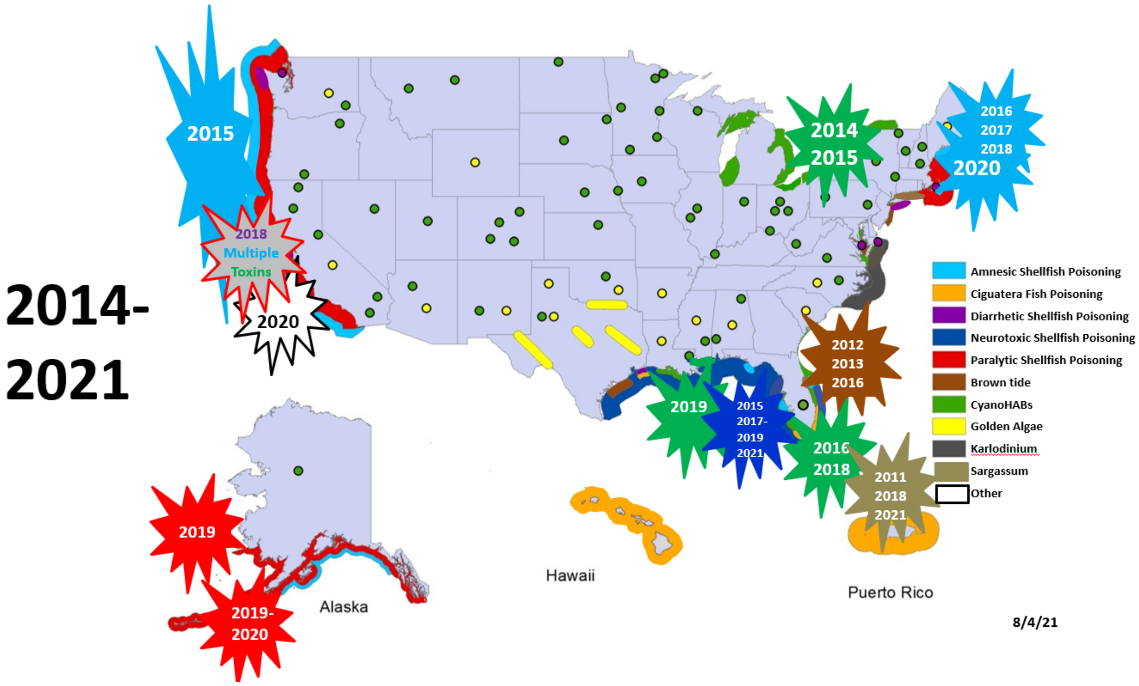
[57] Ibid.

[58] Mote Marine Laboratory and Aquarium. 2022. Florida Red Tide FAQs. Available at https://mote.org/news/florida-red-tide. Accessed on May 4, 2022.

[59] Ibid.

[60] U.S. Environmental Protection Agency. 2022. Cyanobacteria Assessment Network (CyAN). Available at https://www.epa.gov/water-research/cyanobacteria-assessment-network-cyan. Accessed May 4, 2022.

[61] This figure was developed by Quay Dortch, Senior HAB Scientist, NOAA NOS Competitive Research Program.



The HAB-related benefits of GeoXO OC observations are the result of reducing the impacts of HABs and reducing the cost of avoiding those impacts. The high spatial and temporal resolution of GeoXO OC observation should result in fewer false positives and false negatives. False positives occur when error in the HAB forecasts lead to mitigating actions in areas that are not affected by HABs, initiating necessary actions sooner than is necessary, and continuing them longer than is necessary; reducing the error reduces the costs associated with unnecessary mitigating actions and are realized in the form of increased fish and shellfish harvest (both wild harvest and aquaculture), increased tourism activity, and reduced expenses in water treatment. False negatives occur when error in HAB forecasts leads to a failure to take necessary mitigating actions; reducing the error reduces human exposure to toxins and contaminated shellfish, reducing health care expenses associated with that exposure, and the intangible benefits of not becoming sick.

3. Hypoxia. In ocean and freshwater environments, the term "hypoxia" refers to low or depleted oxygen in a water body. Hypoxia is often associated with the overgrowth of certain species of algae, which can lead to oxygen depletion when they die, sink to the bottom, and decompose. In some cases, vast stretches of open water become hypoxic. Unable to sustain life, these areas, called dead zones, may cause die-offs of fish, shellfish, corals, and aquatic plants.

   The dead zone in the Gulf of Mexico is the second largest in the world. In August 2021, the Gulf's dead zone measured an area of 6,334 square miles—30 percent larger than NOAA's predicted size of 4,880 square miles. While that's still substantially smaller than the dead zone of 2017 (which reached a size of 8,776 square miles), the dead zone in 2021 is larger than the current five-year average (5,400 square miles). It's also an alarming leap from the mere 2,116 square mile hypoxic zone of 2020—the third smallest in the 34 years of measuring[62]. The goal of the Mississippi River/Gulf of Mexico Hypoxia Task Force is to reduce the size of the dead zone to less than 5,000 square kilometers (just under 2,000 square miles)[63].

Hypoxic waters can cause habitat loss, stress, and even death to marine organisms, affecting commercial harvests and the health of impacted ecosystems[64]. The area affected by hypoxia in the Gulf of Mexico was once a primary location for the harvest of brown shrimp, a huge commercial fishery. Optimal habitat for brown shrimp has been reduced by 25 percent by hypoxia. This has reduced the size of the harvest, increased the cost of harvesting measured in terms of catch per unit of effort, and, thus, reduced the economic value of this fishery. The impacts of hypoxia on the animal life at the ocean floor reduces the food available for fish and crustaceans, with effects that ripple through the food chain. These food chain impacts can result in further reductions of the value of other fisheries[65].

Over 11 million people in the U.S. and Canada rely upon Lake Erie as a source of drinking water. In addition to its impact on fisheries, hypoxia in Lake Erie also affects water quality at public utility intakes. When oxygen levels in the lake drop during summer, the hypoxic water can become more acidic and corrosive, smelly and discolored, and potentially high in trace contaminants such as iron and manganese. Under certain wind conditions, this hypoxic water can be pushed toward shore where it enters intake pipes used by public water utilities, increasing treatment costs. Furthermore, hypoxic events with elevated manganese can be particularly difficult for public water utilities to treat, since many lack the necessary resources to respond to the problem[66]; prolonged exposure to high concentrations of manganese in drinking water has been associated with a nervous system disease with symptoms similar to Parkinson's disease[67], [68], [69].

[62] Seo, H. 2021. What is the 'dead zone' in the Gulf of Mexico, and why is it super-sized this year? Popular Science. Available at https://www.popsci.com/science/gulf-of-mexico-dead-zone/. Accessed May 4, 2022.
[63] NOAA National Ocean Service. 2022. Hypoxia. Available at https://oceanservice.noaa.gov/hazards/hypoxia/. Accessed May 4, 2022.
[64] NOAA National Centers for Coastal Ocean Science. 2022. Operational Gulf of Mexico Hypoxia Monitoring. Available at https://coastalscience.noaa.gov/project/operational-gulf-of-mexico-hypoxia-monitoring/. Accessed May 4, 2022.
[65] NOAA National Ocean Service. 2022. Dealing with Dead Zones: Hypoxia in the Ocean. Available at https://oceanservice.noaa.gov/podcast/feb18/nop13-hypoxia.html. Accessed May 4, 2022.
[66] Cooperative Institute for Great Lakes Research. 2022. Forecasting Lake Erie Hypoxia. Available at https://ciglr.seas.umich.edu/summer-2018-e-newsletter/featured-research-forecasting-lake-erie-hypoxia/. Accessed May 4, 2022.
[67] Town of Brewster, MA. Warning: Excessive Manganese in Drinking Water Can Now Be Considered A Public Health Risk. Available at https://www.brewster-ma.gov/departments-mainmenu-26/health-department-mainmenu-33/1764-warning-excessive-manganese-in-drinking-water-can-now-be-considered-a-public-health-risk#:~:text=Exposure%20to%20high%20concentrations%20of,(300%20ug%2FL). Accessed May 4, 2022.
[68] Minnesota Department of Health. Manganese in Drinking Water. Available at https://www.health.state.mn.us/communities/environment/water/contaminants/manganese.html#HealthEffects. Accessed May 4, 2022.
[69] Aschner, M., Erikson, K.M., Hernández, E.H. and Tjalkens, R., 2009. Manganese and its role in Parkinson's disease: from transport to neuropathology. Neuromolecular medicine, 11(4), pp.252-266.

GeoXO OC offers high temporal and spatial resolution observations to improve monitoring and forecasting of hypoxia events. NOAA currently measures and forecasts hypoxia in Lake Erie, the Chesapeake Bay, and the Gulf of Mexico. Improved forecasts can reduce the impact of overfishing during hypoxic events (fishermen sometimes focus efforts on the edge of hypoxic zones where food is abundant, increasing the impact of hypoxia on shrimp populations and other species[70]). It can also assist fishermen in deciding when not to fish in instances where the catch per unit of effort is too small to yield profits. Forecasts are used by managers of water treatment facilities when they are likely to experience hypoxic water so they can prepare to adjust their treatment process[71].

By increasing the accuracy of hypoxia monitoring and forecasting, GeoXO OC observations yield benefits to fishermen who are enabled to predict and refrain from unprofitable trips and who avoid future losses associated with overfishing. Benefits to water treatment operations include those associated with reduced consumption of impaired drinking water and reduced costs (through avoidance of false positives) to water treatment facilities in taking the mitigating actions needed to protect public health. Increasing the accuracy of hypoxia monitoring and forecasting can also increase the effectiveness and efficiency of mitigating actions undertaken in inland areas where, for example, agricultural practices in the Mississippi watershed contribute nutrients that worsen HABs and hypoxia.

4. Other Applications.
    a. *California Current and Integrated Ecosystem Assessment (IEA)*. This state-of-the-art biophysical ocean model provides fisheries-relevant data and derived products to end-users, specifically the Pacific Fisheries Management Council and the NMFS West Coast Regional Office. Model-based predictions of species distributions are used for living marine resource management under seasonal forecasting and climate change scenarios. Such models support operational products at multiple temporal scales (near real-time, seasonal forecasts and long-term projections). GeoXO OC observations would improve the IEAs by providing near-real-time estimates of phytoplankton biomass, primary productivity, and other biogeochemical conditions derived from ocean color at a high spatial resolution, within 24 hours and without major gaps from clouds. This will enhance the performance of the IEA, which, through improved management, will increase the value of sablefish harvest along the west coast (currently valued at $110 million). Although this focuses on the California Current and IEA, IEA activities occur throughout the U.S. Exclusive Economic Zone (EEZ). Similarly, the State of the Ecosystem (SOE) Reports from NMFS Science Centers depend on accurate time series measurements of ocean color. Satellite sources that maximize the number of cloud free images per time period improve the time series upon which leading indicators are based.
    b. *Sediment and Turbidity*. Organic and inorganic particles in the water column scatter light and can therefore be detected by certain satellite observations. Turbidity reduces the amount of light reaching submerged aquatic vegetation and is also

[70] NOAA National Ocean Service. 2022. Dealing with Dead Zones: Hypoxia in the Ocean. Available at https://oceanservice.noaa.gov/podcast/feb18/nop13-hypoxia.html. Accessed May 4, 2022.
[71] Cooperative Institute for Great Lakes Research. 2022. Forecasting Lake Erie Hypoxia. Available at https://ciglr.seas.umich.edu/summer-2018-e-newsletter/featured-research-forecasting-lake-erie-hypoxia/. Accessed May 4, 2022.

associated with flows of sediments that can impact coral reefs and fish spawning areas. Since turbidity is often linked to storms where rough seas and high riverine flows suspend particles, the higher temporal resolution of GeoXO OC observations will improve our ability to understand and respond to these often short-lived phenomena. Turbidity-related benefits of GeoXO OC observations will be realized in the improved management of corals and fisheries and the land management practices that contribute to erosion and sedimentation. Water quality measurements are important to aquaculture and contribute to NOAA priorities for Seafood Security. Delivering excellent water quality protects the industry and the Americans who depend on their produce.

c. *Cyclonic Eddies*. Northeasterly trade winds and island topography encourage the generation of eddies on the leeward side of the Hawaiian Islands. These eddies cause upwellings that carry nutrients to the surface layer of the ocean where there is sufficient light to support photosynthesis. This “eddy pumping” and the resulting enhancement of biological processes can greatly influence the ecosystem surrounding the Hawaiian Islands. This biological enhancement can result in an increase in production in the $119 million fishery of the Hawaiian Islands. Cloud cover is common in these areas. Polar satellites provide images of this region about every two days and many of these are blocked by cloud cover. Geostationary satellites provide measures of sea surface temperature that can be used to delineate these eddies during their formation and throughout their duration but no OC measures are available to study the biological processes that are involved. GeoXO OC observations will provide the capacity to directly determine the biological influence of cyclonic eddies near Hawaii. This information will help fishermen avoid wasted trips that miss the area of enhancement and make more successful trips, increasing the value of harvests from this fishery.

d. *Dynamic Ocean Management*. Dynamic Ocean Management (DOM) is an adaptive approach that uses near real-time data to inform the spatial and temporal distribution of management actions[72]. Unlike most marine spatial management approaches that rely on fixed boundaries and timeframes, DOM is dynamic and changes in response to the ocean and its resources, wildlife, and users to increase the effectiveness and efficiency of ocean use and management[73]. GeoXO OC will provide the near-real time observations needed to support DOM efforts including, for example, EcoCoast, WhaleWatch, and some salmon systems in Alaska.

[72] California Sea Grant. 2022. Lindsey Peavey: The Dynamic of Dynamic Ocean Management. Available at https://caseagrant.ucsd.edu/news/the-dynamic-of-dynamic-ocean-management. Accessed May 4, 2022.

[73] Maxwell, S.M., Hazen, E.L., Lewison, R.L., Dunn, D.C., Bailey, H., Bograd, S.J., Briscoe, D.K., Fossette, S., Hobday, A.J., Bennett, M. and Benson, S., 2015. Dynamic ocean management: Defining and conceptualizing real-time management of the ocean. Marine Policy, 58, pp.42-50.

Key attributes of ocean color benefits are shown in the table below.

NOAA Product Improved	Societal Outcome Improved
Inputs to fisheries models	Long-term value of fisheries, increased by reducing overfishing
Inputs to fisheries models	Long-term value of fisheries, increased by reducing unnecessarily restrictive catch limits
Inputs to fisheries models	Complying with mandates, increased effectiveness
Inputs to fisheries models	Complying with mandates, increased efficiency
Harmful Algal Bloom forecasts and monitoring	**Response actions, increased efficiency
Harmful Algal Bloom forecasts and monitoring	**Disease, reduced
Harmful Algal Bloom forecasts and monitoring	**Water Supply Operations, increased efficiency
Harmful Algal Bloom forecasts and monitoring	**Fisheries, increased product safety
Harmful Algal Bloom forecasts and monitoring	**Aquaculture, increased product safety
Harmful Algal Bloom forecasts and monitoring	**Tourism, increased activity when false positives are reduced
Harmful Algal Bloom forecasts and monitoring	**Fisheries, increased productivity when false positives are reduced
Harmful Algal Bloom forecasts and monitoring	**Aquaculture, increased productivity when false positives are reduced
Hypoxia forecasts and monitoring	Long-term value of fisheries, increased by reducing overfishing
Hypoxia forecasts and monitoring	Fisheries, reducing unprofitable trips
Hypoxia forecasts and monitoring	Water Supply Operations, increased efficiency
Hypoxia forecasts and monitoring	Response actions, increased efficiency
California Integrated Ecosystem Assessment	Long-term value of fisheries, increased by reducing overfishing
California Integrated Ecosystem Assessment	Long-term value of fisheries, increased by reducing unnecessarily restrictive catch limits
Measures of sediment and turbidity	Response actions, increased efficiency
Cyclonic Eddies	Fisheries, increasing profitable trips
Dynamic Ocean Management	Response actions, increased efficiency
Dynamic Ocean Management	Response actions, increased effectiveness

** Quantified in full in this study.*
*** Quantified in part in this study.*

Notes on the table above:

- Examples of fisheries models that do or may use ocean color data:
  - Fishery Models can indicate Stock Assessment Models. A few use satellite data, but mostly they are rigidly constructed models.
  - Ecosystem Simulation: describes a suite of models that models climate to physics to fishery to fishers. Some are used to help examine management options, others are used to identify important species in the system.
  - Climate and Fisheries Impact Models: Like Ecosystem Simulations, but with the main focus to be simulating the fishery state based on climate scenarios (like those from IPCC).
  - Habitat Suitability Models: Specialized models that may be called Component Models that take a few parameters and encode if those parameters constitute conditions that are favorable or unfavorable for species survival or presence.
- NOAA Fisheries uses a Red Tide Index from the NOS Lab that helps trigger certain conditions within a couple of our stock assessments in the southeastern United States.

Atmospheric Composition

The benefit description that follows is taken primarily from NOAA's 2020 study on the anticipated benefits of the atmospheric composition instrument[74]. GeoXO atmospheric composition (AC) observations will contribute in numerous ways to NOAA's forecasting and monitoring capabilities by providing observations that are not available from other instruments, that complement and are complemented by observations from other instruments, and that fill temporal gaps in data from polar satellites. These data also contribute to NOAA's foundational understanding of the Earth System, which in turn supports other operational activities[75].

GeoXO's space-based AC observations align with the National Academies of Sciences, Engineering and Medicine's 2017-2027 Decadal Survey (DS2017), which recommends that NOAA prioritize observations that inform the spatial distribution of trace gases and aerosols and the factors that cause temporal changes in these components. The DS2017 clearly highlights the importance of geostationary objectives for AC, particularly with respect to weather, air quality, and climate, and recommends accomplishing them via a range of existing and new missions[76].

NOAA's 2020 study of the benefits of atmospheric composition observations identified six broad classes of benefits: air quality forecasting, weather and climate forecasting, fire weather forecasting, hazards forecasting, stratospheric ozone monitoring, and air quality monitoring.

1. Air Quality Forecasting. GeoXO AC observations are essential to fulfilling NOAA's numerous, long-standing legislative, executive, and international mandates for AC forecasting, monitoring and scientific research[77]. NOAA's National Air Quality Forecast Capability (NAQFC) provides a foundation for official air quality forecasts provided by federal, state, and local government agencies. GeoXO AC observations will significantly improve NAQFC forecast guidance, providing a basis for enhanced evaluations of air quality, better constraints on emissions inventories, and better initialization by chemical data assimilation[78].

   GeoXO AC observations will help to save lives and improve health outcomes. Although weather-related fatalities in the U.S. amount to around 500 each year[79], over 100,000 premature deaths occur annually due to exposure to elevated concentrations of ozone

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[74] National Oceanic and Atmospheric Administration, 2020. A Value Assessment of an Atmospheric Composition Capability on the NOAA Next-Generation Geostationary and Extended Orbits (GEO-XO) Missions.
[75] Ibid., p. 26.
[76] Ibid., pp. 1-2; not a mandate but a National Academies recommendation.
[77] Ibid., pp. 1, 8ff.
[78] Ibid., p. 3.
[79] National Weather Service. 2022. Weather Related Fatality and Injury Statistics. Available at https://www.weather.gov/hazstat/. Accessed August 5, 2022.

and fine aerosol particles[80] like $PM_{2.5}$[81, 82]. These and other components of air pollution have myriad impacts on respiratory and cardiovascular health.

GeoXO AC observations will provide information that can be used to reduce other impacts of impaired air quality:

- poor visibility from dust or smoke from wildfires that impacts air and ground transportation
- impacts to agriculture, both from direct impacts of ozone on vegetation as well as the decrease in visible solar radiation needed for photosynthesis
- impacts to solar energy production which is hampered by smog where aerosols scatter incoming solar radiation away from the Earth's surface.

Geostationary observations of air quality will support a host of new applications, including hourly estimates of anthropogenic emissions and fine aerosol particles. Measures of aerosols and trace gases are contaminated by the presence of clouds but the imager's infrared observations make it possible to develop "cloud masks" that mitigate the effects of such data contamination. The high temporal resolution of geostationary atmospheric composition observations will reveal diurnal variability in the formation of photochemical smog. The current operational GOES imagers have shown how 5-minute observations can be consolidated into one- and three-hour composites to extend spatial coverage of aerosols during extreme fire events. This has been shown to be very valuable to field forecasters supporting boots-on-the-ground firefighters.

2. Weather and climate forecasting. GeoXO AC observations will improve the models that form the basis for NOAA's operational numerical weather predictions. These models comprise the Unified Forecast System (UFS), a comprehensive Earth system modeling system. Aerosols and trace gasses affect weather and climate directly through their radiative impacts and, in the case of aerosols, indirectly through changes to cloud microphysics. Accurate weather and climate forecasts within the UFS must therefore account for atmospheric composition. GeoXO AC observations will help verify and initialize UFS forecasts of aerosols and trace gasses, improve the quality of atmospheric state retrievals such as temperature and water vapor, and more accurately simulate diurnally varying incoming solar radiation[83].

   The UFS spans local to global domains and predictive time scales from sub-hourly analyses to seasonal predictions and supports forecasting activities across the entire Weather Enterprise, including academic, government, and private sector weather

[80] Specifically, Particulate Matter 2.5 ($PM_{2.5}$), which are tiny particles or droplets in the air that are two and a half microns or less in width. From New York State, Department of Health. 2022. Fine Particles (PM2.5) Questions and Answers. Available at https://www.health.ny.gov/environmental/indoors/air/pmq_a.htm#:~:text=What%20is%20Particulate%20Matter%202.5,unit%20of%20measurement%20for%20distance. Accessed May 4, 2022.

[81] Fann, N., Lamson, A.D., Anenberg, S.C., Wesson, K., Risley, D. and Hubbell, B.J., 2012. Estimating the national public health burden associated with exposure to ambient PM2. 5 and ozone. Risk Analysis: An International Journal, 32(1), pp.81-95.

[82] It is important to note that Fann et al, 2012 estimates mortality associated with 2005 air quality levels.

[83] National Oceanic and Atmospheric Administration, 2020. A Value Assessment of an Atmospheric Composition Capability on the NOAA Next-Generation Geostationary and Extended Orbits (GEO-XO) Missions.

providers[84],[85]. Thus, AC observations will lead to incremental increases in value across NOAA's portfolio of weather and climate forecasts that result in reduced threats to human health and safety, reduced losses from severe weather, and improved economic productivity in weather-dependent economic sectors like agriculture.

3. Fire weather forecasting. The direct loss of life, property, and economic opportunity due to wildfires has been addressed above, and wildfires are likely to increase in frequency and severity as climate changes.

   In addition to the direct life and economic losses, wildfire results in poor air quality in much of the United States. GeoXO AC observations of trace gas and aerosols will improve models that forecast fire emissions and downwind smoke chemistry; the high temporal resolution of these geostationary satellites will provide a more accurate understanding of wildfire behavior, which changes dramatically over the course of the day. NOAA plays a lead role in issuing smoke forecasts used by first responders who fight wildfires and protect people and property in harm's way[86],[87].

   In addition, GeoXO data will enable the dynamic behavior of fires to be much more accurately represented in NOAA's UFS, improving NOAA's weather forecasts when they are affected by wildfires. This will result in reduced threats to human health and safety, reduced losses from severe weather, and improved economic productivity in weather-dependent economic sectors like agriculture.

4. Hazards forecasting. NOAA is responsible for forecasting episodic, high-risk events, including dispersion of ash emissions from volcanic eruptions and of chemical, toxic, and radioactive material. Volcanic Ash Advisories (VAAs) that are critically important to the aviation industry combine observations from multiple satellites with model forecasts, and in the future will require more quantitative information on ash concentrations and sulfur dioxide. The high temporal frequency of GeoXO products will be critical to future volcanic ash predictions and could aid in tracking releases of hazardous material from refinery fires, railroad derailments, oil spills, and other industrial accidents. Hazard dispersion also benefits from the improvements to weather forecasts enabled by GeoXO AC observations[88]. Improvements in forecasts of the dispersion of volcanic ash and other hazardous materials will yield benefits to the commercial airline industry, its passengers, and businesses that rely on air travel, reducing costs and threats to safety. These forecast improvements will also help in protecting the general public from the detrimental health effects of exposure to hazardous material and, through increased

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[84] NOAA Virtual Lab. 2022. Unified Forecast System. Available at https://vlab.noaa.gov/web/environmental-modeling-center/unified-forecast-system. Accessed on May 4, 2022.
[85] National Weather Service. 2022. The Weather Enterprise - Working Together to Meet the Needs of Society. Available at https://www.weather.gov/about/weather-enterprise. Accessed on May 4, 2022.
[86] National Oceanic and Atmospheric Administration, 2020. A Value Assessment of an Atmospheric Composition Capability on the NOAA Next-Generation Geostationary and Extended Orbits (GEO-XO) Missions.
[87] National Weather Service. 2022. National Air Quality Forecast Guidance. Available at https://airquality.weather.gov/. Accessed on May 4, 2022.
[88] National Oceanic and Atmospheric Administration, 2020. A Value Assessment of an Atmospheric Composition Capability on the NOAA Next-Generation Geostationary and Extended Orbits (GEO-XO) Missions.

precision, reduce the cost of doing so.

5. Stratospheric ozone monitoring. Stratospheric ozone protects all life on Earth from harmful ultraviolet radiation. NOAA is mandated by the Clean Air Act and the Montreal Protocol to monitor, assess, and report on the state of the stratospheric ozone. In addition to enabling NOAA to fulfill its mandates, GeoXO AC measures of stratospheric ozone will improve weather forecasts, monitor episodic and rapidly-changing stratospheric events, make significant contributions to continuous ozone climate data records, and inform possible future climate intervention approaches.

   The U.S. Clean Air Act mandates that NOAA and NASA regularly report on the state of the stratospheric ozone layer to Congress. The United Nations' Montreal Protocol[89] also requires periodic updates on new scientific findings related to the ozone layer to guide policymakers in strengthening the agreement. NOAA has played a major role in preparing these assessments, which require satellite data in addition to ground-based and balloon-borne observations to monitor the health of the stratospheric ozone layer. NOAA's long-term observations of a variety of compounds that deplete ozone provide confirmation that the Montreal Protocol's bans on these substances are actually working. NOAA activities mandated by the Clean Air Act and the Montreal Protocol currently rely on observations obtained from polar satellites, which are not able to capture the significant diurnal changes that are common. GeoXO AC observations will enhance NOAA's ability to address the requirements of these mandates[90].

   Stratospheric ozone plays an important role in atmospheric structure and large-scale circulation, impacting weather on seasonal to sub-seasonal time scales. GeoXO AC observations can provide insight into the impact on stratospheric ozone from volcanic eruptions and intense fires and the transport of ozone to the troposphere, which can be associated with turbulence and its effects on aviation safety. Further, the high spatial and temporal resolution of GeoXO AC observations will improve our ability to sample episodic, rapidly changing stratospheric events.

   Thus, benefits of the stratospheric ozone monitoring capabilities of GeoXO span from meeting the requirements of U.S. law and international treaties; to improving safety and reducing costs to the aviation industry, airline passengers, and businesses that rely on air travel; and widespread benefits associated with incremental improvements to NOAA's weather forecasts.

6. Air quality monitoring. GeoXO air quality monitoring will provide measurements to complement data from existing surface networks and emissions monitoring operated by national, tribal, state, and local regulatory agencies. NOAA's air quality monitoring is important for evaluating air quality emissions inventories, is useful for the evaluation of the NAQFC, and will inform future NAQFC data assimilation efforts. GeoXO's high

[89] For information on the Montreal Protocol, see United Nations Environment Programme. Undated. About Montreal Protocol. Available at https://www.unep.org/ozonaction/who-we-are/about-montreal-protocol. Accessed on August 5, 2022.

[90] National Oceanic and Atmospheric Administration, 2020. A Value Assessment of an Atmospheric Composition Capability on the NOAA Next-Generation Geostationary and Extended Orbits (GEO-XO) Missions.

spatial and temporal resolution AC measurements are sensitive to abundances and changes of these gases and aerosols in the planetary boundary layer. Species of highest priority are:

- *Ozone*. Because ozone has strong diurnal cycles, measurements of ozone will be greatly enhanced by the high temporal resolution of geostationary observation. Multi-spectral observation offered by GeoXO will better constrain models conducting regional ozone analyses.
- *Nitrogen dioxide*. The standard proxy for nitrogen oxides (NOx) pollution. Nitrogen oxides are a family of poisonous, highly reactive gasses that form when fuel is burned at high temperatures. NOx pollution is emitted by automobiles, trucks and various non-road vehicles (e.g., construction equipment, boats, etc.) as well as industrial sources such as power plants, industrial boilers, cement kilns, and turbines[91]. The high temporal and spatial frequency of NO2 column data from GeoXO are needed to monitor and assess the temporal and spatial variations in different NOx emission sources. This would allow for a more effective assessment of data gaps in EPA National Emission Inventories for NOx emissions, improved quality assurance, and the focusing of resources on improving bottom-up methods for poorly characterized source sectors. Such improvements would greatly assist in the national and local decisions on emission control strategies, via more robust air quality modeling scenarios, which can result in large cost savings while achieving national air quality standards.
- *Formaldehyde*. Formaldehyde is the standard proxy for volatile organic compound (VOC) pollution. Some VOCs are harmful by themselves, including some that cause cancer. Breathing VOCs can irritate the eyes, nose and throat, can cause difficulty in breathing and nausea, and can damage the central nervous system and other organs. VOCs can also react with other gases and form other air pollutants after they are in the air[92]. VOCs contribute to the formation of ground-level ozone, which has many impacts on human health, and is the key pollutant that causes smog. Ground-level ozone acts as a dense barrier blocking pollution from escaping to the higher atmosphere. This pollution remains closer to Earth and traps heat and decreases visibility. Certain groups like children, the elderly, and people with lung diseases are especially at risk of harm from ground-level ozone[93], [94].
- *Glyoxal*. Glyoxal is a secondary proxy for volatile organic compounds (VOC).
- *Carbon monoxide*. Carbon monoxide is an indicator of fossil fuel combustion and wildfires.
- *Sulfur dioxide*. Sulfur dioxide is an indicator of coal combustion and volcanic eruptions.
- *Ammonia*. Ammonia is an indicator of agricultural emissions. It is a major precursor of PM2.5, which is linked to a number of adverse human health

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[91] U.S. Environmental Protection Agency. Nitrogen Oxides (NOx) Control Regulations. Available at https://www3.epa.gov/region1/airquality/nox.html. Accessed May 4, 2022.
[92] American Lung Association. Volatile Organic Compounds. Available at https://www.lung.org/clean-air/at-home/indoor-air-pollutants/volatile-organic-compounds. Accessed May 4, 2022.
[93] Minnesota Pollution Control Agency. Volatile Organic Compounds (VOCs). Available at https://www.pca.state.mn.us/air/volatile-organic-compounds-vocs. Accessed May 4, 2022.
[94] Arizona Department of Environmental Quality. Nitrogen Oxide (NOX). Available at https://azdeq.gov/nitrogen-oxide-nox-pollution. Accessed May 4, 2022.

outcomes. Ammonia also contributes to dry nitrogen deposition which can adversely impact ecologically sensitive areas and aquatic environments; excess nitrogen is accepted as a major driver of biodiversity change[95] as species that have the capacity to assimilate increased nitrogen levels outcompete those that do not, leading to the loss of specialized biological communities and ecosystems[96].

As an indicator of the potential value of benefits of improved health outcomes resulting from AC observations, it should be noted that, in 2011, the U.S. Environmental Protection Agency projected the benefits of the Clean Air Act to be $2 trillion in 2020[97]. The benefits cited in this report are closely aligned with those of the AC observations: reducing risk of early death associated with exposure to ambient fine particle pollution; reducing risks of premature mortality associated with O3 exposure; reducing illnesses such as acute myocardial infarction and chronic bronchitis; and protecting the health of ecosystems and other improvements which enhance quality of life, such as improved agricultural yields and better visibility conditions.

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[95] Sala, O.E., Stuart Chapin, F.I.I.I., Armesto, J.J., Berlow, E., Bloomfield, J., Dirzo, R., Huber-Sanwald, E., Huenneke, L.F., Jackson, R.B., Kinzig, A. and Leemans, R., 2000. Global biodiversity scenarios for the year 2100. science, 287(5459), pp.1770-1774.

[96] Bobbink, R. and Heil, G.W., 1993. Atmospheric deposition of sulphur and nitrogen in heathland ecosystems. In *Heathlands* (pp. 25-50). Springer, Dordrecht.

[97] US Environmental Protection Agency, 2011. The benefits and costs of the Clean Air Act from 1990 to 2020.

Key attributes of the benefits of atmospheric composition instrument benefits are shown in the table below.

NOAA Product Improved	Societal Outcome Improved
Air Quality monitoring/forecasting	*Fatalities, reduced
Air Quality monitoring/forecasting	Health impacts, reduced
Air Quality monitoring/forecasting	Aviation, reduced costs
Air Quality monitoring/forecasting	Ground transportation, reduced impacts
Air Quality monitoring/forecasting	Agriculture, reduced impacts
Air Quality monitoring/forecasting	Solar power siting, increased productivity
Weather forecasting	Health impacts, reduced
Weather forecasting	Fatalities, reduced
Weather forecasting	Personal property losses, reduced
Weather forecasting	Property damage, reduced
Weather forecasting	Agriculture, increased productivity
Fire Weather forecasts	Health impacts, reduced
Fire Weather forecasts	Fatalities, reduced
Fire Weather forecasts	Personal property losses, reduced
Fire Weather forecasts	Property damage, reduced
Fire Weather forecasts	Agriculture, increased productivity
Hazardous particles, forecasts	Response actions, increased efficiency
Hazardous particles, forecasts	Response actions, increased effectiveness
Hazardous particles, forecasts	Health impacts, reduced
Hazardous particles, forecasts	Fatalities, reduced
Stratospheric ozone monitoring	Complying with mandates, increased effectiveness
Stratospheric ozone monitoring	Complying with mandates, increased efficiency
Stratospheric ozone monitoring	Aviation, safety
Stratospheric ozone monitoring	Aviation, reduced costs
Stratospheric ozone monitoring	Fatalities, reduced
Stratospheric ozone monitoring	Personal property losses, reduced
Stratospheric ozone monitoring	Property damage, reduced
Greenhouse Gas Monitoring	Complying with mandates, increased effectiveness
Greenhouse Gas Monitoring	Complying with mandates, increased efficiency
Greenhouse Gas Monitoring	Response actions, increased efficiency
Greenhouse Gas Monitoring	Response actions, increased effectiveness
Wildfire detection	*Response actions, increased efficiency
Wildfire detection	**Response actions, increased effectiveness
Wildfire detection	**Agriculture
Hurricane forecasting	**Response actions, increased efficiency

** Quantified in full in this study.*
*** Quantified in part in this study.*

Hyperspectral Infrared Sounder

The benefit description that follows is taken primarily from NOAA's 2020 study on the anticipated benefits of the hyperspectral infrared (IR) sounder (hereinafter, "sounder").[98] The sounder will provide high vertical resolution atmospheric temperature and water vapor profiles throughout the day and night, as well as information on the wind fields. Infrared sounder observations are currently provided by polar satellites that view the same part of the Earth twice daily; the GEO sounder will offer continuous observation across its field of view. Obtaining multiple views from the same satellite operating in the same atmospheric conditions helps to ensure that the changes that are observed are not influenced by atmospheric conditions, changing view angles, or the satellites themselves.

Ground-based doppler radar emits high frequency electromagnetic waves that are reflected back to the radar station from hydrometeors including objects like rainfall droplets; analysis of these returns provides information on precipitation rates and droplet motion and support the derivation of wind speeds[99]. Radar provides information on current weather conditions that are used to forecast future weather. In contrast, sounders provide information on the atmospheric conditions that influence future weather, including vertical moisture profiles, vertical temperature profiles, and wind fields (the three-dimensional spatial pattern of winds). The high temporal resolution of GEO sounder observations can be used to identify areas of atmospheric instability that can cause severe weather. The added measurements provided by the GEO sounder and the high spatial and temporal resolution of all its observations will greatly enhance weather forecast capabilities.

The GEO sounder will enhance the quality and value of weather forecasts in a number of ways. It will provide real-time, dynamic information (not currently available) that is needed for Nowcasting and mesoscale models that improve situational awareness. GEO sounder's observations provide better information on position and intensity than are available from other sources; their use will improve the regional and global Numerical Weather Prediction models that provide an input to local forecasting. The high temporal and spatial resolution of GEO sounder observations will allow analysts to assess variability that is not observable in the years of data archived from the past. This and the new observations provided by the GEO sounder will allow assessment and improvement of NOAA's weather and climate forecast models and the foundational models that support these forecasts.

Unlike the other instrument-specific benefit studies that were conducted by NOAA in 2020, which provided a broad review of expected benefits, the benefit study for the GEO sounder closely examined three specific use cases where benefits are expected to be large. This report is titled "Geostationary and Extended Orbits (GeoXO) Hyperspectral InfraRed Sounder Value Assessment Report" and underwent the review required for the NOAA Institutional Repository. The benefits associated with two of the use cases are likely to be sufficient to independently offset the cost of the GEO sounder instrument.

The remainder of this section will describe the broad scope of benefits expected to result from GEO sounder observations. These benefits are described below. The quantification of benefits

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[98] National Oceanic and Atmospheric Administration, 2021. Geostationary Extended Observations (GeoXO) Hyperspectral InfraRed Sounder Value Assessment Report.

[99] World Meteorological Organization. 2020. Weather Radar Observations. Available at https://community.wmo.int/weather-radar-observations. Accessed May 4, 2022.

for the three case studies will be discussed later in this report as part of the broader GeoXO benefit analysis.

1. Thunderstorms and Tornadoes. As noted earlier, thunderstorms are common occurrences in the United States, with about 10,000 storms per year generating hail one inch or more in diameter, winds gusting in excess of 50 knots (57.5 mph), or a tornado[100].

   Three important predictors of thunderstorms are vertical moisture profiles, vertical temperature profiles, and wind fields. GEO sounder directly measures radiances associated with these three attributes, providing observations with high temporal and spatial resolution. Analysis of GEO sounder data can also provide information on other atmospheric conditions that contribute to the formation of thunderstorms, e.g., atmospheric instability, water vapor transport, and atmospheric lifting. Thus, observations from the GEO sounder promise significant improvements to thunderstorm forecasting. Because sounders provide observations of atmospheric conditions that generate thunderstorms, they have been shown to generate useful forecast information hours sooner than radar[101].

   Improvements to thunderstorm forecasts and longer lead times resulting from the use of GEO sounder observations will lead to reduced impacts from those storms. Benefits will be realized in the form of reduced loss of life, increased safety, and reduced losses to property (e.g., cars can be moved away from trees and into garages to protect them from falling limbs and hail). As forecasts of the areal extent of thunderstorms becomes more precise, benefits will also be realized in the form of avoiding the cost of unnecessary mitigating actions (e.g., school closures and airline groundings). Although high-impact thunderstorms capture more attention, similar benefits will be realized for less severe but more frequent thunderstorms; the benefits of reducing losses associated with these less-severe but far more frequent storms are expected to be significant.

   The benefit assessment conducted in the fall of 2020 estimated that a one-percent reduction in weather-related airline delays would provide almost $2 of benefits for each dollar spent on the GEO sounder. Such benefits would largely be the result of improved forecasts of thunderstorms.

2. Numerical Weather Prediction. The high temporal and spatial resolution of GEO sounder observations will allow analysts to assess variability that is not observable in the years of archived data, allowing better calibration and refinement of Numerical Weather Prediction (NWP) models. These models process current weather observations to forecast future weather. Output is based on current weather and atmospheric observations, which are assimilated into the model's framework and used to produce predictions for temperature, precipitation, and hundreds of other meteorological

[100] NOAA National Severe Storms Laboratory. 2022. Severe Weather 101 – Thunderstorms. Available at https://www.nssl.noaa.gov/education/svrwx101/thunderstorms/. Accessed May 4, 2022.

[101] Li, J., Jinlong. Li, J. Otkin, T. J. Schmit, and C. Liu, 2011: Warning information in a preconvection environment from the geostationary advanced infrared sounding system – A simulation study using IHOP case, Journal of Applied Meteorology and Climatology, 50, 776 – 783.

elements from the oceans to the top of the atmosphere[102]. The benefits of GEO sounder observations to two important NWP models are described below: the Rapid Refresh model and the North American Mesoscale Forecast System.

The high spatial and temporal resolution of GEO sounder observations will be especially useful in the Rapid Refresh (RAP) model, a continental-scale NWP model that is updated hourly. RAP covers all of North America and consists primarily of a numerical forecast model and a system to analyze and assimilate current observations to initialize the model. RAP is complemented by the higher-resolution (3km) High-Resolution Rapid Refresh (HRRR) model, which is also updated hourly and covers a smaller geographic domain--the continental United States[103].

The North American Mesoscale Forecast System (NAM) is one of NOAA's major models for producing weather forecasts. The NAM generates multiple grids (or domains) of weather forecasts over the North American continent at various horizontal resolutions. Each grid contains data for dozens of weather parameters, including temperature, precipitation, lightning, and turbulent kinetic energy. The NAM uses additional numerical weather models to generate high-resolution forecasts over fixed regions and, occasionally, to follow significant weather events like hurricanes. This model is run four times daily and will significantly benefit from the high temporal resolution of GEO sounder observations of temperature and atmospheric moisture; polar sounders provide this information twice daily[104].

Improvements to these foundational weather and climate forecasts enabled by GEO sounder observations will lead to reduced impacts from adverse weather conditions. These benefits will be realized in the form of reduced loss of life, increased safety, and reduced losses to property. These improvements will also lead to increased productivity in weather-dependent economic sectors like agriculture, construction, and energy.

The benefit assessment conducted in the fall of 2020 estimated that improved inputs to energy load forecasting leading to a 2.5 percent reduction in error would generate benefits of $639 million to the energy sector over the life of GeoXO. Improvements to NWP models are crucial to achieving such reductions of load forecasting error.

3. Hurricane Prediction. The "Geostationary and Extended Orbits (GeoXO) Hyperspectral InfraRed Sounder Value Assessment Report" (2020) assessed the impact of GEO sounder observations on forecasts of hurricane tracks. Reducing uncertainty in hurricane track forecasts can reduce the number of unnecessary evacuations, resulting in large cost savings. Forecasts of hurricane tracks are important but another important consideration in hurricane preparedness and response is hurricane intensity. Although

[102] NOAA National Centers for Environmental Information. Numerical Weather Prediction. Available at https://www.ncei.noaa.gov/products/weather-climate-models/numerical-weather-prediction. Accessed May 4, 2022.
[103] NOAA National Centers for Environmental Information. Rapid Refresh/Rapid Update Cycle. Available at https://www.ncei.noaa.gov/products/weather-climate-models/rapid-refresh-update. Accessed May 4, 2022.
[104] NOAA National Centers for Environmental Information. North American Mesoscale Forecast System. Available at https://www.ncei.noaa.gov/products/weather-climate-models/north-american-mesoscale. Accessed May 4, 2022.

hurricane track forecasts have improved greatly over the past decades, there is still much progress to be made in forecasting hurricane intensity and, in particular, the rapid intensification that occurs when hurricanes pass over warmer coastal waters.

Recent research by Yin et al, 2021[105] "...clearly shows higher temporal resolution [GEO IR sounder] data provides better forecasts than lower resolution observations (such as those obtained from polar satellites)." This study evaluates the effect of observations from China's GEO IR sounder in forecasts of Typhoon Maria (2018) and finds that the higher resolution data provides much more detail on the structure and anomalies of the storm, resulting in improved forecasts of both track and intensity, reducing intensity forecast errors up to 18 percent.

Improvements to hurricane track and intensity forecasts enabled by GEO sounder observations will improve our understanding of these storms and improve the effectiveness and efficiency of actions that are taken to mitigate loss. Benefits will be realized in the form of reduced loss of life, increased safety, reduced losses to property, and increased economic productivity.

4. Nighttime Dust Characterization. Dust storms can occur anywhere in the United States but are most common in the Southwest. A dust storm usually arrives suddenly in the form of an advancing wall of dust and debris which may be miles long and several thousand feet high. They strike with little warning, making driving conditions hazardous. Blinding, choking dust can quickly reduce visibility, causing accidents that may involve chain collisions, creating massive pileups. Dust storms usually last only a few minutes, but the actions a motorist takes during the storm may be the most important of his or her life[106].

   Imagers and other instruments that rely on daytime light provide limited information on dust storms forming or continuing into the night. The GEO sounder provides more information on atmospheric dust than the imager, including dust height and optical thickness. Its IR bandwidth observations allow the GEO sounder to provide this same information day or night. The addition of GEO sounder observations will help to reduce the impacts of dust storms, including accidents and respiratory distress. Benefits will be realized in the form of lower loss of life, increased safety, and decreased property damage.

5. Atmospheric Transport and Dispersion. 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. Among other things, NOSIA-II shows the degree to which the quality of specific NOAA products relies on satellite observations.

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[105] Yin, R., Han, W., Gao, Z. and Li, J., Impact of high temporal resolution FY-4A Geostationary Interferometric Infrared Sounder (GIIRS) radiance measurements on Typhoon forecasts: Maria (2018) case with GRAPES global 4D-Var assimilation system. Geophysical Research Letters, p.e2021GL093672.
[106] National Weather Service. Undated. Dust Storms and Haboobs. Available at https://www.weather.gov/safety/wind-dust-storm. Accessed May 4, 2022.

According to the NOSIA-II data, the product with the highest dependency upon sounder data is the HYSPLIT model. HYSPLIT is one of the most extensively used atmospheric transport and dispersion models in the atmospheric sciences community. A common application of HYSPLIT is to establish source-receptor relationships that are used in certain forms of air quality modeling that quickly assess the impact of emission changes on concentration levels. HYSPLIT is also used to assess the atmospheric transport, dispersion, and deposition of pollutants and hazardous materials. Some examples of the applications include tracking and forecasting the release of radioactive material, wildfire smoke, windblown dust, pollutants from various stationary and mobile emission sources, allergens and volcanic ash[107], [108]. Benefits of improvements to HYSPLIT modeling will be realized in the form of improved health and safety.

Centrec 2007[109] showed that when looking at only five impact areas and using a 7 percent discount rate, the estimated net benefit from a geostationary high-spectral resolution sounder was estimated to be over $2 billion.

[107] NOAA Air Resources Library. Undated. HYSPLIT. Available at https://www.arl.noaa.gov/hysplit/. Accessed May 4, 2022.
[108] Clappier, A., Pisoni, E. and Thunis, P., 2015. A new approach to design source–receptor relationships for air quality modelling. Environmental Modelling & Software, 74, pp.66-74.
[109] Centrec Consulting Group, LLC, 2007. An investigation of the economic and social value of selected NOAA data and products for geostationary operational environmental satellites (GOES).

Key attributes of sounder benefits are shown in the table below.

NOAA Product Improved	Societal Outcome Improved
Weather forecasting	Health impacts, reduced
Weather forecasting	Fatalities, reduced
Weather forecasting	Personal property losses, reduced
Weather forecasting	Property damage, reduced
Weather forecasting	Agriculture, increased productivity
Weather forecasting	Aviation, reduced costs
Weather forecasting	**Aviation, safety
Weather forecasting	**Electric power and natural gas distribution, reduced costs
Thunderstorm and tornado forecasts	Health impacts, reduced
Thunderstorm and tornado forecasts	Fatalities, reduced
Thunderstorm and tornado forecasts	Personal property losses, reduced
Numerical Weather Prediction	Health impacts, reduced
Numerical Weather Prediction	Fatalities, reduced
Numerical Weather Prediction	Personal property losses, reduced
Numerical Weather Prediction	Property damage, reduced
Numerical Weather Prediction	Agriculture, increased productivity
Numerical Weather Prediction	Aviation, reduced costs
Numerical Weather Prediction	Aviation, safety
Hurricane forecasting	**Response actions, increased efficiency
Hurricane forecasting	Personal property losses, reduced
Hurricane forecasting	Property damage, reduced
Hurricane forecasting	Fatalities, reduced
Hurricane forecasting	Injuries, reduced
Nighttime Dust Characterization	Ground transportation, reduced impacts
Nighttime Dust Characterization	Health impacts, reduced
HYSPIT Model	Health impacts, reduced
Air Quality monitoring/forecasting	Health impacts, reduced
Air Quality monitoring/forecasting	Response actions, increased effectiveness
Air Quality monitoring/forecasting	**Fatalities, reduced
Wildfire detection	*Response actions, increased efficiency
Wildfire detection	**Personal property losses, reduced
Wildfire detection	**Property damage, reduced
Wildfire detection	**Agriculture

** Quantified in full in this study.*
*** Quantified in part in this study.*

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Section 2: Description of Selected Value Chains

Introduction

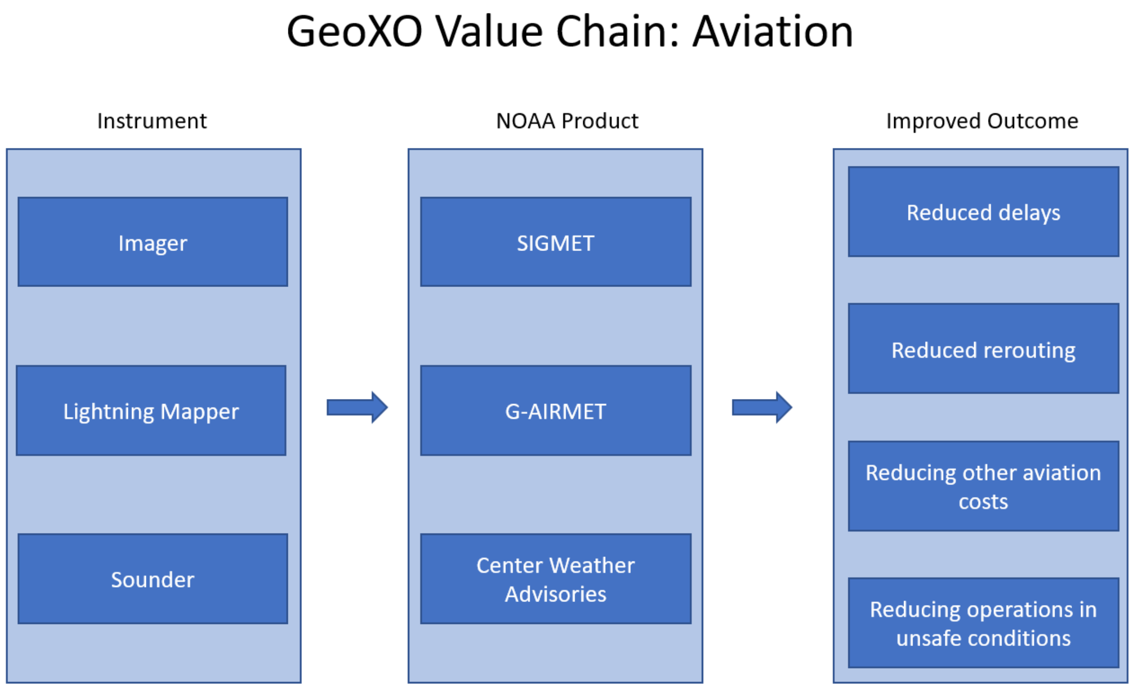
The goal of Section 1 of this report was to provide a comprehensive survey of the benefits that are likely to result from the use of GeoXO observations, realized in the form of improved societal outcomes ranging from human health, safety, and morbidity to reducing losses associated with natural hazards and increasing economic productivity. Since the contents of Section 1 drew largely from instrument-specific studies, content was organized by instrument.

However, a key feature of GeoXO is the fact that the value of observations from one instrument is commonly increased by observations from other instruments also included in GeoXO. To reflect the complementary nature of GeoXO observations, the value chains described below focus on specific applications of GeoXO observations, identifying each instrument that contributes to the improved outcome.

A total of eight value chains are described below, several of which will be the subject of benefit quantification analyses.

Aviation

The figure below provides an overview of the GeoXO instruments with the potential for improving NOAA products supporting the aviation industry and the societal outcomes that are expected to be improved. The diagram is not meant to be comprehensive, but focuses on the content described in this section of the report.



Product Background

NWS provides a number of customized weather forecast products to ensure the safety of aviation. Significant Meteorological event (SIGMET) advisories are provided when weather conditions are potentially hazardous to all aircraft. SIGMETs are issued for the following weather conditions:

- severe icing
- severe or extreme turbulence
- dust storms and sandstorms lowering visibilities to less than three miles
- volcanic ash
- convective weather conditions

G-AIRMETs are graphical advisory of weather that may be hazardous to aircraft, but are less severe than SIGMETs. G-AIRMETS, which are valid only at specific time "snapshots," show the areas and attributes of AIRMET hazards.

Center Weather Advisories (CWA) warn of weather conditions meeting or approaching national in-flight advisory (AIRMET, SIGMET) criteria[110]. The CWA is primarily used by air crews to anticipate and avoid adverse weather conditions in the en route and terminal environments. It is not a flight planning product because of its short lead time and duration. CWAs are issued for any of the following events:

- Conditions meeting convective SIGMET criteria
- Icing, moderate or greater
- Turbulence, moderate or greater
- Heavy precipitation
- Freezing precipitation
- Conditions at or approaching Low Instrument Flight Rules (when ceilings are less than 500 feet above ground level or visibility is less than 1 mile)
- Surface winds or gusts greater than 30 knots
- Low level wind shear (at elevations below 2,000 feet)
- Volcanic ash, dust storms, or sandstorms

Dependence on GeoXO

Benefit studies conducted in 2020s show that four GeoXO instruments have the potential to generate aviation-related benefits:

- Imager
- Lightning Mapper
- Sounder

Most of the weather conditions that affect aviation and the meteorological systems that produce them are short-lived, rapidly evolving, or both. The current GOES-R series system of geostationary satellites provides low-latency observations from advanced baseline imagers (ABI) and geostationary lightning mappers (GLM) that support improved aviation weather forecasting. GeoXO will provide continuation of these observations but at higher resolutions that will further increase the quality of these forecasts.

The GLM's broad spatial coverage and rapid temporal updates complement radar observations over CONUS to support severe weather warning decisions. Rapidly updating GLM observations over vast (often data sparse) regions outside CONUS provide vital information needed to forecast, monitor, and react to thunderstorms, cyclones, and volcanic hazards.

In addition to its contribution to aviation weather forecasting, the GLM observes the complete spatial footprint of total lightning flashes, which helps better characterize the lightning risk and increase confidence/certainty when suspending and resuming aviation ramp operations, leading to enhanced safety, improved efficiency, and cost savings. The GLMs broad coverage and rapid

[110] National Weather Service, Aviation Weather Center. Center Weather Advisory (CWA). Available at https://www.aviationweather.gov/cwamis/help. Accessed May 5, 2022.

updates provide tremendous cost savings to the aviation industry through improved diagnosis and avoidance of thunderstorm hazards, especially over oceans.

Analysis conducted by NOAA shows that sounder observations from polar satellites make enormous contributions to weather forecasting, second only to the advanced baseline imager. Polar satellites currently provide sounder observations showing the three-dimensional structure of atmospheric parameters including temperature, and humidity. However, polar satellites provide information for each location on Earth every 1 to 2 days and therefore fail to capture many short-lived and rapidly evolving conditions. Geostationary sounders can provide multiple observations for short-lived and rapidly evolving weather events, which is needed to generate estimates of the wind field.

A sounder was included in the original design of GOES-R but was de-scoped due to cost and technical considerations. GeoXO will include an advanced hyperspectral infrared sounder whose geostationary observations will open a new set of possibilities for improving weather forecasts by providing much more information about the vertical changes of atmospheric parameters, compared to the imager. The near-continuous observations of a geostationary sounder will also add a fourth dimension compared to polar-orbiters to the profile of atmospheric observations—time. The GeoXO sounder's near-continuous observations of atmospheric conditions, the geostationary sounder will allow monitoring of diurnal cycles and the real-time evolution of atmospheric patterns such as low-level moisture pooling or mid-level drying that is not possible with polar observations. The geostationary perspective will also allow for 'targeted' observations of regions of increased interest.

Storm initiation and development frequently coincide with orbital gaps of polar satellites; this issue is greatly reduced with the high temporal resolution of geostationary sounder observations (30 minutes). The proposed geostationary sounder also has higher spatial resolution than the current polar-orbiting sounders, 4km vs. 12-16kms, respectively, providing a basis for further improvement of weather forecasts by obtaining more clear locations and by being able to monitor finer gradients. The sounder data will also add value to other GeoXO observations; for example, analysis of the use of simulated infrared sounding data on Warn on Forecast systems that are designed to increase tornado, severe thunderstorm, and flash flood warning lead times indicate the possibility of significantly improving forecasts that now rely primarily on data from the advanced baseline imager.

Users

NOAA provides the weather forecasts and other information that are needed to ensure the safe operation of aircraft in the National Airspace System (NAS), which may include as many as 5,000 flights at any point in time[111]. As the nation's aviation authority, the FAA regulates and

[111] NASA Human Systems Integration Division. Undated. How Air Traffic Control Works. Available at https://hsi.arc.nasa.gov/groups/AOL/downloads/HowATCworksToday.pdf. Accessed May 5, 2022.

oversees all aspects of American civilian aviation[112] to ensure safe and efficient aviation within the NAS. FAA operational responsibilities are tailored to address the specific requirements corresponding to different geographic scales.

- The Air Traffic Control System Command Center implements traffic management initiatives affecting the NAS as a whole.
- The NAS is divided into twenty-one regions, where en route traffic is managed by Air Route Traffic Control Centers.
- Air traffic control near the busiest airports is transferred to Terminal Radar Approach Control facilities, which handle the airspace below 20,000 feet and within 30 to 50 miles of the airport.
- For each airport with regularly scheduled flights, air traffic control towers manage takeoffs, landings, ground traffic, and traffic flow[113].

Pilots may receive guidance from twenty or more controllers during a single cross-country flight[114]. As the meteorological services provider for aviation, NOAA generates weather products and services that meet aviation requirements across the spectrum of geographic scales.

Benefits to Society

By far, weather is the largest cause of air traffic delay in the United States, accounting for about 63 percent of all delays[115]. To avoid operating in unsafe weather conditions, flights are rerouted, detained in holding patterns prior to landing, and delayed on the ground. When route changes or extended holding patterns are anticipated, aircraft take on extra fuel prior to take-off, further increasing costs; additional fuel is used due to the increased weight of fuel[116].

Weather-related aviation delays cost airlines, passengers, and businesses an average of more than $20 billion annually; these costs have steadily increased over the past decade[117]. About 12 percent of weather-related delays have been attributed to weather forecast error and uncertainty[118]. Forecasting conditions that are worse than actual weather conditions leads to excessive cancellations, ground delays, and traffic rerouting. Forecasting conditions that are less severe than actual weather conditions leads to inefficient responses, which can also lead to unnecessary delays and rerouting. GeoXO observations will enable forecast improvements that

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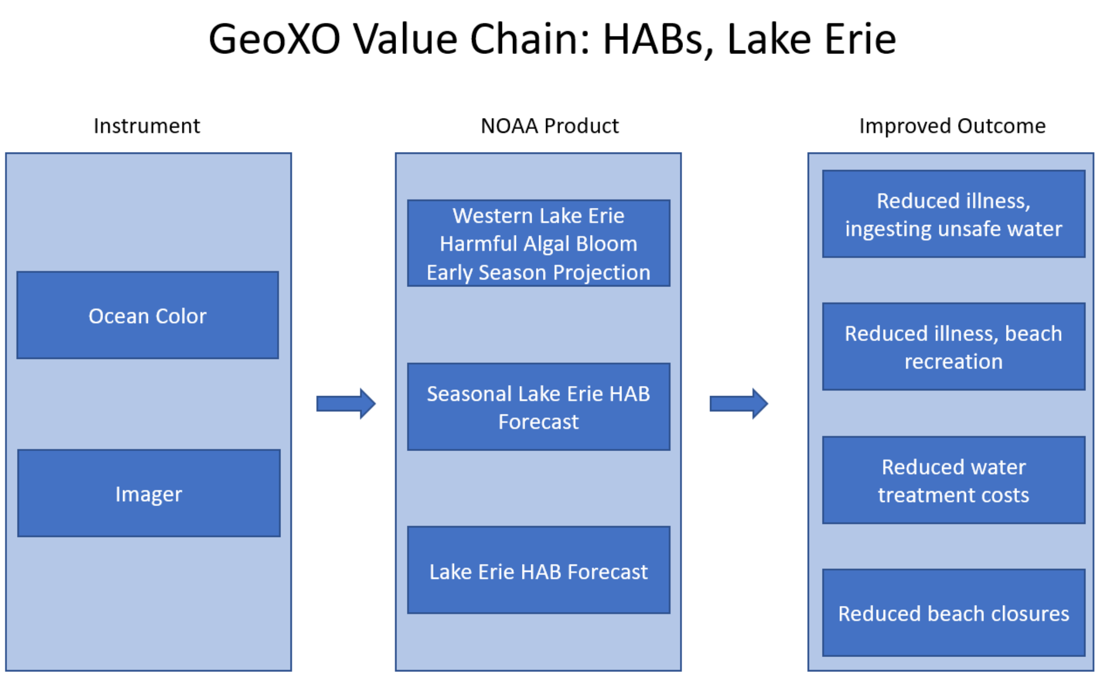
[112] National Oceanic and Atmospheric Administration. 2022. SciJinks: Smooth Flying. Available at https://scijinks.gov/aviation-meteorologist/. Accessed May 5, 2022.
[113] NASA Human Systems Integration Division, op. cit.
[114] Ibid.
[115] Federal Aviation Administration. 2020. 2020 Administrator's Fact Book. Available at https://www.faa.gov/newsroom/administrators-fact-book. Accessed May 5, 2022.
[116] Klein, A., Kavoussi, S., Lee, R. and Craun, C., 2011. Estimating avoidable costs due to convective weather forecast inaccuracy. In 11th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference, including the AIAA Balloon Systems Conference and 19th AIAA Lighter-Than (p. 6811).
[117] Federal Aviation Administration. 2021. Air Traffic by the Numbers. Available at https://www.faa.gov/air_traffic/by_the_numbers/media/Air_Traffic_by_the_Numbers_2021.pdf. Accessed May 5, 2022.
[118] Ibid.

reduce the portion of weather-related delay costs that is attributable to weather forecast error and uncertainty.

Other benefits will result from reducing the number of instances where aircraft and terminals operate in unsafe conditions and where aircraft encounter undesirable but not unsafe levels of turbulence.

Harmful Algal Blooms: Lake Erie

The figure below provides an overview of the GeoXO instruments with the potential for improving NOAA's harmful algal bloom monitoring and forecast products for Lake Erie and the societal outcomes that are expected to be improved. The diagram is not meant to be comprehensive, but focuses on the content described in this section of the report.



Product Background

The NOAA National Centers for Coastal Ocean Science issues three Lake Erie HAB forecast products[119] to provide an early season projection, seasonal forecast, and a near real-time forecast during an ongoing bloom.

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[119] NOAA National Centers for Coastal Ocean Science. Undated. Lake Erie Harmful Algal Bloom Forecast. Available at: https://coastalscience.noaa.gov/research/stressor-impacts-mitigation/hab-forecasts/lake-erie/. Accessed May 11, 2022.

The Western Lake Erie Harmful Algal Bloom Early Season Projections, issued beginning in May, estimate bloom severity based on measurements of phosphorus loading from the Maumee River combined with long-range forecasts and historical records. These projections are issued until NOAA issues the Seasonal Lake Erie HAB Forecast in early July.

The Seasonal Lake Erie HAB Forecast gives coastal managers and drinking water facility operators a general sense of the potential severity of the upcoming bloom season. The seasonal forecast incorporates the results of an ensemble of models based largely upon phosphorus discharge from the Maumee River.

During the bloom season (typically from June until October), the operational NOAA Lake Erie HAB Forecast provides the current extent and 96-hour forecast of the bloom location and concentration, allowing managers to determine whether to take preventative actions. This forecast is updated daily.

Dependence on GeoXO

The three Lake Erie HAB forecasting products listed in the opening of this section do not currently depend on inputs from GOES-R series satellites, but have the potential to be improved by observations from GeoXO's ocean color (OC) instrument. The near-continuous observations from GeoXO's OC instrument will:

- provide better information about bloom size, location, biomass, and projected end date
- reduce the impact of cloud cover (the temporal gaps created by cloud cover are shorter with low-latency observations) which allows for quicker identification of HABs, and
- reduce NOAA's reliance on data provided by other agencies and other countries (the quality and continuity of NOAA products can be affected by budget decisions and constraints outside of NOAA).

GeoXO's OC instrument will have higher spatial resolution than currently available geostationary sources of ocean color observations. The HAB Forecasts are currently produced with 300m Ocean Land Colour Imagery[120] collected onboard the Sentinel-3a and Sentinel-3b satellites provided by EUMETSAT. Satellite imagery is used to show bloom location and extent as well as initiate forecast models[121].

OLCI observes surface conditions and can potentially provide daily observations, if cloud-free. However, clouds can obscure the location of blooms, and therefore it is more realistic to expect

[120] EUMETSAT. Undated. Ocean and Land Colour Instrument (OLCI). Available at https://www.eumetsat.int/olci. Accessed May 11, 2022.
[121] Rowe, M.D., Anderson, E.J., Wynne, T.T., Stumpf, R.P., Fanslow, D.L., Kijanka, K., Vanderploeg, H.A., Strickler, J.R. and Davis, T.W., 2016. Vertical distribution of buoyant Microcystis blooms in a Lagrangian particle tracking model for short-term forecasts in Lake Erie. Journal of Geophysical Research: Oceans, 121(7), pp.5296-5314.

a few clear scenes in a week[122]. Algae move up and down in the water column during the day for light and nutrients. In particular to blooms in Lake Erie, microcystis, the dominant bloom former, has gas vacuoles which allow the cells to move up and down in the water column due to the accumulation and metabolism of carbohydrates during respiration[123], [124].

Furthermore, high winds can cause mixing events which disperse the cells throughout the water column. Since ocean color satellites only see the surface, diurnal variability and mixing events can reduce the concentration of the algae at the surface leading to an underestimate of biomass. Even with two satellites, these events throughout the day cannot be captured by OLCI. The Sentinel-3a and Sentinel-3b satellites track each other closely, and pass the same location in less than an hour. When OLCI observations occur when much of the algae is below the surface and cannot be observed by satellites, this creates the potential for underestimating the extent and concentration of algae.

Other resources contributing to these forecasts include[125]:

- VIIRS observations from the polar-orbiting Suomi satellite
- Observations of surface wind and currents from the Lake Erie Operational Forecast System (LEOFS).
- Analysis of in situ water samples performed by the Great Lakes Environmental Research Laboratory (GLERL).
- Microcystis and toxin sampling from state agencies and academic institutions.
- National Weather Service (NWS) water temperature observations and forecasts.
- Wind data from NOAA's National Data Buoy Center
- Other sources include: (do any of these models ingest satellite data currently? Would any be improved by the inclusion of data from GeoXO OC instrument?)
- NOAA Center for Operational Oceanographic Products and Services (operations, hydrodynamic models, bloom analysis, forecast production, outreach)
- NOAA National Centers for Coastal Ocean Science (scientific development, research, remote sensing data, outreach)
- NOAA CoastWatch (remote sensing data)
- National Aeronautics and Space Administration (remote sensing data)
- NOAA National Centers for Environmental Information (data archives)

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[122] Wynne, T.T., Stumpf, R.P., Tomlinson, M.C. and Dyble, J., 2010. Characterizing a cyanobacterial bloom in western Lake Erie using satellite imagery and meteorological data. Limnology and Oceanography, 55(5), pp.2025-2036.

[123] Paerl, H.W. and Huisman, J., 2009. Climate change: a catalyst for global expansion of harmful cyanobacterial blooms. Environmental microbiology reports, 1(1), pp.27-37.

[124] Wynne et al, 2010. Op. Cit.

[125] NOAA National Centers for Coastal Ocean Science. Undated. Forecast Contributors and Data Providers. Available at https://coastalscience.noaa.gov/research/stressor-impacts-mitigation/hab-forecasts/contributors/. Accessed May 11, 2022.

Users

The Lake Erie HAB products provide information that helps stakeholders minimize the economic, health, and other impacts of harmful algal blooms. The products are used by:

- Operators of drinking water facilities, to develop treatment contingency plans when HABs detected in water exceed predetermined levels and, as necessary, adjust the chemical treatment of water or switch, on a temporary basis, to alternative water sources (e.g., a secondary intake or reservoir).
- State agencies can guide toxin sampling efforts and close beaches when toxins exceed standards for recreational swimming and issue warnings for pets.
- Commercial and recreational boaters can plan activities that are outside of the bloom.

Benefits to Society

Lake Erie HAB products provide benefits to society by reducing unnecessary precautionary actions (when there are fewer false positives or more precise delineation of affected areas) and reducing HAB-related illnesses (when there are fewer false negatives).

About 1 million households reside in Ohio counties that rely on Lake Erie for drinking water. For those households, the complete elimination of health impacts associated with impure drinking water has been valued at ~$700,000/day, with lesser reductions in these impacts valued at ~$460,000/day[126], [127]. Portions of Michigan and New York also border Lake Erie and a portion of their residents would benefit in a similar manner. Estimation of the benefits of Lake Erie HAB products would require:

- a complete estimate of the number of residents that rely on Lake Erie for drinking water
- an estimate of the number of days each year that the HAB Bulletin provides guidance towards mitigation efforts to prevent residents from ingesting toxic water
- the contribution of GeoXO observations to improving this outcome

Additional benefits will result from the avoidance of unnecessary water treatment costs, which are a function of the number of days that facilities avoid actions based on false positives and the contribution of GeoXO to this outcome.

These products also inform HAB-related beach closure decisions. In 2018, coastal tourism and recreation in Ohio contributed $1.7 billion to the nation's GDP[128]. Increased accuracy and precision in HAB forecasts reduce unnecessary beach closures, avoiding losses that have been estimated to be $2.7 million annually in Ohio alone[129]. Additional benefits are likely for anglers

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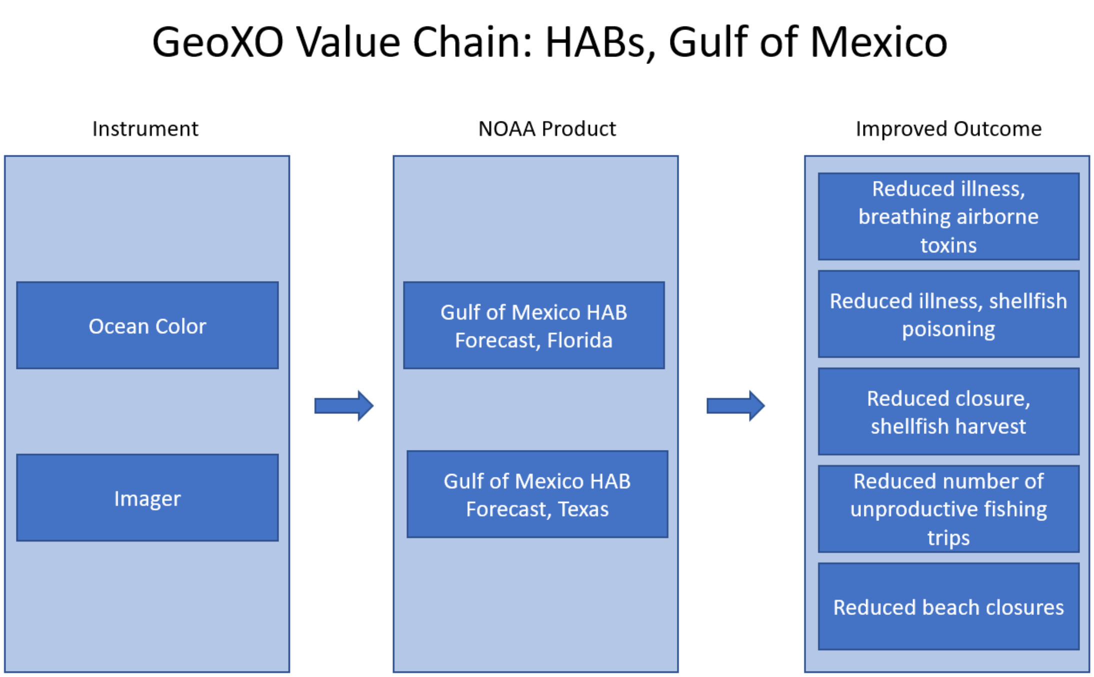
[126] Viscusi, W. Kip, Joel Huber, and Jason Bell, 2012. "Heterogeneity in Values of Morbidity Risks from Drinking Water" Environ. Resource Econ. Vol. 52, pages 23–48.
[127] Adamowicz, Vic, Diane Dupont, and Alan Krupnick, 2005. "Willingness to Pay to Reduce Community Health Risks from Municipal Drinking Water: A Stated Preference Study," Working paper.
[128] National Oceanic and Atmospheric Administration (NOAA). Economics: National Ocean Watch (ENOW) Data. Based on data from the Bureau of Labor Statistics and the Bureau of Economic Analysis. Charleston, SC: NOAA Office for Coastal Management.
[129] Murray, Chris, Brent Sohngen, and Linwood Pendleton, 2001. "Valuing Water Quality Advisories and Beach Amenities in the Great Lakes," Water Resources Research, Vol. 37, No. 10.

and other recreational users of Lake Erie, and Lake Erie beachgoers in Michigan and New York. GeoXO-enabled improvements in these products are likely to increase the value of these benefits.

It is important to note that, although this report focuses on HABs in Lake Erie and the Gulf of Mexico, HABs occur across the entire United States. Further, the number of areas impacted by HABs could increase with climate change. Other areas where HABs pose significant threats include the Pacific Northwest (affecting shellfish harvests), California (affecting shellfish harvest and marine mammal protection), and the Gulf of Maine (affecting shellfish harvest)[130].

Harmful Algal Blooms: Gulf of Mexico

The figure below provides an overview of the GeoXO instruments with the potential for improving NOAA's harmful algal bloom monitoring and forecast products for the Gulf of Mexico and the societal outcomes that are expected to be improved. The diagram is not meant to be comprehensive, but focuses on the content described in this section of the report.



[130] National Oceanic and Atmospheric Administration, 2021. The Value of Geostationary Ocean Color.

Product Background

A number of resources are available to reduce the impacts of harmful algal blooms in the Gulf of Mexico region. The Gulf of Mexico Harmful Algal Bloom Forecasts, operated by the National Center for Coastal Ocean Science (NCCOS), produces forecasts of harmful algal blooms (HABs) caused by *Karenia brevis* (red tide) in the Gulf of Mexico. The modeled forecasts of respiratory irritation at individual beach locations[131] are based on field samples of *Karenia brevis* concentration, wind speed, and direction. Current imagery from the Ocean Land Color Imager (OLCI) are provided to show bloom location and often are the first indication that a bloom has started. In addition, a forecast of bloom intensification is provided which estimates the likelihood of bloom initiation or intensification along the coast of Southwest Florida due to an accumulation of cells at the coast.[132],[133].

Other products[134] informing actions to reduce the effects of harmful algal blooms in the Gulf of Mexico region include:

- Information from Imaging Flow Cytobots (IFCBs) located onshore along the coast to monitor water for red tide.
- The Gulf of Mexico Harmful Algal Blooms Forecast[135], [136], which includes the following products:
    - Respiratory Forecast - Modeled forecast of respiratory irritation at individual beach locations, based on field samples of Karenia brevis concentration, wind speed, and direction.

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[131] NOAA National Centers for Coastal Ocean Science. Undated. Gulf of Mexico Harmful Algal Bloom Forecast. Available at: https://coastalscience.noaa.gov/research/stressor-impacts-mitigation/hab-forecasts/gulf-of-mexico/. Accessed May 11, 2022.

[132] NOAA National Centers for Environmental Information. 2022. Forecast products and associated satellite imagery from the Gulf of Mexico created by the NOAA Harmful Algal Bloom Operational Forecast System (HAB-OFS) from 2004-01-12 to 2021-07-23. Available at: https://www.ncei.noaa.gov/access/metadata/landing-page/bin/iso?id=gov.noaa.nodc:NOS-HABOFS-GoMex. Accessed May 5, 2022.

[133] NOAA National Centers for Environmental Information. 2022. Forecast products and associated satellite imagery from the Gulf of Mexico created by the NOAA Harmful Algal Bloom Operational Forecast System (HAB-OFS) from 2004-01-12 to 2021-07-23. Available at: https://www.ncei.noaa.gov/access/metadata/landing-page/bin/iso?id=gov.noaa.nodc:NOS-HABOFS-GoMex;view=iso. Accessed May 5, 2022.

[134] Note: Responsibility for HAB forecasts for both Lake Erie and Gulf of Mexico was transferred to NOAA National Centers for Coastal Ocean Science in 2021 and weekly-bi-weekly HAB bulletins are no longer produced. This has been replaced by a forecast of respiratory irritation provided every 3 hours for a period of 30 hours; this product is updated every 3 hours. Separate forecasts are provided for individual beaches.

[135] NOAA National Centers for Coastal Ocean Science. 2022. Harmful Algal Bloom Forecasting. Available at: https://coastalscience.noaa.gov/research/stressor-impacts-mitigation/hab-forecasts/. Accessed May 5, 2022.

[136] NOAA National Centers for Coastal Ocean Science. 2022. Gulf of Mexico Harmful Algal Bloom Forecast. Available at: https://coastalscience.noaa.gov/research/stressor-impacts-mitigation/hab-forecasts/gulf-of-mexico/. Accessed May 5, 2022.

- Intensification Forecast - Model results estimating the likelihood of bloom initiation or intensification along the coast of Southwest Florida due to an accumulation of cells at the coast.
- Satellite Imagery - Current imagery from the Ocean Land Color Imager (OLCI) showing bloom location and extent.
- Beach Conditions Reporting System - Provides today's conditions at multiple beaches along the west coast of Florida; this includes respiratory irritation, rip currents, wind, and others.
- State of Florida Observations - State of Florida (FWC-FWRI) bloom status updates and 8-day interactive map of statewide K. brevis cell concentrations in water samples.

Dependence on GeoXO

These products do not currently depend on inputs from GOES-R satellites, but have the potential to be improved by observations from GeoXO's ocean color (OC) instrument. The near-continuous observations from GeoXO's OC instrument will improve HAB products in the same manner as with the Lake Erie HAB products, described above.

Other resources contributing to these forecasts include[137]:

- VIIRS observations from the polar-orbiting Suomi satellite
- NOAA Center for Operational Oceanographic Products and Services (operations, hydrodynamic models, bloom analysis, forecast production, outreach)
- NOAA National Centers for Coastal Ocean Science (scientific development, research, remote sensing data, outreach)
- NOAA CoastWatch (remote sensing data)
- National Aeronautics and Space Administration (remote sensing data)
- NOAA National Centers for Environmental Information (data archives)
- Copernicus (the European Union's Earth observation programme which provides the satellite imagery)
- European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) (Responsible for the delivery of Sentinel 3 satellite imagery)
- Texas General Land Office
- NOAA National Data Buoy Center
- NOAA National Weather Service

[137] NOAA National Centers for Coastal Ocean Science. Undated. Forecast Contributors and Data Providers. Available at https://coastalscience.noaa.gov/research/stressor-impacts-mitigation/hab-forecasts/contributors/. Accessed May 11, 2022.

Users

The Gulf of Mexico HAB forecasts provide information that helps stakeholders minimize the economic, health, and other impacts of harmful algal blooms. The products are used by public health agencies that:

- inform epidemiology staff about the location of red tide and potential seafood related illnesses
- issue advisories to stay out of the water and/or off the beach
- inform the public of HAB risks
- perform in-situ sampling

The products are also used by natural resource managers who:

- monitor shellfish sanitation and inform shellfish closures
- inform water quality warnings/postings for beach goers
- perform in situ sampling
- conduct educational programs on red tide identification and risks
- communicate key information, such as the location or potential impacts of red tide, to other agencies and/or the public

Benefits to Society

Two important sectors of the Gulf of Mexico economy are affected by HABs: coastal tourism and recreation and commercial fishing, including shellfish harvesting. In 2018, these two segments of the Gulf of Mexico economy contributed $18 billion to the nation's GDP[138].

Respiratory impacts and dead fish at beaches due to K. brevis blooms are the most significant impact to coastal tourism and recreation in the Gulf of Mexico.

A benefit of GeoXO-enable improvements to HAB forecasts would accrue to the tourism and recreation sector as the number of false positives is reduced and the onset and termination of HABs is more accurately predicted, both reducing the incidence and duration of beach closures.

Another benefit of GeoXO-enabled improvements to HAB forecasts would accrue to the beachgoers themselves, by reducing the travel time to open beaches, overcrowding of open beaches, and foregone beach recreation trips. With advance warning, tourists are able to avoid travel to an area affected by a HAB event and reduce costs associated with last-minute travel and holiday planning. The economic loss borne by hotels and eating and drinking establishments in this scenario is not avoided. The Gulf of Mexico beaches attract nearly 10 million visitors annually[139].

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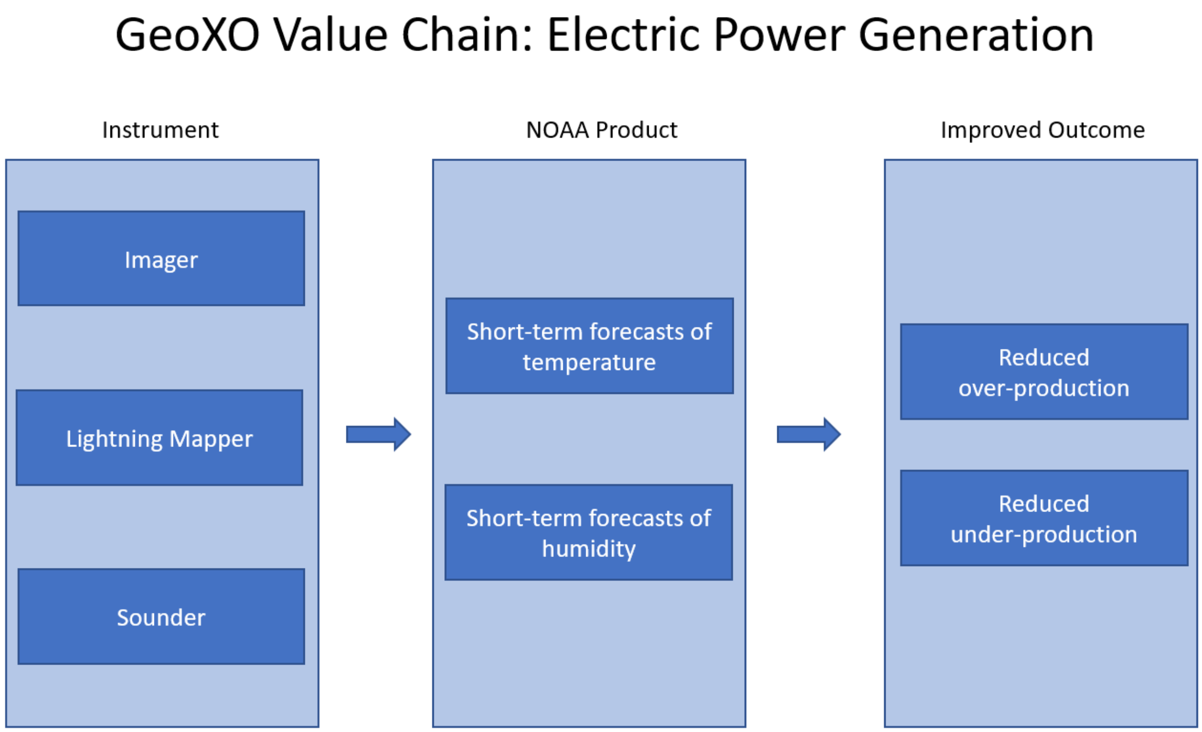
[138] National Oceanic and Atmospheric Administration (NOAA). Economics: National Ocean Watch (ENOW) Data. Based on data from the Bureau of Labor Statistics and the Bureau of Economic Analysis. Charleston, SC: NOAA Office for Coastal Management.

[139] Eastern Research Group and NOAA's National Ocean Service. 2021. Use and Economic Value of NOAA Harmful Algal Bloom Forecasting Products.

GeoXO-enabled improvements to HAB forecasts will also benefit commercial and recreational fishing in the Gulf of Mexico, which account for 8 percent and 23 percent of the national totals, respectively, with a combined contribution to national GDP of nearly $12 billion in 2017[140].

Electricity Power Generation

The figure below provides an overview of the GeoXO instruments with the potential for improving NOAA's numerical weather prediction models and other products that support the efficiency of the electric power generation industry, reducing the cost of energy to final consumers. The diagram is not meant to be comprehensive, but focuses on the content described in this section of the report.



Product Background

Short-term (up to 48-hour) forecasts of temperature and humidity are key inputs into short-term energy demand forecasts (1-hour to 24-hour) that inform decisions by electric utilities

[140] National Marine Fisheries Service. 2022. Fisheries Economics of the United States, 2018. U.S. Dept. of Commerce, NOAA Tech. Memo. NMFS-F/SPO-229, 236 p.

concerning power generation and distribution[141]. Utilities obtain forecasts of temperature and humidity that are used in their demand forecasts from NOAA sources (e.g., numerical weather prediction models) and private vendors[142].

Dependence on GeoXO

The GeoXO team indicates that both the imager and the sounder are expected to improve forecasts of temperature and humidity used by the electric power industry. Lauer et al. 2021[143], which focused on the economic value of the sounder, cite evidence from Observing System Simulated Experiments (OSSE) showing improvements ranging from 4 percent to 33 percent for prediction of temperature, winds, and humidity from baseline scenarios (OSSEs cited in [144], [145], [146]).

Users

Load forecasts (i.e., electricity demand forecasts) help utility companies determine how much electric power to produce. This is important because underproduction of power makes it necessary to purchase additional capacity on the spot market at higher costs and over production incurs unnecessary expense[147]. Weather variables are a key input and one of the primary drivers of load forecast error[148], [149]. There is no one demand forecast model used in the industry. Most companies use proprietary models tailored to a specific set of circumstances for the regions they serve. It is therefore challenging to identify the particular NOAA product used in each model. However, a survey of the available literature suggests forecasts of temperature, wind, humidity and cloud cover are all used as inputs, with temperature being the most

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[141] Suganthi, L. and Samuel, A.A., 2012. Energy models for demand forecasting—A review. Renewable and sustainable energy reviews, 16(2), pp.1223-1240.
[142] Personal communication by video conference with Jie Zhang, Associate Professor of Mechanical Engineering, University of Texas, Dallas.
[143] Lauer, C., Conran, J. and Adkins, J., 2021. Estimating the Societal Benefits of Satellite Instruments: Application to a Break-even Analysis of the GeoXO Hyperspectral IR Sounder. Frontiers in Environmental Science, p.458.
[144] Aune, Bob., Thom, Jonathan., Bayler, Gail., and AllenHuang, Paolo. Antonelli. (2000). "Preliminary Findings from the Geostationary Interferometer Observing System Simulation Experiments (OSSE).,". (NOAA Technical Report).
[145] Wang, H., Huang, X.-Y., and Chen, Y. (2013). An Observing System Simulation Experiment for the Impact of MTG Candidate Infrared Sounding Mission on Regional Forecasts: System Development and Preliminary Results. ISRN Meteorology 2013, 1–18. doi:10.1155/2013/971501
[146] Li, Z., Li, J., Wang, P., Lim, A., Li, J., Schmit, T. J., et al. (2018). Value-added Impact of Geostationary Hyperspectral Infrared Sounders on Local Severe Storm Forecasts-Via a Quick Regional OSSE. Adv. Atmos. Sci. 35 (10), 1217–1230. doi:10.1007/s00376-018-8036-3
[147] Electric Power Research Institute (EPRI). 2001. How Do You Like Your Weather. Available online at https://www.epri.com/research/products/000000000001006028. Accessed May 11, 2022.
[148] Fay, D. and Ringwood, J.V., 2010. On the influence of weather forecast errors in short-term load forecasting models. IEEE transactions on power systems, 25(3), pp.1751-1758.
[149] EPRI, 2001. Op.Cit.

important variable[150],[151],[152], [153], [154], [155]. Ensemble weather models can further improve load forecasts and can be used to provide better probabilistic load forecasts, improving a utility's ability to plan[156], [157].

Load forecasts cover a range of time scales from hours to decades but the demand forecasts most heavily dependent on accurate weather forecasts are short-term forecasts ranging from 3 hours to 24 hours in advance[158]. Some models even explicitly separate base load from the weather-related portion of demand[159].

Increased reliance on renewable energy created a need to also forecast the supply of electricity from renewable sources as well as forecasting total demand [160], [161]. Electric power from renewable sources has a higher dispatch priority than power from coal- and gas-fired plants. Thus, the operation of coal- and gas-fired plants must consider both the anticipated demand for electricity and the anticipated supply from non-renewable sources[162], [163].

Benefits to Society

Error in energy demand forecasts increase the cost of providing electricity to users when these forecasts lead to:

- planning for the production of too little energy (the shortfall must be made up by higher-cost production, purchased on the spot market)

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150 Hong, T., 2014. Energy forecasting: Past, present, and future. Foresight: The International Journal of Applied Forecasting, (32), pp.43-48.
151 Hong, J. and Kim, W.S., 2015. Weather impacts on electric power load: partial phase synchronization analysis. Meteorological applications, 22(4), pp.811-816.
152 PJM Interconnection Resource Adequacy Planning Department. 2016. Load Forecasting Model Whitepaper. Available at: https://www.pjm.com/~/media/library/reports-notices/load-forecast/2016-load-forecast-whitepaper.ashx. Accessed May 11, 2022.
153 Taylor, J.W. and Buizza, R., 2003. Using weather ensemble predictions in electricity demand forecasting. International Journal of Forecasting, 19(1), pp.57-70.
154 Fay and Ringwood, 2010. Op. Cit.
155 Teisberg, T.J., Weiher, R.F. and Khotanzad, A., 2005. The economic value of temperature forecasts in electricity generation. *Bulletin of the American Meteorological Society*, *86*(12), pp.1765-1772.
156 Taylor and Buizza, 2003. Op. Cit.
157 Xu, L., Wang, S. and Tang, R., 2019. Probabilistic load forecasting for buildings considering weather forecasting uncertainty and uncertain peak load. Applied energy, 237, pp.180-195.
158 EPRI 2001. Op. Cit.
159 Taylor and Buizza, 2003. Op. Cit.
160 Sepasi, S., Reihani, E., Howlader, A.M., Roose, L.R. and Matsuura, M.M., 2017. Very short term load forecasting of a distribution system with high PV penetration. *Renewable energy*, *106*, pp.142-148.
161 Li, L., Ota, K. and Dong, M., 2017. When weather matters: IoT-based electrical load forecasting for smart grid. *IEEE Communications Magazine*, *55*(10), pp.46-51.
162 Personal conversation with Jie Zhang, University of Texas, Dallas, Department of Mechanical Engineering on January 13, 2022.
163 Zhang, J., Hodge, B.M., Lu, S., Hamann, H.F., Lehman, B., Simmons, J., Campos, E., Banunarayanan, V., Black, J. and Tedesco, J., 2015. Baseline and target values for regional and point PV power forecasts: Toward improved solar forecasting. *Solar Energy*, *122*, pp.804-819.

- planning for the production of too much energy (the excess power will not be sold despite utilities having incurred the cost of production)

Society bears these costs, whether they are passed on to consumers or borne by the utilities and its shareholders.

Fay and Ringwood 2010[164] find that, "[a]lthough system dependent, weather forecast errors can be significant[165] and have been attributed as the cause of 17 percent[166] to 60 percent[167] of load forecast errors."

According to a 2005 study by Teisberg et al[168], a 1°C improvement in forecast accuracy is worth about $59 million per year. Updating this study (and the studies it builds on) could allow us to calculate the current value of forecast accuracy for improving electricity demand forecasts.

Filling Gaps in Radar Coverage and Outages

The current ground-based radar network does not provide full coverage of the U.S. Some areas lie beyond the range of radar (including, importantly, offshore areas) and the view of others is blocked by mountainous terrain. Gaps in coverage also occur during scheduled maintenance or as the result of equipment failure. The value chain described in this section and depicted in the diagram below focuses on the ability of GeoXO to fill gaps in radar coverage due to scheduled and unscheduled radar outages. The diagram is not meant to be comprehensive, but focuses on the content described in this section of the report.

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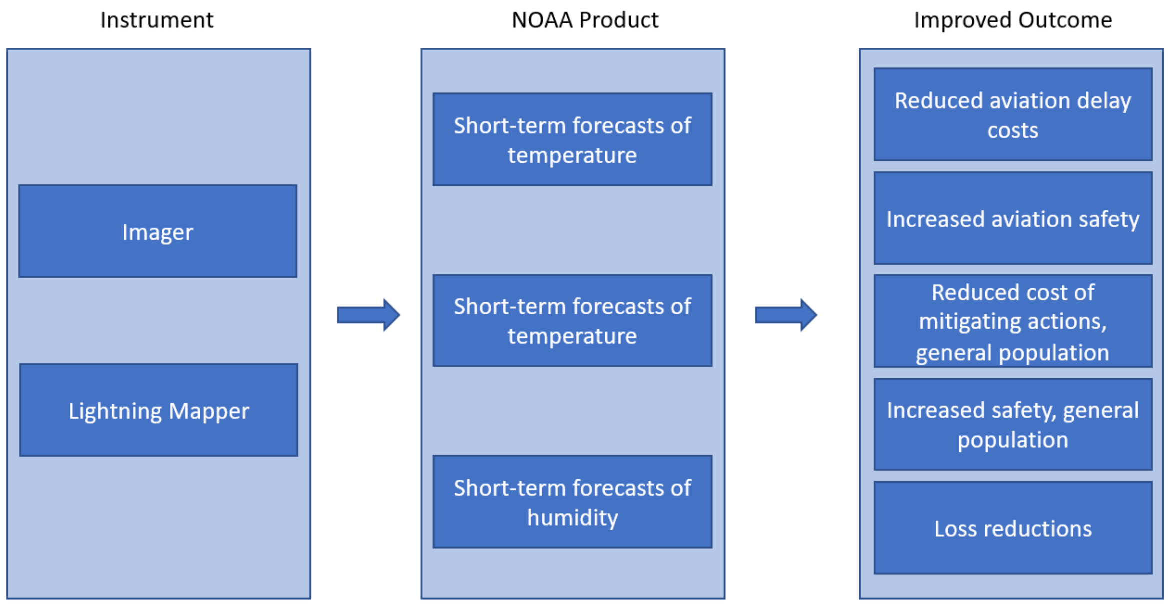
[164] Fay, D. and Ringwood, J.V., 2010. On the influence of weather forecast errors in short-term load forecasting models. IEEE transactions on power systems, 25(3), pp.1751-1758.
[165] Teisberg, T.J., Weiher, R.F. and Khotanzad, A., 2005. The economic value of temperature forecasts in electricity generation. Bulletin of the American Meteorological Society, 86(12), pp.1765-1772.
[166] Douglas, A.P., Breipohl, A.M., Lee, F.N. and Adapa, R., 1998. The impacts of temperature forecast uncertainty on Bayesian load forecasting. IEEE Transactions on Power Systems, 13(4), pp.1507-1513.
[167] Taskforce, "Problems associated with unit commitment in uncertainty," IEEE Trans. Power App. Syst., vol. PAS-104, no. 8, pp. 2072–2078, Aug. 1985
[168] Teisberg et al, 2005. Op. Cit.

GeoXO Value Chain: Filling Gaps During Radar Outages



Product Background

The NWS issues watches and warnings that allow society to be prepared for and take actions that mitigate the effects of severe thunderstorms[169]. Destructive and life-threatening effects of thunderstorms include flooding, lightning, lightning-induced wildfires, tornadoes, damaging wind, and hail[170]. When thunderstorms have the potential to generate tornadoes, NWS issues separate tornado watches and warnings.

A principal input to models used to forecast thunderstorms and tornadoes is lightning data acquired through ground-based radar sensors. Observations from the GeoXO imager and lightning mapper can be used to fill gaps in radar coverage.

Dependence on GeoXO

GeoXO lightning mapper and imager instruments will provide observations for areas and during times for which ground-based radar do not provide coverage. This represents a continuation of the capabilities of GOES-R lightning mapper and imager instruments. There is some indication that radar outages are positively related to severe weather, which increases the importance and

[169] National Weather Service. Undated. Understanding Severe Weather Alerts. Available at https://www.weather.gov/safety/thunderstorm-ww. Accessed on May 10, 2022.
[170] City of Superior, Wisconsin. Undated. City of Superior Hazard Mitigation Plan, Section 8: Thunderstorm Hazards. Available at http://www.ci.superior.wi.us/DocumentCenter/View/1533/Section-8-Thunderstorm-Hazard?bidId=. Accessed May 10, 2022.

value of GeoXO in forecasting severe weather. Furthermore, some radar measurements require multiple scans, increasing the time between observations; the high temporal resolution of the GOES-R lightning mapper has been shown to marginally increase warning time; the GeoXO lightning mapper will provide continuity of this capability. Several attributes of the imager are also useful for filling in radar gaps. These include individual bands and derived products such as ProbServere[171].

Users

For benefits that accrue to aviation, the users of these products are the same as those described above under "Aviation." Emergency managers, government agencies, and others also use these forecasts to inform actions that they undertake to mitigate the harmful effects of thunderstorms, tornadoes, and flash floods. This includes both those actions undertaken to limit direct impacts on government agencies and the guidance issued to the general public to limit impacts more generally within their jurisdiction.

Benefits to Society

Benefits are generally realized in the form of reductions of avoidable losses associated with thunderstorms, tornadoes, and flash flooding. Aviation benefits are described above. Other benefits of GeoXO lightning mapper-enabled improvements to severe thunderstorm, tornado, and flash flood forecasts include those associated with reducing false positives and false negatives. Benefits associated with reductions in false positives include reducing the cost of unnecessary mitigating actions including:

- school/sports arena closures
- advisories that deter travel or prompt early travel (e.g., leaving early to get to work) that can reduce accidents and decrease traffic volume[172]
- moving cars inside garages to protect them from hail damage
- sheltering in place

All these actions have non-trivial economic costs.

Benefits associated with reductions in false negatives include:

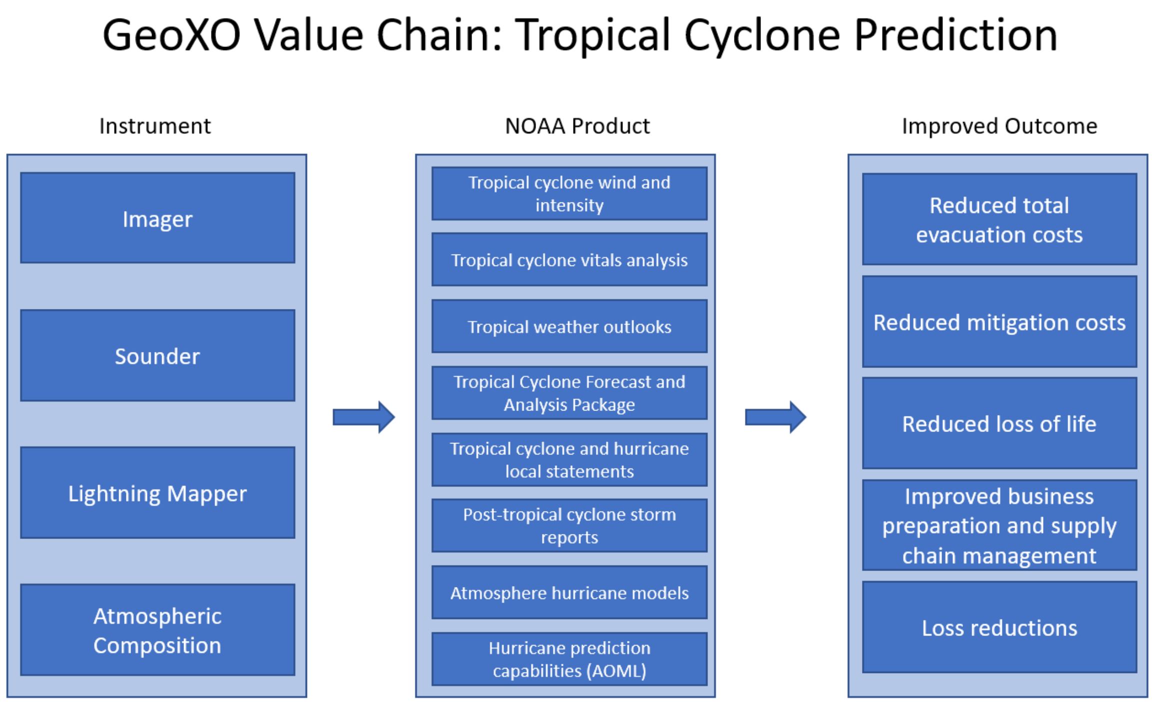
- reducing hail damage to cars and, where mitigating actions are possible, crops
- protection of life
- reduced flood losses (not all are avoidable but some are)
- reduced wind losses (not all are avoidable but some are)

[171] For more information on this model, see Cintineo, J.L., Pavolonis, M.J., Sieglaff, J.M., Cronce, L. and Brunner, J., 2020. NOAA ProbSevere v2. 0—ProbHail, ProbWind, and ProbTor. Weather and Forecasting, 35(4), pp.1523-1543.

[172] Ferris J.S. and Newburn, D.A., 2017. Wireless alerts for extreme weather and the impact on hazard mitigating behavior, v. 82, pp. 239-255.

Tropical Cyclones and Hurricanes

The figure below provides an overview of the GeoXO instruments with the potential for improving NOAA's tropical cyclone and hurricane forecast products and the societal outcomes that are expected to be improved. The diagram is not meant to be comprehensive, but focuses on the content described in this section of the report.



Product Background

NOAA and the National Weather Service (NWS) issue a broad and diverse set of tropical cyclone and hurricane products at primarily two office levels: the National Hurricane Center (NHC) and local Weather Forecast Offices (WFOs). NHC is a component of the National Centers for Environmental Prediction (NCEP) and issues watches, warnings, forecasts, and analyses of hazardous tropical weather supporting the United States and the Caribbean. Within the NHC, are the Hurricane Specialist Unit, the Tropical Analysis and Forecast Branch, the Technology and Science Branch, the Storm Surge Unit, the Aerial Reconnaissance Coordination unit, and the Hurricane Liaison Team.

Core products identified by the NHC include:

- Tropical Cyclone Public Advisory (TCP)
- Tropical Cyclone Forecast/Advisory (TCM)
- Tropical Cyclone Discussion (TCD)
- Tropical Cyclone Surface Wind Speed Probabilities (PWS)
- Tropical Cyclone Update (TCU)

- Tropical Cyclone Position Estimate (TCE)
- Tropical Weather Outlook (TWO)
- Tropical Cyclone Valid Time Event Code (TCV)
- Tropical Cyclone ICAO (Aviation) Advisory (TCA)
- Hurricane Local Statement (HLS)
- Monthly Tropical Weather Summary (TWS)
- Tropical Cyclone Reports (TCR)

Weather Forecast Offices (WFO) operate across the United States, each with an area of responsibility known as a County Warning Area (CWA). As a tropical storm or hurricane approaches a CWA, the local WFOs begin coordination with the NHC and rely upon their own input data to create products for their CWA. The input data includes numerical weather prediction (NWP), satellite imagery and sounding data, radar, water level, in situ modeling, and public weather reports. Using this information, the local WFO creates tailored products that often include automated sections from the National Digital Forecast Database (also known as TCV) and written guidance. Core products identified by WFOs include:

- Extreme Wind Warning (EWW)
- Hurricane Local Statement (HLS)
- Post Tropical Cyclone Report
- Tropical Cyclone Valid Time Event Code
- Tropical Wind Watch and Warning Common Alerting Protocol (CAP) messages
- Storm Surge Watch/Warning Common Alerting Protocol (CAP) messages

As part of NOAA's portfolio analysis, the NESDIS Office of System Architecture and Advanced Planning (OSAAP) coordinates the Technology, Planning, and Integration for Observation division (TPIO) to conduct value tree analysis connecting NOAA observation systems to key products and services. This observation system database and the associated analytical methods are known as NOSIA-II. TPIO data will provide an initial basis for estimating the contribution of specific GeoXO instruments to total benefits. The TPIO classes within which specific NHC and WFO products fall are:

- Tropical Cyclone Wind Position & Intensity
- Tropical Cyclone Vitals Analysis
- Tropical Cyclone Weather Outlooks
- Tropical Cyclone Forecast & Analysis Package
- Tropical Cyclone & Hurricane Local Statements
- Post-Tropical Cyclone Storm Reports (PSH)
- Atmosphere Hurricane Models (Dynamical, Ensemble, Intensity, Trajectory)
- Improving Hurricane Prediction Capabilities (AOML)

Current Reliance on Satellite Data

The products developed by NOAA for tropical storms range from seasonal outlooks to forecasting/nowcasting, and ultimately post-event analysis. The NHC forecasts the track, intensity, size, and structure of tropical cyclones and, using this information, predicts associated surges, rainfall, and tornadoes. It also generally predicts the frequency of hurricanes during the year and the likelihood a tropical storm develops within a 48-hour period. To do this, NHC uses data from ships and buoys, aerial reconnaissance, radiosondes, radar, automated surface stations, and satellites to inform numerical weather prediction and downstream products.

Satellite information is especially useful in the formulation of tropical storm and hurricane products as these storms develop and intensify over the ocean, usually far from land and populated areas. Data from both geosynchronous and polar-orbiting satellites is currently relied upon. The two primary observations used from satellites are from the imager and sounder instruments. Imagers collect data on radiant energy and reflected solar energy from Earth's surface and atmosphere while the sounder provides data on the vertical temperature and moisture profiles of the atmosphere, surface, cloud temperatures, and ozone distribution. Polar orbiting satellites, given their proximity to the Earth (around 800km from surface), are able to provide higher resolution imagery at the expense of frequency. With their sun-synchronous rotation, satellites such as the JPSS-1 from the Joint Polar Satellite System[173] provide updates every 101 minutes. Geostationary satellites such as GOES-16 (formerly GOES-R) orbit at an altitude of around 35,000km and while they lack the resolution capabilities of satellites in low-Earth orbit, are able to provide near real-time observations, offering a full disk image potentially every 5 minutes, but routinely every 10 minutes. While the GOES-R series of satellites lacks a true sounder, this generation of satellite does include a Geostationary Lightning Mapper (GLM) instrument. Sounder data for tropical cyclones is collected from JPSS at a lower data frequency.

With GOES-16 operational in 2016, research[174] has demonstrated that improvements in the imager resolution and frequency positively impact numerical models such as the Hurricane Weather Research and Forecasting (HWRF) allowing for better forecasting of tropical cyclone track and intensity. With a sounder lacking on the GOES-R series, robust high-frequency data is also desired. Certain research[175] suggests that infrared sounder data improves long-lead time forecasts (greater than 72h) and can reduce error in tropical storm track and intensity. In terms of lightning, ground-based data from the World-Wide Lightning Location Network (WWLLN) helps identify a tropical cyclone's inner core, provides information on intensification of cyclones into hurricanes, and can pinpoint the rainband of a tropical cyclone. With improvements to integrating geostationary lightning mapper (GLM) data from the GOES-R generation of

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173 NOAA National Environmental Satellite Data and Information Service. Undated. Joint Polar Satellite System (JPSS) Program Office. Available at https://www.nesdis.noaa.gov/about/our-offices/joint-polar-satellite-system-jpss-program-office. Accessed May 10, 2022.

174 See, for example, Velden, C., Lewis, W.E., Bresky, W., Stettner, D., Daniels, J. and Wanzong, S., 2017. Assimilation of high-resolution satellite-derived atmospheric motion vectors: Impact on HWRF forecasts of tropical cyclone track and intensity. Monthly Weather Review, 145(3), pp.1107-1125.

175 Wang, P., Li, J., Li, Z., Lim, A.H., Li, J., Schmit, T.J. and Goldberg, M.D., 2017. The impact of Cross-track Infrared Sounder (CrIS) cloud-cleared radiances on Hurricane Joaquin (2015) and Matthew (2016) forecasts. Journal of Geophysical Research: Atmospheres, 122(24), pp.13-201.

satellites, near real-time data can be leveraged to support these modeling efforts. The role of GLM data is especially important in understanding the offshore development of hurricanes in locations for which WWLN sensors provide very limited observations.

Although not indicated in the diagram or included in benefit estimates (Section 3), it is possible that improved ocean color observations can aid in forecasts of tropical cyclones. As ocean color alters the absorption of sunlight, it is an important factor in understanding changes in sea surface temperature which in turn impact tropical cyclone activity. NOAA's Geophysical Fluid Dynamics Laboratory (GFDL) proposes ocean color as an input in coupled modeling to help predict tropical cyclone seasonal outlooks[176].

Potential Reliance on GeoXO

GeoXO's full suite of key instruments have a potential to support NOAA's tropical cyclone and hurricane forecasting products and services:

- Advanced Baseline Imager
- Hyperspectral Infrared Sounder
- Geostationary Lightning Mapper
- Atmospheric Composition Instrument
- Ocean Color Instrument

To better understand how GeoXO will impact NOAA's missions, an analysis was requested from TPIO using the NOSIA-II database[177] to identify NOAA products that are sensitive to improvements provided by a GeoXO-like configuration, which TPIO calls a "Room-to-Run" analysis. There are limitations to this analysis as hypothetical analogs were created to estimate impact of the proposed GeoXO configuration. It must be stressed that this information only offers a starting point at estimating the potential improvements provided by GeoXO. Review by subject matter experts must be provided to corroborate and refine this analysis.

The following table is a subset of TPIO's analysis focused on NOAA's tropical cyclone and hurricane products. It identifies each product's "room to run" or sensitivity to improvement from new data provided by a GeoXO-like configuration. This analysis identifies the product sensitivities to new data by each individual instrument but does not account for multiplicative enhancements to the product provided by GeoXO's full suite, or part thereof, of sensors. Similarly, this table does not identify whether these instrument data gaps are independent of each other. The original TPIO data provided 'room-to-run' percentages which have been normalized and converted into ordinal variables of 'High,' 'Medium,' 'Low,' 'Marginal,' and 'None' using a formal classification method (Fisher-Jenks). These rankings are relative to this table only and cannot be generalized.

[176] Gnanadesikan, A., Emanuel, K., Vecchi, G.A., Anderson, W.G. and Hallberg, R., 2010. How ocean color can steer Pacific tropical cyclones. Geophysical Research Letters, 37(18).
[177] Helms, D., Austin, M., Mccullouch, L., Reining, R.C., Pratt, A., Mairs, R., O'Connor, L. and Taijeron, S., 2016. NOAA observing system integrated analysis (NOSIA-II) methodology report.

NOAA Tropical Cyclone Products: Potential Sensitivity to GeoXO Instrumentation (using NOSIA-II Analysis)					
NOAA Key Product	Imager	Sounder	Atmospheric Composition	Ocean Color	Lightning
Tropical Cyclone Wind Position & Intensity	High	High	Low	Marginal	None
Tropical Cyclone Vitals Analysis	Medium	High	Low	Marginal	None
Tropical Cyclone Weather Outlooks	Medium	Medium	Low	Marginal	Marginal
Tropical Cyclone Forecast & Analysis Package	Medium	Medium	Low	Marginal	Marginal
Tropical Cyclone & Hurricane Local Statements	Low	Low	Low	Marginal	Marginal
Post-Tropical Cyclone Storm Reports (PSH)	None	None	None	None	None
Atmosphere Hurricane Models (Dynamical, Ensemble, Intensity, Trajectory)	Medium	Medium	Low	Marginal	None
Improving Hurricane Prediction Capabilities (AOML)	Low	Low	Marginal	Marginal	Marginal

Reviewing these data, it is found within the NOSIA-II data that Tropical Cyclone Wind and Intensity, Tropical Cyclone Vitals Analysis, Tropical Weather Outlooks, Tropical Cyclone Forecast and Analysis, and Atmosphere Hurricane Models are strongly sensitive to improved data provided by both an improved imager and sounder with a high need for data in wind position and intensity. There is also a significant need for data from the hyperspectral sounder in Tropical Cyclone Vitals Analysis. Reviewing Hurricane Local Statements, WFOs such as Miami are reliant on geostationary satellite data but report high satisfaction with current GOES satellite data. Thus, the room-to-run for this product is currently low, but as the operational geostationary satellites are taken offline, the Hurricane Local Statements are expected to rely on GeoXO. As for Post-Tropical Cyclone Storm Reports, this product relies primarily on Automated Surface/Weather Observing Systems (ASOS/AWOS) and human observations. According to NOSIA-II, it does not use satellite observations or any other input.

Reviewing data sensitivities for atmospheric composition, current needs are low. As the proposed GeoXO atmospheric composition instrument currently does not have an analog, it is expected that current operational products do not substantially rely or need data from a not-yet-existent instrument. As GeoXO develops its potential user base and experimental products, new uses for atmospheric composition data are expected. It is understood, however, that a geostationary imager and sounder provide the most important data to support tropical cyclone forecasting.

Similarly, ocean color is ranked as having only marginal data gaps in the above analysis. Once again, this instrument has no present analog and the analysis is limited by the needs of existing NOAA products and services. Furthermore, as ocean color is proposed as an input into coupled modeling, significant work will need to be done to identify the unique improvements provided by ocean color data to inform tropical cyclone and hurricane forecasting.

Finally, lightning data is also listed as having little room to run with operational NOAA tropical cyclone products. While currently operational, GLM remains a new instrument that complements ground-based lightning observations that use diverse data standards. It is important to note that ground-based observations are not available for offshore areas where hurricane formation occurs and the earliest warnings of hurricane impacts are made before ground-based observations are available. The NOSIA-II analysis does show reliance upon ground-based commercial lightning data for Hurricane Local Statements and numerical weather models. There is potential for other tropical cyclone products to consider the GLM over current lightning data buys as NOAA develops its modeling capabilities.

Benefits to Society

Hurricanes, tropical storms, and tropical depressions pose a variety of threats to people and property, and can deepen existing societal disparities[178]. Storm surge and inland flooding have historically been the leading causes of loss of life during hurricanes[179]. According to the Congressional Budget Office (CBO)[180], “the expected annual losses caused by hurricane winds and storm-related flooding total $54 billion. This is equivalent to 0.3% of the nation’s current gross domestic product. This total consists of $34 billion in expected annual economic losses to the residential sector, $9 billion to commercial businesses, and $12 billion to the public sector. About half of these costs are borne by property owners and their insurers. However, under current conditions and policies, the expected annual cost to the federal government—and thus to taxpayers—of damage from hurricane winds and storm-related flooding is $17 billion for the major categories of spending that CBO analyzed”.

NOAA’s tropical cyclone and hurricane products and services reduce the impacts of these storms by providing information to federal, state and local governments, emergency managers, and the general public to inform proper mitigating activities and evacuation orders well in advance of a storm. This information also allows businesses and institutions such as hospitals and universities to prepare for a storm, safely manage their workforce and continue essential operations, and allow for the stock of essential items and hard goods along with services to help the public prepare for weather impacts. Long-term data on tropical cyclone activity helps city planners and academic researchers better understand societal impacts of tropical cyclones and provide policy recommendations focused on ocean, coastal, and inland resiliency to these storms.

Given its improved observing capabilities, GeoXO is expected to enhance and refine the benefits NOAA currently provides to the United States and society. In addition to replacing current GOES observations that support the aforementioned benefits, improvements to track and intensity forecasts for tropical cyclones and hurricanes are expected to reduce both type I (false positive) and type II (false negative) errors in tropical cyclone forecasting and subsequent activities. In reducing type I errors or false alerts of significant tropical storm impacts,

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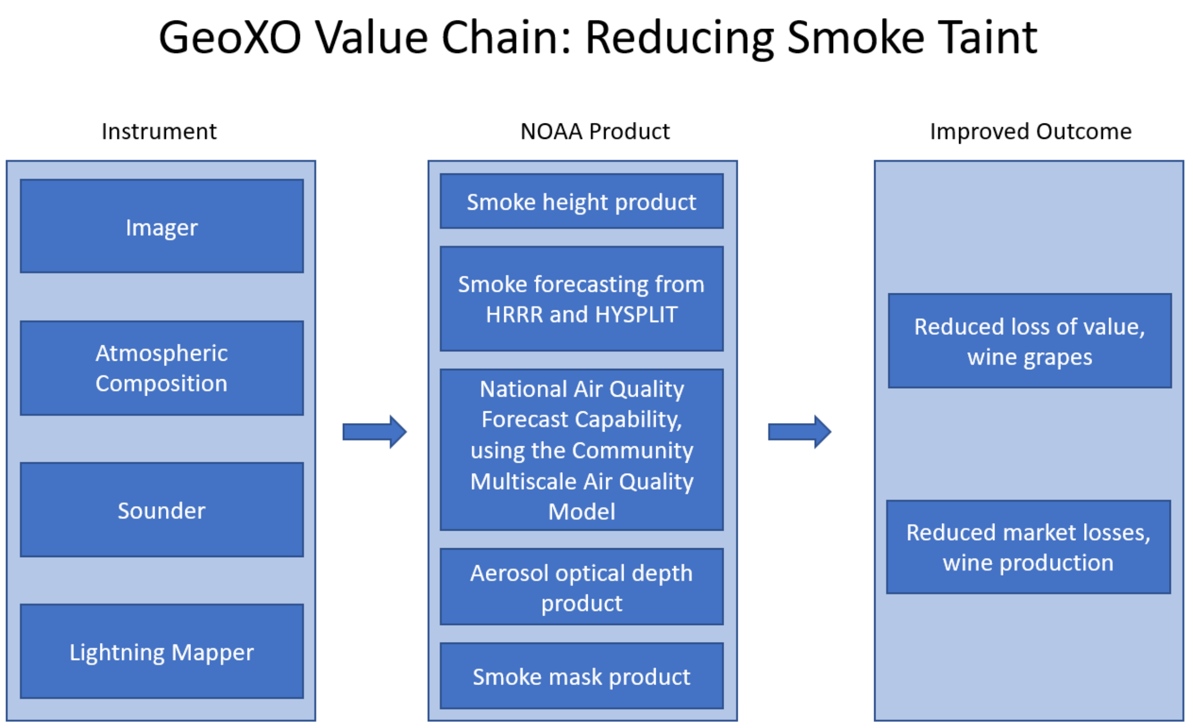
[178] Flores, A.B., Collins, T.W., Grineski, S.E. and Chakraborty, J., 2020. Disparities in health effects and access to health care among Houston area residents after Hurricane Harvey. Public Health Reports, 135(4), pp.511-523.
[179] Rappaport, E.N., 2014. Fatalities in the United States from Atlantic tropical cyclones: New data and interpretation. Bulletin of the American Meteorological Society, 95(3), pp.341-346.
[180] Hall, K., 2019. Expected costs of damage from hurricane winds and storm-related flooding. Congressional Budget Office: Washington, DC, USA, pp.1-48.

governments and emergency managers can more accurately issue warnings and evacuation orders that focus only on those areas that are exposed to weather impacts. This in turn will save government agencies, the general public, and businesses time and money spent on mitigation efforts. Type II errors or false negatives may be less likely given the precautions NOAA takes in issuing warnings and advisories, but the impacts of missing or incorrectly estimating a tropical cyclone's track or intensity can lead to death and significant damage. New observations from GeoXO are expected to reduce these impacts even further.

Pathfinders: E & J Gallo Winery

The figure below provides an overview of the GeoXO instruments with the potential for improving NOAA products that can be used to reduce the harmful effect of wildfire smoke on the grape and wine production and to improve the health and safety of grape harvesters who sometimes work in poor air quality conditions. The diagram is not meant to be comprehensive, but focuses on the content described in this section of the report.



Product Background

Environmental data informs critical decisions across the agriculture cycle, from when to seed a crop to when to harvest and whether to plant cover crops between seasons. This information also underpins the research community's evolving understanding of the implications of a changing climate for the success and security of American agriculture. Remote sensing data has applications in both crop-based and animal agriculture and is a useful tool for growers, insurance companies, and economists alike to understand factors including livestock forage availability, soil moisture, and damage from weather events. NOAA products most directly relevant to ongoing Pathfinder efforts with the E & J Gallo Winery (Gallo) are those associated with monitoring and forecasting the transport of smoke, which impairs the quality of grapes and wine and poses health risks to workers.

NOAA's National Air Quality Forecast Capability (NAQFC) provides operational predictions of smoke and other factors affecting air quality that are critical inputs to air quality forecasts produced by EPA, state and local air quality agencies, and the private sector[181]. The NAQFC is informed by NOAA's Community Multiscale Air Quality Model.

NOAA's Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model computes air parcel trajectories to determine how far and in what direction a parcel of air, and subsequently air pollutants, will travel[182]. HYSPLIT and the High-Resolution Rapid Refresh-smoke (HRRR-smoke) model predict the concentration and movement of smoke in three dimensions across the country, simulating how the weather will impact smoke movement and concentrations, and how smoke will affect visibility, temperature and wind. This system is intended as guidance to air quality forecasters and the public for fine particulate matter emitted from large wildfires and agricultural burning which can elevate particulate concentrations to unhealthful levels[183], [184].

NOAA's HRRR-Smoke is the first U.S. model to forecast smoke's impact on weather. This model predicts the movement of smoke in three dimensions across the country, simulating how the weather will impact smoke movement and concentrations, and how smoke will affect visibility, temperature and wind[185].

The NOAA Global Systems Laboratory's Rapid Refresh - Smoke (RAP-Smoke) model simulates the emissions and transport of smoke from wildfires and predicts the impact of smoke on the weather on a 13km grid. An important feature of RAP-Smoke is its ability to estimate "near-surface smoke" which impacts air quality and visibility and "vertically integrated smoke" which predicts smoke concentrations from the surface to about 25km in the atmosphere. The RAP-Smoke domain covers the entire North and Central Americas[186].

Dependence on GeoXO

The GOES aerosol optical depth and smoke mask products, derived from observations from the GOES-R Advanced Baseline Imager (ABI) are used for verification of operational smoke forecasts. Input to HRRR-Smoke and Community Multiscale Air Quality Model are fire emissions derived using satellite observations of fire detections and fire radiative power. GeoXO's AXI will continue to support the production of fire and aerosol products. Further

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181 National Weather Service. Undated. OSTI Modeling: Air Quality. Available at https://vlab.noaa.gov/web/osti-modeling/air-quality. Accessed May 10, 2022.

182 NOAA entry in Wikipedia. Undated. Available at https://en.wikipedia.org/wiki/HYSPLIT. Accessed on May 10, 2022.

183 National Oceanic and Atmospheric Administration. 2021. NOAA Blue Book: FY22. Available at https://www.noaa.gov/sites/default/files/2021-06/NOAABlueBook2022_final.pdf. Accessed May 10, 2022.

184 NOAA Air Resources Laboratory. Undated. The HYSPLIT-based Smoke Forecasting System. Available at https://www.arl.noaa.gov/hysplit/smoke-forecasting/. Accessed May 10, 2022.

185 National Oceanic and Atmospheric Administration. 2021. NOAA Blue Book: FY22. Available at https://www.noaa.gov/sites/default/files/2021-06/NOAABlueBook2022_final.pdf. Accessed May 11, 2022.

186 NOAA Global Systems Laboratory. Undated. Fire Weather. Available at https://gsl.noaa.gov/focus-areas/fire-weather. Accessed May 11, 2022.

improvements in monitoring and predicting the movement of smoke will be supported by GeoXO's atmospheric composition (AC) and sounder instruments, specifically aerosol layer height and carbon monoxide products.

Users

Members of the agriculture community are both technical and non-technical end-users. This places a premium on easily accessible data designed for non-research audiences. E & J Gallo Winery, a family run winery and distributor headquartered in Modesto, California, is the largest exporter of California wines. Gallo is active in agricultural research and is a commercial user of satellite data. During the 2020 California fires, Gallo, like hundreds of other California vineyards, suffered from smoke damage on grapes (known as smoke taint). As users of GOES ABI data and atmospheric composition data from polar satellites, Gallo will help develop a value chain to understand how improvements in the atmospheric composition products from GeoXO will impact future viticulture challenges and early warning scenarios in California.

Benefits to Society

Smoke from wildfires reduces the value of grapes and wine and poses health risks to harvest workers. In California alone, growing grapes and producing wine contributes more than $100 billion annually to the national economy[187]; in each of the last five years, California has been affected by wildfires causing losses in excess of $1 billion each. The economic impacts of smoke damage to grapes (called "smoke taint") can be significant; a recent lawsuit addresses a case in 2020 where smoke taint reduced the value of Cabernet Sauvignon grapes to just over a third of their original value (or, a 64 percent loss)[188].

When grapes are threatened by smoke, they can sometimes be harvested early to avoid such losses. The sugar content and therefore the value of the grapes harvested early will be lower, additional costs will be incurred in winemaking, and the value of the resulting wine might be lower, but these combined effects still yield a benefit when compared to a loss of more than 60 percent.

Harvesting grapes early to prevent the effects of smoke damage has the potential to generate health risks for workers if they must work in smoky conditions.

GeoXO-enabled improvements in monitoring and forecasting the transport of smoke can reduce the economic losses associated with smoke taint and the adverse health impacts on harvest workers.

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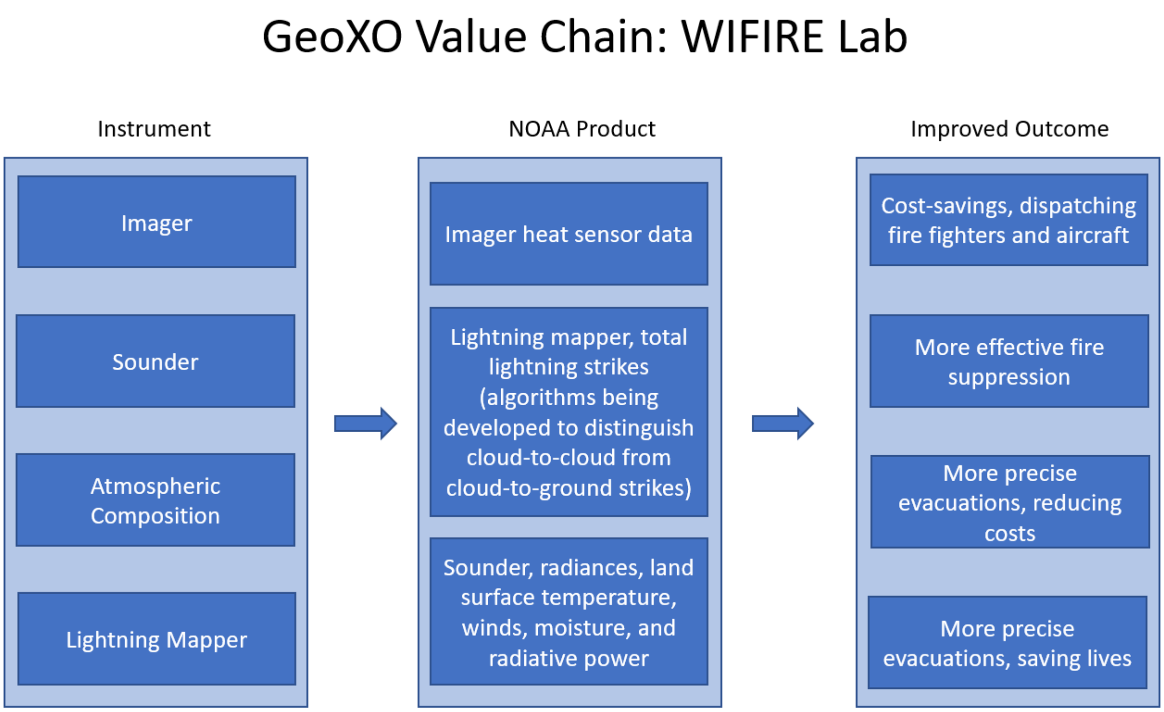
[187] Wine Searcher. 2020. Fires Leave 2020 Vintage in the Balance. Available at https://www.wine-searcher.com/m/2020/09/fires-leave-2020-vintage-in-the-balance. Accessed May 10, 2022.
[188] Wine Business. 2021. E&J Gallo Sues LMR Wine Estates for $420K Alleging Non Payment for 2020 Grapes. Available at https://www.winebusiness.com/news/article/241300/. Accessed May 10, 2022.

Pathfinders: WIFIRE Lab

The figure below provides an overview of the GeoXO instruments with the potential for improving NOAA's inputs to WIFIRE products for detecting, monitoring, and forecasting the spread of wildfires and the societal outcomes that are expected to be improved. The diagram is not meant to be comprehensive, but focuses on the content described in this section of the report.



Product Background

WIFIRE is more dependent than most upon the direct use of data from NOAA's geostationary satellites, as opposed to NOAA products that rely on the data. Two satellite-based data products are of primary importance to WIFIRE: the current use of heat sensor data from the GOES-R imager and the potential future use of data on total lightning strikes from the GLM.

Dependence on GeoXO

Heat sensor data (the 3.9 μm band) from GOES-R are used by WIFIRE to initialize wildfire spread models. The 2 km of GOES-R heat sensor data limits the accuracy of these models. The 1 km spatial resolution of GeoXO heat sensor observations will improve initialization by a factor of four (each 2 km pixel contains four 1 km pixels), significantly improving model initialization, the accuracy of model results, and the efficiency of and effectiveness of the actions that the models inform.

Users

A wide range of stakeholders will benefit from this application of GeoXO observations, assessing wildfire risk in the pre-season and those who respond to wildfires as they occur. Stakeholders include:

- researchers developing models to assess wildfire risk and forecast wildfire spread,
- firefighters and other emergency responders, and
- government officials who are responsible for the evacuation of at-risk residents

The WIFIRE Lab operates an all-hazards cyberinfrastructure that supports real-time simulation, prediction, and visualization of wildfire behavior. They operate as a neutral data resource for and partner to any proposed fire-related activity by adding value to the raw data, preparing real-time data for fire monitoring and performing fire modeling for research and operational use. WIFIRE's BurnPro 3D model supports "collaboration among land managers, burn bosses, plan-approvers, and policy-makers that will significantly increase the proactive application of fire in order to successfully combat devastating megafires[189]." Its Firemap model is "an operational tool for real-time environmental data visualization, fire behavior modeling and forecasting, and 'what-if?' analyses for potential fires[190]." WIFIRE is embedded in the Fire Integrated Real-time Intelligence System (FIRIS) Fusion Center, where all available information is integrated to "formulate the best inputs to an initial attack fire model[191]."

Benefits to Society

Firefighting efforts are highly successful in controlling wildfires; the National Forest Service reports that 97 percent of fires are contained before they exceed 300 acres in size. However, the remaining 3 percent of wildfires can be extremely destructive; the eight largest wildfires occurring between 2011 and 2020 caused damages of nearly $80 billion and led to the loss of 255 lives. GeoXO-enabled reductions in the number of low-probability, high-impact fires will generate significant benefits.

GeoXO-enabled improvements in identifying the location of wildfires will improve the initialization and results of wildfire spread models, leading to:

- fewer unnecessary evacuations (reducing costs),
- fewer at-risk residents left in harm's way (saving lives),
- improving firefighting efficiency by optimizing the location and allocation of firefighting resources (reducing the cost of response),

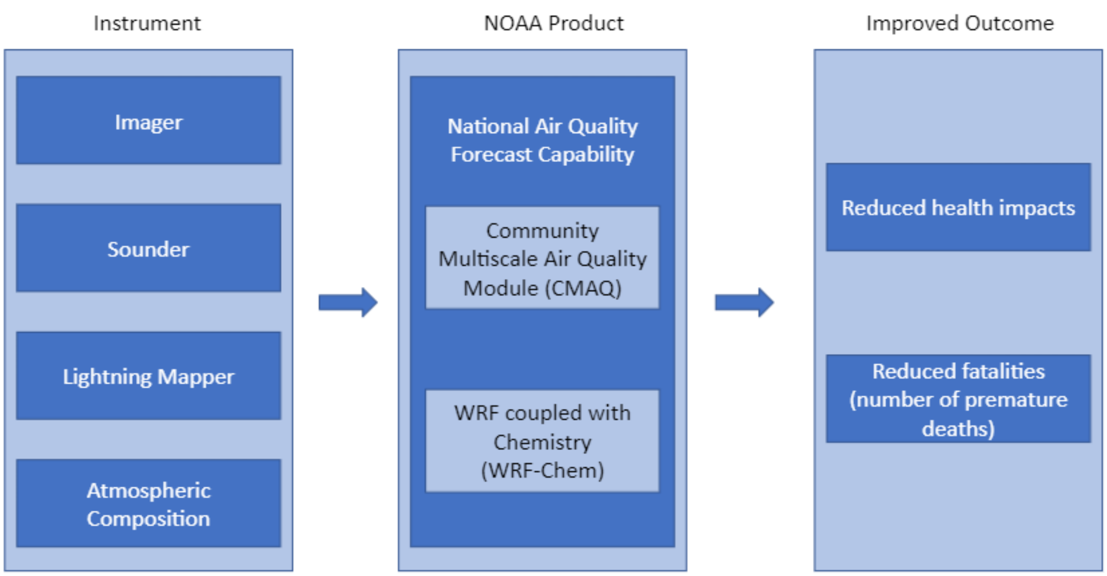
[189] WIFIRE Laboratory. Undated. BurnPro^{3D} Powered by WIFIRE Commons. Available at https://wifire.ucsd.edu/burnpro3d. Accessed May 10, 2022.
[190] WIFIRE Laboratory. Undated. Firemap. Available at https://wifire.ucsd.edu/firemap. Accessed May 10, 2022.
[191] WIFIRE Laboratory. Undated. FIRIS. Available at https://wifire.ucsd.edu/firis-in-depth. Accessed May 10, 2022.

- improving firefighting effectiveness (reducing the area burned and associated economic losses), and
- improving firefighter safety (saving lives).

Pathfinders: NYC Mayor's Office of Climate Resiliency, U.S. EPA

The figure below provides an overview of the GeoXO instruments with the potential for improving NOAA products that inform actions by the New York City Mayor's Office's inputs to protect the health and safety of citizens by reducing their exposure to poor air quality. The diagram is not meant to be comprehensive, but focuses on the content described in this section of the report.

GeoXO Value Chain: NYC Mayor's Office of Climate Resiliency



Product Background

NOAA's National Air Quality Forecast Capability (NAQFC) provides a foundation for official air quality forecasts provided by state and local government agencies. GeoXO AC observations will significantly improve NAQFC forecast guidance, providing a basis for enhanced evaluations of air quality, better constraints on emissions inventories, and better initialization by chemical data assimilation.

The NWS operational Community Multiscale Air Quality (CMAQ) model is a key component of NOAA's NAQFC. The OAR experimental, state-of-the-art Weather Research and Forecasting coupled with Chemistry (WRF-Chem) model simulates the emission, transport, mixing, and chemical transformation of trace gases and aerosols simultaneously with meteorology. The WRF-Chem model is used for investigation of regional-scale air quality, field program analysis, and cloud-scale interactions between clouds and chemistry[192], [193]. The CMAQ and WRF-Chem models both simulate photochemical smog and require emissions inventories of NO2, volatile organic compounds (VOCs), and other gaseous species to drive the photochemistry. The development of inventories needed for these models is a multi-year effort conducted by EPA. NOAA has developed capabilities to update inventories to more recent time periods using publicly available datasets, such as vehicle fuel consumption, chemical manufacturing output, and fossil fuel extraction activity [e.g., see Harkins et al., 2021[194]; Francoeur et al., 2021[195]; McDonald et al., 2018[196]]. Satellite data can also be used to update inventories, as shown by Tong et al., 2016[197].

Dependence on GeoXO

Studies are currently underway to assess the utility of GeoXO's atmospheric composition observations to public health officials in issuing air quality warnings and advisories. These studies will assess the ability of these observations to fill the huge spatial gaps in coverage that occur with the existing sparse network of ground-based monitoring, focusing on fine aerosol particles (PM2.5) and nitrogen oxide [see example of GeoXO-supported work at George Washington University described below].

NOAA's near-real-time updates to the atmospheric composition inventories developed by EPA and required as inputs for NOAA's CMAQ and WRF-Chem models currently rely on observations from polar-orbiting satellites, which make observations only once per day and therefore do not capture the diurnal variation of emissions in urban areas. With the upcoming

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[192] National Center for Atmospheric Research. Undated. WRF-Chem. Available at https://www2.acom.ucar.edu/wrf-chem. Accessed May 10, 2022.
[193] National Oceanic and Atmospheric Administration. Undated. Weather Research and Forecasting model coupled to Chemistry (WRF-Chem). Available at https://ruc.noaa.gov/wrf/wrf-chem/. Accessed May 10, 2022.
[194] Harkins, C., McDonald, B.C., Henze, D.K. and Wiedinmyer, C., 2021. A fuel-based method for updating mobile source emissions during the COVID-19 pandemic. Environmental Research Letters, 16(6), p.065018.
[195] Francoeur, C.B., McDonald, B.C., Gilman, J.B., Zarzana, K.J., Dix, B., Brown, S.S., de Gouw, J.A., Frost, G.J., Li, M., McKeen, S.A. and Peischl, J., 2021. Quantifying Methane and Ozone Precursor Emissions from Oil and Gas Production Regions across the Contiguous US. Environmental Science & Technology, 55(13), pp.9129-9139.
[196] McDonald, B.C., De Gouw, J.A., Gilman, J.B., Jathar, S.H., Akherati, A., Cappa, C.D., Jimenez, J.L., Lee-Taylor, J., Hayes, P.L., McKeen, S.A. and Cui, Y.Y., 2018. Volatile chemical products emerging as largest petrochemical source of urban organic emissions. *Science*, *359*(6377), pp.760-764.
[197] Tong, D., Pan, L., Chen, W., Lamsal, L., Lee, P., Tang, Y., Kim, H., Kondragunta, S. and Stajner, I., 2016. Impact of the 2008 Global Recession on air quality over the United States: Implications for surface ozone levels from changes in NOx emissions. Geophysical Research Letters, 43(17), pp.9280-9288.

launch of NASA's Tropospheric Emissions: Measurement of Pollution (TEMPO) satellite, NOAA will have hourly observations of pollutants like nitrogen dioxide that can be used to quantify the diurnal variation of emissions. GeoXO's atmospheric composition instrument will provide long-term operational observations to extend the benefits of TEMPO into the future.

Observations from three GeoXO instruments will provide information on atmospheric composition and, in particular, air quality: the imager, the sounder, and the atmospheric composition instruments. These observations are complementary in nature, with many capabilities requiring observations from two or all three instruments. The complementary nature of these observations means that the value of the whole is greater than the sum of its parts.

Users

NOAA provides air quality forecast guidance to the Environmental Protection Agency (EPA) and local government agencies, who monitor and forecast air quality, are responsible for issuing pollution alerts, and provide information that is needed to reduce public exposure to poor air quality and to reduce harmful economic impacts[198]. In the GeoXO Pathfinder effort, the New York City (NYC) Mayor's Office of Climate Resiliency and the EPA will provide a detailed description of how information provided by NOAA is scaled to fit the needs of NYC air quality warnings, addressing local tourism, recreation and quality of life.

Benefits to Society

More than 100,000 premature deaths occur annually due to exposure to elevated concentrations of ozone and fine aerosol particles like PM2.5[199]. These and other components of air pollution have myriad impacts on respiratory and cardiovascular health. In terms of fatalities, the impacts of poor air quality greatly exceed those of severe weather—in the United States, an average of 500 people die annually in weather-related fatalities (NWS, 2020b). Annual damages from the effects of air pollution are estimated to total nearly $1 trillion in the U.S. [e.g., see Goodkind et al., 2019[200]]. GeoXO's atmospheric composition capabilities will support improvements in air quality forecasts that can be used to reduce these very significant impacts. Even a marginal improvement to NOAA's air quality forecasts resulting from the inclusion of GeoXO observations could lead to more accurate air pollution alerts, with the

[198] More information about NOAA's efforts can be found at:
https://www.weather.gov/sti/stimodeling_airquality
https://airquality.weather.gov/
https://www.weather.gov/sti/stimodeling_airquality_faq

[199] Fann, N., Lamson, A.D., Anenberg, S.C., Wesson, K., Risley, D. and Hubbell, B.J., 2012. Estimating the national public health burden associated with exposure to ambient PM2. 5 and ozone. Risk Analysis: An International Journal, 32(1), pp.81-95.

[200] Goodkind, A.L., Tessum, C.W., Coggins, J.S., Hill, J.D. and Marshall, J.D., 2019. Fine-scale damage estimates of particulate matter air pollution reveal opportunities for location-specific mitigation of emissions. Proceedings of the National Academy of Sciences, 116(18), pp.8775-8780.

potential of reduced healthcare costs, improved economic productivity, and fewer premature deaths[201].

GeoXO observations will also support the improvement of other health outcomes related to:

- extreme temperatures
- urban heat islands
- harmful algal blooms

Pathfinders: The Nature Conservancy, Conservation International

When economic benefits of a proposed federal action accrue to other nations, OMB A-94 states that the CBA "should focus on benefits and costs accruing to the citizens of the United States" and that any benefits, costs, or other effects of the proposed action that fall outside the United States "should be reported separately."

This Pathfinder effort focuses on GeoXO's contribution to improving predictions of tuna stocks and migration, which might generate economic benefits accruing to citizens of the United States. However, the current focus of this Pathfinder effort reflects the international scope The Nature Conservancy and Conservation International's missions, focusing on the benefits accruing to Small Island Developing States. For this reason, no value chain has been developed for this Pathfinder effort. Although the effort is likely to significantly expedite the beneficial use of GeoXO data, this particular benefit will not contribute to the net benefits accruing to U.S. citizens.

It may be possible to formulate an alternative value chain that does focus on benefits to U.S. fishermen, fish processors, and U.S. consumers. At that point, a value chain could be developed for benefits that fall within the scope of CBA.

This Pathfinder effort focuses on the use of GeoXO's ocean color observations. Other benefits have been identified, such as those associated with Dynamic Ocean Management and WhaleWatch. These may also provide benefits of sufficient magnitude to warrant their inclusion in the final report as value chains and potential candidates for quantification.

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[201] Future studies should include a review of economic benefit estimation by EPA for the Clean Air Act. See, for example, https://www.google.com/url?q=https://www.epa.gov/clean-air-act-overview/benefits-and-costs-clean-air-act-1990-2020-second-prospective-study&sa=D&source=docs&ust=1652214469892870&usg=AOvVaw1TF_uyCu1psNRoluHFBXci. Perhaps comparable analysis could be performed for GeoXO.

Pathfinders: Virginia Emergency Operations Center, the Federal Aviation Administration, and Southwest Airlines

The benefits associated with this Pathfinder effort will be analyzed as part of the Aviation and Hurricane Evacuation value chains. For this reason, a separate value chain description has not been developed.

GeoXO ACX Valuation Study: Value of GeoXO atmospheric composition data for estimating air pollution-related health impacts

Researchers at George Washington University (GWU) studying the health impacts of air pollution among racially and economically disadvantaged populations have recently conducted several studies using NASA and ESA satellite data (OMI and TROPOMI NO2, surface PM2.5 products) to conduct environmental surveillance for environmental justice applications, including assessing persistent intra-urban disparities in NO_2 concentrations during COVID-19 lockdowns (Kerr et al. 2021) and in PM2.5 and NO_2-attributable health impacts (Southerland et al. 2021, Castillo et al. 2021). These studies have highlighted the important advantages of satellite remote sensing in estimating surface concentrations, including full geographical coverage, relatively high spatial resolution especially when paired with statistical downscaling methods, and long observational records. However, they have also identified key challenges when using satellite data for air pollution-related health applications, including the once-per-day flyover time which does not capture the full diurnal cycle of pollutants, the lack of speciated PM2.5 concentrations which vary at the neighborhood scale (e.g. black carbon), and potential upcoming gaps in the observational record if satellite sensors retire before new ones come online.

For GeoXO valuation study, the GWU team is evaluating the influence of remote sensing capabilities for assessing air pollution-related health impacts that may be possible with GeoXO. Specifically, aim to conduct health impact analyses for PM2.5, ozone, and NO2 from a range of synthetic geostationary satellite data and chemical transport model outputs to identify the benefits of GeoXO capabilities compared with datasets lacking GeoXO capabilities. Depending on resolution of the concentration data inputs, the study will also explore the distribution of estimated air pollution-attributable health impacts across population subgroups (e.g. by race, income level, educational attainment level, and/or social vulnerability indices).

In May 2022, the GWU team sent the findings of one study to the GeoXO team:

> ***Air pollution-related health benefits of geostationary atmospheric composition data; Part 1: Air quality alerts improved by additional spatial coverage from geostationary versus polar-orbiting satellites****; preliminary results, May 16, 2022*
>
> *Researchers: Susan Anenberg, Kate O'Dell, Dan Goldberg, Gaige Kerr - George Washington University, Milken Institute School of Public Health*

This research focused on the improved capabilities of a geostationary imager compared to the polar-orbiting imager, finding that these improvements will lead to the aversion of 300 premature deaths annually in California alone. The findings from this study have been incorporated into the final benefit estimates, as described below. Studies by the GWU researches to conducted later in 2022 will:

- Expand from California to the continental U.S.
- Expand from PM 2.5 to other air pollutants, including nitrogen dioxide (NO_2) and ozone.
- Consider additional years, as 2020 is likely an upper bound given the large wildfires experienced that year.
- Characterize improvements in air pollution injustice.
- Explore the sensitivity of estimated health benefits to different choices such as concentration-response functions.

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Section 3: Quantification of Benefits

Background

This section of the report describes the process of quantifying societal benefits of the GeoXO sensors and observations, including the methods, data, assumptions, limitations, and findings of the analysis. For this analysis, we developed value chains for observations focusing on those value chains:

- whose economic value is expected to be large
- for which linkages between GeoXO observations and improved societal outcomes is well-understood
- where data and methods were available to support the analysis.

A total of nine economic studies addressed 44 of the 175[202] value chains identified by the GeoXO team. It is important to note that, in most cases, the economic studies account for only part of the value indicated by the value chains. For example:

- cost-reduction benefits for aviation account only for reducing the cost of aircraft groundings due to severe weather and do not account for reducing delays associated with ramp closure due to lightning or rerouting aircraft due to severe weather along the route
- wildfire-related benefits to agriculture account only for reducing the impacts of smoke taint on wine grapes in California and not similar impacts on wine grapes grown elsewhere in the country or other wildfire-related losses to the agriculture sector
- wildfire-related benefits associated with reducing losses to real and personal property focus on reducing the incidence of wildfires whose losses exceed $1 billion, and do not include similar benefits for smaller, more frequently occurring wildfires
- hurricane benefits account only for reducing the cost of false positives and not reducing the cost of potential injury and loss of life associated with false negatives

The degree to which the total benefits of GeoXO are understated by these nine studies is unknown. On one hand, this analysis gave priority to instances where benefits are expected to be large. On the other hand, only a quarter of the value chains were analyzed and, in most cases, only part of the benefits could be estimated.

Estimating the economic benefits associated with any value chain requires a sound empirical basis. In most cases, this requires national-scale, time series data to characterize the baseline against which benefits are measured. For example, to estimate the benefits of reducing the cost of weather-related aviation delays, data on the frequency and cost of such delays are needed. To estimate national-scale benefits, these data must also be at the national scale. To account for upward or downward trends, time-series data are needed. The lack of such data is an

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[202] It is important to note that no value chains were developed for defense-related applications of GeoXO data and for use cases that primarily benefit other nations.

important limiting factor to both the number of value chains that could be analyzed and the accuracy, precision, and comprehensiveness to which benefits could be estimated.

The GeoXO mission will continue and expand observations provided by the GOES-R Series as NOAA's next generation of geostationary satellites. GOES-R provides observations from its imager and geostationary lightning mapper instruments. GeoXO will provide continuity to those observations and add observations from ocean color, atmospheric composition, and infrared sounder instruments. Without GeoXO, GOES-R capabilities would be lost. Thus, the benefits estimated in this analysis are attributable to both the continuation of GOES-R observations and the addition of new observational capabilities.

Benefit Assessment

The assessment of the benefits of the GeoXO observations was developed based on the following nine selected value studies:

1. Aviation
2. Electric power production
3. Air quality
4. Harmful algal blooms
5. Wildfire destruction
6. Wildfire suppression costs
7. Hurricane evacuation
8. Smoke taint
9. Radar Outages

The benefit assessments are informed by customer engagement activities conducted in 2020, benefit studies completed in 2021, and ongoing Pathfinder efforts. Important components of the analysis include an extensive literature review, the development of value chains that show how observations lead to improved outcomes, and consultation with experts to elicit the potential contributions of the GeoXO as a whole and of each instrument to the benefits that have been analyzed. The table below presents a summary of the findings and general assumptions for each value study. Detailed descriptions of each study are provided at the end of this section of the report, identifying specific data sources, assumptions, methods, and limitations of each study. Short summaries of each study are provided immediately below[203].

[203] The short descriptions of the nine benefit studies presented here are summaries of the detailed descriptions below. For this reason, no citations are provided here but the longer descriptions that follow include all the relevant citations.

Benefit Class	Benefit Description	Benefit Attributed to GeoXO	Annual Benefit ($ million)
Aviation	Reducing avoidable weather-related aviation delays	4% to 6% reduction	$101.2 to $151.8
Electric Power Production	Reducing error in energy demand forecasts that lead to under- and over-production of electricity	4% to 6% reduction	$40.7 to $137.4
Air Quality	Reducing premature mortality due to exposure to poor air quality	0.05 % to 0.1% reduction	$3,695.1 to 4,120.2
Harmful Algal Blooms	Reducing the economic losses associated with harmful algal blooms	5% reduction, applied to range of impacts ($105 million to $1 billion annually)	$5.3 to $50.0
Wildfire Destruction	Reducing the incidence of highly-destructive wildfires	1% to 5% reduction	$34.6 to $173.1
Wildfire Suppression	Reducing the cost of suppressing all wildfires	1% to 3% reduction	$18.7 to $56.1
Hurricane Evacuation	Reducing unnecessary hurricane evacuations	5% to 15% reduction	$11.7 to $35.2
Smoke Taint	Reducing the impact of wildfire smoke on wine grapes and winemaking in California	2.5% to 5% reduction	$0.8 to $1.6
Radar Outages	Reducing the losses associated with scheduled and unscheduled radar outages.	60% reduction applied to low and high incidence of outages	$13.0 to $18.0

Aviation

Weather-related aviation delays result in just over $20 billion of losses annually. Passengers bear more than half of the cost of aviation delays (e.g., the value of lost time), with the remainder falling on the airline industry and businesses who rely on air transportation. About $2.5 billion of those losses could be avoided with improved weather forecasting. GeoXO scientists estimate that the $2.5 billion of annual avoidable losses could be reduced by 4 percent to 6 percent by GeoXO-enabled improvements to forecasts of convection (both where storms will or will not form), low clouds and fog. A 4 percent reduction in avoidable aviation delays will result in savings of $101 million annually; a 6 percent reduction results in savings of $152 million annually. Over the 20-year operational life of GeoXO, this equates to discounted total benefits ranging from $0.5 billion to $1.6 billion. A number of other aviation-related benefits have not yet been quantified, including those associated with reducing the impacts of:

- rerouting flights,
- avoidable cancellations,
- turbulence,

- de-icing/in-flight icing,
- downburst associated with convection,
- reduced visibility due to dust or smoke and
- volcanic ash and SO2 associated with volcanic events.

Electric Power Production

Electric utilities use forecasts of temperature and atmospheric moisture as inputs to their “load forecasts” to minimize utility costs by determining the future consumption and the amount of electric power that will need to be produced. Over- and under-production both are costly, as utilities incur either the cost of producing electricity that won’t be sold or the cost of purchasing electricity on wholesale or spot markets (purchased at costs above the cost of production). The costs associated with load forecast error is about $2.5 billion annually[204]. Between 40 percent and 90 percent of load forecast error is attributable to error in weather forecasts, equating to costs of $1.1 billion annually and $2.3 billion annually, respectively. GeoXO scientists estimate these losses could be reduced by 4 percent to 6 percent by GeoXO-enabled improvements to forecasts of temperature and atmospheric moisture, equating to savings ranging from $41 million annually (a 4 percent reduction in weather forecast error, with weather forecast error accounting for 40 percent of load forecast error) to $137 million annually (a 6 percent reduction in weather forecast error, with weather forecast error accounting for 90 percent of load forecast error). Over the 20-year operational life of GeoXO, this equates to discounted total benefits ranging from $179 million to $1.4 billion. Other benefits to the electric power industry have not yet been quantified, including those associated with:

- accurate deployment of equipment and crews to restore power
- forecasting the availability of electricity from renewable sources
- the cost of maintaining unnecessarily high reserves to offset under-production by renewable energy sources

Air Quality

Numerical predictions of future air quality conditions are produced by NOAA’s National Air Quality Forecast Capability (NAQFC) for use by the U.S. Environmental Protection Agency and state and local agencies in providing air quality warnings that indicate elevated levels of ozone, particulate matter, and other atmospheric pollutants that are harmful to humans. The most recent modeling results available estimate that, each year, between 130,000 and 340,000 premature deaths in the United States are attributable to exposure to poor air quality. Applying current estimates of the value of a statistical life, this equates to economic losses of $1.4 trillion annually. GeoXO includes instruments that will enhance observations of ozone, PM2.5, and

[204] Computations based on findings presented in Anastasio, Elizabeth. (2017) Load Forecasting at PJM [Slides] retrieved 4/30/2020 from: https://www.pjm.com/~/media/committees-groups/committees/oc/20170110/20170110-item-06-load-forecasting-at-pjm.ashx.

other atmospheric pollutants and, in turn, the NAQFC predictions that rely on those observations and the air quality warnings that rely on NAQFC predictions. Improved air quality warnings (most applicable to this analysis, these correspond to fewer instances of failing to warn populations when air quality is hazardous) can reduce the associated number of premature deaths. Given the magnitude of the impact, just a modest reduction in premature mortality of 0.1 percent yields benefits of $1.4 billion annually. Over the 20-year operational life of GeoXO, this equates to discounted total benefits ranging from $6.2 billion to $14.4 billion. Other benefits of enhanced air quality observations have not yet been quantified, including:

- reducing the cost of false alarms
- better response to actual events with fewer false alarms
- fewer hospital visits
- other benefits of reduced morbidity

In May 2022, George Washington University (GWU) completed studies of the mortality reductions associated with the geostationary imager. Although the scope of this study is limited to the State of California, the benefits for California alone greatly exceed those based on the more conservative estimates used in the figures above. The benefit estimates were revised using findings from the GWU study to estimate benefits for the imager and using the more conservative estimates for other instruments (the sounder and atmospheric composition instruments also contribute to this benefit).

Incorporating findings from the 2022 GWU study (applicable to the imager and the State of California alone) yields benefits ranging from $3.7 billion annually to $4.1 billion annually. Over the 20-year operational life of GeoXO, this equates to discounted total benefits ranging from $16.2 billion to $41.7 billion.

Harmful Algal Blooms

When their numbers are high enough, several species of algae and cyanobacteria are toxic to humans and other organisms, producing a diverse array of negative impacts on human health, ecosystems, and the economy. The diversity of impacts from such events, referred to as “harmful algal blooms” (HABs), and their intermittent occurrence make it difficult to estimate average annual impacts. As a consequence, this analysis reflects the use of a broad range of values for estimating the impacts of HABs in the United States, ranging from $105 million to $1 billion annually. The ocean color instrument that is proposed for GeoXO has two advantages over existing observations from polar satellites: it will provide more observations (near-continuous vs. daily) and it will provide better observations (more spectral bands that provide more information about the presence and nature of organisms that cause HABs). This analysis assumes, with a more concrete study being developed, that the improved observations from GeoXO can reduce the effects of HABs on human health and the economy by 5 percent. For the lower bound estimate of impacts, a 5 percent reduction would yield benefits of $5.3 million annually. Over the 20-year operational life of GeoXO, this equates to discounted total benefits ranging from $21.3 million to $53.3 million. For the upper bound estimate of impacts, a 5 percent reduction would yield benefits of $50 million annually. Over the 20-year operational life of GeoXO, this equates to discounted total benefits ranging from $219.8 million to $506.5 million. Other benefits associated with improved ocean color observations have not been estimated, including those associated with:

- providing enhanced input to models used to estimate fish populations
- providing improved information for Integrated Ecosystem Assessments that inform catch limits set by fisheries councils (increasing the long-term sustainable yield of fisheries)
- providing information for the improved management of coral reefs where there's the potential for impact from sediment and turbidity
- increased fish catch in Hawaii during "cyclonic eddies" whose nutrient-laden upwellings attract fish
- enhancing the capabilities of Dynamic Ocean Management, which uses near real-time data to refine the spatial and temporal distribution of fisheries management actions

Wildfires: reducing the incidence of highly destructive fires

The National Forest Service reports that 97 percent of wildfires are contained before they exceed 300 acres in size but some fraction of the remaining 3 percent of wildfires have been extremely destructive. Since 1991, eighteen wildfires have caused in excess of $1 billion of losses each, with total losses of $103.8 billion and averaging $3.5 billion annually. GeoXO will provide enhanced hot spot detection, atmospheric moisture data, imagery, lightning observations, and other data such as wind forecasts that can increase the opportunities for early suppression of wildfires. Reducing the incidence of these extremely destructive fires by an assumed 1 percent would yield benefits of $34.6 million annually. Over the 20-year operational life of GeoXO, this equates to discounted total benefits ranging from $152.2 million to $350.7 million. Reducing the incidence of these extremely destructive fires by 5 percent would yield benefits of $173.1 million annually. Over the 20-year operational life of GeoXO, this equates to discounted total benefits ranging from $760.9 million to $1,753.5 million. These benefit estimates fail to account for several factors, all of which have the potential to increase GeoXO-enabled reductions of wildfire losses:

- accounting for the increased risk associated with climate change
- reducing loss of life
- reducing evacuation costs
- reducing losses from less destructive fires
- mudslides in areas of burn scar

Wildfires: Reducing the cost of suppression

The cost to federal agencies of wildfire suppression has averaged $1.9 billion per year over the past 20 years; this does not include costs to state and local governments, businesses, or individuals. GeoXO will provide enhanced hot spot detection, imagery, lightning observations, and other data such as atmospheric moisture or winds that can increase the opportunities for early detection and more efficient suppression of wildfires. Reducing the cost to federal agencies of suppressing wildfires by 1 percent would yield benefits of $18.7 million annually.

Over the 20-year operational life of GeoXO, this equates to discounted total benefits ranging from $82.2 million to $189.3 million. Reducing the cost to federal agencies of suppressing wildfires by 3 percent would yield benefits of $56.1 million annually. Over the 20-year operational life of GeoXO, this equates to discounted total benefits ranging from $246.5 million to $568.0 million. Other benefits associated with improved suppression of wildfires of all sizes[205] include:

- reduced losses of homes and forests to wildfires due to more effective suppression,
- reduced costs associated with evacuations as a result of reduced growth and size of wildfires.

Hurricane Evacuation

Since 1980, the 56 most destructive hurricanes have claimed almost 5,700 lives for an average of about 140 hurricane-related fatalities each year. To mitigate the loss of life associated with hurricanes, an annual average of almost 1 million people are evacuated at an annual average cost of $200 million. GeoXO will sustain and improve upon the current observations of hurricane location, vertical wind and temperature and moisture fields, along with the Sea Surface Temperature that are used in forecasts of hurricane tracks, intensity, wind fields, and storm surge that inform decisions by state and local governments who issue evacuation warnings and by residents deciding whether and how to comply with those warnings. This analysis estimates the benefits of GeoXO-enabled improvements in hurricane forecasts that reduce the number of persons evacuated without compromising human safety. A 5 percent reduction in evacuations would yield benefits of 11.7 million annually. Over the 20-year operational life of GeoXO, this equates to discounted total benefits ranging from $55.3 million to $122.6 million. A 15 percent reduction in evacuations would yield benefits of $35.2 million annually. Previous work on hurricane evacuations such as for the GeoXO hyperspectral sounder study establishes this percentage range as reasonable. Over the 20-year operational life of GeoXO, this equates to discounted total benefits ranging from $165.8 million to $367.7 million. A number of other benefits associated with GeoXO-enabled improvements to hurricane forecasts have not yet been quantified:

- reducing unnecessary business closures
- reducing unnecessary home and business protection costs
- reducing false negatives that leave people in harm's way, leading to loss of lives
- Reducing the impact on the travel and tourism industry
- hospital evacuations and other high-cost impacts
- due to the increased vulnerability of underserved populations, there may be significant equity gains associated with hurricane forecast improvements

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[205] These additional benefits are identified here because the other class of wildfire-related losses considers only those wildfires with losses exceeding $1 billion.

Smoke Taint

Smoke from wildfires reduces the value of wine grapes, producing undesirable flavors in wine that increase during fermentation and as wines age; the adverse effect of smoke on wine is called “smoke taint.” Insurance claims show that wildfires caused average annual losses of $32.3 million to growers of wine grapes in California between 2014 and 2021. GeoXO will provide observations that allow farmers to anticipate the density and spread of smoke from wildfires and, when grapes are sufficiently mature, to harvest them before they are damaged by smoke. Losses associated with the harvest of grapes that are not completely mature (this, too, affects the quality of wine and the cost of producing it) are less than those associated with smoke taint. This analysis assumes that all wildfire-related losses to vineyards is caused by smoke taint and that GeoXO observations can reduce these losses by 2 percent to 5 percent, with discounted total benefits between 2033 to 2052 ranging from $2.9 million to $16.4 million. Another benefit included in this study is associated with reducing the incidence of wildfires where total losses exceed $1 billion; information in the insurance claims upon which this analysis is based indicates that the benefits of reducing smoke taint are included in the benefits of reducing the incidence of wildfires whose losses exceed $1 billion. For this reason, the benefits of reducing smoke taint losses are not added to total GeoXO benefits but are reported separately to provide insights into this aspect of the larger benefit class and to Pathfinders in the wine industry. Other benefits associated with reducing the harmful effects of wildfire smoke on agricultural products include:

- benefits associated with wine grapes grown outside California
- benefits associated with the impacts of smoke on other agricultural products

Filling Gaps During Radar Outages

Radar improves weather forecasting, saving lives, preventing injuries, protecting property, and reducing the cost of false alarms. Outages in the U.S. radar network result in a loss of benefits, whether the outages are due to scheduled maintenance or equipment failures. GeoXO, along with radar systems located near radars suffering outages, will provide continuity of these benefits during radar outages. A 2019 study by Cho and Kurdzo estimated the value of the U.S. radar network, with separate values estimated for reducing the losses of tornadoes, flash floods, and wind; values estimated by Cho and Kurdzo consider only the reduction of fatalities and injuries and do not consider the value of reducing false alarms. Data from the NWS Radar Operations Center were used to determine the annual duration of radar outages at each radar site. The value of GeoXO in filling gaps in radar coverage during these outages was estimated by multiplying the percentage of time each radar was not operational by the total annual value of the radar; a poll of 20 meteorologists indicates the expectation that GeoXO observations will account for 60 percent of the value of filling these temporal gaps in radar coverage. The analysis was conducted using outage data for the years 2020 and 2021, yielding annual values of $18.0 million (2020) and $13.0 million (2021). Over the 20-year operational life of GeoXO, this equates to discounted total benefits ranging from $57.1 million to $182.4 million. A number of other benefits associated with GeoXO’s ability to fill radar gaps have not yet been quantified:

- providing observations for areas beyond the range of radar and where the view of radar is blocked by terrain
- increased frequency of observations for observations requiring multiple radar scans
- filling radar gaps in the offshore environment with benefits to mariners, fishermen, and recreational boaters
- improved prediction of storms originating in the offshore environment

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Benefit-Cost Comparison: GeoXO Constellation

The table below summarizes the results of the nine value studies that have been conducted for GeoXO. The "high" and "low" estimates should be considered to be the upper and lower bound of the most reasonable range of values[206] and not upper and lower limits. The present value of benefits represents high and low annual values, discounted using 3 percent and 7 percent discount rates, in compliance with guidance from the U.S. Office of Management and Budget[207]. The GeoXO team provided annual cost estimates throughout the GeoXO operational life. These values were also discounted using 3 percent and 7 percent discount rates to determine their present value for comparison with benefits. A more detailed discussion of the economic cost analysis is provided in Appendix 2.

In all cases, total benefits for the limited number of value chains that have been evaluated[208] in this study exceed costs, making a strong case for the economic viability of the GeoXO constellation as a whole.

	Annual Value, Millions of 2019 $		**Present Value, 2033 to 2052, Millions of 2019 $**			
			7 Percent Discount Rate		**3 Percent Discount Rate**	
Value Study	**Low**	**High**	**Low**	**High**	**Low**	**High**
Aviation	$ 101.2	$ 151.8	$ 476.0	$ 714.0	$ 1,055.9	$ 1,583.8
Electric power	$ 40.7	$ 137.4	$ 178.9	$ 603.9	$ 412.3	$ 1,391.7
Air Quality	$ 3,695.1	$ 4,120.2	$ 16,244.2	$ 18,113.0	$ 37,434.4	$ 41,741.0
Harmful algal blooms	$ 5.3	$ 50.0	$ 23.1	$ 219.8	$ 53.3	$ 506.5
Wildfire destruction	$ 34.6	$ 173.1	$ 152.2	$ 760.9	$ 350.7	$ 1,753.5
Wildfire suppression costs	$ 18.7	$ 56.1	$ 82.2	$ 246.5	$ 189.3	$ 568.0
Hurricane evacuation	$ 11.7	$ 35.2	$ 55.3	$ 165.8	$ 122.6	$ 367.7
Smoke taint	$ 0.8	$ 1.6	$ 3.6	$ 7.1	$ 8.2	$ 16.4
Radar outage	$ 13.0	$ 18.0	$ 57.1	$ 79.2	$ 131.6	$ 182.4
Total Benefits (9 value studies)	$ 3,921.1	$ 4,743.4	$ 17,272.6	$ 20,910.2	$ 39,758.3	$ 48,111.0
Total GeoXO Cost			$ 5,498.4	$ 5,498.4	$ 8,801.2	$ 8,801.2
Benefits/Costs			314%	380%	452%	547%

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206 Upper and lower bound estimates are based on the expert opinions of the GeoXO team, often informed by studies of the impacts of real or simulated data on model performance (OSEs and OSSEs). As noted elsewhere, a stronger empirical basis for the upper and lower bounds would improve the quality of this analysis.

207 See OMB Circular A-94, Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs and OMB Circular A-4, Regulatory Analysis.

208 Only 44 of the 175 value chains that were identified in this study are encompassed within the scope of the nine value studies that have been performed in this effort; in most cases, only part of the benefits associated with each value chain was quantified. It is important to note that GeoXO will provide new observational capabilities that are likely to lead to discoveries and additional beneficial applications.

Benefit-Cost Comparison by Instrument

Five instruments are included in current plans for the GeoXO constellation:

- Hyperspectral Infrared Sounder (“sounder”)
- Visible/Infrared Imager (“imager”)
- Atmospheric Composition
- Lightning Mapper
- Ocean Color

To assess the economic viability of each instrument, total benefits for the GeoXO constellation were attributed to the instruments that support these benefits. The following table shows each instrument’s share of benefits for the 9 cases listed above (rows sum to 100 percent). Instrument shares of total benefits are based on the input provided by the GeoXO team.

	Share of Total Benefits				
	Sounder	**Imager**	**Atmospheric Composition**	**Lightning Mapper**	**Ocean Color**
Aviation	40%	45%	0%	15%	0%
Electric power production	50%	50%	0%	0%	0%
Air quality	15%	40%	45%	0%	0%
Harmful algal blooms	0%	0%	0%	0%	100%
Wildfire destruction	10%	60%	20%	10%	0%
Wildfire suppression costs	10%	60%	20%	10%	0%
Hurricane evacuation	35%	50%	5%	10%	0%
Smoke taint	10%	60%	20%	10%	0%
Radar Outages[209]	0%	58%	0%	42%	0%

Applying these shares to the total of benefits that have been estimated for the GeoXO constellation yields instrument-specific benefit estimates that are shown in the tables below. Instrument-specific cost information was provided by the GeoXO team for comparison to benefits. Appendix B describes the methods and assumptions used to compute the incremental cost of each GeoXO instrument

[209] A poll of 20 meteorologists indicate that radar gaps (scheduled and unscheduled) will be filled by observations from the GeoXO imager (35 percent), lightning mapper (25 percent), and ground-based observations (40 percent). Thus, GeoXO benefits account for only 60 percent of the total benefits of filling radar gaps. The imager’s share of total benefits of 35 percent equates to 58 percent of GeoXO benefits (35 / 60); similarly, the lightning mappers share of total benefits of 25 percent equates to 42 percent of GeoXO benefits (25 / 60).

Sounder	Annual Value, Millions of 2019 $		Present Value, 2033 to 2052, Millions of 2019 $ 7 Percent Discount Rate		3 Percent Discount Rate	
	Low	High	Low	High	Low	High
Total Benefits (7 value studies)	$177.59	$379.11	$790.20	$1,681.40	$1,802.90	$3,845.20
Total GeoXO Cost			$871.60	$871.60	$1,335.90	$1,335.90
Benefits / Costs			91%	193%	135%	288%

Imager	Annual Value, Millions of 2019 $		Present Value, 2033 to 2052, Millions of 2019 $ 7 Percent Discount Rate		3 Percent Discount Rate	
	Low	High	Low	High	Low	High
Total Benefits (8 value studies)	$3,383.99	$3,576.82	$14,882.62	$15,736.19	$34,275.65	$36,228.74
Total GeoXO Cost			$3,259.60	$3,259.60	$5,360.80	$5,360.80
Benefits / Costs			457%	483%	639%	676%

Atmospheric Composition	Annual Value, Millions of 2019 $		Present Value, 2033 to 2052, Millions of 2019 $ 7 Percent Discount Rate		3 Percent Discount Rate	
	Low	High	Low	High	Low	High
Total Benefits (5 value studies)	$326.31	$679.65	$1,452.00	$3,014.40	$3,345.70	$6,945.90
Total GeoXO Cost			$256.10	$256.10	$405.50	$405.50
Benefits / Costs			567%	1177%	825%	1713%

Lightning Mapper	Annual Value, Millions of 2019 $		Present Value, 2033 to 2052, Millions of 2019 $ 7 Percent Discount Rate		3 Percent Discount Rate	
	Low	High	Low	High	Low	High
Total Benefits (6 value studies)	$28.03	$58.26	$124.70	$258.40	$280.70	$584.70
Total GeoXO Cost			$474.70	$474.70	$693.70	$693.70
Benefits / Costs			26%	54%	40%	84%

Ocean Color	Annual Value, Millions of 2019 $		Present Value, 2033 to 2052, Millions of 2019 $ 7 Percent Discount Rate		3 Percent Discount Rate	
	Low	High	Low	High	Low	High
Total Benefits (1 value study)	$5.19	$49.56	$23.10	$219.80	$53.30	$506.50
Total GeoXO Cost			$465.40	$465.40	$689.70	$689.70
Benefits / Costs			5%	47%	8%	73%

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Detailed Description of Value Studies

Aviation

Context and Analysis

An average of 442,000 flights annually were delayed between 2017 and 2019, at an annual cost averaging $31.0 billion, or $70,000 per delayed flight. These figures include costs to the airlines, passengers, and businesses relying on air transportation. About 67 percent of these delays and costs (296,000 flight delays costing $20.7 billion annually) were weather-related[210,211].

In their 2009 study, Klein and Lee[212] estimated that about 12 percent of weather-related delays in the United States could be avoided with perfect weather information[213]. Applying this to the figures above implies that improved weather forecasting can reduce the cost of weather-related airline delays by a maximum of $2.5 billion annually.

GeoXO will preserve the forecast improvements enabled by the GOES-R series and provide additional capabilities that will support further forecast improvements. For this reason, the total benefit of GeoXO is estimated as the sum of benefits associated with:

- preserving the gains enabled by GOES-R and
- enabling additional forecast improvements.

Subject matter experts from the GeoXO team estimate that GOES-R has reduced forecast error by 2 percent to 3 percent and that the additional capabilities of GeoXO compared to GOES-R will reduce forecast error by another 2 percent to 3 percent[214]. Thus, in preserving the gains in

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[210] Federal Aviation Administration. 2021. Air Traffic by the Numbers. Available at https://www.faa.gov/air_traffic/by_the_numbers/media/Air_Traffic_by_the_Numbers_2021.pdf. Accessed May 3, 2022.

[211] Federal Aviation Administration. 2020. FAA Administrator's Factbook. Available at https://www.faa.gov/sites/faa.gov/files/2021-09/2020_Administrators_Fact_Book.pdf. Accessed July 26, 2022.

[212] Klein, A., Kavoussi, S. and Lee, R.S., 2009, June. Weather forecast accuracy: Study of impact on airport capacity and estimation of avoidable costs. In Eighth USA/Europe Air Traffic Management Research and Development Seminar.

[213] The 2009 study by Klein and Lee compares delays resulting from the use of "a perfect weather forecast" --ex post "forecasts" constructed from data on actual weather conditions–with delays resulting from the use of the weather forecast that were provided to estimate the full impact of error in weather forecasting on flight delays. The current study estimates the benefit of improving weather forecasts by applying improvement factors to the avoidable portion of weather-related delay, estimated using the results from Klein and Lee.

[214] An important input to all benefit estimates is the degree to which GeoXO improves the societal outcome that is the focus of the benefit estimate. In most cases, the GeoXO team estimated the degree to which the product used to improve decision-making and, in turn, societal outcomes, assuming that the degree to which a product is improved equates to the degree to which the societal outcome is improved. In some but all not all cases, the expert opinion of the GeoXO team was informed by quantitative studies that assess the impact of real or simulated information on a product (OSEs and OSSEs, respectively). The quality of benefit estimates would be improved by further studies to quantify the degree of product

forecast accuracy enabled by GOES-R and enabling further gains in the future, GeoXO accounts for a 4 percent to 6 percent improvement in forecast accuracy compared to forecasts made without GeoXO capabilities.

Preliminary Benefit Estimates

Based on the information above, the benefits provided by GeoXO in reducing weather-related aviation delays are estimated to be:

- $101.2 million annually, corresponding to a 4 percent reduction in forecast error
- $126.5 million annually, corresponding to a 5 percent reduction in forecast error
- $151.8 million annually, corresponding to a 6 percent reduction in forecast error

Assuming that benefits from GeoXO are realized over the 20-year period between 2033 and 2052, the present value of benefits associated with GeoXO are estimated to be:

- $0.5 billion and $1.1 billion, corresponding to a 4 percent reduction in forecast error and discounted at 7 percent and 3 percent, respectively
- $0.6 billion to $1.3 billion, corresponding to a 5 percent reduction in forecast error and discounted at 7 percent and 3 percent, respectively
- $0.7 billion and $1.6 billion, corresponding to a 6 percent reduction in forecast error and discounted at 7 percent and 3 percent, respectively

Key Sources of Uncertainty and Variability

1. It is important to note that the 2007 study titled “An Investigation of the Economic and Social Value of Selected NOAA Data and Products for Geostationary Operational Environmental Satellites” (the “Bard study”) considered a 5 percent reduction in total weather-related aviation delays (vice the avoidable portion of those delays) to be “conservative” and used this value in their benefit estimates. In light of the 2009 study finding that only 12.2 percent of weather-related delays are avoidable with perfect weather information, the 5 percent reduction in total weather-related delays accounts for a 41 percent reduction in the avoidable portion of those delays (5 percent / 12.2 percent).
2. The Bard study considered a 13-year operational life, compared to the 20-year operational life considered for GeoXO. For this reason, the present value estimates developed in these two studies are not comparable.
3. Between 2015 and 2019, weather-related delays trended upward by about 10 percent annually. The figures above do not include projections of future increases in the number of weather-related flight delays. Including this trend would increase the benefits of GeoXO, but this enhancement to the analysis would be complex, requiring forecasts of the total number of flights and the future capacity of airports (increased capacity at airports reduces the time and cost of recovering from a delay event).
4. The benefit estimates described above do not include the benefits of reducing other weather-related costs to the aviation industry such as those related to:

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improvement and the corresponding improvement in societal outcomes associated with GeoXO observations.

a. rerouting flights,
b. turbulence,
c. visibility (due to fog or low stratus and/or smoke),
d. de-icing/in-flight icing,
e. microburst winds,
f. winds for flight planning, and
g. volcanic ash.

Reducing Load Forecast Error

Context and Analysis

Over the last 20 years, monthly retail sales of electricity to residential, commercial, and industrial users averaged just over 300 billion kilowatt-hours (KWH). Based on data from the PMJ[215],[216] regional electricity transmission organization, electric load forecasting error is 1.79 percent, or about 5.5 billion KWH monthly.

Electric load forecasting[217] errors lead to the over- or under-production of electricity. When electric utilities produce more electricity than is demanded by consumers, they incur the cost of producing electricity that cannot be sold at retail prices. In theory, some of that electricity could be sold to other utilities at wholesale prices (at about half of the retail price). However, when error in electric load forecasting is the result of weather forecast error (forecasts of temperature and humidity are key variables in load forecasting), other utilities using the same weather forecast to anticipate load are also likely to overproduce, limiting the opportunities to sell electricity in the wholesale market and, at least in theory, driving down the price that is offered.

When electric utilities produce less electricity than is demanded by consumers, they must purchase additional power in wholesale or spot markets. As with the overproduction of electricity, when load forecast error is a consequence of weather forecast error, multiple producers are likely to be affected similarly, increasing the demand for and price of electricity acquired in wholesale and spot markets.

Data from the Intercontinental Exchange (ICE) that were obtained from the Energy Information Administration (Department of Energy)[218] show the daily volumes of electricity traded on the

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[215] PJM Interconnection coordinates the movement of electricity through all or parts of Delaware, Illinois, Indiana, Kentucky, Maryland, Michigan, New Jersey, North Carolina, Ohio, Pennsylvania, Tennessee, Virginia, West Virginia and the District of Columbia. Source: https://www.pjm.com/about-pjm/who-we-are/territory-served

[216] Anastasio, Elizabeth. (2017) Load Forecasting at PJM [Slides] retrieved 4/30/2020 from: https://www.pjm.com/~/media/committees-groups/committees/oc/20170110/20170110-item-06-load-forecasting-at-pjm.ashx

[217] Load forecasts are used to minimize utility risks by determining the future consumption and the amount of electric power that will need to be produced.

[218] Data downloaded from https://www.eia.gov/electricity/wholesale/.

exchange and high, low, and weighted average prices. Adjusting these prices to 2019 price levels using the GDP deflator yields an average wholesale cost of electricity purchase through the exchange of $38.65/ MWH or $0.039/KWH.

In this analysis, the cost associated with overproduction is assumed to be equal to the cost of underproduction of electricity. The total annual cost of load forecast error is thus computed to be $2,543.9 million (5.5 billion KWH/month X $0.039/KWH X 12 months). The portion of the annual cost of load forecast error that is attributable to weather, ranging from 40 percent and 90 percent[219], equates to $1,017.5 million and $2,289.5 million, respectively.

Preliminary Benefit Estimates

GeoXO is expected to provide enhanced observations for critical inputs to electric power load forecasts (e.g., temperature and moisture). The GeoXO scientists estimate that these enhanced observations could improve the forecast by 4 percent to 6 percent resulting in the following estimated range of benefits.

A 4 percent improvement in the weather forecasts that support load forecasts will yield annual benefits of:

- $40.7 million annually (40 percent of error attributable to weather), for a present value from 2033 to 2052 of $178.9 million to $412.3 million, at 7 percent and 3 percent discount rates, respectively, assuming weather forecast error accounts for 40 percent of load forecast error
- $91.6 million annually (90 percent of error attributable to weather), for a present value from 2033 to 2052 of $402.6 million to $927.8 million, at 7 percent and 3 percent discount rates, respectively, assuming weather forecast error accounts for 90 percent of load forecast error

A 6 percent improvement in the weather forecasts that support load forecasts will yield annual benefits of:

- $61.1 million annually (40 percent of error attributable to weather), for a present value from 2033 to 2052 of $268.4 million to $618.5 million, at 7 percent and 3 percent discount rates, respectively, assuming weather forecast error accounts for 40 percent of load forecast error
- $137.4 million annually (90 percent of error attributable to weather), for a present value from 2033 to 2052 of $603.9 million to $1,391.7 million, at 7 percent and 3 percent discount rates, respectively, assuming weather forecast error accounts for 90 percent of load forecast error

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[219] Altalo, M.G. and Smith, L.A., 2004. Using ensemble weather forecasts to manage utilities risk. Environmental Finance, 20(October), pp.8-9. This article cites a 2003 study by NOAA titled “Northeast Energy Network Performance Analysis” as the source of these figures. Authors have been unable to locate the NOAA study that was cited. Source for 2004 article: https://www.lse.ac.uk/CATS/Assets/Documents/Altalo-Smith-Fcst-Ens.pdf.

Key Sources of Uncertainty and Variability

1. Figures for load forecast error are from a 2017 presentation by Elizabeth Anastasio on load forecasting by PMJ, which operates in a region extending from Virginia to New Jersey on the east to Tennessee to Illinois on the west. Load forecast error may vary in other regions.
2. Does not account for increasing future energy demands, which would increase benefits.
3. Figures for the weather-related component of load forecast error are from a study conducted by or for NOAA in 2003 (cited in the 2004 study by Altalo and Smith). The authors have been unable to locate the underlying research to determine the reason for the wide range of values cited (weather accounting for 40 percent to 90 percent of load forecast error). If the variability is driven by geography or seasonality, it would be possible to endogenize the information and reduce the range of values. Another issue is the fact that the title of the NOAA study indicates that this range may relate specifically to the northeastern United States; these figures could be different for other parts of the United States. Finally, the quality of weather forecasting has improved greatly since 2003, potentially reducing the degree to which weather forecast error contributes to load forecast error.
4. It is not clear that energy purchased to offset a shortfall in production can be obtained at the wholesale prices for which data are available; there are also spot and real-time markets, whose prices might differ significantly from wholesale prices (they are likely to be higher, which would understate the benefits described above).
5. The analysis above reflects long-term average wholesale prices but it is likely, as noted above, that production shortfalls caused by weather forecast error will lead to multiple buyers seeking energy at the same time, which could lead to higher prices and, in turn, benefits.
6. On a per-unit basis, the cost of underproduction is assumed to be equal to the cost of overproduction; future analysis should explicitly model the case of underproduction.
7. Electricity from renewable sources has a higher dispatch priority than electricity from non-renewable sources. For this reason, producers of electricity from non-renewable sources must also predict the amount of electricity that will be available from renewable sources (non-renewable production = demand - renewable production). It is unclear whether the forecast error cited by PMJ includes error in forecasting production from renewable sources.

GeoXO Benefits: Reducing Loss of Life due to PM2.5 and Ozone Exposure

Context and Analysis

NOAA's National Air Quality Forecast Capability (NAQFC) harnesses the advanced modeling capabilities of the National Weather Service and satellite observations to provide the U.S. with forecasts of ozone, particulate matter and other pollutants with enough accuracy and advance notice (48 hours) to take action to prevent or reduce adverse effects. These forecasts form the basis of air quality warnings issued by the U.S. Environmental Protection Agency and state and local air quality agencies.

A 2012 study by Fann et al[220] estimated that between 130,000 and 340,000 premature deaths in the United States are attributable to exposure to PM2.5 and ozone, with the majority of deaths associated with exposure to PM2.5. These findings are based on models that use air quality measurements from 2005. It is important to note that a/ air quality has improved since 2005 and b/ air quality forecasts do not eliminate exposure to poor air quality. In light of this, these estimates reflect very small improvements to mortality outcomes reported in Fann et al. Because the smaller mortality figures from Fann et al. (130,000 annually) are more commonly cited, that figure has been used in this analysis.

After the completion of this analysis, the authors found a 2018 study by Fann et al.[221] estimating that annual premature mortality due to exposure to PM2.5 has declined since 2005. However, Fann et al. 2018 estimates that exposure to PM2.5 led to 150,000 premature-related premature deaths in 2005, 124,000- deaths in 2011, and 121,000 deaths in 2014. Thus, the figures used in this analysis are consistent with the findings of Fann et al., 2018, while failing to account for likely future declines in such mortality. This should be considered in future studies.

"EPA recommends that the … [VSL] estimate of $7.4 million ($2006), updated to the year of the analysis, be used in all benefits analyses that seek to quantify mortality risk reduction benefits regardless of the age, income, or other … characteristics of the affected population[222]." Updating the VSL value recommended by EPA to 2019 price levels using the GDP deflator yields a value of $10.9 million. At this value for VSL, the economic losses associated with 130,000 annual premature deaths due to exposure to PM2.5 and ozone is $1.4 trillion annually.

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[220] Fann, N., Lamson, A.D., Anenberg, S.C., Wesson, K., Risley, D. and Hubbell, B.J., 2012. Estimating the national public health burden associated with exposure to ambient PM2. 5 and ozone. Risk Analysis: An International Journal, 32(1), pp.81-95. "We have estimated the recent burden of PM2.5 and ozone on human health in the United States, using ambient measurements, 2005 and nonanthropogenic background PM2.5 and O3 concentrations simulated by atmospheric chemistry models, and a health impact function. We find that between 130,000 and 340,000 premature deaths are attributable to PM2.5 and O_3."

[221] Fann, N., Coffman, E., Timin, B. and Kelly, J.T., 2018. The estimated change in the level and distribution of PM2. 5-attributable health impacts in the United States: 2005–2014. Environmental research, 167, pp.506-514.

[222] https://www.epa.gov/environmental-economics/mortality-risk-valuation#whatisvsl

Preliminary Benefit Estimates

GeoXO is expected to provide enhanced observations for both PM2.5 and ozone precursor gases, which can be used to improve warnings of poor air quality, reducing exposure and loss of life. A modest 0.1 percent reduction in loss of life yields benefits of:

- $1.4 billion annually, for a present value from 2033 to 2052 of $6.2 billion to $14.4 billion, at 7 percent and 3 percent discount rates, respectively, from a baseline of 130,000 deaths annually

An even more modest 0.05 percent reduction in loss of life yields benefits of:

- $0.7 billion annually, for a present value from 2033 to 2052 of $3.1 billion to $7.2 billion, at 7 percent and 3 percent discount rates, respectively, from a baseline of 130,000 deaths annually

Given the enormity of these values, more rigorous analysis is recommended to improve the empirical and methodological basis for these benefits. Most of the recommended analyses are not economic in nature but will provide vital inputs to the economic analysis. Recommendations for further research include:

- research on the response of mortality to improved air quality information including:
    - the causes of mortality from exposure to poor air quality, including mortality caused by both chronic and acute illness
    - the temporal distribution of mortality reductions (for mortality associated with chronic exposure to poor air quality, these benefits may not be fully realized for many years; conversely, the benefits could continue for many years beyond the life of GeoXO)
- the fractional or parameterized use of VSL to estimate the economic equivalent of premature mortality
- other methods for estimating the economic equivalent of premature mortality, e.g., Years of Remaining Life Lost

Despite the fact that many of these studies do not fall within the domain of economics, economists should be involved in their planning and execution to ensure the utility of findings as inputs to refined economic studies.

An important factor in the benefit estimates described above are estimates of the degree to which GeoXO-enabled improvements to air quality monitoring and forecasting can reduce mortality associated with exposure to poor air quality. At the time the analysis was initiated, no research had been conducted that provided estimates of these mortality reductions, so very small values of 0.1 percent and 0.05 percent were used in the initial analysis.

However, in May 2022, the results of a study by George Washington University (GWU)[223] became available. This study estimates the mortality reductions in California resulting from the use of imager observations from geostationary satellites to improve air quality monitoring and forecasting. The upper bound of the conservative estimates used in the initial analysis of a 0.1 percent reduction in mortality due to exposure to poor air quality equates to 130 lives saved annually at the national scale. The 2022 GWU study estimates that 300 lives will be saved annually in California alone, only considering the use of imager observations; GeoXO's sounder and atmospheric composition instruments will further enhance our ability to monitor and forecast air quality.

The following figures show the results of applying the mortality-reductions estimated in the GWU study to the imager and retaining the other, more conservative estimates for the sounder and atmospheric composition instruments. Thus, benefits for the imager are for California-alone; future studies by GWU that scale the results of their 2022 study to the national scale have not yet been completed.

Using values estimated for the imager based on the findings of the 2022 GWU study and the original results of the upper bound estimates for the sounder and atmospheric composition instruments yields benefits of:

- $4.1 billion annually, for a present value from 2033 to 2052 of $20.6 billion to $47.5 billion, at 7 percent and 3 percent discount rates, respectively.

Using values estimated for the imager based on the findings of the 2022 GWU study and the original results of the lower bound estimates for the sounder and atmospheric composition instruments yields benefits of:

- $3.7 billion annually, for a present value from 2033 to 2052 of $17.5 billion to $40.3 billion, at 7 percent and 3 percent discount rates, respectively.

The values that reflect the findings of the GWU study are reflected in GeoXO benefit totals throughout the remainder of this report.

Key Sources of Uncertainty and Variability

Findings from the 2022 GWU study show benefits for the State of California alone; national-scale estimates of the contribution of the imager to reducing air quality-related mortality are not yet available.

Findings from the 2022 GWU study imply that benefits for the sounder and atmospheric composition instruments are significantly understated; however, in the absence of research specifically focused on the contribution of these instruments to reducing air quality-related mortality, no changes have been made to the original analysis.

[223] Anenberg, S., O'Dell, K., Goldberg, D., Kerr, G. 2022. Air pollution-related health benefits of geostationary atmospheric composition data, Part 1: Air quality alerts improved by additional spatial coverage from geostationary versus polar-orbiting satellites. Results from unpublished research.

Many significant variables are either unknown or roughly estimated:

- Uncertainties in the linkage between GeoXO observations and premature mortality
    - The degree to which GeoXO observations will improve NOAA's National Air Quality Forecast Capability (NAQFC)
    - The degree to which improvements in NOAA's NAQFC translate into improved local warnings
    - The degree to which improved local warnings lead to reductions in loss of life
    - The preventable portion of lives lost due to exposure to poor air quality (is it theoretically possible to bring the number of deaths to zero?).
- Uncertainties in the linkage between loss of life and economic value
    - Although this analysis follows EPA policy in the use of VSL to estimate the economic value of mortality risk reductions[224], other measures could be more applicable to this scenario. Measures like "years of remaining life lost" (YRLL) account for the average years a person would have lived if they had not died prematurely. To apply YRLL to people of average health would require data on the age at which people die prematurely from exposure to poor air quality. These data are not currently available to NOAA analysts.
    - The underlying health conditions of persons dying prematurely from exposure to poor air quality is another important issue. If fatalities from exposure to poor air quality occur primarily among those whose health is significantly compromised, even YRLL measures may overstate the cost of premature death of persons not expected to live an average lifespan.
    - The cumulative effect of past exposure to poor air quality and the degree to which avoiding additional exposure to poor air quality will extend life expectancy.
- Relevant benefits that have not yet been quantified include:
    - reducing the cost of false alarms
    - better response to actual events with fewer false alarms
    - fewer hospital visits
    - other benefits of reduced morbidity

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[224] US Environmental Protection Agency, 2000. Guidelines for preparing economic analyses. Appendix B. Available at https://www.epa.gov/sites/default/files/2017-09/documents/ee-0568-22.pdf.

Harmful Algal Blooms

Context and Analysis

When their numbers are high enough, several species of algae and cyanobacteria are toxic to humans and other organisms, producing harmful human health, ecological, and economic effects. Such events are referred to as “harmful algal blooms” (HABs).

The ocean color instrument that is proposed for GeoXO has two advantages over existing observations from polar satellites: it will provide more observations (near-continuous vs. daily) and it will provide better observations (more spectral bands that provide more information about the presence and nature of organisms that cause HABs).

Many of the organisms that produce HABs move up and down in the water column over the course of the day. Since satellites observe conditions at the surface of the ocean, the near-continuous observations of a geostationary ocean color instrument will allow more accurate measurement of the extent and density of HABs than is possible with polar orbiting satellites that provide measurements once a day. GeoXO will also provide observations for areas not monitored by buoys and other in situ instruments.

More importantly, GeoXO will provide observations of HABs with much less interference by cloud cover. In the daily observations provided by polar satellites, large areas are obscured by clouds. The same is true for geostationary satellites but, because clouds are in constant motion, the areas obscured by cloud cover often can be observed minutes later.

In addition to providing near-continuous observations, individual observations from the ocean color instrument that is proposed for GeoXO will also provide better information on the presence and nature of organisms that cause HABs. Current polar satellites provide observations that produce false positives because other materials in the water cannot be distinguished from chlorophyll. The proposed GeoXO instrument includes more spectral bands, which will reduce false positives for chlorophyll and aid in the identification of specific harmful organisms, like cyanobacteria.

In 2020, Woods Hole Oceanographic Institute (WHOI) held a “Workshop on the Socio-Economic Effect of Marine and Fresh Water Harmful Algal Blooms in the United States[225].” This workshop found that, for a number of reasons, “arriving at a single annual estimate of [the effects of HABs] for the nation has been problematic.” These reasons include but are not limited to:

- the disparate physical characteristics of HABs, including their varying spatial scales, durations, movements and spread, and levels of toxicity
- the fact that different algal species produce toxins with different types of effects on humans, marine animals, and the ecosystems they inhabit

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[225] Woods Hole Oceanographic Institution, National Office for Harmful Algal Blooms. 2021. Proceedings of the Workshop on the Socio-economic Effects of Harmful Algal Blooms in the United States.

- inconsistent, uncoordinated, or non-existent reporting mechanisms and a resulting lack of available data on HAB effects
- the diversity of human contexts, including values, vulnerabilities, and feasible responses and adaptive capacities of individuals, families, and communities
- the variety of ways that human exposures to HAB toxins can, depending on how coastal, marine, or freshwater environments are used or enjoyed in any specific location (e.g., through “the consumption of shellfish or finfish or by drinking water, through contact with bare skin, or by breathing aerosols[226].”

The WHOI workshop concludes that much more research is needed to improve estimates of the impacts of HABs. Many of the existing studies focus on specific events, primarily those with large economic impacts. Collectively, the current body of research may not provide sufficient information to estimate the full range of economic effects. Assessing the benefits of GeoXO requires the use of average annual losses; event-specific studies are an important input into estimating average annual losses but information on the frequency of such events is also needed.

Given the limitations of the literature on the value of HAB impacts and the obstacles to addressing those limitations, this analysis assumes that the upper bound of published values cited in the WHOI proceedings ($105 million in 2019 dollars) represents a lower bound of the annual effects at a national scale and assumes an upper bound value of $1 billion.

Preliminary Benefit Estimates

With annual HAB impacts of $105 million, a 5 percent reduction of those impacts yields benefits of:

- $5.3 million annually, for a present value from 2033 to 2052 of $23.1 million to $53.3 million, at 7 percent and 3 percent discount rates, respectively.

With annual HAB impacts of $1 billion, a 5 percent reduction of those impacts yields benefits of:

- $50.0 million annually, for a present value from 2033 to 2052 of $219.8 million to $506.5 million, at 7 percent and 3 percent discount rates, respectively.

Key Sources of Uncertainty and Variability

The main source of uncertainty in these values is associated with measures of the economic impacts of HABs, which range from $105 million to $1 billion annually. The impacts are diverse in nature, including a number of health-related impacts and losses to commercial fishing, outdoor recreation, and tourism. Many of the studies to date have focused on the effects of specific events, occurring at a specific time and place. Due to the intermittent occurrence of HABs, their wide geographic distribution, and the diverse range of impacts, a significant amount

[226] Ibid.

of research is needed to make more accurate generalizations about their average annual economic impacts.

A second source of uncertainty is the degree to which improved observations can be used to reduce these impacts. The analysis reflects the assumption that GeoXO observations can be used to reduce impacts by 5 percent. Given expert testimony, this assumption is not unreasonable, but the true value of reductions and the mechanisms by which they occur should be further investigated.

Most of the measures undertaken to reduce the impacts of HABs result in some cost (e.g., beach closures and fisheries restrictions). Additional research on the nature and cost of measures undertaken to reduce the impacts of HABs would improve these benefit estimates.

Other benefits associated with reducing the impacts of HABs have not been estimated, including those associated with:

- reducing the cost of fish harvest (less time fishing where there are few fish due to HABs)
- providing enhanced input to models used to estimate fish populations
- providing improved information for Integrated Ecosystem Assessments that inform catch limits set by fisheries councils (increasing the long-term sustainable yield of fisheries)
- providing information for the improved management of coral reefs where there's the potential for impact from sediment and turbidity
- increased fish catch in Hawaii during "cyclonic eddies" whose nutrient-laden upwellings attract fish
- enhancing the capabilities of Dynamic Ocean Management, which uses near real-time data to refine the spatial and temporal distribution of fisheries management actions

Due to potential legal and regulatory implications of the assessment of benefits associated with the management of marine fisheries, this work should be led by NOAA Fisheries.

Additional Notes

Hoagland and Scatasta 2006 estimate the costs of HABs to be $97 million annually in the US, adjusted to 2019 price levels[227].

Costs to "Canadian Lake Erie Basin" estimated at $5.3 billion over 30 years ($176 million annually, 2015 prices)[228].

Hoagland et al. 2014 estimated the cost of illness only associated with Florida red tide to be $60,000 to $700,000 annually; discounted at 3 percent, the present value of the cost of future illness ranged between $2 million and $24 million[229].

Hoagland et al. 2009 found that the "capitalized estimated marginal costs of illness for ED respiratory illnesses associated with K. brevis blooms in Sarasota County, Florida, alone ranged from $0.5 to $4 million, depending on bloom severity[230]."

Kouakou and Poder 2019 looked at cost per incident of HAB impaired human health, based on 16 studies, most in the US. Findings: ". For digestive illness cost, we found $86, $1,015 and $12,605, respectively, for mild, moderate and severe cases. For respiratory illness, costs were $86, $1,235 and $14,600, respectively, for mild, moderate and severe cases. We used Quality-Adjusted Life Years (QALYs) to access the loss of well-being due to illness caused by HABs. We found that breathing difficulty causes the most loss of QALYs, especially in children, with a loss of between 0.16 and 0.771 per child. Having gastroenteritis could cause a loss of between 2.2 and 7.1 QALYs per 1,000 children[231].

For more information, see: Suddleson, M. and Hoagland, P., 2021. Proceedings of the Workshop on the Socio-economic Effects of Harmful Algal Blooms in the United States.

Wildfire: Extreme Loss Reduction

Context and Analysis

As noted elsewhere in this report, firefighting efforts are highly successful in controlling wildfires. The National Forest Service reports that 97 percent of fires are contained before they exceed 300 acres in size[232]. However, the remaining 3 percent of wildfires can be extremely destructive.

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[227] Hoagland, P. and Scatasta, S., 2006. The economic effects of harmful algal blooms. In *Ecology of harmful algae* (pp. 391-402). Springer, Berlin, Heidelberg.

[228] Smith, R.B., Bass, B., Sawyer, D., Depew, D. and Watson, S.B., 2019. Estimating the economic costs of algal blooms in the Canadian Lake Erie Basin. *Harmful Algae*, *87*, p.101624.

[229] Hoagland, P., Jin, D., Beet, A., Kirkpatrick, B., Reich, A., Ullmann, S., Fleming, L.E. and Kirkpatrick, G., 2014. The human health effects of Florida Red Tide (FRT) blooms: An expanded analysis. *Environment International*, *68*, pp.144-153.

[230] Hoagland, P., Jin, D., Polansky, L.Y., Kirkpatrick, B., Kirkpatrick, G., Fleming, L.E., Reich, A., Watkins, S.M., Ullmann, S.G. and Backer, L.C., 2009. The costs of respiratory illnesses arising from Florida Gulf Coast Karenia brevis blooms. *Environmental Health Perspectives*, *117*(8), pp.1239-1243.

[231] Kouakou, C.R. and Poder, T.G., 2019. Economic impact of harmful algal blooms on human health: a systematic review. *Journal of Water and Health*, *17*(4), pp.499-516.

[232] U.S. Forest Service. 2021. U.S. Department of Agriculture Forest Service FY2022 Budget Justification. https://www.fs.usda.gov/sites/default/files/usfs-fy-2022-budget-justification.pdf. Accessed January 4, 2022.

Since 1991, eighteen wildfires have caused in excess of $1 billion of losses each[233], with total losses of $103.8 billion and averaging $3.5 billion annually. It is important to note that many of the most destructive fires have occurred recently, with losses over the last five years averaging $13.7 billion annually. Researchers are studying the degree to which climate change is increasing wildfire risk. Although the more recent and much higher average annual losses may be more indicative of long-term wildfire risks[234], the computations below are based on the more conservative 30-year average.

The analysis that follows focuses on the contribution of GeoXO in reducing the number of wildfires causing $1 billion or more in financial losses. GeoXO is expected to yield other wildfire-related benefits not accounted for in this analysis:

- fewer unnecessary evacuations (reducing costs),
- fewer at-risk residents left in harm's way (saving lives),
- improving firefighting efficiency by optimizing the location and allocation of firefighting resources (reducing the cost of response, estimated separately),
- improving firefighting effectiveness (reducing the area burned and associated economic losses) for smaller wildfires, and
- improving firefighter safety (saving lives).

Grapes grown for winemaking are sometimes damaged by wildfire smoke (resulting in "smoke taint" that adversely affects the flavor of the wine), reducing the value of the grapes and rendering winemakers unable to satisfy contractual obligations for wine production. When these losses are associated with fires whose total financial losses exceed $1 billion, they are included in the totals below. Such extremely destructive wildfires are rare and, thus, the majority of losses associated with smoke taint are not reflected in the totals below.

The calculations below fail to account for several factors, all of which have the potential to increase GeoXO-enabled reductions of wildfire losses:

- accounting for the increased risk associated with climate change
- reducing loss of life
- reducing evacuation costs
- reducing losses from less destructive fires
- more completely accounting for smoke taint and other agricultural losses

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[233] NOAA National Centers for Environmental Information (NCEI) U.S. Billion-Dollar Weather and Climate Disasters (2021). https://www.ncdc.noaa.gov/billions/, DOI: 10.25921/stkw-7w73.

[234] See, for example, Axios. January 3, 2022. Climate scientists grapple with wildfire disaster in their own backyard. https://www.axios.com/climate-scientists-colorado-wildfire-disaster-56480c87-2058-4df9-9266-24911cb0842a.html. Accessed January 4, 2022. Referring to the late-December 2021 wildfires in Boulder County, Colorado, University of Colorado climate scientist Merritt Turesky stated that, "Climate change led to a perfectly built stack of fuels in the fireplace, ready and waiting to be burned. All it needed was a spark and someone/something to blow on it."

Preliminary Benefit Estimates

GeoXO will provide enhanced heat sensor data, imagery, lightning observations, and other data that can increase the opportunities for early suppression of wildfires. Heat sensor data are already used in wildfire spread models that allow firefighters to anticipate the need for suppression resources; improved data will enhance this capability.

Reducing the incidence of the most destructive wildfires[235] by 5 percent yields benefits of:

- $173.1 million annually, for a present value from 2033 to 2052 of $760.9 million to $1,753.5 million, at 7 percent and 3 percent discount rates, respectively

Reducing the incidence of these wildfires by 1 percent yields benefits of:

- $34.6 million annually, for a present value from 2033 to 2052 of $152.2 million to $350.7 million, at 7 percent and 3 percent discount rates, respectively

Key Sources of Uncertainty and Variability

Key sources of uncertainty include:

- the specific nature of observations and derived products that will contribute to improved outcomes
- the specific actions undertaken in response to improved observations and forecasts that have the potential to reduce losses

Key sources of variability include:

- the degree to which GeoXO improves upon existing observations obtained from GOES-R series satellites
- the degree to which early detection and improved wildfire spread models can reduce long-term losses (fuel and wind speed are important determinants of wildfire spread)
- the long-term impact of climate change on losses and loss-reduction benefits

[235] Those with financial losses exceeding $1 billion each.

Wildfire: Suppression Cost Reduction

Context and Analysis

For a number of years, the U.S. Forest Services has reported a 97 percent success rate in suppressing wildfires before they exceed 300 acres in size[236]. However:

- the remaining 3 percent of wildfires are often extremely destructive and
- the cost to federal agencies of fire suppression has averaged $1.9 billion per year over the past 20 years (does not include costs to state and local governments, businesses, or individuals).

This benefit assessment focuses on the ability of GeoXO to reduce federal firefighting costs by supporting early detection, enabling more accurate identification of areas of impact, and providing more accurate information for use in fire spread models[237].

NIFC publishes data[238] on wildfire suppression costs incurred by federal agencies for the years 1985 to 2019[239]. Since cost information published by the NIFC[240] are not adjusted for inflation, the reported values were converted to 2019 price levels using the GDP deflator. As noted above, inflation-adjusted federal suppression costs have averaged $1.9 billion annually over the past 20 years (2000 to 2019). Costs have been increasing, averaging $2.0 billion annually over the most recent 10 years and $2.4 billion over the most recent 5 years (2015-2019). It is important to note that firefighting costs for the record-setting 2020 fire season are not included in these averages.

The more conservative 20-year average is used in the analysis that follows, which focuses on the contribution of GeoXO in reducing federal firefighting costs.

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[236] See, for example, U.S. Forest Service. 2021. U.S. Department of Agriculture Forest Service FY2022 Budget Justification. https://www.fs.usda.gov/sites/default/files/usfs-fy-2022-budget-justification.pdf. Accessed January 4, 2022.

[237] There is no double-counting between the two wildfire-related benefit estimates. The benefits associated with reducing the incidence of extremely destructive wildfires accounts only for damage-reduction and does not account for suppression costs. Also note that, whereas the previous class of wildfire-related benefits was considered only extremely destructive wildfires, the benefits associated with reducing suppression costs consider the total cost of suppressing wildfires of all sizes.

[238] National Interagency Fire Center. 2020. Federal Firefighting Costs (Suppression Only). Available at https://www.nifc.gov/sites/default/files/document-media/SuppCosts.pdf. Accessed May 12, 2022.

[239] As of January 2022, the most recent year for which these data have been reported

[240] The National Interagency Fire Center, whose primary focus is on fighting wildfires, is a partnership of Bureau of Indian Affairs, Bureau of Land Management, U.S. Fish and Wildlife Service, National Park Service, USDA Forest Service, the National Association of State Foresters, the U.S. Fire Administration, and the National Weather Service.

Preliminary Benefit Estimates

GeoXO will provide enhanced heat sensor data, imagery, lightning observations, and other data that can increase the opportunities for early detection and more efficient suppression of wildfires. Heat sensor data are already used in wildfire spread models that allow firefighters to anticipate the need for suppression resources; improved data will enhance this capability.

Reducing the cost to federal agencies of suppressing wildfires by 1 percent yields benefits of:

- $18.7 million annually, for a present value from 2033 to 2052 of $82.2 million to $189.3 million, at 7 percent and 3 percent discount rates, respectively.

Reducing the incidence of these wildfires by 3 percent yields benefits of:

- $56.1 million annually, for a present value from 2033 to 2052 of $246.5 million to $568.0 million, at 7 percent and 3 percent discount rates, respectively.

Key Sources of Uncertainty and Variability

Key sources of uncertainty and variability include:

- the specific nature of observations and derived products that will contribute to improved outcomes
- the specific actions undertaken in response to improved observations and forecasts that have the potential to reduce losses
- the degree to which GeoXO improves upon existing observations obtained from GOES-R series satellites
- the degree to which early detection and improved wildfire spread models can reduce firefighting costs
- the long-term impact of climate change on losses and loss-reduction benefits

GeoXO is expected to yield other wildfire-related benefits not accounted for in this analysis:

- reducing the incidence of extremely destructive wildfires (benefits associated with reducing the incidence of the most destructive wildfires–those with losses exceeding $1 billion each–have been assessed separately),
- fewer unnecessary evacuations (reducing costs),
- fewer at-risk residents left in harm’s way (saving lives),
- improving firefighting effectiveness (reducing the area burned and associated economic losses) for smaller wildfires, and
- improving firefighter safety (saving lives).

Hurricane Evacuation: Reducing Unnecessary Evacuations

Context and Analysis

The economic and human impacts of hurricanes making landfall in the United States are concentrated in the 162 shore-adjacent counties between Virginia and Texas[241]. In 2019, the total population of these coastal counties was 35.4 million persons. On average, about 1 million residents of these high-risk counties evacuate their homes each year to avoid the threats to life and health posed by hurricanes[242].

Since 1980, 56 of the hurricanes making landfall in the United States caused economic losses exceeding $1 billion each. Nearly 5,700 persons were killed by these 56 storms. The disparity between the number of persons evacuating hurricane impact areas (1 million annually) and the number of persons killed by hurricanes (about 140 annually since 1980) suggests that improved hurricane forecasts could lead to an equal or greater degree of safety with far fewer evacuations[243].

The cost of hurricane evacuations in these 56 counties is just over $200 million annually. This estimate is based on a 2003 study by Whitehead that used surveys to examine the expenditures of households that evacuated from hurricanes occurring in years just prior to 2003. The values were updated to 2019 price levels and converted from a per household to per capita basis using the 2015 - 2019 measure of persons per household (2.62[244]).

The Whitehead study surveyed North Carolina residents and, thus, the results are most applicable to the evacuation costs in North Carolina. Many of the factors affecting evacuation costs vary based on location (accessibility to highway routes leading inland, the presence of large urban centers that can result in congestion that increases travel time and therefore costs, and the local cost of living). No adjustments were made to account for the potential variability in evacuation costs except in the Florida peninsula.

The Whitehead study found that residents who evacuated traveled an average of 110 miles inland. On the Florida peninsula, many residents must travel hundreds of miles before they can begin their journey inland. Evacuation costs for counties on the Florida peninsula were adjusted to account for the additional travel costs that residents incur[245]. This adjustment was applied

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[241] Although hurricanes make landfall all along the Atlantic coast, the frequency falls sharply north of Virginia. See https://www.noaa.gov/stories/what-are-chances-hurricane-will-hit-my-home.

[242] This value was estimated based on the 2019 population of each county, the annual probability that each county will be impacted by a hurricane rated as Category 3 or greater (most likely to trigger evacuation warnings), and the weighted average percent of compliance with evacuation orders (from Whitehead 2003).

[243] All figures in this paragraph are from NOAA National Centers for Environmental Information (NCEI) U.S. Billion-Dollar Weather and Climate Disasters (2021). https://www.ncdc.noaa.gov/billions/, DOI: 10.25921/stkw-7w73.

[244] https://www.census.gov/quickfacts/fact/table/US/HCN010212

[245] See data from the Florida Division of Emergency Management on “Regional Destination Rates” showing a strong preference for out of state evacuation destinations. Excluding residents who chose not

only to the components of the Whitehead costs that vary with distance traveled (direct travel expenses and time).

Forecasts of hurricane tracks, intensity, wind field, and storm surge are used to inform decisions by state and local governments who issue evacuation warnings and by residents deciding whether to comply with those warnings. GeoXO will enable the improvement of these forecasts while sustaining the forecast improvements enabled by the GOES-R series satellites that they will replace.

Preliminary Benefit Estimates

The figures above are based on actual hurricane return rates, the likelihood that evacuation orders will be issued, and the likelihood that residents will comply with evacuation orders. They do not account for the additional cost incurred as a consequence of forecast error. However, the cost-savings associated with reducing forecast error can be inferred from these estimates. Since evacuation orders are typically issued at jurisdictional levels (e.g., counties or municipalities), the incremental benefits of improved forecasting can be significant. When, for example, the area impacted by an evacuation order decreases from five counties to four counties (assuming a uniform population distribution), the number of evacuations and, thus, total evacuation costs could be reduced by 20 percent or more.

Future studies will be needed to improve our understanding of the relationship between the degree of forecast improvement and the degree of savings in evacuation costs. Since evacuation orders are generally issued by jurisdictional boundaries, improvements in forecast quality that result in a single jurisdiction (e.g., county) being excluded from an evacuation order can eliminate a large number of unnecessary evacuations. Preliminary estimates of the annual average reductions in evacuation costs enabled by GeoXO are assessed at 5 percent, 10 percent, and 15 percent reduction in evacuations:

- $11.7 million annually, corresponding to a 5 percent reduction in evacuations
- $23.5 million annually, corresponding to a 10 percent reduction in evacuations
- $35.2 million annually, corresponding to a 15 percent reduction in evacuations

Assuming that benefits from GeoXO are realized over the 20-year period between 2033 and 2052, the present value of benefits associated with GeoXO are estimated to be:

- $55.3 million and $122.6 million, corresponding to a 5 percent reduction in evacuations and discounted at 7 percent and 3 percent, respectively
- $110.5 million to $245.2 million, corresponding to a 10 percent reduction in evacuations and discounted at 7 percent and 3 percent, respectively
- $165.8 million and $367.7 million, corresponding to a 15 percent reduction in evacuations and discounted at 7 percent and 3 percent, respectively

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to evacuate to locations outside the planning region (presumably those who go to shelters), the preference to evacuate to out of state destinations exceeds preference for in-state destinations in all eight planning regions. A more refined estimate of evacuation costs in Florida could be determined by applying the actual rates of out of state relocation for each specific county. https://portal.floridadisaster.org/preparedness/RES/Studies/SitePages/RES.aspx.

Key Sources of Uncertainty and Variability

1. Since 1980, hurricanes have caused about 140 fatalities annually. This equates to an economic loss of $1.5 billion annually, measured using the value of a statistical life in 2019 dollars ($10.9 million). If GeoXO-enabled forecast improvements reduce mortalities by 5 percent (the lower bound considered in the analysis above), this equates to an annual benefit of $76 million and discounted benefits ranging from ~$350 million to ~$800 million. Although mortality-reduction benefits have not yet been rigorously estimated, their value could exceed that of reduced evacuation costs by a wide margin. Estimating the degree to which GeoXO-enabled forecast improvement could reduce hurricane-related mortality would require studies of a number of factors that contribute to hurricane mortality. Some residents, for example, are unable or unwilling to evacuate because they don't own an automobile, cannot afford the cost of evacuation, have physical disabilities that make evacuation more difficult. Variability in risk-aversion may also play a role.
2. The benefits identified here are limited to those occurring in shore-adjacent counties from Virginia to Texas, inclusive. Although the frequency of hurricane impacts declines significantly north of Virginia, it is likely that expanding the study area to include the entire Atlantic coast would significantly increase the magnitude of benefits shown here.
3. Nearly all the hurricane-related benefits shown in the 2007 study titled "An Investigation of the Economic and Social Value of Selected NOAA Data and Products for Geostationary Operational Environmental Satellites (the "Bard study") were those associated with reducing structure damage. The study shows a 9 percent reduction in these losses. The models that were used to estimate these values are not available and it's not clear how improved weather forecasting can lead to such reductions in physical damages. Major losses, like roof damage, water damage associated with roof damage, and the partial and complete destruction of structures by storm surge and waves are unlikely to be affected by short-term mitigating actions that are undertaken in response to weather forecasts. Assessing the benefits of short-term mitigation measures like boarding up windows and using sand-bags is complex; due to uncertainty, effective protection using these measures will require undertaking these actions many times to realize the benefits once (you never know which storm will blow debris through a window, so you have to board up windows with every storm).
4. The benefits associated with reducing evacuation costs in this analysis are similar to those estimated by the 2007 Bard study (with the added benefits of having full documentation of methods, assumptions, and computations).
5. These figures do not include projections of population growth in this region, which has grown significantly in recent decades and is likely to continue growing in the future.
6. The adjustment made for the additional trip distance for residents of Florida is based on data from the Florida Division of Emergency Management on "Regional Destination Rates" that show a strong preference for out of state evacuation destinations. The computations in this analysis reflect the assumption that all residents will evacuate to out of state destinations. A more refined estimate of evacuation costs in Florida could be

determined by applying the actual rates of out of state relocation for each specific county[246].

7. Other classes of hurricane-related losses/benefits that could be investigated:
    a. reducing unnecessary business closure
    b. reducing unnecessary home and business protection costs (expenditures at building supply stores, stocking up on groceries stores, etc.)
    c. reducing false negatives that leave people in harm's way
    d. the impact on the travel and tourism industry (with revenues of more than $200 billion annually, roughly half of which occurs between Virginia and Texas, inclusive)
    e. hospital evacuations and other high-cost impacts
    f. due to the increased vulnerability of underserved populations, there may be significant equity gains associated with hurricane forecast improvements

Smoke Taint in Wine Grapes

Context and Analysis

The analysis of benefits associated with reducing the incidence of the most destructive wildfires (those with losses exceeding $1 billion) includes agricultural losses. Analysis of the underlying data revealed that all wildfire-related losses to the wine industry are the result of wildfires whose total losses exceed $1 billion. Thus, the benefits described in this section represent a subset of those already reported for wildfire damage reduction.

Smoke from wildfires reduces the value of grapes and wine and poses health risks to harvest workers. This analysis focuses on the losses that occur when wine grapes are exposed to smoke, creating "smoky, burnt, ashy, …medicinal" or other undesirable flavors that reduce their value; this occurs when compounds in the smoke are absorbed directly into the grapes. The adverse effects of smoke on wine increase during fermentation and as wines age[247].

In California alone, growing grapes and producing wine contributes more than $100 billion annually to the national economy[248]. The economic impacts of smoke damage to grapes (called "smoke taint") can be significant; a recent lawsuit addresses a case in 2020 where smoke taint reduced the value of Cabernet Sauvignon grapes by 64 percent[249].

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[246] Florida Regional Planning Councils website, https://portal.floridadisaster.org/preparedness/RES/Studies/SitePages/RES.aspx#SFRPC. Accessed on March 4, 2022.

[247] The Australian Wine Research Institute. Undated. Smoke Taint. Available at: https://www.awri.com.au/industry_support/winemaking_resources/smoke-taint/. Accessed May 12, 2022.

[248] Wine Searcher. 2020. Fires Leave 2020 Vintage in the Balance. Available at: https://www.wine-searcher.com/m/2020/09/fires-leave-2020-vintage-in-the-balance. Accessed May 12, 2022.

[249] Wine Business. 2021. E & J Gallo Sues LMR Wine Estates for $420K Alleging Non Payment for 2020 Grapes. Available at: https://www.winebusiness.com/news/article/241300/. Accessed May 12, 2022.

When grapes are threatened by smoke, they can sometimes be harvested early to avoid such losses. The sugar content and therefore the value of the grapes harvested early will be lower, additional costs will be incurred in winemaking, and the value of the resulting wine might be lower, but these combined effects still yield a benefit when compared to economic losses associated with smoke-damaged grapes. Thus, GeoXO-enabled improvements in monitoring and forecasting the transport of smoke can reduce the economic losses associated with smoke taint.

Preliminary Benefit Estimates

The U.S. Department of Agriculture's (USDA) Risk Management Agency (RMA) publishes information on USDA crop insurance claims in its "Cause of Loss" dataset[250] that identifies, among other things:

- the reason for the loss (fire-related losses are identified),
- the type of crop (wine grapes are identified, distinct from "table grapes"),
- the amount of loss claimed, and
- relevant spatio-temporal information (i.e., state, county, year, month).

This analysis initially considered Cause of Loss data for the years 2000 to 2021. However, an examination of the data shows very few records for fire-related losses to wine grapes prior to 2014. The reasons for this are uncertain and could include increased incidence of wildfire due to climate change, temporal variability in wildfires unrelated to climate change, and changes in USDA insurance guidelines or loss classification systems.

Since the results of this analysis are a subset of those already estimated for reducing the incidence of the most destructive wildfires and are provided primarily to illustrate the potential value of GeoXO to winemaking, this analysis estimates average annual losses using data for the years 2014 to 2021–years when reported wildfire-related losses were most common. Thus, estimates described below may overstate losses and benefits unless the trends observed in recent years persist. Due to the high concentration of reported losses in California and the difficulty of confirming losses reported by USDA with wildfire activity, this analysis estimates only those benefits accruing to the wine industry in California.

Figures reported by the USDA were first adjusted to 2019 price levels using GDP deflators; this is consistent with all benefit and cost figures in this report, which are presented at 2019 price levels. Wildfire-related losses to wine grapes that were reported to the USDA totaled $259 million for the years 2014 to 2021, averaging $32.3 million annually.

As with estimates for reducing the highly destructive wildfires associated with these agricultural losses, this analysis estimates a range of benefits reflecting GeoXO-enabled loss reductions of 2.5 percent and 5 percent.

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[250] U.S. Department of Agriculture, Risk Management Agency. 2022. Cause of Loss Historical Data Files. Available at: https://www.rma.usda.gov/SummaryOfBusiness/CauseOfLoss. Accessed May 12, 2022.

A 2.5 percent reduction of impacts yields benefits of:

- $0.8 million annually, for a present value from 2033 to 2052 of $3.6 million to $8.2 million, at 7 percent and 3 percent discount rates, respectively.

A 5 percent reduction of impacts yields benefits of:

- $1.6 million annually, for a present value from 2033 to 2052 of $7.1 million to $16.4 million, at 7 percent and 3 percent discount rates, respectively.

Key Sources of Uncertainty and Variability

- The degree to which loss can be reduced (this analysis assumes loss reductions ranging from 2.5 to 5.0 percent)
- Uncertainty in interpreting and applying loss values reported in the USDA RMA data; the analysis could be improved by further investigating the reasons few wildfire-related losses were reported by the wine industry prior to 2014.
- The degree to which climate change accounts for increased reported losses after 2014 and the degree to which climate-related increases in loss will persist.
- Pathfinder representatives report other losses that would not be represented in the USDA RMA data; these include inability to fulfill contractual obligations and the loss of market share to wine producers from other nations. GeoXO is also expected to reduce the impacts of wildfires, which would increase the benefits of GeoXO to the California wine industry.
- Including other US states in this analysis would increase the magnitude of both impacts and benefits.

GLM Value Assessment: Filling Radar Coverage Gaps

Context and Analysis

Radar improves weather forecasting, saving lives, preventing injuries, protecting property, and reducing the cost of false alarms. In the United States, radar observations are provided by a network of more than 180 Weather Surveillance Radars (WSR-88D) and Terminal Doppler Weather Radars (TDWR)[251]. Outages within this network result in a loss of benefits, whether the outages are due to scheduled maintenance or equipment failures. GeoXO, along with radar systems located nearby, will provide continuity of these benefits during radar outages.

This analysis, much of which was conducted by NESDIS staff, estimates the value of GeoXO in providing continuity of benefits during radar outages. Cho and Kurdzo 2020 estimated the value of the U.S. radar system, with separate values estimated for reducing the losses of tornadoes, flash floods, and wind; values estimated by Cho and Kurdzo consider only the reduction of fatalities and injuries and do not consider the value of reducing false alarms. These values, presented at 2018 price levels, were adjusted to 2019 price levels using GDP deflators for

[251] Cho, J.Y. and Kurdzo, J.M., 2020. Weather radar network benefit model for nontornadic thunderstorm wind casualty cost reduction. *Weather, Climate, and Society*, *12*(4), pp.789-804.

consistency with other cost and benefit values in this study. Data from the NWS Radar Operations Center were then used to determine the annual duration of radar outages at each radar site. The cost of gaps in radar coverage during these outages was estimated by multiplying the percentage of time each radar was not operational by the total value of the radar. A poll of 20 meteorologists indicates that GeoXO will be used to fill 60 percent of these gaps in radar coverage, with the remainder filed by radar from nearby systems and other Earth-based observations. Thus, the benefit of GeoXO in filling these gaps in radar coverage is estimated to be 60 percent of the cost of coverage gaps. The analysis was conducted for radar outages that occurred in the years 2020 and 2021, yielding annual values of $18.0 million (2020) and $13.0 million (2021). These values were used as the high and low range of values in the calculations below.

Preliminary Benefit Estimates

Using radar outage data from 2021 yields benefits of:

- $13.0 million annually, for a present value from 2033 to 2052 of $57.1 to $131.6 million, at 7 percent and 3 percent discount rates, respectively.

Using radar outage data from 2020 yields benefits of:

- $18.0 million annually, for a present value from 2033 to 2052 of $79.2 million to $182.4 million, at 7 percent and 3 percent discount rates, respectively.

Key Sources of Uncertainty and Variability

- The degree to which radar outage data for the years 2020 and 2021 are representative of expected outages from 2033 to 2052.
- The accuracy of figures from Cho and Kurdzo 2019.
- This analysis considers only the use of GLM observations to fill radar gaps during outages for three applications: forecasting tornadoes, flash floods, and wind. Other benefits not included include:
  - filling gaps during radar outages, other applications
  - filling other radar gaps, e.g. offshore and areas with poor radar coverage
- GeoXO will complement radar systems in several other ways, generating additional benefits not quantified in this analysis:
  - The failure of the Cho and Kurdzo study to estimate the costs of false positives (and the associated GeoXO benefits of reducing false positives)
  - The current ground-based radar network does not provide full coverage of the U.S.; some areas lie beyond the range of radar and the view of others is blocked by mountainous terrain. The GeoXO will provide observations to fill radar gaps in these areas
  - Some radar measurements require multiple scans, increasing the time between observations. GeoXO’s near-continuous observations will reduce the time between observations.
  - Since radar units are located on land and their coverage quickly diminishes offshore, GeoXO observations will provide tremendous value in forecasting storms in the offshore environment. Many of these storms move to coastal areas where more than one-third of the U.S. population lives and where nearly half of the nation's gross domestic product originates [Source: OCM pocket guide]. Storms remaining offshore threaten marine transportation, commercial and recreational fishing, and offshore oil and gas production. GLM observations improve weather forecasts that protect our coastal populations, our national economy, and those working offshore.

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Appendix A: An Overview of Discounting

Discounting future benefits and costs to determine their value in today's dollars is a central feature of benefit-cost analysis. The total benefit of an investment is not simply the sum of benefits over the life of the project, nor is the total cost the sum of costs. This is so because a dollar received or paid in the future is worth less than a dollar received or paid now. Without discounting, comparing benefits or costs that are realized at different times is like adding apples and oranges.

Both households and businesses prefer to receive benefits sooner and pay costs later. This "time preference" for consumers can be thought of as their ability to earn interest by saving instead of spending; a dollar received today can be invested and that investment will be worth more next year and much more 20 years from now. The time preference for businesses is linked to their ability to grow their business by investing in it.

The body of research on discounting is vast and many issues are unresolved. However, for investments by the US federal government, the Office of Management and Budget (OMB) has estimated the "consumption rate of interest" (for households) to be 3 percent, based on the yield of risk-free bonds; OMB has estimated the "investment rate of interest" (for businesses) to be 7 percent, based on studies of the long-term productivity of capital. For benefit-cost analysis, OMB recommends that the value today of a stream of benefits or costs that are realized in the future be computed twice, once at a 3 percent discount rate and again at a 7 percent discount rate[252]. The consistent use of these two rates by federal agencies allows OMB to fairly consider tradeoffs between federal investments that provide a diverse array of goods and services, ranging from transportation and education to satellites, weather forecasting, and fisheries management.

The most typical pattern for federal investments is to incur costs up front and realize benefits later; thus, discounting typically has a more pronounced effect on benefits than on costs. To illustrate this point, consider a project that costs $1,000 annually for five years[253], after which time the project is complete and no further costs are incurred. Prior to its completion, the project provides no benefits. After its completion, it provides $300 of benefits[254] in each of the following 25 years.

In this case, the total cost of the project is $1,000/year X 5 years, or $5,000[255]. The total benefit of this project is $300/year x 25 years, or $7,500[256]. In a comparison of undiscounted benefits and costs, it appears that this project is worthwhile.

However, businesses use financial resources productively, with long-term gains of about 7 percent annually. For this reason, if a firm invests $935 today, next year that investment would

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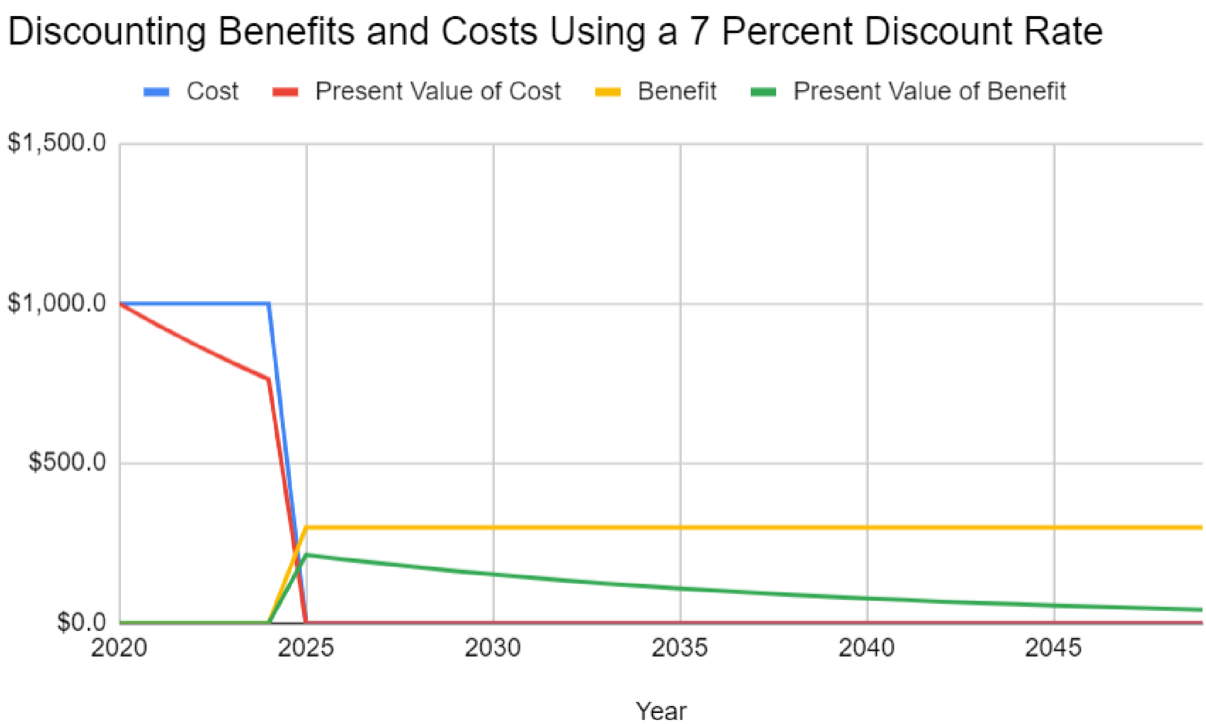
[252] White House Office of Management and Budget. 1992. Circular A-94: Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs. Available at https://www.whitehouse.gov/omb/information-for-agencies/circulars/. Accessed July 26, 2022.
[253] Expressed in today's dollars; that is, without inflation. OMB Circular A-94 recommends that economic analysis be conducted in "constant" dollars that do not include the effects of future inflation.
[254] Expressed in today's dollars.
[255] Expressed in today's dollars.
[256] Expressed in today's dollars.

be worth $1,000. Thus, for businesses, gaining $1,000 next year is the same as gaining $935 today. For the same reason, gaining $1,000 two years from now is the same as gaining $873 today; $1,000 three years from now is equal to $816 today; and so on.

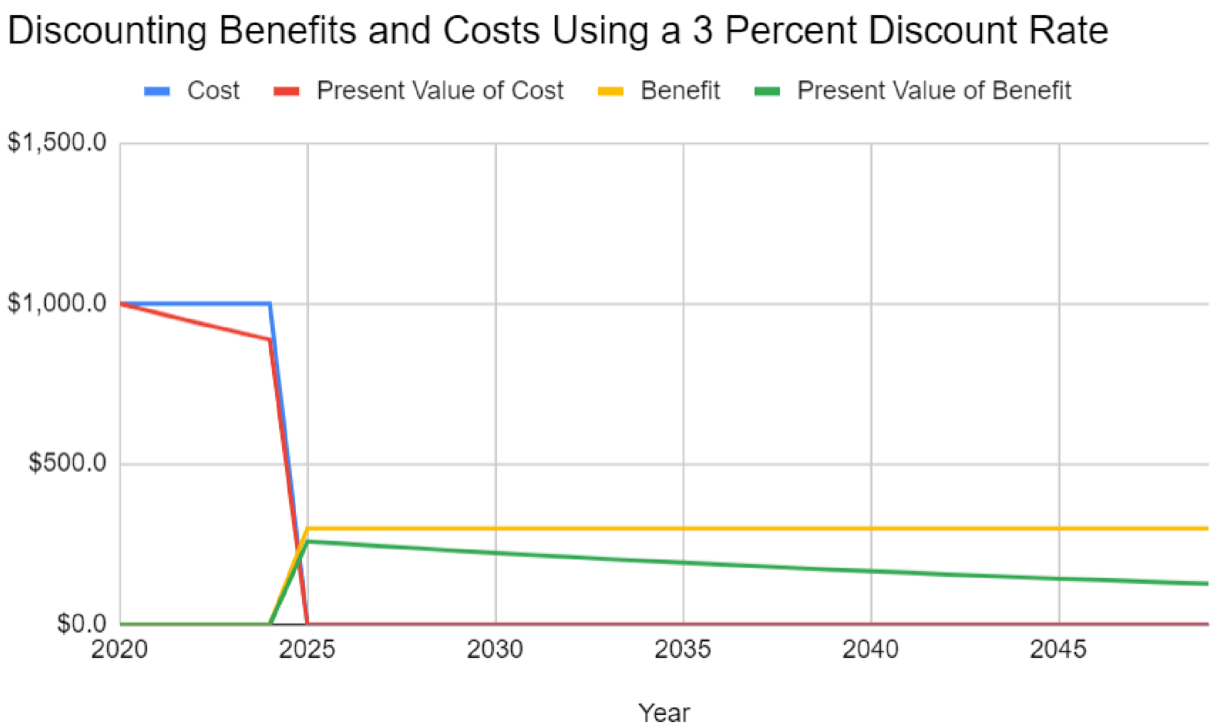
The figure below illustrates the effect of a 7 percent discount rate on the benefits and costs in this example. The total present value of costs and benefits is represented by the areas under the red and green curves, respectively.



Federal investments are funded through taxes on businesses and households. So far, this example examines the effect of discounting from the perspective of businesses that earn 7 percent annually on investments. A similar principle applies to households.

Individuals prefer to consume now rather than later. This is demonstrated by the fact that households defer spending to save only when they earn interest on their savings. The greater the risk involved in an investment, the greater the interest rate that is required to attract investors. Thus, to arrive at an appropriate discount rate to apply to households, the interest on government bonds with virtually no risk is used; for federal investments, this rate is assumed to be 3 percent. The lower discount rate has a less pronounced but nontrivial effect on future benefits and costs.

The figure below illustrates the effect of a 3 percent discount rate on the benefits and costs in this example. Again, the total present value of costs and benefits is represented by the areas under the red and green curves, respectively. The present value of benefits shown in the green curve declines moving further into the future, but not as much as with a 7 percent discount rate.



A summary of this information is provided in Table 1 below where it can be seen that this investment of $5,000 yielding future benefits of $7,500 is not worthwhile to either businesses or households.

Table 1. Summary of Costs and Benefits over 25-year Period[257]

	Undiscounted	Discounted at 7 percent	Discounted at 3 percent
Total Costs	$5,000	$4,387	$4,717
Total Benefits	$7,500	$2,667	$4,641
Benefits / Costs		0.61	0.98

[257] All values are expressed in today's dollars; that is, without inflation as recommended by OMB Circular A-94.

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Appendix B: Economic Cost Analysis

The economic feasibility of GeoXO is based on a comparison of its expected benefits over the life of the program with its expected costs. To ensure an apples-to-apples comparison of benefits and costs:

- all values reflect price levels at the same point in time (in this case, all benefits and costs are presented at January 2019 price levels)
- all benefits and costs are discounted to show their equivalent value in January 2019 (discussed below)

Discounting future benefits and costs to determine their value in today's dollars is a central feature of benefit-cost analysis. The total benefit of an investment is not simply the sum of benefits over the life of the project, nor is the total cost the sum of costs. This is so because a dollar received or paid in the future is worth less than a dollar received or paid now. Without discounting, comparing benefits or costs that are realized at different times is like adding apples and oranges. A brief overview of the ideas behind discounting and its effects is provided in Appendix A.

The cost estimates developed by the GeoXO team, totaling $18.6 billion, include projected inflation. Estimates that include inflation are needed for budgeting purposes but are not suitable for use in economic analysis. For this reason, the GeoXO team developed a second set of cost estimates that do not include inflation for use in the economic analysis.

The GeoXO teams are continuing to refine the specifications for each instrument to maximize the capabilities of the constellation as a whole. Each refinement has the potential to impact the final cost of GeoXO. This economic analysis reflects cost estimates dated December 2021, presented at 2019 price levels. After the effects of projected inflation are removed, the total cost of the constellation is shown to be $13.3 billion between FY2021 and FY2055.

Since benefit studies are presented by calendar year, the first step in the economic cost analysis was to estimate calendar year costs from the cost per fiscal year provided by the GeoXO team. This was accomplished by allocating 25 percent of fiscal year cost to the prior calendar year and the remainder to the current calendar year. For example, 25 percent of costs shown for FY30 are allocated to the year 2029 (representing costs incurred during October, November, and December of 2029), with the remainder allocated to the year 2030 (representing costs incurred from January to September of 2030). Using this approach to allocate all fiscal year costs to calendar years yielded equal total costs (thus, the approach accounts for all costs).

It is intuitive that it is better to receive benefits sooner and incur costs later; this is also supported by economic theory. To account for this time preference in an economic study, future costs and benefits are discounted to estimate their present value--today's value of benefits or costs realized in the future. The present value of a stream of future benefits or costs is less than the sum of those nominal values, with the difference increasing as costs and benefits are realized further into the future.

This preliminary analysis of benefits and costs has been conducted in a manner that will provide a foundation for future analysis that will be needed to support budget requests for GeoXO. Costs incurred prior to a future budget request will be considered "sunk costs" and will not be included in the analysis. For this reason, present value computations exclude costs incurred prior to the year 2024, accounting for less than 2 percent of the total cost of $13.3 billion. The present value of remaining costs is $5.5 billion, discounted at 7 percent, and $8.8 billion, at 3 percent. These are the values against which the present value of benefits will be compared.

Incremental costs and discounted costs are shown in the table below.

Item	Item Description	7 Percent (million)	3 Percent (million)
a	C60-76% CL (Imager, Sounder, LM, OC, AC)	$5,498.4	$8,801.2
b	C60-80% (Imager, Sounder)	$4,131.2	$6,696.7
Calculated, b - f	Incremental Cost of Sounder	$871.6	$1,335.9
c	C60-80% (Imager, AC)	$3,515.7	$5,766.3
Calculated, c - f	Incremental Cost of AC	$256.1	$405.5
d	C60-80% (Imager, OC)	$3,725.0	$6,050.4
Calculated, d - f	Incremental Cost of OC	$465.4	$689.7
e	C60-80% (Imager, LM)	$3,734.3	$6,054.4
Calculated, e - f	Incremental Cost of LM	$474.7	$693.7
f	C60-80% (Imager)	$3,259.6	$5,360.8

The GeoXO team provided costs used in the present value computations for items a through f. Incremental costs of specific instruments are estimated by subtraction as shown in the table above. However, the sum of costs for the imager (item f) and the Incremental costs for other instruments is less than the cost of the full system (item a). This is due to general cost increases associated with having additional instruments on a satellite (e.g., increased cost of communication systems, ground systems). The shortfall is about 5 percent of the total system cost. The estimates shown above will be used in the preliminary analysis but any analysis presented to OMB in the future should resolve this discrepancy.

The table below summarizes the findings of the cost analysis, organized by satellite configurations.

	Millions of 2019 Dollars	
GeoXO East and West	**7 Percent**	**3 Percent**
Imager Only	$3,259.6	$5,360.8
Lightning Mapper	$474.7	$693.7
Ocean Color	$465.4	$689.7
GeoXO Central		
Sounder	$871.6	$1,335.9
Atmospheric Composition	$256.1	$405.5