Mapping marine ecosystems, biogeographic realms, and other regions

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Why?

• Knowing what is where is fundamental to understanding life on Earth, and so
  • how it evolved
  • how it will change (climate change)

• Provides global context for regional and local studies
This talk

1. We like to classify
2. Structured classifications inform of how similar and different areas are (have predictive and heuristic value)
3. What can we learn from bottom-up classifications based on data?
Big data opportunities

- Environmental data e.g. GMED
- Biological data e.g. OBIS
- Do the data support prevailing paradigms?
65,000 species from the Ocean Biogeographic Information System (OBIS)

Prevailing paradigm is that it peaks at the equator and highest in tropics

Global Marine Environment Datasets

> 54 global physical, chemical, biological datasets mapped to standard 5-min spatial resolution published open access online at gmed.auckland.ac.nz

Endorsed as contribution to GEO BON
Longest inhabited and largest habitat on Earth

Data from: Costello et al. 2010. Topography statistics for the surface and seabed area, volume, depth and slope, of the world’s seas, oceans and countries. Environ. Sci. Technol. 44, 8821-8828.
Most marine species grow and reproduce in the 30-40 ppt range. Only estuarine (< 28 ppt) and saline lakes limit species.
Mean annual temperature

Images + 50 more from GMED
where data also available
Nutrients

Sea surface nitrate

Silicate

Sea bottom nitrate

Phosphate
Primary productivity: annual average

Biological response to available nutrients and suitable habitat ~ temperature and light
Biodiversity = variability of …..

- **Species**
  - Richness ~ ecology and evolution
  - Endemicity ~ evolutionary history

  +

- **Ecosystems**
  - Processes ~ nutrient dynamics (nitrate, phosphate, silicate)
  - Structure ~ habitats and biomes
Species richness from samples

$E_{50}$ index based on sampled locations of 65,000 species from OBIS across all taxa.
Species richness from species ranges

Based on predicted ranges (models) of over 10,000 individual maps of fishes, all other marine vertebrates, about 2000 invertebrates, and some algae. Colours on log-scale. From Aquamaps.org
Marine species richness

Aquamaps.org
Colours on log-scale.

(1) Modelled species ranges and
(2) carefully cleaned primary data show

most species occur along coasts and tropics

OBIS 2009 data:
$ES_{50}$ used to standardise for sampling effort.
Cluster analysis

• Species distribution data to group 5° latitude-longitude cells into biogeographic ‘realms’

• Environmental variables to group water masses into ‘Ecological Marine Units (EMU)’

• Both define areas and their boundaries
30 biogeographic regions (= realms)

i.e. areas high endemicity based on field data on 65,000 species

Most realms coastal, offshore realms larger
Species depth ranges increase with depth

Example for sea pens is typical for fish and most other animals.

Means fewer endemics with depth.

3D environmental mapping at ESRI

53 million data points in ArcGIS Pro

0.25° latitude-longitude * 5 m to 500 m deep cells

6 variables:

- temperature
- salinity
- oxygen
- nitrate
- phosphate
- silicate

Note: Depth not a variable but an attribute like latitude and longitude.
How are Ecological Marine Units (EMU) new?

1. Cover all the ocean global
2. volumetric 3-D
3. based on data analysis objective

- They further understanding of how the environment structures biodiversity (fisheries, threatened species, etc.)
  e.g., are there distinct depth zones in ocean?
The data used for EMU

Variables available

1. Temperature
2. Salinity
3. Oxygen
4. Silicate
5. Nitrate
6. Phosphate

Data from

World Ocean Atlas (2013) v2

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Depth interval (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 to 100</td>
<td>5</td>
</tr>
<tr>
<td>100 to 500</td>
<td>25</td>
</tr>
<tr>
<td>500 to 2,000</td>
<td>50</td>
</tr>
<tr>
<td>2,200 to 5,500</td>
<td>100</td>
</tr>
</tbody>
</table>

102 depth bands
Maximum depth 5,500 m
Depth not a variable for cluster analysis
Data analysis

- Data normalised so equal weight each variable
- 52 million data points

Resolution
- Temporal = 57 year averages
- Spatial = 0.25° latitude – longitude, ~27 km
- Depth = 3D in 102 depth bands

Clustering
- K-means with Euclidean distance
- pseudo F-statistic determined optimal number of clusters
EMU vary with depth ~ but most are coastal

regions with 1-3 (dark blue), 6-8 (yellow), 12-21 (red)

Cluster Count Per Location: 1-3 Dark Blue, 6-8 Yellow, 12-21 Red

<table>
<thead>
<tr>
<th>Depth band</th>
<th>Number EMU</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 500</td>
<td>30</td>
</tr>
<tr>
<td>&lt; 1,000</td>
<td>5</td>
</tr>
<tr>
<td>&lt; 2,000</td>
<td>2</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>37</strong></td>
</tr>
</tbody>
</table>
EMU can be viewed at different depths
Do distinct depth zones exist?

- Epi-pelagic
- Meso-pelagic
- Bathy-pelagic
- Abysso-pelagic

Each colour is an EMU

Many coastal EMU not visible
Coastal and enclosed seas

Seas Shallow shelves

Continental shelves

Shallow shelves

60 km

2,000 m

200 m

650 m

2,000 m

7,000 km
Mid-waters

Bottom waters

500,000 km

450,000 km

Offshore open ocean

200 m

800 m
- Epi-pelagic
- Upper Meso-pelagic
- Lower Meso-pelagic
- Upper Bathy-pelagic
- Lower Bathy-pelagic
- Abysso-pelagic ?

Number of clusters

24 20 16 12 8 4 0

----- 200 m
----- 800 m
----- 1,500 m
----- 2,200 m
----- 3,800 m
5,500 m -----
Uniqueness of means of variables characterising EMU clusters

- Depth most unique, next salinity
- No difference between nitrate and phosphate
Variation in variables with depth

**Mean salinity**
- Low salinity in shallow,
- But some exceptions

**Mean temperature**
- Variable in shallow
- Low in deep-sea

**Mean oxygen**
- Variable in shallow
- Mid to low in deep-sea
Low salinity in deep sea – Black & Caspian Seas

Note alternate layering of EMU with depth
Nitrate increases with depth due to less primary production using it.

Phosphate and silicate first increase but then less with depth.
Nutrient relationships not always simple

Outliers Black and Caspian Seas
Similarity of EMU
EMU similarity by MDS
MDS of EMU relationships
1. Cold < 10 °C
2. Shallow < 200 m
3. Low and high salinity clusters
1. Across all oceans
2. Strong influence of latitude (temperature)
3. Open ocean and coastal contrast
4. Arctic and Southern Ocean very different
Ocean mid-water column – 7 Clusters

1. Across all oceans
2. Less influence of latitude
3. Each cluster has open ocean and coastal presence
1. Across all oceans
2. Little or no influence of latitude
3. Each cluster has open ocean and coastal presence
4. Fine scale mixing one cluster within others – biological relevance?
Comparison ecosystems (colour) with realms (lines)

1. Environmental gradients can be biogeographic boundaries.

2. Might some ecosystems be biogeographic boundaries?

3. Role geographic isolation?
Biogeographic realms (lines) | Ecosystems (colours)

% match of area

<table>
<thead>
<tr>
<th>Realm</th>
<th>EMU &gt; 55 %</th>
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<tbody>
<tr>
<td>1</td>
<td>16, 17</td>
</tr>
<tr>
<td>2</td>
<td>6, 7, 22</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
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<td>4</td>
<td>3, 37</td>
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<tr>
<td>5</td>
<td>4, 9, 15</td>
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<tr>
<td>6</td>
<td>5, 12, 20, 25, 27, 28</td>
</tr>
<tr>
<td>7</td>
<td>30</td>
</tr>
<tr>
<td>8</td>
<td>34, 36</td>
</tr>
<tr>
<td>9 to 20</td>
<td>&lt; 47 % match</td>
</tr>
<tr>
<td>22 to 29</td>
<td>&lt; 30 % match</td>
</tr>
<tr>
<td>30</td>
<td>14, 19, 31</td>
</tr>
</tbody>
</table>
Future research

1. Define ‘ecosystems’ based on comparison with biological data
2. Relate biological data to EMU in 3D
3. Develop
   a. Ecological Coastal Units (ECU)
   b. Ecological Freshwater Units (EFU)

Thank you! 😊
Biomes: plant habitat for other species

Terrestrial concept based on different growth forms of plants (e.g. tundra, forest, grassland).
Can it be applied and useful for indicating marine ecosystem structure and function?

Marine biomes
- Phytoplankton?
1. shallow water corals
2. seagrass
3. mangroves
4. kelp

How map?
1. Field observations,
2. expert drawn maps
3. species distribution models
Global plant productivity: land, sea, freshwater
Seabed slope

Linear scale

Scale with slopes exaggerated
Abstract

The world’s oceans have long been mapped by coastal features, political boundaries and ad hoc management areas. Recently, biogeographic realms based on species endemicity have been proposed representing the long-term evolutionary history of species, and marine ecosystems (‘Ecological Marine Units’) have been derived from analysis of recent environmental data. Biodiversity includes both species and their ecosystems. A comparison between the boundaries of realms and ecosystems will indicate what environmental gradients have most strongly influenced the evolution of biodiversity by being barriers to species dispersal. This will inform as to what regions (realms and ecosystems) may be the most suitable for environmental management because of similar environmental conditions and species composition (i.e. biodiversity). Alternative regional mapping systems may complement or be useful for other purposes.