Implementing an Innovative, Robust, and Encompassing Uncrewed System Data Enterprise

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***Abstract*— The use of uncrewed systems within NOAA as a research and operational tool is well-documented. The full benefits of uncrewed systems to achieving the NOAA mission have remained largely unrealized, primarily because of the programmatic nature of these deployments. Establishment of enterprise services to coalesce uncrewed systems activities is essential for NOAA to optimize the use and benefits of these systems. A robust and encompassing data enterprise is principal among these needed enterprise services, and is essential to the success of NOAA's uncrewed systems strategy.**

The NOAA Uncrewed Systems Strategic Implementation Plan presents a comprehensive multi-year plan of action that builds upon the framework established in the NOAA Uncrewed Systems Strategy. This manuscript describes the Uncrewed Systems Data Enterprise as outlined in the Implementation Plan. In Section II we describe the data enterprise milestones. The notional operational framework and planned case studies are described in Sections III and IV, respectively. The advantages of the data enterprise are summarized in Section V.

Keywords*— *data enterprise, Uncrewed Systems Strategy, UxS, NOAA, Strategic Implementation Plan, data assembly center, data management

I. Introduction

The NOAA Uncrewed Systems Strategy establishes a plan for accelerating and integrating Uncrewed Systems (UxS) into every NOAA mission area by *improving the efficiency, effectiveness, and coordination of UxS development, understanding, awareness, and application across every NOAA Line and Staff Office* [1]. The NOAA Uncrewed Systems Strategic Implementation Plan will present a comprehensive five-year plan of action (2021-2025) that builds upon the framework established in the UxS Strategy.

The use of UxS within NOAA as a research and operational tool is well-documented in two UxS Symposiums sponsored by the NOAA UxS Executive Oversight Board [2, 3]. However, the full benefits of UxS to the NOAA mission have remained unrealized, largely because of the programmatic nature of these deployments. Identification and establishment of enterprise services is essential for NOAA to optimize the use of UxS. The implementation of a *UxS Data Enterprise* is principal among these needed services. NOAA has developed six strategies in emerging science and technology with the goal of producing transformative advancements in the quality and timeliness of NOAA's products and services across our mission areas[1]. These strategies are interconnected, such that the UxS Strategy is enabled by the Data, Cloud and AI strategies.

In the context of the UxS Data Enterprise, this strategic interconnectivity will enable efficient, scalable data systems to ensure that these vast data collections provide meaning and context to NOAA's mission, increasing the return on the investment in data collections by transforming an overwhelming amount of disparate data into contextual, actionable information.

II. Data Enterprise Implementation Plan

The NOAA UxS Strategic Implementation Plan presents detailed actions for each of the five UxS Strategy's overarching goals and objectives. Each action identifies NOAA lead offices, key collaborators, and target completion dates. NOAA lead offices are responsible for undertaking actions that fulfill the objectives, and reporting on the progress, challenges, and completion of the actions. UxS Strategic Plan [1] Objective 1.3. identifies as essential, the implementation of a comprehensive Data Enterprise as "Essential to Success."

A functional and adequately resourced data enterprise that accommodates moving large volumes of quality-controlled UxS generated data to shoreside processing and storage centers—and that significantly increases the quantity, quality, and throughput of these data—is essential to the success of NOAA's UxS Strategy.

[1] https://nrc.noaa.gov/NOAA-Science-Technology-Focus-Areas

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This will require fully leveraging NOAA's Cloud Strategy working in close partnership with data users, NOAA's Environmental Data Management Committee, and Big Data Project on cloud storage and computing and use of AI, and overall compliance with existing NOAA data management directives on governance, stewardship, access, and use. These protocols are essential for the effective and timely execution of NOAA's mission priorities [1].

NOAA's National Centers for Environmental Information (NCEI) will lead UxS data enterprise activities in collaboration with representatives from each of the NOAA Line Offices. NCEI is the Nation's leading authority for environmental data and manages one of the largest archives of atmospheric, coastal, geophysical, and oceanic data in the world. Together these partners will form a UxS Data Enterprise Working Group - a community of practice responsible for codifying data exchange standards and best practices for UxS data structures, formats, documentation, and data exchange protocols (including sensor calibration, data quality assurance and quality control protocols). The Data Enterprise Strategic Implementation objectives that are proposed to implement an encompassing UxS Data Enterprise [1] are listed below:

- Document required UxS data enterprise authorities including roles, responsibilities, organizational structures, policies, and resources, to ensure effective data acquisition and public access.
- Establish a NOAA UxS Data Enterprise Working Group within the UxS EOB, composed of subject matter experts who will establish and codify data exchange protocols and standards.
- Define specific Quality Assurance and Quality Control instrumentation protocols to improve and strengthen the overall integrity of UxS observations and measurements.
- Baseline current UxS data management practices by publishing key standards and protocols to reinforce and strengthen principles in the Data, Cloud Computing, and Artificial Intelligence NOAA Science and Technology Strategies.
- Develop and implement a data exchange agreement template to improve access to and use of data from all partners providing mission support.
- Establish a data management system that integrates research and performance data to enable better transition decision-making.
- Through one or more Case Studies, demonstrate practical approaches to improve data delivery, use, and stewardship.
- Document methods for integration of new activities into the Enterprise including a defined on-ramp strategy for R2O.
- Demonstrate the collective return on investment in UxS data collections as derived from defined public facing data and stakeholder interaction.

III. Notional Data Enterprise Framework

A cross-NOAA team is framing a broad implementation plan to bring the NOAA UxS Data Enterprise to an initial operating capacity within five years. This plan relies on: a) establishment of a community of practice to define and codify data exchange protocols and standards; b) a federation of scientific data assembly centers (FS-DAC) providing scientifically valid

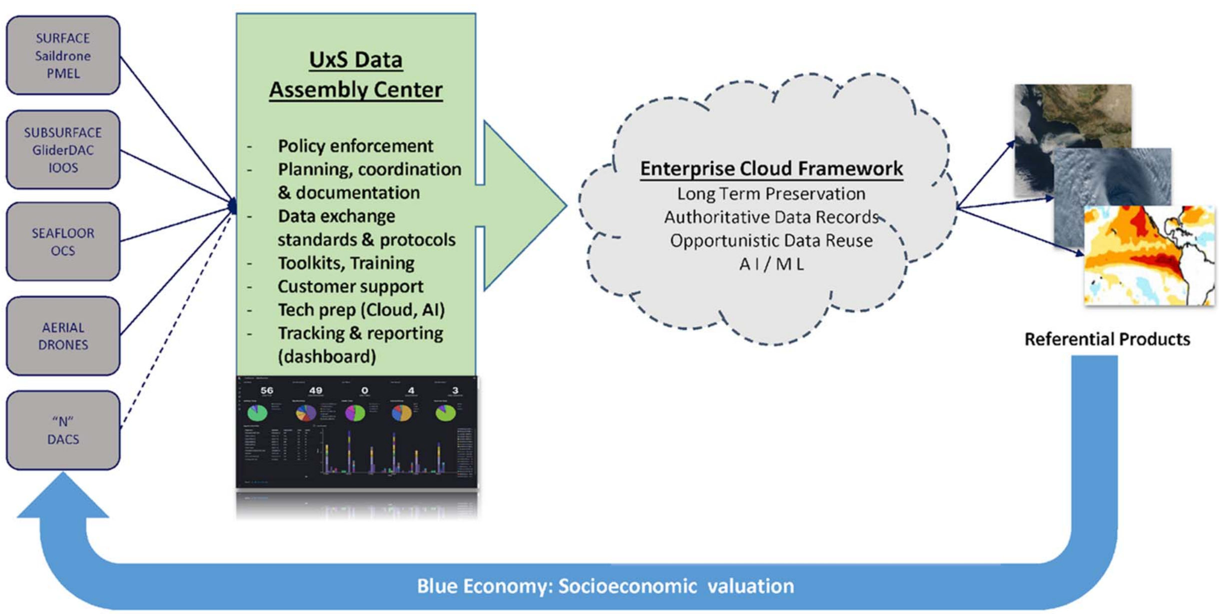

Fig. 1 This graphic depicts the notional architecture of the UxSDAC, which will act as a clearinghouse for data submissions from federated science mission-specific DACs. The UxSDAC will rely on NOAA cloud and AI implementation to provide optimized data services.

standard data packages to a central UxS Data Assembly Center (UxSDAC) for archival, processing and redistribution; and c) access to UxS data that is readily reusable to extend the return on investment in data collections.

The UxS Data Enterprise (Fig. 1) will operate the UxSDAC, which will function as a data clearinghouse to gather and deconflict data from NOAA FS-DAC and also from non-NOAA partners received as the result of data exchange agreements with Federal partners, industry, and academia. The UxSDAC will provide optimized data services to the Enterprise utilizing NOAA's cloud strategy and AI/ML initiatives, and will provide standardized, archive-ready packages to the Enterprise Cloud Framework [4]. UxS observations will be readily accessible and reusable. For example, integrating UxS data into products such as the Surface Underway Marine Database [5] and the World Ocean Database [6], adds value to the data by extending the usage and utility of the data far beyond the original purpose of deployment [7].

A. UxS Data Enterprise Working Group: A Community of Practice

A community of practice is a group of people who share a concern or a passion for something they do, and learn how to do it better as they interact regularly. The UxS Data Enterprise Working Group will foster a broad community of practice as a place where mission scientists, UxS operators and data users connect to promote collaboration and to develop mutually beneficial data exchange relationships within NOAA, and with the U.S. Navy, U.S. Coast Guard, other Federal agencies, industry, and academia.

The Integrated Ocean Observing System (IOOS) QARTOD (Quality Assurance of Real Time Oceanographic Data)[2] is an example of a thriving community of practice, which has worked collaboratively over decades to establish standards for calibration, QA/QC methods, and metadata best practices that have been integrated into the Open Geospatial Consortium (OGC) Sensor Observations Service (SOS) framework.

Building upon the QARTOD example, the cross-agency UxS community of practice will establish and codify best data management practices; develop metadata templates, establish data format and file specifications, and data transmission protocols for the full suite of sensors deployed on the NOAA UxS Fleet. In particular, the community may organize to address unmet needs for protocols for nascent or emerging data streams such as passive acoustics, optical sensors including video and imagery, and the emerging field of eDNA.

B. Data Assembly Centers

Complex data are expensive to manage. DACs simplify data by applying community standards to incoming data streams and by producing standard data packages ready to release in near real time and to archive and integrate into the long-term authoritative data record. Reducing data complexity reduces management costs and increases management efficiencies and data reusability.

The DAC concept is a well-known data management construct, and is not new to NOAA or NOAA data partners. Perhaps the most widely known NOAA-managed DAC is the US Glider DAC[3], implemented through the NOAA Integrated Ocean Observing Systems Program (IOOS). The UxS Data Enterprise will benefit from maximizing use of established, distributed DACs such as the IOOS GDAC that demonstrate operational expertise in the management of selected UxS platforms and/or payloads. In this example, the IOOS GDAC functions as an FS-DAC providing data packages to the UxSDAC.

FS-DACs are essential as to isolate the complexity associated with specific uncrewed platforms into clusters where the platform-specific data handling is isolated. This will allow the FS-DAC connection with the UxSDAC to be standardized and data handling at the UxSDAC to be generalized. One outcome of the UxSDAC will be standardized, archive-ready packages fully prepared for automated ingest into the NOAA Enterprise Cloud Services. An overview of UxSDAC data management functions may encompass:

- **Data planning**: Leverage UxS mission plans to establish data management plans and capacity estimates for any deployment.
- **Data acceptance**: Establish a robust data acceptance infrastructure to access near real time (NRT) UxS data, and to certify data from non-federal sources.Where possible, the IOOS Regional Association (RA) data certification processes may be applied. This includes IT infrastructure to receive data via a variety of communication channels.
- **Quality control**: Provide quality-control (QC) for near-real time raw data at full resolution. Data QC can be either implemented in-house, or leveraged from other NOAA offices applicable to the variable/observing domain/observation feature type.
- **Metadata**: A metadata collection subsystem will be supported at an appropriate level of granularity for platforms and sensors.. The outcomes will be NOAA-mandated standard metadata, currently identified as ISO 19115-2 and transitioning to ISO 19115-1. This practice will leverage mission planning documentation as a framework for development. The community of practice will establish keywords and semantics that utilize and build upon existing vocabularies. The outcomes will be data interoperability across user communities and integration with other data types.
- **Data access**: UxSDACs will be responsible for conversion of submitted data into community based standard formats for rapid access and use. Selected data will be available in NRT through a common dashboard or user interface.
- **Maximize operational use**: The operational value of data diminishes rapidly after observation. The UxSDACs infrastructure will place data on the World Meteorological Organization's (WMO) Information

[2] https://ioos.noaa.gov/project/qartod/

[3] https://data.ioos.us/organization/glider-dac

System (WIS) to ensure operational availability within the operational window for each observing type.

- **Post mission data (delayed mode data)**: Post mission data will be retrieved from uncrewed platforms and made available to the UxSDAC clearinghouse for unification and deconfliction with the NRT data collection from the same mission. Established best practices will be applied in the preparation of archive-ready data packages. Data will be available to the public in compliance with the NOAA Data Strategy.

- **Long term data preservatio**n: UxSDAC will develop standard archive-ready packages for submission to NCEI for long term preservation (archive), metadata publishing, citation (e.g., Digital Object Identifiers), data discovery, access and usability, and for integration into NCEI-developed authoritative records and scientific data products.

C. Tailored User Access, Scientific Products and Services

UxS observations support synthesis products and the development of value-added data products. The UxS Data Enterprise will support a data workflow paradigm so that the value of UxS data will be maximized through integration into authoritative data records and through the production of scientific data products and services. For example, NCEI integrated observations from uncrewed surface vehicles (USV) and underwater vehicles (UUV) into long term databases, extending the foundational reference into coastal and difficult to reach locations where these systems operate.

The UxS Data Enterprise will be capable of providing tailored access and building user-driven products to meet NOAA's mission needs. Future AI and ML-based applications will be better supported by the application of standardized, community-accepted formats. Minimal time will be spent "data wrangling" and the time from innovative idea to user-driven product will be greatly decreased.

D. Extended Enterprise Framework

As UxS data collection capabilities continue to expand with new commercial data sources, improved platforms, architectures, and data transfer technologies, the integration of artificial intelligence (AI) will provide a transformative capacity to significantly improve the quality and timeliness of NOAA's science products.

Elements of the UxS Data Enterprise may be co-located with academic partners to foster Artificial Intelligence (AI) and Machine Learning (ML) development, and facilitate the transition of new technology from research to operations. Academia can provide an innovation framework for cloud storage and computing, and for development of management tools for nascent or emerging data streams such as passive acoustics, optical sensors including video and imagery, and the emerging field of eDNA.

Co-location is envisioned to provide opportunities to: improve and optimize emerging data services, management tools, and techniques; to train the next generation of data scientists and support workforce development; to strengthen partnerships; and to advance research and innovation in support of NOAA's mission.

IV. Case Studies

Based on an initial analysis of ongoing UxS data operations, a subset of uncrewed maritime system (UMS) operations have been identified as initial case studies. Each case study represents a unique opportunity to evaluate mature UMS operations, identify potential operational improvements or bridge gaps in data operations, while gathering lessons learned that may be applied to the broader community needs and toward onboarding new systems.

Each case study has been proposed as a 'smart bets' for investigation into ongoing functions that may lead toward an Initial Operating Capacity (IOC) for the UxSDAC. Focus areas for IOC may result in (a) optimization of functions through automation; (b) integration of delayed mode data processes; (c) advancement of cloud and AI/ML readiness.

Additional case studies may be added over time, as lessons learned are gathered and applied and as the Enterprise evolves. Future studies may include NOAA projects funded by internal UxS request for proposals (RFPs); capabilities development for digital imagery management (e.g. from UAS protected resources missions); or examples of multi-platform and multi-program hydrographic data collections as part of the National Strategy for Mapping, Exploring, and Characterizing the U.S. Exclusive Economic Zone.

A. Uncrewed Surface Vehicles Case Study: Functional Automation

The OAR Pacific Marine Environmental Lab (PMEL) has developed automated data acceptance workflows for data from Saildrone platforms [8]. This workflow integrates existing technologies to accept data, and make data available through programmatic and user interfaces to research and operational users.

The COVID-19 pandemic disrupted NOAA's field operations to an unprecedented degree. The current operational challenges for ships are daunting, and the status of NOAA's planned ship-based fisheries surveys remains unclear. Many

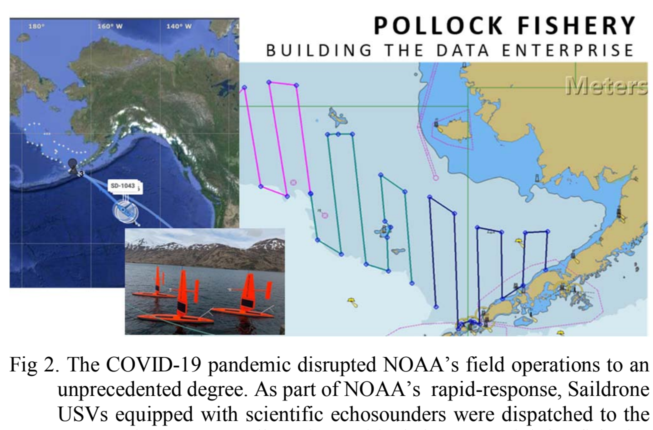

Fig 2. The COVID-19 pandemic disrupted NOAA's field operations to an unprecedented degree. As part of NOAA's rapid-response, Saildrone USVs equipped with scientific echosounders were dispatched to the East Bering Sea to collect time critical data essential for fisheries management. This graphic depicts the mission's survey region.

fisheries surveys were delayed, or cancelled altogether. This posed a significant challenge for fisheries management, which relies on timely abundance surveys of fish stocks to support management decisions. Saildrone USVs equipped with scientific echosounders were used to establish the abundance of walleye pollock in the area of the eastern Bering Sea (EBS)[4] ordinarily sampled by an acoustic-trawl survey conducted by the NOAA ship Oscar Dyson (Fig. 2). Pollock dominate midwater fishes in this area of the EBS, which makes this a favorable environment to use USV measurements of acoustic backscatter without additional trawl sampling to generate an abundance index useful for in stock assessment. During this survey, PMEL accepted all the Saildrone data and made these data available near-real-time.

Building on established workflows, the data acceptance will be hardened to address recent NOAA Cyber Security requirements. Saildrone data will be made available publicly from PMEL through interoperable machine to machine services with data visualizations. Using the established workflows at PMEL for Saildrone data acceptance, a mechanism will be defined and data handling software will be configured to relay data received near-realtime to NCEI. The protocol, timeliness and best practices will be established for this capability.

Saildrone data archival processes at NCEI at present are manual and are limited to the near-real time data collections. Needed are: a) process integration of delayed mode data; b) archive submission process automation. Building on this continuous data feed, NCEI plans to develop automated processes to archive these data and integrate them into synthesized data products such as the Surface Underway Marine Database [5, 7]. When single deployments become part of a global dataset, their vital contribution to large-scale ocean monitoring becomes apparent.

B. *Uncrewed Underwater Vehicles Case Study: Integrating Delayed Mode Data*

The IOOS GDAC provides glider operators world-wide a centralized location to archive, query, distribute, quality control, and visualize glider data [9]. This is done through a community derived national data format and QC standard. Near-real time glider data is uploaded to the WIS hourly through the NOAA National Data Buoy Center where it is made available to forecast models worldwide (Fig. 3). Additionally, NCEI harvests the glider data from the WIS for archival and integration into NCEI synthesized products synthesized products ranging from data-type specific databases like the World Ocean Database [6] to analyses (value-added) products such as climatological mean fields and ocean time series of variables such as ocean heat and oxygen content.

As a strictly voluntary DAC, each glider manufacturer uses their own data format. While the GDAC allows for the interoperability of glider data from any platform, this requires that providers manually establish a conversion process before they can submit glider data to the GDAC. This is a barrier to entry for some. To solve this gap, raw data upload tools need to be developed by the GDAC for each manufacturer. Community understanding and compliance with data standards and QC of metadata requires constant engagement and support within the glider community.

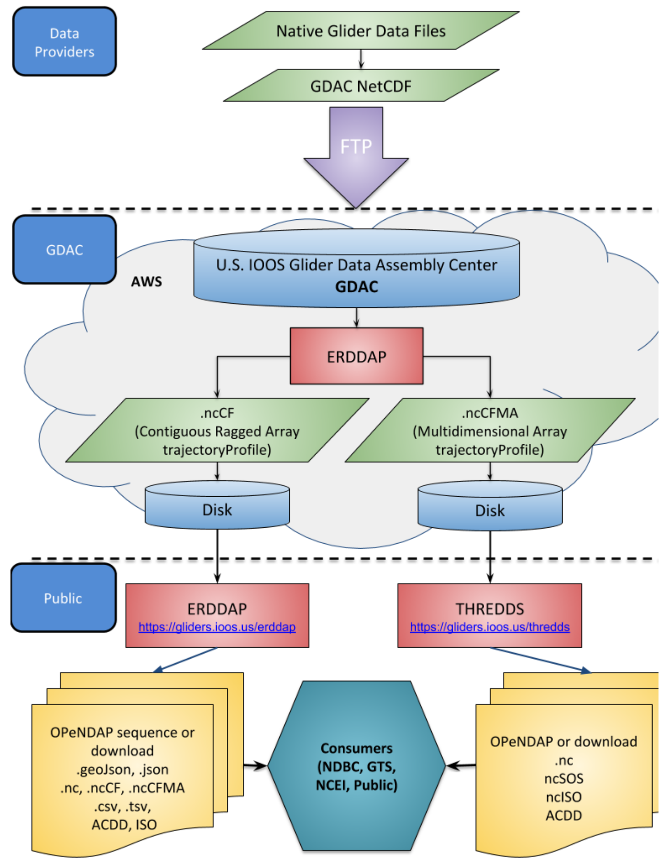

Fig 3. This diagram illustrates the architecture of the U.S. IOOS National Glider Data Assembly Center and end-to-end data flow pathway. *Image courtesy of IOOS.*

Objectives are to: a) Socialize community needs for understanding and compliance with standards; b) increase ease of participation in the GDAC for data providers c) establish pathways for routine transmittal of delayed mode data to the public and to NCEI. Outcomes may be alignment of GDAC standard with International OceanGliders 1.0 Format, develop automated ingestion of raw data from all major manufacturers; codify data exchange agreement (SLA) with NOAA and NOAA Funded glider operators, and establish pathways for routine, automated transmission of delayed mode data from the GDAC to NCEI.

C. *Remotely Operated Vehicle Case Study: Artificial Intelligence Advancement*

NOAA's Office of Ocean Exploration and Research operates NOAA's deep submergence system the Deep Discoverer (D2) from the NOAA Ship Okeanos Explorer. Environmental observations collected on video by D2 and the companion vehicle Seirios are archived and fully accessible to the public [10]. OER video access relies on detailed ISO

[4] https://www.saildrone.com/news/2020-alaska-pollock-survey-begins

metadata records enriched with annotations developed in a 3rd party system and integrated into the metadata over the video time signature. The OER Video Portal provides an eye into the archive, enabling users to easily sort through terabytes of data based on text or keyword search. Data are directly accessible through a self-service online ordering system which requires users to download the data from the archives for viewing and analysis. While this system is effective for searching through large volumes of archived video, the system is not readily extensible to non-OER / non-annotated video; also the data download requirements are resource consumptive.

In 2019 NOAA awarded a Phase I Small Business Innovative Research program contract to CVision to develop (Anno)Tator Online: A Web Application for Exploration and Curation of Underwater Video and Imagery[5]. The application is intended to enable scalable access to vast amounts of video and imagery assets, as well as the ability to curate subsets based on image searching of rich metadata, algorithm results, or other criteria.

Fig. 4 Video data collected by the NOAA ROV Deep Discoverer during the Musicians Seamount exploration (2017) is displayed in the CViision (Anno)Tator Online tool during an algorithm training exercise. *Image courtesy of CVision.*

In 2020 OER and NCEI partnered with the University of Dallas to develop a summer project for students interns to investigate cloud-based video annotations as a precursor for building machine learning datasets in (Anno)Tator with the eventual goal of automating video annotations. Students trained on the tool, learning to isolate organisms in video frames to begin training algorithms to identify deep sea organisms. Students provided feedback that improved the tool, and completed summer research projects based on identifying deep sea creatures from the OER Musician Seamount video data collection[6] (Fig. 4). The student projects characterized the selected sites, analyzed biodiversity, and compared results of different sites within the Musicians Seamount chain. Future planning aims to continue training the algorithm. This project has implications for future cloud data operations, artificial intelligence, and machine learning.

V. Summary

Developing the UxS Data Enterprise will enhance NOAA's ability to meet the rapidly increasing and dynamic requirements of UxS data management in a manner consistent with legislative mandates and NOAA policy. Current NOAA UxS data management practices are highly localized by Line, Staff and Program Offices. Unifying these diverse practices into the UxS Data Enterprise will introduce system-wide efficiencies, standardize best practices, and enable NOAA to present one vision for UxS data management to meet the NOAA science mission objectives.

The broader UxS community also requires a reliable UxS Data Enterprise. Building a shared Enterprise on the foundation of standards and community best practices will meet shared objectives. Multiple federal and state agencies, the academic research community, and commercial industry each routinely rely on NOAA's public facing mission for scientific data stewardship, access to reliable environmental data, and for authoritative scientific data, information products and services to fulfill their own missions.

NOAA's stewardship practices maximize NOAA's investment in environmental research, converting scientific insights into dynamic, usable information that informs strategy and decision making in government, academia, and the private sector.

The UxS Data Enterprise will rapidly add value to the data by seamlessly integrating and augmenting existing long term data collections and by developing authoritative records for public use, scientific advancement, natural resource management, decision support, and national security.

As UxS platforms, sensors, and system architectures continue to evolve and move from research to operations, the NOAA UxS Data Enterprise will enable a transformative capacity to significantly improve the quality, timeliness and accessibility of UxS data collections.

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