Technological Advancements Derived from NOAA Ocean Exploration's Competitive Grant Program

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Abstract—NOAA Ocean Exploration is dedicated to exploring the unknown ocean through scientific discovery, technological advancements, partnerships, and efficient data delivery. One mechanism NOAA Ocean Exploration uses to address this mission is by funding projects through its annual competitive grant program. Since 2001, the NOAA Ocean Exploration competitive grant program has supported more than 280 projects across themes including ocean exploration, technology, and maritime heritage. Through the competitive grant program, NOAA Ocean Exploration has funded diverse partners, including individuals across academia, private sector, tribal and Indigenous communities, and governmental entities, to fill gaps in our understanding of the ocean and Great Lakes.

By using diverse tools and technologies to explore previously unexplored areas of the ocean, competitive grant recipients have developed technologies and workflows to advance ocean sensing for a range of topics. Examples of recent projects include the development of novel *in situ* sensors (e.g., nitrogen and methane) in addition to advancements to technologies and workflows for environmental DNA (eDNA) analyses, including the development of an *in situ* water collection system for sampling microbes and eDNA from depths below 8,000 meters, and designing a framework for eDNA metabarcoding as a standard ocean exploration tool by quantifying, predicting, and testing the temporal persistence of eDNA in deep-sea environments.

Additional projects supported by NOAA Ocean Exploration's competitive grant program have developed and used novel acoustics systems to monitor midwater environments, including developing a towed system outfitted with a side-looking, split-beam echosounder for high-resolution acoustic and environmental sampling of midwater biomass; using of glider-mounted Acoustic Doppler Current Profilers (ADCPs) to detect and quantify midwater organism biomass and movement; and integrating high-resolution, wideband echosounders on ocean gliders with "on-board" data processing to adaptively monitor migrating mesopelagic organisms. These projects provide just a few examples of how NOAA Ocean Exploration's competitive grant program is supporting advances to ocean exploration and sensing.

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The work completed as a part of these projects can further serve to advance science in the field due to the program's efforts to improve data accessibility. In accordance with the 2013 and 2022 White House Office of Science and Technology Policy (OSTP) memorandums to increase access to the results from federally funded research, NOAA Ocean Exploration has partnered with NOAA's National Centers for Environmental Information (NCEI) to improve the data archival, accessibility, and discoverability of projects that have been funded through the NOAA Ocean Exploration competitive grant program. The data derived from grant-funded projects are made publicly accessible through PARR (Public Access to Research Results)-compliant, FAIR (Findable, Accessible, Interoperable, and Reusable) data repositories, allowing the public and scientific community to broadly benefit from the projects. As a part of this effort, NOAA Ocean Exploration and NCEI have developed project landing pages that provide a one-stop-shop for accessing project information, data and products generated by grant-funded projects, and data citation information. In this paper, we will discuss the breadth of work that has been funded through the competitive grant program, highlight several of the outcomes from previously funded projects, and provide information about how to access data from these projects. By promoting collaborative work through technological developments and advancements, NOAA Ocean Exploration's competitive grant program strives to better understand our changing environment and enhance appreciation of the importance of the ocean in our everyday lives and for the future.

Keywords—grant funding, technology, innovation, novel, in situ sensors, eDNA methodology, profilers, data accessibility, FAIR data principles, findable, accessible, interoperable, reusable, PARR compliance

I. INTRODUCTION

NOAA Ocean Exploration is dedicated to exploring the unknown ocean through scientific discovery, technological advancements, partnerships, and efficient data delivery. Continuing since its inception in 2001, NOAA Ocean Exploration has held an annual ocean exploration competitive funding opportunity soliciting and funding projects that advance ocean exploration, education, technology, and maritime heritage (program authority 33 USC 3403(a)). For the purpose of this paper, ocean exploration is defined to be multidisciplinary observations of unknown or poorly understood areas of the seafloor, sub-bottom, and/or water column, and an initial assessment of an area's physical, chemical, and biological characteristics [1]; education proposals as ones that solely address education and outreach activities for a broad range of audiences, typically aimed at K-12 graders; technology as proposals that create a new or novel use of existing ocean technologies or innovative methods that could increase the scope and efficiency of acquiring ocean exploration data and expanding their availability and use; and marine heritage proposals as ones that address the exploration and discovery of significant maritime heritage resources that improve historical knowledge and informs decisions.

Through its grant funding program, NOAA Ocean Exploration has funded diverse partners across academia, the public and private sectors, tribal and Indigenous communities, and non-governmental entities to fill gaps in our understanding of the ocean and Great Lakes [2, 3]. To date, this funding has supported over 668 discrete entities and 226 principal investigators (PIs) and has resulted in 282 projects funded within the representative themes of ocean exploration (n=148), education (n=18), technology (n=42), and maritime heritage (n=74) (Fig. 1).

Recipients of NOAA Ocean Exploration funding, use diverse tools and technologies to explore previously unexplored areas of the ocean and have developed novel technologies and workflows to advance ocean sensing for a broad range of topics. In recent years, there has been a particularly strong desire from the community to increase funding opportunities for technology innovation and advancement in ocean sciences with the proposal submissions for technology dwarfing the submissions for the ocean exploration and maritime heritage themes. Since fiscal year 2017 (FY17), 54% of projects have selected the technology theme during pre-proposal (letters of interest) submission (Table 1). Fiscal year spans from October 1 of the current year to September 31 of the following year.

In response to the increased submission of technology-themed projects, NOAA Ocean Exploration has steadily increased the number of projects funded in this theme, quadrupling the total number funded from FY 2019 to 2023 (Fig. 2). The priorities of these funded technology projects have spanned many topics - from developing novel *in situ* sensors, increasing the collection and utility of eDNA data, development and use of autonomous platforms, and developing and implementing innovative methods to analyze and increase the accessibility of existing archived data.

This paper will summarize some of the recent technological advancements, focusing on FY 2016 to 2018, that have been funded through the NOAA Ocean Exploration competitive grant program (i.e., novel *in situ* sensors, eDNA technological/ methodological advancements, and innovative tools to explore the water column - the least explored area of the planet [4]), in addition to outlining data accessibility through PARR (Public Access to Research Results)-compliant, FAIR (Findable, Accessible, Interoperable, and Reusable) data repositories. This paper is not inclusive of all the technological advancements. For more details about NOAA Ocean Exploration's funded projects

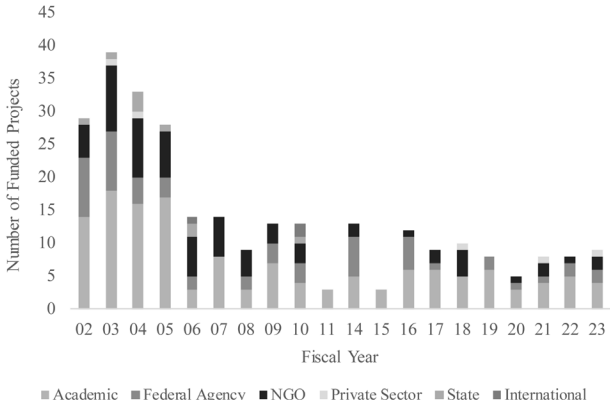

Fig. 1. Distribution of NOAA Ocean Exploration funding awards by sector (international, state, private sector, non-governmental organizations (NGOs), federal agencies, and academic institutions) from fiscal years 2002-2023.

TABLE I. NUMBER OF PRE-PROPOSALS SUBMITTED FROM FY 2017 - 2023 SEPARATED BY THEME

Theme	Fiscal Year[a]						
	17	*18*[b]	*20*	*21*[c]	*22*	*23*	*Total*
Ocean exploration	22	5	16	49	19	21	132
Maritime heritage	8	4	17	23	10	13	75
Ocean exploration, maritime heritage	1	4	4				9
Technology	17	18	26	49	23	28	161
Technology, maritime heritage	5	2	5				12
Technology, ocean exploration, maritime heritage	3	7	6				16
Technology, ocean exploration	27	19	21				67
Total	83	59	95	121	52	62	472

[a] Fiscal year spans from October 1 - September 31.

[b] FY19 was excluded from the table because it did not have standard themes to allow for comparison.

[c] Prior to FY21, proposals could select more than one theme option.

please visit https://oceanexplorer.noaa.gov/about/funding-opps/ffo-recipients.html.

II. TECHNOLOGY DEVELOPMENTS

A. *Novel* in situ *Sensors*

Recently, there has been a growing recognition of the need to develop low-cost sensor solutions to fill gaps in collecting deep-sea exploration variables [5]. In response, NOAA Ocean Exploration funded two projects, in FY 2016 and 2018, that focused on creating novel *in situ* sensors to advance data collection methods and answer a potential gap that currently exists in the deep sea.

For the first project (in FY 2016), PI Craig McNeil teamed up with Eric D'Asaro, Mark Altabet, and a commercial manufacturer to develop an *in situ* profiling sensor to record the nitrogen (N_2) gas within oxygen minimum zones (OMZs) in the deep ocean in order to quantify N-loss processes (Fig. 3). OMZs play important roles in regulating the ocean's global carbon and nitrogen cycles. In the functionally anoxic core waters of the OMZ, denitrifying and anammox microbes remove nitrogenous nutrients from the biosphere by transformation to biologically

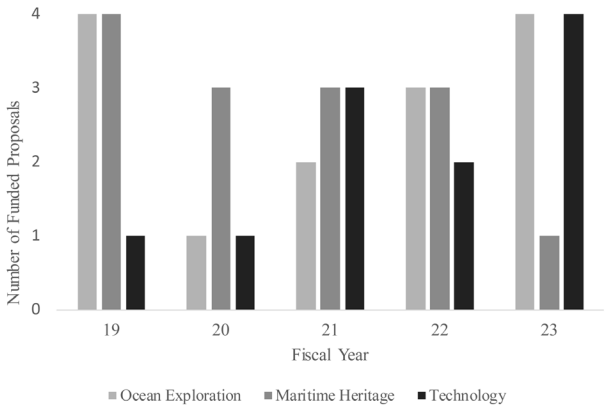

Fig. 2. Total number of NOAA Ocean Exploration-funded projects by theme (ocean exploration, maritime heritage, and technology) from FY 2019 to 2023.

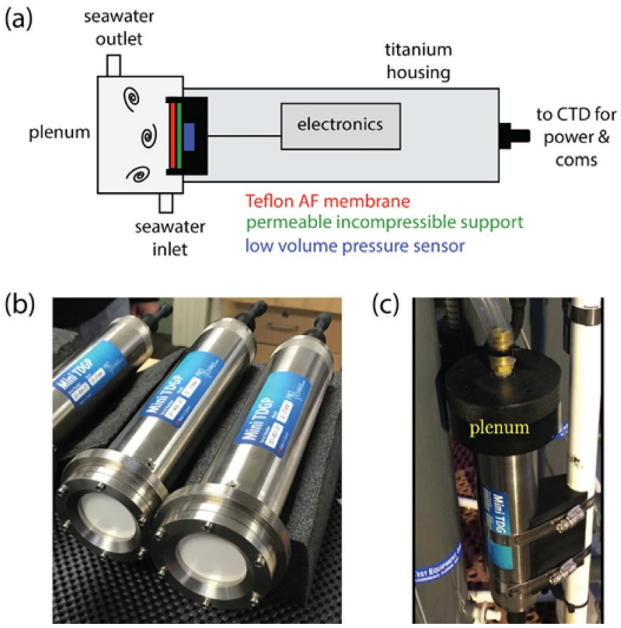

Fig. 3. Overview of the new fast response profiling gas tension device (GTD), showing: (a) schematic, with membrane interface located on one end of the pressure housing's end cap and enclosed by a seawater flushed plenum, the pressure housing, and connections; (b) photograph of three assembled sensors by Pro-Oceanus Systems Inc. (Bridgewater, NS, Canada); and (c) photograph of one sensor mounted on the ship's CTD (conductivity, temperature, depth) rosette. The supported membrane allows exchange of gases between the seawater and the low volume MEMS pressure sensor through a pneumatic port.

unavailable N_2. The new sensor that was developed incorporated reliable and proven technical advances in membrane and pressure sensor technologies. Compared to contemporary fast-response sensors [6, 7], the new sensor had low production cost and complexity, was significantly faster response in the mesopelagic zone (200 to 1000 meters below the surface), and could easily be added to any ship's CTD (conductivity, temperature, depth) rosette. This sensor was tested on two expeditions, including one on NOAA Ship *Okeanos Explorer*, and collected high-quality excess N_2 data in OMZs to document baseline excess N_2 inventories. The long-term goal of this project was to determine if excess N_2 inventories in OMZs are increasing as a result of ocean deoxygenation. The new sensor can be easily adapted for use on other profiling platforms (autonomous underwater vehicles (AUVs), remotely operated vehicles (ROVs), winched profilers, Argo-style floats [8, 9], etc.), and be used more widely to study air-sea gas flux and net community metabolism. More details on the developed sensor and results can be found in [10].

In FY 2018, a project, led by Anna Michel and Jason Kapit, was funded to design, develop, and field test a miniature ultrasensitive dissolved gas sensor that can measure methane (CH_4) *in situ*, utilizing an optical absorption gas detection technique [11]. This sensor was developed for deepwater applications and allowed scientists to measure these important gasses without the need for physical samples (Fig. 4). The sensor was low-cost (under $15,000) and designed for deployment using a range of platforms including ROVs, AUVs, landers, and surface vehicles. During field tests in the Gulf of California, the

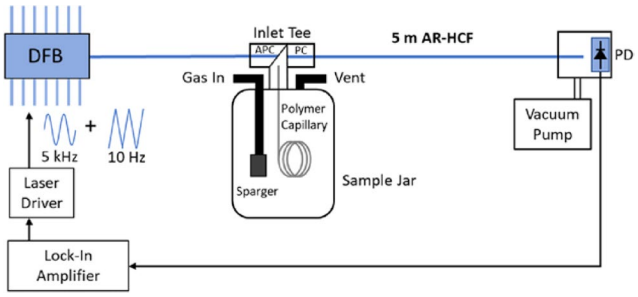

Fig. 4. Diagram of the miniature ultrasensitive dissolved gas sensor setup. Blue lines—optical fiber; Black lines—electrical connections. Light from a 1650.9 nm distributedfeed-back (DFB) is coupled to a 5 m anti-resonant hollow-core fiber (AR-HCF) via an inlet tee. A Teflon AF polymer capillary is also attached to the inlet tee to extract dissolved gas from a solution in a sample jar. The light and the gas exit the AR-HCF in a sealed cell containing a photodiode (PD), and a vacuum pump lowers pressure at the fiber output. A lock-in amplifier provides a laser modulation signal and extracts the 2f signal output. For a dissolved gas measurement, the sample jar is filled with water, and sample gas is bubbled in until equilibrium is reached. A vent on top of the jar allows the sample gas to escape so the pressure in the jar remains at 1 atm (adapted from [12]).

team secured the instrument in separate trials to an AUV, a CTD rosette, and a ROV. They then evaluated their instrument's methane-sensing capabilities by taking measurements at a hydrothermal vent outlet, the base of a collection of tube worms, and other biological and geological sites. Operating this sensor on an AUV enabled three-dimensional chemical mapping of CH_4 in the deep ocean. The team has continued to test the methane sensor opportunistically on other oceanographic research expeditions, deploying the sensor on ROVs, human occupied vehicles (HOVs), and AUVs. Future plans include augmenting the sensor to also measure other important gasses including: CO_2, N_2O, NO, NH_3, and H_2S. More details on the sensor design can be found in [12].

B. eDNA Technological/Methodological Advancements

With the growing interest in improving genetic libraries for species-level environmental DNA (eDNA) analysis of deep-sea species, PIs Santiago Herrera and Jill McDermott were funded in FY 2018 to develop a framework to establish eDNA metabarcoding as a standard ocean exploration tool that enables rapid, economic, and comprehensive diversity assessments of deepwater fauna. While eDNA is an emerging non-invasive methodology for capturing and sequencing this DNA to rapidly explore and characterize biodiversity of an area, there are two urgent challenges to interpret eDNA sequence data obtained from deep seawater samples: 1) understanding the temporal persistence of eDNA in the environment and 2) performing taxonomic identification assignments for eDNA metabarcode sequences. To address these critical challenges that limit the use of eDNA approaches in deepwater ecosystems, this work: 1) developed a general empirical model to predict the temporal persistence of eDNA in seawater under a range of deepwater environmental conditions [13]; 2) developed a new probe-set to enrich and sequence coral DNA from eDNA samples [14]; 3) improved the DNA barcode databases for corals and fishes from the Gulf of Mexico and the southeastern U.S. Exclusive Economic Zone (EEZ) [15] and; 4) explored biodiversity in unknown or poorly known areas in the Gulf of Mexico and the southeastern U.S. EEZ through new *in situ* sampling technologies [16]. While this project to advance eDNA as a tool for exploration in deepwater environments is still ongoing, the development of this technology will greatly enhance the ability to explore the ocean, and more specifically, results from this project will be directly applicable to the management and conservation of areas currently being considered for protection as part of the proposed expansion of the Flower Garden Banks National Marine Sanctuary.

C. Innovative Tools to Explore the Water Column

The water column, from the ocean's surface to the seafloor, is the largest and least explored area on the planet [4], which has led to the impetus to develop novel, low-cost tools to explore this challenging environment. In FY 2017, NOAA Ocean Exploration funded the integration of a side-looking split-beam multi-frequency echo-sounder (Simrad EK80) into the Wire Flyer towed profiling vehicle (Fig. 5) for the purpose of providing unprecedented acoustic and environmental sampling resolution of midwater biomass (led by PI Christopher Roman). The Wire Flyer is a ship-towed autonomous profiling vehicle that slides up and down on a standard towed 0.322 cable using controllable wings for propulsion. This vehicle is able to profile at commanded vertical speeds between 0 and about 2.5 meters per second while being towed at a speed of between 3 to 4 knots. The system can operate over specified depth bands in the water column (e.g., 400 to 800 meters) and is not restricted to the upper few hundred meters like other towed undulating systems. The project was able to exploit the high spatial-resolution sampling capability of the Wire Flyer vehicle and provide complementary acoustic data in regions of the water column that have been traditionally under-sampled. More details of this integration and the data collected can be found in [17].

An additional technological advancement and ocean exploration project was funded in FY 2018 (led by PI Kevin Boswell) to explore migrating scattering layers (SLs) in the water column through multiscale-multimode technologies in the Gulf of Mexico. This project addressed sampling resolution constraints in the deep-sea by providing multi-scale observations of migrating SLs, obtaining simultaneous measurements of individuals through aggregation dynamics using a suite of sensors on autonomous platforms. Mesopelagic communities in the Gulf of Mexico were explored using emerging acoustic and optical sensors on autonomous platforms to discover the dynamics of these animal communities within the complex oceanography of the Gulf of Mexico. Boswell and team 1) integrated a high-resolution, wideband echosounder within an ocean glider to explore migrating animals within

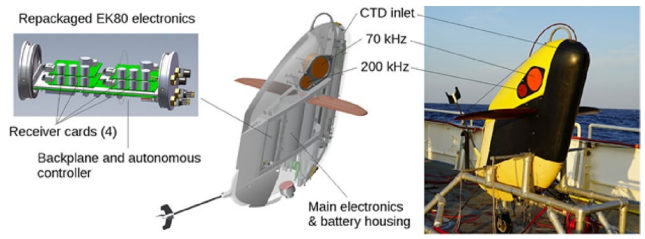

Fig. 5. Wire Flyer mechanical details showing the repackaged of split-beam multi-frequency echo-sounder (Simrad EK80) electronics (left), the transducers inset into the foam flotation on the top of the vehicle (middle), and a photo of the Wire Flyer at sea (right). The oxygen sensor and fluorometer are mounted on the port side of the vehicle, out of view in this image (adapted from [17]).

mesopelagic SLs; 2) developed "on-board" acoustic data processing to facilitate adaptive exploration of migrating SL communities; and 3) integrated a swarm of high-resolution autonomous optical profilers to derive non-invasive *in situ* validation of individuals comprising migrating SLs. More details regarding the integration of high-resolution, wideband echosounders on ocean gliders with "on-board" data processing to adaptively monitor migrating mesopelagic organisms can be found in [18].

III. Data Accessibility

The data, and data access, resulting from these projects is equal in importance to the developed and implemented technologies. The NOAA Ocean Exploration competitive grant program supports advances to science in the field through the program's efforts to improve data accessibility to the public and scientific community. Consequently, NOAA Ocean Exploration requires that a data and information sharing plan [19] is included in the proposal submission and that all the data collected and products developed during each awarded project are PARR-compliant and FAIR. PARR is the abbreviated name for the White House Office of Science and Technology Policy (OSTP) Memorandum Increasing Access to the Results of Federally Funded Scientific Research, issued in 2013 [20]. The Core Principles of the NOAA PARR Plan are that: publications and environmental data funded through taxpayer dollars will be made publicly accessible in a timely fashion; in the case of articles published by limited-access journals, NOAA will require an embargo period of no more than 12 months prior to free public access, consistent with guidance from OSTP; additional paperwork, administrative hurdles, and reporting requirements for researchers creating data or publications will be minimized; and existing activities, systems, and approaches will be leveraged and reused to minimize duplicative, incompatible, or wasted effort [21].

While making the data PARR compliant and ensuring that they are in an approved archive for anyone to access is important, this does not ensure that the data is FAIR-compliant. The FAIR guiding principles are defined in [22] and are summarized as follows: (meta)data are assigned a globally unique and persistent identifier; data are described with rich metadata; metadata clearly and explicitly include the identifier of the data it describes; (meta)data are registered or indexed in a searchable resource; (meta)data are retrievable by their identifier using a standardized communications protocol; the protocol is open, free, and universally implementable; the protocol allows for an authentication and authorization procedure, where necessary; metadata are accessible, even when the data are no longer available; (meta)data use a formal, accessible, shared, and broadly applicable language for knowledge representation; (meta)data use vocabularies that follow FAIR principles; (meta)data include qualified references to other (meta)data; (meta)data are richly described with a plurality of accurate and relevant attributes; (meta)data are released with a clear and accessible data usage license; (meta)data are associated with detailed provenance; and (meta)data meet domain-relevant community standards.

To meet these defined guiding principles, NOAA Ocean Exploration partners with NOAA's National Centers for Environmental Information (NCEI) to develop a unique, end-to-end data management system that collects, manages, archives and disseminates ocean exploration data and information in accordance with nationally accepted formats and standards [23] to improve the data archival, accessibility, and discoverability. The data derived from grant-funded projects are made publicly accessible through PARR-compliant, FAIR data repositories, allowing the public and scientific community to broadly benefit from the projects. Past studies have found that no single access data portal and application will meet the needs of all end users and therefore, as a practical matter, it is preferable to allow for individual user communities to have unique data access portals and to instead develop an inoperable platform that pulls in the data from those various portals [24].

To meet this need and ensure greater accessibility of the data derived from projects, NOAA Ocean Exploration and NCEI have developed project landing pages that provide a one-stop-shop for accessing project information, data citation, archived datasets, processed datasets, data products, list of publications, and additional resources (e.g., websites; https://www.ncei.noaa.gov/waf/ocean-exploration-nofo/). Collating all project information and links to the unique data access portals in one place increases accessibility and allows for a better understanding of what scientific questions have been addressed and what data gaps remain to be investigated in the future. To improve these data accessibility efforts, the NOAA Ocean Exploration competitive grants team is also in the early stages of developing a three-dimensional geospatial platform, which will increase the spatial understanding of existing data collections from these projects and will also allow for synthesis and comparisons of various funded projects.

To build upon these efforts, since 2022, NOAA Ocean Exploration has co-hosted a seminar series with the NOAA Central Library that is designed for grant awardees to present results from their projects to the public and scientific community. To date, NOAA Ocean Exploration has hosted over 14 live seminars, and the recordings are archived and available on YouTube (https://m.youtube.com/playlist?list=PLpb5LINL0Ys-AiXmfsgAWTVtrZEWSwgYP). These seminars provide further information about the projects beyond the state of the science and could lead to additional collaborations in the future.

IV. Conclusion

In recent years, there has been an increased desire for funding novel/innovative technologies and methodologies from the deep-sea exploration community. This has resulted in a four-fold increase in such funding provided by the NOAA Ocean Exploration competitive grant program. The outcome has been, in particular, the development of novel *in situ* sensors, technologies and methodologies to increase the utility of eDNA analysis for the deep sea, and new ways to explore the poorly studied region of the water column.

Along with the development and implementation of these tools and techniques, the data derived from these projects are critical for continued innovations and technological advancements. Therefore, it is important to continue to ensure that the data are PARR-compliant and FAIR. By ensuring data FAIR-ness, access to data is not limited to specific researchers

and is open to anyone working outside their main discipline or institution [24]. This engenders innovation and creative thinking. Along with continued development of new tools and technologies, it is essential to continue to implement innovative and easily accessible mechanisms to display and share data within NOAA and with the public and the scientific community. A universal, easily accessible, data management system will not only enhance the ability to ask more informed questions about these datasets, but it will also encourage the use of these datasets for future technological advancements and discoveries.

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