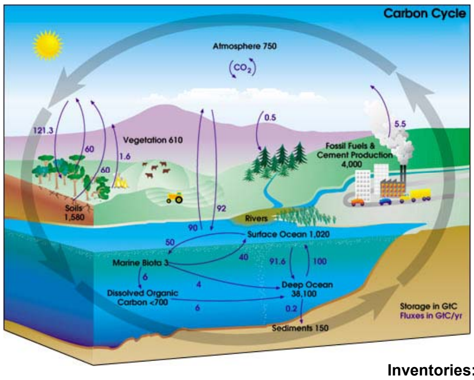
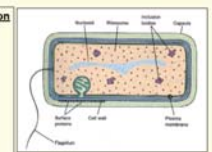
The Carbon Cycle

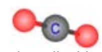


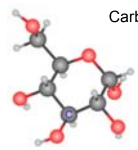
Inventories: black text
Fluxes: purple arrows

WHY CARBON?

Component	Composition
Nucleus (DNA)	C-N-P
Ribosome (RNA)	C-N-P
Membranes	C-P
Cell wall	C-N
Proteins/enzymes/ flagellum	C-N
Storage bodies:	
• PHB	C
• Poly-P	P



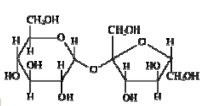

Carbon dioxide (+4)

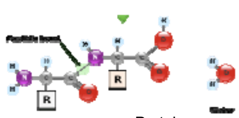


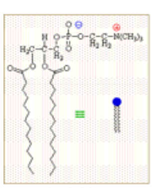
AN = 6 (6P/6N)
AW = 12.011
Oxidation: -4 to +4
Isotopes: ^{11}C, ^{12}C, ^{13}C, ^{14}C

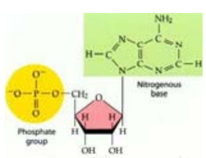

Methane (-4)

Carbon is the currency of life


Carbohydrates


Protein

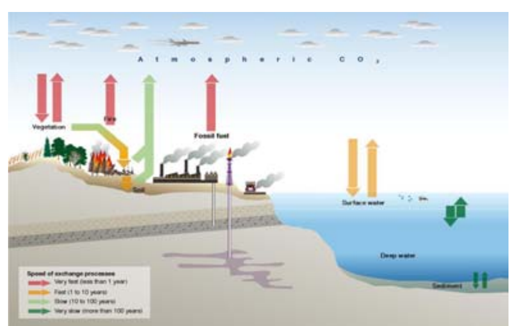

phospholipid



Nucleic acids

All living organisms utilize the same molecular building blocks.

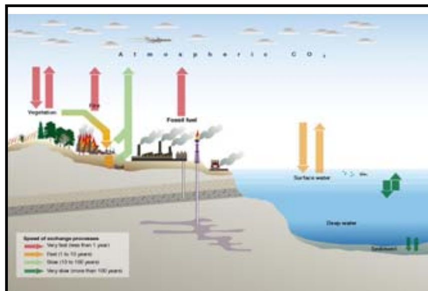
Time Scales of Carbon Exchange in the Biosphere



4 places carbon is stored:
1) Lithosphere, 2) Atmosphere,
3) 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**



0.01 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**

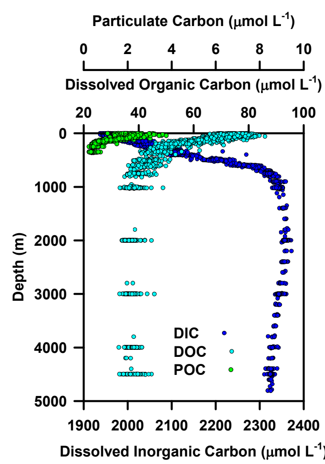
Pools of Carbon in the Sea

- 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.**

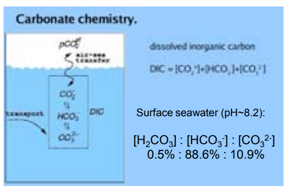
Vertical profiles of carbon in the North Pacific

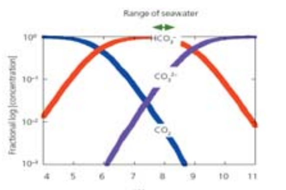


Dissolved inorganic carbon

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

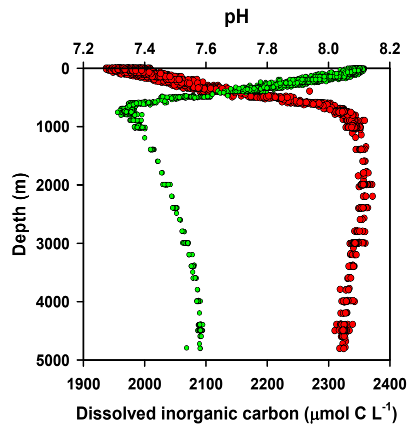
- Solubility of CO_2 in seawater and its equilibrium among these different species depends on temperature, pressure, salinity, pH, and alkalinity.
- The residence time of CO_2 in the atmosphere is ~10 years; it exchanges rapidly with the ocean and terrestrial biome.



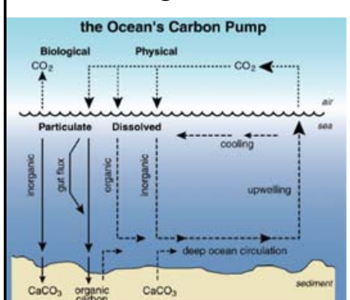


"Ocean acidification due to increasing atmospheric carbon dioxide" The Royal Society 2005. www.royalsoc.ac.uk

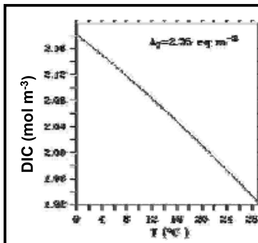
Vertical profiles of DIC and pH at Station ALOHA



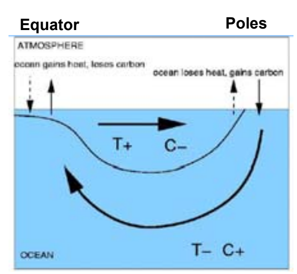
What processes control DIC gradients in the sea?



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

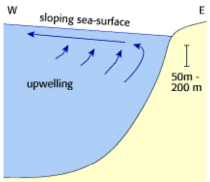


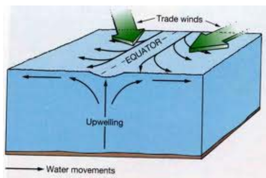
Temperature dependent relationship of DIC at atmospheric pCO_2≅ 280 ppm (preindustrial levels)



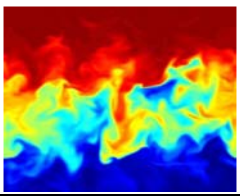
Solubility pump:
- Cooler water gains CO_2-high latitude regions are sinks for CO_2
- Cooler, CO_2 rich waters sink
- Maintains vertical gradient in CO_2
- Air-sea heat fluxes drive air-sea CO_2 fluxes

Physics plays a key role in controlling ocean carbon distributions



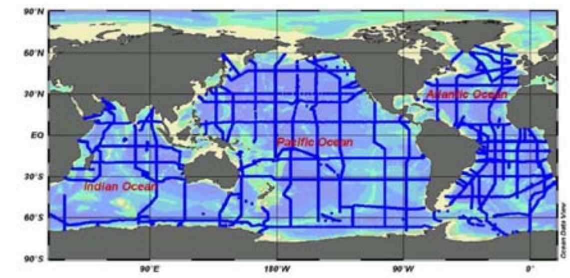


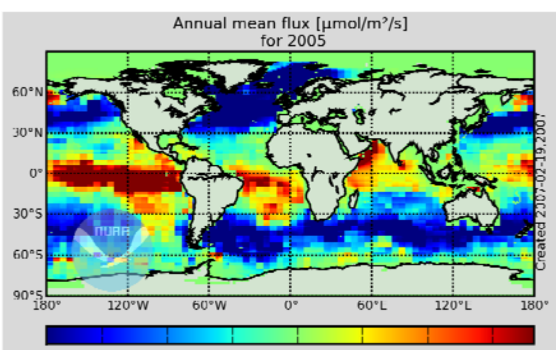
Upwelling



Mixing

The oceanic laboratory: World Ocean Circulation Experiment hydrography transects

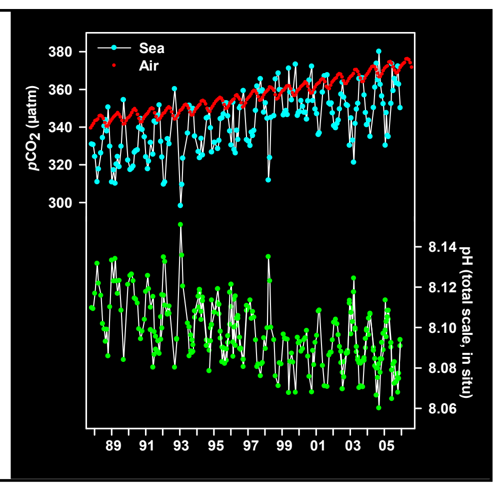


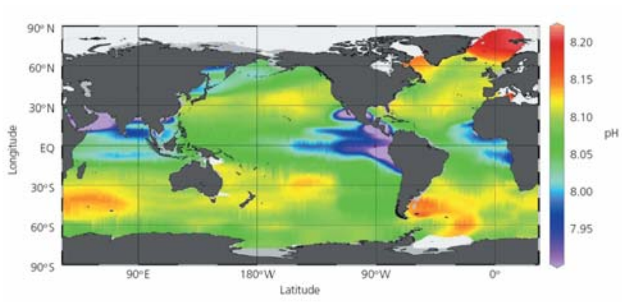


$pCO_2 = pCO_{2(W)} - pCO_{2(A)}$

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

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





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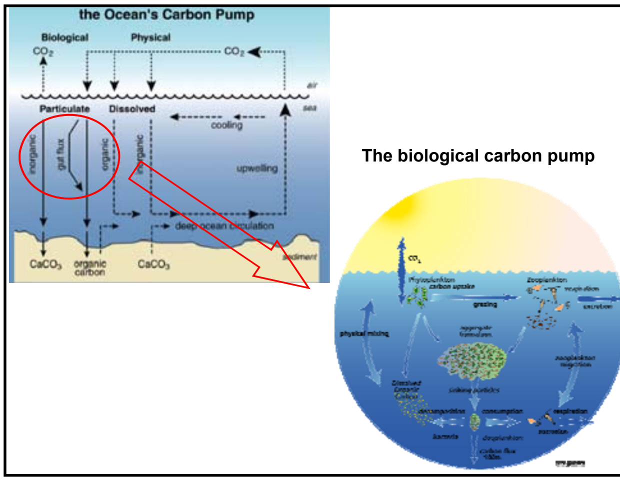
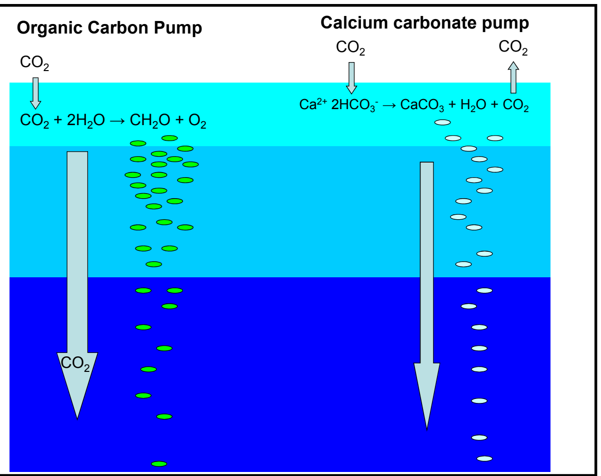
The Royal Society 2005. www.royalsoc.ac.uk





Increasing oceanic DIC has two important implications

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

- Increased H_2CO_3 (lowers pH)
- Decreased CO_3^{2-} (increases solubility of $CaCO_3$)

	Pre-industrial	Today	2× pre-industrial	3× pre-industrial	4× pre-industrial	5× pre-industrial	6× pre-industrial
Atmospheric concentration of CO_2	280 ppm	380 ppm	560 ppm	840 ppm	1120 ppm	1400 ppm	1680 ppm
H_2CO_3 (mol/kg)	9	13	19	28	38	47	56
HCO_3^- (mol/kg)	1768	1867	1976	2070	2123	2160	2183
CO_3^{2-} (mol/kg)	225	185	141	103	81	67	57
Total dissolved inorganic carbon (mol/kg)	2003	2065	2136	2201	2242	2272	2296
Average pH of surface oceans	8.18	8.07	7.92	7.77	7.65	7.56	7.49
Calcite saturation	5.3	4.4	3.3	2.4	1.9	1.6	1.3
Aragonite saturation	3.4	2.8	2.1	1.6	1.2	1.0	0.9

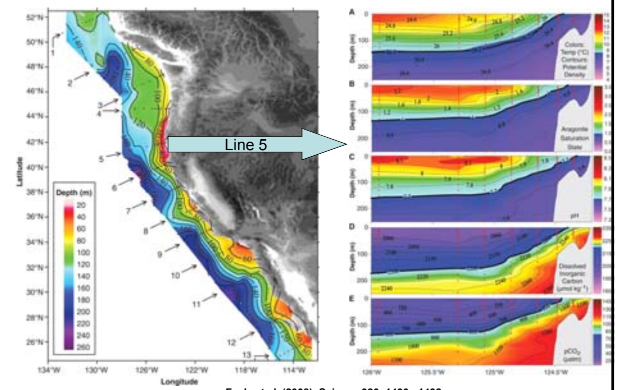
Saturation state:

$$\Omega = ([Ca^{2+}]_{seawater} \text{ X } [CO_3^{2-}]_{seawater}) / ([Ca^{2+}]_{saturated} \text{ X } [CO_3^{2-}]_{saturated})$$

When $\Omega > 1$, $CaCO_3$ supersaturated, shell formation favored.
When $\Omega < 1$, $CaCO_3$ undersaturated, dissolution occurs.

Aragonite: Pteropods and corals
Calcite: Coccolithophores and foraminifera

Dissolution and formation of shells changes $[Ca^{2+}]$ <1%; thus changes in $[CO_3^{2-}]$ largely control Ω



Feely et al. (2008); Science 320: 1490 - 1492

Distribution of the depths of the undersaturated water (aragonite saturation < 1.0; pH < 7.75) on the continental shelf of western North America. On transect line 5, the corrosive water reaches all the way to the surface in the inshore waters near the coast. The black dots represent station locations.

Primary biologically mediated carbon transformations in the sea

- Photosynthesis and respiration

Photosynthesis:

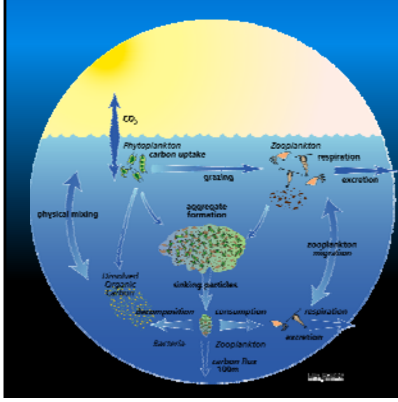
$6CO_2 + 12H_2O$ —Sunlight→ $C_6H_{12}O_6 + O_2 + 6H_2O$ + heat

Respiration:

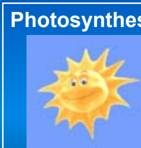
$C_6H_{12}O_6 + 6O_2$ → $6CO_2 + 6H_2O$ + heat

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.

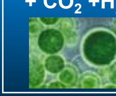
Plankton and carbon



Photosynthesis

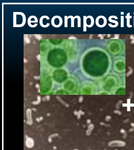


+ CO_2 + H_2O =



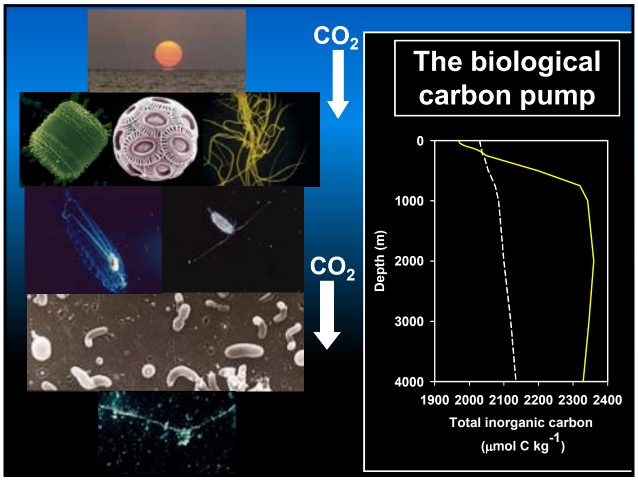
+ O_2

Decomposition

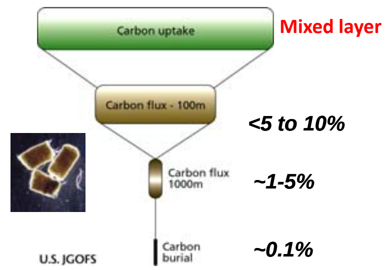


+ O_2

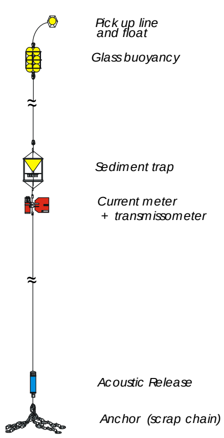
= CO_2 + H_2O



Export and vertical attenuation of particle flux



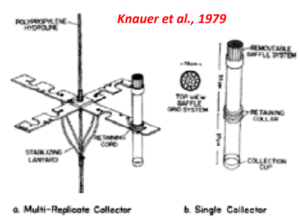
SEDIMENT TRAPS

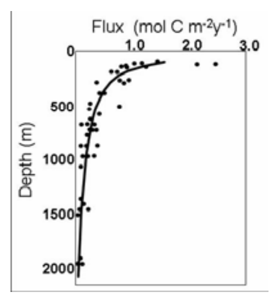


Deep ocean sediment traps. Anchored to the seafloor. Collection interval is determined by the investigator. Provide estimates of sinking particle flux to the deep sea.

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

Knauer et al., 1979



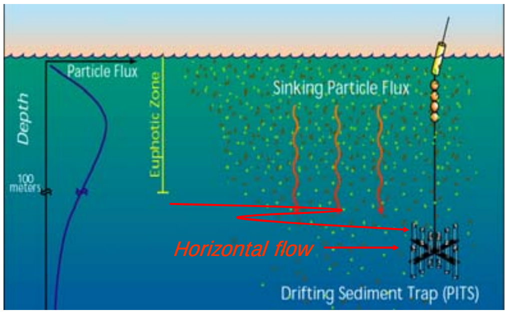


"Martin curve"

$F = F_{100} (z/100)^b$

$F_{100} = 1.53$ (mol m^{-2} y^{-1})

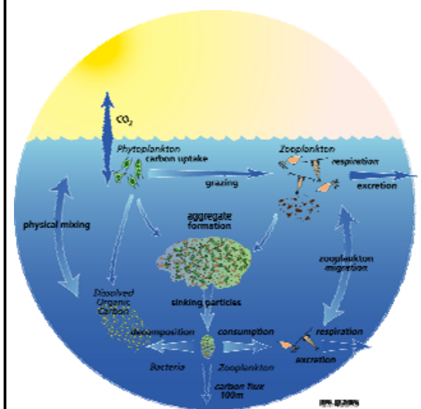
$b = 0.86$



Sinking particles do not sink vertically

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

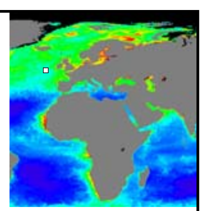
Avg. "sinking" particle:
4 m vertical drop & 520 m horizontal trajectory during 50 min talk



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