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)

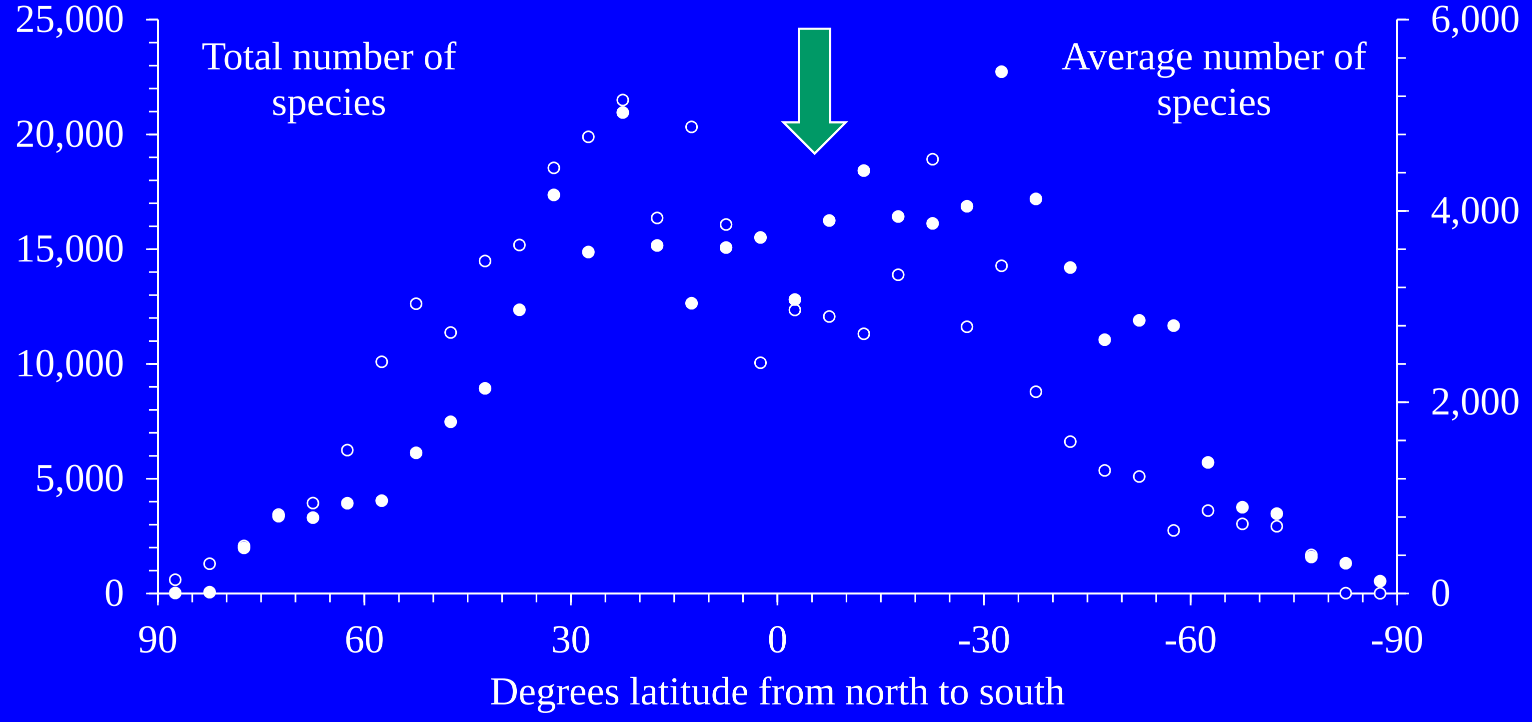
3. What can we learn from bottom-up classifications based on data?

Big data opportunities

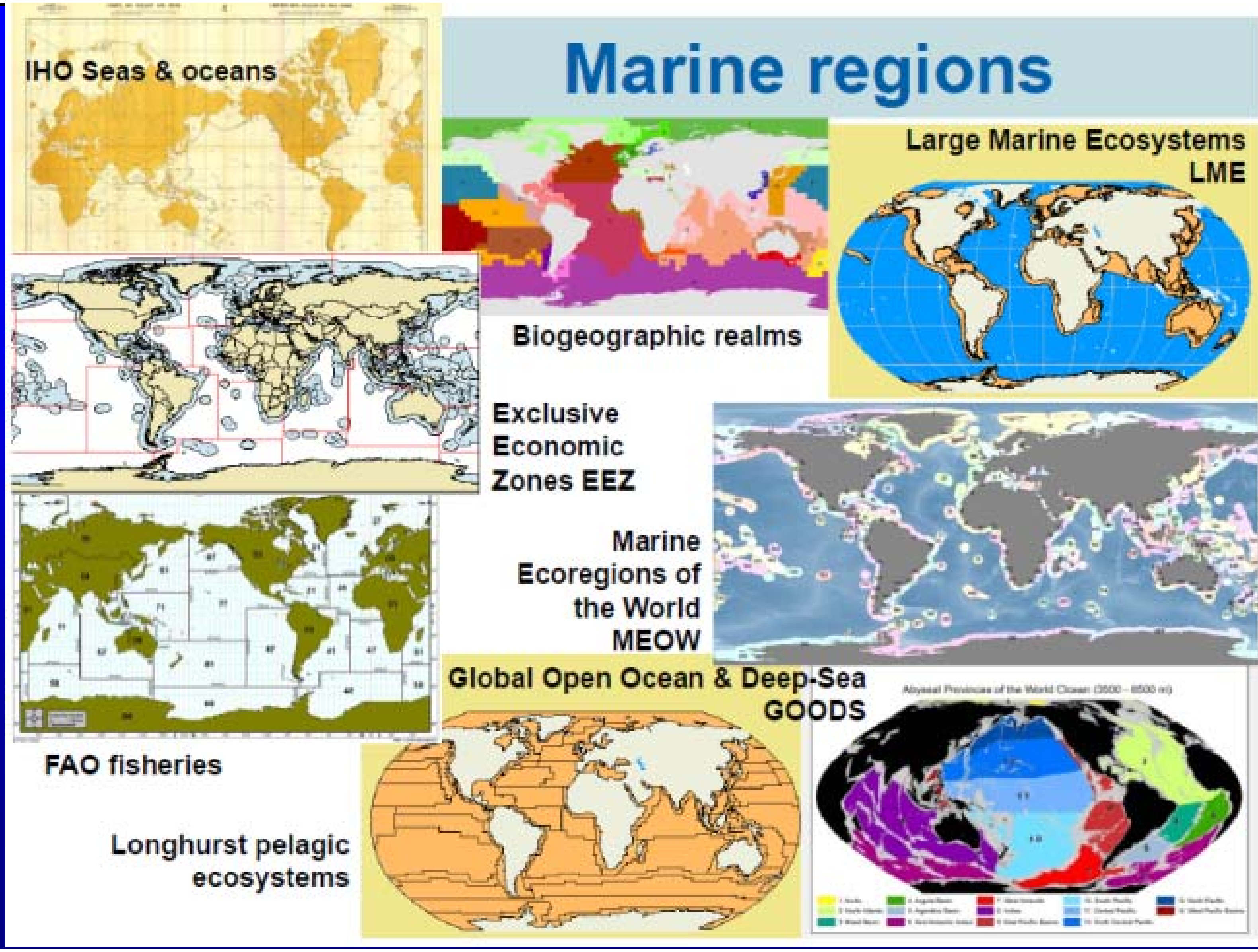
- Environmental data e.g. GMED
- Biological data e.g. OBIS
- Do the data support prevailing paradigms?

65,000 species from the Ocean Biogeographic Information System (OBIS)

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



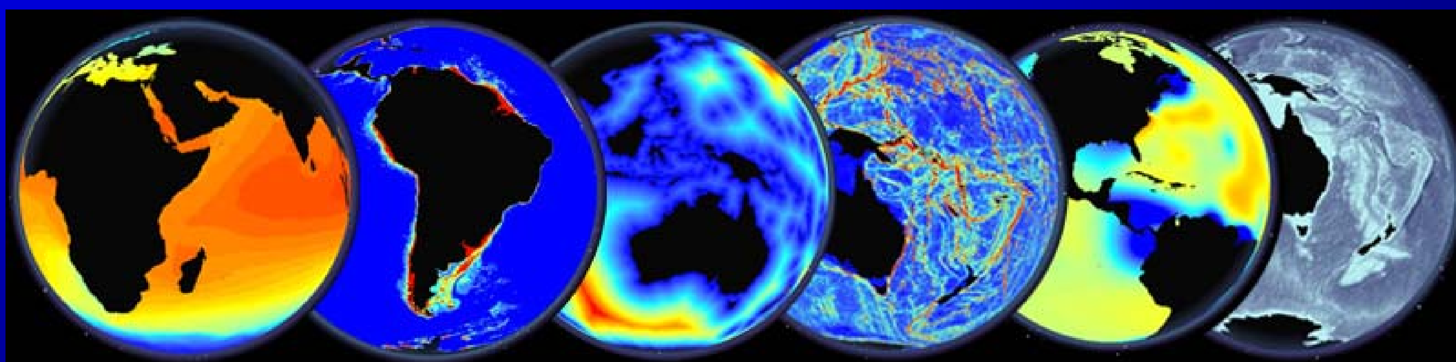
Published:
Chaudhary, Saeedi, Costello 2016. Bimodality of latitudinal gradients in marine species richness. *Trends in Ecology and Evolution*, 31 (9), 670-676.



Marine regions
IHO Seas & oceans
Large Marine Ecosystems
LME
Biogeographic realms
Exclusive
Economic
Zones EEZ
Marine
Ecoregions of
the World
MEOW
Global Open Ocean & Deep-Sea
GOODS
Abyssal Provinces of the World Ocean (3500 - 6500 m)
FAO fisheries
Longhurst pelagic
ecosystems

Global Marine Environment Datasets

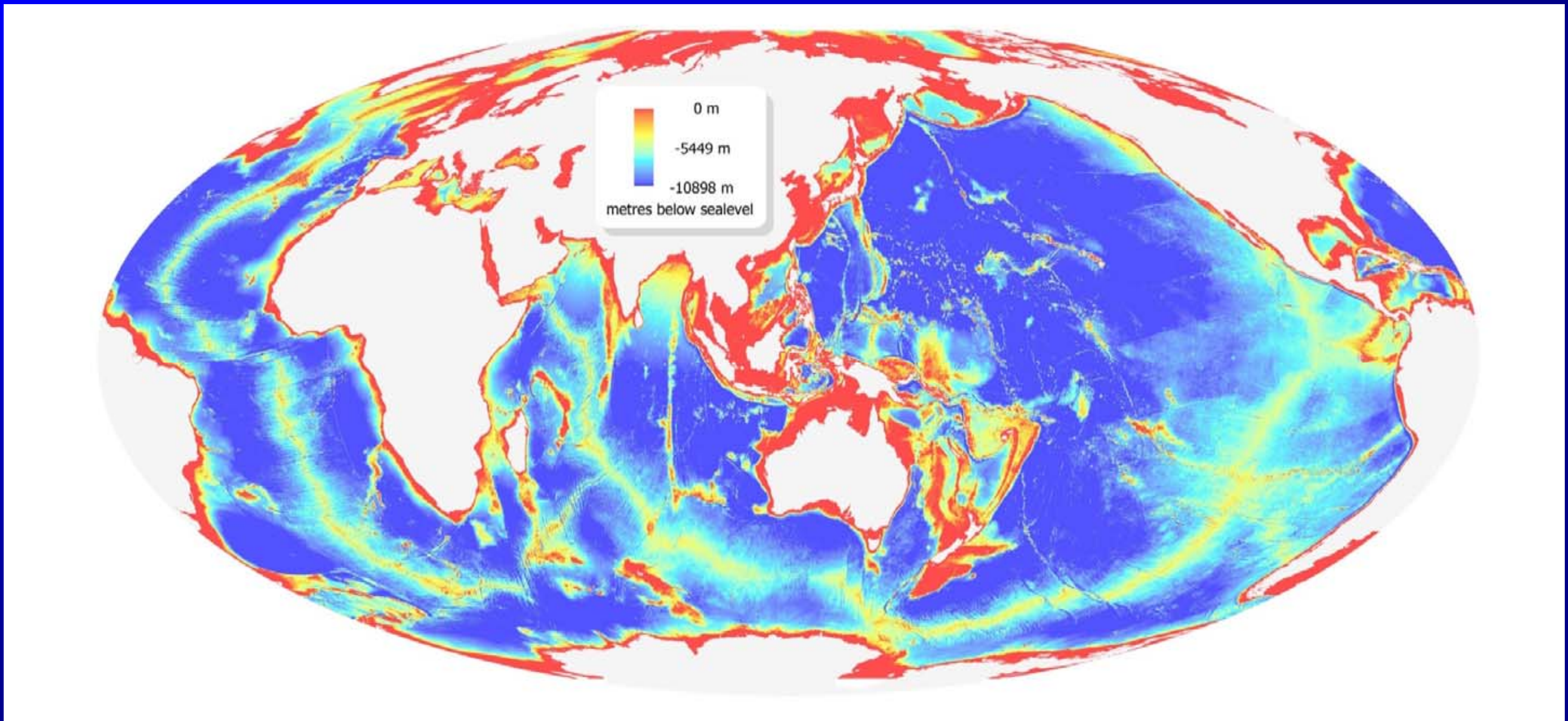
> 54 global physical, chemical, biological datasets
mapped to standard 5-min spatial resolution
published open access online at **gmed.auckland.ac.nz**



Endorsed as contribution to GEO BON

GEO GROUP ON EARTH OBSERVATIONS | GEO BON

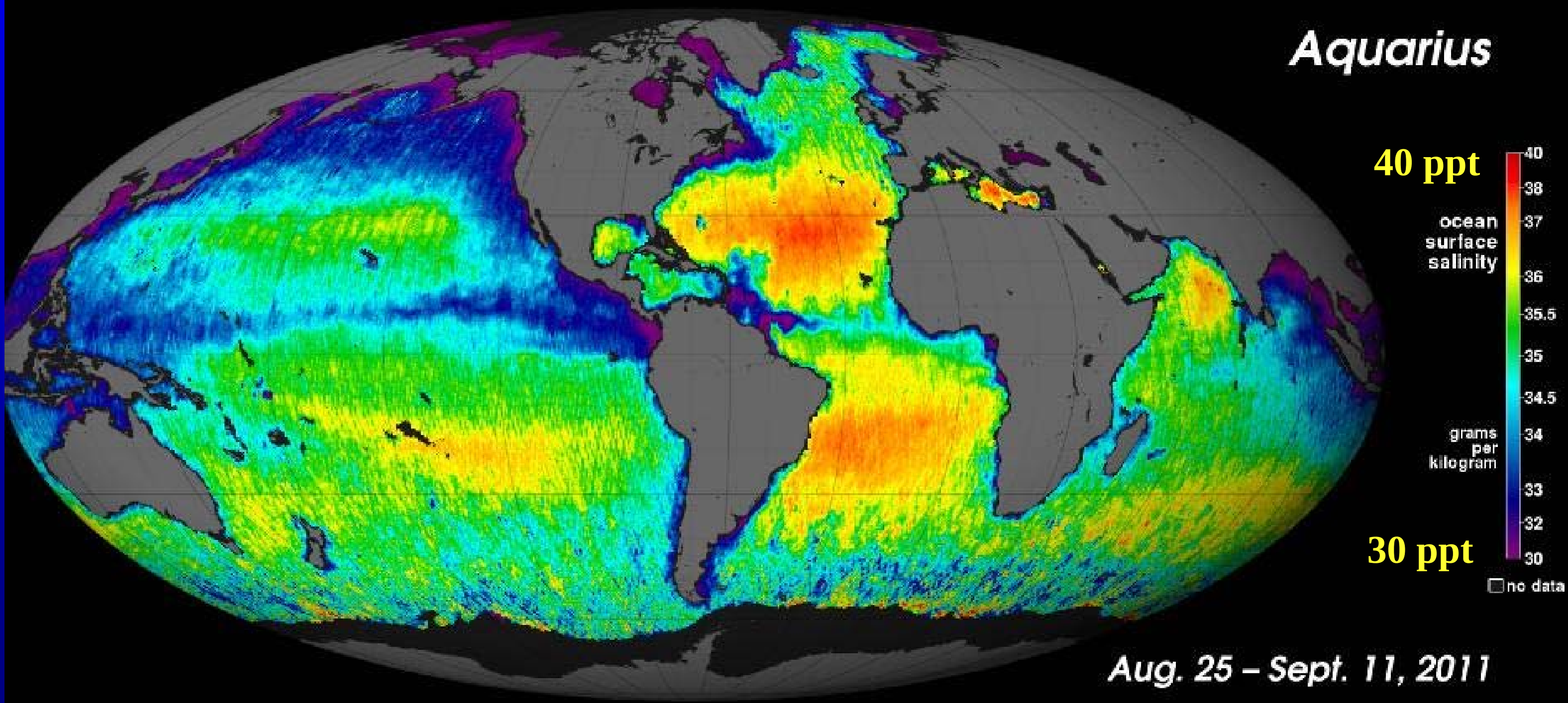
Longest inhabited and largest habitat on Earth



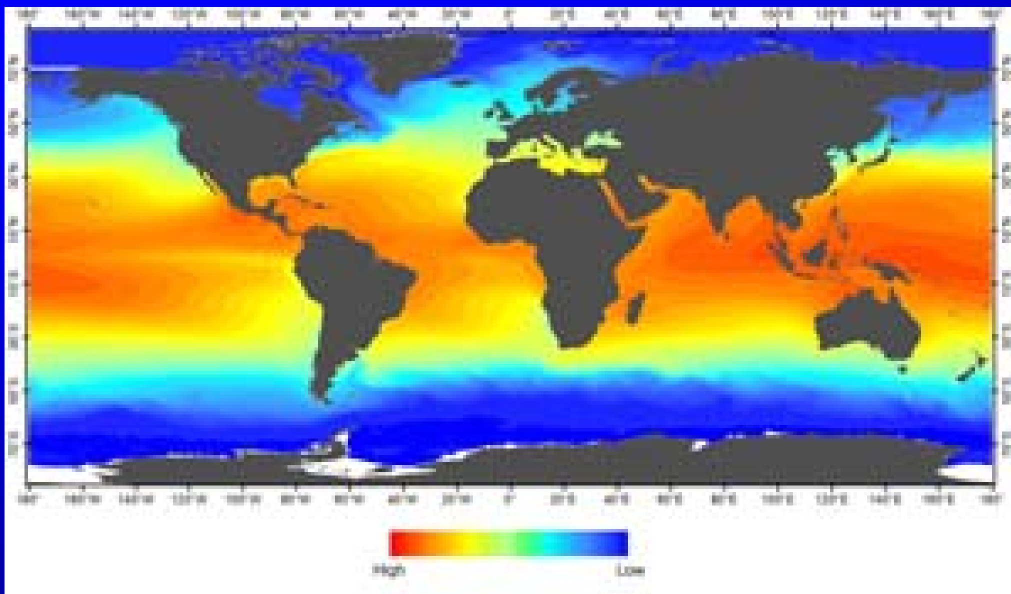
Data from: Costello et al. 2010. Topography statistics for the surface and seabed area, volume, depth and slope, of the world's seas, oceans and countries. *Environ. Sci .Technol.* 44, 8821-8828.

Ocean chemistry - salinity

Most marine species grow and reproduce in the 30-40 ppt range.
Only estuarine (< 28 ppt) and saline lakes limit species.

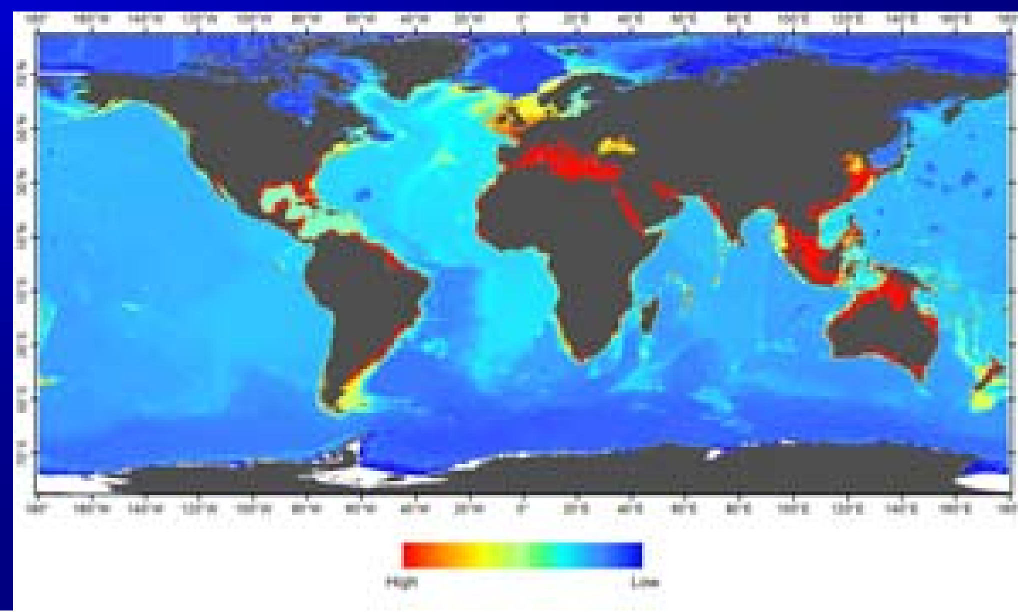


Mean annual temperature



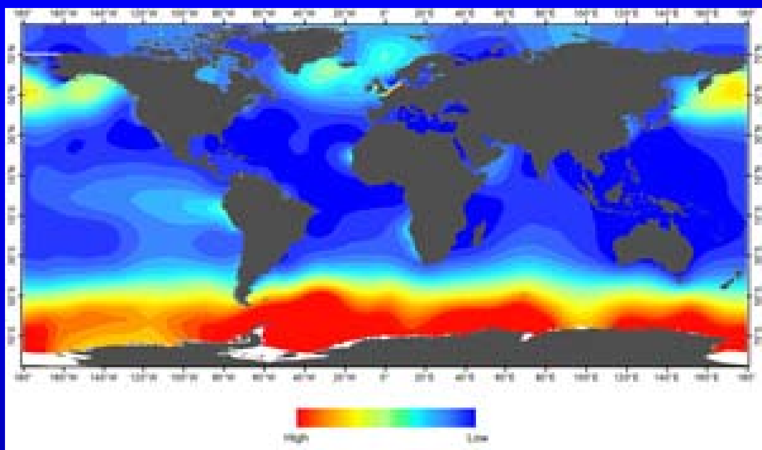
Sea surface

Seabed



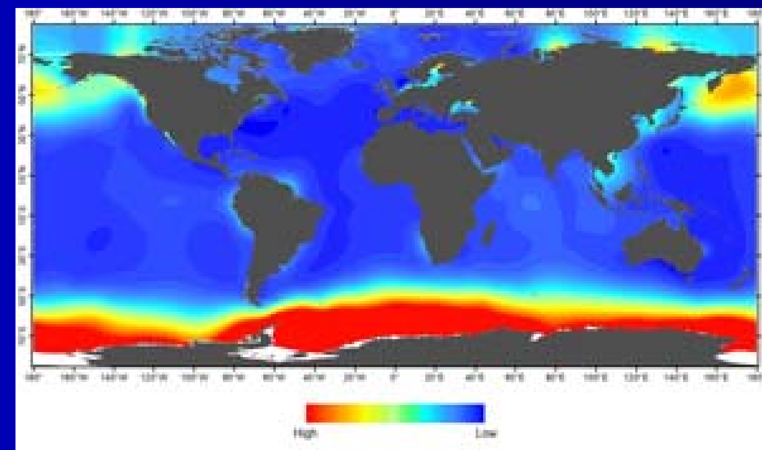
Images + 50 more from GMED
where data also available

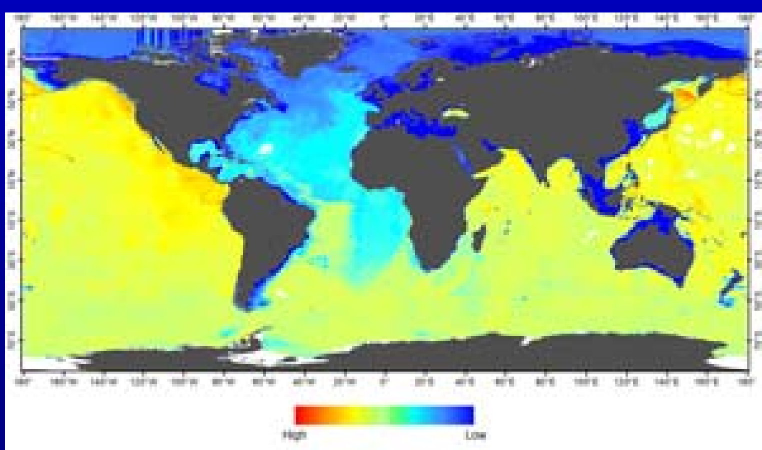
Nutrients



Sea surface nitrate

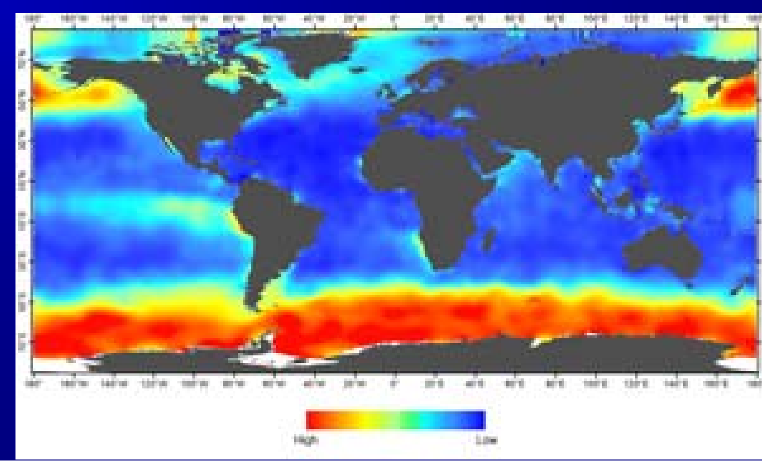
Silicate



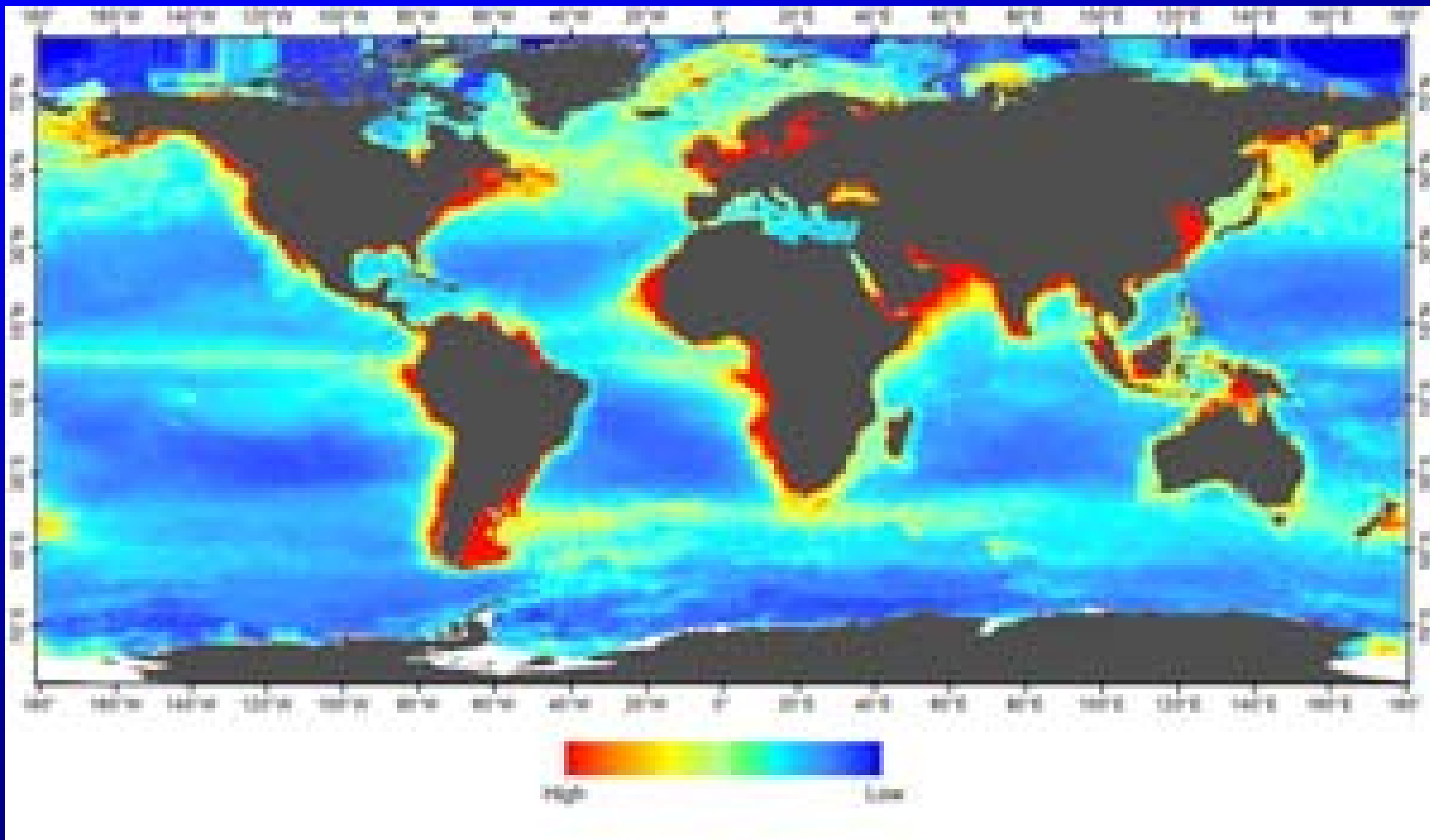


Sea bottom nitrate

Phosphate



Primary productivity: annual average



Biological response
to available nutrients
and suitable habitat
~
temperature and light

Biodiversity = variability of …..

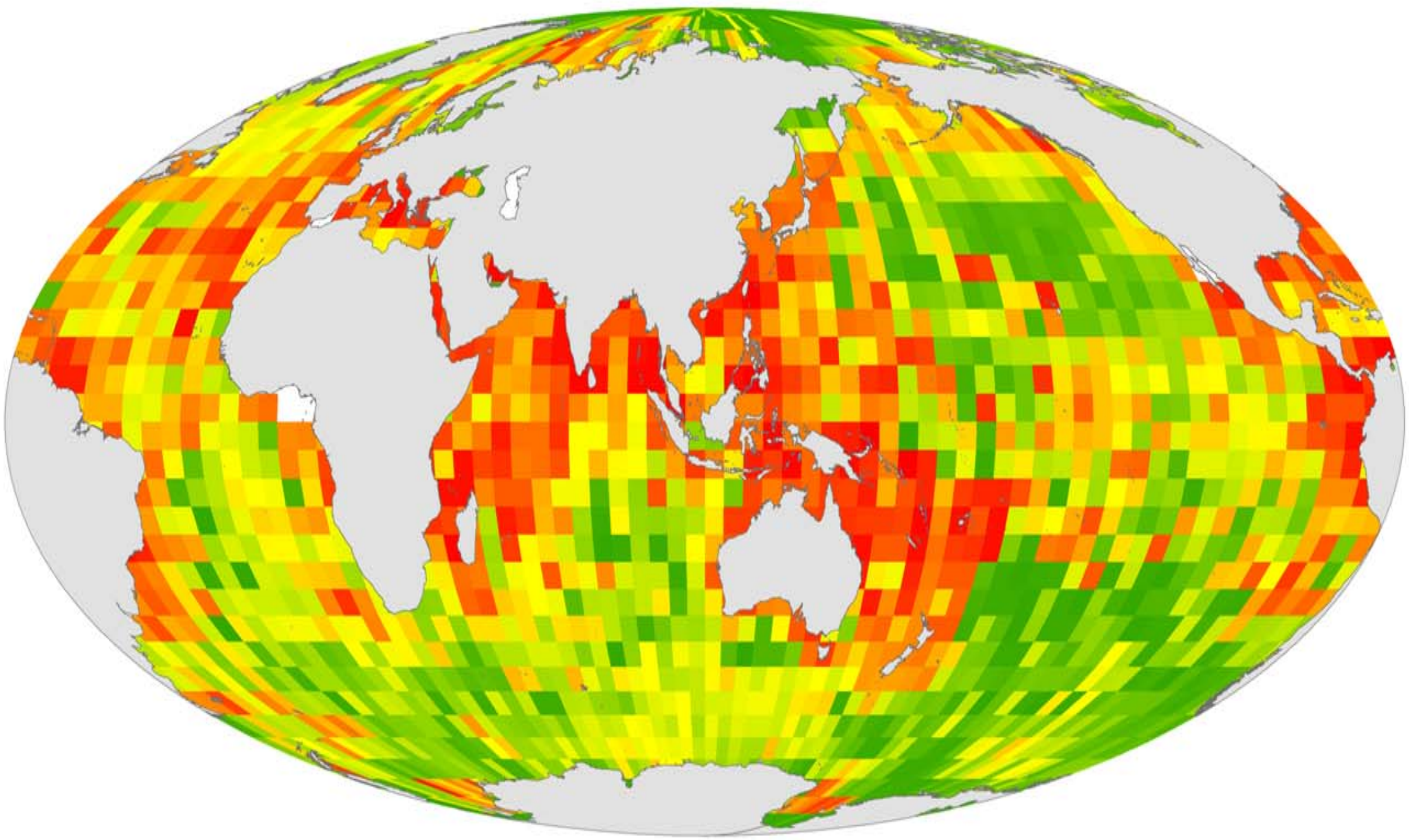
- **Species**
  - Richness ~ ecology and evolution
  - Endemicity ~ evolutionary history

+

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

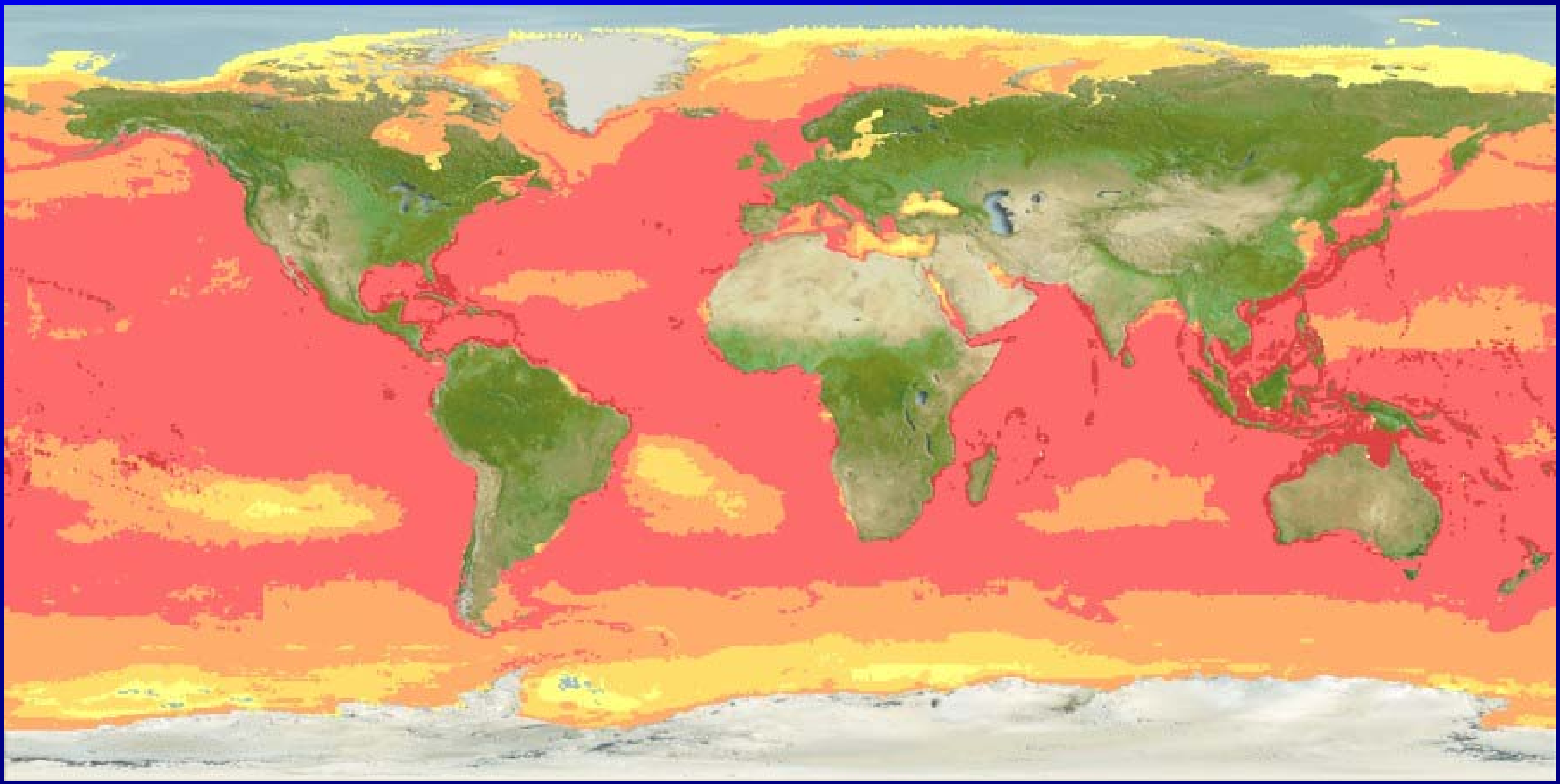
Species richness from samples

ES_{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

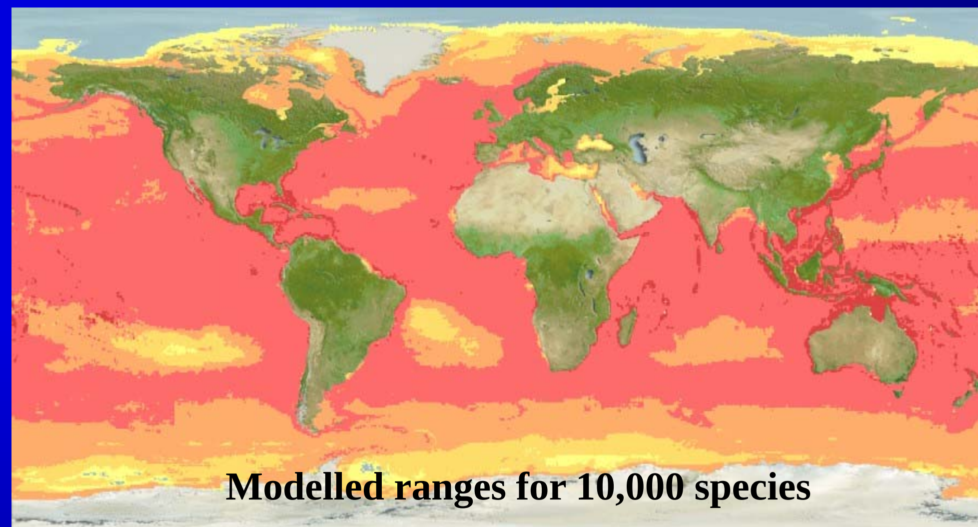
Aquamaps.org
Colours on log-scale.

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

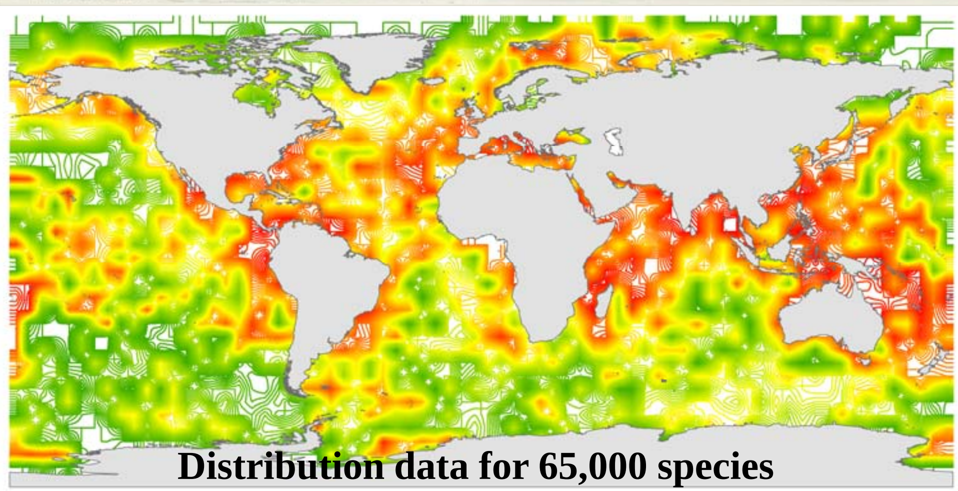
most species occur along coasts and tropics

OBIS 2009 data:

ES_{50} used to standardise for sampling effort.



Modelled ranges for 10,000 species



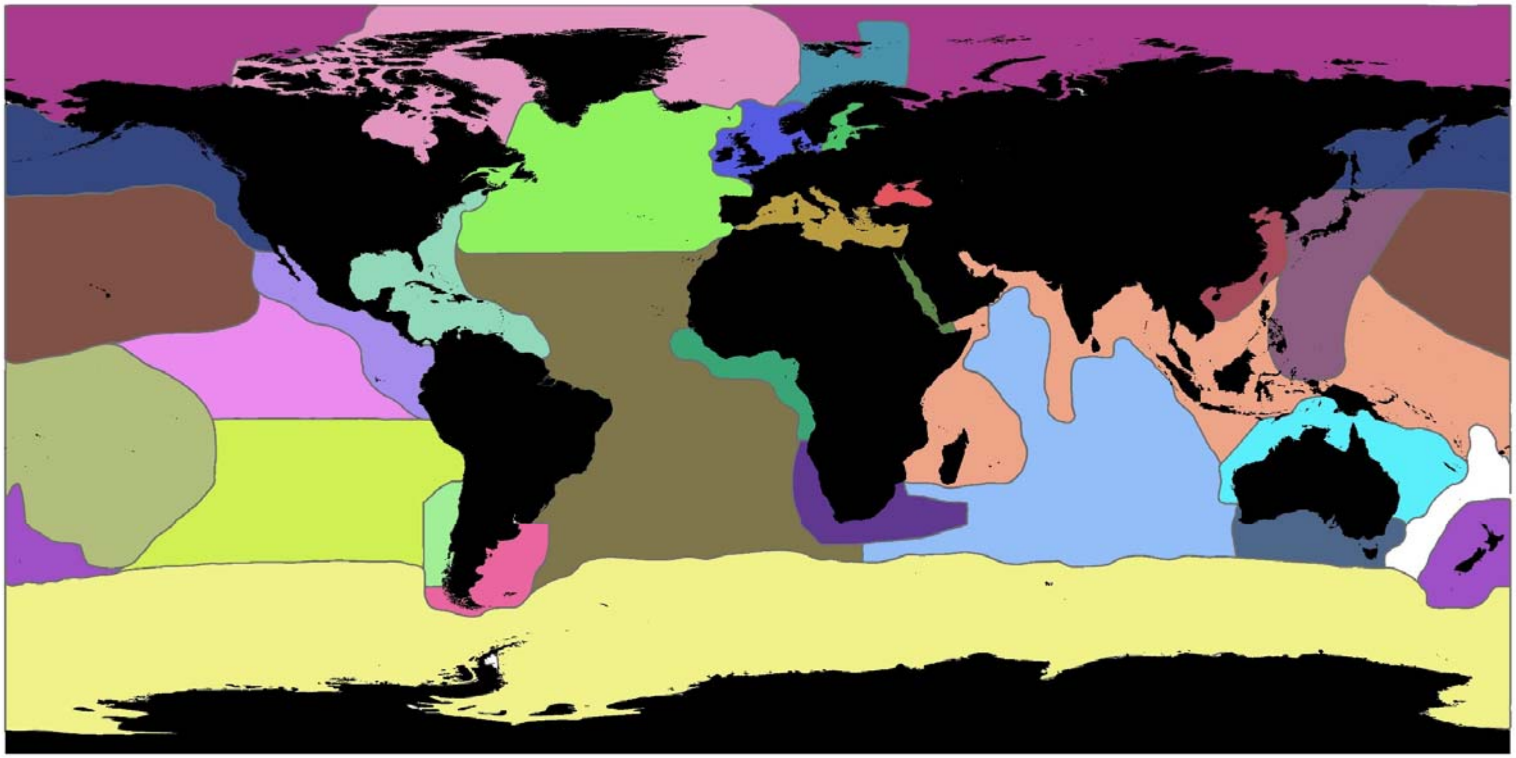
Distribution data for 65,000 species

Cluster analysis

- Species distribution data to group 5º 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

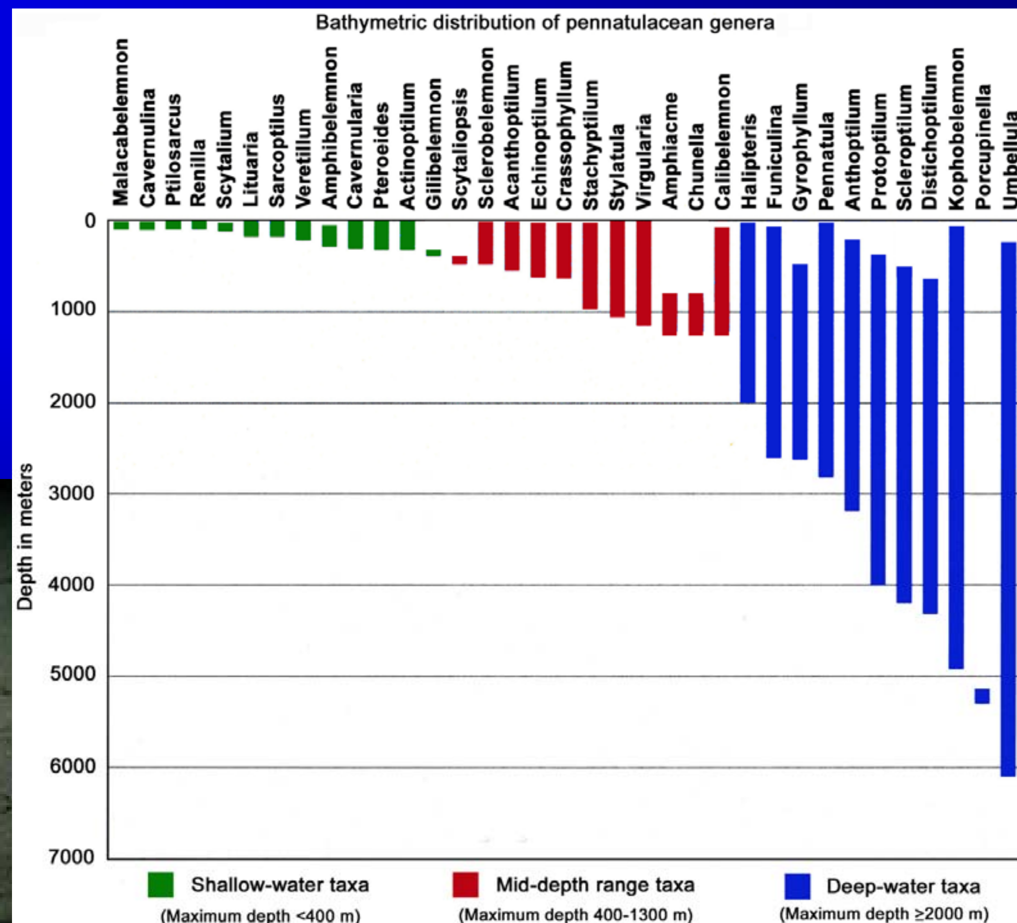


Most realms coastal, offshore realms larger

Species depth ranges increase with depth

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

Means fewer endemics with depth.



Williams. 2011. The Global Diversity of Sea Pens (Cnidaria: Octocorallia: Pennatulacea). PLoS ONE

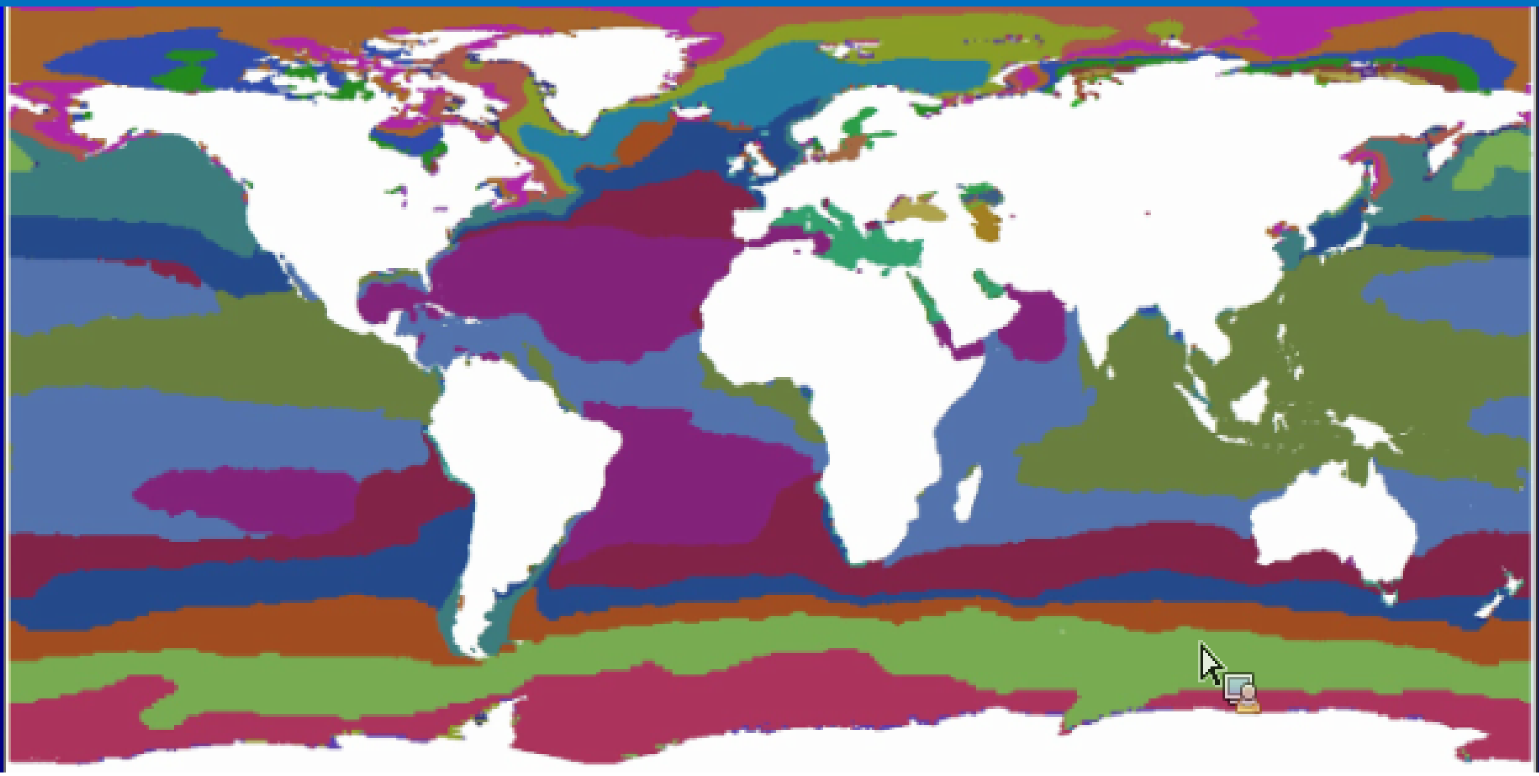
3D environmental mapping at ESRI

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

Depth (m)	Depth interval (m)
0 to 100	5
100 to 500	25
500 to 2,000	50
2,200 to 5,500	100

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

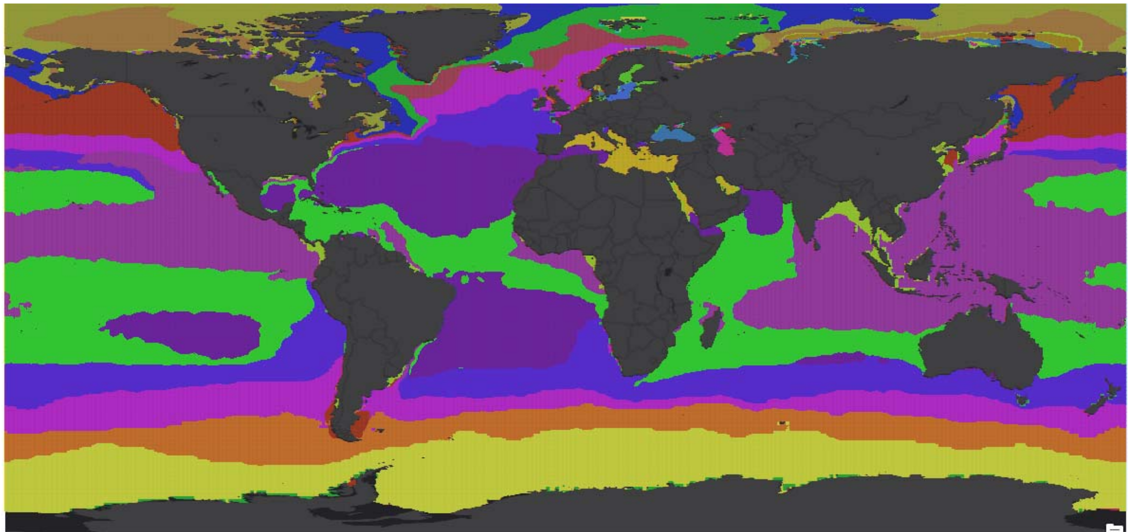
Resolution

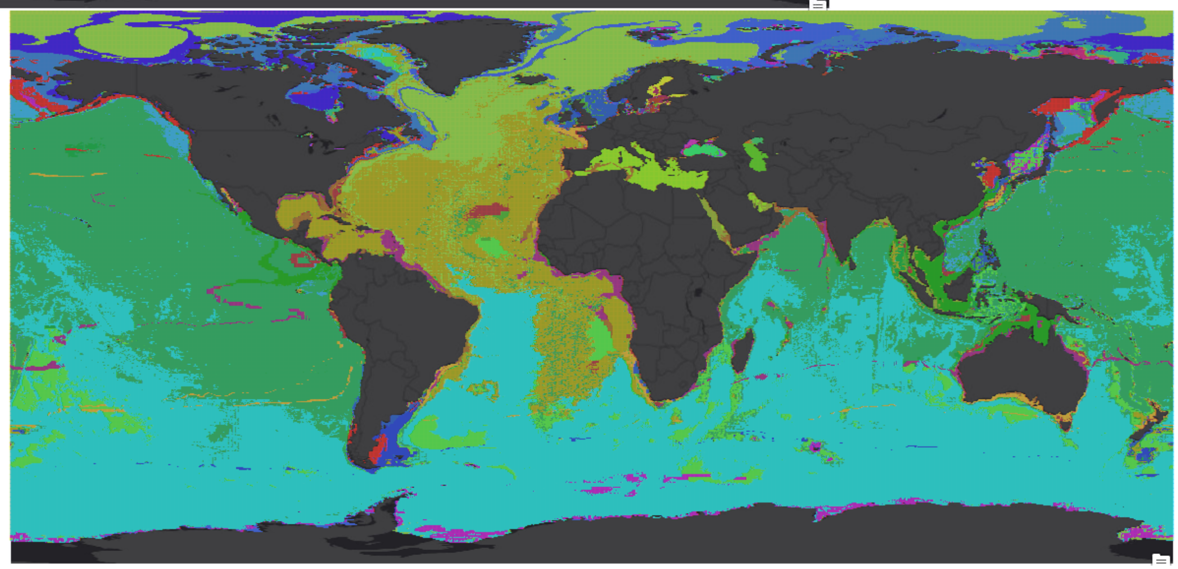
- Temporal = 57 year averages
- Spatial = 0.25^{o} latitude – longitude, ~27 km
- Depth = 3D in 102 depth bands

Clustering

- K-means with Euclidean distance
- pseudo F-statistic determined optimal number of clusters

Top of Water Column

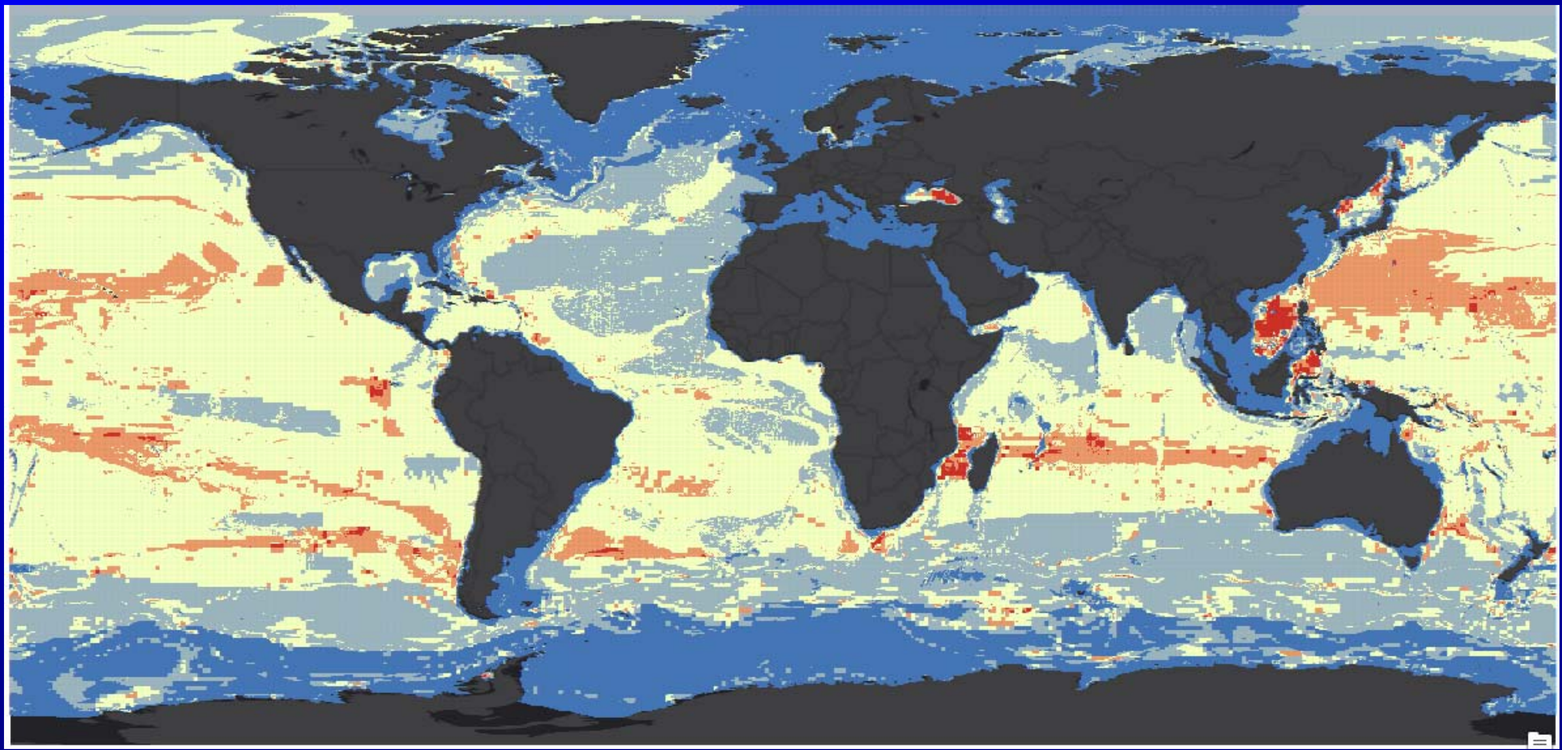




Bottom

EMU vary with depth ~ but most are coastal

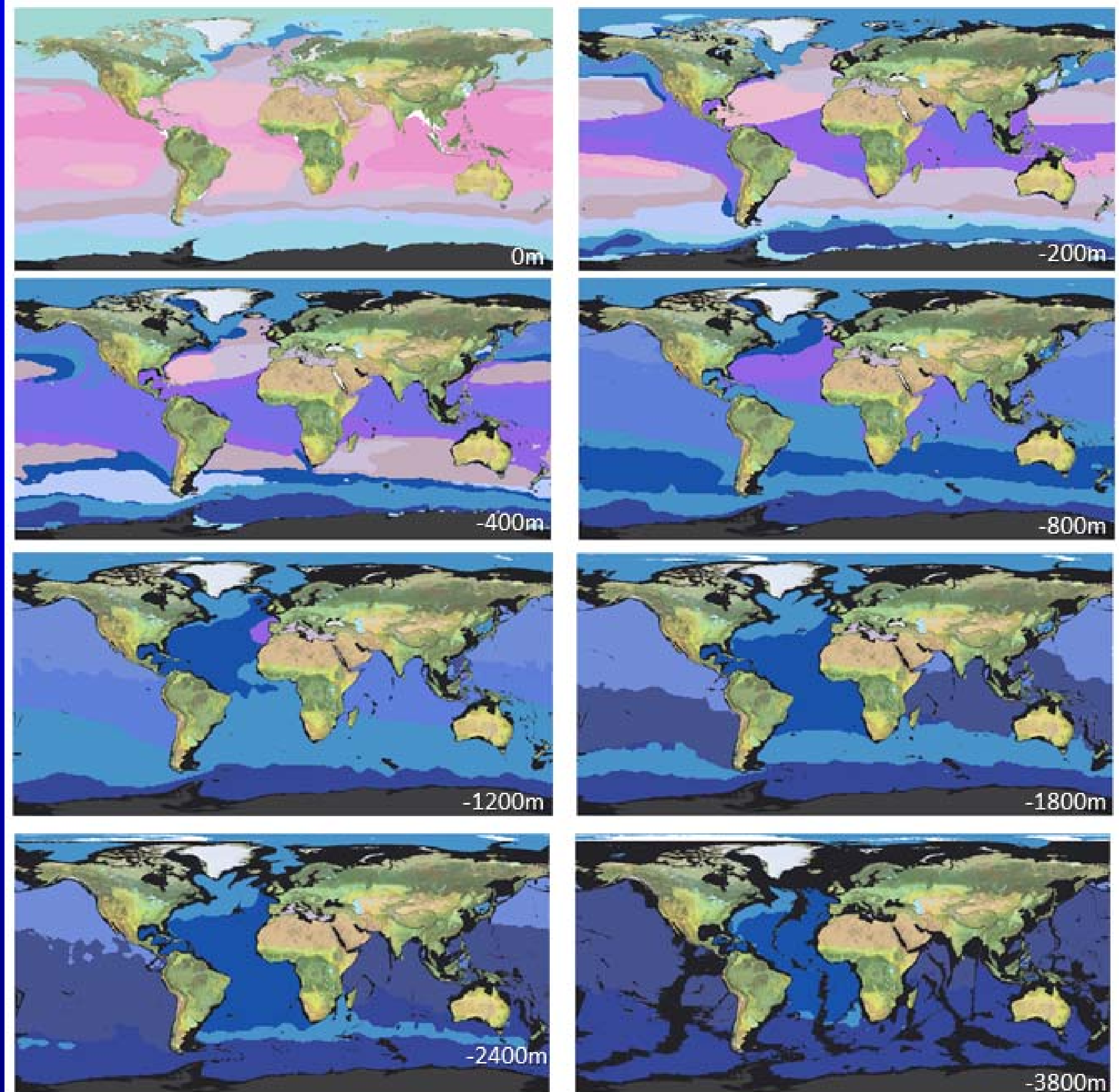
regions with 1-3 (dark blue), 6-8 (yellow), 12-21 (red)



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

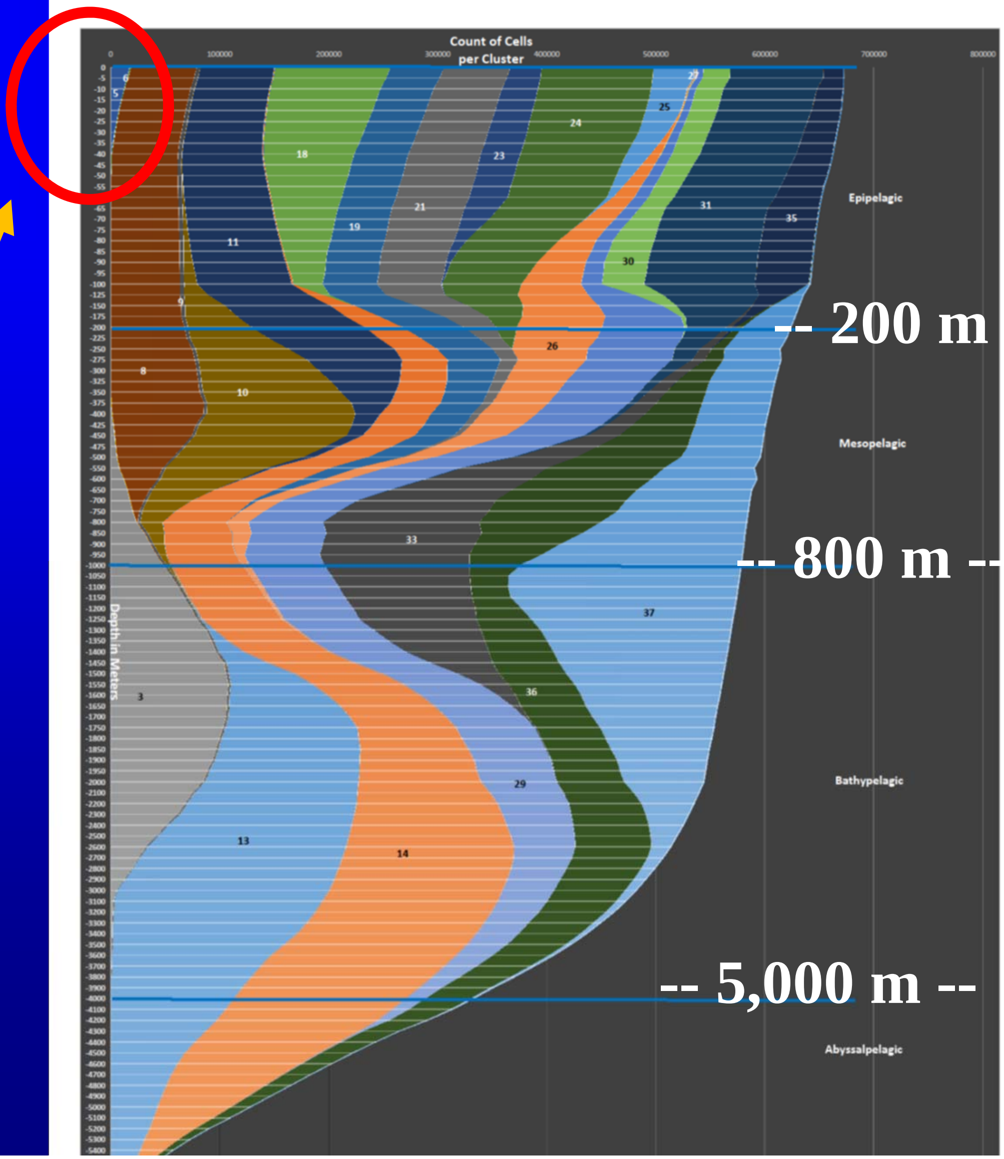
Depth band	Number EMU
< 500	30
< 1,000	5
< 2,000	2
Total	**37**

EMU can be viewed at different depths



Each colour is an EMU

Many coastal EMU not visible



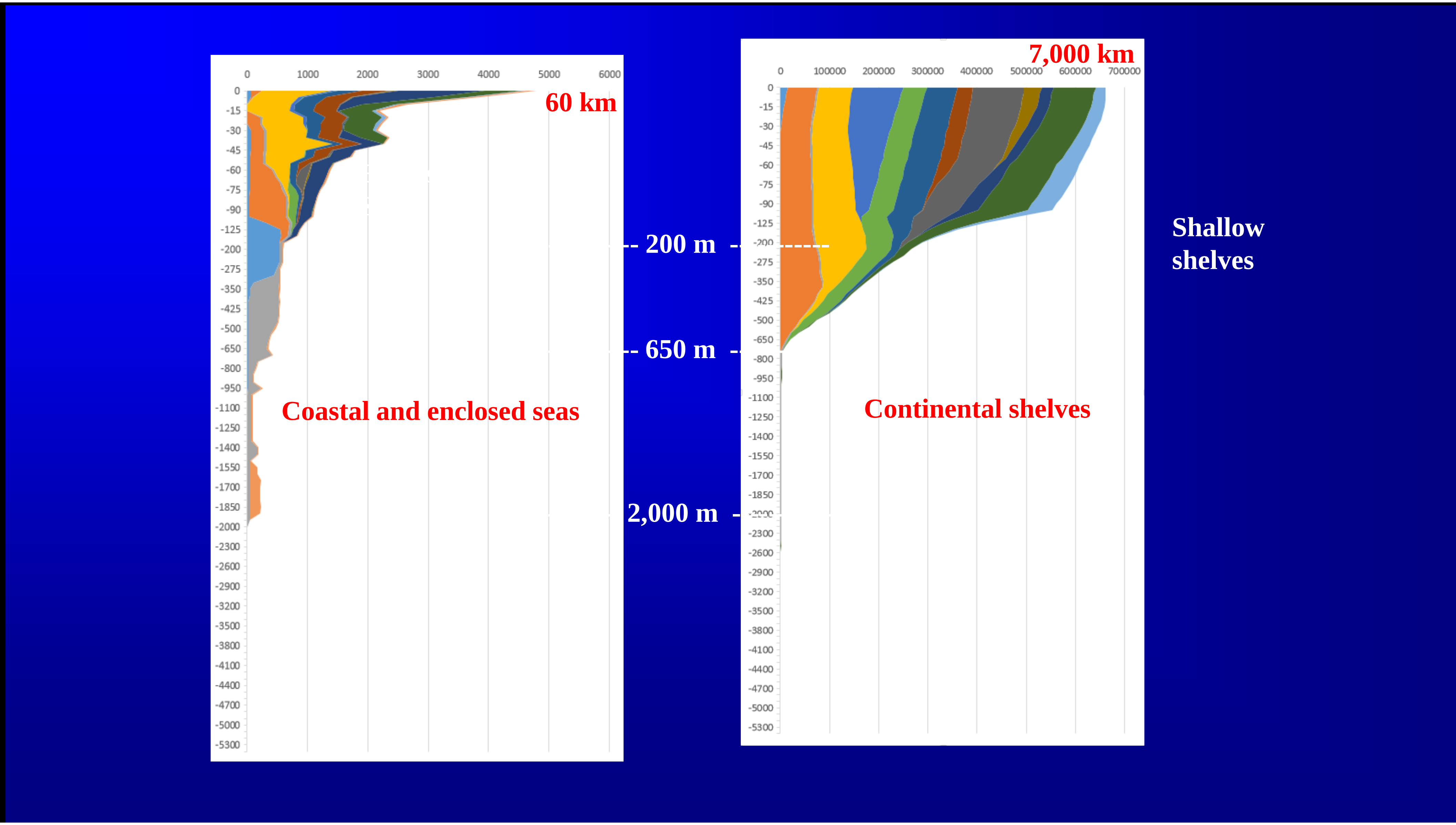
Do distinct depth zones exist?

Epi-pelagic

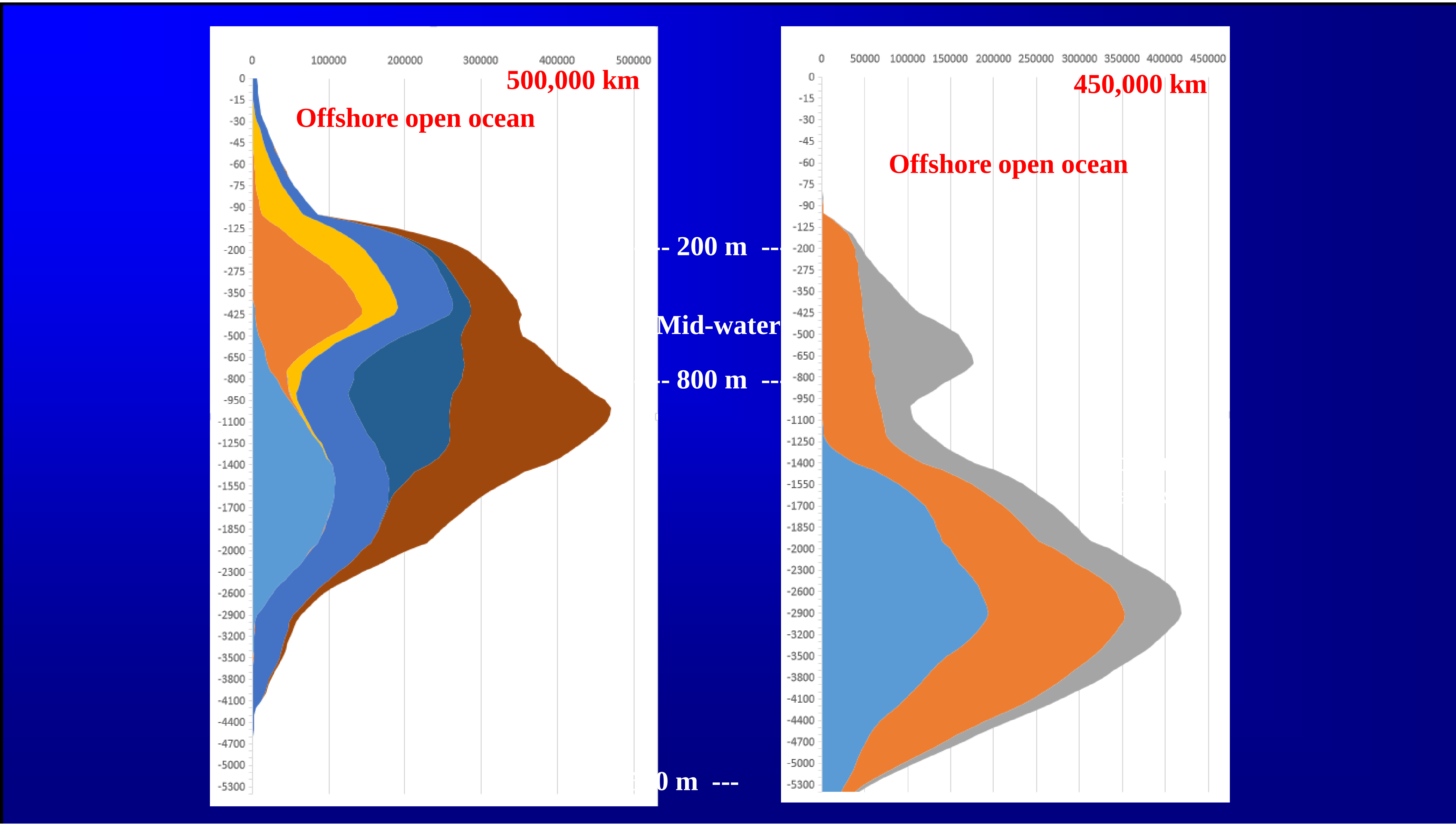
Meso-pelagic

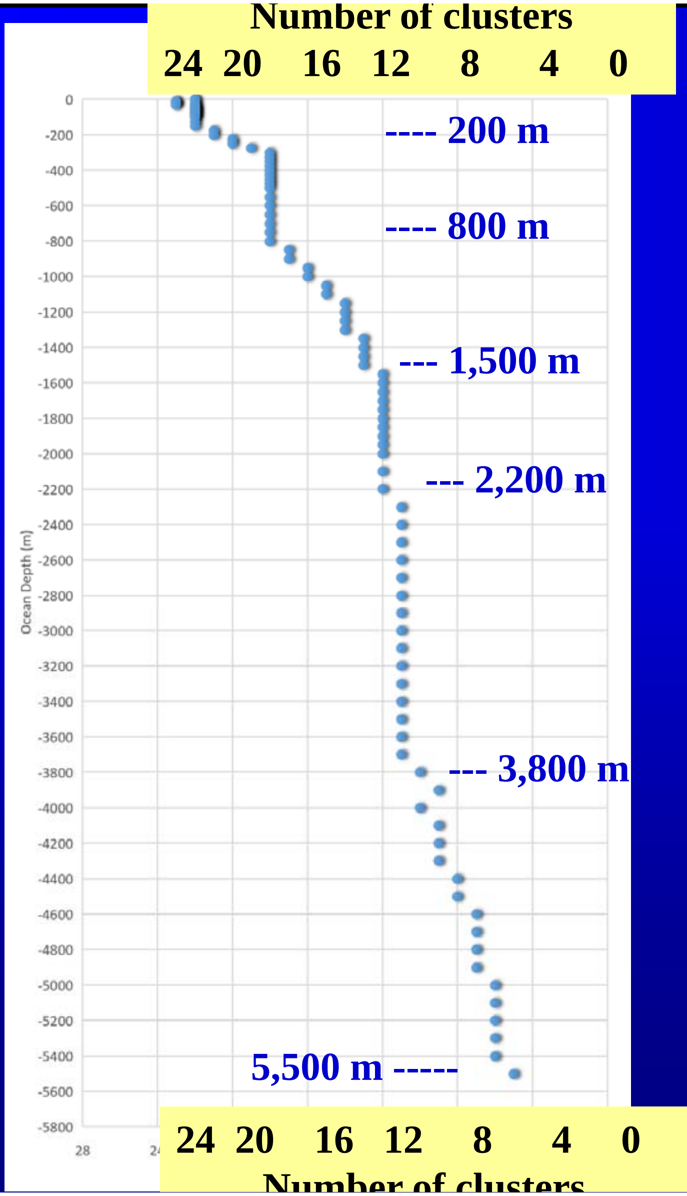
Bathy-pelagic

Abysso-pelagic

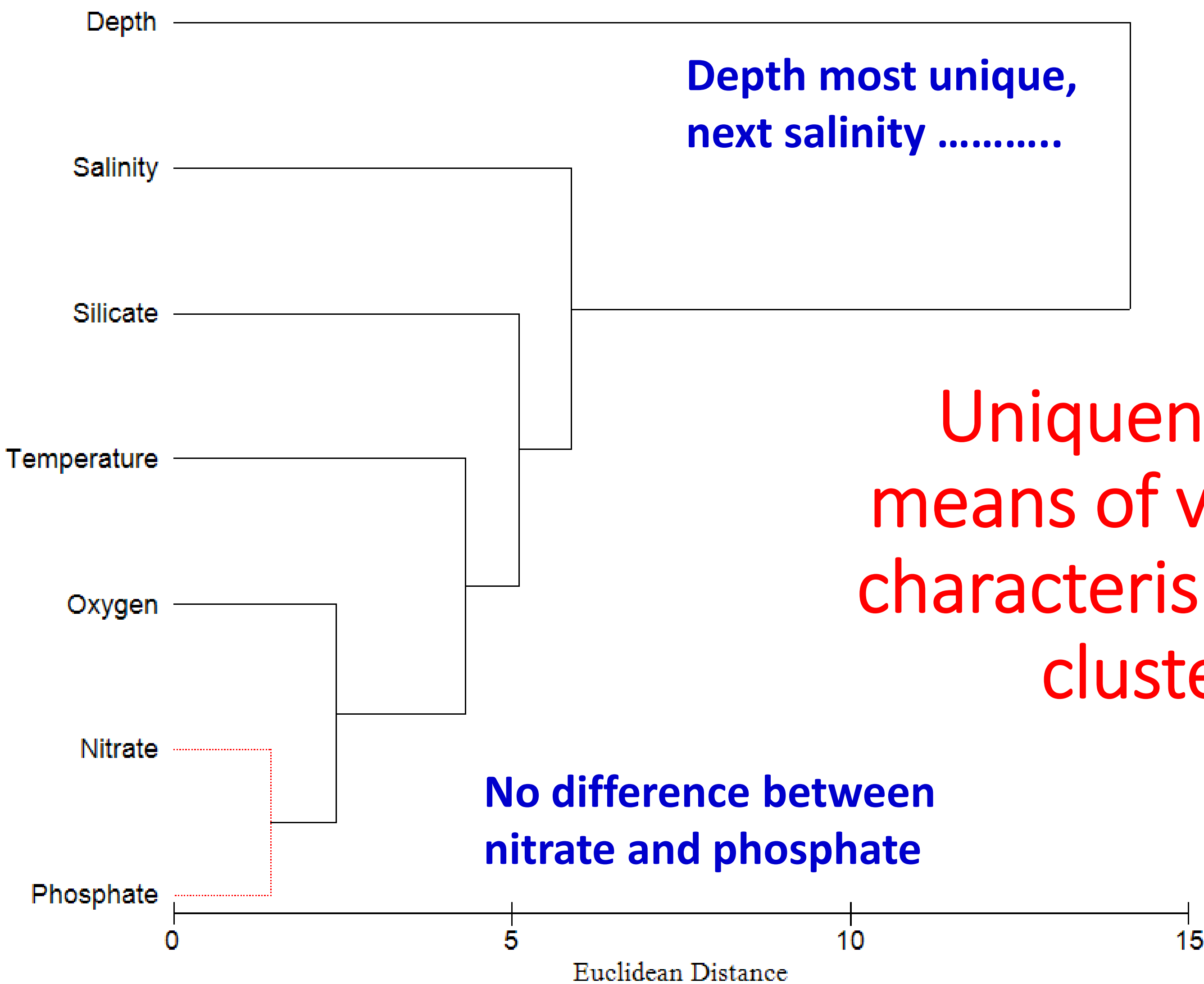


0 1000 2000 3000 4000 5000 6000
60 km
0 -15 -30 -45 -60 -75 -90 -125 -200 -275 -350 -425 -500 -650 -800 -950 -1100 -1250 -1400 -1550 -1700 -1850 -2000 -2300 -2600 -2900 -3200 -3500 -3800 -4100 -4400 -4700 -5000 -5300
Coastal and enclosed seas
200 m
650 m
2,000 m
7,000 km
0 100000 200000 300000 400000 500000 600000 700000
Continental shelves
Shallow shelves


500,000 km
Offshore open ocean
0 100000 200000 300000 400000 500000
0 -15 -30 -45 -60 -75 -90 -125 -200 -275 -350 -425 -500 -650 -800 -950 -1100 -1250 -1400 -1550 -1700 -1850 -2000 -2300 -2600 -2900 -3200 -3500 -3800 -4100 -4400 -4700 -5000 -5300
-- 200 m --
Mid-water
-- 800 m --
0 m ---
450,000 km
Offshore open ocean
0 50000 100000 150000 200000 250000 300000 350000 400000 450000
0 -15 -30 -45 -60 -75 -90 -125 -200 -275 -350 -425 -500 -650 -800 -950 -1100 -1250 -1400 -1550 -1700 -1850 -2000 -2300 -2600 -2900 -3200 -3500 -3800 -4100 -4400 -4700 -5000 -5300

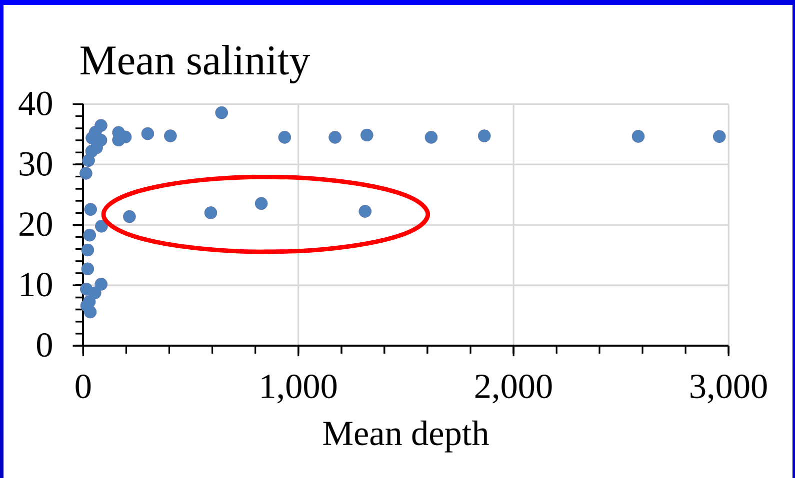


- Epi-pelagic
- Upper Meso-pelagic
- Lower Meso-pelagic
- Upper Bathy-pelagic
- Lower Bathy-pelagic
- Abysso-pelagic ?
- ?



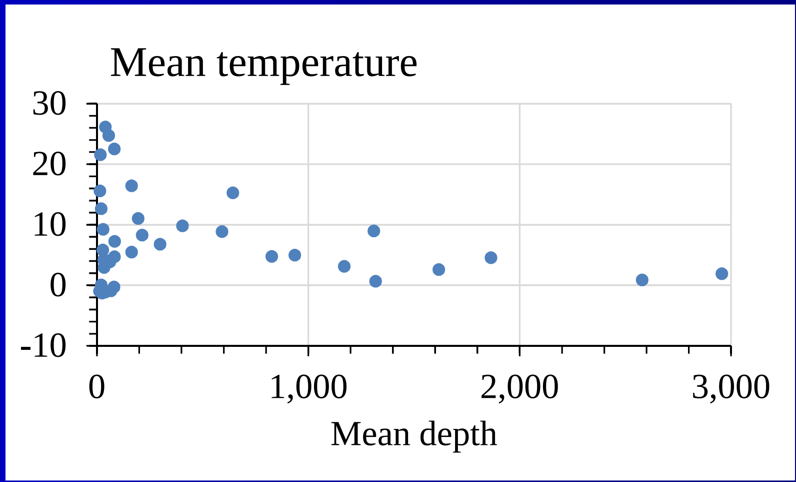
Uniqueness of means of variables characterising EMU clusters

Variation in variables with depth

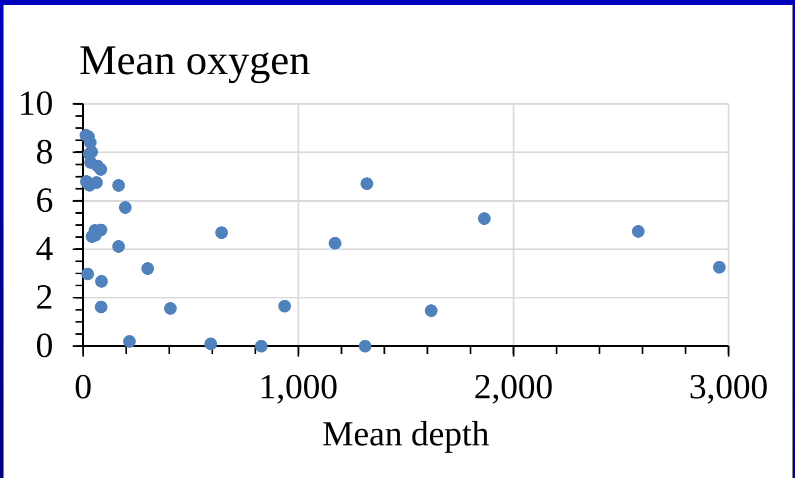


Low salinity in shallow,

But some exceptions



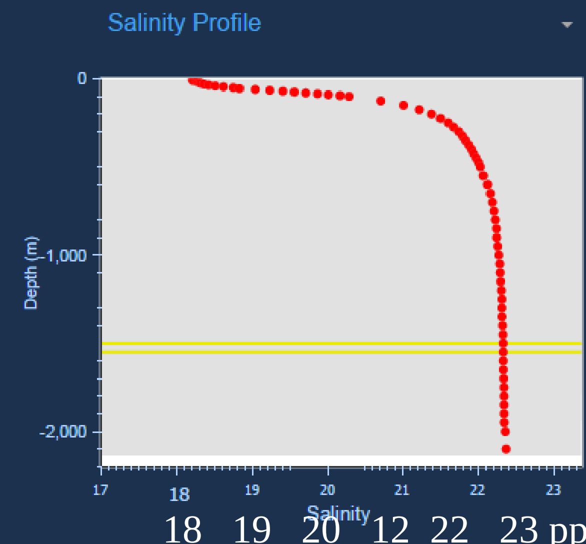
Temperature
Variable in shallow
Low in deep-sea



Oxygen
Variable in shallow
Mid to low in deep-sea

Low salinity in deep sea – Black & Caspian Seas

Ecological Marine Unit Explorer

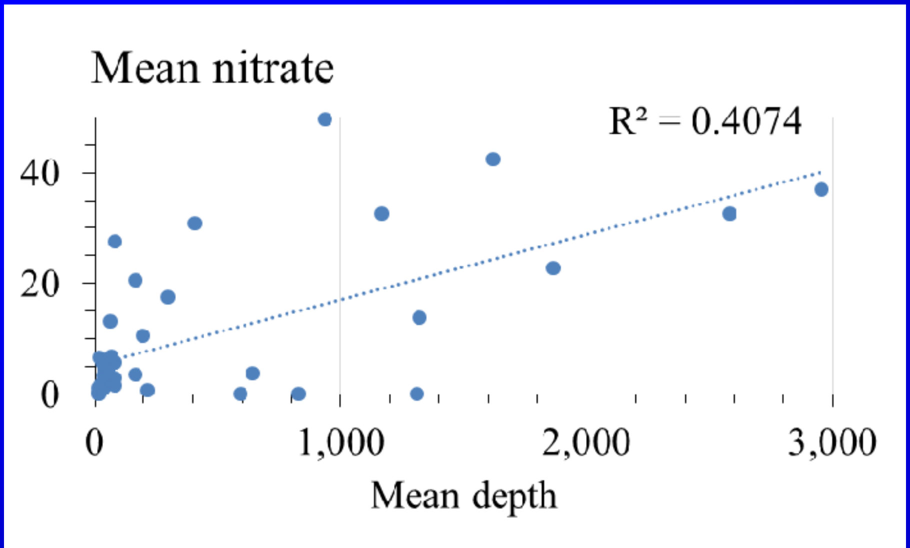


	Temperature	Salinity	Dissolved O_2	Nitrate	Phosphate	Silicate	Thickness	Unit Top
Minimum	4.62	21.72	0.00	0.00	5.13	111.00	5.00	-2000.00
Maximum	14.93	22.40	0.70	1.45	7.27	231.35	100.00	0.00
Average	8.89	22.03	0.10	0.11	6.18	160.29	38.30	-592.35
SD	0.15	0.16	0.11	0.26	0.54	30.75	13.70	285.90

EMU
1
4, 15
4, 15
4, 15
4, 15
34, 15
34, 15

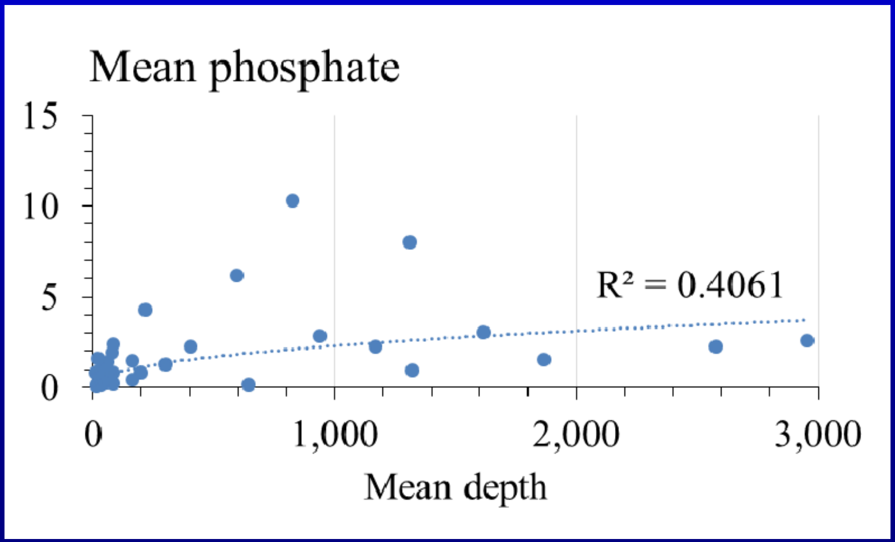
1	-125	225
4	-350	300
15	-650	100
4	-750	50
15	-800	200
4	-1000	50
15	-1050	450
4	-1500	50
15	-1550	100
34	-1650	100
15	-1750	100
34	-1850	150
15	-2000	200

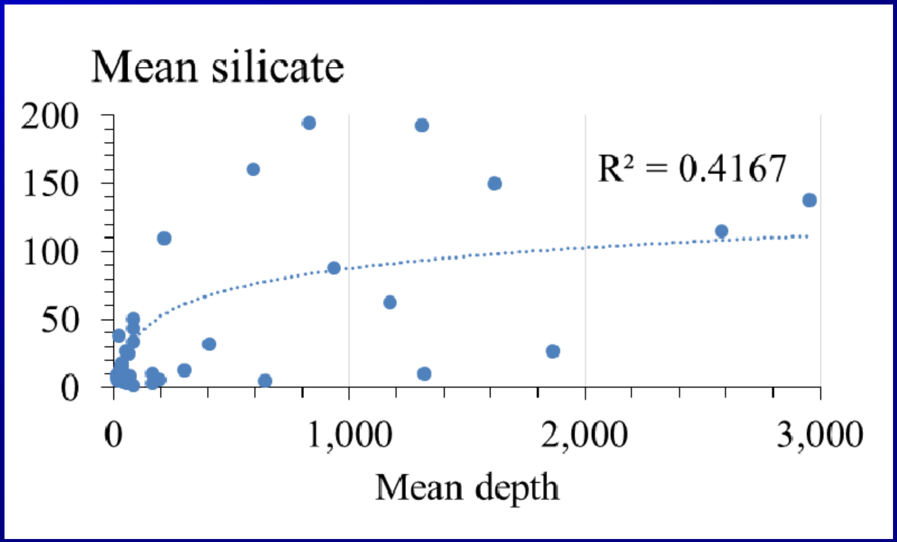
Note alternate layering of EMU with depth



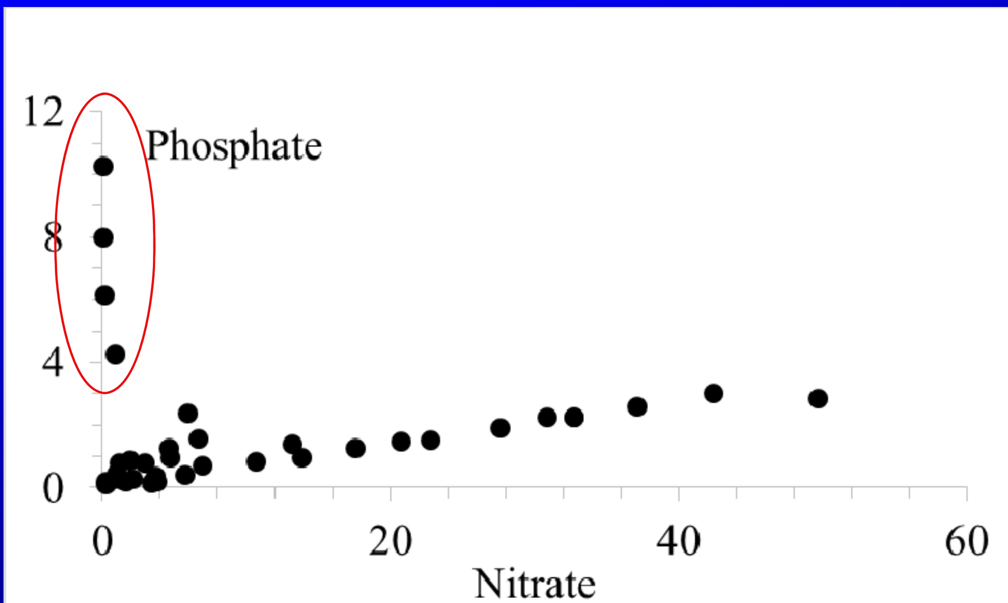
Nitrate increases with depth due to less primary production using it

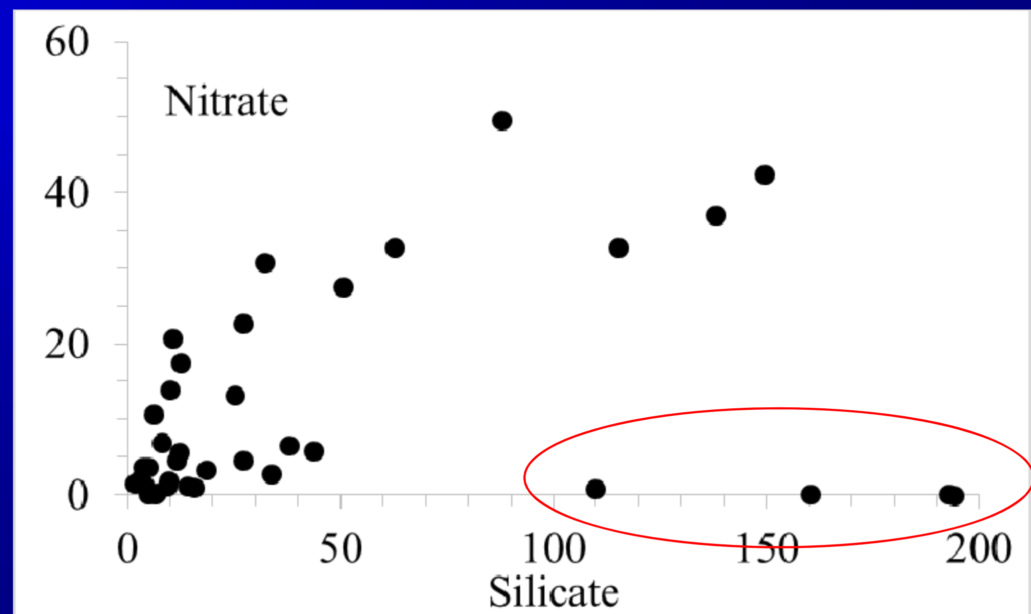
Phosphate and silicate first increase but then less with depth





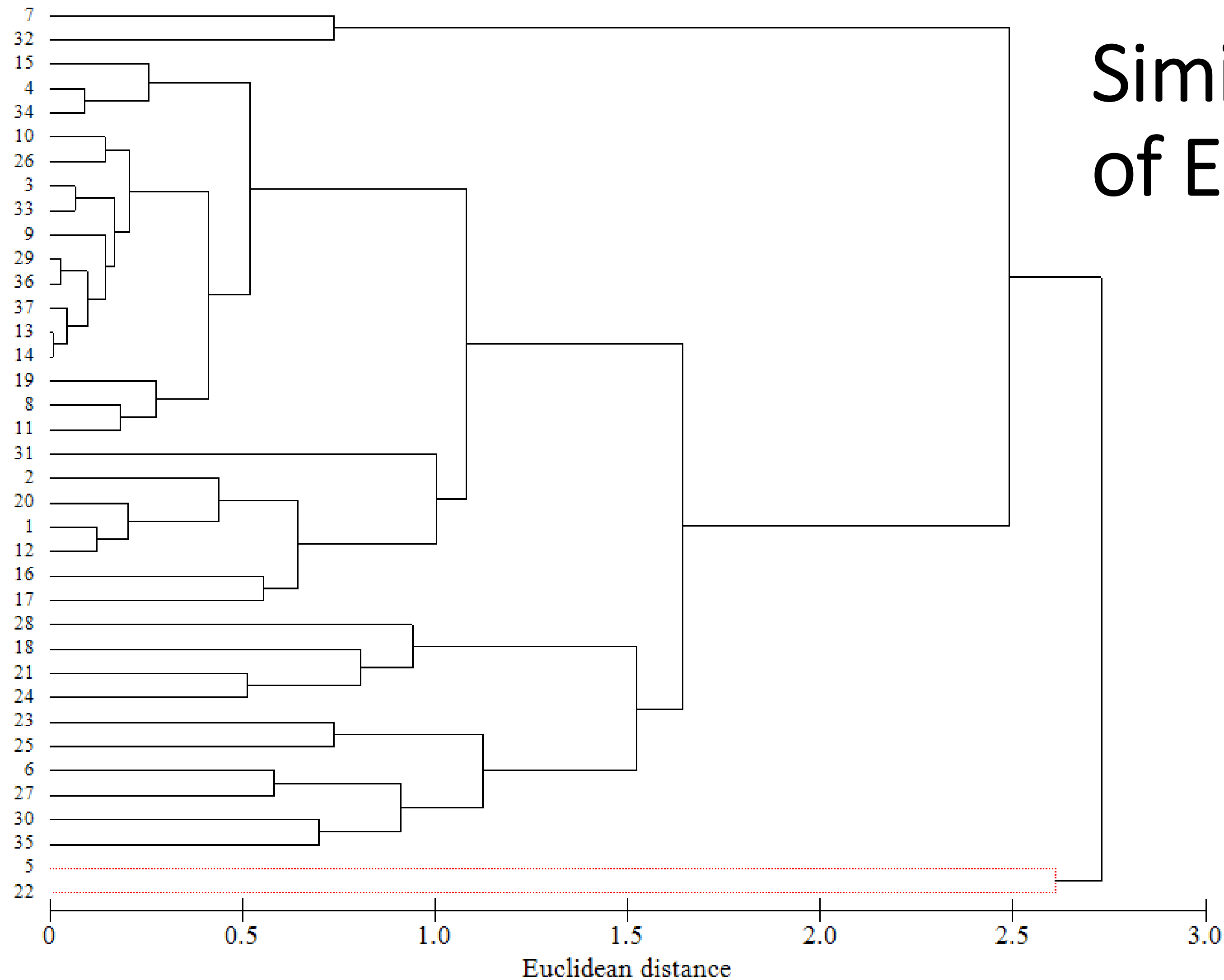
Nutrient relationships not always simple



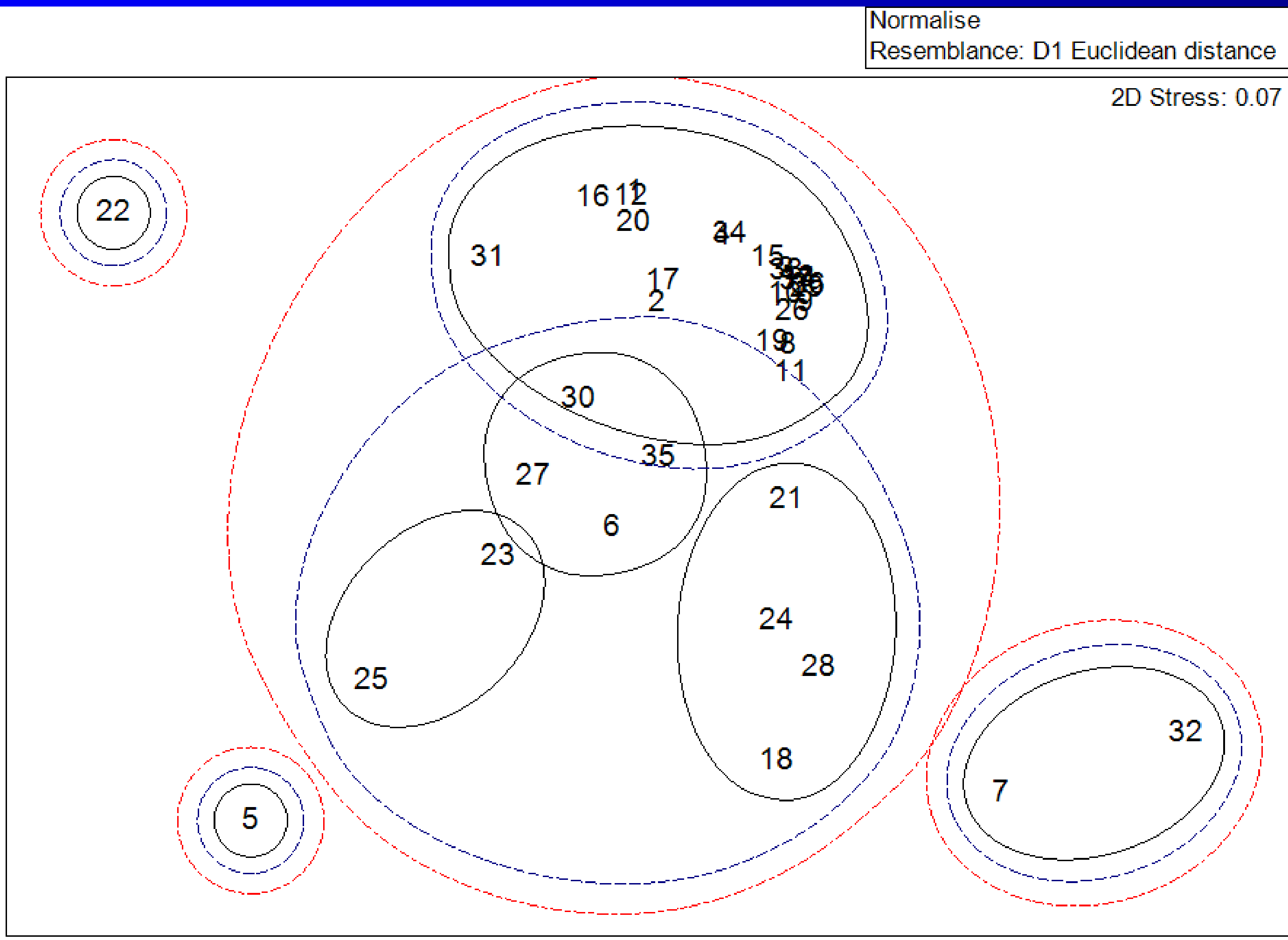


Outliers Black and Caspian Seas

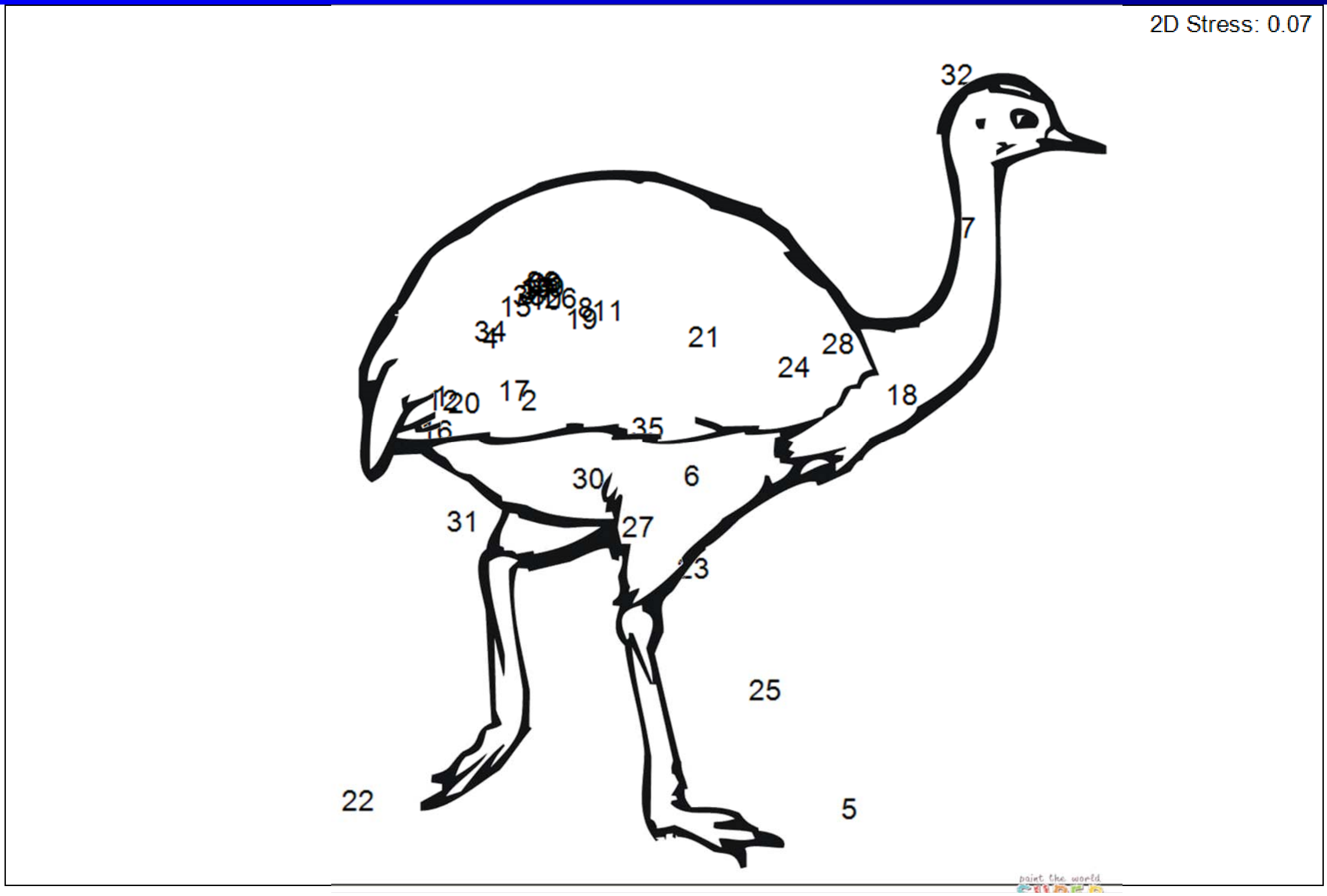
Similarity of EMU



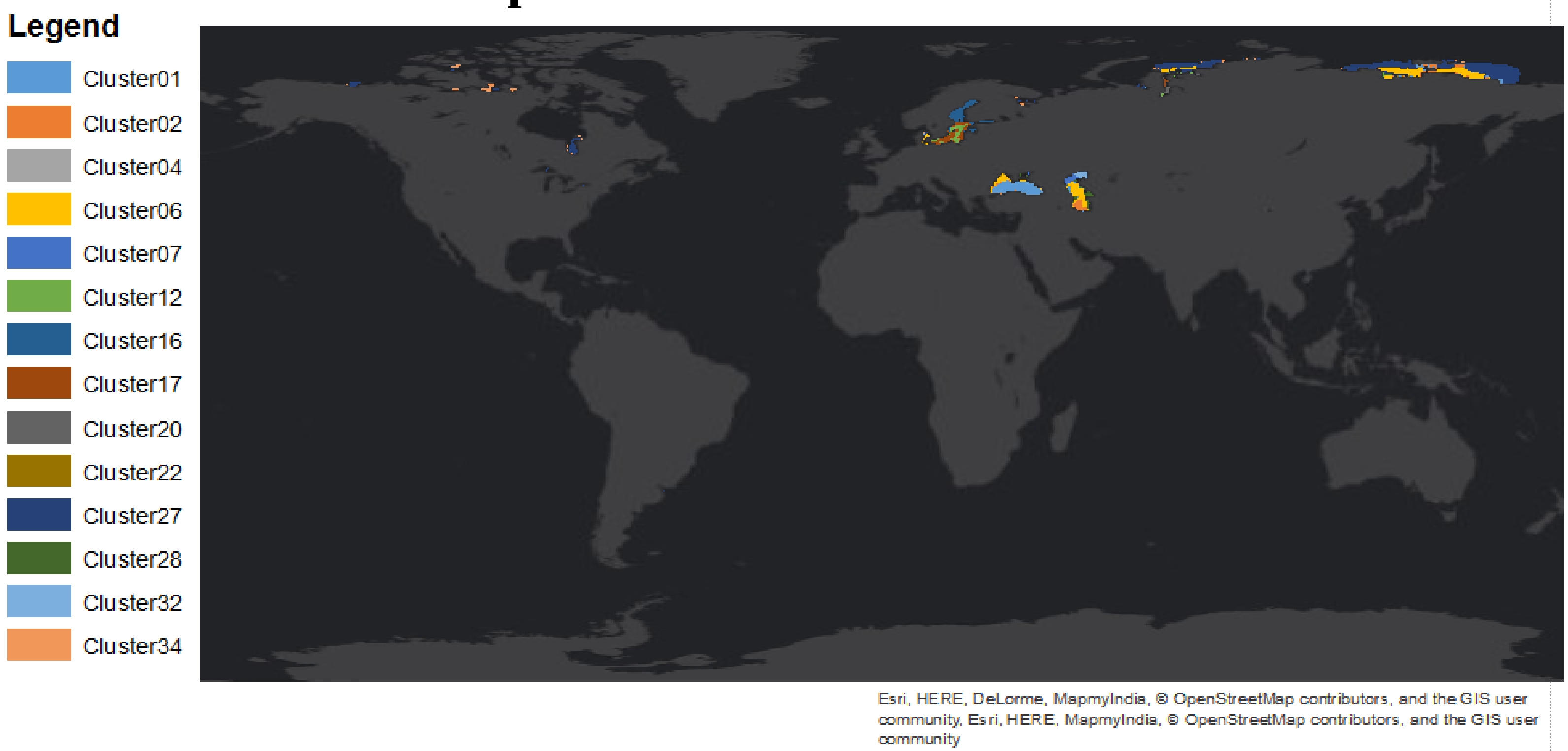
EMU similarity by MDS



MDS of EMU relationships

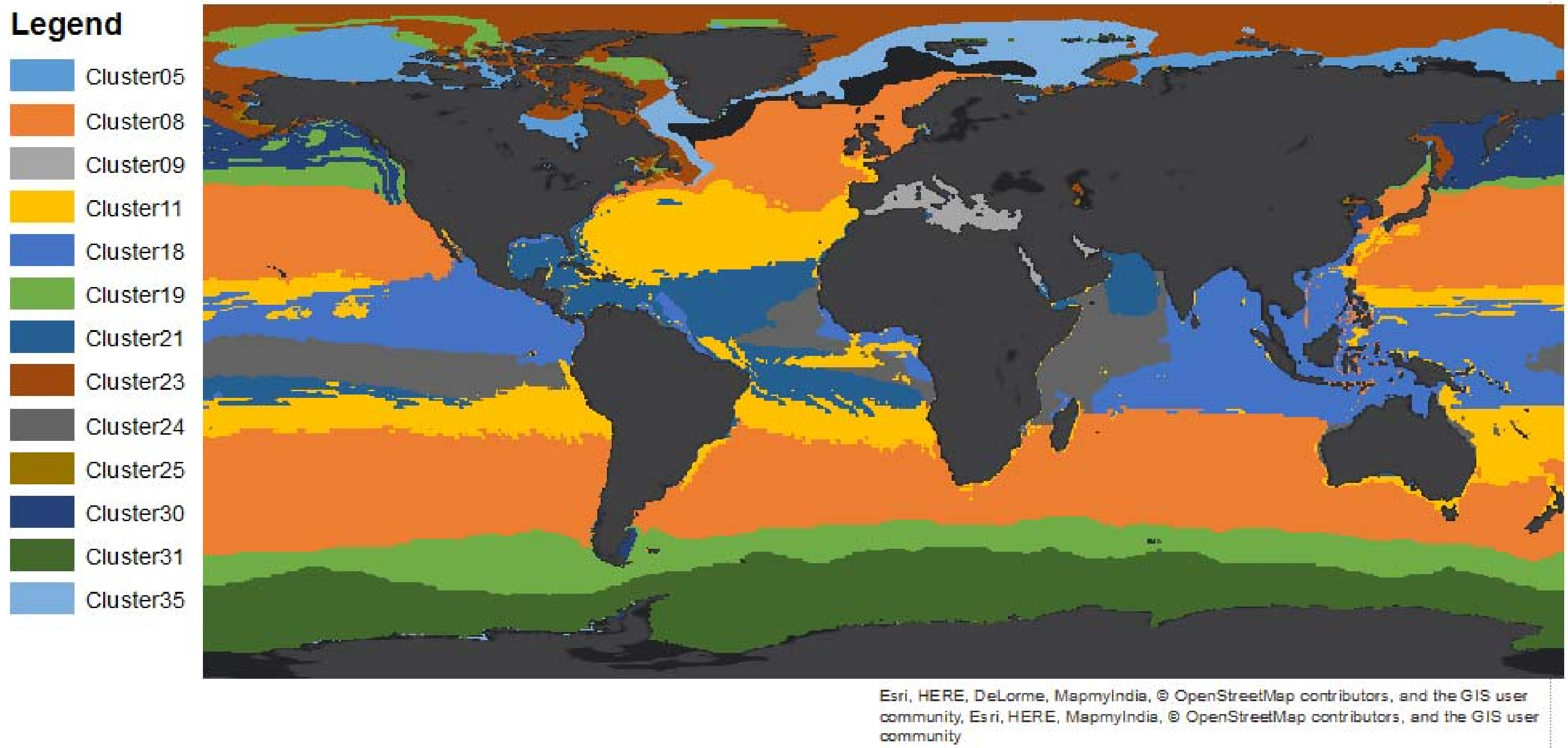


Enclosed European seas and Arctic – 14 Clusters



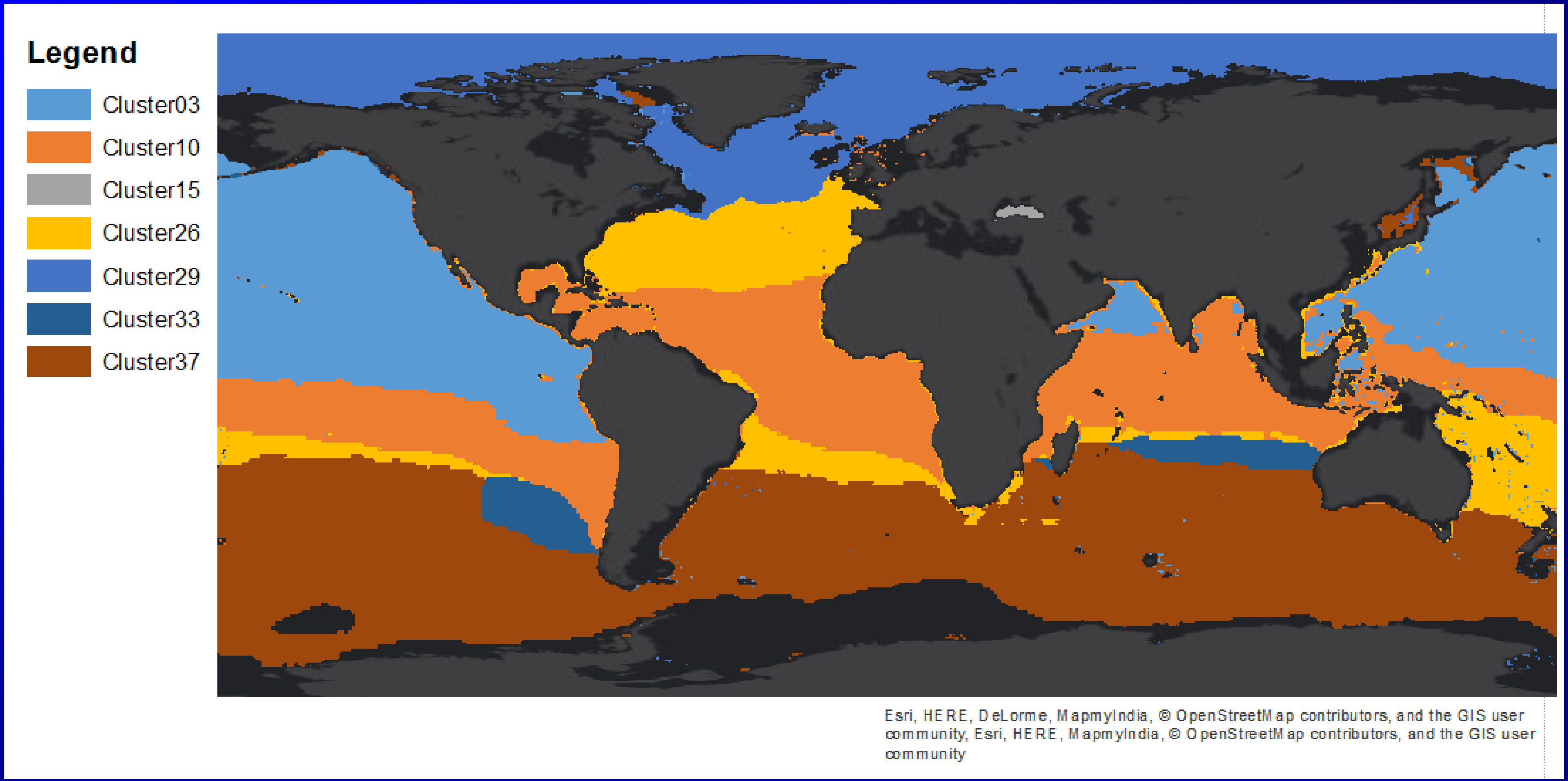
1. **Cold < 10 ºC**
2. **Shallow < 200 m**
3. **Low and high salinity clusters**

Ocean Upper Water Column – 13 Clusters



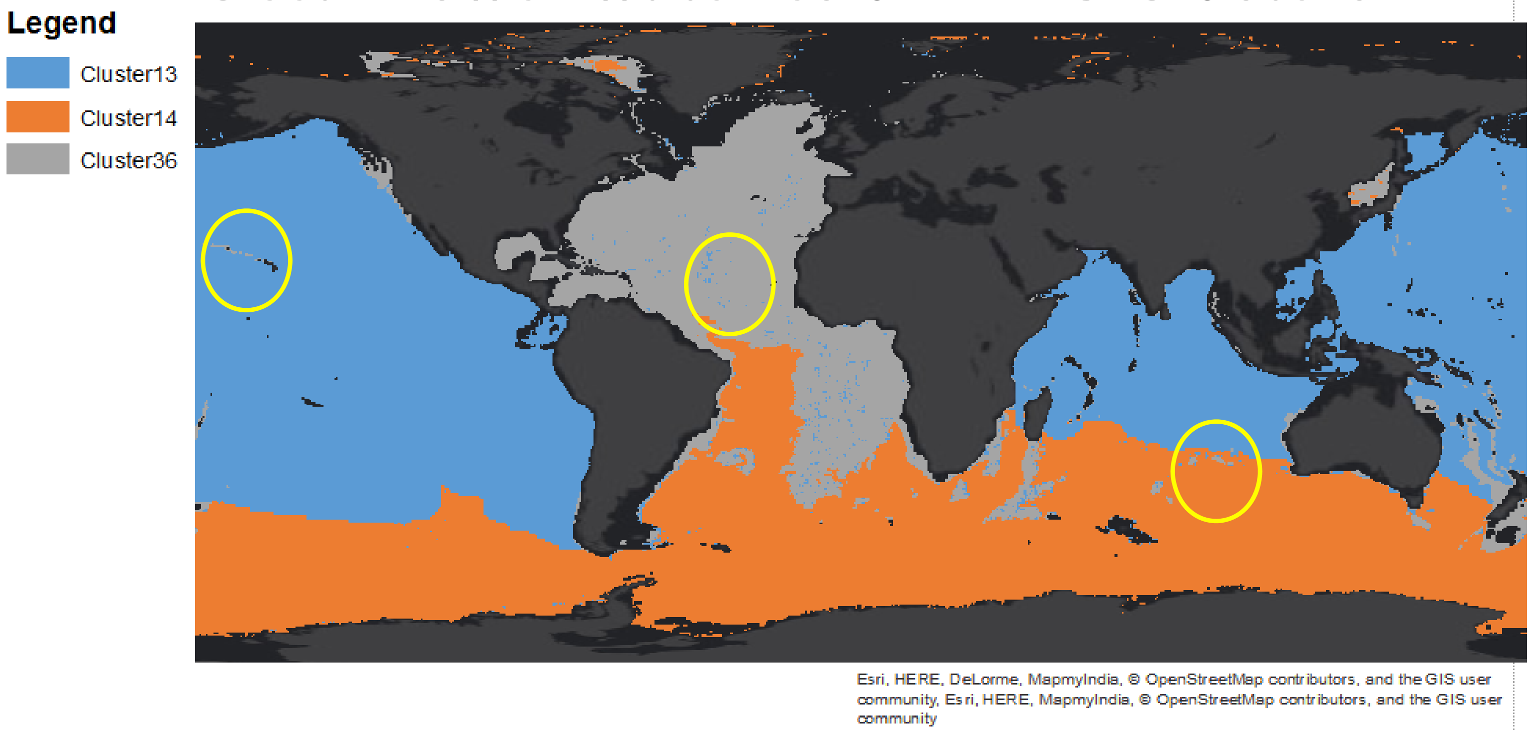
1. **Across all oceans**
2. **Strong influence of latitude (temperature)**
3. **Open ocean and coastal contrast**
4. **Arctic and Southern Ocean very different**

Ocean mid-water column – 7 Clusters



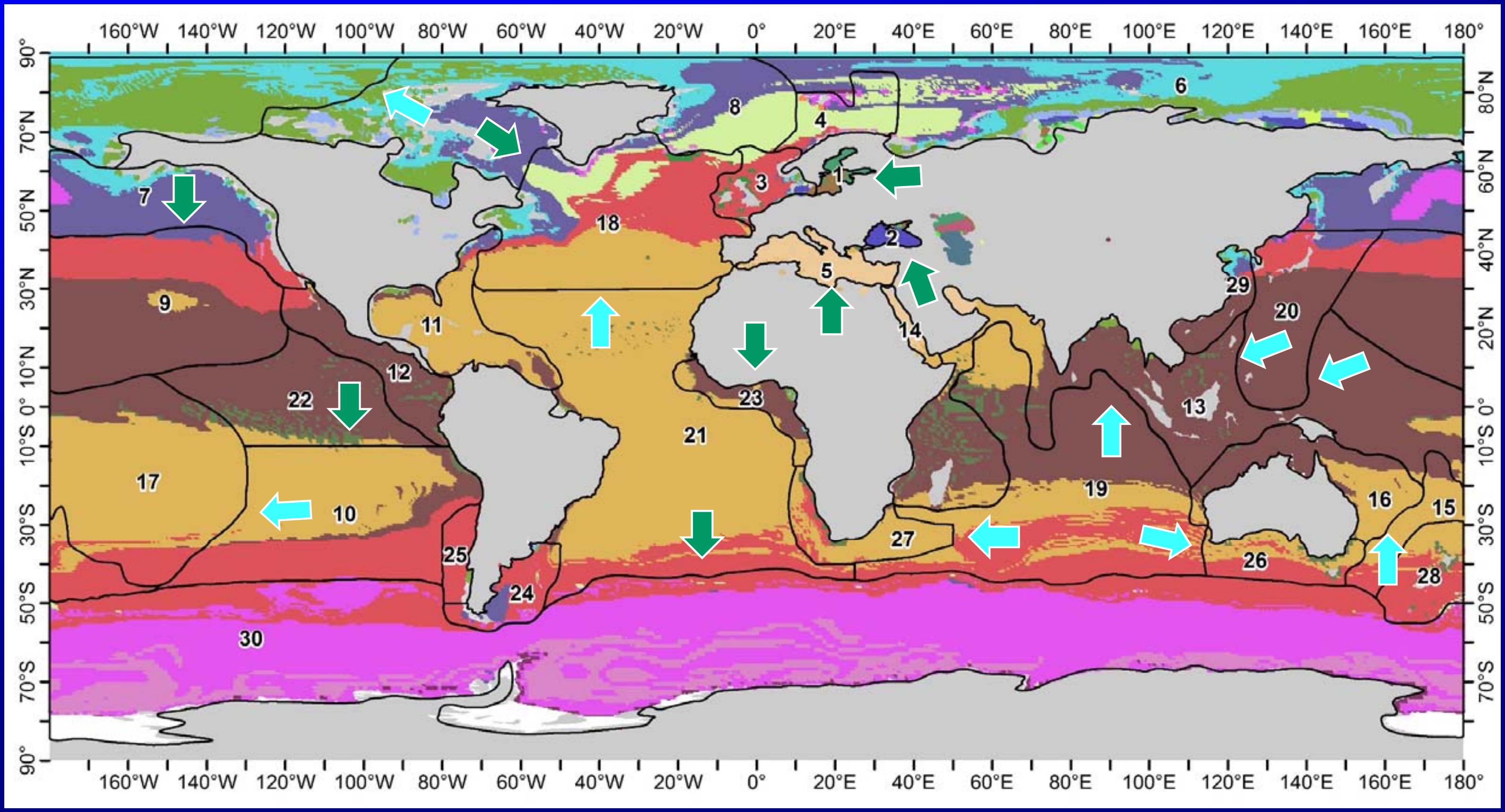
1. **Across all oceans**
2. **Less influence of latitude**
3. **Each cluster has open ocean and coastal presence**

Ocean lower water column – 3 Clusters



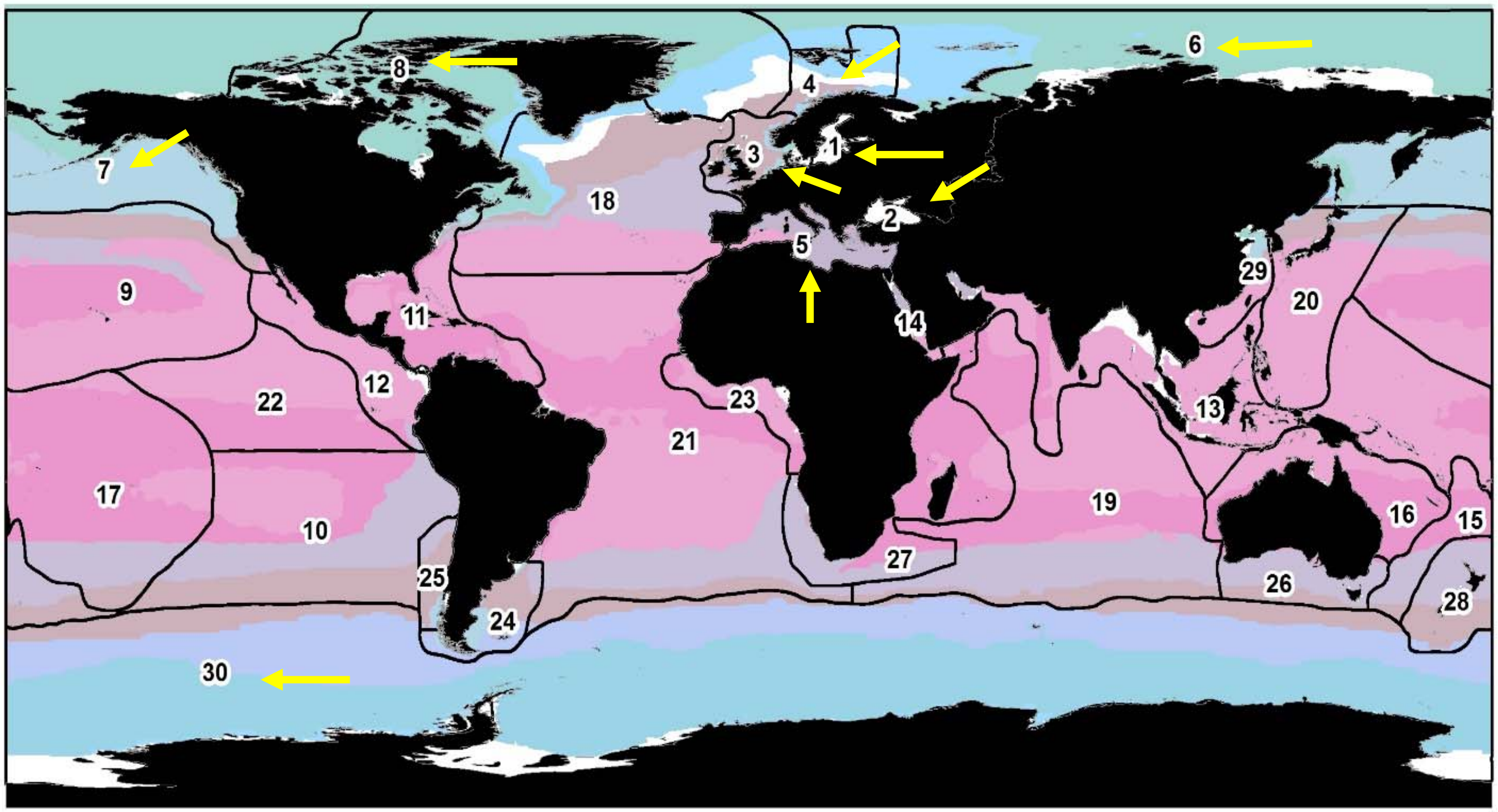
1. Across all oceans
2. Little or no influence of latitude
3. Each cluster has open ocean and coastal presence
4. Fine scale mixing one cluster within others – biological relevance?

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)



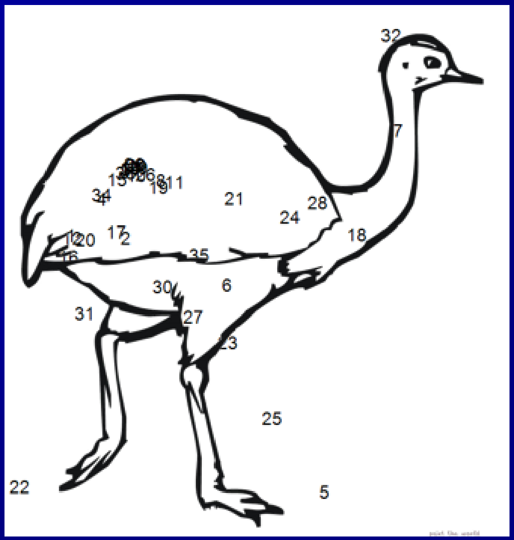
% match of area

Realm	EMU > 55 %
1	16, 17
2	6, 7, 22
3	10
4	3, 37
5	4, 9, 15
6	5, 12, 20, 25, 27, 28
7	30
8	34, 36
9 to 20	< 47 % match
22 to 29	< 30 % match
30	14, 19, 31

Future research

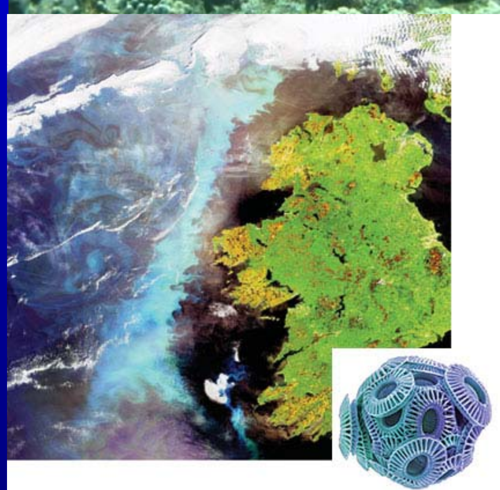
1. Define ‘ecosystems’ based on comparison with biological data
2. Relate biological data to EMU in 3D
3. Develop
   a. Ecological Coastal Units (ECU)
   b. Ecological Freshwater Units (EFU)

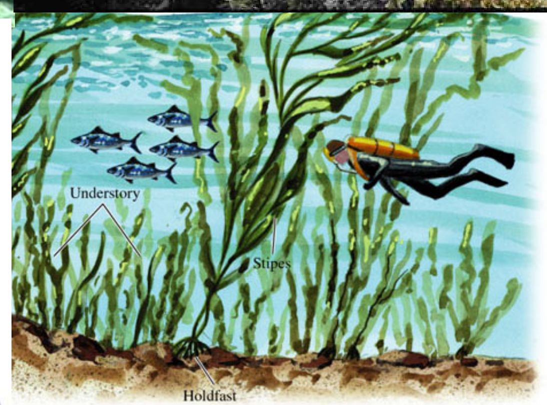
Thank you ! ☺



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

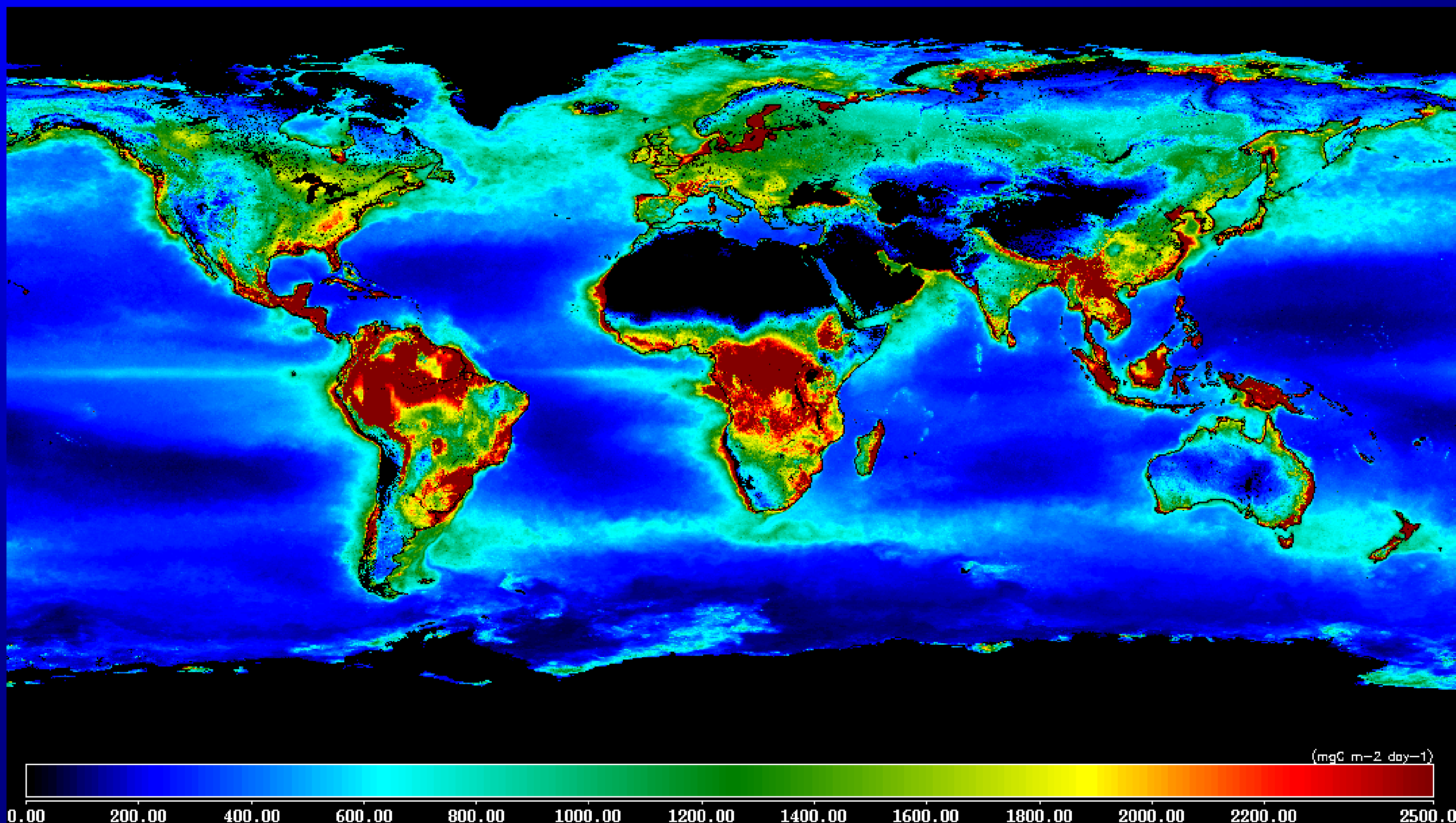
- Phytoplankton?

1. shallow water corals
2. seagrass
3. mangroves
4. kelp

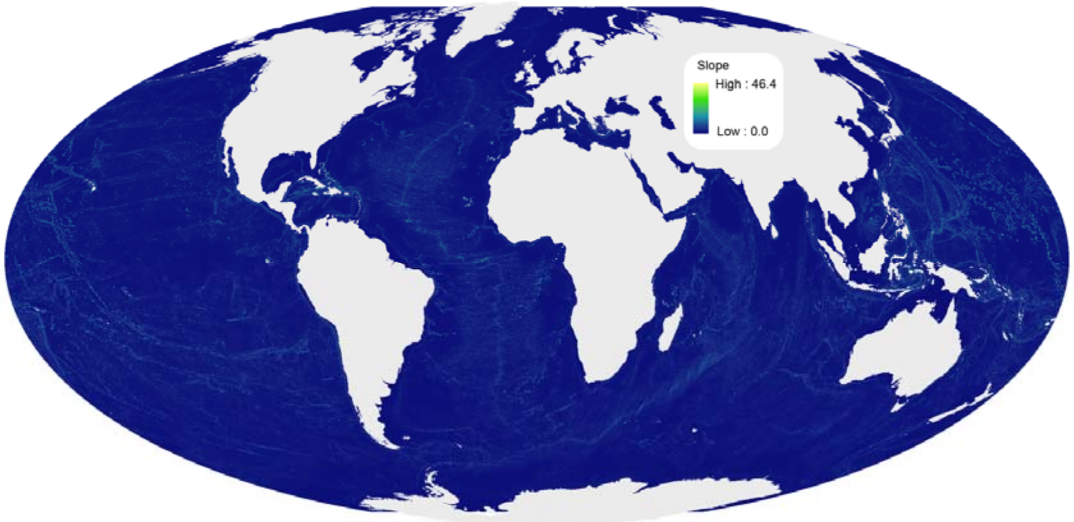
How map?

1. Field observations,
2. expert drawn maps
3. species distribution models

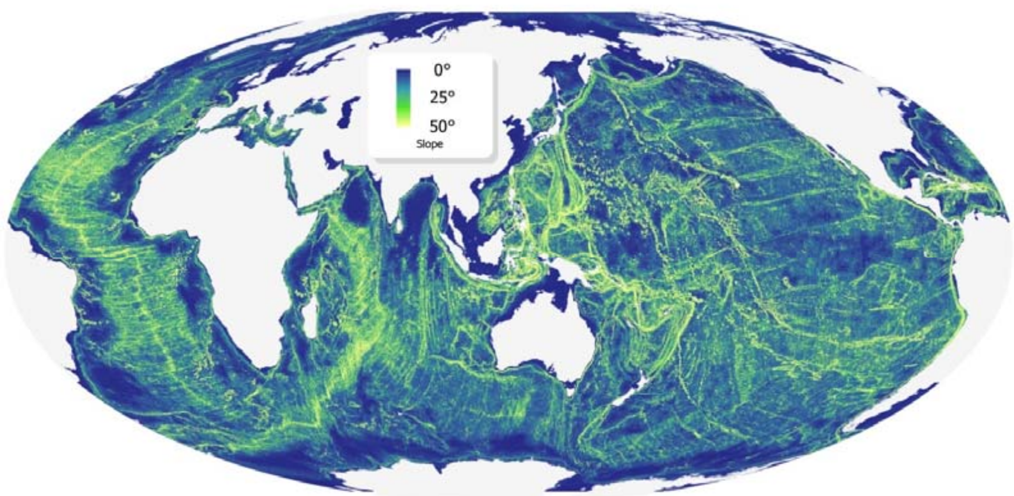
Global plant productivity: land, sea, freshwater



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.