Swells, Soundings, and Sustainability…But "Here be Monsters"

Mapping Oceans of Data for a Sustainable Sea

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18th Annual Roger Revelle Commemorative Lecture
Ocean Studies Board, National Academy of Sciences
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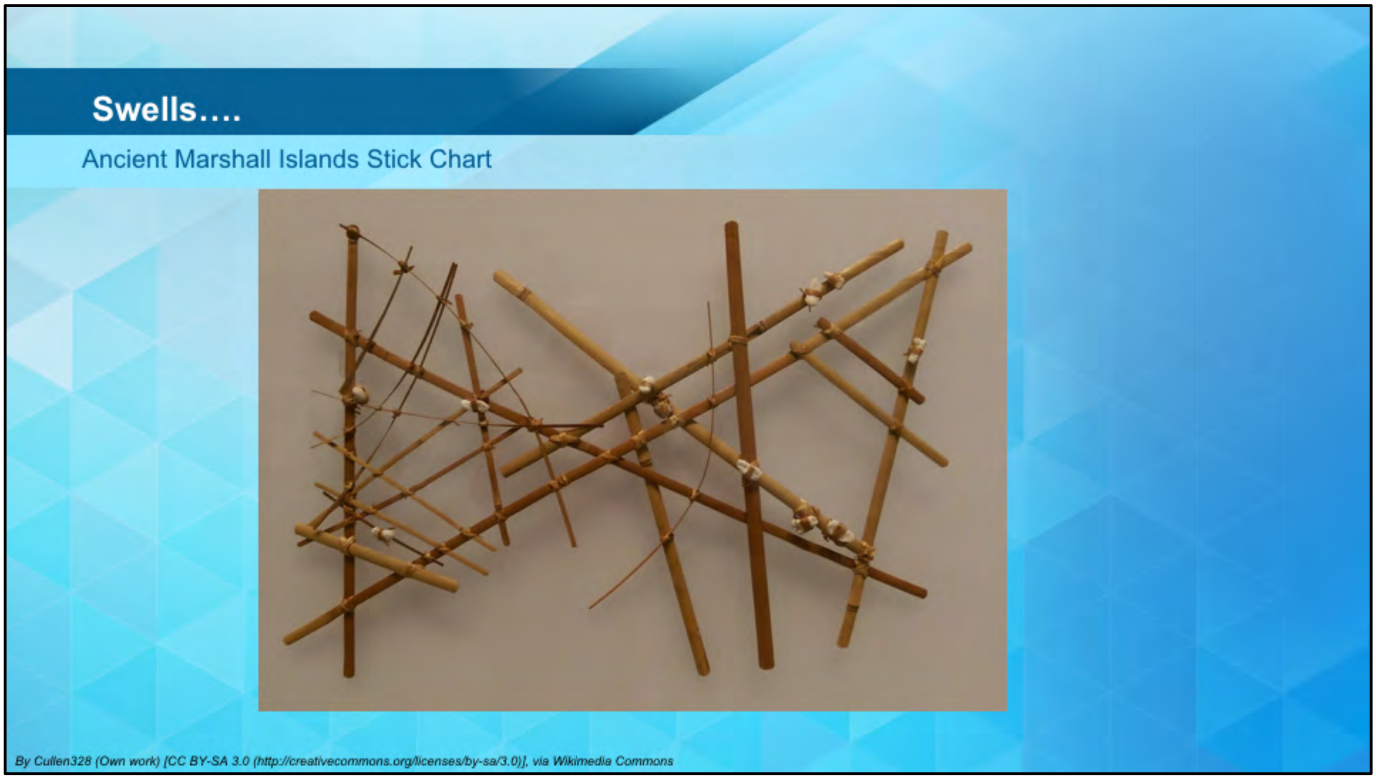
Some Past History

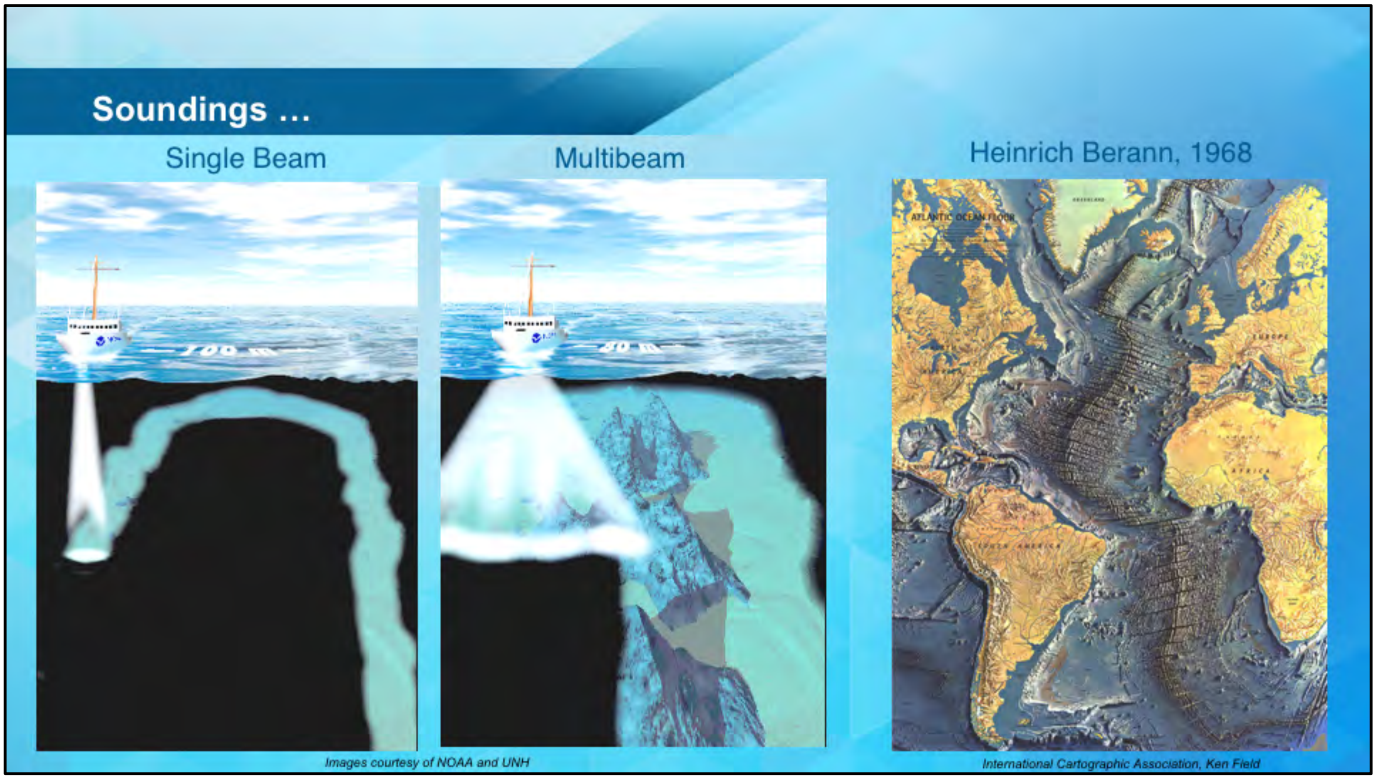
New Innovations

Taming the Monsters



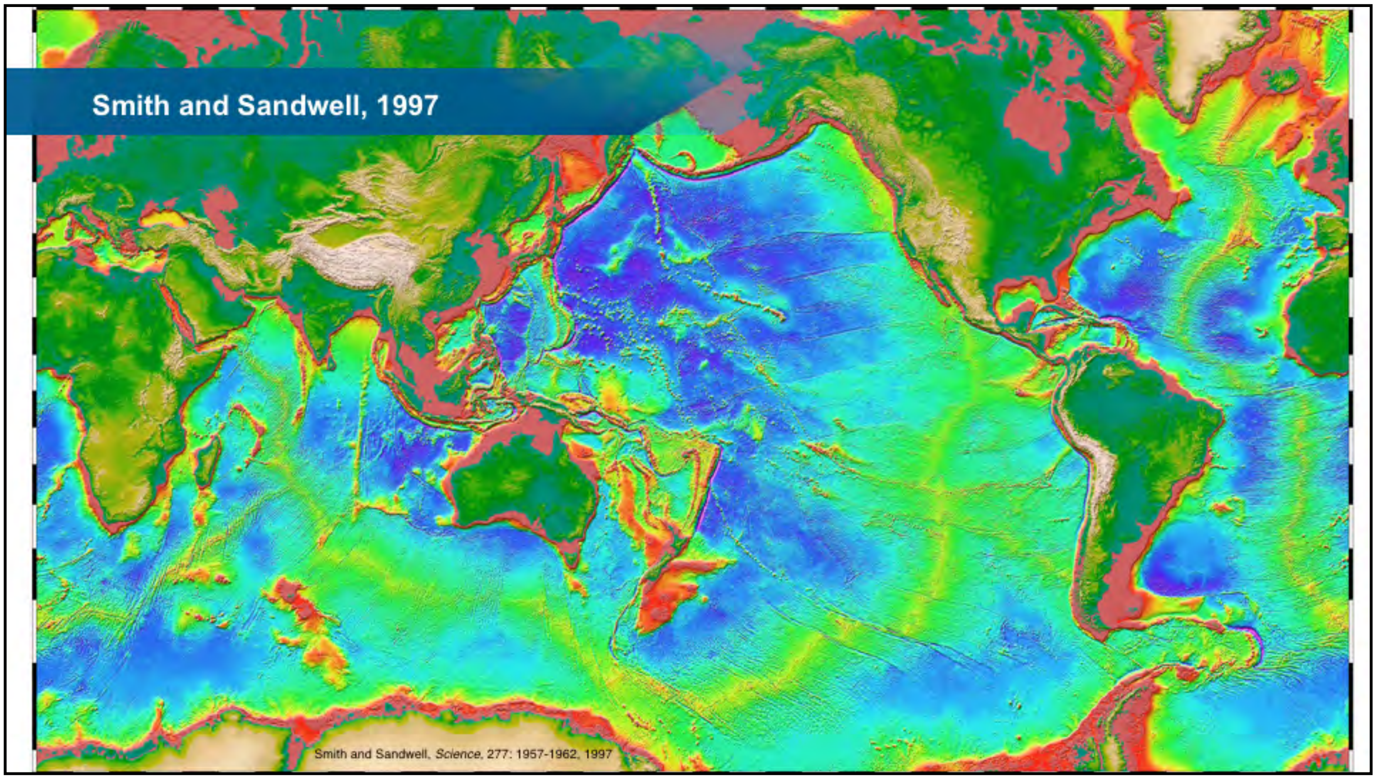
We've been mapping the oceans for hundreds of years from Marshall Island Stick charts made and used by the Marshallese to navigate the Pacific Ocean by canoe off the coast of the Marshall Islands. The charts represented major ocean swell patterns and the ways the islands disrupted those patterns, typically determined by sensing disruptions in ocean swells by islands during sea navigation. **The stick charts are a significant contribution to the history of cartography because they represent a system of mapping ocean swells, which was never before accomplished.** Traditional knowledge, but not described by Western societies until 1862

A navigational chart from the Marshall Islands, on display at the Berkeley Art Museum and Pacific Film Archive. It is made of wood, sennit fiber and cowrie shells. From the collection of the Phoebe A. Hearst Museum of Anthropology at the University of California, Berkeley. Date not known. Photo by Jim Heaphy.
https://en.wikipedia.org/wiki/Marshall_Islands_stick_chart



In 1967, Austrian landscape panoramist and cartographer Heinrich Berann painted the first in a series of plan oblique physiographic maps of the ocean floor which ultimately culminated in the 1977 World Ocean Floor map for Columbia University and the U.S. Navy. He worked in collaboration with Bruce Heezen and Marie Tharp, who as we know together revolutionized the theories of plate tectonics and continental drift. Speaking of Soundings, this is also the title of a book that I would highly recommend, authored by Hali Felt. It tells the story of Marie Tharp, a woman with a background and training unusual for the time in both geology and mathematics, coupled with art, to have the courage of her convictions and her intellect to posit one of the most fundamental proofs of continental drift: a rift valley caused by the faulting of seafloor spreading. But because she was a woman, her contributions were belittled or outright ignored.

A photograph of the famous 1977 World Ocean Floor map by Marie Tharp and Bruce Heezen that hangs on my wall at home.



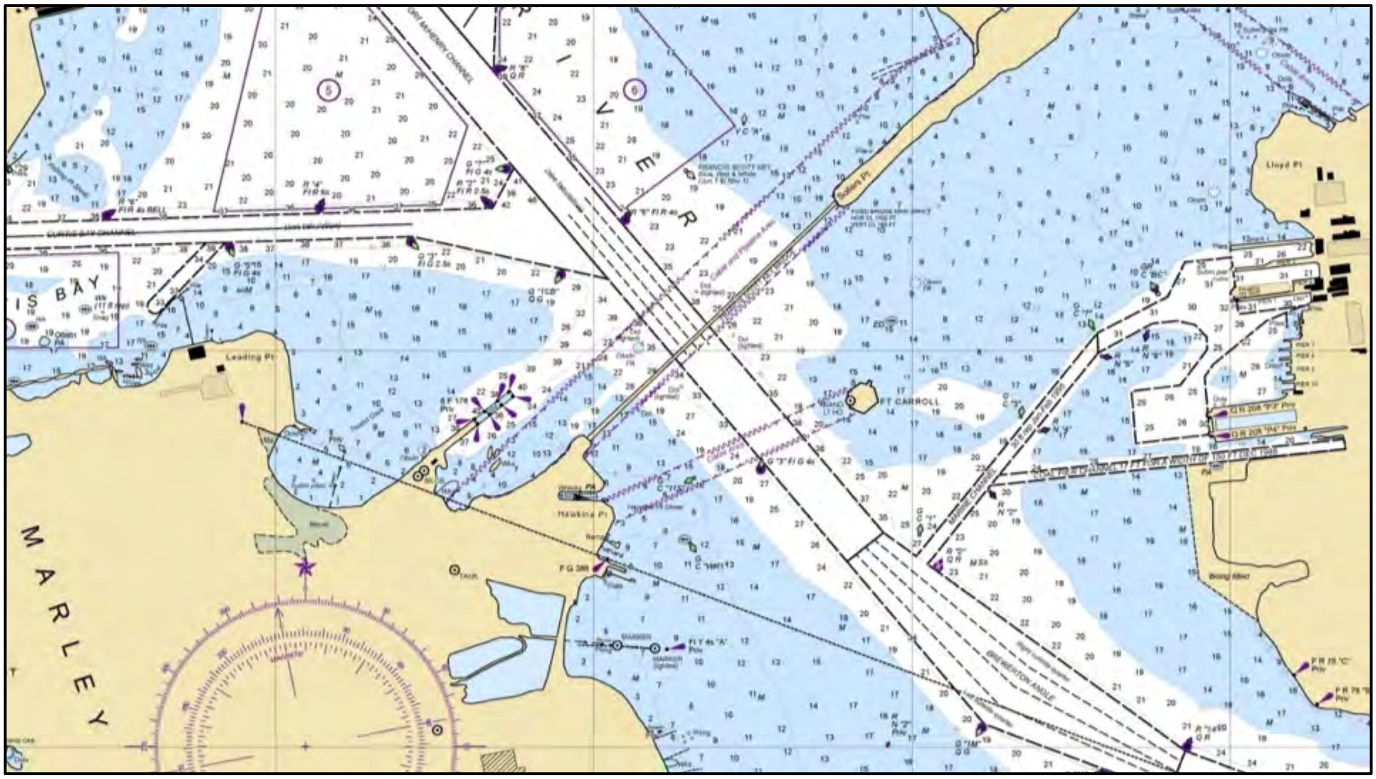
Sandwell & Smith global seafloor topography derived from satellite altimetry (declassified Department of Defense data combined with European data)
Basically measuring “bumps” in sea surface height - these mimic bottom topography

I will use the UN Sustainable Development Goals (SDGs) as an overarching context for my remarks this evening. Despite the leanings of the current administration in the White House many of us are holding fast to the ideal of the SDGs. The universal inclusiveness of the 2030 Agenda for Sustainable Development is an ethical imperative to think, and to act, comprehensively and holistically, e.g., about ending poverty, combating climate change, and ending injustice and inequality.

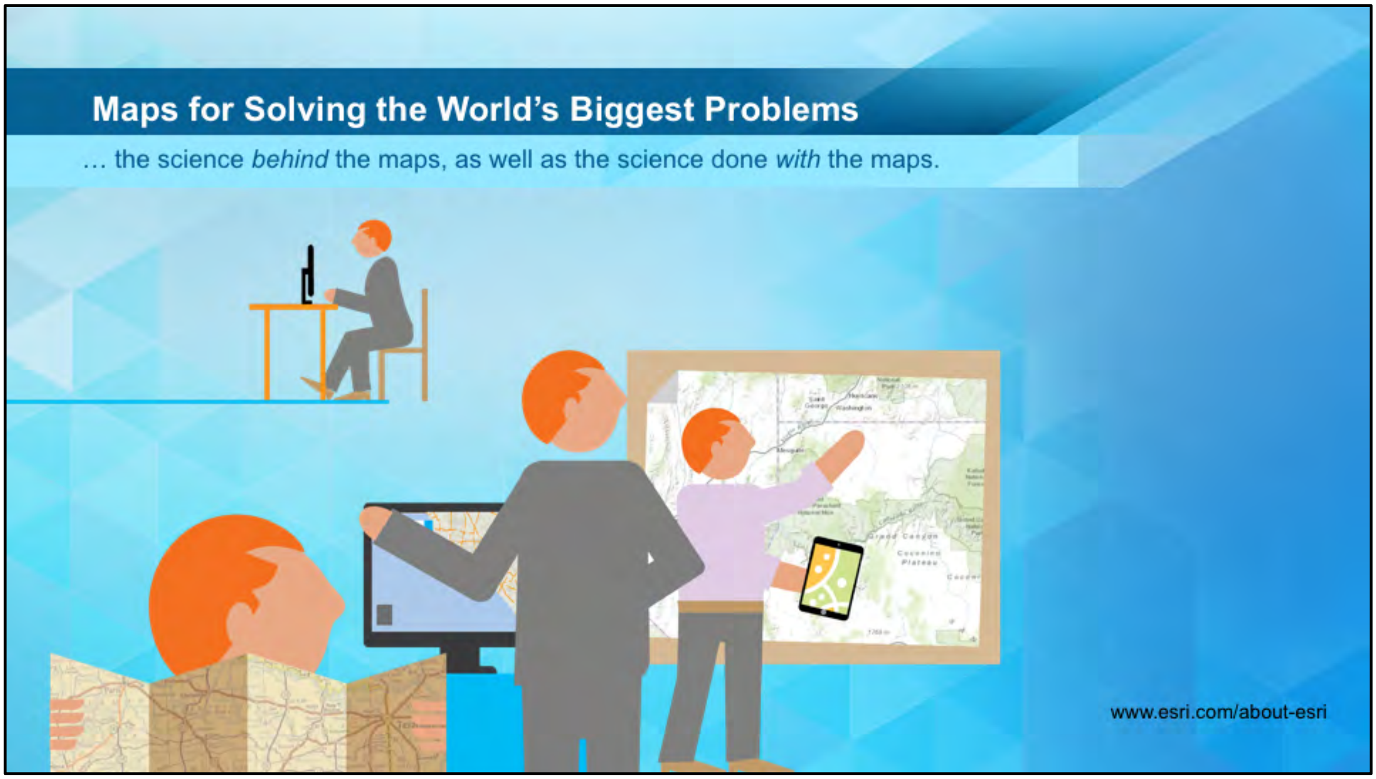
To effectively communicate and achieve the urgent objectives of these sustainability goals, we will need to draw upon a vast wealth of cartographic design and GIS experience.

Especially in the spirit of tomorrow's People's Climate March, and certainly for the ocean, SDG 13 is certainly within our wheelhouse

But it is SDG 14 that we really want to focus on this evening, as it is all about "Life Below Water" with an eye toward reducing marine debris and other types of pollution, managing and protecting the ocean, ending overfishing, addressing ocean acidification



When we think about mapping the oceans many of us think of traditional nautical charts. They contain a wealth of detail and remain important in both paper and digital form. But mapping the oceans for science, for sustainability, and for the science OF sustainability requires different products, new products, immersive and interactive products as well as maps of new data and models.

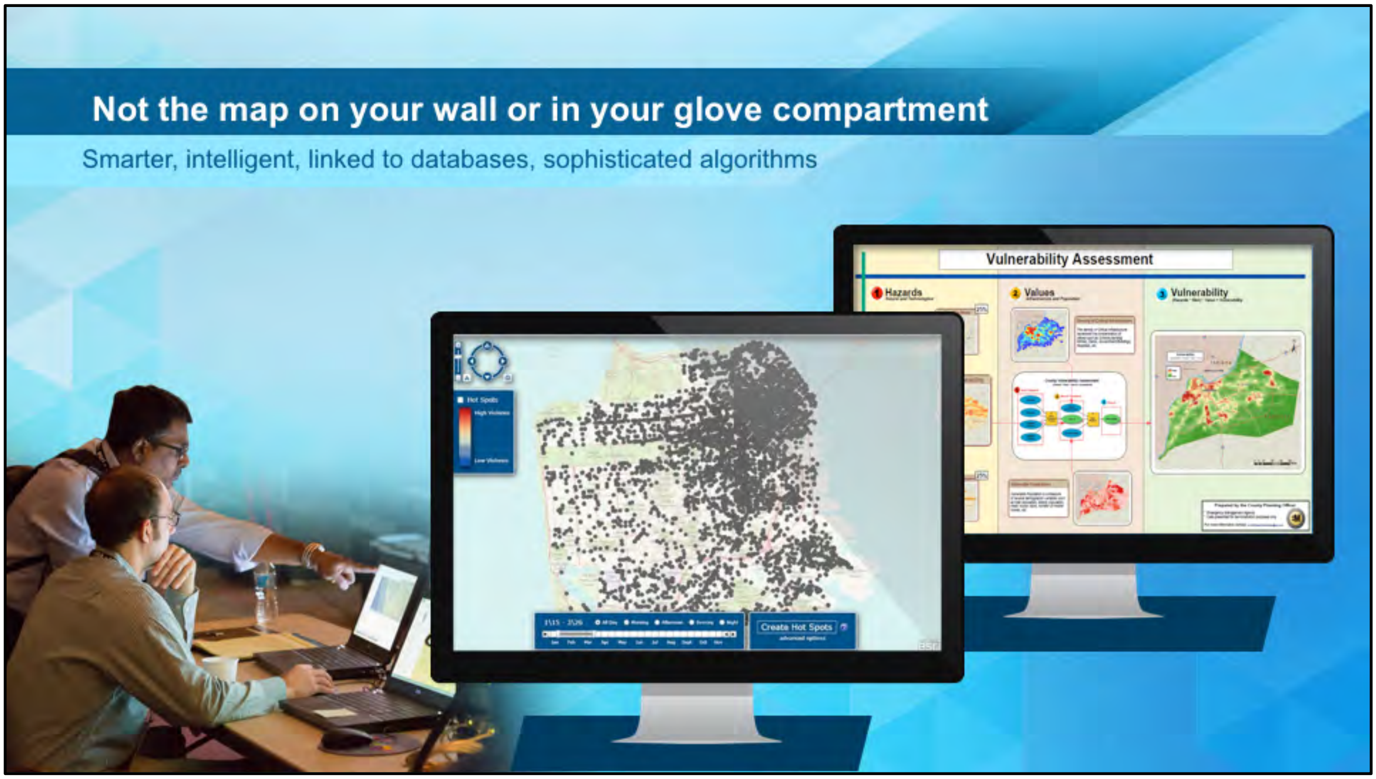


Indeed we are talking about making maps for solving the world's biggest problems, conservation, disaster aid and relief, climate change mitigation and adaptation, "geodesigning" land and ocean space use to more closely follow natural systems, protecting freshwater resources, in short, **using maps and geographic analysis to make the world a better place.**

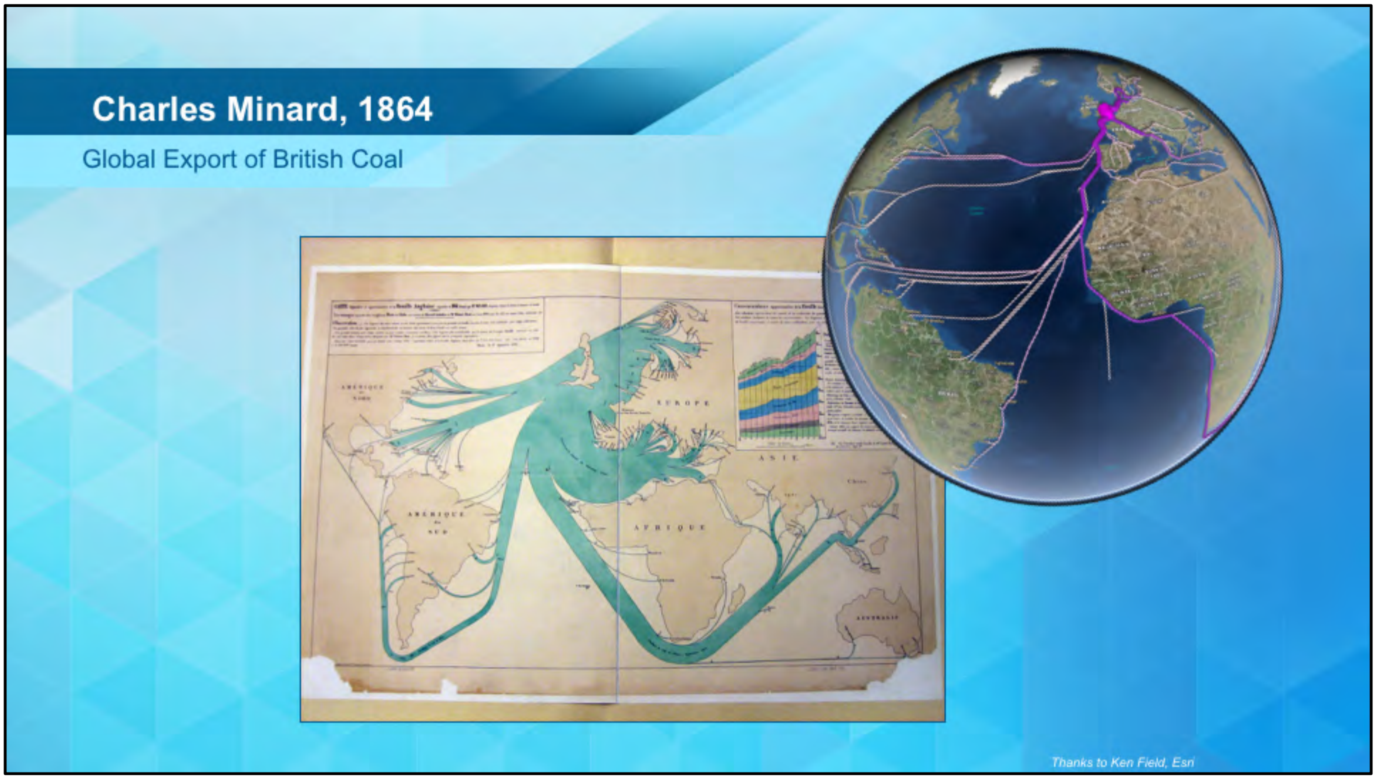
Indeed, we now find ourselves inhabiting a “Digital Earth” composed of technologies from satellites to wristwatches that monitor, map, model and manage virtually everything around us. As such, there are some amazing new innovations in place.

But what is a ”map” in this context? It’s not the paper map on your wall or in the glove compartment of your car.

The slide shows the standard view of the geographic information system or GIS (aka a smart or intelligent map). But in the talk I hope to convey that “this is not just about your eyeballs on a map, it’s looking at the invisible rubber bands of mathematical manipulation of these different layers.” It’s about the coupling of the appropriate data, analysis and manipulation, and compelling design to effectively communicate the results, and when appropriate, the possible models and future scenarios.



These new kinds of maps are smarter, more intelligent
By linking geographic coordinates with extensive databases and sophisticated spatial analysis algorithms in geographic information systems, they do more than feature pushpins, pop-ups or static lines. These maps can tell time, process events through both space and time via statistics and numerical models, send alerts to a computer or mobile device if something enters an area of interest, or help design marine protected areas. They 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 it all. And increasingly this is all taking place in the cloud and becoming more open, without the need for cumbersome desktop hardware and software with their steep, long learning curves.



Many maps of how we use the oceans have become regarded as classics such as Charles Minard's map of the export of British coal in 1864, but this doesn't mean we can't bring the cartography up-to-date for modern audiences and technology.
Here, the same data Minard used has been woven onto a 3D globe replete with 3D symbology.

This is an example of a ‘flow map.”
Flow maps are used to show the movement of goods or people from one place to another. This display shows the export of coal (thousands of tons) from England during 1864.

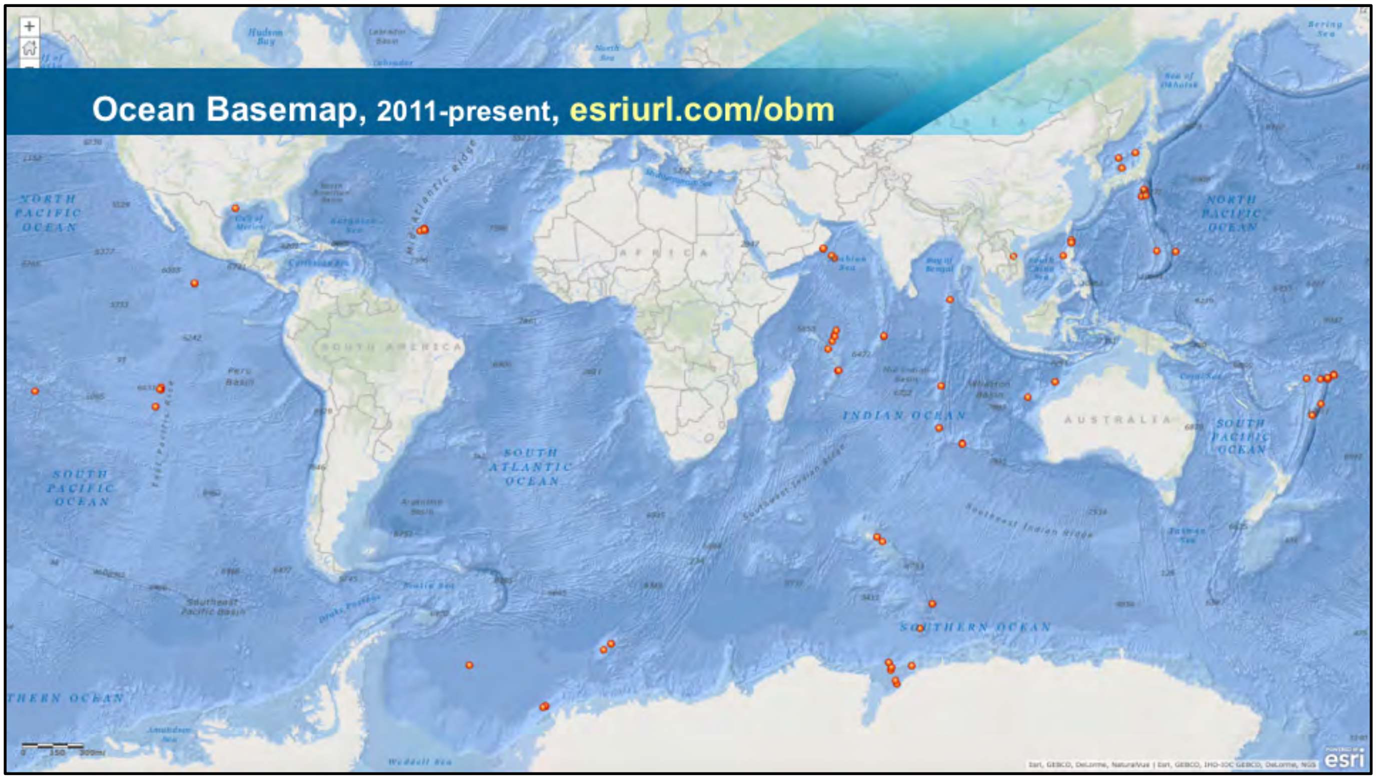
An interesting side note, especially in light of tomorrow’s People’s Climate March, **is that just last week Great Britain went a full day without using coal to generate ANY of its electricity, the first time since the Industrial Revolution (gridwatch.ac.uk)**. Britain plans to phase out coal by 2025 to cut carbon emissions. Whiter the United States?....

GIS deep dive: The tool behind the map generates distributive flow lines from one source to many destination points. If a polygon feature class is used for the source or destinations, centroids will be created and used as starting/ending points. Source, destination, and (optional) impassable and foreground feature classes should all projected for best results. If the processing extent covers the entire width of the globe, flow lines may "wrap around" to the other side of the map resulting in a confusing representation. To prevent this, decrease both the Left and Right extent processing values by at least one "Cell Size". *The tool itself can be downloaded for free at http://www.arcgis.com/home/item.html?id=04fa6ed8746b451892f339011aaf989d*

Heezen and Tharp, 1977

Hanging on Dawn's wall

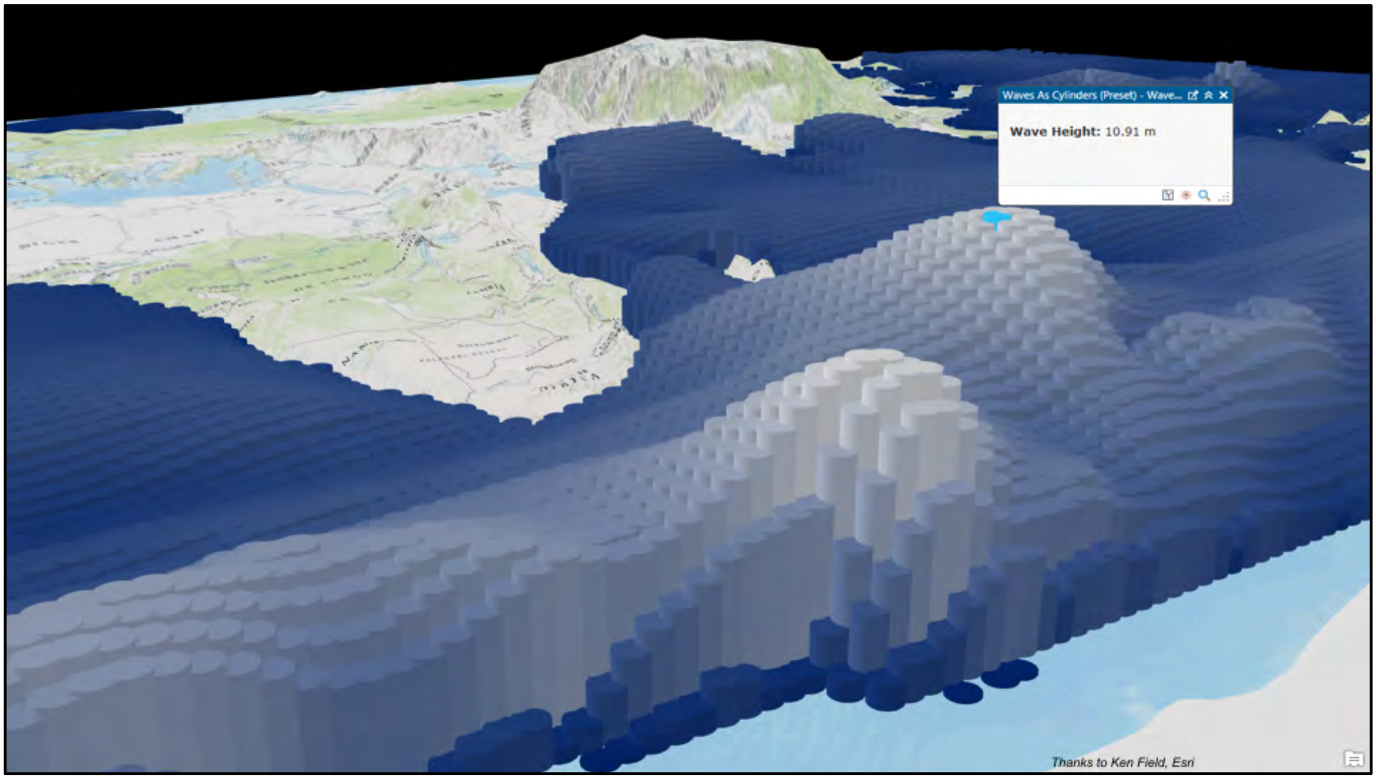
Returning to the old Heezen and Tharp …



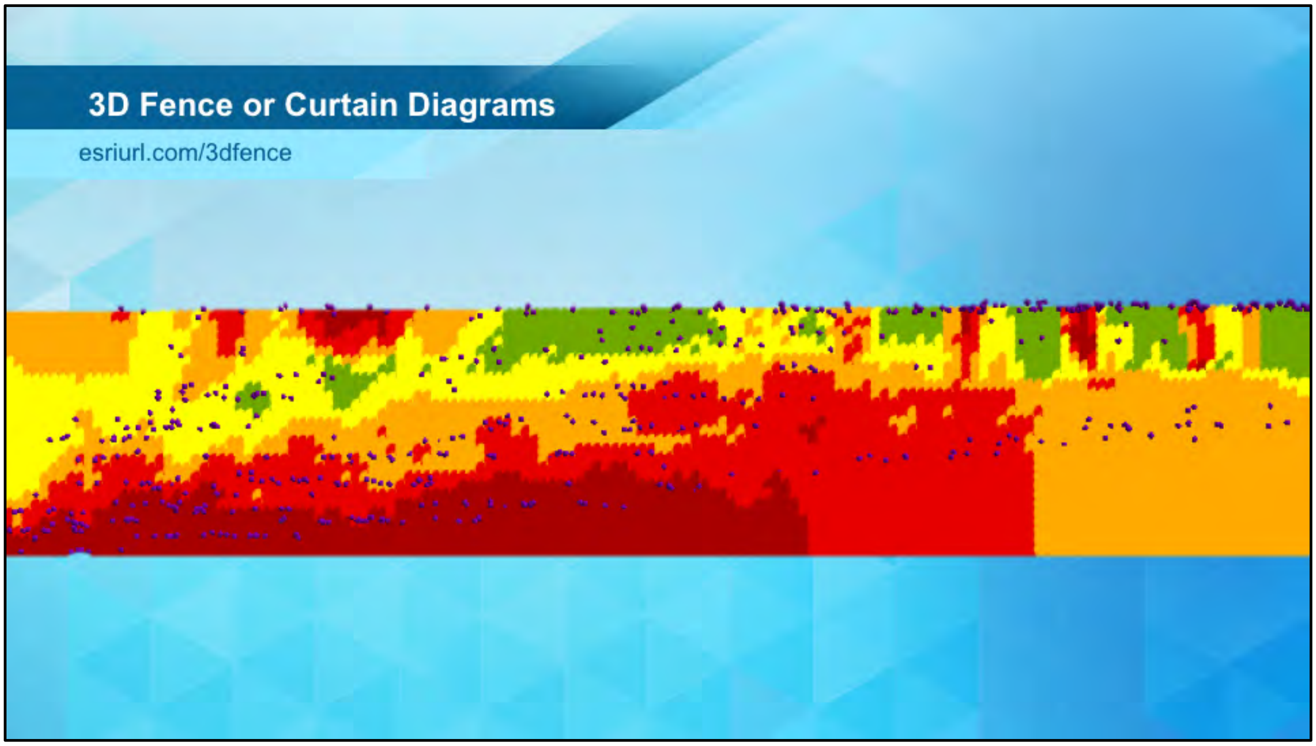
The “new” Heezen and Tharp if you will. An ocean basemap, our effort at Esri to **continue the legacy of Marie Tharp.** Here bathymetry exists as a **web service**, upon which you can interactively overlay any number of points, lines, polygons, other LAYERS of your choice. Dots show places where I have been to sea for deepsea drilling or for surveys, **including aboard the R/V *Roger Revelle.***

Animations can be overlain as well, as seen with this simulation by UH-Manoa of the estimated 1.5 million TONS of debris headed to the US and Canadian west coast from the 2011 Tohoku-Oki earthquake and tsunami. The pictures below show some of the debris already washed ashore. One of the big surprises here has been the sheer number of living sea creatures attached to these debris, some of which are invasive and could devastate local populations. The debris is still a threat to the entire US west coast. The final picture is from as recently as MARCH 2016 on the Oregon Coast, courtesy of Oregon State University, 5 YEARS AFTER the original earthquake and tsunami.

An additional tidbit is that a seafloor pressure sensor manufactured in Redmond, WA but installed offshore of Japan broke loose off the Japanese coast after the 2011 quake and tsunami, was carried across the Pacific in a marine debris field and washed ashore in Willapa Bay, WA in 2016 and STILL WORKED!

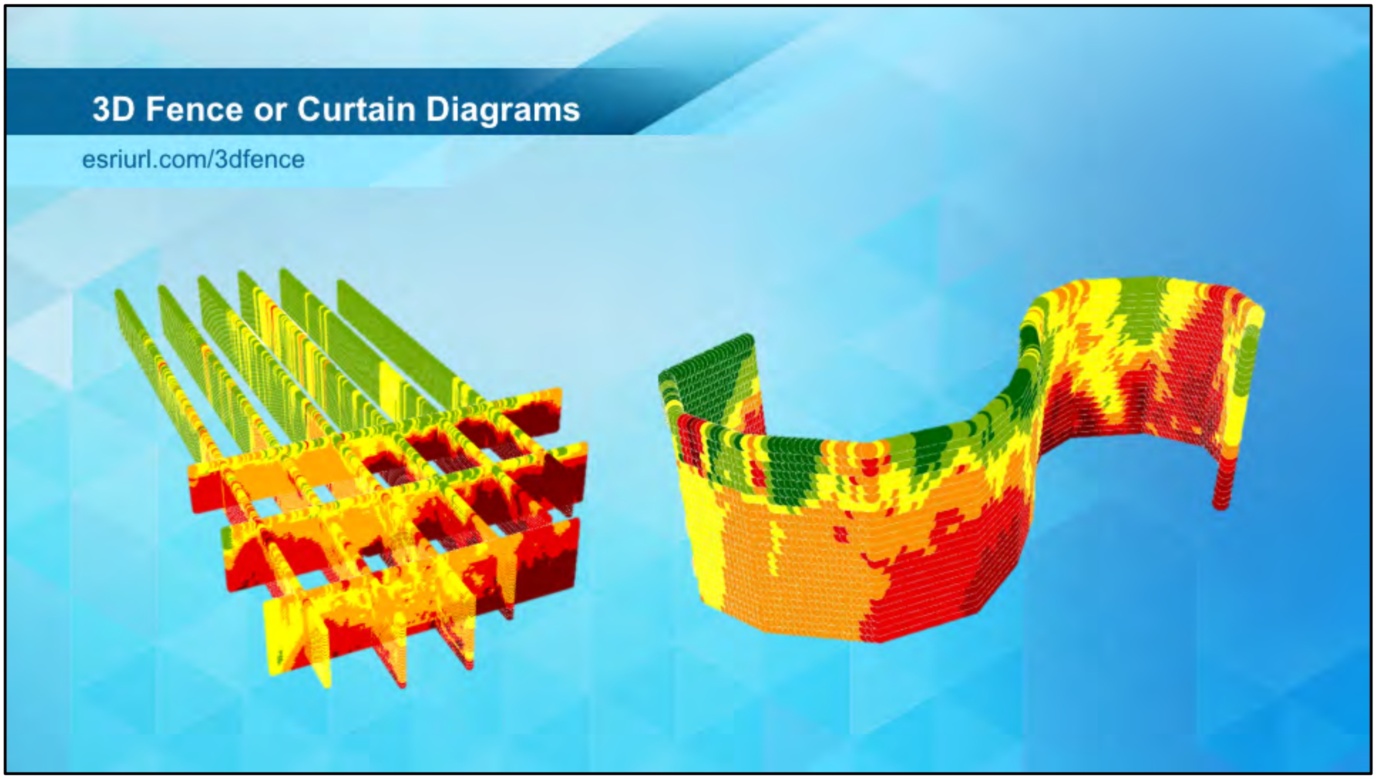


Certainly with the oceans we want to move mapping into the realm of 3D. This 3D view of wave height uses extruded columns of water on an isometric map to illustrate amplitude differences.

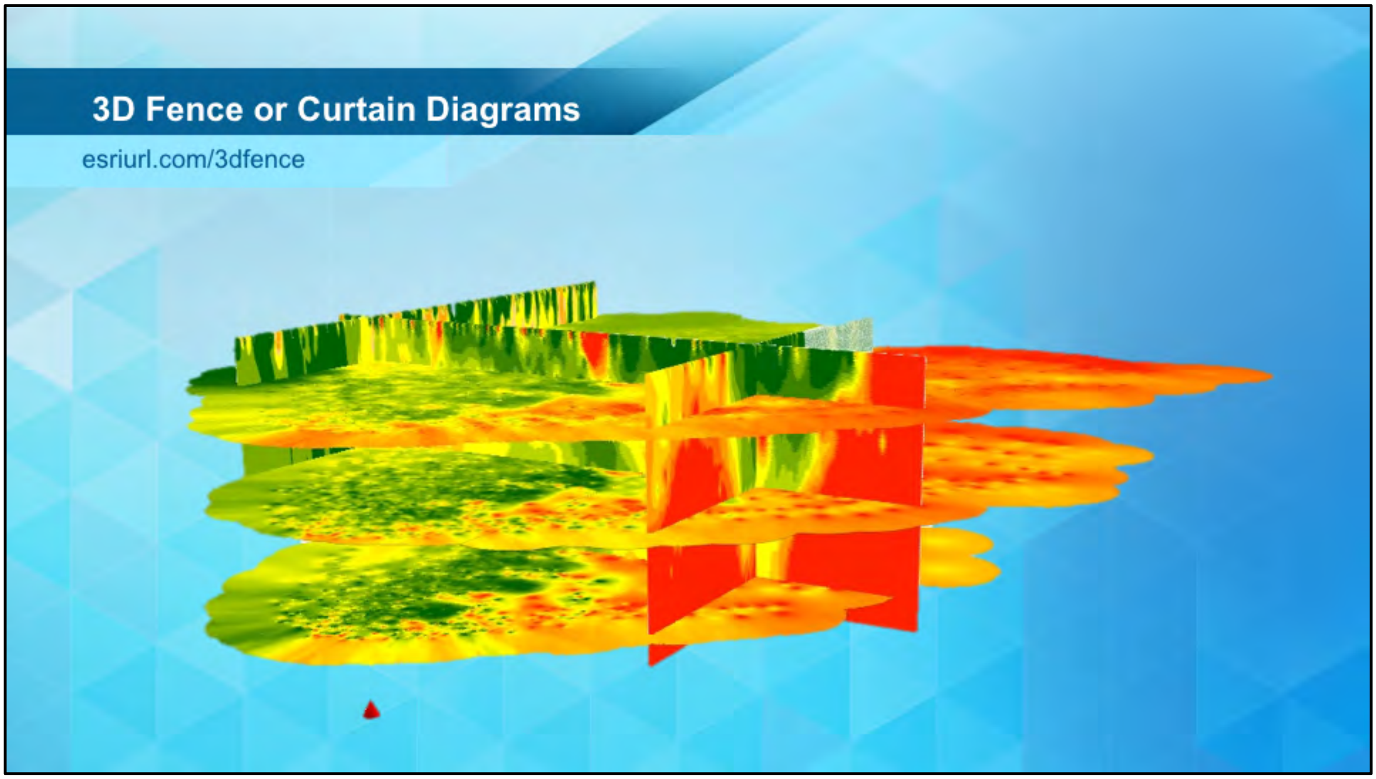


Alternatively, we can use 3D analysis to create vertical fences as a way of interpolating the water column. **The points are measurements of oil in seawater after an oil spill with concentrations of the pollutant from the surface down to a certain depth interpolated into a ”fence” or curtain.”**

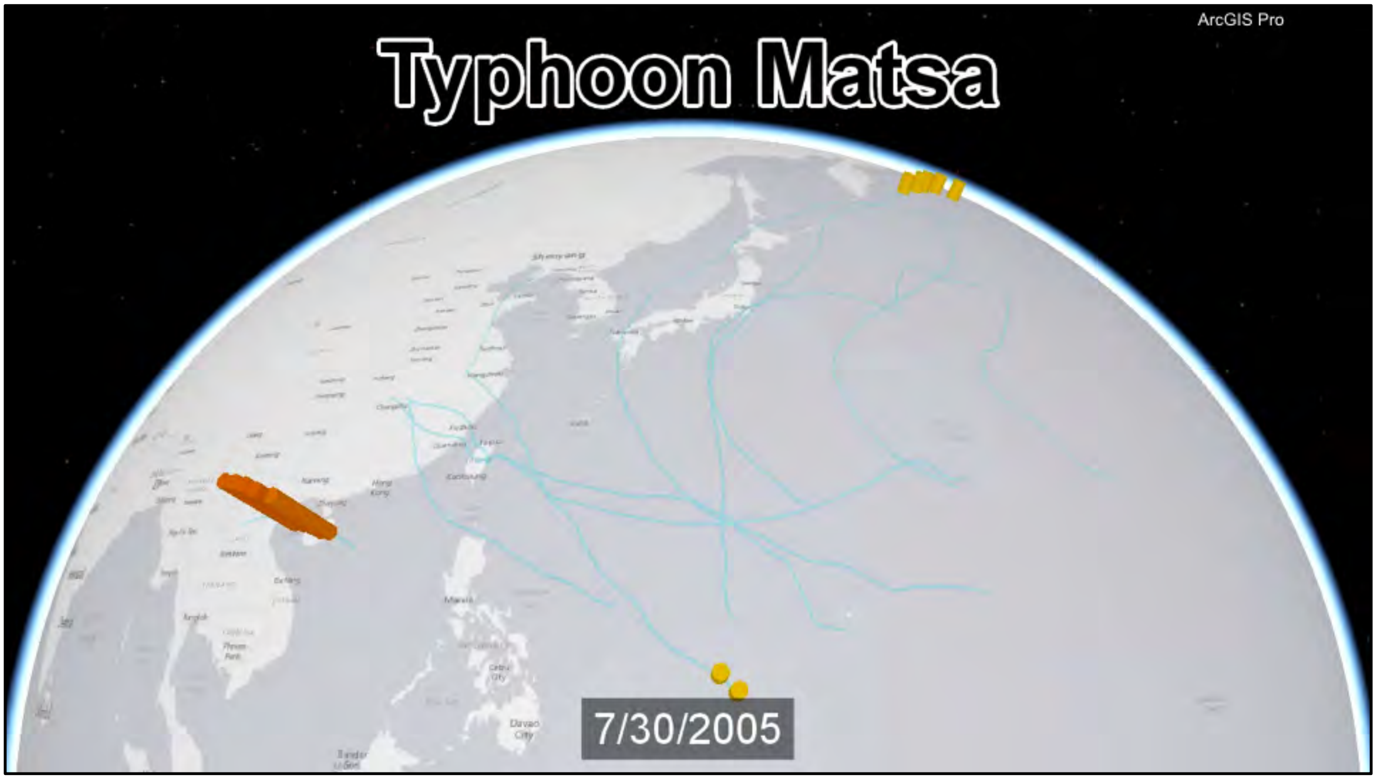
GIS deep dive: a free ArcGIS ToolBox called “3D Fences” cuts slices through 3D point data and applies empirical bayesian kriging analysis to the slices (including error surfaces). Internally the tool uses Empirical Bayesian Kriging (EBK) to interpolate values between samples and then converts the EBK output to points for display. The tools provide an option to output 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 python savvy users can easily change the interpolation method employed by the tools if input data warrant use of a different method or a Geostatistical Analyst license is unavailable



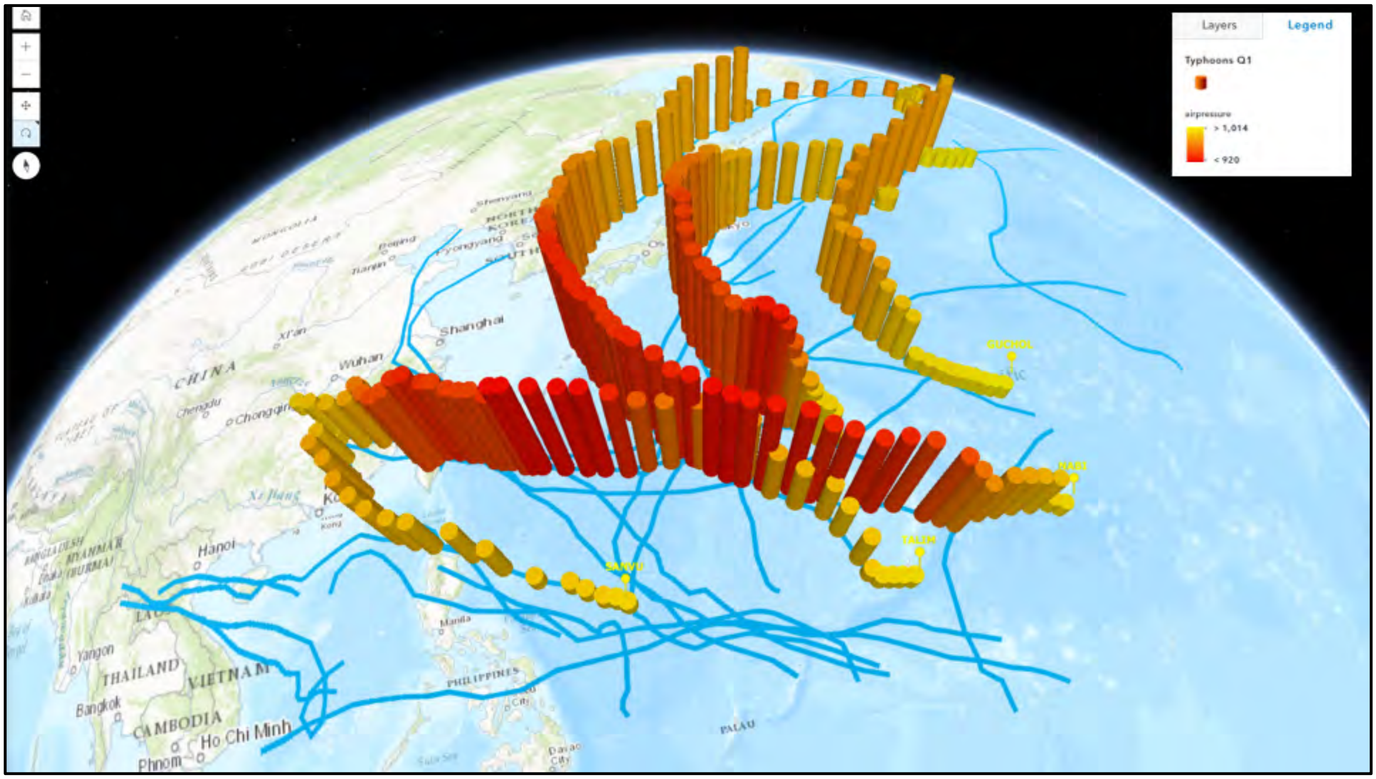
The Parallel Fences option of the tool can generate sets of parallel fences in directions that are related to either longitudes, latitudes, or depths. The Interactive Fences tool can generate fences based on lines digitized on the map



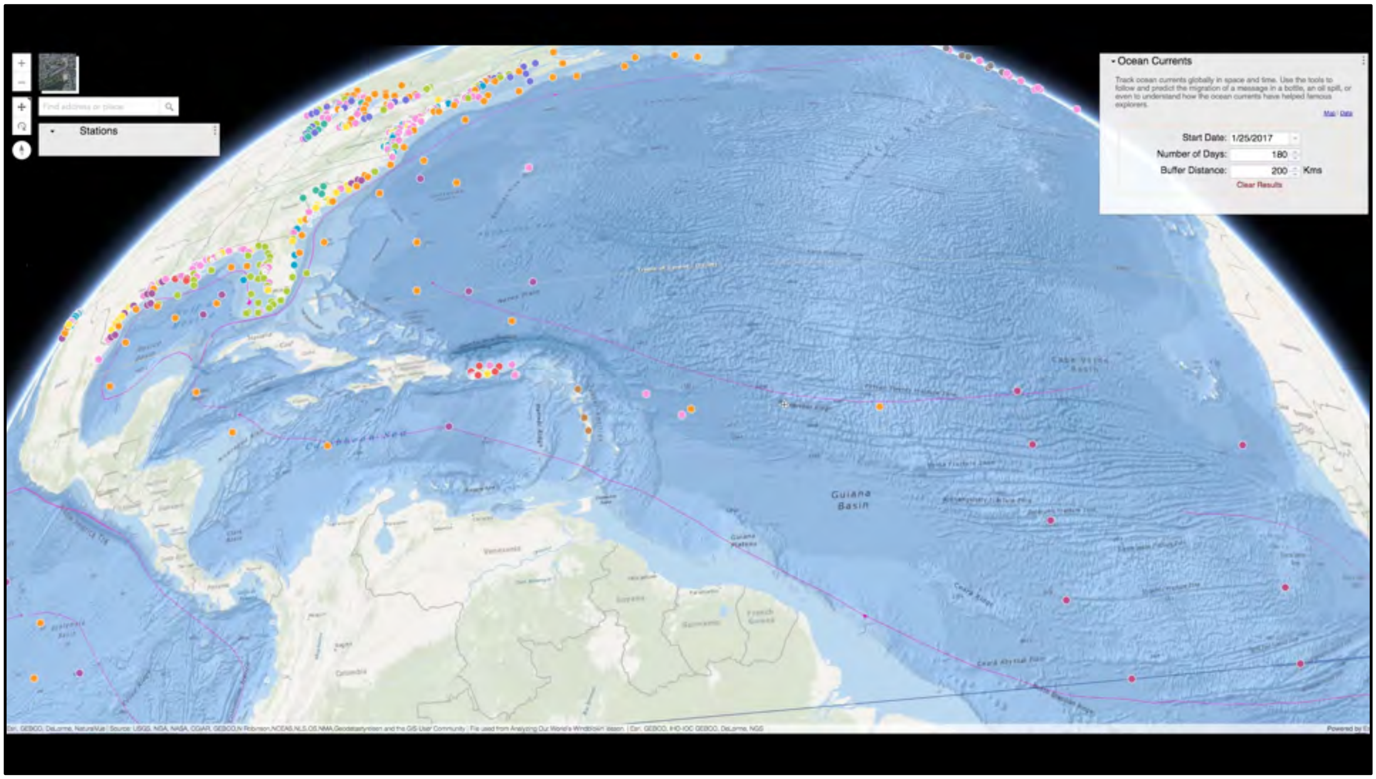
And you can combine entire surfaces at depth in both the horizontal and vertical directions



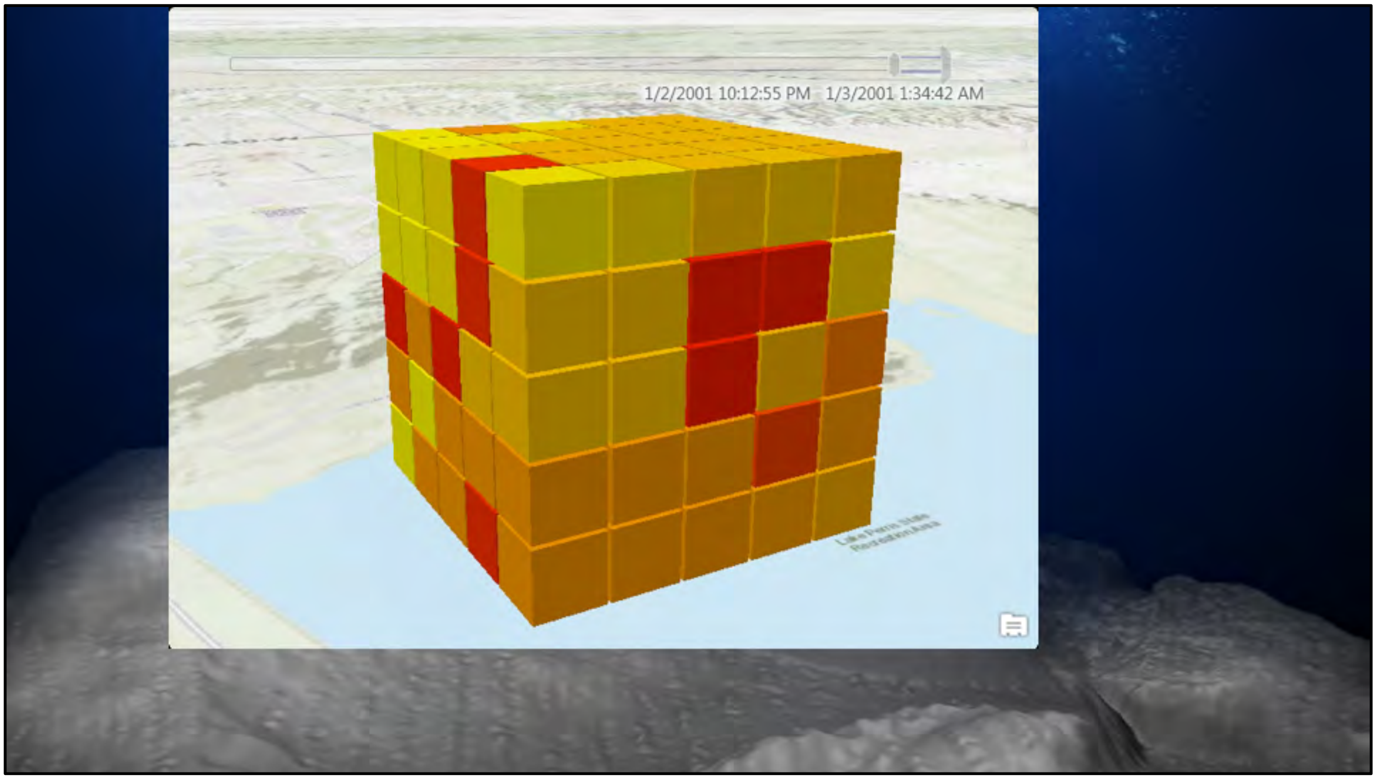
There are all manner of amazing 3D visualization and animation tools that heighten our understanding of how dangerous the ocean can be. This visualization showcases a new way to visualize the major typhoons that raged throughout the Western Pacific in August 2005, along with the variation in their intensity and thus danger to human life.



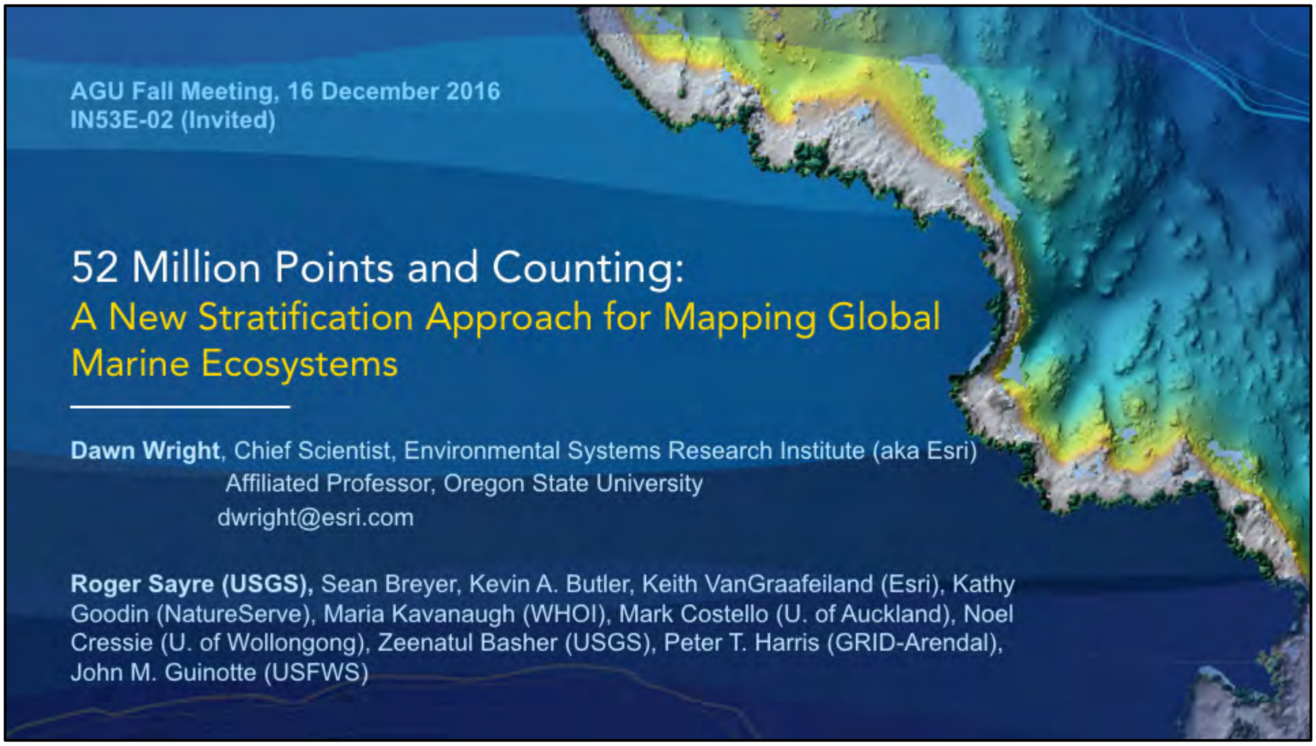
The complete set of visualized storm "pillars" and their tracks for August 2005.



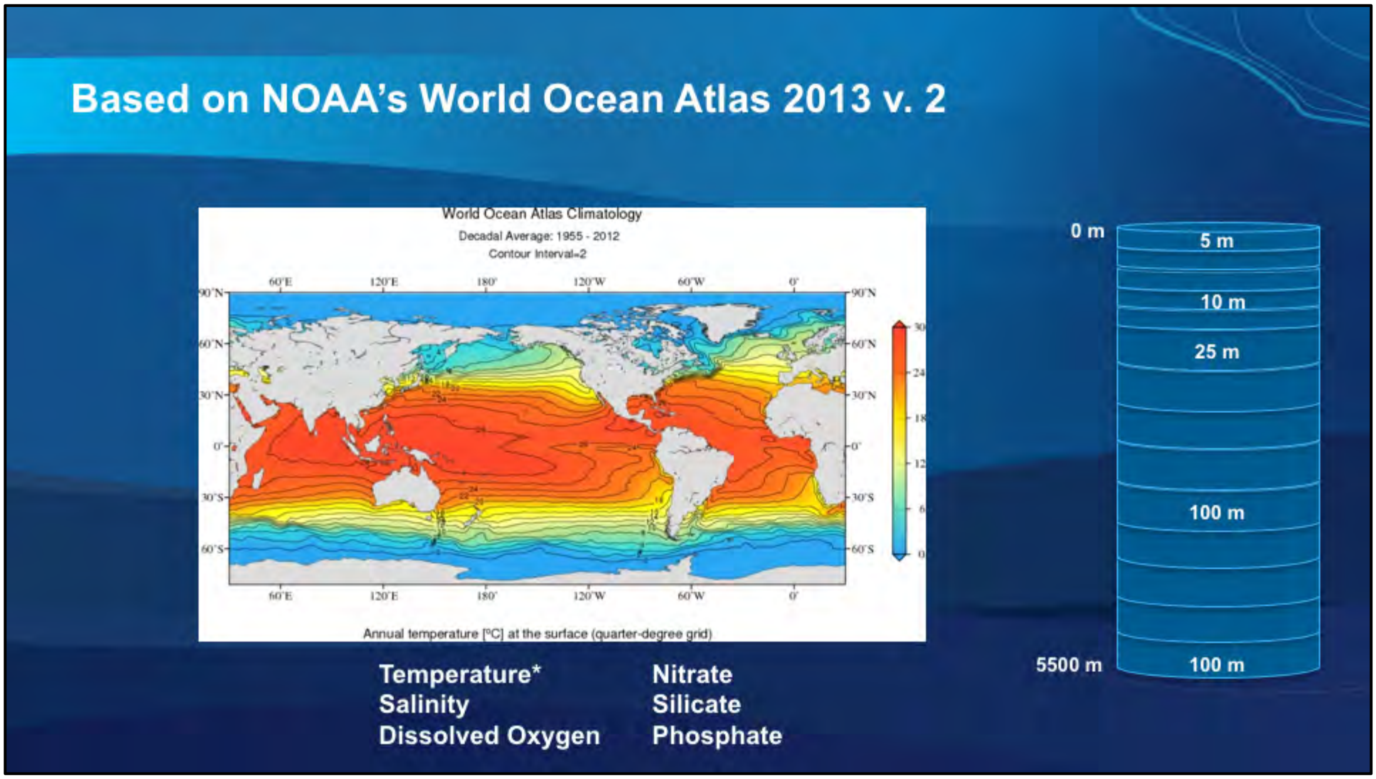
Another virtual globe, returning to the problem of marine debris, this “ship in a bottle” algorithm provides the estimated track of “something” based on a single starting point that you merely click on the map. It does the rest, drawing from a wealth of information provided by Woods Hole stations, NOAA, and others along the way.



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. So we are not just looking at a visualization but 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



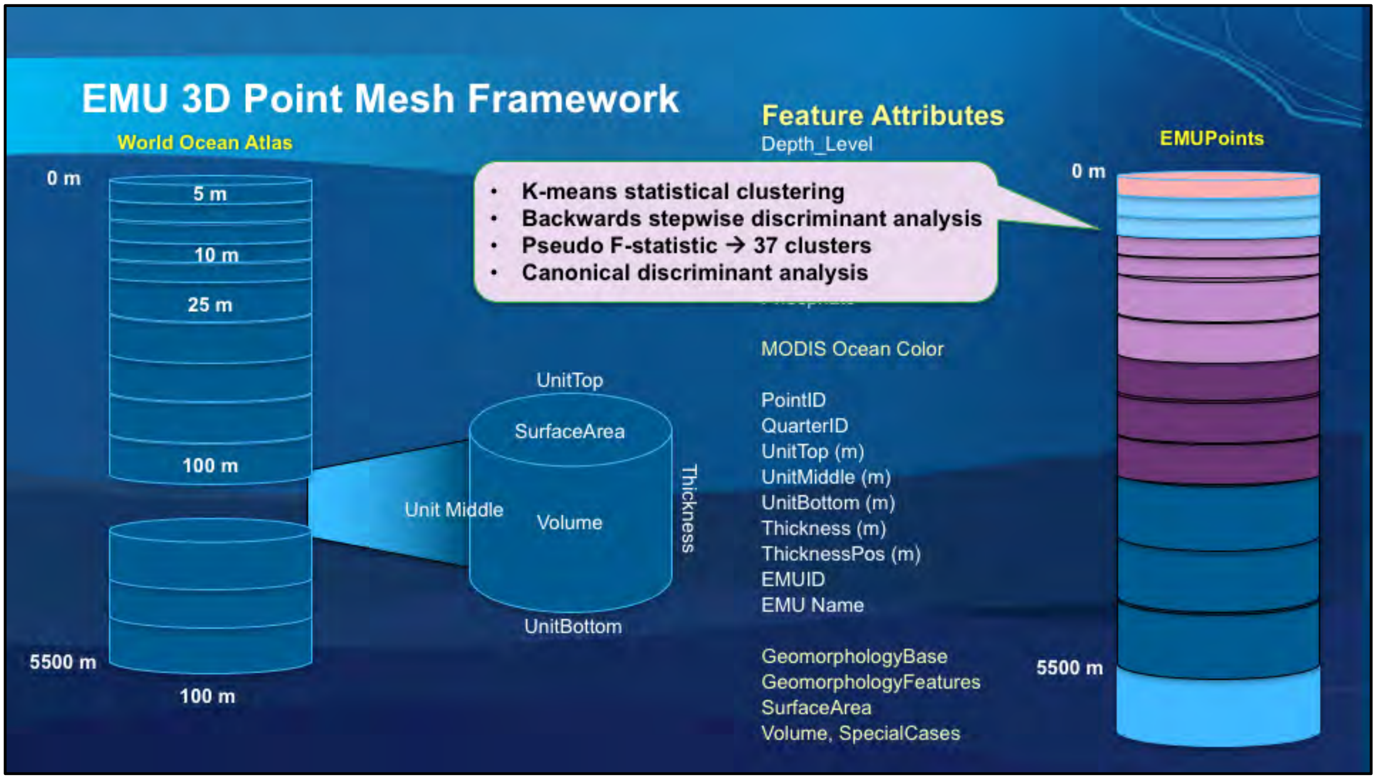
Specific example from a study presented at the most recent meetings of the American Geophysical Union (AGU) and the European Geosciences Union (EGU), and published this year in the journal *Oceanography.*
The work to produce the map and data was commissioned by the Group on Earth Observations, a mini "United Nations" of sorts consisting of almost 100 nations collaborating to build the Global Earth Observation System of Systems (GEOSS) in 9 Societal Benefit Areas (Agriculture, Biodiversity, Climate, Disasters, Ecosystems, Energy, Health, Water, and Weather). The global ecosystem mapping task, as defined here, is a key program within the GEO Biodiversity Observation Network (GEO BON) and the GEO Ecosystems Initiative (GEO ECO).



Where do we get the best "physical setting" for the ocean, which will in turn drives its ecological character? NOAA's World Ocean Atlas (WOA) is probably the best available set of "objectively analyzed climatologies" for the major physical parameters of the world's oceans (interpolated mean fields at standard depth levels).

SPATIALLY
WOA 2013 at finest rez of ¼ degree (27 km at equator) for all variables save for nutrients at 1 km (subsampled nutrients so there is a slight source of error there)
¼ deg horiz and vertical, **102 depth zones ranging in thickness from 5 m at surface to 500 m in deep ocean**

TEMPORALLY
WOA 2013 has 5 or 6 decadal averages
- 1 point in our mesh is the avg of a 57-year period, so it's an average of an average of the prominent mean over 50 years
- trying to conceptualize regions as long-term historical average, possibly stable
- WOA has seasonal averages – we are not dealing with those – we assume that these are already part of the annual/decadal
- but this is the next logical step, to do clustering on monthly avgs as part of a later study; once we understand the decadal we can apply to quarterly/seasonal intervals



NOAA administrator Kathryn Sullivan likens this to a “christmas tree” that we ALL can hang ornaments on now. In GIS-speak this means additional Feature Attributes

1. Step 1 - Build 3-D framework (point mesh), where we extracted the World Ocean Atlas data into a global point mesh framework created from 52,487,233 points, each with at least 6 WOA attributes

2. Step 2 - Attribute mesh points with 6 WOA physical/chemical parameters, in addition to the x, y, and z coordinates (more attributes possible)

3. Step 3 – Used k-means statistical clustering algorithm to identify **physically distinct, relatively homogenous, volumetric regions in the water column (EMUs). Backwards stepwise discriminant analysis** to determine if all of six variable contributed significantly to the clustering – all six were significant. **pseudo F-statistic gave us the optimum # of clusters at 37.** Then used **canonical discriminant analysis** to verify that all 37 clusters were significantly different from one another and they were.

4. Compare/combine surface-occurring EMUs with other sea surface partitioning efforts using ocean color, etc. (e.g., Longhurst, Oliver and Andrew, MBON, Seascapes, etc.)

5. Compare/combine bottom-occurring EMUs with seafloor physiographic regions and features, etc. (e.g., Harris et al.)

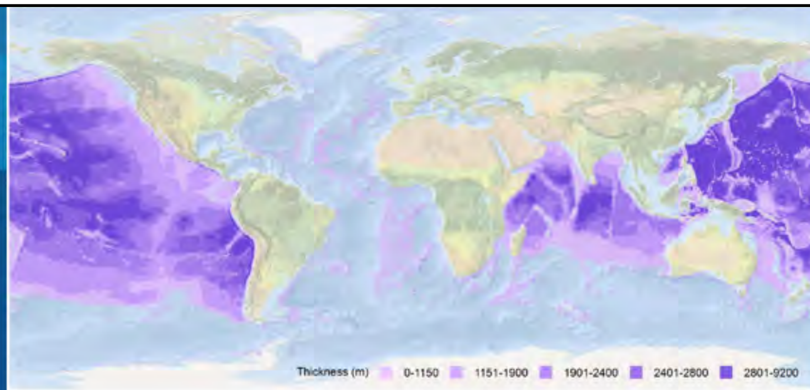
6. Assess relationship between physically distinct regions and biotic distributions (e.g., OBIS Biogeographic Realms, etc.), and maybe combine to incorporate biotic dimension into the EMUs

[In the weeds: A globally comprehensive subset (25,000 points) of all points was used for the determination of the optimum cluster number using the pseudo F-statistics, yielding an optimum of 37 clusters. For the approach, the approximately 52 million global points were then clustered in a series of sequential iterations where the number of clusters requested ranged from 5 to 500, increasing the cluster number by ten for each successive iteration.]

EMU 13 Summary

Technical Name:
- Bathypelagic
- Very Cold
- Euhaline
- Hypoxic
- High Nitrate
- Medium Phosphate
- High Silicate

Common Name:
- Deep
- Very Cold
- Normal Salinity
- Low Oxygen
- High Nitrate
- Medium Phosphate
- High Silicate

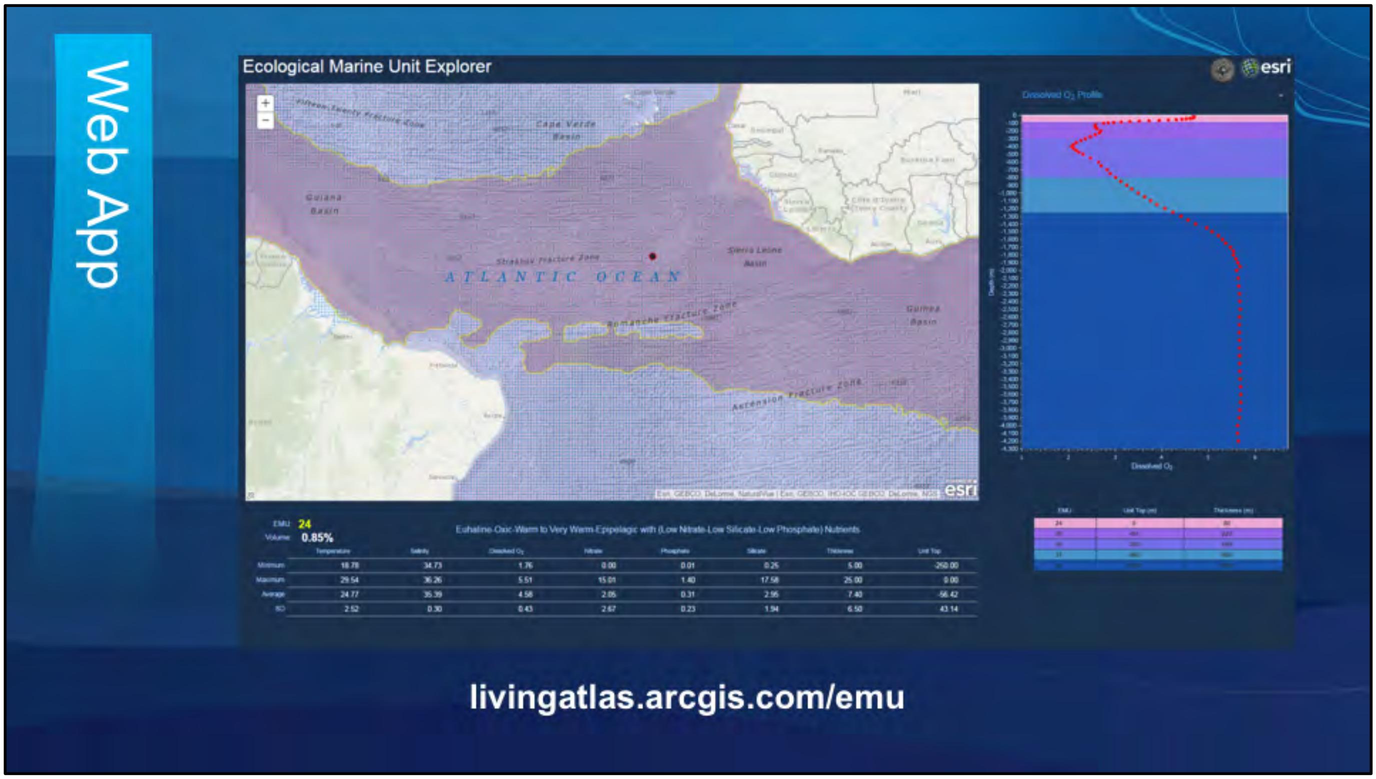


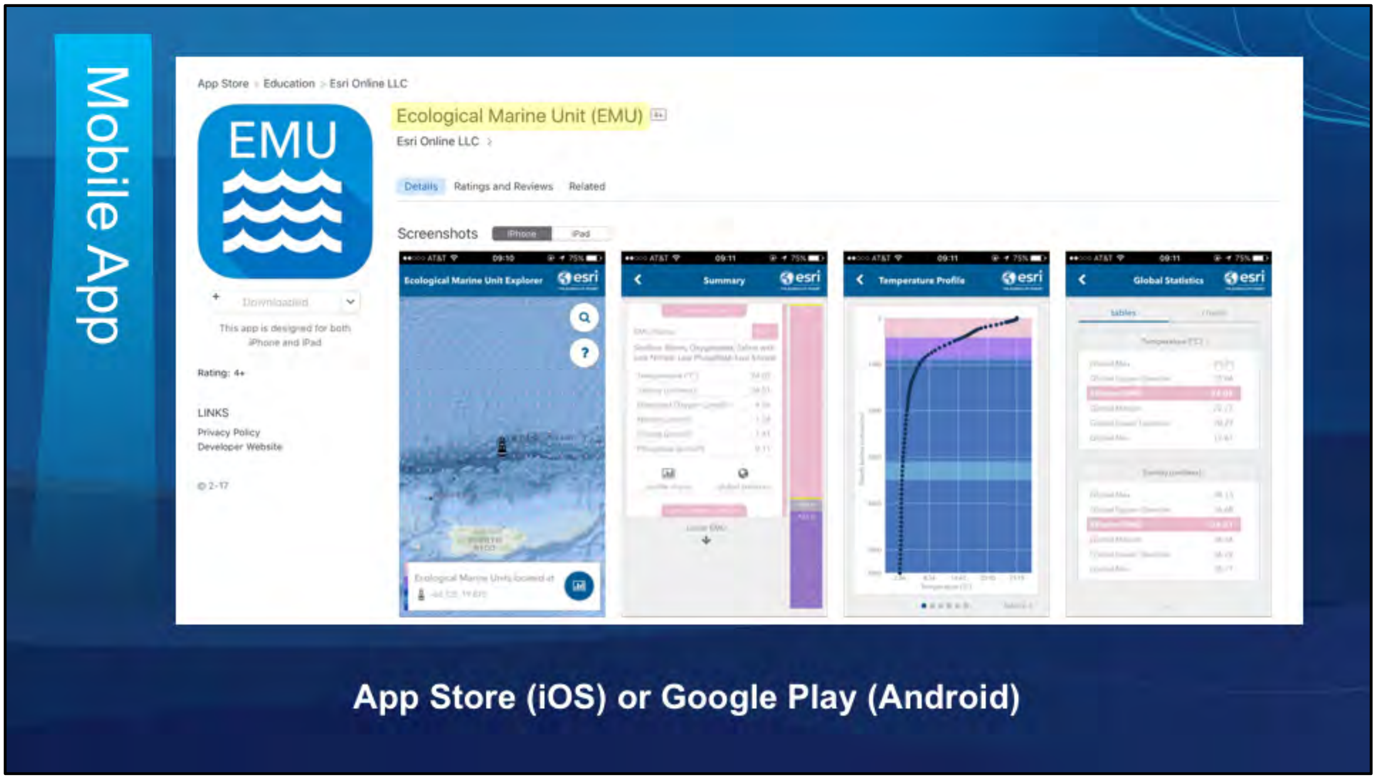
EMU 13 Summary Statistics

	Minimum	Mean	Maximum	Standard Dev.
Temperature (°C)	-0.38	1.93	5.54	0.51
Salinity (unitless)	33.43	34.67	34.93	0.05
Dissolved Oxygen (µmol/l)	1.69	3.26	4.33	0.43
Nitrate (µmol/l)	25.26	37.03	48.49	1.08
Phosphate (µmol/l)	0.53	2.60	3.36	0.12
Silicate (µmol/l)	88.01	138.03	189.63	19.05
Thickness (m)	0.00	90.34	5323.00	36.76
Unit Top Depth (m)	-5500.00	-2955.62	-10.00	998.83

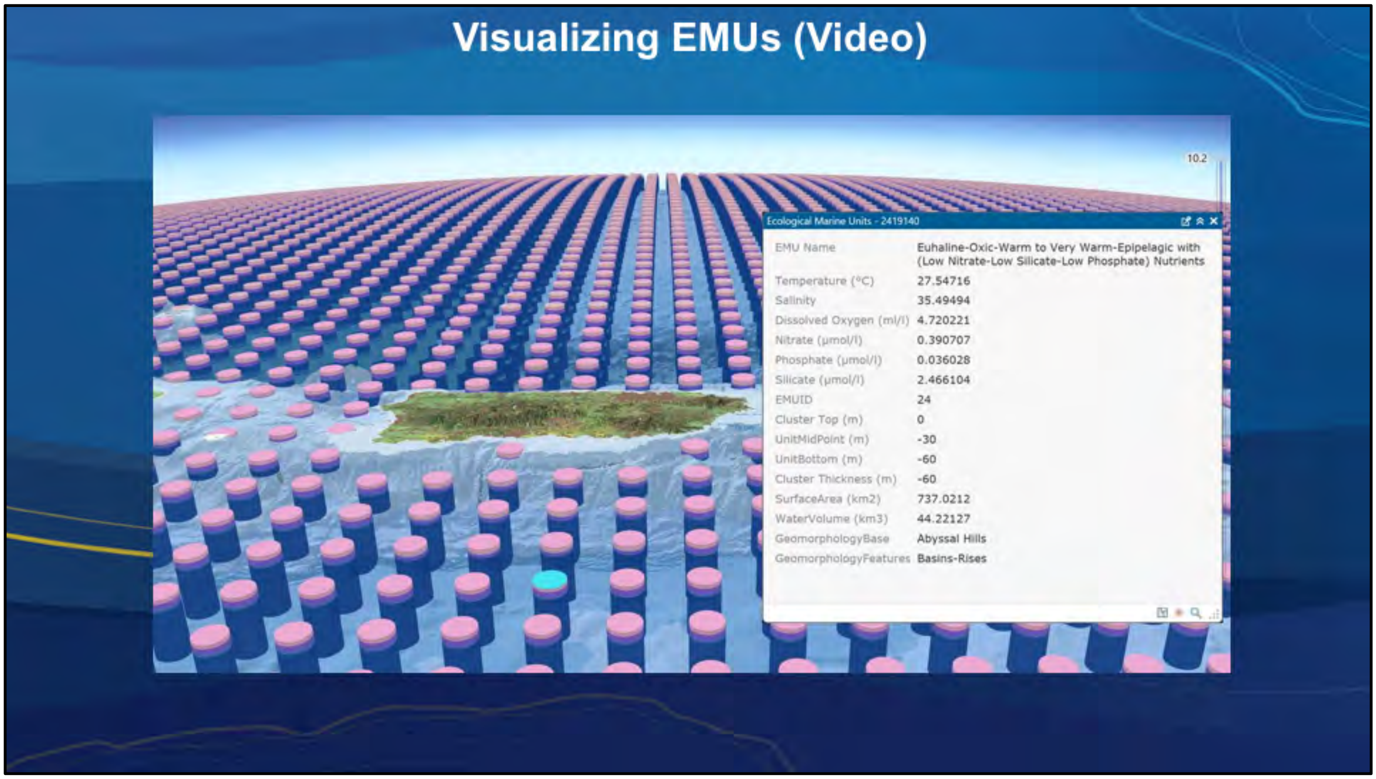
EMU Volume (km^3)	347060603.65
Percent of EMU to Global	25.40%

One summary for each of the 37 – Sean's favorite EMU


Web App
Ecological Marine Unit Explorer
esri
ATLANTIC OCEAN
EMU 24
Volume 0.85%
Euhaline-Oxic-Warm to Very Warm-Epipelagic with (Low Nitrate-Low Silicate-Low Phosphate) Nutrients
livingatlas.arcgis.com/emu



You can download this from your seat right now, but especially for you young people, I hope you'll stay pay attention during the remainder of my talk! ☺



How do we best visualize something that is really continuous and in 3D? One way is to conceptualize the data as columnar stacks of cells whose centroids define the point mesh

As we zoom in, cylinders will pop up, representing data points from NOAA's World Ocean Atlas, 52 million observations over a span of 50 years about the primary physical and chemical characteristics of the oceans at 105 depth levels: in other words, the key variables that enable life throughout the ocean such as salinity, temperature, dissolved oxygen, phosphate, nitrate, silicate.

This is actually a continuous grid of data at the surface and continuous volumes at depth but we are representing the units as columns so that you can see sideways better into the layers at depth.
One major point is that nutrient and oxygen distributions in particular not only shape but ARE SHAPED by biological processes (physicochemical).

Red discs represent a layer of the water that is hypoxic, i.e., depleted in oxygen.

This information will be hugely significant biologically, to be able to see that over a global expanse, where it thins out, where it mixes with other water masses. This is a global framework.

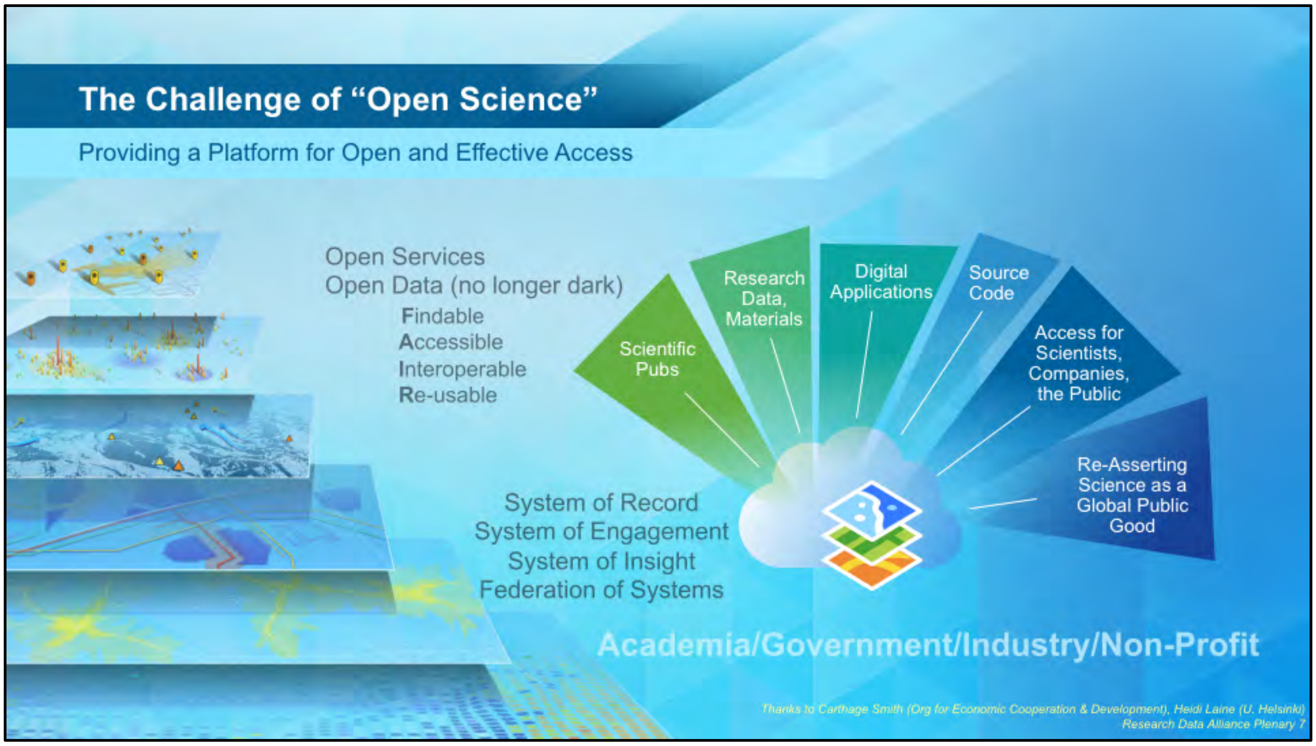
Will soon start time slicing into monthly averages, OBIS has not been added to this yet, but that is in progress.

It will be exciting to be able to continually populate and improve this with data from any cruise or expedition as we go forward in time. NOAA administrator Kathryn Sullivan likens this to a christmas tree that we ALL can hang ornaments on now, and over time really come to a richer understanding of our ocean, while also helping us to understand what's the next science data or target we should go after to make this more useful, especially for MPA designation or evaluation and CMSP.

EMU logo by Esri’s Sean Breyer

Here be Monsters – meaning grand challenges
Sloanes viperfish
Chauliodus sloani is a species of dragonfish. Guinness World Records notes that it has the largest teeth, **relative to the size of its head**, of any fish

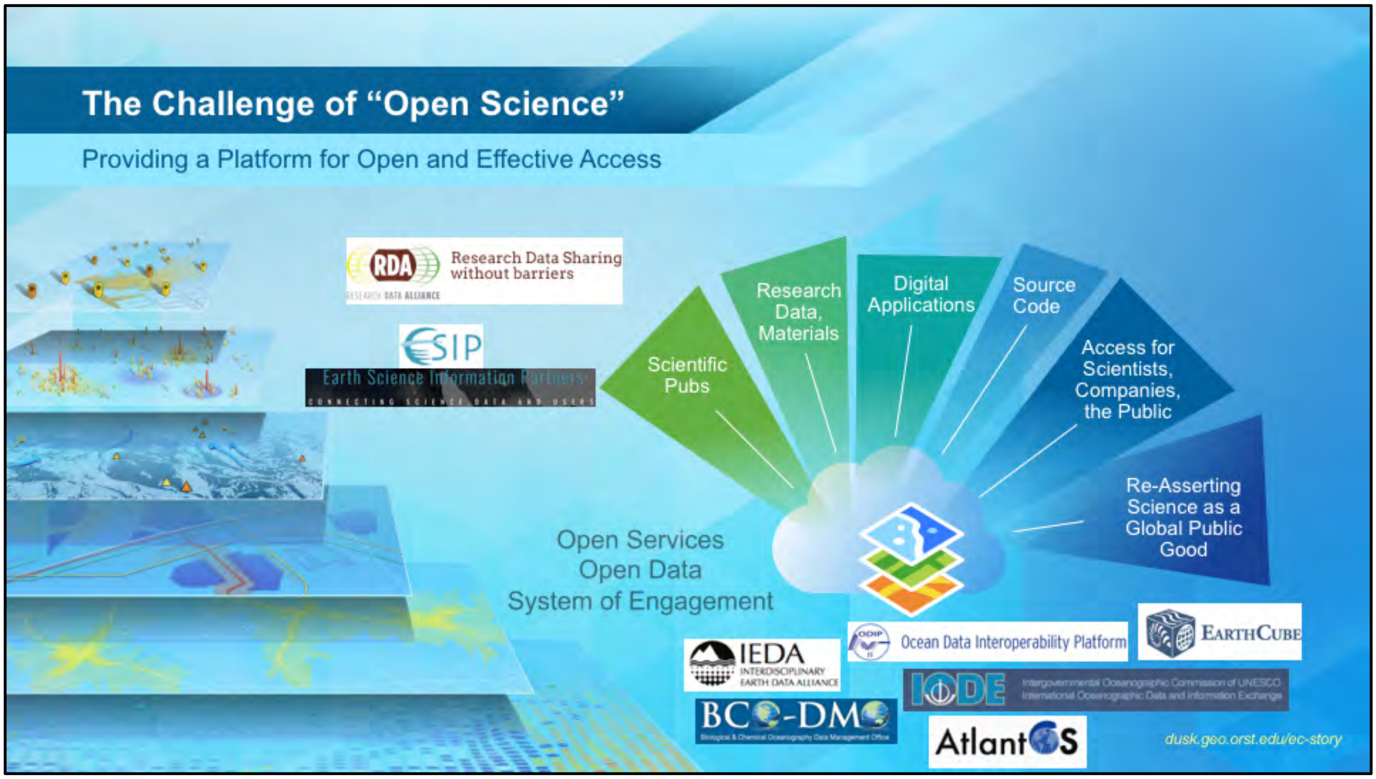
The *Atlantic wolffish (Anarhichas lupus)* is the largest of the wolf fish family



Twitter reference: https://twitter.com/heidiklaine/status/704135333034590208

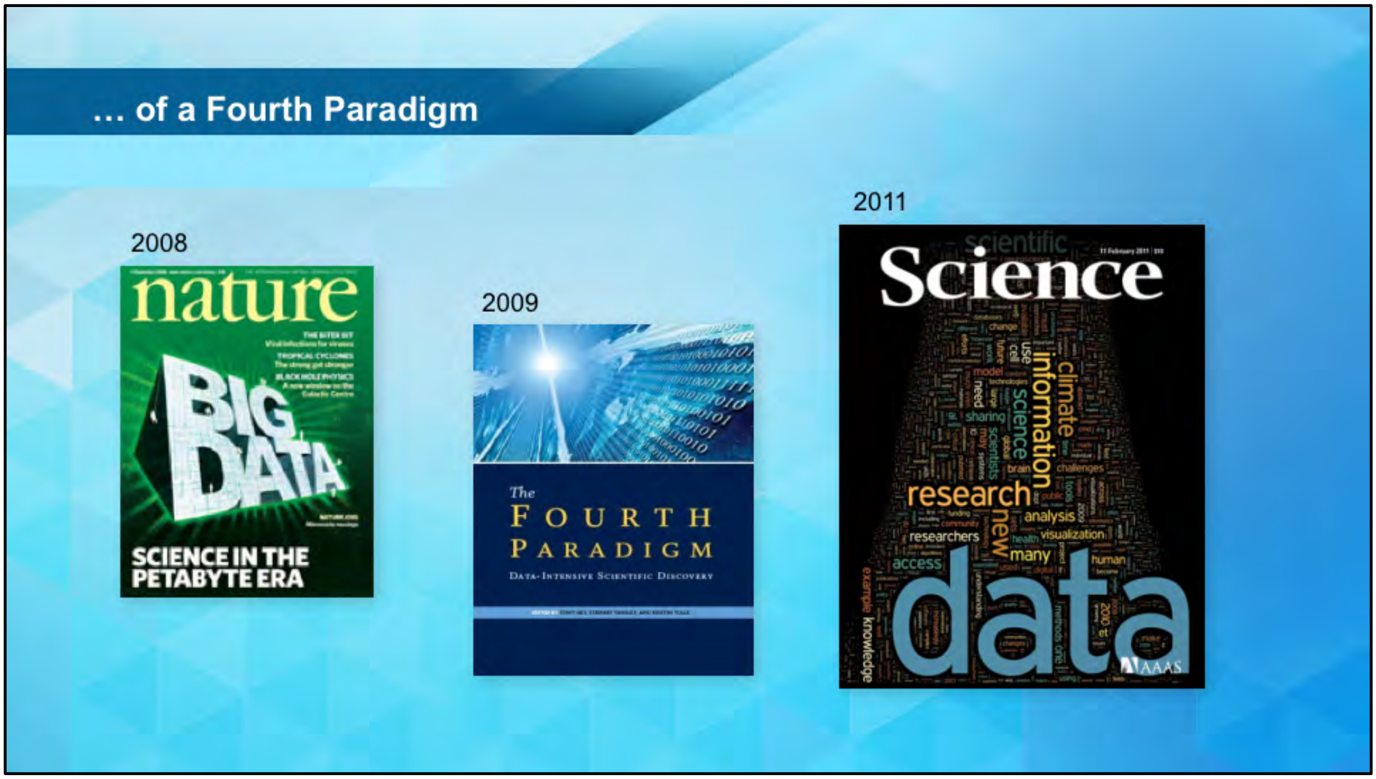
Providing an Open Platform for Collaboration and Innovation

These are the 6 pillars of "open science" advocated around the world.



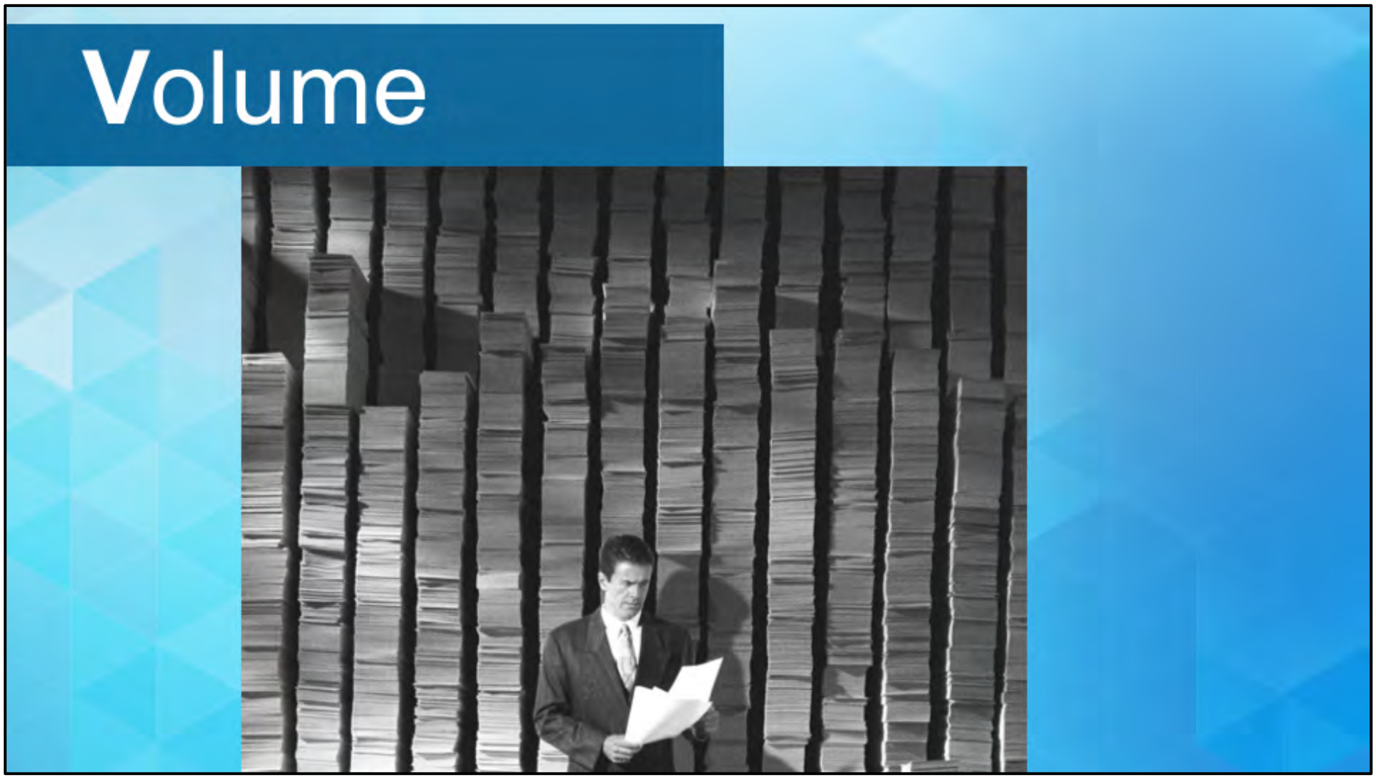
RDA and ESIP shown as examples of multi-/trans-disciplinary "umbrella" organizations working toward open and effective access to data across many disciplines.

Others (lower right) are more ocean-based data management initiatives while AtlantOS is a large ***marine observing network*** bridging N. America with Europe



Data and big data are leading to a new science paradigm, the new science of "big data" (the inundation of data from satellites, sensors, and other measuring systems and the issues associated with those large data sets), as heralded in these special issues of Nature and then Science

And there is also the 2009 book **The Fourth Paradigm, which posits a new paradigm of scientific discovery beyond the existing 3 paradigms of EMPIRICISM, ANALYSIS, and SIMULATION to a 4th where insight is discovered through the manipulation and exploration of large data sets.**



Size and multidimensional nature of the data, e.g., with a modern dual head SONAR capturing bathy, backscatter and water column, that rate is 115GB/hr. That is approximately a 1.5 Billion to 1 ratio. The analogy is that if you take an ~8mm marble and multiply by the ratio, your marble becomes the size of the Earth (approximately). **[HOLD UP MARBLE TO AUDIENCE]**
That's how MUCH data (shallow) we can capture with modern sonars.
In addition, our sensor count of 2 million + will likely double every 5 years
So the oceans have ALWAYS been about big data, despite how much remains to be explored.

Big data indeed has the flip side of dark data. In the case of the seafloor, data from small survey areas that remain unshared and thus hidden in darkness or the vexing problem of having not collected high-rez data for an area of the ocean, especially the "Roaring 40s"
Some of the new topographic complexity of the ocean floor revealed in the Indian Ocean, even though, tragically, the lost Malaysian Air flight MH370 has yet to be found. And IN FACT, much of the seafloor under commercial flight paths around the world remains unmapped,

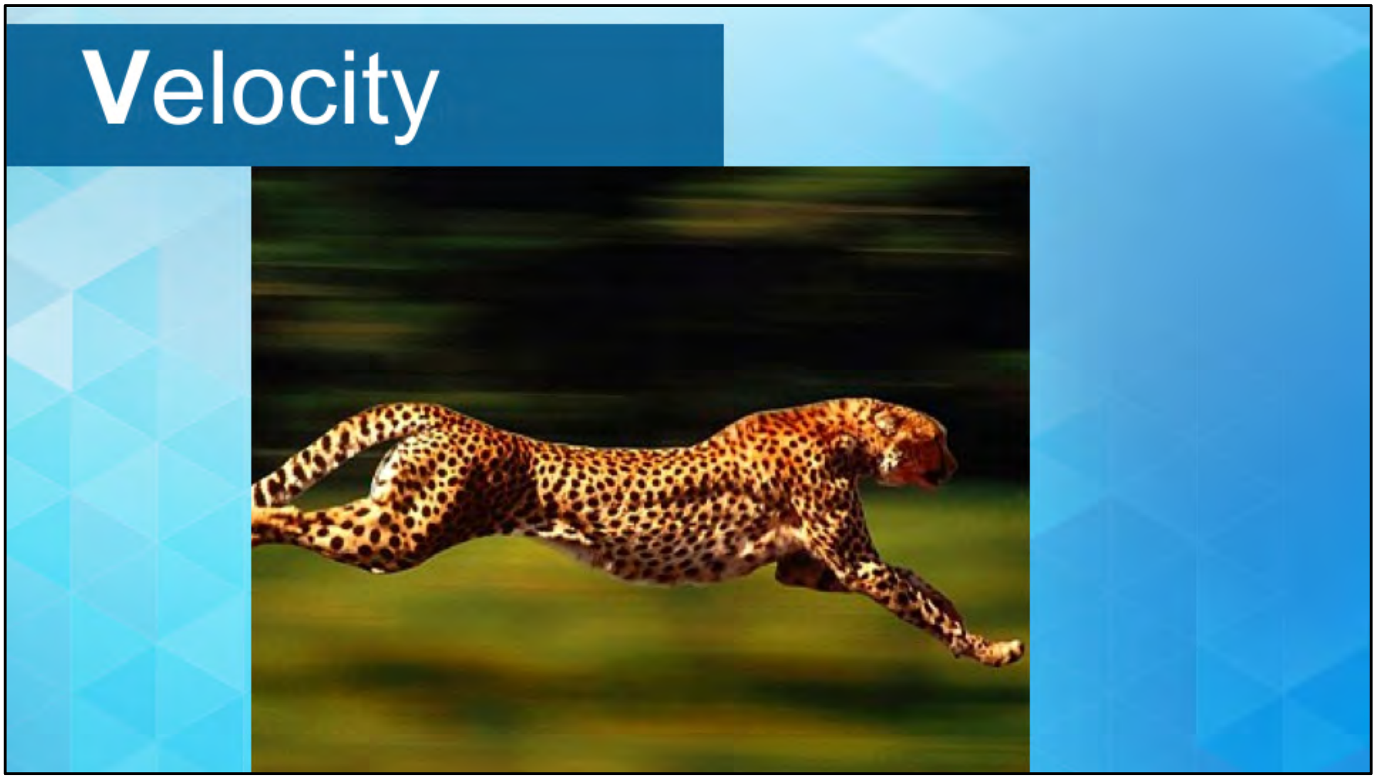
There are even ethical issues in data and information to be taught. A case study of this accident is included in my ethics of geographic information course at Oregon State U. http://dusk.geo.orst.edu/ethics
The USS San Francisco submarine ran aground enroute from Guam to Brisbane, Australia - 8 January, 2005 due in part to the use of 1989 nautical chart that had not been updated with this new feature (dark data)

•One sailor killed, 115 injured

•Crash depth ~160 m, speed 33 kn, Sonar measured a depth of 2000 m, 4 minutes before crash

Reference: Wright, D. and F. Harvey. 2009. *Case Study: Submarine Crashes into Uncharted Seamount*. GIS Professional Ethics Project, http://bit.ly/2mz8hLy.

The Forum for Future Ocean Floor Mapping was held in Monaco in June 2016 and was attended by over 150 senior representatives, scientists, scholars and business associates from major ocean related organizations from around the world. The Forum endorsed the objective of Seabed2030 – that the comprehensive mapping of the entire ocean floor is possible by the year 2030. **More than 85% of the world ocean floor remains unmapped with modern mapping methods.**



So the Gb per HOUR example, leads us to the tenet of VELOCITY or the speed at which data are created and updated, often in near-real time. New challenges for **stream reasoning and rule systems**.
In the world of GIS and mapping we are talking about the ability now to stream **30,000 features per SECOND**.
Given this ability, **one important question may be which data do we keep?**

The VARIETY or structural variability of the data may be the most DELICIOUS and compelling problem for the ocean exploration community.

These are data coming from **multiple sources and types** (photos, video, audio, text, scientific observations, scientific models)**, multiple perspectives** (governments, military, NGOs, etc.), which also have **various cultures of contributing data.**

A single oceanographic survey produces data in scores of different formats. Many physical oceanographic grids and models are **irregularly spaced!**

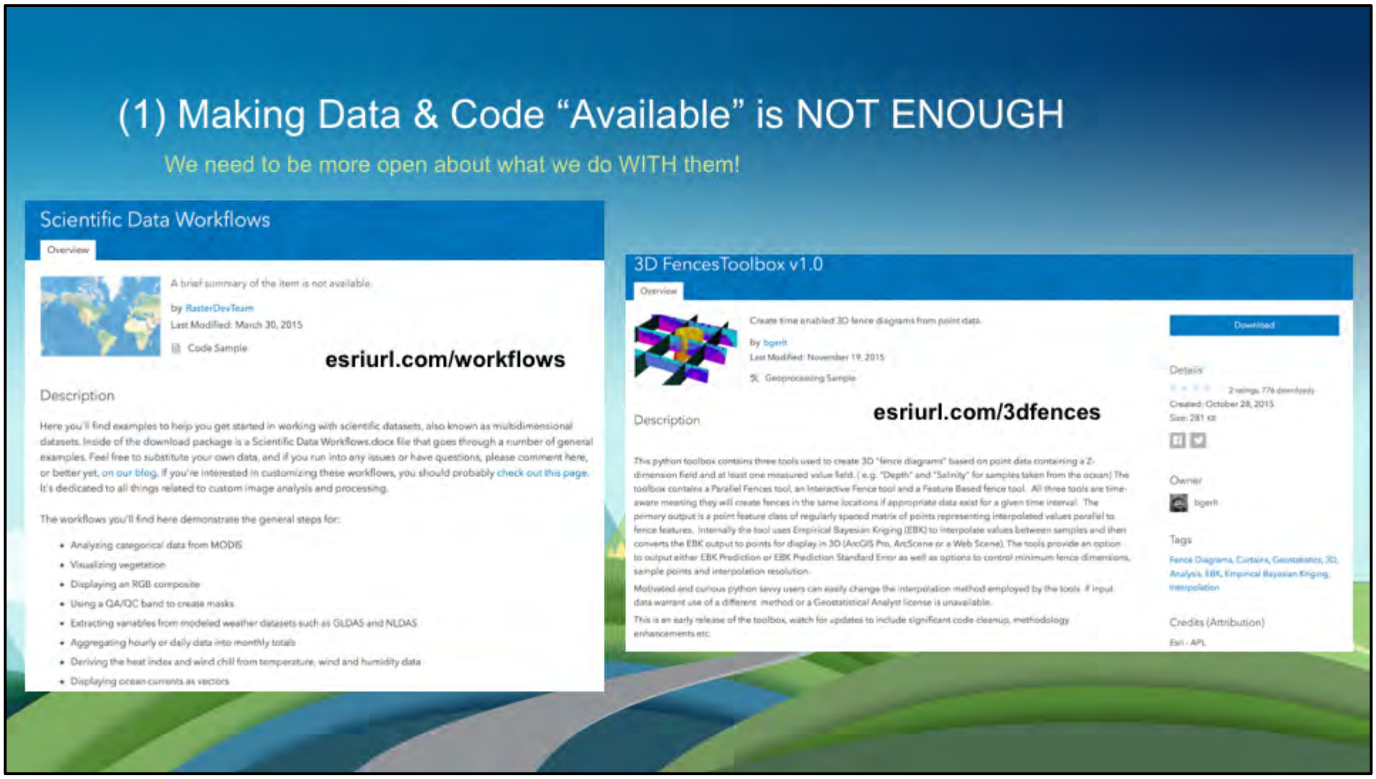
Sensor count doubling every 2 years?
As an example from ocean OBSERVATORIES, here is a look at the technology currently and ~20 years into the future. This graphic, courtesy of the NRC ocean infrastructure report, captures a variety of issues, environments, and tools.

VALUES – people-centric platforms, building communities, empowering communities
…partnerships in conservation, understanding and protecting nature, supporting green infrastructure initiatives. Serving the developing world but also LEARNING from it too.

We aim to foster resilience too – climate resilience, community resilience, ecological resilience, personal resilience, etc.
But what about DATA resilience?

In other words, how can we ensure that the data, information and tools that we work so hard to collect, build, and curate are really used, and used effectively? If we want a resilient world, we need to start with resilient data.
Let me quickly posit 3 ideas, in the web address on the screen I've posed as many as 8, but I only have time for 3. So if you'll allow me to "geek out" a little ...

On a more advanced note, we need to do more than just make our data or our computer code available through a site or portal, even through online coding sharing communities such as GitHub. We need to be more open about what we DO with that dataset or piece of code.



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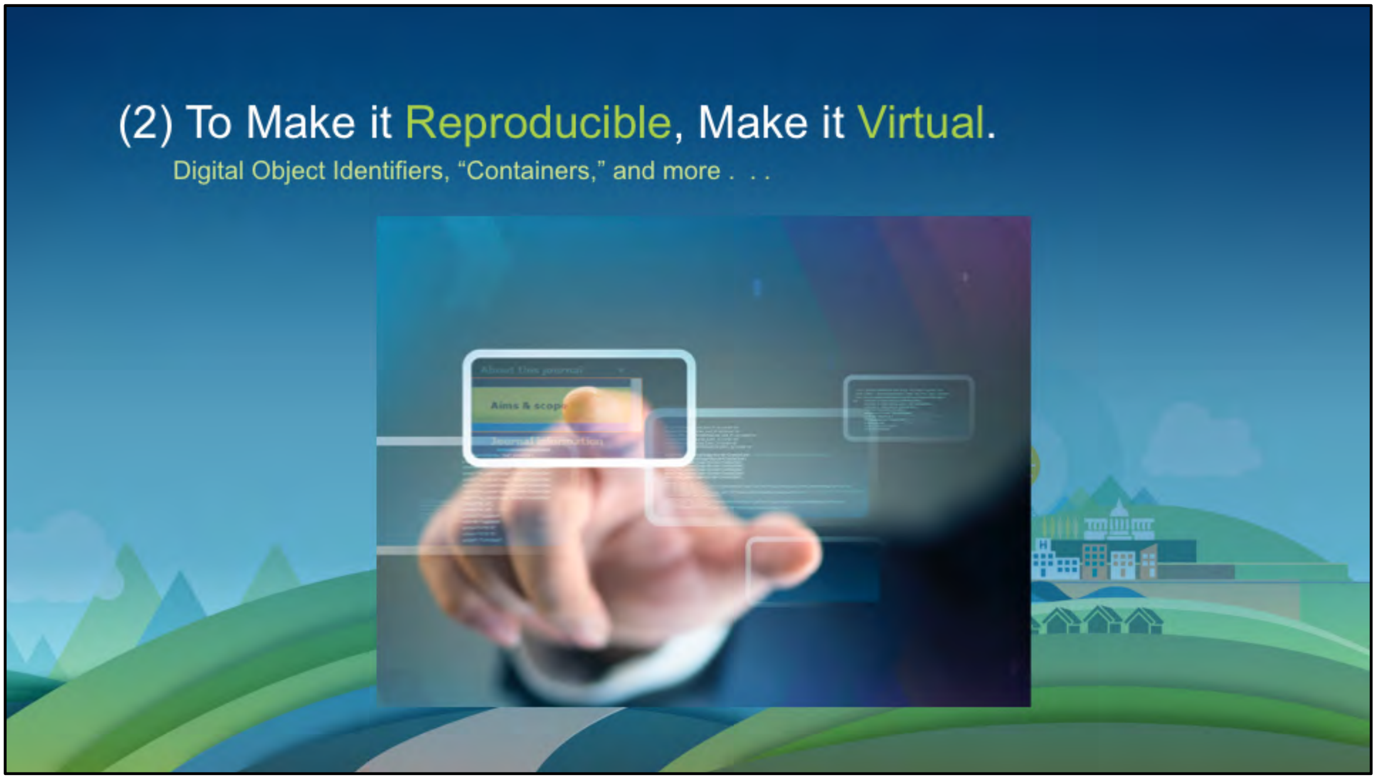
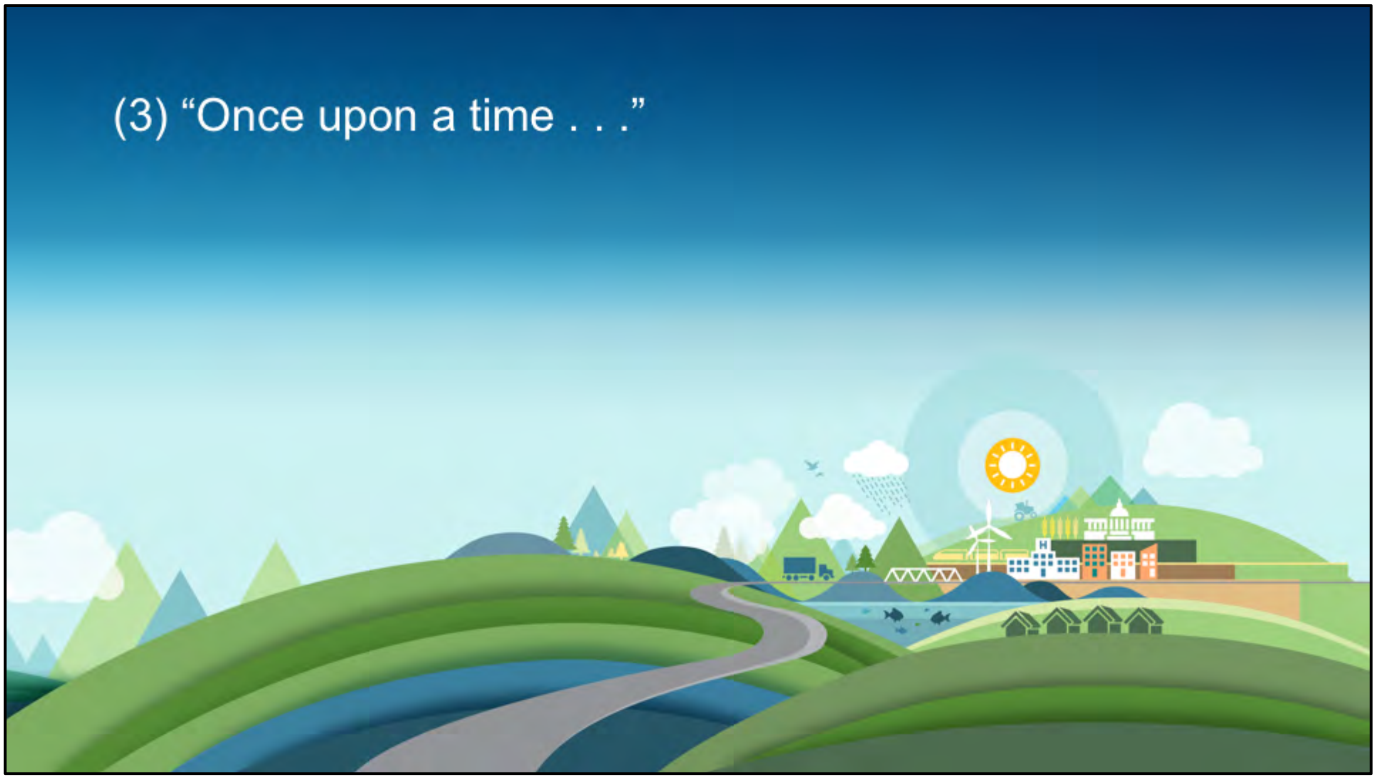


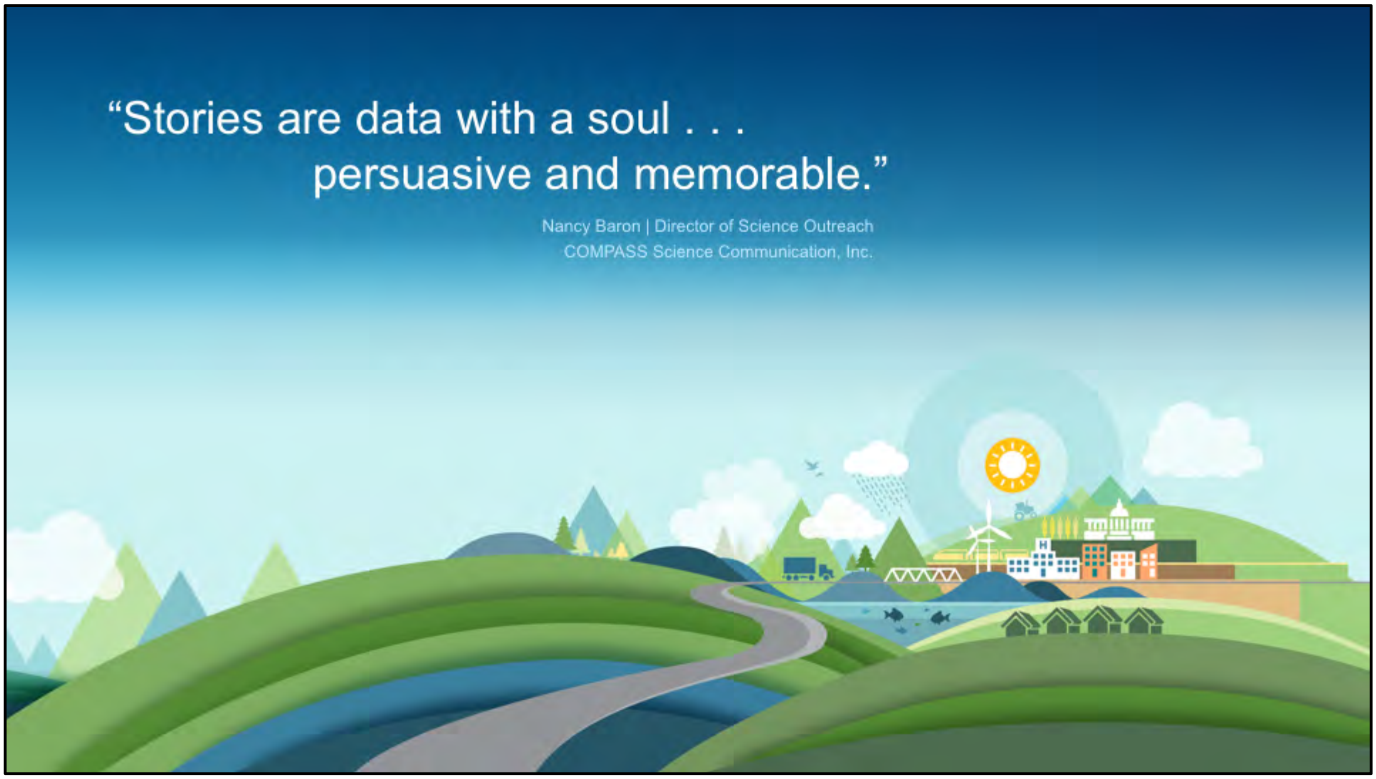
Second, in order to make things reproducible in keeping with solid science, let’s make it virtual. Here I’m referring to emerging cataloging standards such as DOIs (digital object identifiers) and new innovations such as CONTAINERS, where you can **package together an operating system, a server, your database, a Hadoop or Spark big data store, and share that as a single executable that “just runs” for the user**. This may be the future of data sharing and “living” reports and journals.

From: **Ben Domenico of UCAR**
"Data Interactive Publications."
https://sites.google.com/site/datainteractivepublications/
The basic concept is that, with the advent of web services for data access AND data processing, we can consider systems that would enable authors to create publications that enable the reader to interact with the data discussed in the publication and also to rerun computations described in the publication. It would work for educational modules as well as scientific publication.   At the moment the examples we've put together involve just rudimentary data processing, but, with proper access controls, in place, one could envision giving the reader control over very sophisticated scientific processing.



We *MAY* get maps, we often DON'T get graphs, but we ALL understand a good story.

"People are moved by emotion. The best way to emotionally connect other people to our agenda begins with "Once upon a time…"



As such, to connect with communities and inspire action toward resilience, ocean scientists and data scientists MUST tell their STORY and the importance of that story

After all, as scientists we don't want to be caught in this situation from the now "infamous" New Yorker cartoon…

Rush Holt, president of the AAAS has spoken eloquently on the need for scientists not only to tell stories, but to tell the story of the EVIDENCE; the story of the question to be answered. This is all part of science communication which is sorely needed now in the public square. It will be needed tomorrow during the People's Climate March!

One way to tell a story is by way of a story MAP, a new medium for sharing not only MAPS and associated data, photos, videos, even sounds, but for telling a specific and compelling story BY WAY OF that content. This is all done with sophisticated cartographic functionality that does not require advanced training in cartography or GIS.

The Power of Storytelling

"Story Maps"

esriurl.com/ocnstories

The Power of Storytelling

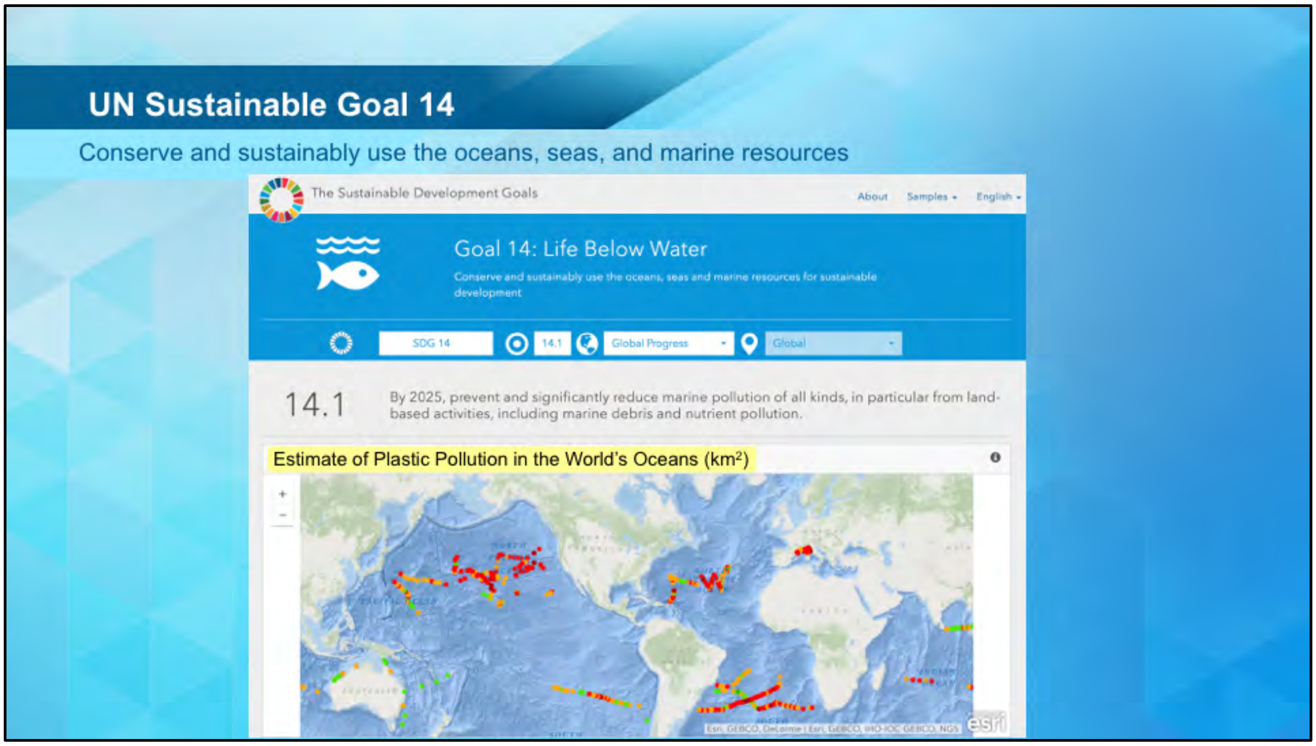
"Story Maps"

esriurl.com/ocnstories

A more sophisticated story map created for the Women's March of January 22, 2017

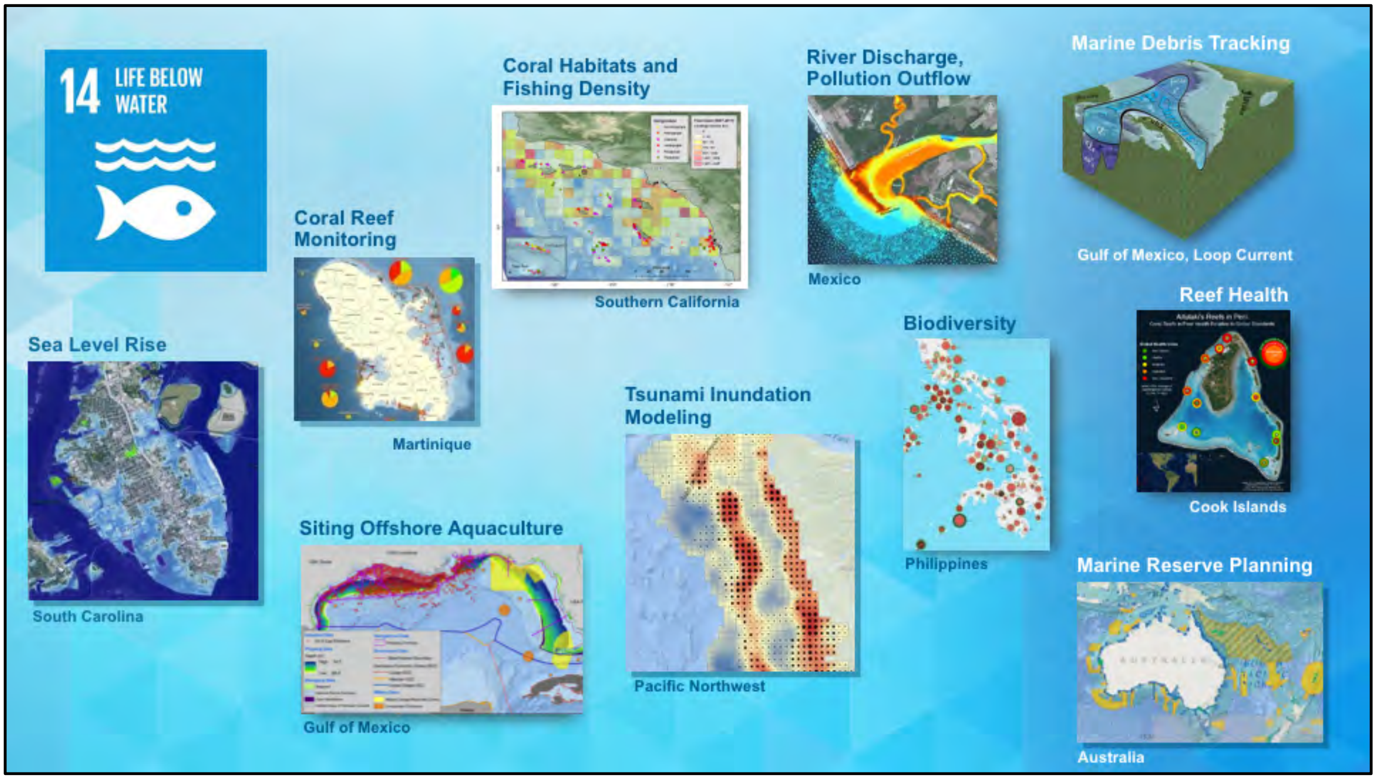
And this brings us full circle back to sustainability and the SDGs. This is a dashboard that the UN commissioned to help them track their progress on ATTAINING these goals by 2030.

The video shows an example of how this is accomplished via a map dashboard.



The portion of the map dashboard devoted to SDG 14
Sky News recently reported on the results of research by the Institute of Marine and Antarctic Studies at the University of Tasmania, which finds that the amount of plastic pollution washing up on the world's beaches may be underestimated by as high as 80%. http://news.sky.com/story/up-to-400-more-plastic-in-oceans-than-thought-study-10849911

Science continues, but we have enough science, enough data collected to know that we must take action on this issue NOW.



Examples of applications of "smart mapping" fueled by geospatial data science within geographic information systems, around the world to implement SDG14

HUGE shout out to OSB's recent report Effective Monitoring to Evaluate Ecological Restoration in the Gulf of Mexico with Chapter 6 on Synthesis and Integration (and Box 6.1 on Geospatial Analysis)

GIS deep dive – map credits:

Monitoring Habitats – USDA Forest Service, NOAA Deep Coral Ecology Lab and Southwest Fisheries Science Center, USFS

Occurrences of deep-sea corals over a grid of fishing intensity for bottom longlines, pots, and traps, in order to understand how fishing overlaps with deep-sea and sponge coral habitat.

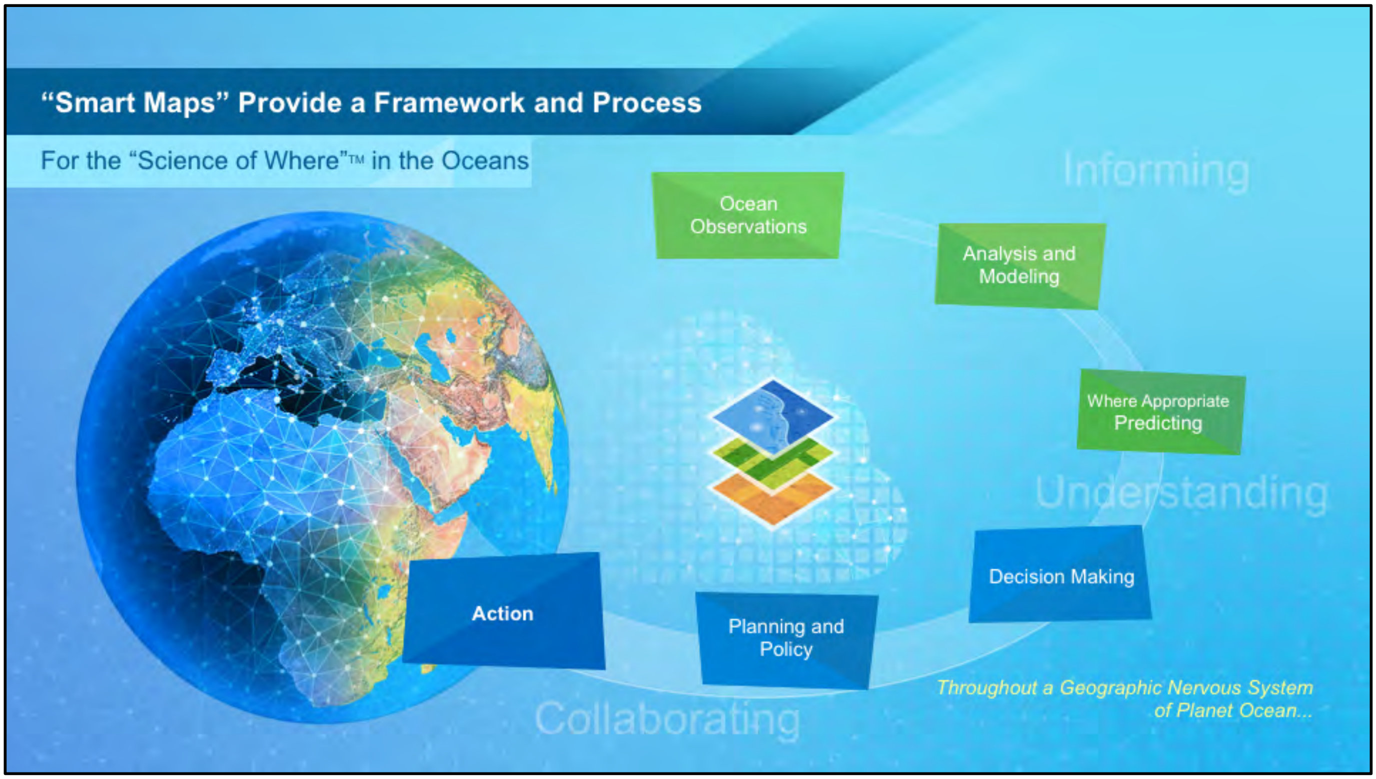
Migration pattern study of the Monarch Butterfly

ArcGIS Online App showing the Rusty Patched Bumble Bee

Reef Health—CSUCI—Cook Islands - This image show a hazard index rating for coral reefs studied on the island of Aitutaki in the South Pacific.

Visualizing a Current—Bureau of Ocean Energy Management - The Loop Current

Siting Offshore Aquaculture—NOAA/NOS/National Centers for Coastal Ocean Science - Spatial analysis for siting offshore aquaculture. Providing guidance for environmentally sustainable coastal aquaculture planning and development in the coastal zone. Coastal aquaculture is an industry that is growing at an unprecedented rate, creating challenges for spatial planning and environmental management in our Nation's coastal areas.



In my talk I have tried to take you through this arc from observing to action (especially in the context of the SDGs)
idea of a Geographic Nervous System for the Planet..

This is a cycle of virtuous effort from measuring to affecting the world.

Best wishes to you in YOUR work, however you fit into this cycle, a collective effort to create a smarter world, a more sustainable future.

XVIII / ROGER REVELLE COMMEMORATIVE LECTURE PRESENTED BY THE OCEAN STUDIES BOARD

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

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.

The National Academy of Engineering was established in 1964 under the charter of the National Academy of Sciences to bring the practices of engineering to advising the nation. Members are elected by their peers for extraordinary contributions to engineering. Dr. C. D. Mote, Jr., is president.

The National Academy of Medicine (formerly the Institute of Medicine) was established in 1970 under the charter of the National Academy of Sciences to advise the nation on medical and health issues. Members are elected by their peers for distinguished contributions to medicine and health. Dr. Victor J. Dzau is president.

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.

WWW.NATIONAL-ACADEMIES.ORG

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).

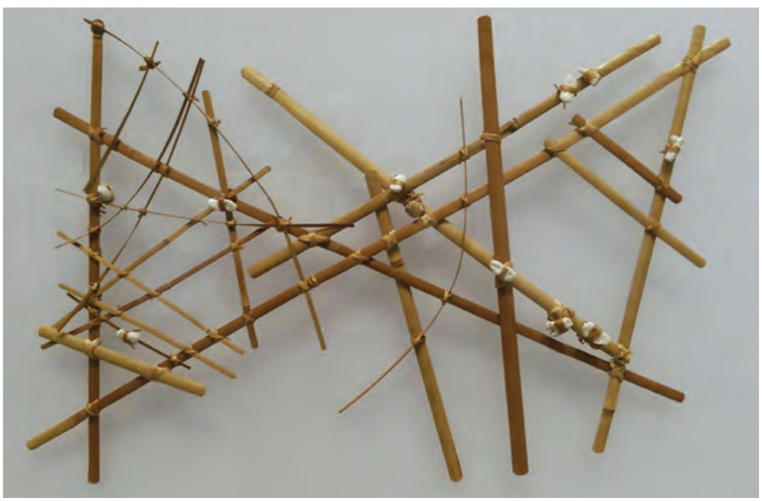


FIGURE 1. A navigational "stick chart" from the Marshall Islands, made of wood, coconut fibers and cowrie shells, with the fibers representing the crests of ocean swells. Chart is on display at the Berkeley Art Museum and Pacific Film Archive, University of California, Berkeley. **Photo by Jim Heaphy 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 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).

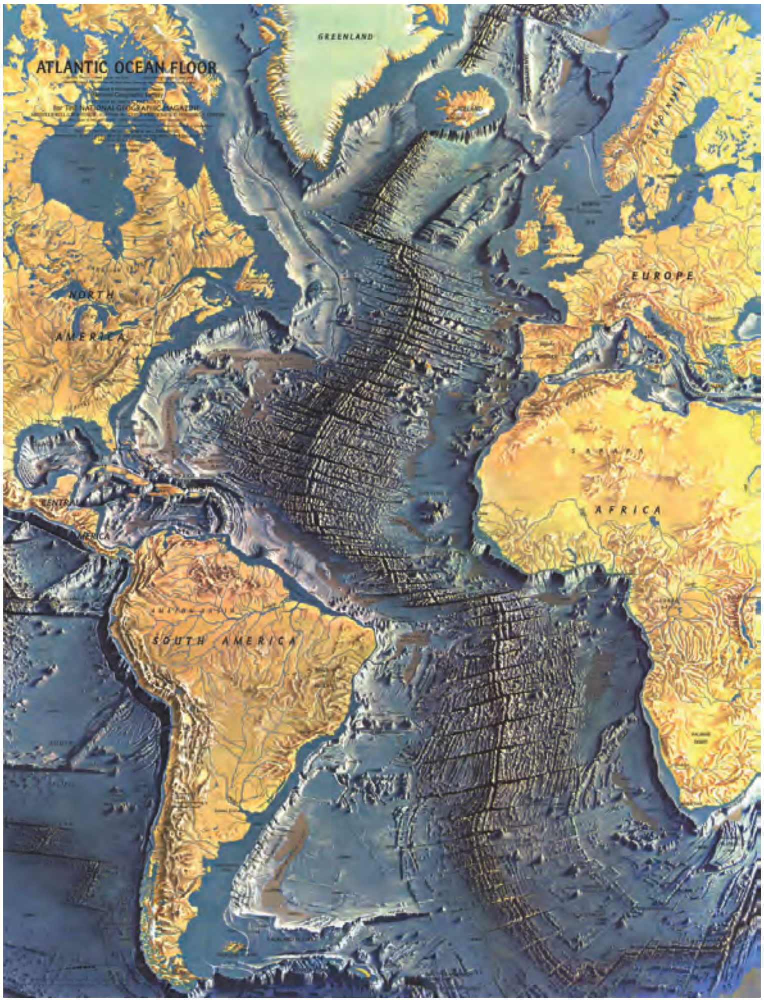


FIGURE 2. 1968 map of the Atlantic Ocean Floor based on a large compilation of deep ocean soundings by Bruce Heezen and Marie Tharp, painted by Heinrich Berann, for the National Geographic Magazine. **Image courtesy of Ken Field, International Cartographic Association.**

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

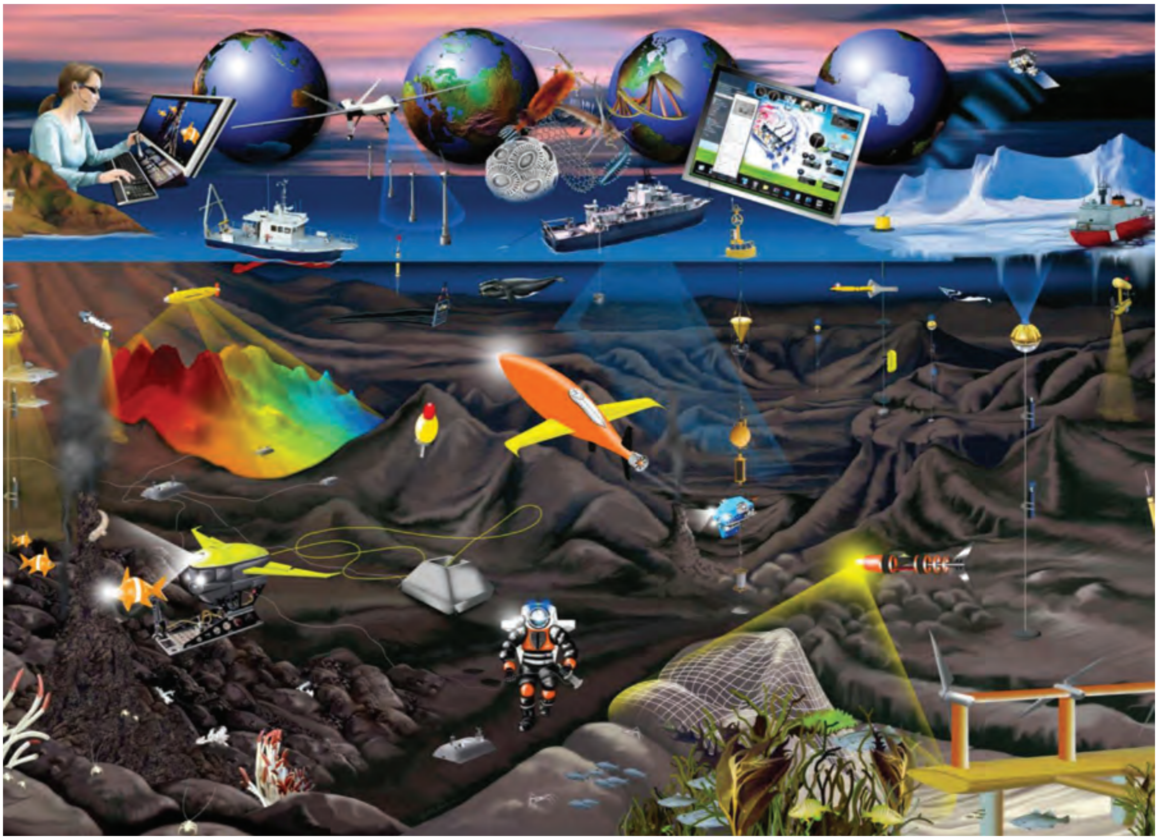


FIGURE 3. An illustration of the broad variety of the ships, vehicles, platforms, and sensors used now and looking 20 years into the future for understanding how the oceans work, and how we need to manage, and protect it. **From National Research Council (2011).**

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

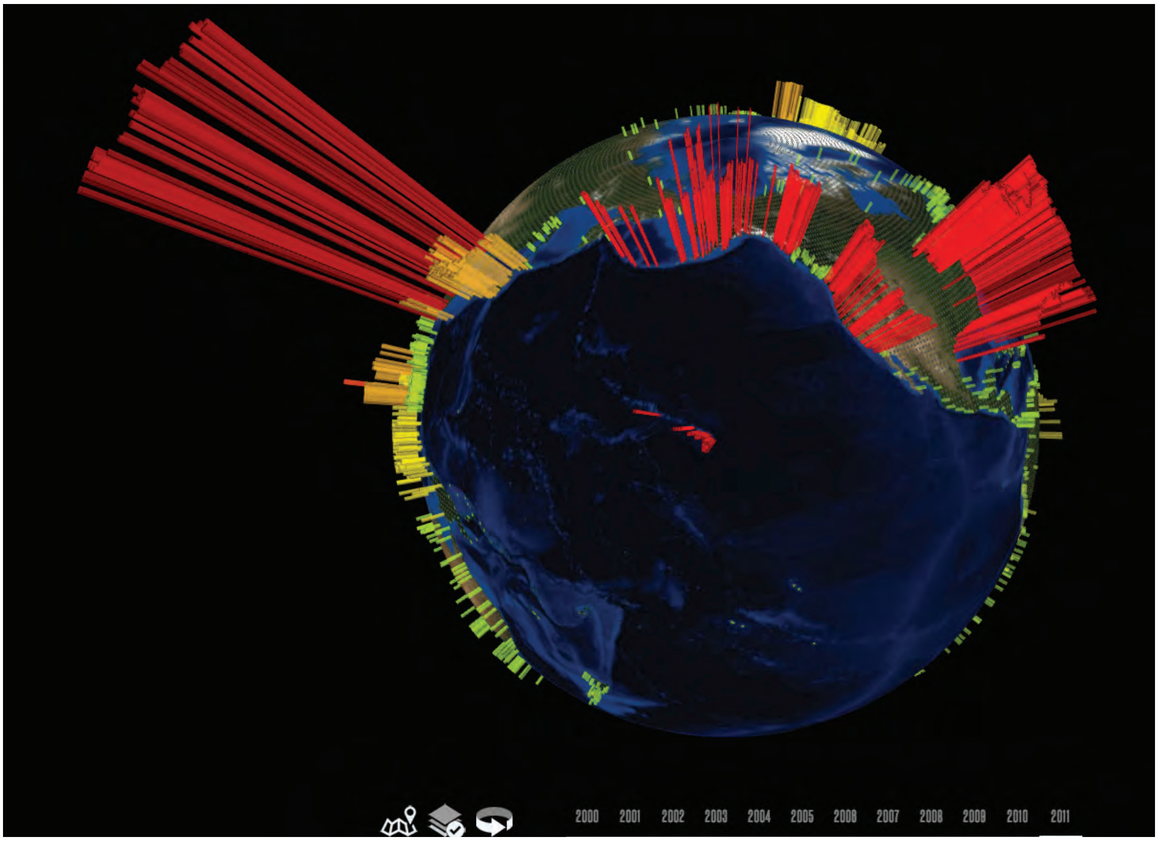


FIGURE 4. Visualization of the high volume of commercial shipping activity into and out of ports rimming the Pacific Ocean. Green bars represent shipping traffic of 1 million vessels, yellow 20 million, and red 50 million+. Lengths of bars represent amount of growth to those numbers over a 10-year period. 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).**

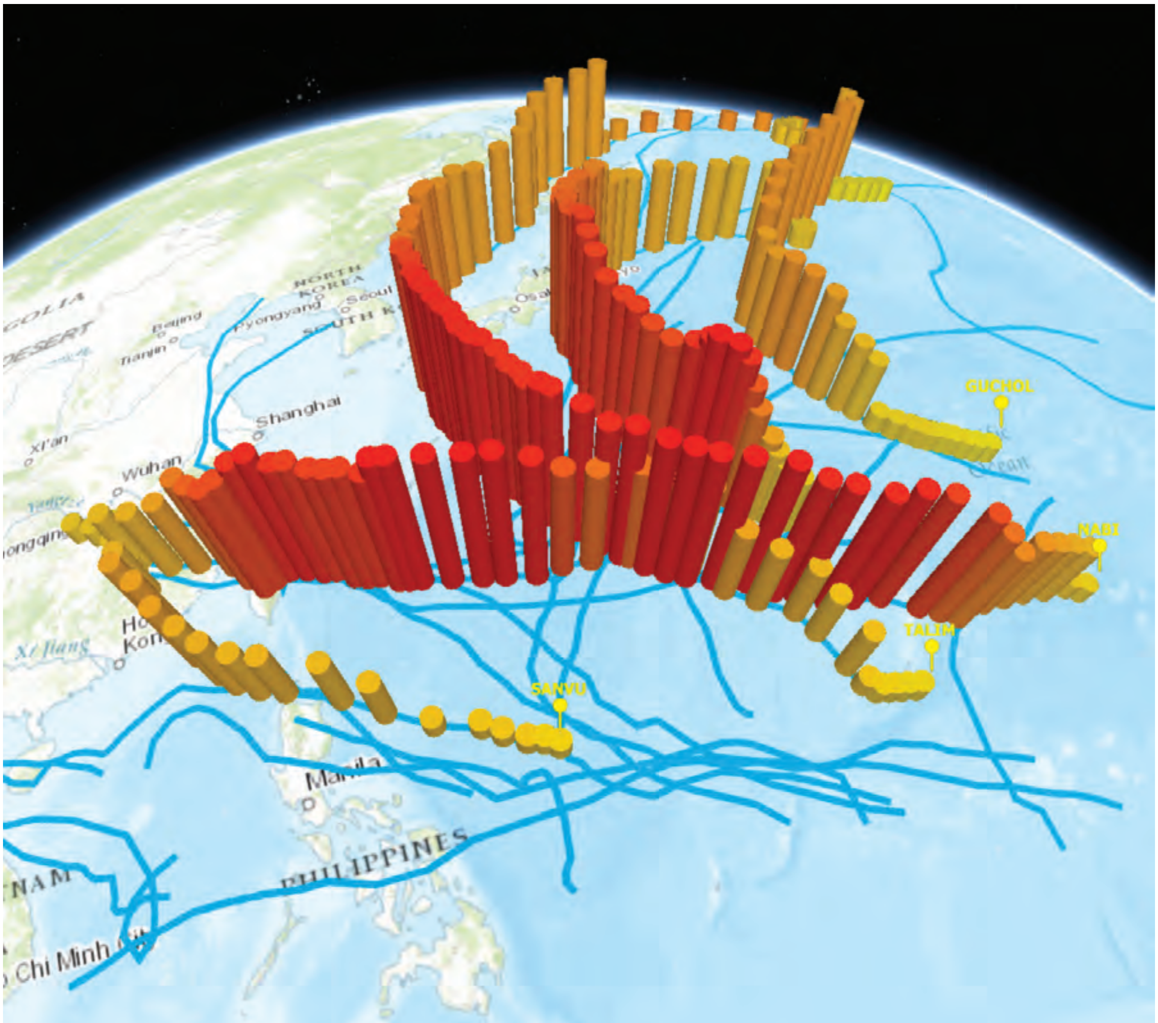


FIGURE 5. A map of typhoons in the Western Pacific during the record-breaking typhoon season of 2005, seeking to visualize the life cycle of the event and compare one storm to another to find unique details and overall patterns. 3D symbols depict the unique signature of every storm. This map shows wind 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

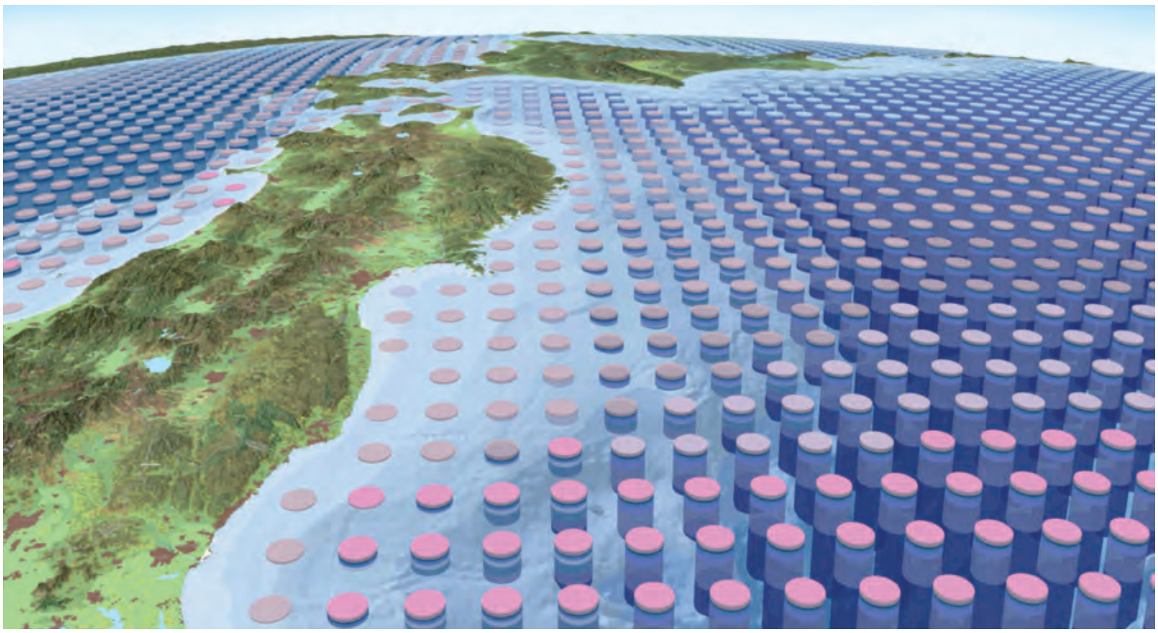


FIGURE 6. Example of a visualization approach taken to represent a new classification for the ocean known as ecological marine units (EMUs) in three dimensions mapped over space. The region shown is largely off the east coast of Japan in the Pacific Ocean. Although the EMUs are mapped as a continuous 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

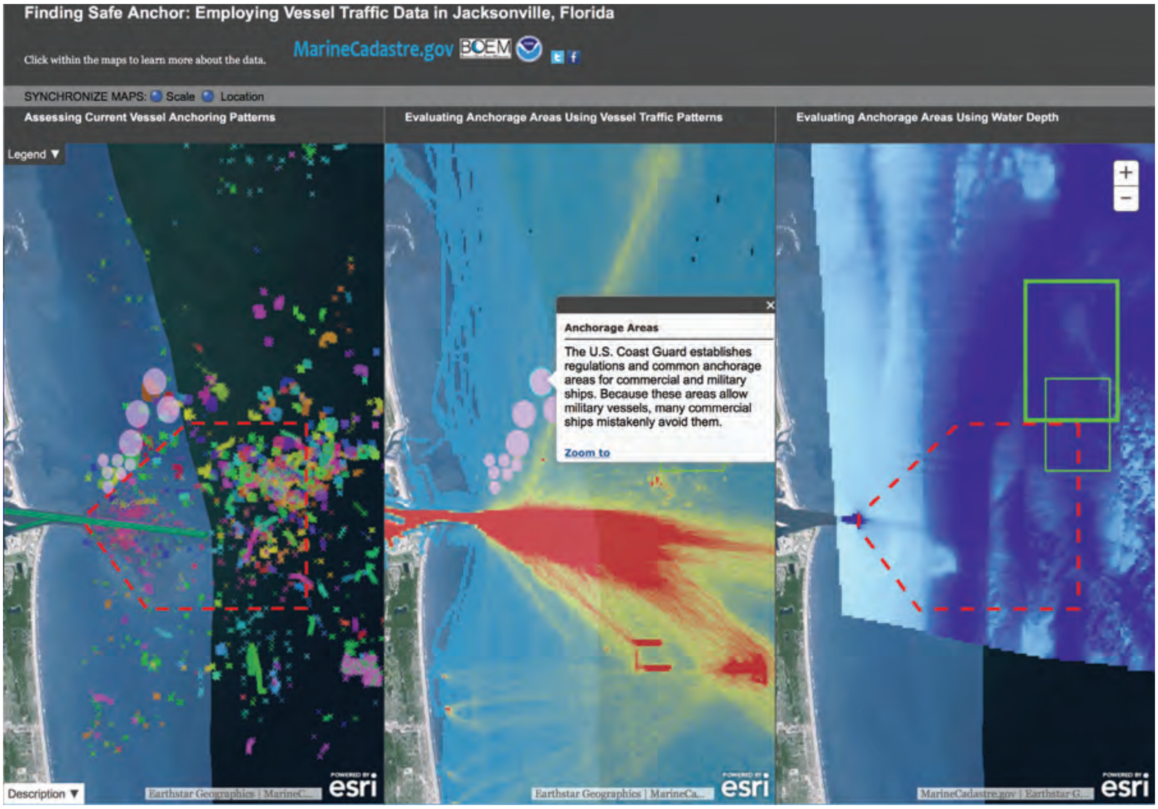


FIGURE 7. Example of a story map used in a US Coast Guard/NOAA workshop. Panning or zooming in one of the map panels synchronizes the same map scale and location for the other two, so that users can simultaneously examine vessel anchoring patterns (left), vessel traffic patterns (middle), and water depth (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.

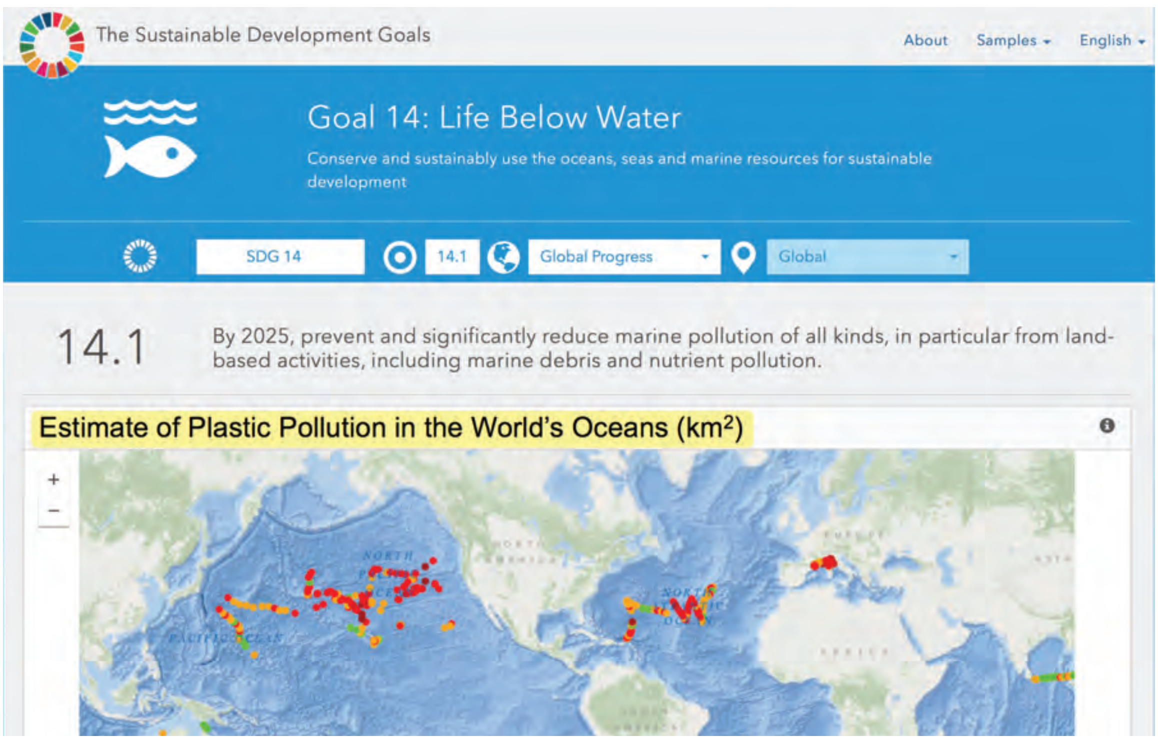
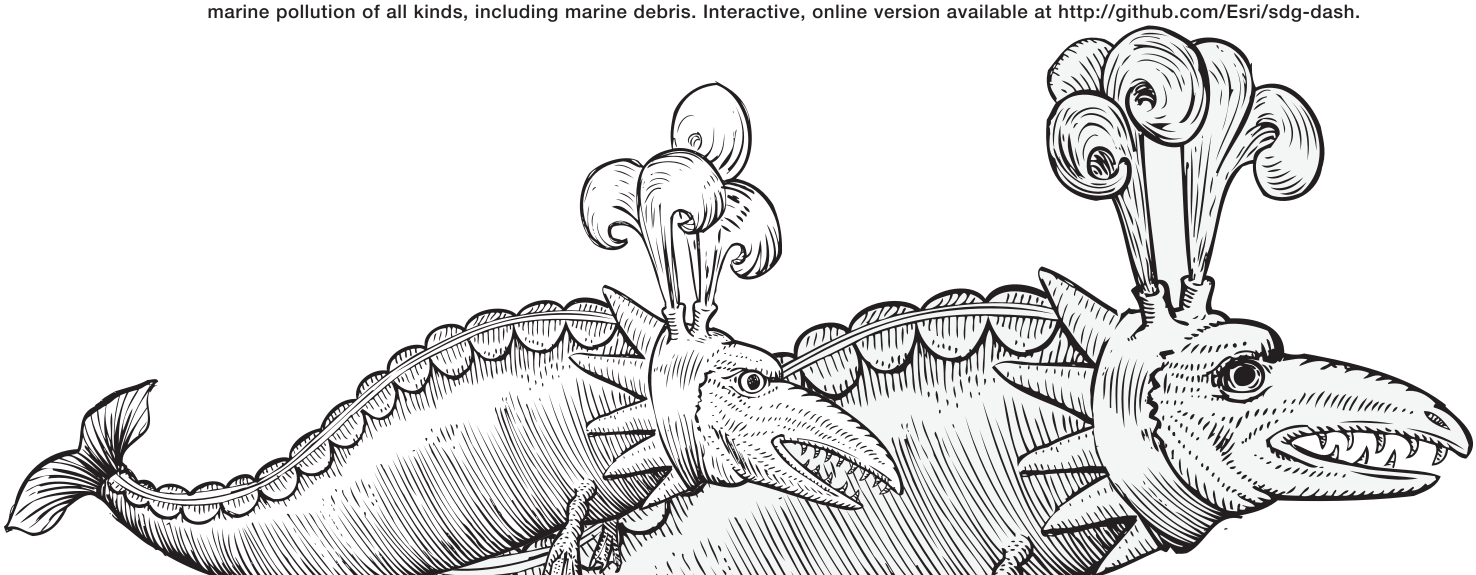
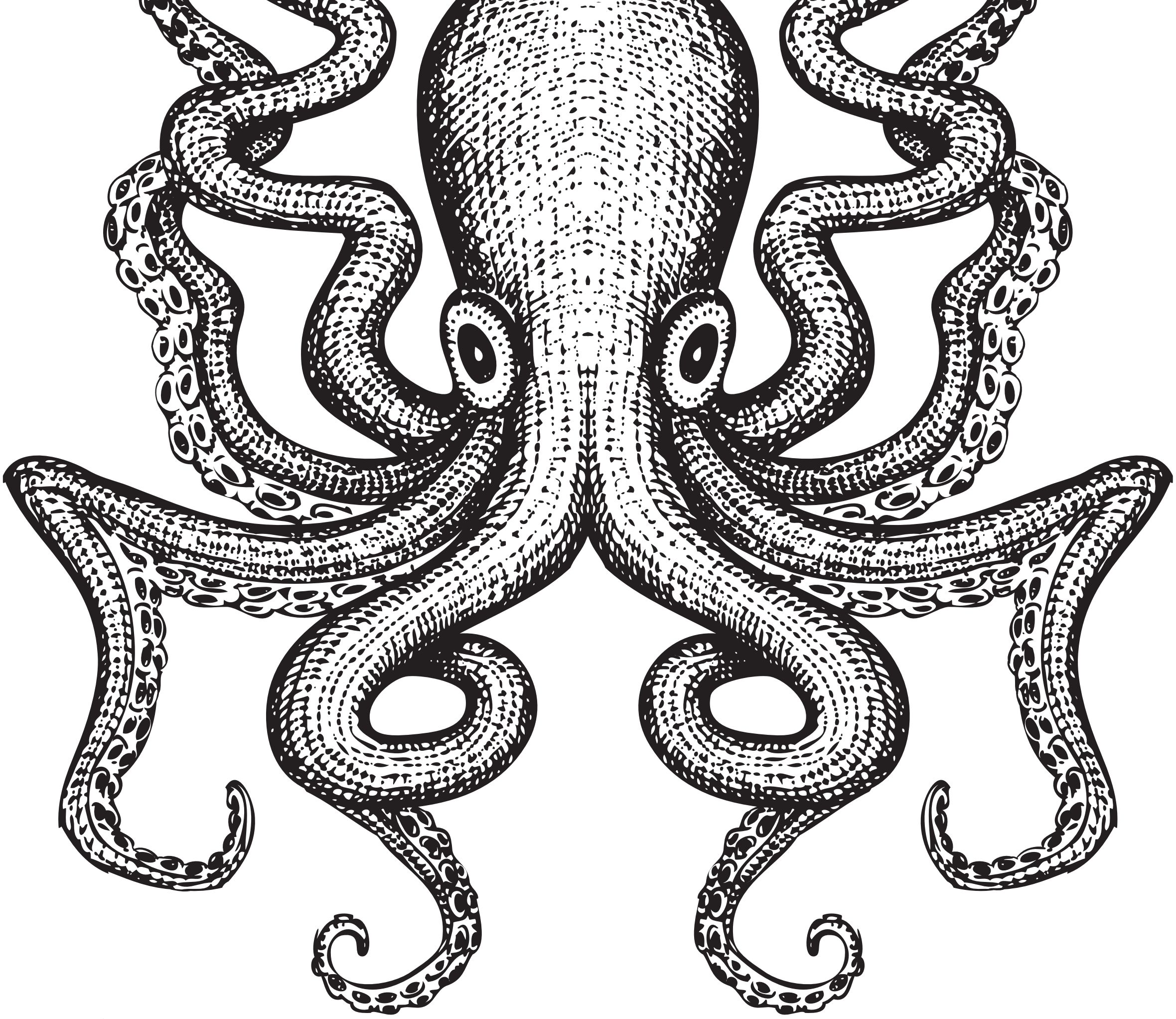


FIGURE 9. A GIS dashboard commissioned by the UN to aid in the implementation and management of the SDGs, in this case for displaying progress on Goal 14, Target 1 about reducing marine pollution of all kinds, including marine debris. **Interactive, online version available at http://github.com/Esri/sdg-dash.**

REFERENCES | Alder, J.R., and S.W. Hostetler. 2015. Web based visualization of large climate data sets. Environmental Modelling & Software 68:175–180. | Baron, N. 2010. Escape from the Ivory Tower: A Guide to Making Your Science Matter, second ed., Island Press, Washington, DC. | Blondel, P., and B. J. Murton. 1997. Handbook of Seafloor Sonar Imagery. John Wiley & Sons, Chichester, UK, 314 pp. | Civic Analytics Network. 2017. An Open Letter to the Open Data Community. http://bit.ly/2m1Uvjo. | Collie, J.S., W.L. Adamowicz, M.W. Beck, B. Craig, T.E. Essington, D. Fluharty, J. Rice, and J.N. Sanchirico. 2013. Marine spatial planning in practice. Estuarine, Coastal, and Shelf Science 117:1–11. | Corfield, R. 2003. The Silent Landscape: The Scientific Voyage of HMS Challenger. Joseph Henry Press, New York, 300 pp. | Doel, R E., T.J. Levin, and M.K. Marker. 2006. Extending modern cartography to the ocean depths: military patronage, Cold War priorities, and the Heezen-Tharp mapping project, 1952-1959. Journal of Historical Geography. 32:605¬–626. | Felt, H. 2012. Soundings: The Story of the Remarkable Woman Who Mapped the Ocean Floor. Henry Holt and Co., New York, 352 pp. | Finney, B. 1998. Nautical cartography and traditional navigation in Oceania. Pp. 443-492 in The History of Cartography: Cartography in the Traditional African, American, Arctic, Australian, and Pacific Societies, vol. 2, book 3. D. Woodward and L.G. Malcolm, eds, The University of Chicago Press, Chicago. | Gantz, J., and D. Reinsel. 2012. The Digital Universe in 2020: Big Data, Bigger Digital Shadows, and Biggest Growth in the Far East. International Data Corporation, Framingham, MA, 16 pp. | Garcia, H.E., R.A. Locarnini, T.P. Boyer, J.I. Antonov, O.K. Baranova, M.M. Zweng, and others. 2013. World Ocean Atlas 2013 version 2 (WOA13 V2), Volume 3: Dissolved Oxygen, Apparent Oxygen Utilization, and Oxygen Saturation. In: NOAA National Centers for Environmental Information, S. Levitus, ed., and A. Mishonov, technical ed., NOAA Atlas NESDIS 75, NOAA National Centers for Environmental Information, Silver Spring, Maryland, 27 pp, doi: 10.7289/V5XG9P2W via http://repository.library.noaa.gov. | Garcia, H.E., R.A. Locarnini, T.P. Boyer, J.I. Antonov, O.K. Baranova, M.M. Zweng, and others. 2013. World Ocean Atlas 2013 version 2 (WOA13 V2), Volume 4: Dissolved Inorganic Nutrients (phosphate, nitrate, silicate). In: NOAA National Centers for Environmental Information S. Levitus, ed., and A. Mishonov, technical ed., NOAA Atlas NESDIS 76, NOAA National Centers for Environmental Information, Silver Spring, Maryland, 25 pp., publication doi: 10.7289/V5J67DWD, dataset doi: 10.7289/V5F769GT via http://repository.library.noaa.gov. | Glover, D. M., P. H. Wiebe, C. L. Chandler, and S. Levitus. 2010. IOC contributions to international, interdisciplinary open data sharing. Oceanography 23 (3):140-151. | Grenley, D. 2016. The ArcGIS Imagery Book: A Geographic Rosetta Stone. https://blogs.esri.com/esri/esri-insider/2016/07/05/the-arcgis-imagery-book-a-geographic-rosetta-stone. | Group on Earth Observations. 2005. Global Earth Observation System of Systems (GEOSS) 10 Year Implementation Plan Reference Document. European Space Agency Publication GEO 1000R/ESA SP 1284, The European Space Agency, Noordwijk, The Netherlands, 210 pp. | Group on Earth Observations. 2017. The Group on Earth Observations. http://www.earthobservations.org. | Hoegh-Guldberg, O., T. Aqorau, R. Arnason, T. Chansiri, N. Del Rio, H. Demone, S. Earle, M.H. Feeley, D. Gutierrez, R. Hilborn, N. Ishii, C. Lischewski, J. Lubchenco, K.A. Nguyen, D.O. Obura, R. Payet, T.N. Slade, J. Tanzer, J. H. Williams, D.J. Wright, and J. Xu. 2013. Indispensable Ocean: Aligning Ocean Health and Human Well-Being – Guidance from the Blue Ribbon Panel to the Global Partnership for Oceans. The Global Partnership for Oceans and the World Bank, Washington, DC, 44 pp. | Landa, E.R. 2010. The ties that bind: Soil surveyor William Edgar Tharp and oceanographic cartographer Marie Tharp. Physics and Chemistry of the Earth 35 (15–18):868–880. | Lewis, D. 1994. We, the Navigators: The Ancient Art of Landfinding in the Pacific. second ed., University of Hawaii Press, Honolulu, 464 pp. | Li, Z., and C. Gold. 2004. Multidimensional geospatial technology for geosciences. Computers and Geosciences 30(4):321–323. | Locarnini, R.A., A.V. Mishonov, J.I. Antonov, T.P. Boyer, H.E. Garcia, O.K. Baranova, and others. 2013. World Ocean Atlas 2013 version 2 (WOA13 V2), Volume 1: Temperature. In: NOAA National Centers for Environmental Information S. Levitus, ed., and A. Mishonov, technical ed., NOAA Atlas NESDIS 73, NOAA National Centers for Environmental Information, Silver Spring, Maryland, pp 40, publication doi: 10.7289/V55X26VD, dataset doi: 10.7289/V5F769GT via http://repository.library.noaa.gov. | Malcolm, H.A., E. Foulsham, R.L. Pressey, A. Jordan, P.L. Davies, T. Ingleton, N. Johnstone, S. Hessey, and S. D. A. Smith. 2012. Selecting zones in a marine park: Early systematic planning improves cost-efficiency; combining habitat and biotic data improves effectiveness. Ocean & Coastal Management 59:1–12. | Mascarelli, A.L. 2009. Data's shameful neglect. Nature 461:145. | McHarg, I. 1995. Design with Nature, 25th Anniversary Edition. Wiley, New York, 208 pp. | McNutt, M., K. Lehnert, B. Hanson, B.A. Nosek, A.M. Ellison, and J.L. King. 2016. Liberating field science samples and data. Science 351(6277):1024–1026. | National Research Council. 2004. A Geospatial Framework for the Coastal Zone: National Needs for Coastal Mapping and Charting. The National Academies Press, Washington, DC, 149 pp. | National Research Council. 2011. An Ocean Infrastructure Strategy for U.S. Ocean Research in 2030. The National Academies Press, Washington, DC, 98 pp. | North, G.W. 2010. Marie Tharp: The lady who showed us the ocean floors. Physics and Chemistry of the Earth 35 (15–18):881–886. | Organisation for Economic Co-operation and Development. 2015. Making Open Science a Reality. OECD Science, Technology and Industry Policy Paper, OECD Publishing, Paris, 108 pp. | Paolo, D., A. Leadbetter, and H. Glaves, eds. 2017. Oceanographic and Marine Cross-Domain Data Management for Sustainable Development. IGI Global, Hershey, PA, 425 pp. | Paul, E., W. McClintock, and D. Wright. 2012. SeaSketch for oil spill response. Journal of Ocean Technology 7(4):130–131. | Picard, K., B. Brooke, and M.F. Coffin. 2017. Geological insights from Malaysia Airlines flight MH370 search. Eos, Transactions American Geophysical Union 98, https://doi.org/10.1029/2017EO069015. | Sandwell, D., S. Gille, J.A. Orcutt, and W. Smith. 2003. Bathymetry from space is now possible. Eos Transactions American Geophysical Union 84(5):37, 44. | Sayre, R., D.J. Wright, S.P. Breyer, K.A. Butler, K. Van Graafeiland, M.J. Costello, P.T. Harris, K.L. Goodin, J.M. Guinotte, Z. Basher, M.T. Kavanaugh, P.N. Halpin, M.E. Monaco, N.A. Cressie, P. Aniello, C.E. Frye, and D. Stephens. 2017. A three-dimensional mapping of the ocean based on environmental data. Oceanography 30(1):90—103. | Seife C. 2015. Big data: The revolution is digitized. Nature 518(7540):480–481. | Smith, W.H.F., and D.T. Sandwell. 1994. Bathymetric prediction from dense satellite altimetry and sparse shipboard bathymetry. Journal of Geophysical Research 99:21803¬–21824. | Smith, W.H.F., and D.T. Sandwell. 1997. Global seafloor topography from satellite altimetry and ship depth soundings. Science 277:1957–1962. | Smith, W.H.F., K.M. Marks, and T. Schmitt. 2017. Airline flight paths over the unmapped ocean. Eos, Transactions American Geophysical Union

98, https://doi.org/10.1029/2017EO069127. | Steinitz, C. 2012. A Framework for Geodesign: Changing Geography by Design. Esri Press, Redlands, CA, 224 pp. | Stelzenmuller, V., J. Lee, A. South, J. Foden, and S.I. Rogers. 2013. Practical tools to support marine spatial planning: A review and some prototype tools. Marine Policy 38:214–227. | Strickland-Munro, J., H. Kobryn, G. Brown, and S.A. Moore. 2016. Marine spatial planning for the future: Using Public Participation GIS (PPGIS) to inform the human dimension for large marine parks. Marine Policy 73:15–26. | United Nations. 2015a. Sustainable Development Goals: 17 Goals to Transform our World. http://www.un.org/sustainabledevelopment. | United Nations. 2015b. Sustainable Development Goal 14: Conserve and Sustainably Use the Oceans, Seas, and Marine Resources. http://www.un.org/sustainabledevelopment/oceans. | Walters, M., and R.J. Scholes, eds. 2017. The GEO Handbook on Biodiversity Observation Networks. Springer International Publishing, Cham, Switzerland, 326 pp. | Wessel, P., and M.T. Chandler. 2011. The spatial and temporal distribution of marine geophysical surveys. Acta Geophysica 59 (11):55-71, https://doi.org/10.2478/s11600-010-0038-1. | White, C., B.S. Halpern, and C.V. Kappel. 2012. Ecosystem service tradeoff analysis reveals the value of marine spatial planning for multiple ocean uses. Proceedings of the National Academy of Sciences of the United States of America 109(12): 4696–4701. | Wright, D. 2014. Mapping the Course. Ensia. https://ensia.com/voices/mapping-the-course. | Wright, D.J., A. Verrill, M. Artz, and R. Deming. 2014. Story maps as an effective social medium for data synthesis, communication, and dissemination, Transactions American Geophysical Union, 95, http://esriurl.com/agustories. | Wright, D.J. 2015a. Toward a digital resilience. Elementa Science of the Anthropocene. 4(000082), http://dx.doi.org/10.12952/journal.elementa.000082. | Wright, D.J. 2015b. 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. 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.





Thank you

The Ocean Studies Board would like to thank the founding and continuing sponsors for their generous support of the Revelle Lecture. This lecture series would not be possible without their generous contributions.

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