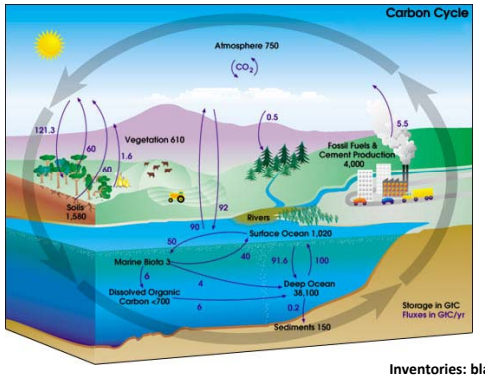
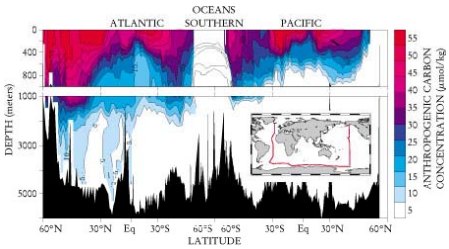
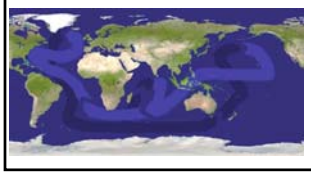
**1 Gt = 1 billion tonnes = 1 Petagram = $10^{15}$ g C**




**Inventories: black text**
**Fluxes: purple arrows**

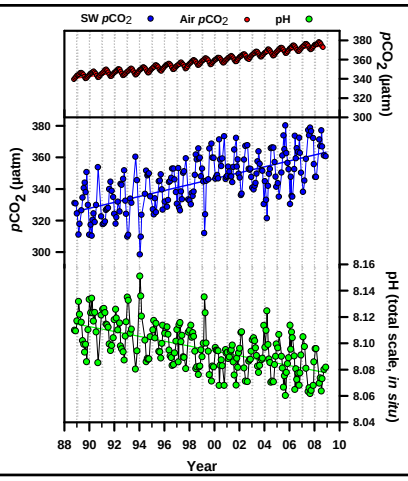
- Penetration of anthropogenic carbon partly reflects ocean conveyor belt model of thermohaline circulation



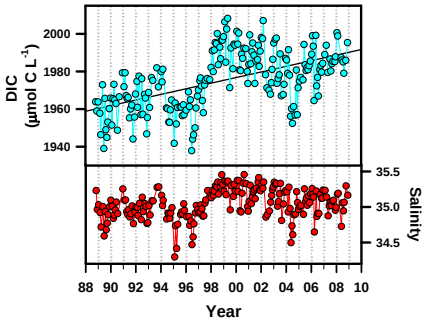



Measurements of DIC concentrations combined with carbon isotope ratios ($^{13}C/^{12}C$) and stoichiometry of $O_2/CO_2$ makes it possible to reconstruct how much anthropogenic carbon has penetrated into the ocean. Note that the Southern Ocean remains poorly characterized. In addition, note that anthropogenic carbon has penetrated significantly below about 2000 meters of the water column only in the North Atlantic.

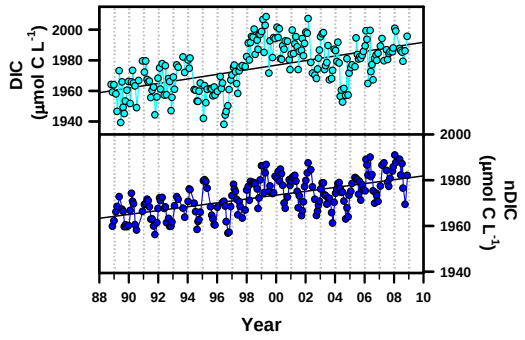
**Long-term changes in the ocean carbon in the subtropical North Pacific.**




**Temporal variability in mixed layer inorganic carbon**



## Interannual variability in inorganic carbon pools

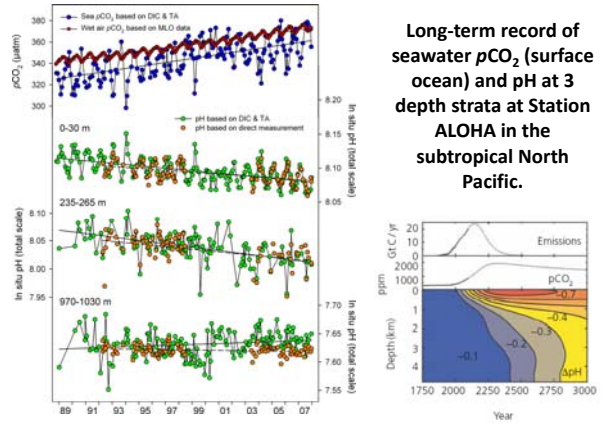



Winn et al. 1994, Dore et al. 2003, 2009

## Increasing oceanic DIC has two important implications

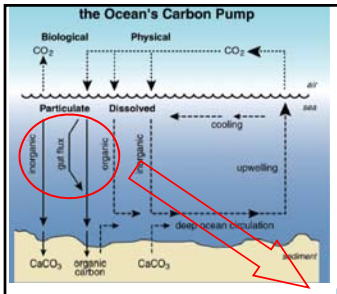
- $H_2O + CO_{2(g)} \Leftrightarrow H_2CO_3$
- $H_2CO_3 \Leftrightarrow H^+ + HCO_3^-$
- $HCO_3^- \Leftrightarrow H^+ + CO_3^{2-}$

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

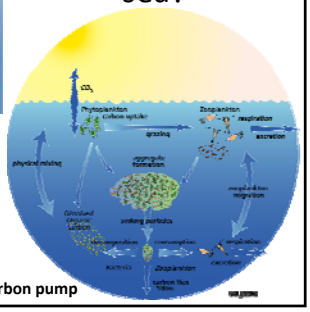



**Long-term record of seawater $pCO_2$ (surface ocean) and pH at 3 depth strata at Station ALOHA in the subtropical North Pacific.**

Dore et al. (2009) PNAS 106: 12235-12240

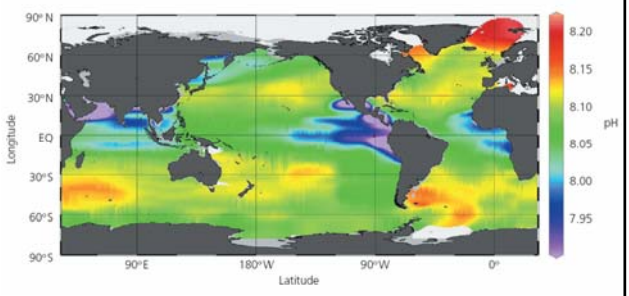



## What processes control carbon gradients in the sea?



**The biological carbon pump**

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




# Biologically mediated carbon transformations in the sea

- Photosynthesis and respiration

**Photosynthesis:**

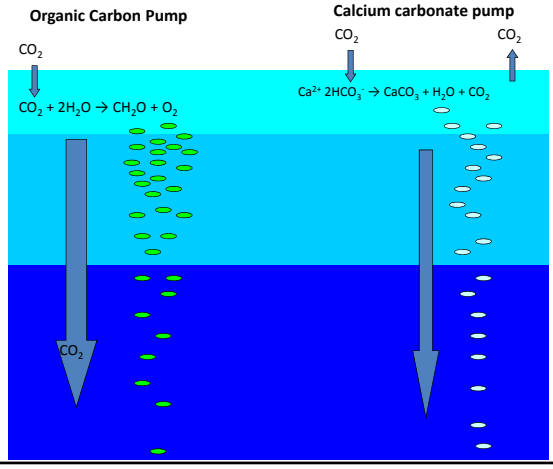
$6CO_2 + 12H_2O \xrightarrow{\text{Sunlight}} C_6H_{12}O_6 + O_2 + 6H_2O + \text{heat}$

**Respiration:**

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

**Calcification:**

$Ca^{2+} + 2HCO_3^- \rightarrow CaCO_3 + H_2O + CO_2$




| | 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 |

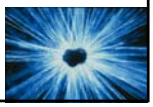
**Saturation state:**

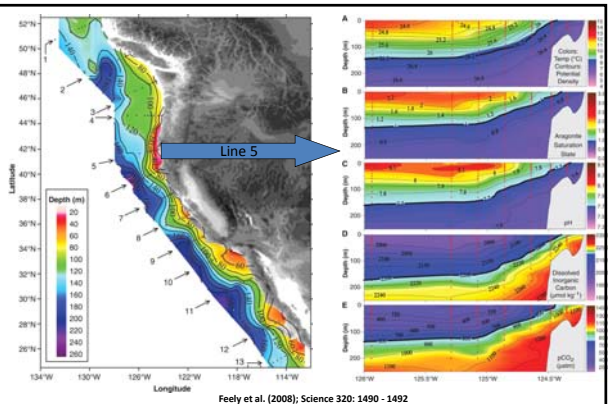
$\Omega = ([Ca^{2+}]_{seawater} \times [CO_3^{2-}]_{seawater}) / ([Ca^{2+}]_{saturated} \times [CO_3^{2-}]_{saturated})$

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

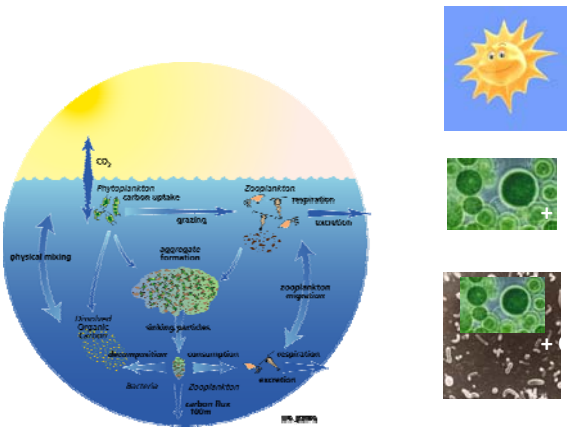
- Photosynthesis and respiration

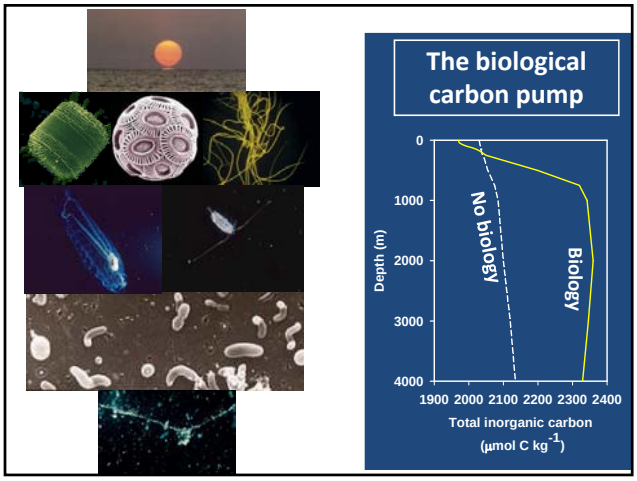
Sunlight

**Photosynthesis:**
$6CO_2 + 12H_2O \rightarrow C_6H_{12}O_6 + O_2 + 6H_2O + heat$

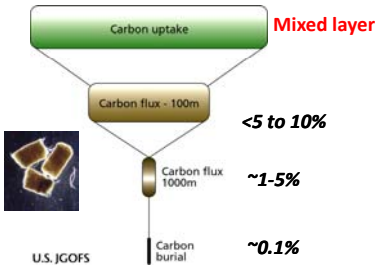
**Respiration:**
$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + heat$

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.

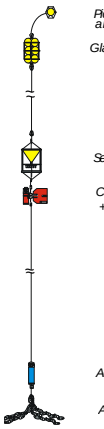


## Export and vertical attenuation of particle flux



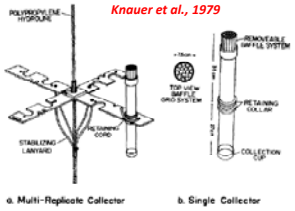

## SEDIMENT TRAPS

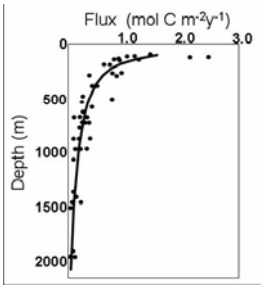



Deep ocean sediment traps. Anchored to the seafloor. Collection interval is determined by the investigator. Provide estimates of sinking particle flux to the deep sea.

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

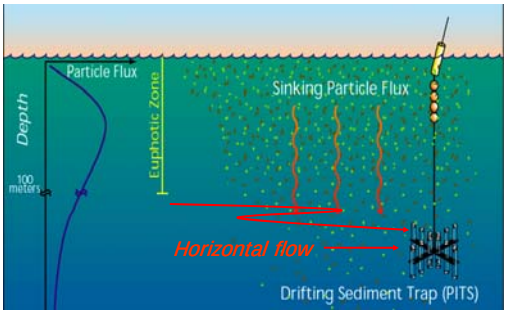
*Knauer et al., 1979*




"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*