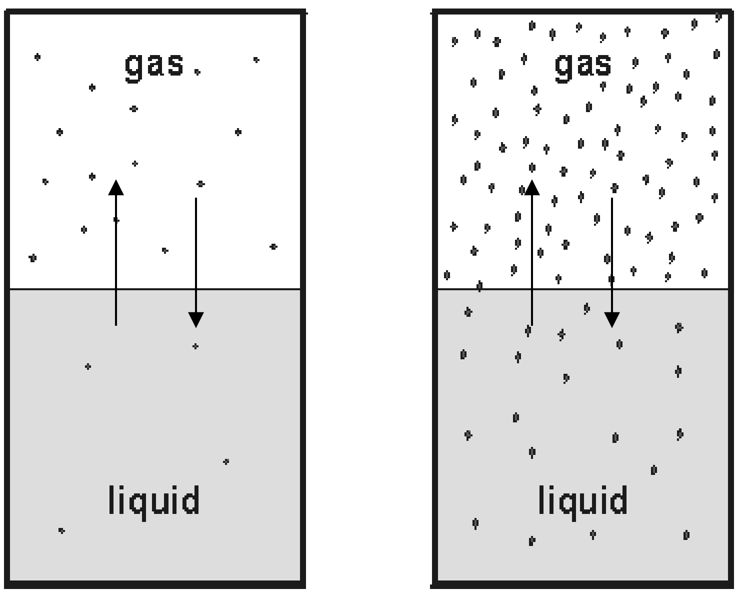
Carbon cycle theme

- The Earth's carbon cycle has a stabilizing mechanism against sudden addition of CO_2 to the atmosphere
  - About 50% of carbon emission is absorbed into land and ocean surfaces
  - Climate warming would be twice as severe if there were no such carbon sink
  - Ocean carbon uptake is helpful but it comes with certain consequences: ocean acidification

Henry's Law



Low Gas Pressure *High Gas Pressure*

At equilibrium:
$[CO_2]_{ocean} = K_0 \times pCO_2^{atm}$

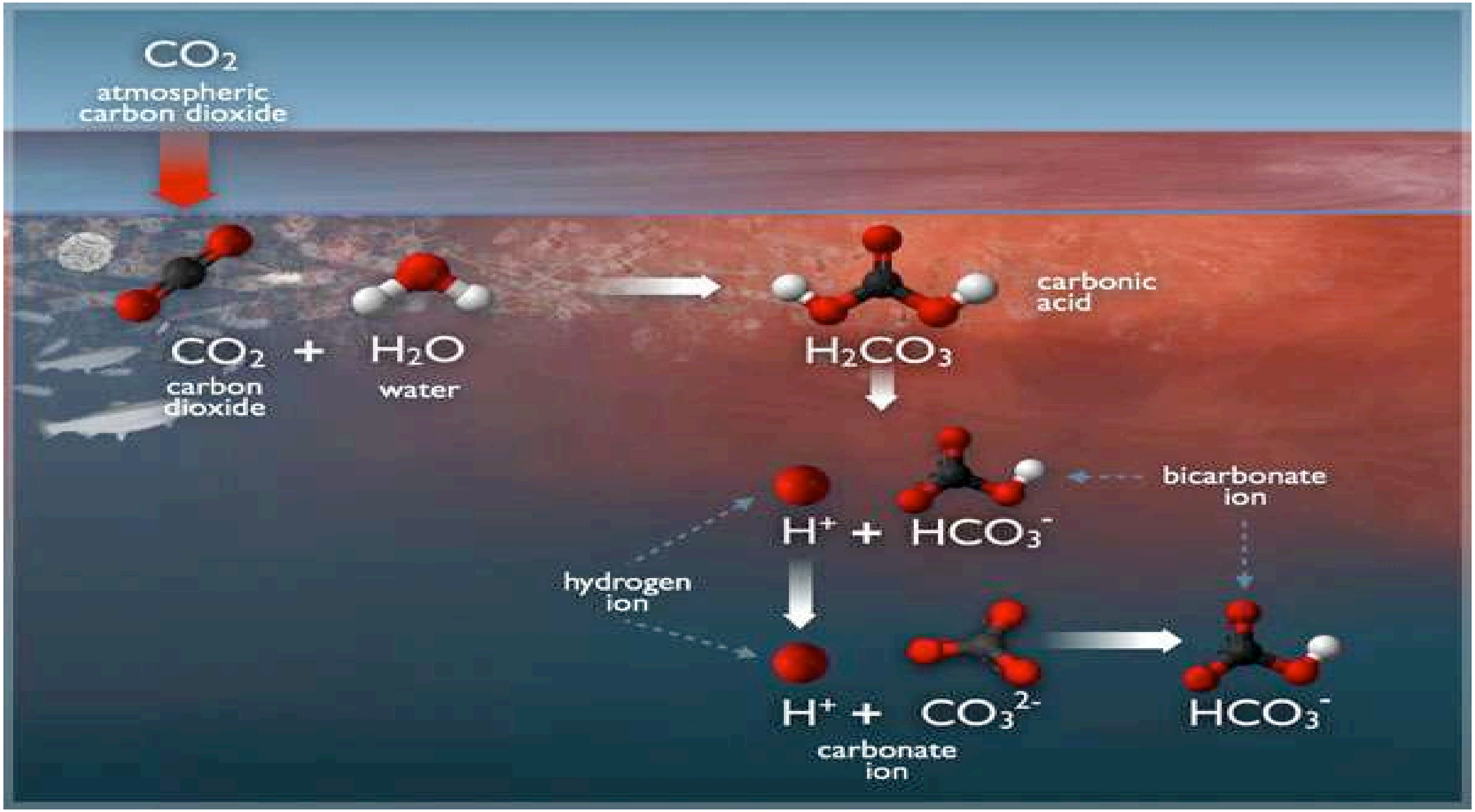
Where K_0 the solubility constant for CO_2 and increases with decreasing temperature and salinity

Define:
$pCO_2^{oce} = [CO_2]_{ocean} / K_0$

At equilibrium:
$pCO_2^{oce} = pCO_2^{atm}$

If $pCO_2^{oce} < pCO_2^{atm}$, net transfer of CO_2 into ocean
If $pCO_2^{oce} > pCO_2^{atm}$, net transfer of CO_2 out of ocean

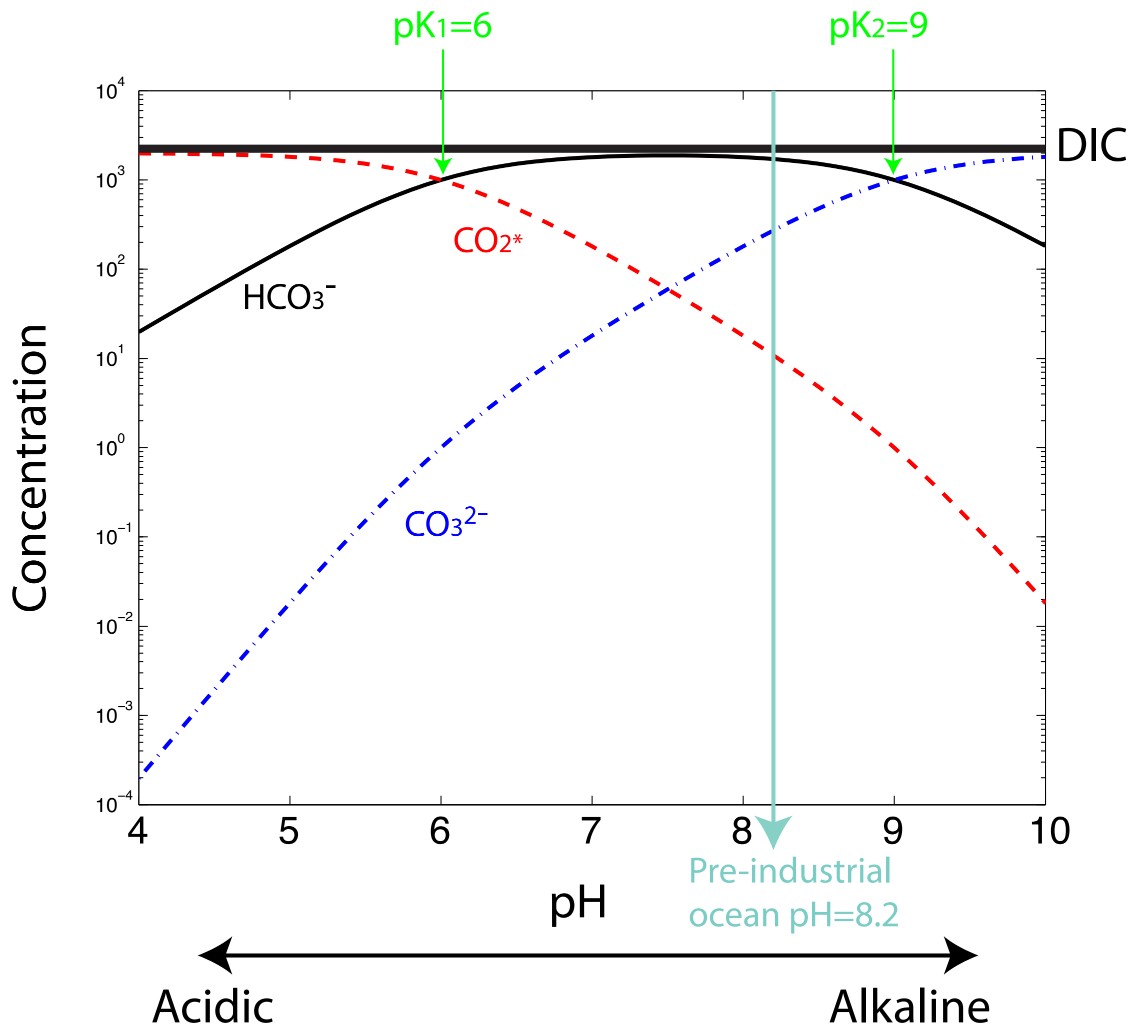
Ocean carbon cycle (2)



$CO_2 + CO_3^{2-} + H_2O \longrightarrow 2HCO_3^{-}$

Carbonate chemistry

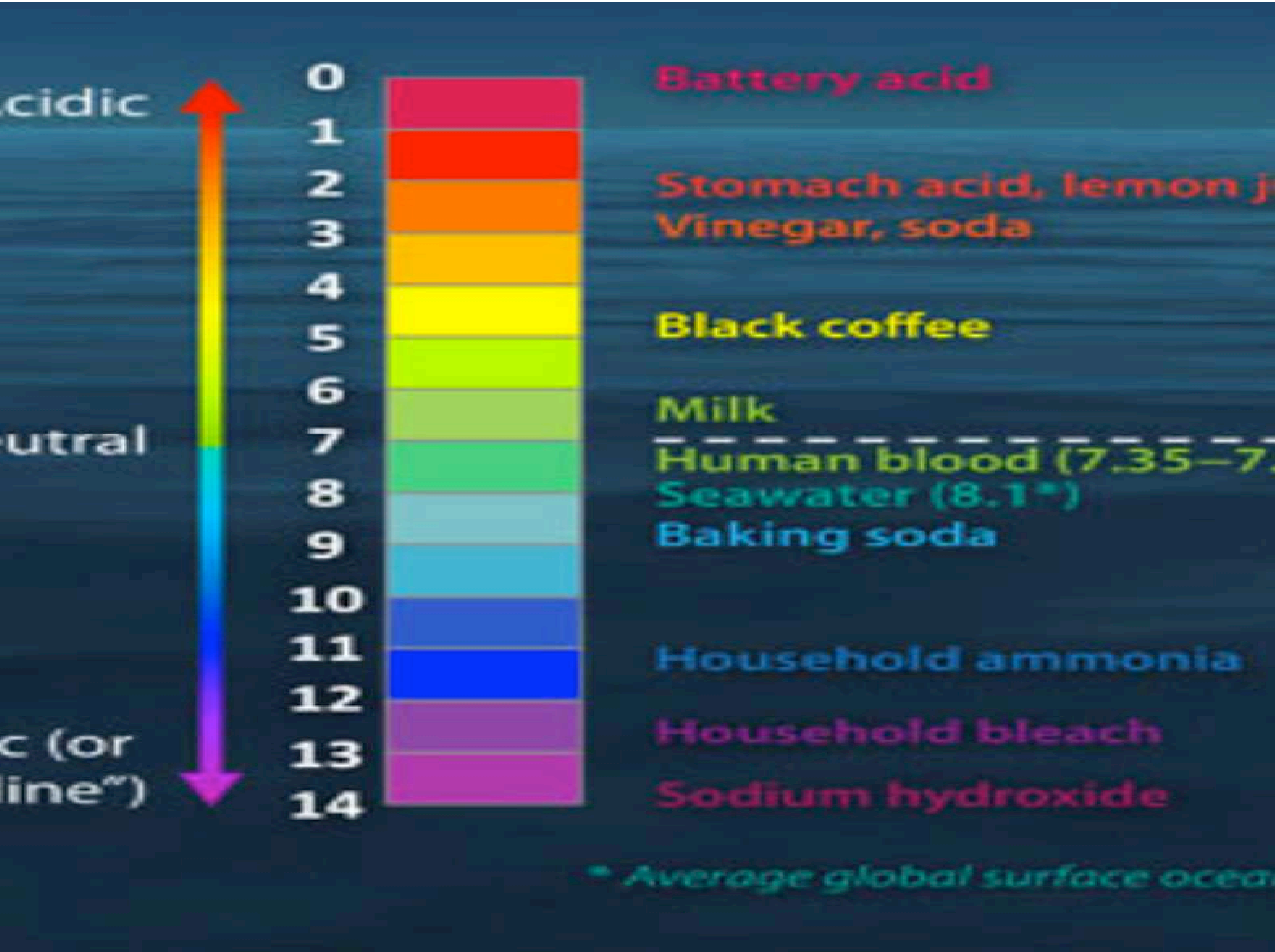
- $DIC = [CO_2^*] + [HCO_3^-] + [CO_3^{2-}]$



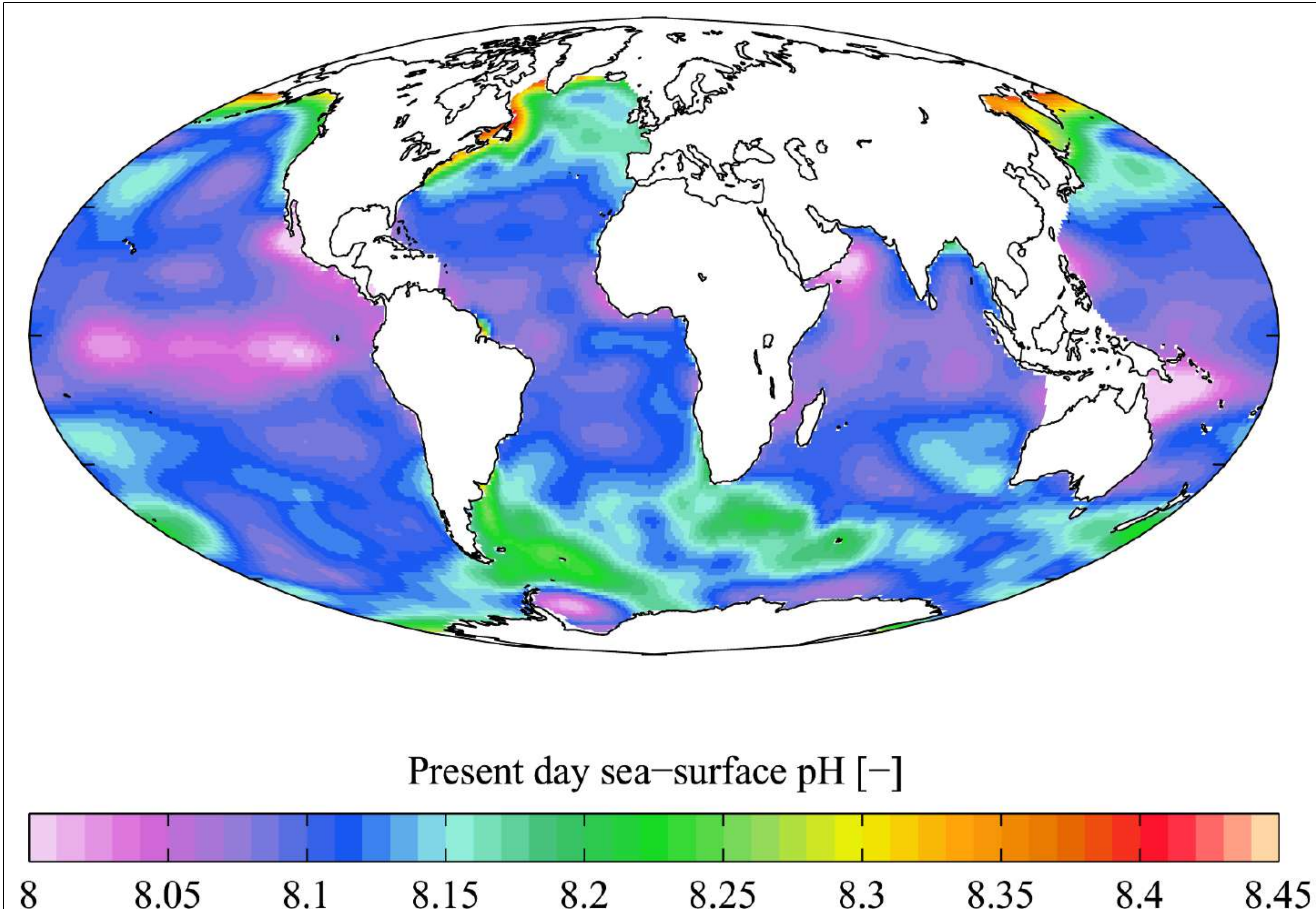
What is pH?

- pH = $-\log_{10}[H^+]$
  - Lower pH value indicate increasing acidity
- Notation: pX = $-\log_{10}X$
  - Potential of X
  - Logarithmic scale: If pH decreases by 1, it’s a factor of ten increase in acidity

pH	H+ (moles per liter)	change in acidit
7.2	6.3×10^{-8}	+900%
7.3	5.0×10^{-8}	+694%
7.4	4.0×10^{-8}	+531%
7.5	3.2×10^{-8}	+401%
7.6	2.5×10^{-8}	+298%
7.7	2.0×10^{-8}	+216%
7.8	1.6×10^{-8}	+151%
7.9	1.3×10^{-8}	+100%
8.0	1.0×10^{-8}	+58%
8.1	7.9×10^{-9}	+26%
8.2	6.3×10^{-9}	



cidic
utral
c (or
line")
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
Battery acid
Stomach acid, lemon j
Vinegar, soda
Black coffee
Milk
Human blood (7.35–7.
Seawater (8.1*)
Baking soda
Household ammonia
Household bleach
Sodium hydroxide
* Average global surface ocea


Present day sea−surface pH [−]
8
8.05
8.1
8.15
8.2
8.25
8.3
8.35
8.4
8.45

What controls the pH of seawater?

- Ions in the seawater
  - Cations and anions
  - Na^+, Mg^{2+}, Ca^{2+}, K^+, Cl^-, F^-, SO_4^{2-}, NO_3^-, HCO_3^-, CO_3^{2-}, H^+, OH^-, $B(OH)_4^-$, etc…
- **Charge balance**
  - The charge-weighted sum of positively and negatively charged ions must be zero.
- Alkalinity
  - The net positive charge from strong ions

Definition of Alkalinity

Alkalinity: is the net molar concentration, in charge-equivalents, of the cations of strong bases in excess of the anions of strong acids

Strong base cations

$$A = \left\{[Na^+] + [K^+] + 2[Mg^{2+}] + 2[Ca^{2+}]\right\} -$$

(less) strong acid anions

$$\left\{[Cl^-] + 2[SO_4^{2-}] + [Br^-]\right\}$$

$$\approx \left\{[HCO_3^-] + 2[CO_3^{2-}]\right\}$$

Weak acid anions

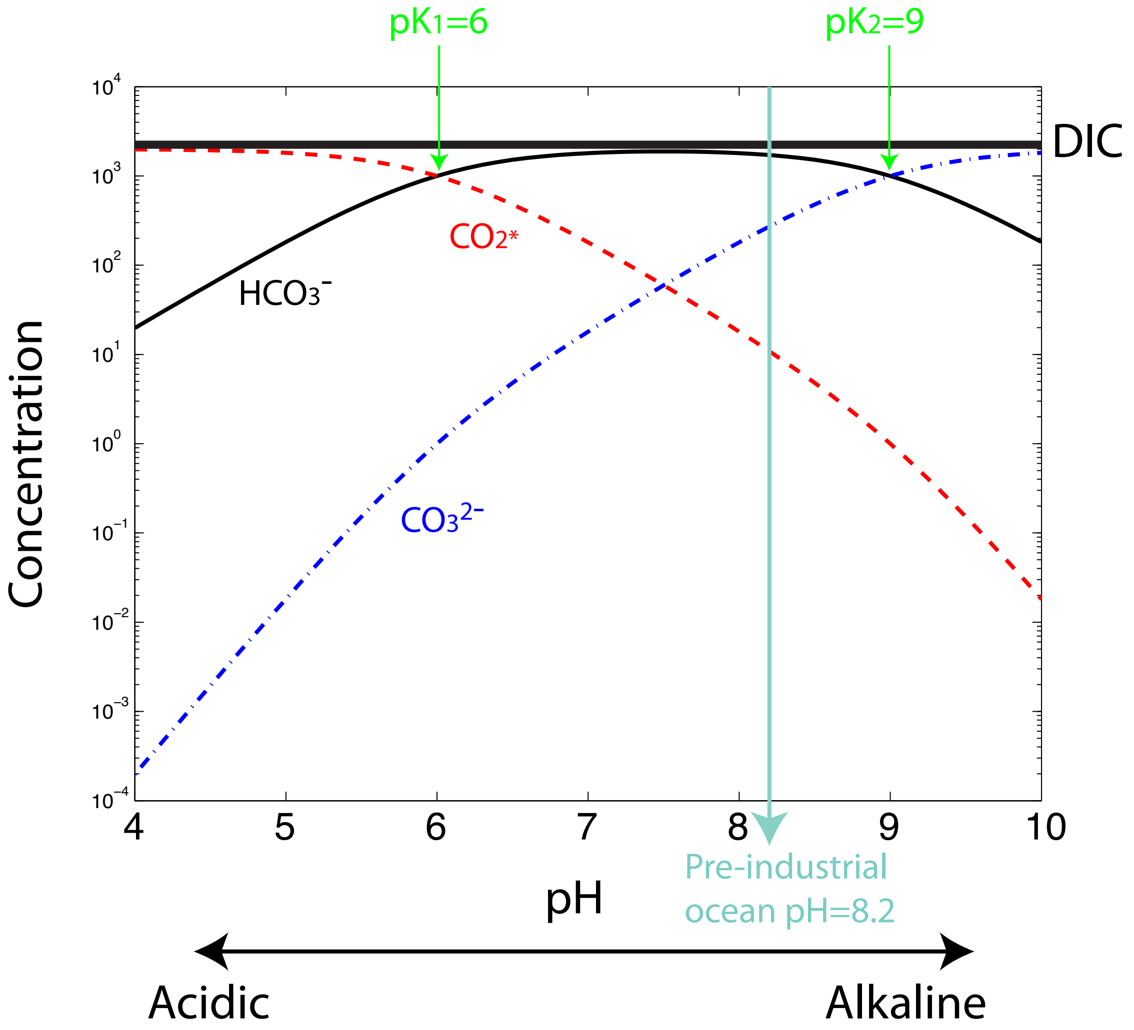
Approximate relation

$$Alk \approx \left\{[HCO_3^-] + 2[CO_3^{2-}]\right\}$$

$$DIC \approx \left\{[HCO_3^-] + [CO_3^{2-}]\right\}$$

$$[CO_3^{2-}] \approx Alk - DIC$$

- $DIC = [CO_2^*] + [HCO_3^-] + [CO_3^{2-}]$
- $Alk = [HCO_3^-] + 2[CO_3^{2-}]$



FAQs about Ocean Acidification


Woods Hole Oceanographic Institution

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KNOW YOUR OCEAN

- Ocean Topics
  - Climate & Ocean
  - Coastal Science
  - Hazards
  - Ocean Chemistry
    - Biogeochemistry
    - Carbon Cycle
    - Ocean Acidification
  - Ocean Circulation
  - Ocean Life
  - Ocean Resources
  - Polar Research
  - Pollution
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Visual WHOI

Image of the Day

FAQs about Ocean Acidification

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Introduction

Ocean acidification is a new field of research in which most studies have been published in the past 10 years. Hence, there are some certainties, but many questions remain. Ocean acidification is also a multi-disciplinary research area that encompasses topics such as chemistry, paleontology, biology, ecology, biogeochemistry, modeling, and social sciences. Furthermore, some aspects of ocean acidification research, for example the carbonate chemistry, are intricate and counterintuitive. For these reasons, the media and the general public find some scientific issues or results confusing.

The U.S. Ocean Carbon and Biogeochemistry (OCB) program, supported by the European Project on Ocean Acidification (EPOCA) and the UK Ocean Acidification Research Programme, has compiled a list of frequently asked questions (FAQs). These questions were widely distributed to the research community with the request to draft concise replies summarizing current knowledge, yet avoiding jargon. The replies were then subject to an open peer-review and revision process to ensure readability without any loss of scientific accuracy. The response of the community was

https://www.whoi.edu/page.do?pid=83380&tid=3622&cid=131410

Carbon Pumps

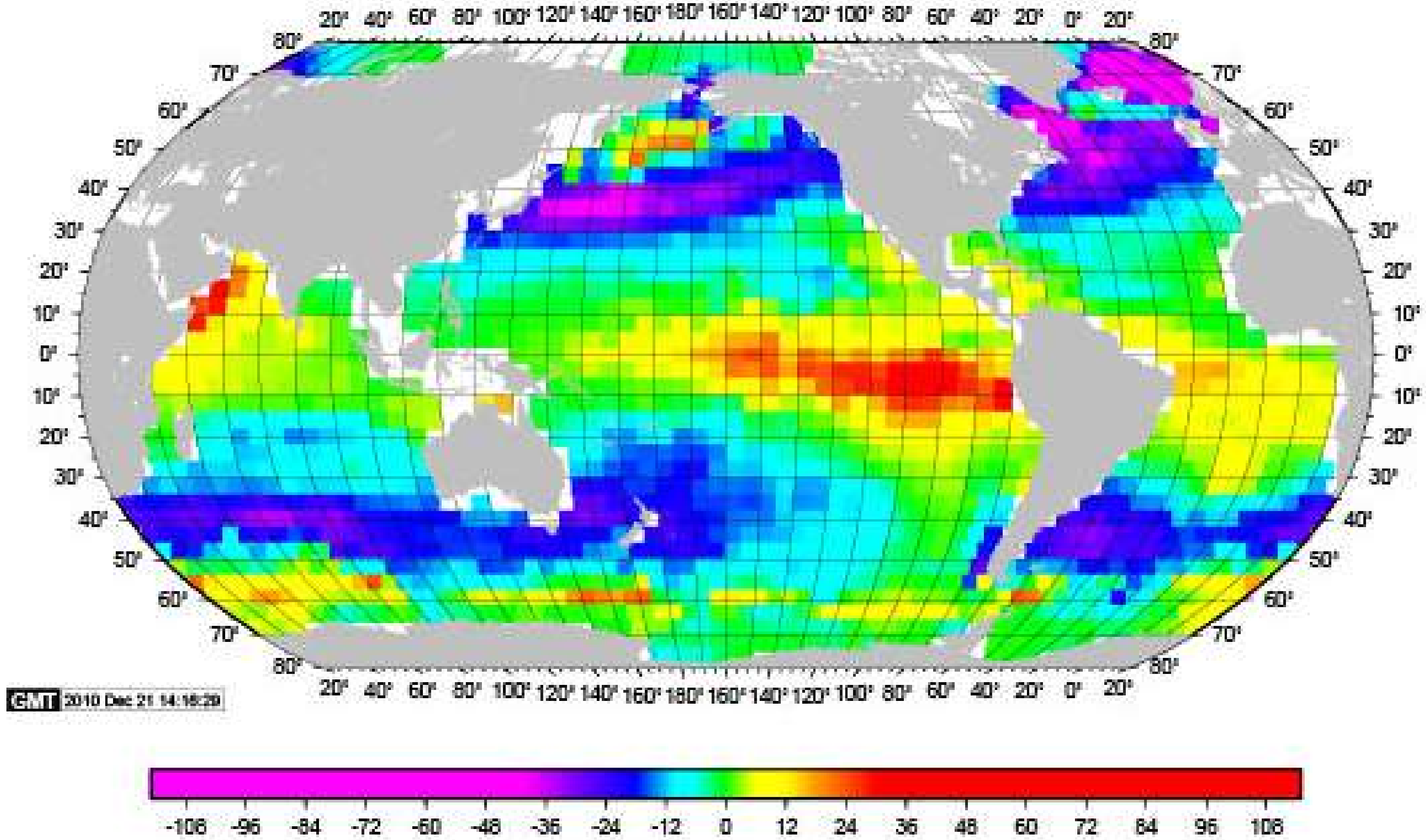
- Solubility pump
- Soft-tissue pump
- Carbonate pump

) Biological Pump

Air-sea carbon exchange

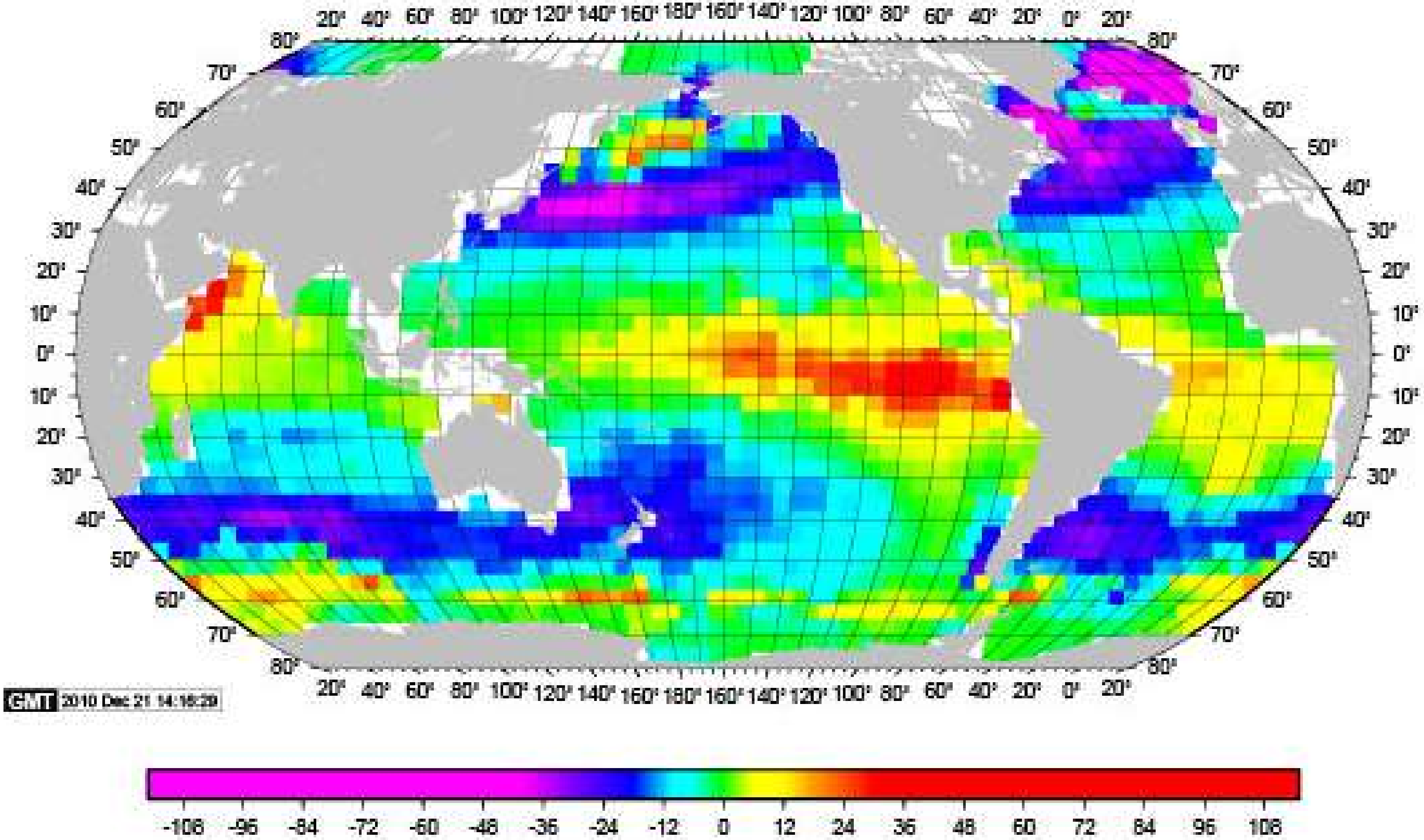
Note: positive upward

Takahashi et al., (2009)

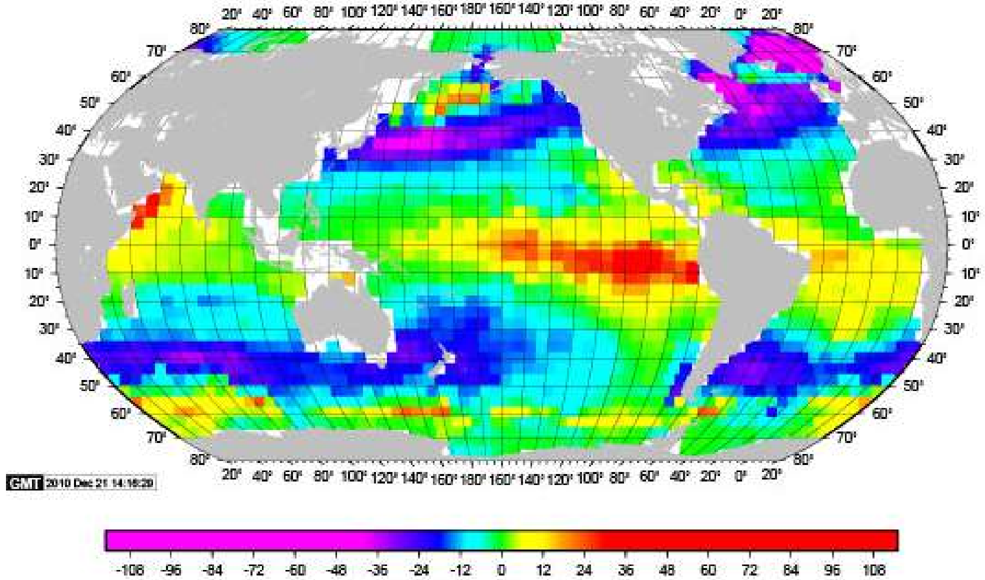


Into the ocean

Out of the ocean

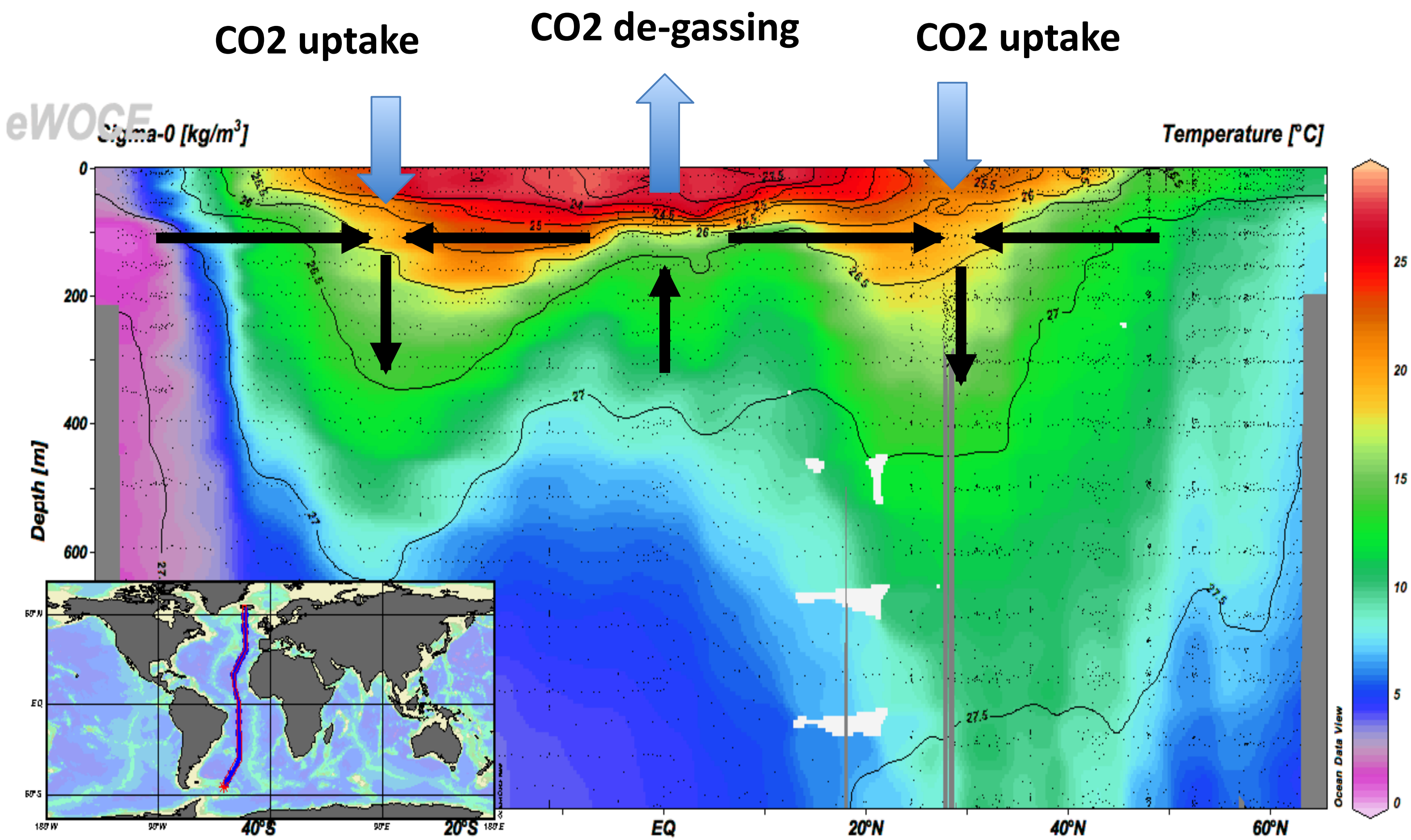


$\Delta pCO_2 = pCO_2^{ocean} - pCO_2^{atm}$ When > 0 outgassing of CO_2 from the Ocean, when < 0 invasion of CO_2 into the ocean



- Timescale for CO_2 equilibration is about 10X longer for ordinary gas and surface ocean is not in equilibrium with atmosphere.
- pCO_2^{ocean} is high where cold waters are warmed, and where carbon rich deep waters are exposed to the surface
- pCO_2^{ocean} is low where warm waters are cooled
- At steady state, for entire ocean $pCO_2^{ocean} = pCO_2^{atm}$

Air sea heat and carbon flux

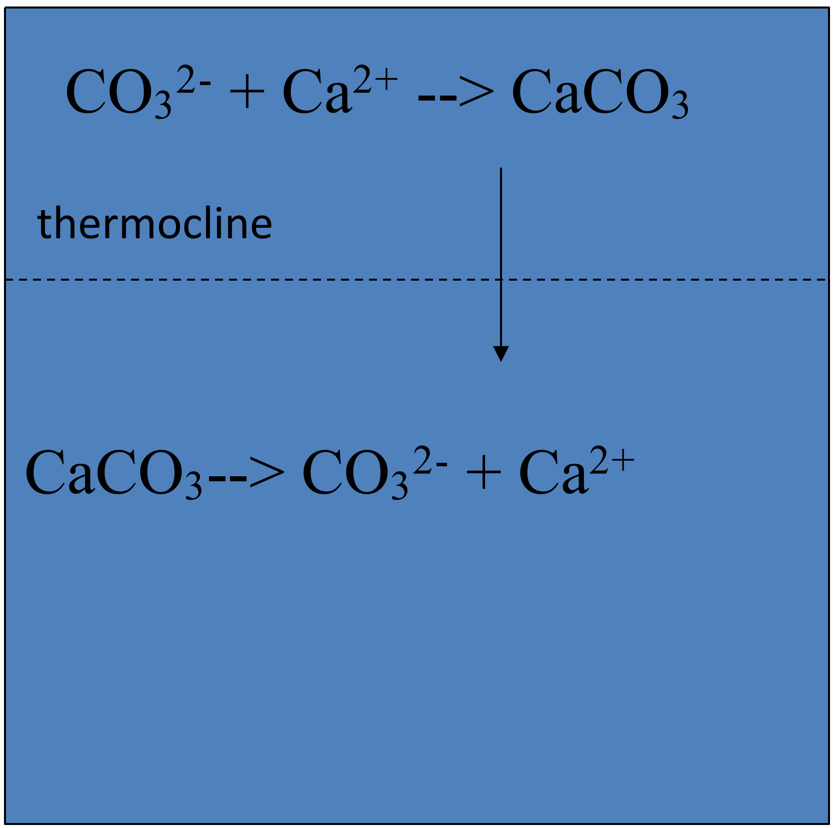


Carbon Pumps

- Solubility pump
- Soft-tissue pump
- Carbonate pump

) Biological Pump

Carbonate pump



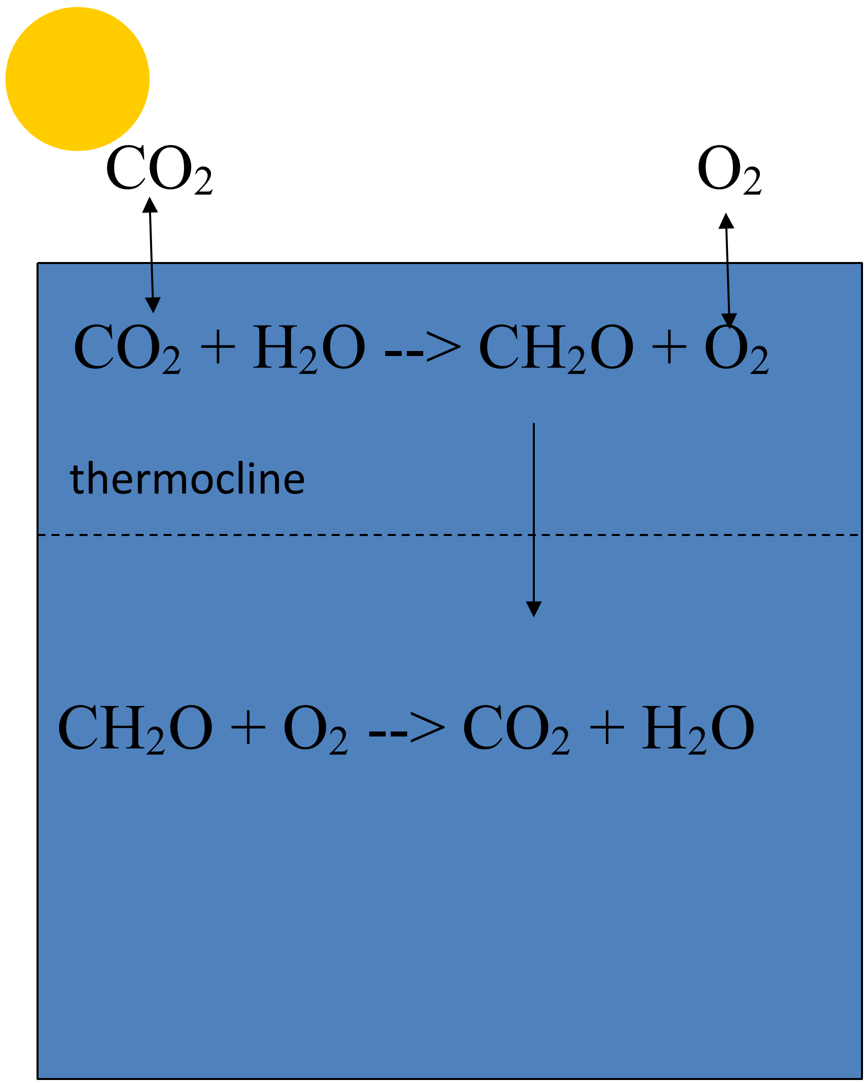
- Carbon is taken up to form $CaCO_3$ shells in surface ocean
- The $CaCO_3$ dissolves in the deep ocean

Carbon Pumps

- Solubility pump
- Soft-tissue pump
- Carbonate pump

) Biological Pump

Biological (soft-tissue) pump



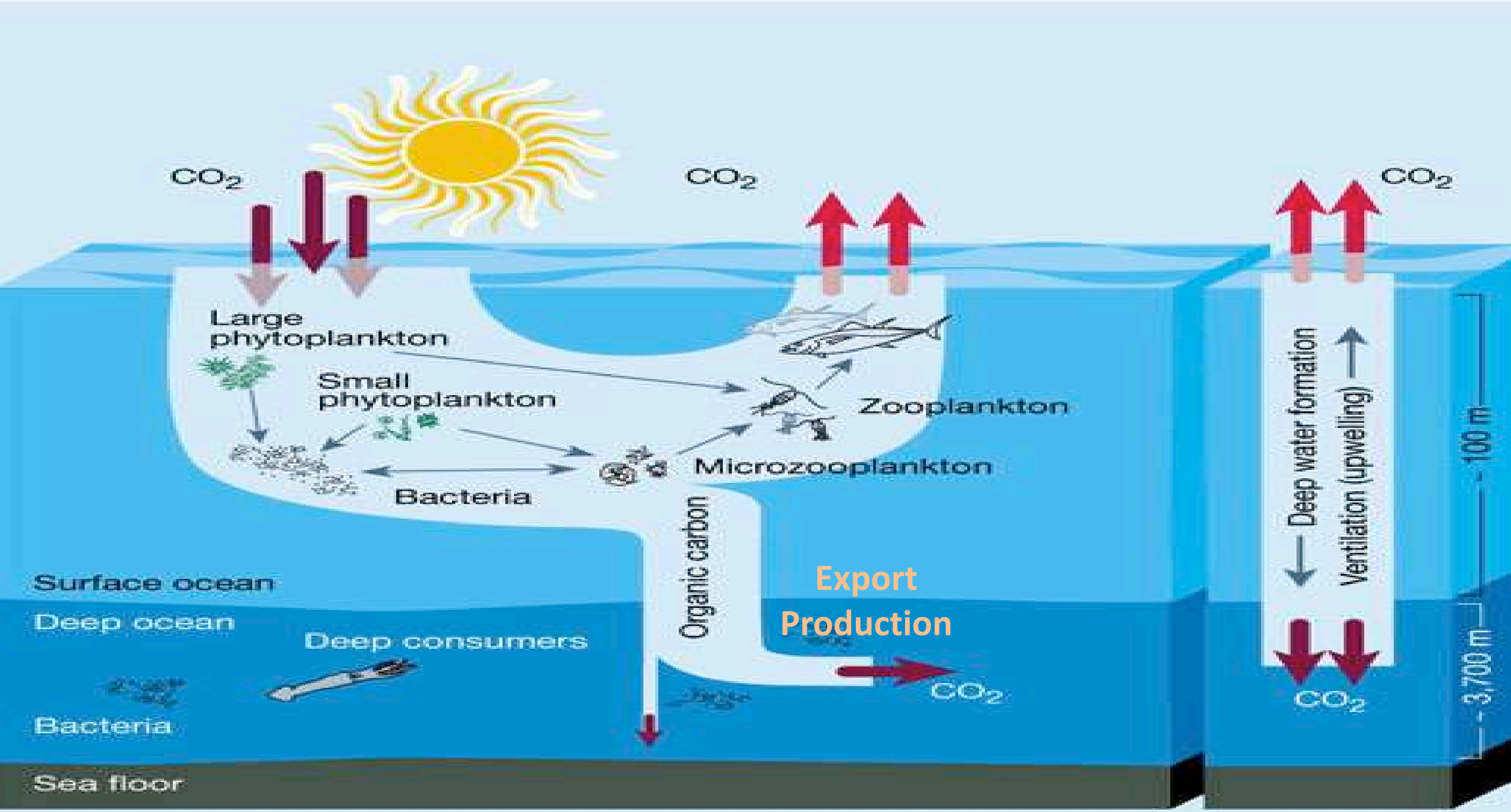
- Organisms take up carbon during photosynthesis in the surface ocean
- When they die they sink into the deep ocean
- The carbon is returned to seawater when the organic material is broken down by bacteria

Primary production

- Photosynthesis measured by the amount of carbon molecule in the newly generated organic matter

(Solar radiation) + Nutrient + CO_2 + Water
$\rightarrow$ Organic matter + O_2

Vertical transfer of carbon

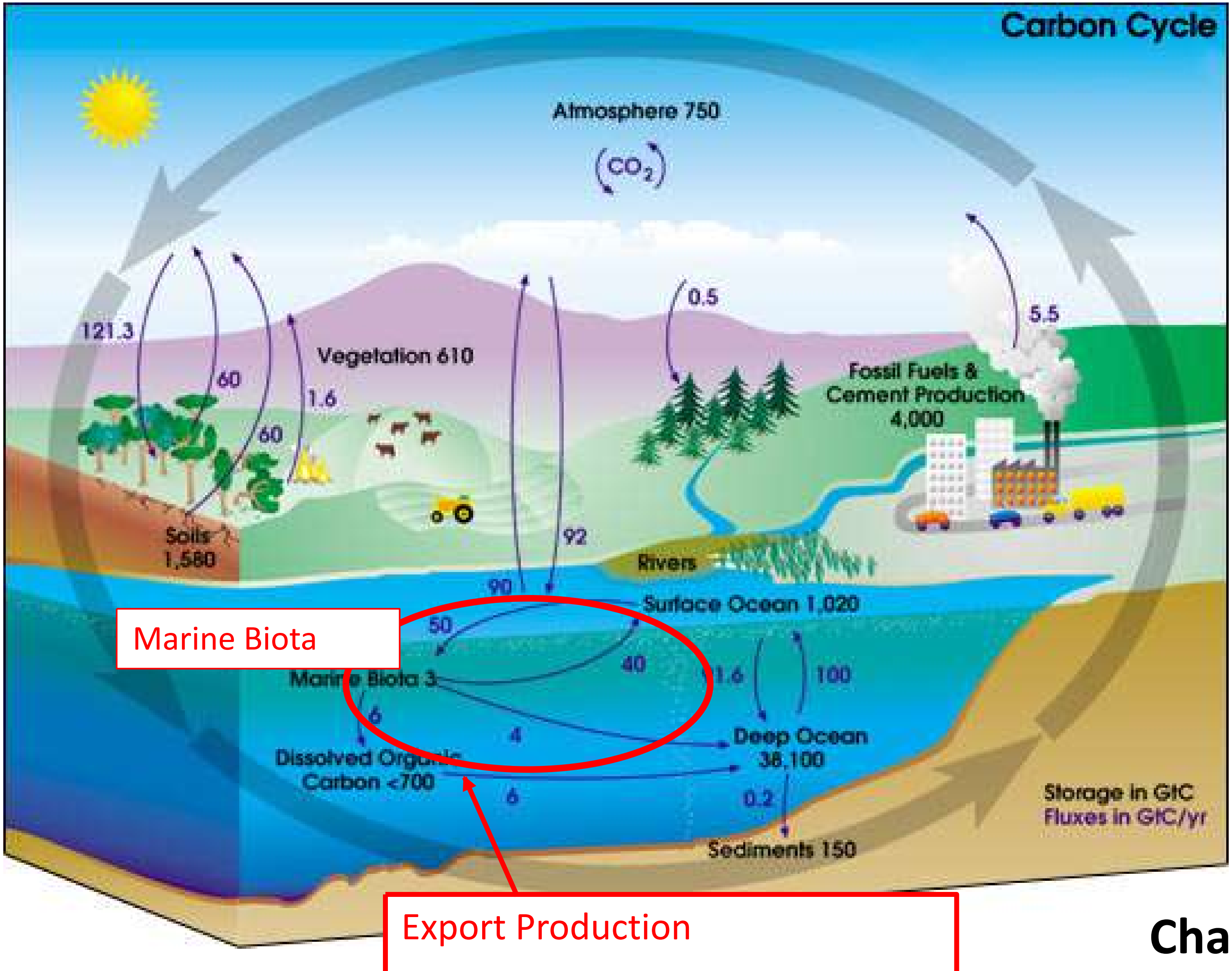


Export production

- Sinking organic matter
- Sinking speed depends on particle sizes and density
  - Particle sizes depends on ecosystem structure

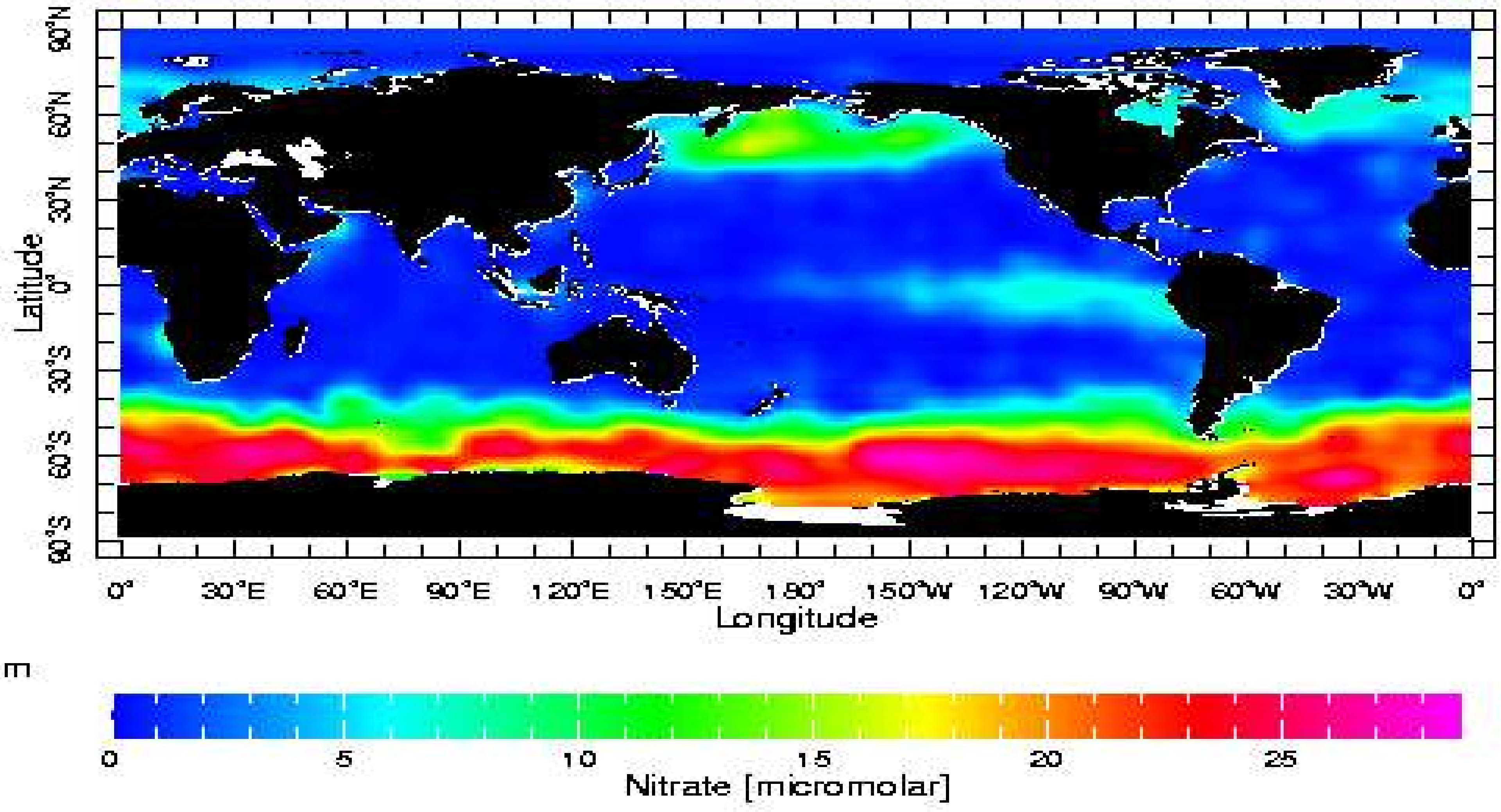
About 10% of primary production gets exported to the deep ocean

Biological pump



Chapter 14

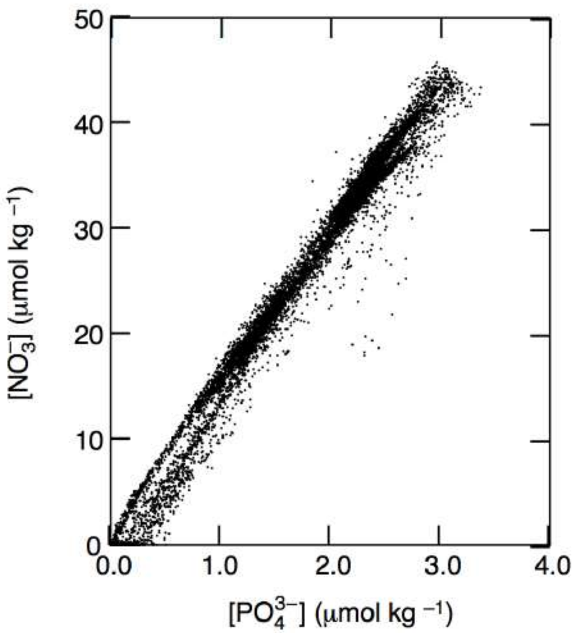
What regulates the strength of biological carbon pump?



Redfield ratio

- Average composition of organic matter in typical marine snow

$$P : N : -O_2 : C_{org} = 1 : 16 : 170 : 106$$



N:P ratio of seawater

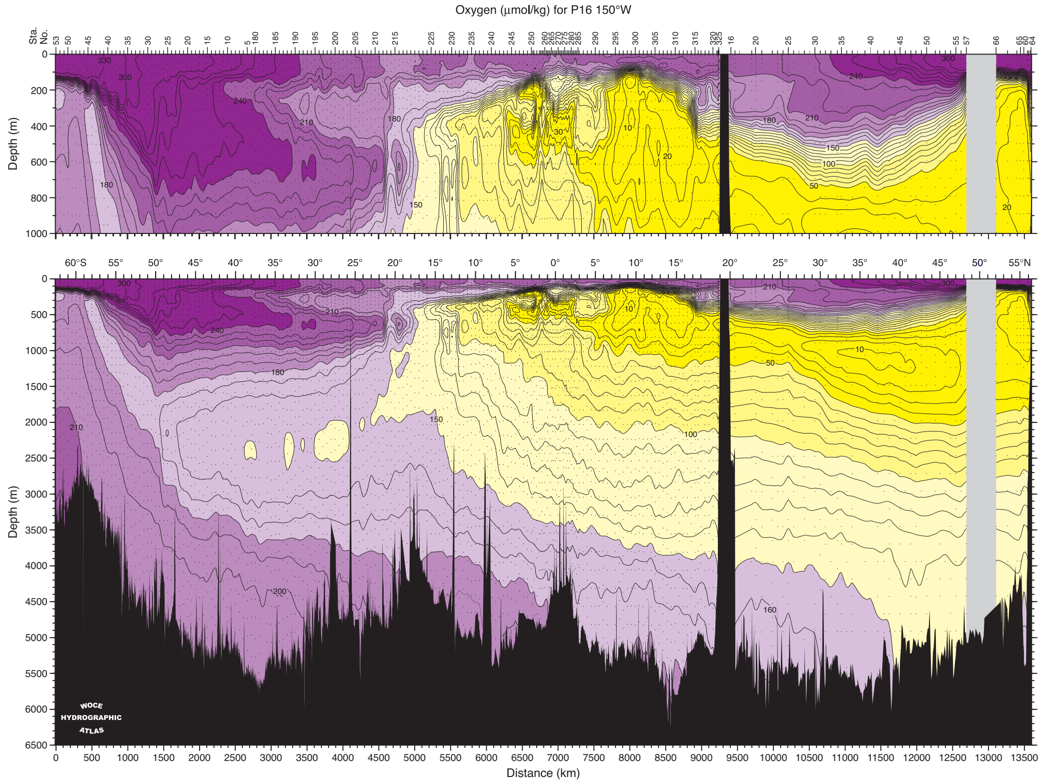
Tyrell (1999)

Controls on biological pump

- *Bottom up control:* availability of nutrients (PO_4, NO_3)
  - Ocean nutrient inventory
  - Supply of nutrients to the surface ocean by ocean upwelling and mixing
- *Top-down control*
  - Predators can limit prey population
  - Ecosystem processes

Remineralization

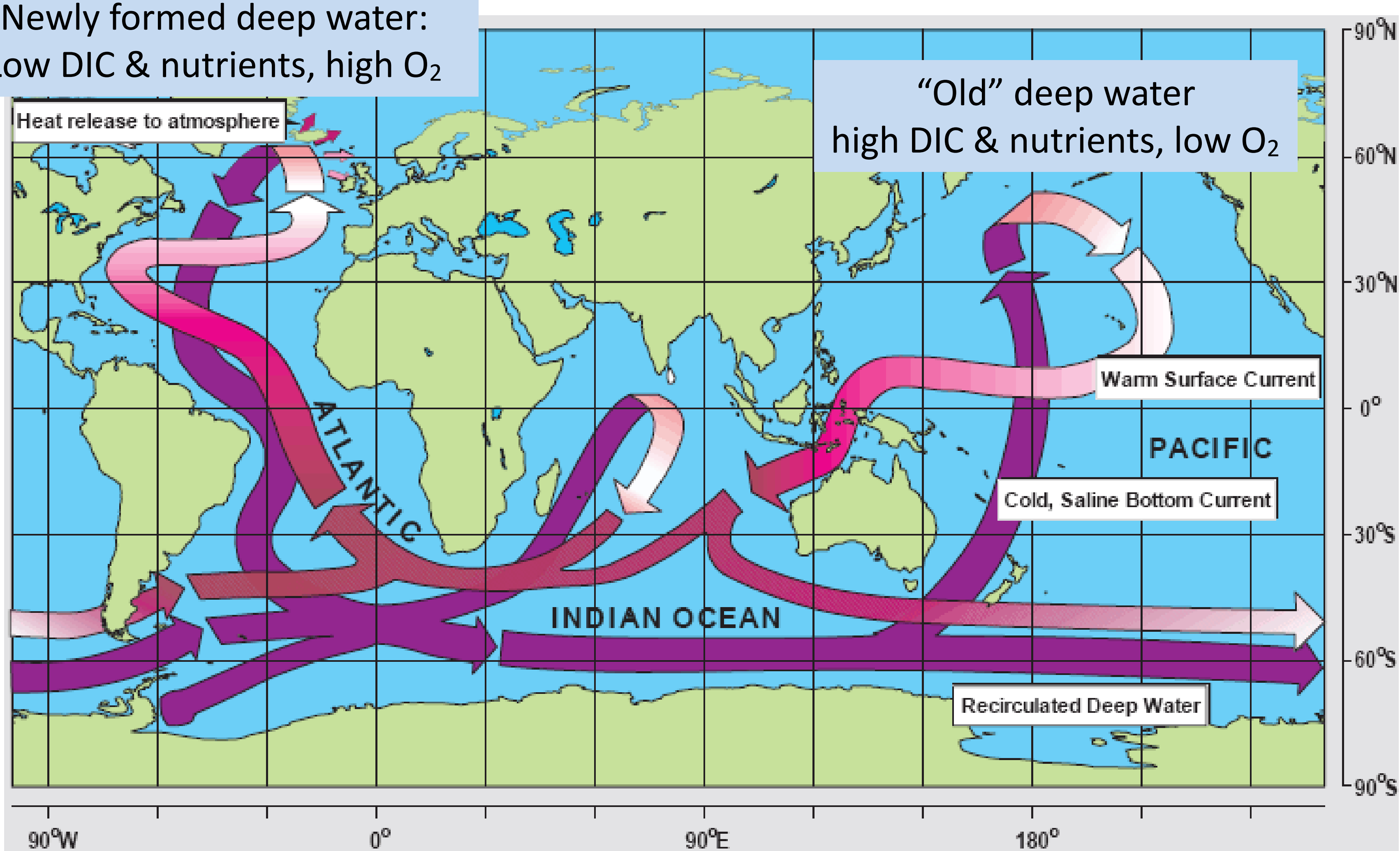
- Sinking organic matter is consumed by bacteria
  - Regeneration of nutrients, DIC
  - Consumption of oxygen



A model of the vertical overturning circulation

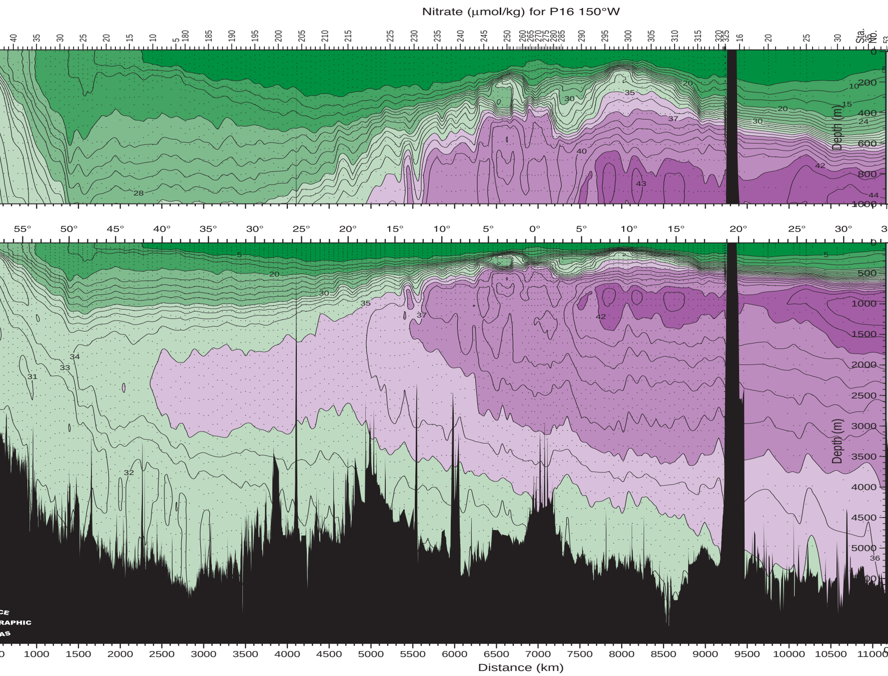
Newly formed deep water:
Low DIC & nutrients, high O_2

"Old" deep water
high DIC & nutrients, low O_2

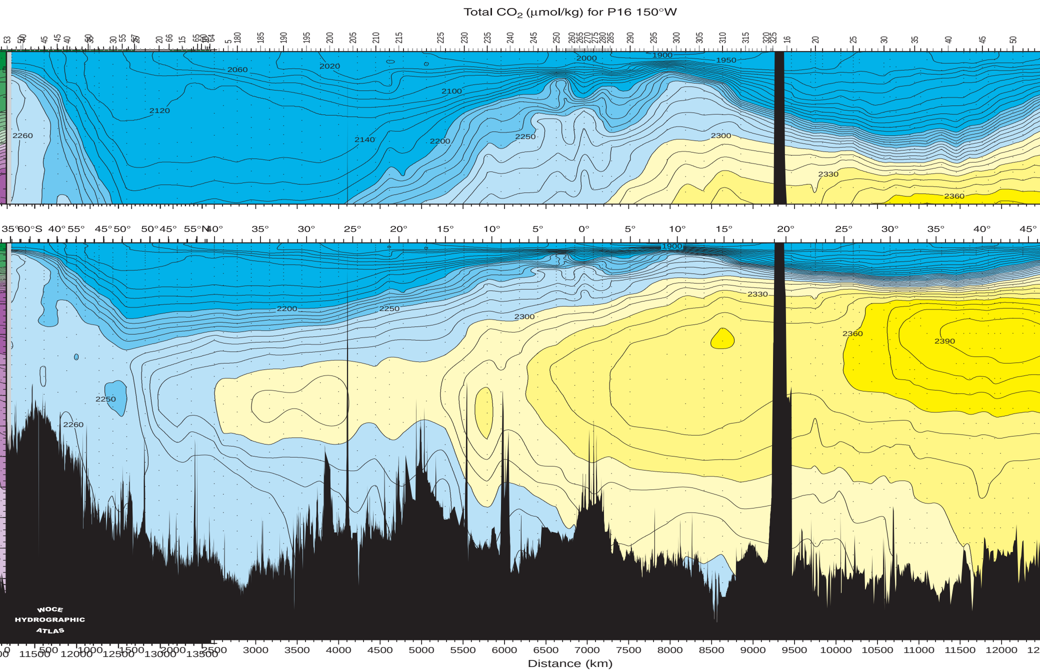


Distribution of nutrients vs DIC

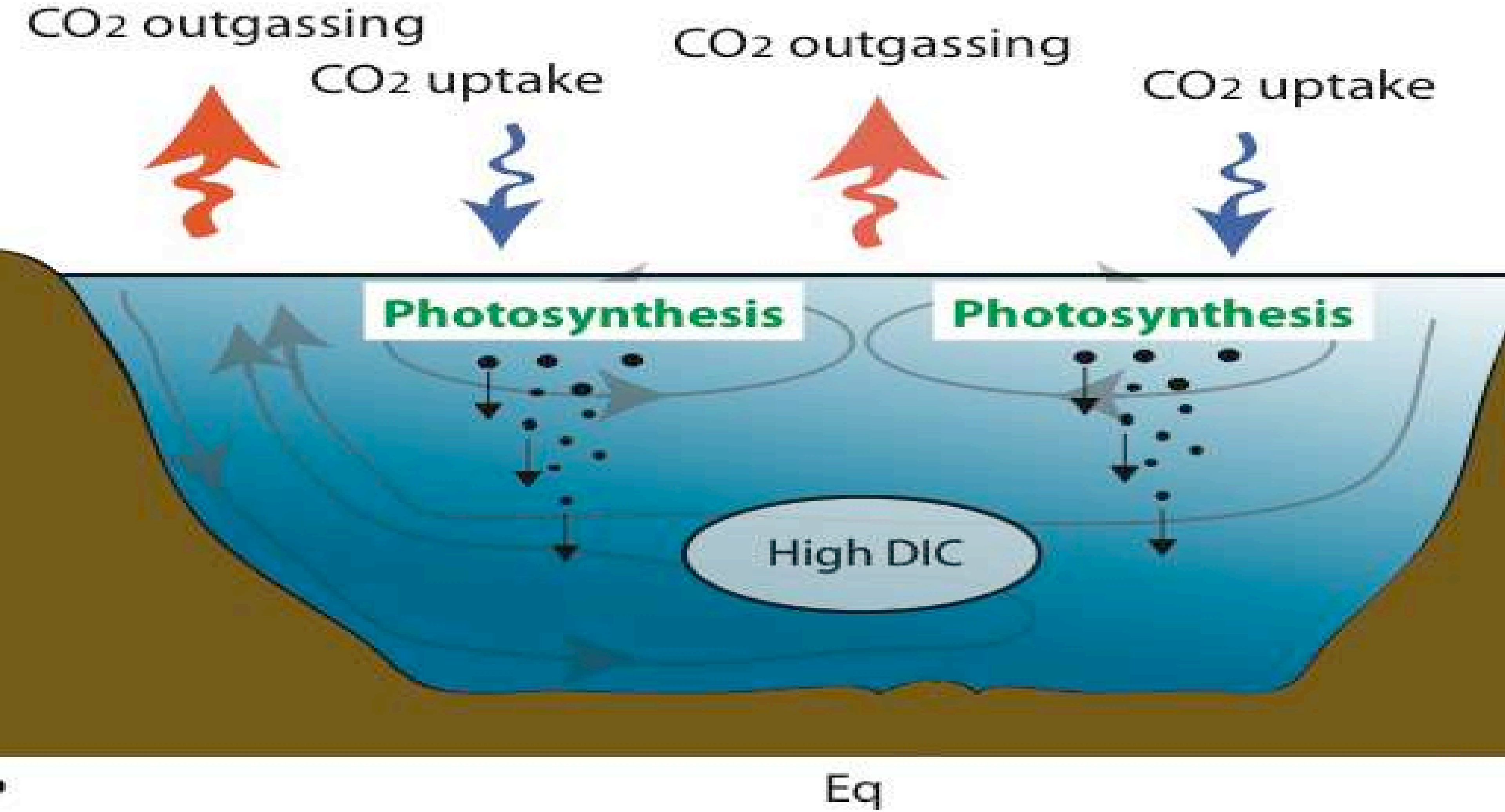
Nitrate: NO_3

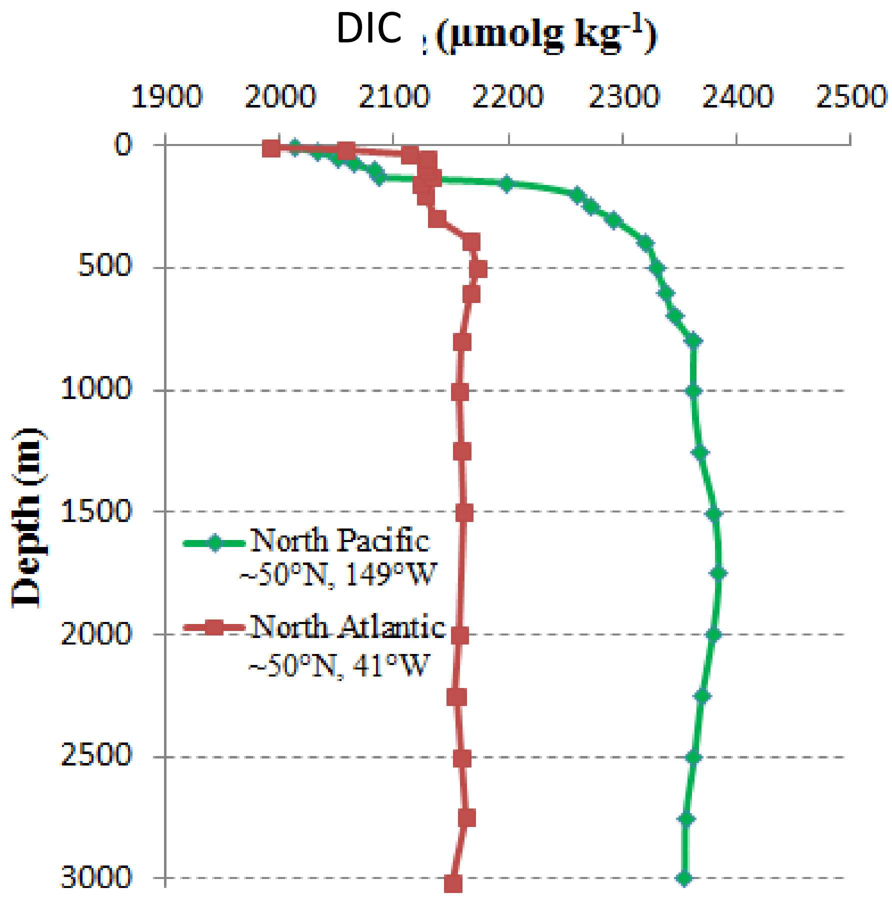


DIC



Air-sea CO_2 flux driven by the biological pump




DIC (µmolg kg-1)
1900
2000
2100
2200
2300
2400
2500
0
500
1000
1500
2000
2500
3000
Depth (m)
North Pacific
~50°N, 149°W
North Atlantic
~50°N, 41°W