THE NATIONAL ACADEMIES OF SCIENCES, ENGINEERING, AND MEDICINE

Swells, soundings, and sustainability, but...

here be monsters

FEATURED SPEAKER
Dr. Dawn Wright
ENVIRONMENTAL SYSTEMS RESEARCH INSTITUTE (ESRI) AND OREGON STATE UNIVERSITY


SALMON POPULATION
EARLY SEASON HUMPBACK WHALE SIGHTING
ECOSYSTEM

The National Academy of Sciences

The National Academy of Sciences was established in 1863 by an Act of Congress, signed by President Lincoln, as a private, nongovernmental institution to advise the nation on issues related to science and technology. Members are elected by their peers for outstanding contributions to research. Dr. Marcia K. McNutt is president.

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The three Academies work together as the National Academies of Sciences, Engineering, and Medicine to provide independent, objective analysis and advice to the nation and conduct other activities to solve complex problems and inform public policy decisions. The National Academies also encourage education and research, recognize outstanding contributions to knowledge, and increase public understanding in matters of science, engineering, and medicine.

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Dear Lecture Participant:

On behalf of the Ocean Studies Board at the National Academies of Sciences, Engineering, and Medicine, we would like to welcome you to the Eighteenth Annual Roger Revelle Commemorative Lecture. This lecture was created by the Ocean Studies Board in honor of Dr. Roger Revelle to highlight the important links between the ocean sciences and public policy.

ROGER REVELLE

For almost half a century, Roger Revelle was a leader in the field of oceanography. Revelle trained as a geologist at Pomona College and the University of California, Berkeley. In 1936, he received his Ph.D. in oceanography from the University of California, Berkeley. As a young naval officer, he helped persuade the Navy to create the Office of Naval Research (ONR) to support basic research in oceanography and was the first head of ONR's geophysics branch. Revelle served for 12 years as the Director of Scripps (1950–1961, 1963–1964), where he built up a fleet of research ships and initiated a decade of expeditions to the deep Pacific that challenged existing geological theory.

Revelle's early work on the carbon cycle suggested that the sea could not absorb all the carbon dioxide released from burning fossil fuels. He organized the first continual measurement of atmospheric carbon dioxide, an effort led by Charles Keeling, resulting in a long-term record that has been essential to current research on global climate change. With Hans Suess, he published the seminal paper demonstrating the connection between increasing atmospheric carbon dioxide and burning of fossil fuels. Revelle kept the issue of increasing carbon dioxide levels before the public and spearheaded efforts to investigate the mechanisms and consequences of climate change. Revelle left Scripps for critical posts as Science Advisor to the Department of the Interior (1961–1963) and as the first Director of the Center for Population Studies at Harvard (1964–1976). Revelle applied his knowledge of geophysics, ocean resources, and population dynamics to the world's most vexing problems: poverty, malnutrition, security, and education.

In 1957, Revelle became a member of the National Academy of Sciences to which he devoted many hours of volunteer service. He served as a member of the Ocean Studies Board, the Board on Atmospheric Sciences and Climate, and many committees. He also chaired a number of influential Academy studies on subjects ranging from the environmental effects of radiation to understanding sea-level change.

SMITHSONIAN'S NATIONAL MUSEUM OF NATURAL HISTORY

The Ocean Studies Board is pleased to have the opportunity to present the Revelle Lecture in cooperation with the Smithsonian National Museum of Natural History through our partnership with the Smithsonian Science Education Center. The museum maintains and preserves the world's most extensive collection of natural history specimens and human artifacts and supports scientific research, educational programs, and exhibitions. The museum is part of the Smithsonian Institution, the world's largest museum and research complex. Dr. Kirk R. Johnson is the director.

The Smithsonian Science Education Center (SSEC) was founded in 1985 by the National Academy of Sciences and the Smithsonian Institution and continues today as a successful unit of the Smithsonian Institution. The mission of the SSEC is to develop STEM literate students from early childhood through the workplace. The SSEC does this through the implementation of a truly systemic approach that engages participants at every level, from students and classroom teachers up through the highest levels of district, state, national and international leadership.

TONIGHT'S LECTURE

In her lecture this evening, Dr. Dawn Wright, Chief Scientist of the Environmental Systems Research Institute (Esri), will provide a brief history of how the ocean has been mapped with ships, satellites, and intuition. In her lecture, Dr. Wright will also explain how modern-day mapping systems have become increasingly intelligent. These systems are changing what we measure, how we analyze, what predictions we make, how we plan and regulate, how we design, how we evaluate and ultimately how we manage it all. And yet there remain compelling challenges in coping with both the overabundance and paucity of data in the ocean, its multidimensionality, and how to make it accessible to the myriad audiences in great need of it.

SPONSORSHIP

The Ocean Studies Board thanks the National Oceanic and Atmospheric Administration, the National Science Foundation, the National Aeronautics and Space Administration, the Office of Naval Research, and the U.S. Geological Survey. This lecture series would not be possible without their generous support. The Board also extends gratitude to the Smithsonian Science Education Center and the Smithsonian Institution for their continued partnership in hosting the lecture at the National Museum of Natural History.

We hope you enjoy tonight's event.

Larry Mayer,
CHAIR, OCEAN STUDIES BOARD

Susan Roberts,
DIRECTOR, OCEAN STUDIES BOARD

In October 2011 Dr. Dawn Wright was appointed Chief Scientist of the Environmental Systems Research Institute (aka "Esri"), a world-leading geographic information system (GIS) software, research and development company, after 17 years as a professor of geography and oceanography at Oregon State University. As chief scientist of Esri, Dawn works directly with the CEO on strengthening the scientific foundation for Esri software and services, while also representing Esri to the national and international scientific community. She maintains an affiliated faculty appointment within the College of Earth, Ocean, and Atmospheric Sciences at Oregon State University.

Dr. Dawn Wright

Dawn's research interests include geographic information science; ocean informatics and cyberinfrastructure; benthic terrain and habitat characterization; and the processing and interpretation of high-resolution bathymetry, video, and underwater photographic images. She has authored or co-authored more than 150 articles and 10 books on marine GIS, hydrothermal activity and tectonics of mid-ocean ridges, and marine data modeling. Dawn has participated in over 20 oceanographic research expeditions worldwide, including 10 legs of the Ocean Drilling Program, three dives in the deep submergence vehicle Alvin and two dives in Pisces V. Her fieldwork has taken her to some of the most geologically active regions of the planet, including the East Pacific Rise, the Mid-Atlantic Ridge, the Juan de Fuca Ridge, the Tonga Trench, and volcanoes under the Japan Sea and the Indian Ocean.

Dawn's recent advisory board service includes the Science Advisory Boards of NOAA and the EPA, the Science Advisory Council of Conservation International, the Blue Ribbon Panel of the Global Partnership for Oceans, and many journal editorial boards. She served on the U.S. National Academy of Sciences Ocean Studies Board from 2007-2013. Dawn was the recipient of an NSF Early Career Award in 1995, was awarded a Fulbright to Ireland in 2004, the OSU Milton Harris Award for Excellence in Basic Research in 2005, and elected a Fellow National to the Explorers Club in 2013. In 2007 the Council for Advancement and Support of Education (CASE) and the Carnegie Foundation for the Advancement of Teaching named her Oregon Professor of the Year. She is also a Fellow of the AAAS and the Geological Society of America, as well as a fellow of Stanford University's Leopold Leadership Program. Dawn holds an Individual Interdisciplinary Ph.D. in Physical Geography and Marine Geology from the University of California, Santa Barbara, an M.S. in Oceanography from Texas A&M, and a B.S. cum laude in Geology from Wheaton College (Illinois).

A Brief History of Mapping in the Ocean

Humankind has been mapping the oceans for hundreds of years, with one of the earliest examples being the "stick charts" comprised of pieces of wood, coconut fronds, and cowrie shells, as devised the ancient Marshall Islanders to navigate their part of the Western Pacific Ocean via canoes (Lewis, 1994; Figure 1). These charts are significant in the history of cartography because they are the first known representation of ocean swells, including how the islands disrupted those wave patterns, and thus provided an aid to navigation (Finney, 1998). This traditional knowledge of the ocean had existed for centuries, but was not described by Western societies until the 1860s (Lewis, 1994; Finney, 1998).

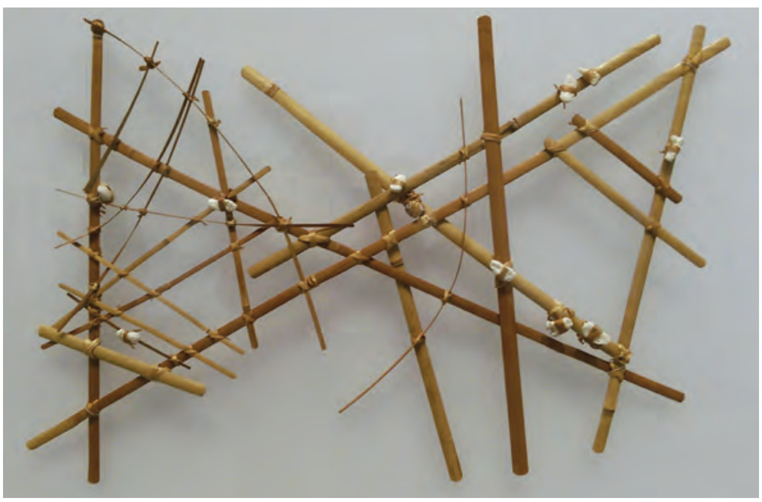

FIGURE 1. A navigational "stick chart" from the Marshall Islands, made of wood, coconut fibers and cowrie shells, with the fibers representing the crests of ocean swells. Chart is on display at the Berkeley Art Museum and Pacific Film Archive, University of California, Berkeley. **Photo by Jim Heaphy and reproduced under Creative Commons License CC BY-SA 3.0 by Cullen328 via Wikimedia Commons.**

Scientists aboard the HMS Challenger (during a global expedition from 1872-1876 that laid the foundation for modern oceanography), conducted the first systematic survey of the ocean floor (aka bathymetric survey), establishing that the global ocean floor was not the flat, featureless plain first hypothesized (Corfield, 2003). The survey was accomplished by leadline, where a large piece lead was lowered to the ocean floor by rope in order to measure the water depth at that location. In the 1920s, the German ship Meteor conducted the first detailed bathymetric survey

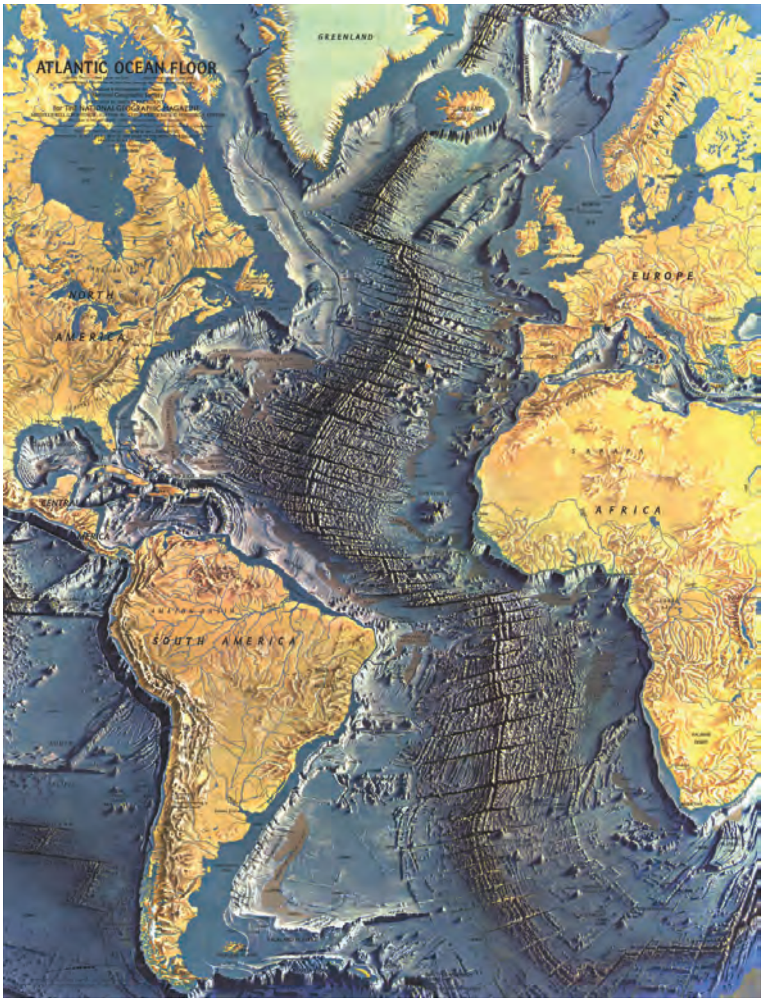

FIGURE 2. 1968 map of the Atlantic Ocean Floor based on a large compilation of deep ocean soundings by Bruce Heezen and Marie Tharp, painted by Heinrich Berann, for the National Geographic Magazine. **Image courtesy of Ken Field, International Cartographic Association.**

of the South Atlantic Ocean floor by way of early SONAR (SOund Navigation And Ranging). As the acronym suggests, the depth of the water is determined by emitting pulses of sound from an instrument, listening for the echo, and calculating the depth by way of the pulse's travel time to its target and back, considering the speed of sound in water in varying salinities, temperatures, and pressures. Fast forward to World War II and the navies of the United States, Great Britain, Germany, and Japan were leaders in further developing the capabilities of SONAR for knowledge of the enemy, as well as of the ocean.

By the 1950s and 1960s the provision of single, focused, high-frequency, short wavelength sound beams (aka, single beam SONAR) had become an invaluable tool for mapping not only the ocean floor, but also detecting specific targets within the water column such as marine mammals or large schools of fish. In 1968 (Figure 2), the Austrian landscape panoramist and cartographer Heinrich Berann, working in collaboration with marine cartographer Marie Tharp and marine geophysicist Bruce Heezen painted the Atlantic Ocean floor, the first in a series of physiographic maps of the ocean floor, a work which culminated in Heezen and Tharp's famous 1977 World Ocean Floor Panorama. This 1977 map revealed for the first time the globe-encircling mid-ocean ridge system of volcanoes and earthquakes, as well as a host of other features that turned Earth science on its head. As has been recounted in numerous sources (e.g., Doel et al., 2006; Landa, 2010; North, 2010; Felt, 2012) the early maps of Marie Tharp helped to turn Bruce Heezen away from the expanding Earth hypothesis and correctly toward the theories of continental drift and plate tectonics. Tharp's work in particular has been called "one of the most remarkable achievements in modern cartography" (North, 2010; Felt, 2012).

While a leadline approach yielded an estimated 1,000-2,000 soundings per survey, and the single-beam approach, 500,000-700,000, the modern multibeam

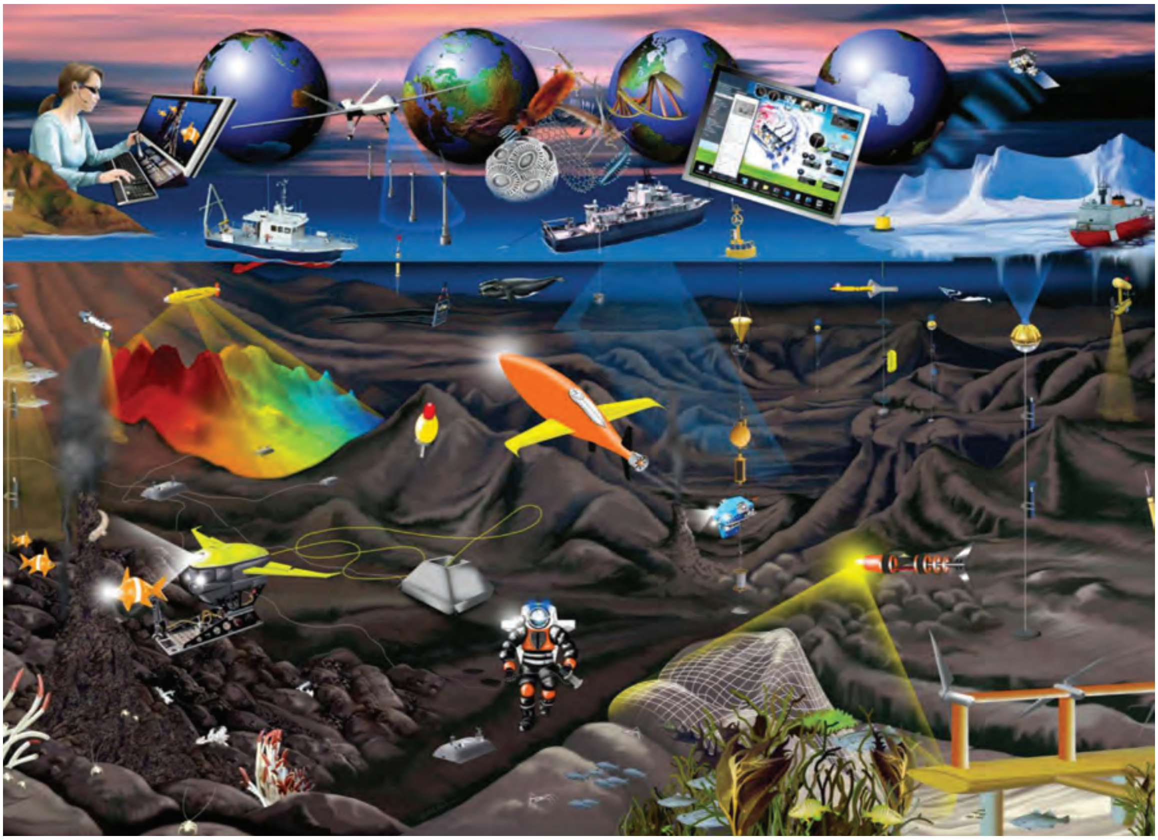

FIGURE 3. An illustration of the broad variety of the ships, vehicles, platforms, and sensors used now and looking 20 years into the future for understanding how the oceans work, and how we need to manage, and protect it. **From National Research Council (2011).**

systems of the 1970s and 1980s, yielded as many 1 million per survey (Blondel and Murton, 1997). The work of Sandwell et al. (2003) and Smith and Sandwell (1994; 1997) provided yet another significant advance by combining shipboard depth soundings gathered from thousands of individual surveys, with estimates of bathymetry derived from the Earth's gravity field as measured in space by satellite-based altimeters (where measurements of the "bumps" in sea surface height are remarkably accurate in mimicking the topography of large crustal features such as deep ocean trenches, fracture zones, and mountain ranges).

The individual shipboard survey is still at the heart of marine science and marine resource management because of the superior level of detail that can be acquired. This modern higher-resolution mapping of the oceans is still accomplished with mapping systems located beneath a ship, but may also be linked to underwater video or photography collected from vehicles towed behind a ship, and further collated to samples and measurements collected from an instrument or vehicle launched away from a ship or operating independently on the ocean floor, as well as to sensors mounted on marine mammals (Wright et al., 2007; Wright 2014; Figure 3). The resulting maps continue to reveal the bathymetry of the oceans for science, navigation, finding of lost objects, and pinpointing of hazards due to sea level rise and coastal flooding, but there also maps of the temperature and salinity of the ocean water itself that help us track El Niño events and storm systems; the abundance, diversity and overall health of hundreds of species of ocean life (including those in commercial fisheries); the speed and direction of currents and tsunamis; and so much more (National Research Council, 2004; Wright, 2014).

Much of the general public focuses on more traditional uses of ocean maps such as nautical charts that provide aids to navigation, tide predictions, and locations of hazards such as shoals and shipwrecks. The mapping of the oceans for science, for sustainability, and for the science of sustainability requires not only the accurate collection of measurements, but the use of these measurements for analysis, visualization, and policy decision-making. Further, it requires new and different products that are interactive, even immersive, as well as maps incorporating live data streams and numerical models. Ultimately, how do we create maps that make the world a better place by addressing the world's biggest problems such as conservation, resource management (including fisheries), pollution tracking, disaster aid and relief, climate change mitigation and adaptation, and design of human uses of coastal and deep ocean space to more closely follow natural systems (e.g., McHarg, 1995; Steinitz, 2012)?

New Innovations

But what is a "map" in the modern, 21st century context? It's no longer just the paper map on one's wall or in the glove compartment of a car. Indeed, we now find ourselves inhabiting a "Digital Earth" composed of technologies from satellites to wristwatches that monitor, map, model, and manage virtually everything around us (Wright, 2015a).

Maps have evolved into "intelligent web maps" that encapsulate the rich knowledge that used to be embedded only in a desktop geographic information system (GIS), largely disconnected from the web. But now, these maps – and the data from which they are built – commonly reside in Software as a Service (SaaS) infrastructures, aka "the cloud," creating a veritable data and web services nervous system for the planet. For instance, using only a web browser, the user can choose from data residing on a local machine, but also from any number data services and web mapping services worldwide that are freely available on the Internet. As such, just about anyone can access platforms to make maps; to combine their maps with other layers to create new maps; and to share these maps via e-mail, phones, tablets, and similar devices, or to embed them in applications, web sites, or blogs. The maps can be accessed by a variety of free, easy-to-use viewers or open application programming interfaces (APIs) that are designed expressly for the Internet, are scalable, modifiable, and interchangeable between different kinds of software. This is an evolutionary step in the dissemination and accessibility of oceanographic knowledge and is a key building block for making oceanographic information pervasive and widely accessible to everyone.

These new maps are also smarter because of numerical recipes that will automatically update and provide map symbols of the correct color, size, and style as new data become available. Some map platforms enable the user to view mapped distributions of marine habitats, energy resources, and infrastructure, and then using these as a reference, sketch on the screen the boundaries of potential marine protected areas (e.g., Malcolm et al., 2012; White et al., 2012; Collie et al., 2013; Strickland-Munro et al., 2016). The smart map can adjust accordingly, automatically saving this design that can be shared with other stakeholders either in the room or on the Internet, via threaded discussion windows adjacent to the mapping interface, hopefully as a step toward shared consensus of the efficacy of this new management area (e.g., Paul et al., 2012; Stelzenmuller et al., 2013).

By linking geographic coordinates with extensive databases and sophisticated spatial analysis algorithms in GIS, these maps do more than feature pushpins, pop-ups, or static lines. As noted by Grenley (2016), "the map of the future is [also] an intelligent image," with visual and acoustic imagery from ships, satellites, aircraft, and drones at its core, along with strong analytic and modeling features. These smart maps process events through both space and time via statistics and numerical models that are used to predict currents, sea water temperatures, salinity, water levels, sea state, and other parameters in real-time. They can send alerts to desktops or mobile devices if something enters an area of interest, and are thus of critical use for storm surge warnings, rescue operations, abatement of marine pollution, ship routing, integrated coastal zone management, approval processes of offshore facilities, or in the design of new marine protected areas. Geospatial tools that generate distributive flow lines from one source

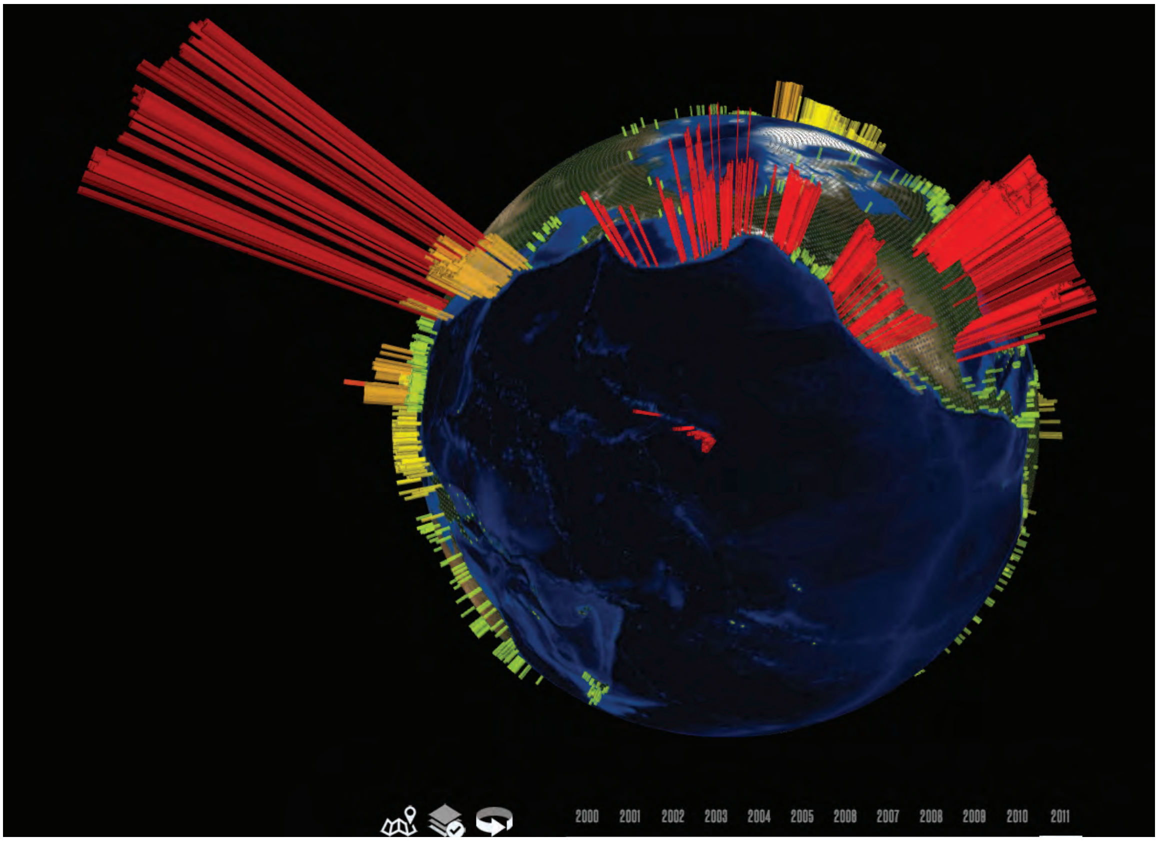

FIGURE 4. Visualization of the high volume of commercial shipping activity into and out of ports rimming the Pacific Ocean. Green bars represent shipping traffic of 1 million vessels, yellow 20 million, and red 50 million+. Lengths of bars represent amount of growth to those numbers over a 10-year period. The data were analyzed using an open-source collection of GIS tools for the spatial analysis of big data (https://esri.github.io/gis-tools-for-hadoop/). **Visualization by Mansour Raad and Sajit Thomas, Esri. Interactive, online version available at http://coolmaps.esri.com/BigData/ShippingGlobe (best with the Chrome web browser running WebGL).**

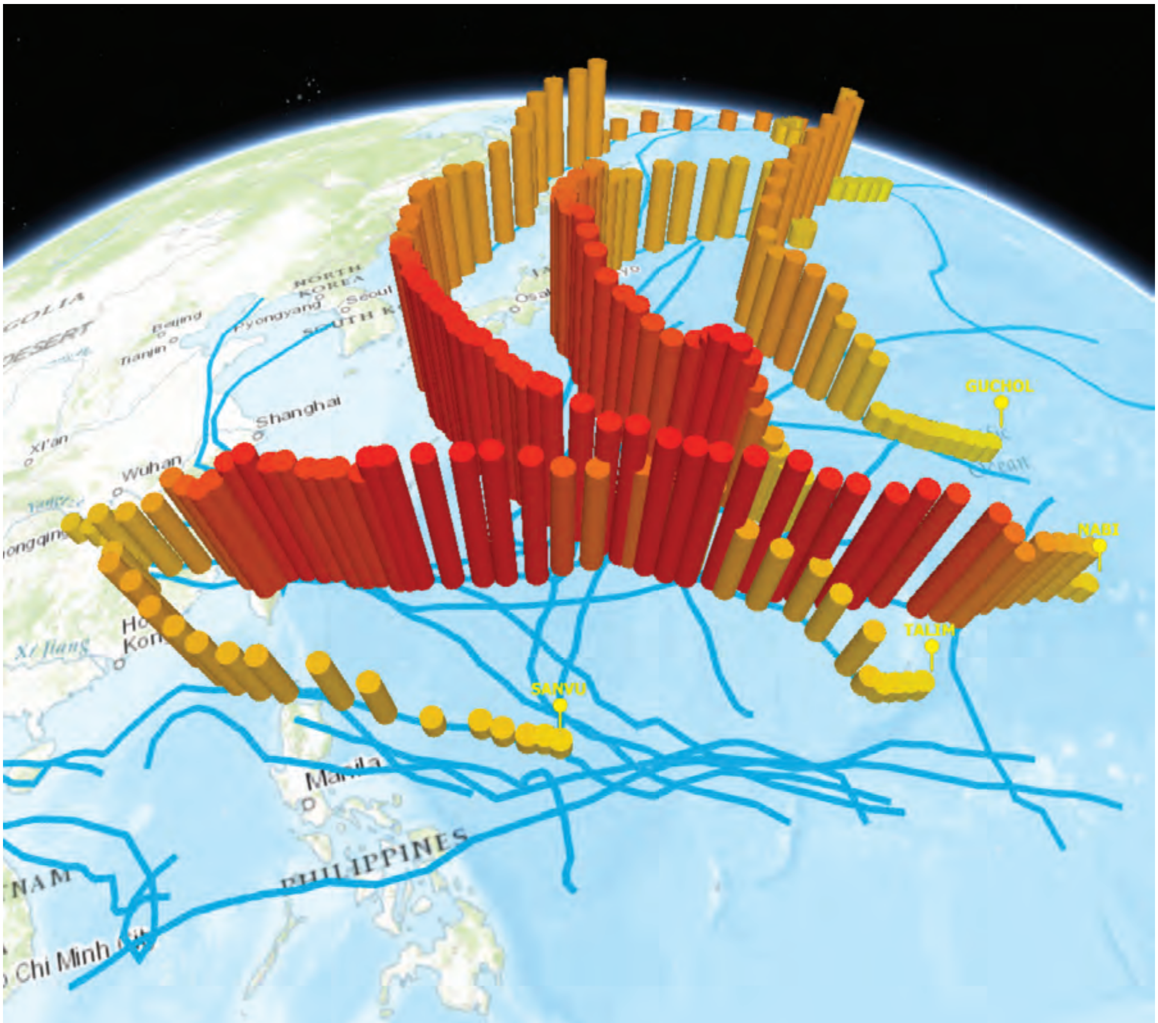

FIGURE 5. A map of typhoons in the Western Pacific during the record-breaking typhoon season of 2005, seeking to visualize the life cycle of the event and compare one storm to another to find unique details and overall patterns. 3D symbols depict the unique signature of every storm. This map shows wind speed as cylinder height and barometric pressure as cylinder color along with speed of travel, total distance traveled, and storm duration. **Visualization by Nathan Shephard, Esri. Interactive, online version available at http://www.esri.com/products/maps-we-love/pacific-typhoons.**

to many destination points can be used to create "flow maps" that show the movement of goods or people from one place to another. These smart maps are changing what we measure, how we analyze, what predictions we make, how we plan, how we design, how we evaluate and ultimately how we manage the Earth System. As these processes are increasingly taking place in the cloud, mapping is becoming more open, without the need for cumbersome desktop hardware and software with their steep, long learning curves.

To capture the dynamics of the oceans, it is necessary to move mapping into the realm of the multidimensional, where the two geospatial dimensions of longitude (x) and latitude (y) are combined with a third dimension of depth (z), a fourth dimension of time (t), and/or a fifth dimension, consisting of measurements from a specific ocean instrument or the iterative results of models that may go forward or backward in time (Li and Gold, 2004; Wright et al., 2007). Such multidimensionality is critical for the mapping of natural phenomena such as currents, tides, shorelines, ice movements, El Niño/La Niña effects, and biotic distributions, as well as anthropogenic features such as navigational obstacles or maritime boundaries that appear and disappear, shipping activity in and out of ports (Figure 4), and much more. The oceans present so many multidimensional challenges, especially because they are very hard to access at full depth from sea surface to sea floor. Satellites and light detection and ranging (LiDAR) sensors, for example, cannot "see" all the way through the water in all places. As a result, only 8-15% of the oceans are mapped in the same detail as on land (e.g., Wessel and Chandler, 2011; Picard et al., 2017; Smith et al., 2017).

There are all manner of amazing three-dimensional (3D) visualization and animation tools that heighten our understanding of how the oceans work, as well as how dangerous they can be. Figure 5 shows a new way to visualize the major typhoons that raged throughout the Western Pacific in August 2005, along with the variation in their intensity and thus danger to human life. From a more analytical standpoint, the intelligence of maps in 3D is allowing us to slice our data in both the horizontal and vertical directions, as well as by data values. Thus, we are not just seeing a static image, but instead we're working with an entire database that is associated with each "voxel" (short for volume element, as "pixel" is short for picture element). This allows for powerful spatial analysis (for example, k-means statistical clustering of point measurements in the oceans to identify and map environmentally-distinct 3D regions within the water column – termed "candidate ecosystems" by Sayre et al., 2017).

But Here be Monsters: Can we Tame Them?

Despite the growing intelligence of mapping systems, "there be monsters" – the major research challenges that continue to confound us. For example, how do we best cope with both the overabundance and the paucity of ocean data (i.e., "big data" and "dark data"), as well as its multidimensionality? How do we best address these major issues to create open and effective access to ocean science that will contribute to the global public good and ultimately to the sustainability of Planet Ocean? How do we increase not only the resilience of communities to climate change but the resilience of digital data and maps that they rely on?

BIG DATA

We are in an era of regional- to global-scale observation and simulation of the oceans. As an example, from the world of ocean observatories, Figure 3 (NRC, 2011), provides a glimpse of the technology of today, as well as ~20 years into the future. These observatories produce the so-called "big data," defined in Gantz and Rainsel (2012) as "a new generation of technologies and architectures, designed to economically extract value from very large volumes of a wide variety of data by enabling high-velocity capture, discovery, and/or analysis." Big data, with its three main characteristics of volume, velocity, and variety, are in turn leading to a new science that deals with the issues associated with the inundation of data from satellites, sensors, and other measuring systems (Alder, 2015; Seife, 2015; Wright 2015a). These issues are certainly challenging computer science, but they are also squarely in the crosshairs of geographic information science, geospatial data science, image science, analytical cartography, and other fields that underlie modern, intelligent mapping systems. Indeed, the lack of a complete understanding about the nature of data in both space and time (i.e., both velocity and variety) leads to problematic data models, inefficient data structures, and erroneous hypotheses (Yuan and Hornsby, 2008; Wright and Wang, 2011; Wright, 2015a). And yet a paradigm shift is afoot that is driving an evolution from desktop and server enterprise solutions into a Software as a Service (SaaS) model in the cloud, and mapping applications (especially GIS) are building upon that important shift.

The variety or structural variability of data for and from mapping may be among the most compelling problems for the ocean science and management communities (e.g., Paolo et al., 2016). Data are coming from multiple sources and types (photos, video, audio, text, scientific observations, scientific models), multiple perspectives (governments, military, industry, nongovernmental organizations or NGOs, etc.), which in turn have their various cultures for contributing and visualizing data. Although the number and type of ocean mapping applications continue to grow, there still exist overall inconsistencies in ocean data models, formats, standards, tools, services, and terminology.

Tackling these problems has largely been in the realm of academia and federal agencies, but there is a new ocean data industry that is evolving to help meet these needs. It is estimated that: (1) 80% of the decision-making processes in ocean science and business depend on data collection, management, processing, and distribution; (2) accordingly, the data acquisition market is over $80 billion, including ships, buoys, satellites, robots, ship-to-shore communications; and further (3) the data management market is estimated at $5 billion, including software and associated costs (Rainer Sternfeld, PlanetOS, pers. comm., April 23, 2013). As explained in detail in Hoegh-Guldberg et al. (2013), this is fodder for effective public-private partnerships (PPPs) among academia, government, industry, and NGOs, especially when society is searching for sustainable solutions to multi-tiered environmental challenges.

One such example of a successful PPP around big data is the Ecological Marine Units (EMU) project officially commissioned by the Group on Earth Observations (GEO). GEO is an intergovernmental partnership of 101 nations, the European Commission, and 106 organizations collaborating to build the Global Earth Observation System of Systems (GEOSS; Group on Earth Observations, 2005 and 2017; Walters and Scholes, 2017). The EMU delineates the oceans into thirty-seven physically- and chemically-distinct volumetric regions, from the ocean surface all the way down to the ocean floor (Figure 6; Sayre et al., 2017). Additional information such as species abundance, primary productivity, direction and velocity of currents, seafloor geomorphology, and much more are being digitally attached to these units in the second phase of the project. The aim is to provide scientific support for the design of new marine protected areas, for ocean planning and management, and for enabling the understanding of impacts to ecosystems from climate change and other disturbances.

This big data project is comprised of an unprecedented set of 52 million data points, set in a mapping coordinate system, and having been collected over a 50-year period as derived from NOAA's World Ocean Atlas (Garcia et al., 2013; Locarmini et al., 2013; Zweng et al., 2013; Garcia et al., 2014).

OPEN SCIENCE

As compelling as big data (and small data) are, there is also the challenge of "dark data." As aptly stated by Mascarelli (2009): "More and more often these days, a research project's success is measured not just by the publications it produces, but also by the data it makes available to the wider community. Research cannot flourish if data are not preserved and made accessible. All concerned must act accordingly." As discussed in the sections above, the massive amounts of data produced using modern digital technologies (including mapping technologies) has enormous potential for science and its applications in public policy, the nonprofit sector, and business. But how should this deluge be shared and managed to support innovative and productive research that also reflects public values?

Many organizations such as the Research Data Alliance (RDA), the Federation of Earth Science Information Partners (ESIP), and specifically for the oceans community, the Intergovernmental Oceanographic Data and Information Exchange (IODE) of UNESCO's Intergovernmental Oceanographic Commission, the Ocean Data Interoperability Platform, the Interdisciplinary Earth Data Alliance

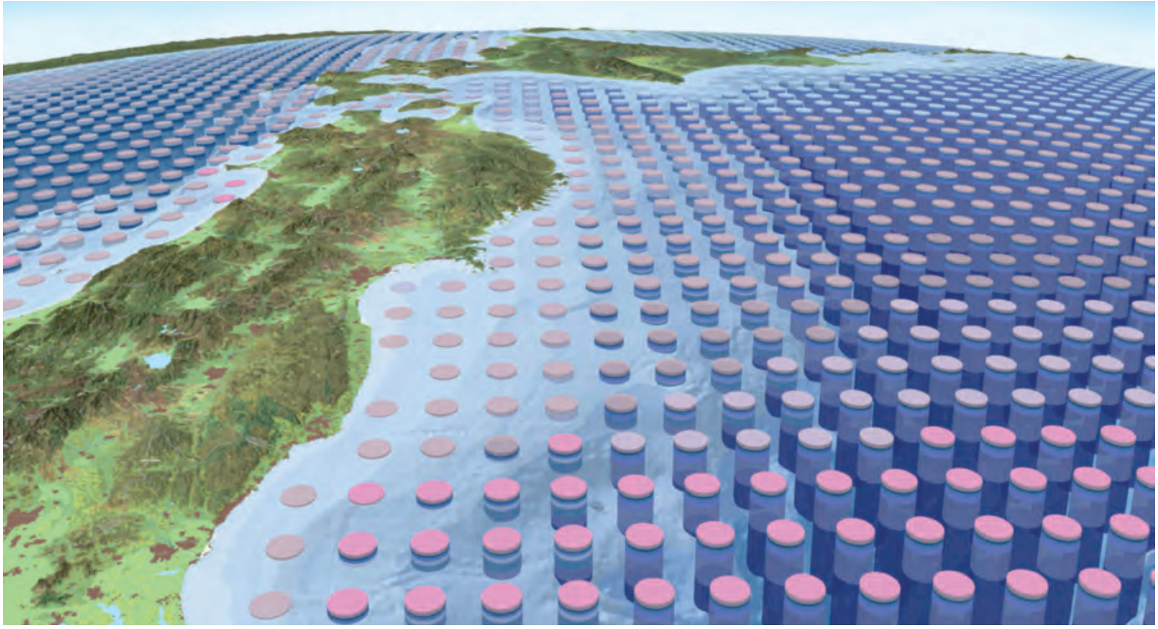

FIGURE 6. Example of a visualization approach taken to represent a new classification for the ocean known as ecological marine units (EMUs) in three dimensions mapped over space. The region shown is largely off the east coast of Japan in the Pacific Ocean. Although the EMUs are mapped as a continuous surface, representing them in 3D is facilitated using columnar stacks, allowing visualization of EMUs beneath the ocean surface at evenly-spaced locations. In the coastal zone, EMUs are single or few, whereas offshore there are more and deeper EMUs. **Visualization by Sean Breyer and Keith Van Graafeiland, both of Esri.**

of Columbia University and the Biological & Chemical Oceanography Data Management Office of the Woods Hole Oceanographic Institution, the National Science Foundation's EarthCube initiative, and many more, have fully dedicated themselves to fostering a data-centric "counter culture." For example, not only the tables, figures, statistics, and printed maps in published papers are readily accessible, but the actual digital datasets themselves. This further pertains to not only data from the laboratory, but also to data collected in the field in sciences such as geology, ecology, archaeology, and certainly oceanography (McNutt et al., 2016).

These organizations are developing best practices for fully cataloging and provisioning the data using the same persistent identifiers in force for published papers, such as Digital Object Identifiers (DOIs). RDA is also leading the way in fostering PPPs focusing on data use and data quality. The IODE has been focused for many years on organizing oceanographic data and information management at the global level, with globally agreed-upon standards and practices for the free open exchange of data, including maps and GIS data, and to make everything available quickly, easily and with the highest quality. This is particularly due to the fact that poor-quality data will lead to poor policy advice and thus to poor decision-making (Glover et al., 2010; Organisation for Economic Co-operation and Development, 2015).

Perhaps most importantly, many organizations are exercising the FAIR principle (Findable, Accessible, Interoperable, Reusable) as part of several pillars of "open science" (e.g., Organisation for Economic Co-operation and Development, 2015), with regard to the "what" (scientific publications, research data and materials, digital apps, source code), the "who" (scientists, companies, the public), and the "why" (re-asserting science as a global public good). And particularly in local government circles where scientific data is used for public policy, there are efforts to move map data (i.e., geospatial data) from that of an underdeveloped or undervalued asset within an open data framework to that of a first-class data type, on par with spreadsheets (Civic Analytics Network, 2017).

DIGITAL RESILIENCE AND STORYTELLING

Another "monster," if you will, is the challenge of keeping data resilient as well as open and accessible. For example, if mapping and information tools and the data they are based upon are to help communities to adapt to and be resilient to climate change, it stands to reason that they must be resilient themselves. Wright (2015a) makes the case that standard definitions of resilience (e.g., the ability to deal with changes or threats; the capacity for absorbing disturbance, stress, or catastrophe; the ability to recover quickly to a prior desired state) can and should apply to digital data and mapping systems too. As such, if these systems are accessible, interchangeable, operational, and up-to-date, they are resilient.

Wright (2015a and 2015b) discusses as many as eight ideas toward a digital resilience, with some relating to the open science discussion above in terms of:

- fostering better reproducibility through the citation of data via DOIs, especially in journals that require data not just to be available but to be re-usable;

- practicing interoperability and crosswalking via the integration of data with a host of scientific tools and libraries; and

- sharing not just data and not just computer code but how these should be best deployed. In other words, sharing workflows and use cases.

Another recommendation for digital resilience is to adopt the practice of storytelling as a means of science communication. Especially for those seeking to make their science matter to policy, this involves taking the knowledge developed within academia writ large and transmitting it into

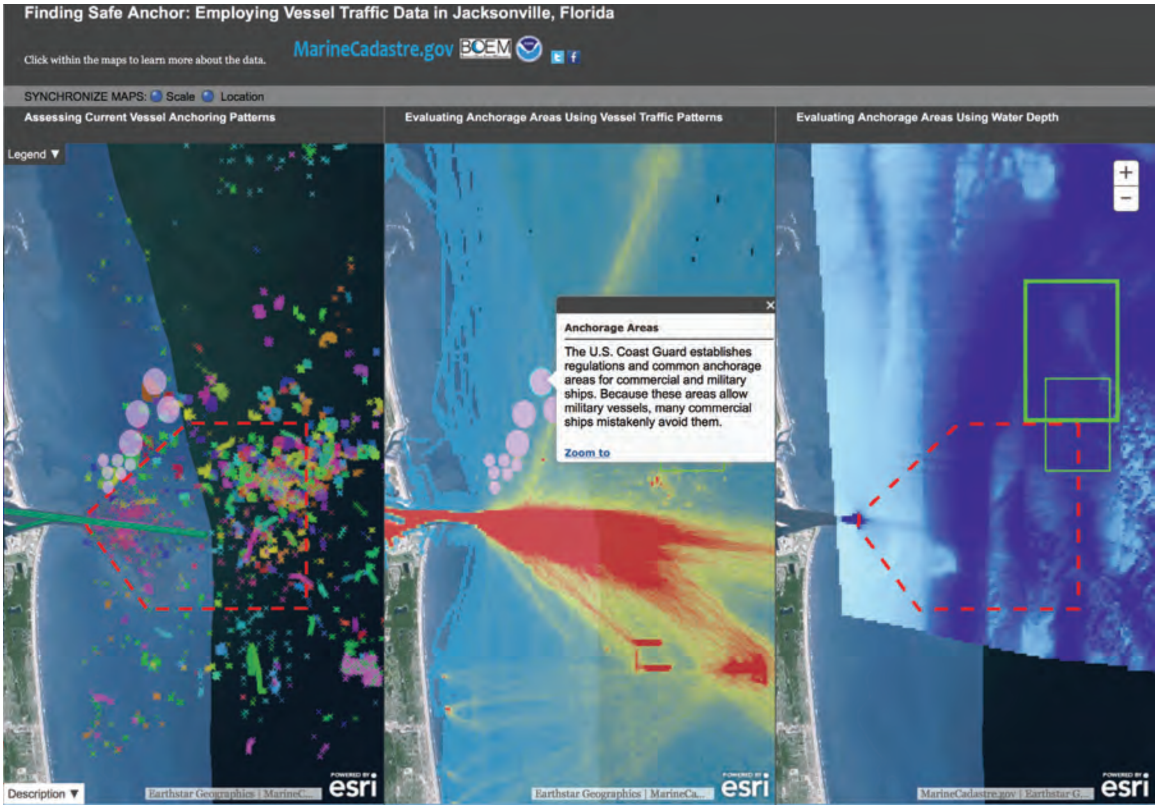

FIGURE 7. Example of a story map used in a US Coast Guard/NOAA workshop. Panning or zooming in one of the map panels synchronizes the same map scale and location for the other two, so that users can simultaneously examine vessel anchoring patterns (left), vessel traffic patterns (middle), and water depth (right) in order to propose the safest new anchorage areas. **Link to story map available from http://esriurl.com/ocnstories.**

mainstream society in ways that elicit significant action (Baron, 2010; Wright 2015a). Indeed, as scientists we are often encouraged not to publish our work until it constitutes a complete "story." There are ways to take this to a different audience with different mediums, especially to take advantage of the power of maps and geography to educate, inform, and inspire people to action.

For example, Figure 7 is an example of a "story map," a new medium provided as a series of free apps for sharing not only maps and associated data sets, photos, videos, even sounds, but for telling a specific and compelling story by way of that content (Wright et al., 2014). Scientists are learning how to combine smart web maps to synthesize the data and a primary interpretative message so as to inform, educate, and inspire about a wide variety of ocean science and policy issues. Figure 7 tells the story of a workshop conducted by the US Coast Guard and NOAA navigation managers to help stakeholders in Jacksonville, Florida review existing anchorage areas and propose new areas for improved navigation safety. During the workshop the group used the smart web maps to evaluate automatic identification system (AIS) vessel tracking data, bathymetry, and anchorage data. This quickly revealed major lanes of shipping traffic and allowed the group to collaboratively propose new anchorages in safer areas away from dense shipping traffic, but also in areas deep enough to accommodate larger ships. The story map provides a digital story book or lasting record of their data and approaches for use in subsequent efforts but also a communication tool for the Jacksonville Port Authority, the Florida Department of Transportation, field scientists, hydrographic surveyors, recreational boaters, and local politicians.

Toward Sustainability

Perhaps the biggest monster of all will be achieving the Sustainable Development Goals (SDGs) of the United Nations (Figure 8; United Nations, 2015a). These 17 SDGs were adopted in 2015 with a mission to tackle many of the world's most pressing challenges by the year 2030. SDG 14 (Life Below Water) seeks by that year to "conserve and sustainably use the oceans, seas and marine resources," by way of 10 targets, including reducing marine debris and other types of pollution; managing, protecting, and conserving the ocean; ending overfishing and destructive fishing practices; and addressing ocean acidification (United Nations, 2015b).

Although national science organizations, developments agencies and many others have a mission and mandate to support the SDGs in their everyday work, achieving the goals will still require unparalleled effort. It is most fortuitous that these goals are more aligned with mapping and geography than ever before. Indeed, the SDGs provide a unique opportunity to deploy a range of mapping dashboards (Figure 9), and other common reporting systems that will monitor SDG progress indicators as governments and organizations take on each of the targets. This will in turn enable all data stakeholders to actively participate in the

FIGURE 8. Infographic of the 17 United Nations Sustainable Development Goals **(from http://www.un.org/sustainabledevelopment/sustainable-development-goals).**

progress, no doubt with healthy debate along the way, with direct access to authoritative information that is near-real-time and cross-comparable, and useful for prioritization of activities and programs across the human and physical landscape.

Smart mapping provides the framework and the process for creating a smarter world. It brings together all the data. It integrates the data. It manages the data. It brings data from the abstract into a visualization that is more easily understood and can be used to inform the world. GIS can organize SDG information into various types of layers that can be visualized, analyzed, and combined to help us better understand the issues facing future development. GIS delivers a platform that can be used for the observation, tracking, and management of shared SDGs worldwide—an integrated global goals GIS. This creates a development nervous system for the planet that will integrate data across disciplines, support the evaluation of planetary health using global measures for SDGs, identify the results and impacts of development interventions, and be a platform for communication and understanding.

The time scales at which ocean issues develop and can be addressed (e.g., sea level rise, ocean acidification, coral bleaching, loss of biodiversity) often stretch over decades – or centuries – whereas political cycles and management regimes often last for only a few months or years. As we move from swells to soundings to sustainability, it is hoped that the mapping technologies we can now bring to bear will help erase the disconnect between the time scales of problem development and policy response. Let us keep working with the innovations in mapping and information toward long-term solutions despite shifting governance and priorities.

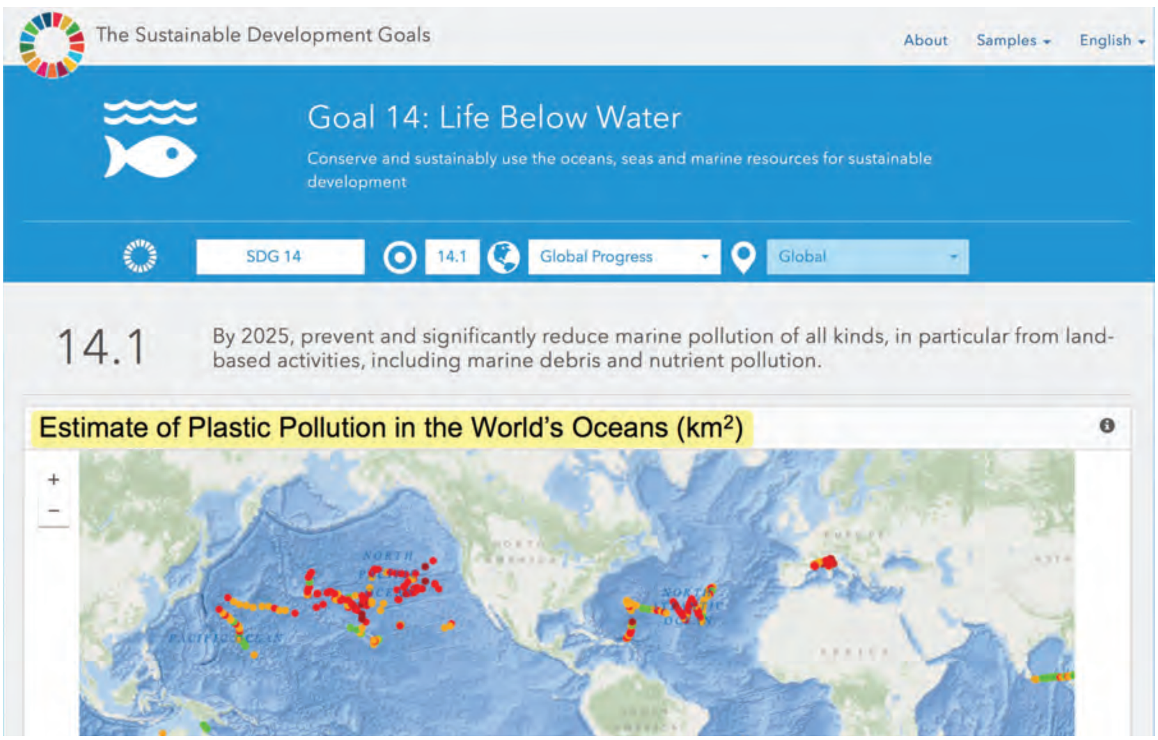

FIGURE 9. A GIS dashboard commissioned by the UN to aid in the implementation and management of the SDGs, in this case for displaying progress on Goal 14, Target 1 about reducing marine pollution of all kinds, including marine debris. **Interactive, online version available at http://github.com/Esri/sdg-dash.**

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Toward a digital resilience (with a dash of location enlightenment). Eos Transactions American Geophysical Union, 96, http://dx.doi.org/10.13140/RG.2.1.2224.6489. | Wright, D.J., M.J. Blongewicz, P.N. Halpin, and J. Breman. 2007. Arc Marine: GIS for a Blue Planet. Esri Press, Redlands, California, 202 pp. | Zweng, M.M., J.R. Reagan, J.I. Antonov, R.A. Locarnini, A.V. Mishonov, T.P. Boyer, and others. 2013. World Ocean Atlas 2013 version 2 (WOA13 V2), Volume 2: Salinity. In: NOAA National Centers for Environmental Information, S. Levitus, ed., and A. Mishonov, technical ed., NOAA Atlas NESDIS 74, NOAA National Centers for Environmental Information, Silver Spring, Maryland, 39 pp. | LIST OF FIGURES | FIGURE 1. A navigational "stick chart" from the Marshall Islands, made of wood, coconut fibers and cowrie shells, with the fibers representing the crests of ocean swells. Chart is on display at the Berkeley Art Museum and Pacific Film Archive, University of California, Berkeley. Photo by Jim Heaphy and reproduced under Creative Commons License CC BY-SA 3.0 by Cullen328 via Wikimedia Commons. | FIGURE 2. 1968 map of the Atlantic Ocean Floor based on a large compilation of deep ocean soundings by Bruce Heezen and Marie Tharp, painted by Heinrich Berann, for the National Geographic Magazine. Image courtesy of Ken Field, International Cartographic Association. | FIGURE 3. An illustration of the broad variety of the ships, vehicles, platforms, and sensors used now and looking 20 years into the future for understanding how the oceans work, and how we need to manage, and protect it. From National Research Council (2011). | FIGURE 4. Visualization of the high volume of commercial shipping activity into and out of ports rimming the Pacific Ocean. The data were analyzed using an open-source collection of GIS tools for the spatial analysis of big data (https://esri.github.io/gis-tools-for-hadoop/). Visualization by Mansour Raad and Sajit Thomas, Esri. Interactive, online version available at http://coolmaps.esri.com/BigData/ShippingGlobe (best with the Chrome web browser running WebGL). | FIGURE 5. A map of typhoons in the Western Pacific during the record-breaking typhoon season of 2005, seeking to visualize the life cycle of the event and compare one storm to another in order to find unique details and overall patterns. 3D symbols depict the unique signature of every storm. This map shows wind speed as cylinder height and barometric pressure as cylinder color along with speed of travel, total distance traveled, and storm duration. Visualization by Nathan Shephard, Esri. Interactive, online version available at http://www.esri.com/products/maps-we-love/pacific-typhoons. | FIGURE 6. Example of a visualization approach taken to represent a new classification for the ocean known as ecological marine units (EMUs) in three dimensions mapped over space. The region shown is largely off the east coast of Japan in the Pacific Ocean. Although the EMUs are mapped as a continuous surface, representing them in 3D is facilitated by the use of columnar stacks, allowing visualization of EMUs beneath the ocean surface at evenly-spaced locations. In the coastal zone, EMUs are single or few, whereas offshore there are more and deeper EMUs. Visualization by Sean Breyer and Keith Van Graafeiland, both of Esri. | FIGURE 7. Example of a story map used in a US Coast Guard/NOAA workshop. Panning or zooming in one of the map panels synchronizes the same map scale and location for the other two, so that users can simultaneously examine vessel anchoring patterns (left), vessel traffic patterns (middle), and water depth (right) in order to propose the safest new anchorage areas. Link to story map available from http://esriurl.com/ocnstories. | FIGURE 8. Infographic of the 17 United Nations Sustainable Development Goals (from http://www.un.org/sustainabledevelopment/sustainable-development-goals). | FIGURE 9. 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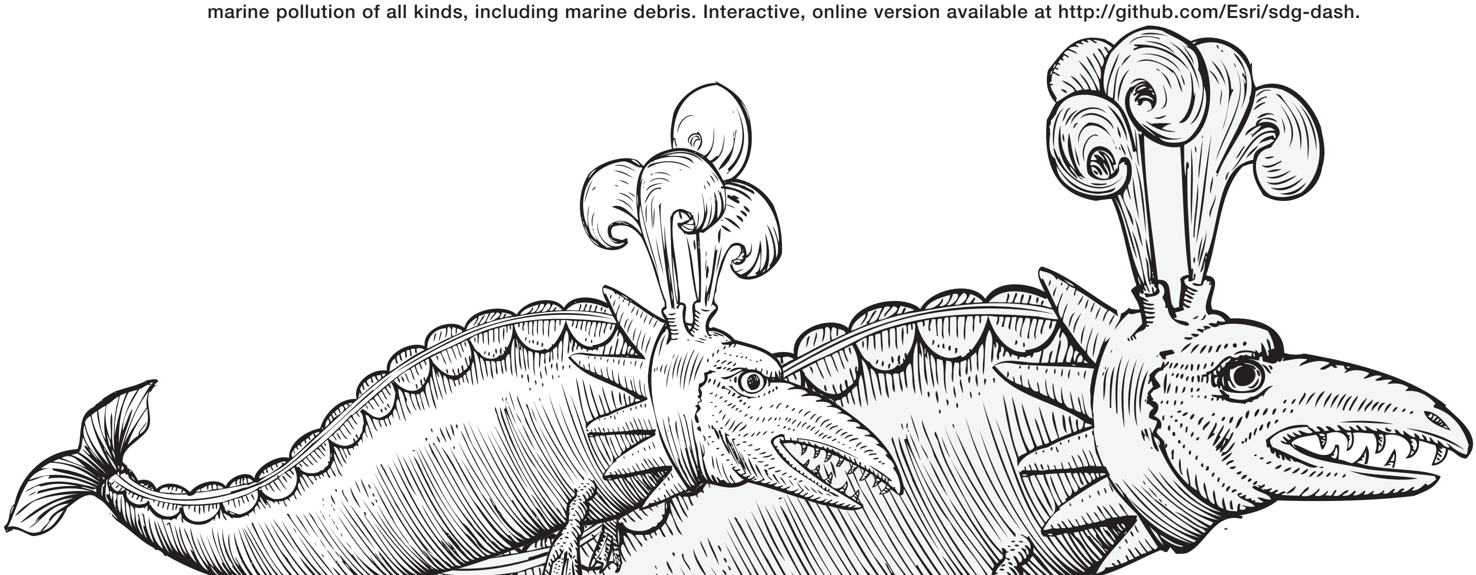

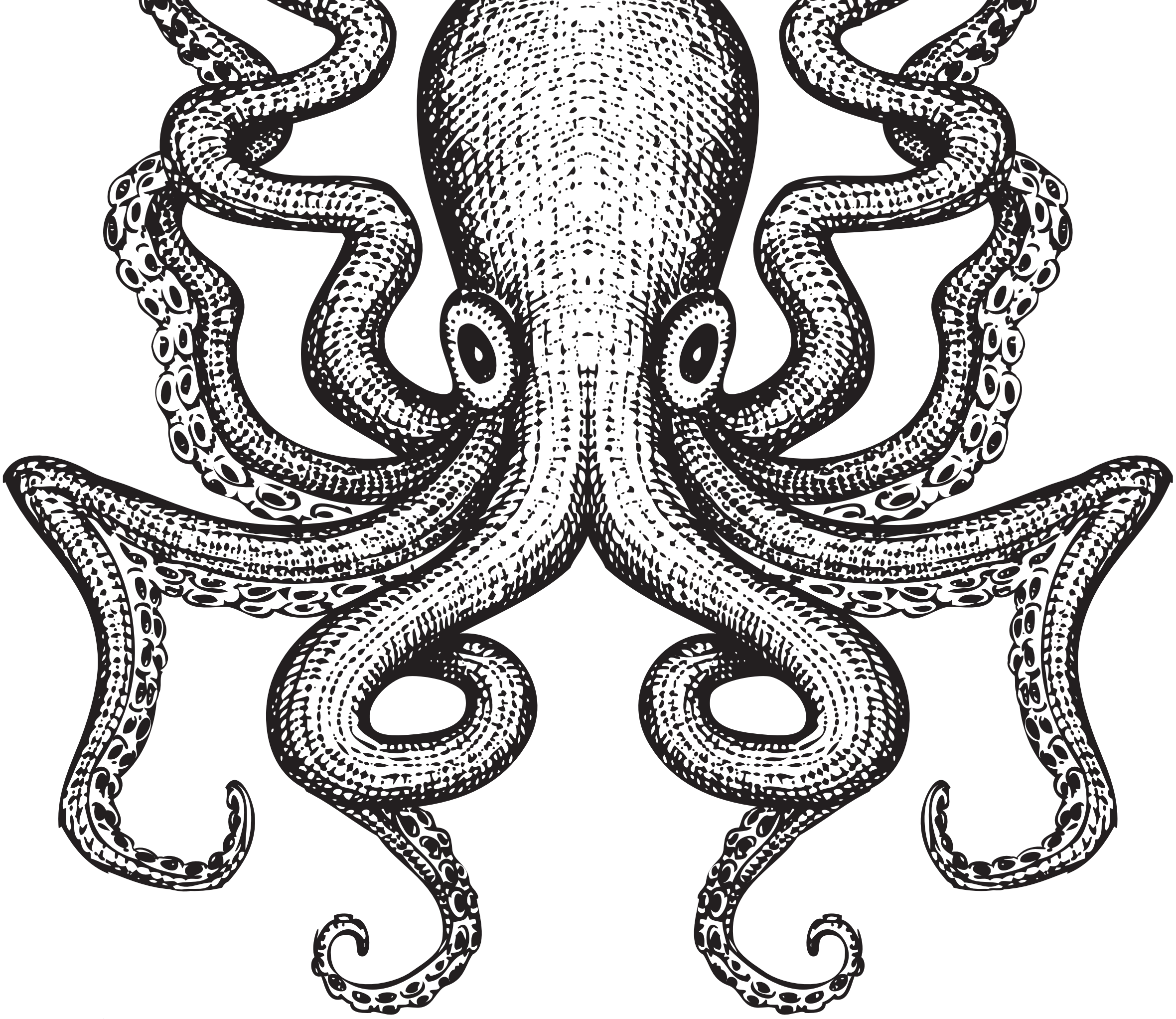

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