

Lecture 8 questions and answers – The Biological Pump

(1) How long would it take a particle of about 2micron in size and a density of 1.5 g/cm³ to get to the bottom of the sea (4000m)? How do particles make it to the bottom?

$$V = 1/18 g [(\rho - \rho_{sw})/\mu] d^2$$

V sinking speed in m/s

$$g = 9.8 \text{ m/s}$$

$$d = 2 \times 10^{-6} \text{ m}$$

$$\rho = 1.5 \times 10^3 \text{ kg/m}^3$$

$$\rho_{sw} = 1.0 \times 10^3 \text{ kg/m}^3$$

$$\mu = 10^{-3} \text{ N s m}^{-2}$$

1.09 x 10⁻⁶ m/s; 255 hours per meter or > 100 years for 4,000 meters
Particles make it to the bottom via fecal pellets or marine snow

The "f ratio": (a, c, d, e)

- o is defined as: nitrate uptake/(nitrate + ammonia) uptake.
- o is defined as: new production / gross productivity.
- o is defined as: (P-R) / P where P is photosynthesis and R is respiration in the upper mixed layer, or photic zone.
- o tends to increase with higher total production.
- o is a good indicator of how efficient biological recycling is in the mixed layer.

The iron hypothesis: (a, b)

- o is based, in part, on evidence that Fe stimulates phytoplankton growth in bottles, especially large diatoms.
- o states that the trace metal Fe is a limiting nutrient in all ocean environments.
- o is based, in part, on evidence that pCO₂ in a Fe fertilized patch of ocean in the Equatorial Pacific, decreased rapidly.
- o is based, in part, on evidence that [NO₃⁻] increased by a factor of two in the Fe fertilized patch of ocean in the Equatorial Pacific.

(2) During a recent cruise to the equatorial Pacific (at 0°, 140°W in September 1992) new production was measured, using the NO₃ uptake technique, to be 2.89 mmol N m⁻² d⁻¹ while particulate organic carbon export was measured using drifting sediment traps to be 10.0 mmol C m⁻² d⁻¹.

- Were new and particulate export fluxes in balance on a carbon basis?
- If not, what might be the explanation?

To be in balance the NO_3 uptake should correspond to the C export flux as estimated from the sediment trap. If NO_3 uptake experiments accurately represent the export of new production and the RKR ratios are applicable then $2.89 \text{ mmol N m}^{-2} \text{ d}^{-1}$ would require $19 \text{ mmol C m}^{-2} \text{ d}^{-1}$ export. This is almost twice the observed value. Therefore the answer in NO it is not in balance.

Possible explanations might include that the NO_3 uptake incubation experiments which are done in bottles do not accurately reflect the real export flux (over estimate) due to exclusion of grazing and mixing below the critical depth. Alternatively the traps might under sample as the export could be in the form of DOC or smaller particles that are not sampled. Also the time scales that the different methods relate to are significantly different hours in the NO_3 incubation and days in the traps.

(3) You have measured O_2 and Ar concentrations in the surface ocean over the course of a month during the summer. Average water temperature and salinity were 25°C and 35 respectively for the period of observation. Average O_2 and Ar concentrations were $225 \text{ } \mu\text{moles/kg}$ and $10.7 \text{ } \mu\text{moles/kg}$ respectively. Both concentrations appeared to be at steady state.

a. Calculate the % saturation for O_2 and Ar in the surface layer at your site.

215 and 10.5 respectively are the saturation values; 104.6% and 101.9%

b. Calculate the air-sea gas exchange using the stagnant boundary layer model. Assume that $\text{DO}_2 = 2.3 \times 10^{-5} \text{ cm}^2 \text{ s}^{-1}$, $\text{D}_{\text{Ar}} = 1.7 \times 10^{-5} \text{ cm}^2 \text{ s}^{-1}$, and z (the stagnant boundary layer thickness) = $30 \mu\text{m}$. $F = -D/Z_{\text{film}} (C_{\text{eq}} - C_{\text{s}})$

for Ar : $1.14 \times 10^{-6} \text{ } \mu\text{mol cm}^2 \text{ sec}^{-1}$ for O_2 : $76.6 \times 10^{-6} \text{ } \mu\text{mol cm}^2 \text{ sec}^{-1}$

c. Determine the magnitude of the bubble injection term for both Ar and O_2 . You can assume that bubble injection introduces gases into the ocean in the same proportions as they have in air.

For Ar this will be $1.14 \times 10^{-6} \text{ } \mu\text{mol cm}^2 \text{ sec}^{-1}$ for O_2 this should be multiplied by oxygen/argon ratio (22.5) which yields $25.65 \times 10^{-6} \text{ } \mu\text{mol cm}^2 \text{ sec}^{-1}$

d. Determine the magnitude of the biological oxygen signal.

$76.6 \times 10^{-6} \text{ } \mu\text{mol cm}^2 \text{ sec}^{-1} - 25.65 \times 10^{-6} \text{ } \mu\text{mol cm}^2 \text{ sec}^{-1} = 50.95 \times 10^{-6} \text{ } \mu\text{mol cm}^2 \text{ sec}^{-1}$

e. What is the equivalent carbon production in $\text{mol C m}^{-2} \text{ y}^{-1}$ based on this biological oxygen signal (assume that $1 \text{ kg} = 1 \text{ L}$). How does it compare to total primary productivity estimates in the world's oceans? New primary productivity? Which of these fluxes should your estimate agree with and why?

Convert the $50.95 \times 10^{-6} \text{ } \mu\text{mol cm}^{-2} \text{ sec}^{-1}$ to $16 \text{ mol m}^{-2} \text{ y}^{-1}$

Convert the oxygen flux to carbon equivalents using the stoichiometric equivalents

$16 \text{ mol O}_2 \text{ m}^{-2} \text{ y}^{-1} \times 106 \text{ C} = 12 \text{ mol C m}^{-2} \text{ y}^{-1} = 144 \text{ gC m}^{-2} \text{ y}^{-1}$

$144 \text{ gC m}^{-2} \text{ y}^{-1} \times 361 \times 10^{12} \text{ m}^2 = 51.9 \times 10^{12} \text{ gC y}^{-1} = 51.9 \text{ GtC y}^{-1}$
(ocean area)

The best estimate of global average primary production is about 50 Gt C y^{-1} . But both Martin et al (1987) and Chavez and Toggweiler (1995) estimated global new production

to be about 7 Gt C yr^{-1} . The O_2 flux should equal the new production estimate but in this case is much larger than new production. The sampling site might not be representative of the average yearly oceanic saturation conditions.

(4) What do you expect the relationship between oxygen supersaturation in the surface ocean and the f ratio to be? Assume that the euphotic zone of the ocean is a well-mixed reservoir open to the atmosphere but closed to the waters below except for particulate flux. Write an equation for the steady state mass balance for oxygen involving only photosynthesis, respiration and gas exchange. Given the information below demonstrate the relationship between the extent of biological oxygen recycling in the mixed layer $f = [(P-R)/P]$ and oxygen supersaturation. For example, if $f = 0.2$ how supersaturated would the surface waters be?

$[\text{O}_2]$, saturation equilibrium = **280** $\mu\text{mol/l}$

Productivity = **500** $\text{mg C m}^{-2} \text{ day}^{-1}$

G_{O_2} , gas exchange rate = **4** m day^{-1}

The flux of a gas across the air/water interface is: Flux = $G \{ [C_i] - [C_{eq}] \}$

$G = D_i/z$ where

D_i = molecular diffusion coefficient

z = stagnant boundary layer thickness

$[C_i]$ = measured concentration in surface water

$[C_{eq}]$ = equilibrium concentration = $p_i K_i$ p_i : atmospheric partial pressure

K_i : Henry's Law constant

What assumption(s) is/are implied in this steady state that might result in our answer being different than the "real" ocean? Justify any assumptions that you have made to answer this question.

Mass balance for oxygen :

$$d[\text{O}_2]/dt = P - R - G \{ [\text{O}_2]_{\text{meas}} - [\text{O}_2]_{\text{equil}} \} = 0 \text{ (steady state)}$$

$$G = 4 \text{ m/day}$$

$$[\text{O}_2]_{\text{equil}} = 280 \mu\text{mol/liter} = 0.280 \text{ mol O}_2 \text{ m}^{-3}$$

$$[\text{O}_2]_{\text{meas}} = \text{measured concentration in surface water}$$

$$\text{Assume } \Delta\text{O}_2:\Delta\text{C} = 138:106$$

$$P = 0.5 \text{ g C m}^{-2} \text{ d}^{-1} / 12 \text{ g C mol}^{-1} \times 138 \text{ mol O}_2 / 106 \text{ mol C} = 0.0542 \text{ mol O}_2 \text{ m}^{-2} \text{ d}^{-1}$$

$$f: \text{ extent of biological recycling} = (P-R) / P \implies R = P (1-f)$$

$$\text{oxygen supersaturation} = \frac{[\text{O}_2]_{\text{meas}} - [\text{O}_2]_{\text{equil}}}{[\text{O}_2]_{\text{equil}}}$$

from mass balance eq'n:
$$\frac{P - R}{G[O_2]_{equil}} = \frac{[O_2]_{meas} - [O_2]_{equil}}{[O_2]_{equil}}$$

$$\Rightarrow \frac{P - \{P(1 - f)\}}{G[O_2]_{equil}} = \frac{P \times f}{G[O_2]_{equil}} = \frac{[O_2]_{meas} - [O_2]_{equil}}{[O_2]_{equil}} = \text{degree of supersaturation}$$

$$O_2 \text{ supersaturation}(\%) = \frac{P \times f}{G[O_2]_{equil}} \times 100$$

so when f increases the supersaturation with respect to oxygen (% O_2 supersaturation) also increases.

The assumptions include:

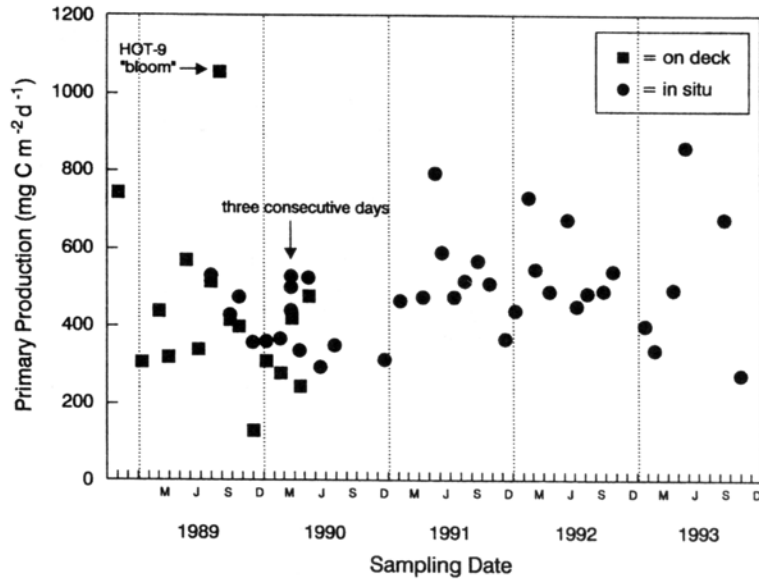
1. $O_2:C$ molar ratio is 138:106, Redfield ratio, which is not always an accurate value in the oceans, but still a reasonable assumption.
2. bubble injection and upwelling are not included. This is NOT a good assumption, as bubble injection is very important in gas exchange.
3. steady state for O_2 .

(5) Attached are results of productivity from the Hawaii Ocean Time Series (HOTS) from 1988 to 1993. The first is based on ^{14}C incubations both on deck and in situ; the second is based on sediment trap flux at 150 m (sediment traps were deployed for two to four days).

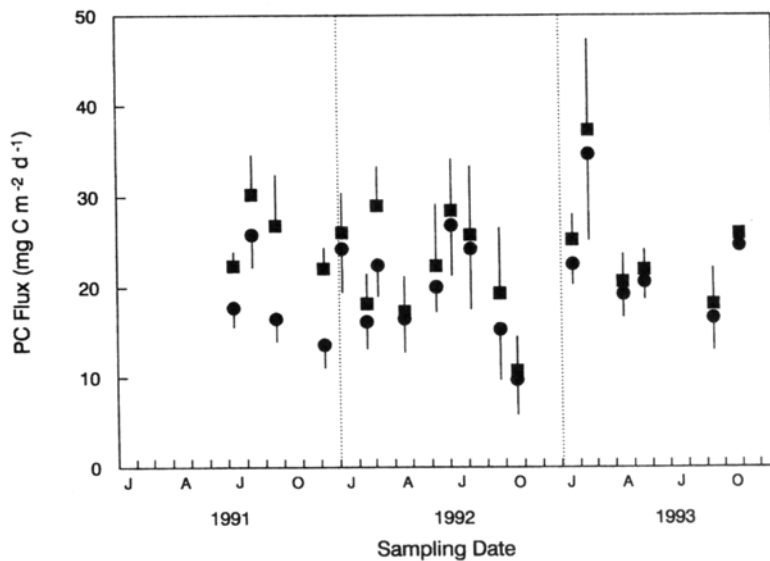
a) What reasons can you attribute for the observed variability over time in the production values in figure a, ^{14}C incubations, and for figure b, sediment trap flux?

b) Calculate a value for new production based on the time series of ^{14}C incubations using one of the suggested empirical relations between primary production and new production. How does this compare with the average value determined from sediment trap deployments? Include and justify the assumptions you are making.

c) Net O_2 production at the same site was determined to be 1-3 mol O_2 m⁻² yr⁻¹. Compare this value with the other two methods. Again, state and justify your assumptions.



Temporal variability in primary production estimates for Sta. ALOHA based on on-deck and *in situ* incubation field experiments. Each data point represents the euphotic zone (0–200 m) depth-integrated value for primary production based on trace metal-clean $^{14}\text{C}\text{-HCO}_3$ uptake at eight depths, as described in the Materials and Methods section. During the HOT-15 cruise, primary production was measured on three consecutive days.



Particulate carbon (PC) fluxes at the 150 m reference level for HOT-28 (July 1991) to HOT-50 (October 1993) with and without post-screening ($335 \mu\text{m}$ Nitex) removal of swimmers by direct microscopy. Data shown are the mean and one standard deviation estimates: (\blacksquare) with small zooplankton included, (\bullet) with all zooplankton removed. Overall, the samples with zooplankton removed averaged 88.0% ($s = 8.4$, $n = 19$).

C-14 variability is due to seasonal variability (e.g. light, nutrients) and episodic productivity, short bursts of productivity as a consequence of upwelling events, which would provide a burst of nutrients. Some variability might also be due to "bottle effects" C-14 incubations might, or might not catch the short bursts of production since the duration of these incubations is typically 12 - 24 hours.

Sediment trap variability is also due to seasonal effects. However, because the trap measurement is an integrated measurement over time, all high productivity events should be measured, unlike incubation. Additional variability might be due to traps that are not 100% efficient, eg they under or over-trap particles.

b) Average value for primary production = about 450 mg C m⁻² day⁻¹

$$450 \frac{\text{mgC}}{\text{m}^2\text{d}} \times \frac{\text{mmol C}}{12 \text{ mg}} \times 0.1 = 3.75 \text{ mmol C m}^{-2} \text{ d}^{-1}$$

|
f ratio = 0.1

Sediment trap flux = 35 mg C m⁻² day⁻¹ x 1/12 = 2.9 mmol C m⁻² day⁻¹

This is reasonably good agreement, considering the following assumptions we had to make:

- $f = 0.1$, for oligotrophic ocean, this is OK
- O:C ratio is 138:106. This is variable around the world ocean; based on stoichiometric ratio
- Sed traps are assumed to be 100% efficient; no advection of particles, etc. This assumption needs to be made, but is not always true.
- Bottles simulate the environment well (probably also not true).

c)

$$1 - 3 \frac{\text{molO}_2}{\text{m}^2\text{year}} \times \frac{106 \text{ C}}{138 \text{ O}_2} \times \frac{1 \text{ year}}{365 \text{ day}} = 2.1 - 6.3 \text{ mmol C m}^{-2} \text{ d}^{-1}$$

This corresponds well with the above values. Assumptions include that physical processes including bubble injection, gas exchange advection, vertical mixing are accounted for or unimportant (usually the former is true).

(6) Answer the following questions given the sediment trap data from the Equatorial Pacific (all traps are the same size and shape and have been deployed for the same time length). Plotting the data may help visualize results

- (a) What are the general features for OrgC, N, P and Ba, fluxes with depth?
- (b) Compute a degradation rate in mg/day for OrgC between sampling depths. Assume that the only source of particles to the tarp is from downward vertical transport and that the sinking rate is 10m/day
- (c) Can you comment about the C:N, C:P and C:Ba changes and explain?

Units for total flux are in $\text{mg m}^{-2} \text{day}^{-1}$ for the elements in is in $\mu\text{mol m}^{-2} \text{day}^{-1}$

Depth	Total particulate	OrgC	Porg	Norg	Ba _{bio}
880	33.3	416	3.2	51.4	3.8
1280	27.5	206	1.4	35.28	3.0
2280	24.5	95	0.56	11.2	2.1
3620	22.2	37	0.2	4.0	1.05

The general feature is that all the particulate fluxes decrease with depth
 To calculate the degradation flux you need to calculate the difference in Org C flux between two depths and the difference in depth (thus time assuming 10m/day) and dividing these would yield the degradation rate.
 For example between 880 and 1280 are 400 meters which correspond to:
 $400\text{m} / 10 \text{ m day}^{-1} = 40 \text{ days}$. The change in C flux: $416-206 = 210 \text{ mg m}^{-2} \text{day}^{-1}$
 Therefore $210 \text{ mg m}^{-2} \text{day}^{-1} / 10 \text{ days} = 21 \text{ mg m}^{-2}$. A similar calculation can be done for each depth interval so between 1280m and 2280 the rate 1.11 mg m^{-2} .

C:N and C:P increase with depth suggesting preferential remineralization of P and N relative to C while C:Ba decreases with depth suggesting particulate Ba formation associated with organic matter degradation

(7) The water age at isopycnal surface $\sigma_\theta = 27$ (600m depth) off the north coast of California was determined by CFC ratios to be about 30 years; this isopycnal outcrops around BC Canada the surface temperature there is about 10 degrees. The oxygen content of the water off CA at this isopycnal surface is 100 $\mu\text{mol/liter}$. Estimate the OUR as the water travels along this isopycnal. What is the organic C consumption rate?

$$280 - 100 = 180;$$

$$(180\mu\text{M}/1000\text{cm}^3) \times 60000\text{cm}/30\text{yr} = 360\text{mM cm}^{-2} \text{yr}^{-1} = 3.6 \text{ mol m}^{-2} \text{yr}^{-1}$$

$$= 2.76 \text{ mol C m}^{-2} \text{yr}^{-1}$$