PART 1
HOW EARTH WORKS

This section includes examples of GIS helping scientists to gain better insight and understanding of Earth processes and functions in natural science fields such as oceanography, geology, climatology, and conservation biology. Using reliable, verifiable spatial analysis and visualization, GIS helps physical scientists answer a myriad of questions about spatial patterns in the natural environment (geosphere, biosphere, hydrosphere, atmosphere) and what process is responsible for those patterns. GIS is also a modern platform for the open sharing of data and for compelling science communication at multiple scales (e.g., individual researcher, lab workgroup, multi-department, multi-university, university-to-agency collaboration, and citizen engagement).

Lake Mead in the Nevada desert. Water levels in the critical resevoir in June 2021.

EARTH'S COASTLINES

With approximately half the world's population living less than 65 miles from the ocean, coastal ecosystems are arguably Earth's most critical real estate. Yet coastlines are among the more difficult features to accurately map; until now, no comprehensive high-resolution geospatial dataset existed. This chapter presents a new map and ecological inventory of global coastlines developed by Esri, the U.S. Geological Survey, and other partners.

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Horseshoe Bay Beach, Bermuda.

A COASTLINE JOURNEY

Imagine sailing every coastline of planet Earth. We are all familiar with the stories of intrepid seagoing explorers who set out from safe havens to cross the vast expanses of unknown oceans in hopes of discovering new lands. Their reasons were many—expanding empires, escaping persecution, seeking treasure, and satisfying basic human and scientific curiosity. They sailed with simple navigation tools and relied on maps adorned with drawings of fantastic sea creatures and the ominous warning "Here Be Lions" (contrary to popular opinion, only one surviving map, the 1510 *Hunt-Lenox Globe*, contains the phrase "Here Be Dragons"). These famous explorations were largely transoceanic—crossing the oceans to reach new lands.

Cropped portion of the 1510 Hunt–Lenox Globe, showing the infamous "Here Be Dragons" text.

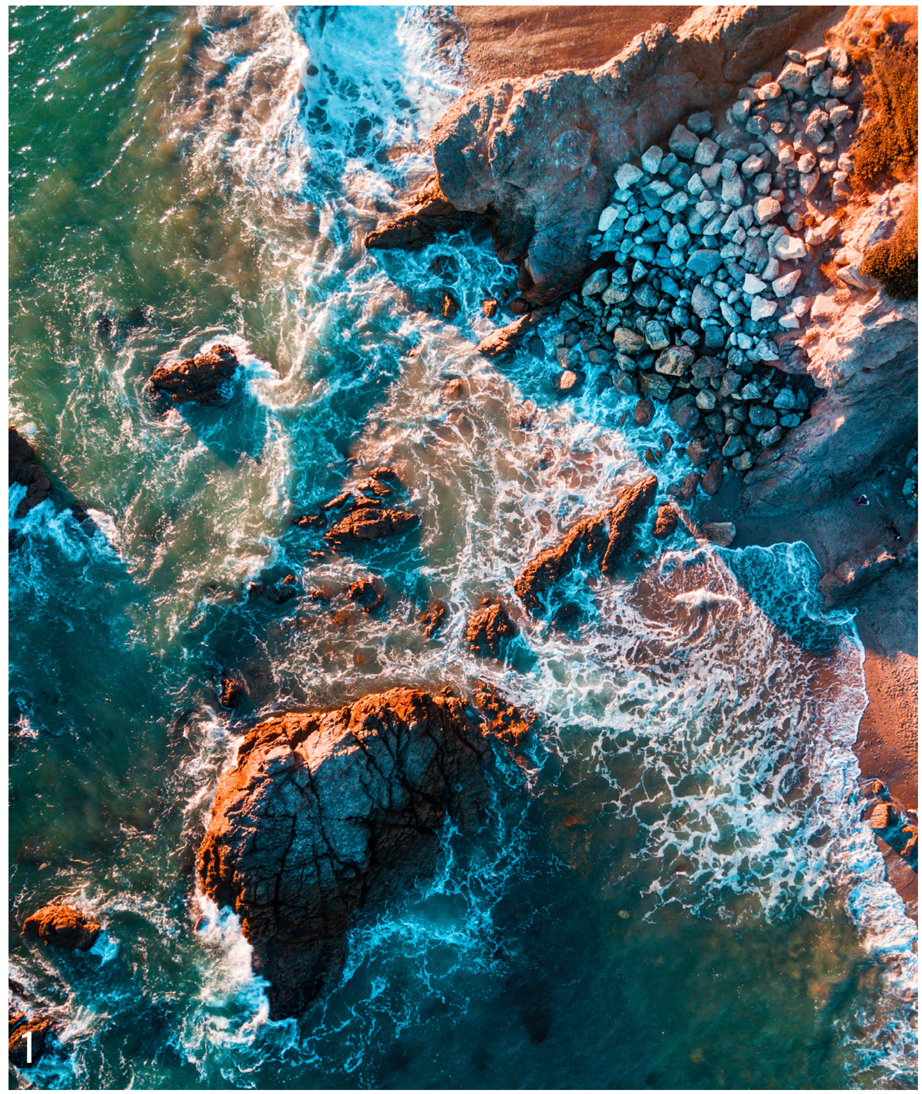
The purpose of this journey is not to cross the ocean, but rather to sail all of its shores. This exploration will ply the waters along every coast, sailing parallel to them at a distance close enough to the coastlines to observe all of their magnificent characteristics. The voyagers are in for a treat because there is an astonishing diversity of coastal areas on Earth by any measure—rocky versus sandy, tropical versus polar, calm waters versus pounding waves, vegetated versus barren, long and straight versus twisty and tortuous, and yes, humans absent versus common. There are many ways of classifying coastal areas, and many criteria for distinguishing differences from one stretch of coastline to another.

Sailing all of the world's coastlines would take several years. By our own calculations (and yes, we mapped the coastlines of the world—more on that later), the planet has about 2.5 million kilometers (more than 1.5 million miles) of coastline. A ship traveling nonstop at speeds of 20 knots—a typical speed in the cargo container and cruise ship industries—would take almost eight years to complete the voyage. That doesn't include time spent at ports, island hopping, or slow-steaming in interesting or navigationally tricky areas.

The time and resources needed for such an endeavor make such a long voyage "running the coastline" impractical in ships or even aircraft. But orbiting satellites provide coverage of Earth in regular, repeating time cycles, meaning that satellite imagery exists for every stretch of coastline on the planet. So instead of a voyage by ship, the journey becomes one of looking at satellite images to capture every coastline of the Americas, Eurasia, Africa, Australia, and hundreds of thousands of big, small, and tiny islands in the global ocean.

Our team has already taken that journey through a collection of coastal satellite images, extracting new information about coastline positions to make a new high-resolution map called the *Global Shoreline Vector* (GSV). After publishing that coastline mapping work,[1] our team—as often happens on journeys—took an interesting detour. Our team had set out to characterize coastal environments, and the first step in doing that was to produce a new map of the global coastline. But having mapped the global shoreline in the finest detail to date, our team was ready to make the most definitive geographic characterization of global islands. We published the results[2] in Esri's *GIS for Science, Volume 2*, the predecessor to this volume. That work provided a definitive count and geolocation of global islands, and it happened as a fortuitous "by-product" of our global coastline inventory work. However, it also caused us to get temporarily sidetracked from our original intention of producing a definitive characterization of the world's coastlines.

Leaving aside the magical allure of islands, this chapter focuses on the task at hand, a characterization of global coastal environments. This work comes at a time when spacecraft have explored the heavens and submersibles have explored the seafloor. Our team was profoundly moved and inspired by the accomplishments of Dr. Kathryn Sullivan, the only person to walk in space (1984) and dive to the deepest part of the ocean (2020) in the Marianas Trench (see a related ArcGIS StoryMap linked within this book's companion website found at GISforScience.com). Although perhaps not as headline-grabbing as her outer-space and inner-space explorations, our team's virtual "surface-space" scientific exploration of the global shorelines is the first of its kind.



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In addition to the diversity of physical, ecological, and human factors used to classify coastal areas, important geographic and temporal dimensions help frame coastline classification efforts. These four images represent different spatial vantage points for coastal exploration that influence classification scale and granularity: 1) low altitude (Malibu, California), 2) on-shore (Portland Head, Maine), 3) high altitude (North Sentinal Island, Andaman Islands, India), and 4) off-shore (the Australian research vessel Sprightly*).*

COASTAL VARIATION

The coastline is universally understood as the intersection of Earth's land masses and oceans. Coastal areas are extremely important to humans, in that approximately half of the world's population lives within 100 km (62.1 mi) of the ocean.[3] The very survival of many human societies depends on the provision of ecosystem goods and services as benefits from coastal environments, and the supply of those benefits is a function of the health of the coastal systems. Highly degraded coastal ecosystems are compromised in their ability to satisfy human needs for food and other goods and services.[4, 5] To continue producing important benefits for humankind, coastal ecosystems must be well-managed, and that will require a comprehensive understanding of the types, distributions, ecology, and condition of Earth's coastal ecosystems. In other words, researchers will need well-documented maps that provide a digital canvas for ecosystems data.

Coastal settings exhibit spectacular geomorphological diversity (as shown in the coastal photographs on these two pages). Coastal classification aims to classify diversity and partition the coastline into distinct units with similar properties. It is expected that similar units will exhibit similar responses to environmental perturbations or management interventions. Classifying coastlines is an application-specific exercise, and coastal systems can be classified in numerous ways depending on the intended emphasis (e.g., geomorphological, biological, socioecological, or oceanographic). Because coastal areas are often densely populated and subject to natural and human-caused disasters, much coastal classification work has been focused on hazards, risk, vulnerability, and sensitivity. Many nations, for example, classify their coastlines using an environmental sensitivity index (ESI), which characterizes the sensitivity of coastal assets (biodiversity, centers of economic production, cultural features, etc.) to oil spills.[6] These classifications are intended as management tools for the protection of valuable coastal resources. Most coastline sensitivity classifications include, among other factors, aspects of the physical environmental settings in which coastlines occur.

Characterizing the geomorphological nature of coastal physical environments is key to understanding coastal variation,[7, 8] and there is a long history of coastal classification based on physical features. Either sea-level rise or land subsidence can cause submergence of a coastline, and a simple binary classification of submerged versus emerged coastlines was already in use at the start of the 20th century.[9] At coarse scales (e.g., thousands of kilometers), and from a geological perspective, tectonic activity is a primary determinant of coastal variation, as explained in the classic paper by Inman and Nordstrom.[10] The presence of coastal mountains, the width of continental shelves and continental plains, the existence of volcanic and barrier islands, the location of major river systems—all these features result from the movement of tectonic plates on the lithosphere. This type of genetic classification approach emphasizes the origin of coastal landforms. Classifications emphasizing geomorphological structure and processes have evolved from initial considerations of submergence and tectonic history to include emphases on dominant coastal processes,[11] coastal systems,[12] and the morphodynamic coevolution of form and process.[13]

Another fundamental class of approaches to understanding coastal variation deals with hydrodynamic forcing features. These approaches focus on how water movements shape coastlines. Many coastal areas are underlain by bedrock, which slowly erodes over time due to the actions of water and wind. This weathering process is erosional in nature, and these generally rocky coastlines are classified as erosional. In contrast, the sediments produced from weathering can be deposited in the coastal zone to form depositional environments. The sediments that are deposited along the shore create beaches, tidal flats, and dunes, and the sediments that are transported to the coast by rivers create deltas and estuaries. These coastal areas, built up over the long term from sediment deposition, are classified as depositional. These next images are examples of geomorphological diversity in coastal areas based on substrate type. Although the distinction between erosional and depositional coastlines has

Chalky bluffs at the White Cliffs of Dover, England.

long been understood and even mapped at very coarse scales,[10] the first higher-resolution global characterization and map of these two fundamental shoreline types was only recently produced.[14] Neilson and Costello[15] classified lengths of coastline on the mainland and islands of Ireland into cliff, rocky, stony, sandy, and muddy habitats as part of an ecological survey to design a national network of marine protected areas. Those erosional and depositional habitats were found to be primary determinants of species and ecological community occurrences.[16] Delving deeper into the classification of depositional environments, three hydrodynamic influences are of primary importance, as described in the classic paper by Boyd et al.[17] In this characterization of depositional environments, a coastal area is classified according to the relative influence of waves, tides, and rivers as hydrodynamic forces that move sediment. Coastal areas are then identified as wave-dominated, tide-dominated, or river-dominated. Using this framework, Harris et al.[18] classified Australian coastal depositional environments based on a quantitative analysis of wave power, tidal power, and river power. Nyberg and Howell[14] extended this previous work to classify the three hydrodynamic forces shaping depositional environments of global coastlines.

Hexagonal basalt columns, Jeju Island, South Korea.

Sandy beaches abutting coastal mountains, National Park of American Samoa.

Rocky coasts and outcrops, Asilomar State Beach, California.

INTEGRATED AND MULTIDISCIPLINARY COASTLINE CLASSIFICATION

The classification approaches described earlier generally focus on a single classification variable, whether it is environmental sensitivity to a disturbance, tectonic setting, erosional versus depositional nature, or dominant hydrodynamic influence. In recognition of the strong physical, ecological, and human diversity associated with coastal environments, there have also been important attempts to classify coastal environments using multiple factors. Cooper and McLaughlin[19] presented a review of emerging coastal classification approaches and argued that advances in spatial analytical technologies (GIS and remote sensing) enabled increased focus on multifactor classification at that time. Evaluating and quantifying the classic "holistic" view of coastlines as integrated products of geomorphological and oceanographic processes[7] was more easily accomplished using geographic analysis and spatial technologies. These emerging technologies allowed for complex multidisciplinary analysis and mapping of the many physical, ecological, and human aspects of coastal environments. For example, Jelgersma et al.[20] classified low-lying deltaic areas using 18 variables, which were grouped into four main categories: Offshore water environment (six marine variables); Coastline properties (seven shoreline morphology variables); Deltaic system properties (four variables describing land and river conditions); and Human activity (one variable). This study was an early example of a complex delta classification approach aimed at including "everything that matters."

Globally comprehensive, standardized, integrated, high spatial resolution characterizations and maps of coastal systems are still relatively lacking. At the turn of the 21st century, a major World Resources Institute analysis concluded, "Information on the location and extent of coastal features and ecosystems types often provides the basis for subsequent analyses of condition of the ecosystem, relationships between different habitats, and overall trends. Yet, despite this fundamental importance, such information is incomplete and inconsistent at the global level."[4] In response to many similar calls for the detailed mapping of Earth's ecosystems, the Group on Earth Observations (GEO), a consortium of more than 100 nations and participating organizations seeking to advance the use of earth observation for environmental problem-solving, has commissioned a task (task T1 in the 2020-2022 GEO Ecosystems Implementation Plan published at www.earthobservations.org) to produce a standardized, robust, and practical classification and map of the planet's terrestrial, freshwater, and marine ecosystems. The work we have done to characterize coastal ecosystems, described next, was undertaken in response to that official commission from GEO and complements our earlier related GEO work to characterize global pelagic ecological marine units (EMUs).[21]

Our approach—coastal segment units (CSUs) and ecological coastal units (ECUs)

Our team produced a standardized, consistent, high spatial resolution, and globally comprehensive characterization of the coastlines of the world to integrate coastal water properties, coastal land properties, and properties of the coastline itself. The team partitioned the coastlines of the world into 4 million 1 km or shorter segments and attributed those segments with data on 10 variables that describe the basic ecological settings in which the coastline segments occur. The partitioning and attribution have resulted in a new open data resource with which any 1 km coastline segment, anywhere in the world, can be queried, and the values for 10 ecologically meaningful characteristics of that segment returned.

Our primary objective in undertaking this work was to produce globally comprehensive data that describe the ecological settings of coastlines. A 1 km coastline segment may be an appropriate spatial resolution and analytical unit for coastal managers. As such, our team hopes that while the characterization is global, the resulting product may have management utility at place-based scales. Moreover, it appeared that 1 km is a large enough distance to aggregate summaries of other environmental data, yet small enough to show rich variety in those summaries. Integrating the data on features of the land, water, and coastline showed the potential of spatial data integration. The data product is intended to be useful to managers as an extensive inventory of the ecological settings of coastal areas. Every 1 km segment with a unique set of class labels for the 10 attributes is called a coastal segment unit (CSU). The data are also intended to be useful for coastal zone research, including coastal zone assessments related to the Sustainable Development Goals (SDGs) of the United Nations 2030 Agenda for Sustainable Development. (Readers can find a link to this document and other digital resources relating to the work at GISforScience.com.)

A secondary objective in undertaking this work was to identify groups of similar coastal areas based on their *aggregate* ecological setting, as determined from a global statistical clustering of all the segments data. The "all-in" clustering was performed with all 10 attributes included and with equal weighting of the attribute variables. The global clustering was exploratory in nature, and the preliminary results identified 16 distinct coastline environments. These 16 distinct coastline environments are called ecological coastal units (ECUs). The ECUs represent broad groups of globally similar coastal environments.

Remote coastline, Eucla, Western Australia.

METHODOLOGY

Initial plans and evolution of the segmentation approach

Our paper describing the development of the global shoreline vector[1] also presented a preliminary vision for how we would conceptualize and map ECUs, wherein we committed to develop global ECUs as an objective, quantitative segmentation of the global coastal zone into environmentally distinct and ecologically meaningful units. That initial vision included a notion to bound the global coastal zone as a set of nearshore coastal waters extending out to the 30 m bathymetric contour line, offshore coastal waters extending from the 30 m bathymetric contour out to the continental shelf edge, and coastal land areas extending from the coastline landward to the edge of the continental plain or to mountain systems. We then anticipated attributing the area inside this coastal zone with relevant ecological setting variables in a wall-to-wall (completely spatially tessellated) fashion. We held a workshop to elicit expert opinion on the specifics of bounding the coastal zone on land and in the water and to generate the list of variables that would adequately describe the coastal settings. (Workshop resources are linked at GISforScience.com.)

Initial attempts to delineate a global polygonal coastal zone area within which we would characterize coastal ecosystems proved challenging, mainly with respect to bounding the landside area. While the much narrower shore-zone concept is understood as that portion of the profile subject to wave action, the larger coastal zone is an onshore and offshore area influenced by proximity to the coast, with ill-defined limits on both sides.[22] Deciding how far out in the water and how far in on the land we should extend the coastal zone proved problematic due to the difficulty in knowing the nature and magnitude of coastal influence at progressively longer distances seaward or inland.

Ultimately, we abandoned the attempt to delineate a standardized polygonal global coastal zone within which we would map ecological settings in a wall-to-wall fashion as impractical and overly ambitious. We do see the value of such an effort and encourage future attempts to do so. For our purposes, however, we decided that adopting a coastline segmentation approach would provide a simpler and more practical opportunity to characterize coastal environments while still retaining the ability to include considerations of landside and waterside ecological settings. Coastal segmentation is focused on partitioning the coastline into a set of relatively homogenous reference units based on physical and ecological (and sometimes socioeconomic) properties and using these coastline units for resource management or research programs. Coastline segmentation approaches seek to identify similar coastal systems that may exhibit similar responses to disturbances or management interventions.[23]

Our work to identify the coastal segment units (CSUs) and ecological coastal units (ECUs) represents a global partitioning of the coastline into 1 km segments, an attribution of those segments with ecological setting data followed by a classification, and a spatial statistical analysis of the segment properties. The work proceeded in four steps:

Step 1 - Development of the global shoreline vector (GSV)

To develop a strong global characterization of coastal ecosystems, we first needed to produce a new, high-resolution global shoreline vector (GSV) as the spatial and linework foundation for the effort. We produced that vector shoreline through a semiautomated interpretation of year 2014 annual composite Landsat images for every image on the planet that contained a coastline. That work was published in a special GEO Blue Planet (a GEO oceans initiative) issue of the *Journal of Operational Oceanography.*[1] It contains the details about how the GSV was extracted from

Lava enters the sea on the shore of Hawaii island, creating new low-erodibility coastline.

imagery, cleaned, and rendered topological. Our team also presented our initial thinking about the development of global ECUs in that paper.

Step 2 - Segmenting the GSV and identifying segment midpoints as the basic spatial analytical unit

The GSV was then segmented into approximately 4 million segments, most of which were 1 km in length, and none of which were greater than 1 km. A perfect segmentation of the GSV into only 1 km segments was not possible given the realities of coastline lengths. The segmentation was accomplished by starting at the origin vertex of every island or continental mainland polygon and inserting endpoints at every 1 km linear distance. The last segment before returning to the origin vertex was always shorter than 1 km. Islands whose shoreline lengths were less than 1 km also resulted in a number of segments that were less than 1 km. Approximately 4 million segments resulted from the segmentation process, and these features were considered the basic spatial analytical unit of the data development effort.

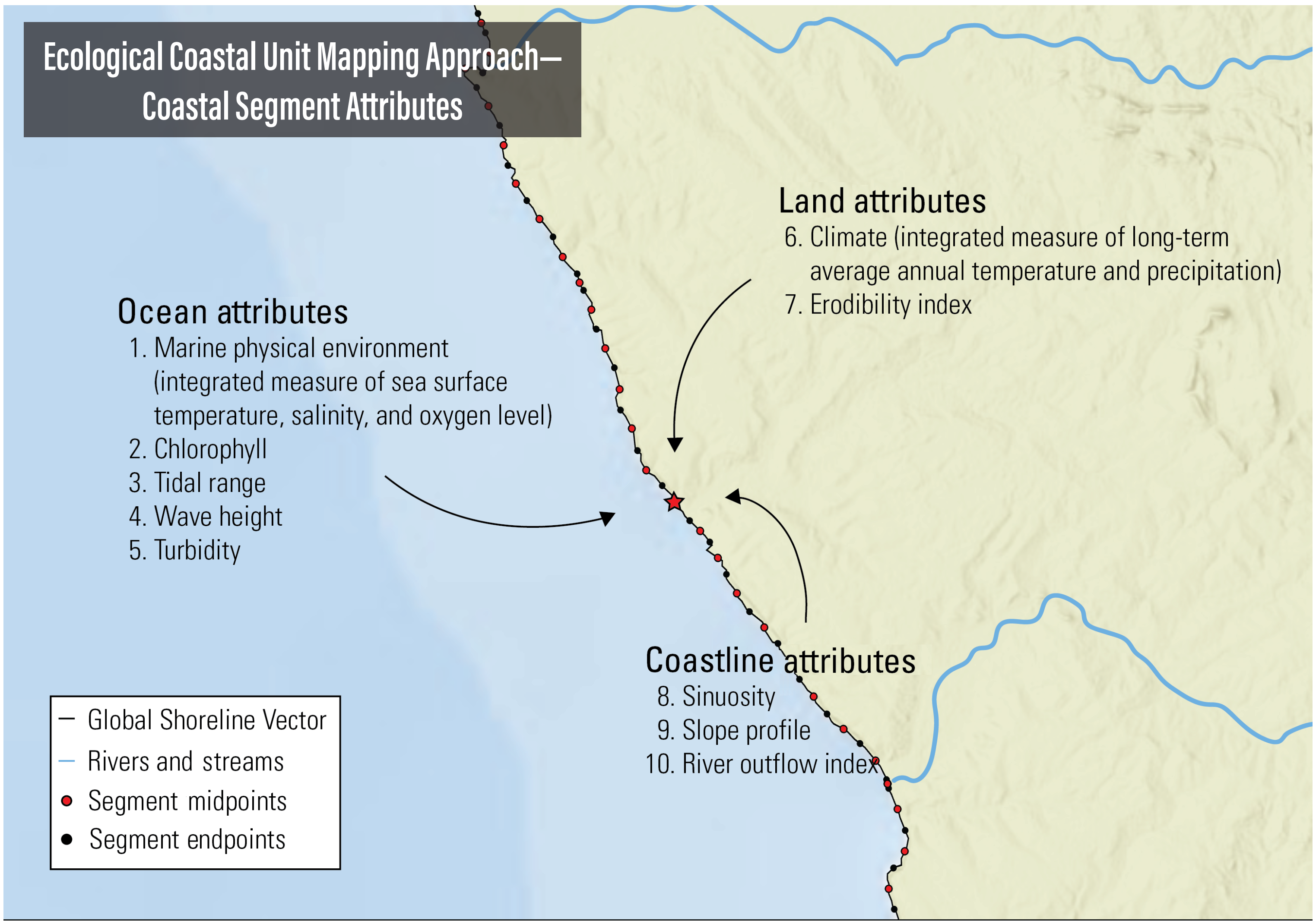
The midpoints of these segments were subsequently extracted into a global shoreline points dataset. The 1 km segments are always conceptually and numerically represented by their midpoints, and all of the attribution and spatial analysis was facilitated by using point features rather than line features. As such, the statistical clustering was in essence an analysis of the similarity of a set of global points, and any references we might make to "clustering the segments" in reality refers to clustering the data associated with the segment midpoints. A similar approach was taken in the development of the ecological marine units (EMUs),[21] where a 3D point mesh was developed and individual points spatially represented a cuboidal volume of water around the point.

Step 3 – Variable selection, attribution of segments, and classification

The team selected 10 variables to represent the ecological settings of coastal environments—two land variables, five ocean variables, and three coastline variables (as seen in the map of coastal segment attributes). Each segment midpoint was then attributed with values for each of the 10 variables. The variables describing the ocean environment included an integrated measure of physical properties (temperature, salinity, and dissolved oxygen), and chlorophyll concentration, tidal range, wave height, and turbidity. The variables describing the land environment were climate setting, (as an integrated measure of long-term temperature and precipitation), and an index of erodibility. The variables describing the coastline were its regional sinuosity, the slope profile of a 200 m perpendicular line segment extending 100 m landward and 100 -m seaward from every segment midpoint, and an index of river outflow. Following the attribution of the segments, they were classified by establishing class labels and associated ranges of class values for each of the 10 variables. Where possible, the class labels and class value ranges were consistent with the Coastal and Marine Ecological Classification Standard (CMECS)[24] nomenclature and breakpoints. The classification step resulted in the development of the coastal segment units (CSUs), defined as any segment with a unique set of class labels for the 10 attributes. The variables are more fully described later.

Step 4 - Statistical clustering

Preliminary statistical clustering was conducted on all points, with all 10 attributes included, to group points with similar landside, waterside, and coastline properties. The clustering routine accommodated the mix of categorical and continuous variables in the 10 inputs and included an effort to reduce dimensionality. The statistical analysis is more fully described in a later section.



The set of 10 attributes for describing the aggregated ecological setting in which the coastal segments occur. The values for these variables, which describe characteristics of the adjacent ocean, the adjacent land, and the coastline itself, are drawn from a variety of data sources and attributed to the coastal segment midpoints.

Rugged coastal geomorphic landforms in western Alaska.

VARIABLE DESCRIPTIONS

The selection of variables (as shown in the tables) to represent the ecological settings in which coastlines occur was a subjective exercise supported by expert elicitation. The decision to include variables representing the landside, the waterside, and the coastline itself follows earlier integrative classification work[7,20] and acknowledges that coastal variation is multidimensional, with strong geomorphological and oceanographic drivers. This section describes each of the variables, their source data and how their values were attributed to the segments (segment midpoints):

Ocean variables

1. Marine physical environment—*an integrated measure of sea surface temperature, oxygen, and salinity.*

Temperature, primary productivity, and oxygen level vary spatially throughout the ocean and are recognized as key drivers of marine ecology.[25,26,27] Organisms have varying tolerances to salinity levels, and changing salinity is therefore another important driver of marine species distributions,[28] but salinity in the open ocean has long been recognized as relatively uniform and stable.[29] In the coastal zone, however, salinity levels are more variable due to the influences of tidal action, fluvial discharge, and evaporation; salinity is therefore recognized as a key driver of coastal zone ecology.[28]

In 2017, our team developed a comprehensive set of 3D global ecological marine units (EMUs)[21] from an analysis of NOAA World Ocean Atlas data on the marine physical and chemical environment. Data on the sea surface physical environment from the set of EMUs distributed along the coastlines were used to attribute the coastal segments. For every coastline segment, an integrated measure of temperature, salinity, and dissolved oxygen was obtained from the closest EMU point to the segment midpoint. The integrated measure is a categorical variable that expresses the combination of the three inputs: salinity, oxygen, and temperature. There were 23 classes of the integrated measurement, as presented in table 1.

Salinity Class	Dissolved Oxygen Class	Temperature Class
Euhaline	Highly Oxic	Superchilled
Euhaline	Oxic	Warm to Very Warm
Euhaline	Oxic	Moderate
Euhaline	Oxic	Moderate to Cool
Euhaline	Oxic	Cold
Euhaline	Oxic	Very Cold
Euhaline	Oxic	Superchilled
Euhaline	Hypoxic	Moderate to Cool
Euhaline	Severely Hypoxic	Cold
Euhaline	Severely Hypoxic	Very Cold
Polyhaline	Highly Oxic	Superchilled
Polyhaline	Oxic	Cold
Polyhaline	Oxic	Very Cold
Polyhaline	Severely Hypoxic	Cold
Polyhaline	Severely Hypoxic	Very Cold
Polyhaline	Anoxic	Cold
Polyhaline	Anoxic	Very Cold
Mesohaline	Highly Oxic	Very Cold
Mesohaline	Oxic	Moderate to Cool
Mesohaline	Oxic	Cold
Mesohaline	Oxic	Very Cold
Mesohaline	Hypoxic	Cold
Mesohaline	Severely Hypoxic	Very Cold

Table 1

2. Chlorophyll a concentration

Primary production is another key driver of marine ecology, and chlorophyll concentration as a measure of plankton abundance, the base of the ocean food web, is used as a proxy variable for representing primary production.[27,30] The data on chlorophyll a concentration were obtained from the European Space Agency Ocean Colour Climate Change Initiative (linked at GISforScience.com). This dataset contains merged chlorophyll measurements from 1997 to 2020 provided from SeaWiFS, MODIS, MERIS, and VIIRS sensors.[31] The chlorophyll variable is continuous and was used as such in our analyses. The chlorophyll data are in a 4 km raster format. We averaged the long-term (1997–2020) monthly mean chlorophyll values to identify a long-term annual average. The derived long-term annual average will likely have smoothed seasonally high and low values of chlorophyll, precluding straightforward classification into CMECS trophic productivity levels (oligotrophic, mesotrophic, and eutrophic). We therefore simply identified three chlorophyll classes (low, moderate, and high) according to natural breaks[32] in the chlorophyll data and did not assign a CMECS trophic productivity class label. The chlorophyll value attributed to each segment was the value from the raster cell whose center was closest to the segment midpoint. The three chlorophyll classes are presented in table 2.

Chlorophyll Level	Concentration (µg/l)
Low	Less than 2.0
Moderate	2.0–5.0
High	More than 5.0

Table 2

3. Tidal range

Tidal activity is an important hydrodynamic driver of coastal zone ecology, mediating salinity levels,[33] nutrient availability,[34] temperature,[35] root zone aeration,[36] carbon flux,[37] species distributions,[38] and other environmental features of importance to organisms. The tidal range, the difference between low and high tide, establishes the vertical limits within which waves and tidal currents interact. Tides create a gradient of environmental conditions wherein species have adapted to various tidal regimes (e.g., see the paper on pulsing ecosystems[39] written by William Odum, his father Eugene Odum, and Eugene's brother Harold Odum. The two Odum brothers were seminal in establishing ecosystem ecology as a discipline and wrote the pioneering textbook Fundamentals of Ecology.*[40]) Of course, tidal variation is also an extremely important and regular environmental phenomenon impacting human livelihoods and behavior. As Davis and Fitzgerald[8] noted, "the rise and fall of the tides is one of the major rhythms of planet Earth."*

Tidal Range Category	Tidal Range (m)
Atidal	Less than 0.1
Microtidal	0.1–0.3
Minimally Tidal	0.3–1.0
Moderately Tidal	1.0–4.0
Macrotidal	4.0–8.0
Megatidal	More than 8.0

Table 3

Tidal range data were obtained from the French Space Agency (CNES) through the AVISO+ data dissemination program (website linked at GISforScience.com). The dataset used is the FES2014 finite elements solution. The data are derived from a compendium of global satellite altimetry measurements and are available in a 1/16th° (~6 km) raster grid. The tidal range data are continuous data and were used as such in the analysis. For subsequent classification grouping and labeling purposes, our team used six CMECS classes to describe tidal ranges (table 3). Each coastline segment midpoint was attributed with a tidal range value from the raster cell whose center was closest to the segment midpoint.

4. Wave height

In the coastal zone, wave energy is a key determinant of marine physical environmental structure through its influence on erosional and depositional processes.[17] Similarly, wave height and exposure influence the composition and distribution of biological assemblages.[41] Mean significant wave height data were obtained from the NOAA WaveWatch III® 30-year Hindcast Phase 2 resource. The data are available as a 30-minute (~55 km) global grid. The wave height data are continuous data and were used as such in the analysis. For the subsequent classification grouping and labeling purposes, the team used seven CMECS classes to describe wave height ranges (table 4). Each coastline segment midpoint was attributed with a wave height value from the raster cell whose center was closest to the segment midpoint.

Wave Height Category	Wave Height Range (m)
Quiescent	Less than 0.1
Very Low Wave Energy	0.1–0.25
Low Wave Energy	0.25–1.0
Moderate Wave Energy	1.0–2.0
Moderately High Wave Energy	2.0–4.0
High Wave Energy	4.0–8.0
Very High Wave Energy	More than 8.0

Table 4

5. Turbidity

Turbidity in the coastal zone is a function of water-driven sediment movement in riverine discharge and shoaling waves. Turbidity influences the distribution of aquatic vegetation primarily through reduction of light.[42] Water turbidity is often used as a measure of water quality, and events such as cyclones, floods, and algal blooms can increase total suspended matter to levels detrimental to primary productivity and nutrient exchange.[43]

Turbidity Level	Diffuse Attenuation Coefficient (m^{-1})
Clear	Less than 0.1
Moderately Turbid	0.1–0.3
Turbid	More than 0.3

Table 5

We obtained turbidity data from the NASA Ocean Biology Processing Group, which developed and maintains a global MODIS (Moderate Resolution Imaging Spectroradiometer) Diffuse Attenuation Coefficient at 490 nm (Kd490). The data are a measure of light penetration (attenuation) into the water column as a function of the concentration of organic and inorganic particles. The data are available as a 1 km spatial resolution global raster. The turbidity data are continuous data and were used as such in the analysis. For subsequent classification grouping and labeling purposes, we used three turbidity classes (table 5) from Shi and Wang.[43] Each coastline segment midpoint was attributed with a turbidity value from the raster cell whose center was closest to the segment midpoint.

Land variables

6. Climate setting

Every location on Earth can be classified by its climate regime. The two most common and widely understood climate properties are the temperature regime and the moisture regime. The distribution of vegetation and terrestrial ecosystems in the coastal zone, as elsewhere in the terrestrial domain, is largely controlled by temperature and precipitation.[27,40,44] Integrated measurements of long-term temperature and precipitation describe a fundamental climate expression for a region. To characterize the coastal zone climate setting, we used an integrated measure of long-term average annual temperature and precipitation. The data are from a delineation of World Climate Regions.[45]

Temperature Regime	Moisture Regime	Climate Region
Polar	Desert	Polar Desert
Polar	Dry	Polar Dry
Polar	Moist	Polar Moist
Boreal	Desert	Boreal Desert
Boreal	Dry	Boreal Dry
Boreal	Moist	Boreal Moist
Cold Temperate	Desert	Cold Temperate Desert
Cold Temperate	Dry	Cold Temperate Dry
Cold Temperate	Moist	Cold Temperate Moist
Warm Temperate	Desert	Warm Temperate Desert
Warm Temperate	Dry	Warm Temperate Dry
Warm Temperate	Moist	Warm Temperate Moist
Subtropical	Desert	Subtropical Desert
Subtropical	Dry	Subtropical Dry
Subtropical	Moist	Subtropical Moist
Tropical	Desert	Tropical Desert
Tropical	Dry	Tropical Dry
Tropical	Moist	Tropical Moist

Table 6

The World Climate Regions analysis identified 6 temperature regime classes and 3 moisture regime classes for a total of 18 classes of integrated temperature and precipitation (table 6). The data are in raster format at a 250 m spatial resolution. The temperature and precipitation input data are from WorldClim version 2.0.[46] The input temperature and precipitation data are continuous, but the 18 resulting IPCC-compatible[47] World Climate Region classes represent categorical data. Each coastline segment midpoint was attributed with a climate region value from the raster cell whose center was closest to the segment midpoint.

7. Erodibility class

The effect of waves, tides, and rivers acting as hydrodynamic forces on substrates depends mostly on the erodibility of those substrates. Substrate erodibility is therefore an important element of the ecological setting of a coastal area. Relatively erodible substrates are the source of materials characteristic of depositional environments such as beaches and estuaries, whereas relatively inert substrates are associated with erosional environments such as rocky coasts.

Lithological Class	Erodibility Class
Acid Plutonics, Acid Volcanics, Intermediate Plutonics, Metamorphics, Carbonate Sedimentary, Mixed Sedimentary	Low
Basic Plutonics, Basic Volcanics, Intermediate Volcanics, Siliciclastic Sedimentary, Evaporite	Medium
Unconsolidated Sedimentary, Pyroclastics	High
Water, Ice, Glacier, Other	Not Assigned

Table 7

To include erodibility as one of our determinants of coastal ecological settings, we developed a simple erodibility index data layer using the Global Lithological Map (GLiM)[48] and the logic and definitions presented in Moosdorf et al.[49] We had used the GLiM previously in the development of the GEO-commissioned global ecological land units (ELUs),[50] but in that case we used lithology because it is an important driver of the distribution of vegetation assemblages due to differences in substrate chemistry.[51] We used a rasterized 250 m version of the GLiM that we developed previously when delineating the ELUs. We assigned a relative erodibility class of high, medium, and low to the 13 Level 1 classes in the set of GLiM attributes (table 7) using the logic and average global erodibility indices developed for the GEroID (global erodibility index) framework.[49] Four additional minor classes in the lithology dataset (water, ice, glacier, and other) were assigned an erodibility class of "Not Assigned". Our erodibility data layer is therefore represented by categorical data, and the erodibility class value assigned to a segment midpoint was from the raster cell whose center was closest to the segment midpoint.

Coastline variables

8. Regional sinuosity

The sinuosity of a stretch of coastline is a measure of its geometric complexity and is defined as the ratio of the length of the actual, curvilinear coastline to the length of a straight line connecting both ends of the segment. Also known as the roughness index (RI), sinuosity is a geometric indicator that can provide information about the type of coastline structure.[14] Relatively smooth and straight coastlines with a low RI are likely to represent beaches, bluffs, or rocky headlands, depending on the erosional and depositional nature of the substrate. Stretches of coastline with a relatively high RI are more likely to be deltaic or estuarine in nature.

Sinuosity Class	Sinuosity (unitless)
Straight	Less than 1.5
Sinuous	1.5–5.0
Very Sinuous	More than 5.0

Table 8

Ecologically, coastline sinuosity has terrestrial and marine dimensions. Terrestrial impacts of coastline complexity include the distribution of freshwater, groundwater, nutrients, and sediments to the coastal zone. In the marine domain, sinuosity influences wave energy, water residence time, and protection or exposure of biotic communities.[52]

Our team calculated the RI of every 10 km stretch of coastline, rather than calculating the sinuosity of the individual 1 km segments, and as such, our index is more a measure of regional sinuosity. This decision was made in response to the observation of Nyberg and Howell[14] that calculating sinuosity from 5 km segments was inadequate for the "capture" of many landward-intruding, funnel-shaped coastline complexes. The RI values are continuous data and were used as such in the analysis. The regional sinuosity value calculated from the 10 km segment was attributed to each of the segment midpoints of the

10 1 km segments comprising the 10 km coastline length. For subsequent classification and description purposes, we identified three sinuosity classes (straight, sinuous, and very sinuous) based on ranges of the RI (table 8).

9. Slope profile

Coastal areas can contain steeply sloping mountains plunging into the ocean, low gradient mudflats with almost imperceptible sloping in a seaward direction, and everything in between. Slope is a determinant of the width of the littoral zone, which can range from narrow steep beaches to wide tidal flats.[53] The slope gradient at the coastline influences many aspects of wave energy and shoaling, swash zone morphodynamics, sediment deposition and erosion,[54] and associated differences in biotic distributions.[55] Slope gradient is a strong determinant of changing coastline position and is particularly important in the analysis of shoreline retreat from sea-level rise.[56] Interest in assessing change in coastline position has led to the development of methods (e.g., Doran et al.[57]) for calculating coastal slope gradient.

Slope Class	Slope Range (%)
Flat	Less than 8.75
Sloping	8.75–57.3
Steeply Sloping	57.3–173.2
Vertical	More than 173.2

Table 9

Our team developed a global coastline slope profile data layer by extending a perpendicular line from each segment midpoint 100 m in landward and seaward directions. The endpoints of this 200 m vector were attributed with elevation values from the corresponding raster cells that contained the 200 m perpindiculars. The elevation data source was the 15 arc seconds (~500 m) resolution GEBCO (General Bathymetric Chart of the Oceans) bathymetry and topography resource,[58] sharpened and gap-filled using data from an Airbus® global 12 m spatial resolution DEM. The slope values of the 200 m segments were attributed as continuous data to the segment midpoints. For subsequent classification and description purposes, we grouped the slope values into four categories: (flat, sloping, steeply sloping, and vertical (table 9) based on CMECS classes and value ranges.

10. River outflow index

Rivers and streams are the source of freshwater inputs and particulate matter to the coastal zone, structuring important ecosystems such as estuaries and deltas. Sediment discharge at the mouth of rivers along the coast is the source of most sediment in the coastal zone,[8] and river outflow influences coastal zone dilution processes, nutrient levels, sediment and particulate organic matter composition, pollutant and pathogen exposure levels, etc.[59] River-dominated systems are one of three fundamental depositional morphotypes in coastal areas, along with tide-dominated and wave-dominated systems.[17,18]

Fluvial Importance	River Outflow Index (unitless)
Low	0–.000012
Moderate	.000013–.001128
High	.001129–1.0

Table 10

Using data from approximately 160,000 rivers, we developed a global coastal river outflow index to capture the global distribution and magnitude of annual discharge of rivers at the coastline. The river outflow index was the most complex of the 10 ecological settings variables attributed to the coastline segments. Unlike the other nine variables, all of which represent physical measurements of the coastal environment, the river outflow index is a modeled value of the magnitude and extent of riverine influence. We first obtained global river mouth data from the MERIT (Multi-Error-Removed Improved Terrain) Hydro resource.[60] MERIT Hydro rivers are interpreted from a hydrologically conditioned 3 arc second (~ 90 m) global digital elevation model (DEM), and, unless they drain internally in an inland basin, terminate at a river mouth where the land meets the ocean. River mouth locations were obtained from the MERIT Hydro resource and subsequently "transferred" to corresponding locations on the GSV. MERIT Hydro rivers are associated with basin delineations, and these basin areas were used to approximate the average annual discharge for the rivers.

Using the WorldClim version 2.0 data,[46] the long-term (30 years) average annual precipitation figures for all 1 km cells containing river mouth locations were obtained. This river mouth precipitation value was treated as a uniform measure of the quantity of water falling in every cell in the basin, acknowledging that in reality there will be some level of spatial variation in precipitation input across the watershed. The precipitation quantity at the river mouth was multiplied by the total number of cells in the basin as an approximation of the average annual total amount of water falling in the watershed. This total watershed input quantity was used as a proxy for the discharge amount at the river mouth location in a "what pours in must spill out" sense, acknowledging that some of the input precipitation will be evapotranspirated or lost to groundwater flow and therefore will not arrive at the river mouth. The river discharge was then spatially distributed from the river mouth into the ocean using a statistical smoothing (kernel density) operation to identify a normalized spatial footprint and magnitude of river outflow.

When freshwater discharges into estuaries and the ocean, the spatial dynamics of the mixing waters are complex.[61] Plumes form in the mixing zone based on properties of the freshwater inputs (quantity, velocity, composition, etc.) and the receiving ocean environment (currents, tides, waves, obstructions, etc.).[59] Differences in the magnitude of freshwater influence in the coastal zone from one river to the next could indeed be assessed from a robust characterization of plume dynamics, but the spatial and temporal characterization of riverine discharge plumes globally is currently impractical and well beyond the scope of this exercise.

The team instead developed a standardized, spatial measure of freshwater "influence" using a quartic statistical kernel density algorithm[62] that spread the river discharge into the ocean as a probability smoothing function. This measure, which we call a river outflow index, describes the relative spatial distribution and magnitude of the riverine input and is in essence a potential spatial footprint of river influence in the coastal zone. Importantly, the spatial distribution and magnitude of the modeled river outflow is not intended to represent actual plume shapes and sizes; rather, it is a conceptual geospatial model of the relative influences of fluvial processes in the coastal zone. Essentially, we have modeled a standardized, potential river discharge footprint in the absence of currents or other directional energies or non-coastal barriers. This variable captures spatial differences in river outflows as a simple measure of land-to-sea influence.

A 1 km raster framework was established for the purpose of calculating a river outflow index for each segment using a moving neighborhood analysis window (NAW), such as is commonly used in DEM processing for calculations of terrain attributes. The NAW size was 1 decimal degree (~ 110 km). The spreading function was constrained seaward to a distance of approximately 55 km, the seaward limit of the NAW. Landward, the shoreline vector acted as a hard boundary preventing the spreading function from allowing the backward flow of water onto the land. The river outflow index data are continuous data in a 1 km raster grid and represent a NAW-derived measure of the magnitude (expressed as the spatial distribution) of the amount of precipitation/riverine discharge that has been spread from the cell. Specifically, the river outflow index characterizes the size (expected number of pixels) of the spatial footprint created by the spread of discharge into the ocean. The coastline segment midpoints were attributed with the river outflow index value from the raster cell whose center was closest to the segment midpoint. For subsequent classification and description purposes, the river outflow index values were rescaled from zero to one using a minimum-maximum method and grouped into three levels (low, moderate, and high) of fluvial importance (table 10).

Geba River estuary, Guinea-Bissau.

CLUSTERING AND CLASSIFICATION

In addition to the data development effort to create coastal segments and attribute them with values for the 10 variables, we sought to identify global groups of segments with similar aggregate ecological settings. We therefore performed a TwoStep[63] statistical clustering analysis in which all variables were included and given equal weightings, an "all-in and all-equal" clustering approach. However, the clustering was complex due to the number (10) and types (categorical and continuous) of variables, and the big data nature (4 million segments) of the inputs. Rather than operate in 10-dimensional data space, we sought to reduce dimensionality through statistical reduction of the complexity (variance) of the input data. We included all the data from the seven continuous variables in a t-stochastic neighbor embedding (t-sne) analysis,[64] reducing the number of continuous variables from seven to two. The t-sne reduction is similar to a principal components analysis (PCA) but more appropriate for use with non-orthogonal data. Sonnewald et al.[65] used t-sne to reduce dimensionality when clustering global plankton community structure and nutrient flux data for the delineation of marine ecological provinces.

Our final clustering routine included the three categorical variables and the two reduced continuous variables. Although the number of variables was reduced, it is important to note that all 10 variables were used to assess statistical variability of the aggregate ecological setting. None of the variables was dropped as unimportant or weighted less than any other variable. Our team did not constrain the clustering to output a desired number of classes and instead used the collective variability in the input data to identify an optimal number of clusters using a ratio of distance measure approach.[66]

Results and discussion

Coastal segment units (CSUs)

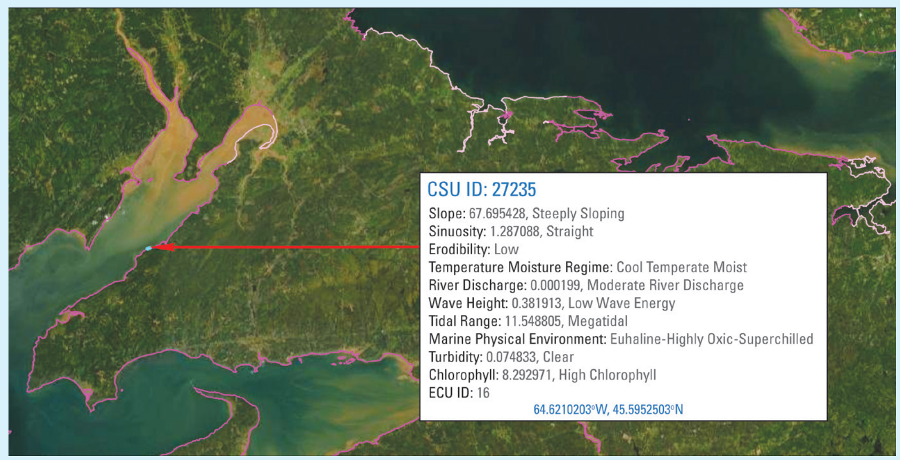
After attributing and classifying the 4 million segments, there were 22,534,848 total possible combinations (23 marine physical environment classes x 3 chlorophyll classes x 6 tidal range classes x 7 wave height range classes x 3 turbidity classes x 18 climate region classes x 4 erodibility classes x 3 sinuosity classes x 4 slope profile classes x 3 river outflow index classes), of which a total of 80,977 unique coastal segment units (CSUs) were actually identified. A summary name descriptor for each CSU was developed as a simple concatenation of the attribute classes in this order: slope, sinuosity, erodibility, temperature and moisture regime, river discharge, wave height, tidal range, marine physical environment, turbidity, and chlorophyll. An example CSU label follows:

> *Steeply sloping, straight, medium erodibility, warm temperate dry, low river discharge, moderate wave energy, moderately tidal, euhaline-oxic-cool, clear, low chlorophyll.*

Any one CSU may differ markedly from another CSU with considerable differences in the classes of all or most of the 10 attributes. Similarly, any two CSUs might be almost identical, with only slight differences in the classes of one or a few of the 10 variables. The sheer number of CSUs precludes a rigorous analysis of their individual global distributions and comparisons of the differences between them. However, in a basic inventory sense, the CSU data may have great utility for managers at local scales as a comprehensive inventory of ecological properties for a 1 km stretch of coastline in a management area.

Working with the data

Clicking any coastal segment brings a pop-up with the query results. Shown here are the attribute queries from two 1 km segments from very different coastal environments.



The top panel shows the coastlines that surround Parque Nacional del Este *in the southeast peninsula of the Dominican Republic. The bottom panel shows the coastal zone around the top end of the Bay of Fundy, New Brunswick, Canada. The Bay of Fundy has the largest tidal range in the world, and a query of its tidal range at this location reveals a range of 11.5 m, contrasted with a tidal range of 0.3 m in the southeast region of the Dominican Republic. As a tide-dominated system, the Bay of Fundy is a low-wave energy system (0.39 m mean significant wave height), whereas the segment from the Dominican Republic is in a moderate wave energy class (1.2 m). The Bay of Fundy is eutrophic at this location, where the primary productivity as indicated by the chlorophyll level (8.3 micrograms per liter, or µg/L) is high. In the Dominican Republic site, the chlorophyll level is relatively low (0.3 µg/L), indicating a lower productivity from an oligotrophic system. The climate regions obviously differ dramatically from Cool Temperate Moist (Bay of Fundy) to Tropical Dry (*Parque Nacional del Este*). The marine physical environment also differs from Euhaline-Highly Oxic-Superchilled (Bay of Fundy) to Euhaline-Oxic-Warm to Very Warm (*Parque Nacional del Este*). Neither segment is strongly turbid or strongly sloping, and their sinuosities are similar. Each segment has low erodibility. Importantly, fluvial importance in the Bay of Fundy segment is four times greater than the segment in the Dominican Republic. Note that the last attribute listed in the pop-up query box is the ECU/cluster to which the segment belongs.*

The intended practical value of the CSU data is that any 1 km segment on the global coastline can be queried in this manner, supporting the understanding of place-based coastal zone dynamics, and facilitating the comparison of stretches of coastline at local scales. Coastal classifications are used in many ways, including coastline vulnerability studies;[6,23,56] conservation planning;[4] ecosystem services assessments;[5] understanding of coastal ecosystem structure, function, and distributions;[24,27,28] design of marine protected area (MPA) networks;[15] and other applications. Our team hopes that the practical value of the CSU classification will be realized by its adoption and use in these and other applications.

Ecological coastal units (ECUs)

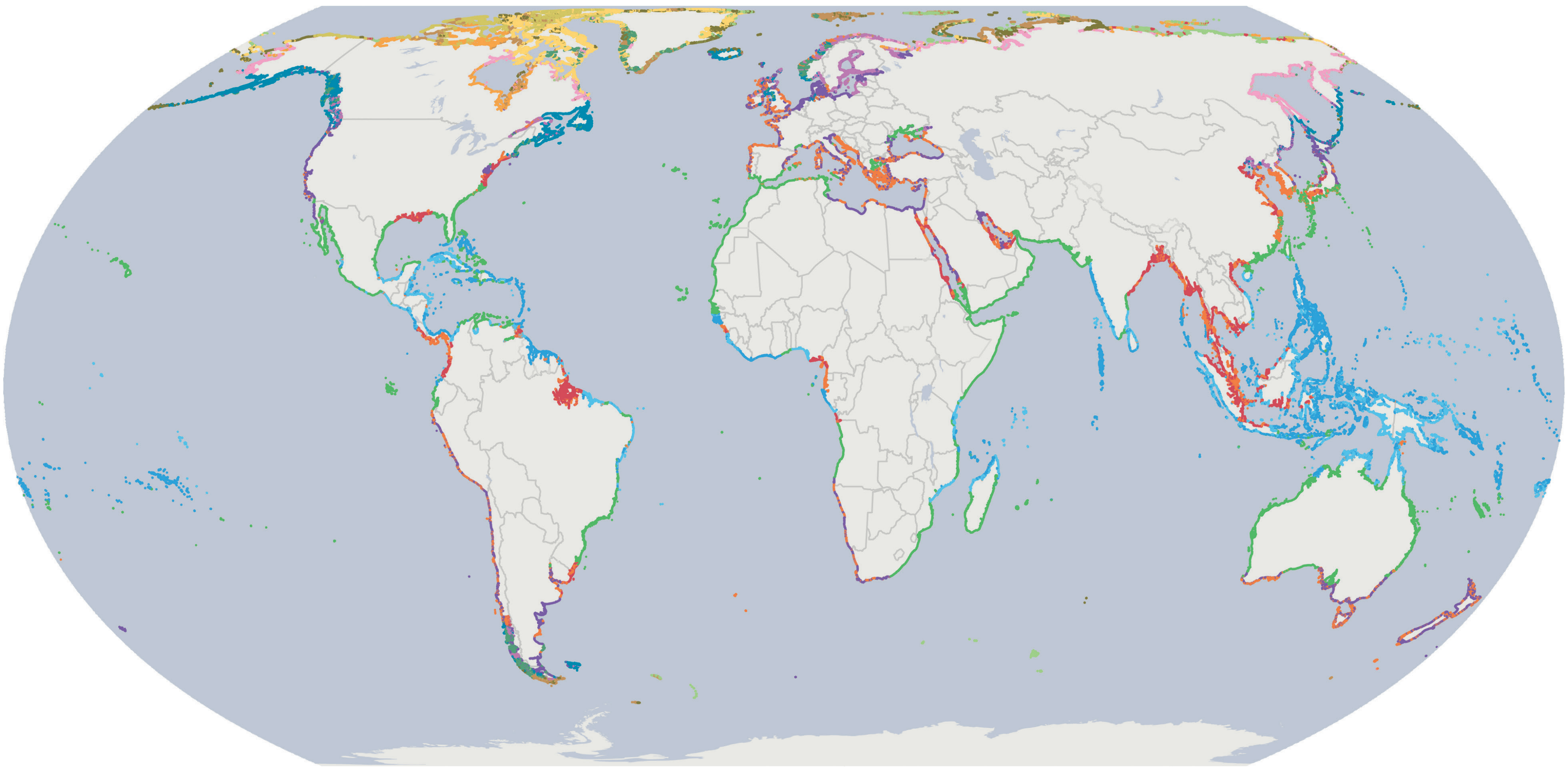
The global assessment of optimal cluster numbers identified 16 clusters, shown in the world map of ECUs. Fewer than 16 clusters appeared largely responsive to latitudinal gradients, whereas more than 16 clusters did not identify new regional groupings, instead demonstrating successive partitioning of the parent clusters. The 16 clusters represent the identification of a preliminary set of standardized and replicable ECUs with potential utility for understanding global scale differences in coastal ecological settings and for global scale conservation assessments and priority setting. The world map below depicts the ECUs at a glance with maximum color separation. An easier interpretation of the individual ECU distributions is presented in the set of 16 maps on the next pages showing the global distributions of each ECU.

Several ECU distributions appear to have strong climate region associations, mainly driven by latitudinal temperature gradients. ECUs 1 and 4 are clearly tropical systems. ECU 2 has a more subtropical distribution with extensions into the warm temperate climate regions. ECU 6 is largely distributed in warm temperate regions. ECUs 7, 9, 15, and 16 are largely boreal. ECUs 8, 10, 11, 12, and 14 are largely distributed in polar regions, and of these, two (ECUs 8 and 12) are only distributed in the Northern Hemisphere, while ECUs 10, 11, and 14 are found in both hemispheres.

While none of the ECUs show a strong pole-to-pole distribution, ECUs 3 and 5 span multiple latitudes, indicating that the climate region influence in these clusters is low. ECU 5 exhibits a strong pattern of distribution along major estuaries/river mouths. ECU 16 shows an interesting distribution in coastal areas characterized by numerous coastal islands (Chile, Norway) and island chains.

The 10-dimensional nature of the dataset complicates visual identification of additional patterns in ECU distributions. The exact nature of each ECU, including the relative influences of the input variables driving their existence and distributions, can be quantitatively described, and the data are available. We summarize the main properties and descriptive statistics of the ECUs in the appendix. The team did not present a rigorous assessment and comparison of the ECU compositional properties herein, as our purpose is rather to describe the development of the ECUs

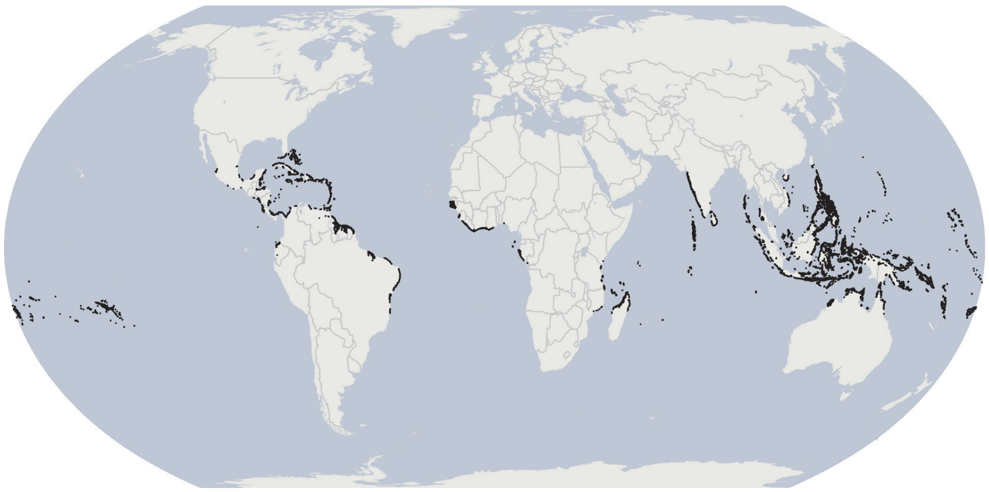
(continued on page 24)



The global distributions of the 16 ECUs, with maximum color separation for easier visual differentiation.

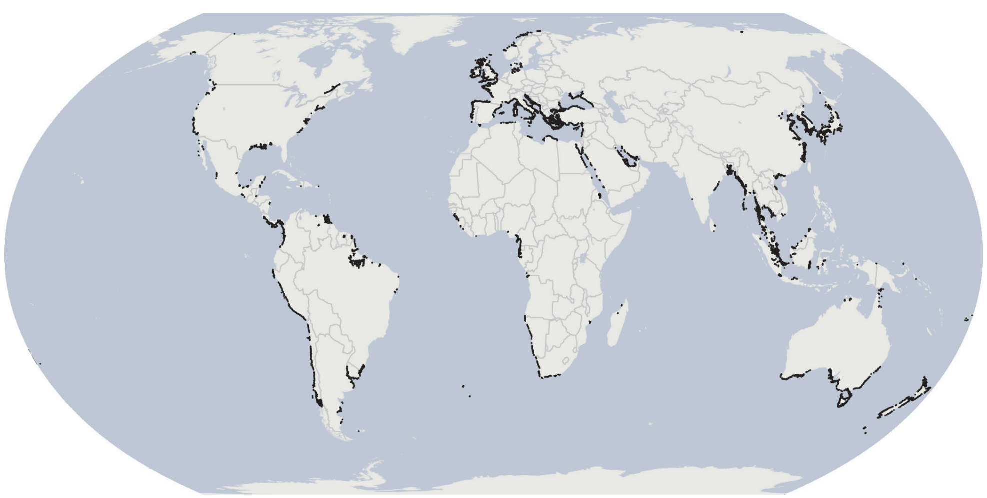
GLOBAL ECU DISTRIBUTION: UNITS 1–8

Shown in black for each of the 16 ecological coastal units

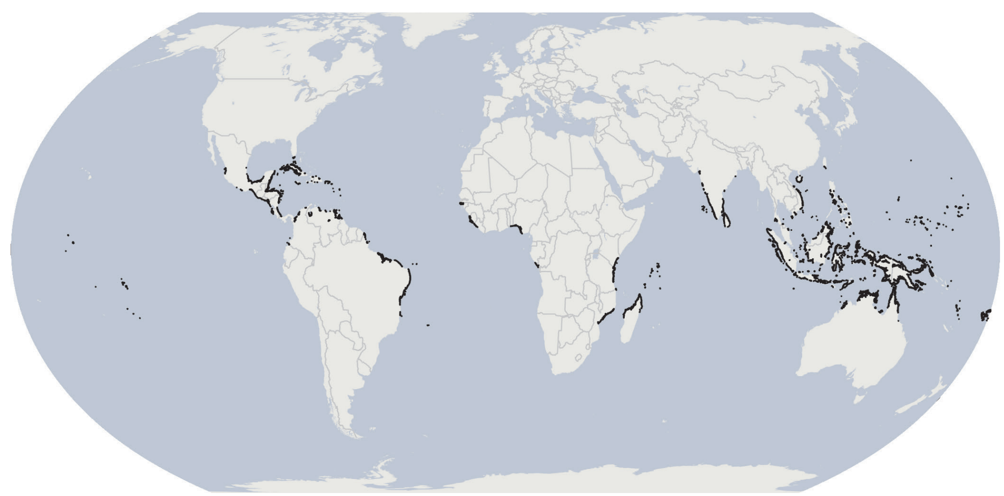


1 *ECU 1—Steeply sloping, sinuous, low erodibility, tropical moist, moderate river discharge, low wave energy, moderately tidal, euhaline-oxic-warm to very warm, moderately turbid, low chlorophyll.*

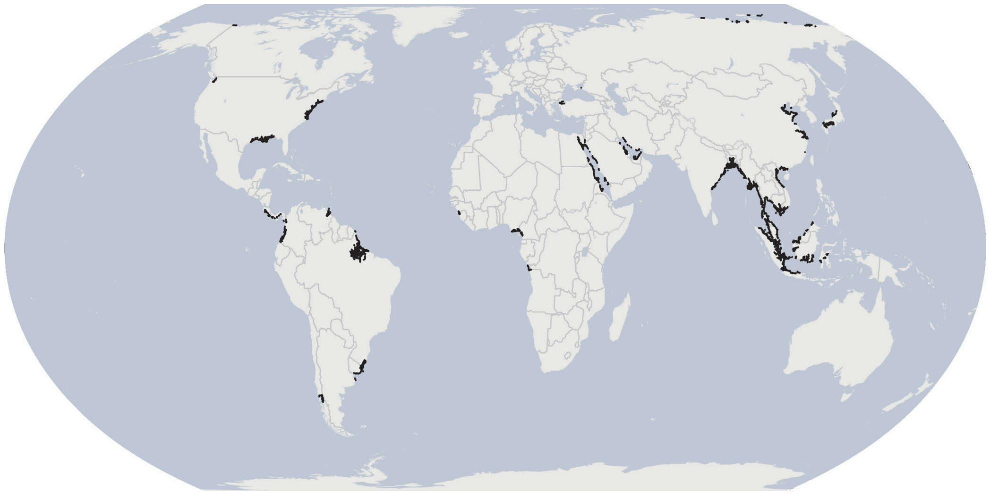
2 *ECU 2—Steeply sloping, sinuous, high erodibility, tropical dry, moderate river discharge, low wave energy, moderately tidal, euhaline-oxic-warm to very warm, moderately turbid, moderate chlorophyll.*



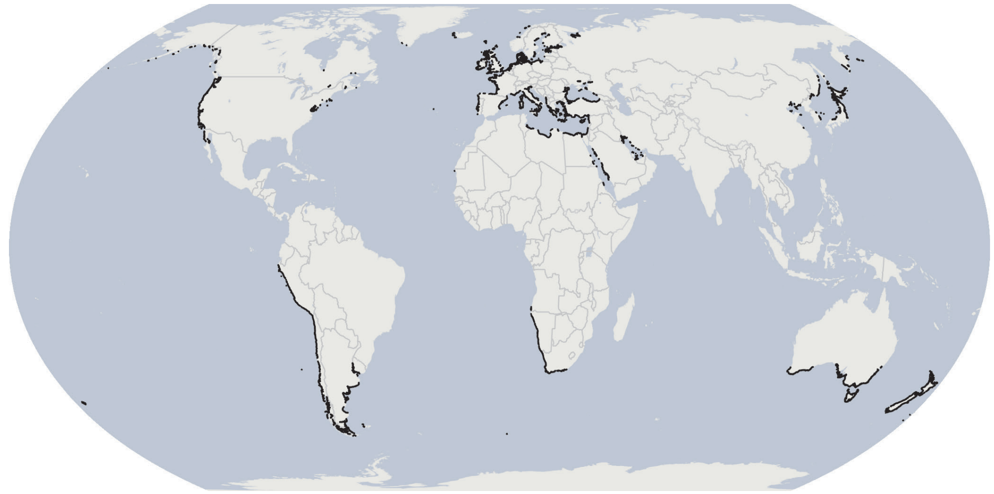
3 *ECU 3—Steeply sloping, sinuous, low erodibility, warm temperate moist, high river discharge, low wave energy, moderately tidal, euhaline-oxic-moderate, moderately turbid, moderate chlorophyll.*



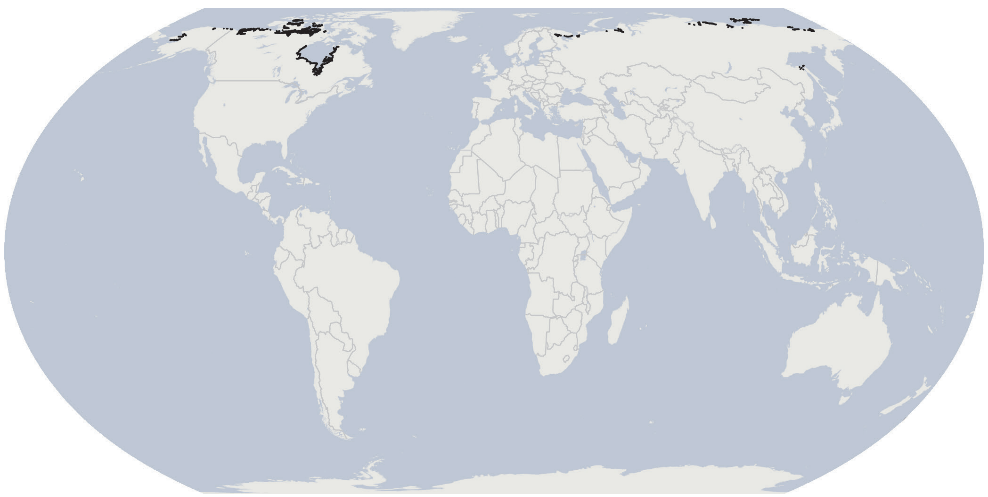
4 *ECU 4—Sloping, sinuous, high erodibility, tropical moist, high river discharge, low wave energy, moderately tidal, euhaline-oxic-warm to very warm, moderately turbid, moderate chlorophyll.*



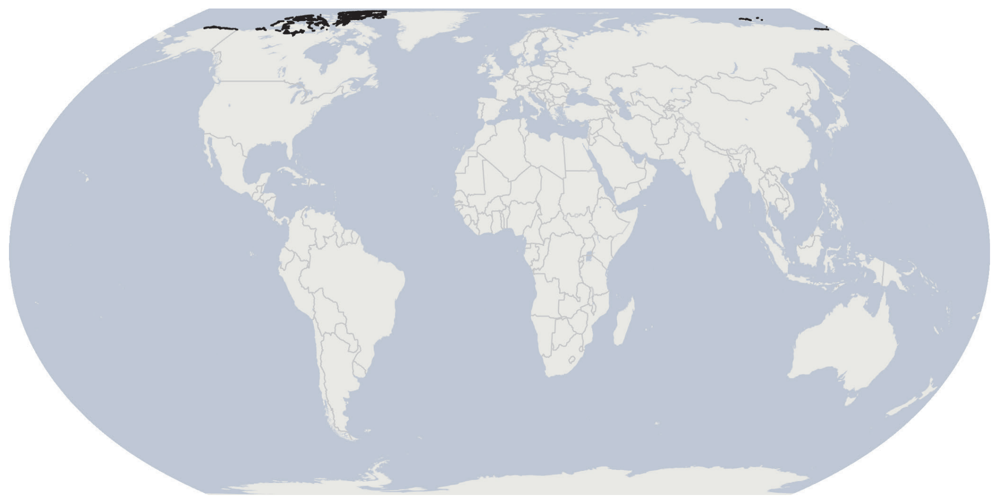
5 *ECU 5—Sloping, sinuous, high erodibility, tropical moist, high river discharge, low wave energy, moderately tidal, euhaline-oxic-moderate, moderately turbid, high chlorophyll.*



6 *ECU 6—Sloping, sinuous, high erodibility, cool temperate moist, moderate river discharge, moderate wave energy, moderately tidal, euhaline-oxic-moderate to cool, turbid, moderate chlorophyll.*



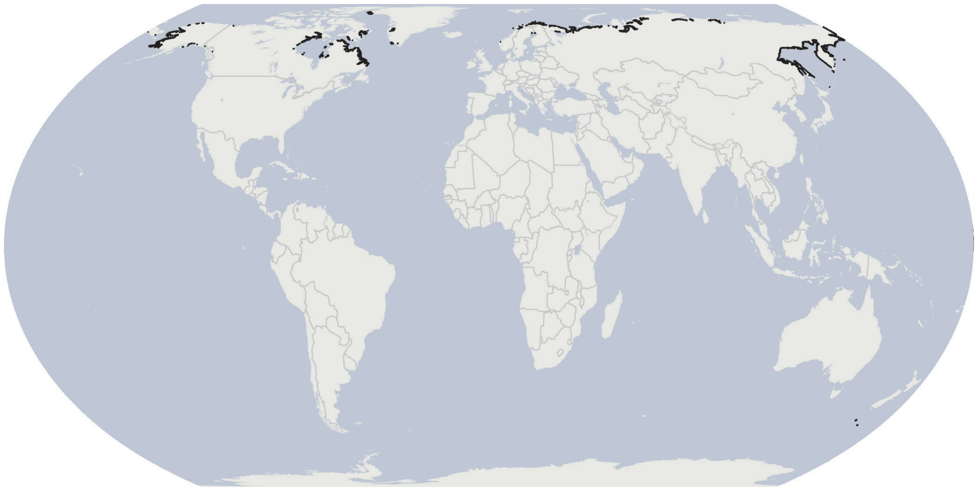
7 *ECU 7—Sloping, sinuous, low erodibility, polar dry, moderate river discharge, low wave energy, moderately tidal, polyhaline-anoxic-very cold, turbid, moderate chlorophyll.*



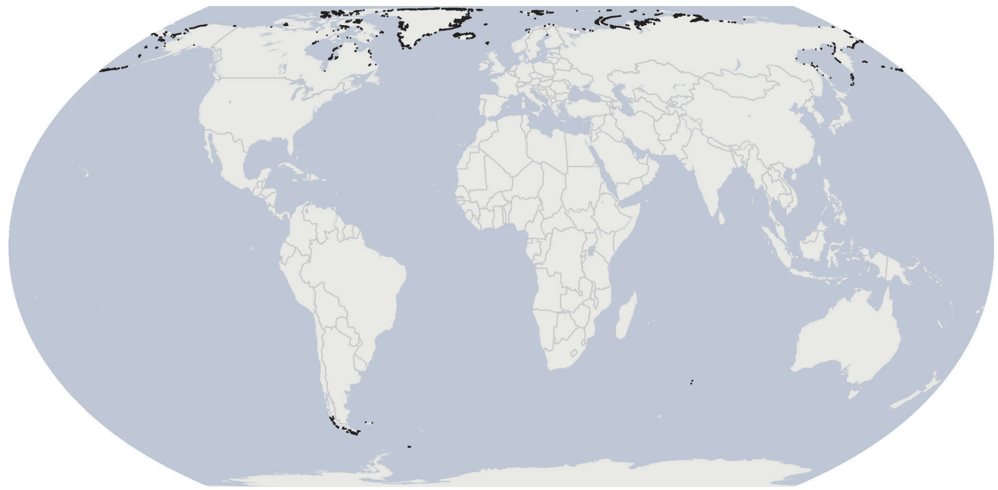
8 *ECU 8—Sloping, very sinuous, low erodibility, polar dry, low river discharge, low wave energy, minimally tidal, polyhaline-highly oxic-superchilled, turbid, low chlorophyll.*

GLOBAL ECU DISTRIBUTION: UNITS 9–16

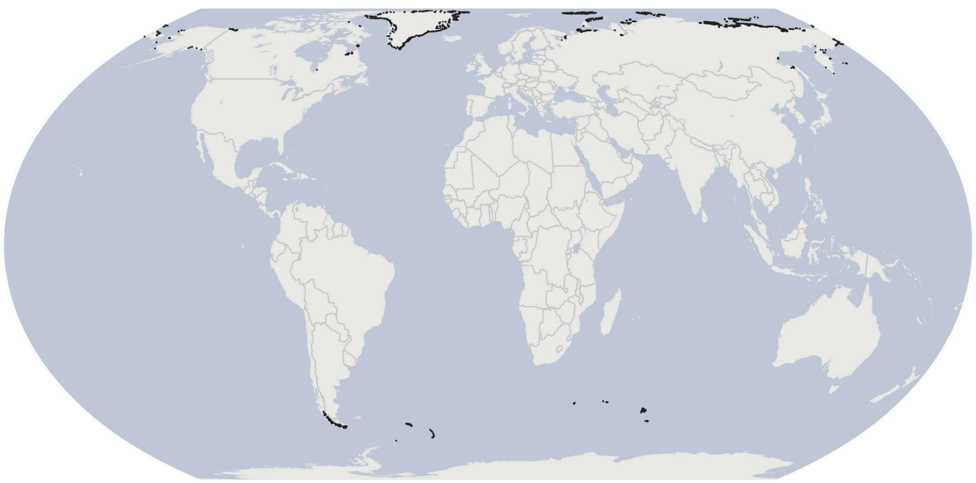
Shown in black for each of the 16 ecological coastal units



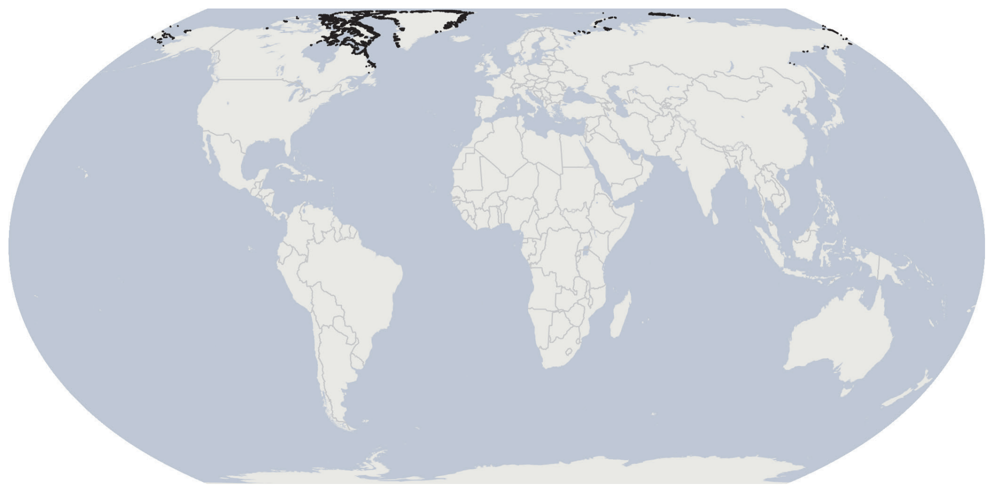
9 *ECU 9—Sloping, sinuous, low erodibility, boreal moist, moderate river discharge, low wave energy, moderately tidal, euhaline-highly oxic-superchilled, turbid, moderate chlorophyll.*



10 *ECU 10—Sloping, sinuous, medium erodibility, polar moist, low river discharge, low wave energy, moderately tidal, euhaline-highly oxic-superchilled, turbid, moderate chlorophyll.*

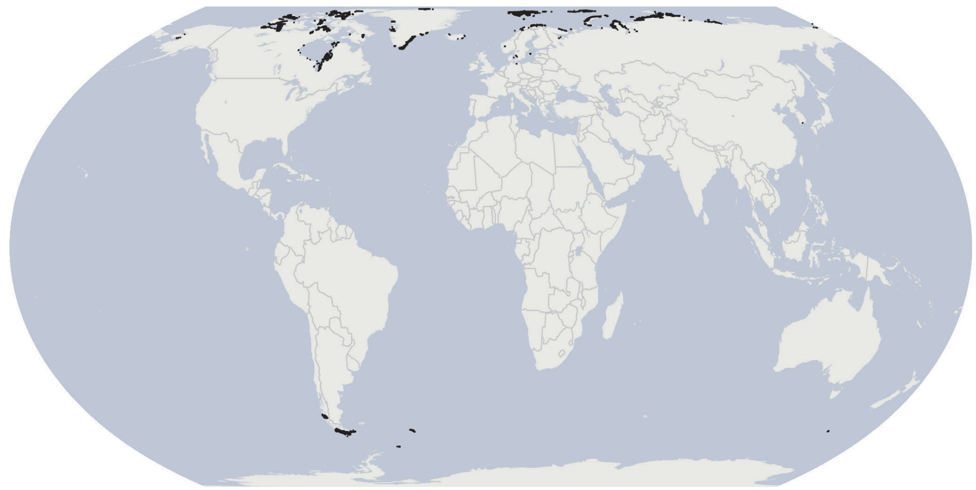


11 *ECU 11—Sloping, sinuous, high erodibility, polar moist, moderate river discharge, low wave energy, minimally tidal, mesohaline-severely hypoxic-very cold, turbid, high chlorophyll.*

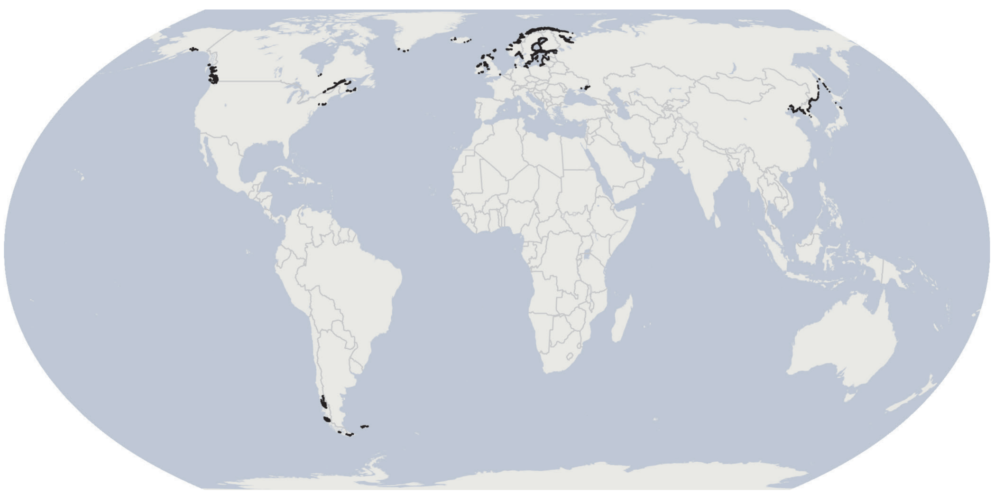


12 *ECU 12—Sloping, sinuous, low erodibility, polar moist, low river discharge, low wave energy, moderately tidal, euhaline-highly oxic-superchilled, turbid, low chlorophyll.*

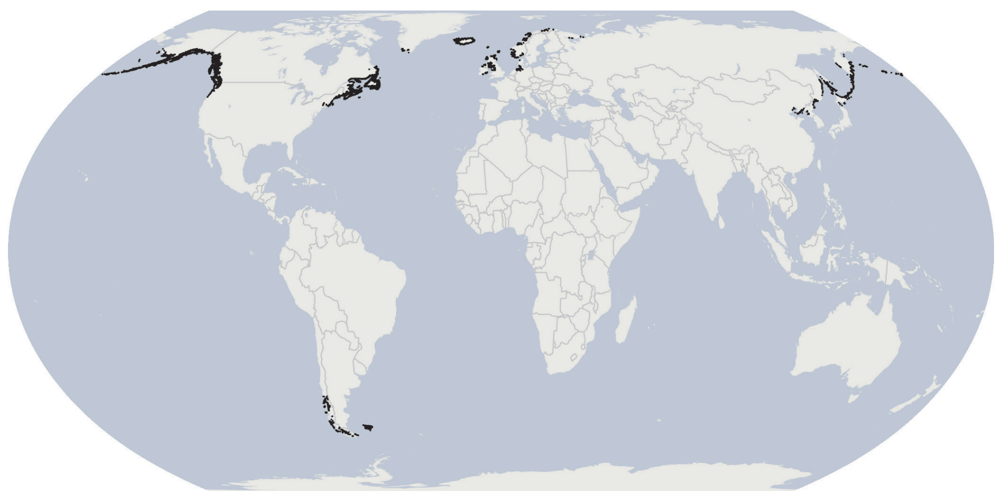
13 ECU 13—Steeply sloping, sinuous, low erodibility, cool temperate moist, low river discharge, moderate wave energy, moderately tidal, euhaline-oxic-very cold, turbid, low chlorophyll.



14 ECU 14—Sloping, very sinuous, low erdodibility, polar moist, low river discharge, low wave energy, moderately tidal, polyhaline-highly oxic-superchilled, turbid, moderate chlorophyll.



15 ECU 15—Steeply sloping, sinuous, low erodibility, cool temperate moist, moderate river discharge, low wave energy, moderately tidal, mesohaline-highly oxic-very cold, turbid, moderate chlorophyll.



16 ECU 16—Steeply sloping, sinuous, medium erodibility, cool temperate moist, moderate river discharge, moderate wave energy, moderately tidal, euhaline-highly oxic-superchilled, turbid, moderate chlorophyll.

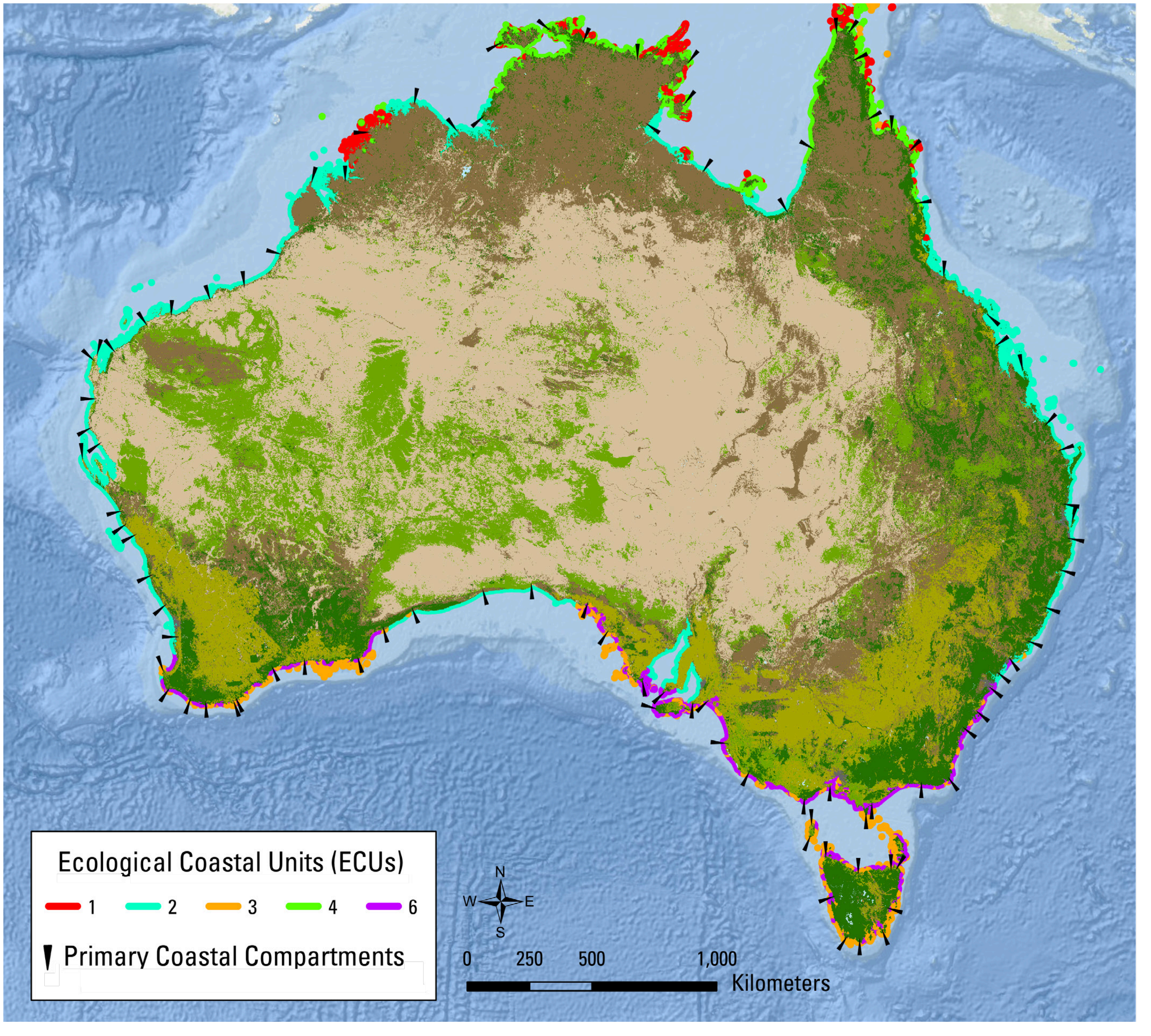
(continued from page 19)
as a preliminary set of 16 macroscale global coastal ecosystems based on integrated information about the coastline and adjacent land and water environments. The ECUs are composed of many different coastal segment units (CSUs). Importantly, there is no hierarchical relationship or perfect spatial nesting between CSUs and ECUs.

One aspect in evaluating the accuracy and potential use of the ECUs relates to how well they line up with existing coastline segmentation and coastal ecosystem delineation efforts. This map of Australia shows the ECUs distributed along the Australian coast compared with the locations of Primary Coastal Compartments from a national sediment compartments assessment.[66] Five ECUs occur in mainland Australia, Tasmania, and territorial islands (a sixth ECU is found on an Australian island south of New Zealand not shown in the map). The distribution of the Primary Coastal Compartments is based on "major, usually distinctive structural features such as rocky headlands or major changes in orientation."[66]

The ECUs are globally distributed and are relatively few in number. They were developed to explore coastal variation at the global scale, and using them to attempt to explain local phenomena is not advised, in a "scale-inappropriate" sense. For example, it is common knowledge that Hawaiian islands have sandy beaches, rocky coasts, mangroves, and steep coastal cliffs, so an ECU user might ask, "Why are all Hawaiian islands just one ECU?" It would appear that the aggregate coastal variation among Hawaiian islands is less than the aggregate coastal variation between Hawaii and other locations. The CSU data, not the ECU data, should be considered the go-to resource for addressing these types of questions dealing with local and regional variation in coastal environments. But for global scale comparisons of similarity in coastal ecological setting, the ECU data are likely appropriate. Moreover, the ECU data might be used to frame new research collaborations between, say, Norwegians, Chileans, and Alaskans seeking to better understand their common ECU.

The ECUs do not contain any information on rocky headlands or coastal orientation, and as such would not necessarily be expected to predict the Primary Coastal Compartment geographies. Importantly, however, many of the locations along the coast where ECUs change are at or near a coastal compartment boundary. This may indicate that, as expected,[7] changes in the macro-level geology and orientation are associated with changes in other features of the general ecological setting that in turn are "captured" by ECUs.

Although ECUs often change at coastal compartment boundaries, they do not predict them. For example, one ECU in particular (ECU 2) has an extensive distribution along the Australian mainland, occurring on all four (eastern, western, northern, and southern) coasts. ECU 2 is subdivided into numerous coastal compartments. It would be interesting to see whether the much finer resolution CSUs would have stronger predictive value in identifying the coastal compartment locations.



A visual comparison of the distribution of ECUs along the Australian coast and the set of Primary Coastal Compartments from an Australian sediment compartments assessment.[66] The coastal compartments, bounded by black markers, were approximated from figure 1 in Thom et al.[66] and used with permission. The data for the interior represent the Australian distributions of World Terrestrial Ecosystems.[45] Bathymetry data are from Esri's Ocean Basemap®.

CONCLUSION

The publication of this information introduces the availability of a detailed and comprehensive global dataset detailing 10 aspects of coastal ecological settings. This is a first-of-its-kind inventory of the properties of 4 million coastal segments at a management-appropriate spatial resolution (1 km). We classified those 4 million segments into 81,000 distinct coastal segment units (CSUs) using authoritative data and standards for describing the classes and their associated value ranges for each of the 10 variables. The data are freely available as an ArcGIS Online resource found at GISforScience.com. Our team plans to actively curate this data layer as an authoritative geospatial resource in ArcGIS Living Atlas of the World. The fully attributed, classified segment units data and the preliminary ECU data are available. The data will also be placed in the public domain after additional preparation and review, including making the data available in an open data format such as an OGC® (Open Geospatial Consortium) GeoPackage file or similar.

The CSU data permit spatial analysis and mapping of coastal ecological settings at any scale, anywhere on Earth. This comprehensive inventory of coastline environments should be useful for researchers, planners, managers, and policy makers. The community is invited to evaluate the data and provide feedback to improve the accuracy and utility of the data. Our team anticipates the development of a simple, web-based data visualization and query tool, the Global Coastline Explorer, which will allow anyone with an internet connection to access the data.

Ultimately, the utility of the classification will be judged by the end user who has assessed the CSU data and evaluated them for fitness of purpose. The classification has three major advantages in that regard: 1) it is exhaustive (every coast is classified), 2) the classes are mutually exclusive (every coast fits into only one class, but that class can be described in rich taxonomic detail), and 3) standardized comparisons of coasts across any oceanic or continental geography are enabled.

This presentation also includes a scientific assessment of the global similarity of these coastline environments. A statistical clustering of the 4 million segments identified 16 ecological coastal units (ECUs) that differ from each other based on their aggregate ecological setting as established by the 10 variables. The ECU work is intended for the scientific community and other interested parties seeking to understand global patterns of variation in coastal ecological settings. The ECU data may be useful in understanding global patterns of biodiversity distribution, helping biogeographers answer that enduring question, "Why are species distributed where they are?"

The ECU data are considered preliminary, and we anticipate feedback from the community on their veracity and utility. The statistical analysis was rigorous and defensible, but the selection of variables in any clustering exercise is always the subject of debate. Did we omit an important variable or variables, such as, for example, elevation change at the coast, important for understanding uplift and subsidence effects on coastal landforms?

Regardless of the research value of the current clustering results, the newly created set of granular, management-appropriate, and globally comprehensive coastline segments represents an advance in coastal ecology. It is our hope that this resource will contribute to better understanding and wise stewardship of the planet's many coastal environments.

Appendix

ECU	N (# pixels)	% of total N	Predominant Marine Physical Environment (% of total distribution of occurrences in cluster)	Average Chlorophyll Concentration (μ/l)	Average Tidal Range (m)	Average Significant Wave Height (m)	Average Turbidity (m-1)	Predominant Climate Region (% of total distribution of occurrences in cluster)	Predominant Erodibility Class (% of total distribution of occurrences in cluster)	Average Regional Sinuosity (unitless)	Average Slope (%)	Average Outflow Density (unitless)
1	234,549	6	Euhaline-Oxic-Warm to Very Warm (100)	1.8	2.1	0.77	0.22	Tropical Moist (100)	Low (67)	2.57	97.87	0.0003
2	308,444	8	Euhaline-Oxic-Warm to Very Warm (97)	2.99	2.37	0.88	0.22	Tropical Dry (33)	High (59)	2.69	60.9	0.0006
3	263,112	7	Euhaline-Oxic-Moderate (45)	2.85	2.68	0.88	0.29	Warm Temperate Moist (37)	Low (71)	2.26	79.7	0.0015
4	206,534	5	Euhaline-Oxic-Warm to Very Warm (100)	3.44	2.48	0.7	0.24	Tropical Moist (100)	High (100)	2.64	53.48	0.0017
5	248,600	6	Euhaline-Oxic-Moderate (100)	6.14	2.41	0.58	0.29	Tropical Moist (65)	High (100)	2.27	29.48	0.0115
6	206,328	5	Euhaline-Oxic-Moderate to Cool (49)	3.54	1.98	1.02	0.36	Cool Temperate Moist (43)	High (64)	2.53	49.95	0.0007
7	192,253	5	Polyhaline-Anoxic-Very Cold (33)	3.57	1.06	0.38	0.46	Polar Dry (47)	Low (94)	2.89	20.87	0.0002
8	199,849	5	Polyhaline-Highly Oxic-Superchilled (54)	1.8	0.93	0.3	0.33	Polar Dry (100)	Low (81)	6.01	25.25	0
9	179,728	4	Euhaline-Highly Oxic-Superchilled (51)	4.98	3.06	0.58	0.55	Boreal Moist (98)	Low (48)	1.9	47.2	0.0008
10	183,614	5	Euhaline-Highly Oxic-Superchilled (42)	3.46	1.22	0.58	0.44	Polar Moist (100)	Medium (100)	1.87	47.35	0.0001
11	215,600	5	Mesohaline-Severely Hypoxic-Very Cold (16)	5.69	0.77	0.5	0.42	Polar Moist (64)	High (83)	1.96	27.01	0.0005
12	401,296	1	Euhaline-Highly Oxic-Superchilled (100)	1.69	3.26	0.42	0.43	Polar Moist (100)	Low (100)	2.58	49.28	0
13	341,997	9	Euhaline-Oxic-Very Cold (100)	1.88	2.95	1.27	0.43	Cool Temperate Moist (53)	Low (100)	2.63	110.51	0.0001
14	271,424	7	Polyhaline-Highly Oxic-Superchilled (29)	2.28	1.46	0.74	0.36	Polar Moist (100)	Low (100)	5.07	54.33	0.0001
15	285,583	7	Mesohaline-Highly Oxic-Very Cold (33)	3.15	1.54	0.88	0.58	Cool Temperate Moist (100)	Low (100)	2.25	66.02	0.0004
16	266,931	7	Euhaline-Highly Oxic-Superchilled (49)	2.66	3.53	1.29	0.43	Cool Temperate Moist (100)	Medium (77)	1.97	84.27	0.0002

Descriptive statistics on the distributions and average compositional characteristics of the ecological coastal units (ECUs).

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