Plumbing of the biological pump.

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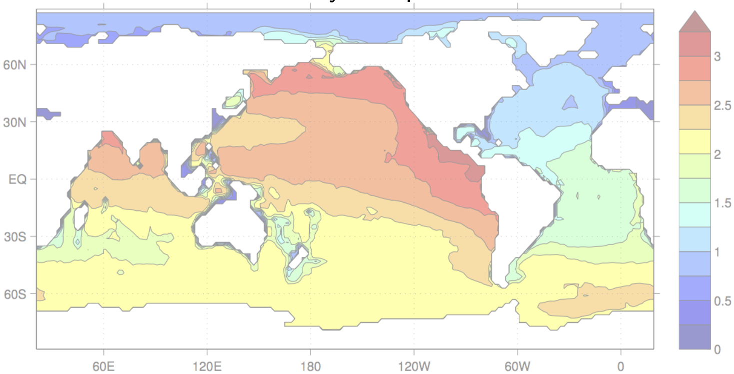
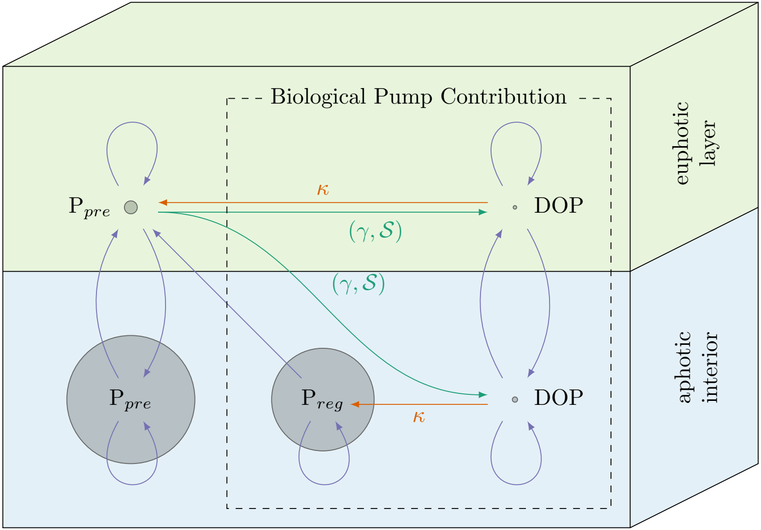


Motivations and questions

- What is the biological pump?
- Why is it important?
- Where are its origins and leaks?
- What are the dominant global teleconnections?
- What are the associated flow rates and timescales?
- What are the associated pathways?

Phosphorus cycle



Equations

The Model, a linear diagnostic model constructed by data assimilation of the phosphorus cycle. We solve the partial differential equation:

$$(\partial_t + \mathbf{A})\,\chi(\mathbf{r}, t) = \mathbf{S}$$

where the tracer is:

$$\chi = \begin{bmatrix} \chi_I \\ \chi_O \end{bmatrix}, \qquad (\chi_I = [\mathrm{PO_4}] \text{ and } \chi_O = [\mathrm{DOP}])$$

and where cicrulation, uptake, remineralization, and spatial boundary conditions are included in

$$\mathbf{A}(\mathbf{r}) = \begin{bmatrix} \mathcal{T} + \gamma + \gamma_a & -\kappa \\ 0 & \mathcal{T} + \kappa \end{bmatrix}.$$

The linearity allows the use of a Green function $\mathbf{G}(\mathbf{r}, t|\mathbf{r}', t')$ to propagate dirac sources or boundary conditions to diagnose the nutrient cycle.

"In" and "Out" equations

The concentration fields contribution $dt\,\mathbf{g}^{\downarrow}$ are given by r

$$\mathbf{g}^{\downarrow}_X(\mathbf{r},t|\Omega_i,t_i) = \int d^3\mathbf{r}_i\,\mathbf{G}(\mathbf{r},t|\mathbf{r}_i,t_i)\,\mathbf{S}_X(\mathbf{r}_i)\,\Omega_i(\mathbf{r}_i),$$

and the total masses, regardless of time, is

$$\mu^{\downarrow}_X(\Omega_i) = \int dt \int d^3\mathbf{r}\,\mathbf{g}^{\downarrow}_X(\mathbf{r},t|\Omega_i).$$

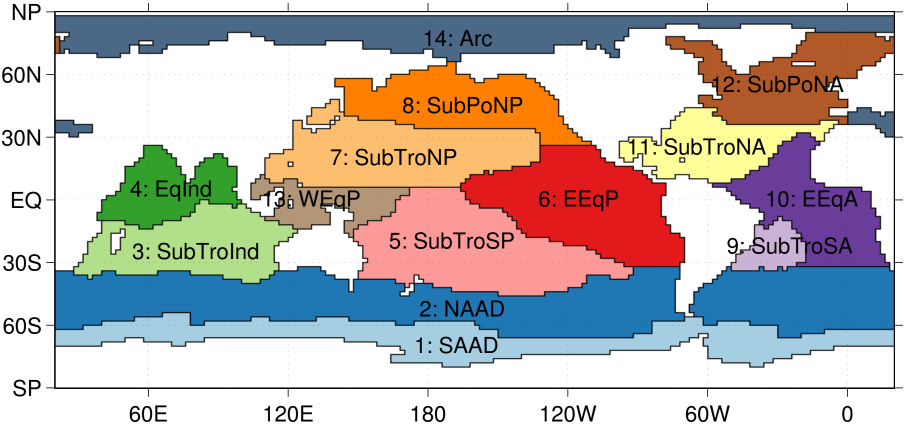
The concentration field contribution $dt\,g^{\uparrow}$ is given by

$$g^{\uparrow}(\mathbf{r},t|\Omega_f,t_f) = \int d^3\mathbf{r}_f\,\chi^T\,\mathbf{G}^{\dagger}(\mathbf{r},t|\mathbf{r}_f,t_f)\left[\begin{array}{c}\gamma_a\\ \kappa\end{array}\right]\Omega_f(\mathbf{r}_f),$$

from which we get the fraction $dt\,\widetilde{\mathcal{G}}$ defined by

$$\widetilde{\mathcal{G}}(\mathbf{r},t|\Omega_f,t_f) = \int d^3\mathbf{r}_f\,\mathbf{G}^{\dagger}(\mathbf{r},t|\mathbf{r}_f,t_f)\left[\begin{array}{c}\gamma_a\\ \kappa\end{array}\right]\Omega_f(\mathbf{r}_f).$$

Global tiling of the euphotic layer



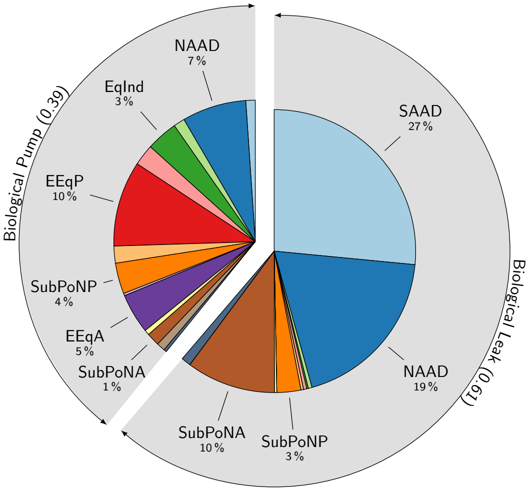
Origins and Leaks

On the left side, the efficiency contribution is

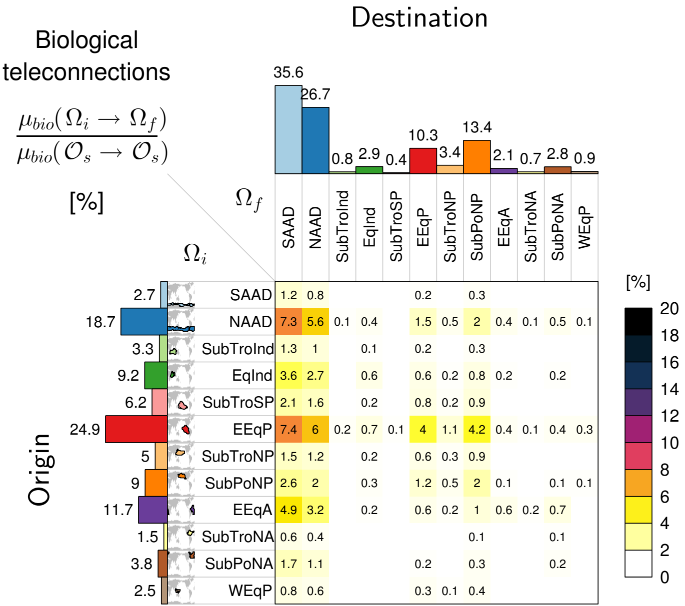
$$\frac{\mu^{\downarrow}_{bio}(\Omega_i)}{\mu^{\downarrow}_{tot}}.$$

And on the right side, the leak contribution is

$$\frac{\mu^{\downarrow}_{pre}(\Omega_i)}{\mu^{\downarrow}_{tot}}.$$

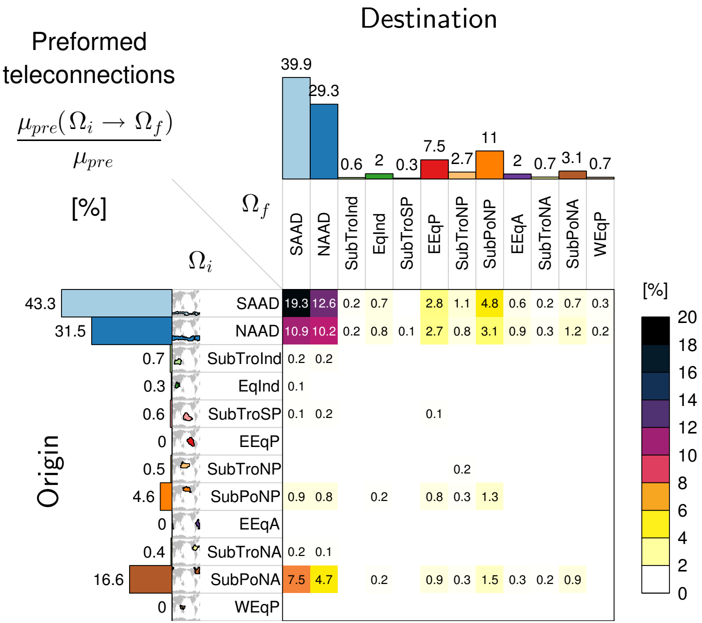


Biological teleconnections



Origin (Ω_i)	Origin total	SAAD	NAAD	SubTroInd	EqInd	SubTroSP	EEqP	SubTroNP	SubPoNP	EEqA	SubTroNA	SubPoNA	WEqP
Destination total		35.6	26.7	0.8	2.9	0.4	10.3	3.4	13.4	2.1	0.7	2.8	0.9
SAAD	2.7	1.2	0.8				0.2		0.3				
NAAD	18.7	7.3	5.6	0.1	0.4		1.5	0.5	2	0.4	0.1	0.5	0.1
SubTroInd	3.3	1.3	1		0.1		0.2		0.3				
EqInd	9.2	3.6	2.7		0.6		0.6	0.2	0.8	0.2		0.2	
SubTroSP	6.2	2.1	1.6		0.2		0.8	0.2	0.9				
EEqP	24.9	7.4	6	0.2	0.7	0.1	4	1.1	4.2	0.4	0.1	0.4	0.3
SubTroNP	5	1.5	1.2		0.2		0.6	0.3	0.9				
SubPoNP	9	2.6	2		0.3		1.2	0.5	2	0.1		0.1	0.1
EEqA	11.7	4.9	3.2		0.2		0.6	0.2	1	0.6	0.2	0.7	
SubTroNA	1.5	0.6	0.4						0.1			0.1	
SubPoNA	3.8	1.7	1.1				0.2		0.3			0.2	
WEqP	2.5	0.8	0.6				0.3	0.1	0.4				

Preformed teleconnections



Path density equations

The path density $dt\,\eta$ of biologically utilized phosphorus is given by

$$\eta_{bio}(\mathbf{r},\tau|\Omega_i \to \Omega_f) = \int_0^{\tau} dt\,\widetilde{\mathcal{G}}(\mathbf{r},t|\Omega_f,\tau)^T \mathbf{g}^{\downarrow}_{bio}(\mathbf{r},t|\Omega_i,0).$$

They can be volume-integrated to give the mass in transit μ_{bio} defined by

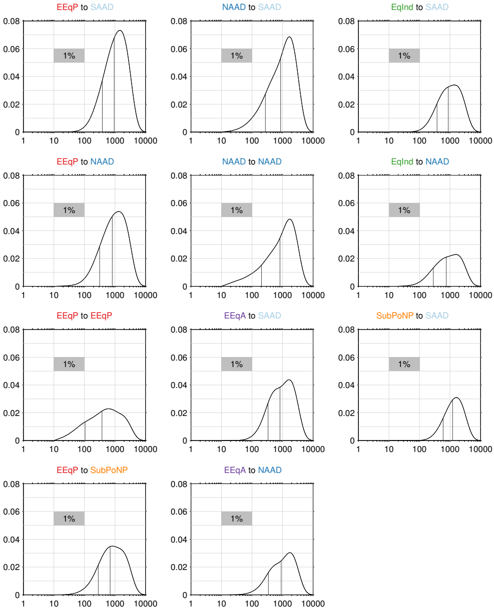
$$\mu_{bio}(\tau|\Omega_i \to \Omega_f) = \int d^3\mathbf{r}\,\eta_{bio}(\mathbf{r},\tau|\Omega_i \to \Omega_f).$$

and can be integrated in time bands, as for example in

$$\overline{\eta}_{bio}(\mathbf{r}|\tau_{min},\tau_{max}|\Omega_i \to \Omega_f) = \int_{\tau_{min}}^{\tau_{max}} d\tau\,\eta_{bio}(\mathbf{r},\tau|\Omega_i \to \Omega_f).$$

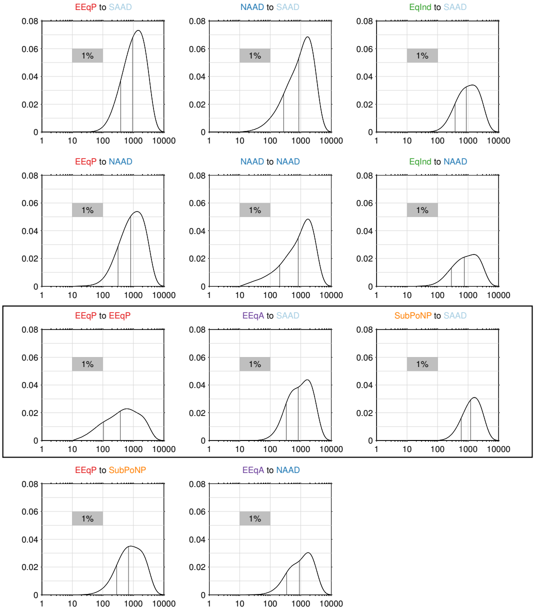
mass in transit and timescales

$$\mu_{bio}(t|\Omega_i \rightarrow \Omega_f)$$



mass in transit and timescales

$\mu_{bio}(t|\Omega_i \to \Omega_f)$



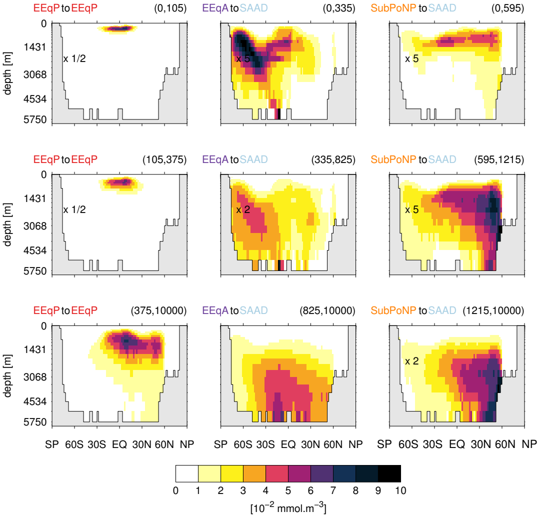
Pathways

$$\overline{\eta}_{bio}(\mathbf{r}|\tau_{min}, \tau_{max}|\Omega_i \to \Omega_f)$$

fast paths

medium paths

slow paths



Conclusions

- The contribution to the biological pump matches production (not intuitive!)
- Roughly 2/3 of the global interior phosphate reemerges in the SO
- 97% of the leak comes from high latitude regions (SO + Sub-polar North Pacific and Atlantic)
- 11 of the 196 possible teleconnections contribute to 50% of the biological pump efficiency
- The uptake to re-emergence nutrient transport occurs over a broad range of timescales
- Nutrients undergo complex pathways along but also against well-known water masses