Global Predictions of Primary Productivity

towards ecosystem applications

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Geophysical Institute, Bergen University
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BJERKNES CENTRE
for Climate Research

My background

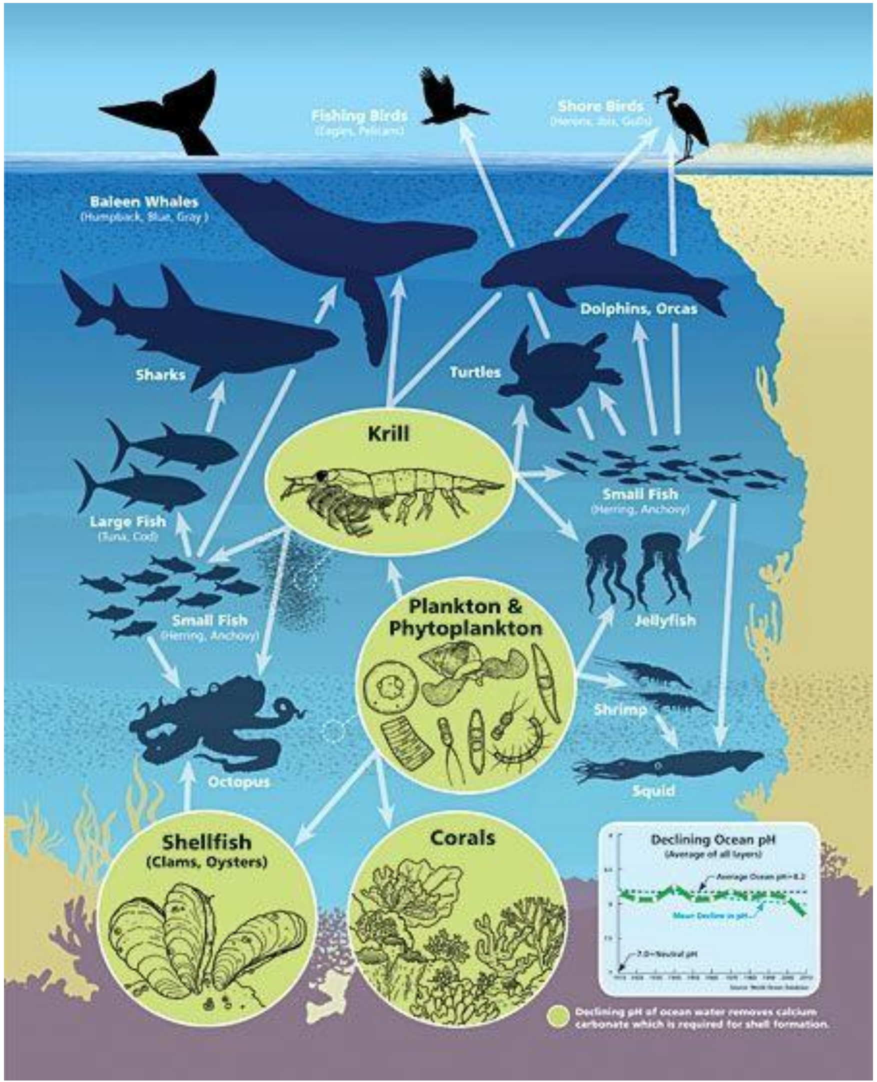
- **Göteborg:** Physical oceanography
- **Grenoble:** Environmental Fluid
  Dynamics - *3D ocean modelling*
- **Stockholm**: Baltic Sea carbon cycle
  3D physical – biogeochemical modelling
- **Bergen:** Biogeochemical predictions of the Barents Sea

  - *Climate prediction modelling*

the Nansen LEGACY

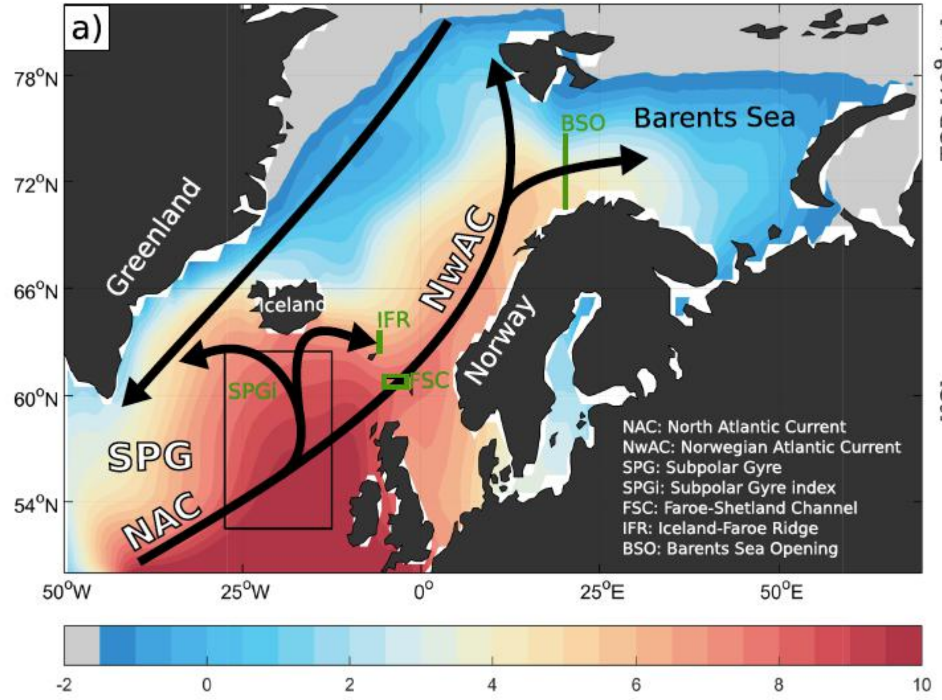
Can changes in marine ecosystems be predicted?

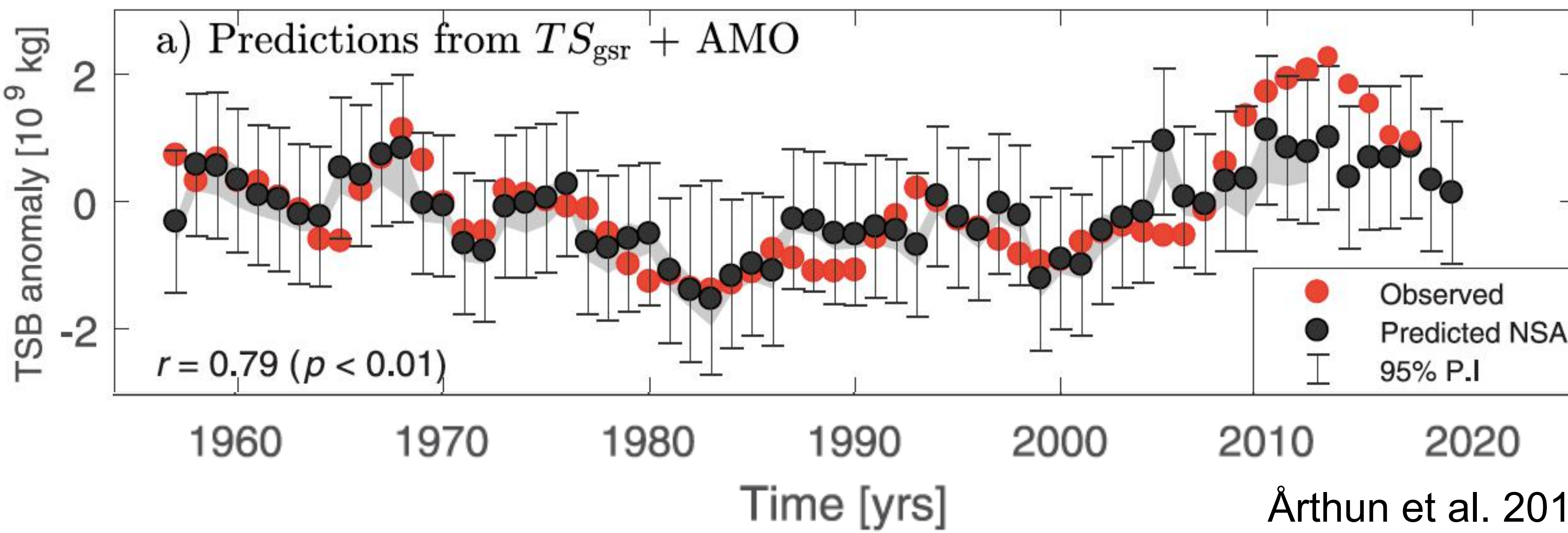
- There are several examples of predictability of the ocean physical state (as shown by Noel).
- Ocean physics has a large impact on living organisms.
- Could predictability in ocean physics also lead to predictability of marine ecosystems?



Teaser

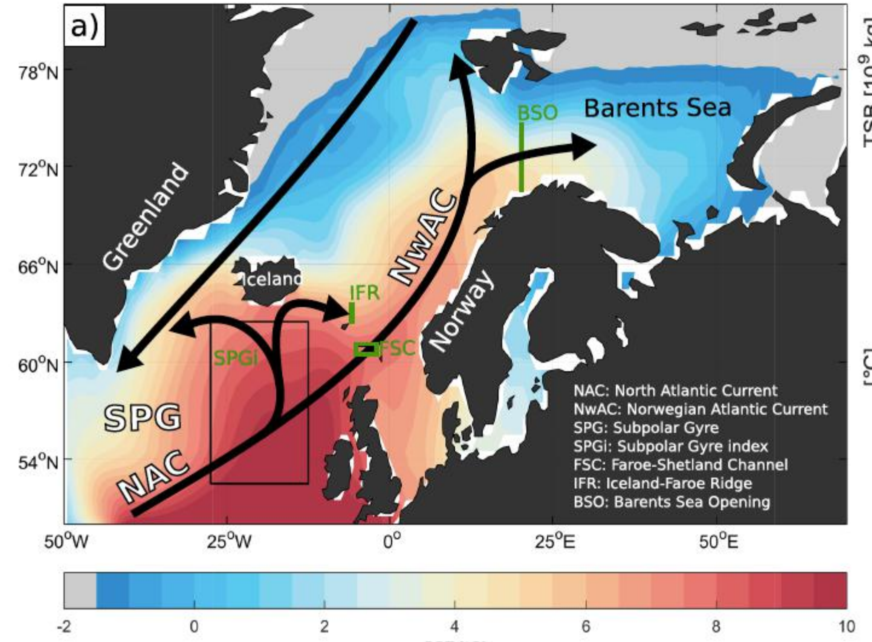
Årthun et al. showed that the cod-stock of the Barents Sea can be predicted up to 7 years in advance by using downstream temperature and salinity anomalies.



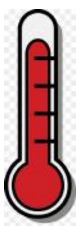


Årthun et al. 2018

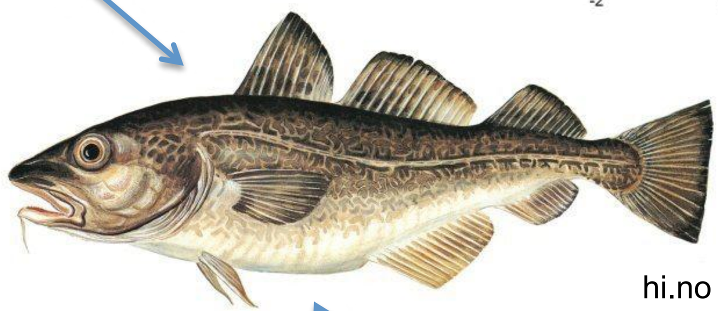
Teaser



Physical environment:
- temperature
- sea ice extent
- …



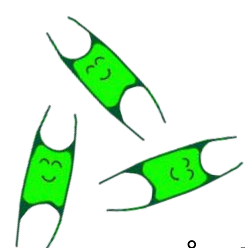
direct impact



hi.no

indirect impact

Bio environment (bottom-up):
- primary production and how it translates to higher tropical levels



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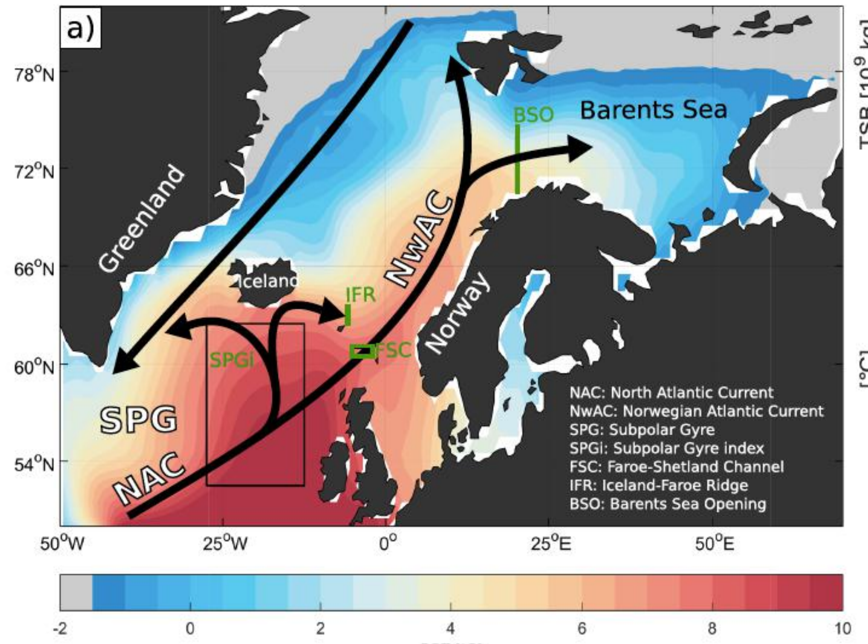

Physical environment:
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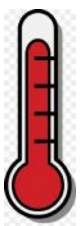

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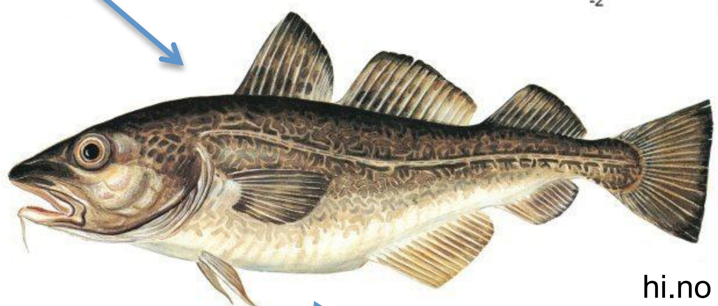


hi.no

indirect impact

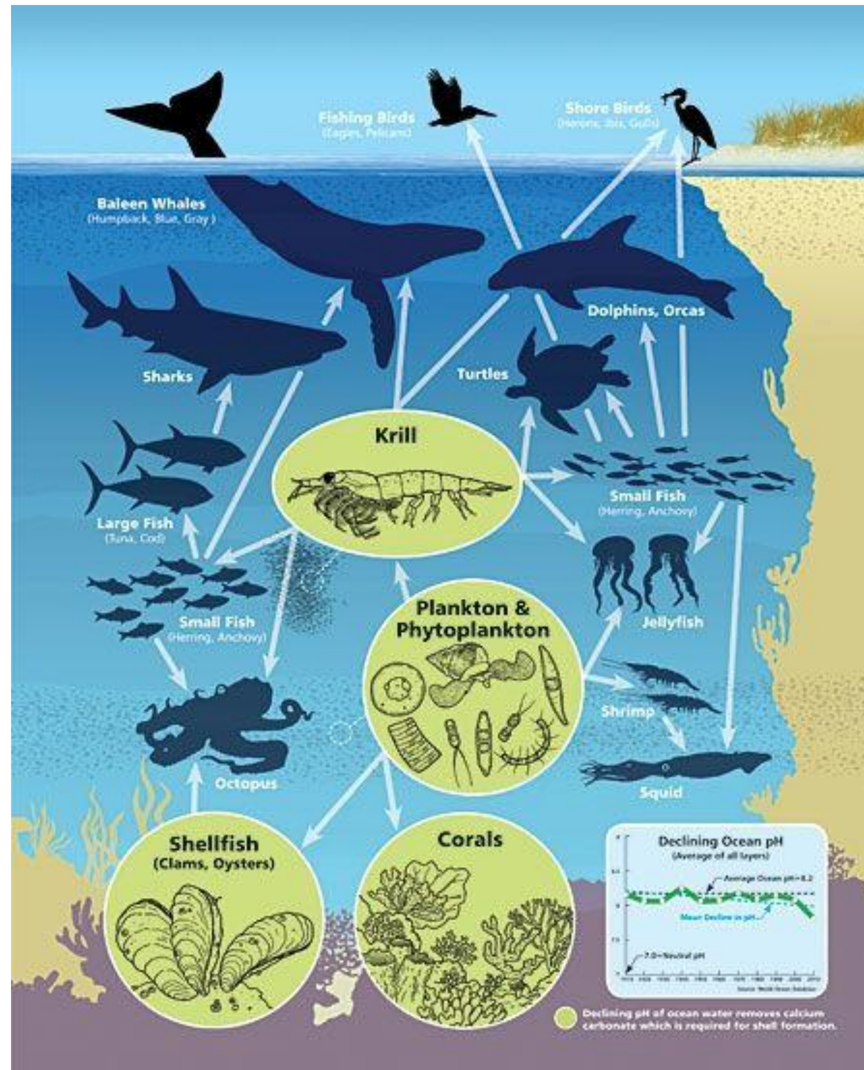
Bio environment (bottom-up):
- primary production and how it translates to higher tropical levels

?

Årthun et al. 2018

Can changes in marine ecosystems be predicted?

- There are several examples of predictability of the ocean physical state.
- Ocean physics has a large impact on living organisms.
- Could predictability in ocean physics also lead to predictability of marine ecosystems?
- Is marine primary productivity predictable?



Outline

- Ocean primary production (biogeochemistry)
  - introduction/definitions
  - controlling factors
    - ?
    - ?
    - …
- Ocean biogeochemical models
  - what's a biogeochemical model?
  - coupling to ocean physical models
  - examples of biogeochemical models in CMIP
- Biogeochemical Predictions
  - ongoing research

Outline

- Ocean primary production (biogeochemistry)
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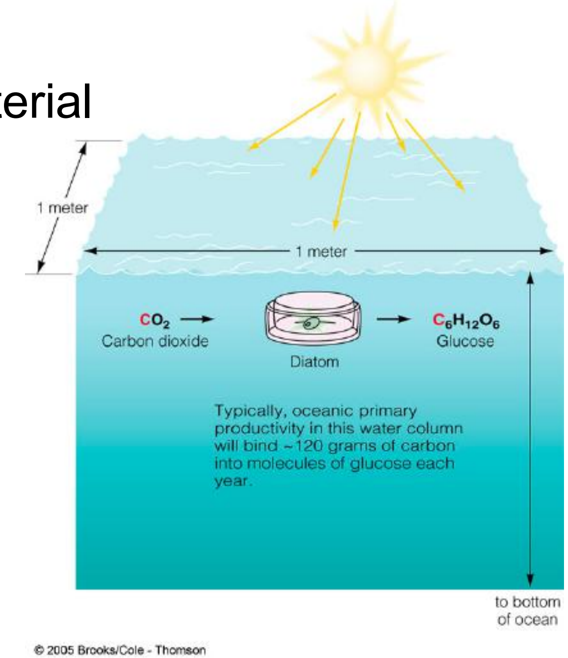
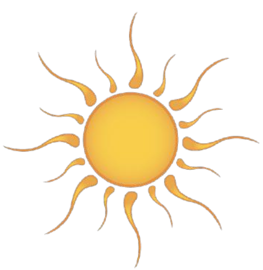
Ocean primary production

Primary production: production (synthesis) of organic material from energy and inorganic material



Photosynthesis



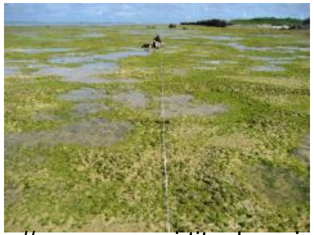
$$6CO_2 + 12H_2O \rightarrow C_6H_{12}O_6 + 6H_2O + 6O_2$$

carbon dioxide | water | organic matter | water | oxygen

Ocean primary production

1


2


3

http://www.wv.mei.titech.ac.jp/nadalab/photo/2007-8-shiraho2/2007-8-shiraho2.html

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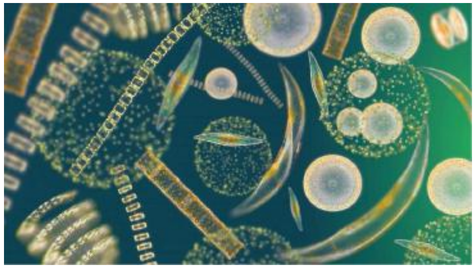


Oceanic photosynthesizers

- 1, Seaweed
- 2, Macro algae
- Micro algae (unicellular)
  - 3, Benthic
  - 4, Planktonic (90 % of oceanic primary production)

Ocean primary production

Gross Primary Production (GPP):
Fixation of CO_2 into organic material

Photosynthesis

$$6CO_2 + 12H_2O \rightarrow C_6H_{12}O_6 + 6H_2O + 6O_2$$

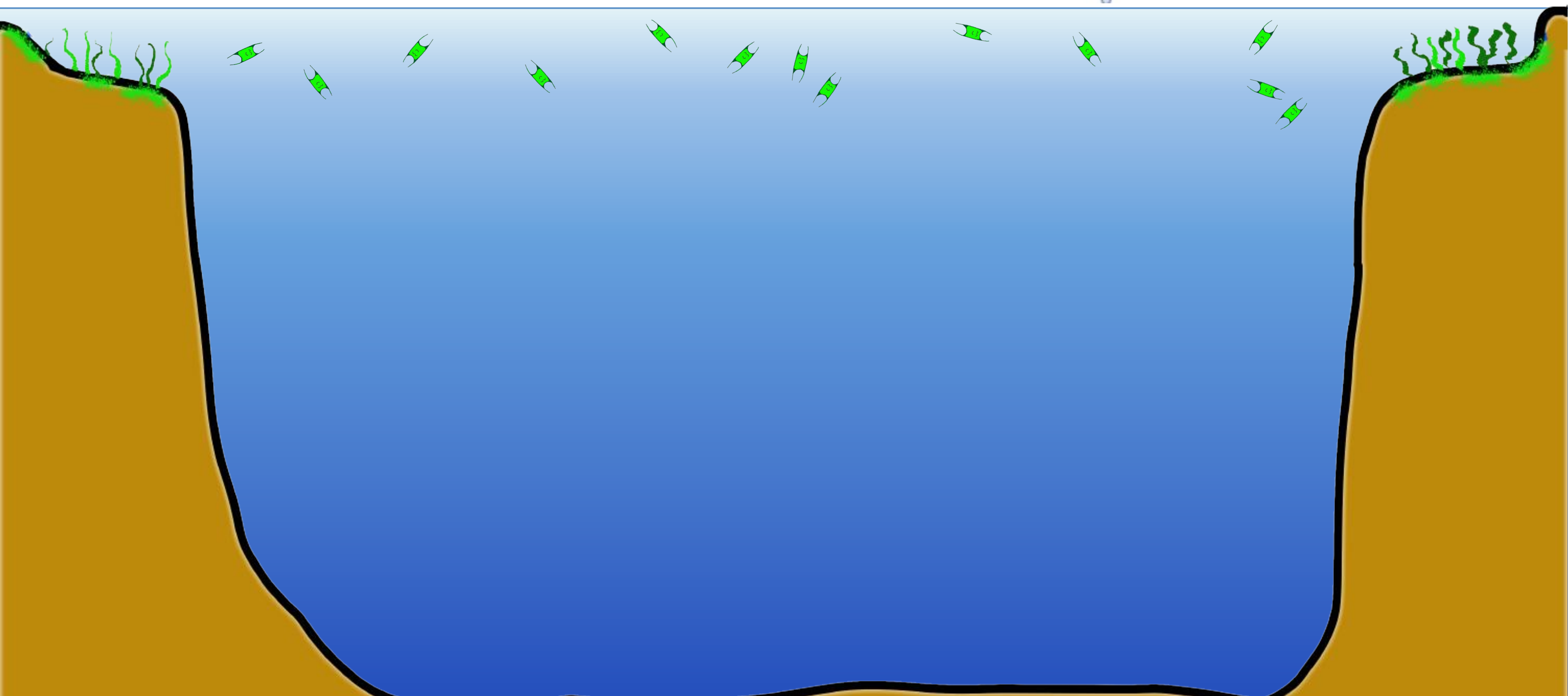
carbon dioxide | water | organic matter | water | oxygen

Net Primary Production (NPP):
NPP = GPP – respiration

Respiration

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$$

organic matter | oxygen | carbon dioxide | water



Ocean primary production

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Net Primary Production (NPP):
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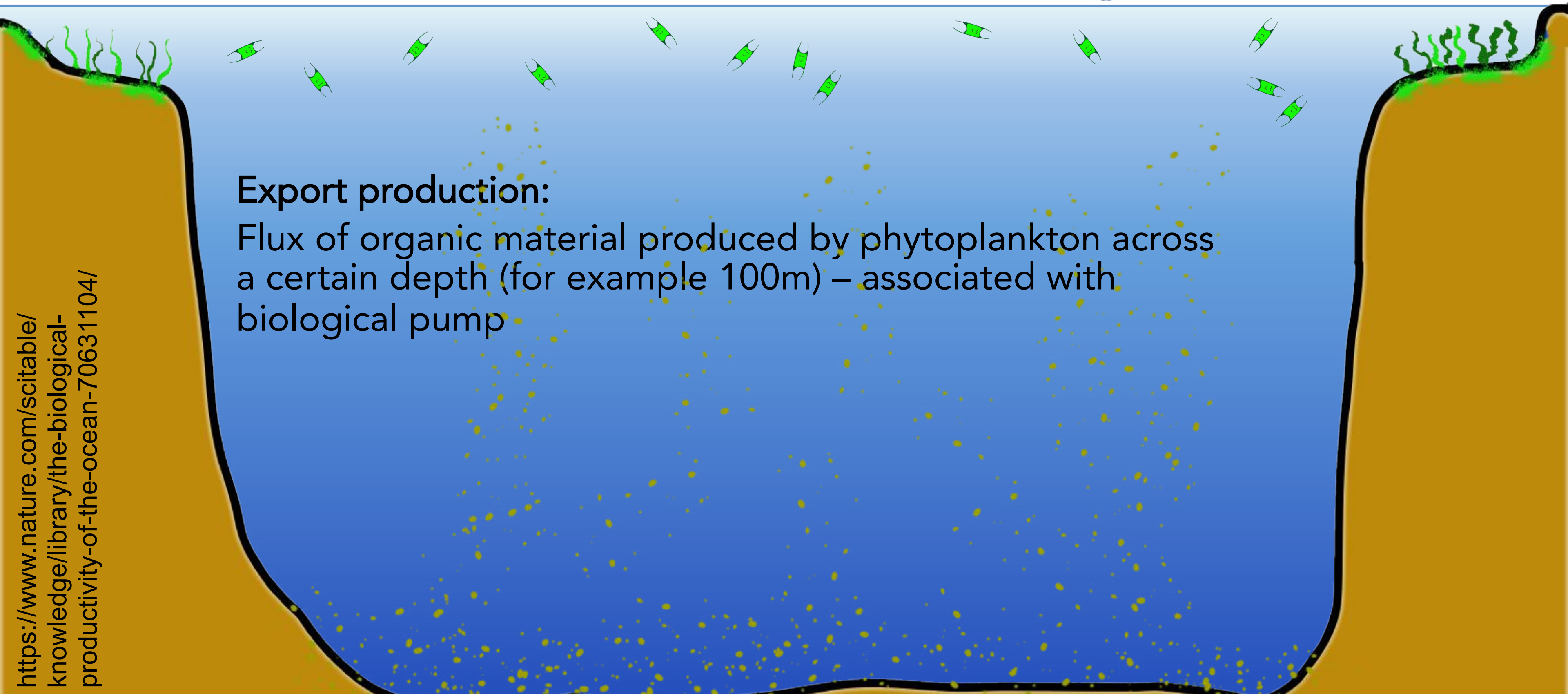
Respiration

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$$

organic matter | oxygen | carbon dioxide | water



Export production:
Flux of organic material produced by phytoplankton across a certain depth (for example 100m) – associated with biological pump

https://www.nature.com/scitable/knowledge/library/the-biological-productivity-of-the-ocean-70631104/

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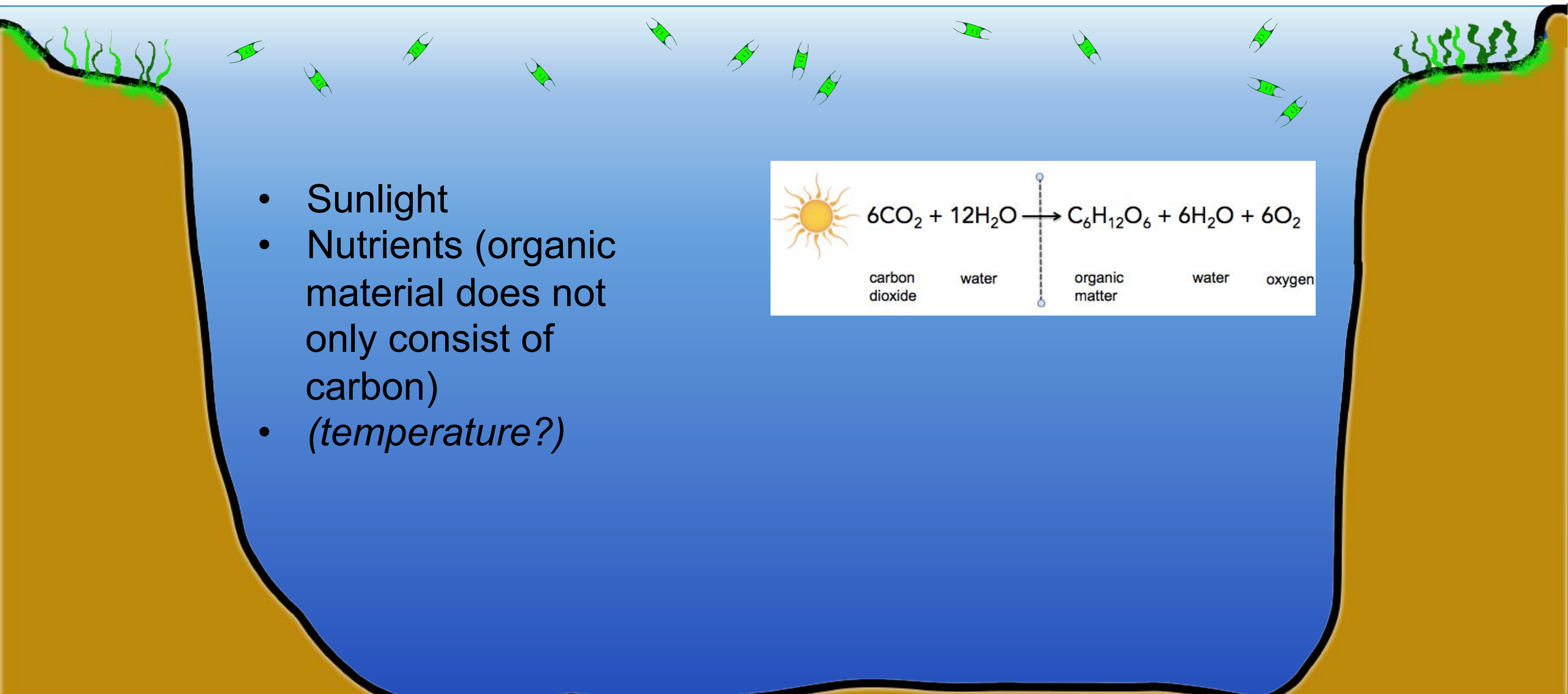
Ocean primary production -controlling factors



- Sunlight
- Nutrients (organic material does not only consist of carbon)
- *(temperature?)*

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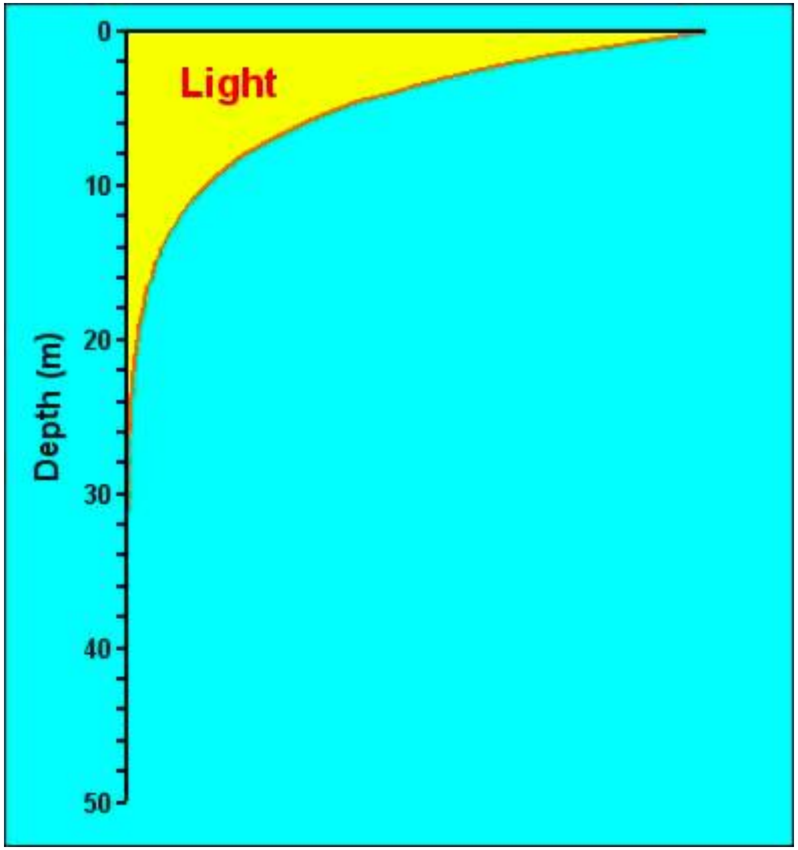
carbon dioxide | water | organic matter | water | oxygen

Ocean primary production -controlling factors: light

Light intensity decreases as an exponential function of depth:

$I(z)=I_0e^{-kz}$

$I(z)$= light intensity at depth z
I_0= light intensity at surface
k = light attenuation coefficient



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$I(z)$= light intensity at depth z
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k = light attenuation coefficient

The light attenuation coefficient depends on the turbidity of seawater, which is influenced by:

- Phytoplankton concentration
- Concentration of dissolved and particulate organic material

It can vary between 0.04 m^{-1} in clear water up to 0.1 in turbid coastal waters

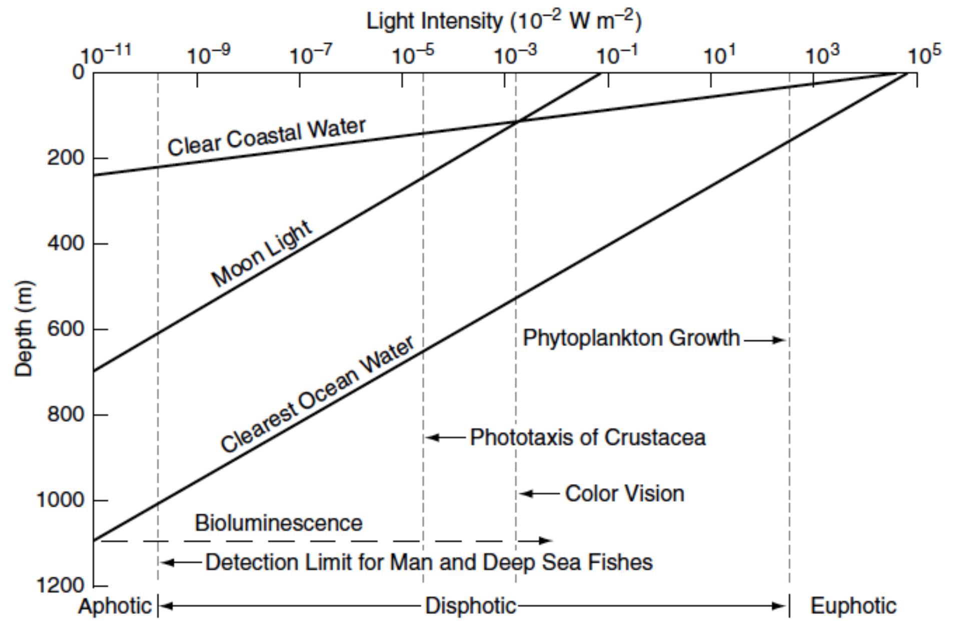
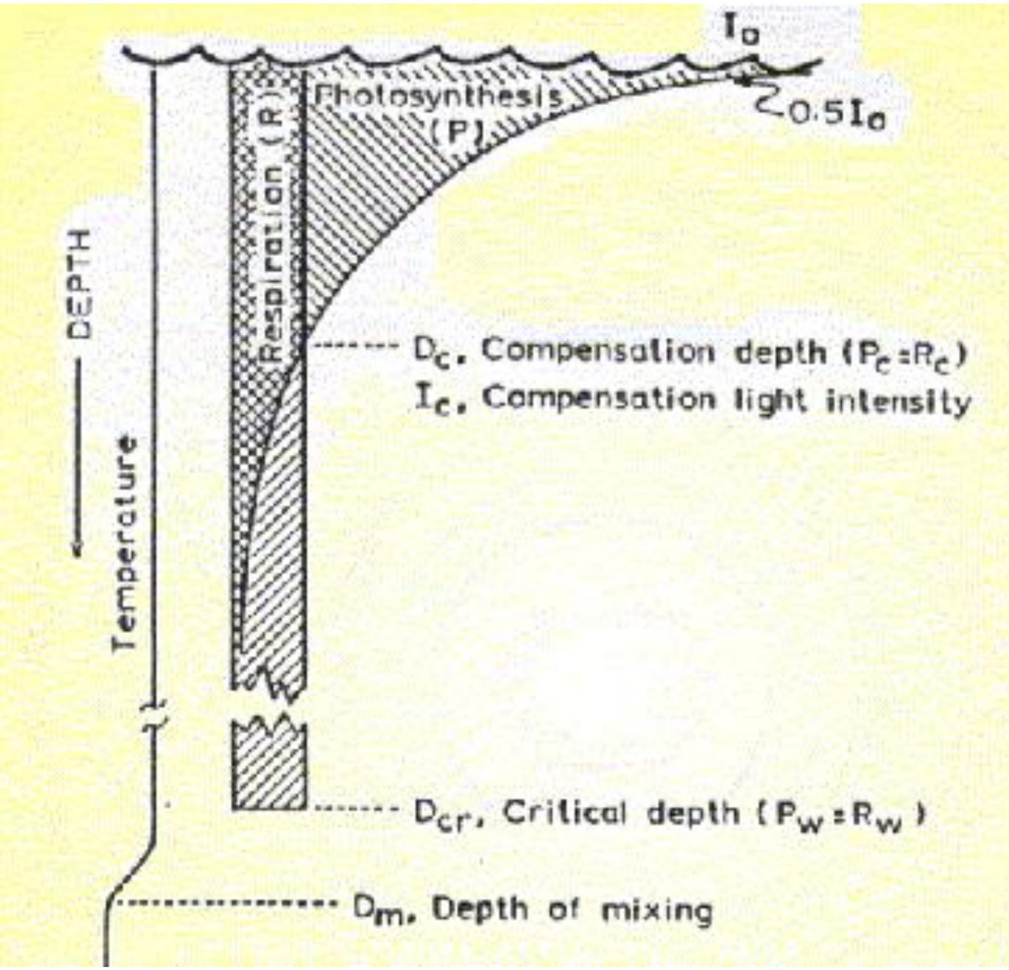


FIGURE 4.2.7: The sloping lines depict the light intensity versus depth for clear coastal and clearest open ocean waters, as well as for moonlight. Note that the horizontal scale is logarithmic. Also shown on the diagram are vertical lines depicting the light intensity cutoff for various biological processes. Taken from *Parsons et al.* [1984].

Sarmiento and Gruber, Ocean Biogeochemical Dynamics 2006

Critical Depth Hypothesis

by Harald Sverdrup



Compensation depth: respiration=photosynthesis in each phytoplankton

Critical depth: Respiration= primary production (integrated from the critical depth to the surface)

Sverdrup H. 1953. On conditions for the vernal blooming of phytoplankton. Journal du Conseil/ Conseil Permanent International pour l'Exploration de la Mer 18: 287–295.

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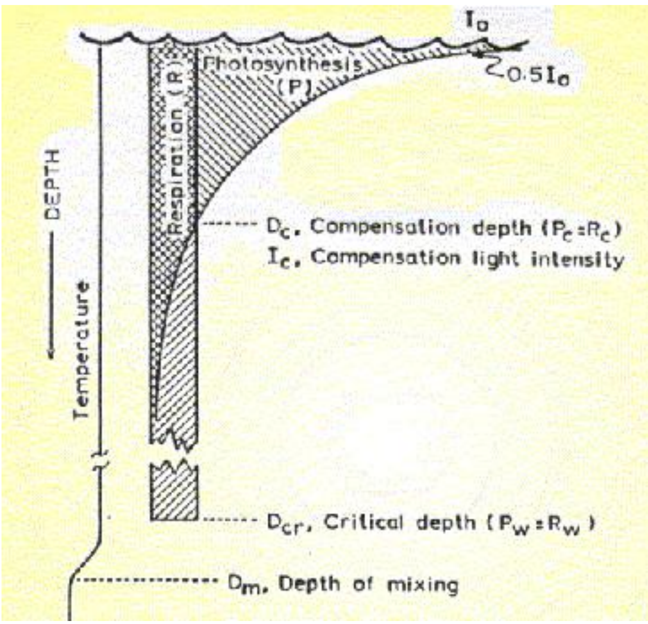
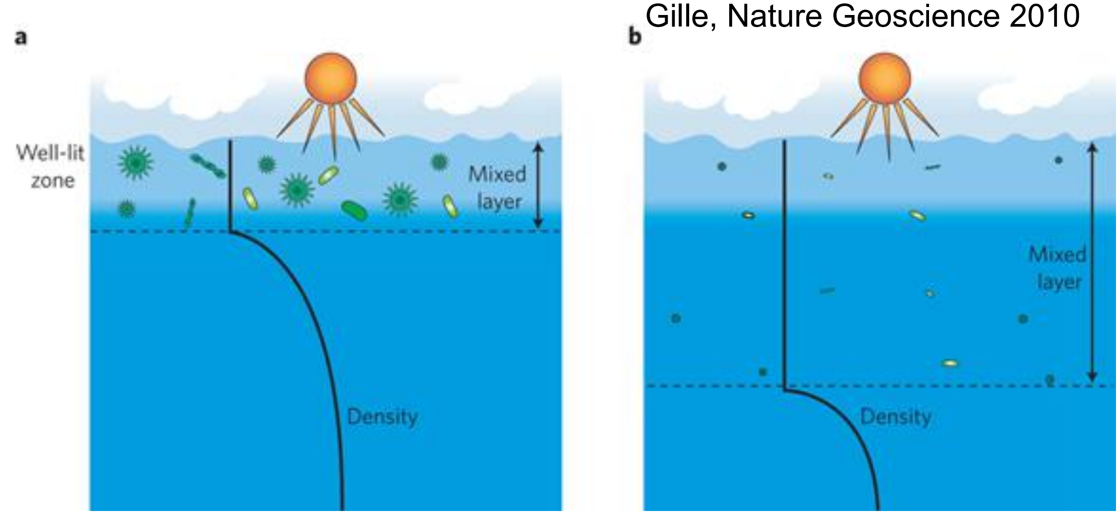


Gille, Nature Geoscience 2010



If the mixed layer is shallower than the critical depth, you can have a net growth of phytoplankton and increase in biomass.

Compensation depth: respiration=photosynthesis in each phytoplankton

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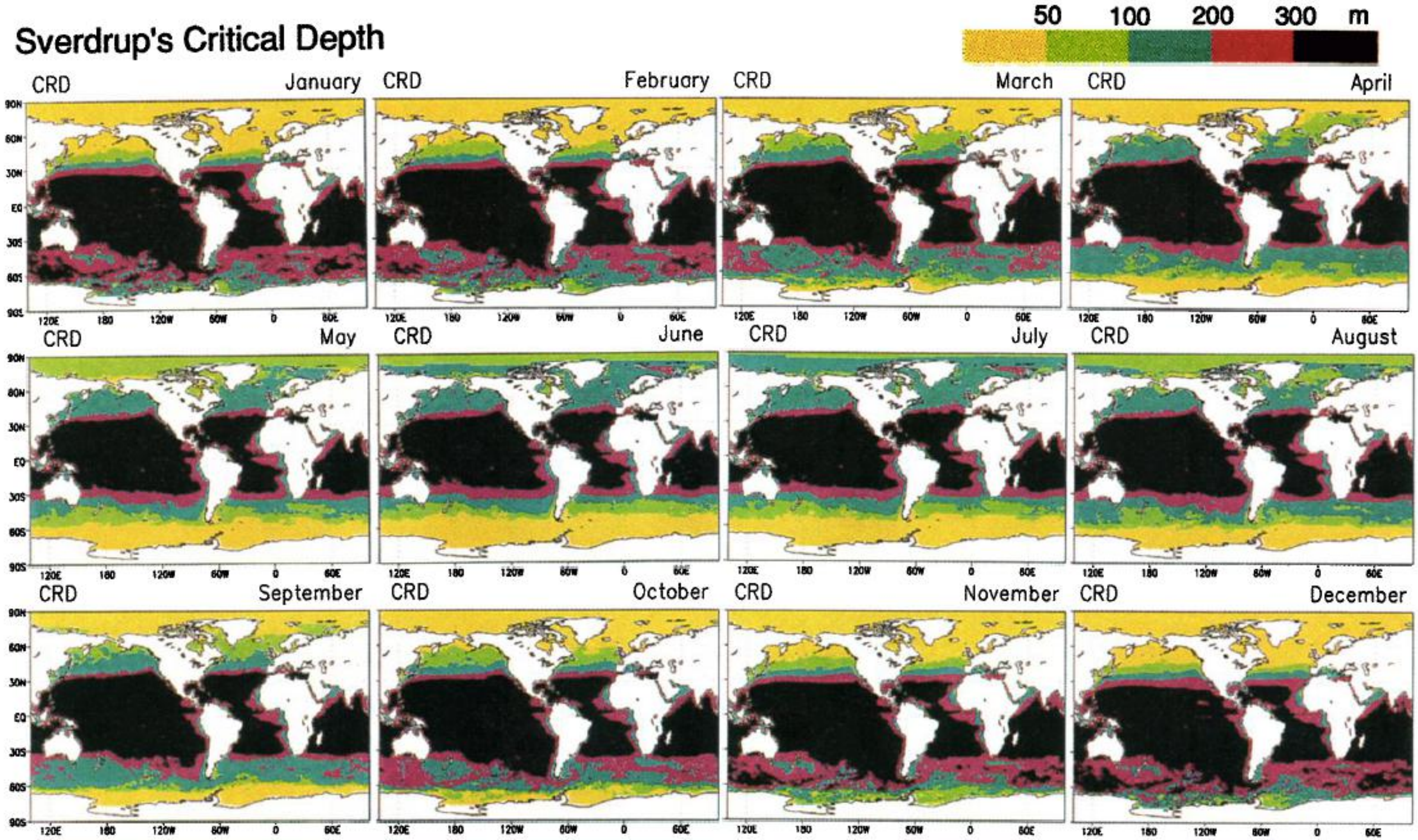
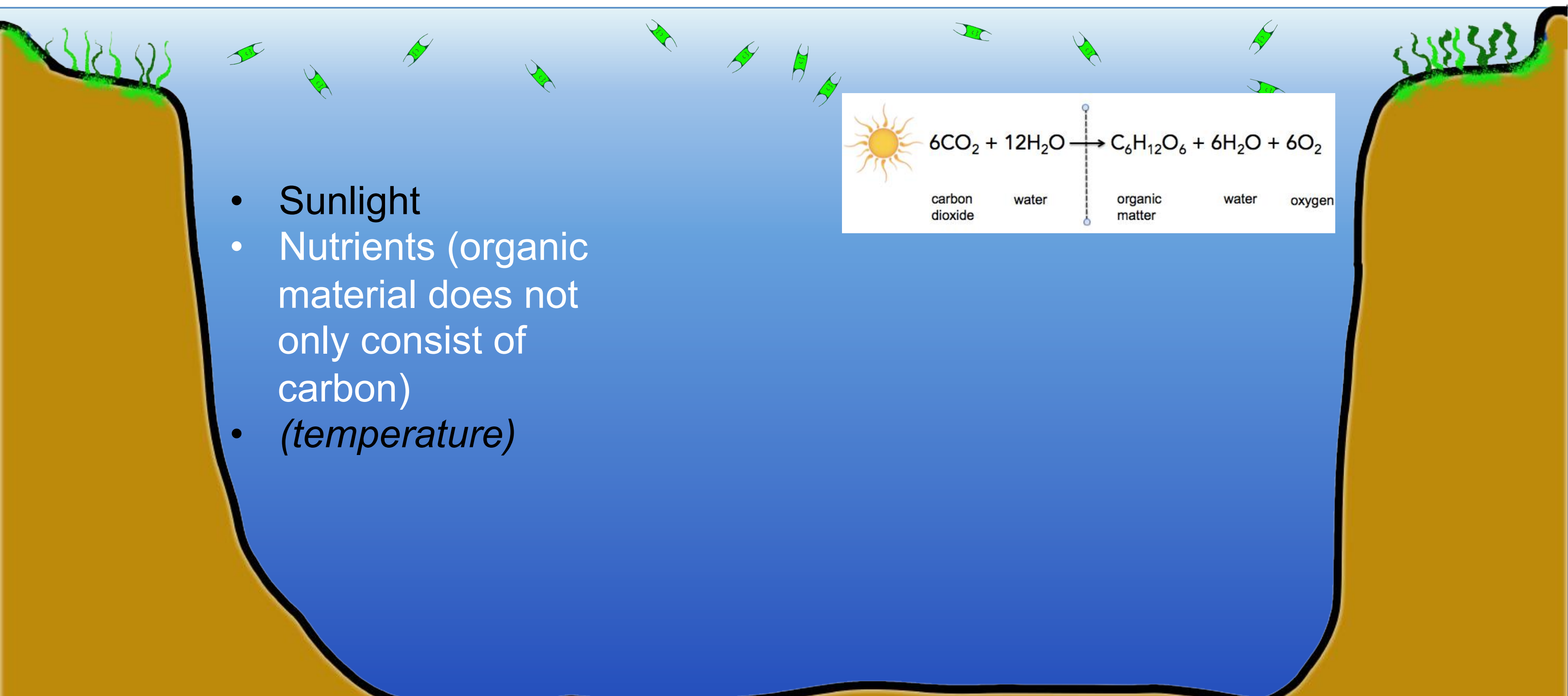
Obata et al., 1996



Ocean primary production -controlling factors



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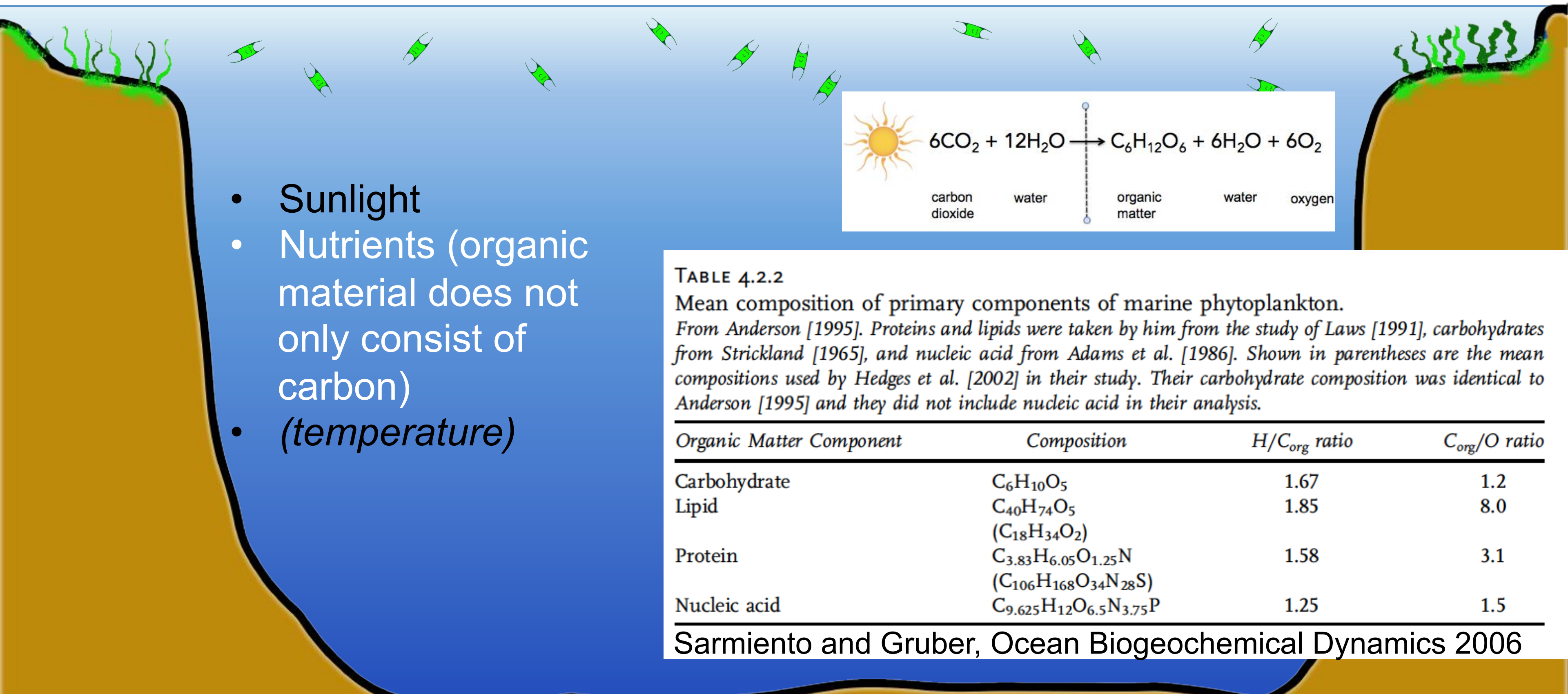
- Sunlight
- Nutrients (organic material does not only consist of carbon)
- *(temperature)*

Ocean primary production -controlling factors



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$$6CO_2 + 12H_2O \rightarrow C_6H_{12}O_6 + 6H_2O + 6O_2$$

carbon dioxide — water — organic matter — water — oxygen

TABLE 4.2.2

Mean composition of primary components of marine phytoplankton.

From Anderson [1995]. Proteins and lipids were taken by him from the study of Laws [1991], carbohydrates from Strickland [1965], and nucleic acid from Adams et al. [1986]. Shown in parentheses are the mean compositions used by Hedges et al. [2002] in their study. Their carbohydrate composition was identical to Anderson [1995] and they did not include nucleic acid in their analysis.

Organic Matter Component	*Composition*	*H/C_{org} ratio*	*C_{org}/O ratio*
Carbohydrate	$C_6H_{10}O_5$	1.67	1.2
Lipid	$C_{40}H_{74}O_5$ ($C_{18}H_{34}O_2$)	1.85	8.0
Protein	$C_{3.83}H_{6.05}O_{1.25}N$ ($C_{106}H_{168}O_{34}N_{28}S$)	1.58	3.1
Nucleic acid	$C_{9.625}H_{12}O_{6.5}N_{3.75}P$	1.25	1.5

Sarmiento and Gruber, Ocean Biogeochemical Dynamics 2006

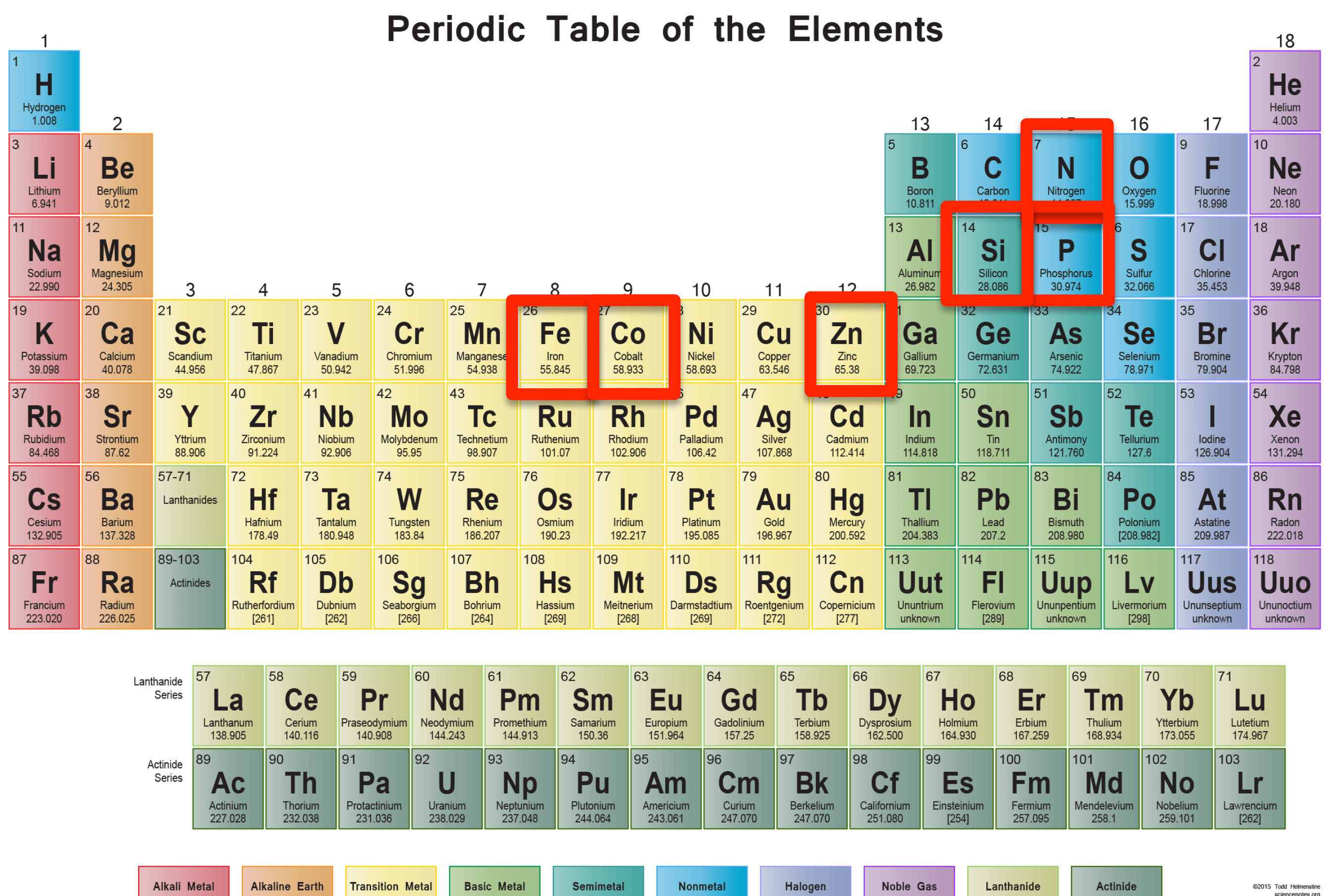
Ocean primary production -controlling factors: nutrients

Macronutrients: (Needed in larger quantities, often limiting the growth of phytoplankton)

- Nitrogen (N)
- Phosphorus (P)
- Silicon (Si), *only diatoms*

Micronutrients: (Essential but only in small quantities)

- Iron (Fe)
- Copper (Cu)
- Zink (Zn)
- …



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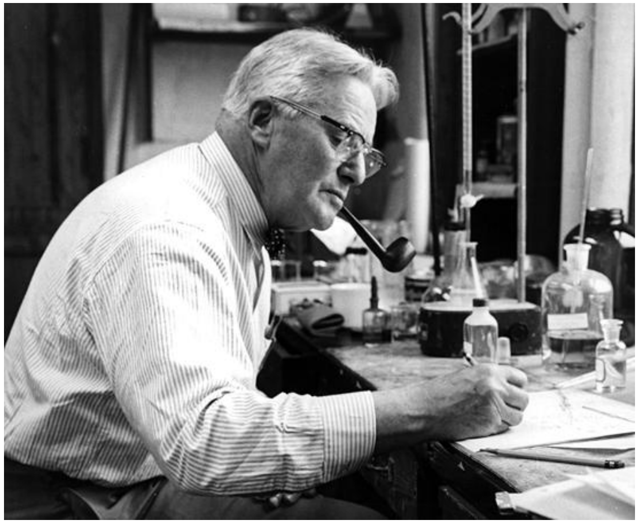
Element	Dissolved forms in seawater	Chemical formula	Commonly referred to
Nitrogen (N)	Nitrate	NO_3^-	Dissolved Inorganic Nitrogen (DIN)
	Nitrite	NO_2^-	
	Ammonium	NH_4^+	
Phosphorus (P)	Phosphate	PO_4^{3-}	Dissolved Inorganic Phosphorus (DIP)
Silicon (Si)	Silicate	SiO_4^{-4}	

Alfred Redfield

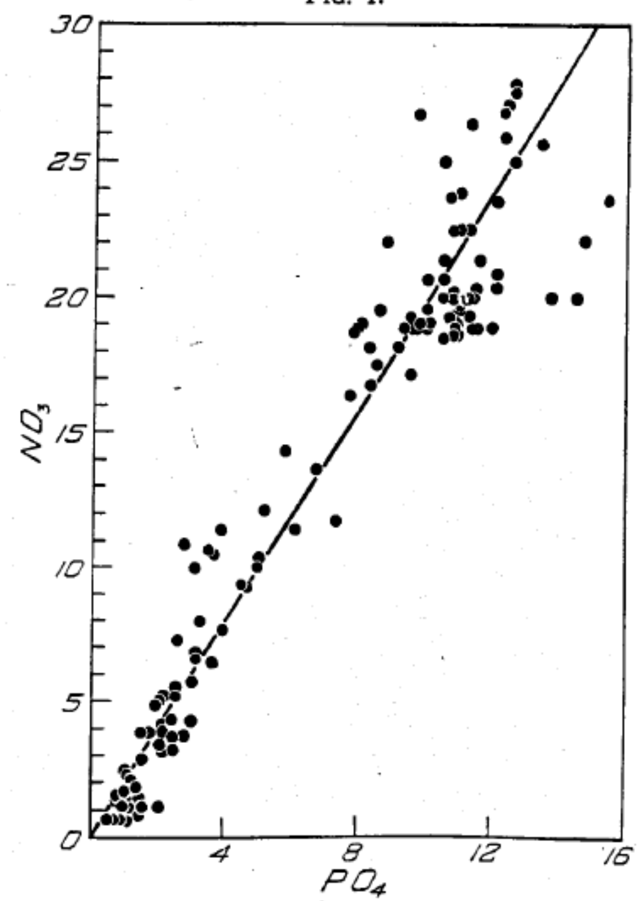


"Life in the sea cannot be understood without understanding the sea itself."

Found that the proportions of nitrogen and phosphorus are strikingly similar in phytoplankton and in seawater.

Chicken and egg problem: Does phytoplankton reflect the composition of seawater, or is it the phytoplankton that affect the composition of seawater?

FIG. 1.



Correlation between concentrations of nitrate and phosphate in the waters of western Atlantic Ocean. Ordinate, concentration of nitrate, units 10^{-3} millimols per liter; abscissa, concentration of phosphate, units 10^{-4} millimols per liter. The line represents a ratio of $\triangle N : \triangle P = 20 : 1$ milligram atoms.

Redfield, 1934

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- Zink (Zn)
- …

Redfield ratio

Phytoplankton carbon: nitrogen: phosphorus ratio

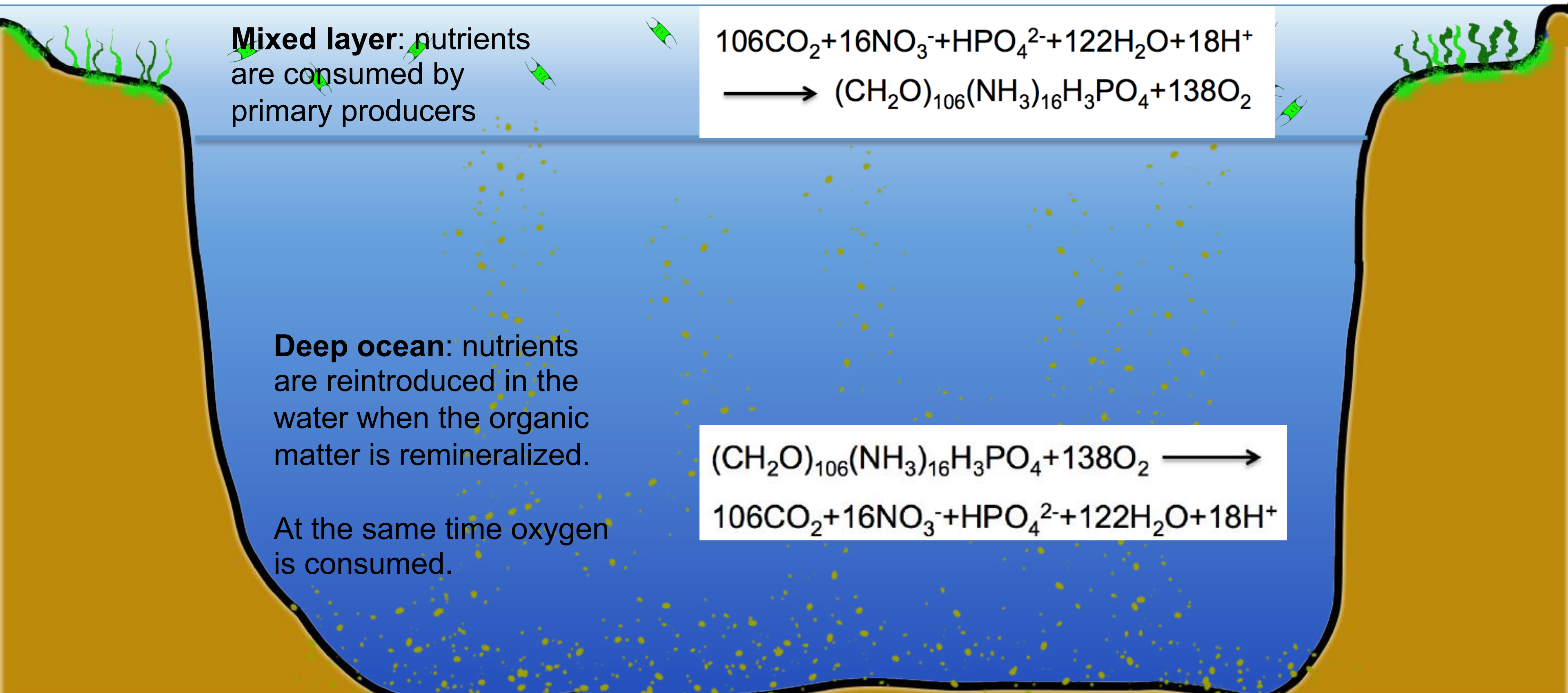
C:N:P ≈ 106:16:1

(in number of atoms)

Formula summarizing the production of organic matter:

$$106CO_2 + 16NO_3^- + HPO_4^{2-} + 122H_2O + 18H^+ \longrightarrow (CH_2O)_{106}(NH_3)_{16}H_3PO_4 + 138O_2$$

Ocean primary production -controlling factors: nutrients



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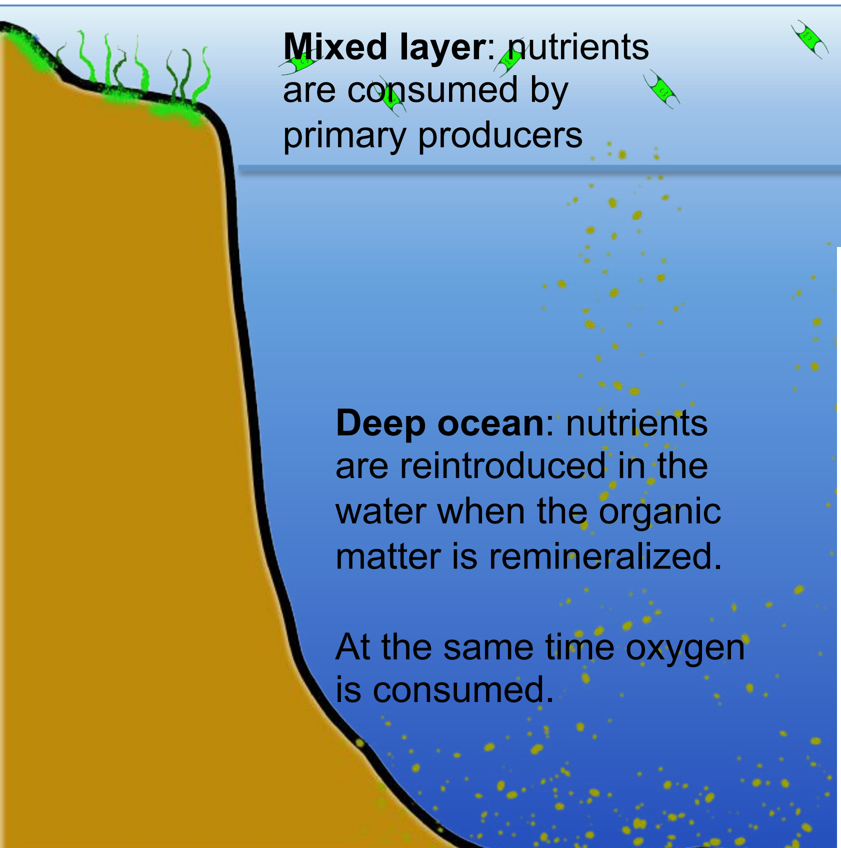


Mixed layer: nutrients are consumed by primary producers

Deep ocean: nutrients are reintroduced in the water when the organic matter is remineralized.

At the same time oxygen is consumed.

Introduction to Oceanography by Paul Webb

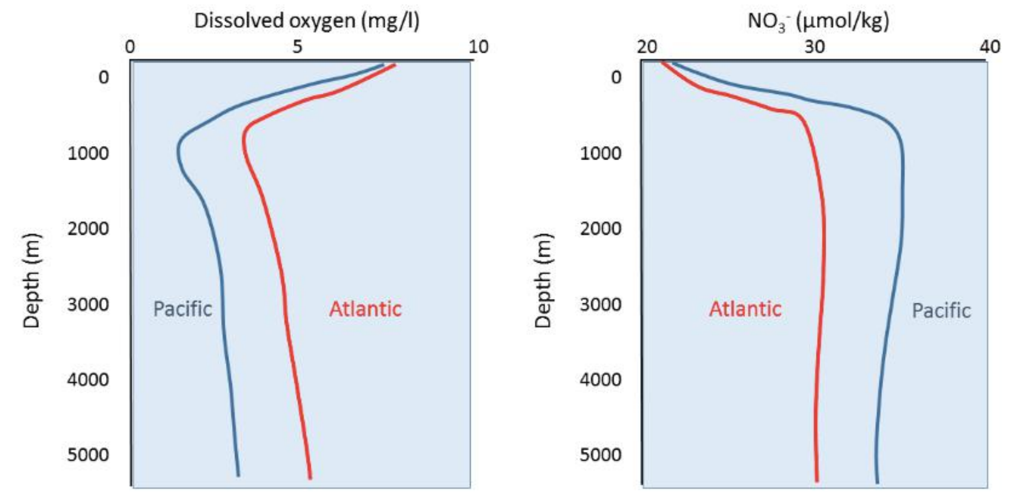
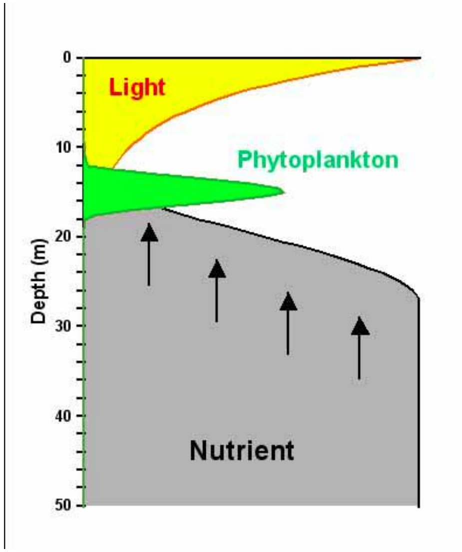
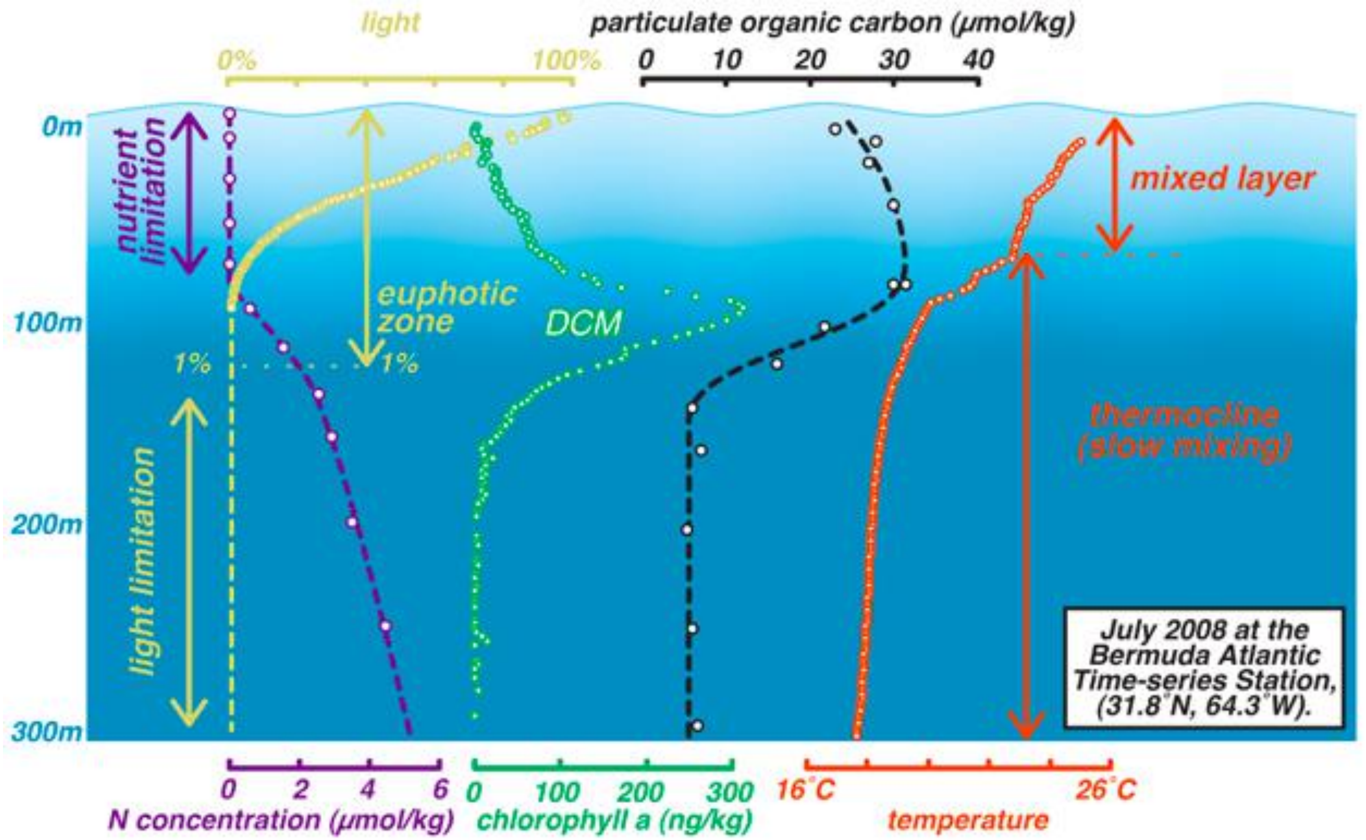


***Figure 5.6.3** Dissolved oxygen (left) and nutrient (right) profiles for the Pacific and Atlantic Oceans. As water circulates from the Atlantic to the Pacific, oxygen is consumed while nutrients accumulate (PW).*

Ocean primary production -controlling factors: nutrients

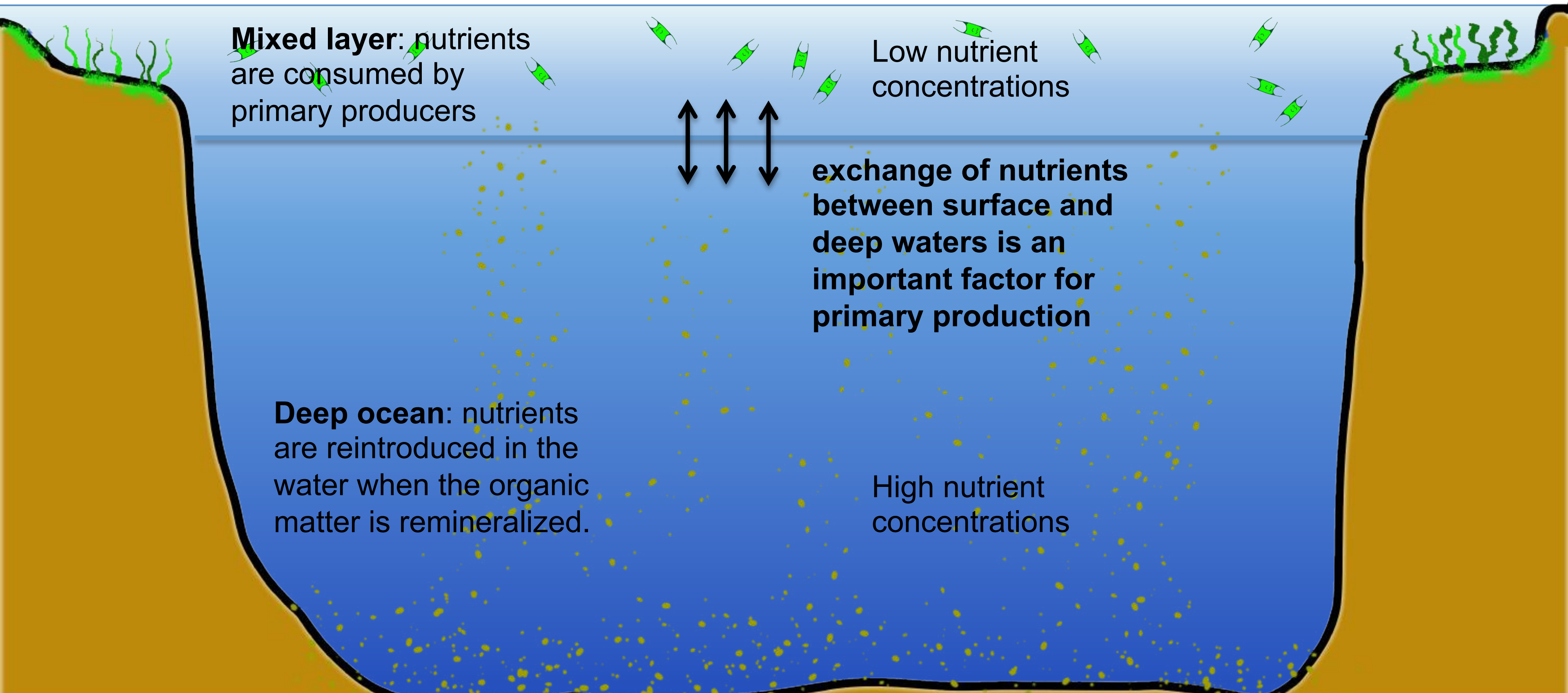




Opposing vertical gradients in light and nutrients can result in accumulation of phytoplankton at the base of the mixed layer.

Sigman, D. M. & Hain, M. P. (2012) The Biological Productivity of the Ocean. Nature Education Knowledge 3(10):21

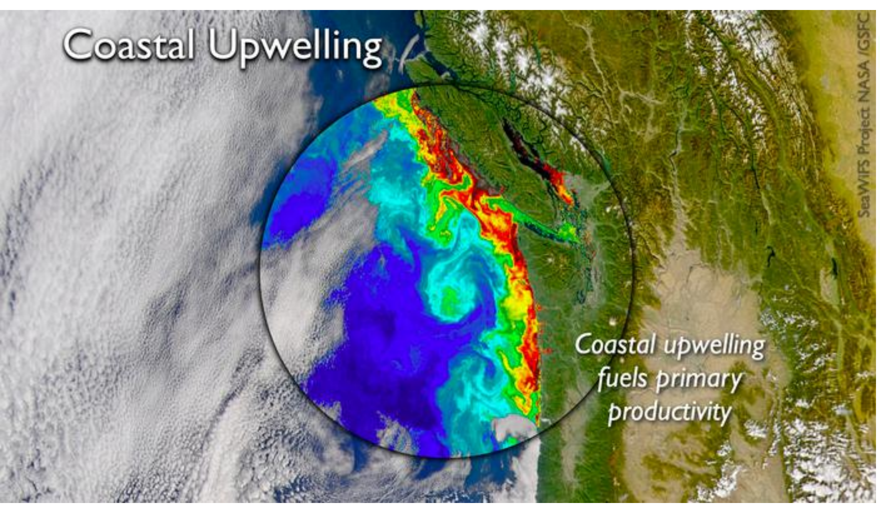
Ocean primary production -controlling factors: nutrients

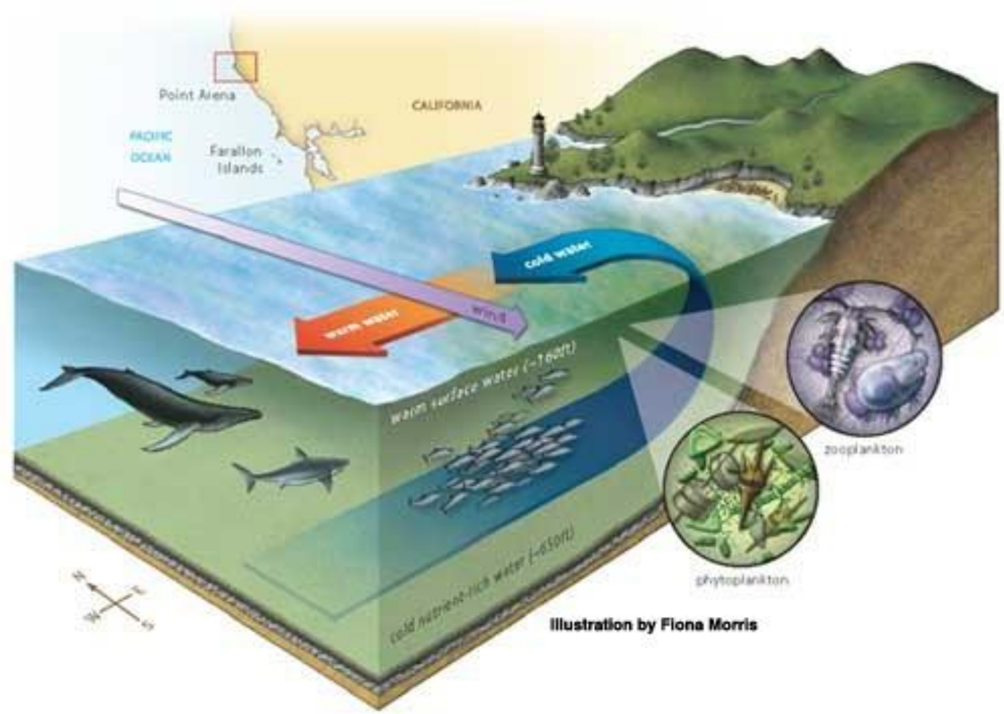


Ocean primary production -controlling factors: nutrients

Examples of processes influencing vertical exchange

- Coastal upwelling
- Equatorial upwelling
- Convective overturning/ Winter convection (seasonally stratified oceans)
- Rossby waves





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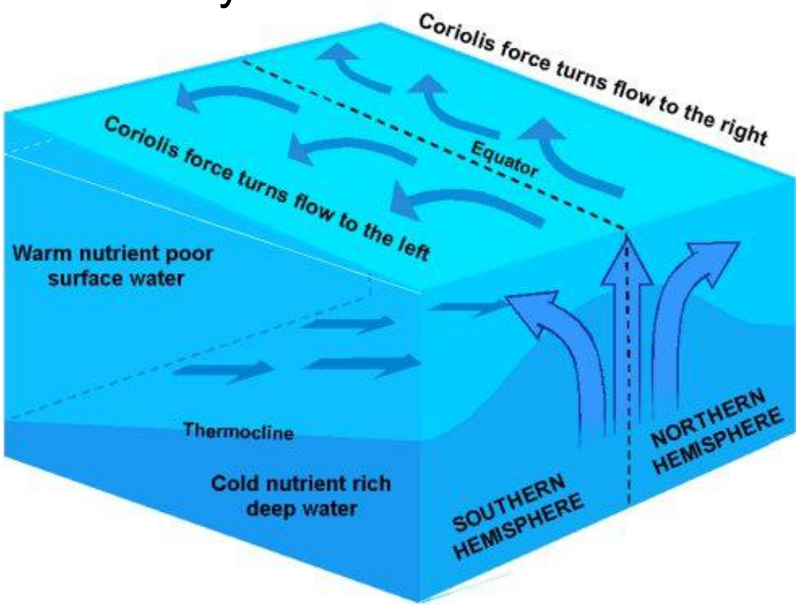

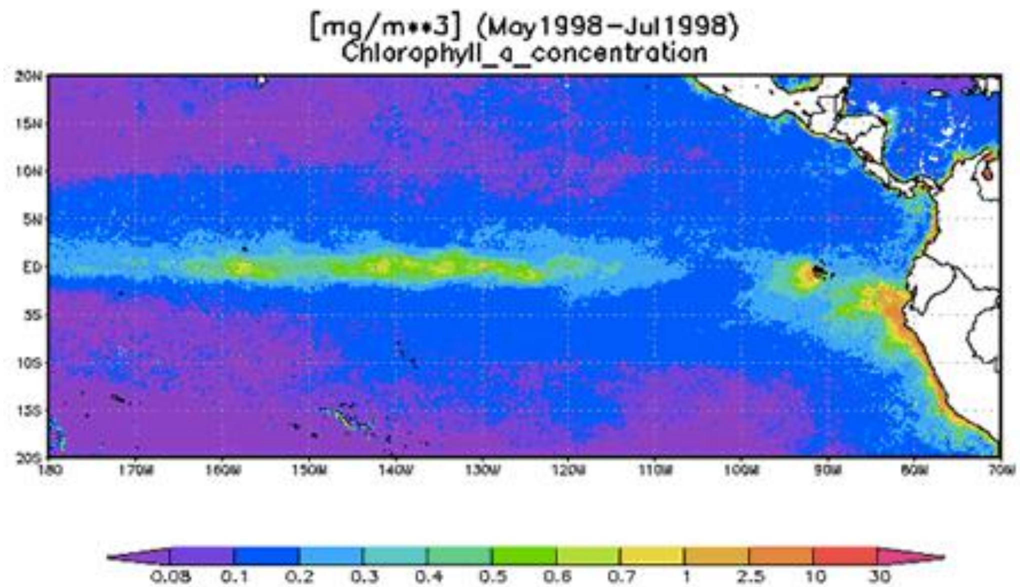

https://seos-project.eu/oceancurrents/oceancurrents-c04-s01-p01.html

Ocean primary production -controlling factors: nutrients

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Example from the Southern Ocean

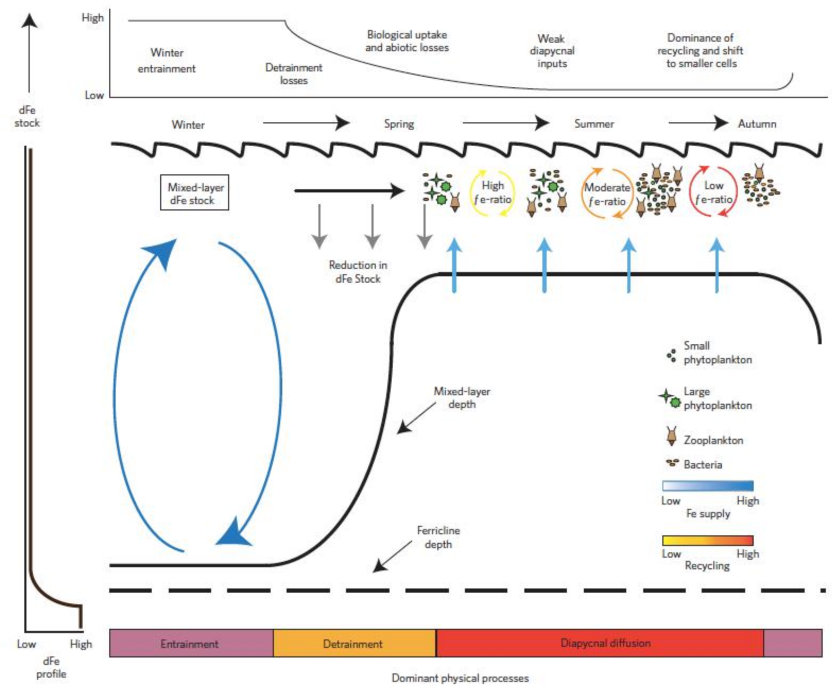

Figure 4 | A schematic representation of the seasonal variability in Southern Ocean Fe cycling. We emphasize seasonal changes in the physical supply of Fe (blue arrows), mixed-layer depth and the mixed-layer DFe inventory, as well as the magnitude of recycling (yellow, orange and red arrows) and pelagic community composition. The dominant physical processes over the season is conceptualized at the bottom of the figure. We note that some recycling probably occurs below the mixed layer and can be entrained the following winter.

Tagliabue et al. Nature Geoscience 2014

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- Rossby waves

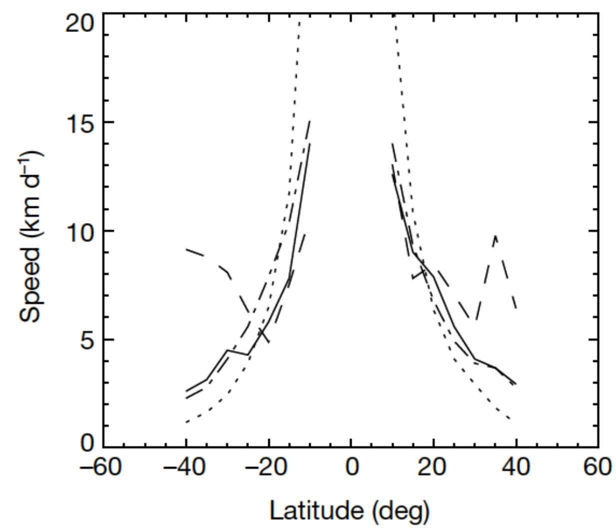
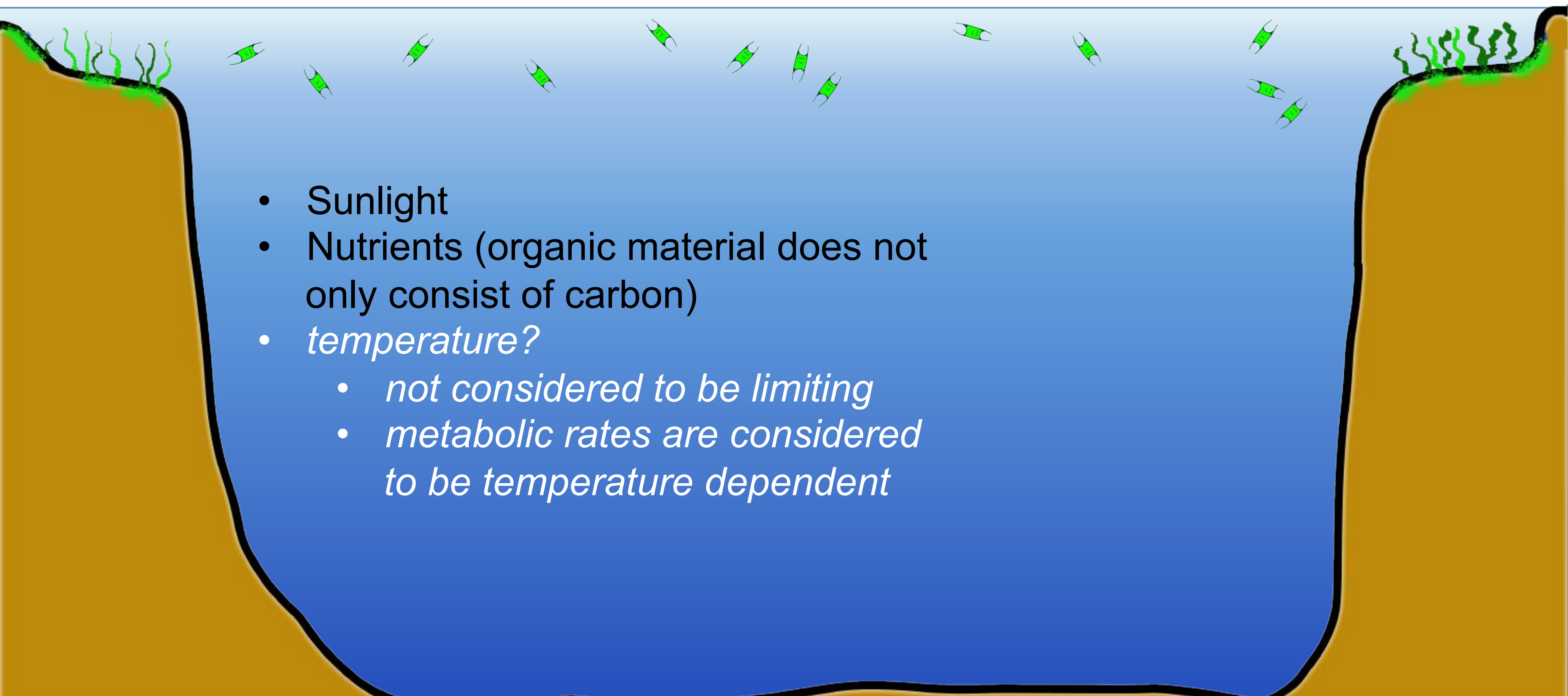


Figure 3 Propagation speeds of Chl and SSH anomalies. The figure shows that propagation speeds of chlorophyll anomalies associated with baroclinic features vary with latitude in nearly the same way as do the theoretical phase speeds of Rossby waves (dotted lines). The propagation speeds are estimated from the wavenumber spectra of chlorophyll (dash-dot line), sea surface height (SSH; dashed line) and chlorophyll–SSH coherence (solid lines) in the Pacific Ocean. The theoretical speeds are based on baroclinic radii of deformation from ref. 15.

Uz et al. 2001, Letters to Nature

Ocean primary production -controlling factors

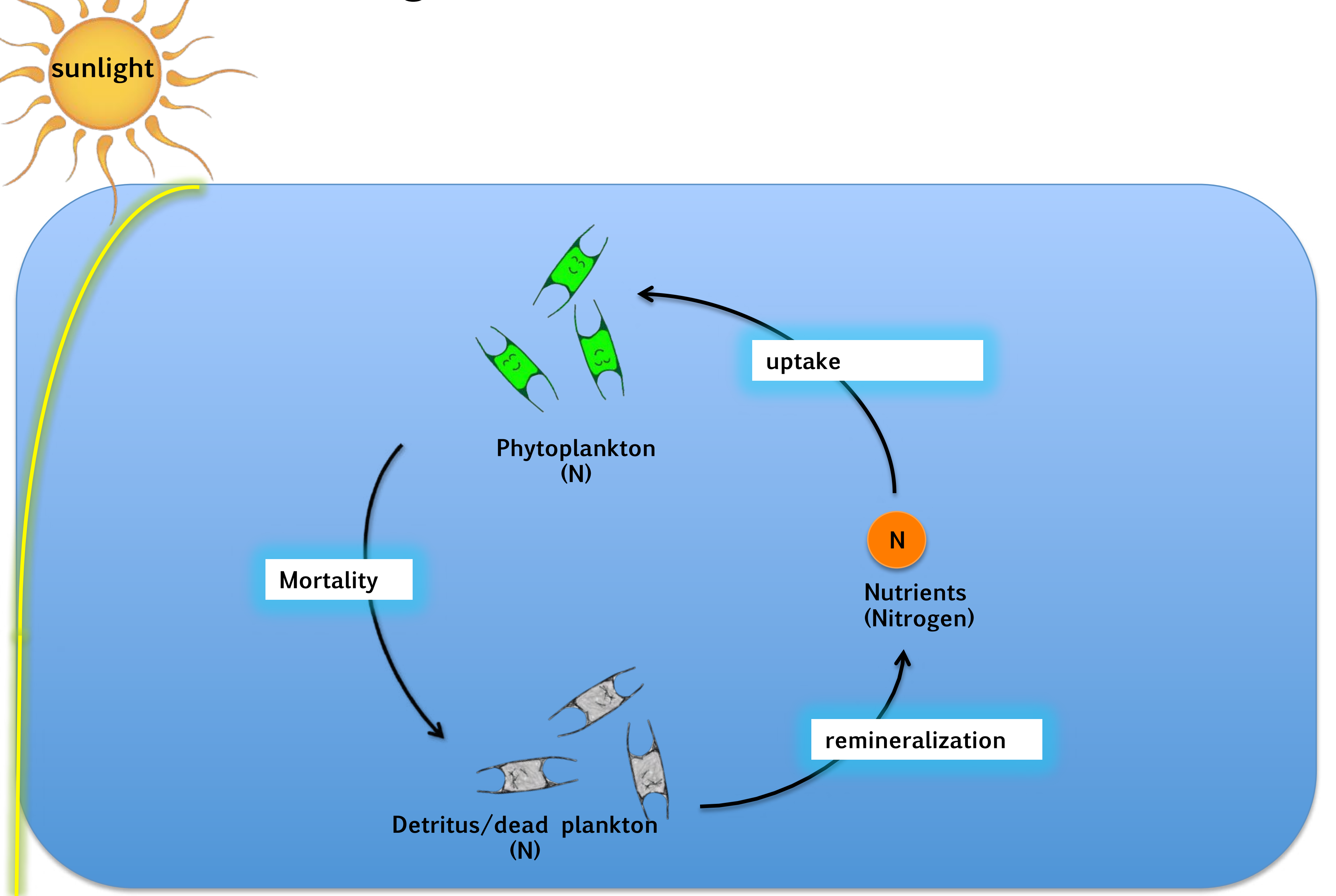


- Sunlight
- Nutrients (organic material does not only consist of carbon)
- *temperature?*
    - *not considered to be limiting*
    - *metabolic rates are considered to be temperature dependent*

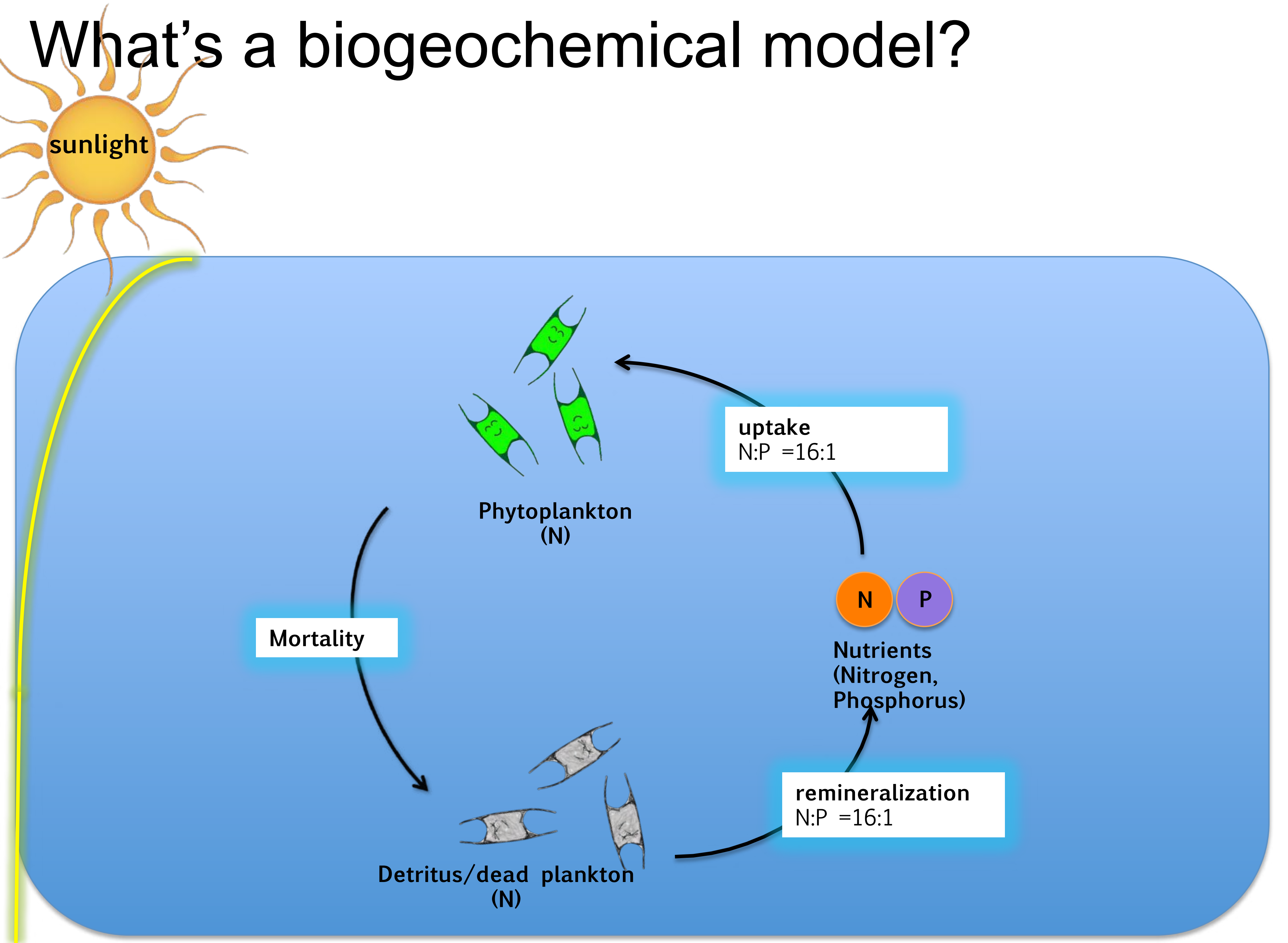
Outline

- Ocean primary production (biogeochemistry)
  - introduction/definitions
  - controlling factors
    - light
    - nutrients
    - (temperature?)
- Ocean biogeochemical models
  - what's a biogeochemical model?
  - coupling to ocean physical models
  - examples of biogeochemical models in CMIP
- Biogeochemical Predictions
  - ongoing research

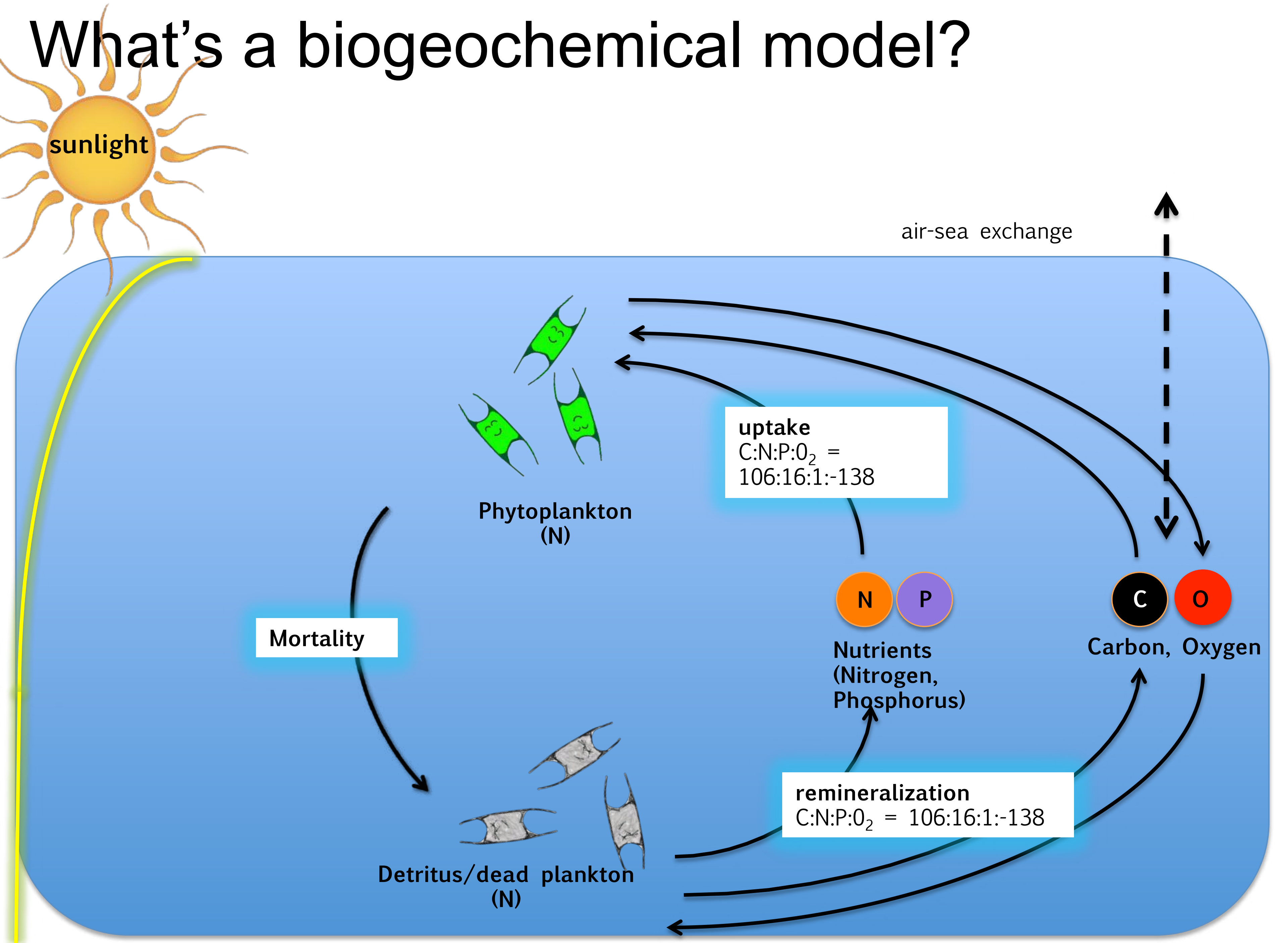
What's a biogeochemical model?



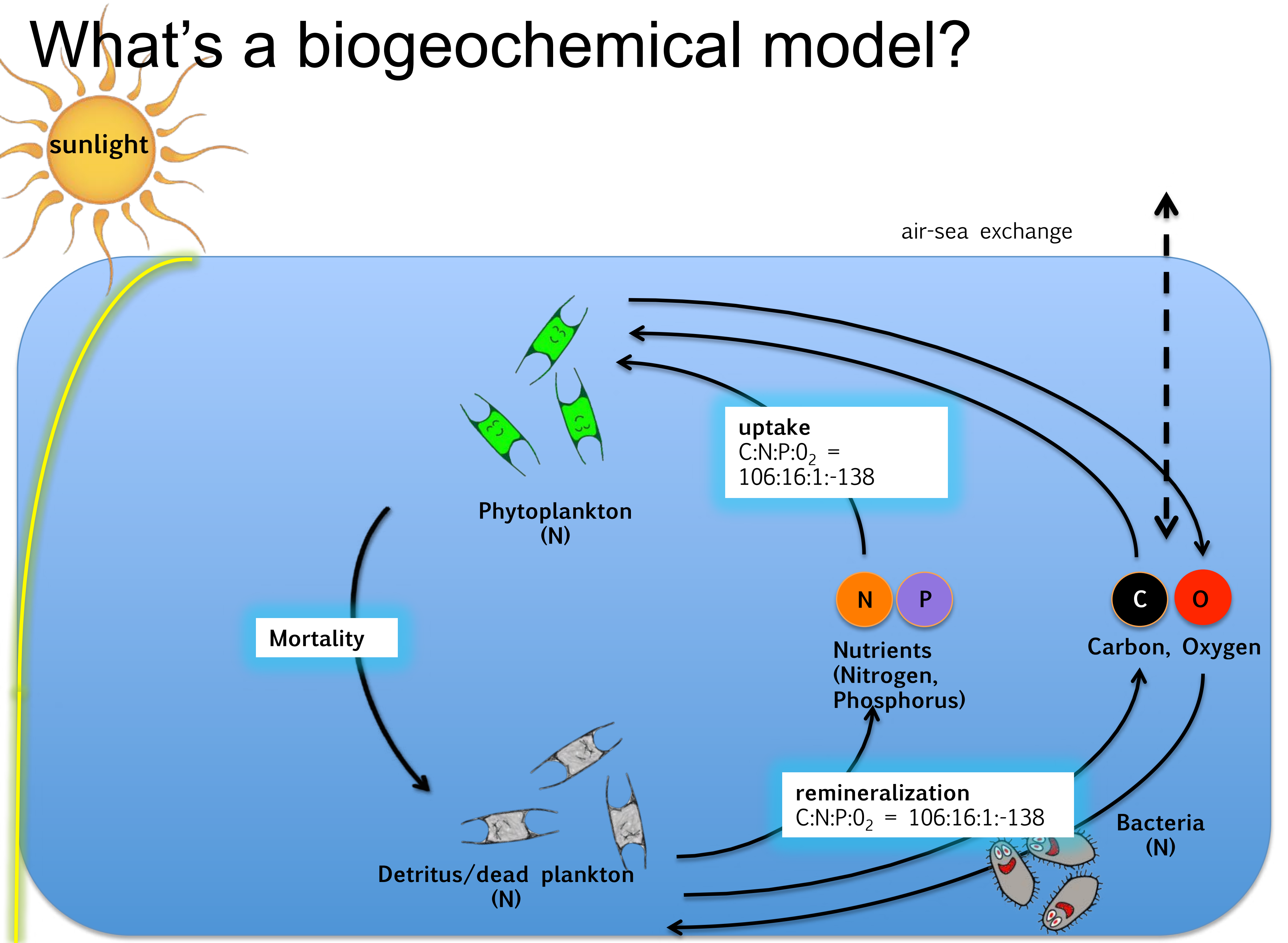
What's a biogeochemical model?



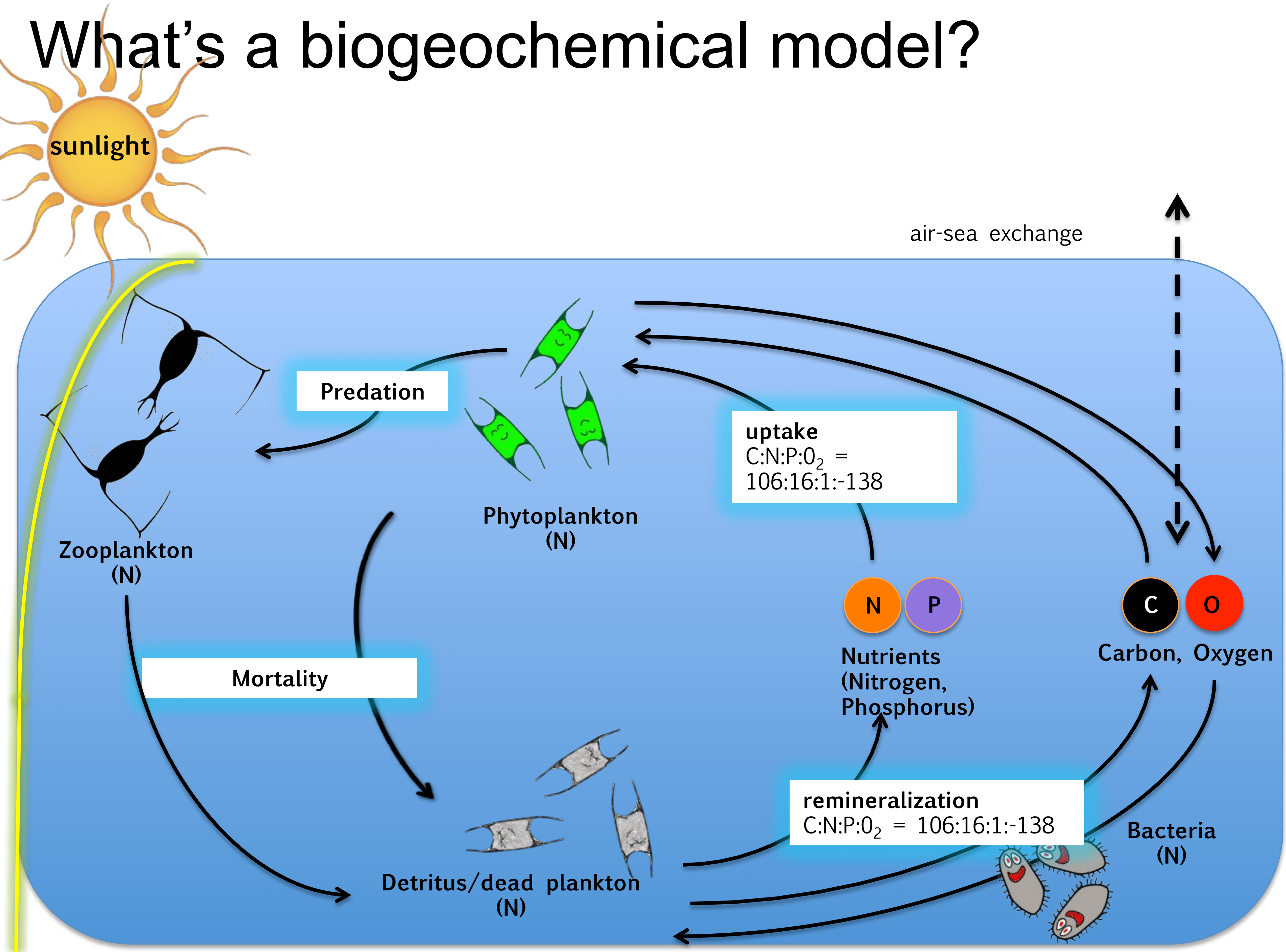
What’s a biogeochemical model?



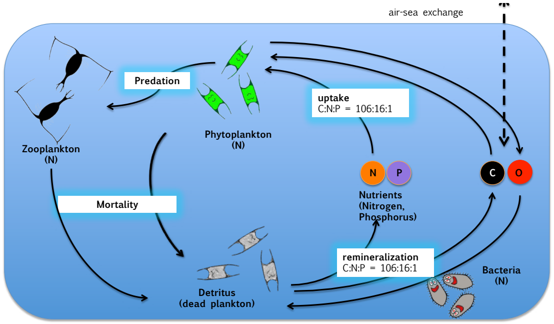
What's a biogeochemical model?



What's a biogeochemical model?



Biogeochemical modelling



Biogeochemical models

- model the cycling of material between organic and inorganic forms

- contain from 1 to up to more than 100 state variables that all have their own sources/sinks (**F**)

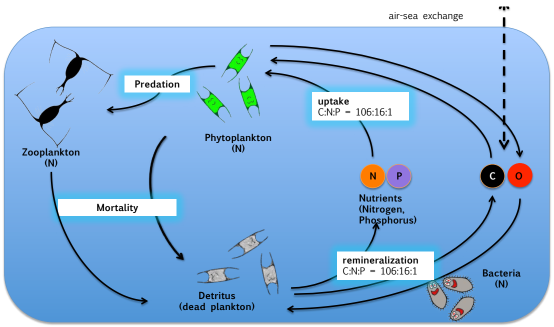
- Sources/sinks (**F**):
  - Internal (material stays in the system): mortality, predation, remineralization, uptake, primary production
  - External (material leaves/enters the system): sedimentation/burial, terrestrial input, air-sea exchange

Biogeochemical modelling

- Biogeochemical models can be coupled to ocean circulation models.

- State variables are treated as tracers (C):

$$\frac{\partial C}{\partial t} = -\mathbf{u} \cdot \nabla C + \nabla_h (K_h \nabla_h) C + \frac{\partial}{\partial z}\left(K_z \frac{\partial C}{\partial z}\right) + F$$



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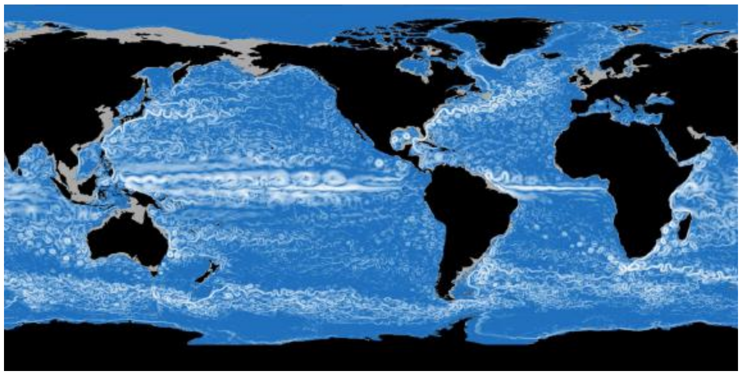

nemo-ocean.eu

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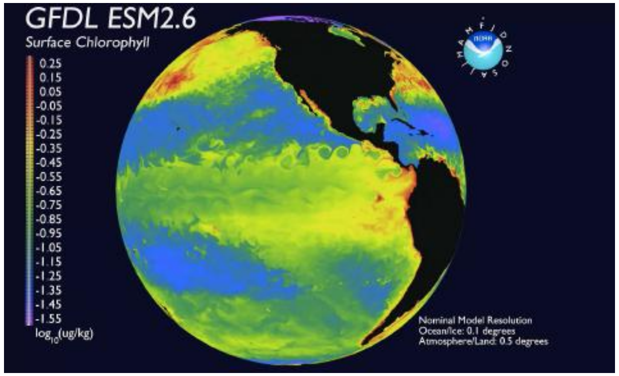
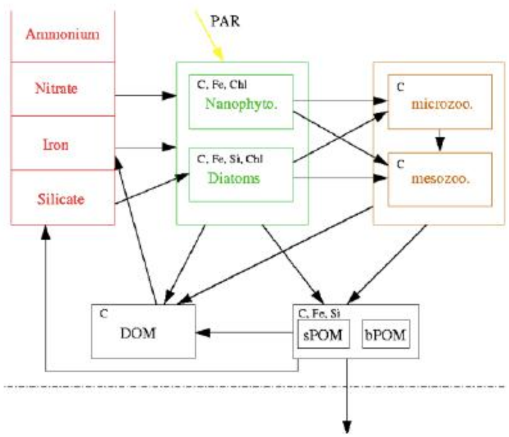


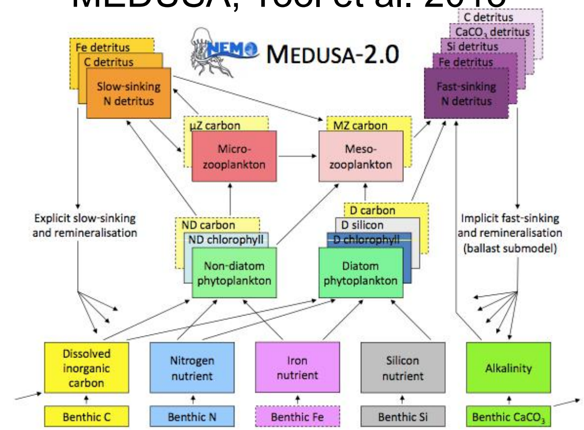
Biogeochemical modelling

Examples of biogeochemical models in CMIP

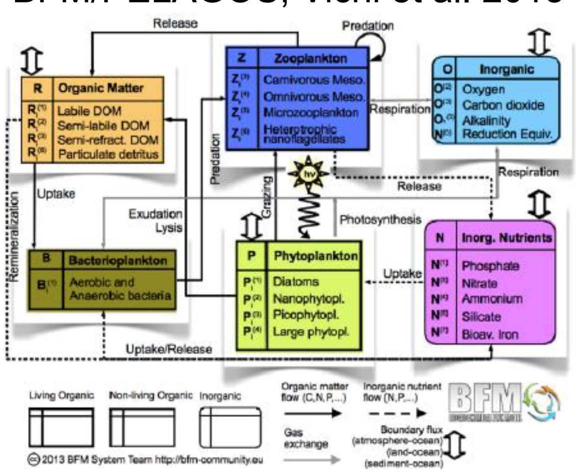
PISCES, Aumont et al. 2015



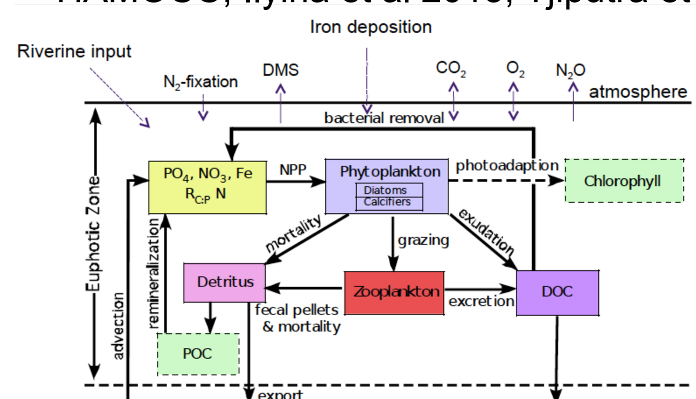
MEDUSA, Yool et al. 2013



BFM/PELAGOS, Vichi et al. 2015

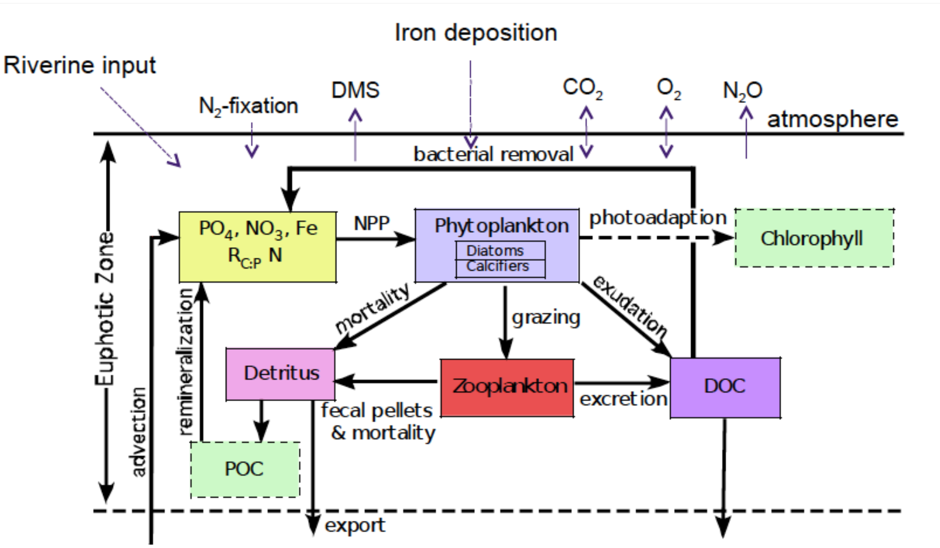


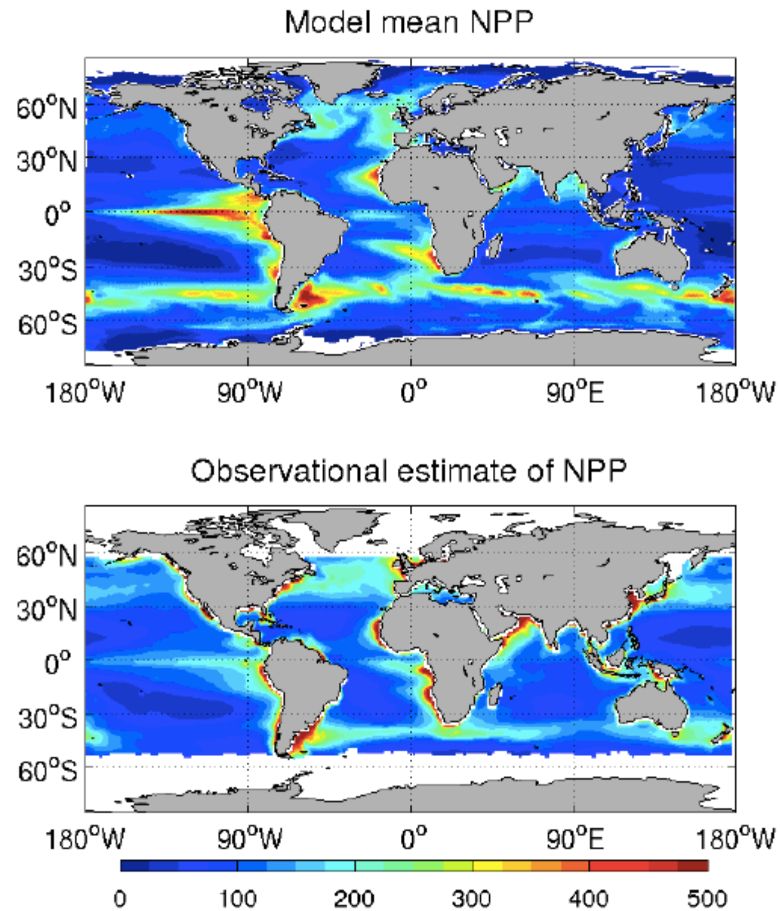
HAMOCC, Ilyina et al 2013, Tjiputra et al. 2013



Biogeochemical modelling

HAMOCC in NorESM (Tjiputra et al. 2013)





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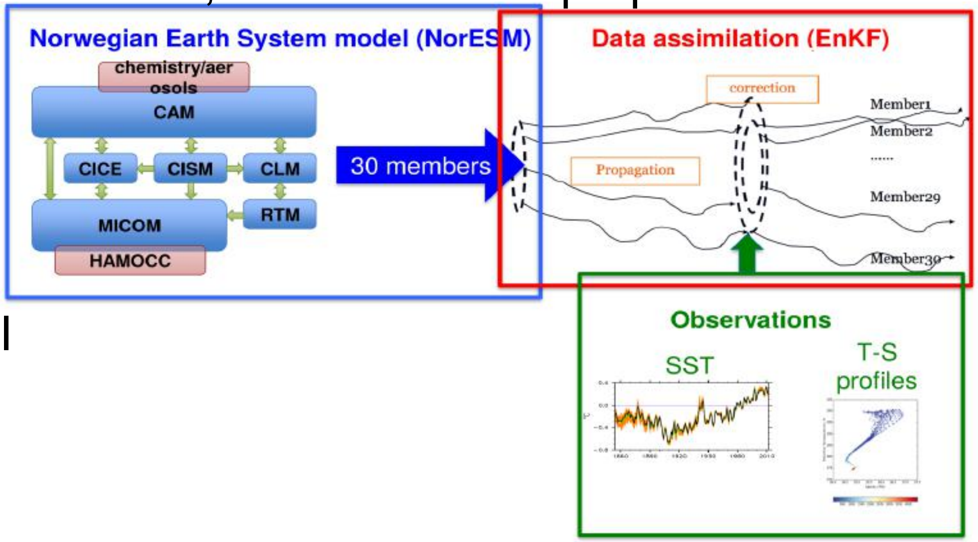
Biogeochemical predictions

What is a climate prediction model?

Climate prediction models
- Earth system model
    - Dynamic atmosphere
    - Land model
    - Sea ice model
    - Ocean circulation model
    - Ocean biogeochemical model
- Possibility to assimilate observational data

NorCPM, Bethke et al. in preparation



Biogeochemical predictions

Predictions involves two types of simulations:

- Assimilation runs (Reanalyses): observational data is assimilated into the model to nudge the climate/ocean state as close to the "truth" as possible. These are later used as initial conditions for predictions.

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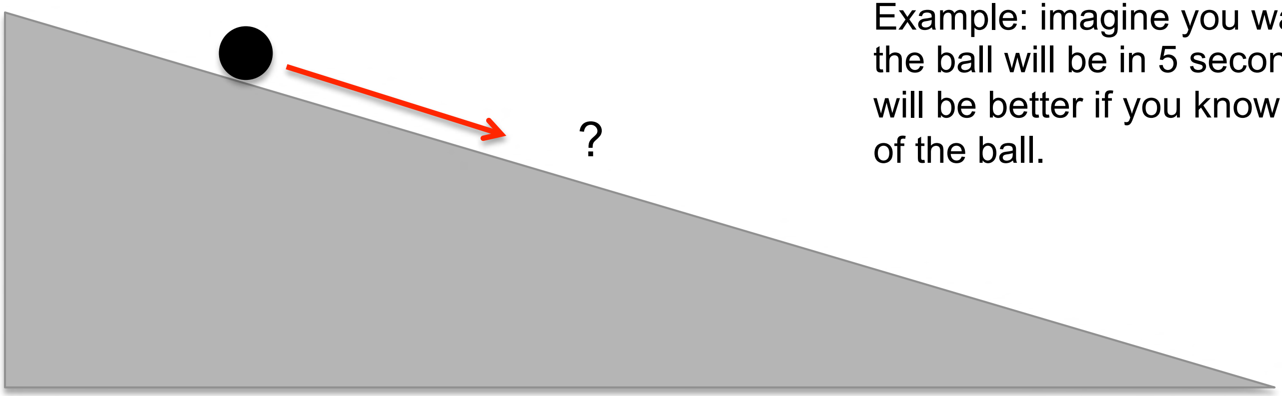

Example: imagine you want to predict where the ball will be in 5 seconds. The prediction will be better if you know the initial position of the ball.

Biogeochemical predictions

Predictions involves two types of simulations:

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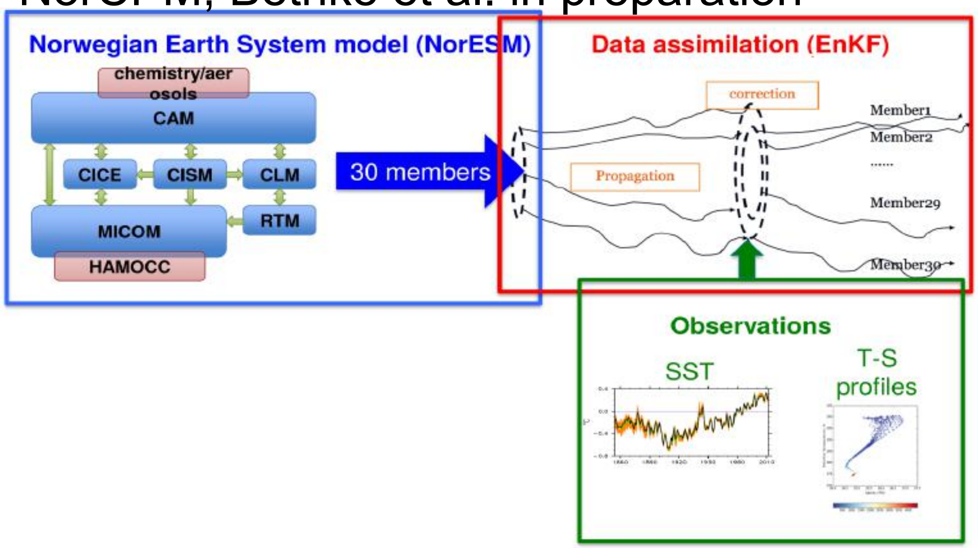
Commonly assimilated variables include SST and temperature and salinity profiles.

NorCPM, Bethke et al. in preparation



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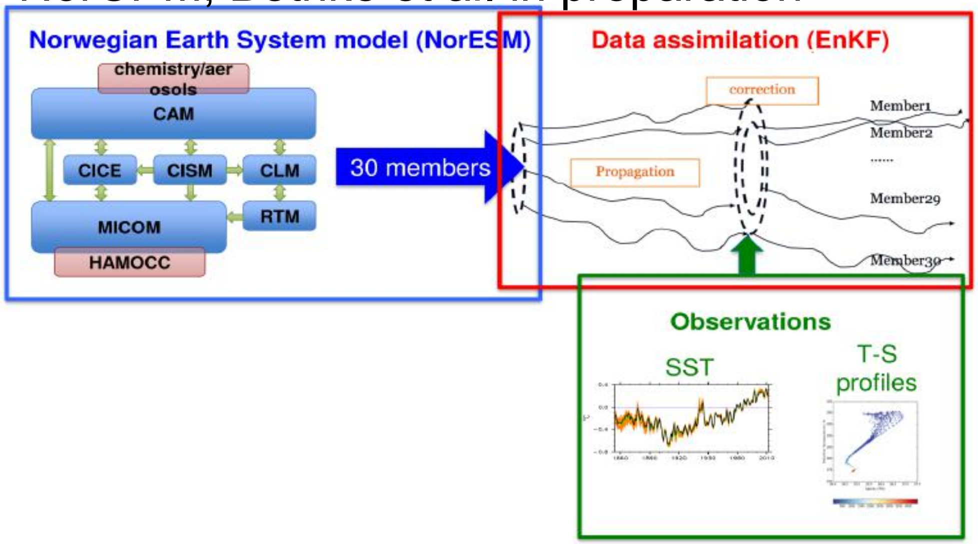
NorCPM, Bethke et al. in preparation



Commonly assimilated variables include SST and temperature and salinity profiles.

Until now no climate prediction model includes assimilation of biogeochemical tracers. Does this matter?

Biogeochemical predictions

Do the BGC initial conditions matter?

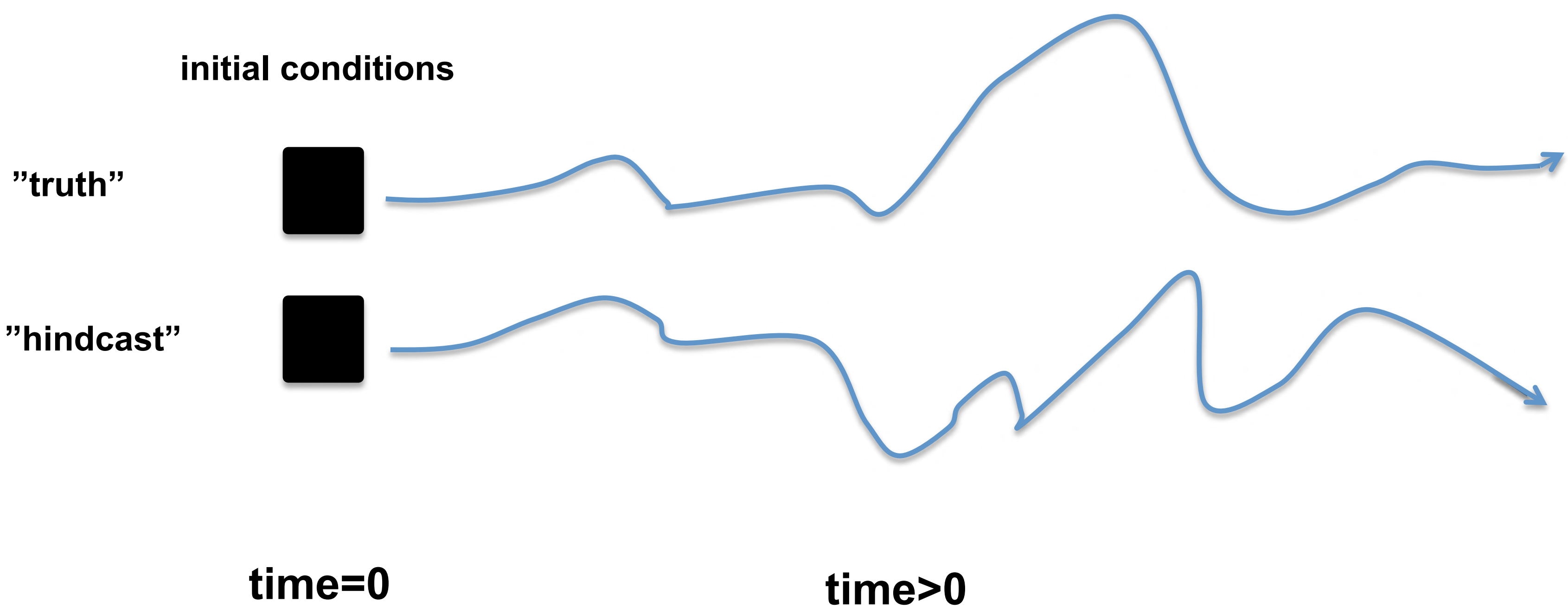
Fransner et al., in revision

Biogeochemical predictions

Do the BGC initial conditions matter?

Experiment in a perfect model framework

- how well can the model predict itself?



Fransner et al., in revision

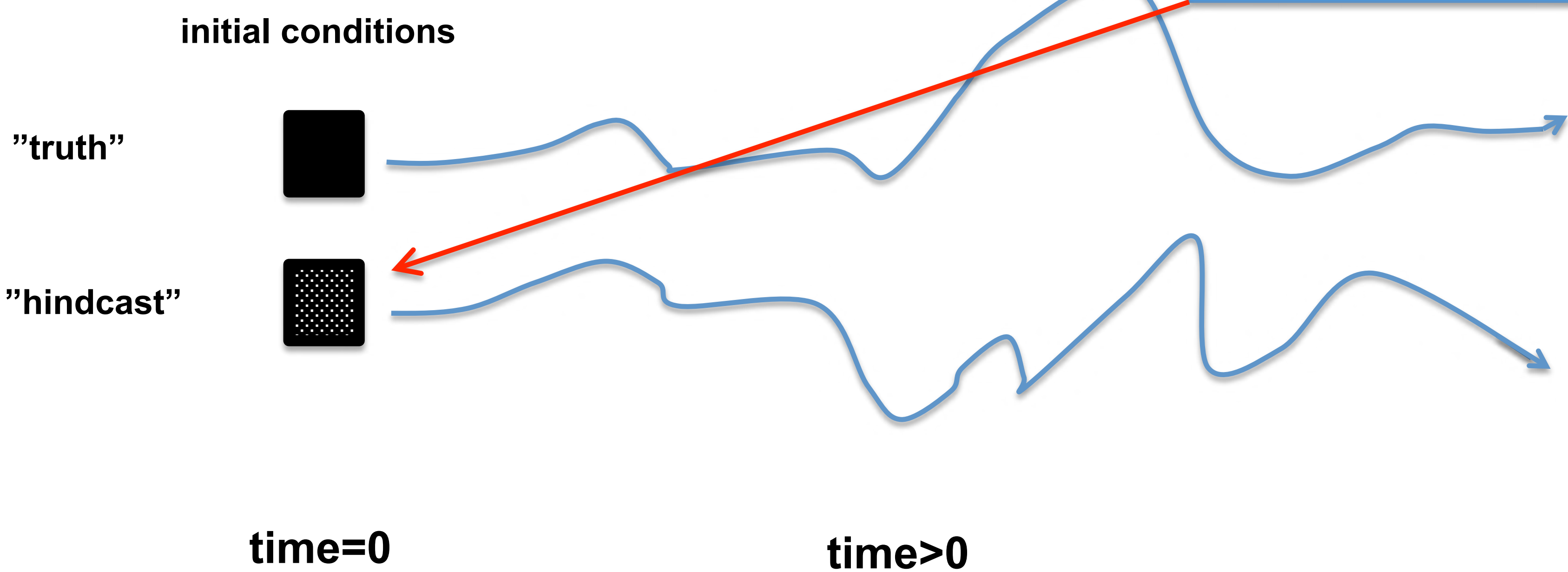
Biogeochemical predictions

Do the BGC initial conditions matter?

Experiment in a perfect model framework

- how well can the model predict itself?

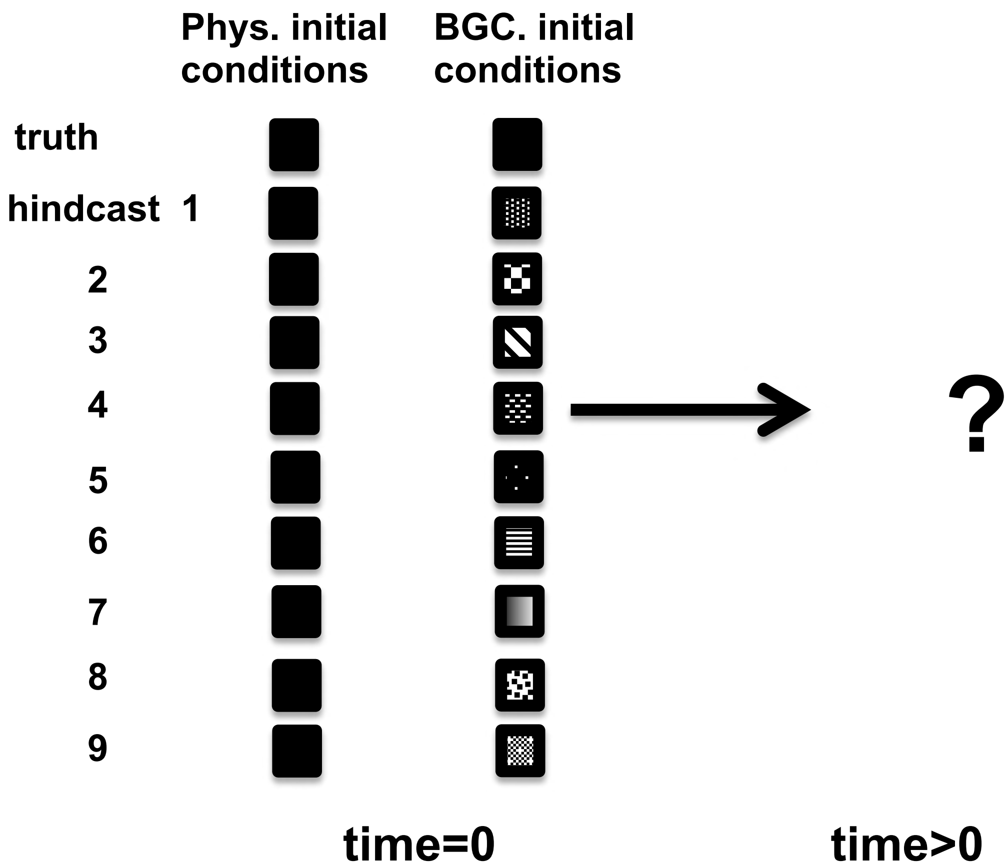
initial conditions are perturbed to mimic the fact that we do not know the true state of the ocean



Fransner et al., in revision

Biogeochemical predictions

Do the BGC initial conditions matter?



Perfect model experiment:

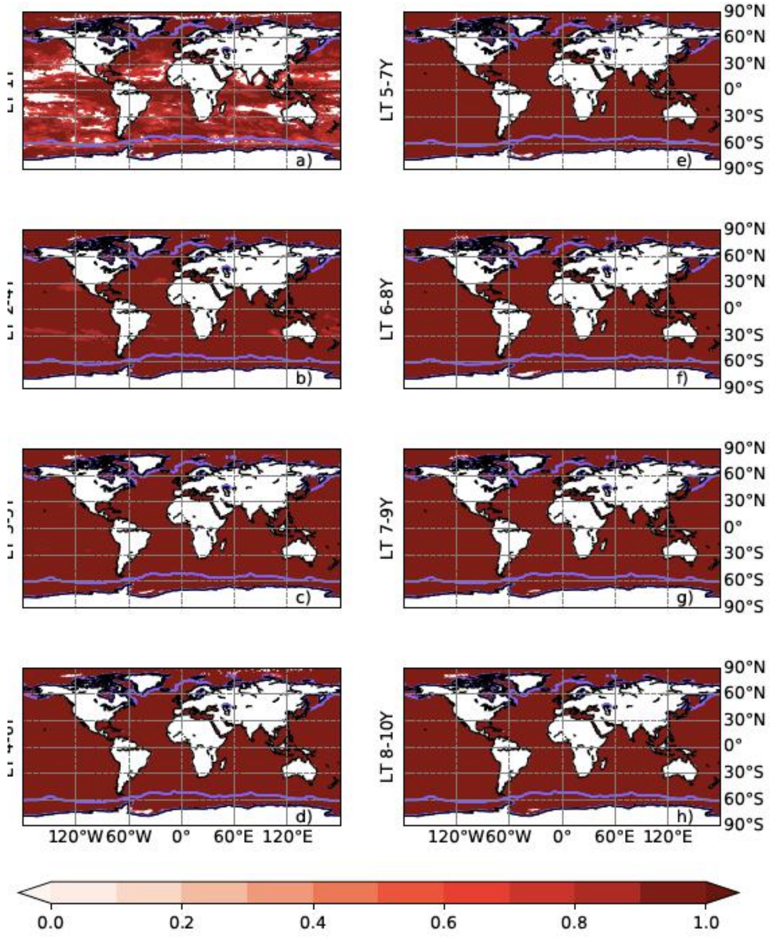
- An ensemble with 10 members
- Member 1=truth
- Members 2-10 = hindcasts
- Identical physical initial conditions
- BGC initial conditions with perturbations

Fransner et al., in revision

Biogeochemical predictions

Do the BGC initial conditions matter?

- Biogeochemical initial conditions are only important for the first lead year.
- A good knowledge of the initial state of the ocean physics is sufficient for skillfull BGC predictions (assimilation of BGC observations not needed)



Fransner et al., in revision

Biogeochemical predictions

Predictions involves two types of simulations:

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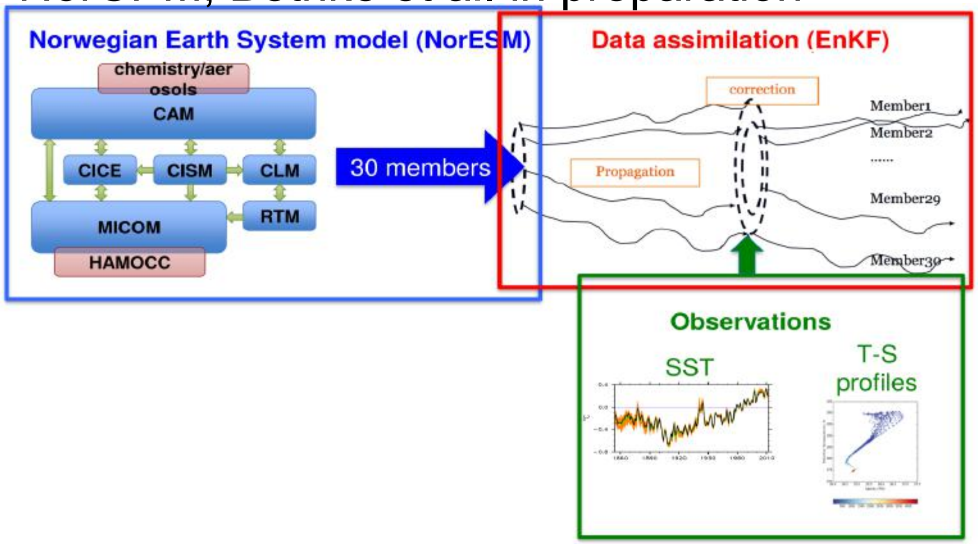
NorCPM, Bethke et al. in preparation



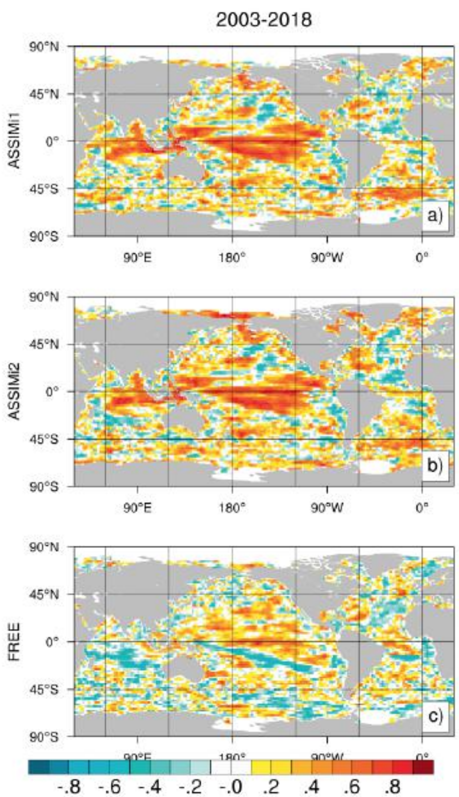
Commonly assimilated variables include SST and temperature and salinity profiles.

Until now no climate prediction model includes assimilation of biogeochemical tracers. Does this matter? - Not for interannual to decadal predictions.

Biogeochemical predictions

Predictions involves two types of simulations:

- Assimilation runs (Reanalyses): observational data is assimilated into the model to nudge the climate/ocean state as close to the "truth" as possible. These are later used as initial conditions for predictions.



Assimilation run 1

Assimilation run 2

FREE (historical) run
- no data assimilation

Anomaly correlation between modelled NPP and observed NPP (annual means).

In NorCPM, assimilation of SST and T & S profiles improves the representation of annual mean primary production especially in the tropical Pacific and Indian Oceans.

Bethke et al. in preparation

Biogeochemical predictions

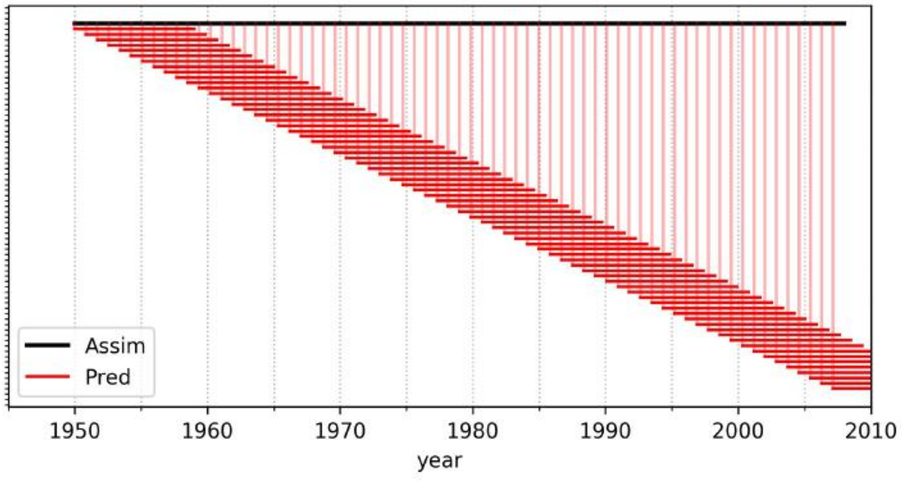
Predictions involves two types of simulations:

- Assimilation runs (Reanalyses)
- Prediction runs: The model is launched, using output from the assimilation run as initial conditions, and runs freely with only external forcing (i.e. anthropogenic and volcanic).

Biogeochemical predictions

Predictions involves two types of simulations:

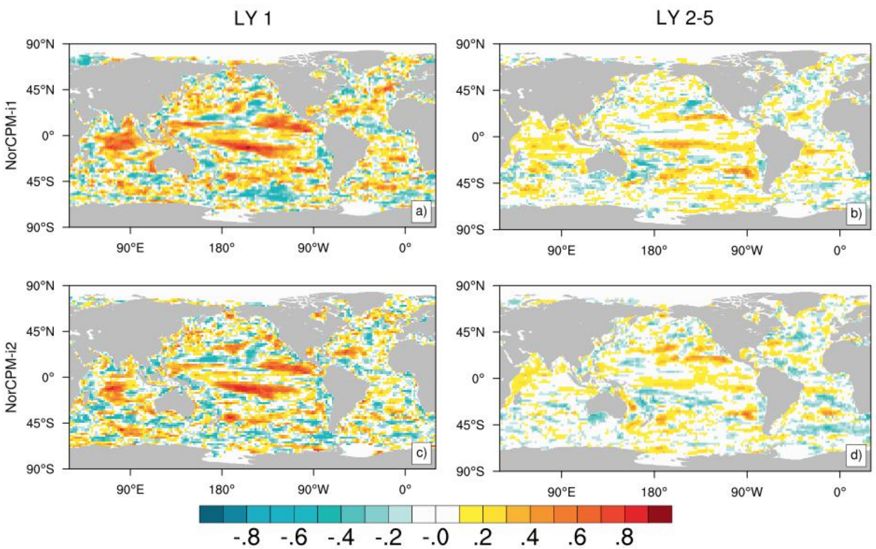
- Assimilation runs (Reanalyses)
- Prediction runs: The model is launched, using output from the assimilation run as initial conditions, and runs freely with only external forcing (i.e. anthropogenic and volcanic).
  - Seasonal predictions – 1 year long runs, staring every 3rd month
  - Decadal predictions – 10 year long runs, starting every year



Biogeochemical predictions

Predictability of NPP

Bethke et al. in preparation



Anomaly correlation between modelled NPP and observed NPP (annual means).

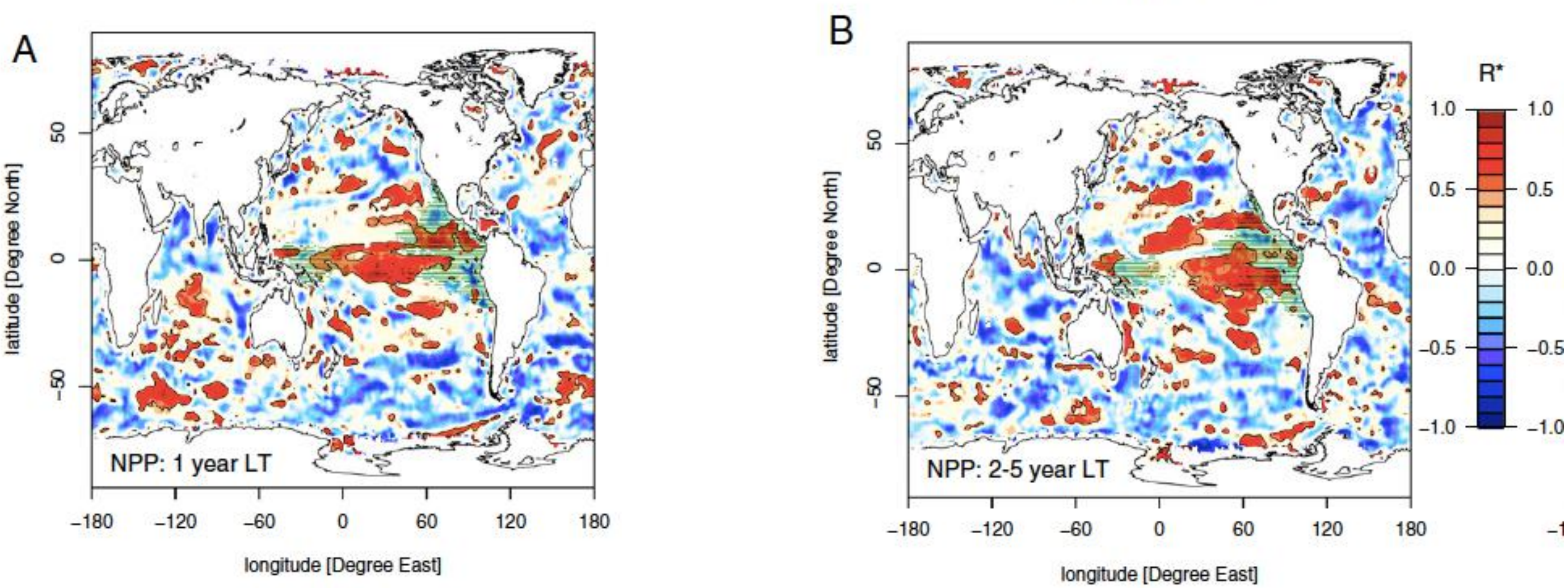
Decadal predictions/hindcasts: NorCPM shows predictive skill of primary production one year after the initialization of the hindcasts in the tropical Pacific and Indian Oceans.

Biogeochemical predictions

Predictability of NPP

Predictability of NPP in the tropical Pacific Ocean was also found by Seferian et al. 2014.

- Initial conditions from reanalyzes with assimilated SST
- Comparison with NPP calculated based on satellite chlorophyll data
- Predictive skill of net primary production of up to 2-5 years



Biogeochemical predictions

Can they be extended into ecosystems?

Biogeochemical predictions

Can they be extended into ecosystems?

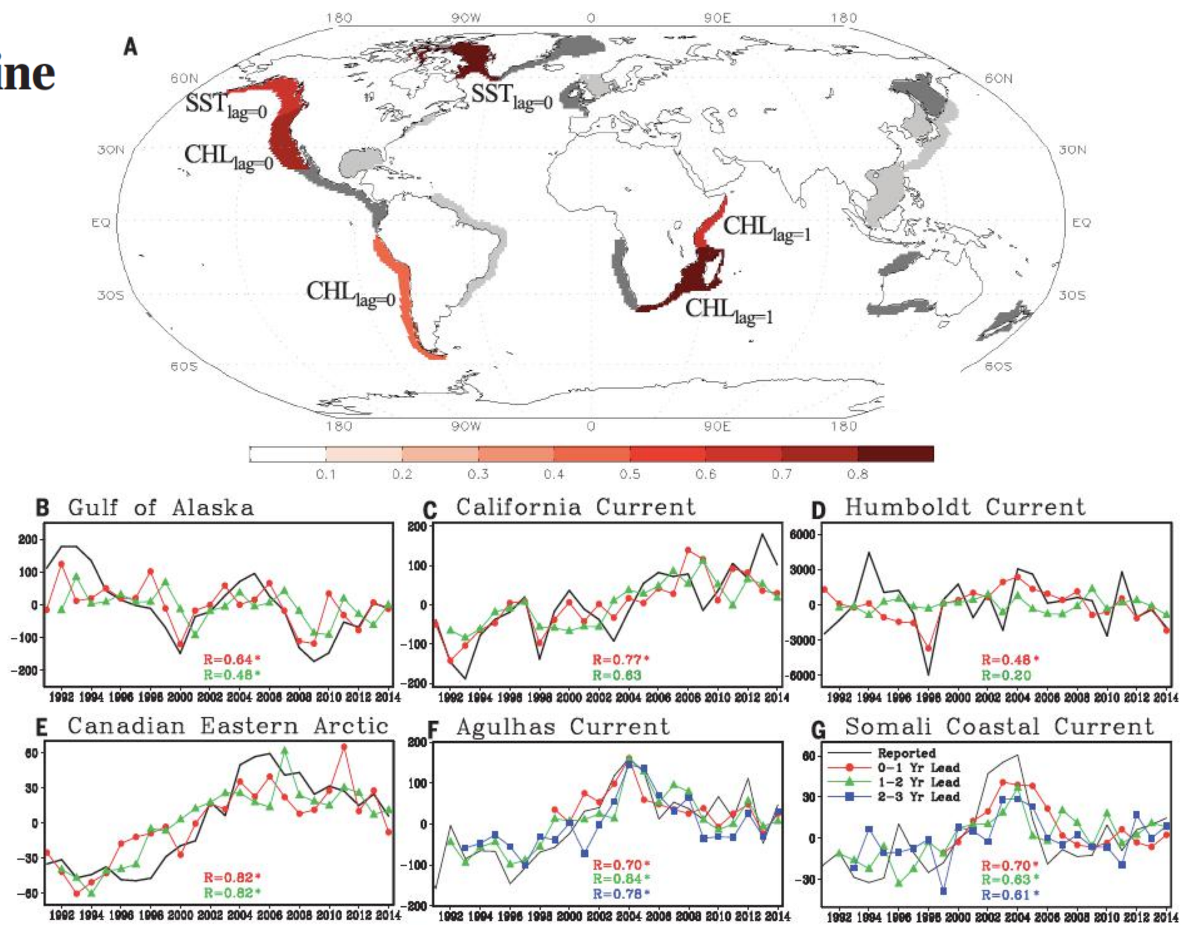
RESEARCH

MARINE MANAGEMENT

Seasonal to multiannual marine ecosystem prediction with a global Earth system model

Jong-Yeon Park[1,2,3]*†, Charles A. Stock[2]†, John P. Dunne[2], Xiaosong Yang[2], Anthony Rosati[2]

Park et al. 2019



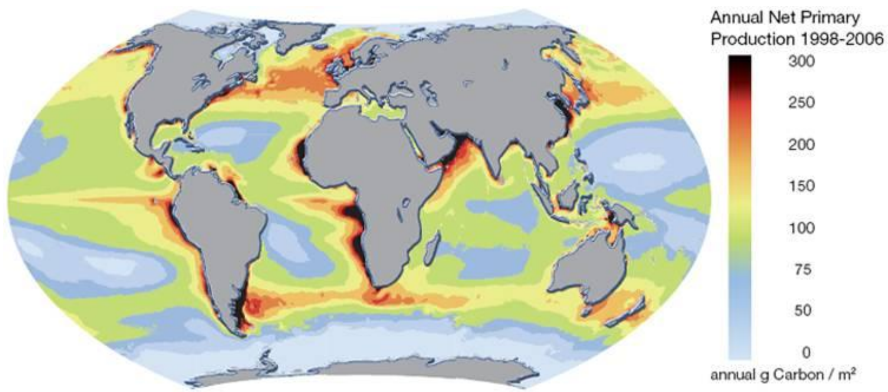
Skillfull prediction of fish catches 2-5 years ahead by using SST and chlorophyll output from decadal prediction runs.

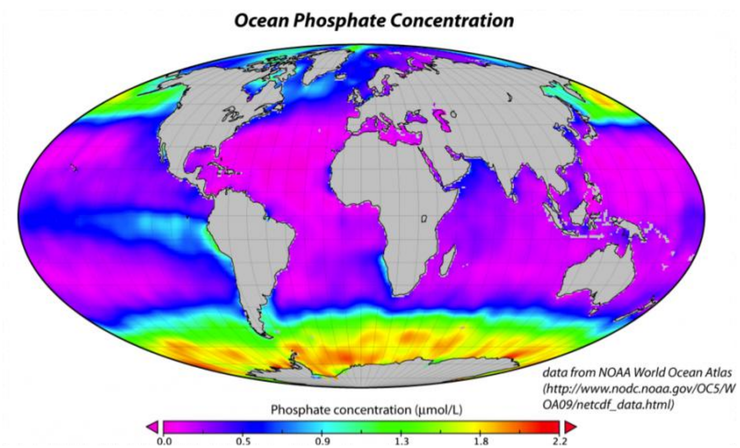
Thank you!

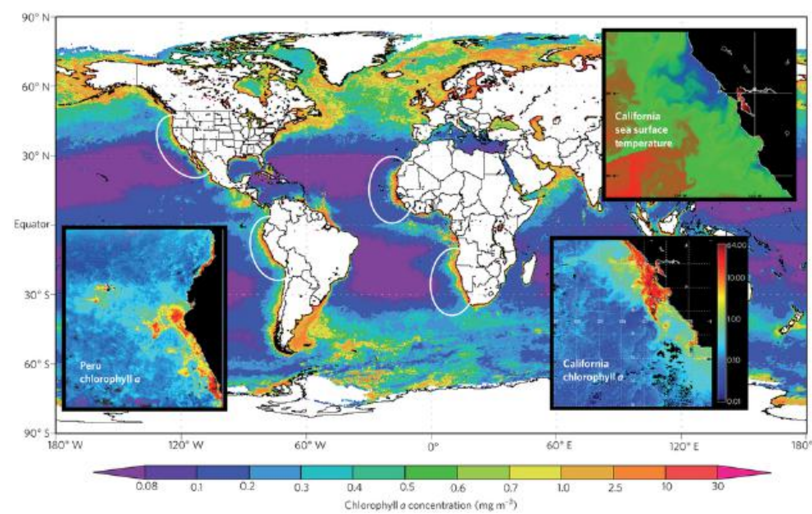
Ocean primary production -controlling factors: nutrients

Examples of processes influencing vertical exchange

- Coastal upwelling
- Equatorial upwelling
- Convective overturning/ Winter convection (seasonally stratified oceans)
- Rossby waves





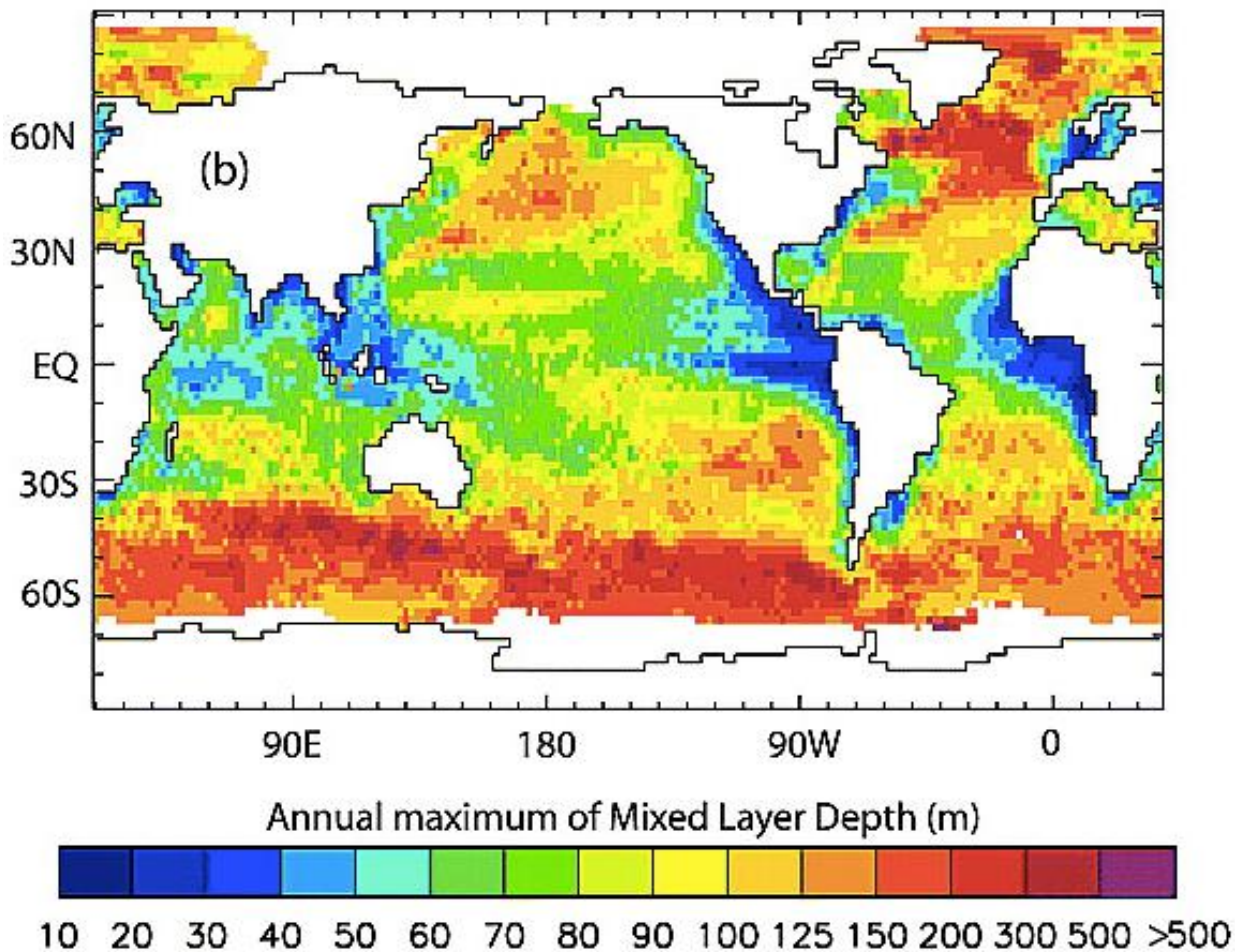


Bralower and Bice, https://www.e-education.psu.edu/

Extra slides

$$106CO_2+16NO_3^{-}+HPO_4^{2-}+122H_2O+18H^{+}$$
$$\longrightarrow (CH_2O)_{106}(NH_3)_{16}H_3PO_4+138O_2$$

$$(CH_2O)_{106}(NH_3)_{16}H_3PO_4+138O_2 \longrightarrow$$
$$106CO_2+16NO_3^{-}+HPO_4^{2-}+122H_2O+18H^{+}$$



de Boyer Montégut et al 2004

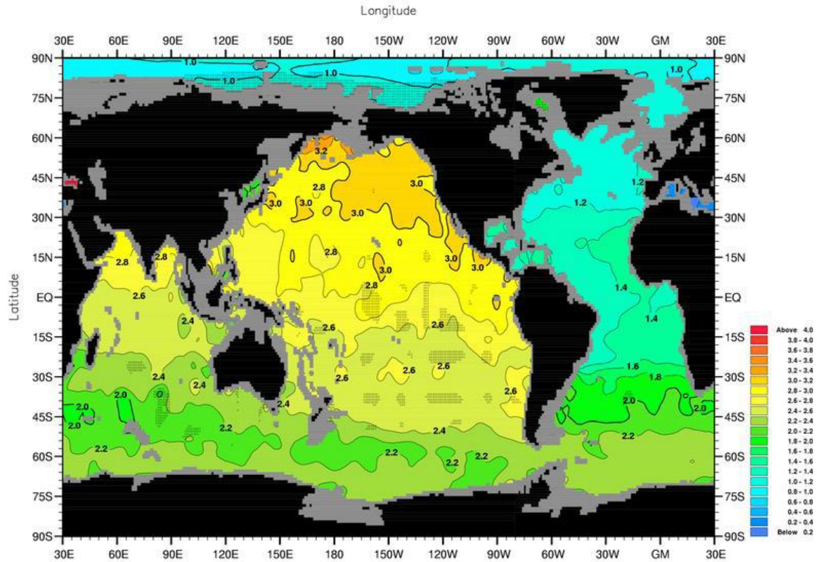


Fig. A2-26. Annual mean phosphate (μM) at 2000 m. depth.
Minimum Value= 0.11 Maximum Value= 4.50 Contour Interval: 0.20

World Ocean Atlas 2001
Ocean Climate Laboratory/NODC

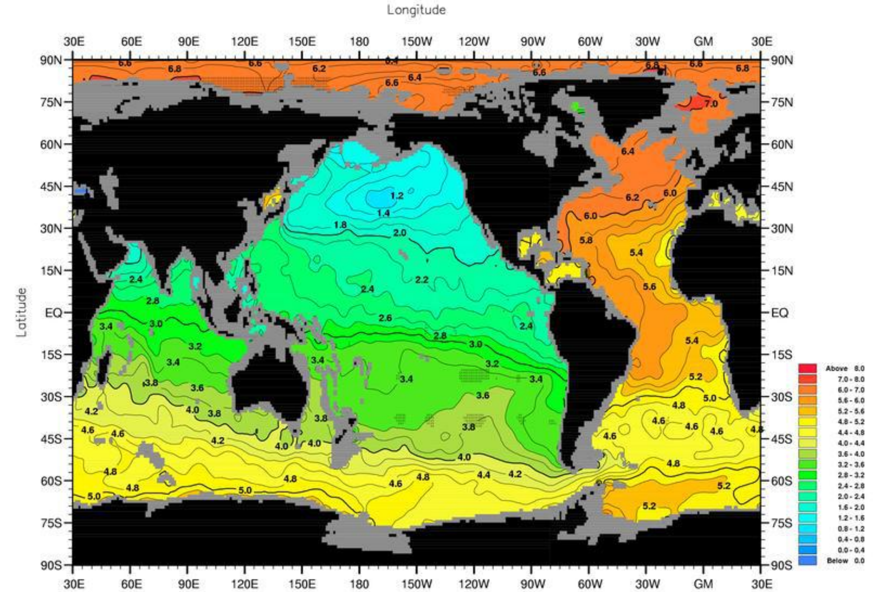
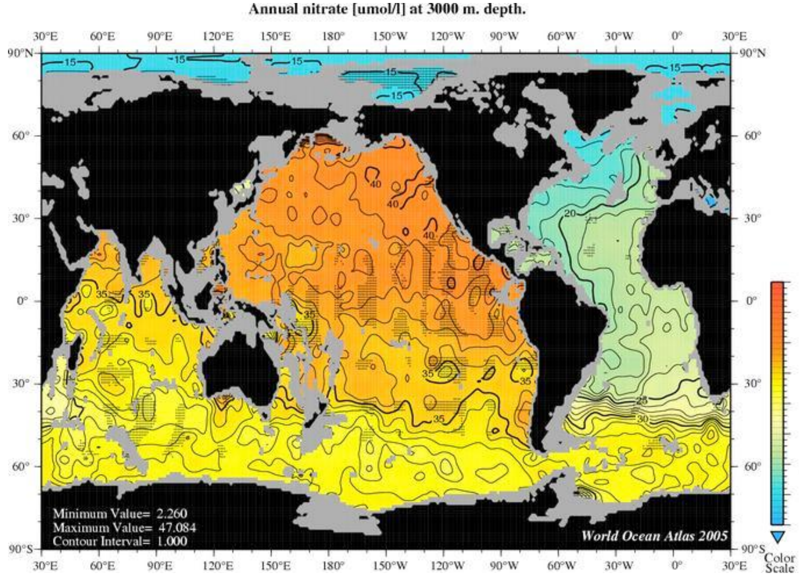
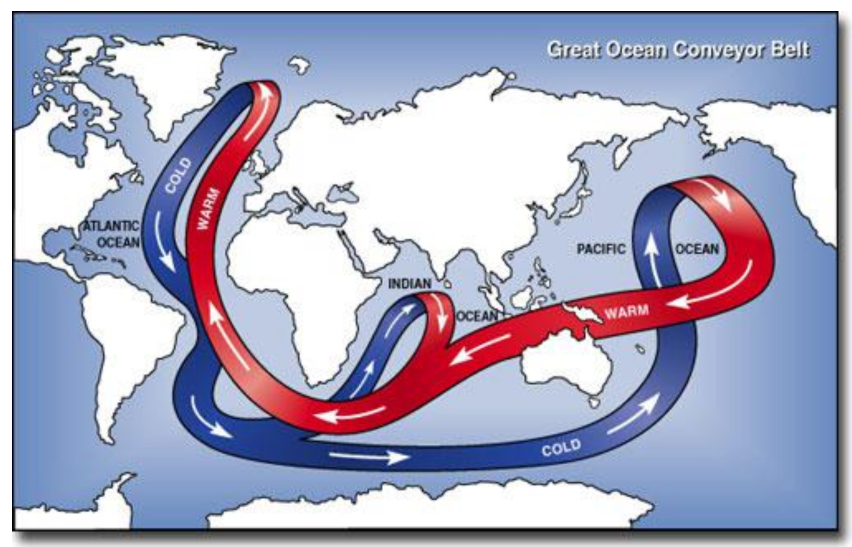


Fig. A2-26. Annual mean oxygen (ml/l) at 2000 m. depth.
Minimum Value= 0.00 Maximum Value= 7.16 Contour Interval: 0.20

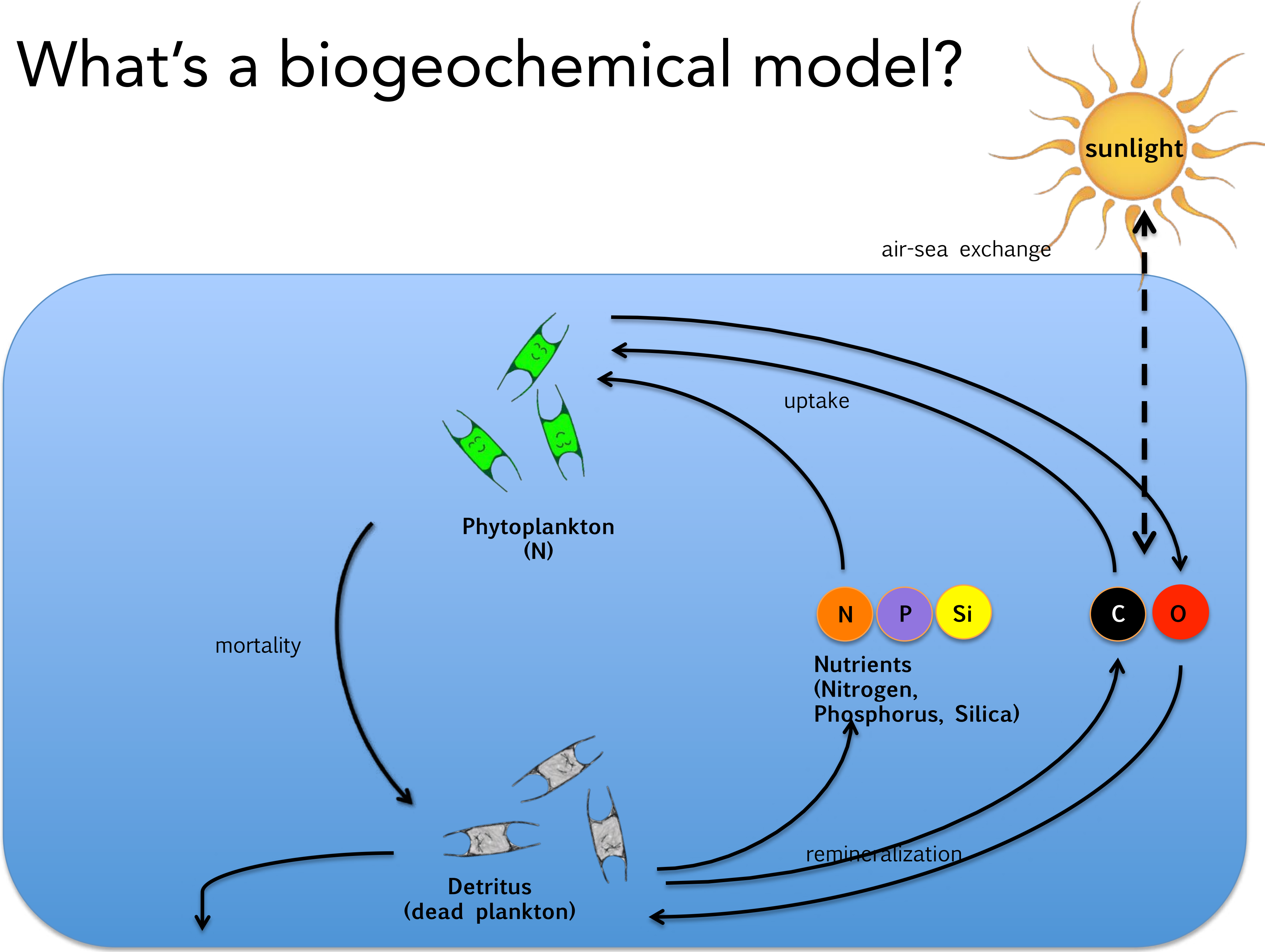
World Ocean Atlas 2001
Ocean Climate Laboratory/NODC

Annual nitrate [umol/l] at 3000 m. depth.





What's a biogeochemical model?



Ocean primary production -controlling factors: nutrients

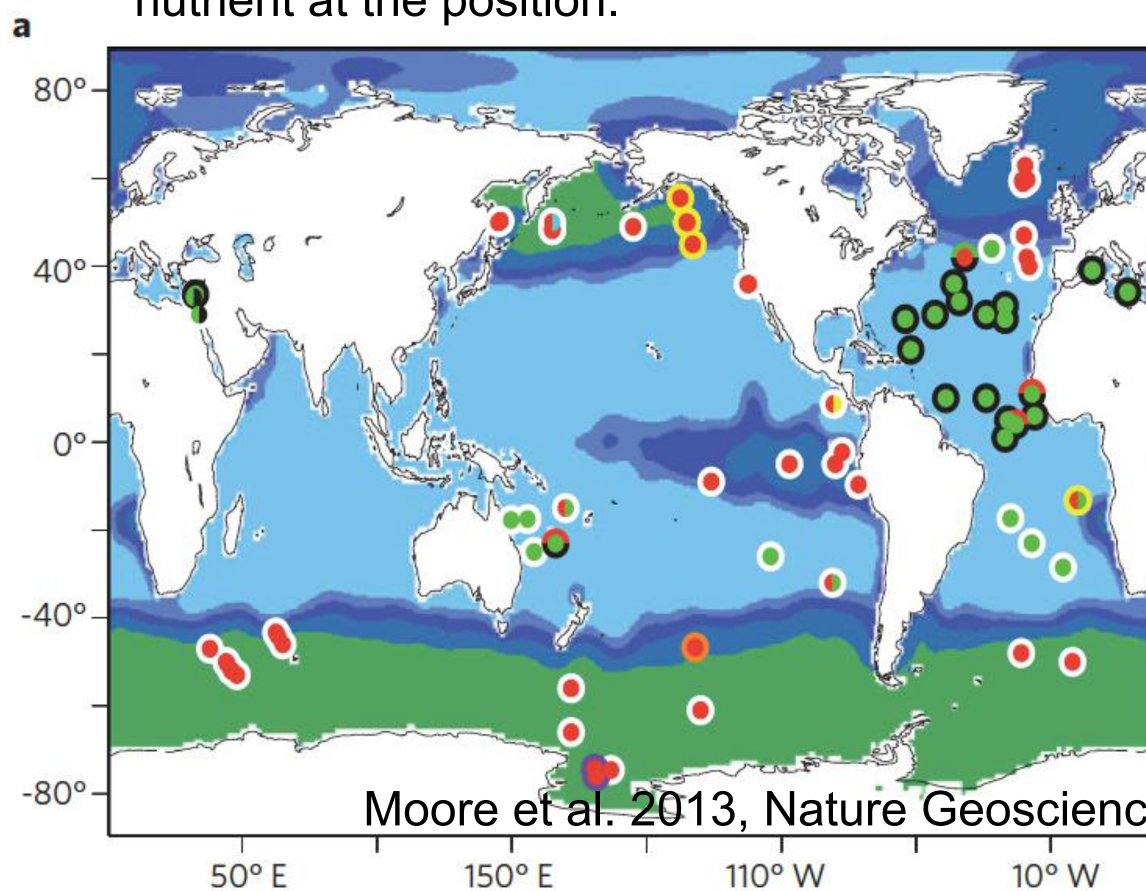
Macronutrients: (Needed in larger quantities, often limiting the growth of phytoplankton)

- Nitrogen (N)
- Phosphorus (P)
- Silicon (Si)

Micronutrients: (Essential but only in small quantities)

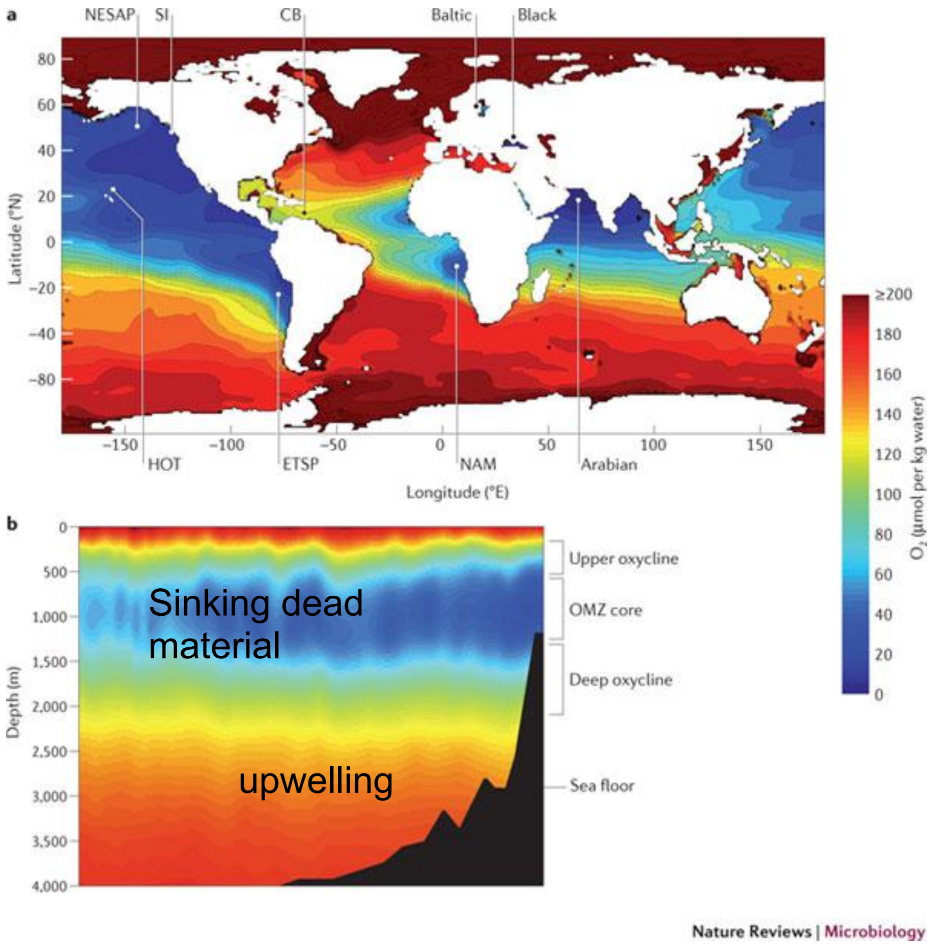
- Iron (Fe)
- Copper (Cu)
- Zink (Zn)
- …

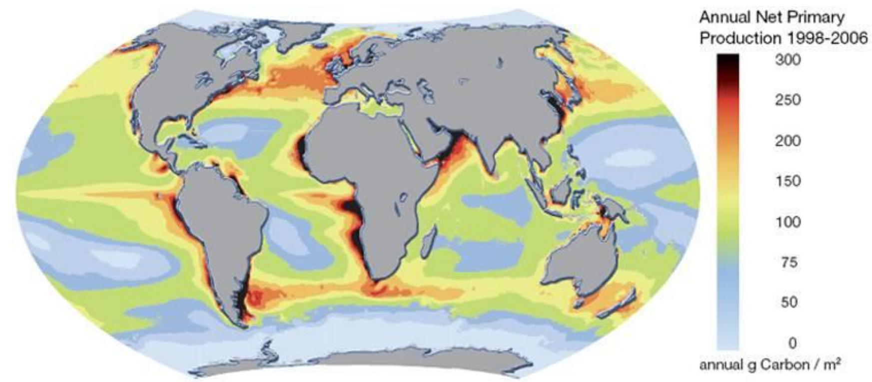
Colors of filled circles show the major limiting nutrient at the position.



Moore et al. 2013, Nature Geoscience

Oxygen minimum zones





Jody J. Wright, Kishori M. Konwar & Steven J. Hallam, Nature Reviews Microbiology 10, 381-394 (June 2012)

Ocean primary production
-controlling factors: temperature?

- Temperature is generally not considered to be a limiting factor for primary production (there are for example phytoplankton blooms under sea ice).

- Metabolic rates (for example primary production and respiration) are consider to be temperature−dependent, with higher rates related to higher temperatures.

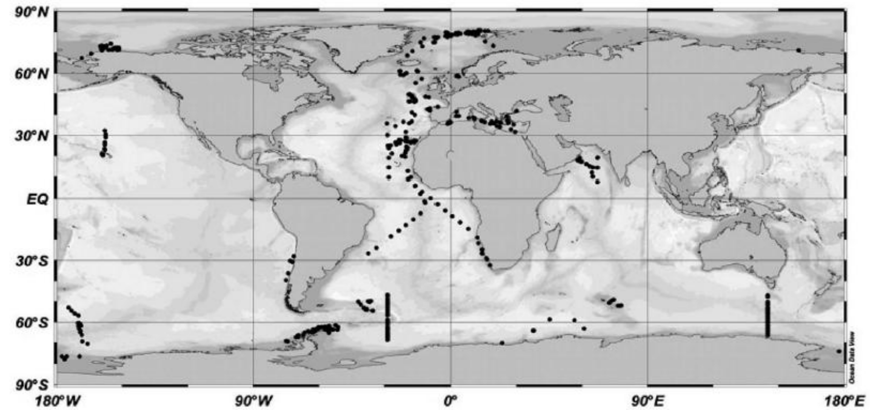
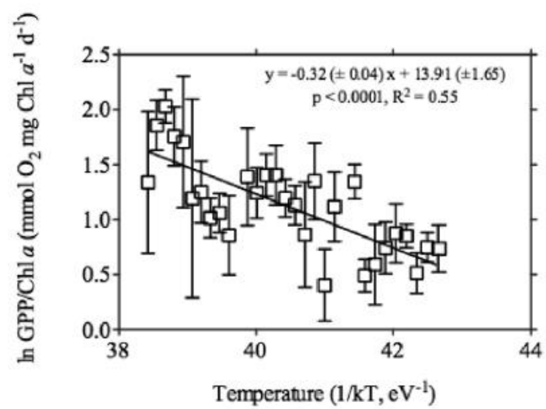


Figure 1. Map showing the locations in the data set (Table 1) containing records of plankton metabolic rates, water temperature and chlorophyll a concentration (Table 1).



Regaudie-de-Gioux and Duarte 2012