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Surface Area and the Seabed Area, Volume, Depth, Slope, and Topographic Variation for the World's Seas, Oceans, and Countries

MARK JOHN COSTELLO,*,† ALAN CHEUNG,‡ AND NATHALIE DE HAUWERE§

Leigh Marine Laboratory, University of Auckland, P.O. Box 349, Warkworth 0941, New Zealand, School of Environment, University of Auckland, Auckland, New Zealand, and VLIZ - Vlaams Instituut voor de Zee, InnovOcean site, Wandelaarkaai 7, B-8400 Oostende, Belgium

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Depth and topography directly and indirectly influence most ocean environmental conditions, including light penetration and photosynthesis, sedimentation, current movements and stratification, and thus temperature and oxygen gradients. These parameters are thus likely to influence species distribution patterns and productivity in the oceans. They may be considered the foundation for any standardized classification of ocean ecosystems and important correlates of metrics of biodiversity (e.g., species richness and composition, fisheries). While statistics on ocean depth and topography are often quoted, how they were derived is rarely cited, and unless calculated using the same spatial resolution the resulting statistics will not be strictly comparable. We provide such statistics using the best available resolution (1-min) global bathymetry, and open source digital maps of the world's seas and oceans and countries' Exclusive Economic Zones, using a standardized methodology. We created a terrain map and calculated sea surface and seabed area, volume, and mean, standard deviation, maximum, and minimum, of both depth and slope. All the source data and our database are freely available online. We found that although the ocean is flat, and up to 71% of the area has $a < 1$ degree slope. It had over 1 million approximately circular features that may be seamounts or sea-hills as well as prominent mountain ranges or ridges. However, currently available global data significantly underestimate seabed slopes. The 1-min data set used here predicts there are 68,669 seamounts compared to the 30,314 previously predicted using the same method but lower spatial resolution data. The ocean volume exceeds 1.3 billion km^3 (or 1.3 sextillion liters), and sea surface and seabed areas over 354 million km^2. We propose the coefficient of variation of slope as an index of topographic heterogeneity. Future studies may improve on this database, for example by using a more detailed bathymetry, and in situ measured data. The database could be used to classify ocean features, such as abyssal plains, ridges, and slopes, and thus provide the basis for a standards based classification of ocean topography.

* Corresponding author e-mail: m.costello@auckland.ac.nz.
† Leigh Marine Laboratory, University of Auckland.
‡ School of Environment, University of Auckland.
§ VLIZ - Vlaams Instituut voor de Zee.

Introduction

Maps provide the spatial context for exploration and indications of where resources occur. However, the seabed of the Earth is less well mapped than some planets and moons because ships have only measured the depth in less than 10% of the area (*1*), largely along transects between main centers of human population, with significant gaps in the midoceans and southern hemisphere (*2*). However, new technologies, including satellites and computer programs, have provided new opportunities to model the seabed bathymetry.

Although textbooks and Web sites commonly refer to how large areas of the ocean are, there are no readily accessible statistics of the areas of all the seas, oceans, or countries' Exclusive Economic Zones (EEZ) that were derived by documented and standardized methods (e.g. ref *3*). Furthermore, for some applications the sea surface area may not be the most appropriate metric, and perhaps the seabed area, volume, or slope may be of interest; and similarly these statistics have not been reported at a global scale. These topographic statistics would enable a standardized approach to classifying seascapes (underwater landscapes) (*4*). Such classifications are increasingly in demand for standards based approaches to data management (e.g. ref *5*) and have provided a structured approach to ecosystem-based management of ocean resources (*4*). The Global Earth Observation System of Systems will need objective classification of the Earth's land and ocean surface to provide spatial context to environmental data.

On land, the most fundamental environmental variable for predicting species distributions is terrain (*6*). In the ocean, depth and topography constrain environmental conditions, such as light penetration, sedimentation, and current direction and velocity and thereby temperature, stratification, and oxygen concentration. Thus patterns of biodiversity, such as species composition, richness, and productivity, are likely to be correlated to this topography (*7, 8*). At regional and local scales, depth and substrata are the most important parameters in determining the benthic habitats and their associated communities (i.e., biotopes) (*9*−*13*). The millions of species distribution records now available online through the Ocean Biogeographic Information System (www.iobis.org) (*14*) and the Global Biodiversity Information Facility (www.gbif.org) provide new opportunities for correlating environmental and biodiversity data to predict species ranges (e.g. ref *15*), explain patterns of biodiversity, and produce insights valuable for species conservation and resource management (*16*).

Previous studies have used different approaches to identify terrain features; notably seamounts which while officially defined as conical undersea mountains rising more than 1000 m from the seafloor (*17*) are considered to encompass sea hills in terms of ecological function (*18*). Kitchingman and Lai (*19*) predicted seamount locations by comparing adjacent cells in a bathymetric data set. Burl et al. (*20*) took a very different approach to automate the recognition of volcanoes on Venus by utilizing human selected training samples. Stepinski et al. (*21*) used methods similar to mainstream remote sensing applications where cells of satellite images were classified before identifying what each class was. In this paper we improved on Kitchingman and Lai's result by using an improved primary data set while

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using similar analytical procedures. We also utilized a different method to indicate potential circular elevated features (probable volcanoes) that may be seamounts or seahills (>100 m high).

The available world bathymetries vary in their resolution and suitability for regional and global studies (*22, 23*). We used the best available data for analysis of the world's oceans at the time of our analysis and then updated this with an improved data set at the same spatial resolution. This was based on satellite measured gravitational anomalies of the ocean surface that reflect the underlying terrain and have a spatial accuracy of 20 to 160 km. This terrain was trained using empirical depth measurements from ship soundings (sonar) to provide an accuracy of around 2 km (*24*). The ship soundings had a finer spatial resolution than the satellite derived bathymetry, but their occurrence was very limited spatially and particularly poor in the midoceans and southern hemisphere (*24*). Thus, while the derived global bathymetry may have a resolution of 2-min (2 km at the equator), it will not have captured many depth variations smaller than 20 km and will thus have underestimated the true heterogeneity of the seafloor terrain. While the spatial accuracy of our approach was thus limited by the geographic resolution of the source data, it is useful at regional and global scales. Because the process uses a standard data set and process, and all the source data, methods, and results are freely available online, this method may be repeated with improved data and computational resources. For all seas, oceans, and EEZ, we have calculated (a) surface and seabed area, (b) maximum, mean, median, and standard deviation of depth, (c) maximum, mean, and standard deviation of slope, and (d) volume. Comparisons show which countries and seas have the greatest areas, depth, slope, and topographic variation and how the metrics of topography relate to each other.

Methods

Topography Data. The global 1-min topography, gravitational anomaly, and curvature data set called "Global topography V12.1" provided the primary data for the initial phase of this study (*25*−*27*). Because the data set excluded the Arctic Ocean and most of the Lincoln Sea, we used the more recently available GEBCO (*31*) bathymetry of the same spatial resolution to provide a complete global coverage. The major difference between the databases was improved resolution on slope statistics. We first analyzed the data set following a method used by Kitchingman and Lai (*19*). The bathymetry was cleaned by removing all above water data and inverting depth to express it as absolute numbers. Then a 5 by 5 cell (about 5-by-5 nautical miles on the equator) analysis was used to find areas where the standard deviation of depth between neighboring cells was more than 300 m. To identify candidate seamounts, "sinks" were located using the 'flow' and 'sink' hydrological functions in ArcGIS; the GIS considered these sinks to be hollows that water would flow into from higher ground but they were actually conical seamounts or seahills. The raster-based sinks data set was converted into a polygon layer, and then the centroids' of sinks were found by performing field calculations in ArcGIS.

Our second approach to identify seamounts created 'extraction circles' with a 40 cell diameter (about 80 * 80 km at the equator) centered on an elevated feature (a potential seamount). This size was chosen so that nearby anomalies could be largely excluded, while larger spatial features could still be contained in one circle. To build extraction circles from centroids, a function called "Extract by Circle" from ArcTools was used. The extraction circles were used to clip the original bathymetric data set. These clips were fed into the Hough shape recognition algorithm in MatLab to assess their "circularity". The postulation was that the more rounded it was, then the more likely it was to be a seamount. We captured the edges of spatial features in the clips by using the Gaussian edge detection algorithms in MatLab. Dangling and outlying artifacts that did not constitute a "shape" were then removed, leaving the main intact shapes in the image. Once the outlines became a proper shape, we could generate the boundaries and assess the roundness of the features by estimating the features' area and perimeter.

The second method used by Kitchingman and Lai (*19*) detected differences of >300 m depth between cells along any of eight radii from each cell and then predicted seamounts where a difference of >1000 m occurred between at least five of the radii compared to the center cell. We also explored this approach to detect cells with >500 m depth variation but had insufficient computer resources to complete it.

Seas, Oceans, and Countries' EEZ Maps. The global maps of countries' Exclusive Economic Zones (EEZ) and the world's seas and oceans produced by VLIZ (*28, 29*) were overlaid on the terrain map to the produce the statistics reported in this paper. All the EEZ shapefiles, together with more details of the methods, and a change history, are available through the Web site, http://www.vliz.be/vmdcdata/marbound/. Some of the EEZ boundaries between countries are disputed and may change in the future. The IHO Sea Areas geodatabase represents the standardized boundaries for the major oceans and seas of the world. There were 101 seas and oceans and 240 EEZ (see the Supporting Information). We report EEZ for countries separately for their disjunct areas as this may be of more practical interest than aggregated data. Countries' complete EEZ may be summed from these areas and would result in different rankings of their statistics.

Calculation of Surface Area, Mean Elevation, and Slope. The above IHO and EEZ maps in shapefile format were extracted individually and automatically from the data using ArcGIS and python scripts directly from the bathymetry data set. The result was a separated elevation (raster), slope (raster), and shapefile for each individual area (i.e., country, sea, or ocean). Mean elevation was then calculated from the sum elevation which was also derived during the automatic extraction process divided by the total grid in each individual raster. However, the existing Mercator projection was found to be unsuitable for calculating areas due to increasing distortion away from the equator. Instead, the data set was projected onto a Mollweide Equal Area Projection (*30*). To calculate the areas of EEZ, seas and oceans, each of the areas were extracted as individual shapefiles. Then the areas were clipped and overlaid on the global 1-min bathymetry, and the areas, slopes, and volumes were calculated. The 'zonal statistics' function was used to calculate minimum, maximum, mean, median, and standard deviation of depth.

Sea surface area was calculated from the function "Area and Volume Statistics" by the ArcGIS 3D Analyst tool. Because the calculation for seabed surface area and volume was underwater, the plane setting for this calculation was set at zero meter in depth, with areas and volume below plane calculated.

Statistics for slopes were also generated during the process based on the extracted area elevation. Although slope was in raster format, the numerical value within each grid was not a whole number integer that could be used for mean slope calculation. At the initial automatic information extraction process, the slope for each area was generated separately based on the individual area elevation using the slope function from the ArcGIS 3D Analyst Tool. Default settings were unchanged for this process. As mentioned above, values in each raster grid are in double format (i.e., 1.08) which cannot be used to do mean slope calculation and total grid calculation like mean elevation calculation in ArcGIS. If the slope value was converted into an integer format, all the values would be rounded up, losing detail. In

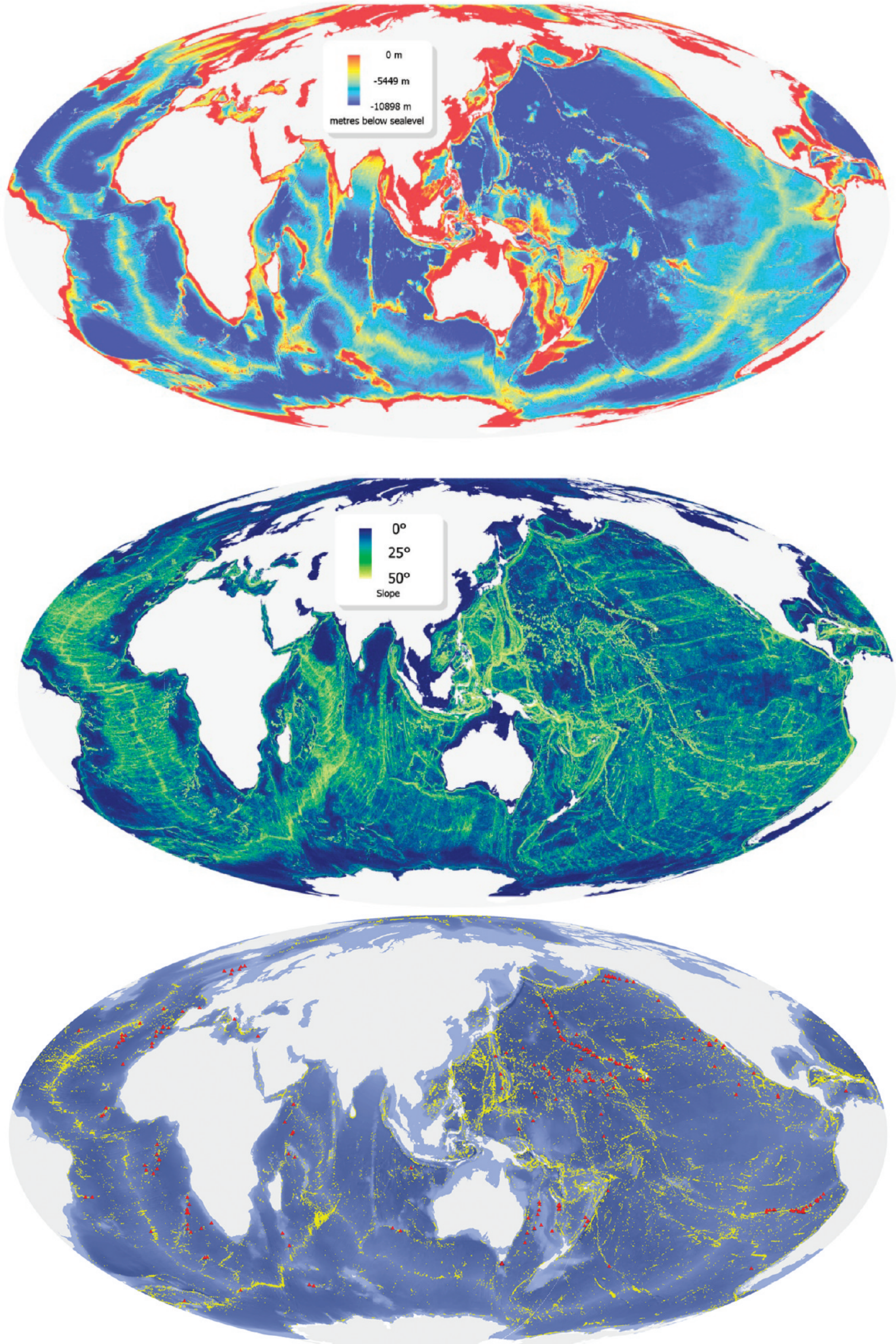

FIGURE 1. World bathymetry (top), slope, and seamounts (bottom). Known seamount locations are indicated by red triangles. Note the scale of the slopes map exaggerates the areas of high slope because on a linear scale these areas would be almost invisible.

this case, to calculate more realistic slope calculation, each slope raster was converted into a text file in ASCII format which included all the unwanted values in integer format and slope values in double format. Mean slope was then calculated after the removal of unwanted values by Matlab.

Our final database used to calculate the results in this paper may be downloaded from http://www.vliz.be/vmdcdata/vlimar/.

Results

Contrasting the maps of the ocean bathymetry and slope showed that while the deep sea dominated the total ocean area, it contained striking ridges not so apparent from the bathymetry alone (Figure 1). Seamount locations were on areas of high slope and matched well with known seamount locations, thereby validating the terrain mapping methods

TABLE 1. Seas' and Oceans' Surface and Seabed Areas (km^2), Volume (km^3), and Mean and Maximum Slope (degrees) and Depth (m)[a]

	surface, km^2	seabed, km^2	volume, km^3	maximum slope, degrees	mean depth, m	deepest depth, m
South Pacific Ocean	76,568,076	76,744,204	305,912,057	73.46	−3993	−10811
North Pacific Ocean	64,550,459	64,703,952	299,647,701	70.63	−4641	−10977
Indian Ocean	57,824,473	57,917,753	233,439,157	63.73	−4036	−7883
South Atlantic Ocean	40,251,619	40,309,382	159,487,582	63.15	−3961	−8185
North Atlantic Ocean	34,265,825	34,329,334	132,798,134	67.15	−3872	−8648
Southern Ocean	20,258,878	20,297,161	70,710,828	62.00	−3486	−7318
Philippine Sea	5,688,163	5,718,199	24,785,853	68.57	−4347	−10061
Arctic Ocean	5,088,780	5,107,800	11,745,840	57.50	−2307	−5449
Arabian Sea	4,237,083	4,242,174	13,908,640	49.83	−3279	−5864
Coral Sea	4,026,898	4,036,241	10,059,264	76.12	−2492	−9055
Tasman Sea	3,346,649	3,353,534	11,297,474	52.13	−3369	−6601
South China Sea	3,309,289	3,315,500	4,247,615	58.65	−1277	−5315
Caribbean Sea	2,861,114	2,871,910	7,262,931	59.96	−2529	−8201
Bering Sea	2,390,206	2,398,082	4,008,920	59.26	−1670	−6939
Bay of Bengal	2,192,511	2,193,763	5,723,805	39.94	−2603	−4482
Sea of Okhotsk	1,637,321	1,638,525	1,304,764	64.71	−793	−5475
Gulf of Mexico	1,539,257	1,541,002	2,361,133	48.33	−1528	−4011
Norwegian Sea	1,442,704	1,444,101	2,542,565	36.57	−1754	−3941
Barentsz Sea	1,393,193	1,393,317	278,627	40.10	−199	−1811
Mozambique Channel	1,373,667	1,375,051	3,129,248	51.79	−2271	−4534
Great Australian Bight	1,343,383	1,344,657	4,300,116	33.05	−3191	−6116
Mediterranean Sea - Eastern	1,162,621	1,164,747	1,952,560	51.30	−1673	−5272
Greenland Sea	1,159,318	1,160,728	1,655,459	39.59	−1416	−5601
Japan Sea	1,054,075	1,056,295	1,641,026	53.10	−1543	−4283
total	360,663,099	361,383,969	1,335,819,297	--	--	--
average	3,570,922	3,578,059	13,225,934	32	−1185	−3397
maximum value	76,568,076	76,744,204	305,912,057	76	−8	−37
minimum value	1,445	1,455	58	1	−4641	−10,977

[a] Standard deviations of slope and depth and data for seas and oceans less than 1 million km^2 are in the Supporting Information. Note totals, averages, maxima, and minima are calculated over all oceans and seas, not only those listed here.

TABLE 2. Sea Surface and Seabed Areas, Volume, Mean, and Standard Deviations of Depth and Slope, and Maximum Slope, for Depth Zones in the World Ocean[a]

depth zone, m	sea surface, km^2	% area	seabed, km^2	volume, km^3	% volume	mean slope	max slope	SD slope	mean depth	SD depth
<100	18,185,169	5.56	18,185,531	796,975	0.07	0.13	42.13	0.38	48	27
101−500	13,440,275	4.11	13,444,335	3,238,442	0.27	0.29	36.81	0.70	248	114
1000	5,585,253	1.71	5,590,540	4,076,123	0.33	0.78	39.29	1.57	694	142
2000	13,637,292	4.17	13,666,704	20,800,869	1.71	1.44	44.65	2.26	1522	292
3000	26,462,622	8.09	26,515,819	68,018,359	5.58	1.46	43.98	2.15	2569	285
4000	72,507,422	22.16	72,601,702	257,824,587	21.15	1.28	44.79	1.71	3543	280
5000	106,815,071	32.65	106,906,998	480,963,364	39.46	1.09	42.24	1.39	4492	285
6000	67,434,793	20.61	67,480,194	363,477,784	29.82	1.06	46.38	1.24	5357	252
7000	2,768,344	0.85	2,772,246	17,211,445	1.41	1.75	45.58	2.00	6208	223
8000	238,059	0.07	239,235	1,765,746	0.14	3.53	33.35	2.95	7378	272
9000	75,004	0.02	75,522	632,854	0.05	5.06	29.88	3.63	8412	279
10000	21,058	0.01	21,211	197,853	0.02	5.40	28.21	3.72	9325	254
10898	1020	0.00	1027	10,555	0.00	5.52	22.57	3.42	10,274	232

[a] The percent that each depth zone comprises of the sea surface area and volume is also shown.

(Figure 1). This data set makes the ocean appear very flat, such that 71.2% of the seabed had a slope of <1°, 82.4% < 2°, 88.3% < 3°, 91.8% < 4°, 95.5% < 6°, and only 4.5% of the seabed has as slope >6°. However, our highest slope was only 76°, whereas more vertical cliffs closer to 90° may be expected. The lower slopes for EEZ reflect their coastal distribution.

The total sea surface area was 360.663 × 10^6 (million) km^2 and volume 1.335819 × 10^9 (billion) km^3 (1.3 sextillion liters = 1.3 zettaliters) (Table 1). The sea surface and seabed areas were similar for all oceans and seas because most of the ocean had a slope of <1°. The volume of seas and oceans increased with area but became more variable when smaller seas were examined (Figure S2).

Excluding the seas, each of the oceans except the Arctic were over 20 million km^2, while the largest sea, the Philippine Sea, was 5.6 million km^2 in sea surface and seabed areas (Table 1). This sea, and the North and South Pacific Oceans, had depths over 10 km deep. The nearby Coral and Solomon Seas had depths over 8 km, as did the Caribbean Sea and the North and South Atlantic Oceans. The Coral Sea had the greatest maximum slopes at 76° (Table 1), and the Philippine Sea, Gulf of Alaska, Sea of Okhotsk, and larger oceans had maximum slopes of over 60°.

According to the source database used here, the Earth is 511.2 million km^2 in area, and the seas and oceans analyzed here comprise 70.55% of the planet area. The deep-sea comprises most of the ocean (Table 2). Only 11% of the ocean area and <1% of the volume is shallower than 1000 m. Most of the ocean, 75% of the area and 90% of the volume, is between 3000 and 6000 m depth, and <1% is deeper than 6000 m (Table 2).

TABLE 3. Countries' Exclusive Economic Zones Surface and Seabed Areas (km^2), Volume (km^3), and Mean and Maximum Slope (degrees) and Depth (m)[a]

country	surface, km^2	seabed, km^2	volume, km^3	mean slope, degrees	maximum slope, degrees	mean depth, m	deepest depth, m
Antarctica	8,452,703	8,467,704	20,735,687	1.91	62.00	−2525	−6101
Russia	7,495,725	7,503,863	7,929,616	0.98	57.23	−597	−9558
Australia	6,925,888	6,935,663	15,407,168	1.45	76.12	−2027	−6591
Indonesia	5,923,493	5,936,952	12,299,571	2.11	53.08	−2242	−9552
Canada	5,558,141	5,561,859	5,003,368	0.91	46.83	−682	−5282
French Polynesia	4,784,119	4,798,618	19,240,452	2.45	55.50	−4119	−5837
Japan	4,193,548	4,215,512	15,710,367	3.07	68.57	−4098	−10,340
New Zealand	4,058,942	4,071,855	9,957,470	2.39	67.55	−2881	−10,188
Alaska	3,610,902	3,624,426	8,583,549	2.11	66.86	−2348	−7824
Mexico	3,268,512	3,278,359	9,036,411	2.22	52.54	−2797	−6692
Brazil	3,172,086	3,177,070	8,264,684	1.47	55.08	−2727	−5571
Micronesia	3,006,358	3,015,822	11,854,626	2.34	66.45	−3664	−10,898
Chile	2,838,356	2,846,251	10,055,831	2.28	73.46	−3307	−8202
Hawaii	2,470,985	2,481,238	11,285,057	2.25	61.04	−4676	−6944
United States	2,418,687	2,422,738	4,421,383	1.26	58.35	−1742	−5307
Papua New Guinea	2,388,742	2,395,722	6,485,625	2.37	54.33	−3137	−9030
Greenland	2,202,970	2,205,700	3,342,012	1.30	50.26	−1404	−4371
Marshall Islands	1,999,586	2,006,890	9,299,560	2.37	50.58	−4837	−6557
Cook Islands	1,968,481	1,973,699	9,170,931	2.25	53.60	−4743	−6642
Philippines	1,809,462	1,816,949	5,910,413	2.98	57.85	−3603	−10,070
Norway	1,741,155	1,742,241	1,813,857	0.83	40.10	−839	−5646
Line Group	1,651,155	1,655,208	7,718,217	2.10	56.24	−4727	−6418
India	1,626,382	1,627,645	3,140,788	1.13	42.72	−2074	−4799
Solomon Islands	1,598,119	1,604,929	4,980,507	3.21	50.29	−3166	−9036
Sth Georgia and Sth Sandwich Is.	1,442,073	1,446,530	4,976,111	2.82	48.33	−3590	−8159
New Caledonia	1,419,960	1,423,961	3,837,096	2.36	64.27	−3196	−7410
Seychelles	1,337,399	1,340,438	4,952,576	2.09	60.34	−3729	−5863
Mauritius	1,276,765	1,280,490	4,372,737	2.56	62.82	−3553	−5627
Fiji	1,256,759	1,262,464	3,410,204	3.23	58.79	−2567	−5859
Madagascar	1,197,042	1,198,437	3,701,945	1.68	34.89	−3228	−5593
Argentina	1,073,996	1,074,922	813,485	0.79	43.73	−1211	−5612
South Africa	1,063,761	1,064,741	2,713,619	1.29	41.05	−2432	−5719
Kiribati	1,054,071	1,056,494	4,774,962	1.67	54.65	−4537	−6461
maximum value	**8,452,703**	**8,467,704**	**20,735,687**	**5.99**	**76.12**	**123**	**−25**
minimum value	**141**	**141**	**3**	**0.05**	**0.49**	**−5489**	**−10,898**

[a] Standard deviations of slope and depth and data for EEZ less than 1 million km^2 are in the Supporting Information. Note maxima and minima are calculated over all EEZ, not only those listed here.

Our first method to detect seamounts returned 68,669 possible sites for the world. When the same method was run on the 2-min bathymetry data set it identified 28,743 seamounts, reasonably similar to the 30,314 found by Kitchingman and Lai (*19*) using the same method and 2-min bathymetric data set. Of our 56,741 predicted seamount locations, 84.6% (208 of 246) were within 30 min distance of known seamount locations (http://seamounts.sdsc.edu), an improvement over the 60% accuracy of Kitchingman and Lai (*19*) that we attribute to our use of 1-min rather than 2-min spatial resolution data. Our second method predicted locations of 1,021,949 circular elevated features which included seamounts but will be mostly knolls and sea-hills.

The standard deviations (SD) of slope and depth indicate topographic variability. However, mean depth was dependent on the area encompassed by that sea, ocean, or country, whereas the slope was calculated for each 2 km by 2 km square bathymetry cell and its neighbors. Thus slope was a more appropriate metric for topographic variation or heterogeneity. The highest seabed SD of slope were found for the Gulf of Aqaba and Banda and Solomon Seas (see the Supporting Information). The SD for depth were greatest for the Great Australian Bight, Bay of Biscay, and Celebes and Solomon Seas (see the Supporting Information). These figures support the patterns evident in the maps (Figure 1). However, the SD and mean of the slope were highly correlated ($r^2 = 0.92$ for EEZ; $= 0.91$ for seas and oceans) so the SD was dependent on the mean. To avoid this dependency, the coefficient of variation (SD/mean) would be a better metric of topographic variation.

Although a continent rather than a country, Antarctica had the largest EEZ (200 nm zone) in terms of both volume and sea surface and seabed areas (Table 3). Of the individual countries, French Polynesia had the largest volume, and Russia the largest sea surface and seabed area. However, note that we report disjunct EEZ for a country separately, such that EEZ for countries such as USA, France, UK, Canada, Denmark, Chile, Portugal, Japan, Norway, and New Zealand are greater if their parts are aggregated (Table S2). The Pacific island nations of Micronesia, Northern Mariana Islands and Guam, Tonga, Japan, New Zealand, and Philippines had maximum depths over 10 km. The greatest seabed slopes were off Australia, Chile, Japan, New Zealand, Northern Mariana Islands and Guam, American Samoa, Alaska, and Micronesia. The most topographically variable areas were thus around the islands in the midwestern Pacific and Indo-Pacific (Figure 1).

Discussion

While most of the world appeared flat and below 1000 m depth in the ocean, significant areas of steep slope also traversed the oceans, representing huge underwater mountain ranges and volcano cones. Moreover, the present data set significantly underestimated the true seabed slope, particularly in the abyssal hills at the edges of midocean ridges (*2*). This is because the satellite altimetry has a spatial accuracy of about 20 to 160 km, and the ship soundings that provide for greater accuracy are variably distributed globally. The true maximum slopes should include values up to 90°, whereas our maximum was 76°. This would also be significant, but less so, if the new 30-s bathymetric grid (*31*) was used to estimate sea bed slope. However, this larger data set was not available when we first conducted our analyses and would require significantly greater computing resources than used in our study.

Because of the low slope, we found little difference between sea surface and seabed areas for countries, seas, and oceans. It may be expected that the sea surface area would be larger than the sea bed area due to the curvature of the Earth. We have not accounted for such an effect in using the UTM projection, so the differences we did find between these areas should be considered maximal. However, because the maximum ocean depth is <1% of the radius of the Earth, the effect of the Earth's curvature on the difference between the ocean surface and seabed areas was less than the increased seabed area due to topographic variation.

While area and volume were positively correlated at a global scale, this correlation was weaker for smaller areas. A database with different spatial resolution than used here would show different slopes as well as different areas and volumes. The use of spatial statistics as published here must consider their fractal nature, scale, and accuracy in relation to any other data they may be compared with (*6*). Regional bathymetric data with greater spatial resolution and more direct measurements should be more accurate that the figures reported here. For example, national data for the area of Japan reported that the maximum depth of the Japan Sea and Japan EEZ (3796 m and 9780 m) are 7% and 5% less than reported here (4578 m and 10,340 m), respectively (Fuijkura, personal communication).

Seamounts are of particular scientific interest because they may be centers of fishery productivity, fish abundance, endemism, and/or habitat diversity (*18, 32*). We found a similar number (>1000 m high) to Kitchingman and Lai (*19*) using the same resolution data set but over 25,000 more using our 1-min resolution data set. Wessel (*33*) predicted the locations of 14,600 seamounts globally using a coarser resolution data set but later revised this to 12,000 (*34*). Considering the limitations of such predictions, he considered that there may be over 100,000 seamounts worldwide and subsequently that there may be 125,000 (range 45,000−350,000) but did not map their locations. Batiza (*35*) estimated there were probably 22,000 to 55,000 seamounts in the Pacific Ocean, of which 1500−2000 were active volcanoes, while Hillier and Watts (*36*) predicted the distribution of 5681 seamounts globally from ship soundings and that there may be 40,076 in total. Thus we consider our prediction of 68,669 seamounts >1000 m high to be reasonable.

Our prediction of over 1 million sea-mountain and sea-hill (>100 m) locations using our second method compares with predictions of hills ranging from 142,000 (*19*), to 201,055 from ship soundings extrapolated to a possible 3 million (*36*), to 25 million (range 8 to 80 million) (*34*). For the Pacific Ocean alone, ranges of estimates for the number of seamounts and sea-hills are 1900−130,000 and 4000−970,000, respectively (*37*). Because we used a standard deviation of 300 m depth our 1 million would have excluded smaller features. Nevertheless, all these features are considered ecologically important and considered as seamounts in a recent review (*18*). Because the present paper maps the sea hill locations, the accuracy of our predictions can be verified by future field data.

It should be noted that the current methods used to predict the occurrence of seamounts will miss those that are not circular or elliptical, such as those along ridges or on slopes. All methods overlook many abyssal hills due to the underlying data sets resolution (*2, 24*). However, some of the sea-hills will be buried to varying extents by sediments, especially those along continental margins. Thus, for ecological purposes they may not be significant as the seabed sediment surface may not be as deep or variable as the gravitational anomaly data may indicate.

The circular features found by our second method were geographically associated with known seamounts, the regions with higher slopes, and the >500 m high seamounts predicted using Kitchingman and Lai's (*19*) method (Figure 1). Seamounts and hills are likely to occur along volcanic ridges where tectonic plates converge, so this combination of approaches illustrates the distribution of undersea mountain ranges. To determine if the 'circular features' would be strictly seamounts would involve matching these features to the depths of their peak and the neighboring seabed. Thus, at an ocean scale our seamounts closely match the distribution of known seamounts and areas with high slope and provide the best current prediction of their locations and abundance. At regional scales the predictions will be less accurate. A comparison of estimates with field data in the southwest Pacific found that the number of potential seamounts may be (a) overestimated due to the occurrence of duplicates, shallow atolls, and islands, arising from the spatial resolution of the altimetry derived bathymetry, while (b) some seamounts may have been overlooked (*38*). For example, the more conservative second method of predicting seamount locations by Kitchingman and Lai (*19*) estimated 430 around New Zealand, but local bathymetry recorded 260 (Clark, personal communication).

Since the present analyses were conducted, further improvements to the bathymetric data set have been made (*1, 2, 31*). Accurately mapping the world's oceans could take over 120 years for the deep seas, and 700 years for the shallow seas (*39*). Thus, future maps will be produced by a combination of improved digital modeling and empirical field observations. This would be facilitated by a mechanism for the formal publication of bathymetric data in quality assured, standardized formats (*4*). In addition the publication of data on seabed substrata (*40*) is also essential for predicting benthic species habitats. This topographic and substratum data can then be combined as a basis for mapping benthic habitats (*9*−*12, 41, 42*).

The midwestern Pacific and Indo-West Pacific islands were the most topographically diverse regions identified in this study. This may be significant in that they are also considered to be the most biologically diverse regions in the world (*43*). A diversity of physical habitats usually results in a diversity of species adapted to the different environments therein (e.g. refs *13* and *44*). For example, disturbance by waves and ocean swell, and current velocities, are strongly influenced by depth and topography. In turn, these oceanographic conditions influence temperature and salinity. The data provided in this paper provide biologists an opportunity to compare biodiversity patterns with topographic diversity at global and regional scales (*45*). Ardron (*7*) proposed indices of slope as indicators of benthic species biodiversity. Because the SD and mean of slope were highly correlated, we suggest the coefficient of variation (SD/mean) may be a more appropriate index of topographic heterogeneity. Because of the limitations of the data set used here, our topography will underestimate actual slopes and topographic variation. However, at what spatial scale topography influences biodiversity is little studied and is likely to vary between different species in relation to their habitat requirements (*4*). Thus whether the topographic index proposed here will correlate to biodiversity patterns requires further research.

The Group on Earth Observations is a partnership of over 80 countries that aims to make all climatic, environmental, and biodiversity data publicly available online. It is developing a system for the classification of land ecosystems that includes five main data layers: namely elevation, land-forms, climate, geology, and land cover. A parallel approach is possible for marine ecosystems using the database and methods in the present paper. Similarly, bathymetry can be used to provide elevation and seabed-forms (topographic features or seascapes) and the water masses to define the ocean climate. However, it may be necessary to divide the ocean into pelagic surface waters and benthic seabed habitats (*4*). The availability of standardized metrics of topography provides a structured and verifiable approach to developing ecosystem and habitat classifications that are environmentally coherent and relevant to the management and conservation of biodiversity. For example, areas of topographic complexity are likely to have high habitat and beta-diversity and can be considered candidate 'Vulnerable Marine Ecosystems' (*46*). The database and results presented here thus provide a platform for future research and ocean data management.

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Supporting Information Available

(a) Maps indicating the distribution of the seas, oceans, and countries and (b) tables of the topographic statistics for these areas. The statistics are sea surface area, seabed area, volume, mean slope, maximum slope, standard deviation of slope, mean depth, median depth, maximum depth, and standard deviation of depth. This material is available free of charge via the Internet at http://pubs.acs.org.

Literature Cited

(1) Charette, M. A.; Smith, W. H. F. The volume of Earth's ocean. *Oceanography* **2010**, *23*, 112–114.
(2) Becker, J. J.; Sandwell, D. T.; Smith, W. H. F.; Braud, J.; Binder, B.; Depner, J.; Fabre, D.; Factor, J.; Ingalls, S.; Kim, S.-H.; Ladner, R.; Marks, K.; Nelson, S.; Pharaoh, A.; Trimmer, R.; Von Rosenberg, J.; Wallace, G.; Weatherall, P. Global Bathymetry and Elevation Data at 30 Arc Seconds Resolution: SRTM30_PLUS'. *Mar. Geod.* **2009**, *32* (4), 355–371.
(3) Anonymous. Exclusive Economic Zones; 2009. http://en.wikipedia.org/wiki/Exclusive_Economic_Zone (accessed September 27, 2009).
(4) Costello, M. J. Distinguishing marine habitat classification concepts for ecological data management. *Mar. Ecol.: Prog. Ser.* **2009**, *397*, 253–268.
(5) UNESCO. *Global Open Oceans and Deep Seabed (GOODS) - biogeographic classification*; IOC Technical Series 84, UNESCO-IOC: Paris, 2009.
(6) Chapman, A. D.; Muňoz, M. E. S.; Koch, I. Environmental information: placing biodiversity phenomena in an ecological and environmental context. *Biodiversity Inf.* **2005**, *2*, 24–41.
(7) Ardron, J. A GIS recipe for determining benthic complexity: an indicator of species richness. In *Marine Geography: GIS for the oceans*; Brennan, J., Ed.; ESRI Press: Redlands, CA, 2002; pp 169−175.
(8) Burnes, R. V.; Parvey, C. A. Marine geography and the benthic habitat. In *Marine Geography: GIS for the oceans*; Brennan, J., Ed.; ESRI Press: Redlands, CA, 2002; pp 127−136.
(9) Neilson., B.; Costello, M. J. The relative lengths of seashore substrata around the coastline of Ireland as determined by digital methods in a Geographical Information System. *Estuarine, Coastal Shelf Sci.* **1999**, *49*, 501–508.
(10) Butler, A.; Harris, P.; Lyne, V.; Heap, A.; Passlow, V.; Smith, R. *An interim, draft bioregionalisation for the continental slope and deeper waters of the South-east marine region of Australia*; CSIRO and National Oceans Office: Hobart, 2001; 35pp.
(11) Costello, M. J.; Emblow, C. A classification of inshore marine biotopes. In *The intertidal ecosystem: the value of Ireland's shores*; Wilson, J. G., Ed.; Royal Irish Academy: Dublin, 2005; pp 25−35.
(12) Connor, D. W.; Gilliland, P. M.; Golding, N.; Robinson, P.; Todd, D.; Verling, E. *UKSeaMap: the mapping of seabed and water column featues of UK seas*; Joint Nature Conservation Committee Report; Peterborough, 2006.
(13) Wedding, L. M.; Friedlander, A. M. Determining the influence of seascape structure on coral reef fishes in Hawaii using a geospatial approach. *Mar. Geod.* **2008**, *31*, 246–266.
(14) Costello, M. J.; Stocks, K.; Zhang, Y.; Grassle, J. F.; Fautin, D. G. About the Ocean Biogeographic Information System. Retrieved from http://hdl.handle.net/2292/5236.
(15) Kaschner, K.; Ready, J. S.; Agbayani, E.; Rius, J.; Kesner-Reyes, K.; Eastwood, P. D.; South, A. B.; Kullander, S. O.; Rees, T.; Close, C. H.; Watson, R.; Pauly, D.; Froese, R. AquaMaps: Predicted range maps for aquatic species. World wide web electronic publication, Version 10/2008, 2008. www.aquamaps.org (accessed September 18, 2009).
(16) Costello, M. J.; Vanden Berghe, E. "Ocean Biodiversity Informatics" enabling a new era in marine biology research and management. *Mar. Ecol.: Prog. Ser.* **2006**, *316*, 203–214.
(17) International Hydrographic Organization. *Limits of oceans and seas*; International Hydrographic Organization Special Publication No. 23; 1953; 39pp. Available online at http://www.iho.shom.fr/publicat/free/files/S23_1953.pdf (accessed September 18, 2009).
(18) Clark, M. R.; Rowden, A. A.; Schlacher, T.; Williams, A.; Consalvey, M.; Stocks, K. I.; Rogers, A. D.; O'Hara, T. D.; White, M.; Shank, T. M.; Hall-Spencer, J. M. The ecology of seamounts: structure, function and human impacts. *Ann. Rev. Mar. Sci.* **2010**, *2*, 253–278.
(19) Kitchingman, A.; Lai, S. Inferences on potential seamount locations from mid-resolution bathymetric data. In *Seamounts: Biodiversity and Fisheries*; Morato, T., Pauly, D., Eds.; 2004; pp 7−12.
(20) Burl, M. C.; Fayyad.; U. M.; Perona, P.; Smyth, P.; Burl, M. P. Automating the hunt for volcanoes on Venus. 1994 IEEE Computer Society Conference on Computer Vision and Pattern Recognition, 1994. Institute of Electrical and Electronics Engineerers (IEEE), 1994.
(21) Stepinski, T. F.; Ghosh, S.; Vilalta, R. *Automatic Recognition of Landforms on Mars Using Terrain Segmentation and Classification*, Proc. Int'l Conf. Discovery Science, LNAI 4265, Springer: 2006; pp 255−266.
(22) Smith, W. H. F.; Sandwell, D. T. Global sea floor topography from satellite altimetry and ship depth soundings. *Science* **1997**, *277*, 1956–1962.
(23) Marks, K. M.; Smith, W. H. F. An evaluation of publicly available global bathymetry grids. *Mar. Geophys. Res.* **2006**, *27*, 19–34.
(24) Becker, J. J.; Sandwell, D. T. Global estimates of seafloor slope from single-beam ship soundings. *J. Geophys. Res.* **2008**, *113*, 1–14, C05028.
(25) Sandwell, D. T. Topography Dataset V 12.1; 2008a. http://topex.ucsd.edu/WWW_html/mar_topo.html (accessed 2009−09−18).
(26) Sandwell, D. T. Global 1-minute Gravity Anomaly Dataset V16; 2008b. ftp://topex.ucsd.edu/pub/global_grav_1min_V16/ (accessed 2009−09−18).
(27) Sandwell, D. T. Global 1-minute Curvature Dataset V16; 2008c, ftp://topex.ucsd.edu/pub/global_grav_1min_V16/ (accessed 2009−09−18).
(28) VLIZ. IHO Sea Areas; 2005. Available online at http://www.vliz.be/vmdcdata/vlimar/downloads.php. (accessed September 18, 2009).
(29) VLIZ. Maritime Boundaries Geodatabase, version 5; 2009. Available online at http://www.vliz.be/vmdcdata/marbound. (accessed September 18, 2009).

(30) Synder, J. P. *Map Projections -A Working Manual*; U. S. Geological Survey Professional Paper 1395; 1987; pp 57−64.
(31) General Bathymetric Chart of the Ocean (GEBCO). Gridded bathymetry data; 2010, http://www.gebco.net/data_and_products/gridded_bathymetry_data/ (accessed April 23, 2010).
(32) McClain, C. R. Seamounts: identify crisis or split personality. *J. Biogeog.* **2007**, *34*, 2001–2008.
(33) Wessel, P. Global distribution of seamounts inferred from gridded Geosat/ERS-1 altimetry. *J. Geophys. Res.* **2001**, *106* (B9), 19431–19441.
(34) Wessel, P.; Sandwell, D. T.; Kim, S.-S. The global seamount census. *Oceanography* **2010**, *23* (1), 24–33.
(35) Batiza, R. Abundances, distribution and sizes of volcanoes in the Pacific Ocean and implications for the origin of non-hotspot volcanoes. *Earth Planet. Sci. Lett.* **1982**, *60*, 195–206.
(36) Hillier, J. K.; Watts, A. B. Global distribution of seamounts from ship-track bathymetry data. *Geophys. Res. Lett.* **2007**, *34*, L13304.
(37) Kitchingman, A.; Lai, S.; Morato, T.; Pauly, D. How many seamounts are there and where are they located? In *Seamounts: ecology, fisheries, and conservation*; Blackwell Fisheries and Aquatic Resources Series 12; Pitcher, T. J., Morato, T., Hart, P. J. B., Clark, M. R., Haggan, N., Santos, R. S., Eds.; Blackwell Publishing: Oxford, 2007; pp 26−40, 527pp.
(38) Allain, V.; Kerandel, J.-A.; Andrefout, S.; Magron, F.; Clark, M.; Kirby, D. S.; Muller-Karger, F. E. Enhanced seamount location database for the western and central Pacific Ocean: screening and cross-checking of 20 existing datasets. *Deep-Sea Res.* **2008**, *55*, 1035–1047.
(39) Becker, J. J. Improved global bathymetry, global sea floor roughness, and deep ocean mixing,Ph.D. Thesis, University of Southern California, San Diego, 2008; 76pp.
(40) Carron, M. J.; Vogt, P. R.; Jung, W.-Y. A proposed international long-term project to systematically map the world's ocean floors from beach to trench: GOMaP (Global Ocean Mapping Program). *Int. Hydrogr. Rev.* **2001**, *2* (3), 49–50.
(41) Jenkins, C. dbSEABED: An information processing system for marine substrates; 2008, http://instaar.colorado.edu/~jenkinsc/dbseabed/ (accessed August 20, 2009).
(42) Coggan, R.; Curtis, M.; Vize, S.; James, C.; Bulat, J.; Passchier, S.; Mesday, C.; Mitchell, A.; Smit, C. J.; Foster-Smith, B.; White, J.; Piel, S.; Populus, J.; Van Lancker, V.; Deleu, S.; Davies, J. *Review of standards and protocols for seabed habitat mapping*; 2005. http://www.searchmesh.net (accessed February 23, 2009).
(43) Briggs, J. C. *Marine zoogeography*; Elsevier: Amsterdam, 1995.
(44) Guinottte, J. M.; Bartley, J. D.; Iqbal, A.; Fautin, D. G.; Buddemeier, R. W. Modeling and understanding habitat distribution from organism occurrences and correlated environmental data. *Mar. Ecol.: Prog. Ser.* **2006**, 316.
(45) Costello, M. J.; Coll, M.; Danovaro, R.; Halpin, P.; Ojaveer, H.; Miloslavich, P. A census of marine biodiversity knowledge, resources and future challenges. *PLoS One* **2010**, *5* (8), e12110. Doi:10.1371/journal.pone.0012110.
(46) Food and Agriculture Organisation. *Deep-sea fisheries in the high seas*; Food and Agriculture Organisation: Rome, 2009.

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