OneNOAA Science Webinar
January 25, 2017
Audio is over the phone; please dial 1-877-708-1667
passcode is 7028688#

Ecological Marine Units:
A 3-D Mapping of the Ocean Based on NOAA's World Ocean Atlas

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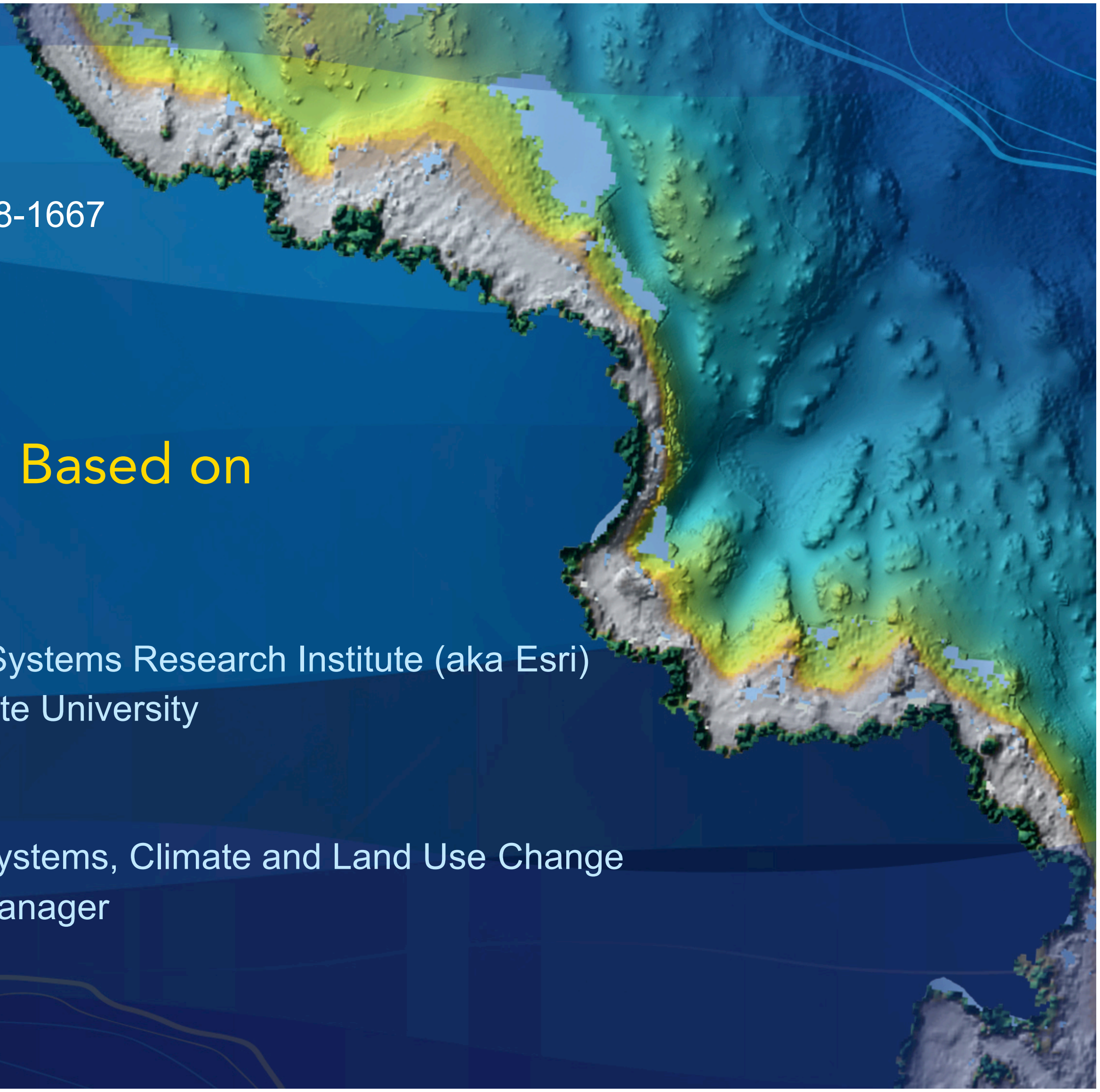
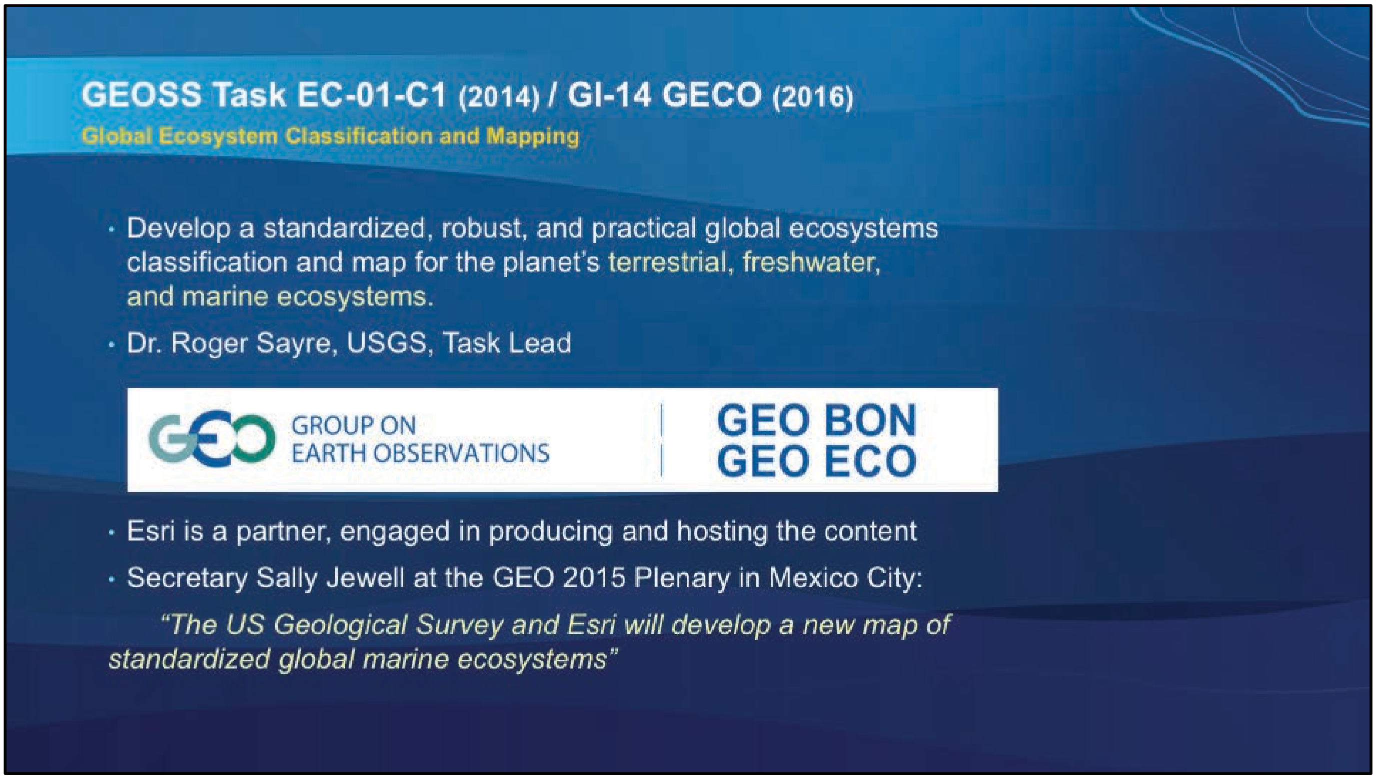
Sean Breyer, Esri ArcGIS Content Program Manager

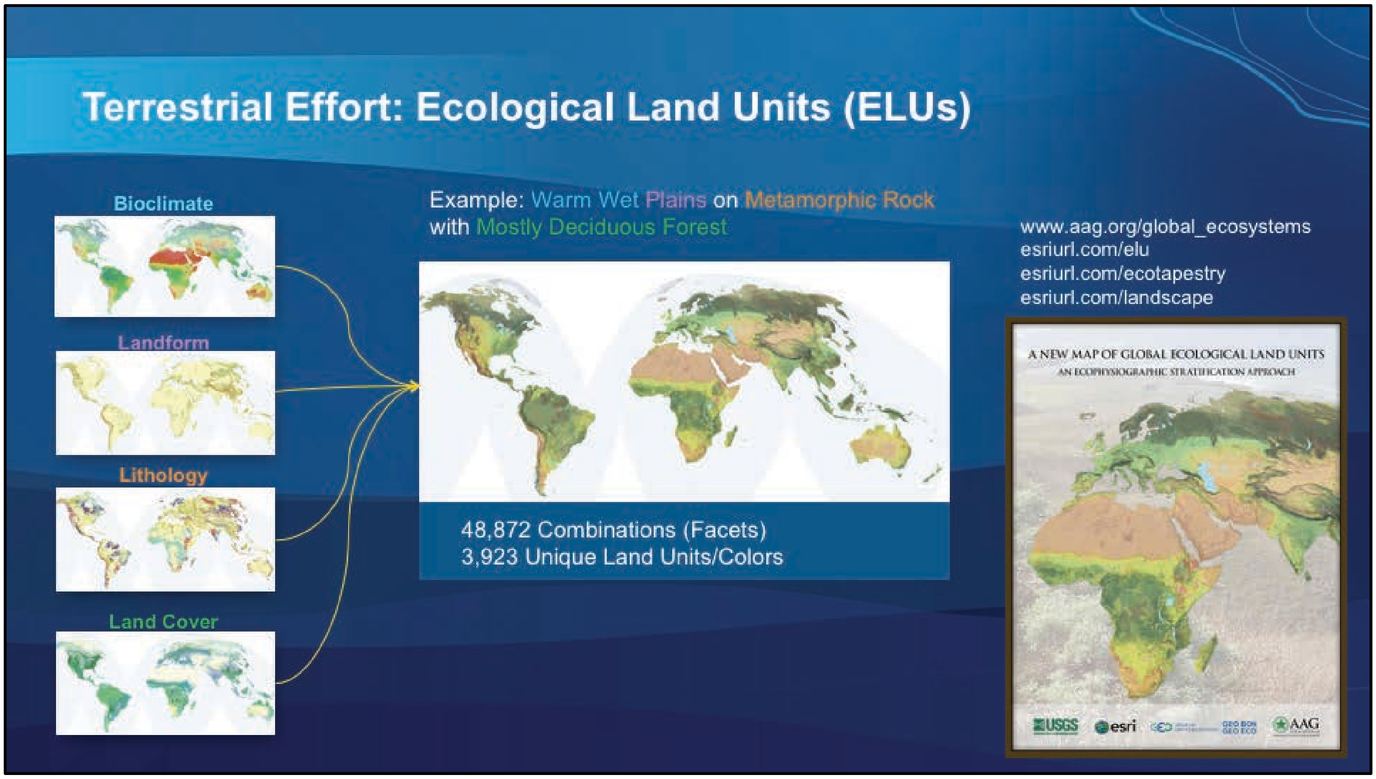




The work to produce the map and data was commissioned by the Group on Earth Observations, a mini "United Nations" of sorts consisting of almost 100 nations collaborating to build the Global Earth Observation System of Systems (GEOSS) in 9 Societal Benefit Areas (Agriculture, Biodiversity, Climate, Disasters, 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).

One impt thing to mention is that the ELUs were released and launched as an earlier contribution to the President's Climate Data Initiative.
The ELUs are now on that list of Climate Data Initiative (CDI) resources, and of course are registered on data.gov. Now the EMUs should be considered a similar contribution but for the marine environment. Since Fabien was and is apparently still engaged with the CDI, this is a major hook into White House interest.

EMU is now under the new **GEO Global Ecosystems initiative (GECO)** arising from the **GEO 2016 Transitional Workplan**. The former Ecosystems Societal Benefit Area and the former Biodiversity Societal Benefit Area have been combined into a new Biodiversity and Ecosystems Sustainability SBA.
The GECO is a new task, and it has four pieces to it related to 1) the European Horizon 2020 ECOPOTENTIAL project, 2) the H2020 SWOS (Satellite-based Wetlands Observation System) project, 3) global EMUs, and 4) global EFUs.



So why do we need a global ecosystem map anyway? Such a map, and more importantly, the data, will provide scientific support for planning and management, and enable understanding of impacts to ecosystems from climate change and other disturbances. The map and data should also prove useful as an ecologically meaningful spatial accounting framework for assessments of the economic and social values of ecosystem goods and services.

- Should aid in REPEATABLE landscape mgmt - a platform for geo-accounting (instead of reducing so much by national boundaries, we are using real ecological units)

A standard repeatable accounting framework

A global view of environmental diversity

Ecosystems defined by humans for humans as opposed to ecosystem HEALTH, a healthy ecosystem vs a service that the ecosystem provides - the next level to resilient ecosystems rather than ecosystem services
Research goal in future? what are the indicators that if merged together in a better way would provide better services; one can still be SICK and provide services
Example – indicators may be relative to the status of the fish stock but not indicators as to how the ecosystem is working.

Specific needs include:
•*Assessments of Economic and Social Value of Ecosystem Goods and Services*
•*Biodiversity Conservation Planning*
•*Analysis of Climate Change Impacts to Ecosystems* (*and other impacts e.g. fire, invasive species, land use, etc*.)
•*Resource Management*
•*Research*

Bioclimate, Landform, and Lithology = Drivers of Ecological Character (physical setting)
Land Cover = Response to the Physical Setting

We found 48,872 unique combinations aggregated to 3923 ELUs. In 2015 106,959 unique combos thanks to the updated land forms and land cover, 2010 epoch, Global Land Cover, v. 1.4
Bioclimate, Landform, and Lithology = Drivers of Ecological Character (physical setting)
Land Cover = Response to the Physical Setting
Bioclimates - Global Environmental Stratification (GEnS), U. of Edinburgh **-** 50 year avg of temp/precip from met stations throughout world
30 arc sec raster, down-sampled to 250-m raster
Landforms – USGS – 250-m raster, derived from GMTED2010
Surficial Lithology - Global Lithological Map (GLiM), Hamburg University, Vector Polygons converted to 250-m raster
Land Cover - GlobCover, 2009, European Space Agency - MARIS satellite, 300 m rez resampled to 250 m
Version 2 recently released in 2015 with updated land cover, 2010 epoch, Global Land Cover, v. 1.4
Only layer that we had an option: GlobCover 2009, GlobeLand30 or MDA's NaturalVue
GlobCover 2009 offered a richer, more flexible classification, which is compatible with USGS NLCD
NaturalVue was too old.
Both had significant quality issues relative to broad audience acceptance
Today, there are more options. Globeland30 continues to be improved. MDA has produced BaseVue

How did we make the map? Again, we define ecosystems as distinct physical environments and their associated vegetation, so we map ecosystems by first mapping, and then combining in a GIS, global bioclimates, global landforms, global geology, and global land cover.
1. Characterize the principle ecological land components of the terrestrial surface of the earth in a micro-scale, bottom-up, hierarchical classification process.
2. Subdivide the land surface of the earth into macro-scale physiographic (geomorphological) areas in a top-down, hierarchical regionalization process.
3. Combine the physiographic regionalization process with the ecological classification process to develop a hierarchical, ecophysiographic segmentation of the planet.
4. Weightings of 4 layers: 3, 3, 2, 1

EMU Steering Committee (* Indicates Core Leadership Team)

*Roger Sayre, Ph.D. U.S. Geological Survey	*Dawn Wright, Ph.D. Esri	*Sean Breyer Esri	Nawajish Noman, Ph.D. Esri
*Kevin Butler, Ph.D. Esri	*Keith VanGraafeiland Esri	Steve Kopp Esri	Nathan Shepherd Esri
Mark Costello, Ph.D. University of Auckland	Doug Cribbs Esri	Miles Macmillan-Lawler GRID Arendal, Norway	Drew Stephens Esri
Peter Harris, Ph.D. GRID Arendal, Norway	Charlie Frye Esri	Mark Monaco, Ph.D. NOAA National Center for Coastal Monitoring & Assessment	Pat Halpin, Ph.D. Duke University Marine Geospatial Ecology Lab
Pete Aniello Esri, now with Sandia Natl Labs	Kathy Goodin NatureServe	Lance Morgan, Ph.D. Marine Conservation Institute	Beata Van Esch Esri
Zeenatul Basher, Ph.D. U.S. Geological Survey	John Guinotte, Ph.D. Marine Conservation Institute, now with USFWS	Guy Noll Esri	Randy Vaughan, Ph.D. Esri

Additional Collaborators
Maria Kavanaugh, Ph.D.
Pelagic Seascape Ecology & Biogeochemistry
WHOI
Dick Feely, Ph.D.
Carbon Program
NOAA PMEL - Seattle
Mike Williams, Ph.D.
Physical Oceanography
NIWA, New Zealand
Rob Brumbaugh, Ph.D.
The Nature Conservancy
Liqing Jiang, Ph.D.
NOAA NCEI – Silver Spring
Simone Alin, Ph.D.
Carbon Program
NOAA PMEL - Seattle
Nina Bednarsek, Ph.D.
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NOAA PMEL - Seattle
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Geography, Marine Geomatics Research
Memorial University of Newfoundland, Canada
Noel Cressie, Ph.D.
Distinguished Prof of Math & Applied Statistics
U. of Wollongong, Australia
Distinguished Visiting Scientist, NASA JPL
(formerly at U. of Iowa and Ohio State)

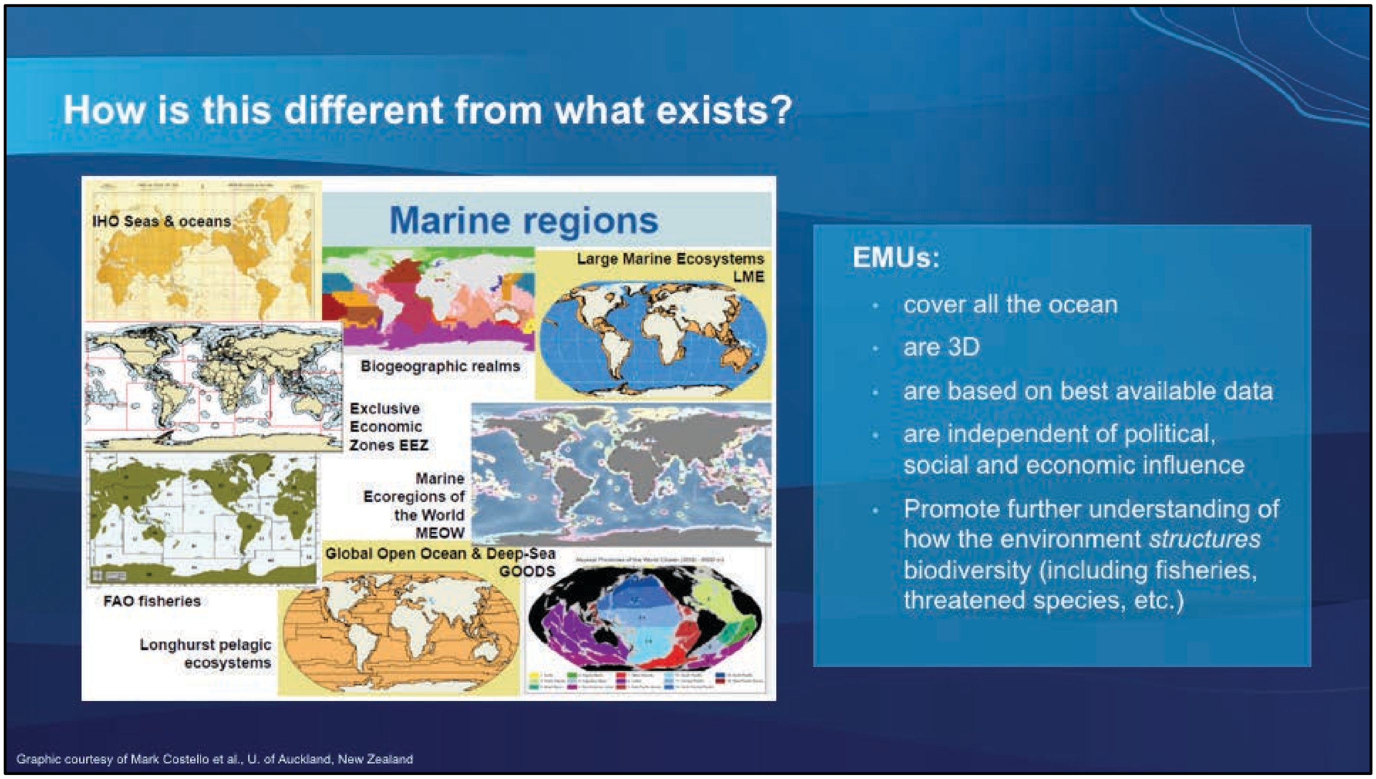
Ecological Marine Units (EMUs)

Who wants one?

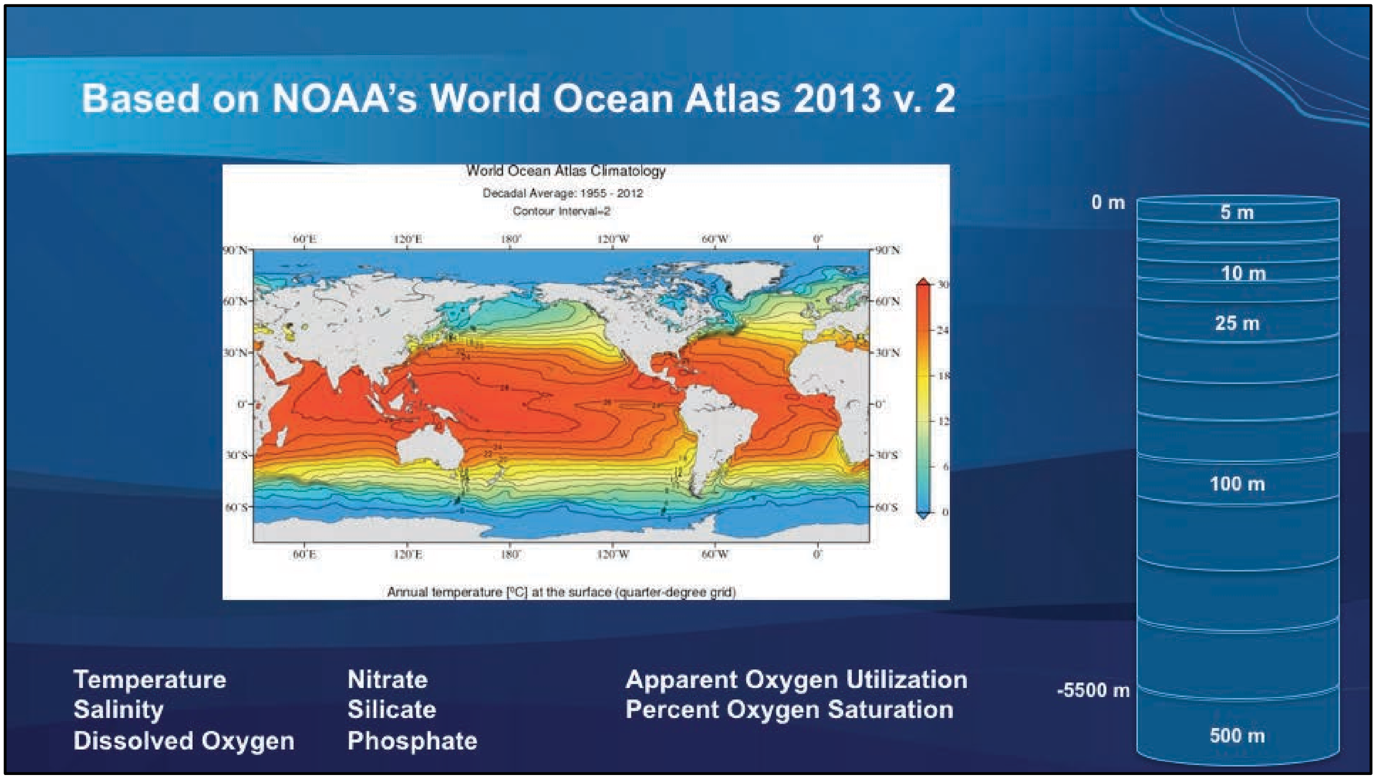
- GEO & GEOSS (GEO BON MBON, GECO)
- Global Ocean Refuge System (GLORES)
- IUCN, WWF, CI, Mission Blue Sylvia Earle Alliance
- FAO and ICES
- OOI and IOOS/GOOS
- Essential Ocean Variables community (e.g., World Climate Research Program)
- Researchers
- Educators
- Local agencies who want the global context
- Natl science agencies
- Editors of textbooks

Why?

- **Ecosystem Health, Resilience, Ecosystem Goods & Services; Ecosystem Services Valuation**
- Nature Conservation Reporting
- Conservation planning
- Ecosystem Classification
- Ecosystem Based Management
- Fisheries Management
- Marine Data Management
- Indicating Species Distributions
- Explaining and Understanding Nature
- Risk Reduction
- Context: Local related to Global
- System Connectivity



Instead of reflecting JUST researchers perceptions and local experiences, our EMUs provide quantifiable definitions for these such as epipelagic, mesopelagic, bathypelagic, etc.



Where do we get the best "physical setting" for the ocean, which will in turn drives its ecological character? 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 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 the 5 or 6 decadal averages, 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

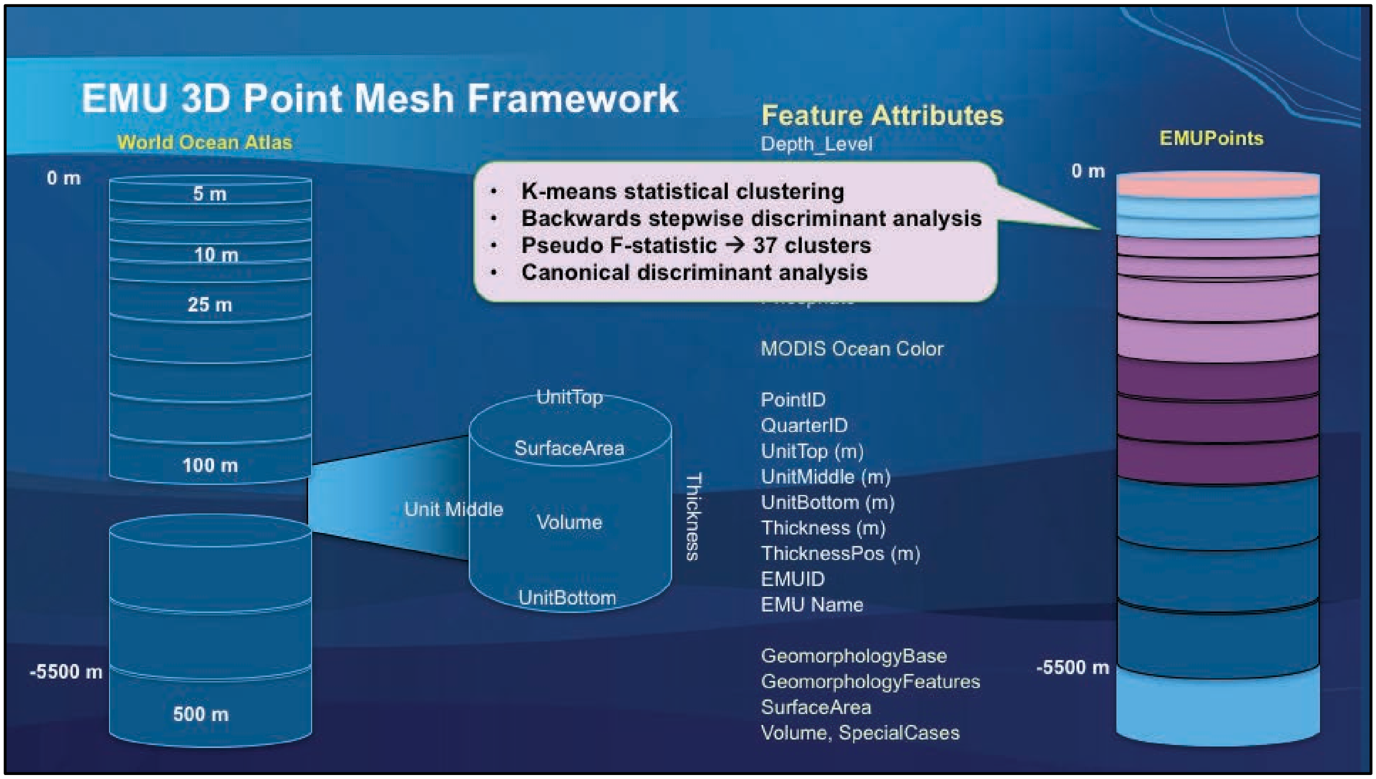
In collaboration with NOEL CRESSIE:
The extraction of the World Ocean Atlas data into a global point mesh framework created 52,487,233 points, each with eight attributes in addition to the x, y, and z coordinates. A globally comprehensive subset (25,000 points) of all points was used for the determination of the optimum cluster number using the **Tibshirani's gap statistic**, yielding an optimum of 37 clusters. For the **pseudo F-statistic** 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.

Statistical Clustering Background
The approach to aggregating comprehensive marine environment data through statistical clustering builds on previous efforts. For example, Harris and Whiteway (2009) used a multivariate statistical method with 6 biophysical variables (depth, seabed slope, sediment thickness, primary production, bottom water dissolved oxygen and bottom temperature) to objectively classify the ocean floor into 53,713 separate polygons comprising 11 different categories. The 11 categories had mean polygon sizes ranging between ~1,000 km^2 to 22,000 km^2 and were restricted to the seafloor. To our knowledge, there has never been a similar attempt to objectively classify the entire global ocean water column into discrete regions.

We implemented a 3D statistical clustering of the point mesh to identify environmentally distinct regions in the water column. The "big data" nature of the clustering of the entire ocean volume required sophisticated spatial processing and functionality drawn from several platforms (SAS, R, and ArcGIS Pro). A separate paper on these detailed statistical methods is in development. In general, we developed and implemented a k-means clustering algorithm to identify the physico-chemical structure of the water column. The statistical approach was prototyped on a subset of the global point mesh representing the ocean volume off the coast of California out to the EEZ. Subsequently, the global clustering was implemented on all cells with all variables included. The statistical clustering and aggregation of the data in the mesh identified ecological marine units (EMUs) as clusters of relative homogeneity in the underlying environmental data. The classification was unsupervised, and used a geographic constraint such that regions which are similar in data space but are widely separated geographically were not clustered into the same EMU occurrence.

Two approaches were used to determine the ultimate number of clusters to be produced which would best represent the collective variation in the input data. Tibshirani's gap statistic compares the within-cluster dissimilarity for the transformed data with the same quantity for a randomly generated set of features where no clusters are present. (Reference: Tibshirani, 2001, *J. Roy. Statist. Soc., Ser. B*). A plot of this statistic against number of clusters should show a *statistically significant* "bump" at the correct number of clusters. A Tibshirani gap statistic algorithm was developed in the R statistical analysis software on a globally comprehensive sample of the original data. Secondly, clustering of all the points was executed in repeated, sequential runs, where the number of clusters produced was incremented by ten with each iteration, starting with five clusters, and ending with five hundred clusters. For data processing reasons, only temperature, salinity and dissolved oxygen variables were used in the testing of desired cluster number using the pseudo F-statistic. This statistic is the ratio of "between sum of squares" (appropriately normalized) to "pooled sum squares" (again appropriately normalized). A plot of this statistic against number of clusters should show a "bump" at the correct number of clusters. (References: Calinski, and Harabasz, 1974, *Communications in Statistics;* Milligan and Cooper, 1985, *Psychometrika*). A total of 52 iterations were implemented, and the largest decline in the pseudo-F statistic was noted at 70 clusters, with another large decline noted at 19 clusters. Based on the results from the gap statistic (37 clusters), and the general corroboration of this optimal cluster number from the decline in pseudo F-statistic approach (one optimum noted at 19 clusters) we established 37 as the desired number of clusters for subsequent clustering of the global data.

It should be noted that the gap statistic has a distributional component and hence statistical inference can be implemented, while the pseudo-F-statistic can only be interpreted "by-eye."



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.)

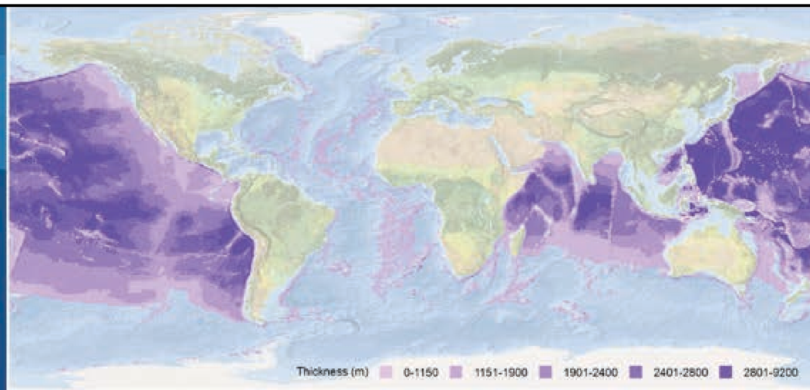
6. Assess relationship between physically distinct regions and biotic distributions (e.g., OBIS Biogeographic Realms, etc.), and maybe combine to incorporate biotic dimension into the EMUs

[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

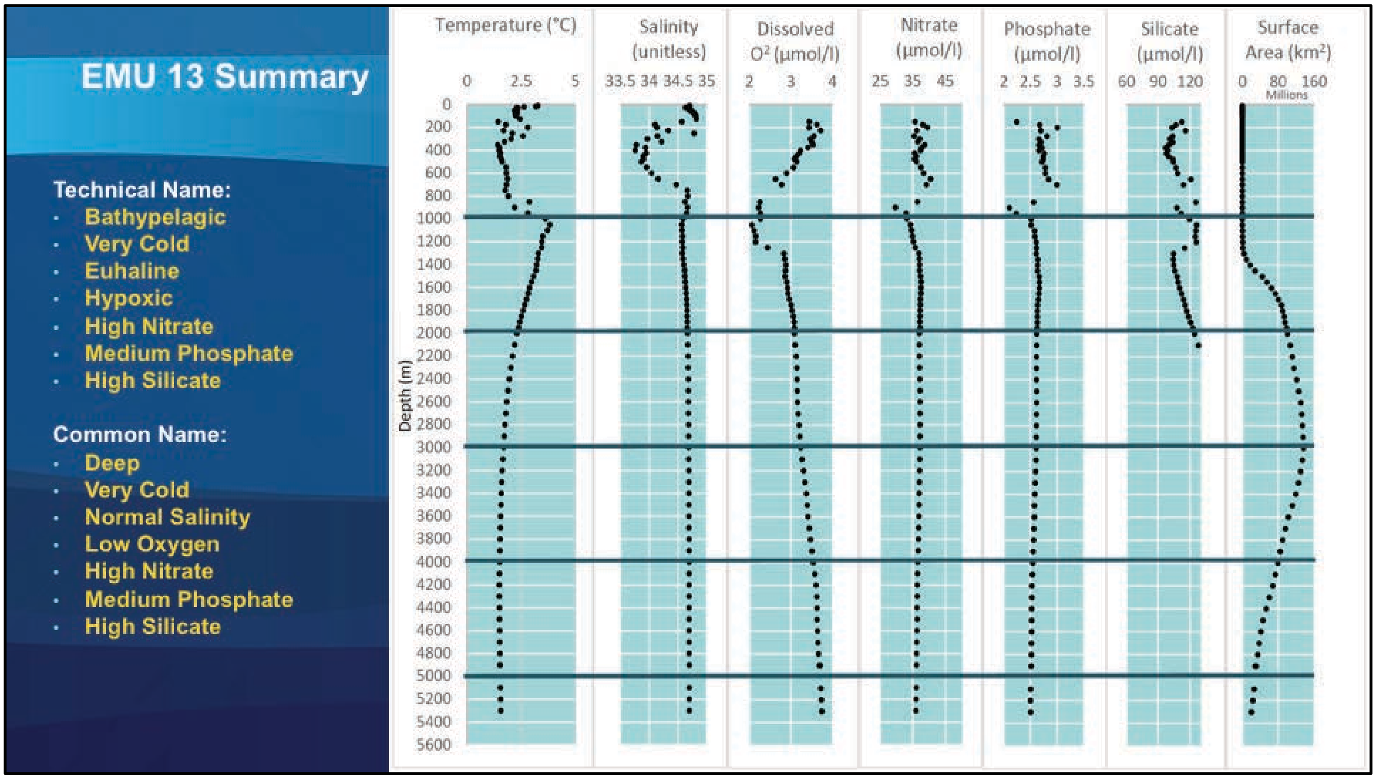


EMU 13 Summary Statistics

	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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Technical Name:
Bathypelagic
Very Cold
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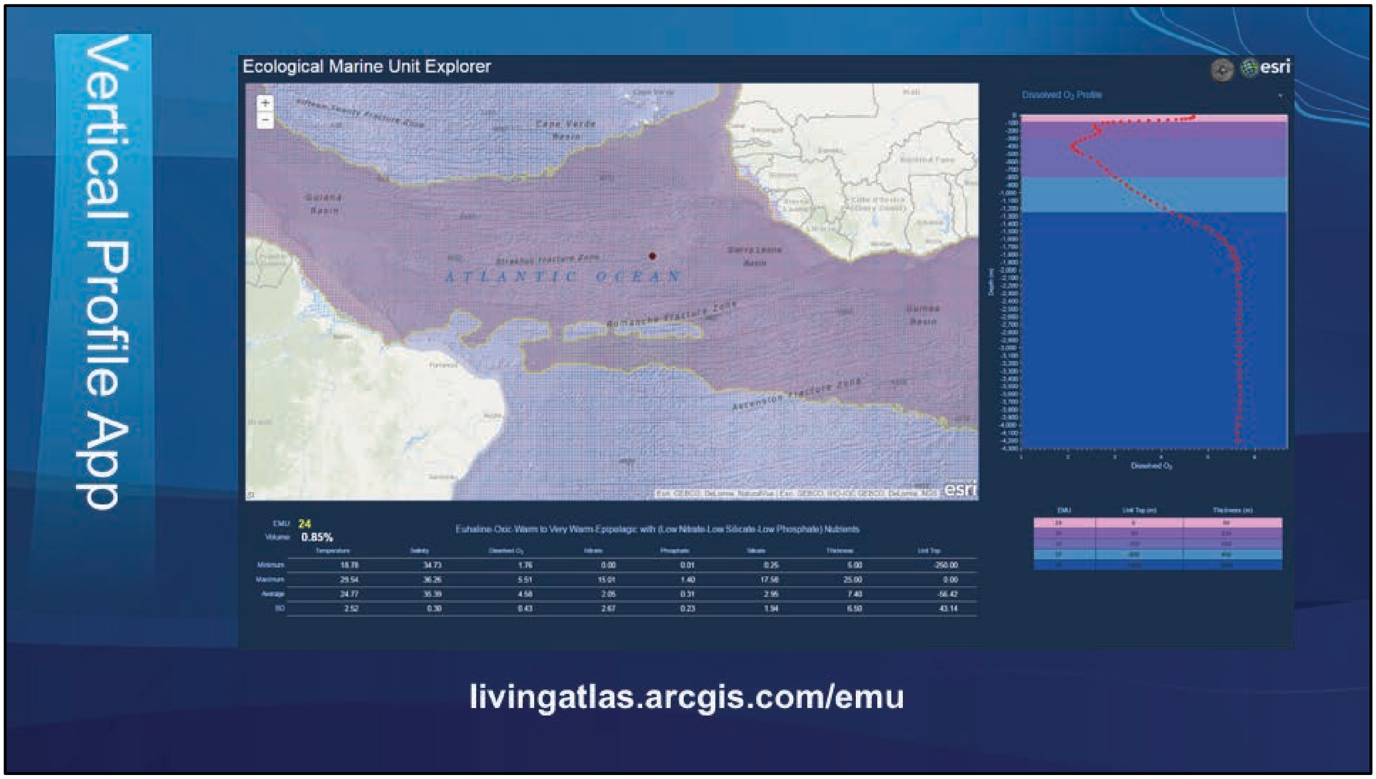
Common Name:
Deep
Very Cold
Normal Salinity
Low Oxygen
High Nitrate
Medium Phosphate
High Silicate
Temperature (°C)
0 2.5 5
Salinity (unitless)
33.5 34 34.5 35
Dissolved O2 (µmol/l)
2 3 4
Nitrate (µmol/l)
25 35 45
Phosphate (µmol/l)
2 2.5 3 3.5
Silicate (µmol/l)
60 90 120
Surface Area (km2)
0 80 160
Millions
Depth (m)
0 200 400 600 800 1000 1200 1400 1600 1800 2000 2200 2400 2600 2800 3000 3200 3400 3600 3800 4000 4200 4400 4600 4800 5000 5200 5400 5600


Vertical Profile App
Ecological Marine Unit Explorer
esri
ATLANTIC OCEAN
livingatlas.arcgis.com/emu

Paper for peer-reviewed journal *Oceanography*

Full Title:
A Three-Dimensional Mapping of the Ocean Based on Environmental Data

Short title:
A 3D Mapping of the Global Oceans

Author List

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Do Our Depth Findings Support Traditional Ocean Zonation Concepts?

Divisions of the Marine Environment

Figure 9-1

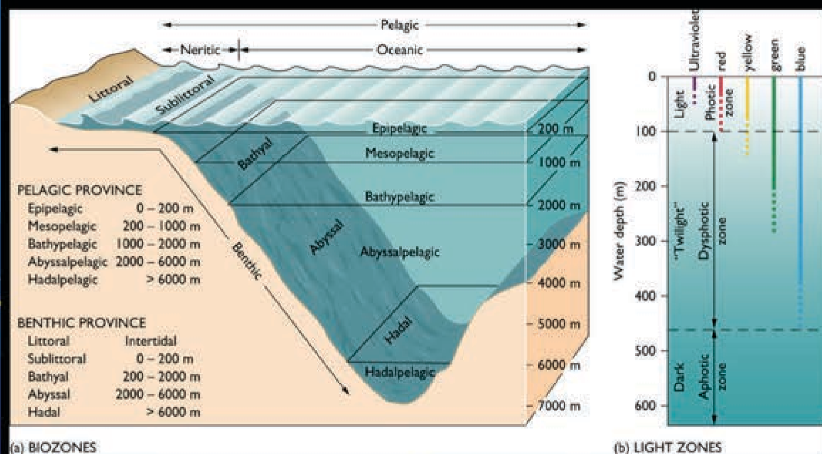
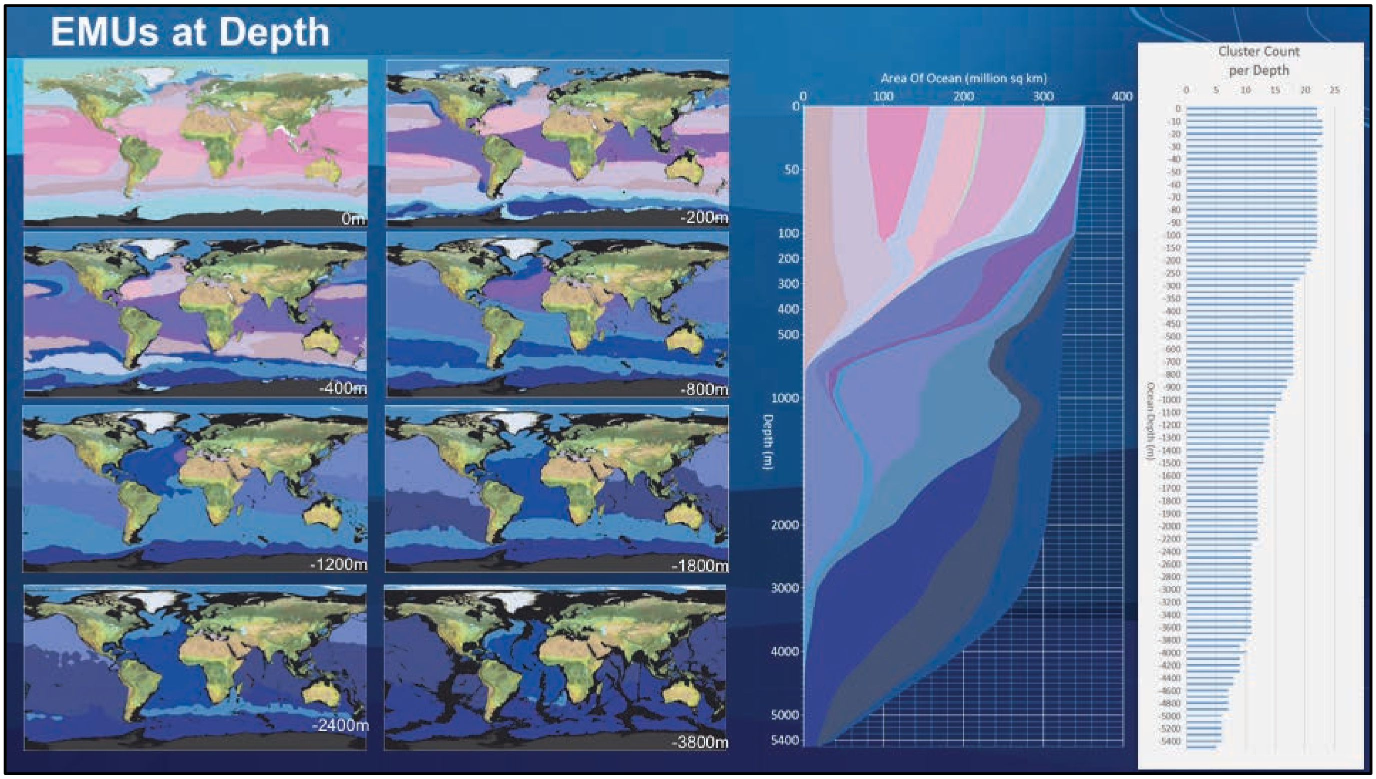


Figure courtesy of Paul R. Pinet, *Invitation to Oceanography*, 5th ed., Jones and Bartlett Publishers

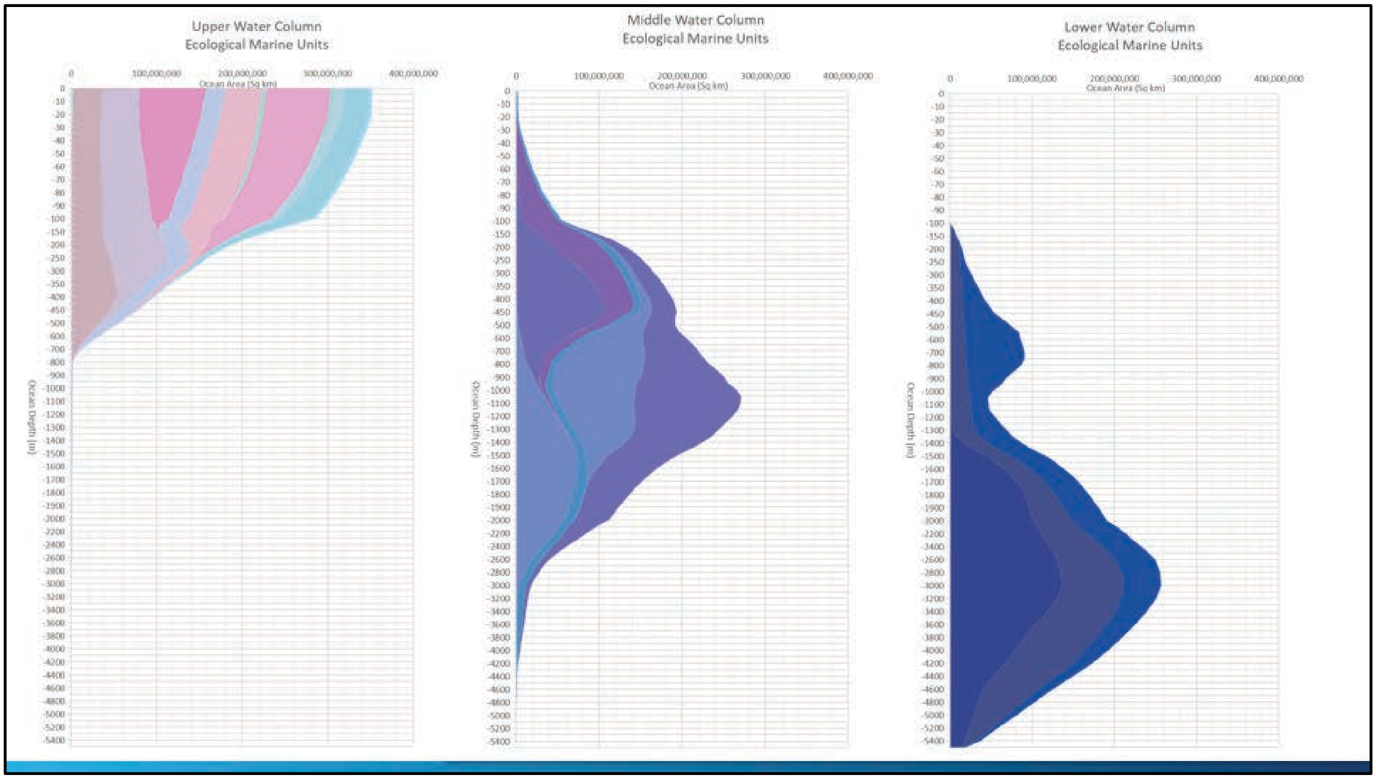


HORIZONTALLY on the LEFT
VERTICALLY on the RIGHT

ON THE LEFT: 37 mutually exclusive EMU clusters (shown with ELUs) representing the maximum global horizontal dimensions of the clusters AT SELECTED DEPTHS AND in different colors

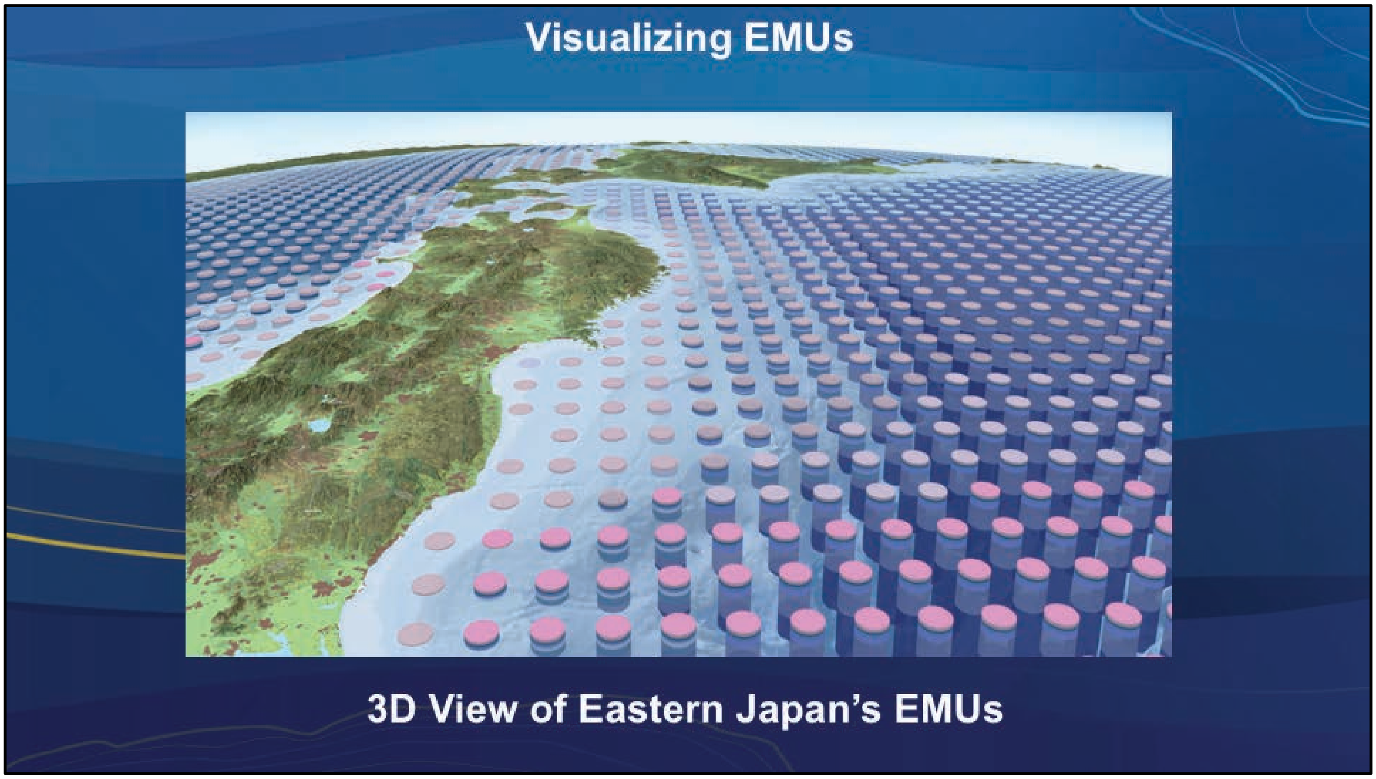
ON THE RIGHT: Vertical profile area graph with depth on Y-axis and cell count for each Cluster/area it covers on X-axis. This graph shows the cluster variety at the top of the water column and through the water **column we can see how each Cluster either slowly disappears with depth or in some cases deep water clusters become more dominant.** It also help illustrate how in some cases the cluster is spread across the CMECS depth terms and we may need a better data-driven depth name for the clusters. Interesting too that there are apparent depths where groups of clusters end -100 to -200m and -500 to -700m and -1400 to -1600m.

In the literature the 200 m depth approximates the edge of the continental shelf of NE Europe and the 200 nautical mile boundary. Due to the dominance of research in this region many texts assume this is a deep-sea boundary. However, the taxonomic experts in the World Register of Deep-Sea Species (WoRDSS) choose 500 m because in a review of deep-sea biology a US based author suggested this was a better boundary. The boundaries for bathyal and abyssal seem to have no clear rationale except to 'follow' a previous author (yet sometimes they are split at 1,000 m apart!).
Our diagram illustrates that there is no simple clear-cut boundary for water attributes – an overlay of depth distribution on it will also be informative



Upper, Middle, and Lower separated out
Instead of reflecting JUST researchers perceptions and local experiences, our EMUs provide quantifiable definitions for these such as epipelagic, mesopelagic, bathypelagic, etc.

Additional work by Mark Costello, U. of Auckland
1. Mark has produced dendrograms of 37 Clusters. This will show how similar Clusters are to each other based on the present 6 variables. Sean to send mark current-final table means per cluster.
2. Basher will match % of each realm in each cluster, and each cluster in each realm. This will help say which Clusters best match biological realms.
3. provide lat-long-depth for each cluster so can find which species in OBIS occur in which Clusters.



Would like to show 2 videos:
(1) The west coast fly-by and mention the ELUs as well
(2) The Hawaii fly-by

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 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.

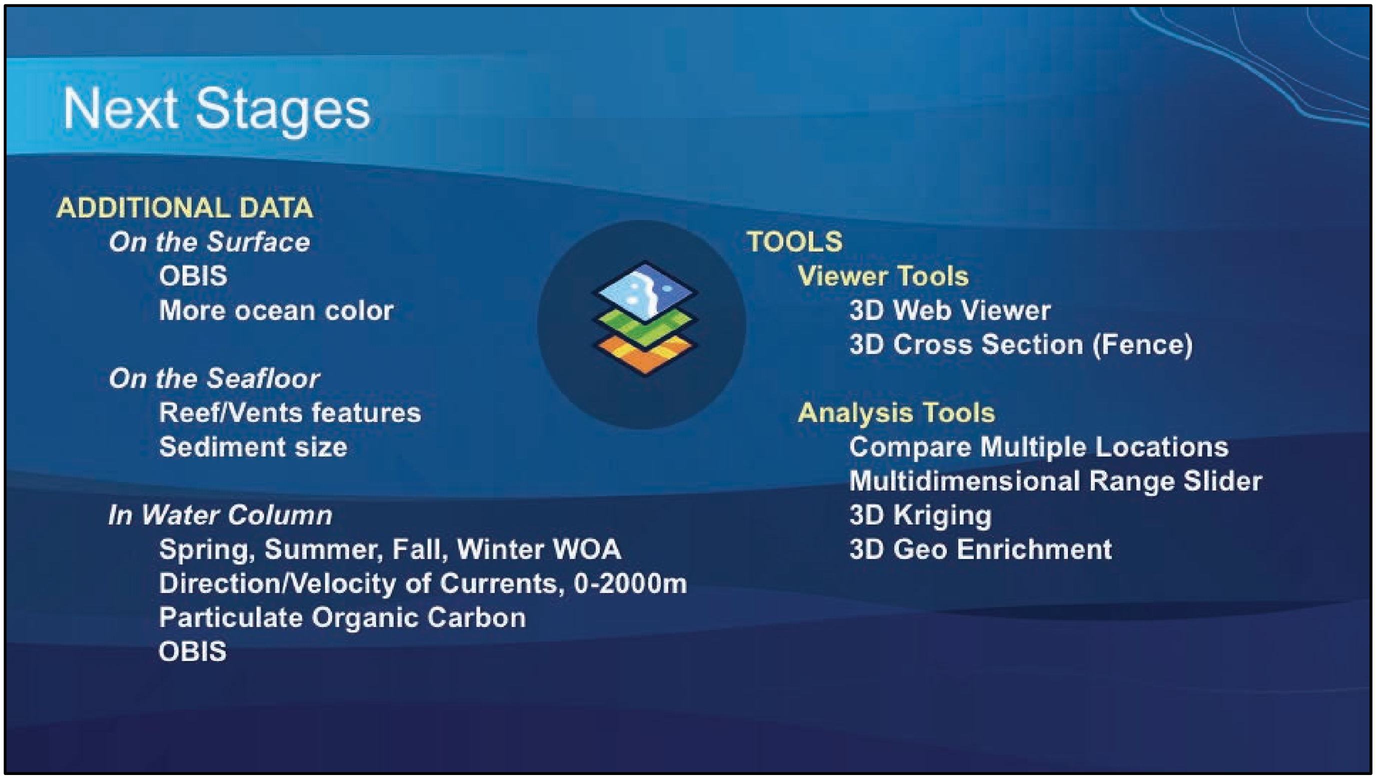
EMU Data Products

Open Access

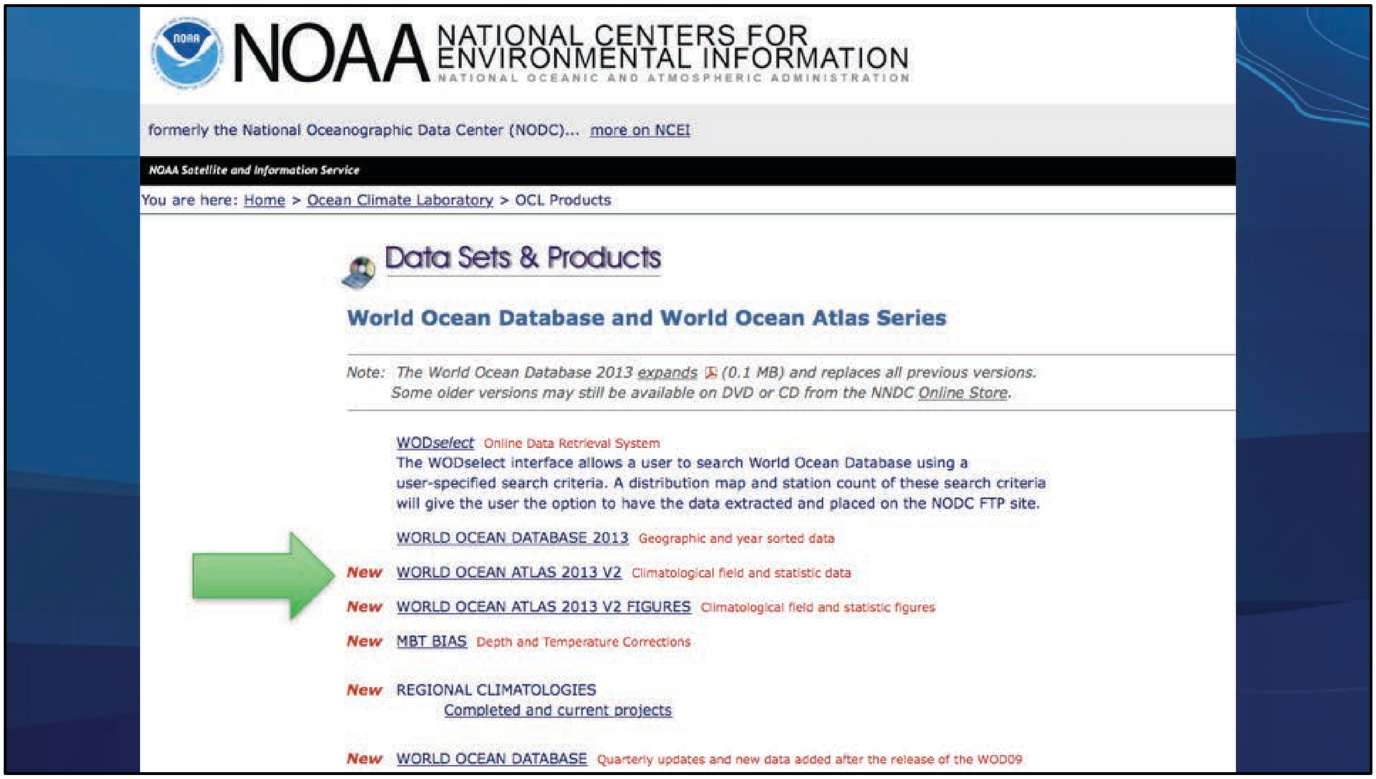
- Ecological Marine Unit Explorer Web App (Mobile App too)
- 3D Point Mesh (Download)
- 3D EMU Clusters Optimized (Download)
- 2D TopEMU (Download)
- 2D BottomEMU (Download)
- Data Dictionary (Download)
- Explorer App Source Code (Download)
- EMU Data Sheets (Download)
- Peer Reviewed Journal Article
- USGS/AAG Peer-Reviewed Tech Report

Esri Platform Users

- Connected
  - 3D Point Mesh – 52M
  - 3D EMU Clusters Optimized – 3.9M
  - 2D TopEMU – 700K
  - 2D BottomEMU – 700K
  - Data Dictionary
  - EMU Data Sheets
  - Explorer App
- Offline
  - Map Packages
  - ArcGIS Pro Project
  - Data Dictionary
  - EMU Data Sheets

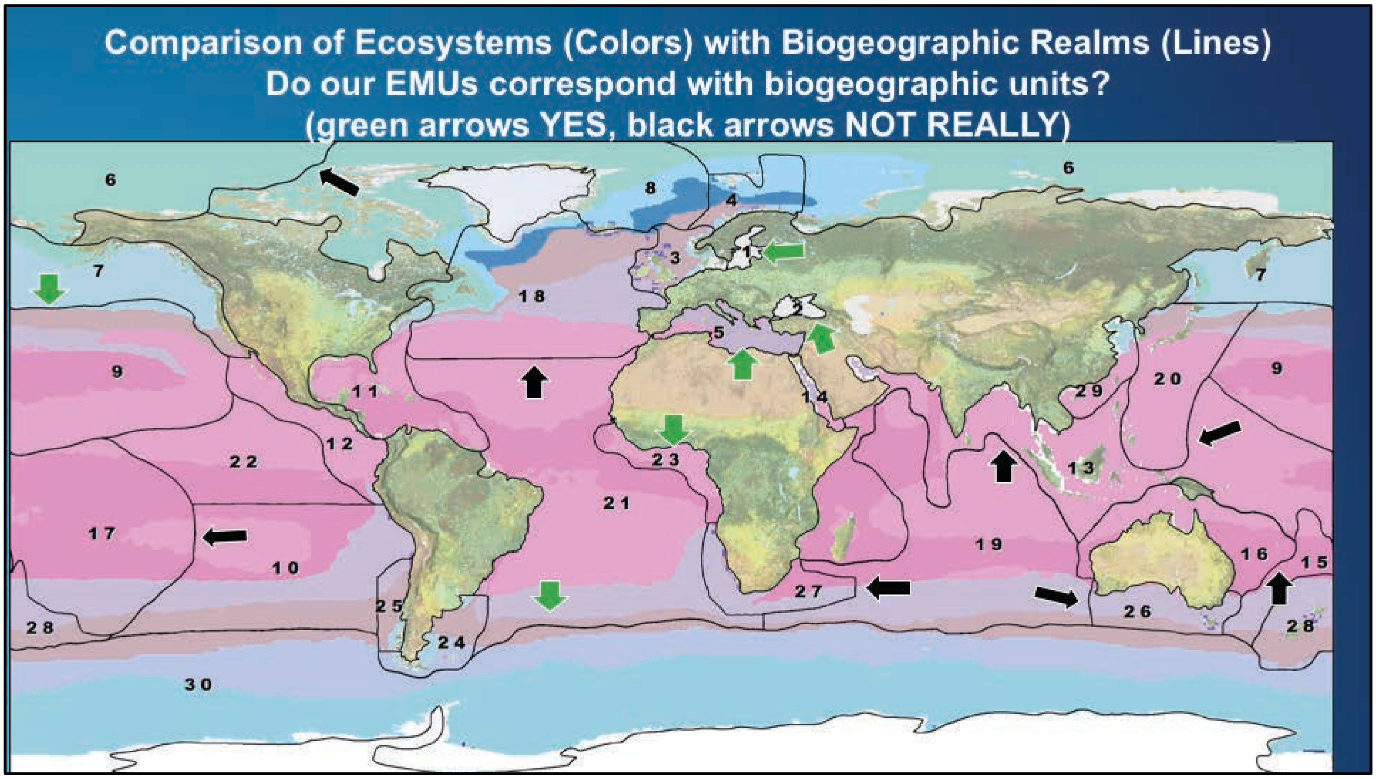


POC may be useful more as a **validation** of the clustering rather than as input (POC data are scattered, hard to obtain from Lutz or to compile from NASA, hard to recalculate for entire global water column)

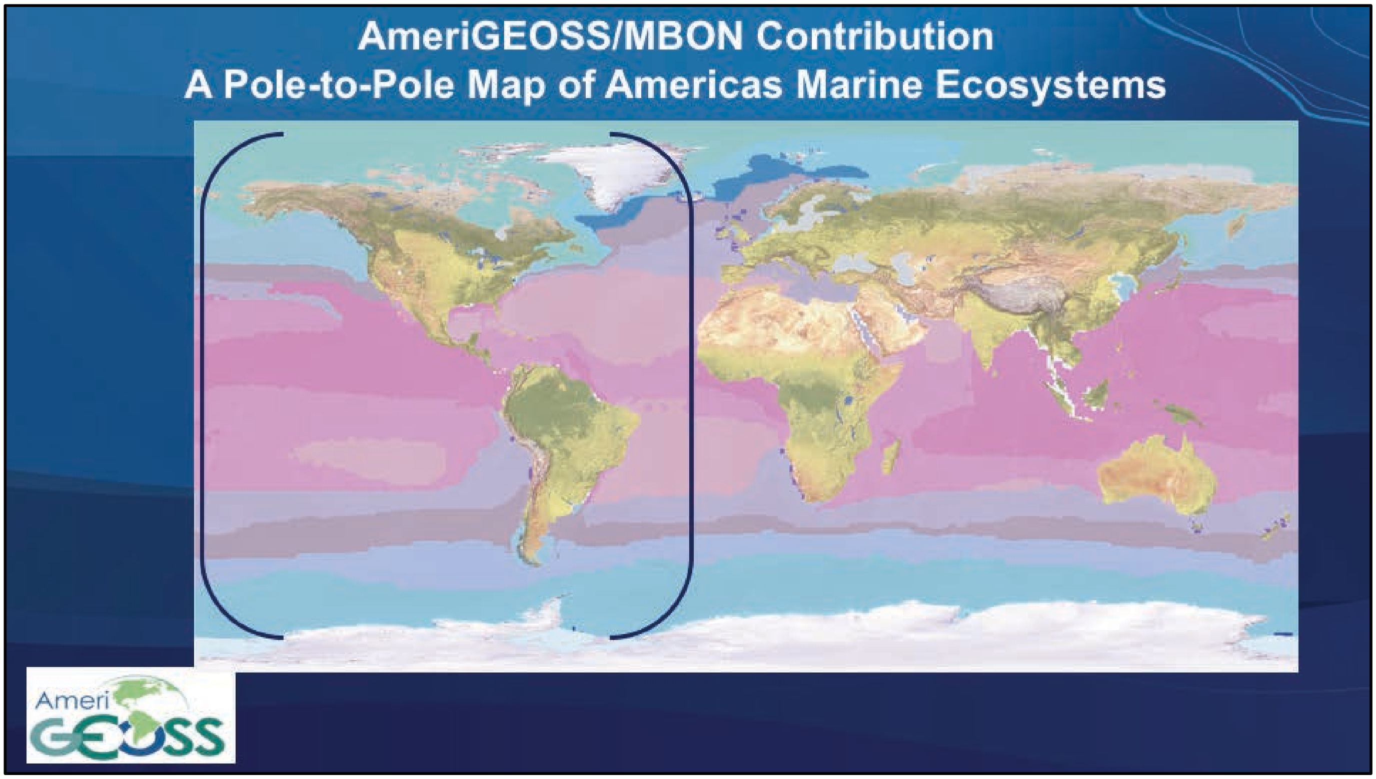

NOAA NATIONAL CENTERS FOR ENVIRONMENTAL INFORMATION
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
formerly the National Oceanographic Data Center (NODC)... more on NCEI
NOAA Satellite and Information Service
You are here: Home > Ocean Climate Laboratory > OCL Products
Data Sets & Products
World Ocean Database and World Ocean Atlas Series
Note: The World Ocean Database 2013 expands (0.1 MB) and replaces all previous versions. Some older versions may still be available on DVD or CD from the NNDC Online Store.
WODselect Online Data Retrieval System
The WODselect interface allows a user to search World Ocean Database using a user-specified search criteria. A distribution map and station count of these search criteria will give the user the option to have the data extracted and placed on the NODC FTP site.
WORLD OCEAN DATABASE 2013 Geographic and year sorted data
New WORLD OCEAN ATLAS 2013 V2 Climatological field and statistic data
New WORLD OCEAN ATLAS 2013 V2 FIGURES Climatological field and statistic figures
New MBT BIAS Depth and Temperature Corrections
New REGIONAL CLIMATOLOGIES
Completed and current projects
New WORLD OCEAN DATABASE Quarterly updates and new data added after the release of the WOD09

EMU logo by Esri’s Sean Breyer

Extra Slides



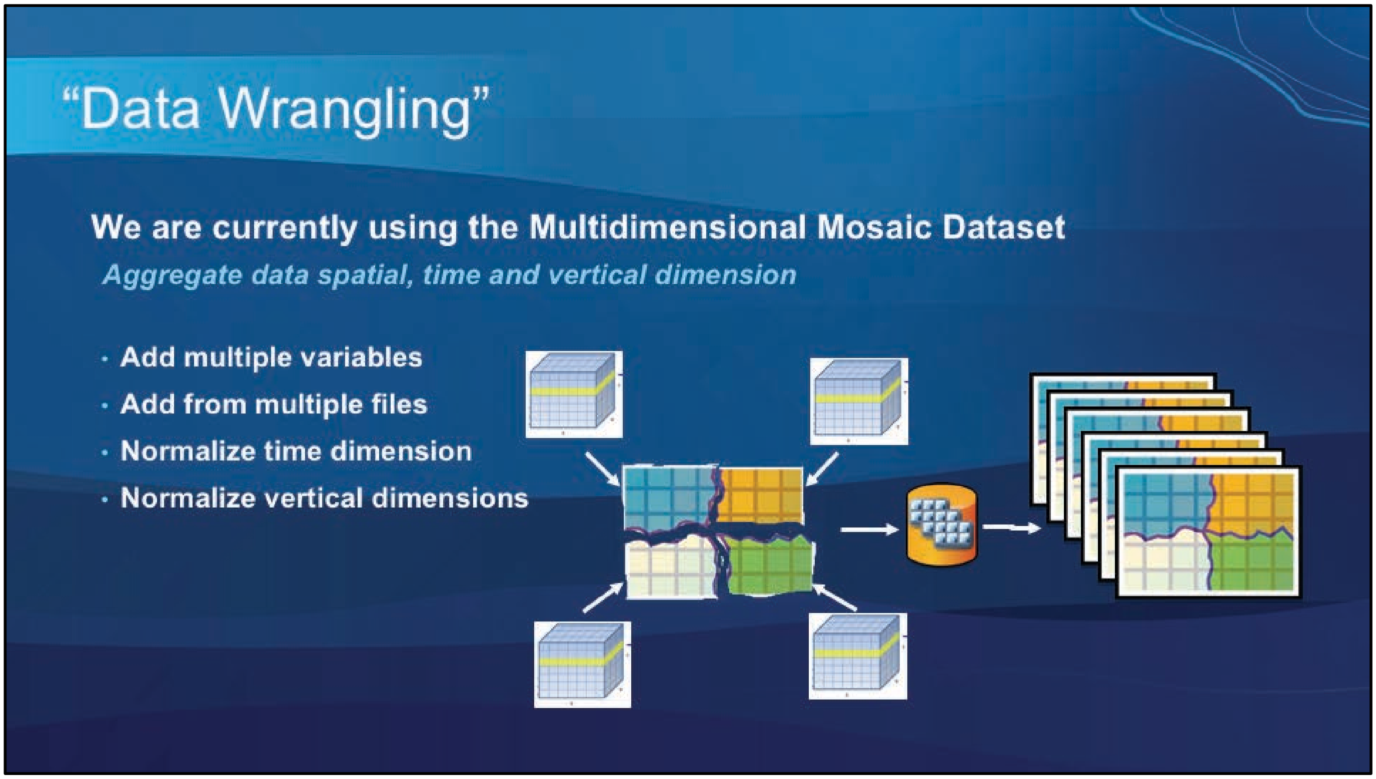
Another line of inquiry to address
Relationship between surface-occurring EMU distributions (colors) and marine biogeographic realms (numbered, outlined polygons). Spatial congruence between biogeographic realms and surface-occurring EMUs is apparent for some realms (e.g. 5, 7, 26, 30, etc.) but not for others (e.g. 18, 21, 22, etc.).

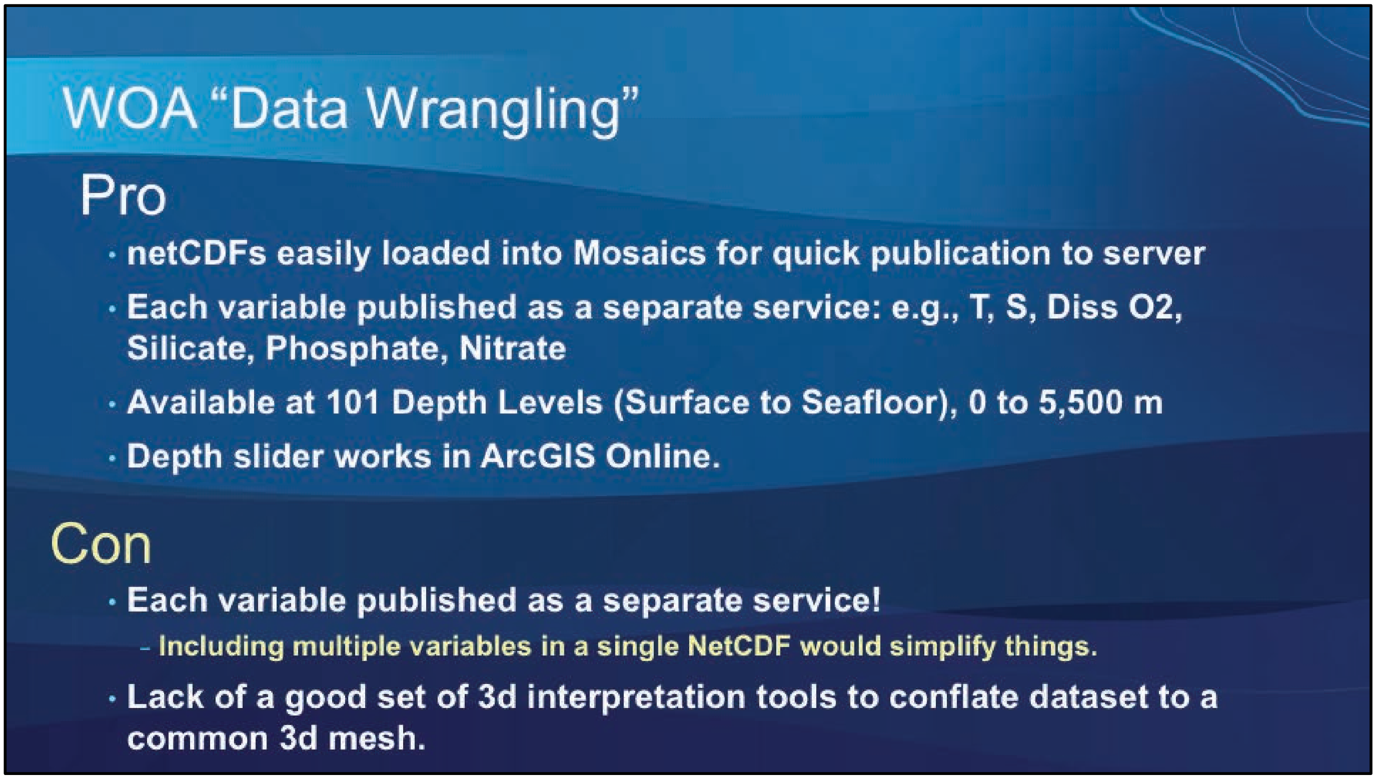

AmeriGEOSS/MBON Contribution
A Pole-to-Pole Map of Americas Marine Ecosystems

"Data Wrangling"

- Unified multidimensional data model
- netCDF, GRIB, and HDF formats
- Each variable is a multidimensional array
  - Temperature at multiple times or depths
  - Salinity at multiple times or depths
  - Wind at multiple times

- Can store many variables (measures) in one file


"Data Wrangling"
We are currently using the Multidimensional Mosaic Dataset
Aggregate data spatial, time and vertical dimension
• Add multiple variables
• Add from multiple files
• Normalize time dimension
• Normalize vertical dimensions



NOAA provides 8 oceanographic variables available in NetCDF format through the World Ocean Atlas. This data is multi-dimensional in nature (X,Y,Z,variable). For our project we focused on the "Objectively analyzed climatologies". Objectively analyzed climatologies are the objectively interpolated mean fields for oceanographic variables at standard depth levels for the World Ocean.

Data Summary:
Format: NetCDF files

Easily loaded into a Mosaic Dataset and able to be published to server quickly.
Each variable published as a separate service.
Total of 8 services (Temperature, Salinity, Dissolved Oxygen, Percent Oxygen Saturation, Apparent Oxygen Utilization, Silicate, Phosphate, and Nitrate)
Available at 101 Depth Levels (Surface to Seafloor) 0m to 5,500m
Depth slider works in ArcGIS Online.

Including multiple variables in a single NetCDF would simplify things.
Lack of a good set of 3d interpretation tools to conflate dataset to a common 3d mesh.