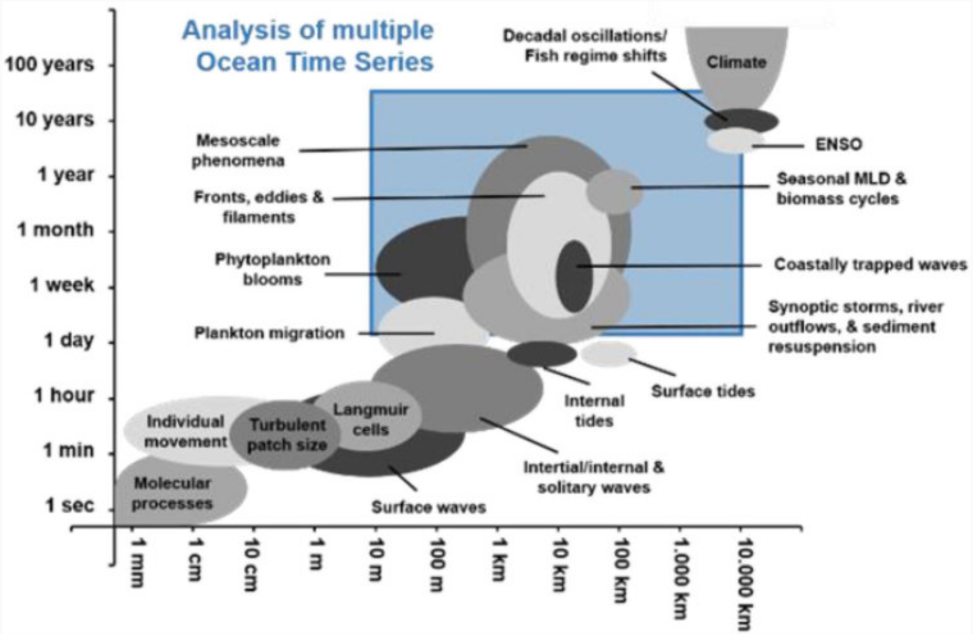
Experimental Design and Analysis

Scales in oceanic ecosystems

Daniel Vaulot

2020-02-19



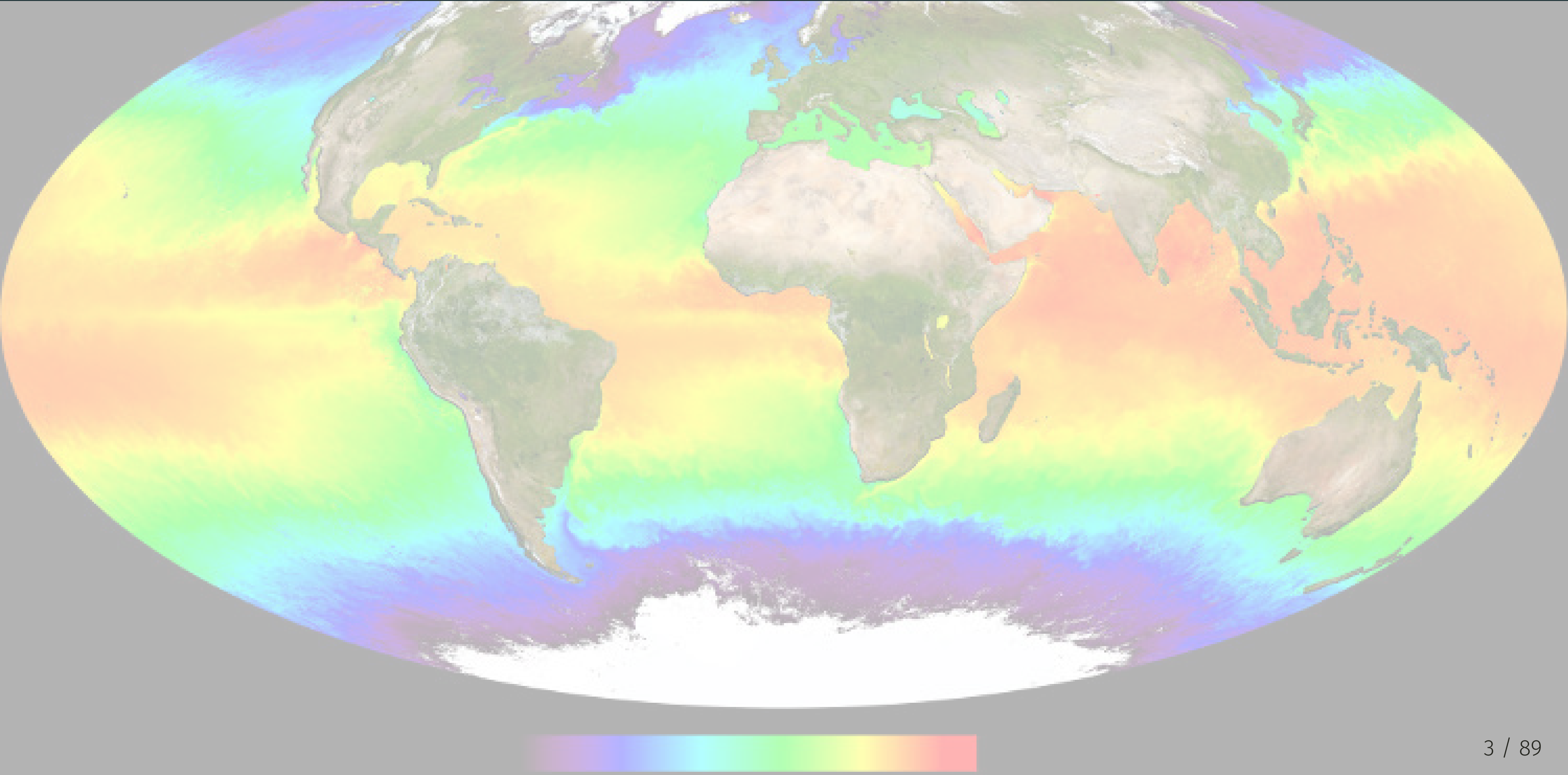
NANYANG TECHNOLOGICAL UNIVERSITY SINGAPORE

CNRS • SORBONNE UNIVERSITÉ Station Biologique de Roscoff

Outline

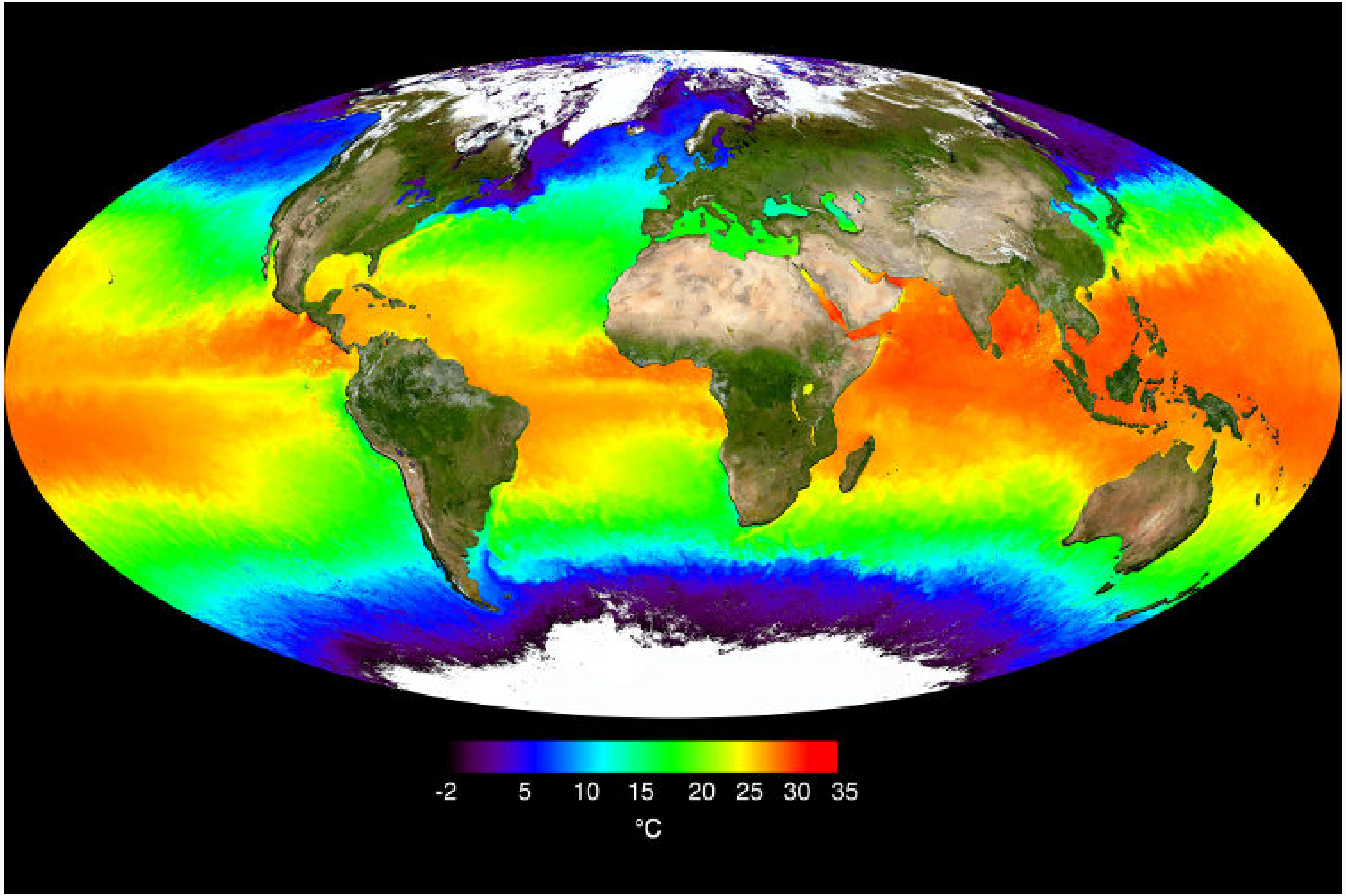
- The marine Environment
- Marine Phytoplankton
- Spatial Scales
- Temporal Scales
- Time Series

The Marine Environment

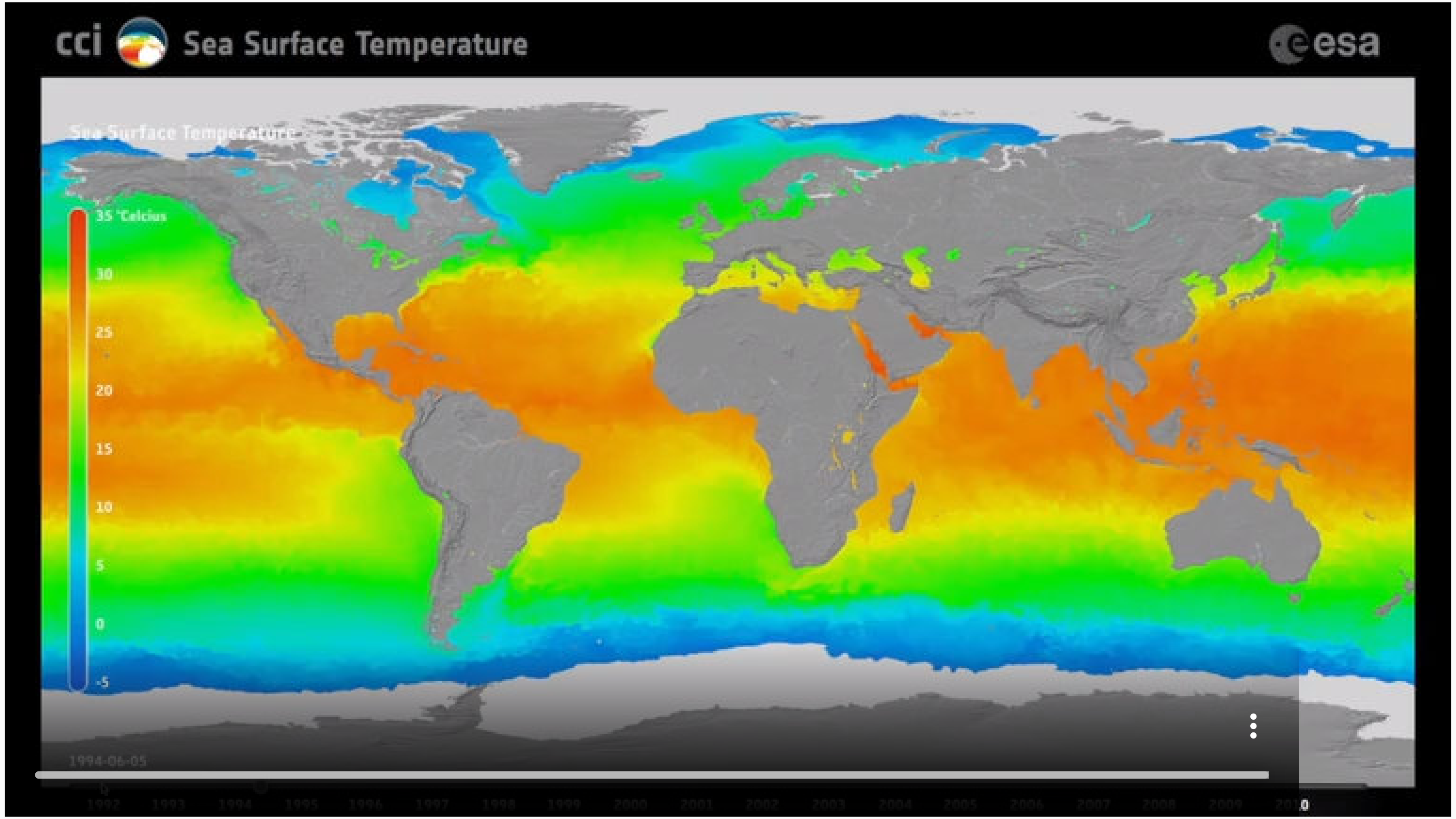


The Marine Environment

Temperature



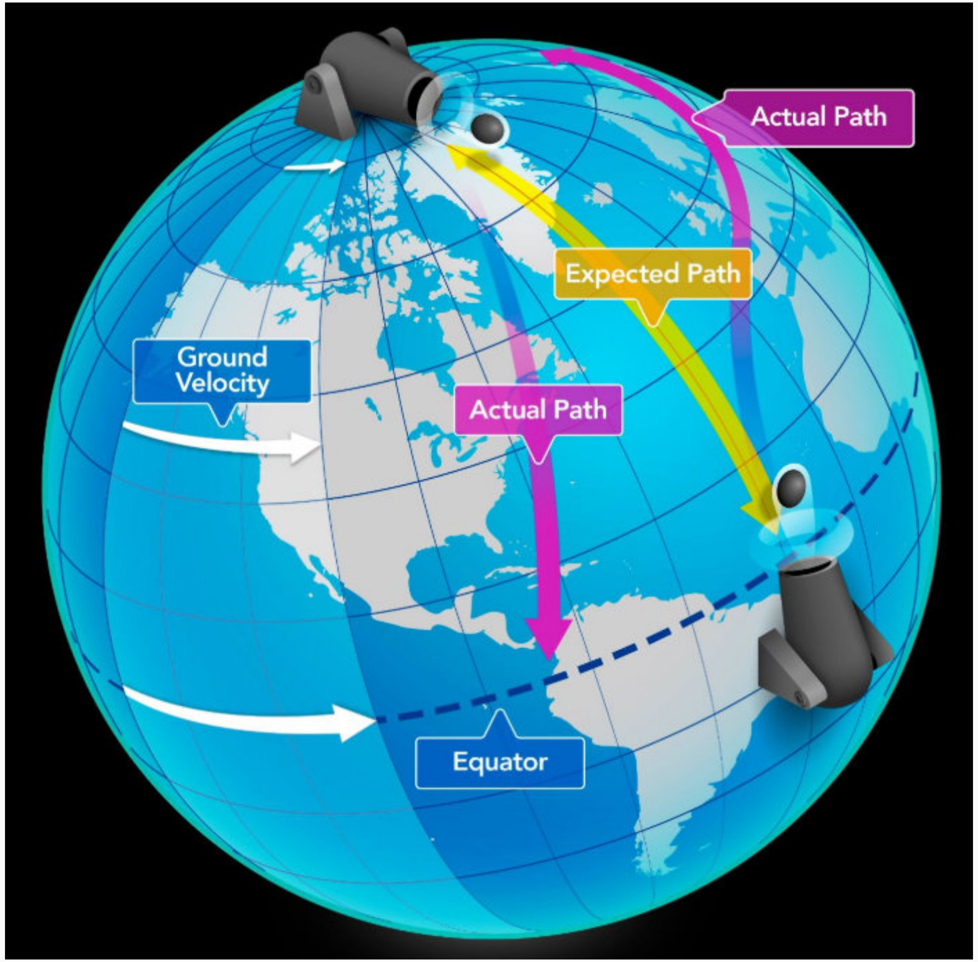
Marine Environment is highly dynamic



The Marine Environment

Currents

- Wind (Atmospheric Circulation)
- Coriolis effect
- Coast line

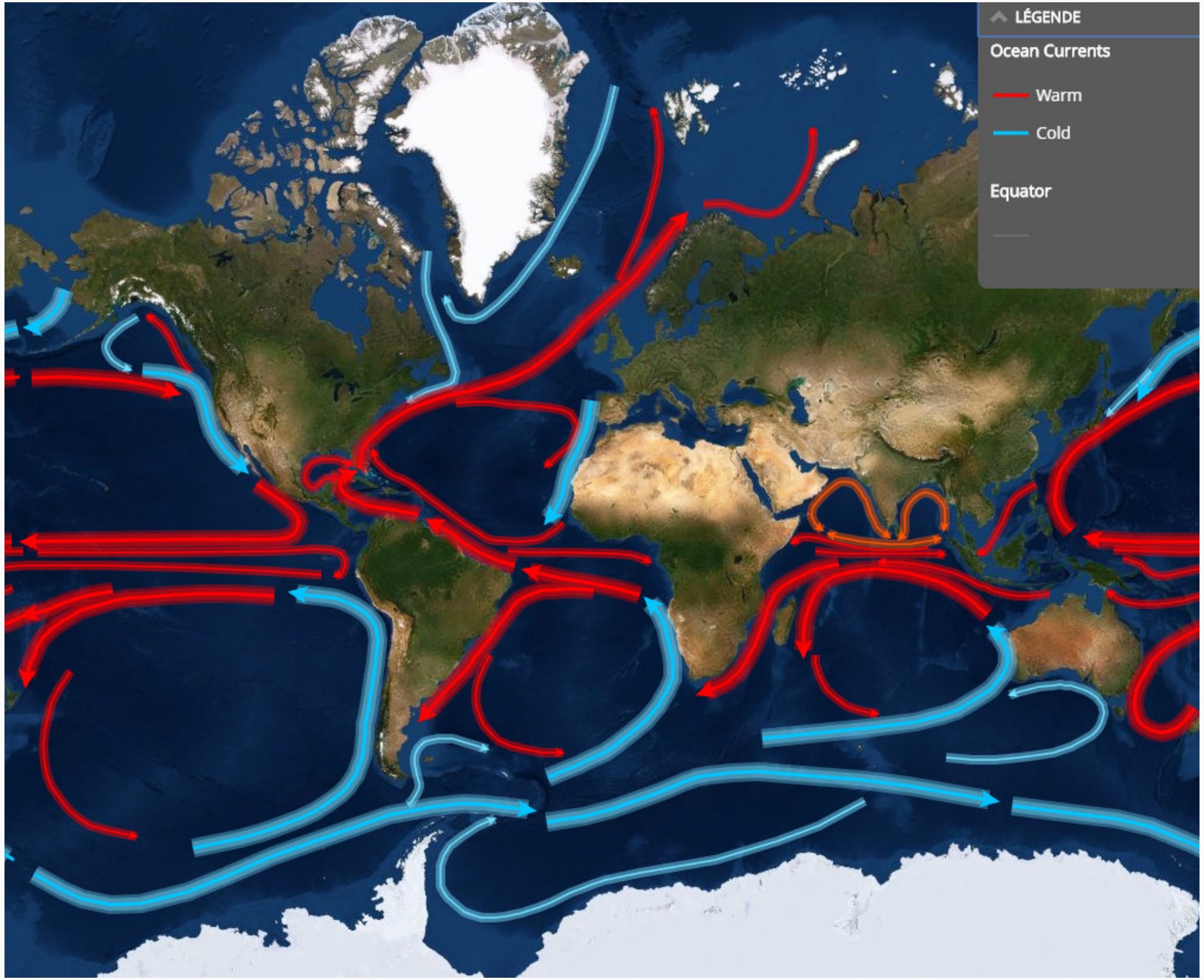


https://www.arcgis.com/apps/MapJournal/index.html?appid=d629dd5cc3fe48ea9fc744dada861da0

The Marine Environment

Currents

- Wind (Atmospheric Circulation)
- Coriolis effect
- Coast line



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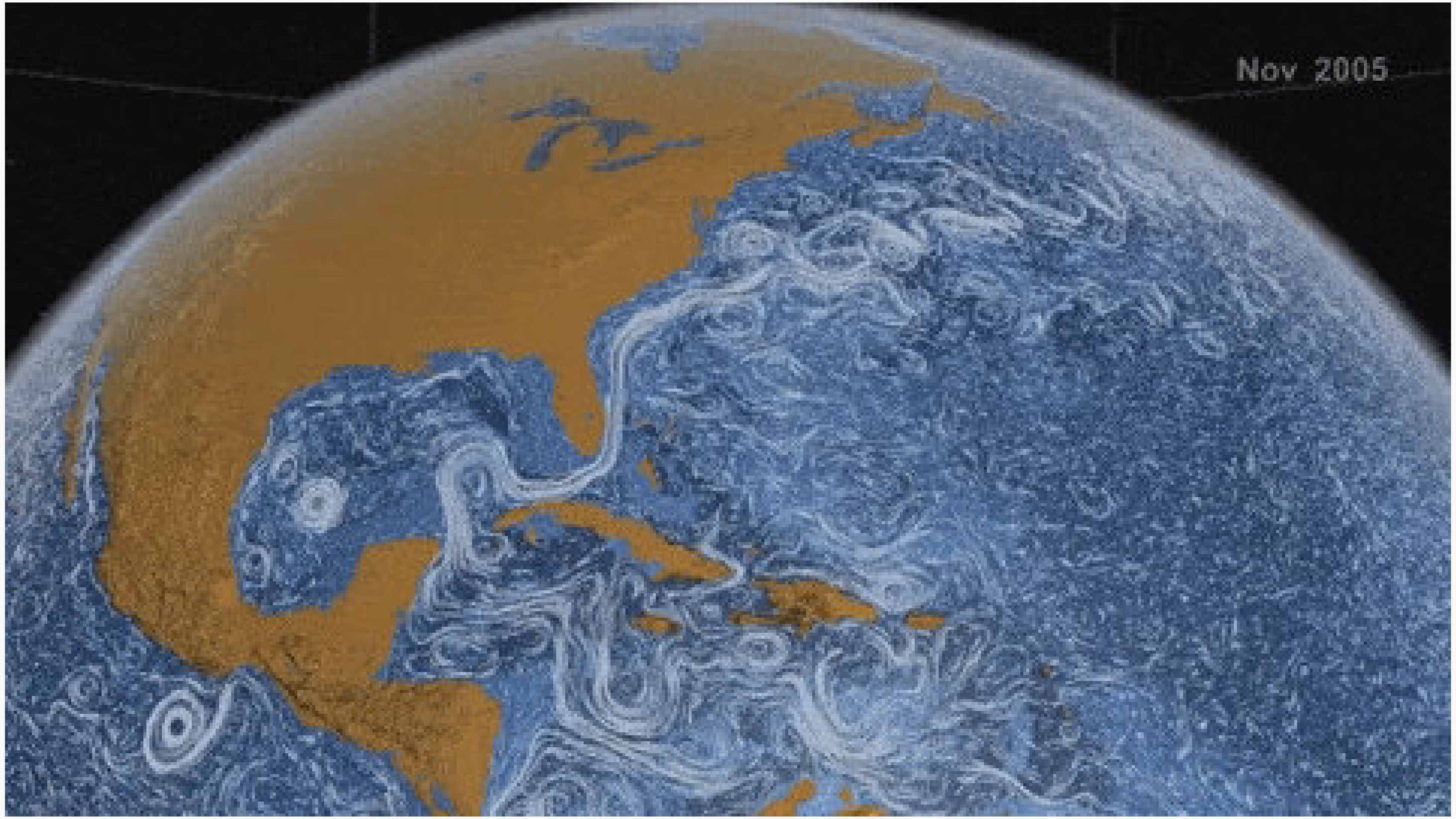
Currents

- Turbulence

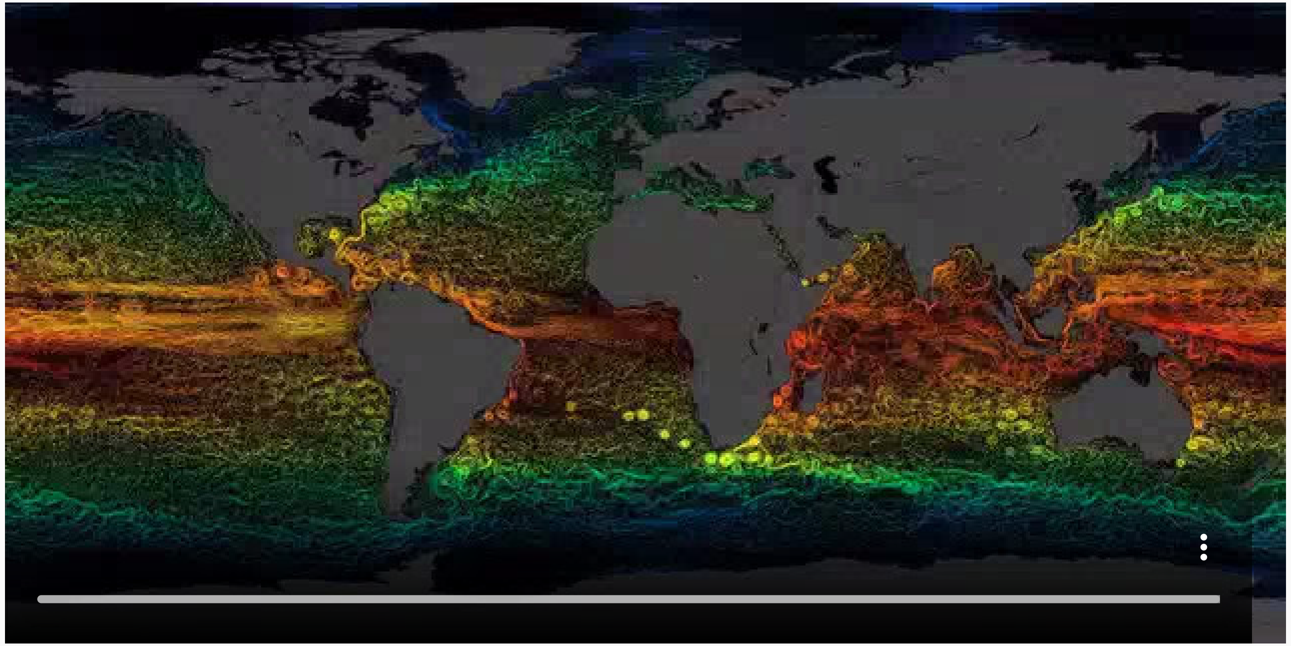


https://svs.gsfc.nasa.gov/3827

The Marine Environment

Currents

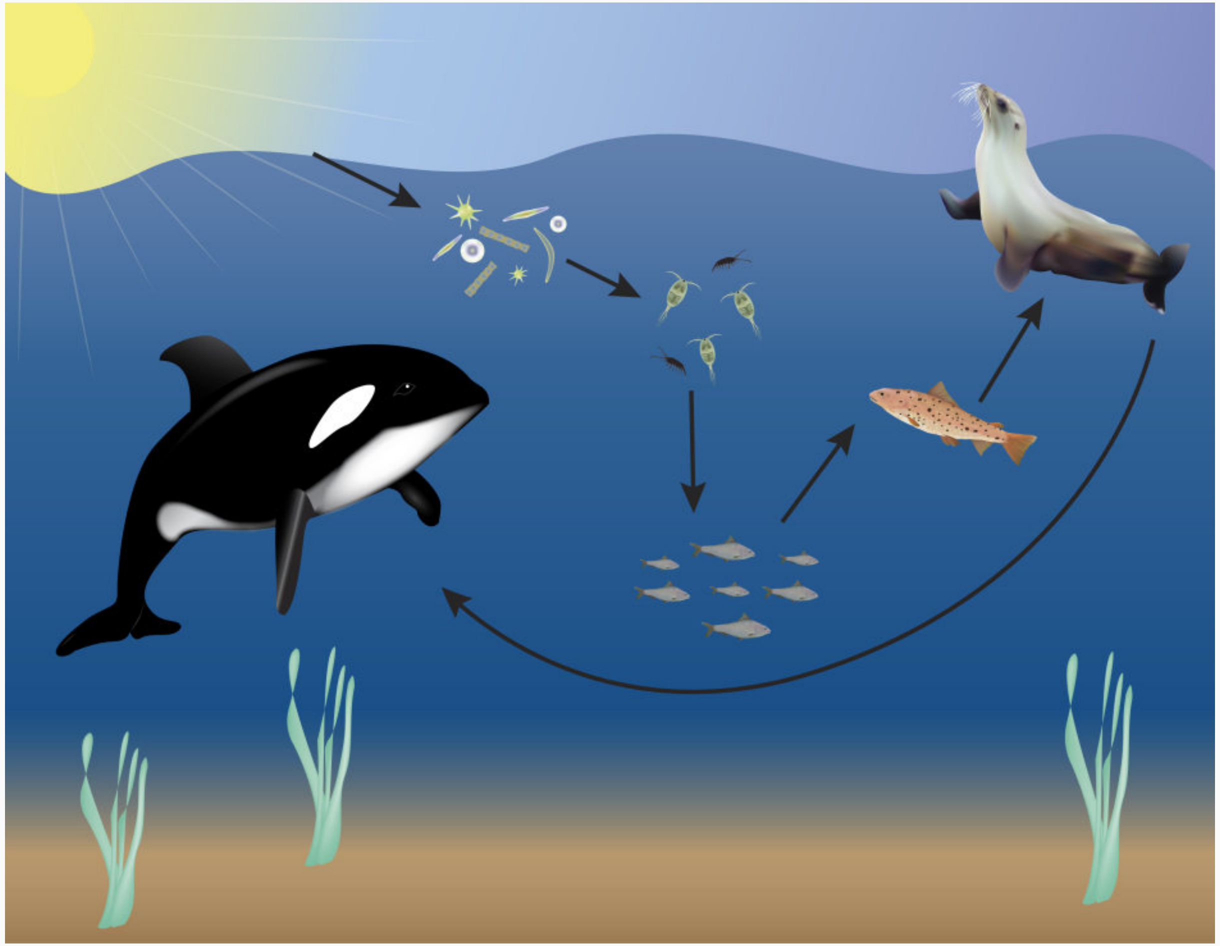
- Turbulence



Marine phytoplankton

Marine phytoplankton

Classical view of marine foodwebs



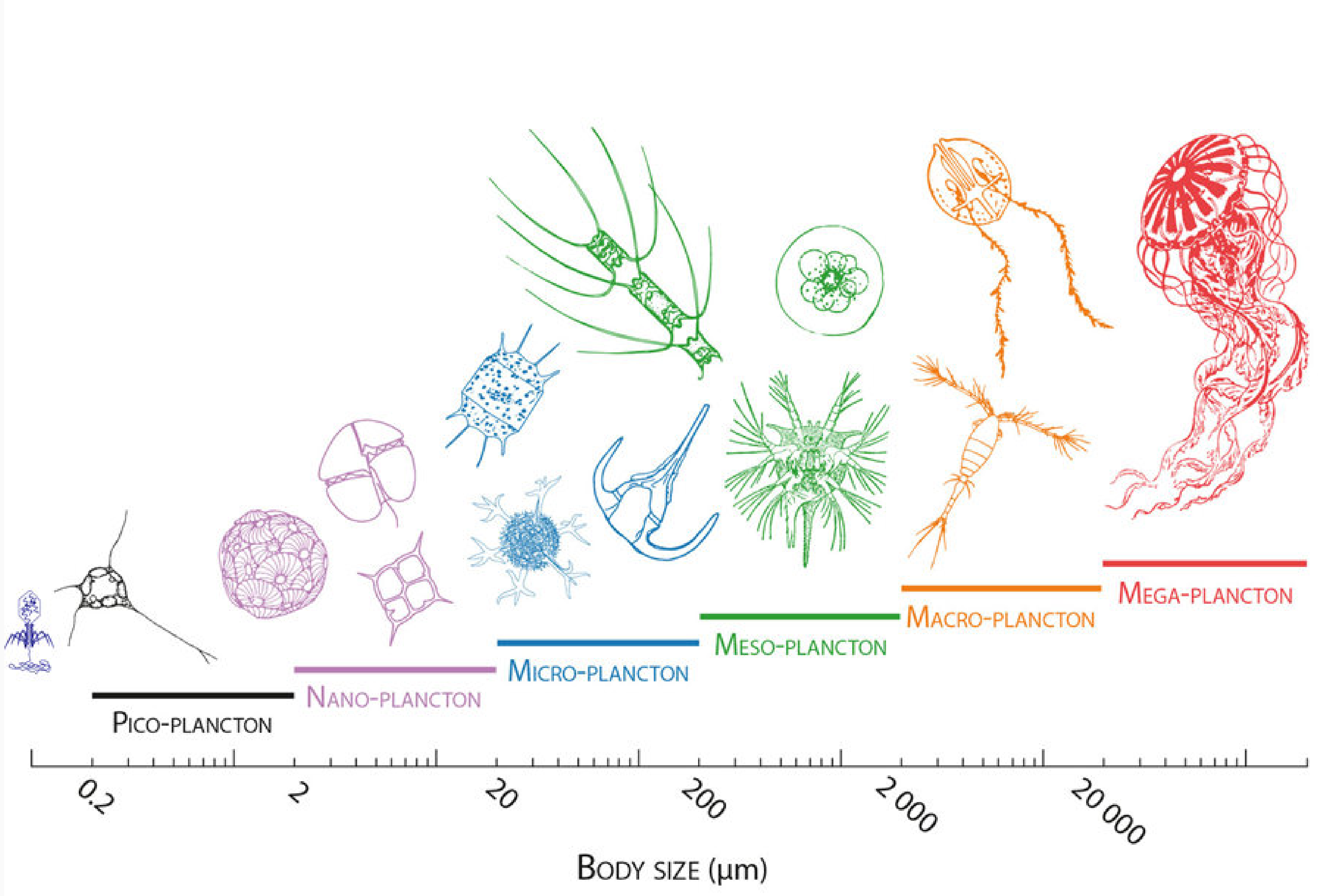
Marine phytoplankton

Plankton diversity

- Phytoplankton
- Zooplankton
- Bacteria
- Viruses

Marine phytoplankton

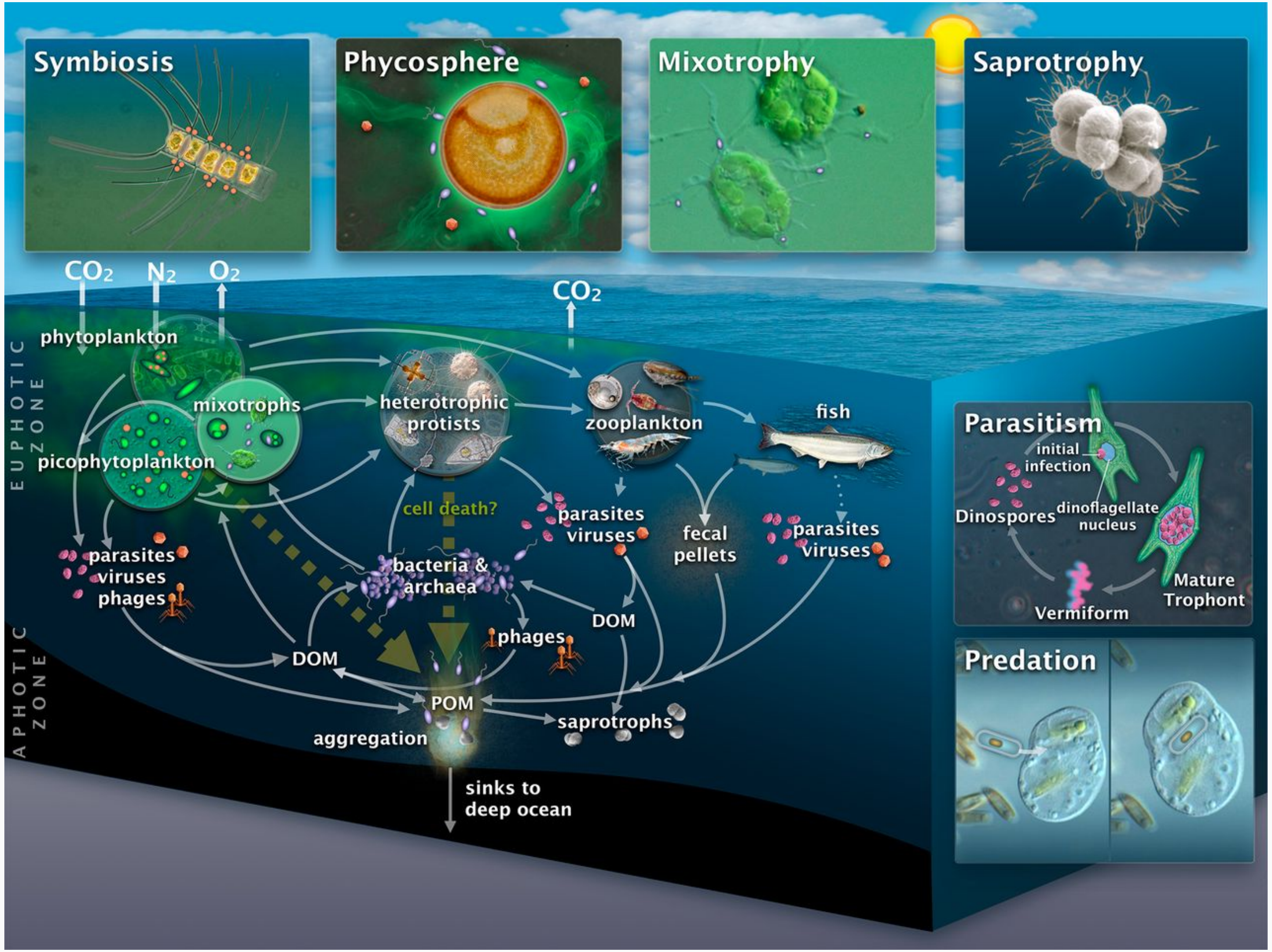
Size classes



Marine phytoplankton

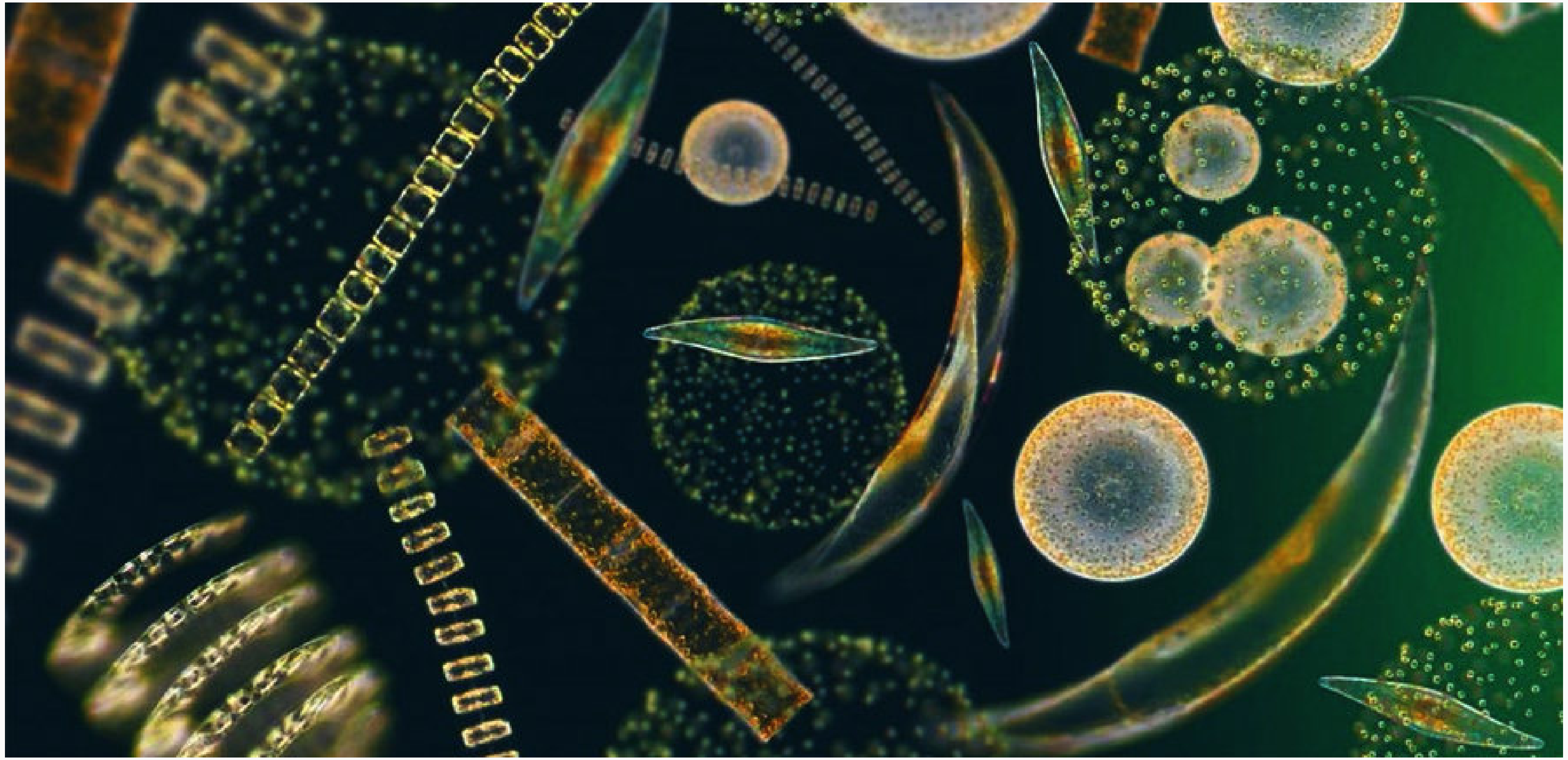
Complex processes

- Predation
- Symbiosis
- Mixotrophy
- Parasitism



Marine phytoplankton

Phytoplankton

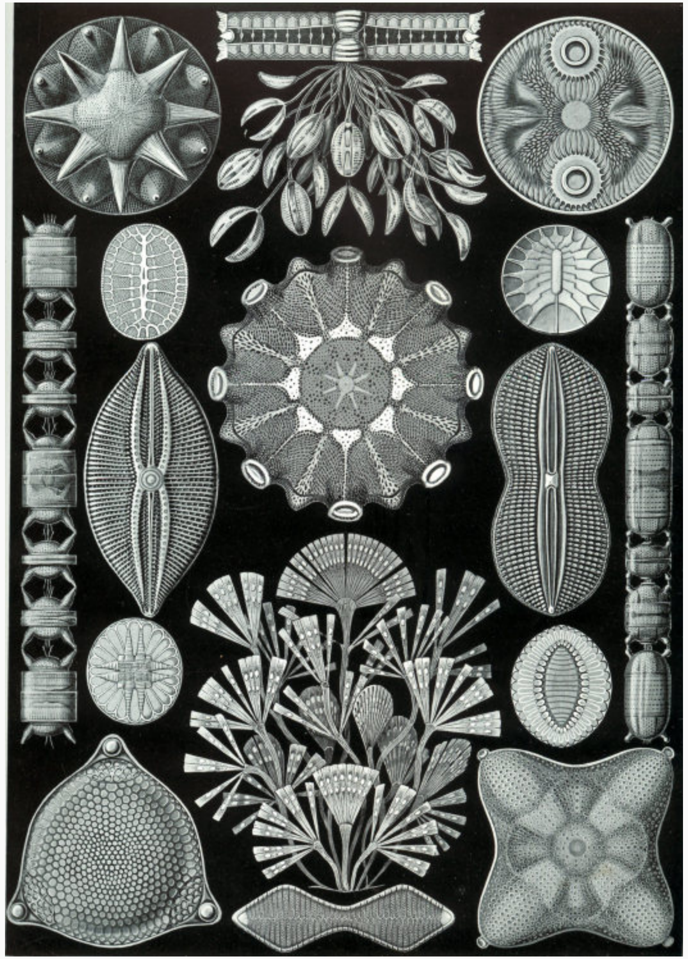


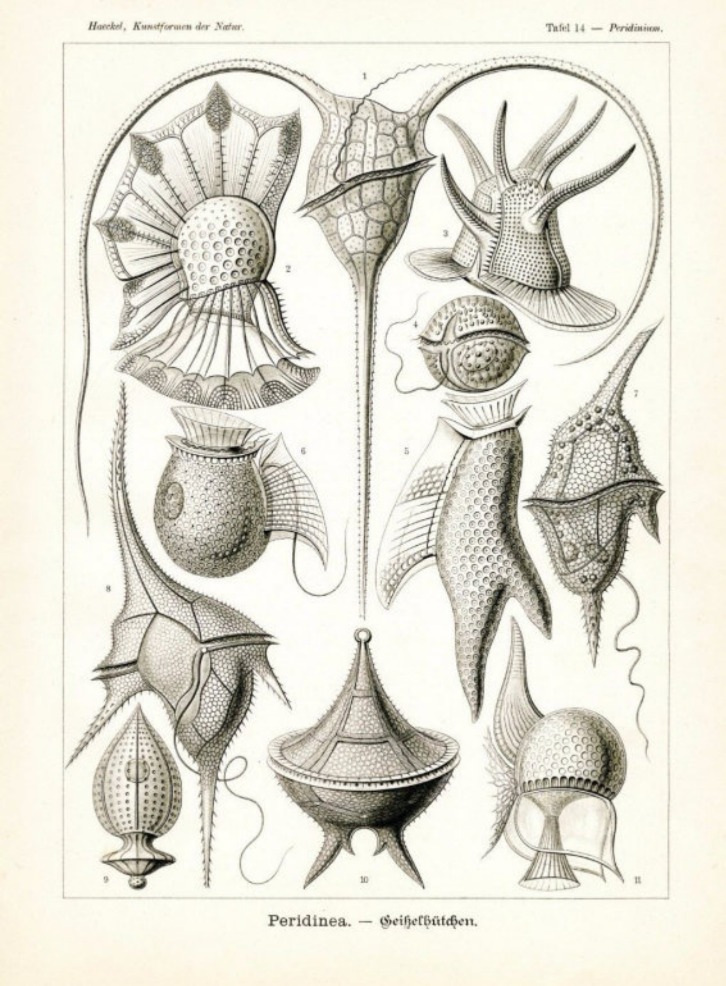
Marine phytoplankton

Major groups

Marine phytoplankton

Diatoms and dinoflagellates: 20-200 µm

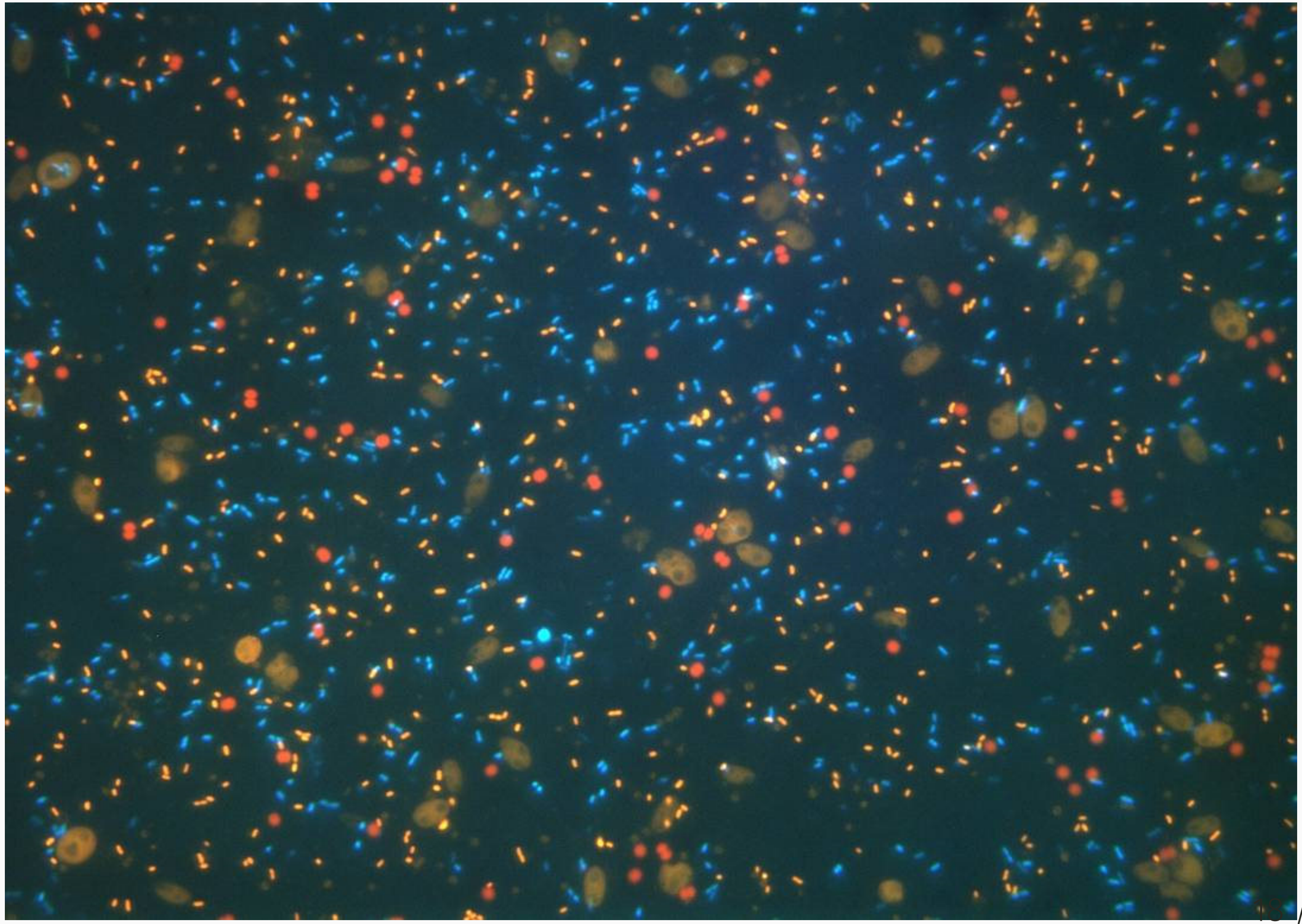




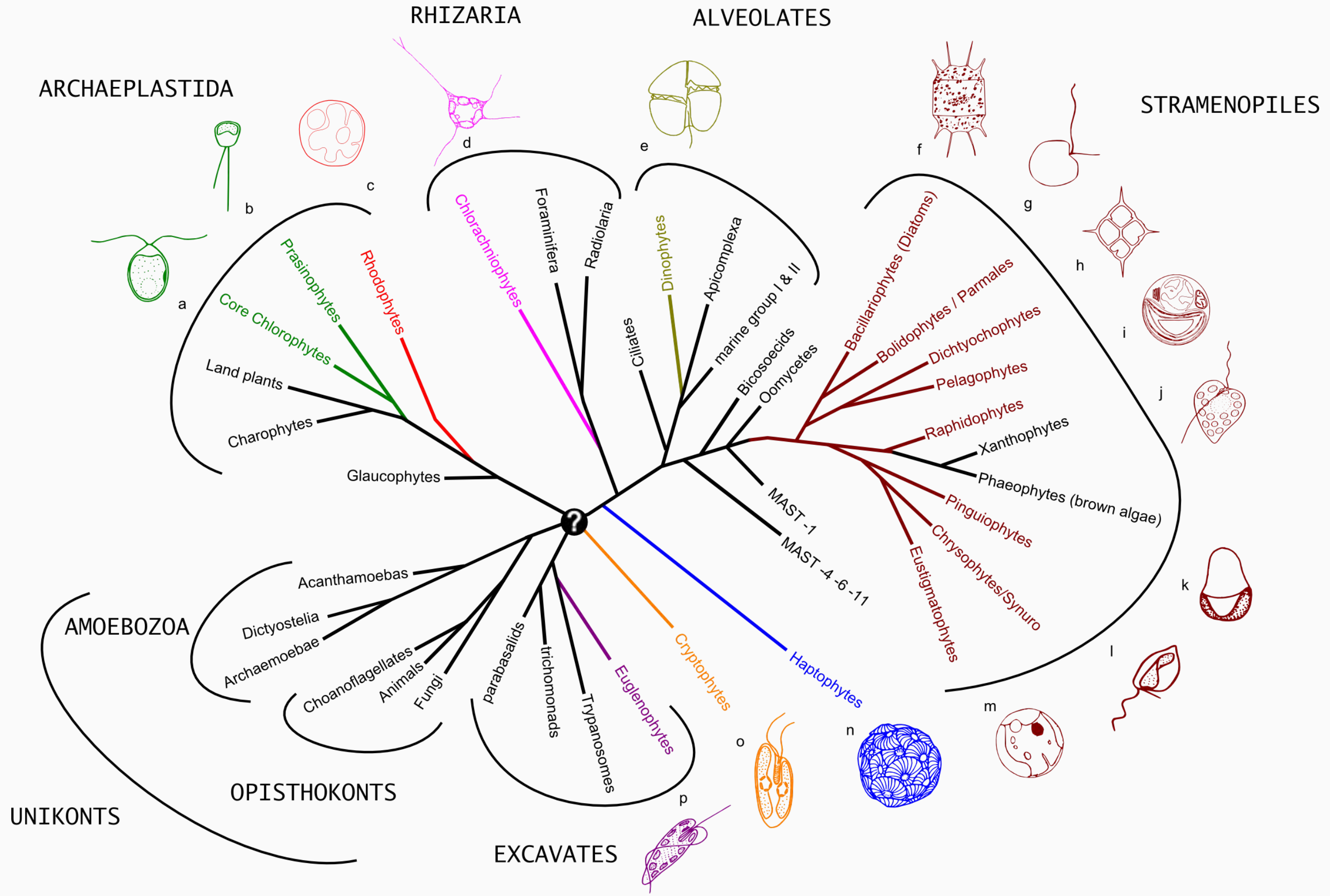
Marine phytoplankton

Picoplankton: 0.2-2 μm

- Very small eukaryotes (*Ostreococcus*)
- Cyanobacteria (*Synechococcus*)

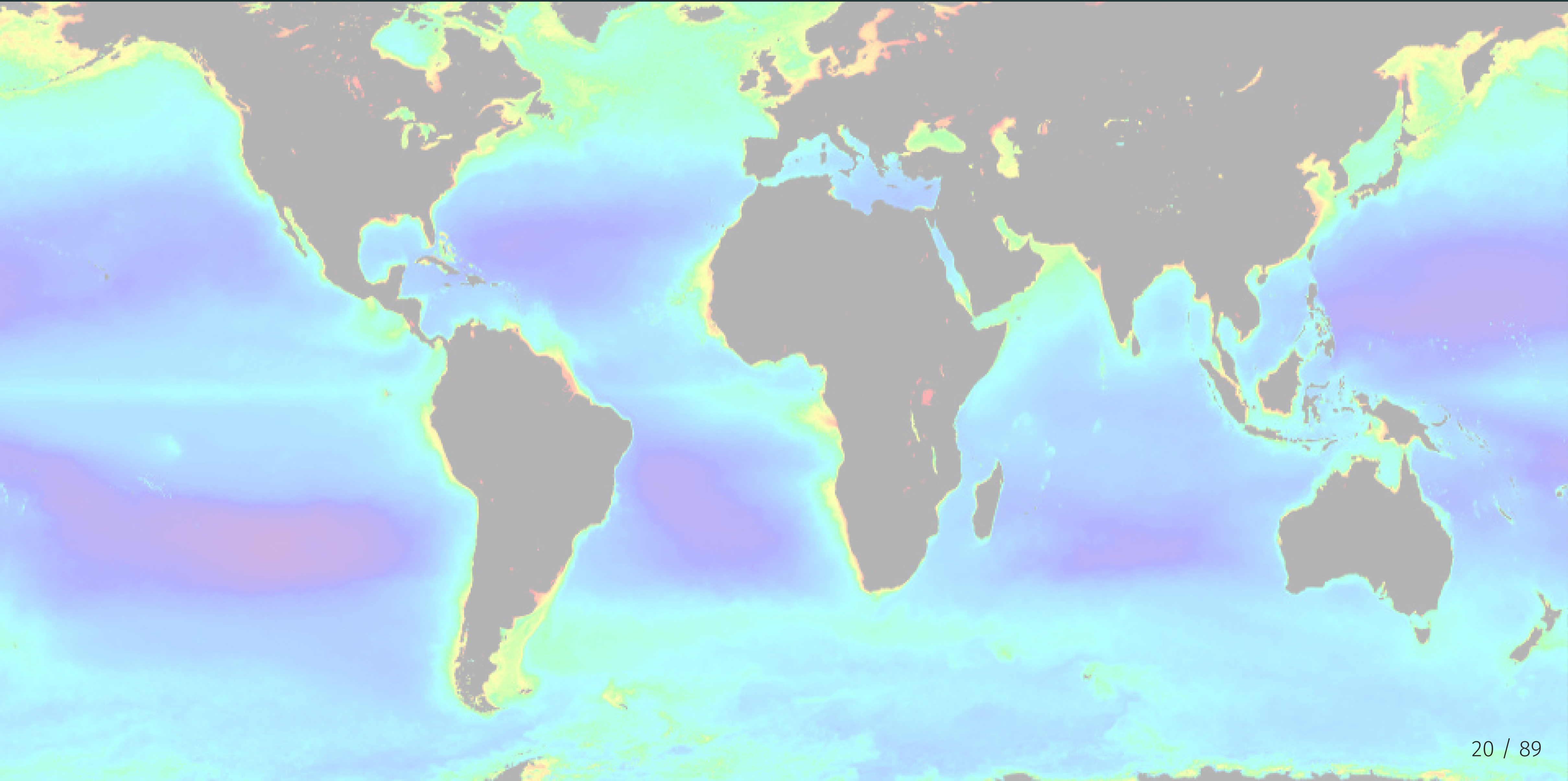


Wide phylogenetic diversity



Not, F., Siano, R., Kooistra, W.H.C.F., Simon, N., Vaulot, D. & Probert, I. 2012. In Piganeau, G. [Ed.] Genomic Insights Gained into the Diversity, Biology and Evolution of Microbial Photosynthetic Eukaryotes. Elsevier.

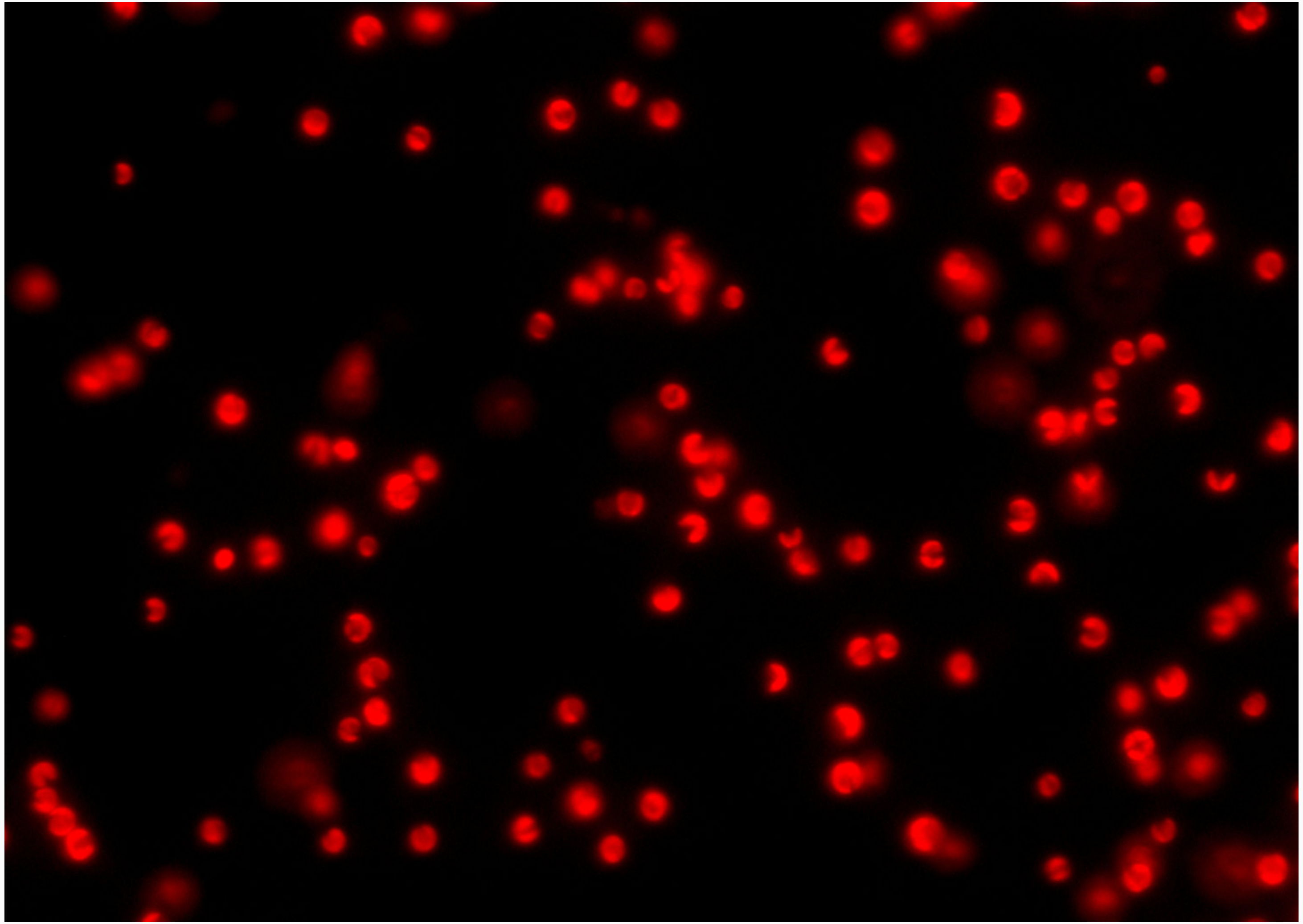
Spatial scales



Spatial scales

Chlorophyll

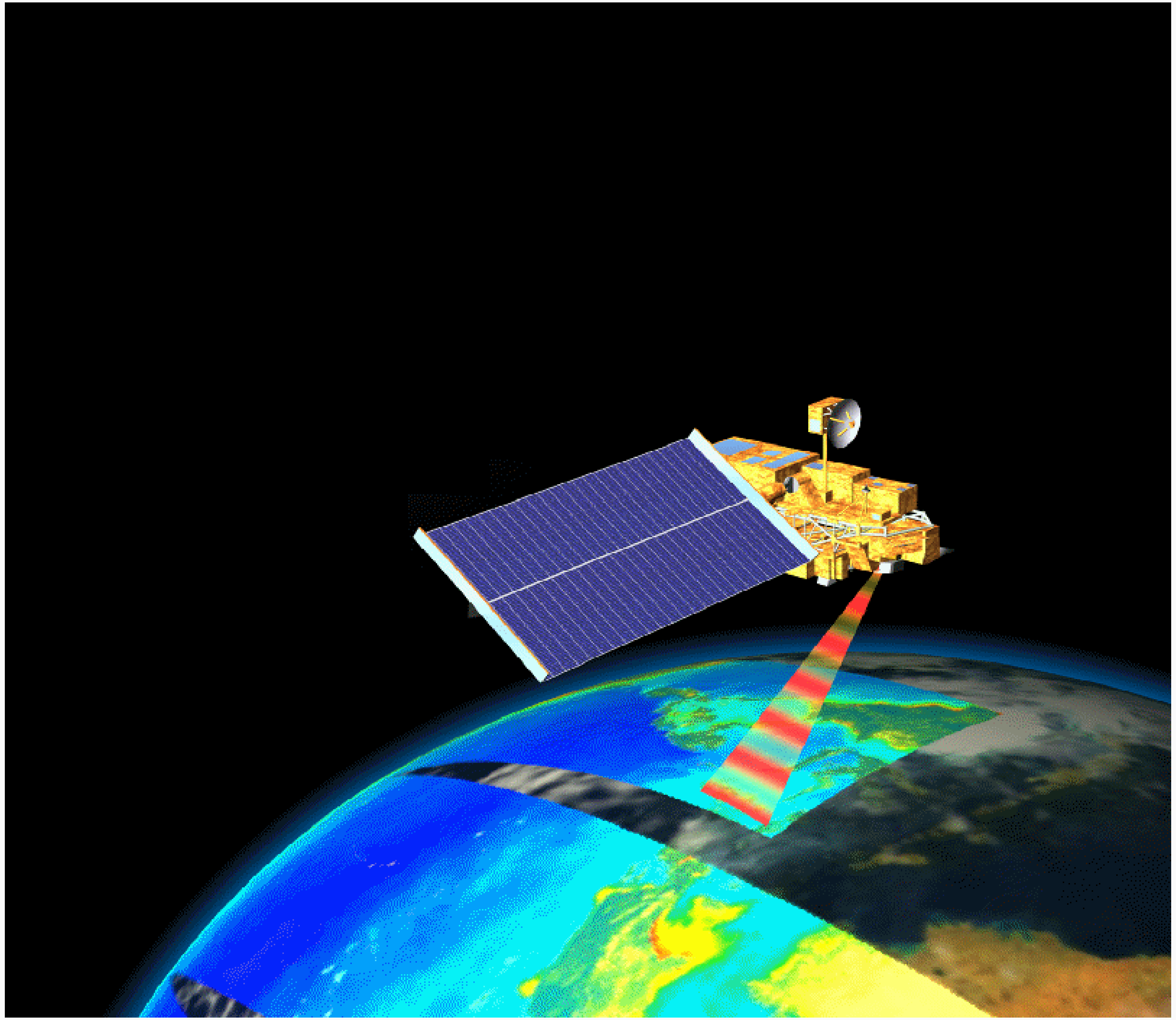
Proxy of phytoplankton biomass



Spatial scales

Chlorophyll

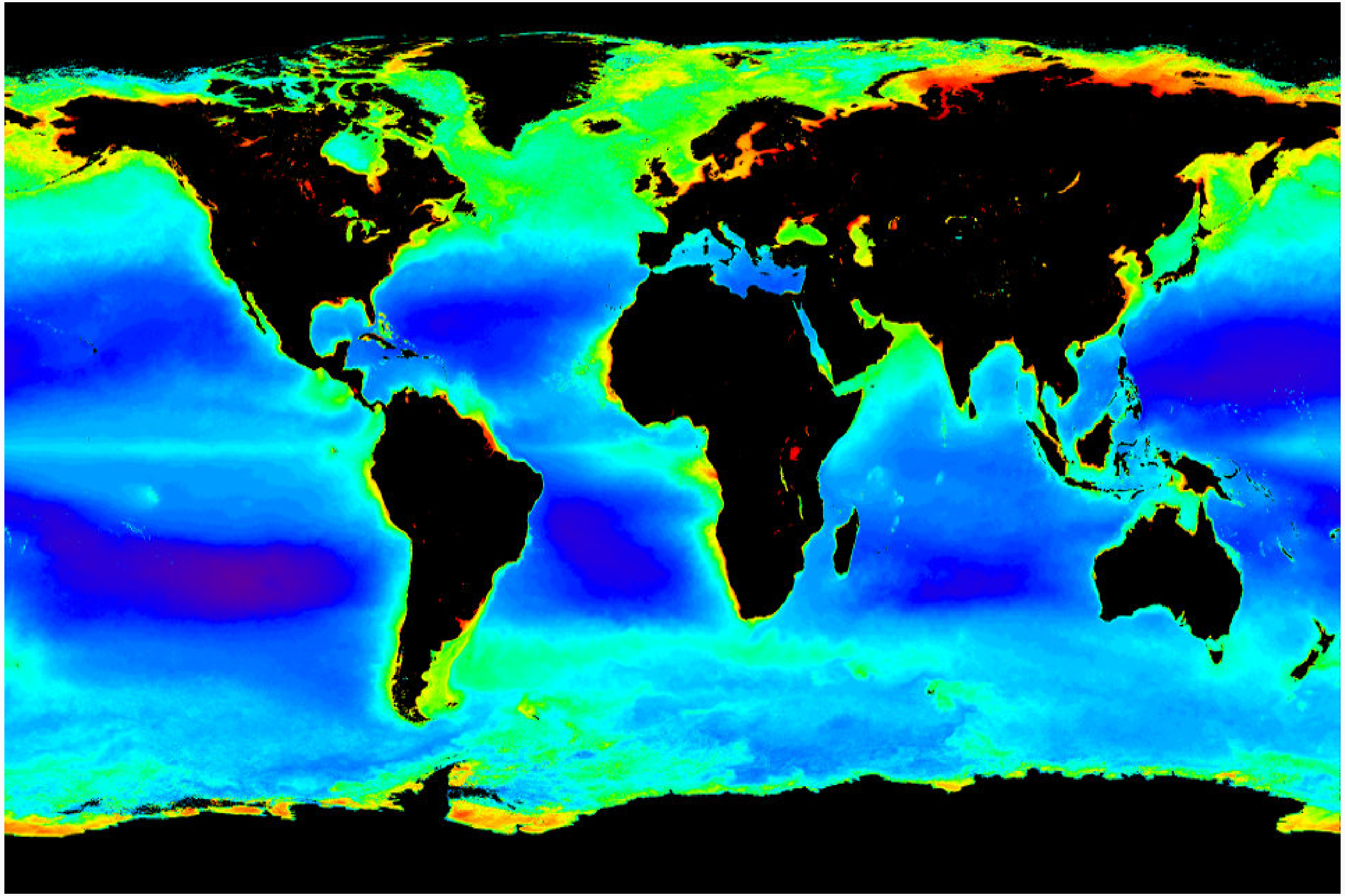
Can be measured from space



Spatial scales

Chlorophyll

What can you see ?

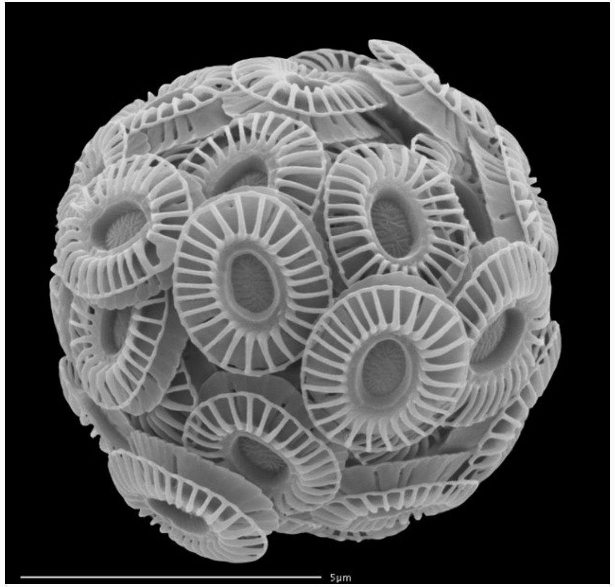


Spatial scales

Blooms

English Channel

Coccolithophorids



Spatial scales

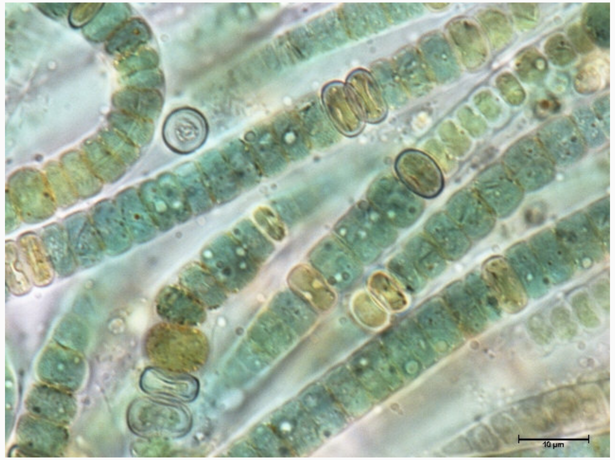
Blooms

New Zealand

Blooms

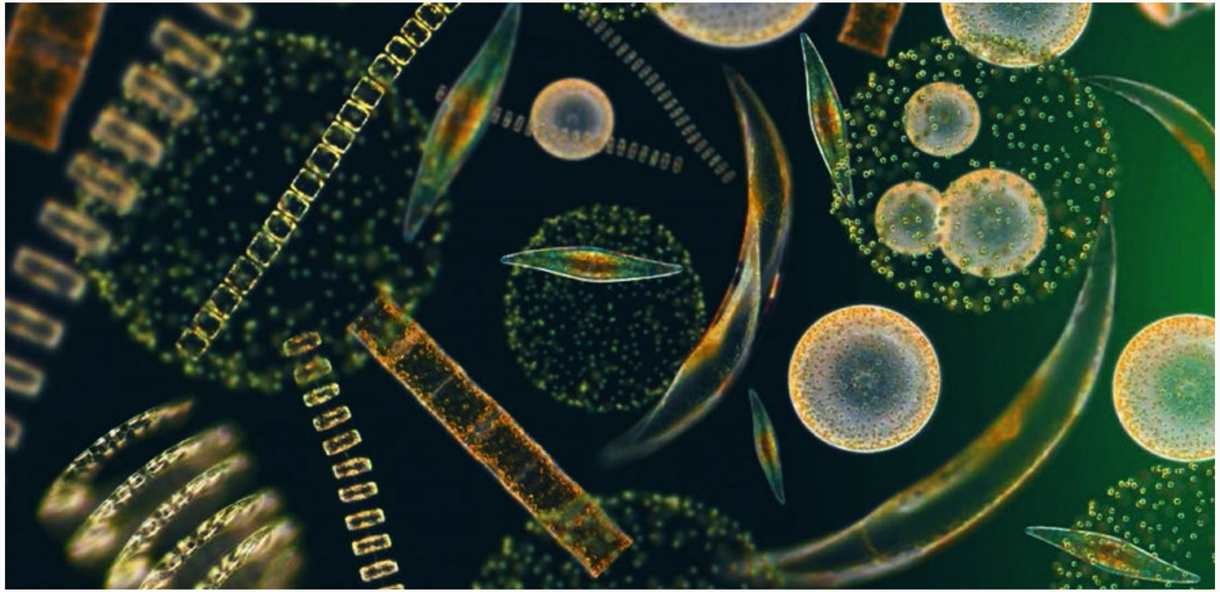
Baltic

Cyanobacteria



Spatial scales

What factors control phytoplankton ?



What controls phytoplankton ?

Positive

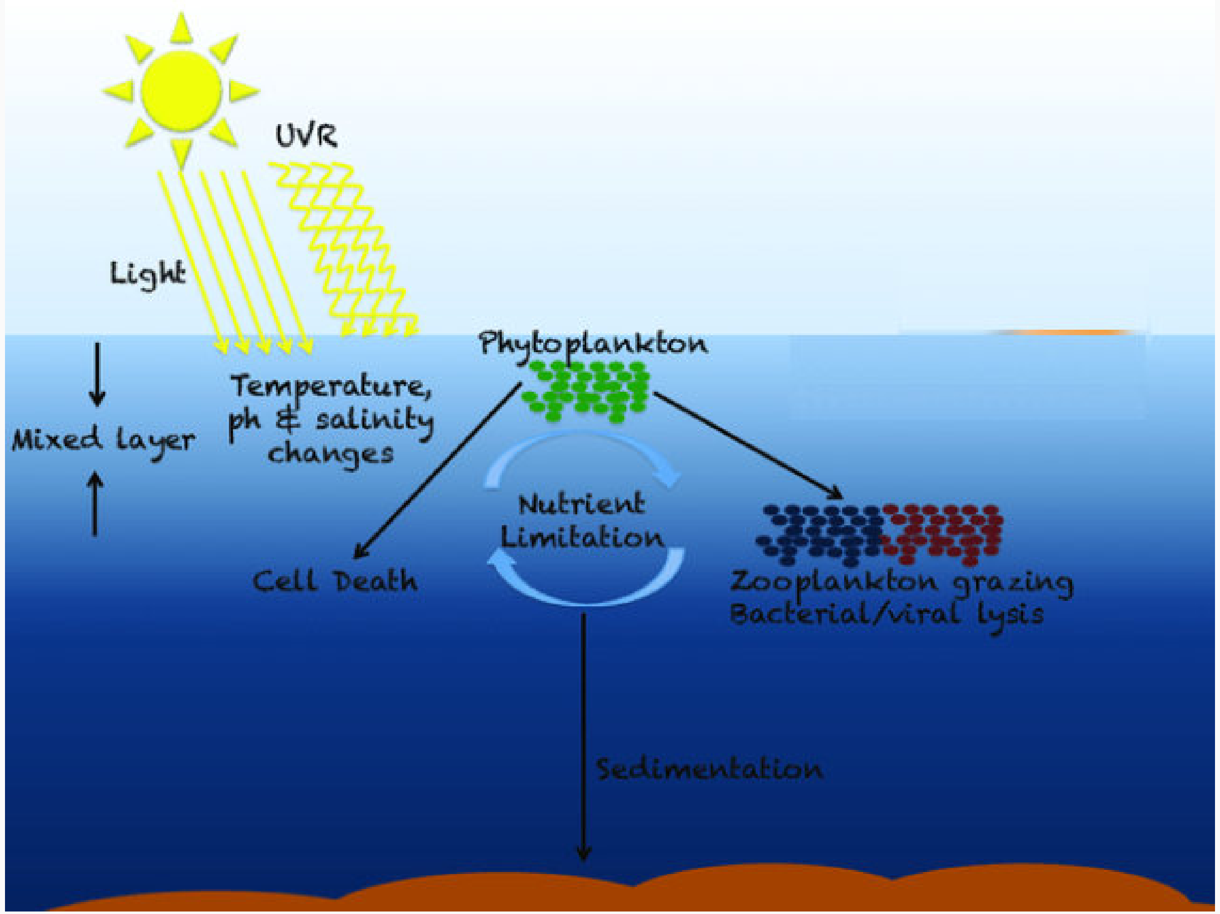
- Light
- Nutrients (Nitrogen, Phosphorus)
- Trace elements (Iron)

Negative

- Predation
- Parasites (e.g. viruses)
- Death

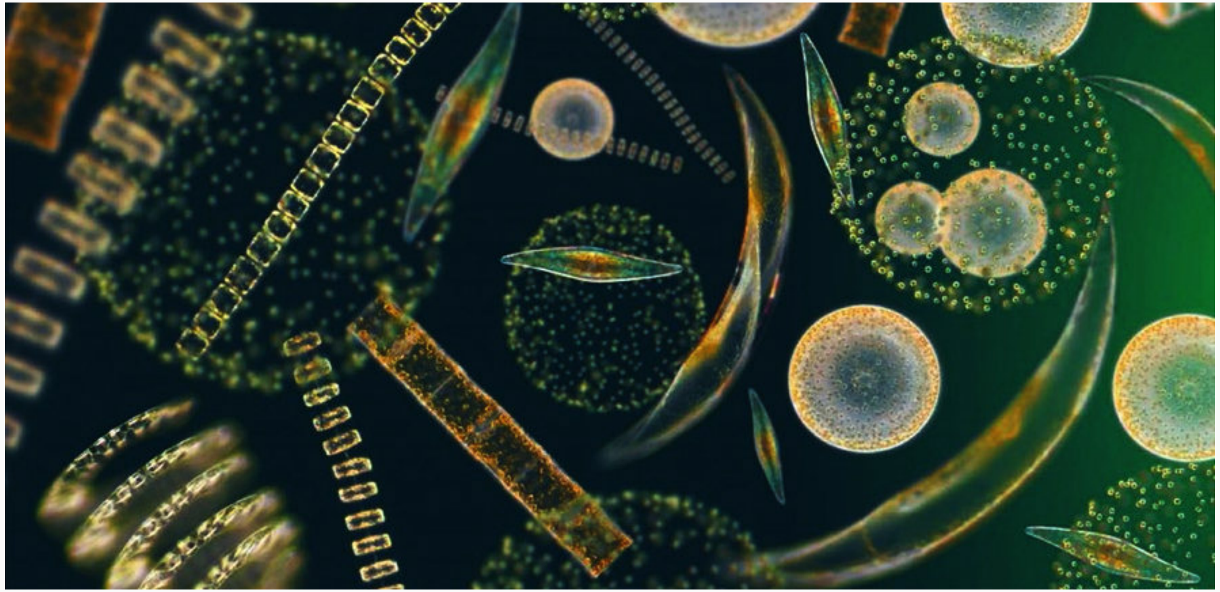
Species selection

- Temperature
- Salinity



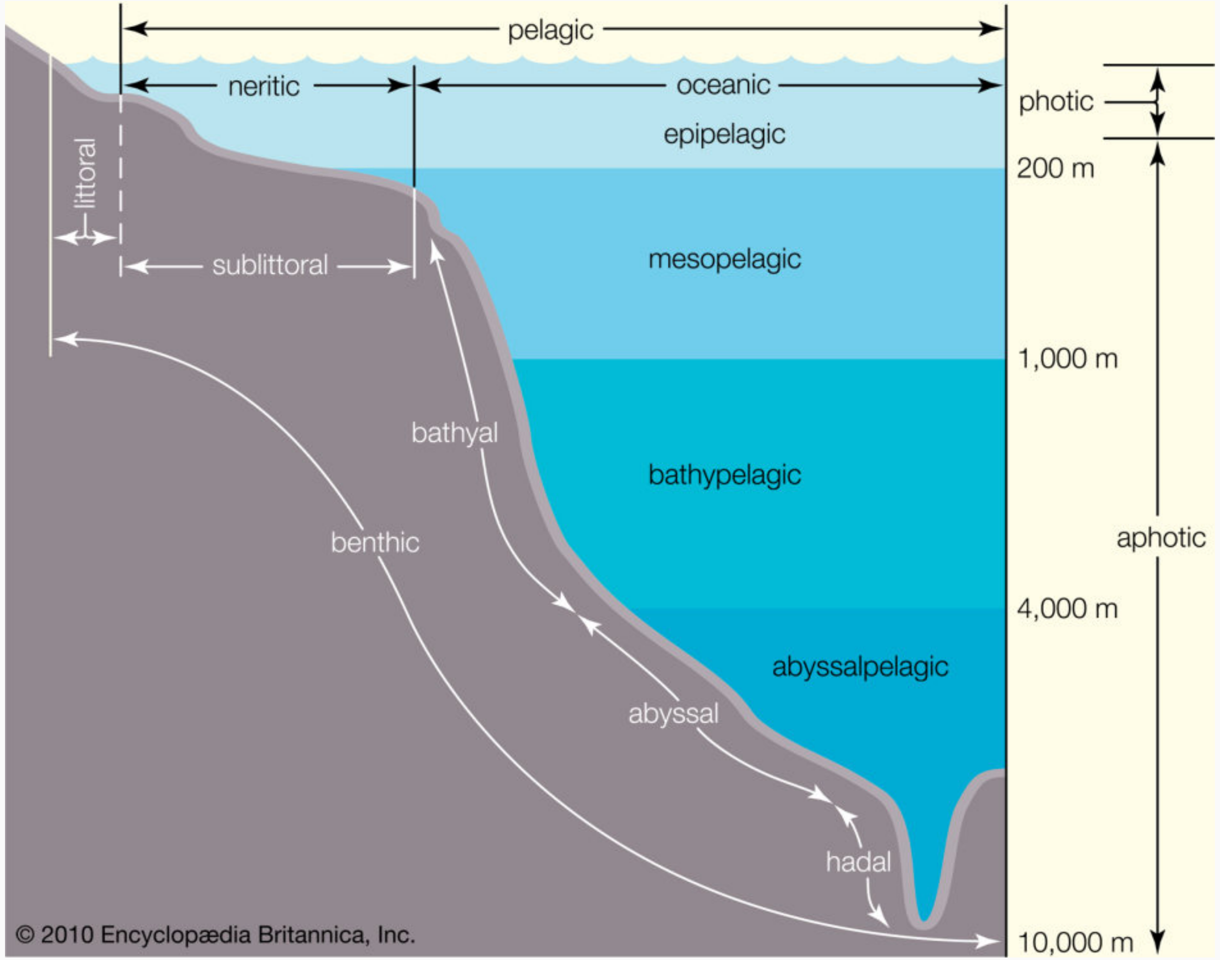
Spatial scales

Is phytoplankton uniformly distributed in the water column?



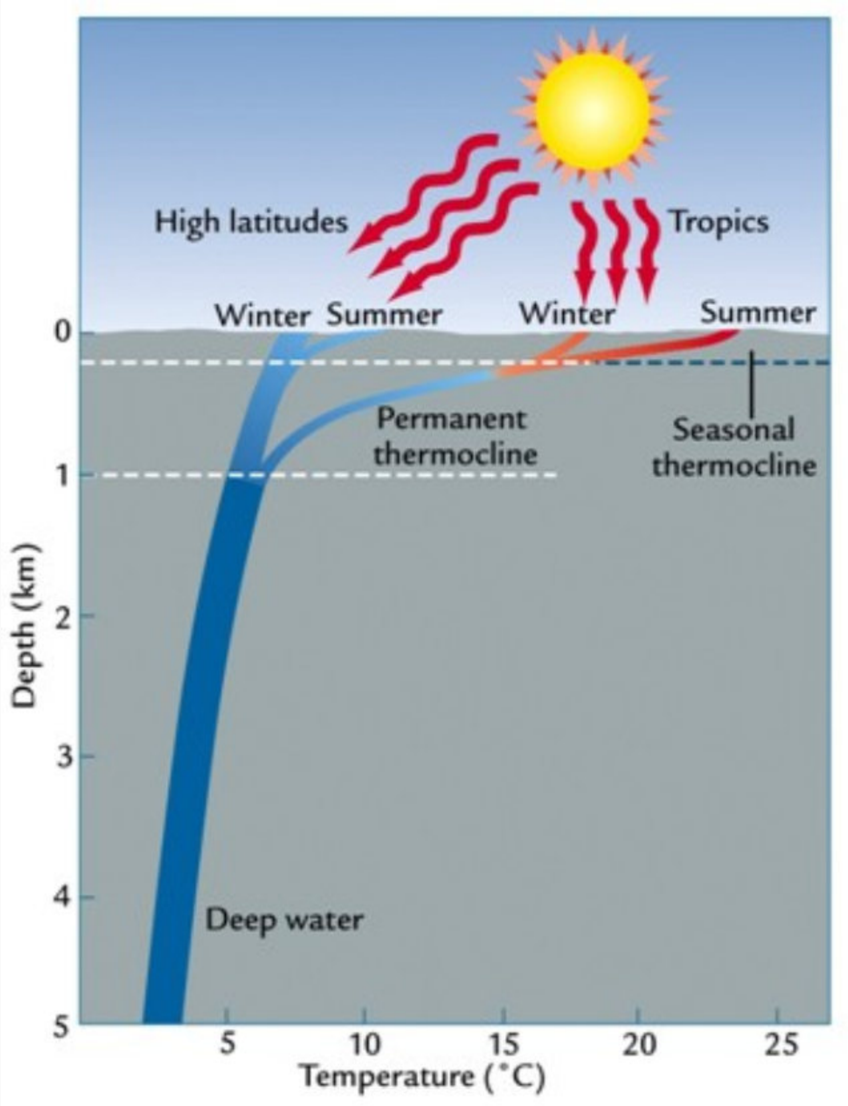
Spatial scales

Water column

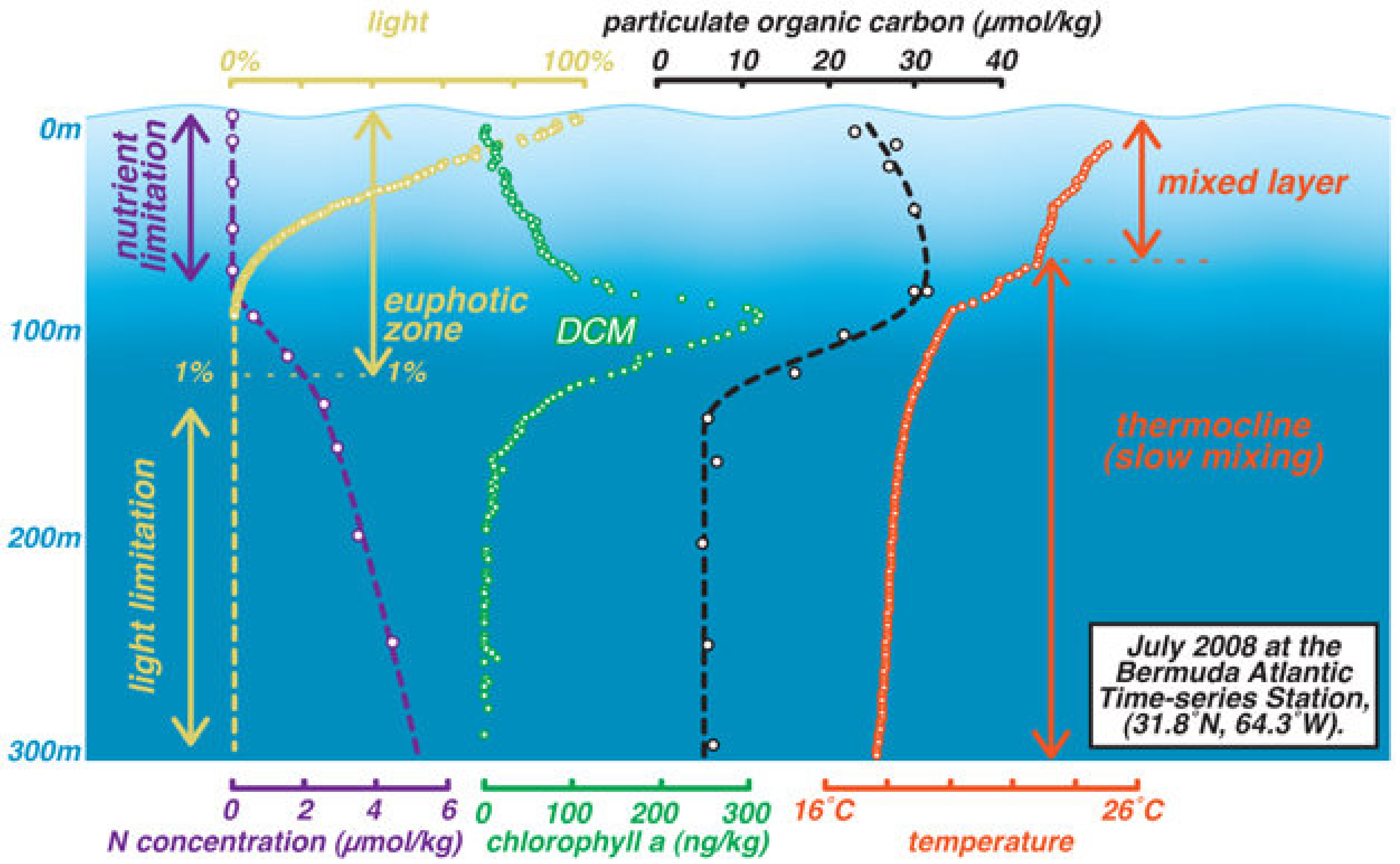


Spatial scales

Euphotic layer



Chlorophyll maximum



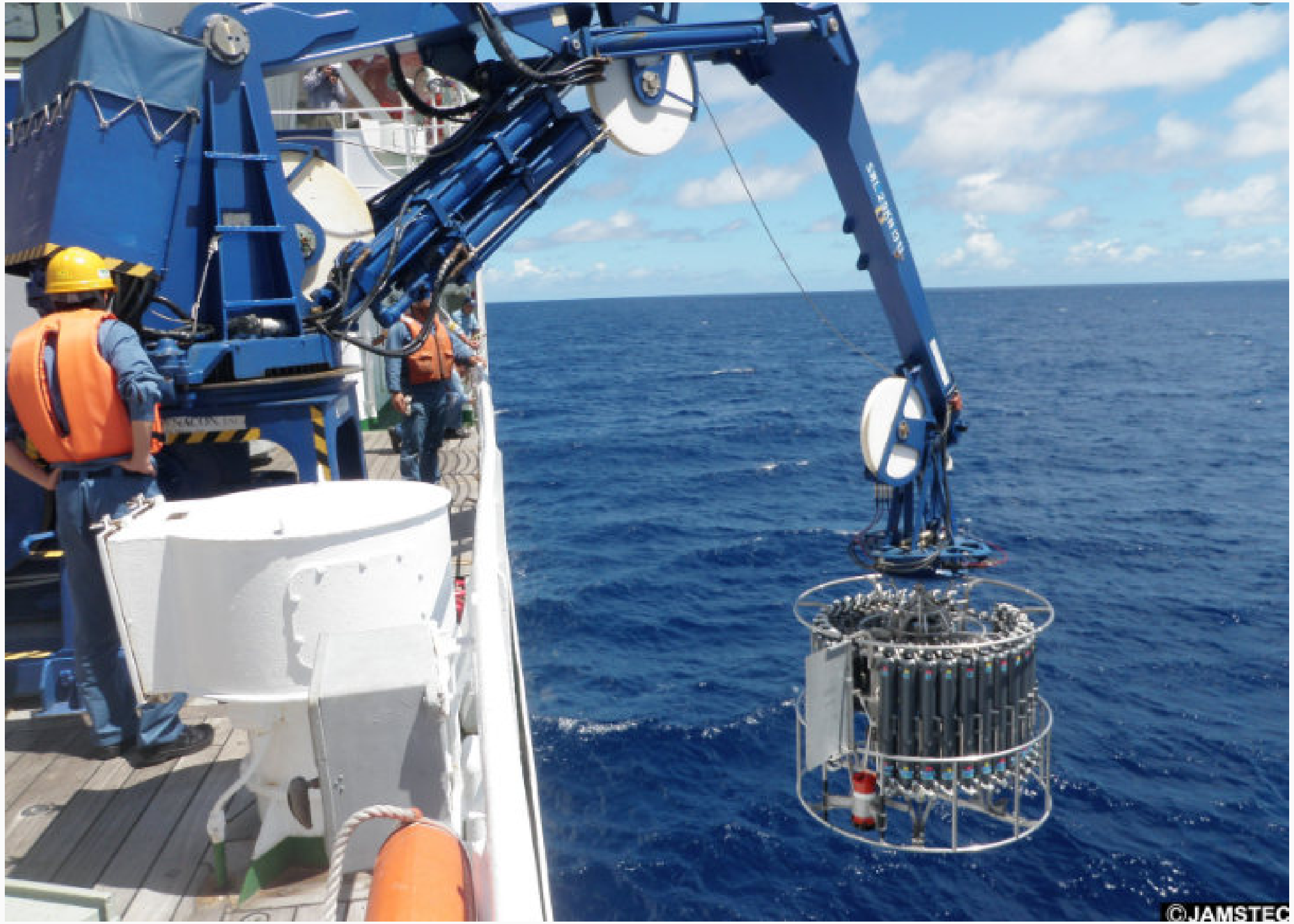
Spatial scales

Sampling the ocean

- Bucket sampling

Sampling the ocean

- Bottles on a Rosette
- CTD - Conducitivity, Temperature, Depth



Spatial scales

Sampling the ocean

- Filtration

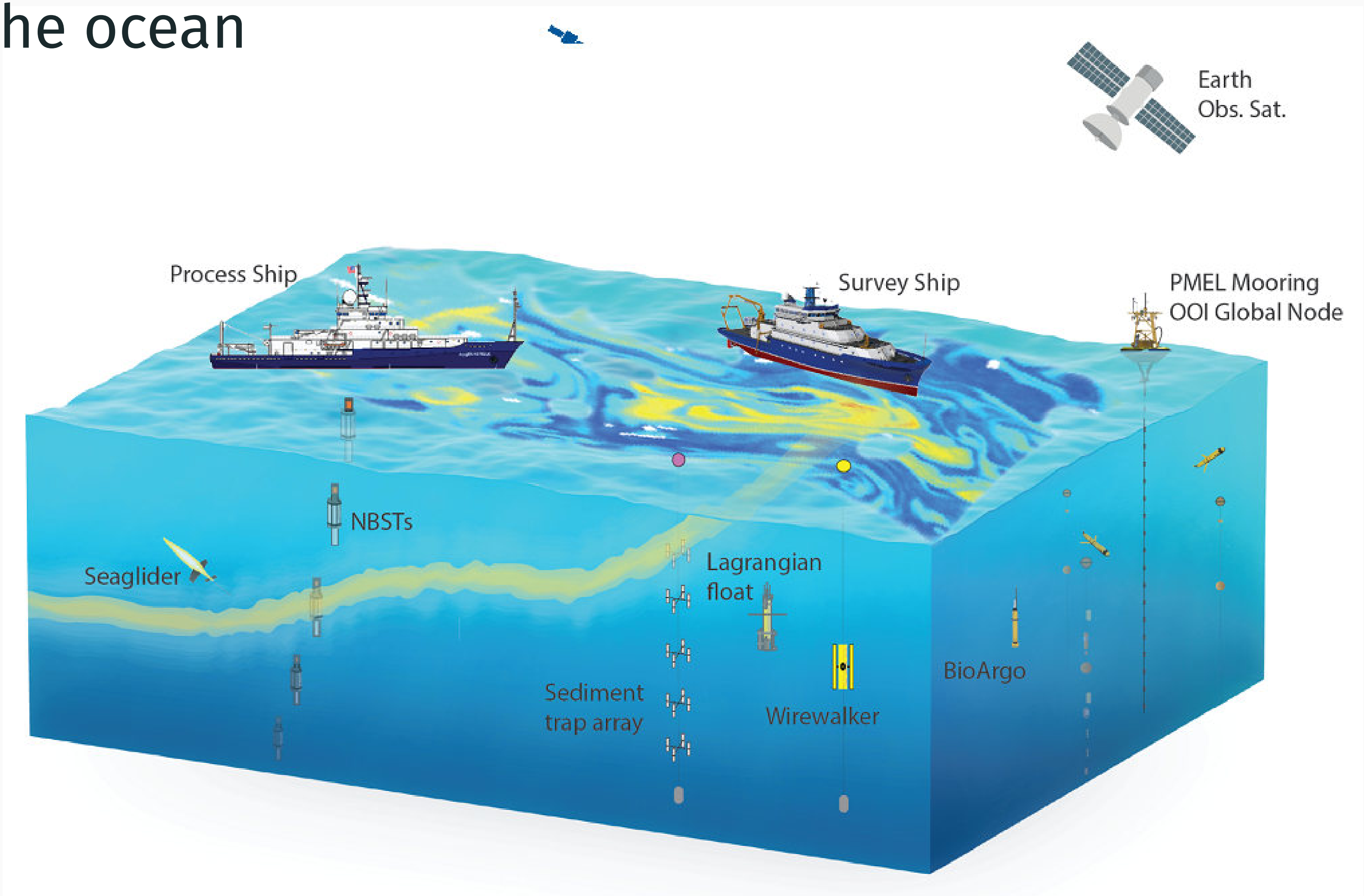
Spatial scales

Sampling the ocean

- Nets

Sampling the ocean

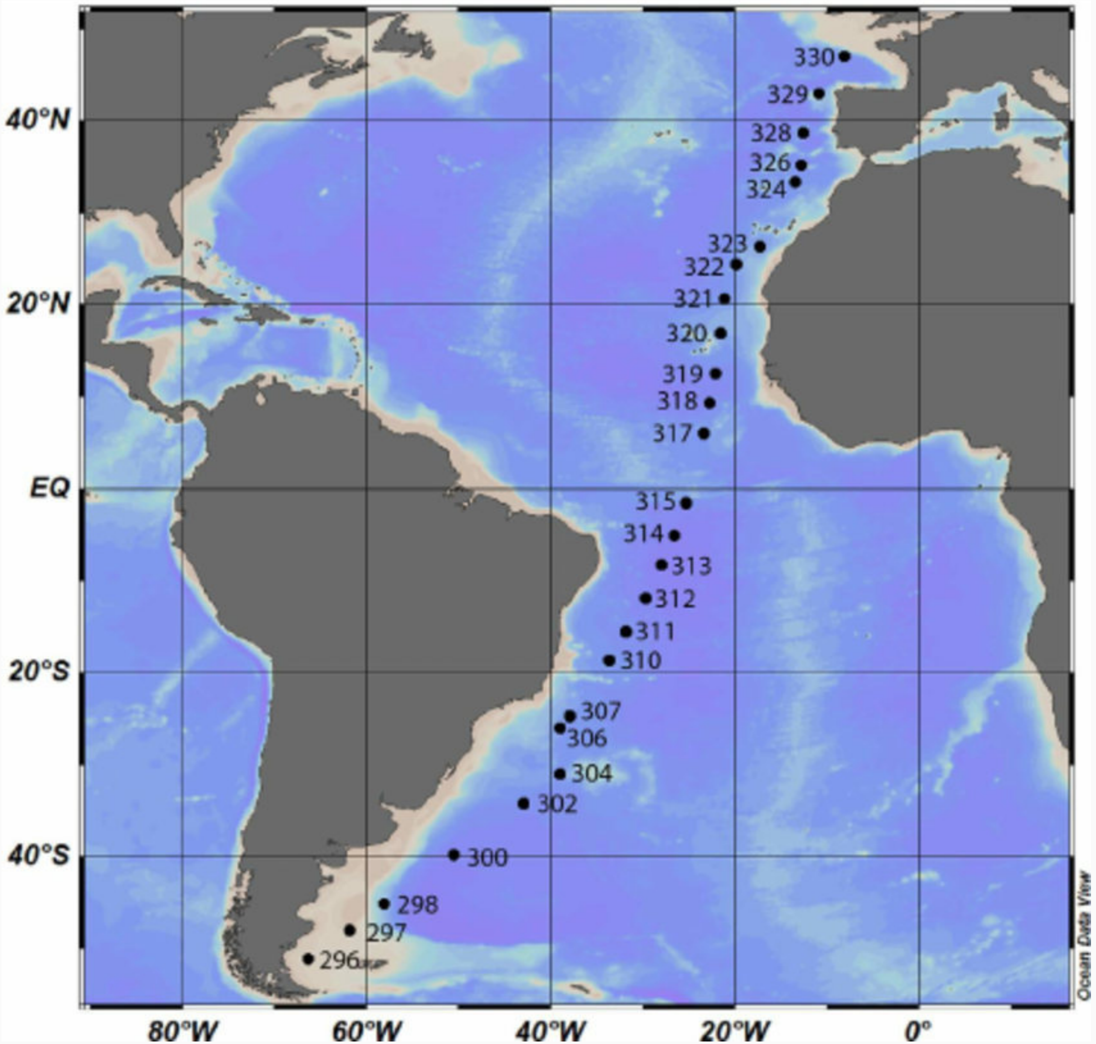
- Eulerian
- Lagrangian



Spatial scales

Sampling the ocean

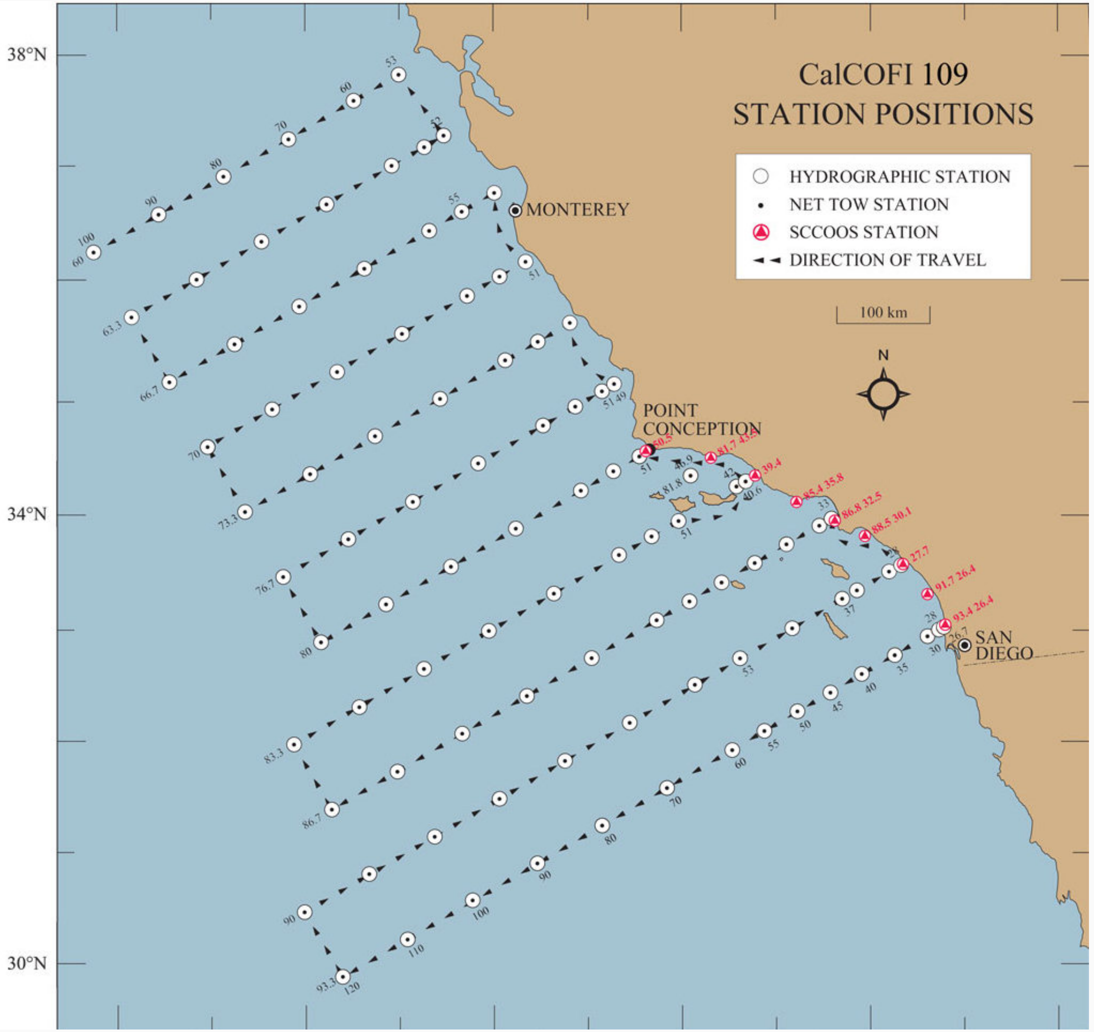
- Transects (Eulerian)



Spatial scales

Sampling the ocean

- Grids (Eulerian)



https://calcofi.org/index.php

Sampling the ocean

- Drifting buoy (Lagrangian)

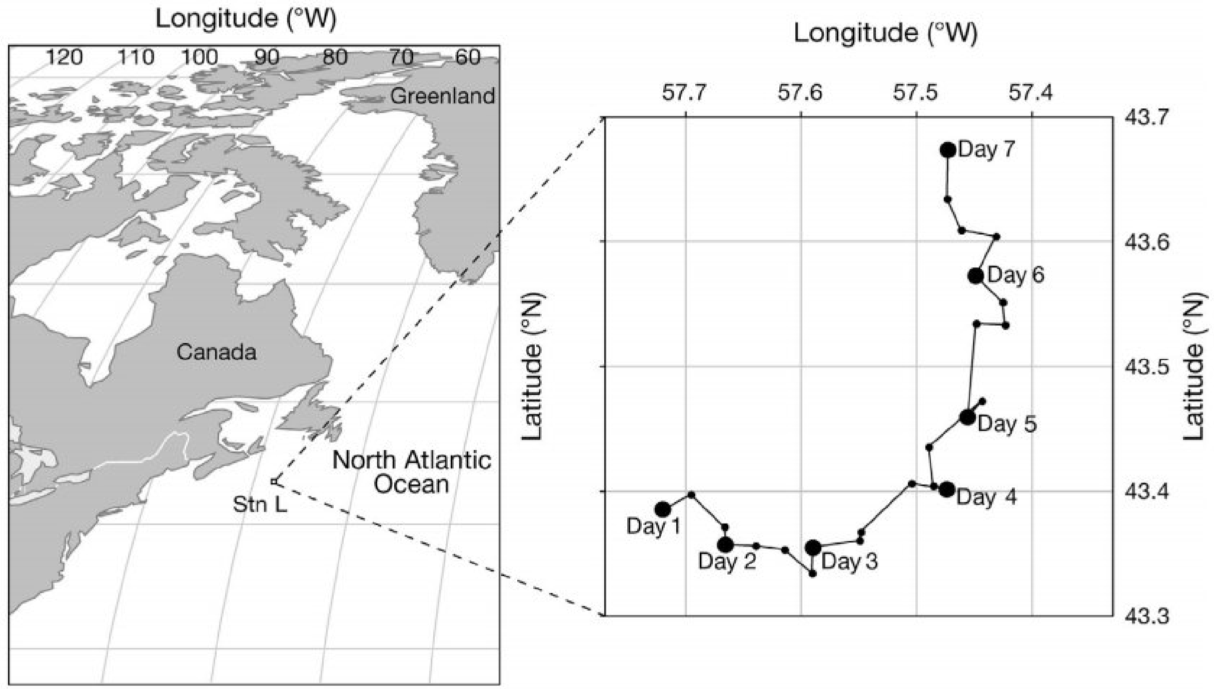
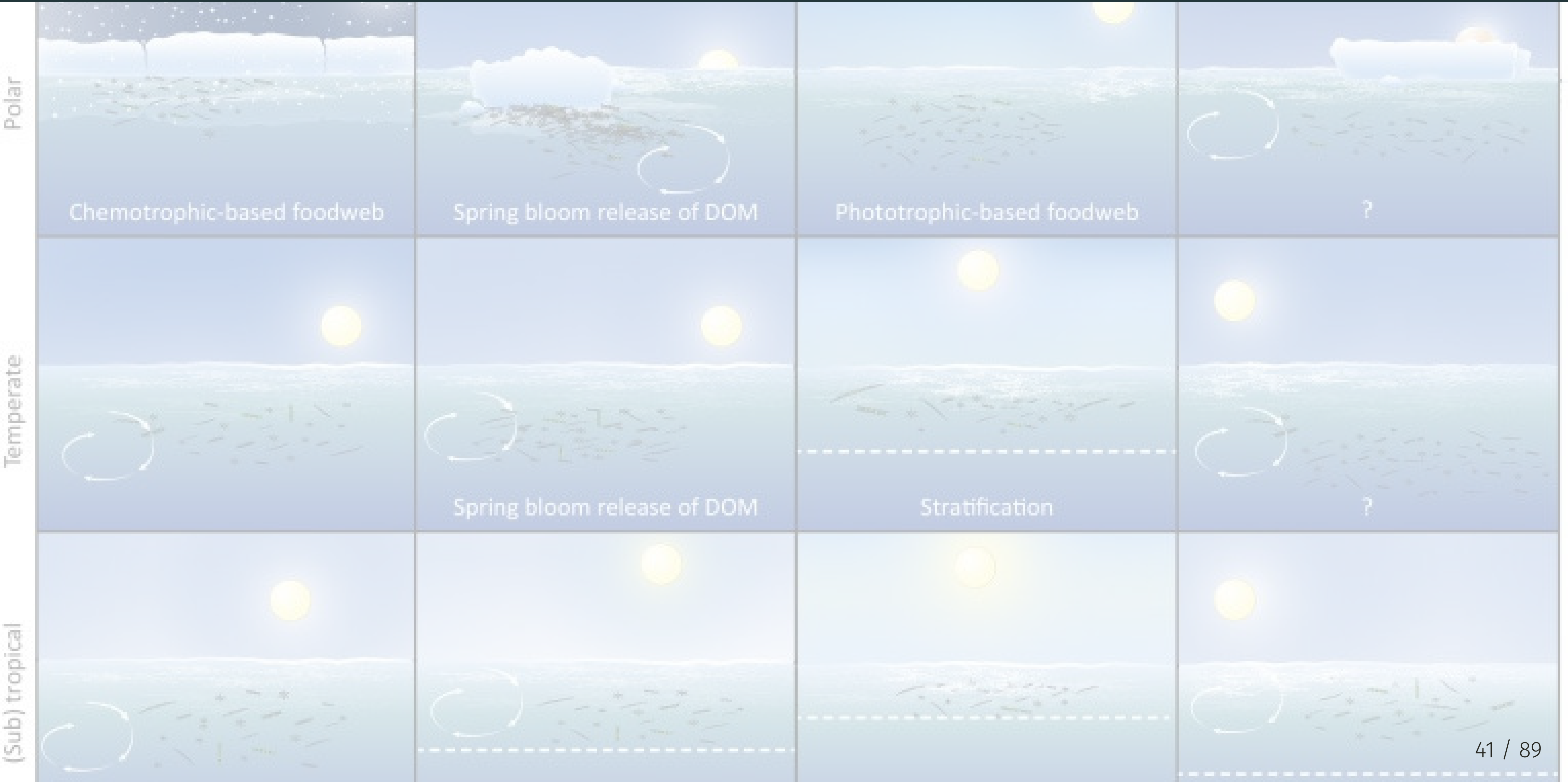


Fig. 1. Location of the Lagrangian station in the northwest Atlantic Ocean over the 7 day period (Day 1 to Day 7). Position of the drifting buoy at every 6 h time point is indicated

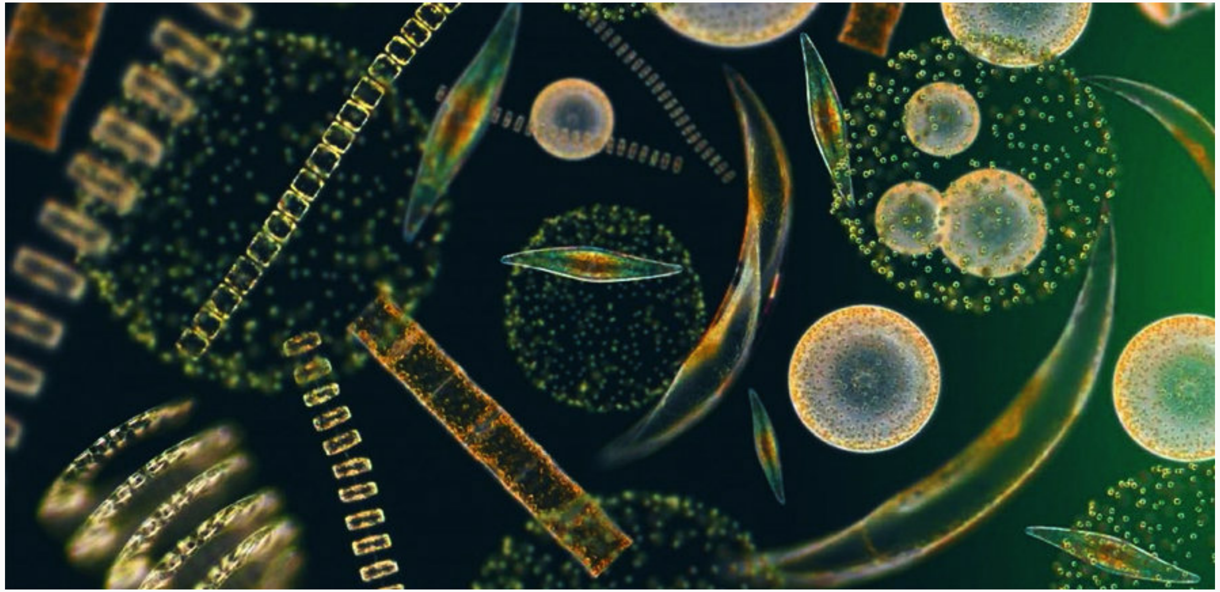
Lizotte et al.(2008) Fate of dimethylsulfoniopropionate (DMSP) during the decline of the northwest Atlantic Ocean spring diatom bloom. Aquat Microb Ecol 52:159-173

Temporal scales



Temporal scales

What are the most important scales in the ocean?

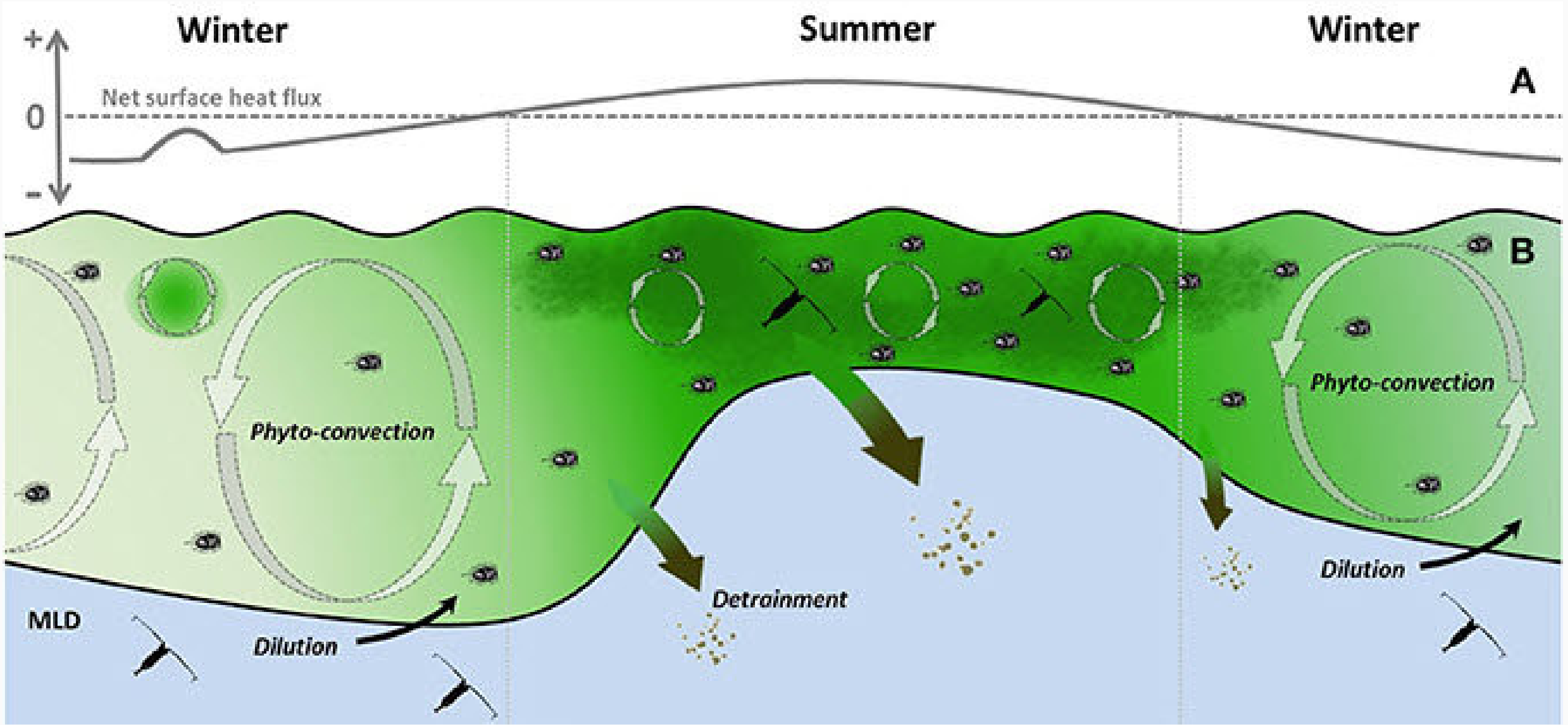


Temporal variations

Bloom populations in the North Atlantic and North Pacific oceans from March 2003 to October 2006: https://svs.gsfc.nasa.gov/10971

Annual scale - Spring bloom

- Diatoms
- Dinoflagellates

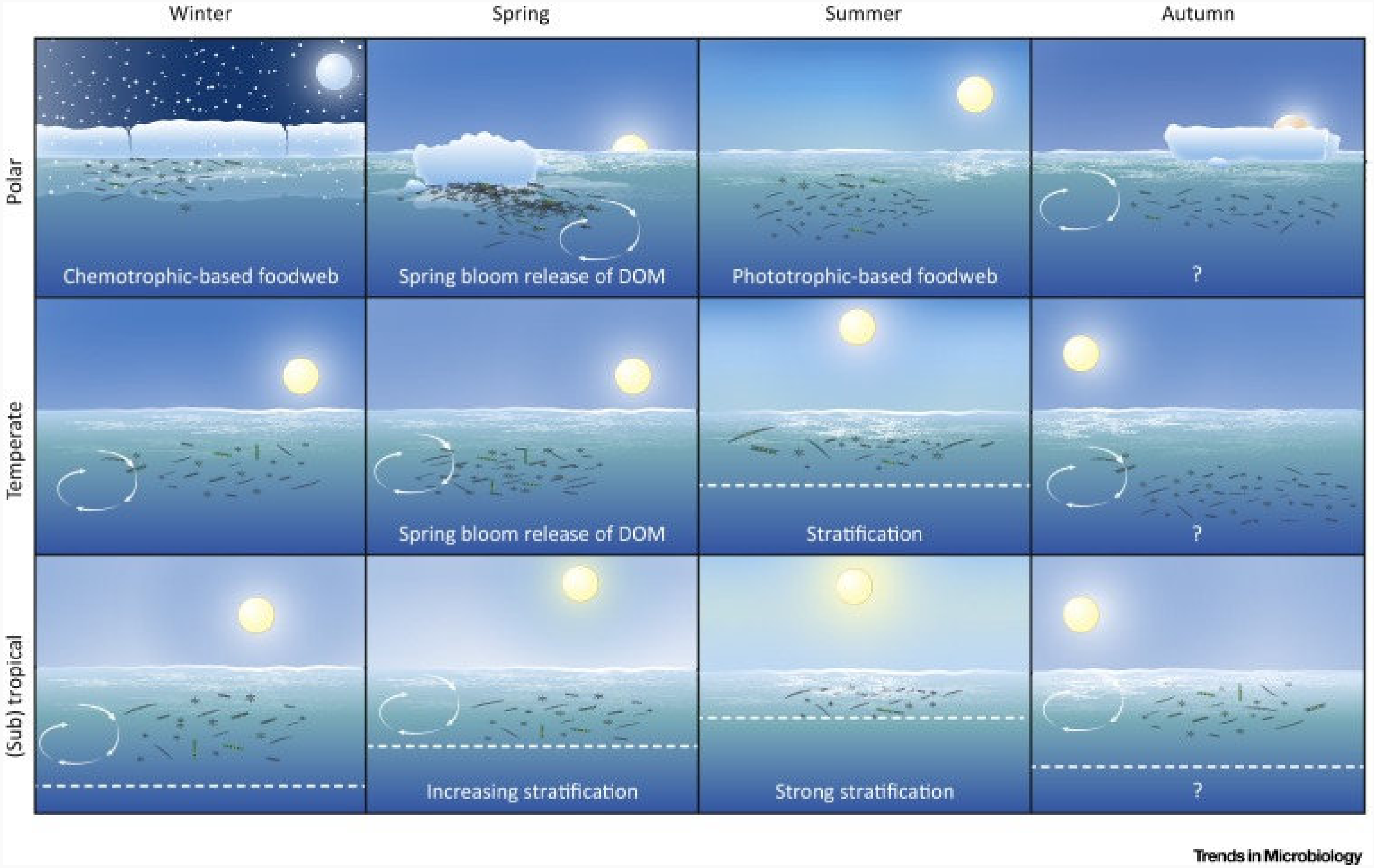


Lindemann C and St. John MA (2014) A seasonal diary of phytoplankton in the North Atlantic. Front. Mar. Sci. 1:37

Temporal scales

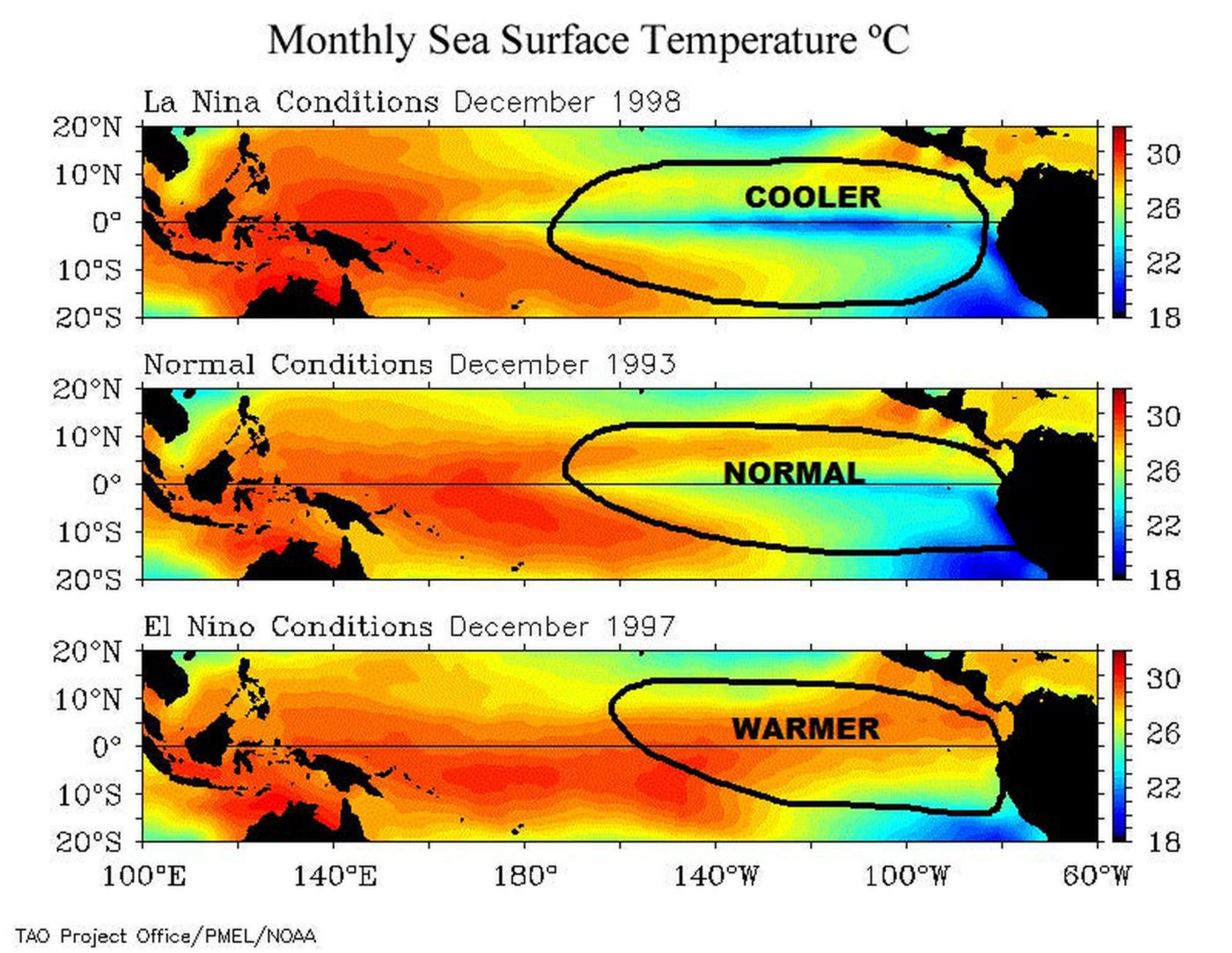
Annual scale - Spring bloom

- Depends on latitude
  - Temperate
  - Tropical
  - Arctic



Multi-year scale - El Niño

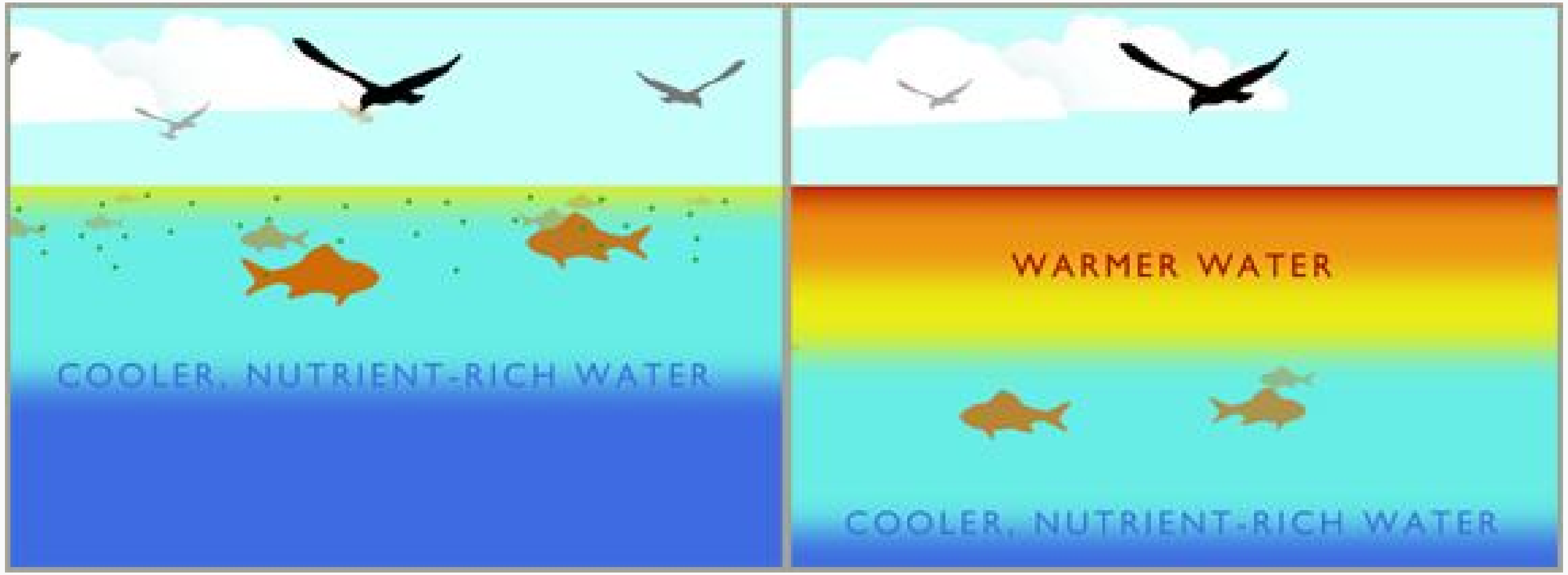
Warm water accumulates over East Pacific



Temporal scales

Multi-year scale - El Niño

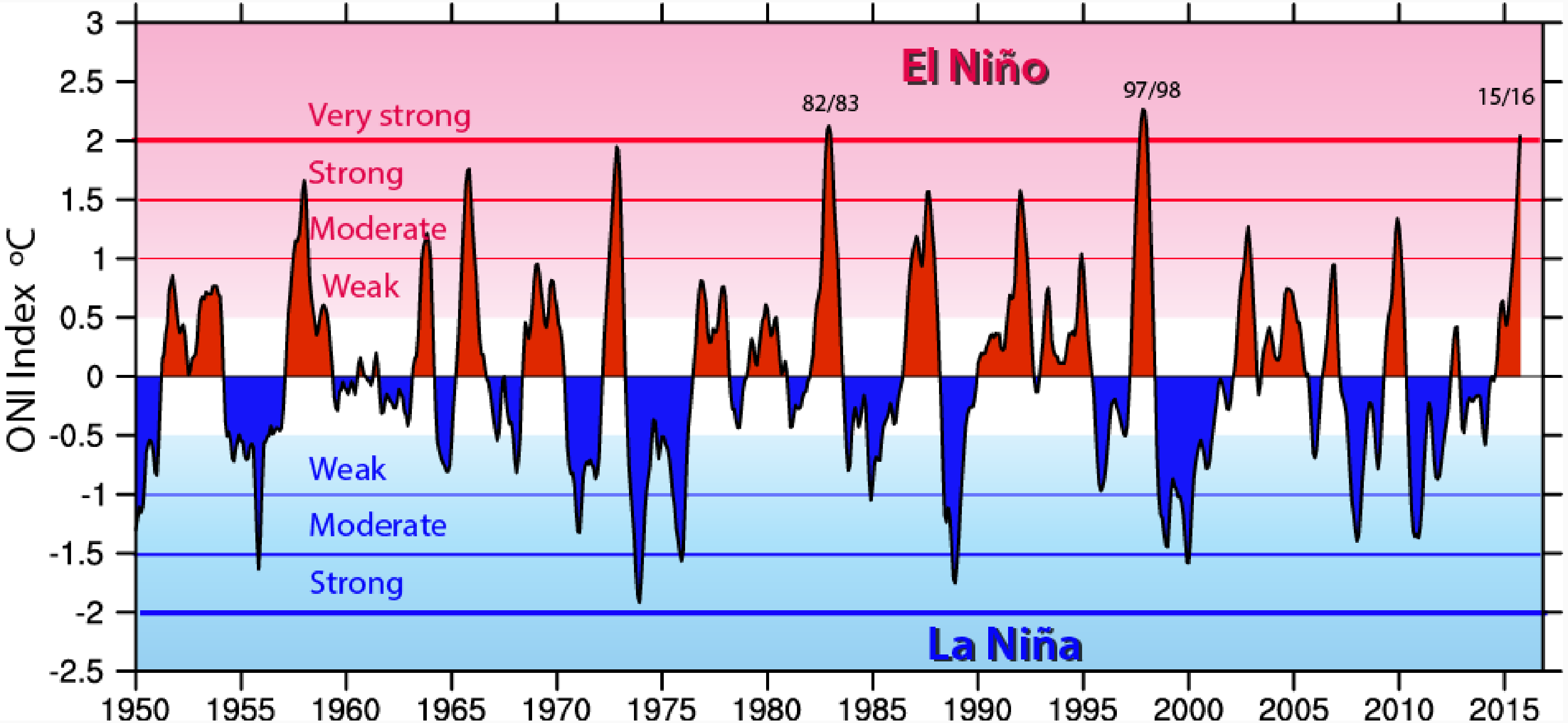
- Blocks upwelling
- Phytoplankton decrease
- Lower fish capture (anchovy)



Temporal scales

Multi-year scale - El Niño

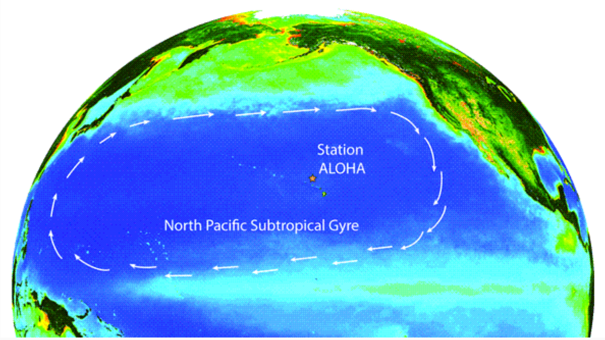
- Year to year change in intensity

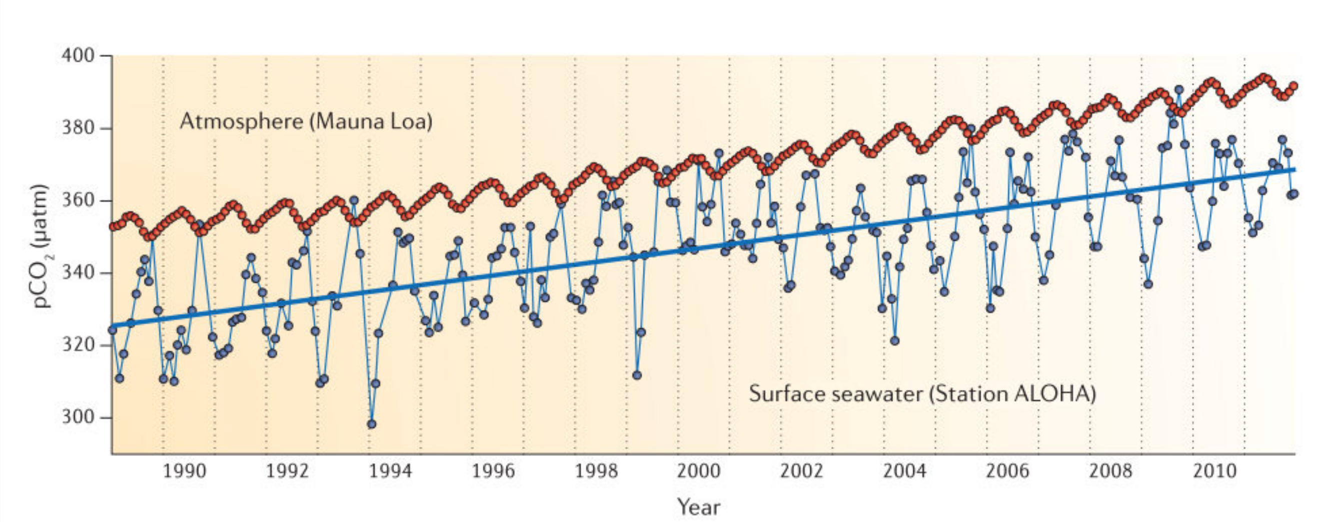


Temporal scales

Climatic change

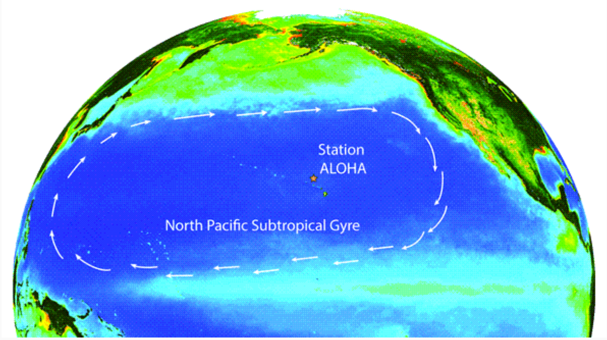
- ALOHA station

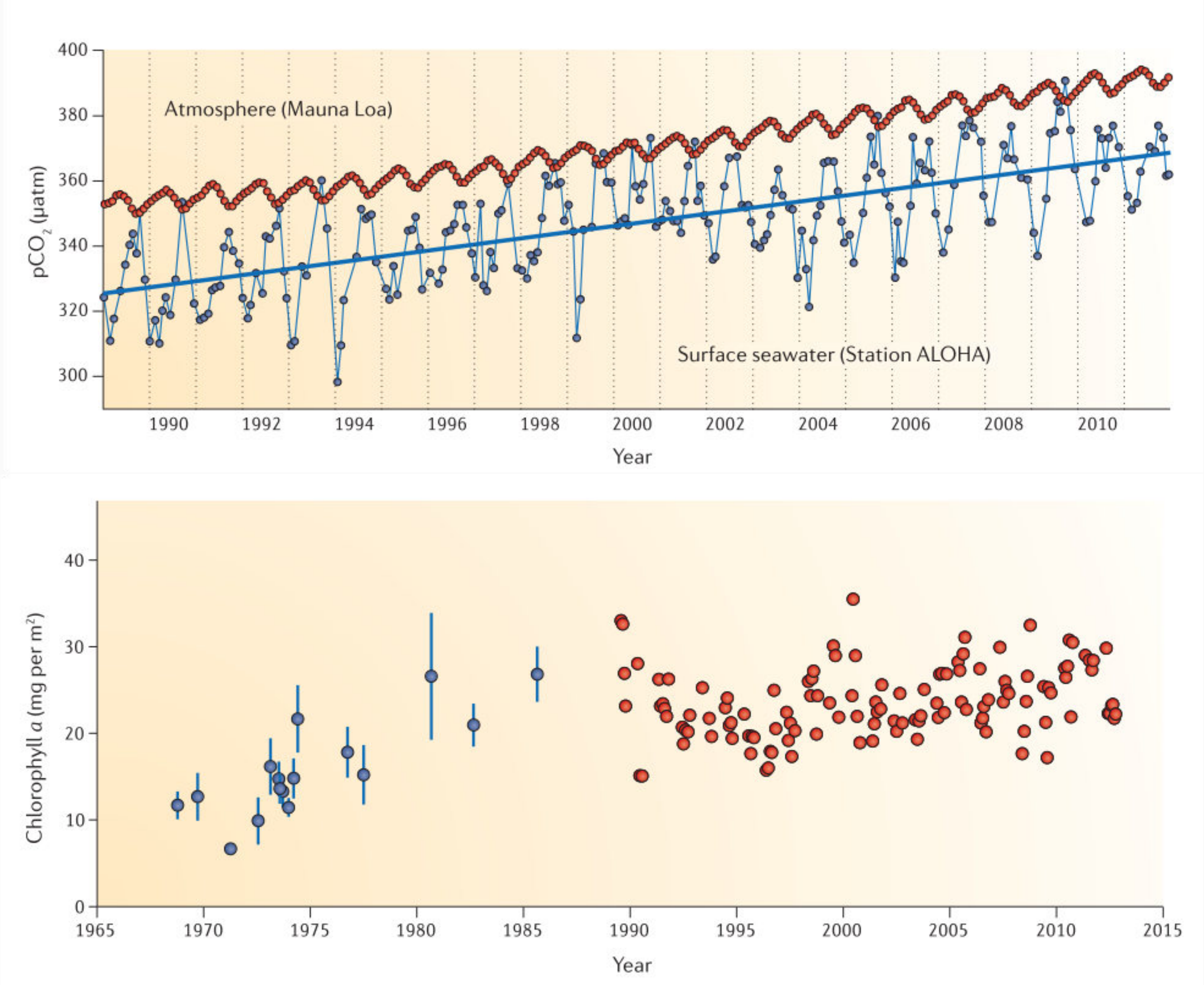




Climatic change

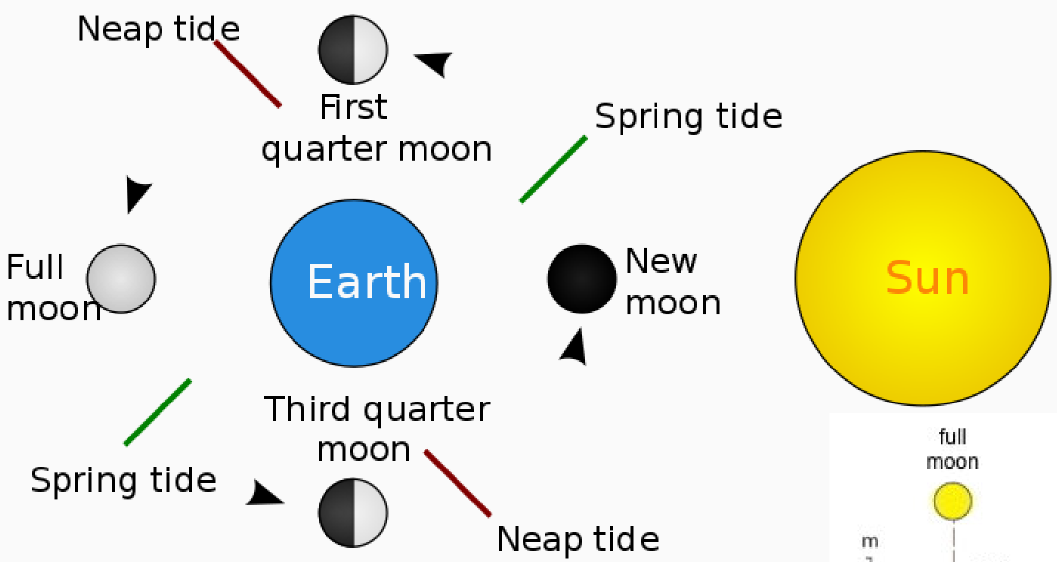
- ALOHA station

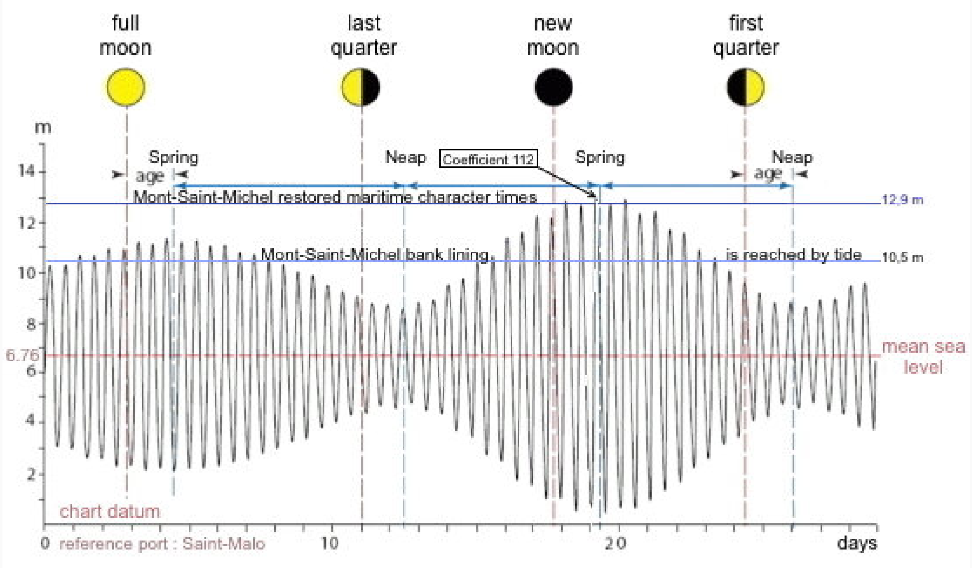




Monthly scale

- Neap tide
- Spring tide

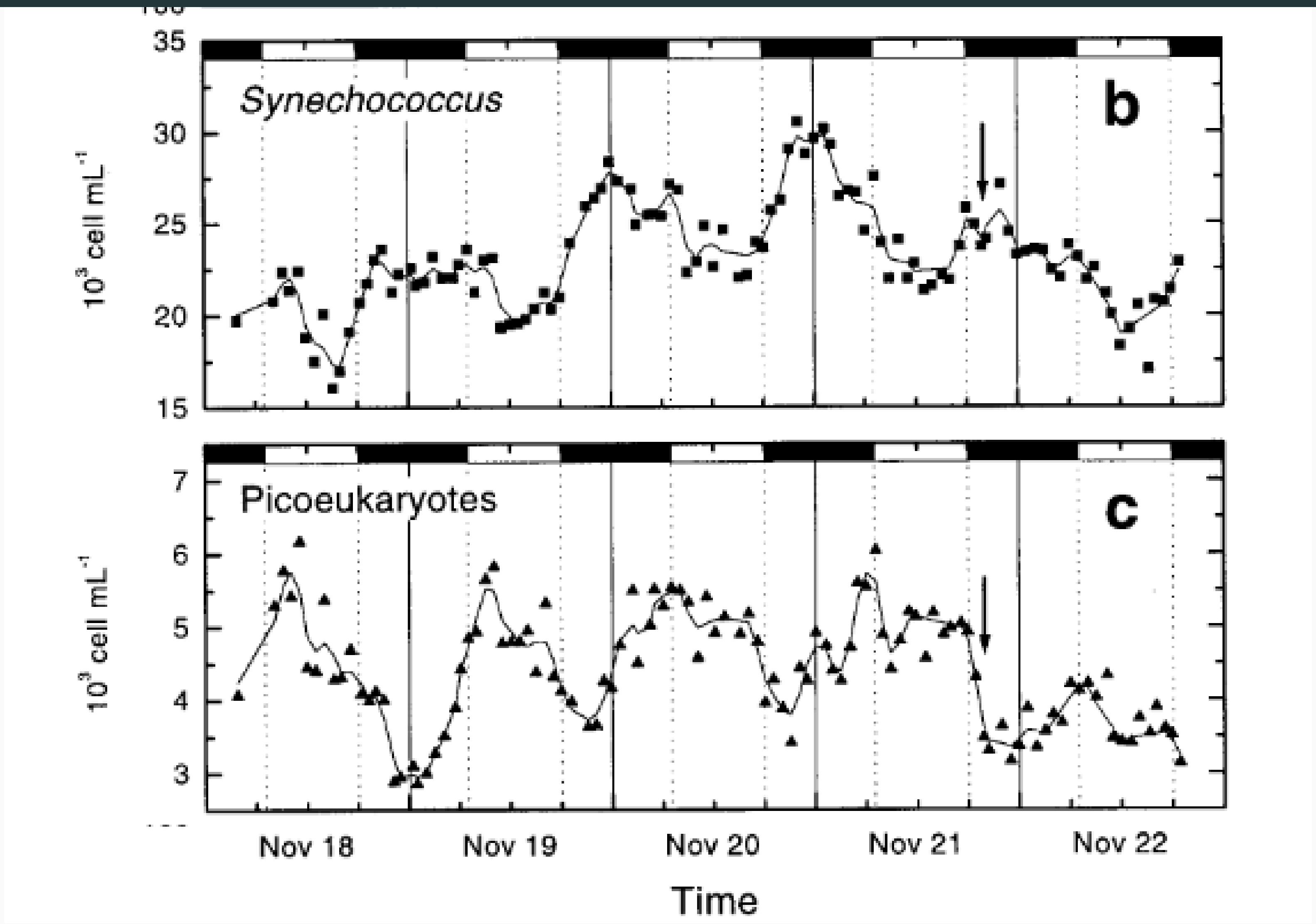




Temporal scales

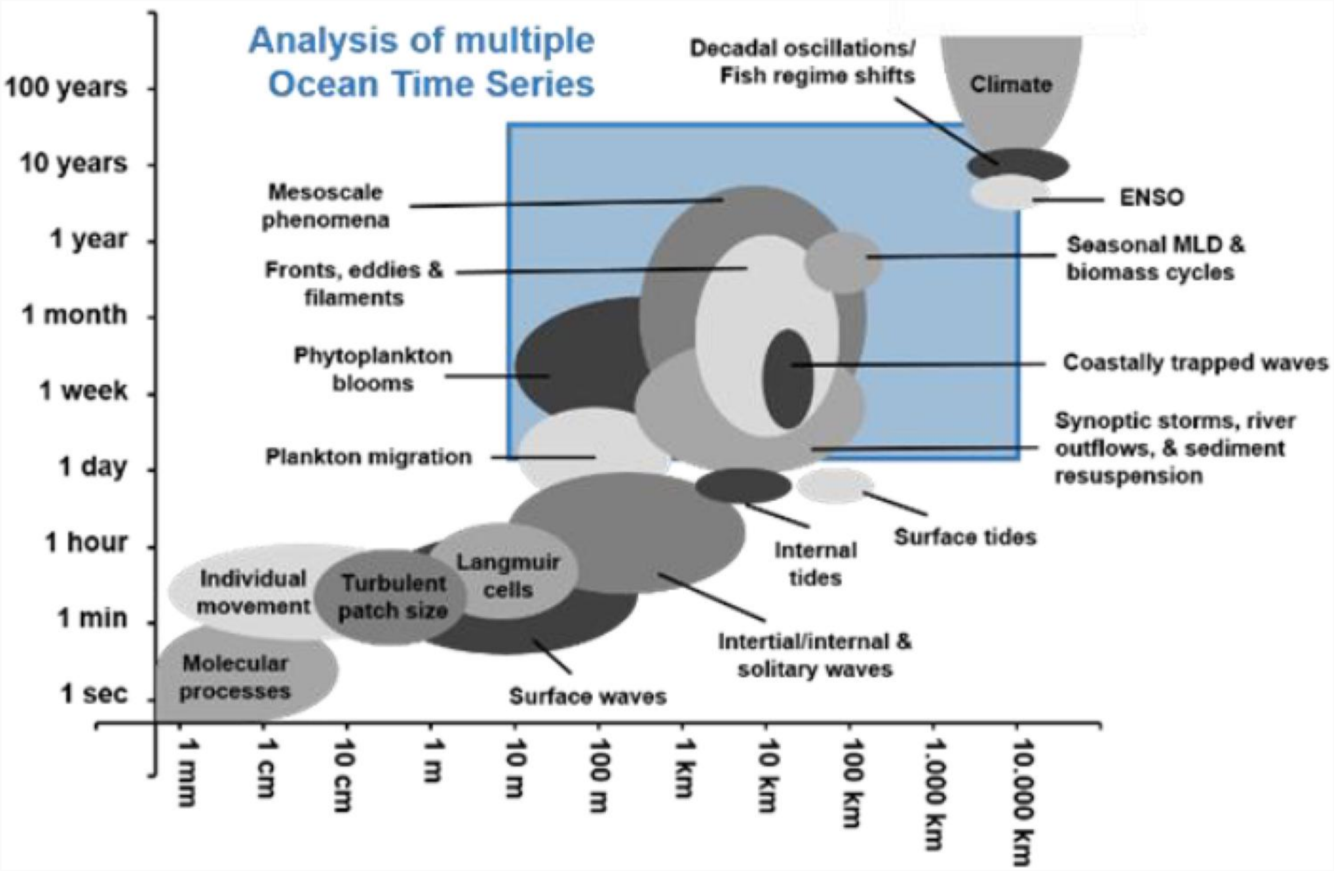
Daily scale

Unique to marine systems



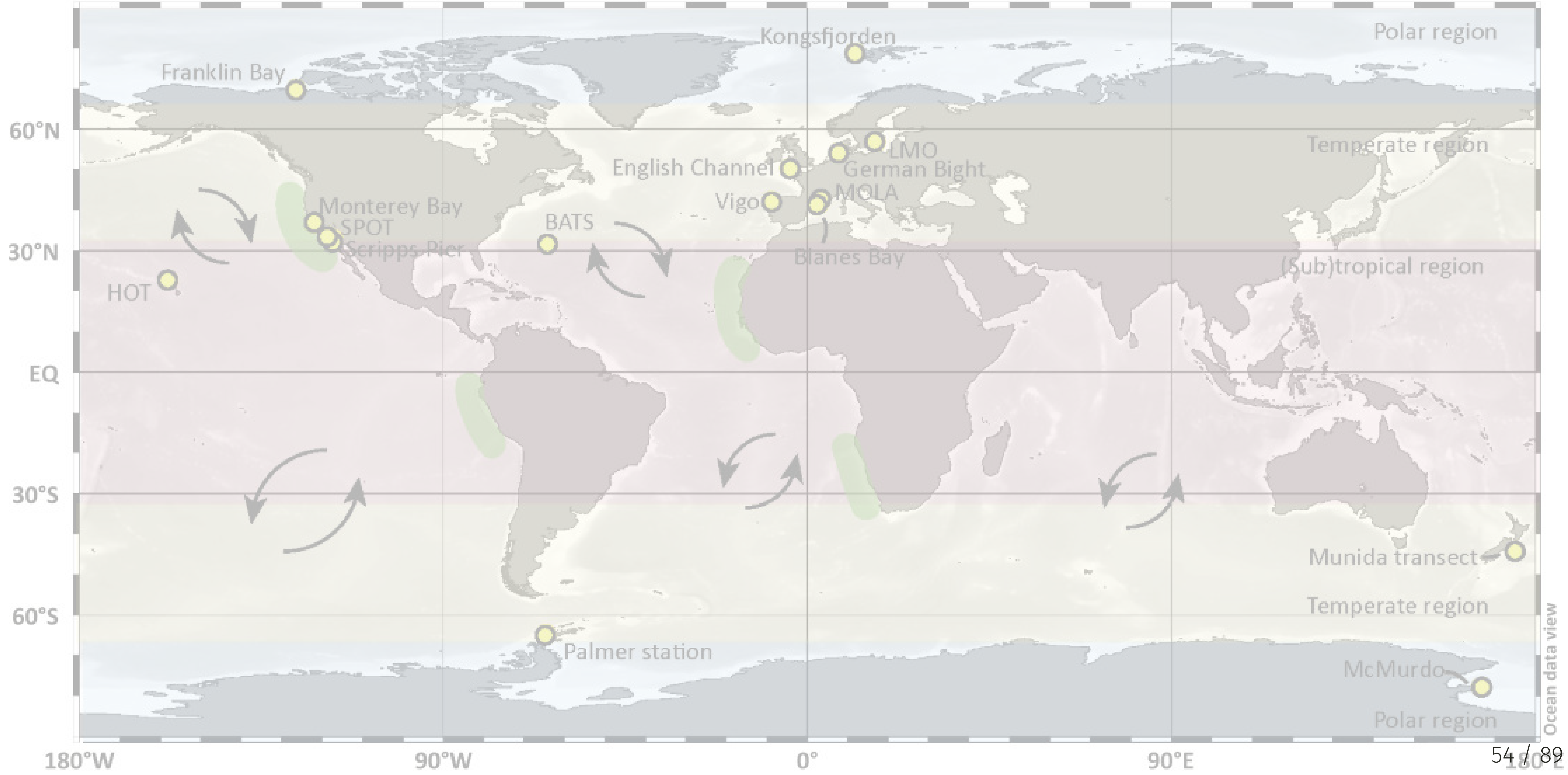
Vaulot D., Marie D. 1999. Diel variability of photosynthetic picoplankton in the equatorial Pacific. Journal of Geophysical Research 104:3297.

Spatial and temporal scales



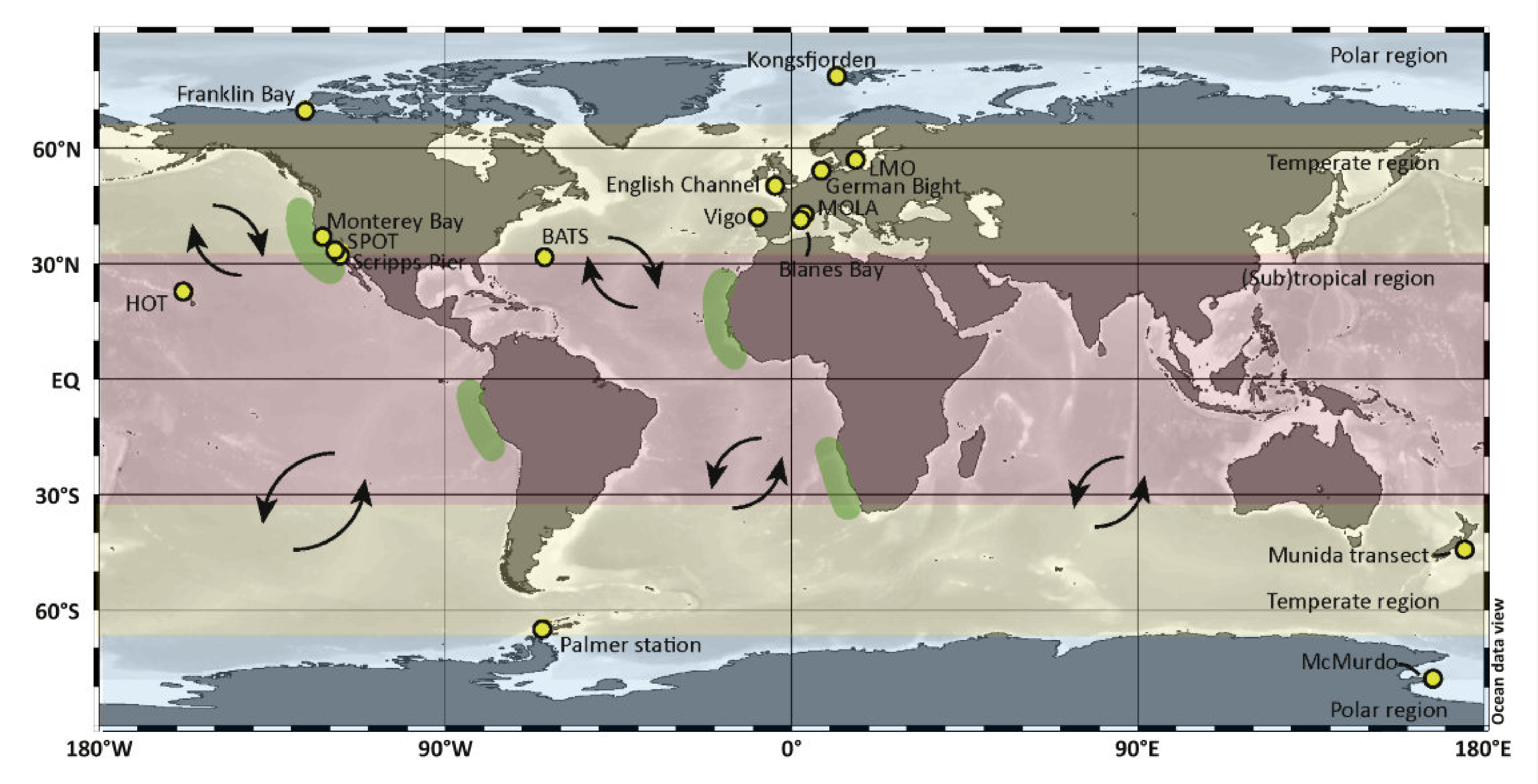
Benway HM. et al. 2019. Ocean Time Series Observations of Changing Marine Ecosystems: An Era of Integration, Synthesis, and Societal Applications. Frontiers in Marine Science 6:1–22.

Time series



Kongsfjorden
Polar region
Franklin Bay
60°N
LMO
Temperate region
English Channel
German Bight
MOLA
Vigo
Monterey Bay
SPOT
Scripps Pier
BATS
30°N
Blanes Bay
(Sub)tropical region
HOT
EQ
30°S
Munida transect
60°S
Temperate region
Palmer station
McMurdo
Polar region
Ocean data view
180°W
90°W
0°
90°E
180°E

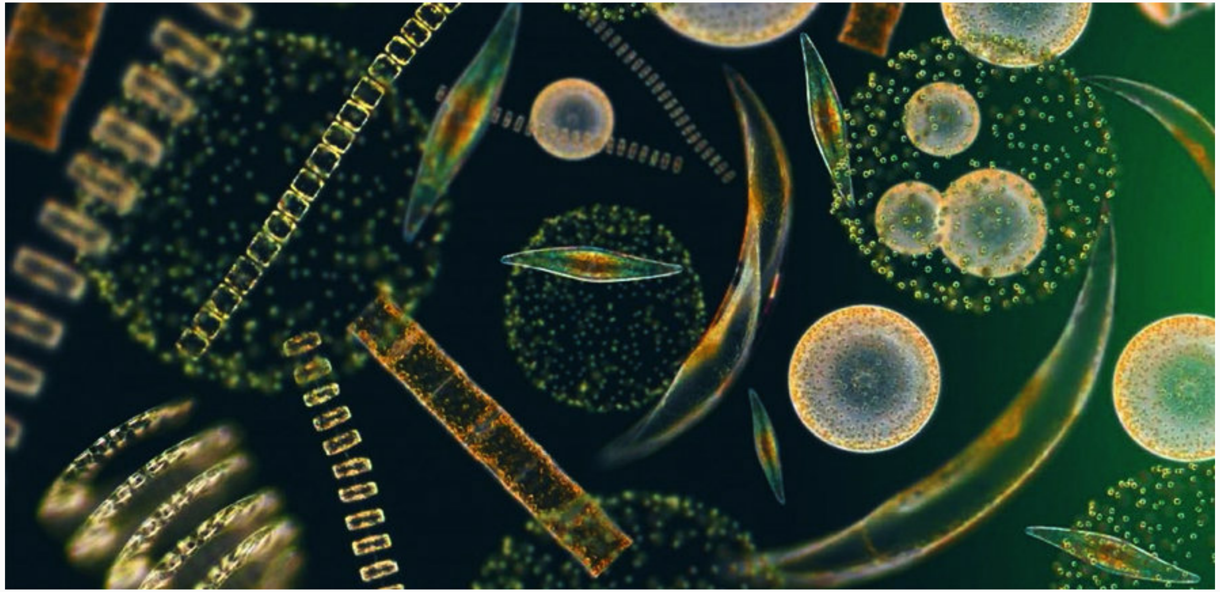
Long term stations



Bunse C., Pinhassi J. 2017. Marine Bacterioplankton Seasonal Succession Dynamics. Trends in Microbiology 25:494–505.

Time series

What kind of questions can be adressed by such long term series?

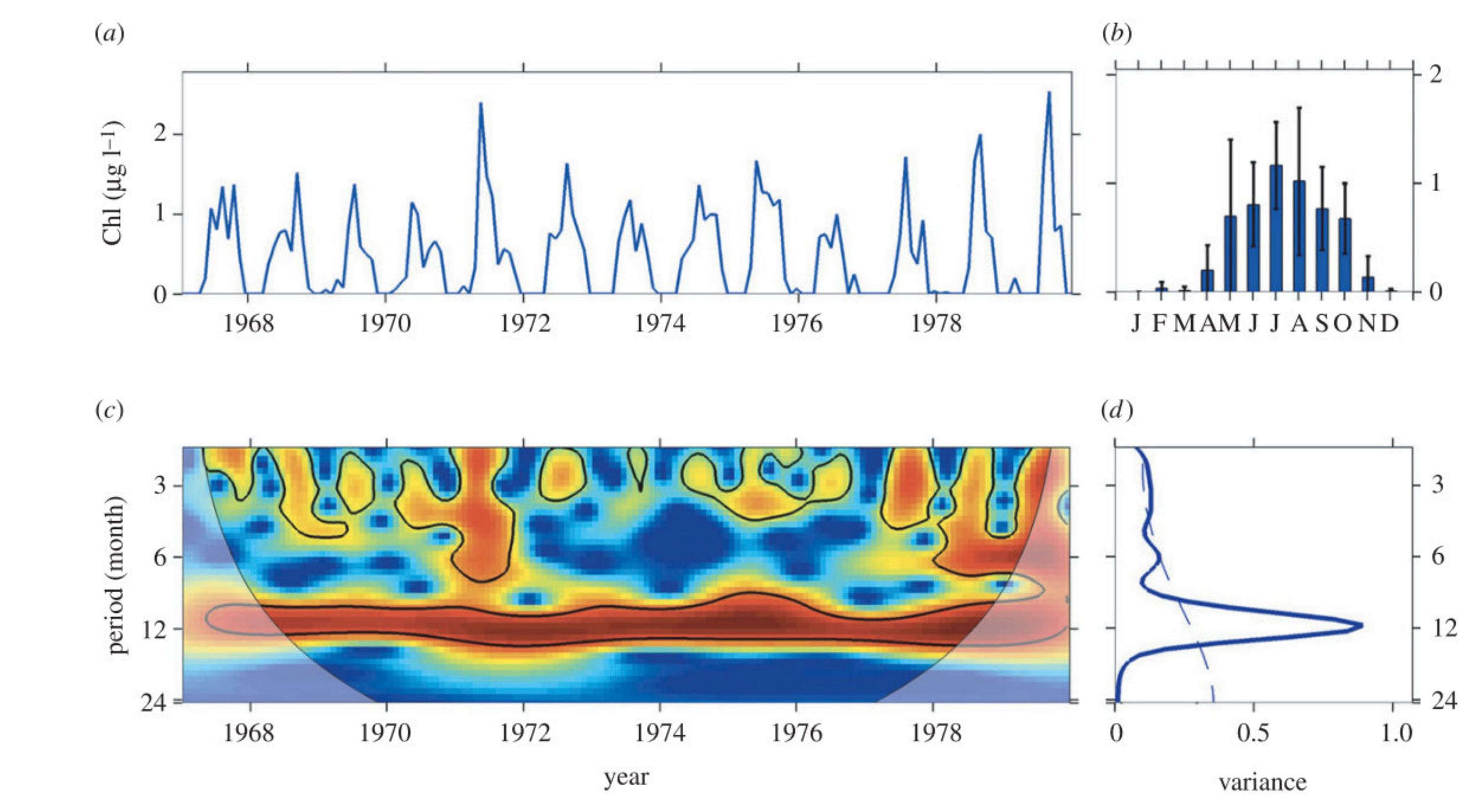


Time series

- What are the key periodicities ?
  - annual (what about equator ?)
  - tides (monthly)
  - daily
- Long term climatic trends
- What drives the year to year variability
- Recurring species ?

Chlorophyll time series

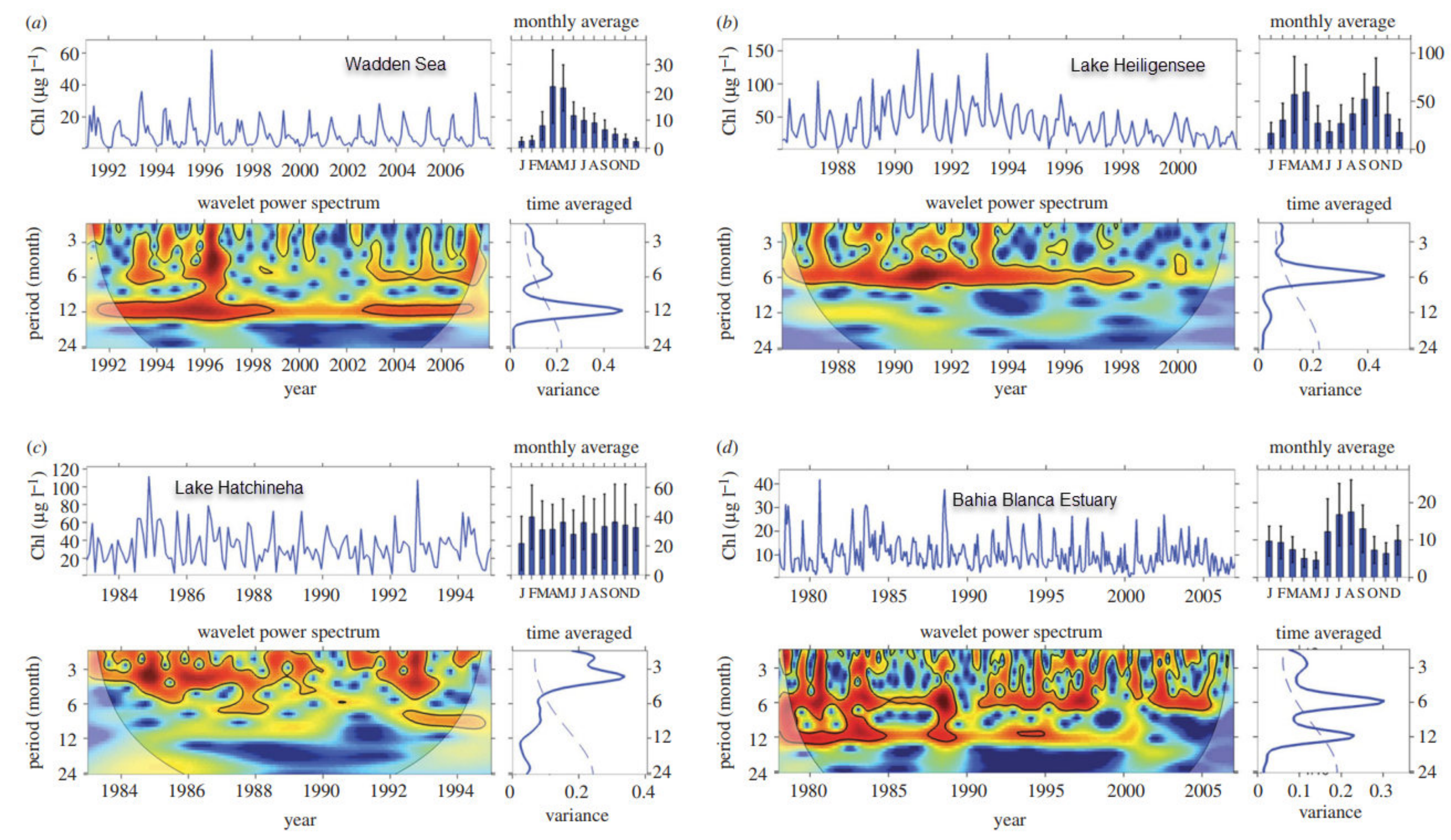
- North Atlantic Chl-a time series (57–628 N, 20–108 W) from 1967 to 1979



Winder M., Cloern JE. 2010. The annual cycles of phytoplankton biomass. Philosophical Transactions of the Royal Society B: Biological Sciences 365:3215–3226.

Chlorophyll time series

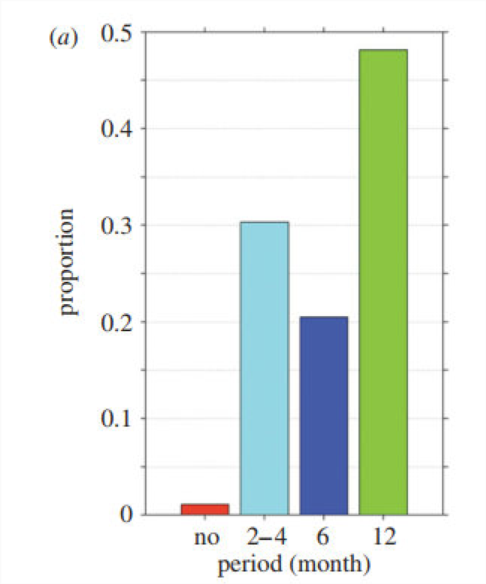
What can you see ?

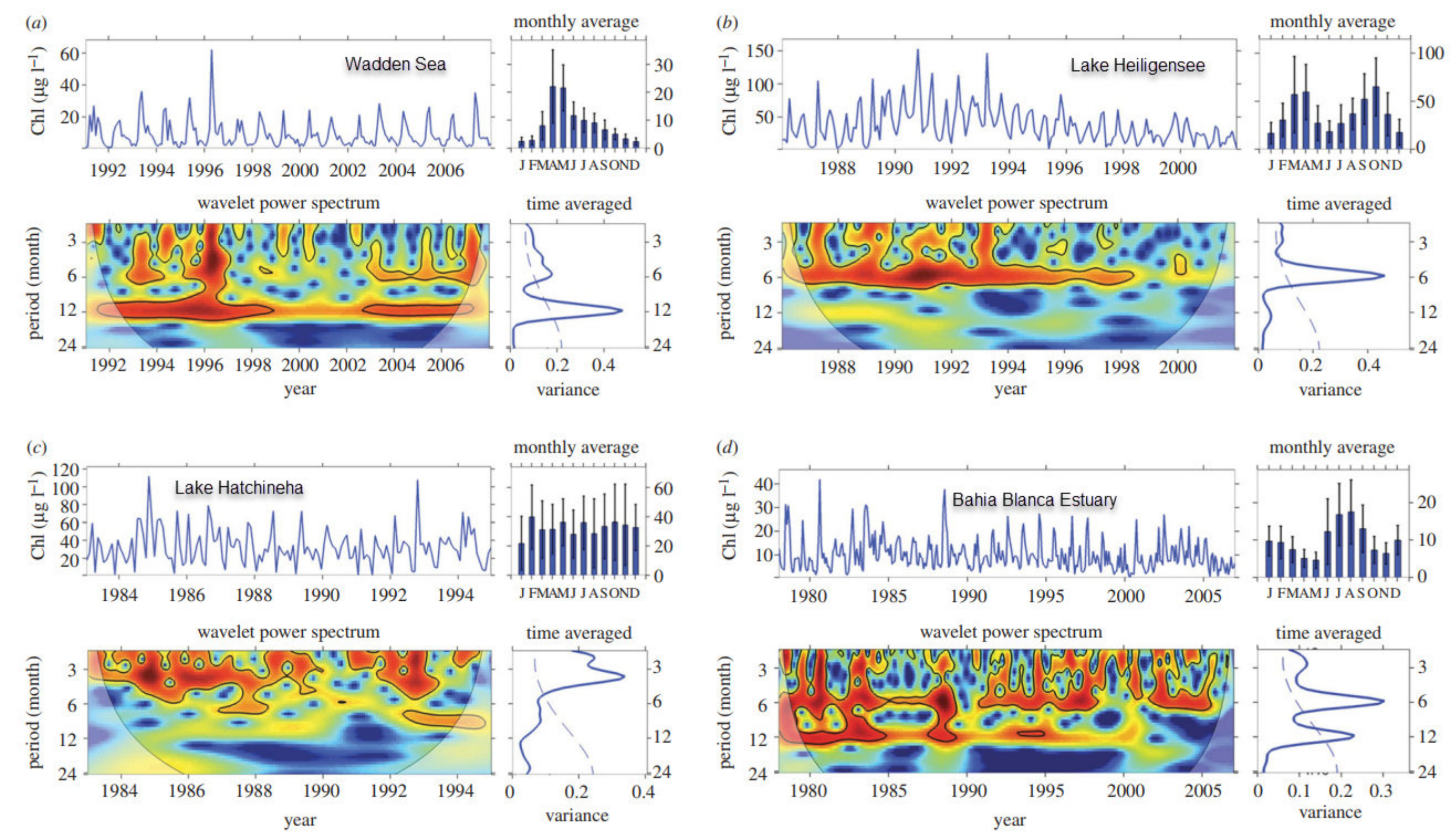


Winder M., Cloern JE. 2010. The annual cycles of phytoplankton biomass. Philosophical Transactions of the Royal Society B: Biological Sciences 365:3215–3226.

Chlorophyll time series

- Different environments have different frequencies





Winder M., Cloern JE. 2010. The annual cycles of phytoplankton biomass. Philosophical Transactions of the Royal Society B: Biological Sciences 365:3215–3226.

What drives the *Synechoccus* bloom ?

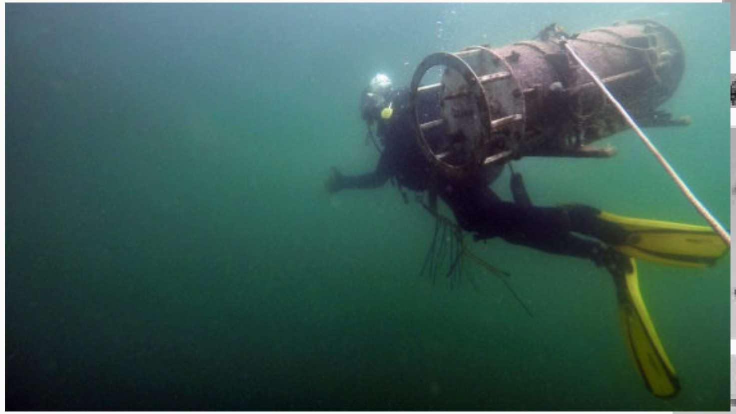
Physiological and ecological drivers of early spring blooms of a coastal phytoplankter

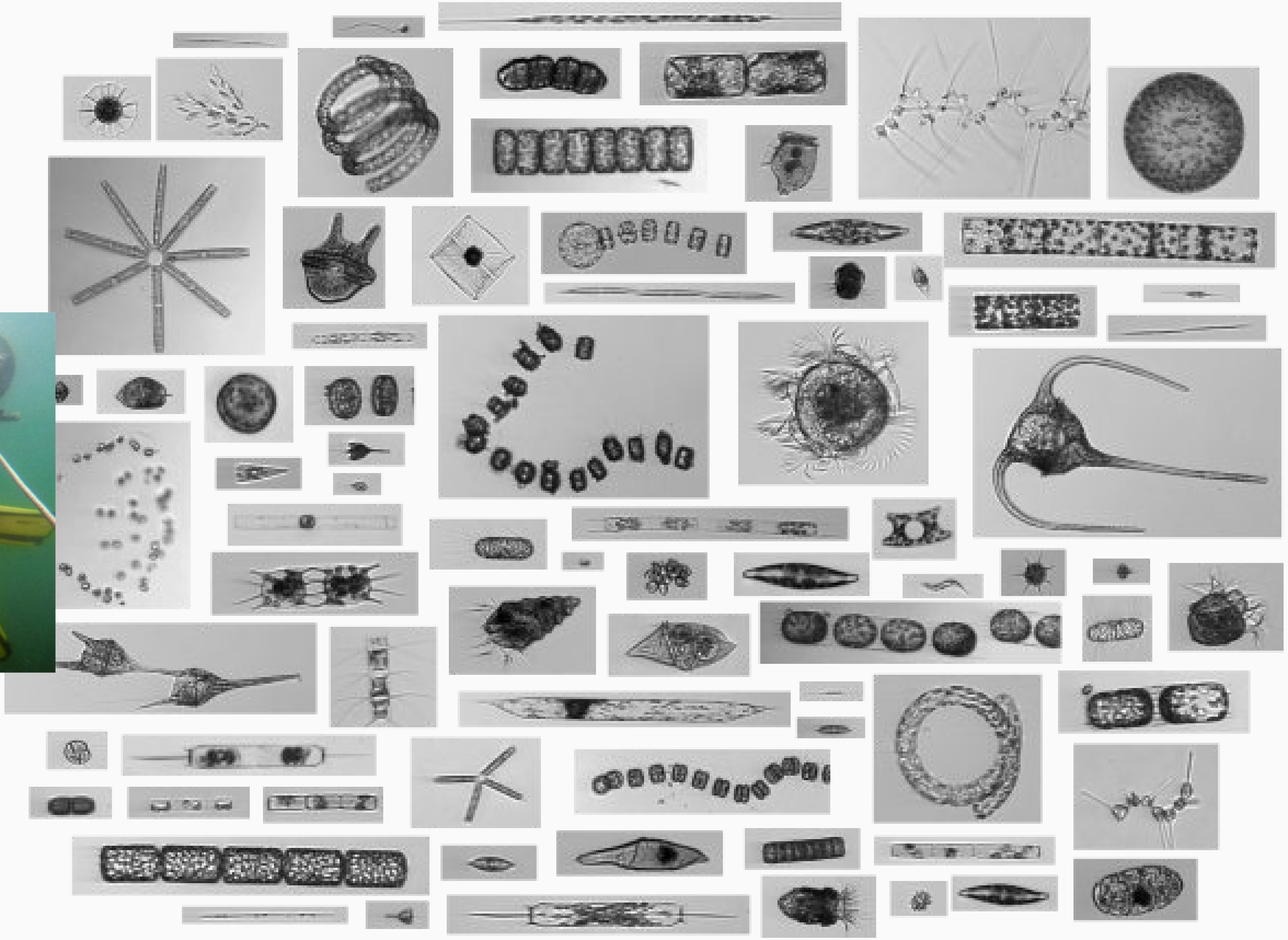
Kristen R. Hunter-Cevera,[1] Michael G. Neubert,[1] Robert J. Olson,[1] Andrew R. Solow,[2] Alexi Shalapyonok,[1] Heidi M. Sosik[1*]

Climate affects the timing and magnitude of phytoplankton blooms that fuel marine food webs and influence global biogeochemical cycles. Changes in bloom timing have been detected in some cases, but the underlying mechanisms remain elusive, contributing to uncertainty in long-term predictions of climate change impacts. Here we describe a 13-year hourly time series from the New England shelf of data on the coastal phytoplankter *Synechococcus*, during which the timing of its spring bloom varied by 4 weeks. We show that multiyear trends are due to temperature-induced changes in cell division rate, with earlier blooms driven by warmer spring water temperatures. *Synechococcus* loss rates shift in tandem with division rates, suggesting a balance between growth and loss that has persisted

Flow Cytobot

- Imaging and flow cytometry

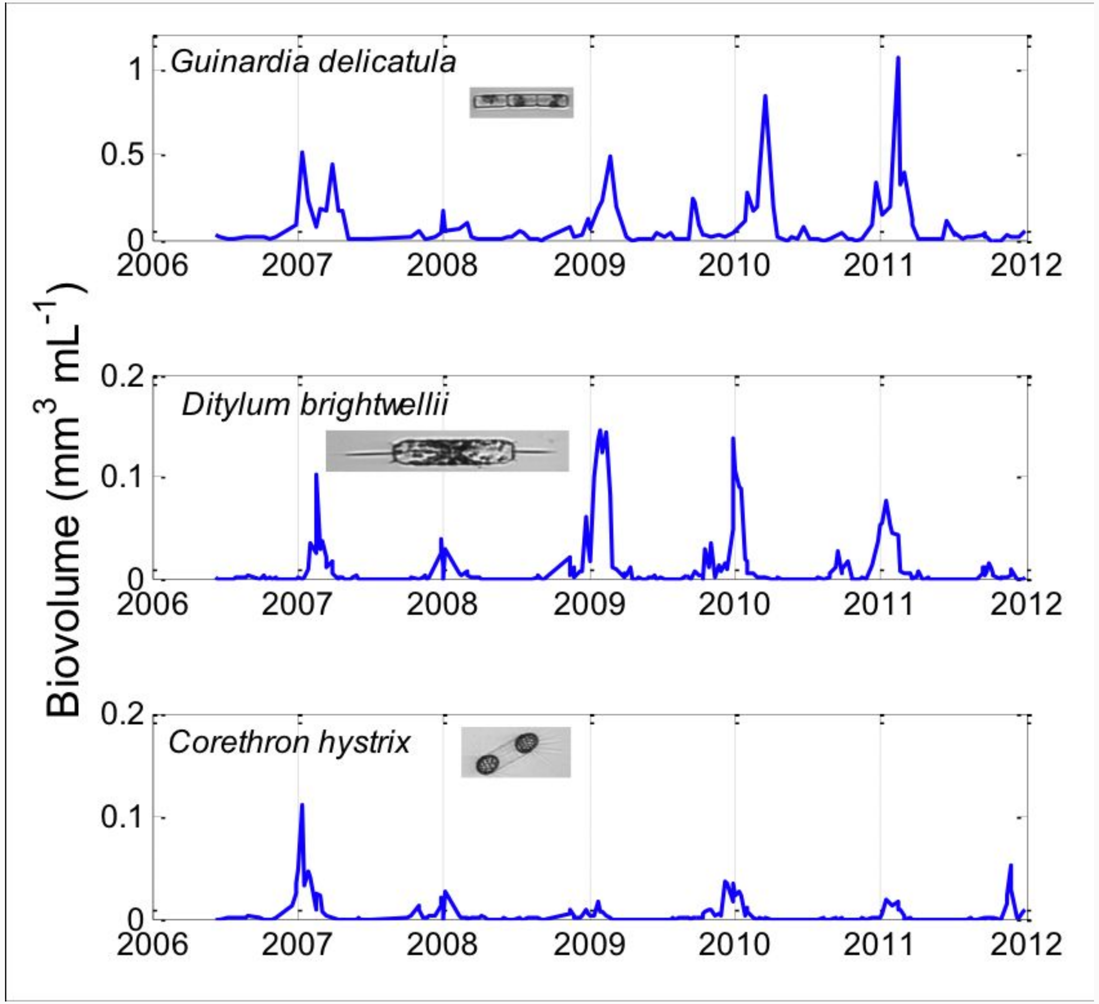




What drives the *Synechoccus* bloom ?

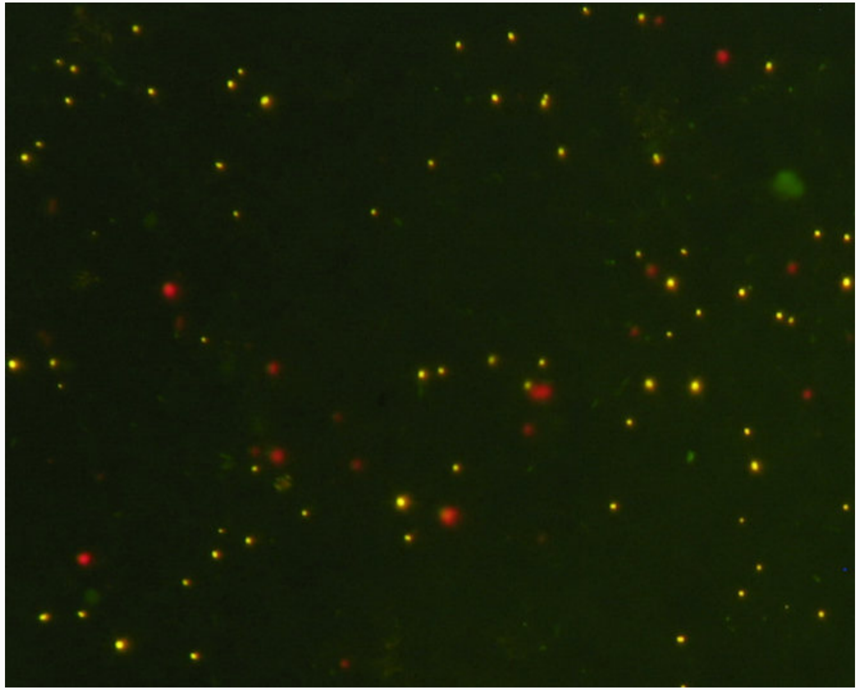
Flow Cytobot

- Diatoms



Synechococcus

- Discovered in 1979 by John Waterbury - *Epifluorescence microscopy*



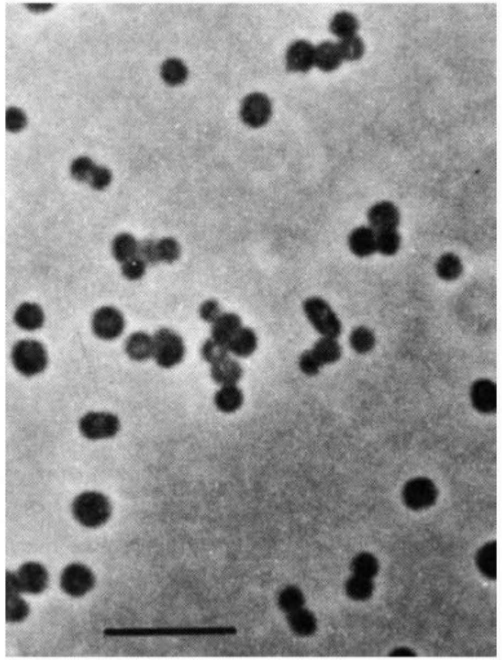


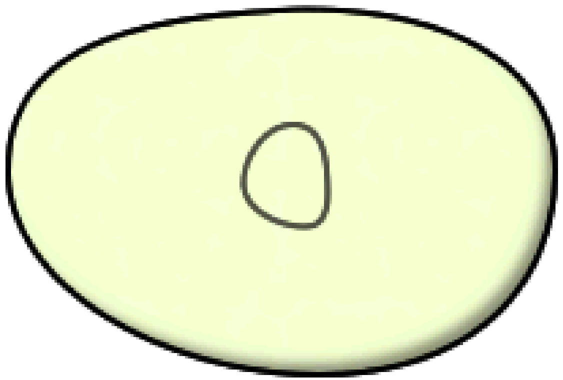
Fig. 1 Phase contrast photomicrograph of *Synechococcus* sp. (strain Syn-48) illustrating general cell morphology (scale bar, 5.0 μm).

Waterbury, J.B., Watson, S.W., Guillard, R.R.L. & Brand, L.E. 1979. Nature. 277:293–4.

What drives the *Synechoccus* bloom ?

Cell multiplication

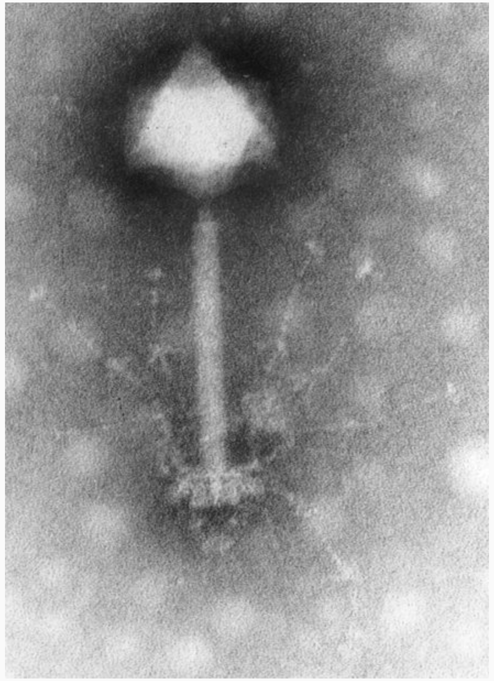
- Binary fission
- Typically once every day

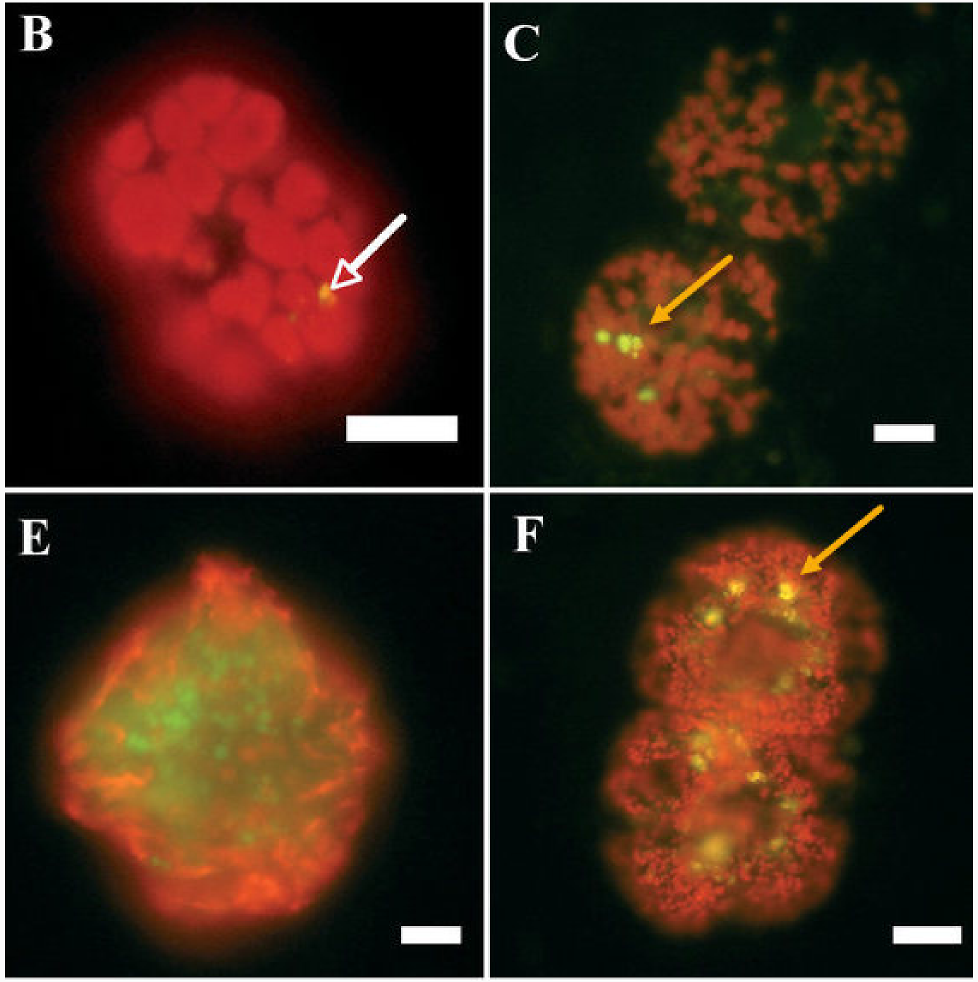


What drives the *Synechoccus* bloom ?

Cell disappearance

- Virus
- Predation
- Cell death (UV, nutrient deprivation)





What drives the *Synechoccus* bloom ?

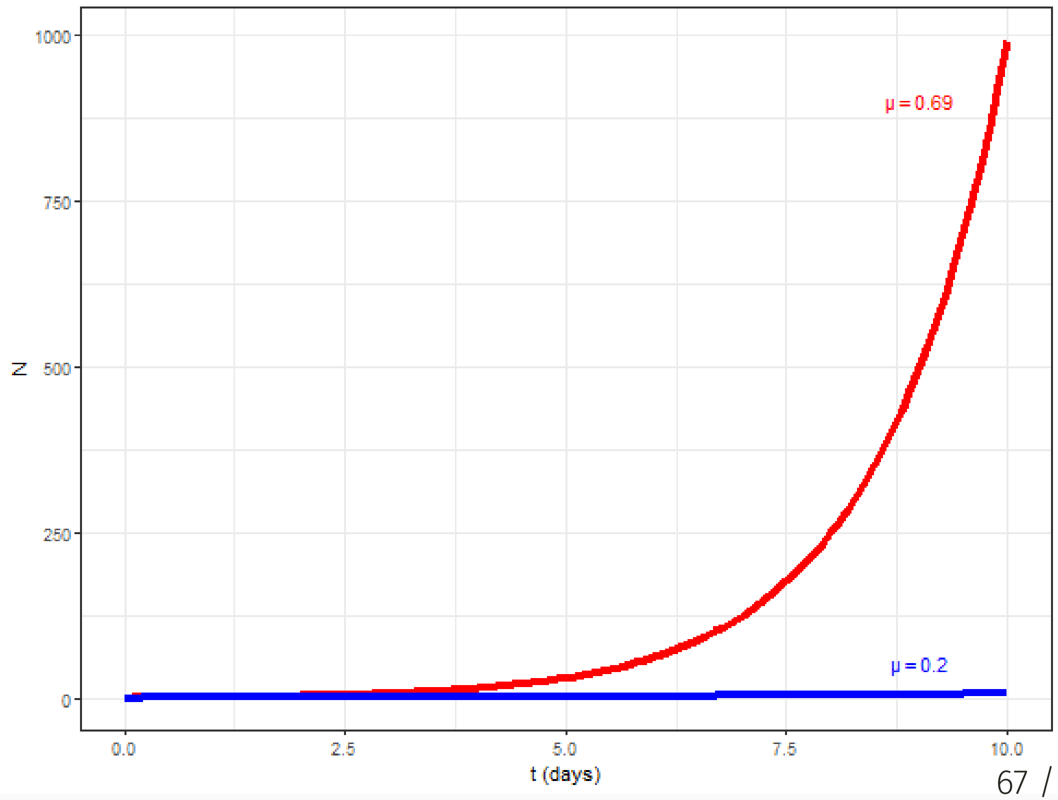
Growth rate vs Loss rate

$$\frac{\mathrm{d}N}{\mathrm{d}t} = \mu_{net} * N$$

$$N = N_0 \exp^{\mu_{net} * t}$$

$$\mu_{net} = \mu_{growth} - \mu_{loss}$$

- Growth rate = division
- Loss rate = cell death, predation, viruses



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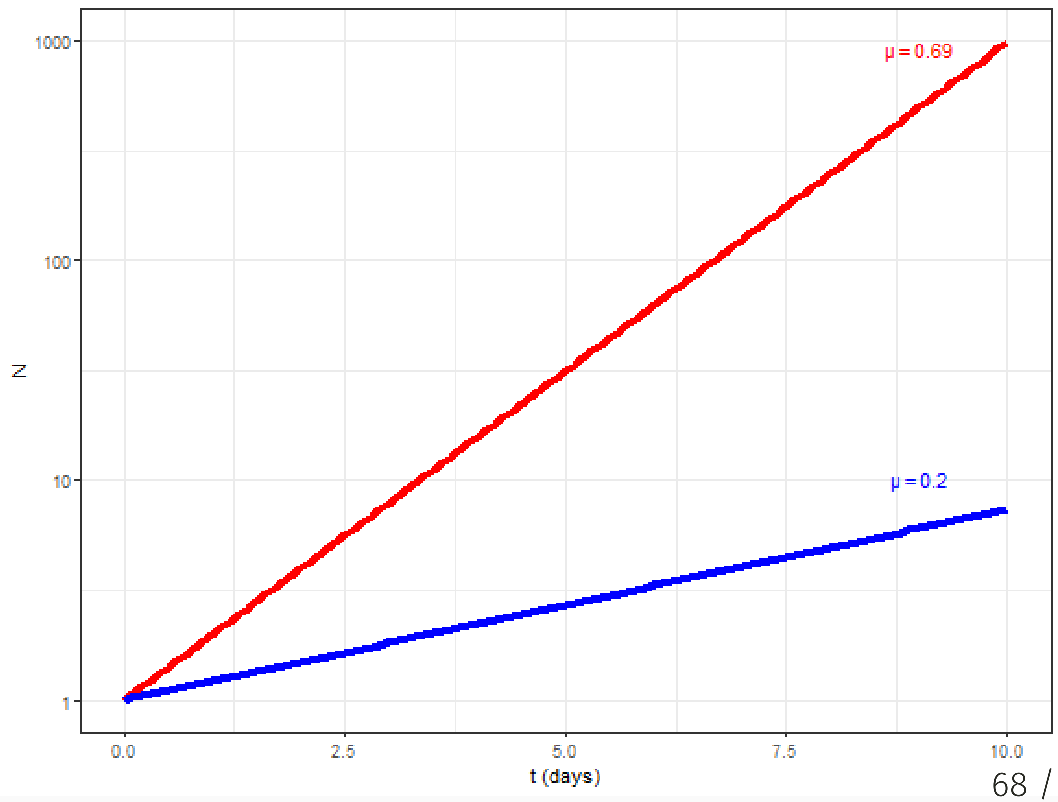
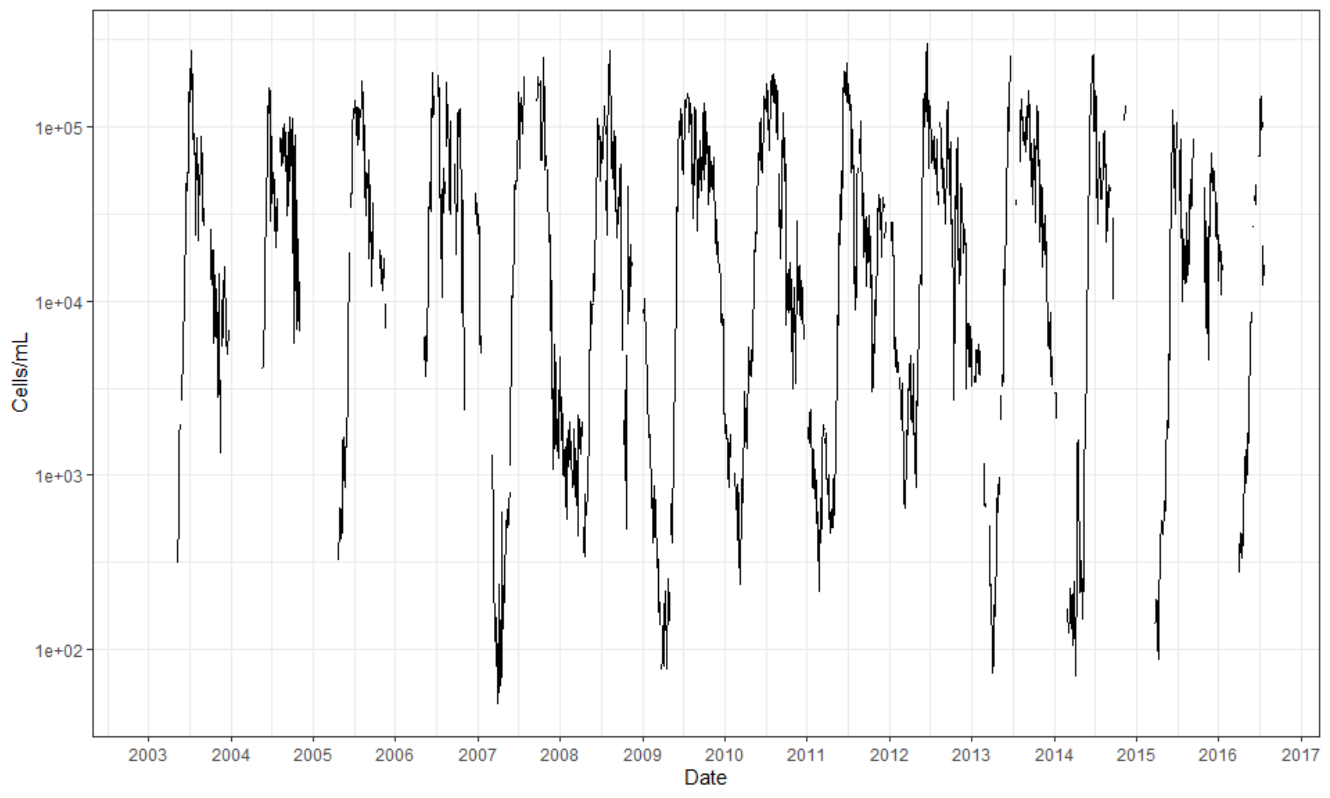


What drives the *Synechoccus* bloom ?

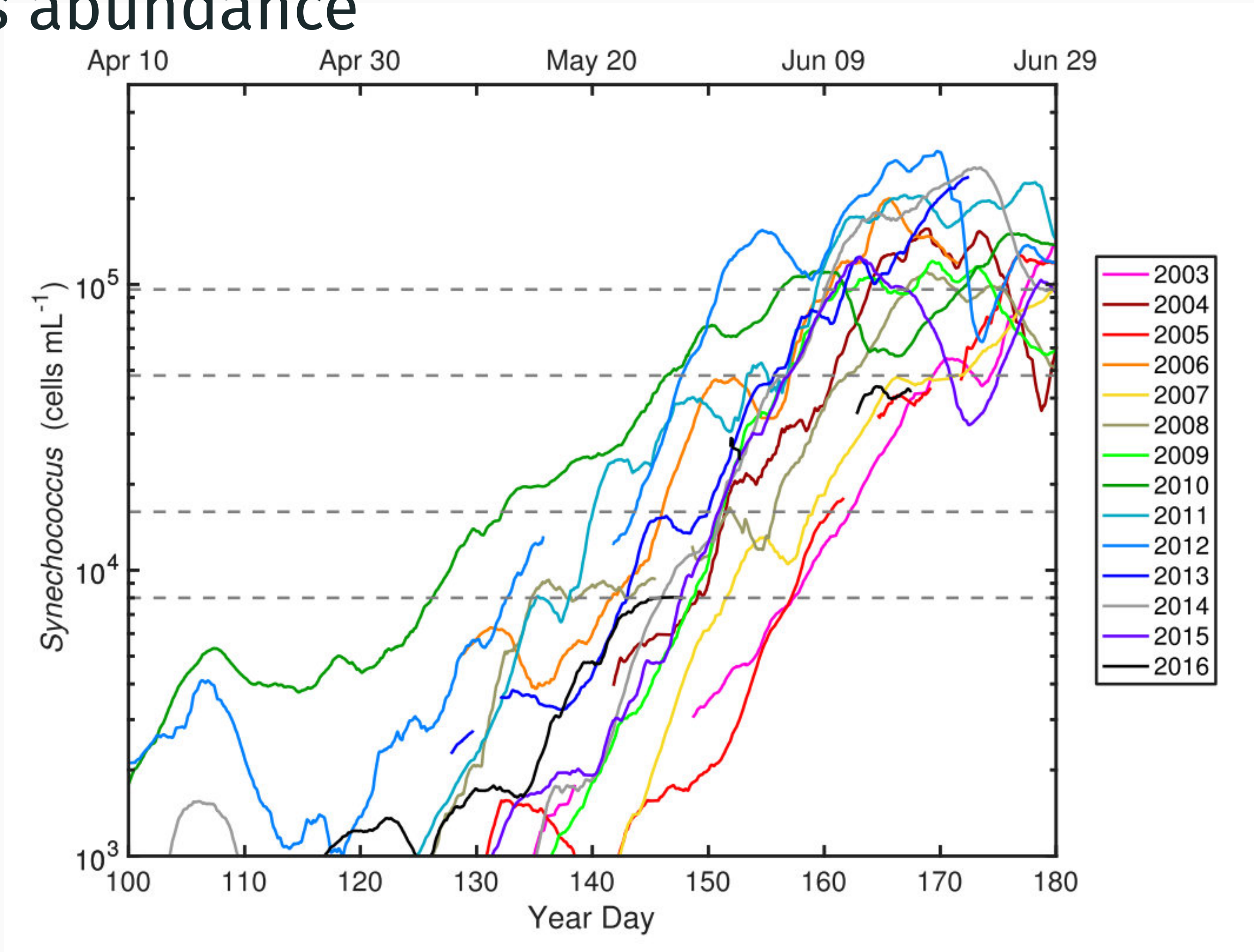
Synechococcus abundance



Hunter-Cevera et al. 2016. Physiological and ecological drivers of early spring blooms of a coastal phytoplankter. Science 354:326–329.

What drives the *Synechoccus* bloom ?

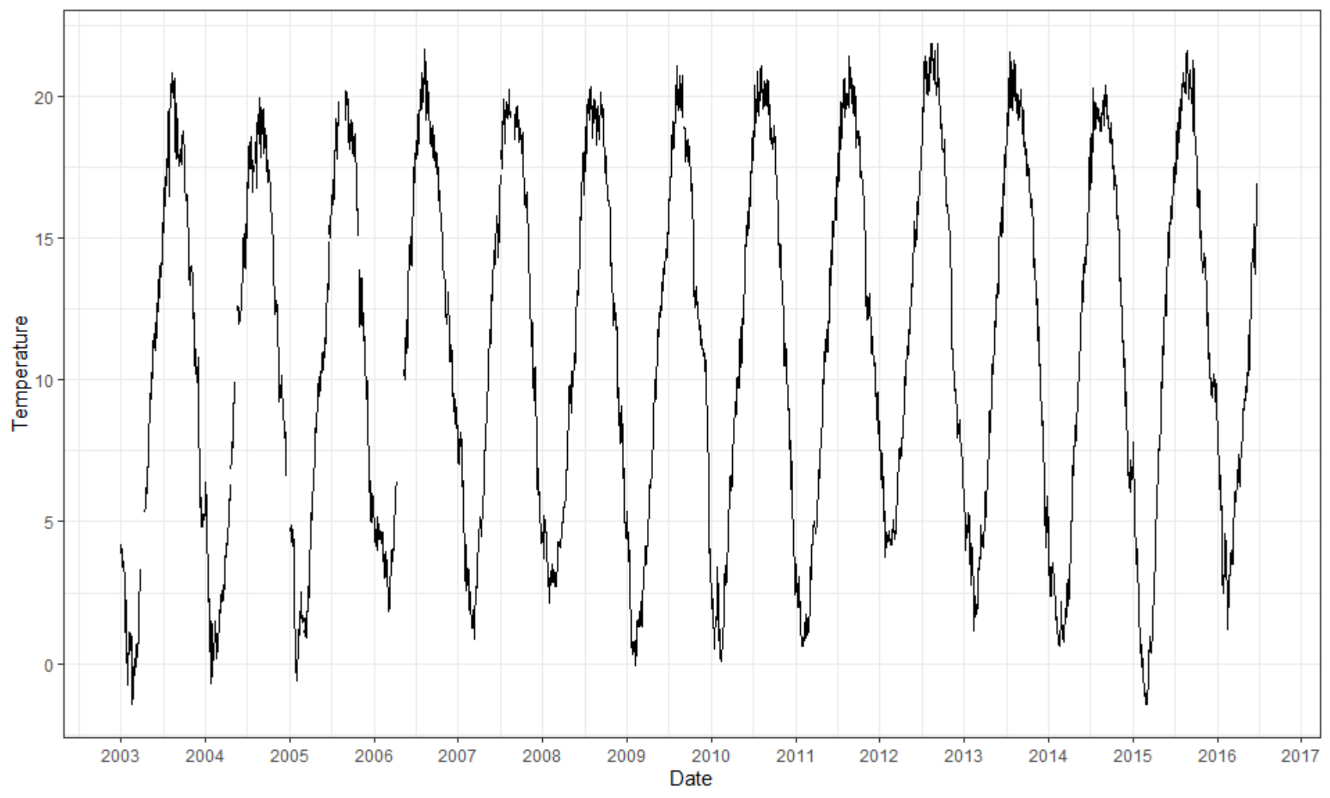
Synechococcus abundance



Hunter-Cevera et al. 2016. Physiological and ecological drivers of early spring blooms of a coastal phytoplankter. Science 354:326–329.

What drives the *Synechoccus* bloom ?

Temperature



Hunter-Cevera et al. 2016. Physiological and ecological drivers of early spring blooms of a coastal phytoplankter. Science 354:326–329.

What drives the *Synechoccus* bloom ?

Temperature anomaly

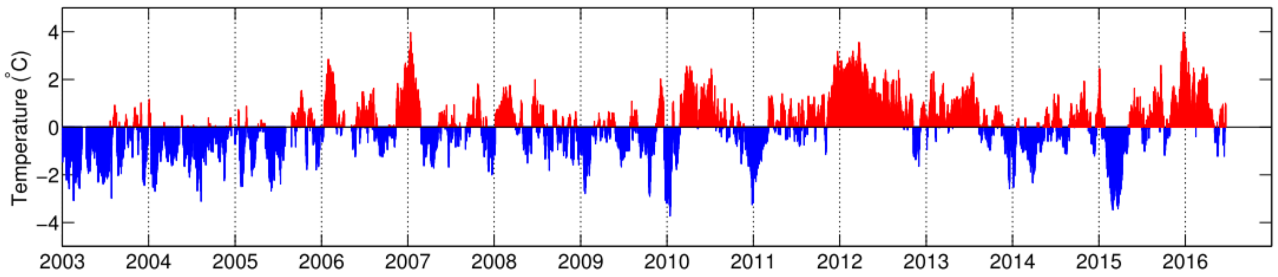


Figure S3. Daily temperature anomalies (ºC) from daily climatological average for 2003 to available 2016. Red values indicate positive anomalies, while blue indicates negative anomalies.

Hunter-Cevera et al. 2016. Physiological and ecological drivers of early spring blooms of a coastal phytoplankter. Science 354:326–329.

What drives the *Synechoccus* bloom ?

Synechococcus vs. Temperature

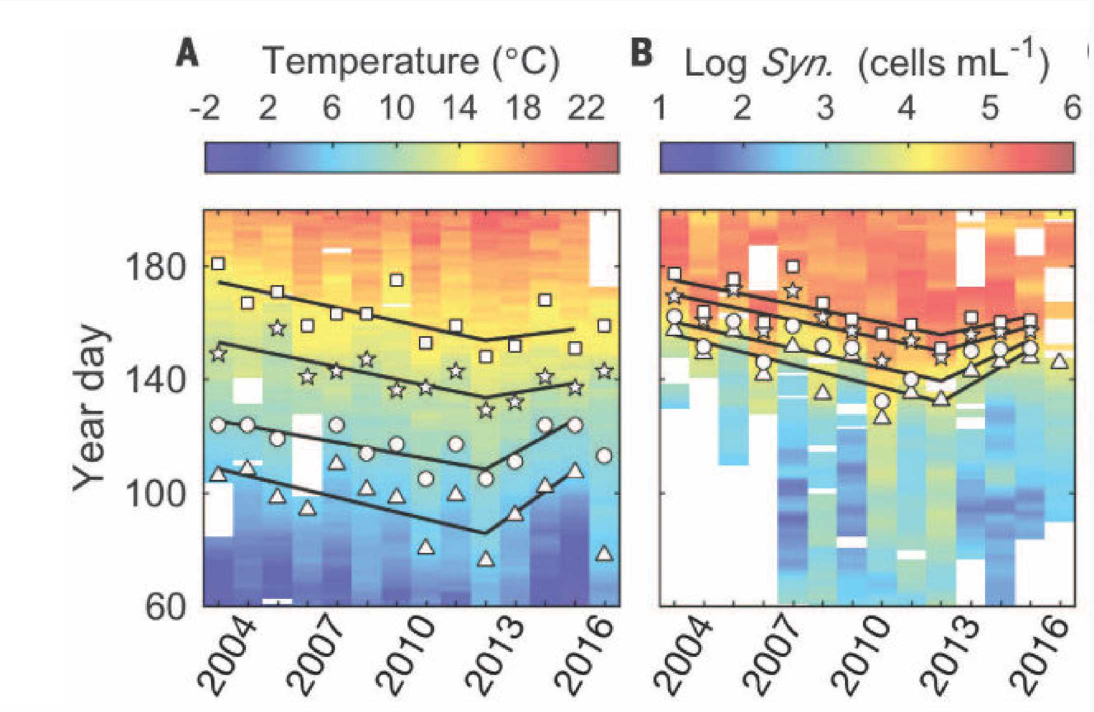
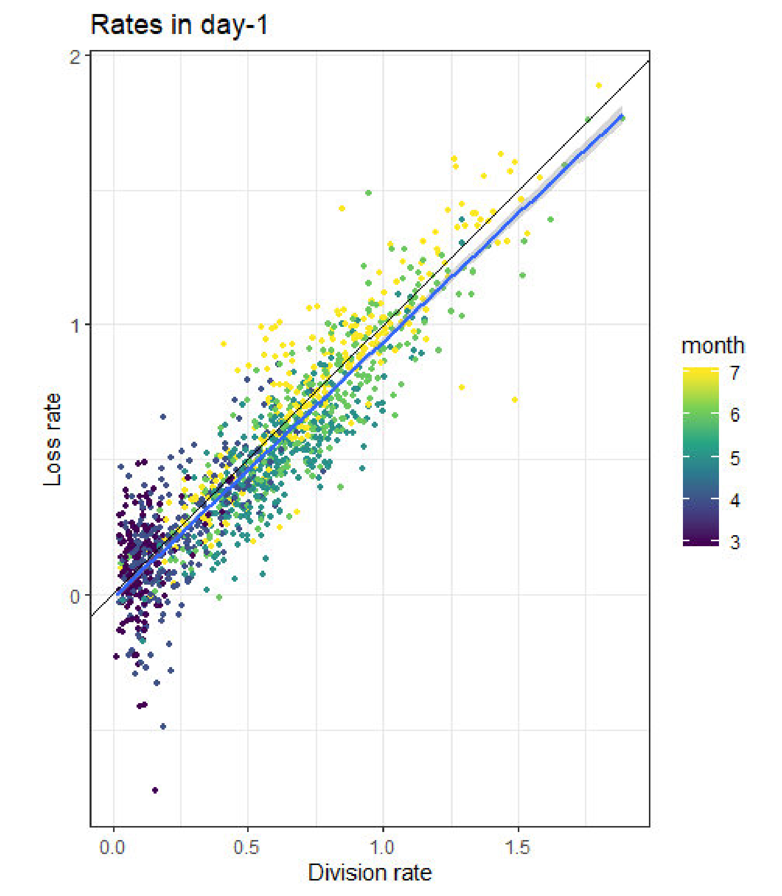


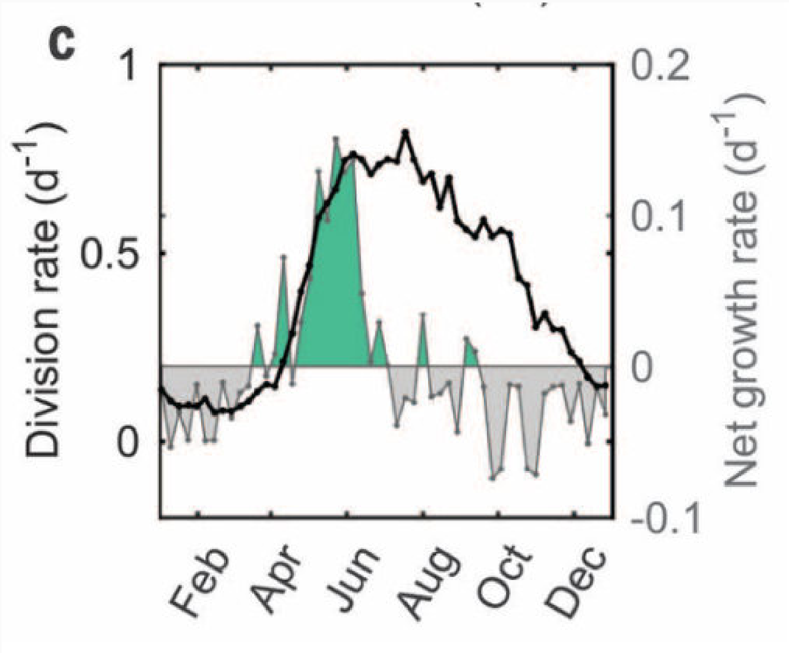
Fig. 2. Multiyear trends showing spring temperature changes and *Synechococcus* bloom shifts from 2003 to 2016. The data are shown by day of the year (vertical axis), with values denoted by color. (**A**) Temperature. Markers indicate the day in each year when water temperature first exceeds 6° (triangles), 9° (circles), 12° (stars), or 15°C (squares). (**B**) *Synechococcus* cell concentration. Markers indicate the day in each year when cell concentration exceeds 8×10^3 (triangles), 1.6×10^4 (circles), 4.8×10^4 (stars), or 9.6×10^4 (squares) cells ml^{-1}. (**C**) Integrated division rate (cumulative summed division

Hunter-Cevera et al. 2016. Physiological and ecological drivers of early spring blooms of a coastal phytoplankter. Science 354:326–329.

What drives the *Synechoccus* bloom ?

Loss *vs.* Division rate





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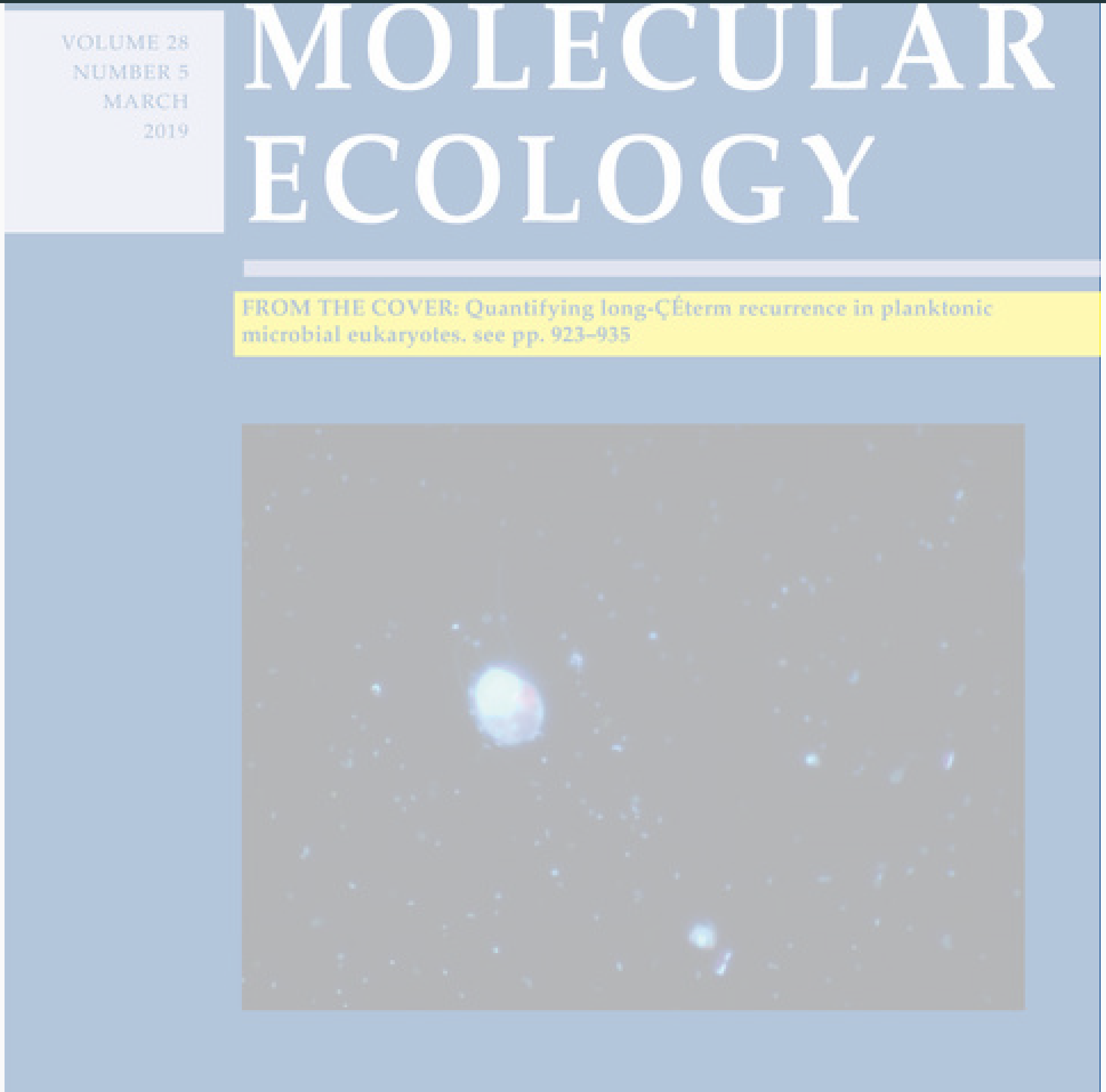
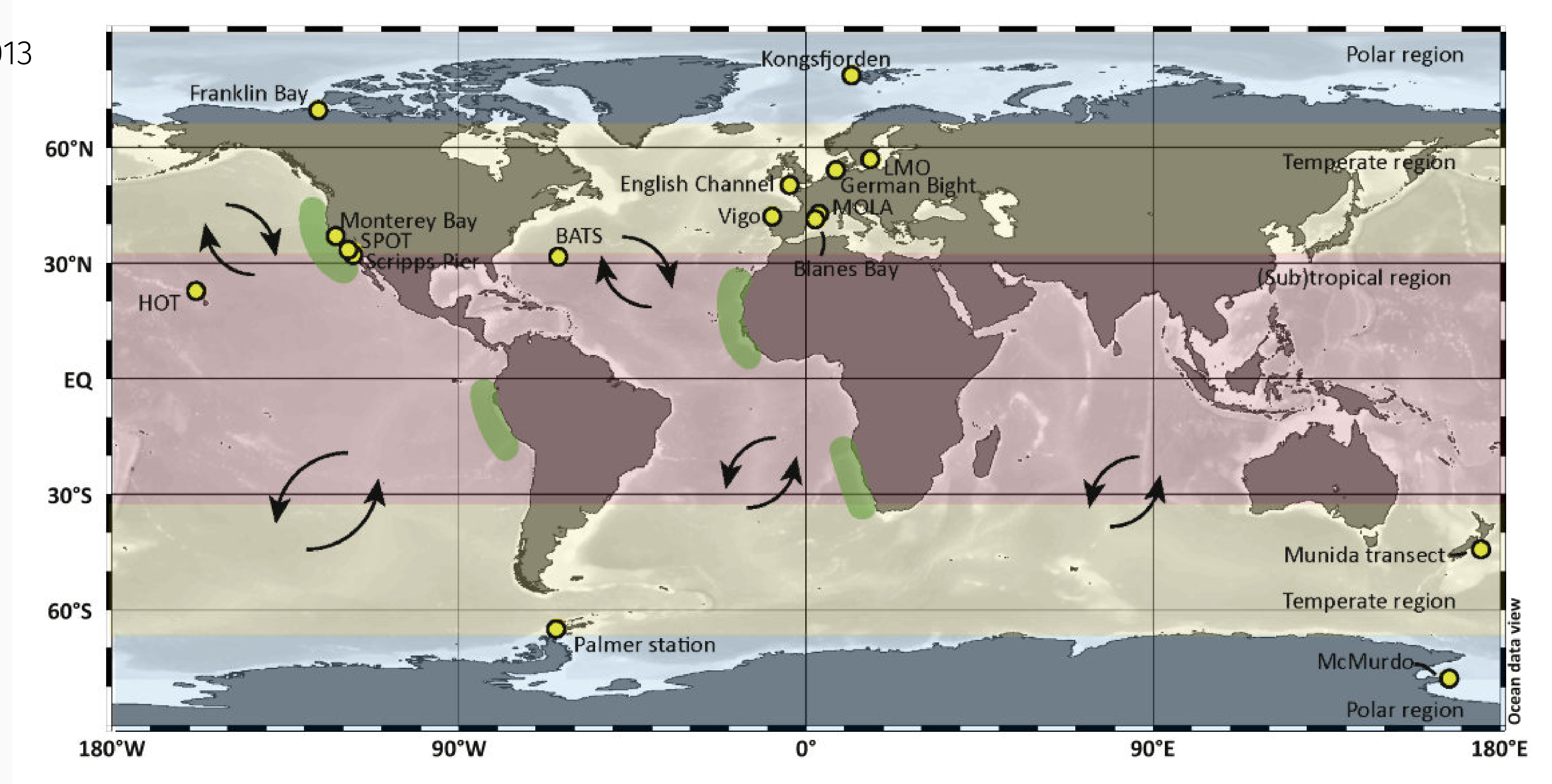
Which groups/species exhibit periodic recurrence ?



Which groups/species exhibit periodic recurrence ?

Study in the Mediterranean Sea

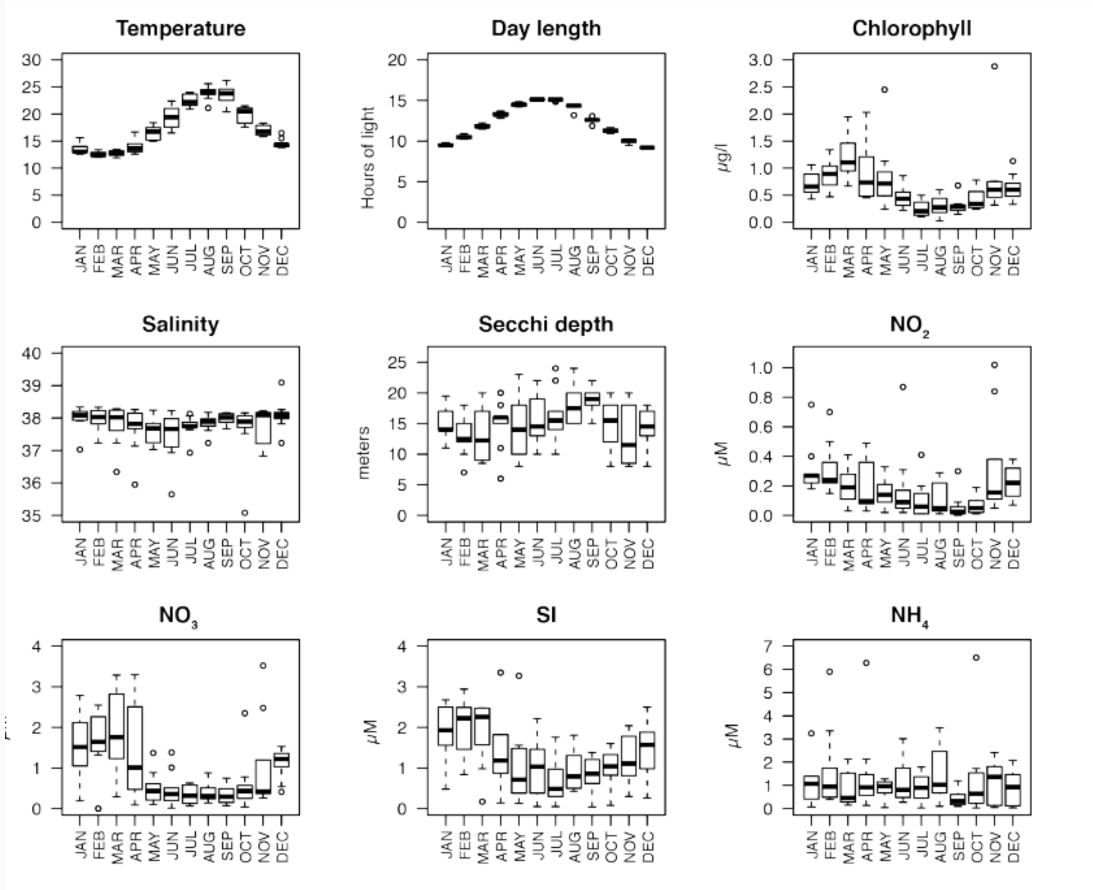
- 2014-2013



Giner et al. 2019. Quantifying long-term recurrence in planktonic microbial eukaryotes. 28:923-935. Molecular Ecology

Which groups/species exhibit periodic recurrence ?

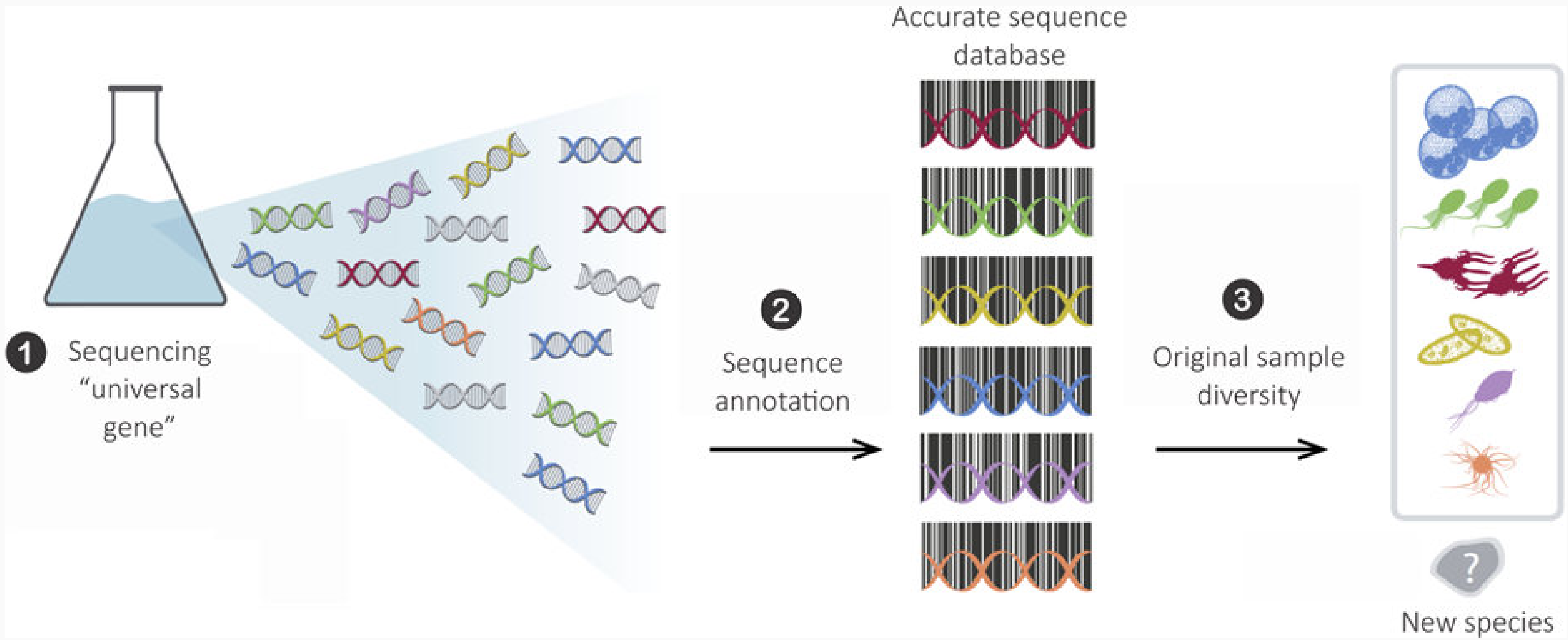
Yearly cycles



Giner et al. 2019. Quantifying long-term recurrence in planktonic microbial eukaryotes. 28:923-935. Molecular Ecology

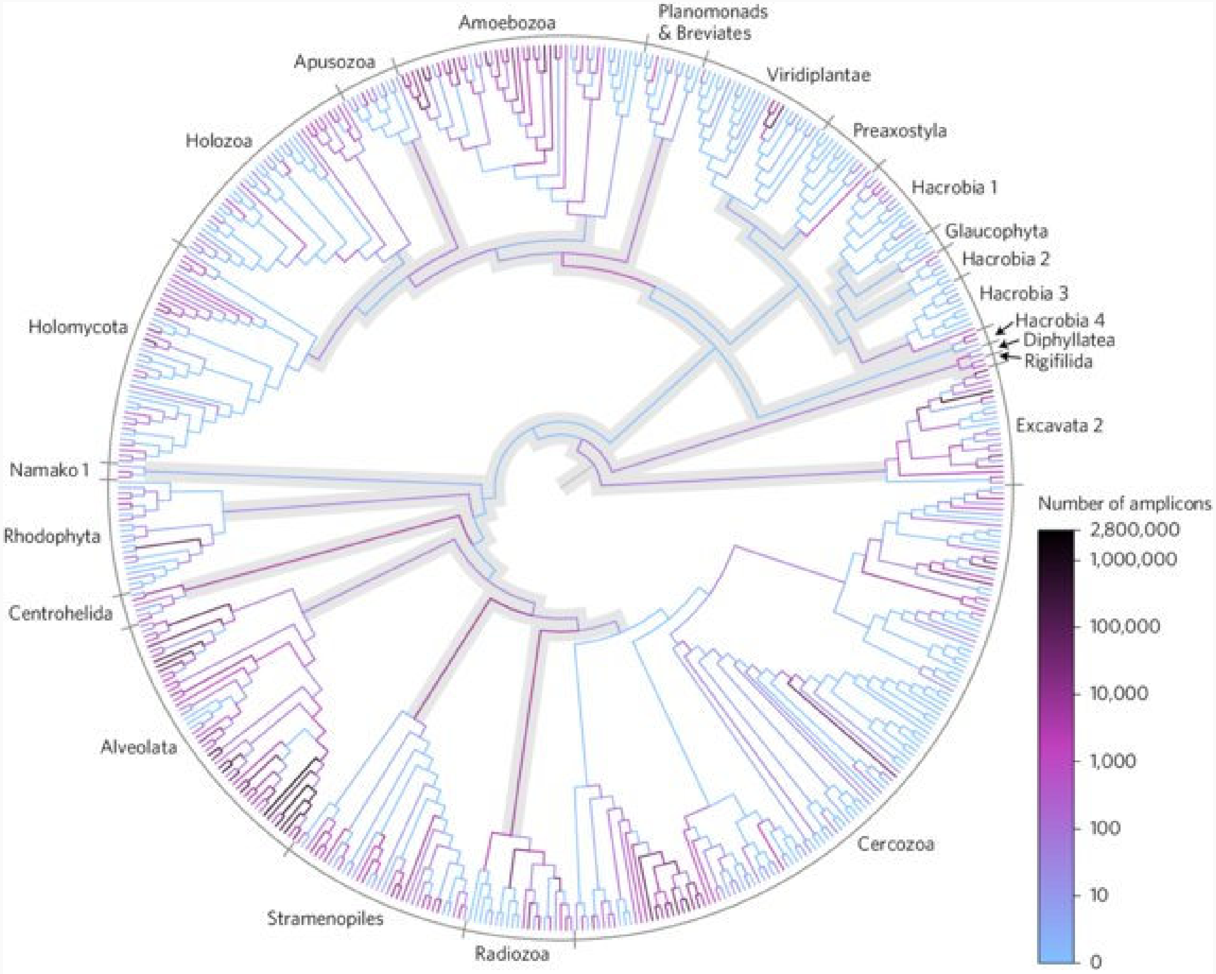
Which groups/species exhibit periodic recurrence ?

Metabarcoding



Which groups/species exhibit periodic recurrence ?

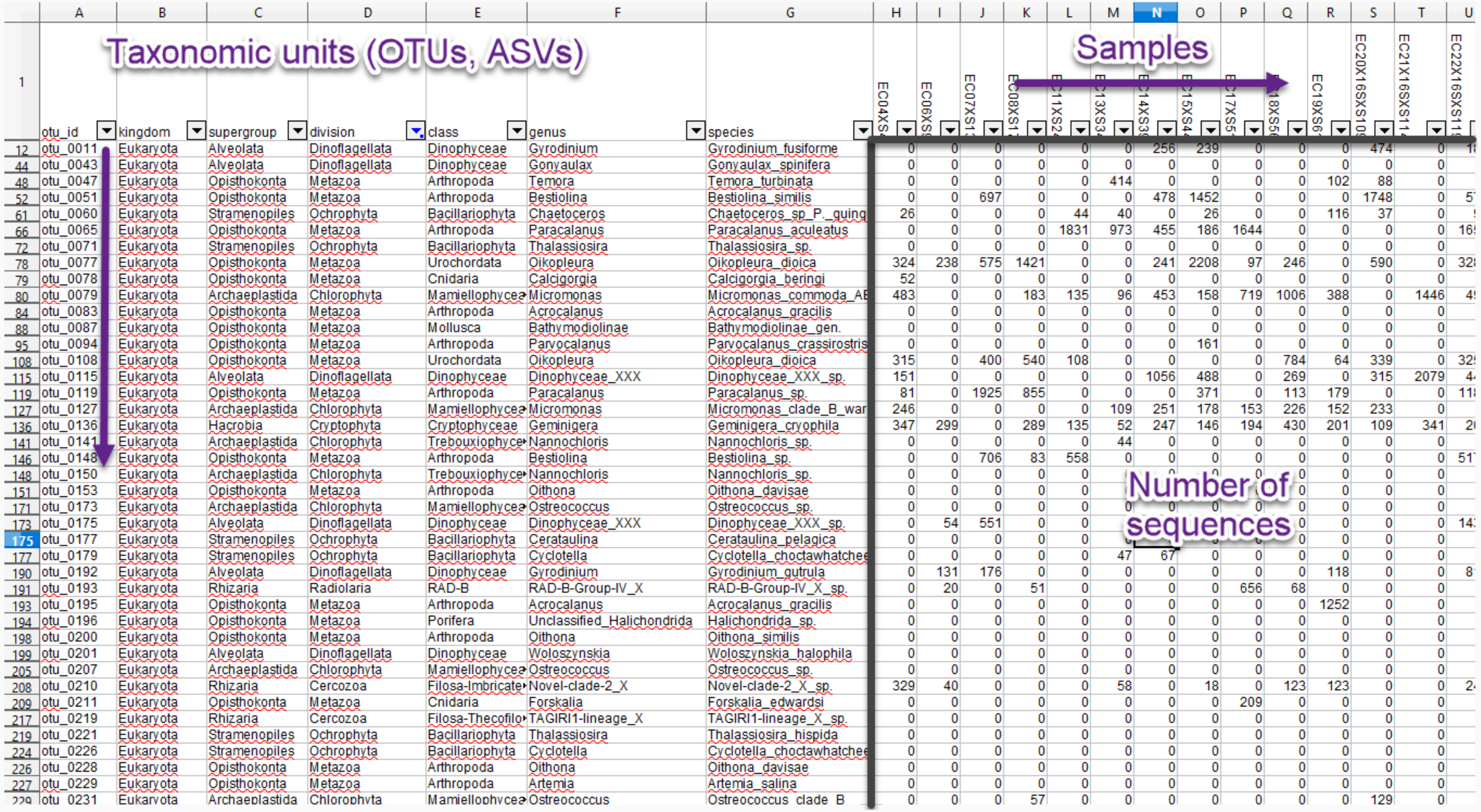
Metabarcoding



Mahé et al.. 2017. Parasites dominate hyperdiverse soil protist communities in Neotropical rainforests. Nature Ecology & Evolution 1:0091.

Which groups/species exhibit periodic recurrence ?

Metabarcoding



	otu_id	kingdom	supergroup	division	class	genus	species	EC04XS	EC06XS	EC07XS1	EC08XS1	EC11XS2	EC13XS3	EC14XS3	EC15XS4	EC17XS5	18XS5	EC19XS6	EC20X16SXS10	EC21X16SXS11	EC22X16SXS11
12	otu_0011	Eukaryota	Alveolata	Dinoflagellata	Dinophyceae	Gyrodinium	Gyrodinium_fusiforme	0	0	0	0	0	0	256	239	0	0	0	474	0	1
44	otu_0043	Eukaryota	Alveolata	Dinoflagellata	Dinophyceae	Gonyaulax	Gonyaulax_spinifera	0	0	0	0	0	0	0	0	0	0	0	0	0	
48	otu_0047	Eukaryota	Opisthokonta	Metazoa	Arthropoda	Temora	Temora_turbinata	0	0	0	0	0	414	0	0	0	0	102	88	0	
52	otu_0051	Eukaryota	Opisthokonta	Metazoa	Arthropoda	Bestiolina	Bestiolina_similis	0	0	697	0	0	0	478	1452	0	0	0	1748	0	5
61	otu_0060	Eukaryota	Stramenopiles	Ochrophyta	Bacillariophyta	Chaetoceros	Chaetoceros_sp_P._quing	26	0	0	0	44	40	0	26	0	0	116	37	0	
66	otu_0065	Eukaryota	Opisthokonta	Metazoa	Arthropoda	Paracalanus	Paracalanus_aculeatus	0	0	0	0	1831	973	455	186	1644	0	0	0	0	16
72	otu_0071	Eukaryota	Stramenopiles	Ochrophyta	Bacillariophyta	Thalassiosira	Thalassiosira_sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	
78	otu_0077	Eukaryota	Opisthokonta	Metazoa	Urochordata	Oikopleura	Oikopleura_dioica	324	238	575	1421	0	0	241	2208	97	246	0	590	0	32
79	otu_0078	Eukaryota	Opisthokonta	Metazoa	Cnidaria	Calcigorgia	Calcigorgia_beringi	52	0	0	0	0	0	0	0	0	0	0	0	0	
80	otu_0079	Eukaryota	Archaeplastida	Chlorophyta	Mamiellophycea	Micromonas	Micromonas_commoda_AE	483	0	0	183	135	96	453	158	719	1006	388	0	1446	4
84	otu_0083	Eukaryota	Opisthokonta	Metazoa	Arthropoda	Acrocalanus	Acrocalanus_gracilis	0	0	0	0	0	0	0	0	0	0	0	0	0	
88	otu_0087	Eukaryota	Opisthokonta	Metazoa	Mollusca	Bathymodiolinae	Bathymodiolinae_gen.	0	0	0	0	0	0	0	0	0	0	0	0	0	
95	otu_0094	Eukaryota	Opisthokonta	Metazoa	Arthropoda	Parvocalanus	Parvocalanus_crassirostris	0	0	0	0	0	0	0	161	0	0	0	0	0	
108	otu_0108	Eukaryota	Opisthokonta	Metazoa	Urochordata	Oikopleura	Oikopleura_dioica	315	0	400	540	108	0	0	0	0	784	64	339	0	32
115	otu_0115	Eukaryota	Alveolata	Dinoflagellata	Dinophyceae	Dinophyceae_XXX	Dinophyceae_XXX_sp.	151	0	0	0	0	0	1056	488	0	269	0	315	2079	4
119	otu_0119	Eukaryota	Opisthokonta	Metazoa	Arthropoda	Paracalanus	Paracalanus_sp.	81	0	1925	855	0	0	0	371	0	113	179	0	0	11
127	otu_0127	Eukaryota	Archaeplastida	Chlorophyta	Mamiellophycea	Micromonas	Micromonas_clade_B_war	246	0	0	0	0	109	251	178	153	226	152	233	0	
136	otu_0136	Eukaryota	Hacrobia	Cryptophyta	Cryptophyceae	Geminigera	Geminigera_cryophila	347	299	0	289	135	52	247	146	194	430	201	109	341	2
141	otu_0141	Eukaryota	Archaeplastida	Chlorophyta	Trebouxiophyce	Nannochloris	Nannochloris_sp.	0	0	0	0	0	44	0	0	0	0	0	0	0	
146	otu_0148	Eukaryota	Opisthokonta	Metazoa	Arthropoda	Bestiolina	Bestiolina_sp.	0	0	706	83	558	0	0	0	0	0	0	0	0	51
148	otu_0150	Eukaryota	Archaeplastida	Chlorophyta	Trebouxiophyce	Nannochloris	Nannochloris_sp.	0	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	0	0	0	0	
151	otu_0153	Eukaryota	Opisthokonta	Metazoa	Arthropoda	Oithona	Oithona_davisae	0	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	0	0	0	0	
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173	otu_0175	Eukaryota	Alveolata	Dinoflagellata	Dinophyceae	Dinophyceae_XXX	Dinophyceae_XXX_sp.	0	54	551	0	0	[illegible]	[illegible]	[illegible]	[illegible]	0	0	0	0	14
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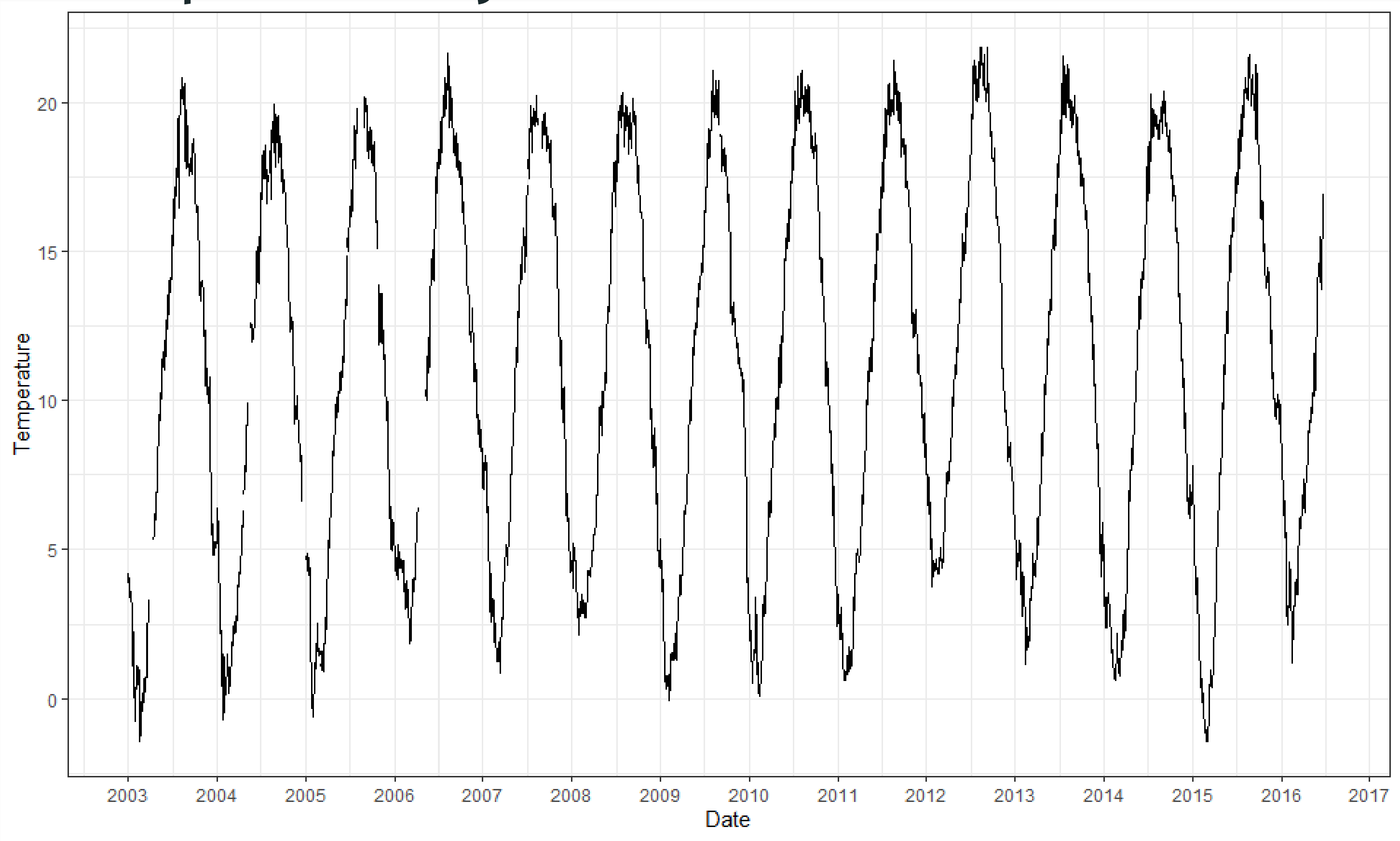
177	otu_0179	Eukaryota	Stramenopiles	Ochrophyta	Bacillariophyta	Cyclotella	Cyclotella_choctawhatchee	0	0	0	0	0	47	67	0	0	0	0	0	0	
190	otu_0192	Eukaryota	Alveolata	Dinoflagellata	Dinophyceae	Gyrodinium	Gyrodinium_gutrula	0	131	176	0	0	0	0	0	0	0	118	0	0	8
191	otu_0193	Eukaryota	Rhizaria	Radiolaria	RAD-B	RAD-B-Group-IV_X	RAD-B-Group-IV_X_sp.	0	20	0	51	0	0	0	0	656	68	0	0	0	
193	otu_0195	Eukaryota	Opisthokonta	Metazoa	Arthropoda	Acrocalanus	Acrocalanus_gracilis	0	0	0	0	0	0	0	0	0	0	1252	0	0	
194	otu_0196	Eukaryota	Opisthokonta	Metazoa	Porifera	Unclassified_Halichondrida	Halichondrida_sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	
198	otu_0200	Eukaryota	Opisthokonta	Metazoa	Arthropoda	Oithona	Oithona_similis	0	0	0	0	0	0	0	0	0	0	0	0	0	
199	otu_0201	Eukaryota	Alveolata	Dinoflagellata	Dinophyceae	Woloszynskia	Woloszynskia_halophila	0	0	0	0	0	0	0	0	0	0	0	0	0	
205	otu_0207	Eukaryota	Archaeplastida	Chlorophyta	Mamiellophycea	Ostreococcus	Ostreococcus_sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	
208	otu_0210	Eukaryota	Rhizaria	Cercozoa	Filosa-Imbricate	Novel-clade-2_X	Novel-clade-2_X_sp.	329	40	0	0	0	58	0	18	0	123	123	0	0	2
209	otu_0211	Eukaryota	Opisthokonta	Metazoa	Cnidaria	Forskalia	Forskalia_edwardsi	0	0	0	0	0	0	0	0	209	0	0	0	0	
217	otu_0219	Eukaryota	Rhizaria	Cercozoa	Filosa-Thecofilo	TAGIRI1-lineage_X	TAGIRI1-lineage_X_sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	
219	otu_0221	Eukaryota	Stramenopiles	Ochrophyta	Bacillariophyta	Thalassiosira	Thalassiosira_hispida	0	0	0	0	0	0	0	0	0	0	0	0	0	
224	otu_0226	Eukaryota	Stramenopiles	Ochrophyta	Bacillariophyta	Cyclotella	Cyclotella_choctawhatchee	0	0	0	0	0	0	0	0	0	0	0	0	0	
226	otu_0228	Eukaryota	Opisthokonta	Metazoa	Arthropoda	Oithona	Oithona_davisae	0	0	0	0	0	0	0	0	0	0	0	0	0	
227	otu_0229	Eukaryota	Opisthokonta	Metazoa	Arthropoda	Artemia	Artemia_salina	0	0	0	0	0	0	0	0	0	0	0	0	0	
229	otu_0231	Eukaryota	Archaeplastida	Chlorophyta	Mamiellophycea	Ostreococcus	Ostreococcus_clade_B	0	0	0	57	0	0	0	0	0	0	0	129	0	

Which groups/species exhibit periodic recurrence ?

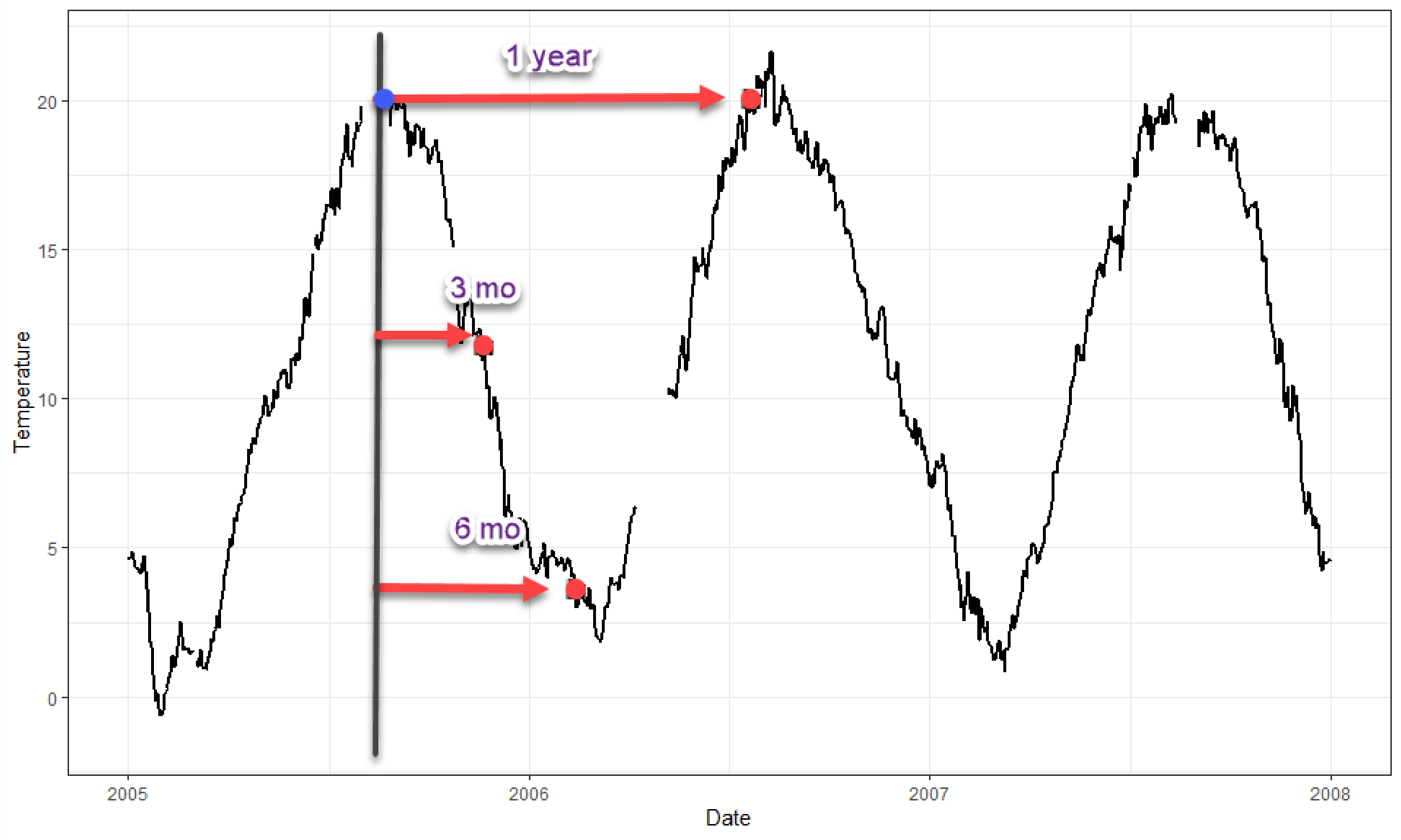
How to determine periodicity ?



Which groups/species exhibit periodic recurrence ?

How to determine periodicity ?

- Autocorrelation



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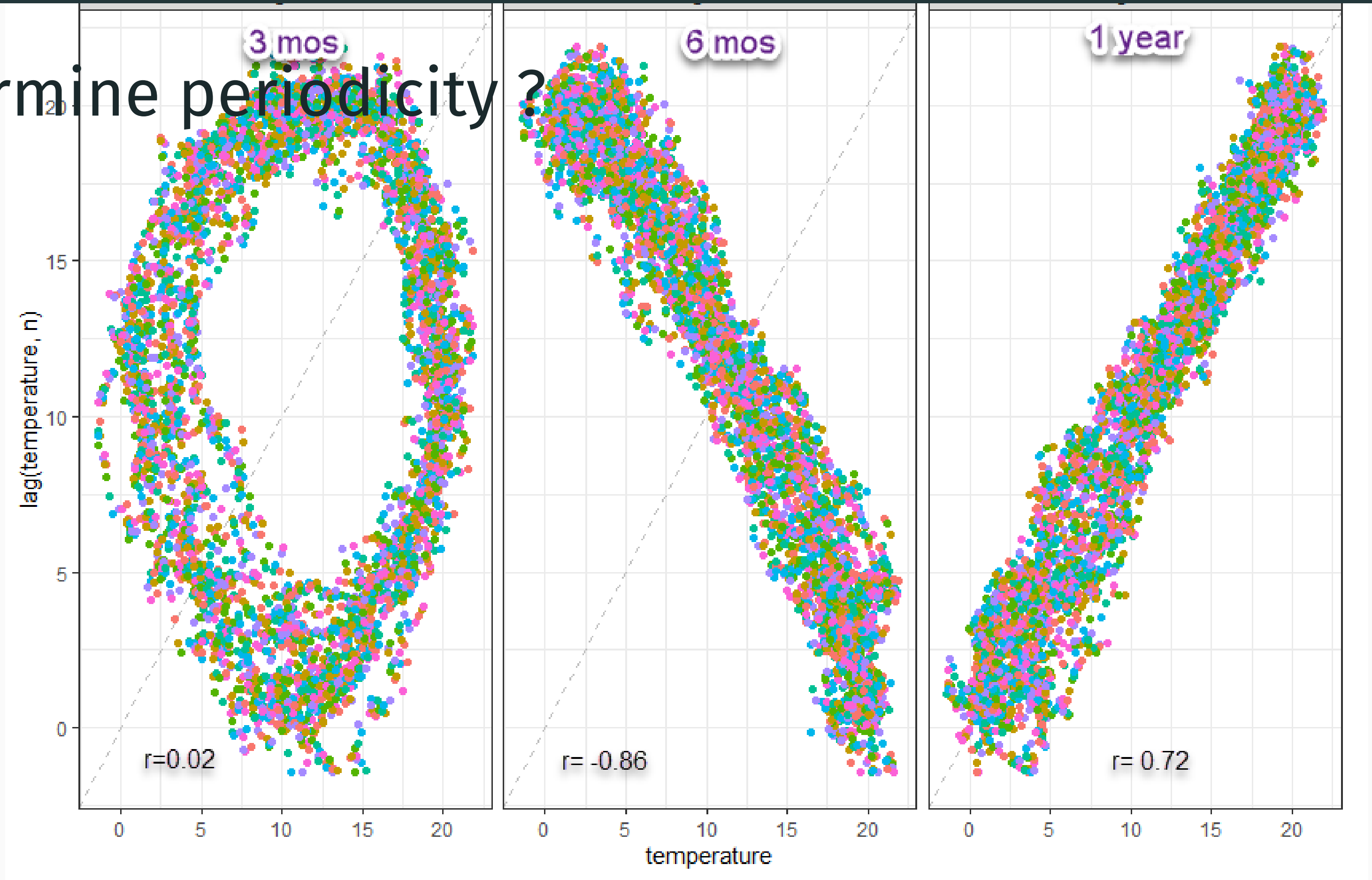
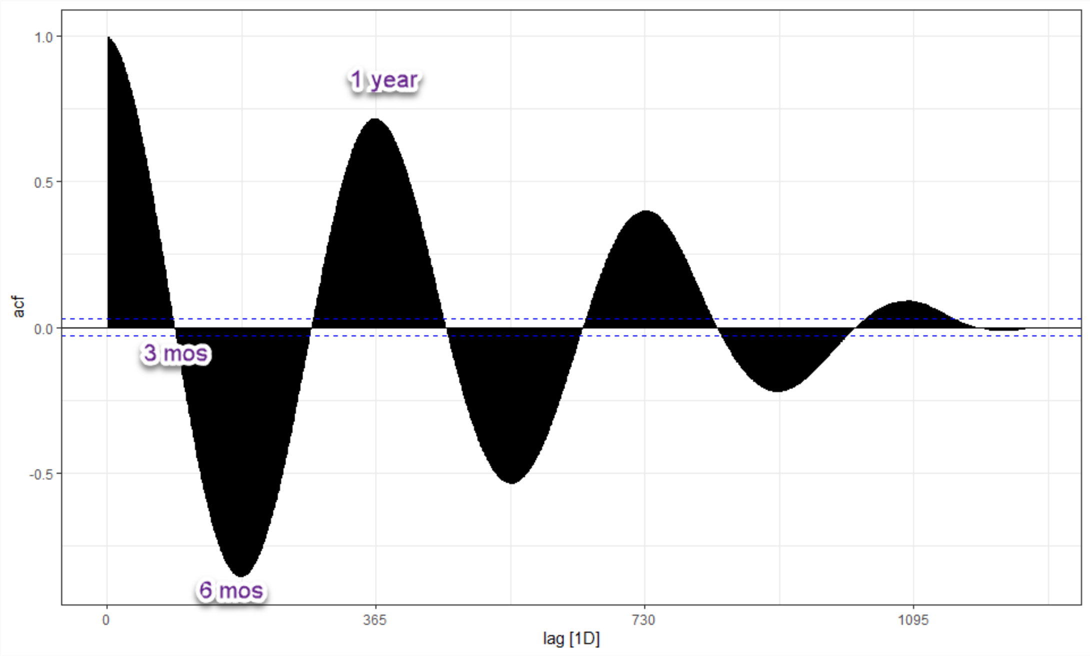


$$r_{xy} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}}$$

Which groups/species exhibit periodic recurrence ?

How to determine periodicity ?

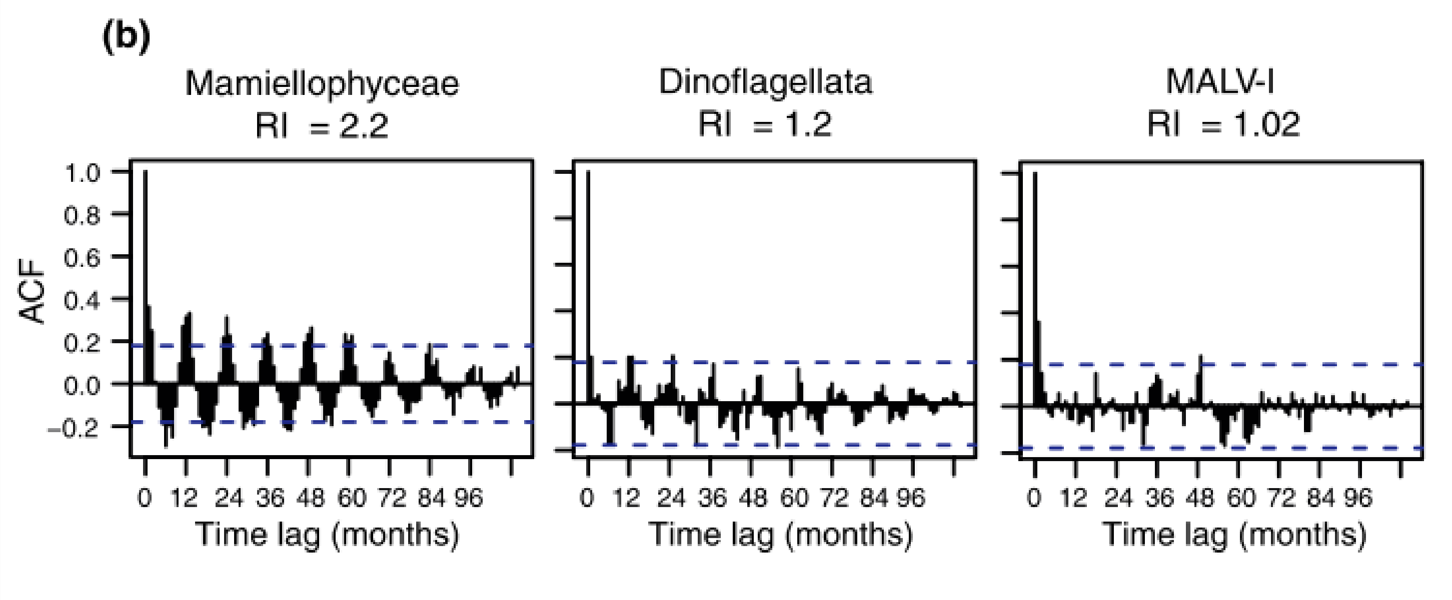
- Autocorrelation



Which groups/species exhibit periodic recurrence ?

Group periodicity

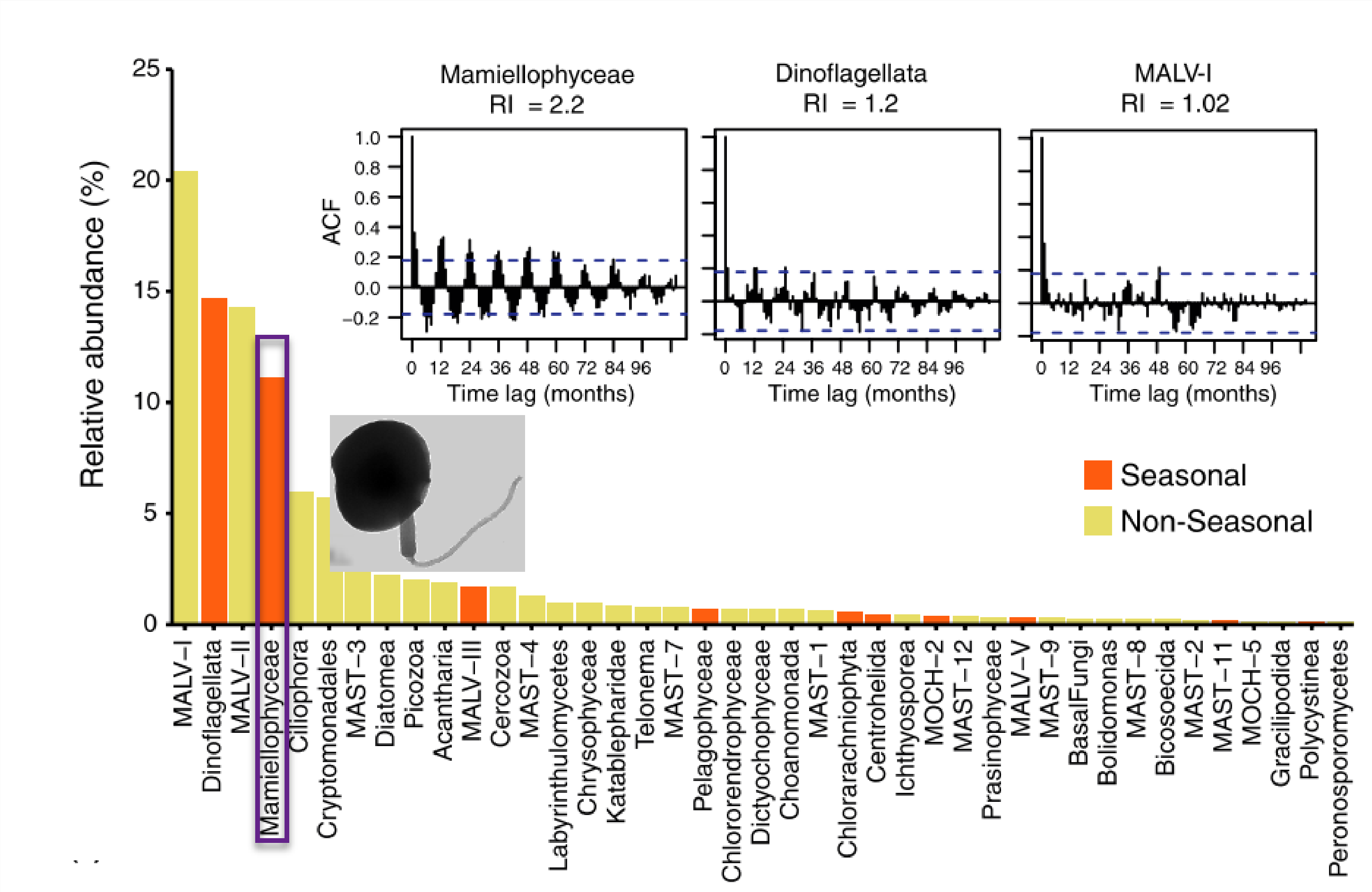
- Autocorrelation function



Giner et al. 2019. Quantifying long-term recurrence in planktonic microbial eukaryotes. 28:923-935. Molecular Ecology

Which groups/species exhibit periodic recurrence ?

Group periodicity



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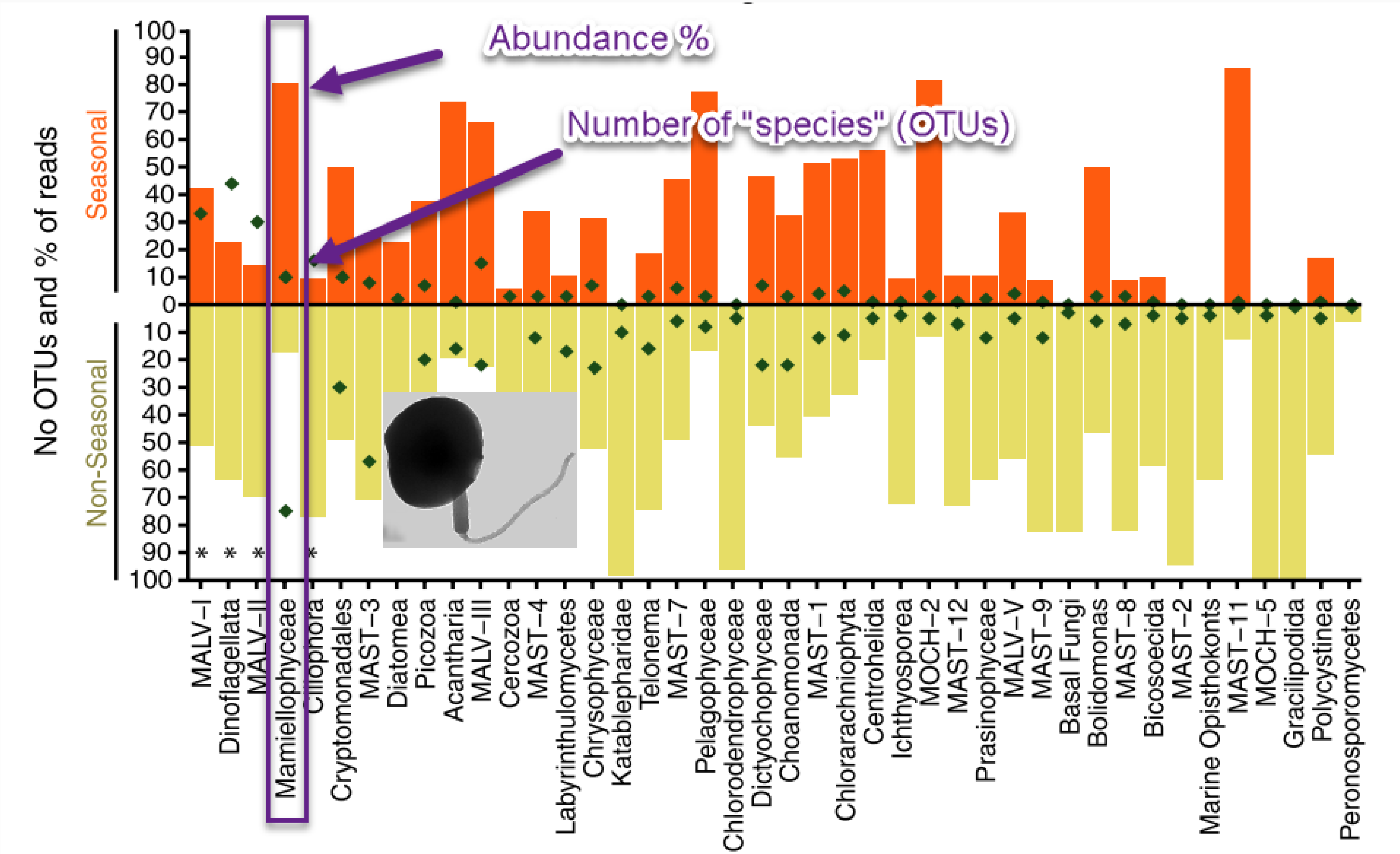
Which groups/species exhibit periodic recurrence ?

Species periodicity



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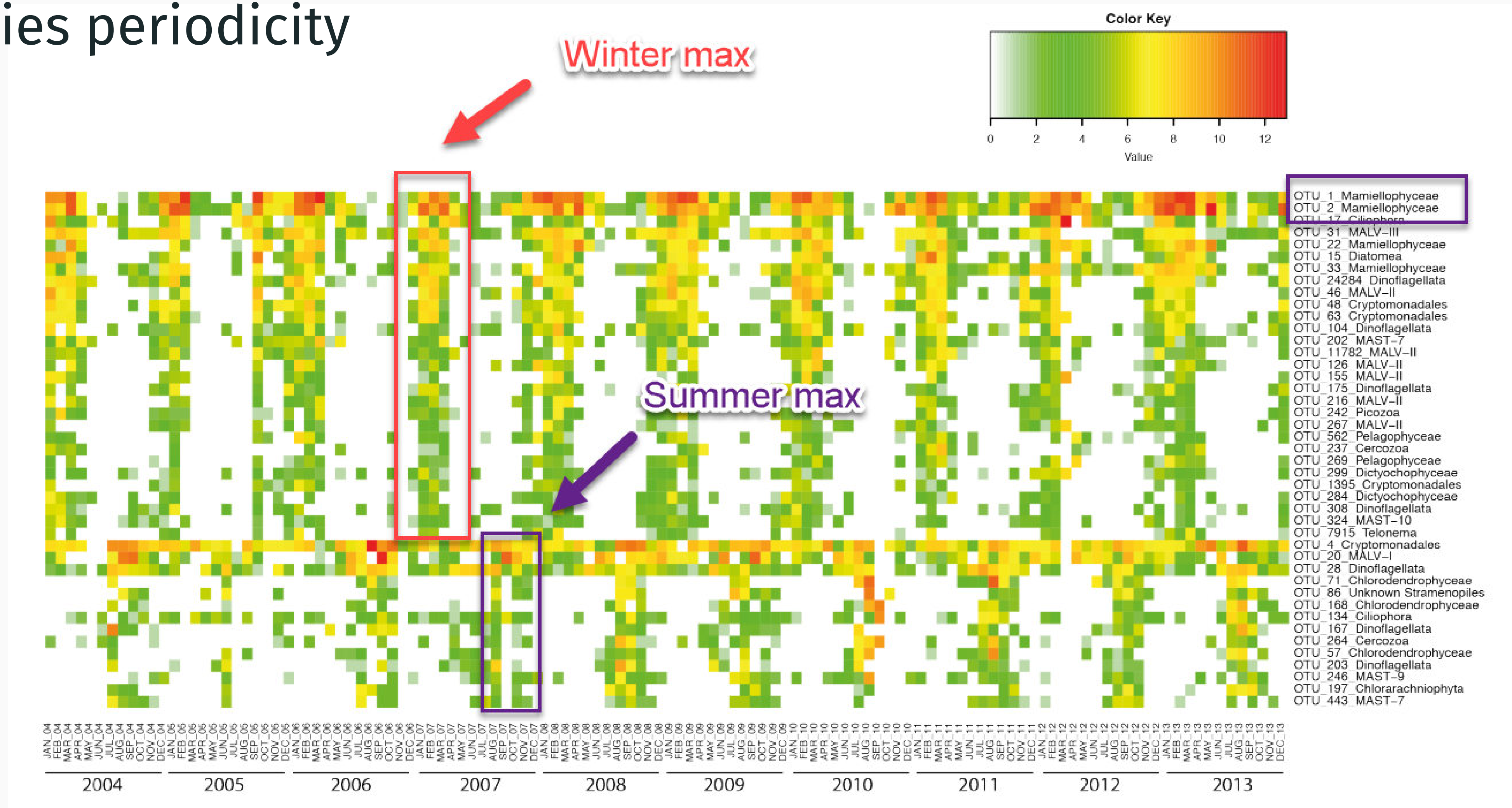
Which groups/species exhibit periodic recurrence ?

Species periodicity



Giner et al. 2019. Quantifying long-term recurrence in planktonic microbial eukaryotes. 28:923-935. Molecular Ecology

What did we talked about ?

- Spatial scales
- Time scales
- Sampling the Ocean
- Time series
  - Chlorophyll periodicity
  - Bloom dynamics
  - Which species are periodic ?