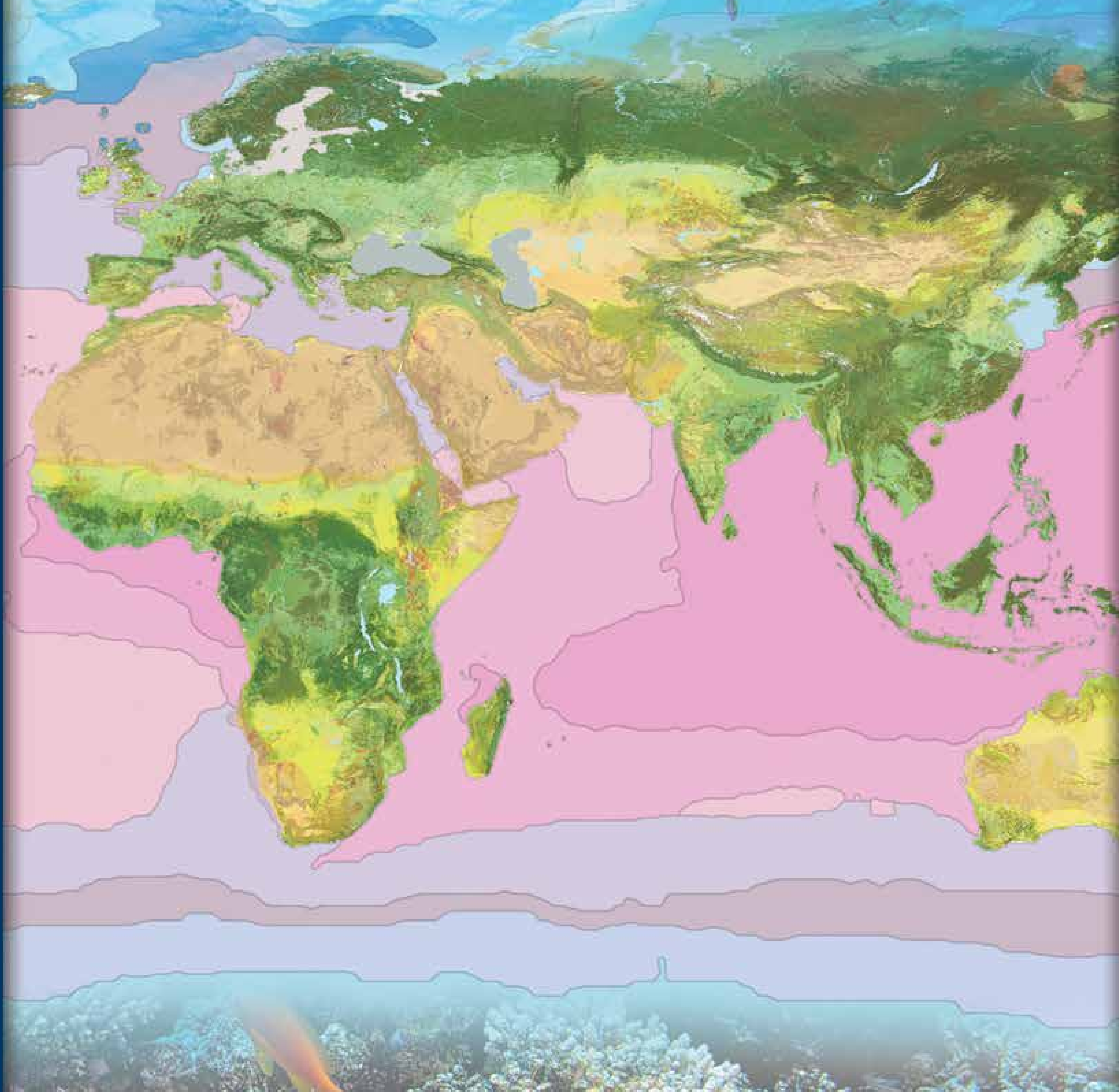
A NEW MAP OF GLOBAL ECOLOGICAL MARINE UNITS

AN ENVIRONMENTAL STRATIFICATION APPROACH



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A New Map of Global Ecological Marine Units — An Environmental Stratification Approach

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Foreword

AAG is pleased to present another publication in a series of global ecosystem mapping efforts commissioned by the Group on Earth Observations (GEO), a consortium of over 100 nations advocating the use of earth observations to address some of society's most pressing challenges. The alteration and loss of ecosystems is one of those challenges, and increasing shortages of ecosystem goods and services so important for our survival and persistence on this planet are likely. Understanding the distributions and condition of global ecosystems will help us to manage them more sustainably. As an important first step in that direction, the USGS, Esri, and a steering committee of international marine scientists has produced a new map of global marine ecosystems, presented herein.

In 2014 USGS and Esri joined forces in a public/private partnership to map standardized, robust, and practical terrestrial ecosystems, called ecological land units (ELUs). Recognizing the groundbreaking nature and importance of that work, AAG produced a special publication, entitled "A New Map of Global Ecological Land Units – An Ecophysiographic Stratification Approach," and launched the resource at the 2015 AAG Annual Meeting. Continuing the collaboration, USGS and Esri then turned their attention to an ecological partitioning of the global ocean. This work is a first-of-its-kind mapping of marine ecosystems that is globally comprehensive, objectively produced, and three-dimensional from sea surface to seafloor. The ocean was subdivided into 37 chemically and physically distinct volumetric regions called ecological marine units (EMUs), a marine ecosystem analog to the terrestrial ELUs. AAG offers this work as a companion document to the ELU booklet, and considers it the second in an emerging series of global ecosystem mapping characterizations.

The work was co-led by Dr. Roger Sayre, an Ecosystems Geographer at USGS; Dr. Dawn Wright, Esri's Chief Scientist; and Sean Breyer, Esri's Living Atlas of the World Program Manager. Other Esri staff contributed significant statistical support (Dr. Kevin Butler) and geospatial data development and analysis (Keith VanGraafeiland). The Esri team was very giving of their time and expertise, and that support was courtesy of the vision and generosity of Esri's founder and CEO Jack Dangermond, a life-long supporter of the AAG.

Douglas Richardson
Executive Director
American Association of Geographers

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A New Map of Global Ecological Marine Units An Environmental Stratification Approach

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Abstract

In response to an intergovernmental commission for a high resolution and data-derived global marine ecosystems map, distinct marine physical and chemical volumetric regions were characterized in an environmental stratification of the global ocean. The stratification produced 37 ecological marine units (EMUs) at a base resolution of ¼° (approximately 27 kilometers at the equator). The EMUs were objectively derived from non-supervised statistical clustering of over 52 million points from NOAA's World Ocean Atlas 2013 (WOA) database, an authoritative 57 year archive of global water column data. We organized the WOA data into a 3D ocean point mesh which represents a standardized geospatial framework for organizing physical, chemical, and biological data that characterize ocean composition and processes. The points are currently attributed with values for temperature, salinity, dissolved oxygen, nitrate, phosphate, and silicate, the six input values used in the stratification. The data represent the most accurate, current, globally comprehensive, and finest spatial resolution data available for each of the six inputs organized in a standardized geospatial framework for improved understanding of ocean environments. While the methodology and initial findings are reported elsewhere, we provide herein a more detailed description of the open data geospatial resources and and associated tool development. We present the EMU Explorer as a web-based query application that allows for the exploration of both the modeled EMUs as volumetric regions, and the comprehensive point data from the WOA.

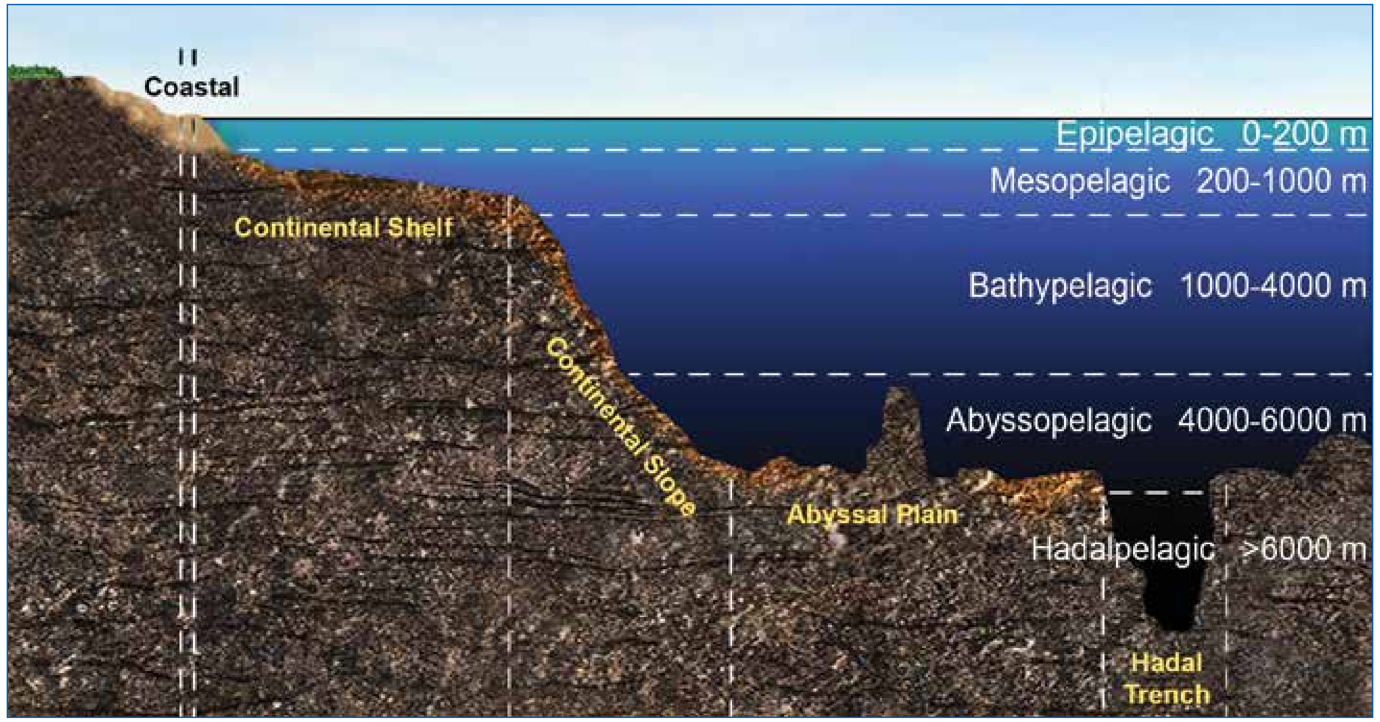
Introduction

Marine Ecosystems and Ocean Zones

As assemblages of biotic communities interacting with each other and with their physical environment (Tansley, 1935; Odum, 1971), ecosystems are understood as existing in terrestrial, freshwater, and marine domains, and as having both biotic and abiotic components. Mapping assemblages of biological communities, which are themselves assemblages of species, can be a difficult undertaking given the enormous amount of species distribution data required. Marine biogeographic regions have nevertheless been quantitatively delineated from data using tens of thousands of species distribution records (Costello et al., submitted) or derived from interpretive, largely expert opinion-based processes (UNESCO, 2009). Another approach to spatial delineation of marine ecosystems emphasizes the characterization of the abiotic environment as it structures the physical forcing of biological processes (Longhurst, 2007), also known as the controlling factors approach (Bailey, 1996). Longhurst's ocean biomes and provinces, and Bailey's ecoregions of the oceans maps are both examples of global ocean subdivision using physical factors. Reygondeau et al. (2017) objectively subdivided the Mediterranean Sea into 63 biogeochemical regions using environmental data.

In addition to the geographic distribution of ocean regions, there is interest in the vertical variation of the ocean environment, and the associated subdivision of the water column into different depth zones. Vertical zonation in the ocean is broadly accepted as a fundamental oceanographic concept, and many textbooks include a diagram similar to **Figure 1,** showing vertical zones in the water column. Ocean zones are often named and generally depth-bounded as in **Figure 1:** epipelagic (0 to 200 m), mesopelagic (200 to 1000 m), bathypelagic (1000 to 4000 m), abyssopelagic (4000 to 6000 m) and hadalpelagic (>6000 m), although the depth boundaries can vary from one characterization to the next.

Figure 1. Ocean depth zones (white text labels) and physiographic regions (yellow text labels). The depth zone names and boundary limits are as recognized in the Coastal and Marine Ecosystem Classification System (CMECS), the Federal Geographic Data Committee (FGDC, 2012) standard for the United States. The horizontal and vertical dimensions are not to scale, and are intended to facilitate visualization of depth zones.



The Coastal and Marine Ecosystem Classification System (CMECS) presents standardized definitions and criteria for describing marine ecosystem properties, and is recognized as the standard for the United States (FGDC, 2012). The CMECS depth zone boundaries are as above and in **Figure 1.**

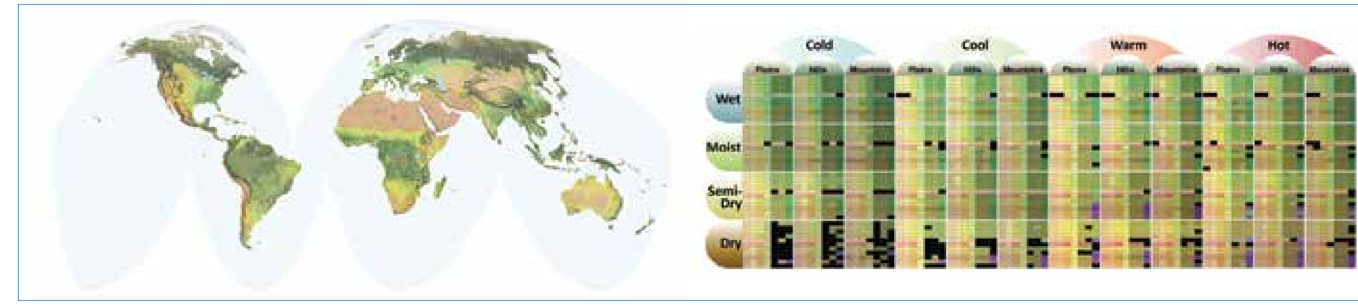
While there have been many attempts to subdivide the ocean for a variety of applications, none have been globally comprehensive, three-dimensional, and based on objective statistical clustering of long-term, time-averaged data. Adopting the controlling factors approach, we mapped physically and chemically distinct volumetric regions of the ocean and called them ecological marine units (EMUs) given their role in establishing the ecological potential of the environment to which marine biota respond. The EMU development process was a first of its kind, 3D statistical clustering of global ocean environment data averaged over a 57 year period. The methodological details and intial findings are reported elsewhere (Sayre et al., submitted). Herein we describe the global EMU resource as a set of open data geospatial products.

The GEO (Group on Earth Observations) Global Ecosystem Mapping Task

The Group on Earth Observations (GEO) is a consortium of over 100 nations which seeks to leverage the use of Earth observations to help solve some of society's greatest challenges (GEO, 2005). To that purpose, GEO has developed an intergovernmental protocol and associated workplan which includes an initiative (GI-14 GEO ECO, *http://www.earthobservations.org/activity.php?id=116*) on global ecosystems. The initiative formally commissions the development of a standardized, robust, and practical map of global ecosystems for terrestrial, freshwater, and marine environments (Sayre et al., 2007). The United States is the member nation of GEO leading this activity, and the U.S. Geological Survey (USGS) is the designated federal agency implementing the work.

In response to that commission from GEO, the USGS and Esri established a public/private partnership and mapped terrestrial ecosystem distributions using a structure-based mapping approach where the ecosystems were delineated from a vertical integration of the climate regime, landforms, substrate, and land cover (Sayre et al., 2014). That effort produced a set of global ecological land units, or ELUs (**Figure 2**), as physically distinct areas and their associated vegetation. Subsequent to that terrestrial ecosystem mapping effort, and again responding to the GEO intergovernmental charge to produce standardized, robust, and practical global ecosystem maps for marine environments, the USGS/Esri team then developed a similar method for stratifying the global ocean into physically and chemically distinct volumetric regions. For the marine ecosystem mapping effort, the team included a steering committee of international marine scientists.

Figure 2. Global ecological land units (ELUs) produced from a global ecophysiographic stratification by climate, landform, lithology, and land cover (Sayre et al., 2014), in response to a commission from the Group on Earth Observations (GEO) to produce a standardized, robust, and practical global ecosystems map for terrestrial environments.



Summary of Method and Results

The fundamental approach undertaken herein was to stratify the ocean into physically and chemically distinct areas. The stratification was produced from unsupervised statistical clustering of data from NOAA's 2013 World Ocean Atlas version 2 (Locarnini et al., 2013; Zweng et al., 2013; Garcia et al., 2013a; Garcia et al., 2013b). A full description of the data and the statistical clustering approach is provided elsewhere (Sayre et al., submitted), and we provide a brief summary herein. The data used in the clustering represent 57 year average values for temperature, salinity, dissolved oxygen, nitrate, phosphate, and silicate. There are approximately 52 million ocean data points representing the entire water column. The horizontal resolution of the data is ¼°, or approximately 27 km near the equator. The depth intervals are variable from 5 m near the surface to 100 m in the deeper regions (>2000 m) for a total of 102 depth levels.

The EMUs were produced from a k-means statistical clustering of the point data, resulting in 37 distinct clusters. Each cluster, or EMU, is a physically and chemically distinct volumetric region. The clusters were neither constrained geographically nor by depth, but strong regional and depth zone separation was nevertheless observed, supporting the existence of regional compositional geographies in the ocean in x, y, and z dimensions. This objectively-produced, three-dimensional, and globally comprehensive clustering of the ocean is a first-of-its-kind planetary stratification of the marine environment.

EMU Data and Maps

The input to the clustering algorithm was the set of approximately 52 million points, each containing values for the following attributes: x, y, z, temperature, salinity, dissolved oxygen, nitrate, phosphate, and silicate. The output from the clustering was the same set of points with an additional attribute for the EMU (cluster) it was grouped into. As such, the EMU data resource is in essence a geodatabase of over 52 million points in x, y, and z dimensions which allows for the query and analysis of two kinds of spatial entities, the points themselves, or the EMU clusters they belong to. Descriptive statistics were produced to characterize the depth, thickness, and physico-chemical composition of each EMU (**Table 1**).

The EMUs can be assessed as a 2D surface at any depth for the 102 depth levels. As examples, we show the maps of EMU distributions at the ocean surface (**Figure 3**), at a depth of 1000 m (**Figure 4**), and at the seafloor **(Figure 5)**. Each of these maps has the same legend, which is a master legend showing the color assignments for all 37 EMUs, however, all EMUs are not present on each map because they occur at different depths. Cartographically, the EMUs are symbolized with a color that reflects the average temperature of the EMU, with pinks and reds denoting relatively warmer EMUs, and blues and blacks representing colder EMUs.

To better understand the geographic distributions of the EMUs, we present a series of maps showing the number, name, geographic distribution, and thickness of each EMU in **Figure 6.** These maps facilitate comparisons of EMU size, EMU vertical distribution, and the representation of the EMUs in the different oceans and seas.

Table 1. Depths, thicknesses, and compositional properties of EMUs.

EMU	Depth (m)		Temperature (°C)				Salinity (unitless)				Dissolved Oxygen (µmol/l)				Nitrate (µmol/l)				Phosphate (µmol/l)				Silicate (µmol/l)			
	Unit Middle Median (m)	Thickness Mean (m)	Mean	Std Dev	Min	Max	Mean	Std Dev	Min	Max	Mean	Std Dev	Min	Max	Mean	Std Dev	Min	Max	Mean	Std Dev	Min	Max	Mean	Std Dev	Min	Max
1	220.87	148.13	8.30	1.62	-0.65	14.72	21.42	0.34	20.19	22.32	0.20	0.15	0.00	0.83	0.83	0.74	0.00	4.38	4.27	0.56	2.47	5.22	109.61	25.15	58.88	196.55
2	85.28	52.21	7.27	2.04	-0.44	9.56	19.82	0.71	18.43	21.61	2.68	1.13	0.52	4.67	2.85	1.04	0.00	4.22	0.82	0.35	0.18	2.50	33.65	13.16	4.28	64.21
3	1598.10	1253.52	2.60	0.62	0.47	5.16	34.54	0.12	33.52	35.03	1.47	0.62	0.21	2.98	42.34	1.82	26.67	56.12	3.03	0.15	2.27	4.10	149.53	19.52	106.22	247.19
4	498.16	445.63	8.89	0.15	4.62	14.93	22.03	0.16	21.72	22.40	0.10	0.11	0.00	0.70	0.11	0.26	0.00	1.45	6.18	0.54	5.13	7.27	160.29	30.75	111.00	231.35
5	12.32	18.47	-0.96	1.05	-1.62	12.10	28.59	0.78	25.99	29.63	8.71	0.48	5.03	9.89	1.16	1.08	0.00	15.24	0.79	0.24	0.00	2.24	9.36	5.37	0.31	32.87
6	30.45	26.94	9.24	4.06	-0.38	19.38	18.35	0.45	16.22	20.65	6.65	1.05	4.13	9.57	1.13	0.79	0.05	5.80	0.28	0.15	0.10	1.11	13.86	6.79	4.04	56.85
7	13.85	18.74	15.62	3.05	4.81	20.91	9.40	0.86	7.81	10.96	6.80	0.44	5.05	7.93	0.25	0.45	0.02	2.78	0.17	0.11	0.05	0.70	6.64	5.22	3.38	29.29
8	151.24	219.21	11.05	1.96	3.39	18.44	34.59	0.45	32.57	35.65	5.73	0.61	3.75	7.29	10.62	4.14	0.01	22.70	0.84	0.23	0.11	1.83	5.96	4.18	0.41	34.17
9	301.77	1481.43	15.28	2.86	12.52	29.53	38.62	0.41	37.34	40.77	4.69	0.53	2.04	5.98	3.75	2.84	0.00	15.02	0.19	0.11	0.02	0.77	4.76	2.78	0.31	26.46
10	390.89	339.64	9.83	2.26	4.66	24.20	34.78	0.30	33.63	36.94	1.56	0.87	0.03	3.55	30.84	4.20	9.87	43.71	2.28	0.31	1.26	3.36	31.96	12.38	6.75	96.02
11	101.22	172.49	16.46	2.26	10.07	21.67	35.33	0.41	33.93	36.46	5.23	0.46	3.25	6.46	3.66	3.27	0.01	19.98	0.39	0.19	0.05	1.40	3.33	1.86	0.27	20.34
12	88.50	33.47	4.73	1.36	0.72	14.05	10.22	0.64	8.98	12.03	1.62	0.64	0.29	4.36	5.85	0.82	3.15	7.72	2.39	0.39	1.20	3.85	43.60	4.95	28.70	60.68
13	2871.85	2010.79	1.93	0.51	-0.38	5.54	34.67	0.05	33.43	34.93	3.26	0.43	1.69	4.33	37.03	1.57	25.26	48.49	2.60	0.12	0.53	3.36	138.03	19.05	88.01	189.63
14	2595.55	2096.30	0.88	0.69	-2.05	3.31	34.70	0.04	33.27	34.90	4.74	0.41	2.96	6.86	32.71	1.21	16.96	40.33	2.27	0.09	1.49	3.02	115.20	13.89	72.25	167.23
15	1297.92	962.14	9.00	0.17	7.18	15.16	22.29	0.06	21.98	23.44	0.00	0.01	0.00	0.07	0.03	0.20	0.00	1.45	8.02	0.55	6.84	9.76	192.79	25.59	91.49	258.23
16	25.20	49.24	4.22	1.73	1.76	11.99	5.61	0.45	5.01	6.49	8.41	0.49	6.43	8.95	3.35	1.85	0.07	7.51	0.18	0.12	0.05	0.67	18.46	6.17	9.06	29.67
17	25.50	40.59	5.84	2.06	1.34	14.24	7.32	0.42	6.33	8.91	7.94	0.37	6.11	8.51	1.97	0.72	0.12	5.68	0.42	0.14	0.14	1.01	12.13	2.61	2.01	29.90
18	39.45	75.65	26.15	2.64	16.42	30.33	34.43	0.43	31.89	35.01	4.53	0.41	1.50	5.83	1.39	2.17	0.00	21.45	0.27	0.18	0.03	1.37	3.73	2.52	0.38	28.85
19	114.29	257.08	5.50	1.85	-1.52	13.74	34.09	0.20	33.11	34.70	6.64	0.51	4.21	7.74	20.64	3.51	9.30	32.16	1.49	0.20	0.49	2.20	10.46	6.04	0.00	54.73
20	65.63	12.41	4.04	1.23	1.11	8.88	8.79	0.54	7.47	11.00	4.78	1.06	2.69	7.20	4.54	0.89	2.33	6.03	1.30	0.37	0.54	2.11	26.88	5.50	14.59	40.52
21	63.96	182.66	22.53	3.00	12.67	29.73	36.48	0.36	35.77	38.13	4.80	0.40	2.43	5.88	1.56	2.34	0.01	16.50	0.20	0.15	0.01	1.40	1.72	1.14	0.39	18.82
22	7.67	10.43	8.15	4.89	0.07	15.55	15.87	0.84	13.37	17.01	2.98	0.55	2.32	3.79	6.62	0.35	6.13	6.97	1.60	0.21	1.30	1.86	37.82	4.62	31.11	43.72
23	40.18	33.21	-1.13	1.31	-1.88	14.03	32.22	0.45	30.92	33.24	8.02	0.51	4.50	10.38	4.65	2.63	0.00	17.03	0.96	0.31	0.05	2.49	11.44	6.19	0.61	45.16
24	50.00	94.99	24.77	2.52	18.78	29.54	35.39	0.30	34.73	36.26	4.58	0.43	1.76	5.51	2.05	2.67	0.00	15.01	0.31	0.23	0.01	1.40	2.95	1.94	0.25	17.58
25	25.28	29.37	-1.27	1.11	-1.76	13.84	30.70	0.48	29.54	31.64	8.65	0.43	5.08	10.39	1.91	1.35	0.03	16.50	0.88	0.23	0.01	2.21	9.56	3.75	0.61	37.57
26	242.26	159.79	14.27	3.62	6.80	26.44	35.14	0.46	33.59	36.91	3.21	0.75	0.47	4.99	17.48	4.37	1.80	32.24	1.27	0.28	0.47	2.43	12.37	6.41	1.61	60.31
27	26.81	15.74	2.95	4.03	-1.26	19.23	22.60	1.29	20.42	25.32	7.59	1.38	4.63	9.59	0.92	1.19	0.00	6.53	0.46	0.32	0.06	1.52	15.62	9.33	1.62	49.03
28	19.60	33.56	12.67	3.43	0.19	19.84	12.76	0.36	10.96	14.27	6.72	0.60	3.79	9.34	0.19	0.69	0.00	6.13	0.20	0.10	0.06	1.30	6.49	7.02	2.10	56.85
29	1127.70	2168.50	0.69	1.72	-2.00	7.40	34.89	0.12	33.93	35.38	6.71	0.30	4.83	8.31	13.83	2.17	1.69	22.58	0.96	0.13	0.10	1.60	9.87	3.28	0.29	41.33
30	66.47	75.72	3.88	4.28	-1.79	18.56	32.82	0.33	30.95	33.78	6.76	0.50	4.20	8.31	13.11	5.02	0.00	29.71	1.40	0.36	0.25	2.70	25.00	10.61	0.61	78.33
31	65.30	170.49	-0.27	1.39	-2.05	5.81	34.05	0.27	32.12	34.92	7.30	0.52	4.98	8.98	27.53	2.21	12.71	39.64	1.94	0.15	0.99	3.08	50.42	18.01	8.21	103.82
32	15.56	27.92	21.59	2.45	12.46	26.49	6.66	0.58	5.18	7.90	6.79	0.56	4.94	7.62	0.15	0.09	0.02	0.45	0.11	0.05	0.05	0.30	4.67	1.37	2.13	13.41
33	935.40	603.19	4.99	1.33	0.74	10.44	34.53	0.26	33.39	35.69	1.65	0.71	0.04	3.38	39.25	2.77	19.00	49.67	2.87	0.20	1.84	3.88	87.61	18.54	25.97	127.58
34	157.95	52.39	4.79	4.24	-1.10	14.49	23.58	1.20	22.32	25.56	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	10.29	0.40	9.76	11.62	194.10	14.06	158.85	218.22
35	60.08	80.45	-0.90	1.40	-2.04	10.37	33.89	0.43	32.88	34.88	7.44	0.53	5.08	9.17	6.88	2.45	0.22	24.60	0.74	0.23	0.09	1.49	8.03	4.71	0.44	74.12
36	1580.53	957.82	4.58	2.12	-0.99	12.05	34.76	0.30	33.23	35.86	5.27	0.53	3.21	6.36	22.74	3.00	12.16	35.69	1.53	0.22	0.73	2.23	27.13	13.82	0.00	80.48
37	1139.29	779.85	3.13	1.23	-1.97	10.51	34.52	0.20	32.67	35.12	4.25	0.52	2.39	6.02	32.70	2.29	10.54	41.95	2.26	0.17	1.45	3.07	62.60	18.90	12.00	101.91

Figure 3. A 2D representation of surface-occurring EMUs. On land, the terrestrial ecological land units (ELUs) are also shown (Sayre et al., 2014). Pink colors indicate warmer EMUs and blue colors indicate colder EMUs. While each EMU is compositionally distinct, generally similar EMUs in proximity can share the same name.

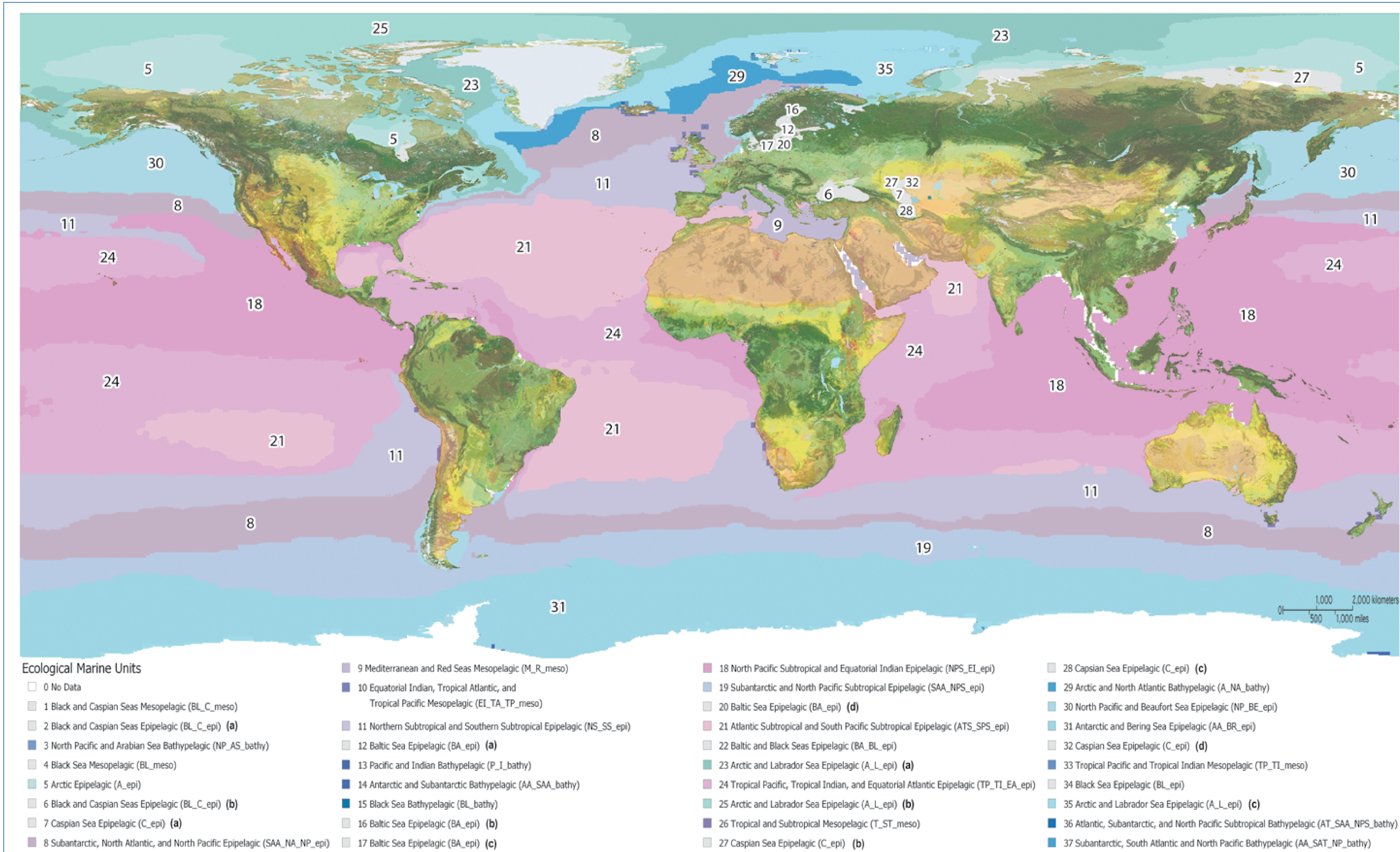
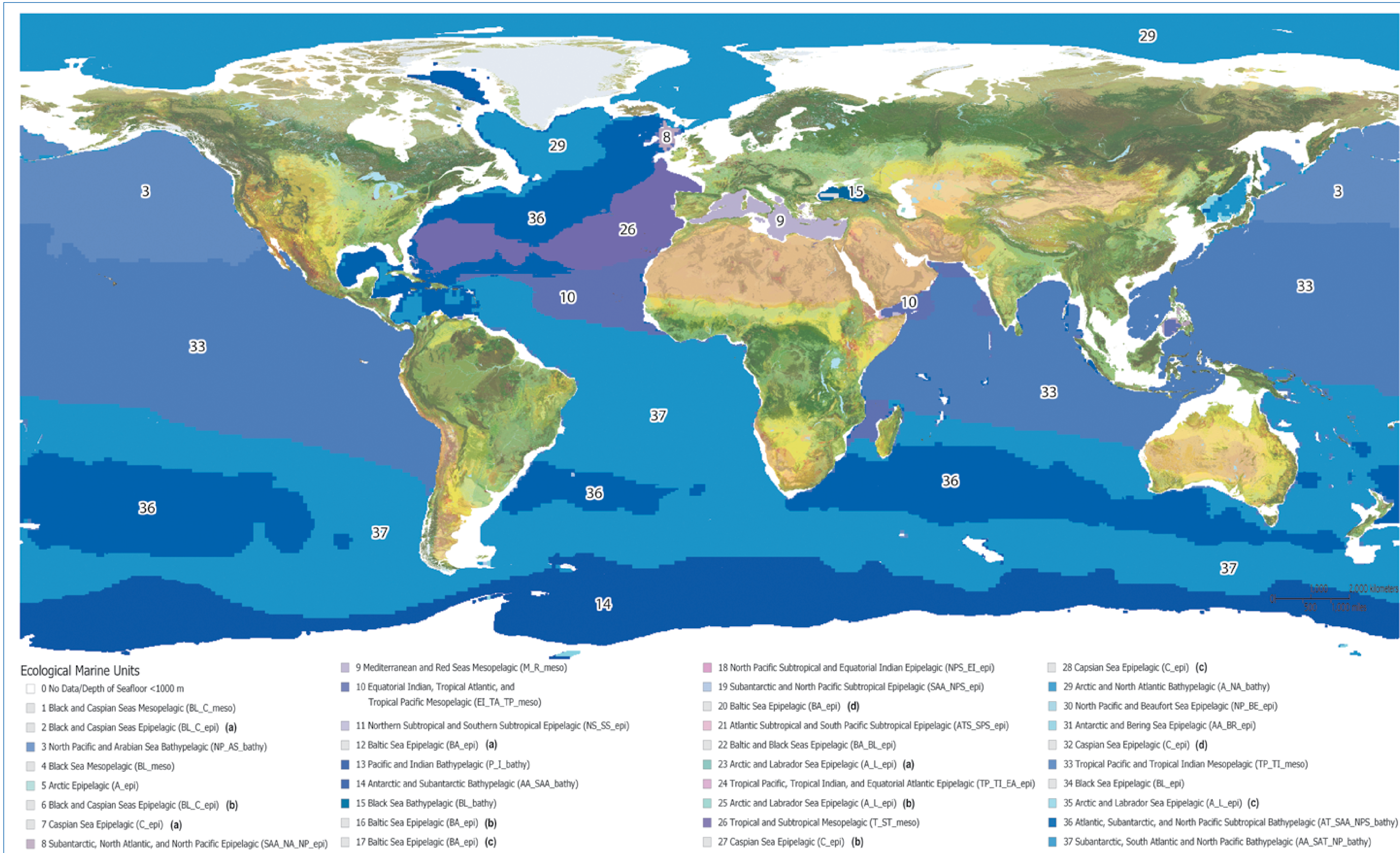


Figure 4. A 2D representation of EMUs occurring at a depth of 1000 m. On land, the terrestrial ecological land units (ELUs) are also shown (Sayre et al., 2014). Pink colors indicate warmer EMUs and blue colors indicate colder EMUs. While each EMU is compositionally distinct, generally similar EMUs in proximity can share the same name.



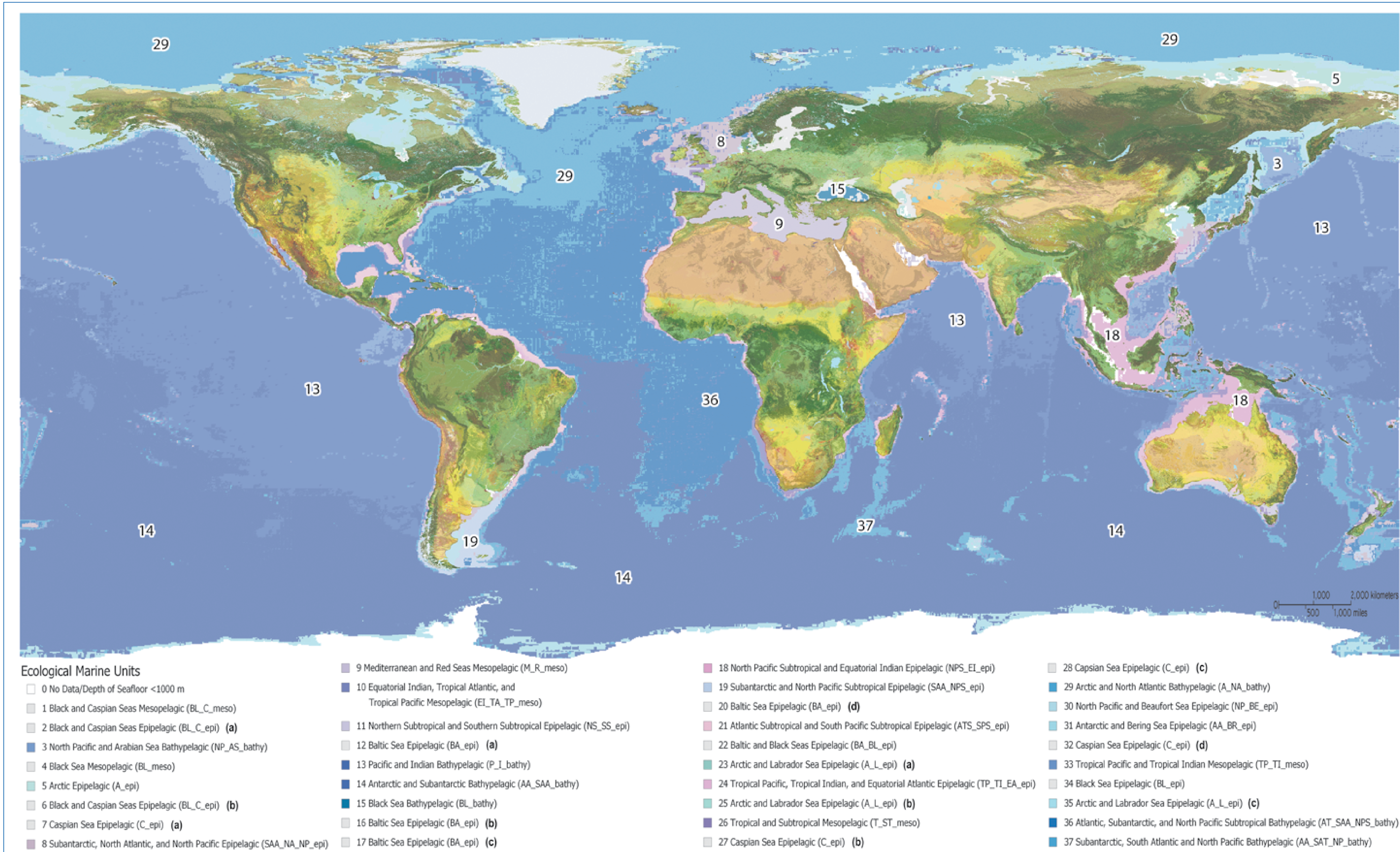
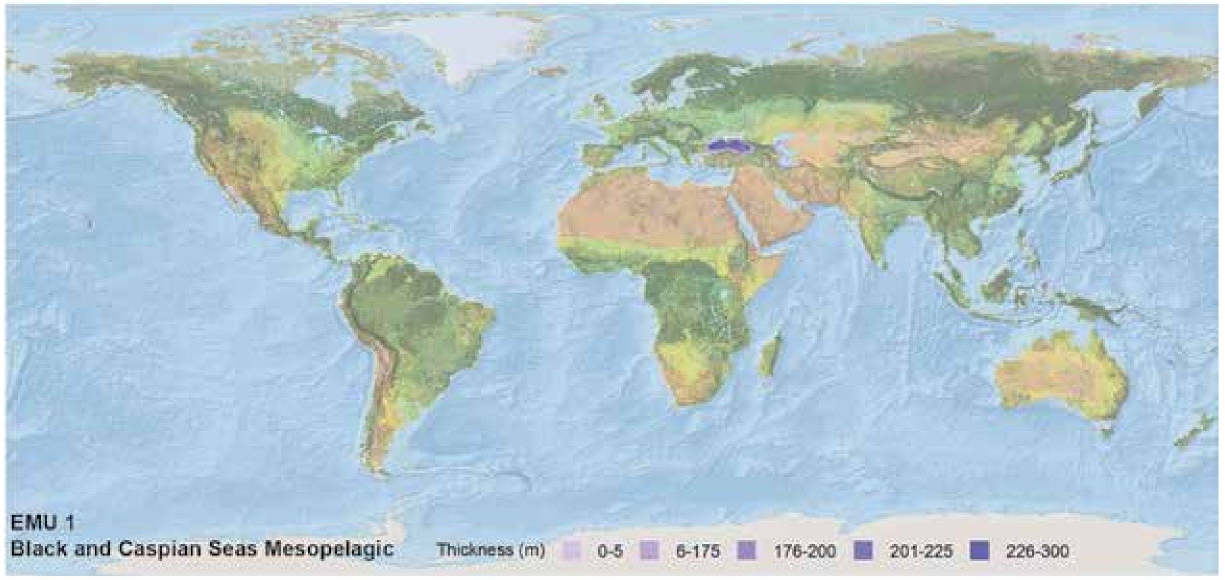
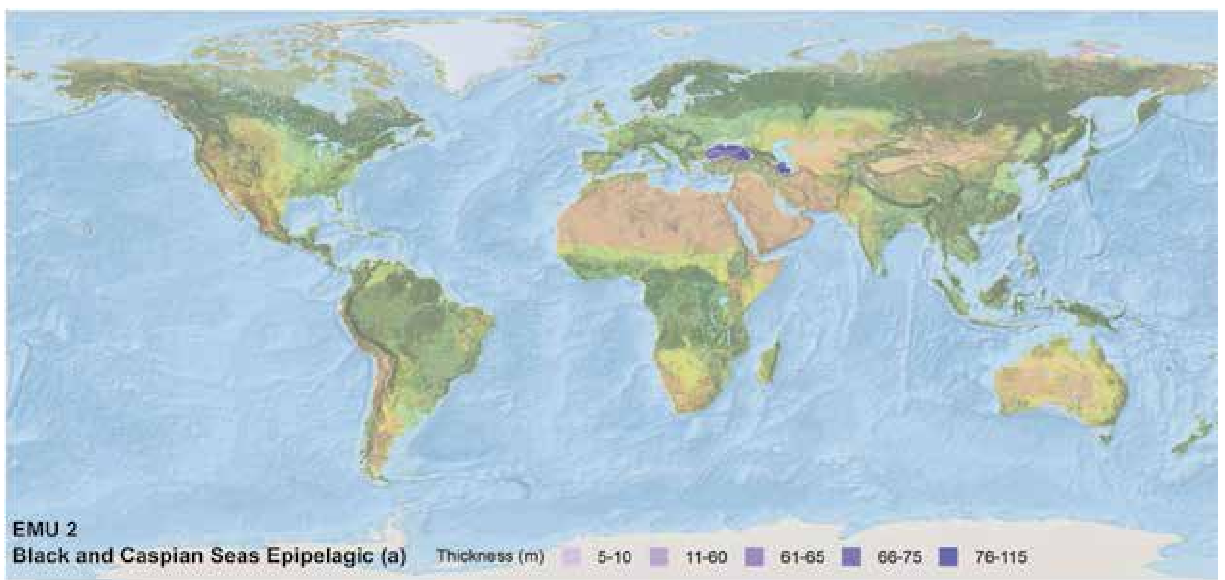
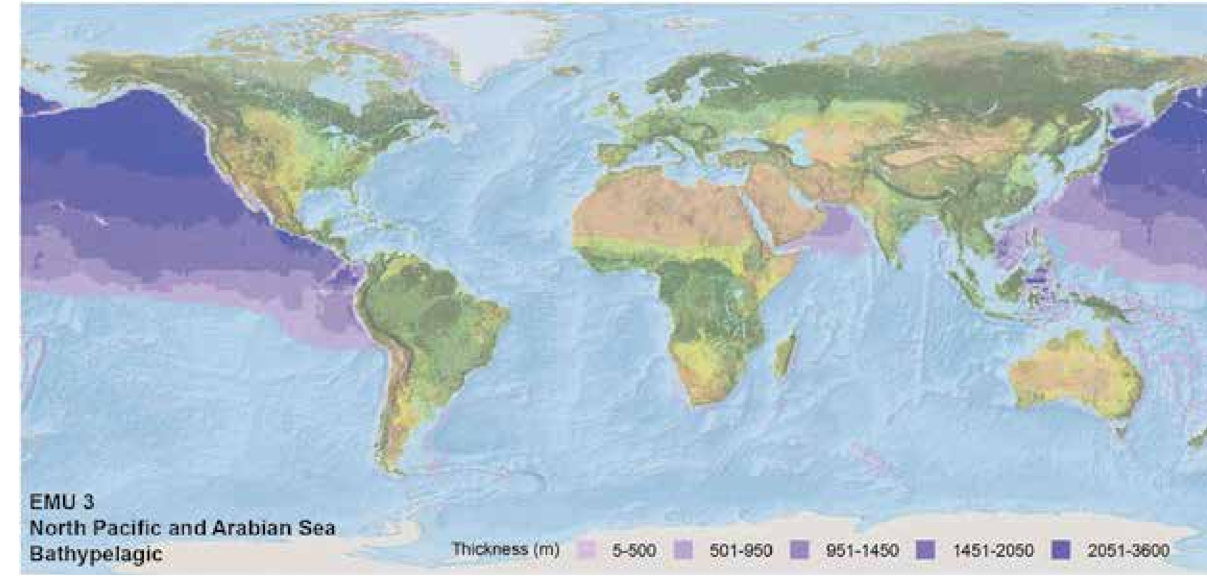


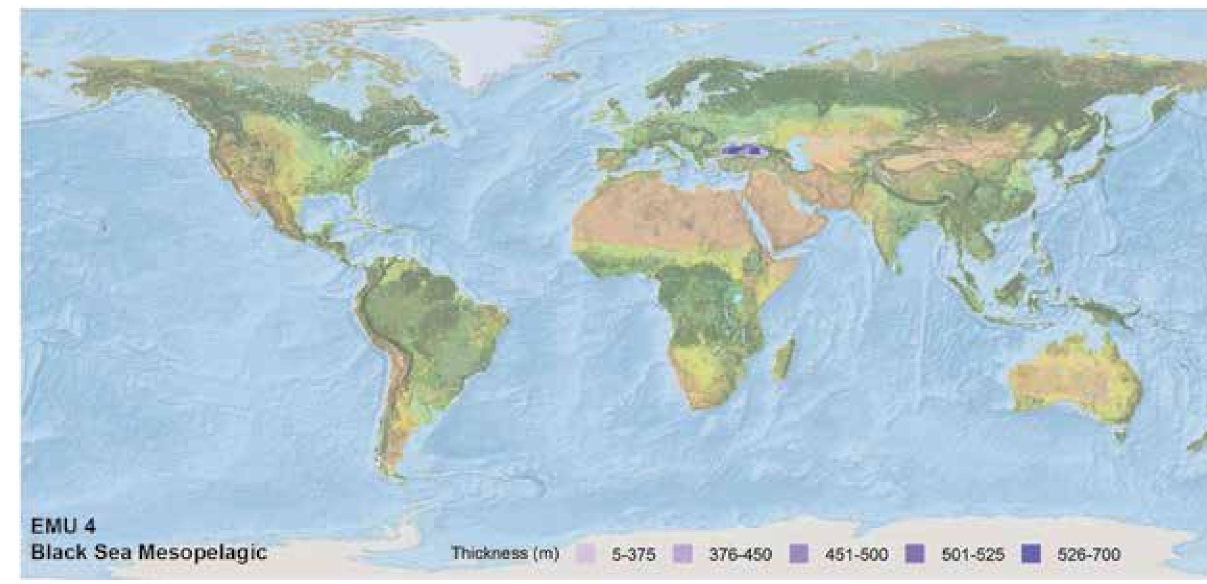
Figure 5. A 2D representation of bottom-occurring EMUs. On land, the terrestrial ecological land units (ELUs) are also shown (Sayre et al., 2014). Pink colors indicate warmer EMUs and blue colors indicate colder EMUs. While each EMU is compositionally distinct, generally similar EMUs in proximity can share the same name.

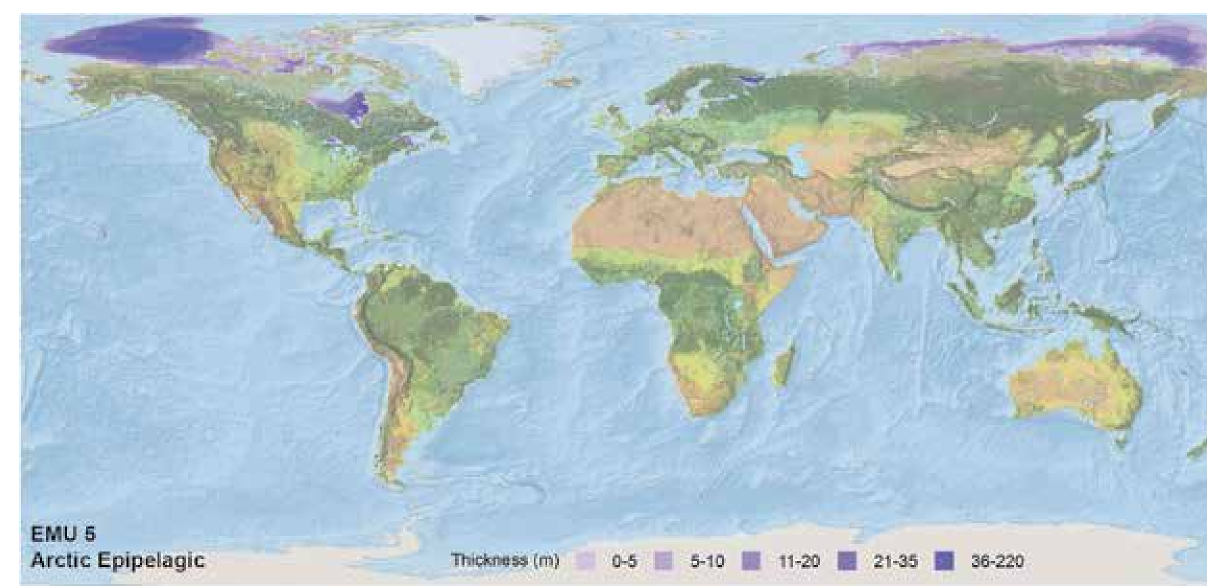
Figure 6. A series of maps showing the numbers, names, geographic distributions, and thicknesses of each EMU. Each panel shows the distribution of a single EMU, for a total of 37 panels in the following several pages. The horizontal geographic distribution of the EMU is shown in purple. Darker purple colors show where the EMU is relatively thicker in the vertical dimension, while lighter purple colors indicate where the EMU is relatively thinner. The number and name of each EMU is found in the lower left corner of each map panel. While each EMU is compositionally distinct, generally similar EMUs in proximity can share the same name.

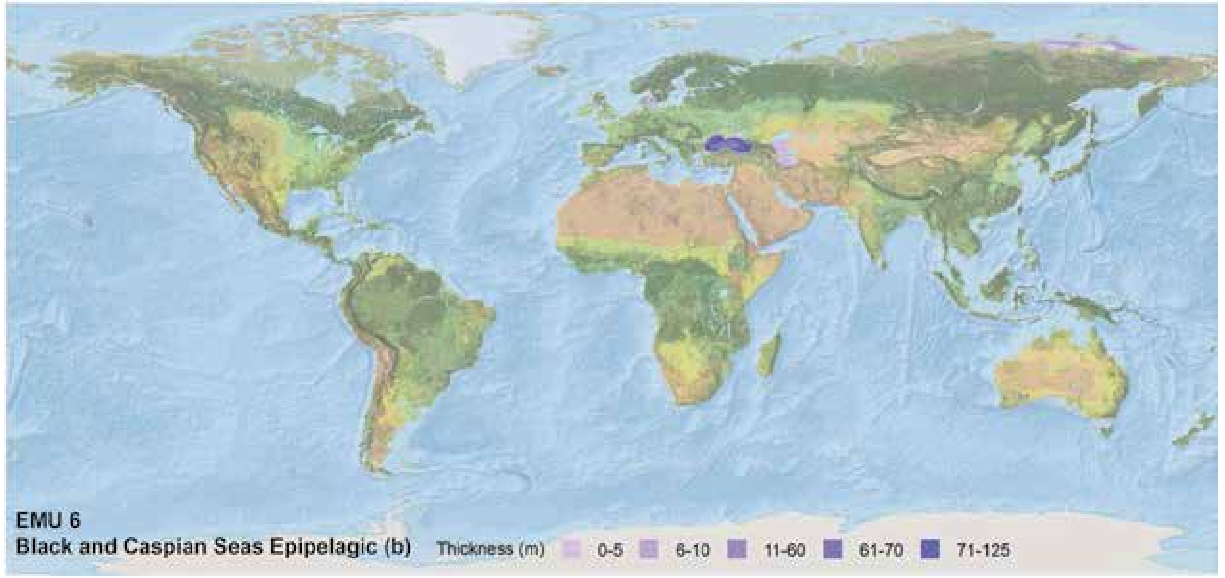


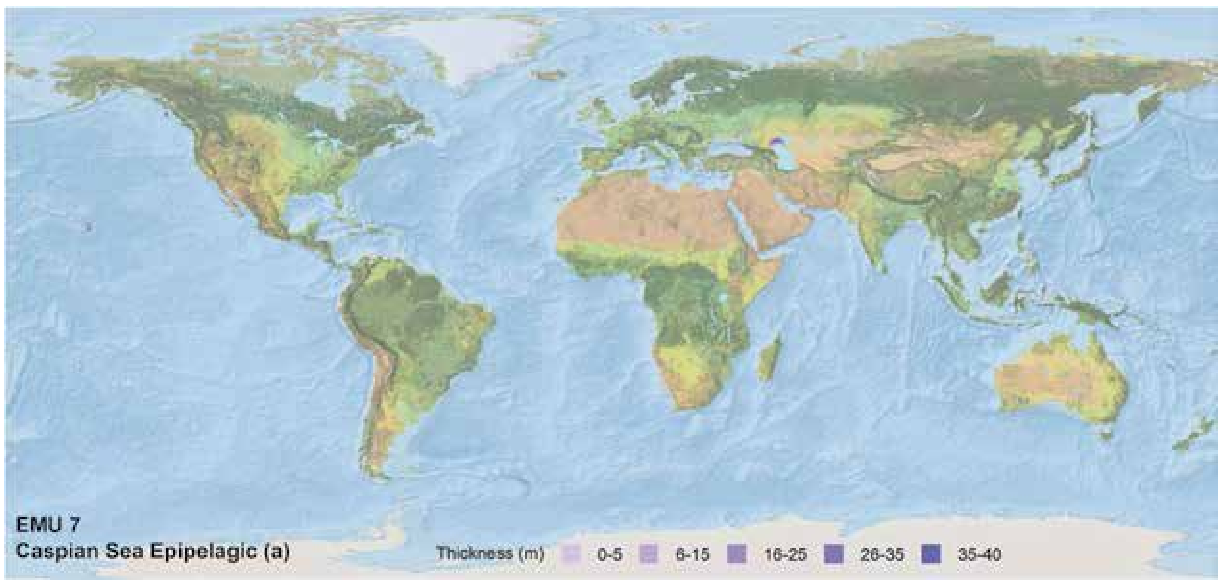


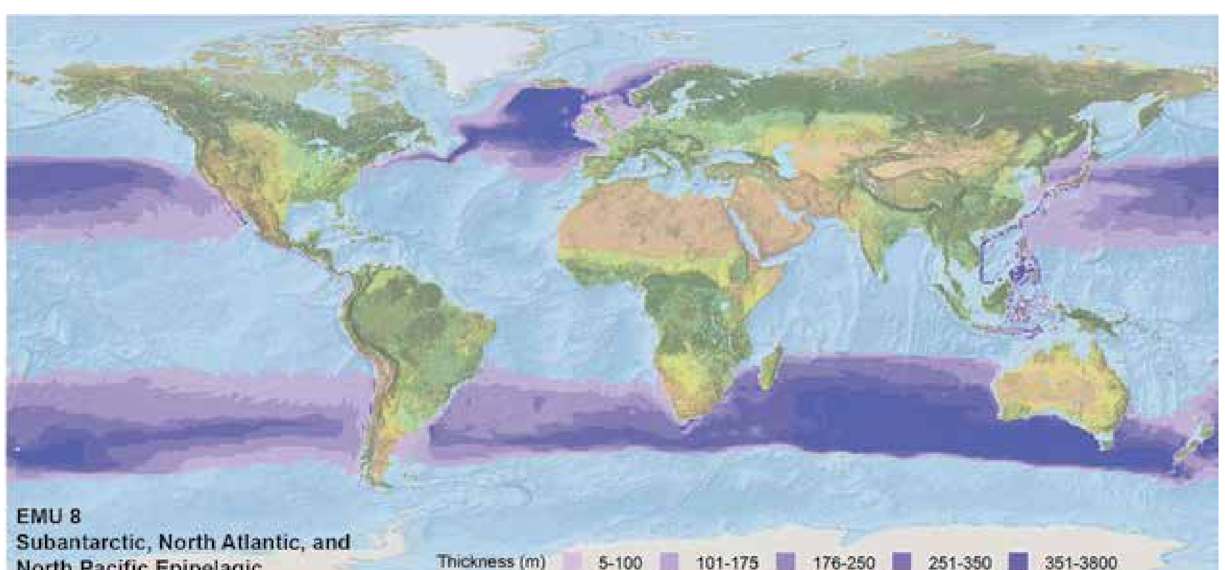


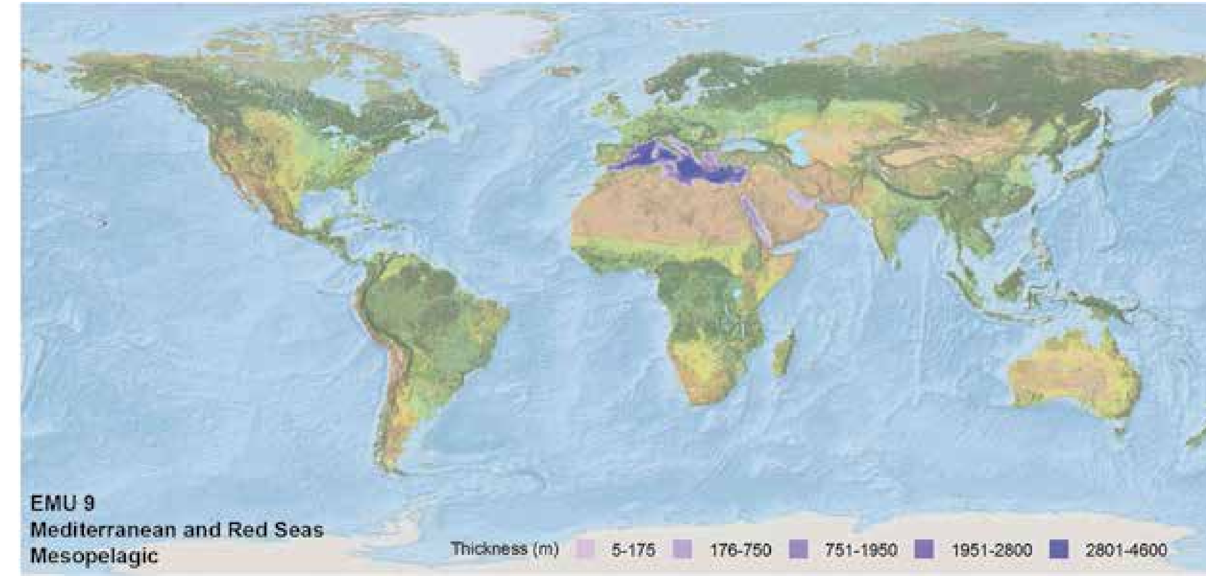


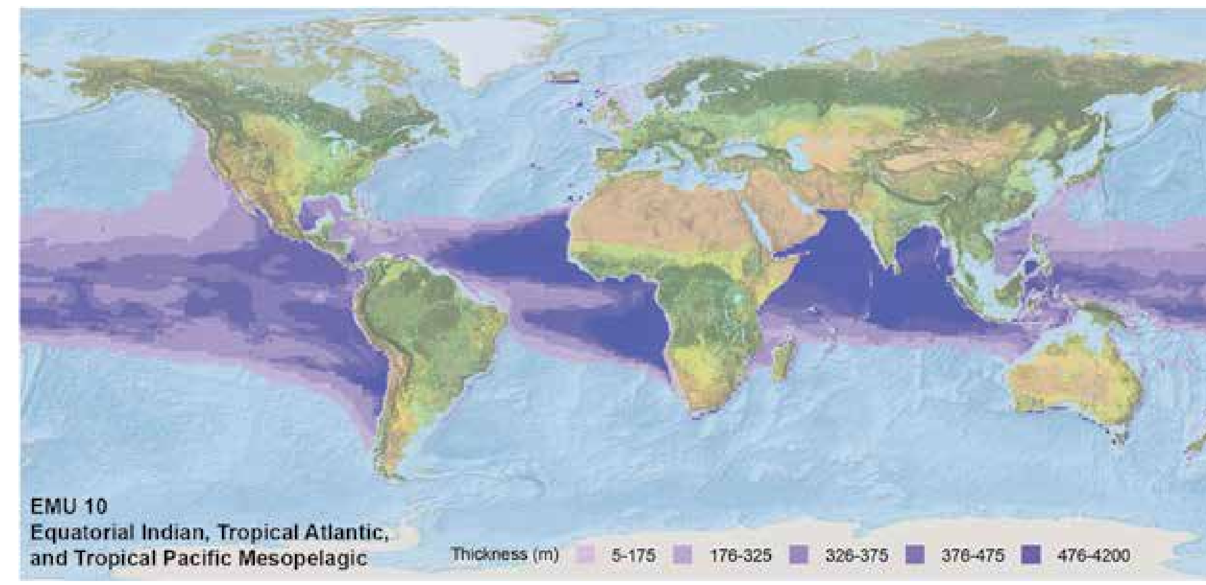


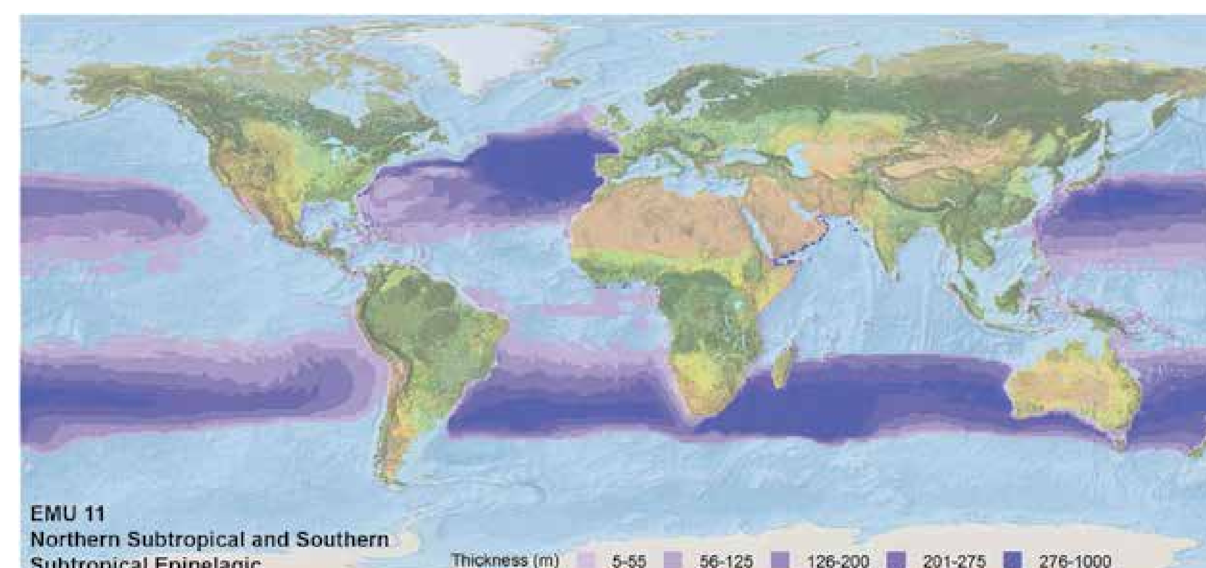

EMU 6
Black and Caspian Seas Epipelagic (b)
Thickness (m)
0-5
6-10
11-60
61-70
71-125

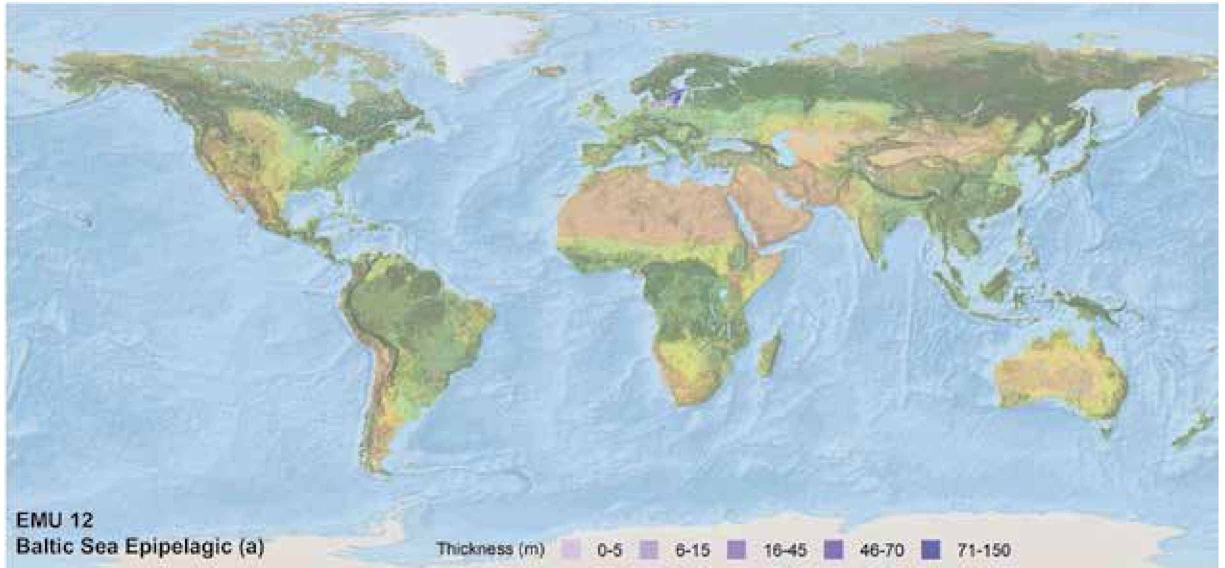

EMU 7
Caspian Sea Epipelagic (a)
Thickness (m)
0-5
6-15
16-25
26-35
35-40

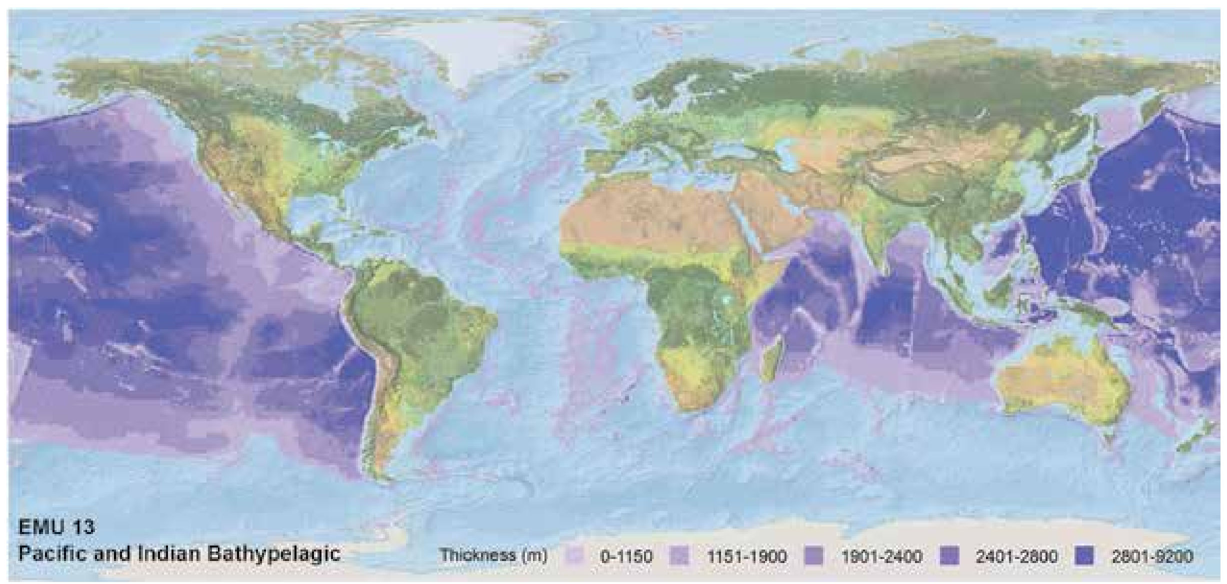

EMU 8
Subantarctic, North Atlantic, and
North Pacific Epipelagic
Thickness (m)
5-100
101-175
176-250
251-350
351-3800

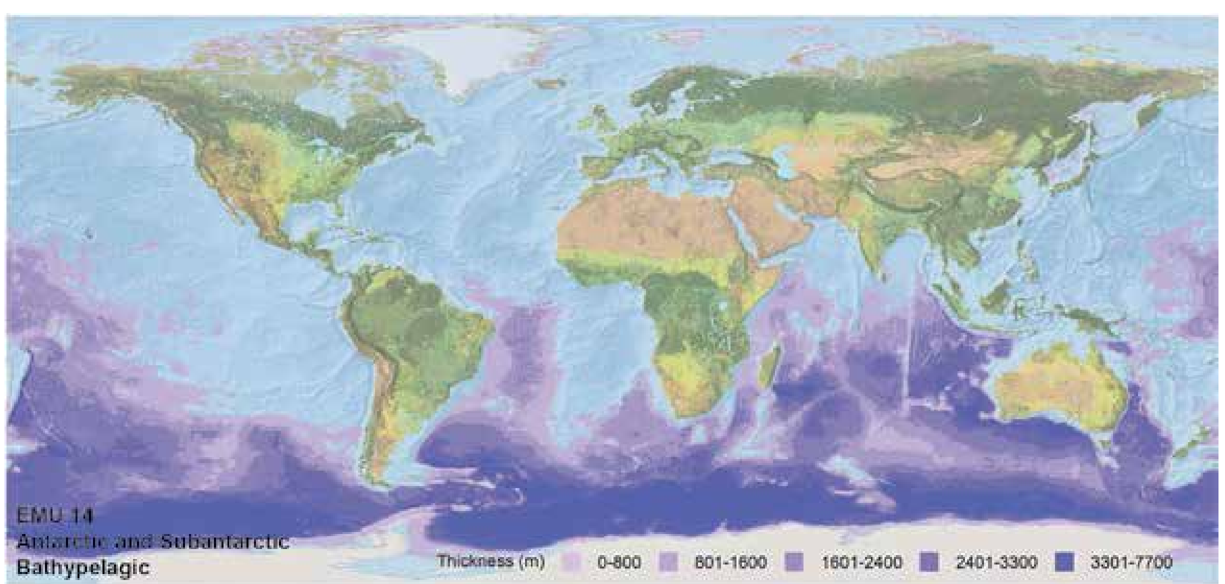

EMU 9
Mediterranean and Red Seas
Mesopelagic
Thickness (m)
5-175
176-750
751-1950
1951-2800
2801-4600

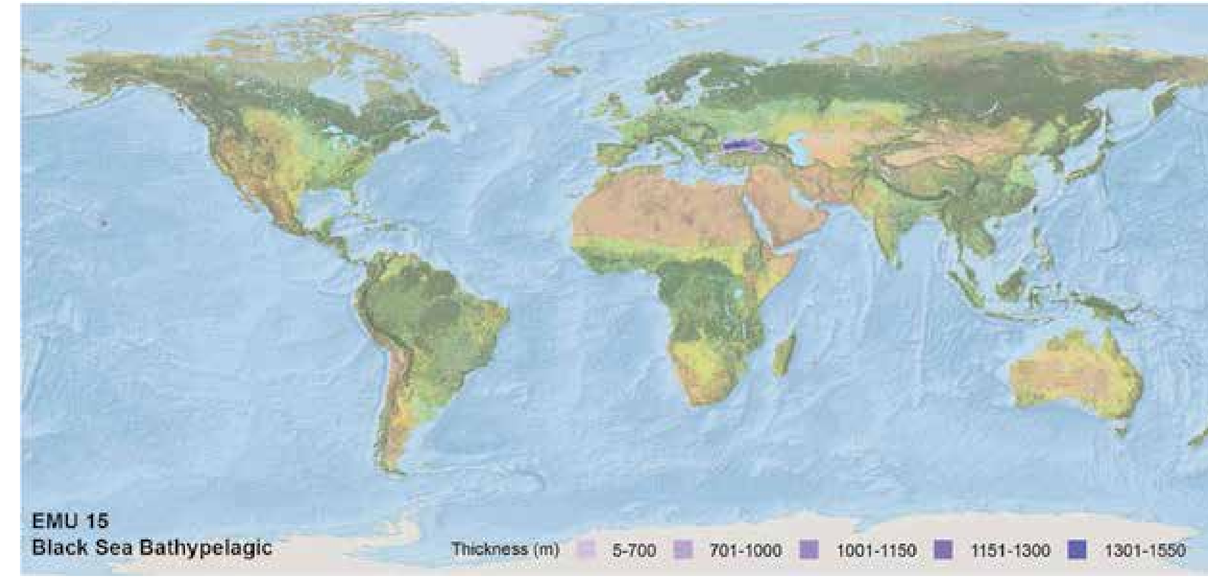

EMU 10
Equatorial Indian, Tropical Atlantic,
and Tropical Pacific Mesopelagic
Thickness (m)
5-175
176-325
326-375
376-475
476-4200

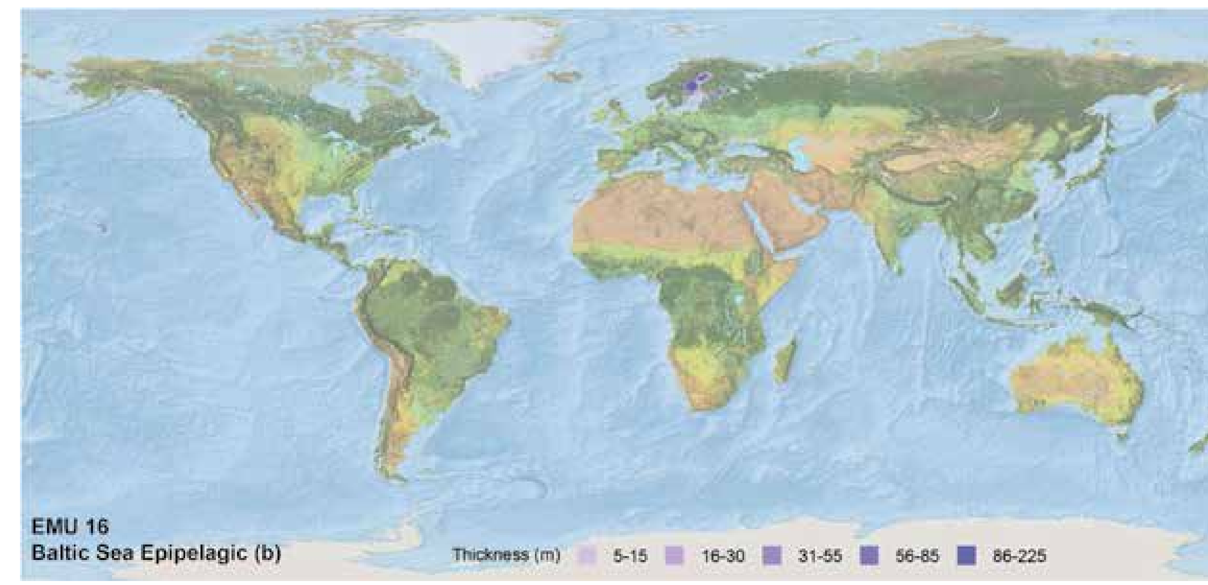

EMU 11
Northern Subtropical and Southern
Subtropical Epipelagic
Thickness (m)
5-55
56-125
126-200
201-275
276-1000

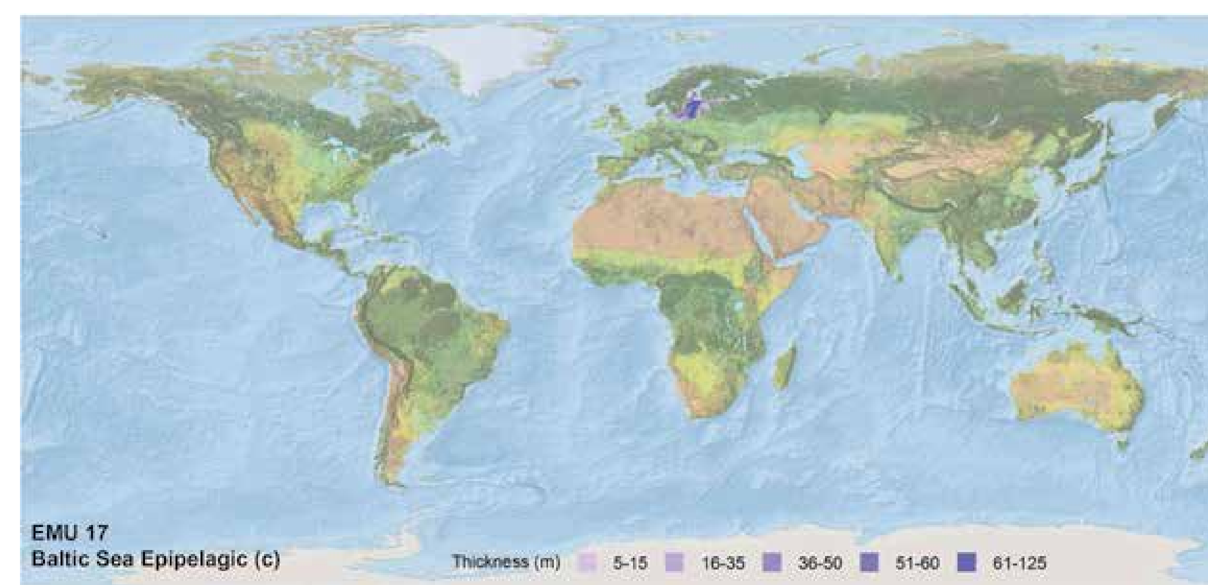

EMU 12
Baltic Sea Epipelagic (a)
Thickness (m) 0-5 6-15 16-45 46-70 71-150

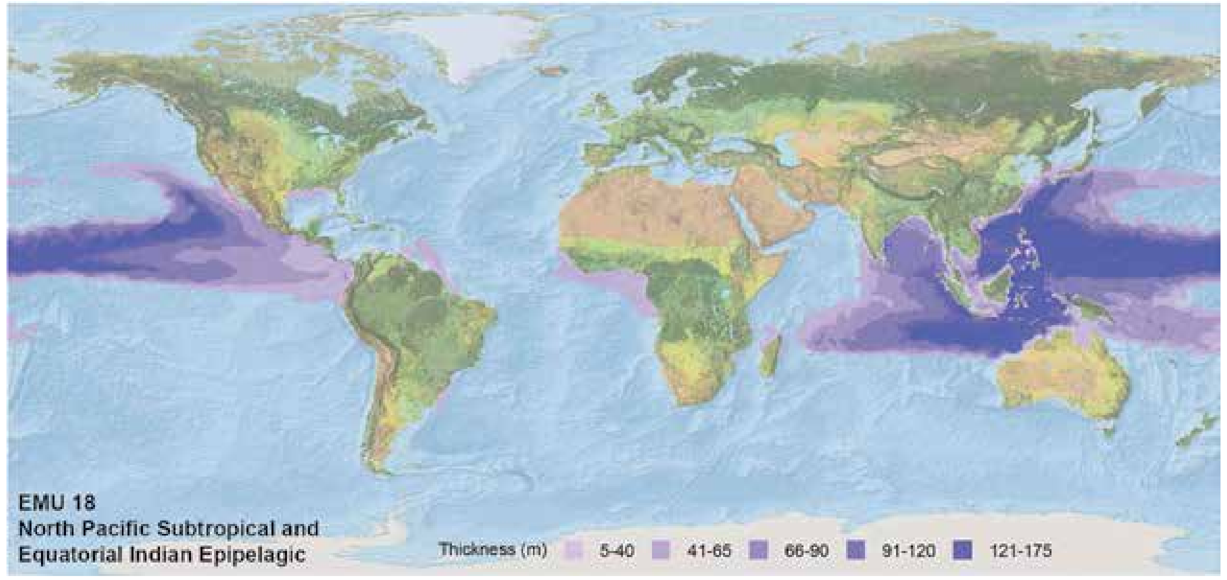

EMU 13
Pacific and Indian Bathypelagic
Thickness (m) 0-1150 1151-1900 1901-2400 2401-2800 2801-9200

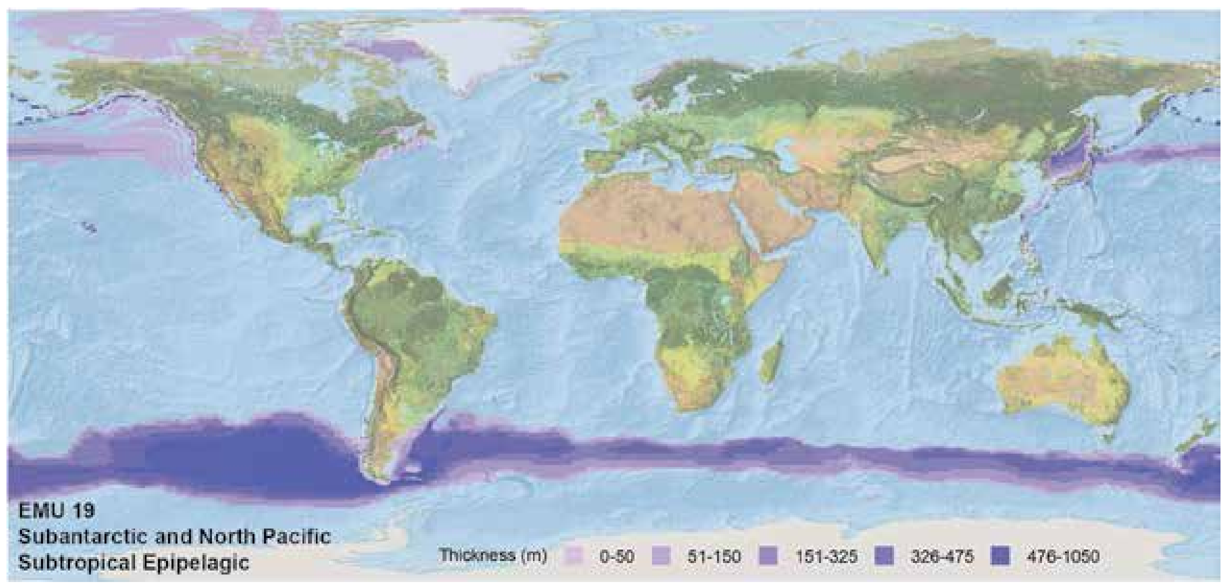

EMU 14
Antarctic and Subantarctic
Bathypelagic
Thickness (m) 0-800 801-1600 1601-2400 2401-3300 3301-7700

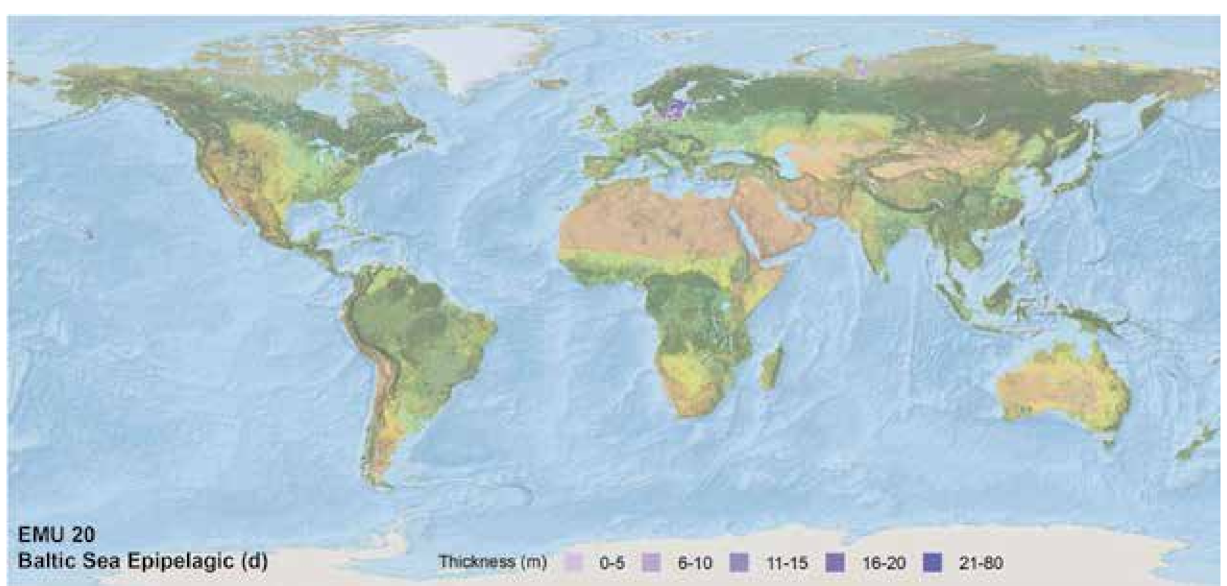

EMU 15
Black Sea Bathypelagic
Thickness (m) 5-700 701-1000 1001-1150 1151-1300 1301-1550

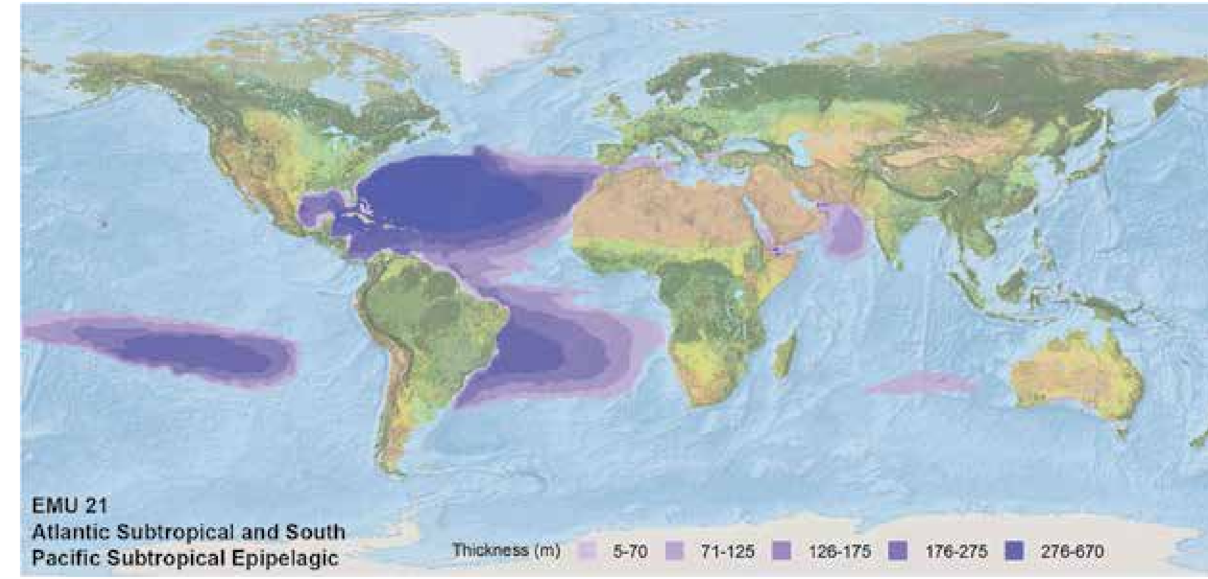

EMU 16
Baltic Sea Epipelagic (b)
Thickness (m) 5-15 16-30 31-55 56-85 86-225

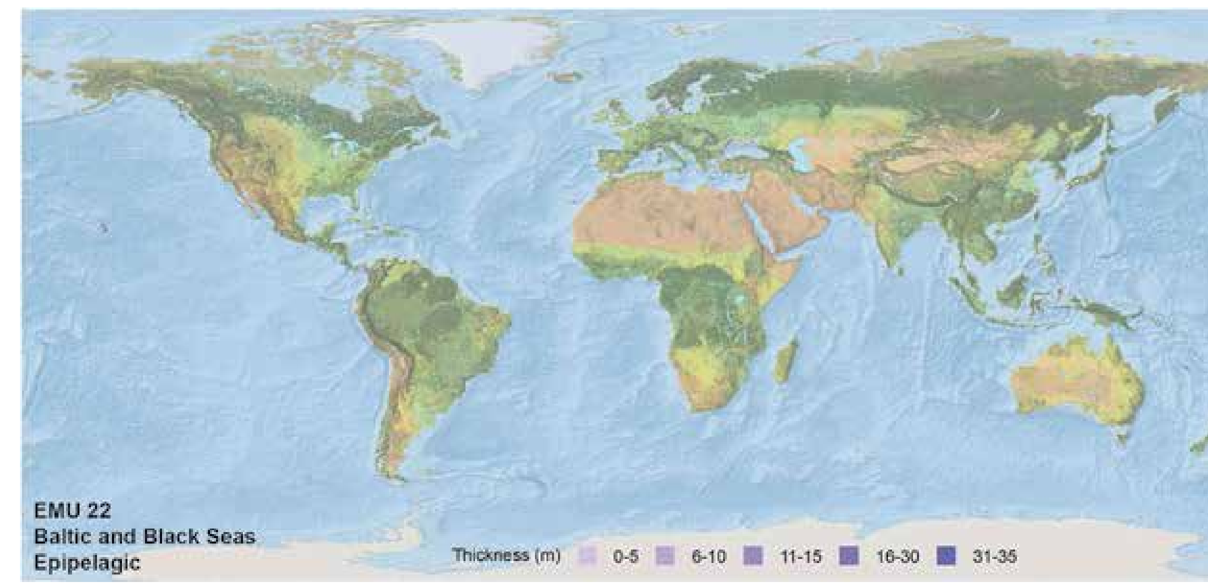

EMU 17
Baltic Sea Epipelagic (c)
Thickness (m) 5-15 16-35 36-50 51-60 61-125

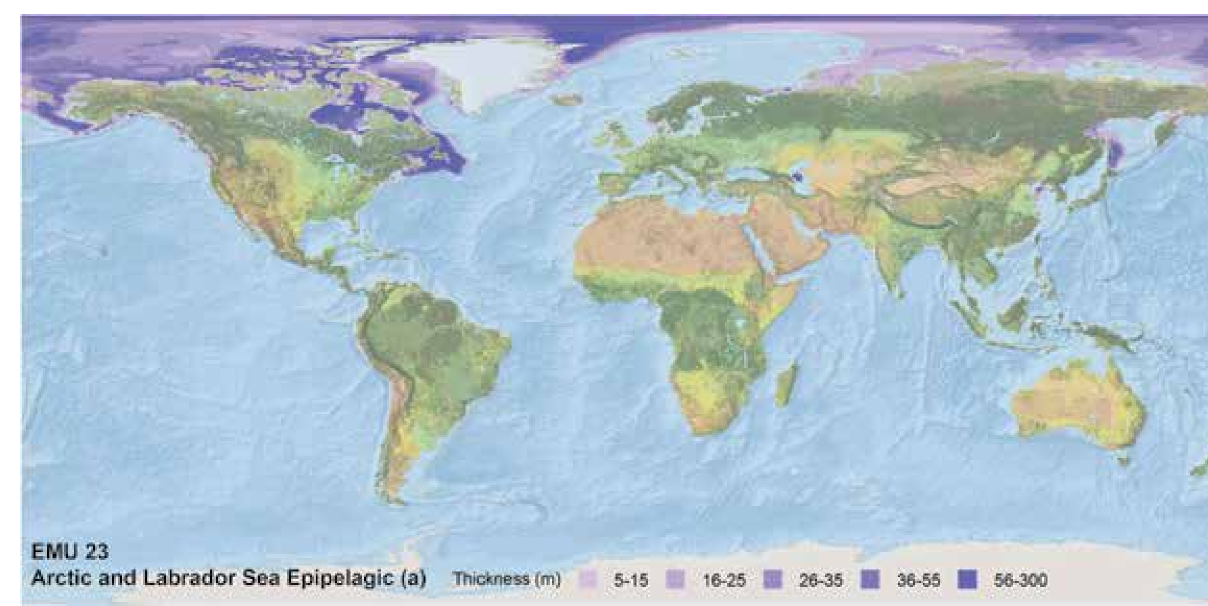

EMU 18
North Pacific Subtropical and
Equatorial Indian Epipelagic
Thickness (m) 5-40 41-65 66-90 91-120 121-175

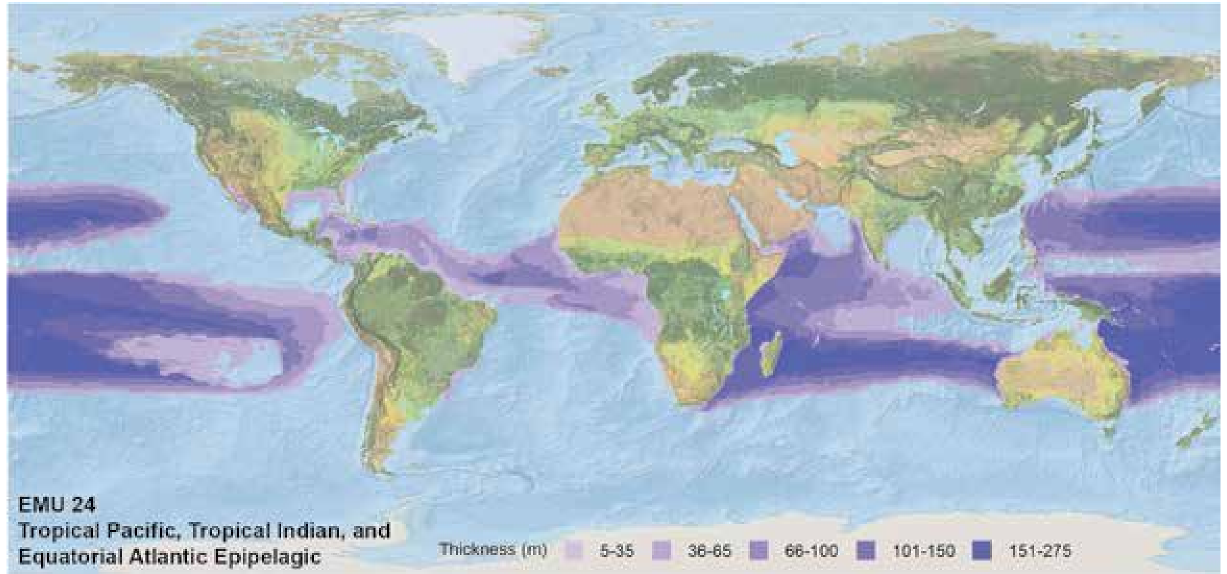

EMU 19
Subantarctic and North Pacific
Subtropical Epipelagic
Thickness (m) 0-50 51-150 151-325 326-475 476-1050


EMU 20
Baltic Sea Epipelagic (d)
Thickness (m) 0-5 6-10 11-15 16-20 21-80

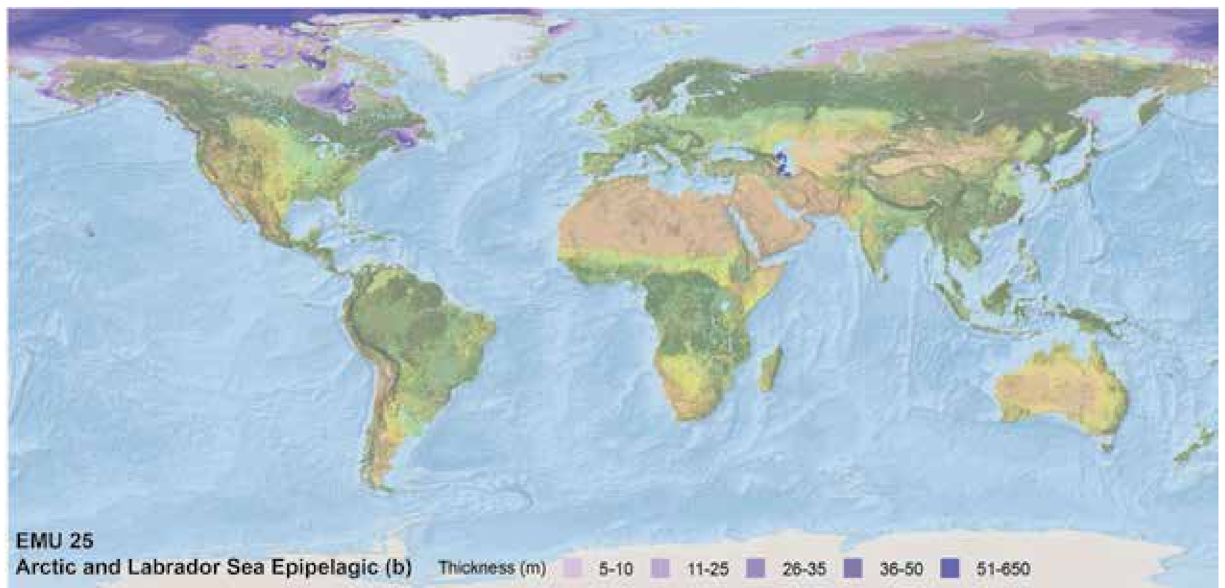

EMU 21
Atlantic Subtropical and South
Pacific Subtropical Epipelagic
Thickness (m) 5-70 71-125 126-175 176-275 276-670


EMU 22
Baltic and Black Seas
Epipelagic
Thickness (m) 0-5 6-10 11-15 16-30 31-35

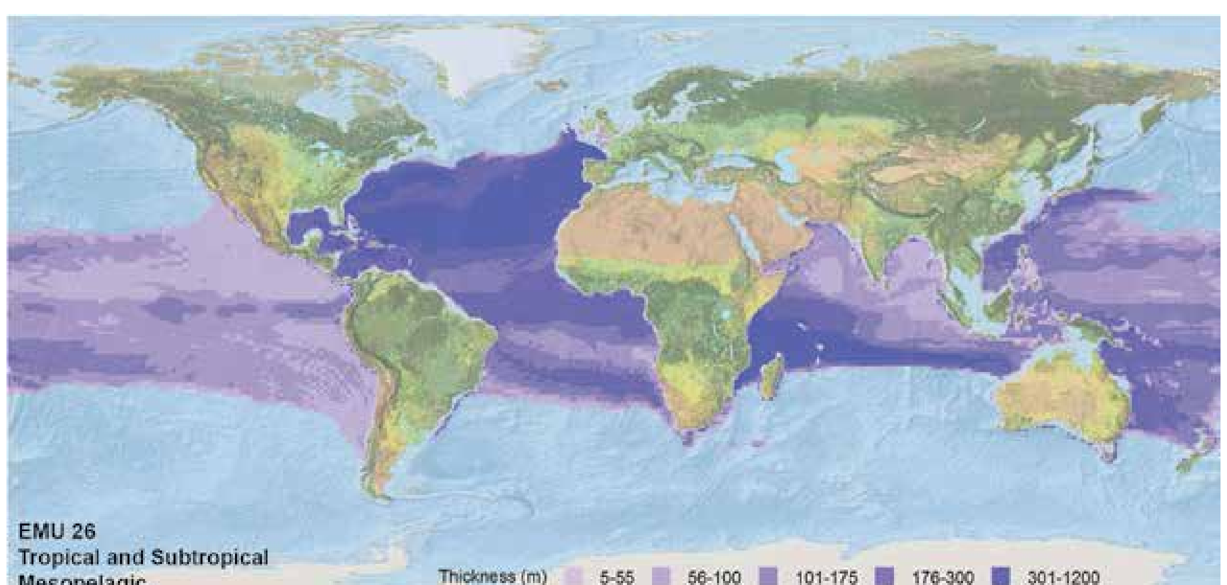

EMU 23
Arctic and Labrador Sea Epipelagic (a)
Thickness (m) 5-15 16-25 26-35 36-55 56-300



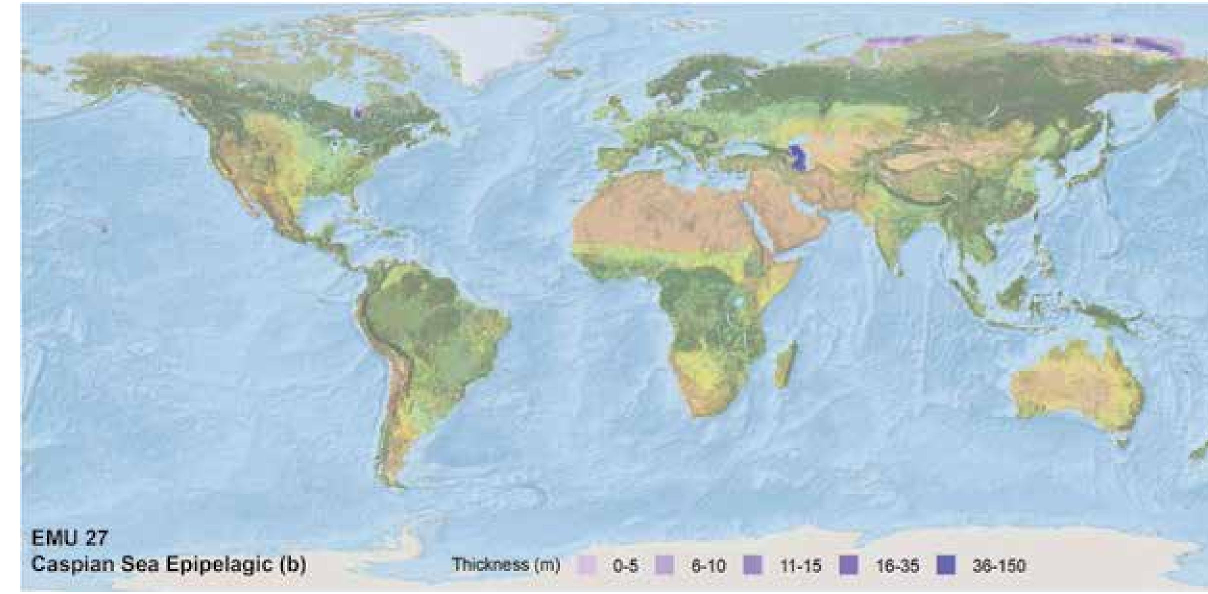
EMU 24
Tropical Pacific, Tropical Indian, and Equatorial Atlantic Epipelagic



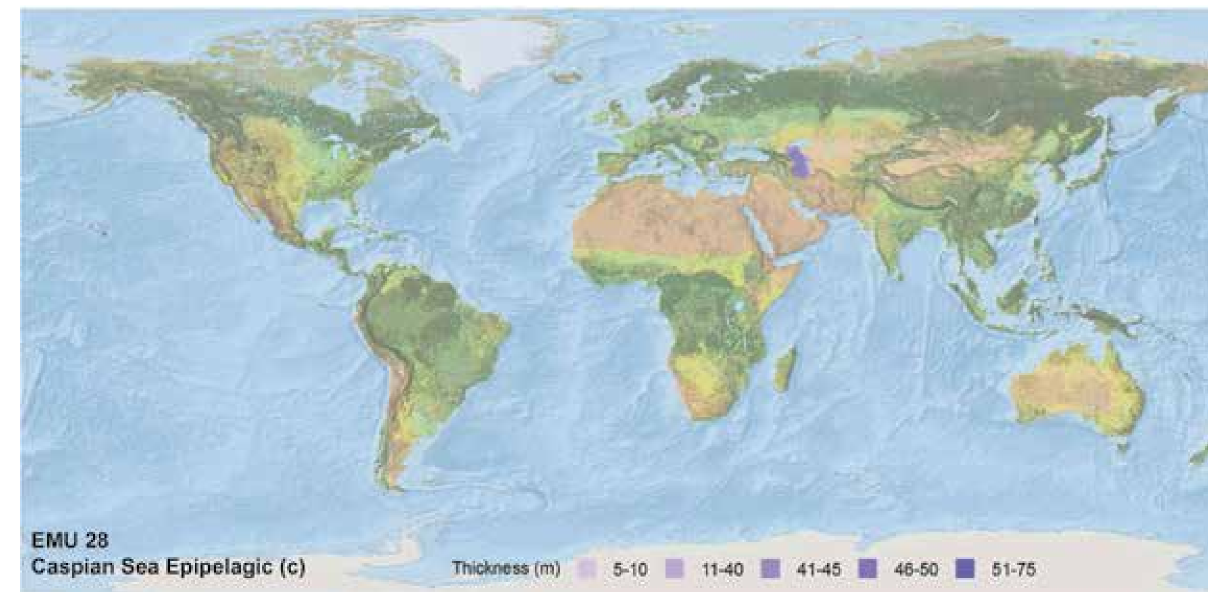
EMU 25
Arctic and Labrador Sea Epipelagic (b)



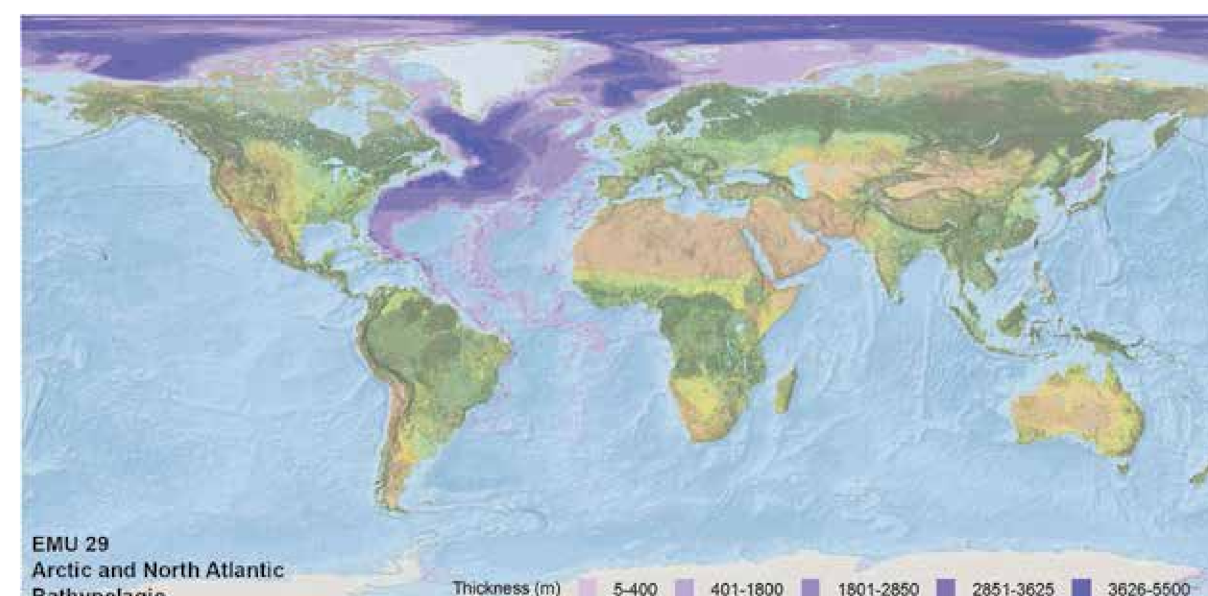
EMU 26
Tropical and Subtropical Mesopelagic



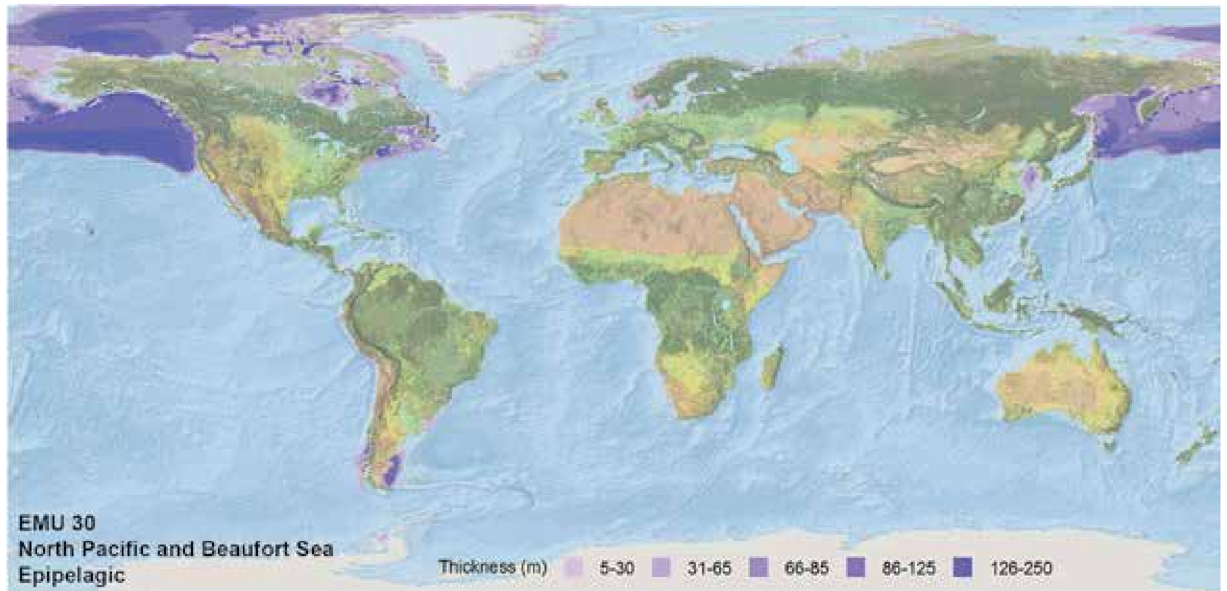
EMU 27
Caspian Sea Epipelagic (b)



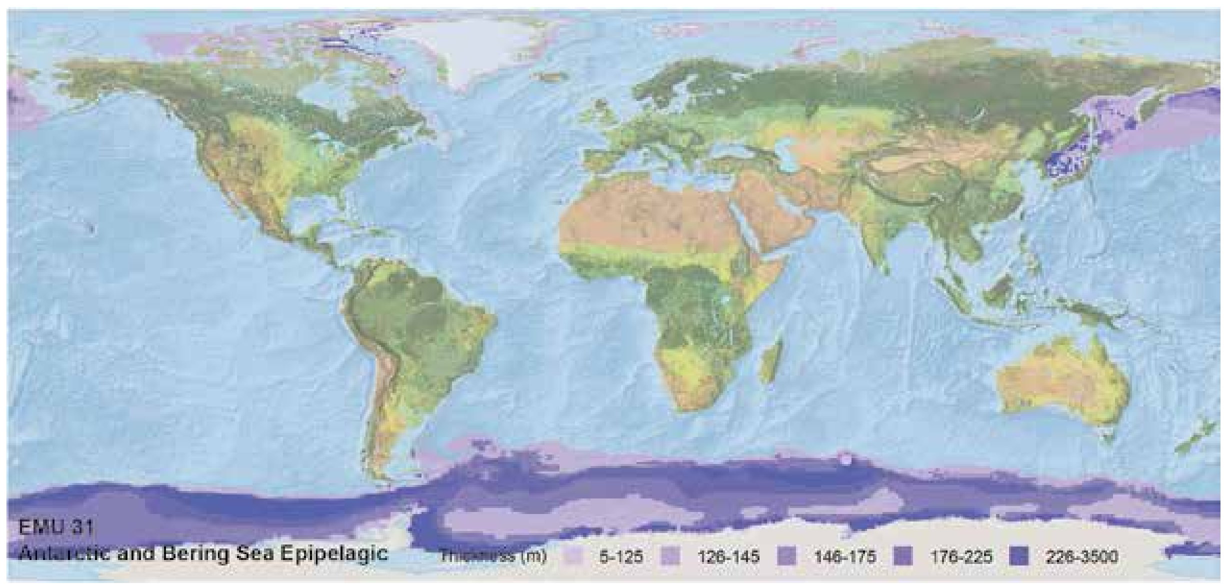
EMU 28
Caspian Sea Epipelagic (c)



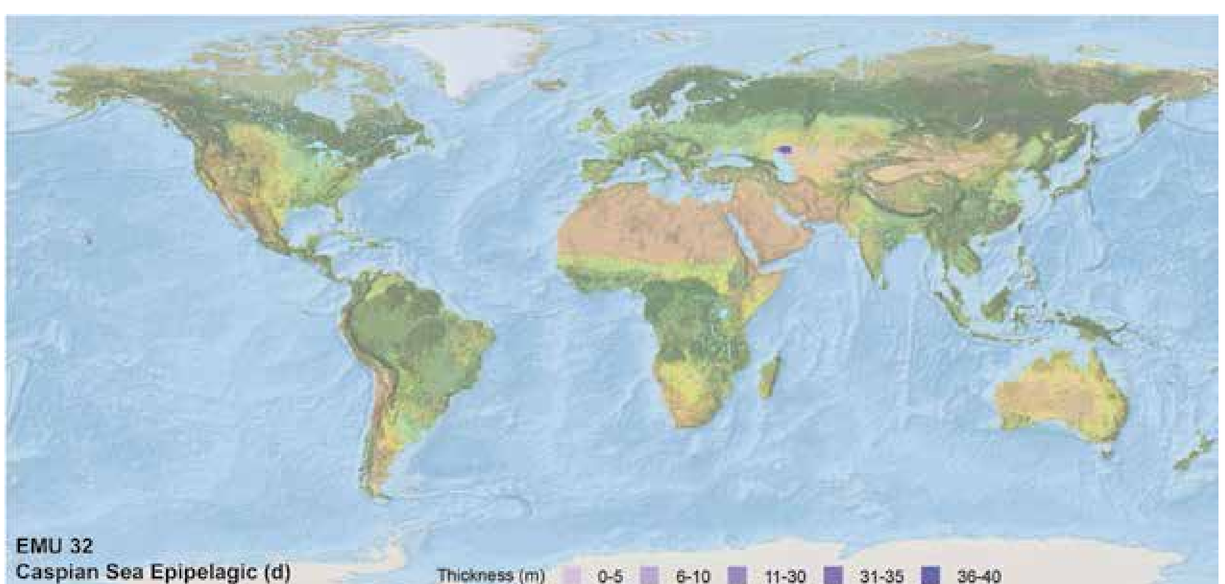
EMU 29
Arctic and North Atlantic Bathypelagic



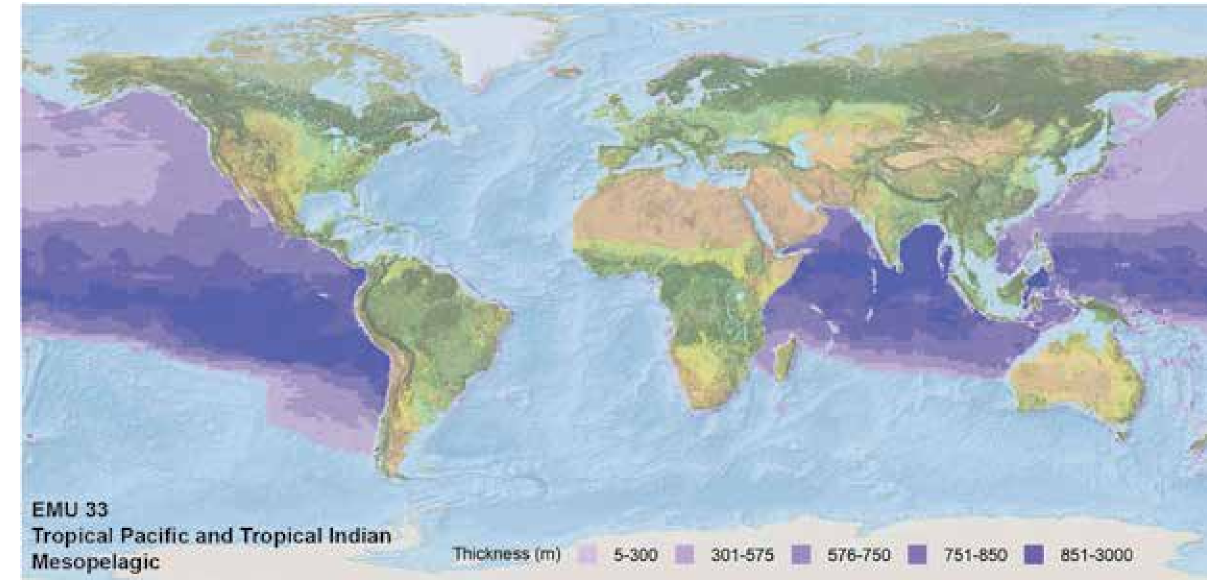
EMU 30
North Pacific and Beaufort Sea Epipelagic



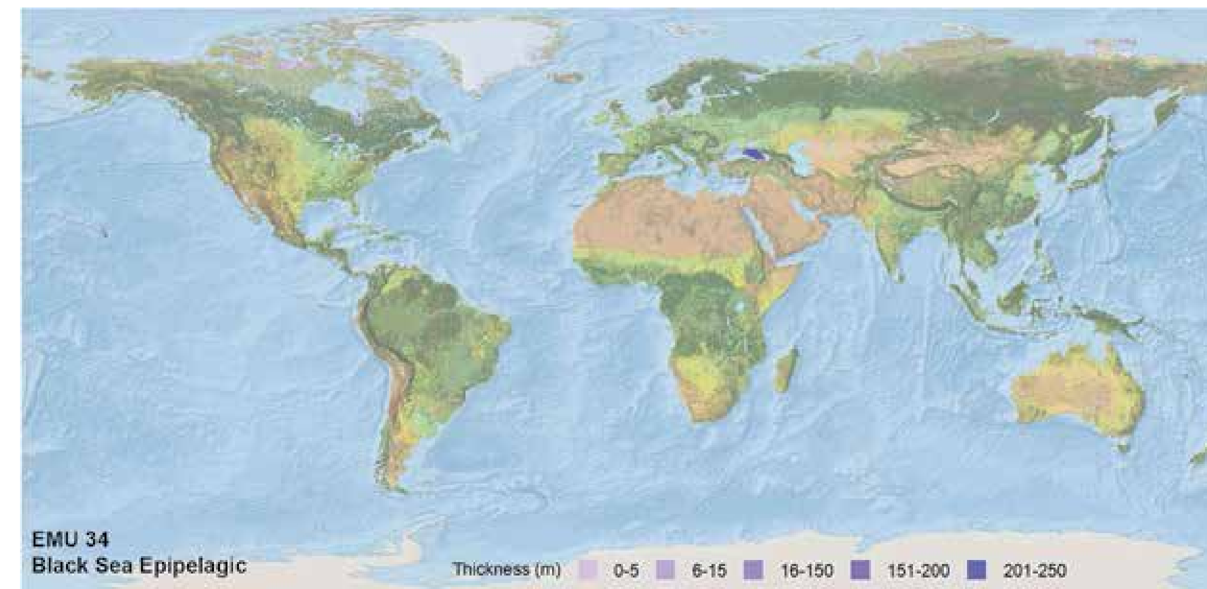
EMU 31
Antarctic and Bering Sea Epipelagic



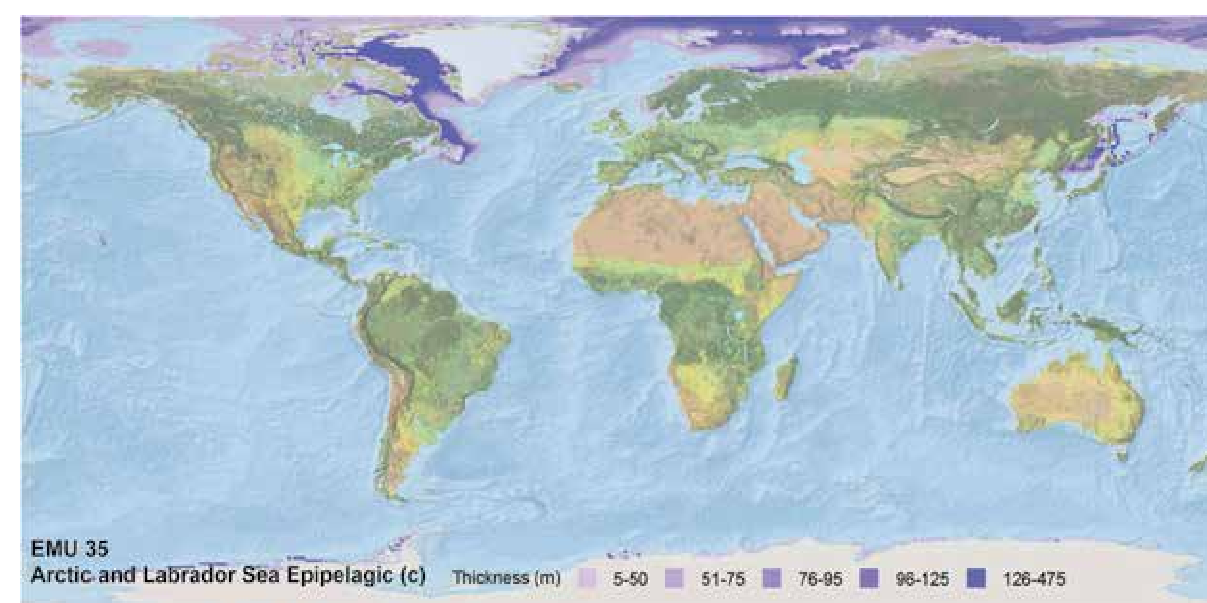
EMU 32
Caspian Sea Epipelagic (d)



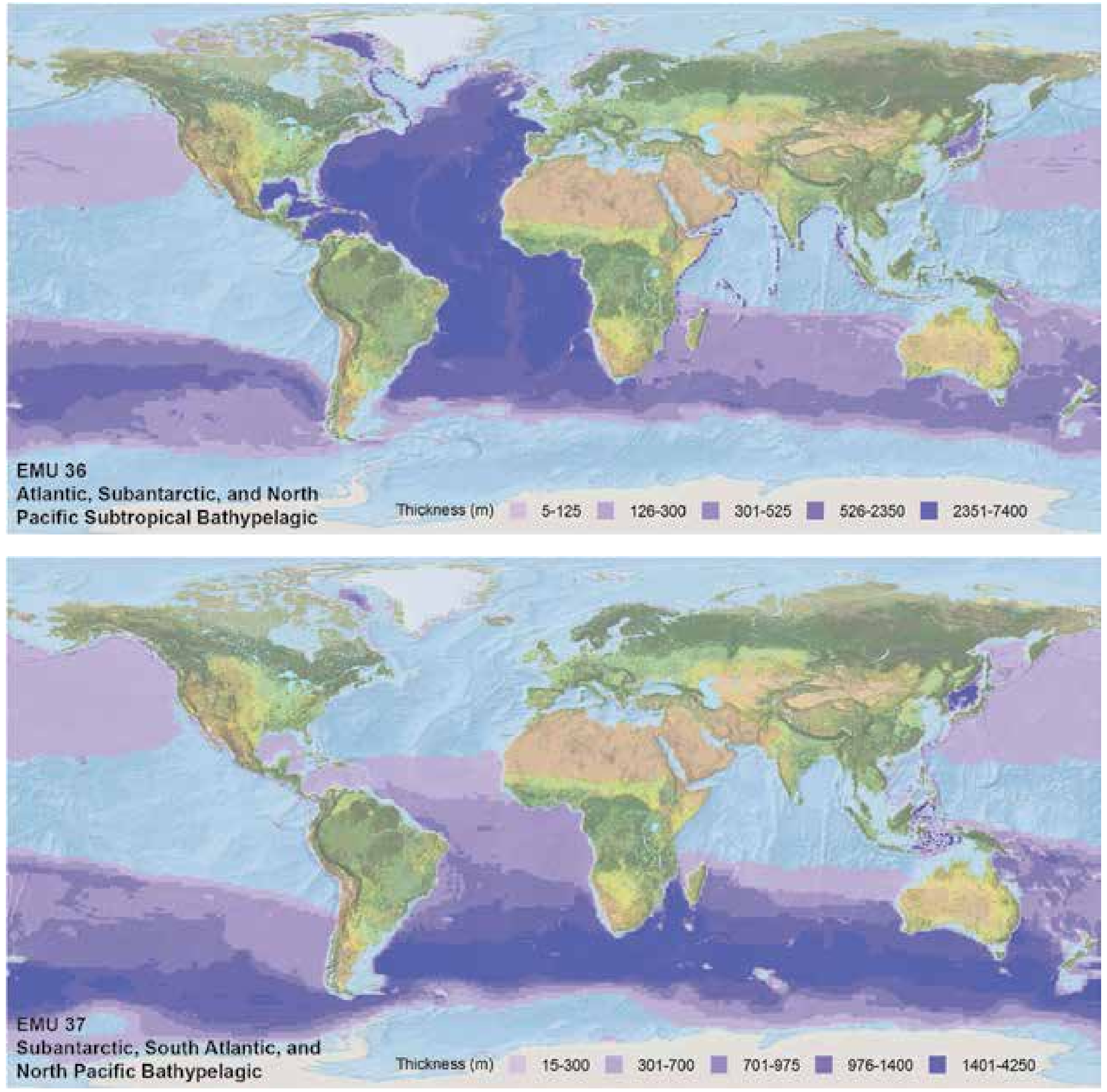
EMU 33
Tropical Pacific and Tropical Indian Mesopelagic



EMU 34
Black Sea Epipelagic



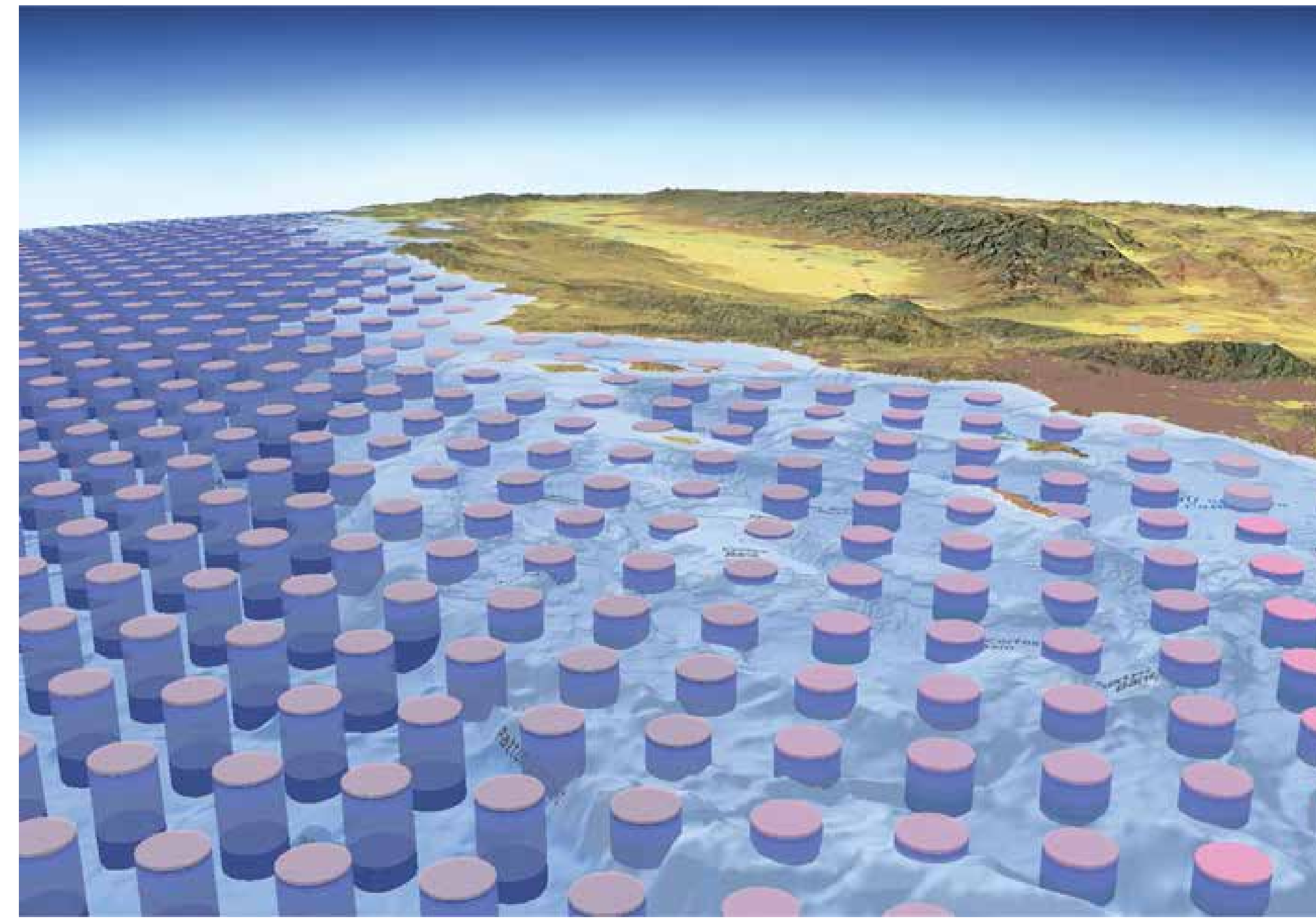
EMU 35
Arctic and Labrador Sea Epipelagic (c)



Three-dimensional Visualization of EMUs

The EMU data are a de facto example of a "big data," three-dimensional database, and as such present a visualization challenge. While it is quite straightforward to select, analyze, and visualize any two-dimensional horizontal "slice" of the global EMUs, as in **Figures 3**, **4**, and **5**, it is more difficult to visualize them simultaneously in x, y, and z dimensions. Spatial analytical software capable of 3D visualization is required. We used ArcGIS Pro version 1.3 to successfully render the data in a 3D visualization environment (**Figure 7**). The EMU data, while in reality a continuous surface, are visualized as cylinders where the vertical centerline of the cylinder is defined from the vertically aligned points in the ocean point mesh. Different colored bands on each cylinder represent the different EMUs that are encountered with increasing depth. Representing the data as a cylinder instead of a continuous surface has the effect of cutting away volume between the gridded points, enabling the viewer to "see between" the points and observe the stacked EMUs from the sea surface to the seafloor in many cases. In addition to the visualization functionality, the EMU data are queryable as well from user interaction with the colored bands.

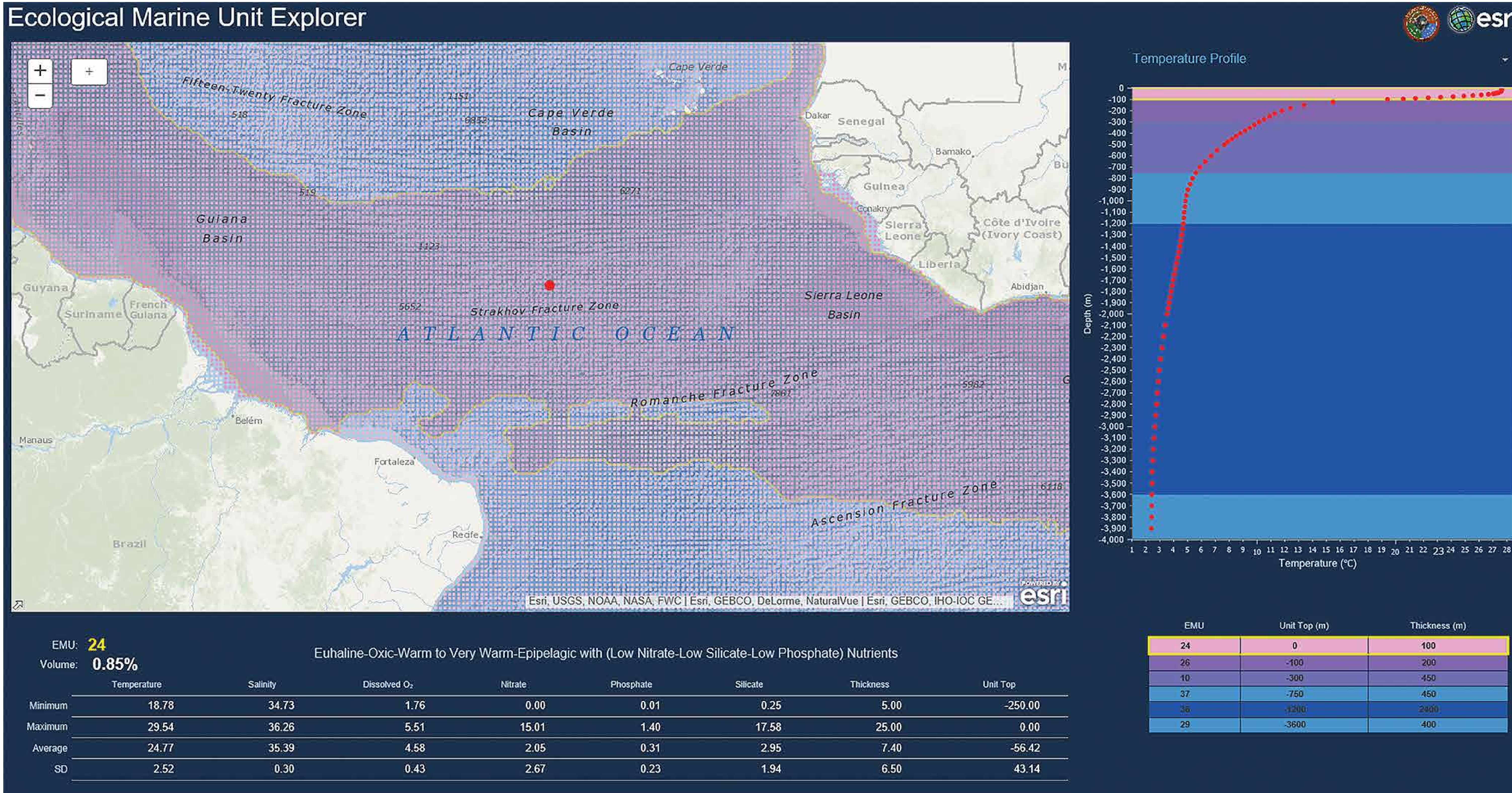
Figure 7. A 3D visualization of EMUs off the coast of California. On land, the ecological land units data (ELUs) from Sayre et al. (2014) are shown, with features like the Central Valley and Sierra Nevada Mountains in the upper center, and Southern California landscapes in the lower right. In the water, the EMUs are portrayed as bands on cylinders, where each EMU is a different colored band on the cylinder. Reddish/pink colors denote shallower, warmer EMUs, while blueish/black colors denote deeper, colder EMUs. Temperature gradients are evident from inshore to offshore regions, and from southern to northern coastal areas. Although the EMUs exist as continuous surfaces, representing them as cylinders and removing some of the volume between the mesh points enables the visualization of multiple, stacked EMUs at depth.



The EMU Explorer Application

While the data are visualizable and queryable with the advanced functionality provided by sophisticated GIS software, it was also desirable to develop an open data, web-based application which would allow access to the resource with the only criteria being Internet connectivity. We therefore developed the EMU Explorer application, accessible at http://livingatlas.arcgis.com/emu. This tool allows the user to select a point anywhere on the surface of the ocean, and obtain information about the selected point (x,y) on the sea surface and at all of the points at that same latitude and longitude with differing depth (z) values (the vertical profile). In addition to the information on the points, information is also provided on the EMU that the point belongs to. **Figure 8** shows the EMU Explorer Interface. The interface has four panels, a pan and zoom-capable map of the global ocean in the upper left panel, and three information panels in the upper right, lower right, and lower left of the screen. The upper right panel shows the entire vertical profile of the attribute values for any one of the six parameters (temperature, salinity, dissolved oxygen, nitrate, phosphate, and silicate), the choice of which is user-selected. The lower left panel underneath the map presents descriptive statistics for all of the parameters of the selected EMU. The lower right panel shows the depth and thickness dimensions of all the EMUs occurring in the vertical profile. All the panels are cross-linked such that a change of query to another point or EMU in any panel changes the information presented in the other panels accordingly.

Figure 8. The interface of the EMU Explorer application, a web-based (http://livingatlas.arcgis.com/emu) query tool for interacting with the EMU data. A point is selected on the surface of the ocean (red point in the middle of the Atlantic Ocean) and all the points with the same EMU as the selected point are shown. A vertical profile is shown on the right, where the user can select one of the six parameters used to cluster the EMUs (temperature, salinity, dissolved oxygen, nitrate, phosphate, and silicate) and see the attribute values down through the vertical profile at that x,y coordinate. The two lower panels contain descriptive statistics on the EMU physical and chemical parameters (lower left) and depth and thicknesses (lower right).



Accessing and Using the Data

The EMU web page is accessible at http://esri.com/ecological-marine-units. The EMU data products and the EMU Explorer are open data resources available without a login requirement from the Esri Living Atlas (http://livingatlas.arcgis.com) and elsewhere in the ArcGIS Online content pool (http://esriurl.com/emudata). The EMU data are therefore easily integrated with hundreds of other datasets representing the most current, detailed, authoritative, and curated GIS-ready global data available. This integration is easily accomplished without the need for downloading, preparing, and reconciling disparate datasets by the user. The entire EMU geodatabase (~38 GB) is addressable and can be accessed using either ArcMap or ArcGIS Pro technologies. A number of datasets, information products (pdfs), storymaps, browse and query applications, and other resources are now freely available to users, and the number of curator-supplied (Esri) and associated user-supplied resources is rapidly growing. An ArcGIS Online search on “ecological marine units EMUs)” will return descriptions of and links to these expanding resources.

The global data are accessible either through map packages (ArcMap) or project packages (ArcGIS Pro). In the ArcMap resource, three 2D slices of the global data, corresponding to the maps shown in **Figures 3** (top), **4** (1000 m), and **5** (bottom), are also provided as pre-prepared individual layers. In addition to the global EMU resource, the data have been sub-regionalized into Arctic Ocean, Atlantic Ocean, Pacific Ocean, Indian Ocean, Southern Ocean and Oceania subsets. Esri provides the source data as a cloud-based image (raster) service on its geospatial portal, ArcGIS.com, and the provided data are available as layers in ArcGIS Online and in ArcGIS for Desktop. The data are stored in the WGS_1984 geographic coordinate system to minimize the amount of data loss that will ocurr when projecting to other coordinate systems.

In addition to the EMU open data provision from Esri, the EMU geodatabase in .gdb format (~38 GB) with associated map packages (for use in ArcMap) and project packages (for use in ArcGIS Pro) is also available for download from the USGS Global Ecosystems Mapping webpages (https://rmgsc.cr.usgs.gov/ecosystems/ (main page) and https://rmgsc.cr.usgs.gov/ecosystems/datadownload.shtml (download site). This collection of resources includes information, data, and a viewer for the analog ELU (ecological land units) terrestrial product as well. Point features data are also available as an Open Geospatial Consortium (OGC) Geo Package or similar.

Conclusion

In a first-of-its kind effort to objectively partition the global ocean into volumetric regions using 3D data on ocean physical and chemical properties, 37 ecological marine units (EMUs) were mapped. The standardized EMU ocean regions data could be used in assessments of marine biodiversity, marine ecological processes, and marine ecosystem accounting, and could inform resource management and planning. Maps and data describing each EMU are presented herein. Access to the data is open, and a visualization approach for working with the data in 3D is presented. The EMU Explorer, a sophisticated web-based query and analysis application, is described. The EMUs represent a standardized geospatial framework for storing existing ocean physico-chemical data, and for adding new ocean information as it becomes available.

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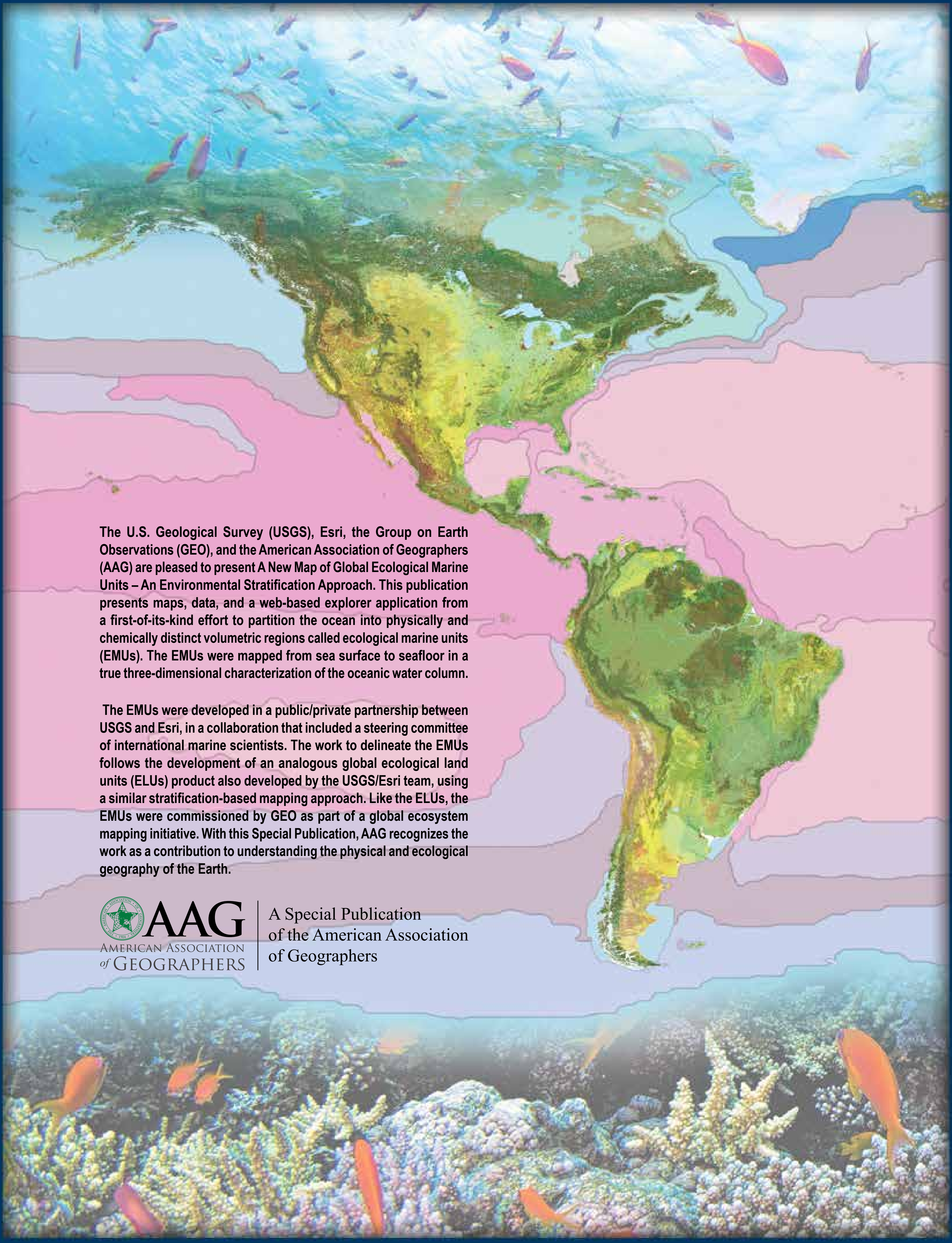
PHOTO BY JACQUES DE VOS (ALSO APPEARS IN COVER ILLUSTRATION)

Ecological Marine Units
GEOMORPHOLOGY CHEMISTRY SPECIES MARINE ZONES
Global EMU



The U.S. Geological Survey (USGS), Esri, the Group on Earth Observations (GEO), and the American Association of Geographers (AAG) are pleased to present A New Map of Global Ecological Marine Units – An Environmental Stratification Approach. This publication presents maps, data, and a web-based explorer application from a first-of-its-kind effort to partition the ocean into physically and chemically distinct volumetric regions called ecological marine units (EMUs). The EMUs were mapped from sea surface to seafloor in a true three-dimensional characterization of the oceanic water column.

The EMUs were developed in a public/private partnership between USGS and Esri, in a collaboration that included a steering committee of international marine scientists. The work to delineate the EMUs follows the development of an analogous global ecological land units (ELUs) product also developed by the USGS/Esri team, using a similar stratification-based mapping approach. Like the ELUs, the EMUs were commissioned by GEO as part of a global ecosystem mapping initiative. With this Special Publication, AAG recognizes the work as a contribution to understanding the physical and ecological geography of the Earth.

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