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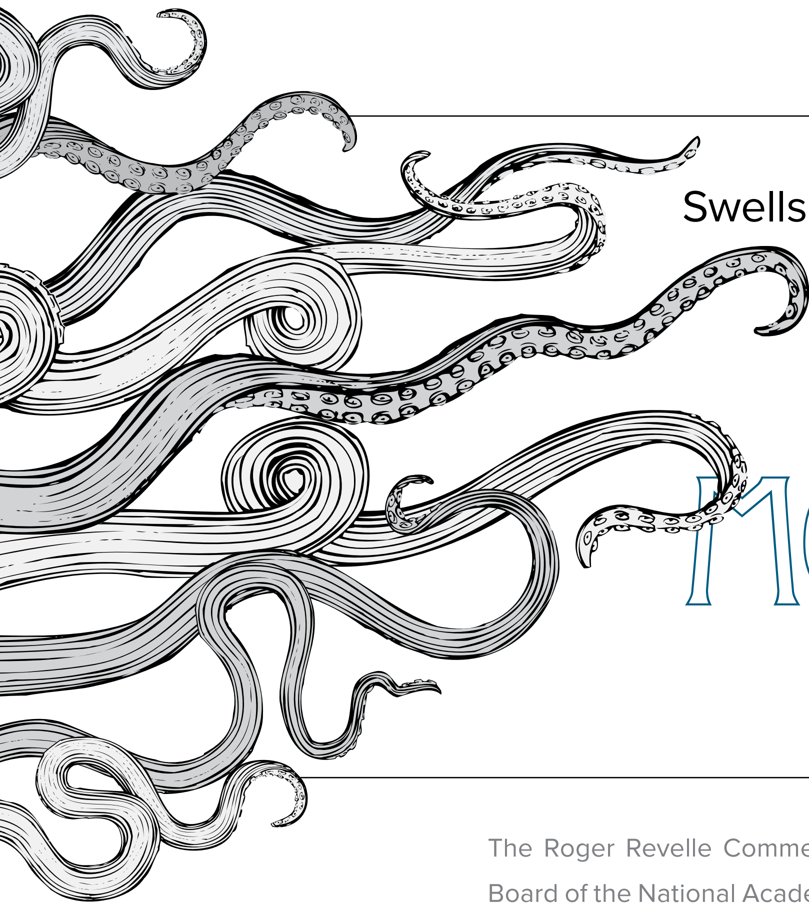

Swells, Soundings, and Sustainability, but…

"HERE BE MONSTERS"

By Dawn J. Wright

The Roger Revelle Commemorative Lecture Series was created by the Ocean Studies Board of the National Academies in honor of Roger Revelle to highlight the important links between ocean sciences and public policy. Dawn J. Wright, the eighteenth annual lecturer, spoke on April 28, 2017, at the Smithsonian National Museum of Natural History.

ABSTRACT. We have been mapping the ocean for hundreds of years, from the stick charts of the ancient Marshall Islanders, to the initial soundings of the nineteenth-century *Challenger* expedition, to the multibeam sonars and robots of modern surveys. Today we map the ocean not only to increase fundamental scientific understanding of the ocean system but also to protect life and property, promote economic vitality, and inform ecosystem-based management and policy. Toward this end, the United Nations Sustainable Development Goals provide an overarching context for modern map development, drawing upon a vast wealth of maps and mapping experience that couples appropriate data with spatial analyses. At the same time, there is an overarching need for more compelling map design to help effectively communicate results and future predictions across a wide variety of research areas. Indeed, modern-day mapping systems have become increasingly "intelligent," and these "smart maps" are changing what we measure, how we analyze and evaluate systems, how we forecast, and even how we develop new regulations. Intelligent maps are addressing myriad challenges, from the tracking of marine debris and marine mammals, to "geodesigning" the ocean to support multiple uses (commercial fishing, recreation, alternative energy, transportation, conservation), to creating scientific cyberinfrastructures for ocean observatories. Yet "there be monsters"—the major research challenges that continue to confound us. Despite the growing intelligence of mapping systems, we must cope with both the overabundance and the paucity of ocean data (i.e., "big data" and "dark data"), data multidimensionality, the need to increase data resiliency, and the ability to make data more accessible to many audiences. How do we 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?

SUSTAINABILITY AS OVERARCHING CONTEXT

At the turn of the twenty-first century, following a three-day Millennium Summit of world leaders at the headquarters of the United Nations (UN) in New York City, the UN General Assembly adopted the Millennium Declaration. Within the Declaration were eight Millennium Development Goals (MDGs) listing 21 targets designed to tackle some of the world's most pressing challenges, including ensuring environmental sustainability. Building on the success of the MDGs, the United Nations Conference on Sustainable Development (aka Rio+20) began the process of creating 17 Sustainable Development Goals (SDGs) as part of the 2030 Agenda for Sustainable Development. These 17 SDGs were adopted in 2015, along with 169 targets to be achieved by 2030 with over 200 indicators (ways for assessing the extent to which targets are met; Figure 1; United Nations, 2015a). While the MDGs were focused on developing countries, the SDGs are universal and thus more interconnected as they cover three types of sustainable development: economic growth, social inclusion, and environmental protection. The ultimate goal is to significantly reduce a host of global inequalities within 10–15 years' time, including ending poverty, fighting injustice and inequality, combating climate change, and protecting the entirety of Planet Earth.

SDG 14 (Life Below Water) seeks by 2030 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). From a physical standpoint, SDG 14 is motivated by the problem of heat (Figure 2), along with the fact that 30% of carbon dioxide produced by humans is absorbed by the ocean, which is buffering the impacts of global warming (NRC, 2010; Trenberth, 2010; Hönisch et al., 2012; Abraham et al., 2013). From a socioeconomic and public policy standpoint, Goal 14 is motivated by the fact that billions of people worldwide rely on the ocean's biodiversity for their livelihoods, reflecting a global market value of ocean resources and industries at $3 trillion per year, or about 5% of global GDP (United Nations, 2015b). The news is replete with stories of the hazards of hurricanes, tsunamis, rogue waves, sea level rise and coastal flooding, toxic spills, oxygen-poor "dead zones," and more. This is reflective of the ocean in a state of deep crisis. Indeed, we have changed the ocean to the point where there will be a wide range of negative consequences for ecosystems, fisheries, and tourism (e.g., NRC, 2010). And while SDG 14 is the only goal solely focused on ocean issues, there are numerous other goals that depend on or influence ocean health (e.g., SDGs 1 and 2 on Eliminating Poverty and Hunger, SDG 7 on Affordable and Clean Energy, SDG 8 on Decent Work and Economic Growth, and SDG 13 on Climate Action; Marine Ecosystems and Management, 2017).

The universal inclusiveness of the 2030 Agenda for Sustainable Development provides an ethical imperative to think, and to act, comprehensively and holistically, with important implications for public policy. Given the incredible power of maps to communicate, persuade, inspire, understand, and elicit action (e.g., Wood, 1992; Field and Demaj, 2012; Gale, 2013; Wright, 2015a,b), it stands to reason that they can be important tools for effectively communicating and achieving

FIGURE 1. Infographic of the 17 United Nations Sustainable Development Goals (from http://www.un.org/sustainabledevelopment/sustainable-development-goals).

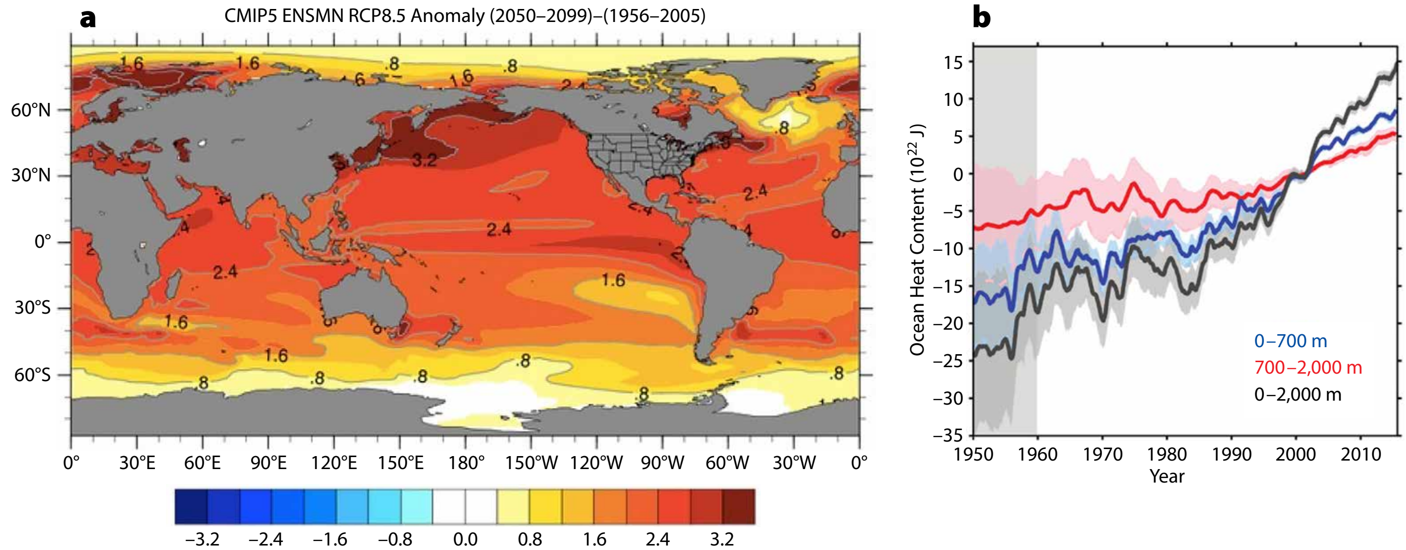

FIGURE 2. The problem of heat in the ocean, at the surface and at depth. (a) Changes in the mean sea surface temperature for the latter half of the twenty-first century via coupled model intercomparison project 5 (CMIP5) experiments for the period 1956–2005 (National Oceanic and Atmospheric Administration Earth System Research Laboratory, 2009). The map also shows averages of all models and the difference in mean climate in the future time period 2050–2099 (representative concentration pathway, RCP8.5) compared to the historical reference period. Ocean warming is greatest in the Northern Hemisphere and weakest in the North Atlantic and the Southern Ocean. (b) Global ocean heat content at 0–700 m depth (blue), 700–2,000 m depth (red), and 0–2,000 m depth (black) for the period 1955–2015, with the uncertainty of the ±2σ interval shown in gray shading. *Adapted from Cheng et al. (2017)*

the objectives of SDG 14, as well as the other SDGs. This is especially important because no SDG can be achieved without consideration of other, related goals (Lu et al., 2015; Brown, 2017). Mapping out the indicators is a natural first step, especially via integration, visualization, and analysis of heterogeneous, georeferenced data. If this is provided via geographic information systems (GIS), which often include interactive map "dashboards," decision-makers are better able to monitor and compare indicators for policy development and action at multiple geographic scales (Kraak, 2016). In recent years, our ability to measure change in the ocean is increasing, not only because of improved measuring devices and scientific techniques but also because new mapping technology is aiding us in better understanding this dynamic environment. The domain of ocean mapping (often codified in GIS) has progressed from applications that merely collect and display data to modeling and complex simulations as well as the development of new research methods and concepts (e.g., Manley and Tallet, 1990; NRC, 2004; Devillers and Gillespie, 2008; Wright, 2016).

A BRIEF HISTORY OF MAPPING IN THE OCEAN

Humankind has been mapping the ocean for hundreds of years, with one of the earliest examples being the "stick charts," comprised of pieces of wood, coconut fronds, and cowrie shells, devised by the ancient Marshall Islanders to help them navigate their part of the western Pacific Ocean in canoes (Lewis, 1994; Figure 3). These charts are significant in the history of cartography because they are the first known representations of ocean swells, including island disruption of these

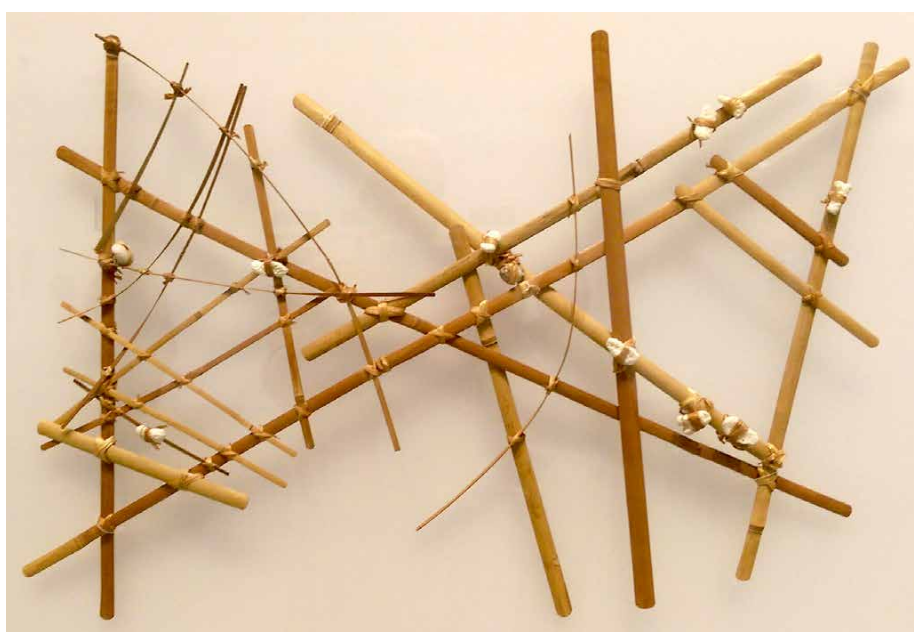

FIGURE 3. A navigational "stick chart" from the Marshall Islands made of wood, coconut fibers, and cowrie shells, with the fibers representing the crests of ocean swells. This chart is on display at the Berkeley Art Museum and Pacific Film Archive, University of California, Berkeley. *Photo by Jim Heaphy and reproduced under Creative Commons License CC BY-SA 3.0 by Cullen328 via Wikimedia Commons*

wave patterns (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).

During the 1872–1876 global expedition that laid the foundation for modern oceanography, scientists aboard HMS *Challenger* conducted the first systematic (bathymetric) survey of the ocean floor, 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 of lead was lowered to the ocean floor by rope in order to measure the water depth. In the 1920s, the German ship *Meteor* conducted the first detailed bathymetric survey of the South Atlantic Ocean floor by way of early sonar (SOund Navigation And Ranging), determining the depth of the water 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 when the navies of the United States, Great Britain, Germany, and Japan were leaders in further developing sonar capabilities for knowledge of the enemy, as well as of the ocean.

FIGURE 4. A map of the Atlantic Ocean floor published in 1968 based on a large number of deep ocean soundings compiled by Bruce Heezen and Marie Tharp, painted by Heinrich Berann for *National Geographic Magazine*. *Image courtesy of Ken Field, International Cartographic Association*

By the 1950s and 1960s the single, focused, high-frequency, short wavelength sound beams (aka single-beam sonar) had become an invaluable tool not only for mapping the ocean floor but also for detecting specific targets within the water column such as marine mammals or large schools of fish. In 1968 (Figure 4), the Austrian landscape panoramist and cartographer Heinrich Berann, working in collaboration with marine cartographer Marie Tharp and marine geophysicist Bruce Heezen, produced a painting of the Atlantic Ocean floor, thus creating the first in a series of physiographic maps of the ocean floor, work that 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 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 systems of the 1970s and 1980s yielded as many one 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, combined with estimates of bathymetry derived from Earth's gravity field as measured 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 ocean is still accomplished with mapping systems located *beneath* a ship, but it 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 5). The resulting maps continue to reveal ocean bathymetry for science, navigation, finding of lost objects, and pinpointing of hazards due to sea level rise and coastal flooding, but there also maps of ocean water temperature and salinity 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 (NRC, 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 ocean for science, for sustainability, and for the science *of* sustainability requires not only the accurate collection of measurements but also 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)?

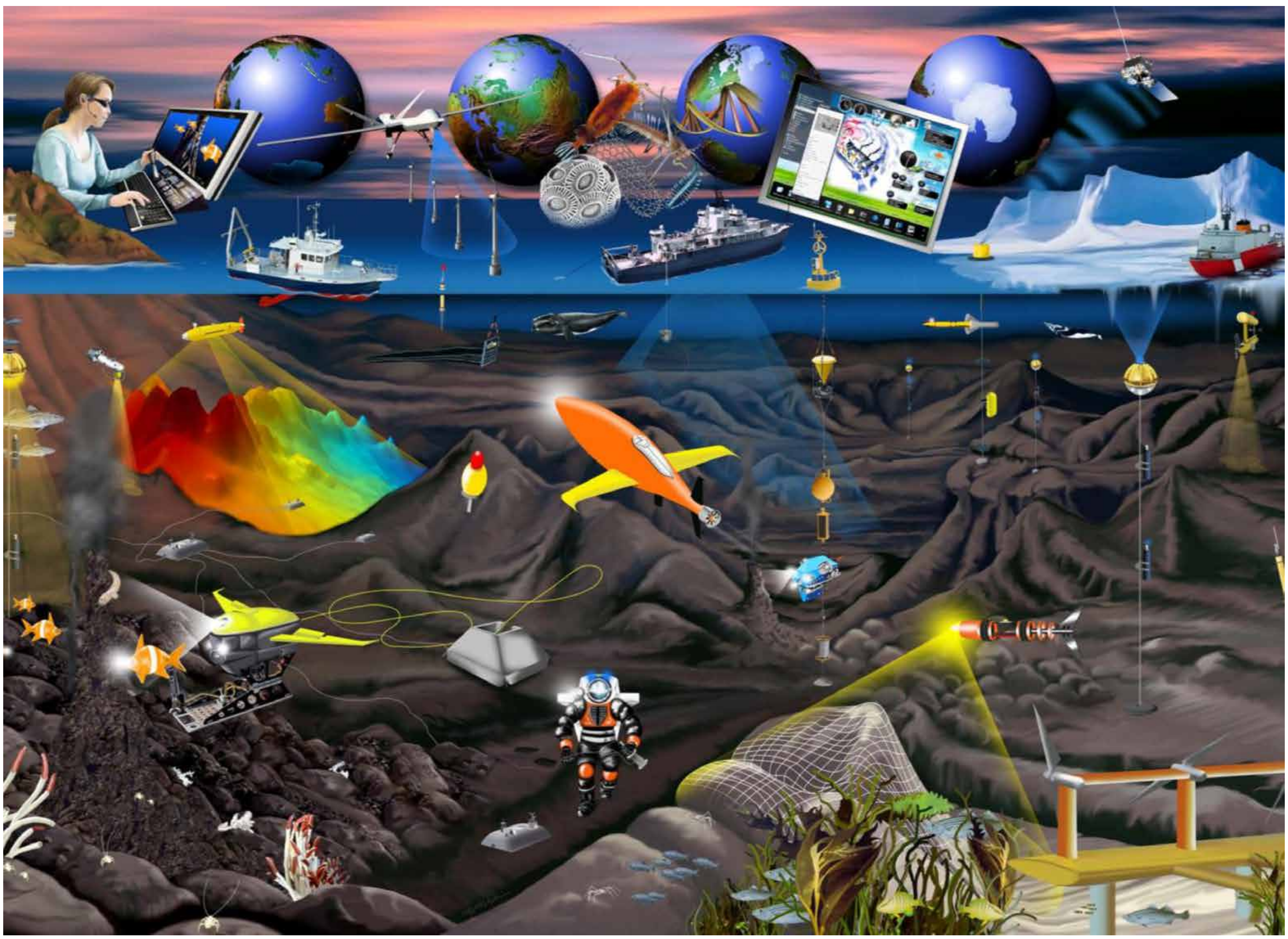

FIGURE 5. An illustration of the broad variety of the ships, vehicles, platforms, and sensors used now and looking 20 years into the future for understanding how the ocean works, and how we need to manage and protect it. *From National Research Council (2011)*

NEW INNOVATIONS

But what is a "map" in the modern, twenty-first 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 desktop GIS. 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 or from any number of data and web mapping services worldwide that are freely available on the Internet. In fact, just about anyone can access platforms to make maps; to combine their maps with other layers to create new maps; 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 often available as Representational State Transfer (REST) services (Yang et al., 2012), which are designed expressly for the Internet and 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, smarter maps contain 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 distributions of marine habitats, energy resources, and infrastructure, and then, using these as a reference, to sketch on the screen the polygonal 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 intelligent web map can adjust accordingly, automatically saving the polygon as a 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 regarding 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 intelligent maps process events through both space and time via statistics and numerical models that are used to predict currents, seawater 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

Photo credit: SIO Archives, UCSD

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 received his PhD in oceanography from the University of California, Berkeley, in 1936. 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.

marine protected areas. Geospatial tools that generate distributive flow lines from one source 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 intelligent 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 ocean, 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 that consists 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 6), and much more. The ocean presents so many multidimensional challenges, especially because it is very hard to access at full depth from the sea surface to the seafloor. Satellites and LiDAR (Light Detection And Ranging) sensors, for example, cannot see all the way through the water in all places. As a result, only 8%–15% of the ocean is 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 ocean works, as well as how dangerous it can be. Figure 7 shows a new way to visualize the major typhoons that raged throughout the western Pacific

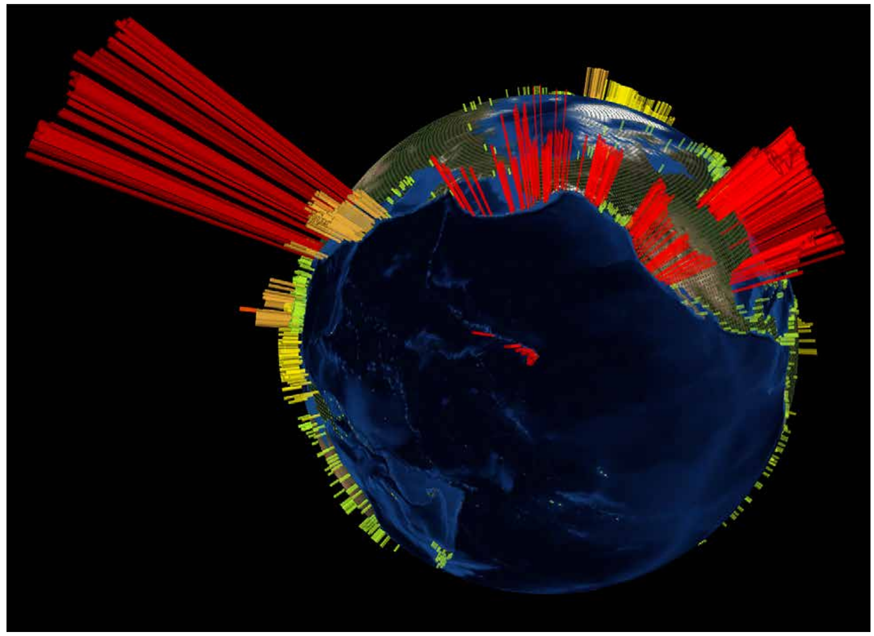

FIGURE 6. Visualization of the high volume of commercial shipping activity into and out of ports rimming the Pacific Ocean. Green bars represent shipping traffic of 1 million vessels, yellow 20 million, and red 50 million+. Lengths of bars represent amounts of growth in those numbers over a 10-year period. 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)*

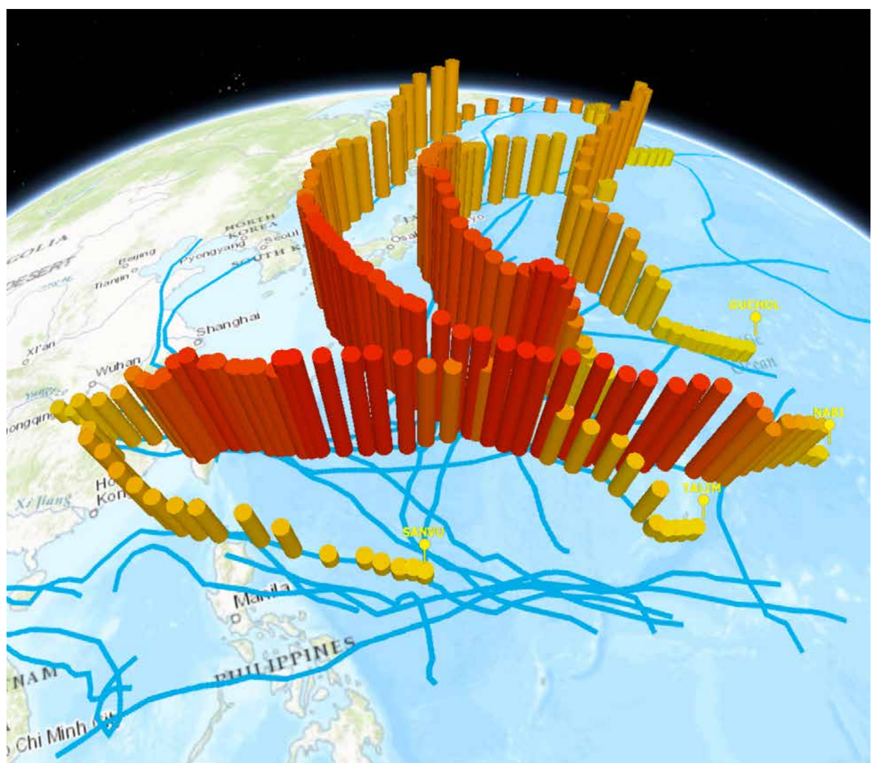

FIGURE 7. A map of typhoons in the western Pacific during the record-breaking typhoon season of 2005, seeking to visualize the life cycle of the event and compare one storm to another in order to find unique details and overall patterns. Three-dimensional symbols depict the unique signature of every 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*

in August 2005, along with the variation in their intensity and thus danger to human life. From a more analytical standpoint, intelligent 3D maps allow 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 are 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 (e.g., k-means statistical clustering of point measurements in the ocean to identify and map environmentally distinct 3D regions within the water column—termed "candidate ecosystems" by Sayre et al., 2017).

Another powerful mode of spatial analysis involves the interpolation of point measurements or samples in the water column. In Figure 8, the points are measurements of oil in seawater after an oil spill, with pollutant concentrations integrated from the surface to a specific depth interpolated into a "fence" or "curtain." The GIS toolbox of Fraczek and Gerlt (2016) allows the scientist to cut slices through 3D point data and apply to the slices a geostatistical technique known as empirical Bayesian kriging (EBK, which includes the provision of statistical error surfaces). This technique is used to interpolate values between points and then convert the EBK output to points for display (as either EBK prediction or EBK prediction standard error), as well as options to control minimum fence dimensions, sample points, and interpolation resolution. Motivated and curious users with Python scripting skills can modify the tool to change the interpolation method if the input data warrant use of a different geostatistical method.

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 "intelligent" 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 ocean. As an example, from the world of ocean observatories, Figure 5 (NRC, 2011) provides a glimpse of today's technology as well as that ~20 years into the future. These observatories produce the so-called phenomenon of "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." This big data phenomenon, with its three main characteristics of volume, velocity, and variety, is 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 also affect 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

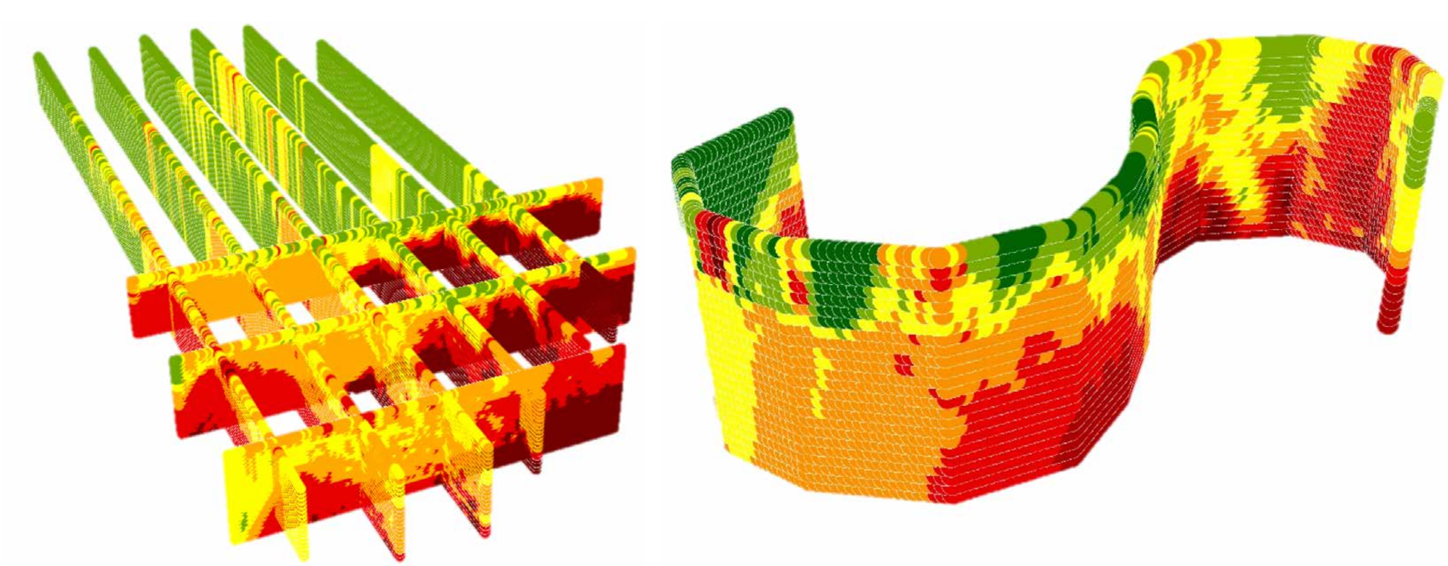

FIGURE 8. (left) Output from a GIS analytical tool (freely available from http://esriurl.com/3dfence) that can generate sets of parallel fence diagrams in directions that are related to longitudes, latitudes, or depths. (right) An interactive function in the tool can generate fences based on lines digitized on a map by the analyst. These 3D fence diagrams represent interpolated concentration of oil at depth after an oil spill in the Gulf of Mexico. Entire surfaces can be combined at depth in both horizontal and vertical directions.

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 toward an 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 (e.g., governments, military, industry, nongovernmental organizations [NGOs]), 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.

Though tackling these problems has largely been in the realm of academia and federal agencies, a new ocean data industry 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 example of a successful PPP based 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) in nine Societal Benefit Areas: Agriculture, Biodiversity, Climate, Disasters, Ecosystems, Energy, Health, Water, and Weather (Group on Earth Observations, 2005, 2017; Walters and Scholes, 2017). To meet the challenge set forth by GEO, an innovative PPP was formed, led by the U.S. Geological Survey and the Environmental Systems Research Institute (Esri) in collaboration with NatureServe, the Marine Conservation Institute, Duke University, the Woods Hole Oceanographic Institution, the National Oceanic and Atmospheric Administration, and the National Aeronautics and Space Administration in the US, the University of Auckland and the National Institute of Water and Atmospheric Research in New Zealand), and GRID-Arendal in Norway (Environmental Systems Research Institute, 2016). The EMU delineated the ocean into 37 physically and chemically distinct volumetric regions, from the ocean surface all the way down to the ocean floor (Figure 9; Sayre et al., 2017). Additional information attributes 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 that are set in a mapping coordinate system and that have been collected over a 50-year period as derived from NOAA's World Ocean Atlas (Garcia et al., 2013a,b; Locarnini et al., 2013; Zweng et al., 2013). The EMUs resulted from a rigorous k-means statistical clustering of six ocean variables most likely to drive ecosystem responses (temperature, salinity, dissolved oxygen, nitrate, phosphate, and silicate; Sayre et al., 2017).

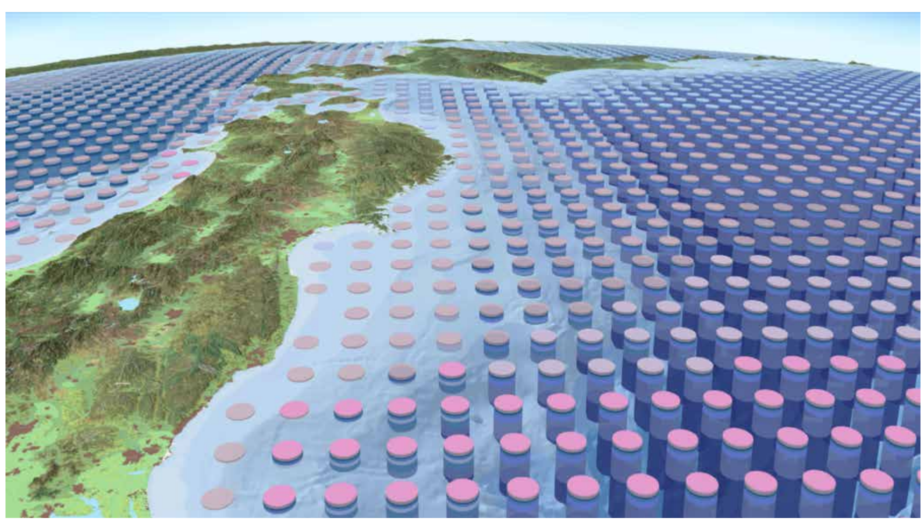

FIGURE 9. Example of a visualization approach taken to represent a new classification for the ocean known as ecological marine units (EMUs) in three dimensions mapped over space. The region shown is largely off the east coast of Japan in the Pacific Ocean. Although the EMUs are mapped as a continuous 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*

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, including the fostering of sustainability as championed by the SDGs?

A full treatise on all aspects of open science is beyond the scope of this paper (see instead Baker and Chandler, 2008; Gargouri et al., 2010; Glover et al., 2010; Tenopir et al., 2011; The Royal Society, 2012; Costello and Wieczorek, 2014; Gallagher et al., 2015; Assante et al., 2016; Cutcher-Gershenfeld et al., 2016; Singleton et al., 2016). But suffice it to say that many organizations have fully dedicated themselves to fostering a counterculture in which not only are the tables, figures, statistics, and printed maps in published papers readily accessible but also the actual digital data sets themselves; these dedicated organizations include the Research Data Alliance (RDA), the Federation of Earth Science Information Partners, and specifically for the ocean community, the Intergovernmental Oceanographic Data and Information Exchange (IODE) of UNESCO's Intergovernmental Oceanographic Commission, the Ocean Data Interoperability Platform (funded in parallel by the European Commission, the Australian government, and the US National Science Foundation), the Interdisciplinary Earth Data Alliance (Lamont-Doherty Earth Observatory), the Biological & Chemical Oceanography Data Management Office (Woods Hole Oceanographic Institution), the National Science Foundation's EarthCube initiative, and many more. 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. 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 and 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). Despite these efforts, it remains a challenge to find a balance between individual and national interests (e.g., intellectual property rights versus national defense) and those of the global community (Glover et al., 2010).

Perhaps most importantly, many organizations are exercising the FAIR principle (Findable, Accessible, Interoperable, Re-usable) 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" (reasserting that science is a global public good). And particularly in local government circles where scientific data are used for public policy, there are efforts to move map data (i.e., geospatial data) from being regarded as 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,b) 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 reusable
- Practicing interoperability and crosswalking via the integration of data with a host of scientific tools and libraries
- 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 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 10 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, and even sounds but also for telling specific and compelling stories by way of that content (Wright et al., 2014). Scientists are learning how to combine "intelligent web maps" to synthesize data along with a primary interpretative message to inform, educate, and inspire about a wide variety of ocean science and policy issues. Figure 10 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 intelligent 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 and in areas deep enough to accommodate larger ships. The story map provides a digital storybook or lasting record of their data and approaches for use in subsequent efforts and as a communication tool for the Jacksonville Port Authority, the Florida Department of Transportation, field scientists, hydrographic surveyors, recreational boaters, and local politicians.

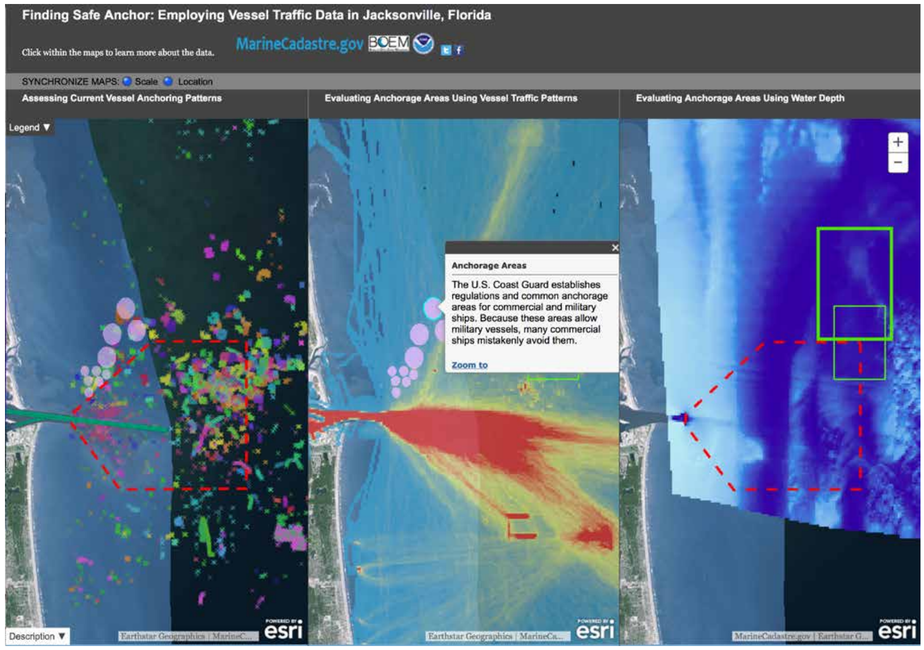

FIGURE 10. Example of a story map used in a US Coast Guard/NOAA workshop. Panning or zooming in one of the map panels synchronizes the same map scale and location for the other two so that users can simultaneously examine vessel anchoring patterns (left), vessel traffic patterns (middle), and water depth (right) in order to propose the safest new anchorage areas. Link to story map available from http://esriurl.com/ocnstories.

FIGURE 11. A GIS dashboard commissioned by the United Nations to aid in the implementation and management of the Sustainable Development Goals listed under the 2030 Agenda for Sustainable Development, in this case for displaying progress on Goal 14, Target 1, regarding reducing marine pollution of all kinds, including marine debris. Interactive, online version available at http://github.com/Esri/sdg-dash.

CONCLUSION

Perhaps the biggest monster of all will be achieving the SDGs by 2030. 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 these goals are more aligned with mapping and geography than ever before. Indeed, the SDGs provide a unique opportunity to deploy a range of map dashboards (Figure 11) 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 participate actively in the progress, no doubt with healthy debate along the way, with direct access to authoritative information that is near-real time, cross-comparable, and useful for prioritization of activities and programs across human and physical landscapes.

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 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 disconnects 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.

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