1 The Large Scale Distribution of Phosphate in the Ocean.

Figure 1: Observed meridional sections of phosphate, $PO_4$ ($\mu$mol kg$^{-1}$): (a) Atlantic, (b) Pacific.

Figure 2: Observed distribution of phosphate, $PO_4$, ($\mu$mol kg$^{-1}$) on potential density surfaces (a) $\sigma_\theta = 26.5$, (b) $\sigma_\theta = 27.0$, (c) $\sigma_\theta = 27.5$
2 Nutrient Utilization.

The distribution of phosphate (and other nutrients) in the ocean (Figs. 1 and 2) reflects the combined effect of physical transport and biological sources and sinks. What are the relative contributions of preformed and regenerated phosphate (see Box 2) to the large scale patterns?

Preformed and regenerated quantities.

Below the mixed-layer, the concentration of a biologically active element, $B$, can be described as the sum of two contributions: The preformed concentration, $B_{\text{pre}}$, is the concentration in water parcel at the time of subduction. The regenerated or biological contribution, $A_{\text{bio}}$, is the accumulation of $B$ in the water parcel since subduction due to the remineralization of sinking particulate or dissolved organic matter. (MICK-REF FOR PREFORMED? BROECKER?).

$$B = B_{\text{pre}} + B_{\text{bio}}$$

The concentration of phosphate below the mixed-layer is the sum of two components: Preformed phosphate, $PO_{4,\text{pre}}$, the concentration of phosphate in a water parcel at the time of subduction, and biological phosphate, $PO_{4,\text{bio}}$, the subsequent accumulation of phosphorus from the remineralization of dissolved and particulate organic matter:

$$PO_{4} = PO_{4,\text{pre}} + PO_{4,\text{bio}}$$

The relative magnitude of the biogenic and total phosphate concentrations provides a measure
of the biological contribution. We define a local measure of “nutrient utilization”:

\[ P_* = \frac{P_{O_4,\text{bio}}}{P_{O_4}} \]  

(3)

\( P_* \) can vary between 0 and 1: \( P_* = 1 \) indicates that all of the local phosphate arrived in the water parcel in the form of organic matter. Conversely, where \( P_* = 0 \), all of the phosphate in the water parcel was present at the time of subduction and, locally, the biological pump is very inefficient.

2.1 What is the Contribution of the Biological Pump to the Phosphate Distribution the Oceans?

Combining observed phosphate and oxygen concentrations we may estimate \( P_* \), a measure of nutrient utilization, throughout the ocean. As with other biologically active elements, the subsurface concentration of oxygen can be described in terms of preformed and regenerated contributions (see Box 2):

\[ O_2 = O_{2,\text{pre}} + O_{2,\text{bio}} \]  

(4)

If the elemental ratio of oxygen and phosphorus transformations to and from organic matter is constant, \( R_{OP} \), then we may relate the biogenic contributions to phosphate and oxygen at depth, \( O_{2,\text{bio}} = R_{OP} P_{O_{4,\text{bio}}} \). Redfield (MICK-REF) evaluated \( R_{OP} = -138 \) based on the elemental ratios in organic matter and dissolved inorganic concentrations in the ocean. \(^1\) Dissolved oxygen equilibrates with the atmosphere on timescales of a few weeks in the surface ocean (see Section MICK-GAS-EXCHANGE-SECTION). The residence time of waters in the mixed layer is generally long enough that surface waters, where preformed concentrations are set, are generally close to saturation: \( O_{2,\text{pre}} \sim O_{2,\text{sat}} \) (MICK-ILLUSTRATION?) where the saturation oxygen concentration, \( O_{2,\text{sat}}(T,S) \), is a known function of local temperature and salinity. With these assumptions we may redefine (4) as

\[ O_2 \sim O_{2,\text{sat}} + R_{OP} P_{O_{4,\text{bio}}} . \]  

(5)

Rearranging, we may evaluate the regenerated phosphate concentration, \( P_{O_{4,\text{bio}}} \), from the observed oxygen concentration, temperature and salinity:

\[ P_{O_{4,\text{bio}}} \sim \frac{1}{R_{OP}} (O_2 - O_{2,\text{sat}}(T,S)) , \]  

(6)

In the upper thermocline of the subtropical gyres \( P_{O_{4,\text{bio}}} \) increases as water parcels move away from the isopycnal outcrops, accumulating nutrients from regeneration of dissolved organic matter and sinking organic particles. This is evident on the \( \sigma_{\text{theta}} = 26.5 \) surface (Fig. 3a) with gradients of \( P_{O_{4,\text{bio}}} \) increasing towards the equatorial regions in both Atlantic and Pacific basins. The equatorial regions on this surface are characterized by an tongue of regenerated nutrients emanating from the eastern margins where coastal upwelling fuels productivity and subsequent remineralization focuses nutrients onto these shallower isopycnals.

\(^1\)The negative coefficient indicates that oxygen is produced/consumed during photosynthesis/regeneration while phosphate is consumed/produced. Takahashi et al. (MICK-REF) re-evaluated \( R_{OP} = -170 \) using deep ocean observations and it is this value we use for the diagnostics presented here.
In the Atlantic basin this pattern persists on deeper isopycnals (Fig. 3b,c). In contrast, $PO_{4,bio}$ becomes uniformly elevated in the Pacific basin on the same density surfaces. This contrast between basins reflects the different pathways flooding the deep thermocline: In the Atlantic these surfaces are dominated by ventilation from the surface outcrops but are significantly influenced by the older, mid-depth waters which have accumulated significant amounts of regenerated nutrients in the Pacific.

WHAT ABOUT INDIAN OCEAN?

REMINERALIZED FRACTION ALSO ADVECTED AND MIXED...

DEEPER ISOPYCNALS - WHICH WOULD BE APPROPRIATE? ARE THESE APPROPRIATE?

![Image of Figure 3: Regenerated phosphate, $PO_{4,bio}$, evaluated from hydrographic data on isopycnal surfaces in the thermocline: (a) $\sigma_\theta = 26.5$, (b) $\sigma_\theta = 27.0$, and (c) $\sigma_\theta = 27.5$.]

Over most of the deep ocean, $P^* = PO_{4,bio}/PO_4$, ranges between 0.4 and 0.6, (Fig. 4) suggesting that about half the local phosphate arrives from the surface in the form of organic matter. On the global scale nutrient utilization is far from its potential efficiency and half of surface macronutrients are subducted before being utilized biologically.²

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²It is likely that the ocean’s deep waters are undersaturated in oxygen at the time of subduction or ventilation $O_{2,pre} < O_{2,sat}$ (MICK-OBSERVATION-REF, 2004). Hence, due to the assumption that $O_{2,pre} = O_{2,sat}(T,S)$ the estimated $PO_{4,bio}$ and $P^*$ (Fig. ??) represent upper bounds with $P^*$ overestimated by as much as 0.2 units in some water masses.
Figure 4: Local nutrient utilization, $P_*$, estimated from hydrographic data along meridional transects in (a) the Atlantic and (b) Pacific basins.