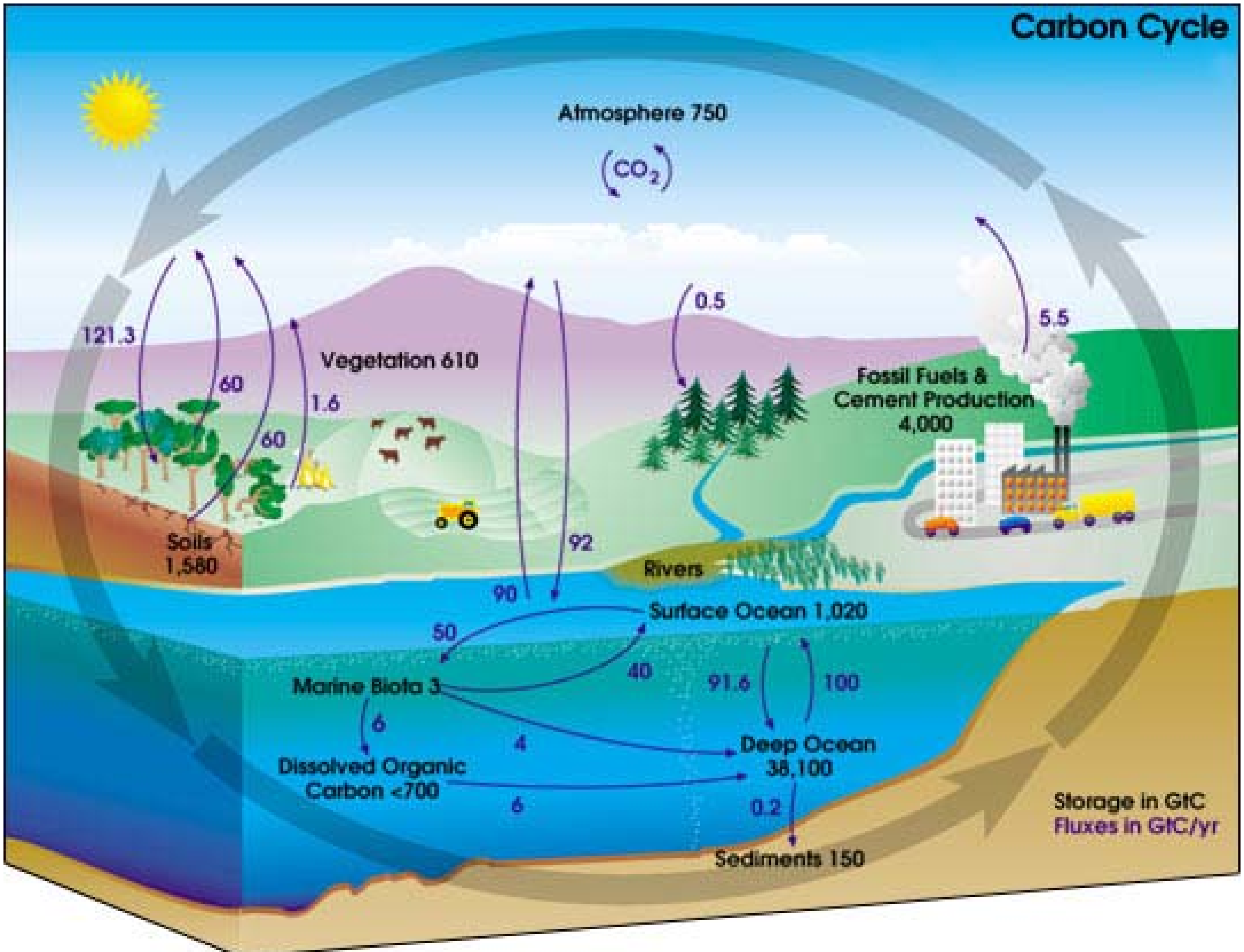
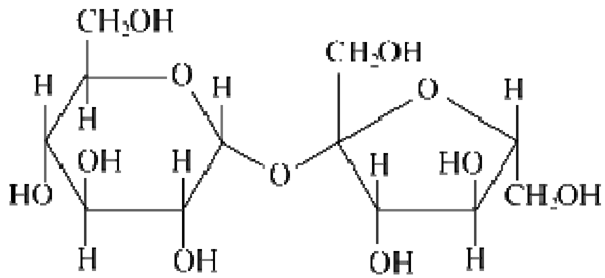
The Carbon Cycle

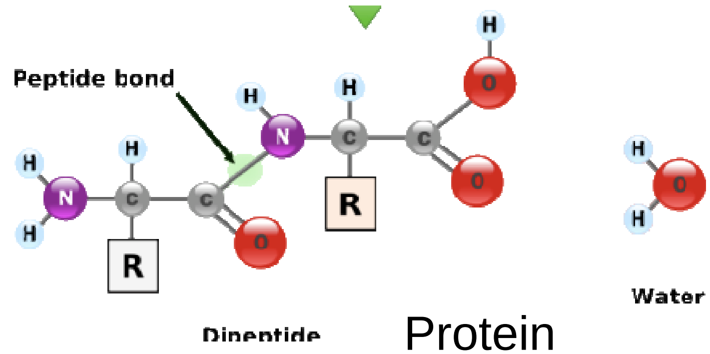


Inventories: black text
Fluxes: purple arrows

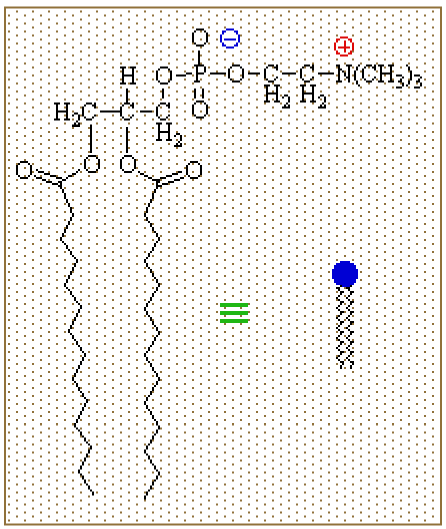
Carbon is the currency of life



Carbohydrates

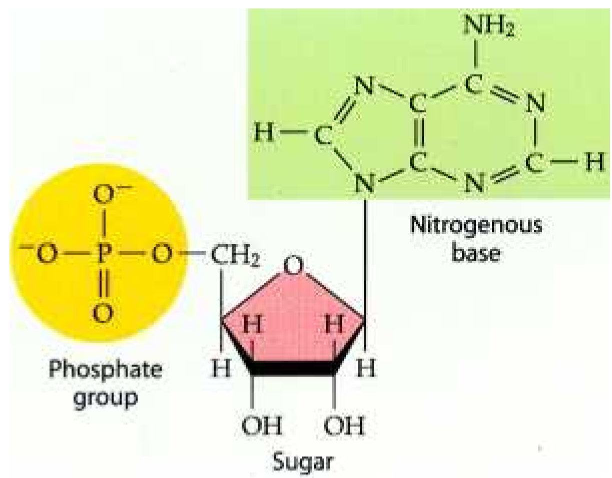


Protein



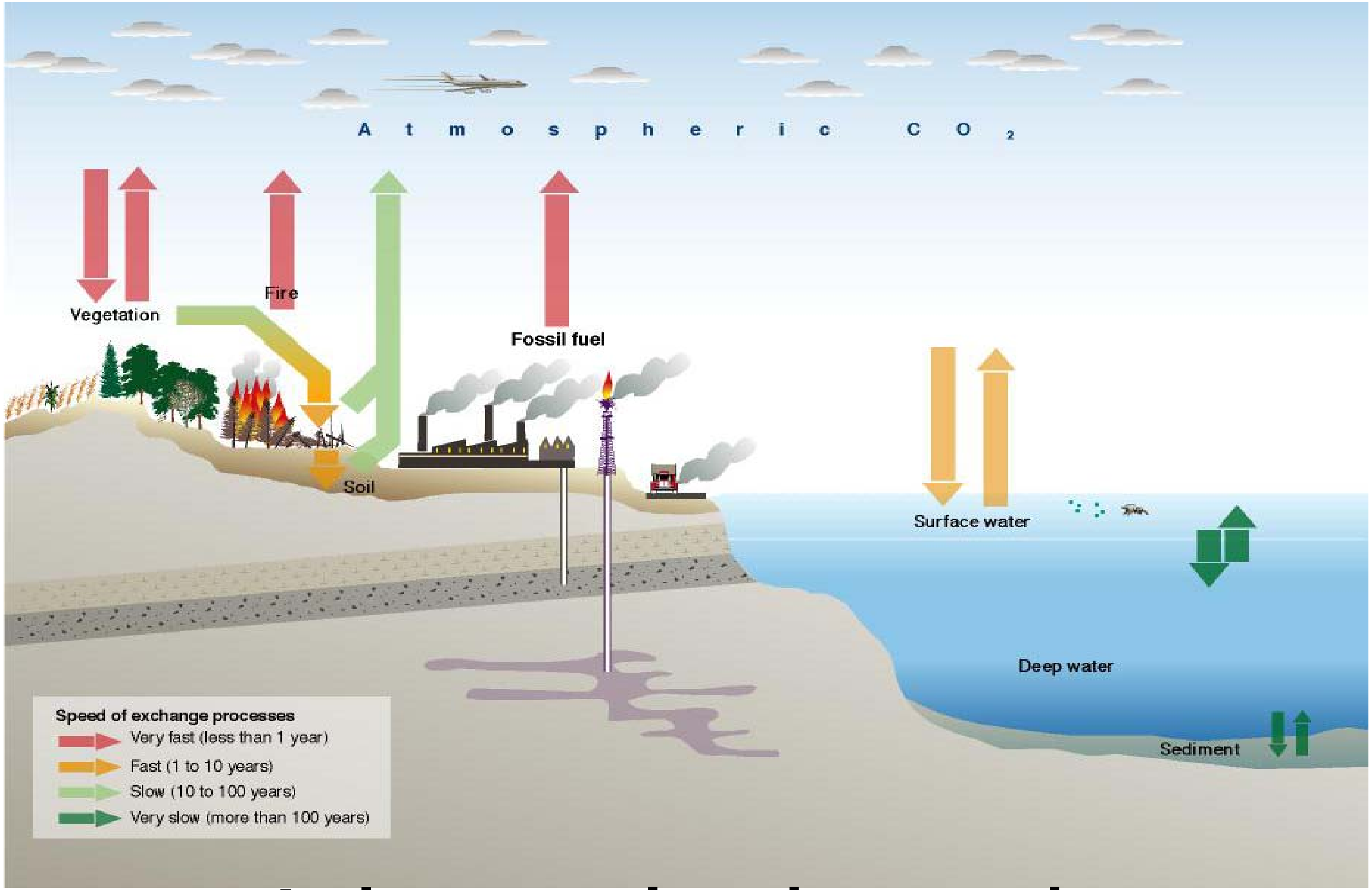
phospholipid

Nucleic acids



All living organisms utilize the same molecular building blocks.

Time Scales of Carbon Exchange in the Biosphere



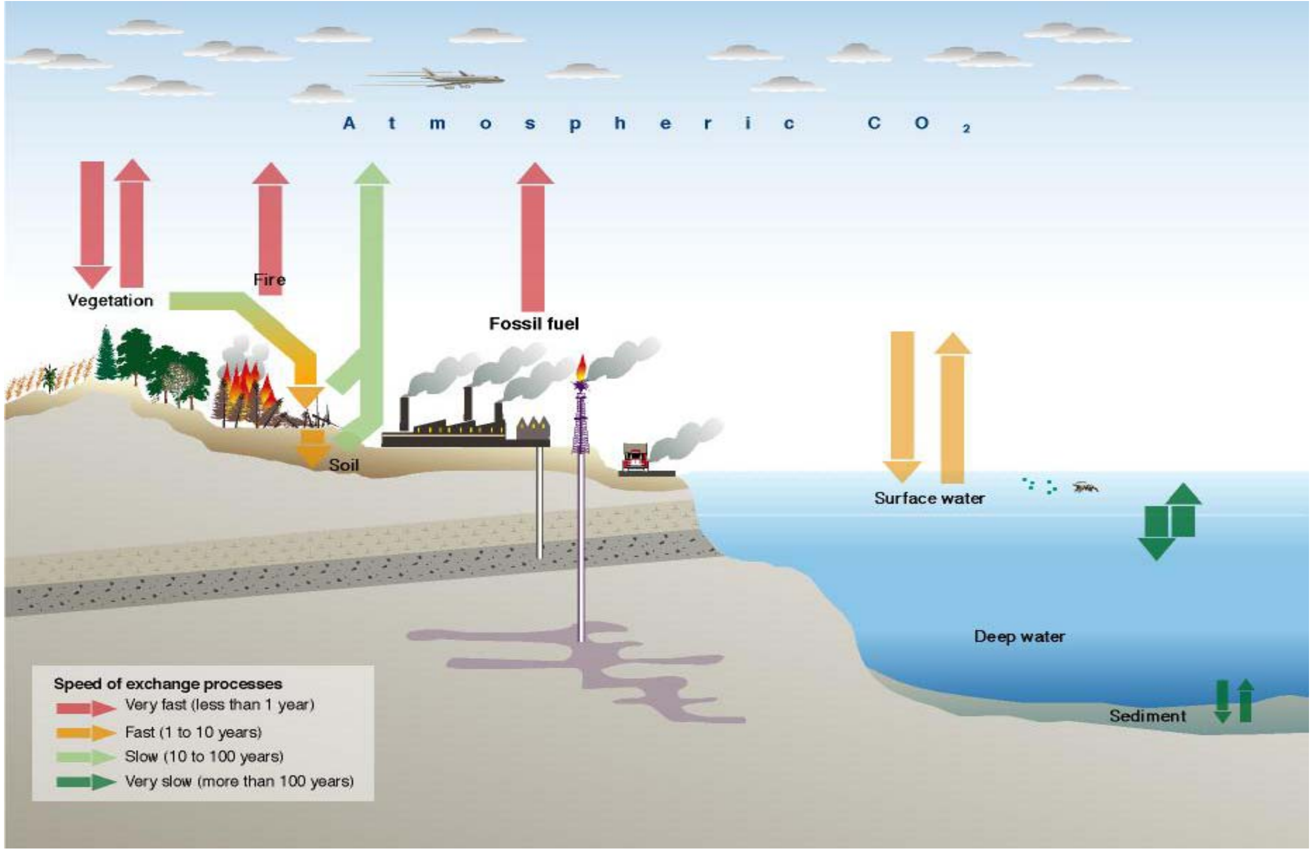
4 places carbon is stored:

1) Lithosphere, 2) Atmosphere,

3) Hydrosphere (Ocean), 4) Terrestrial biosphere

The oceans carbon cycle

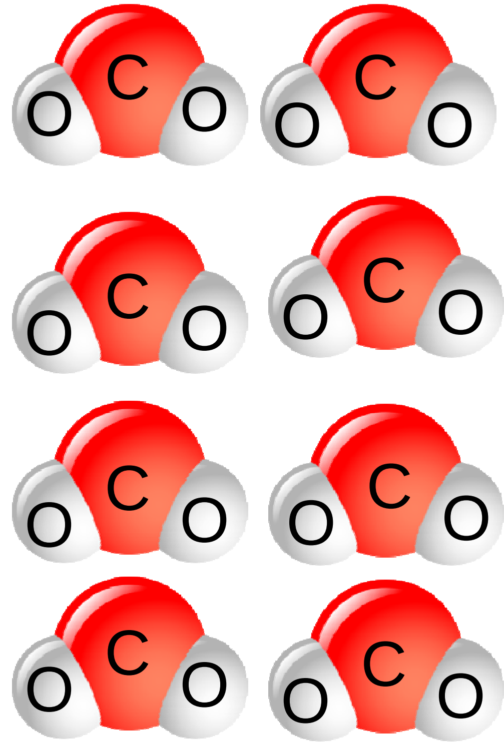
- The main components:
  - DIC, DOC, PC (includes POC and PIC)
- Primary processes driving the ocean carbon cycle:
  - abiotic: solubility, ventilation, transport;
  - biotic: photosynthesis, respiration, calcification



1 g C in a sugar cube

The ocean holds 50 grams of CO_2 for every 1 gram of CO_2 in the atmosphere

CO_2 in the atmosphere	**~750,000,000,000,000,000 g C**
CO_2 in oceans	**~39,120,000,000,000,000,000 g C**
Dissolved organic carbon	**~700,000,000,000,000,000 g C**
Living and dead particles	**~3,000,000,000,000,000 g C**



Every year, each person in the US releases ~20 tons of CO_2 to the atmosphere, equivalent to the mass of 4 adult elephants, and nearly half (2 elephants) ends up in the ocean.

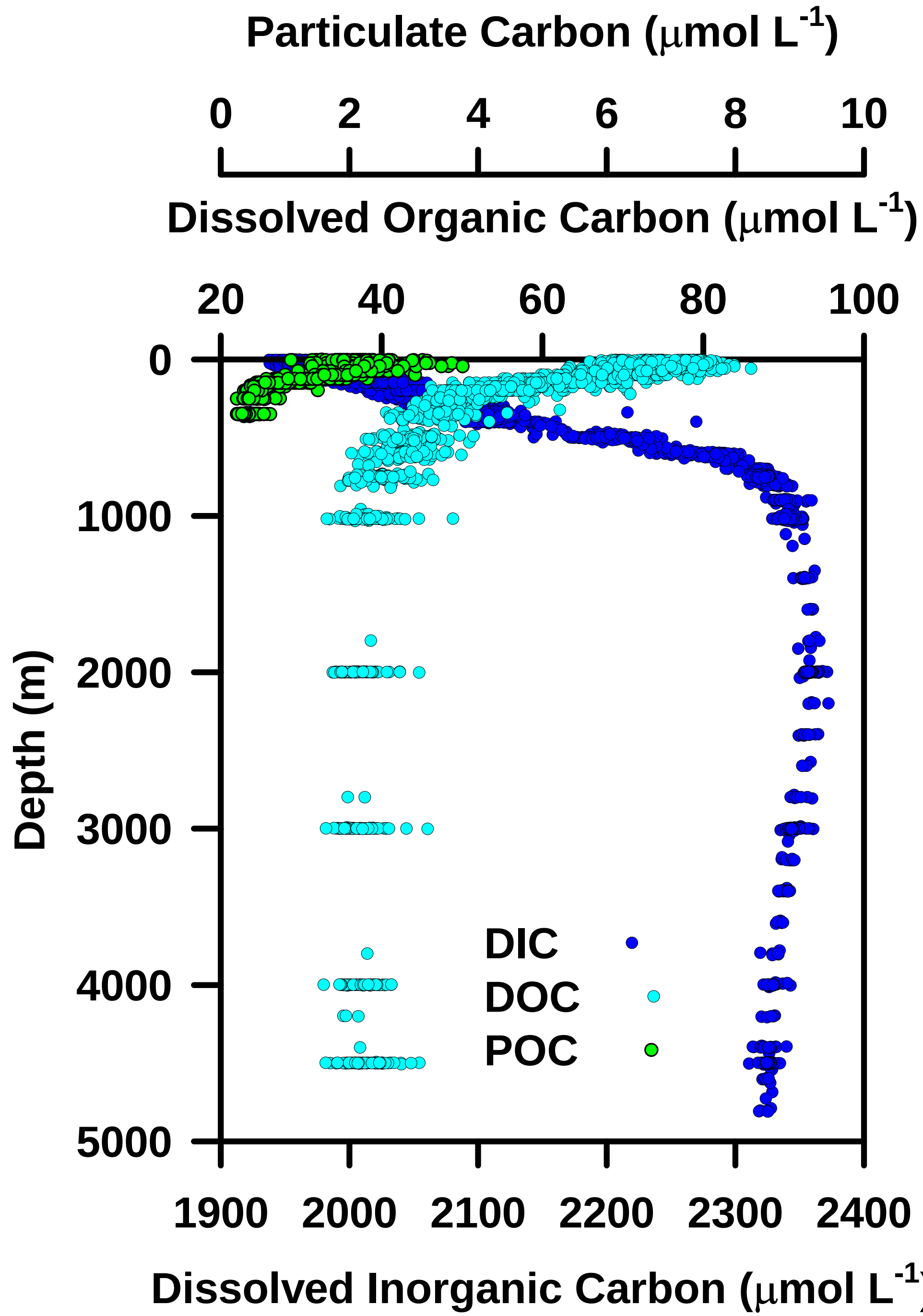
Pools of Carbon in the Sea

- DIC in the oceans ~37500 x 10^{15} g C
  - H_2CO_3-carbonic acid
  - HCO_3^--bicarbonate
  - CO_3^{2-}-carbonate
- DOC ~700 x 10^{15} gC
- POC (living and detrital organic particles)-22 x 10^{15} g C
- PIC ($CaCO_3$)- <1 x 10^{15} g C

- **Because of its solubility and chemical reactivity, CO_2 is taken up by the oceans more readily than other atmospheric gases.**

- **Over the long term (1000s of years) the oceans will consume ~90% of anthropogenic CO_2 emissions.**

Vertical profiles of carbon in the North Pacific

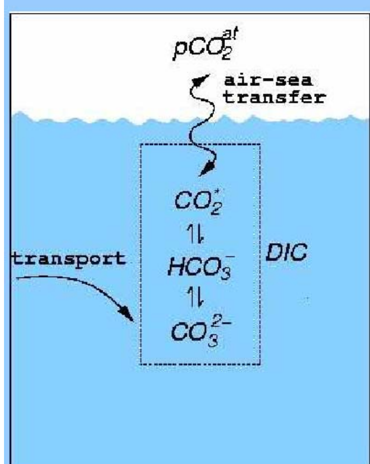


Dissolved inorganic carbon

- $H_2O + CO_{2(g)} \Leftrightarrow H_2CO_3$
- $H_2CO_3 \Leftrightarrow H^+ + HCO_3^-$
- $HCO_3^- \Leftrightarrow H^+ + CO_3^{2-}$

- Solubility of CO_2 in seawater and its equilibrium among these different species depends on temperature, pressure, salinity, pH, and alkalinity.
- The residence time of CO_2 in the atmosphere is ~10 years; it exchanges rapidly with the ocean and terrestrial biome.

Carbonate chemistry.



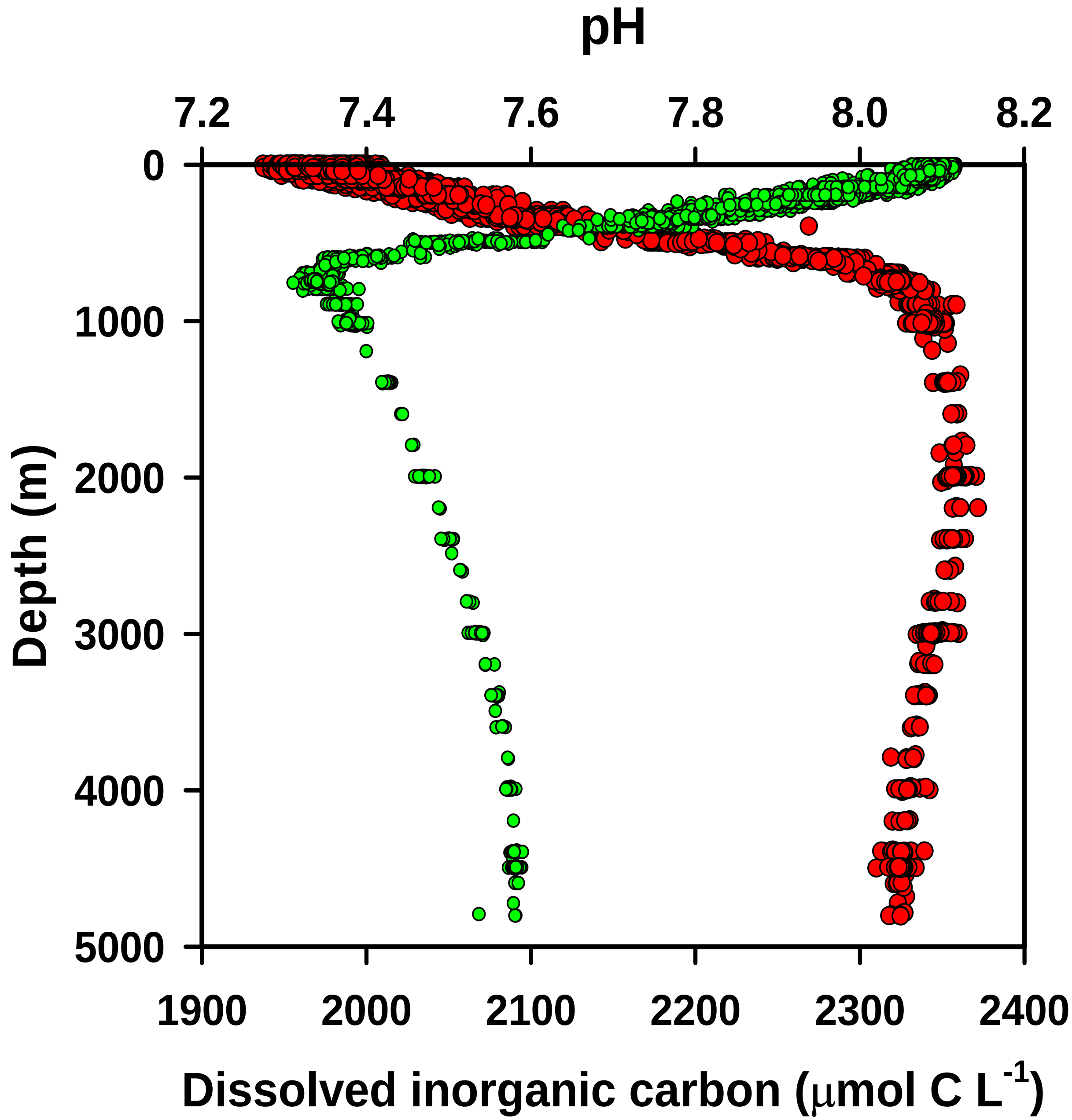
dissolved inorganic carbon

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

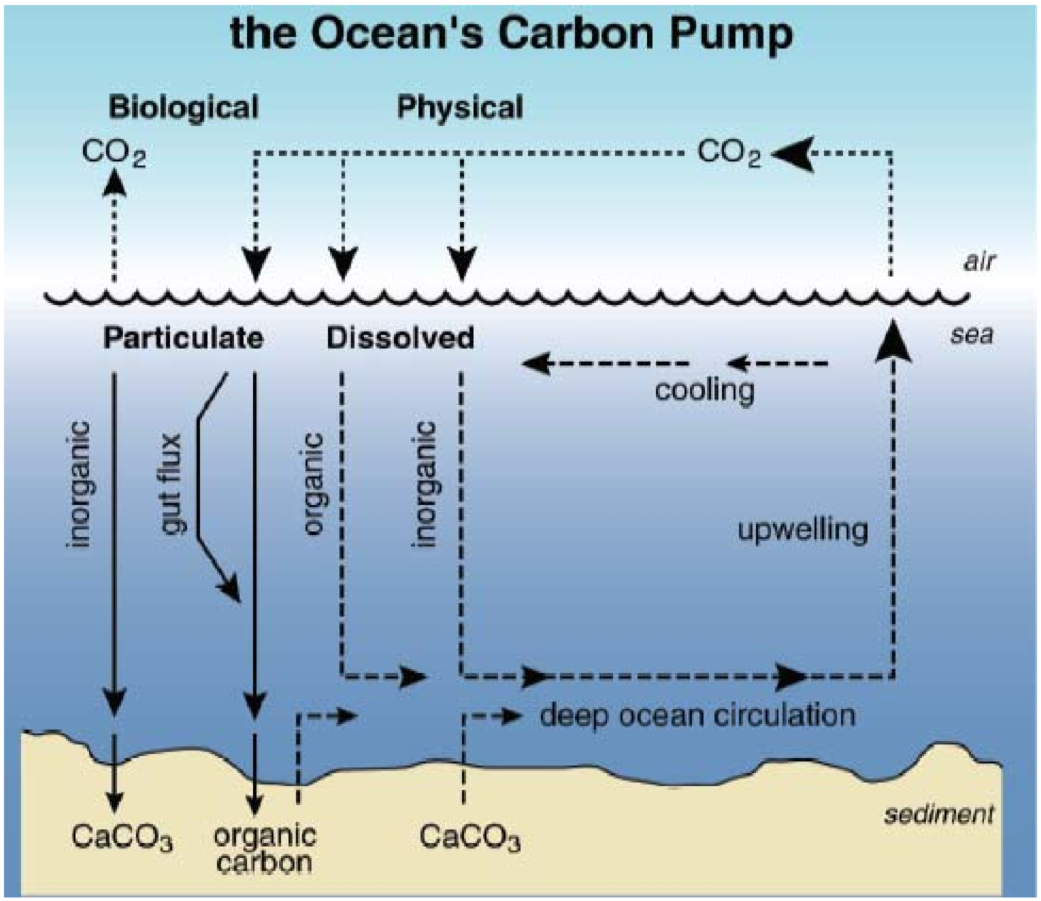
Surface seawater (pH~8.2):

$[H_2CO_3] : [HCO_3^-] : [CO_3^{2-}]$
0.5% : 88.6% : 10.9%

Vertical profiles of DIC and pH at Station ALOHA

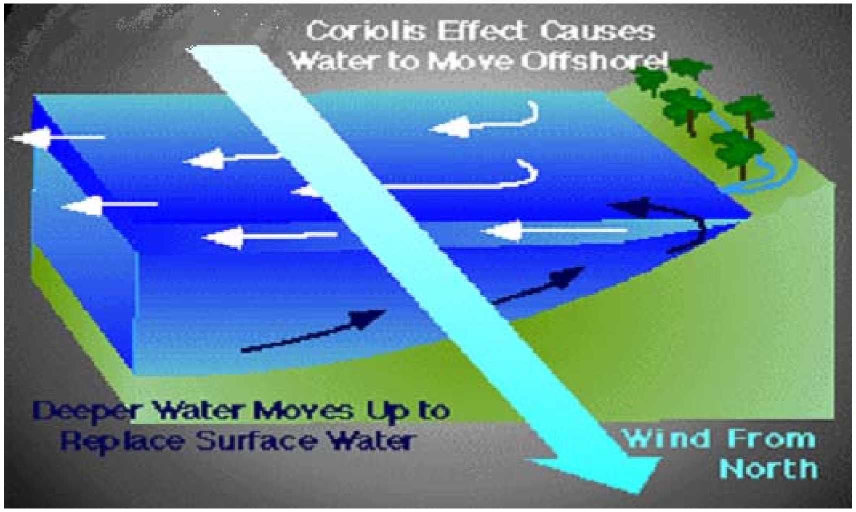


What processes control DIC gradients in the sea?

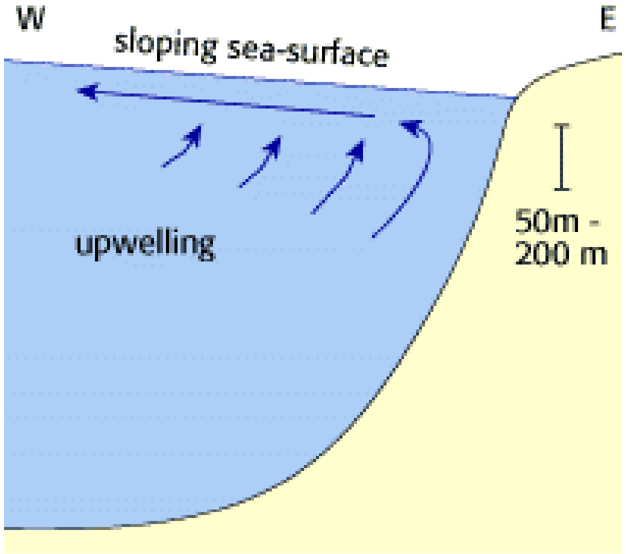


- Abiotic and biotic processes control carbon distributions in the sea.
- Need to understand controls on the variability of these processes

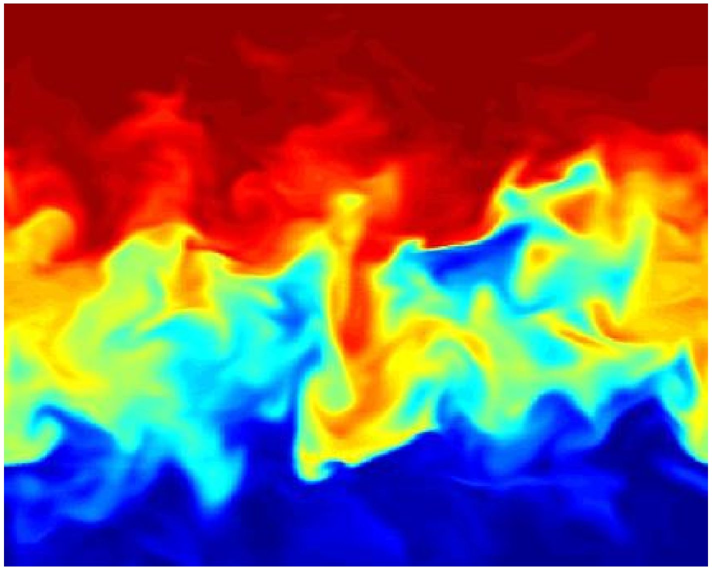
Physics plays a key role in controlling ocean carbon distributions



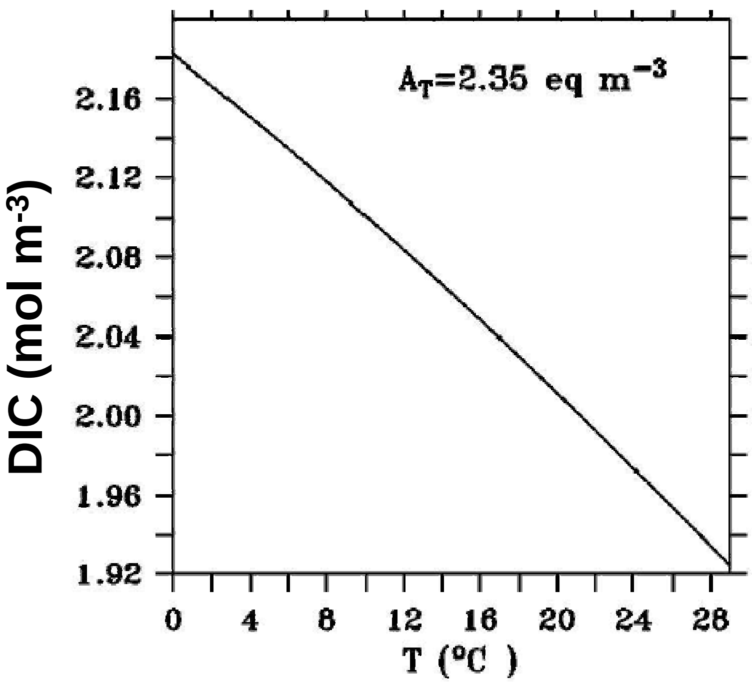
Upwelling in coastal regions



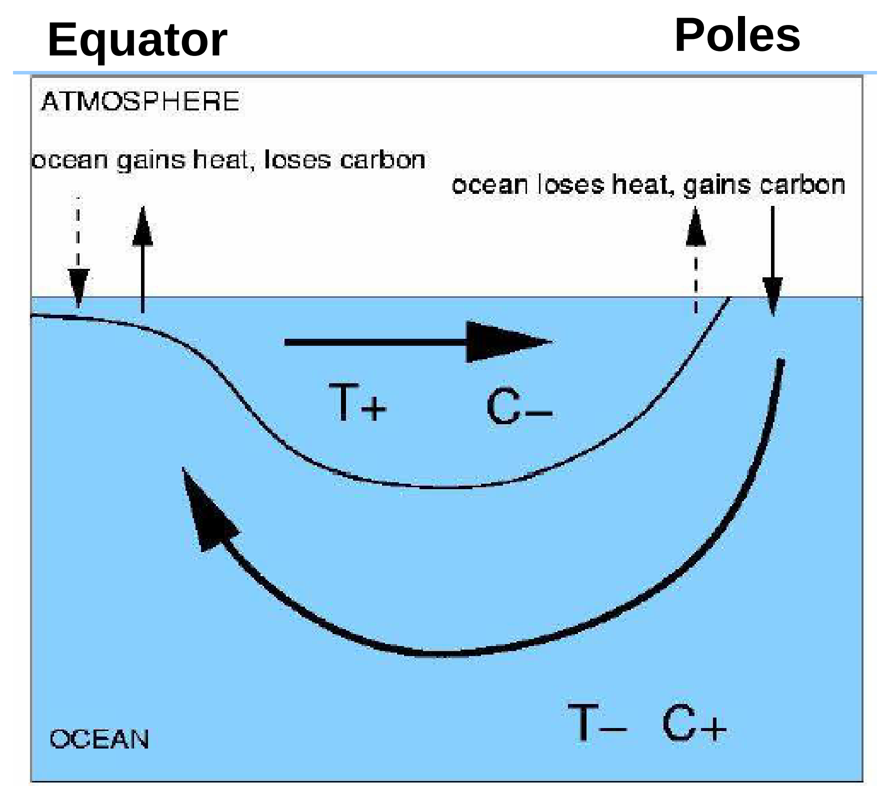
Equatorial upwelling



Mixing



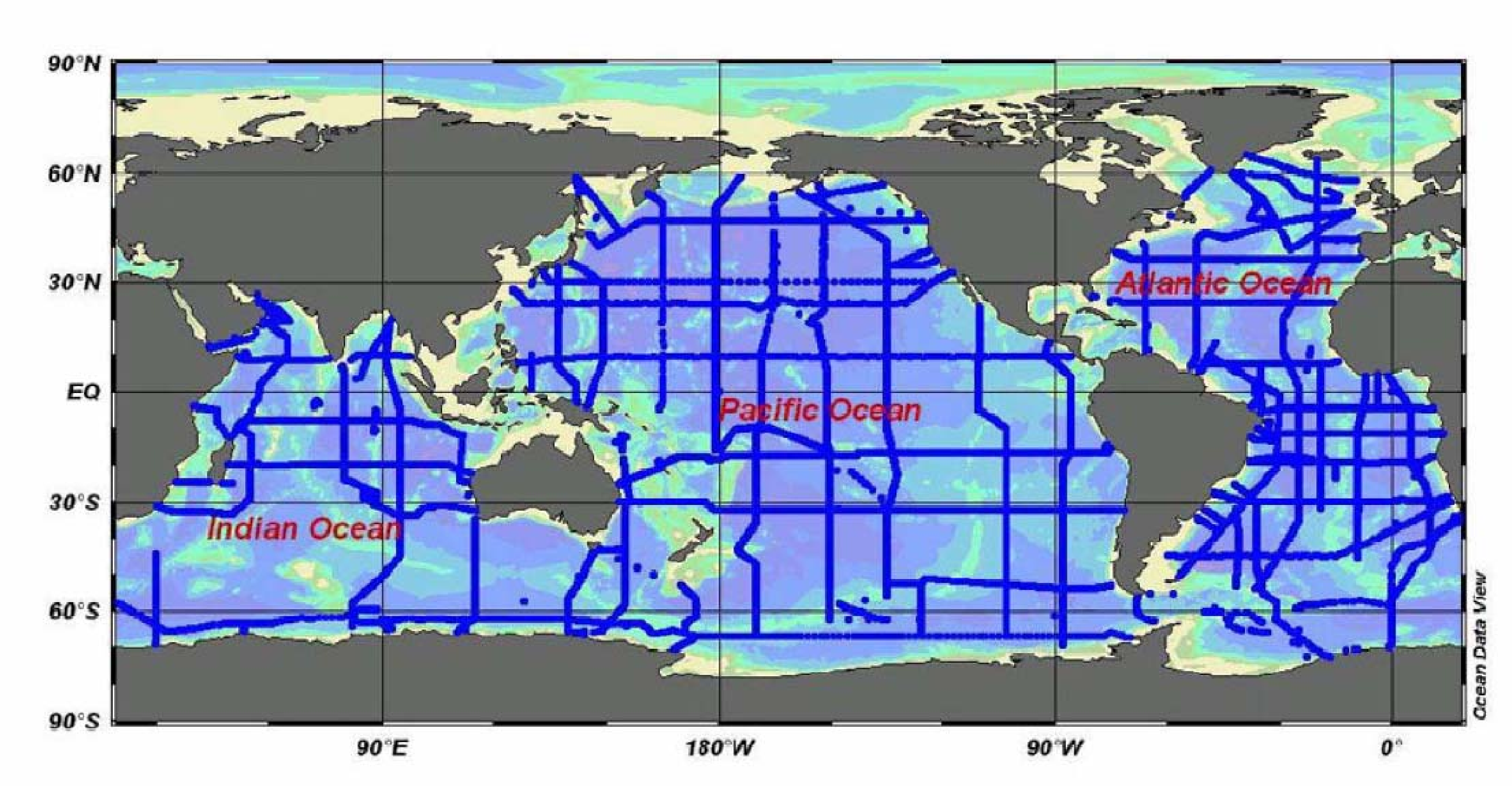
Temperature dependent relationship of DIC at atmospheric $pCO_2 \cong$ 280 ppm (preindustrial levels)

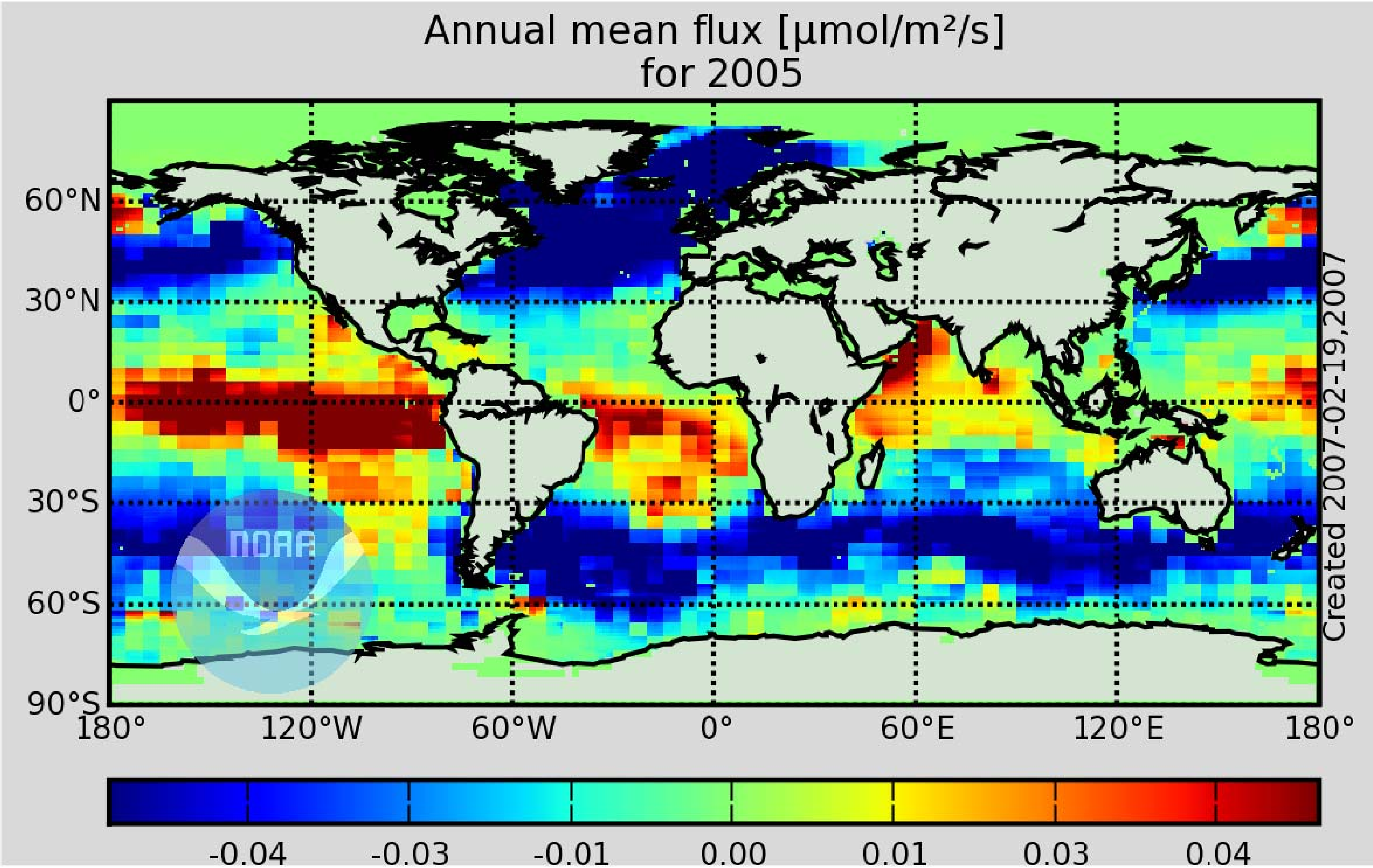


Solubility pump:

- •Cooler water gains CO_2-high latitude regions are sinks for CO_2
- •Cooler, CO_2 rich waters sink
- •Maintains vertical gradient in CO_2
- •Air-sea heat fluxes drive air-sea CO_2 fluxes

The oceanic laboratory:
World Ocean Circulation Experiment hydrography transects

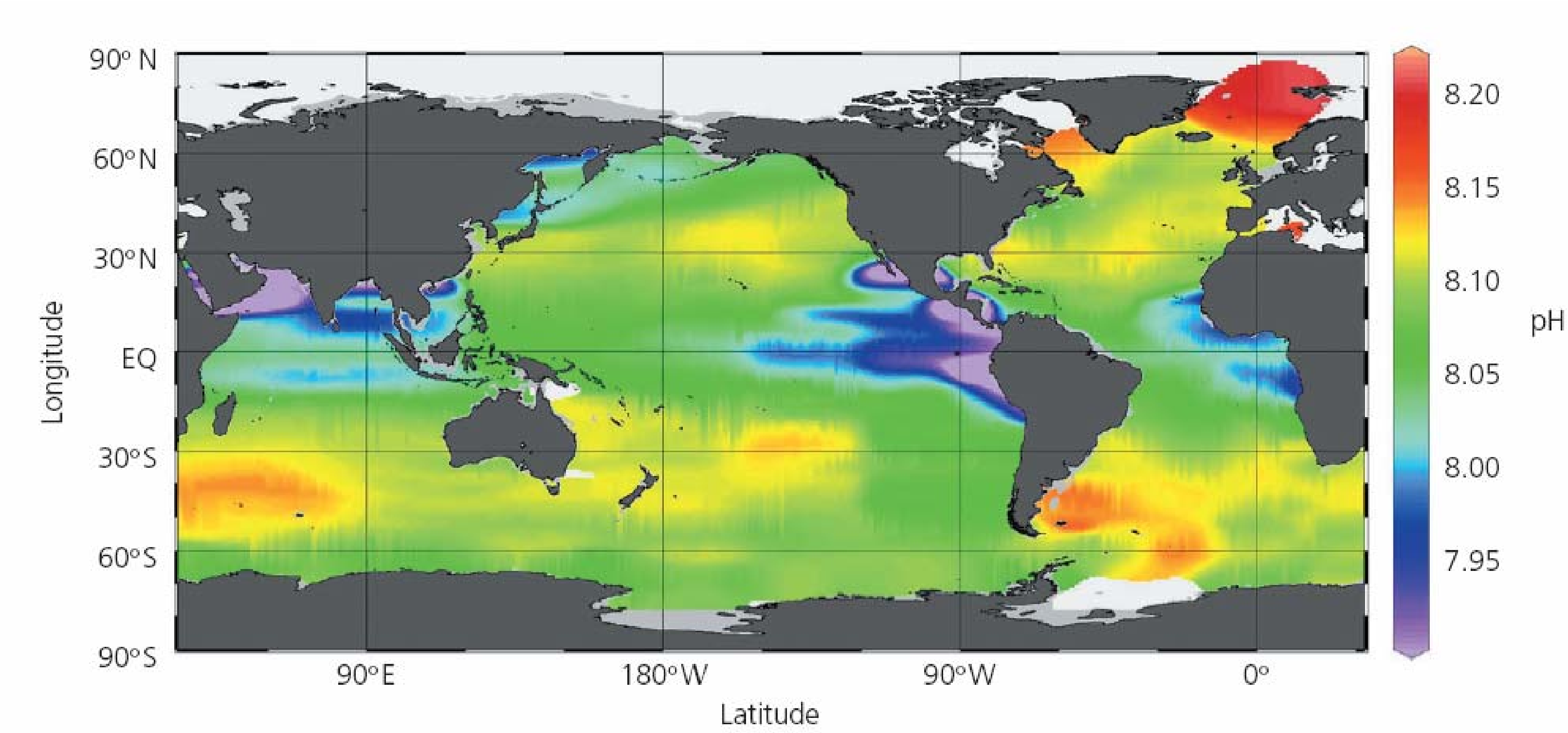




$pCO_2 = pCO_{2(W)} - pCO_{2(A)}$

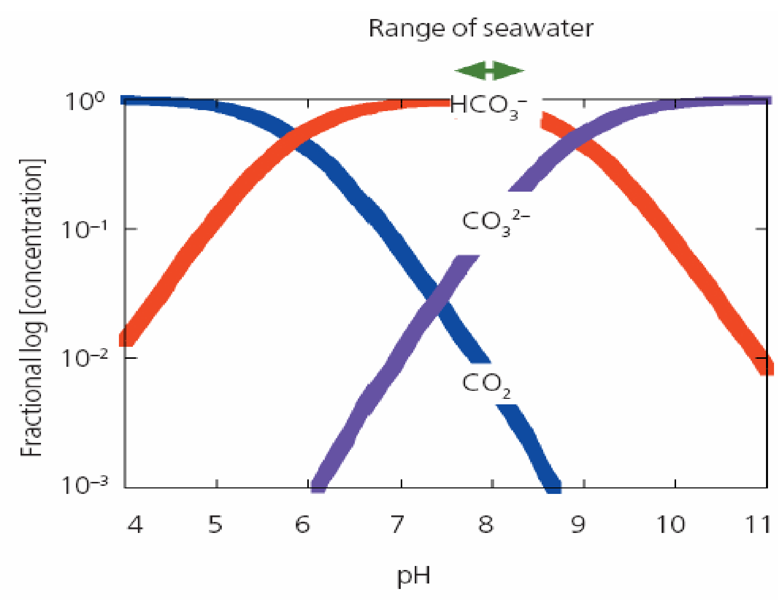
Surface ocean pCO_2

Regions of negative pCO_2 flux are regions where the ocean is a net sink for atmospheric CO_2

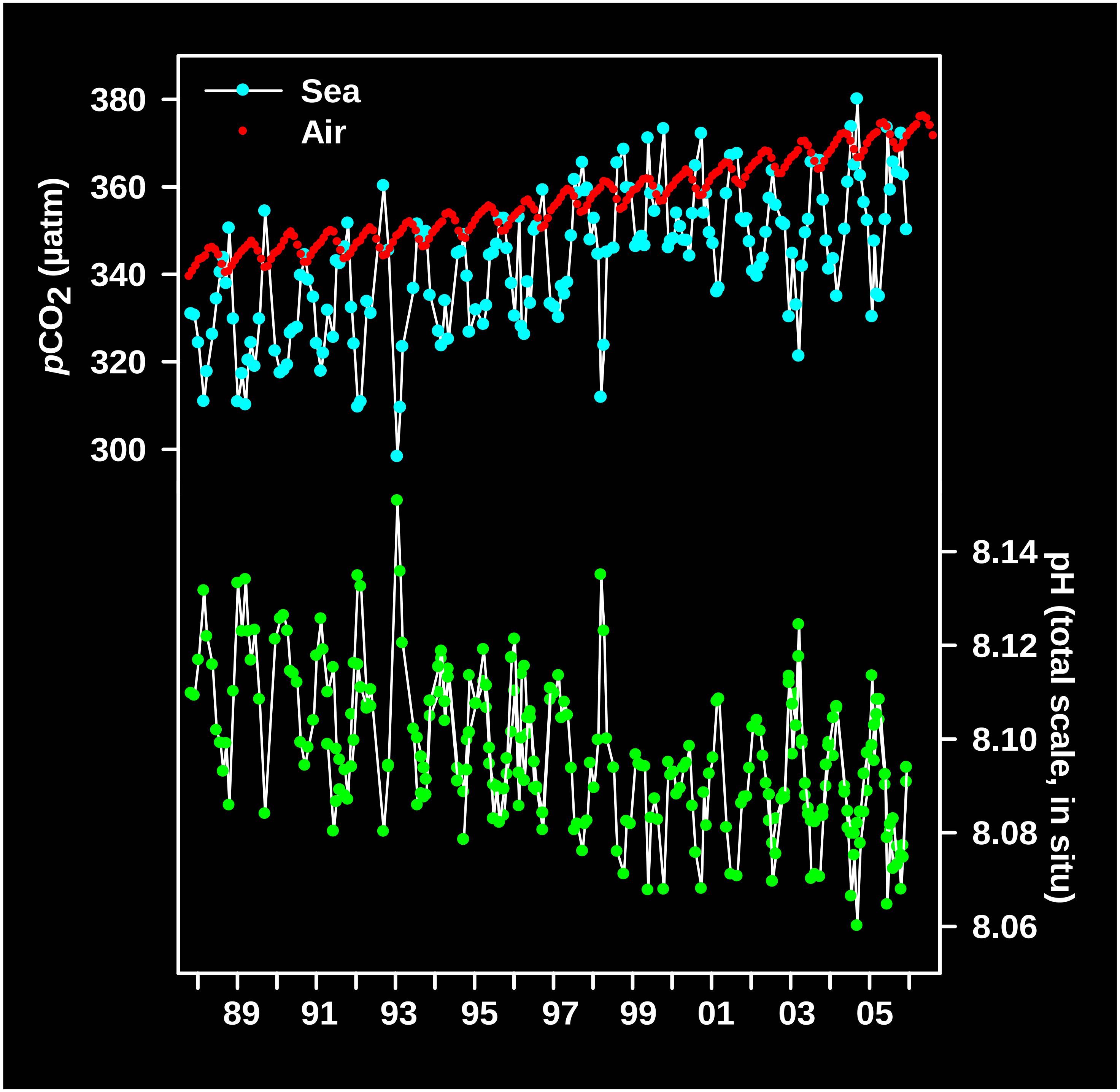


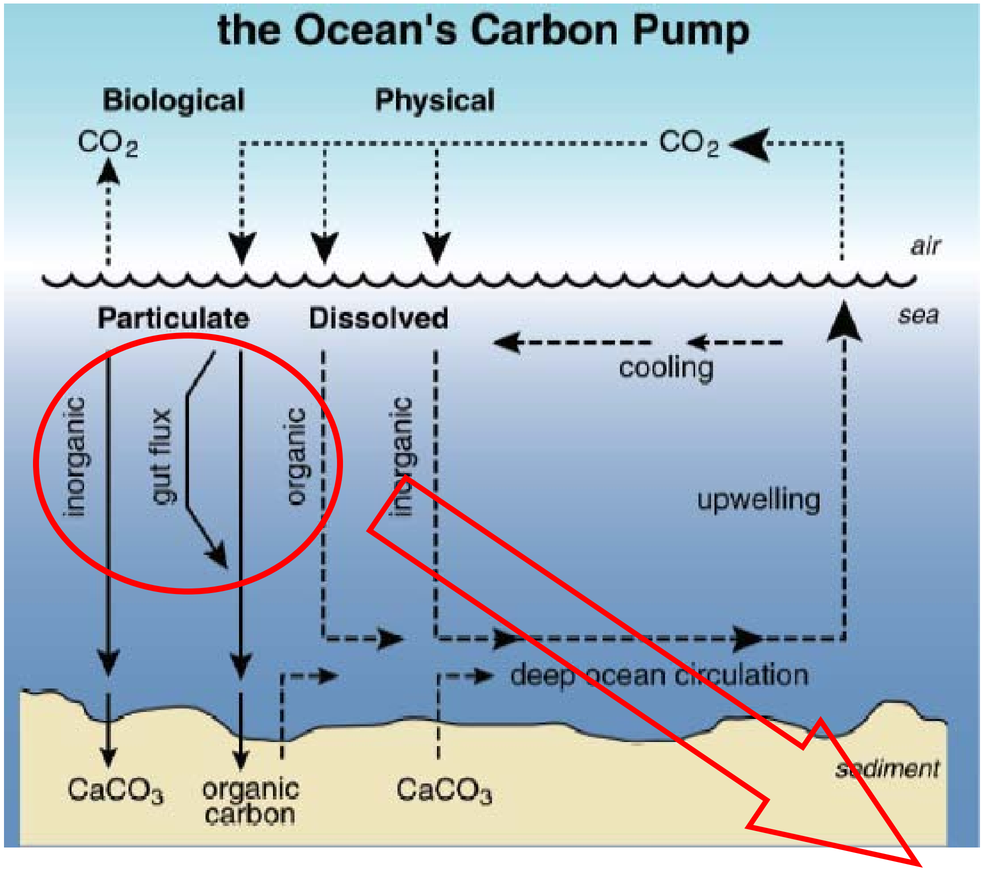
"Ocean acidification due to increasing atmospheric carbon dioxide"
The Royal Society 2005. www.royalsoc.ac.uk

Carbonate chemistry plays a major role in controlling seawater pH

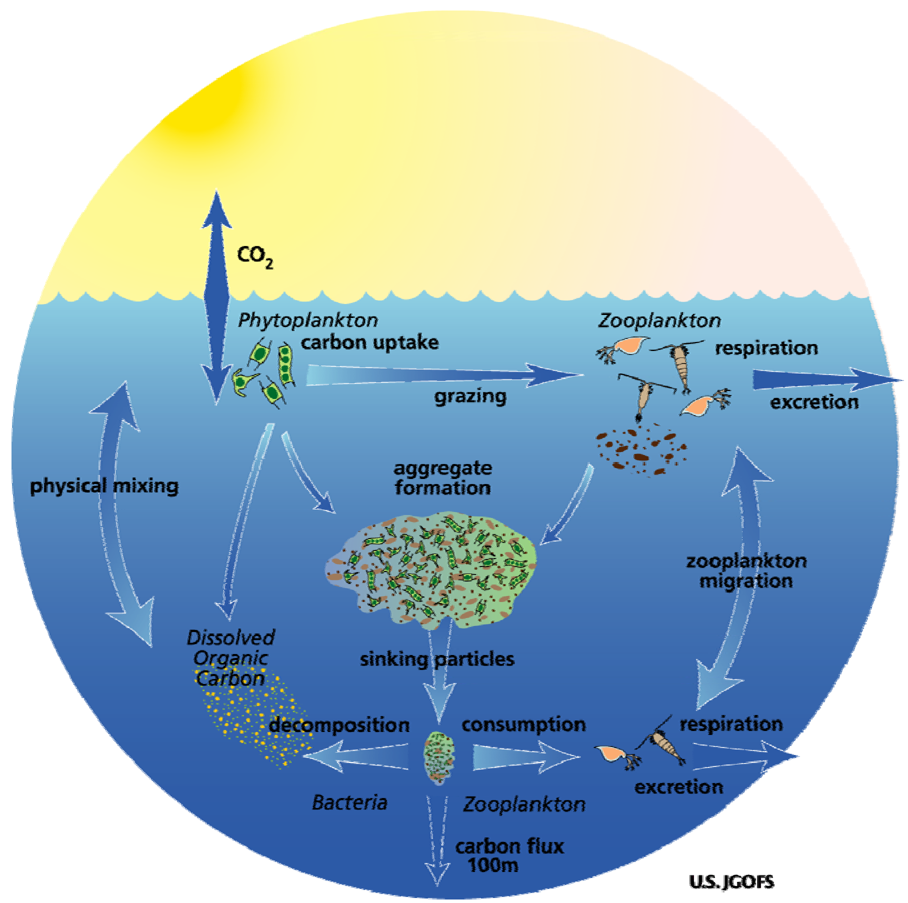


Long-term changes in the ocean carbon system in waters off Hawaii. Oceanic uptake of CO_2 also influences seawater pH.





The biological carbon pump



Primary biologically mediated carbon transformations in the sea

- Photosynthesis and respiration

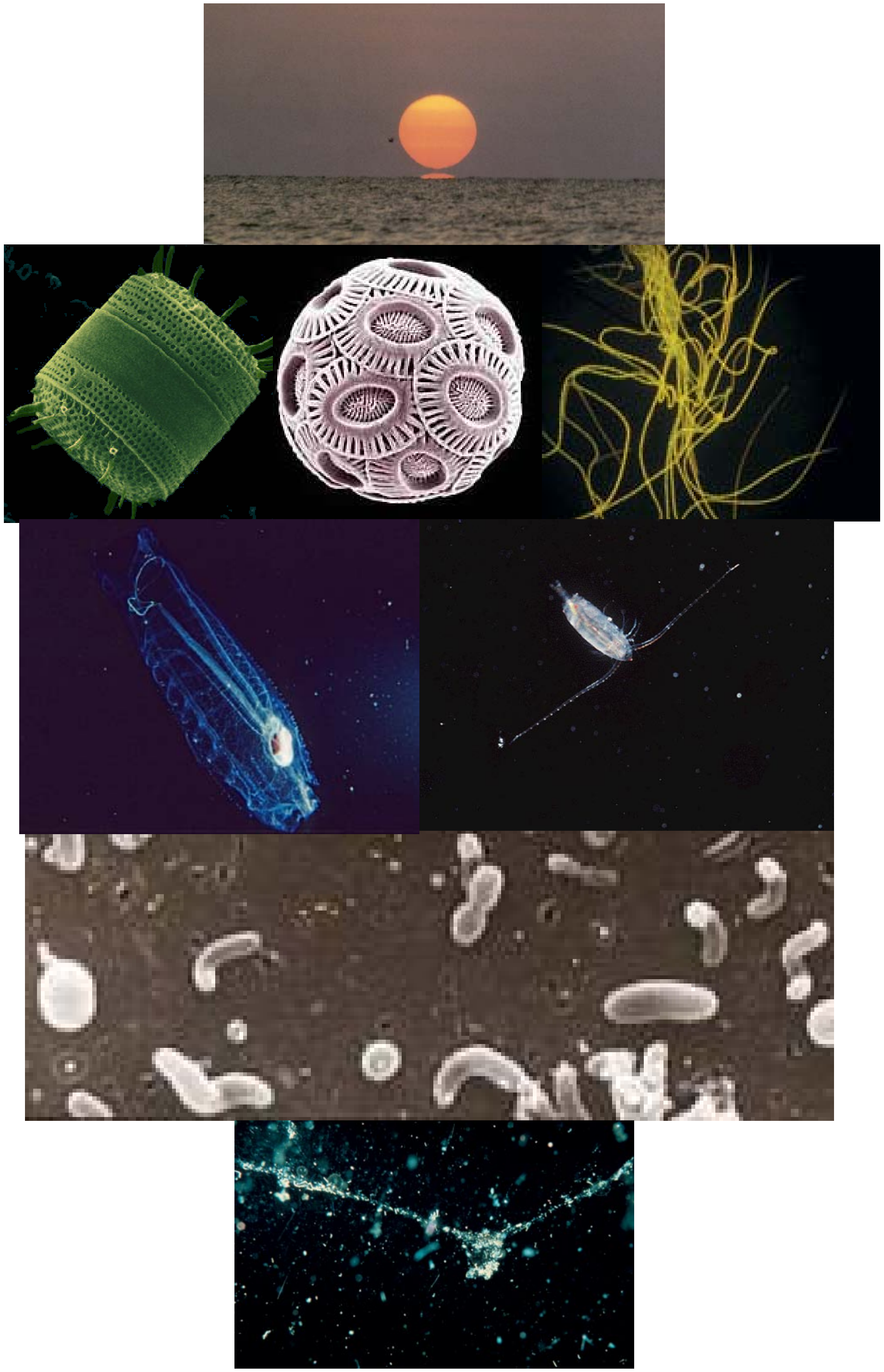
Photosynthesis:

$$6CO_2 + 12H_2O \xrightarrow{\text{Sunlight}} C_6H_{12}O_6 + O_2 + 6H_2O + \text{heat}$$

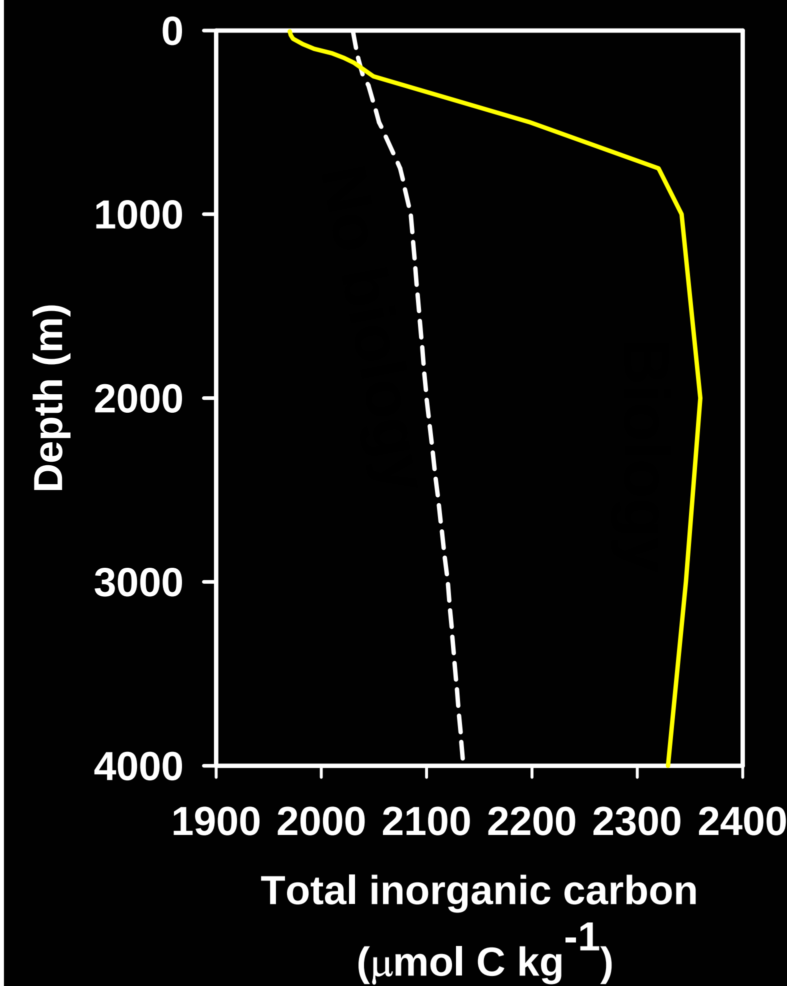
Respiration:

$$C_6H_{12}O_6 + 6O_2 \longrightarrow 6CO_2 + 6H_2O + \text{heat}$$

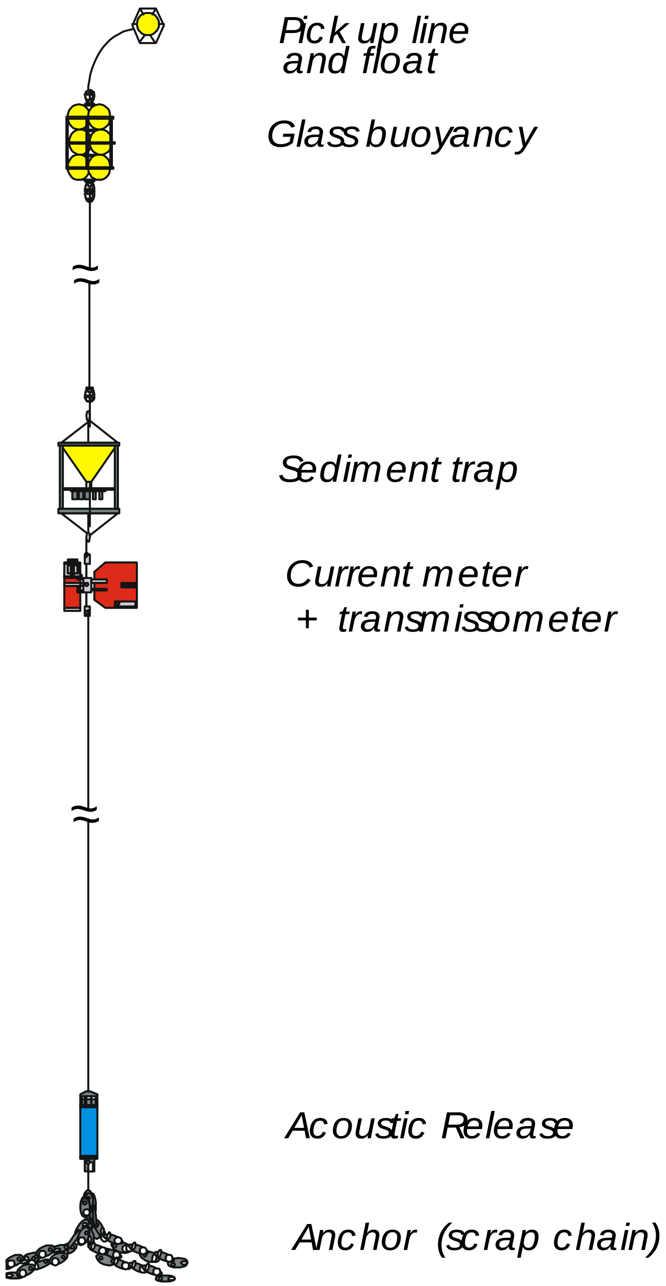
Note that these reactions are VERY generalized: does not include other bioelements (N, P, S, Fe, etc.) that also are involved in these biological transformations.



The biological carbon pump



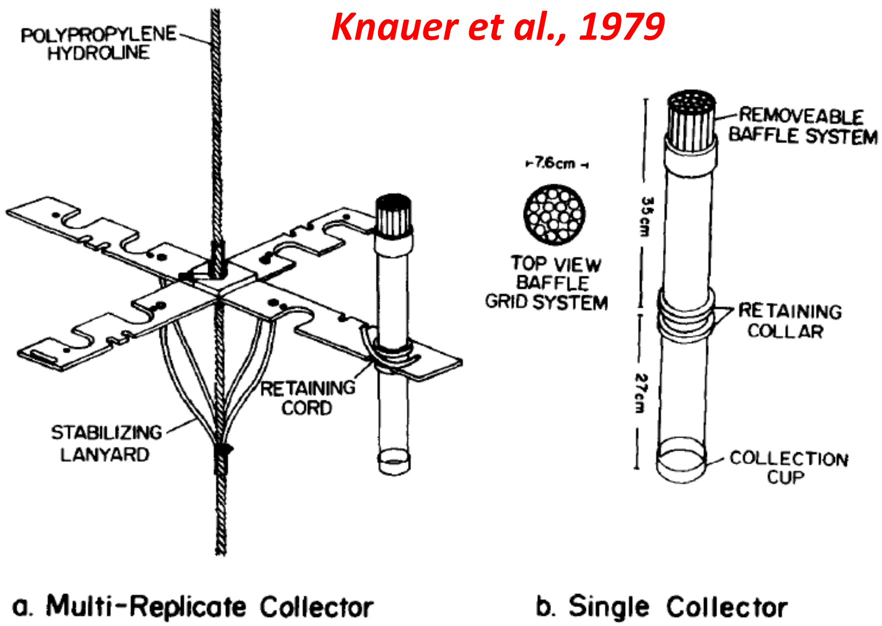
SEDIMENT TRAPS

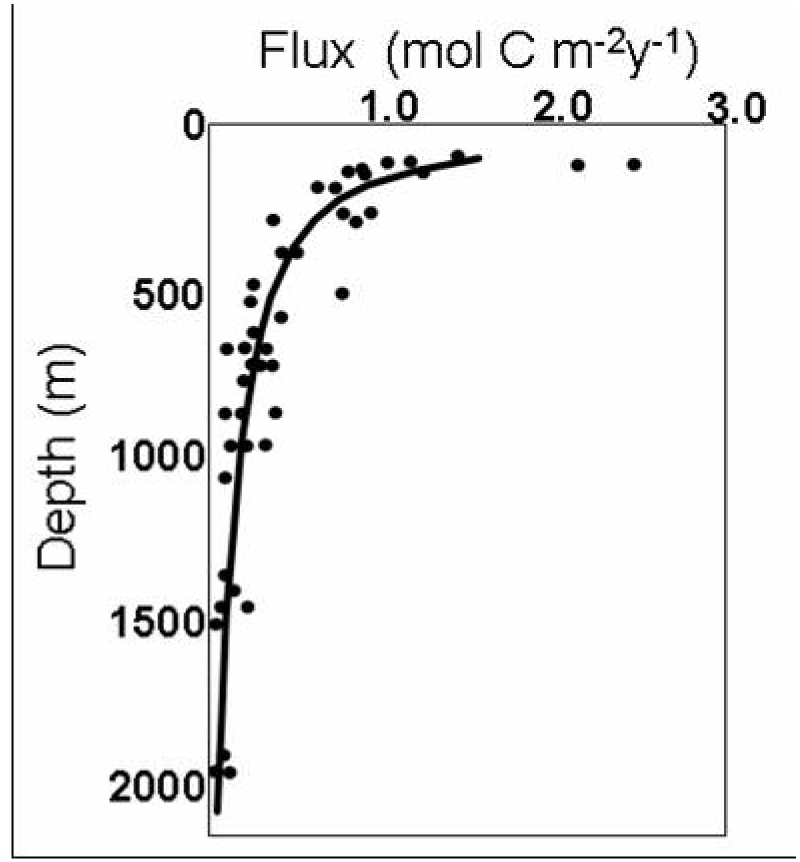


Deep ocean sediment traps. Anchored to the seafloor. Collection interval is determined by the investigator. Provide estimates of sinking particle flux to the deep sea.

VERTEX program- late 70's – mid 80's
Extensive upper ocean trap studies

Knauer et al., 1979

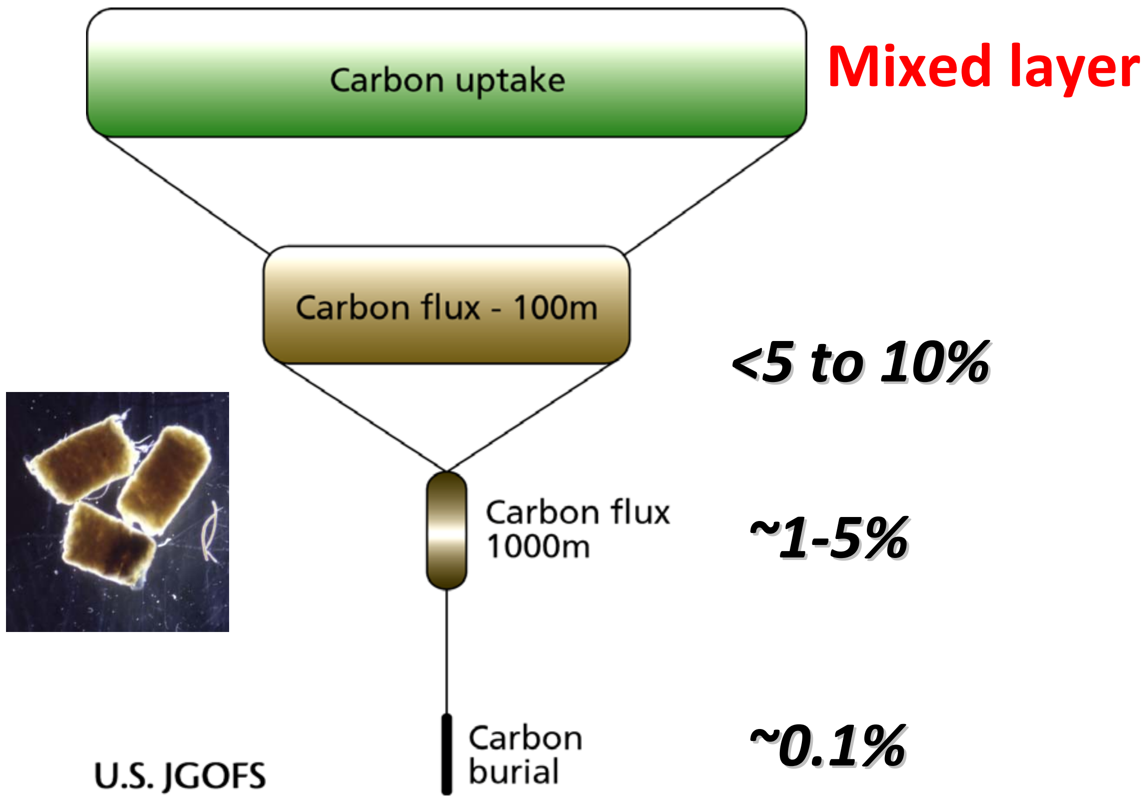




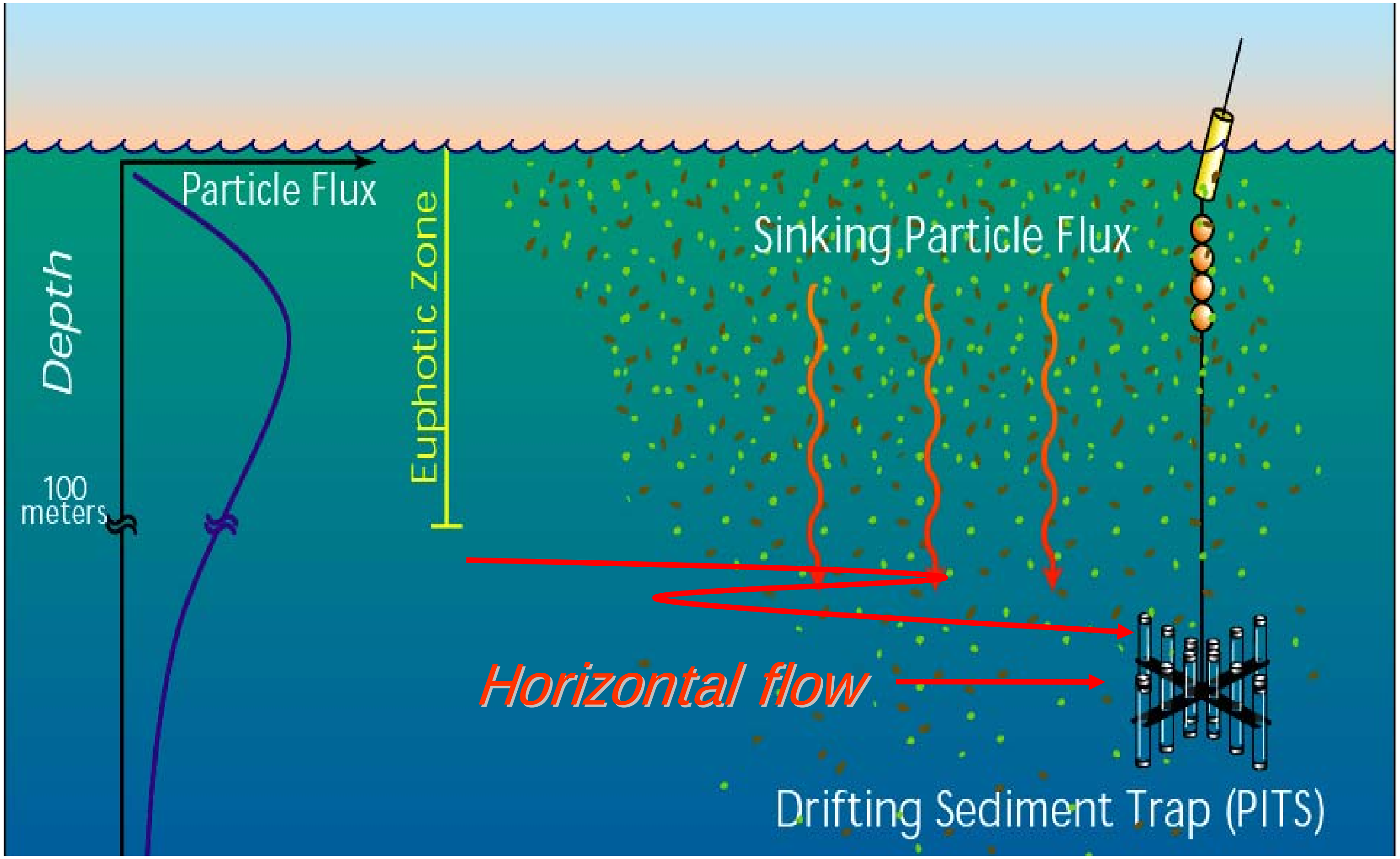
"Martin curve"

$$F = F_{100}\,(z/100)^{b}$$
$$F_{100} = 1.53\ (\text{mol m}^{-2}\ \text{y}^{-1})$$
$$b = 0.86$$

Export and vertical attenuation of particle flux



U.S. JGOFS

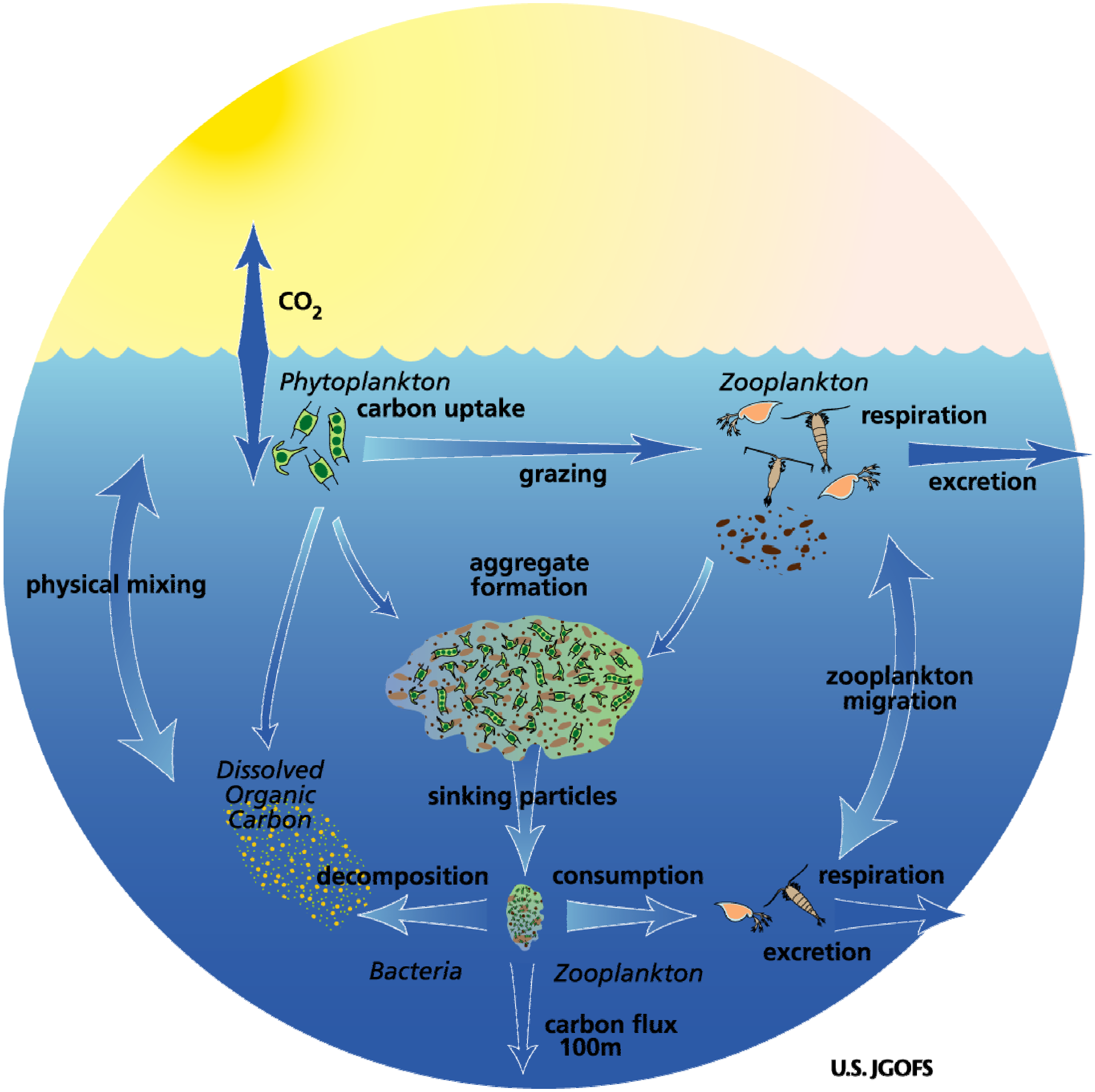


Sinking particles do not sink vertically

- **sinking velocity = 10's - >500 m/day**
- **horizontal velocity = 1 - 10's cm/sec**

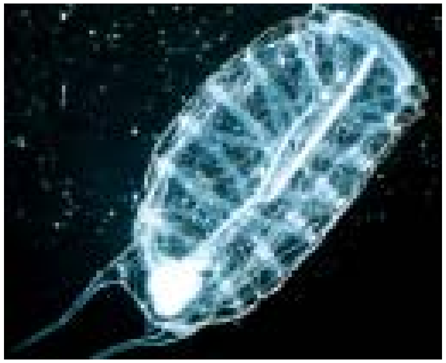
Avg. "sinking" particle:

4 m vertical drop & 520 m horizontal trajectory during 50 min talk

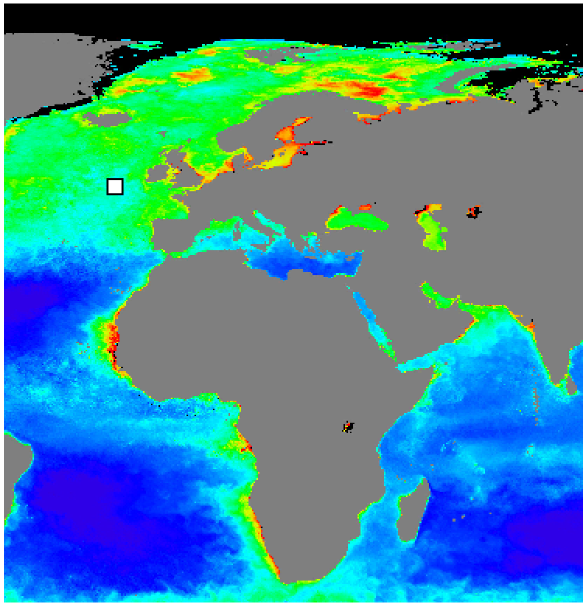


Food web structure is a key determinant on carbon fluxes:

1) Cell size and geometry influence sinking rate
2) Zooplankton repackage material and vertically migrate
3) Small cells support longer food webs = more carbon recycled to CO_2

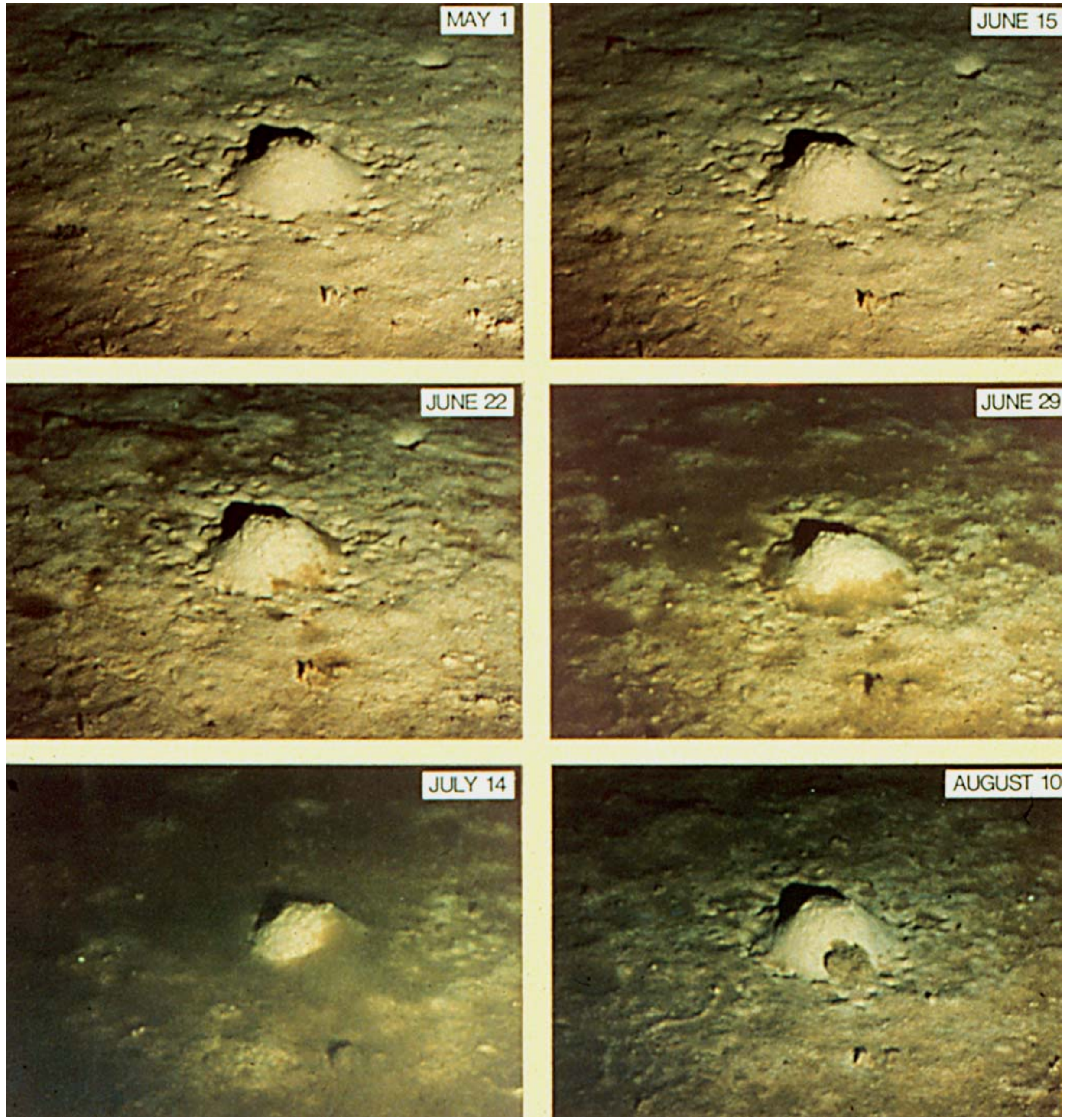


Zooplankton repackage plankton into rapidly sinking fecal material



Sedimentation of diatom-rich salp fecal pellets > 1 mm long, 350 µm wide, 10 µg C per pellet---these things sink FAST...

Direct aggregation and pulsed export is also important



Flux of labile phytodetritus to the deep North Atlantic