Revisiting the biological pump using the new continuous vertical sequestration approach

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SUPPLEMENTARY INFORMATION

1. Mechanisms involved in ocean carbon sequestration, including the ocean carbon pumps

2. Functioning of the biological carbon pump mechanisms

3. Comparisons between our calculations or results for the mixing and migrant pumps and values from the literature

4. Supplementary Tables S1 to S7

5. Supplementary Figures S1 to S4

6. Supplementary Methods

7. Additional references

1. Mechanisms involved in ocean carbon sequestration, including the ocean carbon pumps

Marine biogeochemists group carbon sequestration mechanisms into *carbon pumps*. This concept was originally created to explain the observed increasing DIC concentration with depth in the global ocean[45] and consequently did not consider the storage of organic carbon in the sediment. The carbon pumps were later applied to ocean carbon sequestration, in which case their definition included organic carbon transport to the ocean interior and possibly the sediment. Indeed, IPCC[7] definitions of the ocean carbon pumps are as follows: the *solubility pump* is “a physicochemical process that transports dissolved inorganic carbon from the ocean’s surface to its interior […] primarily driven by the solubility of carbon dioxide (CO_2) […] and the large-scale, thermohaline patterns of ocean circulation”; the *carbonate pump* consists of "the biological formation of carbonates, primarily by plankton that generate bio-mineral particles that sink to the ocean interior, and possibly the sediment […] accompanied by the release of CO_2 to surrounding water and subsequently to the atmosphere"; and the *biological carbon pump*, which is the focus of this study, transports POC and DOC "to the ocean interior, and possibly the sediment".

Other biologically-driven sequestration mechanisms that are technically not part of the BCPs include[7]: the *microbial carbon pump*, which consists of "microbial processes that transform organic carbon from rapidly-degradable states to biologically-unavailable forms, resulting in long-term carbon storage in the ocean, […] and is the principal mechanism generating and sustaining refractory dissolved organic carbon in the ocean"[17,34,35]; and coastal *blue carbon*, which consists of "rooted vegetation in the coastal zone, such as tidal marshes, mangroves and seagrasses. The latter ecosystems have high carbon burial rates on a per unit area basis and accumulate carbon in their soils and sediments". Coastal blue carbon sequestration is actively debated in the literature[46-49].

2. Functioning of the biological carbon pump mechanisms

Six BCP mechanisms contribute to global ocean carbon sequestration[12]. In the following bullets, we briefly describe the functioning of the six mechanisms, and Fig. 3a (main text) illustrates the maximum depth to which each of them transports POC and/or DOC. Organic carbon is progressively remineralized to CO_2 in the water column, and part of the resulting DIC_{bio} is sequestered at different depths (Fig. 3).

The remineralization processes of POC transported by BCPs include ingestion by heterotrophs, which respire part of their food to CO_2, and transformation of POC into DOC by various food-web processes such as solubilization by bacterial exoenzymes and excretion by microbes and animals. Most of the DOC, either remineralized *in situ* or transported downwards by BCP mechanisms, is used and respired to CO_2 by heterotrophic bacteria. Respiratory CO_2 fuels DIC_{bio}.

The different BCP mechanisms are grouped into pumps, which are known under different names proposed by various authors. The settling of organic particles is known as *biological gravitational pump*[12], the three physically-driven mechanisms (mixed layer, eddy subduction, and large scale advection and overturning) as *physical (injection) pumps*[26] or *mixing pump*[50], the diel vertical migrations as *mesopelagic migrant pump*[12]; the seasonal vertical migrations as *seasonal lipid pump*[38], and all mechanisms other than gravitational as *particle injection pumps*[12].

• *Biological gravitational mechanism.* Part of the organic particles produced by photosynthesis and other processes of the pelagic food web in the upper ocean's layer continuously sinks downwards. The sinking POC is progressively remineralized to CO_2 during its downward journey, and the non-remineralized POC may be sequestered in sediment for times reaching millions of years[17].

• *Mixed layer mechanism.* During the seasonal transition from the deepest winter mixed layer to summer stratification at high and mid-latitudes, there are variations in the depth of the mixed layer. These variations cause the downward injection, by deep mixing, of POC and DOC produced in the upper layer, and their isolation at depth when a new shallower mixed layer is formed. The succession of shoaling and deepening of the mixed layer injects POC and DOC to depths between 200 and 1000 m[24].

• *Eddy subduction mechanism.* Frontal circulation with horizontal dimensions ranging from the mesoscale (10–100 km) to the sub-mesoscale (1–10 km) creates "hotspots" of downward vertical transport (i.e. subduction). In these hotspots, POC and DOC are injected down to depths of 150 to 400 and even 500 m[25,26].

• *Large-scale advection and overturning (or Ekman) mechanism.* Large-scale wind-driven circulation causes the injection of POC and DOC from the seasonal mixed layer into the ocean interior, down to depths of 500 to 1000 m[27-29].

• *Diel (nycthemeral) vertical migrations.* During their diel vertical migrations, zooplankton and also fish, jellies and other animals larger than zooplankton[31] ingest organic particles at surface, generally at night time, and release part of the ingested material at depth, a few hours later, under the form of faecal material (POC, mostly zooplankton faecal pellets), excreted DOC and respiratory CO_2. Migrating animals also defecate, excrete and respire during their vertical journeys. The depth of these migrations does not generally exceed 200 m, but can reach a maximum of 600 m in some cases[36,37].

• *Seasonal (ontogenic) vertical migrations.* At high latitudes, some zooplankton taxa spend several months of the year at depths >600 and even 1000 m or more, where they release part of the carbon they had acquired at surface under the form of faecal pellets, excreted DOC, respiratory CO_2 and carcasses of dead organisms. The carbon transported by these organisms is largely under the form of lipid reserves. This pump transports POC down to depths that can reach 1400 m[38].

3. Comparisons between our calculations or results for the mixing and migrant pumps and values from the literature

Our F_{seq} for the gravitational pump in CONVERSE 1-3 are compared with flux values from the literature Table S3, and this comparison is included in the main text. As a complement, our CONVERSE calculations or results for the two other pumps are compared with values from the literature in the following paragraphs.

• *Mixing pump*. We use eq. 13 to estimate the remineralization flux of DOC driven by the mixing pump ($F_{reminDOC}$). In the field, the downward mixing flux of DOC and total export flux below 50 m were estimated to be 15 and 92 mg C m^{-2} d^{-1}, respectively, in the eastern North Atlantic Ocean[51]. Assuming that the two fluxes were entirely remineralized below 50 m, then $F_{reminDOC}$ accounted for ~15% of all F_{remin} ($F_{reminAll}$). This does not necessarily mean that F_{seqDOC} accounted for ~15% of F_{seqAll}, as differential sequestration of $F_{reminDOC}$ and $F_{reminAll}$ may have happened depending on their remineralization depths. Nevertheless, our CONVERSE 1-7 estimates of 11-23% of the biological pump F_{seq} accounted for by the mixing pump F_{seq} (Supplementary Tables S3 and S4) are of the same order as the above field ~15% for F_{remin}, which suggests that our estimates are realistic.

• *Migrant pump: diel vertical migrations.* Our eq. 16 computes F_{remin} for diel vertical migrations by all animals as follows:

$$F_{reminMigrD} = 0.25\ F_{expPOC}, \text{ at } z_{exp} = 100 \text{ m} \tag{16}$$

Hence:

$$F_{reminMigrD} / F_{expPOC} = 0.25 \tag{16a}$$

A synthesis of literature values for zooplankton diel migrations[52] provides the following relationship (parameters of the regression equation derived from the line drawn on Fig. 5b in that review):

$$F_{reminMigrD}\ /\ F_{expPOC} \simeq 0.1 + 0.017\ F_{reminMigrD}, \text{ at } z_{exp} = 100\text{-}200 \text{ m} \tag{16b}$$

where the units of $F_{reminMigrD}$ and F_{expPOC} are mg C m^{-2} d^{-1}. According to eq. 16b, our eq. 16 corresponds to $F_{reminMigrD} \simeq 9$ mg C m^{-2} d^{-1}. This $F_{reminMigrD}$ is in the bulk of values used to derive eq. 16b, indicating that our CONVERSE $F_{seqMigrD}$ values (eq. 17) are realistic.

• *Migrant pump: seasonal vertical migrations*. The study[38] from which we derived our eq. 18 was conducted in the northern North Atlantic and concerned the seasonal vertical migrations of the copepod *Calanus finmarchicus*, which were estimated to export 2 to 6 g C m^{-2} y^{-1}. Similar values for other cold waters are[52]: 3.1 g C m^{-2} y^{-1} (Arctic Ocean, mostly large copepods *C. hyperboreus* and *C. glacialis*), 2.0 to 4.3 g C m^{-2} y^{-1} (subarctic North Pacific, *Neocalanus* copepods), and 1.7 to 9.3 g C m^{-2} y^{-1} (subantarctic Southern Ocean, *N. tonsus*). These values are in the same range as those of the study on which we based our CONVERSE calculations, which suggest that our approach could also be used in other cold-water areas than the northern North Atlantic Ocean.

4. Supplementary Tables

Table S1 lists the acronyms and symbols used in the main text.

In order to assess the significance of the CONVERSE approach, we estimated BCP F_{seq} and their pathways (POC, DOC, and diel and seasonal vertical migrations). We used data from three sources[4,15,42], and computed flux estimates with seven different CONVERSE versions which combined data from the three sources differently. Characteristics of the seven versions are summarized in Table S2.

In Table S3, the F_{seq} from CONVERSE 1-3 are summarized and compared with corresponding POC F_{seq} from studies in the literature. Table S4 summarizes the F_{seq} results from CONVERSE 4-7. Table S5 summarizes the fluxes calculated below, at and above 1,000 m and 2,000 m corresponding to CONVERSE 1-7.

Table S6 gives global-ocean median F_{TOC}(pixel)[42] and number of observations in different depth bins from surface to bottom, and Table S7 provides information on the use of F_{TOC} in the calculation of F_{seq}.

Table S1. Acronyms and symbols used in the main text, excluding those used only in the Methods and/or the Supplementary Information.

Symbols	**Definitions**	**Notes**
All_{owc}	F_{seq} for all carbon pumps (i.e., the whole biological carbon pump) over the water column	Only used in Table 1
CONVERSE	Continuous vertical sequestration	
CDR	Carbon Dioxide Removal	
C1 to C7	CONVERSE versions 1 to 7	
DIC	Dissolved inorganic carbon	DIC = $CO_2 + H_2CO_3 + HCO_3^- + CO_3^{2-}$
DIC_{bio}	Biogenic DIC, i.e. DIC resulting from the remineralization (respiration) of organic matter	Also called C_{soft}[3] and C_{seq}[1]
DOC	Dissolved organic carbon	
F_{exp}	Downward flux of organic carbon at the export depth z_{exp}	F_{org} at z_{exp}
F_{org}	Downward flux of organic carbon	Flux driven by the biological carbon pump
F_{remin}	Remineralization flux of organic carbon to DIC_{bio}	Fraction of F_{org}, computed differently for each pump
F_{seq}	Sequestration flux of DIC_{bio}	$F_{seq} = F_{remin} \times f_{100}$
F^*_{seq}	Sequestration flux normalized to POC export flux at the export depth z_{exp}	$F^*_{seq} = F_{seq}/F_{exp}$
f_{100}	Fraction of a parcel of water at a given location and depth that will remain in the ocean for ≥100 years	From a published paper[2]
POC	Particulate organic carbon	
z_{exp}	Export depth	100 m, or bottom of the euphotic zone (z_{eu})

Table S2. Characteristics of the seven versions of CONVERSE F_{remin} estimates for POC, DOC, vertical migrations, and sediment. To further obtain F_{seq}, the F_{remin} estimates were multiplied by corresponding f_{100}, i.e. $F_{seq} = F_{remin} \times f_{100}$. The initial computations for POC and DOC produced values for successive depth intervals in the water column (Δz), which were summed up from shallowest to deepest: $F_{seq}(\text{pixel}) = \sum_{\Delta z=shallowest}^{deepest} F_{seq}(\Delta z)$. Further calculations were: $F_{seq}(\text{global}) = \sum_{\text{All pixels}} [F_{seq}(\text{pixel}) \times \text{Area}(\text{pixel})]$; and $F_{seqAll} = \sum_{4\ \text{components}} F_{seqComponent}$. The sources of data are identified **He**[15], **DW**[4], and **Ha**[42]. References to CONVERSE results are abbreviated C#, e.g. C5 refers to CONVERSE 5.

CONVERSE	1	2	3	4	5	6	7
				Export depth (z_{exp})			
	100 m	100 m	100 m	z_{eu}	100 m	100 m	100 m
				Global ocean (gravitational pump)			
No. pixels	9202	9202	9202	10,309	10,276	10,276	9202
Area (10^6 km^2)	343	343	343	352	352	352	343
				Estimation of $F_{remin}(\Delta z)$			
b	0.86	Variable	Regional	C4-C5: None		0.86	0.86
Gravitational pump*	C1-C3: $F_{orgPOC}(z)$ - $F_{orgPOC}(z+1)$, values being computed using *b* **He**			C4-C5: $[([POC]_{slow} \times k_{slow}) + ([POC]_{fast} \times k_{fast})] \times \Delta z$ **DW**		C5 × Export ratio‡	Same as C1
Mixing pump	C1-C3: C5 × Export ratio‡			C4-C5: $\sum_{4\ \text{fractions}} ([DOC] \times k \times \Delta z)$§ **DW**		C5 × Export ratio‡	F_{expPOC} at 100 m × 0.25 **He**
				Estimation of F_{remin}(pixel)			
Migrant pump diel	C1-C3: F_{expPOC} × 0.25 (z_{exp} = 100 m) **He**			C4-C5: F_{expPOC} × 0.25 (z_{exp} = 100 m) **DW**		Same as C1-C3	Same as C1-C3
Migrant pump seasonal†	C1-C3: $F_{expPOC} \times (z/z_{exp})^{-b} \times$ 0.5 (z = 597 m and z_{exp} = 100 m) **He**			C4-C5: $F_{orgPOC}(z)$ × 0.5 (z = 619 m) **DW**		C5 × Export ratio‡	Same as C1
Sediment	C1-C7: F_{TOC} **Ha**						

* Water column only, i.e. does not include F_{seqSed}

† Northern North Atlantic only

‡ Export ratio: F_{expPOC}(global, C1) / F_{expPOC}(global, C5) at z_{exp} = 100 m, from **He** and **DW**, respectively

§ DOC concentration ([DOC]; g C m^{-3}) and remineralization rate (k; y^{-1}) in 4 fractions (labile, semi-labile, semi-refractory, and refractory) within depth interval Δz (m), from **DW**

Table S3. Estimates of sequestration fluxes (F_{seq}, Pg C y^{-1}) in the whole water column corresponding to seven versions characterized by different sequestration depths (CONVERSE, or z_{seq}), *b* and F_{exp} at 100 m (same z_{exp} = 100 m), calculated in this study (CONVERSE) or taken from previously published works. The CONVERSE POC sequestration fluxes were computed with the same *b* as in the corresponding previous studies. Because the values for DOC and diel vertical migrations were computed without using *b*, these are the same across the Table. The F^*_{seq} ratios (eq. 1, values in italics) are dimensionless.

CONVERSE, or z_{seq}	**CON-VERSE 1**	**2000 m†**	**CON-VERSE 2**	**2000 m‡**	**CON-VERSE 3**	**2000 m****	**σ_θ = 1027.6 kg m^{-3}****
b	**0.86**[43]		**Geographically variable**[15]		**Regionalized**[18]		
F_{exp}(global) at 100 m (Pg C y^{-1})	**3.0**	**5.7**	**3.0**	**4.0**	**3.0**	**4.0**	**4.0**
Pumps and flux	***Global water-column sequestration fluxes (F_{seq})***						
Gravitational	0.63	0.43	0.92	0.66	0.71	0.33	0.72
Mixing	0.13	–	0.13	–	0.13	–	–
Migrant diel	0.11	–	0.11	–	0.11	–	–
Migrant seasonal*	0.004	–	0.004	–	0.001	–	–
Biological (all)	0.88	0.43	1.16	0.66	0.95	0.33	0.72
Sediment	0.03	–	0.03	–	0.03	–	–
Pumps and flux	***% Biological pump (all)***						
Gravitational	72	–	79	–	75	–	–
Mixing	15	–	11	–	14	–	–
Migrant diel	12	–	9	–	12	–	–
Migrant seasonal*	0.4	–	0.3	–	0.1	–	–
Sediment	3	–	3	–	3	–	–
Pumps and flux	***Global sequestration fluxes normalized to POC export fluxes at z_{exp} = 100 m (F^*_{seq})***						
Gravitational	*0.21*	*0.08*	*0.31*	*0.17*	*0.24*	*0.08*	*0.18*
Mixing	*0.04*	–	*0.04*	–	*0.04*	–	–
Migrant diel	*0.04*	–	*0.04*	–	*0.04*	–	–
Migrant seasonal*	*0.001*	–	*0.001*	–	*0.001*	–	–
Biological (all)	*0.29*	*0.08*	*0.39*	*0.17*	*0.32*	*0.08*	*0.18*
Sediment	*0.008*	–	*0.008*	–	*0.008*	–	–
Pumps	F^*_{seq}***(global)$_{CONVERSE}$ / F^*_{seq}(global) from published studies††***						
Gravitational		2.6		1.8		3.0	1.3
Biological (all)		3.6		2.3		4.0	1.8

* Northern North Atlantic only

† Deep sediment trap data normalized to 2,000 m using *b* = 0.86[14]

‡ Modelling estimates[15]

** Estimates do not include pixels with water depths between 100 and 200 m; σ_θ = 1027.6 kg m^{-3} corresponds to the top of the permanent pycnocline[18]

†† For example, the first value, 2.6, was calculated as follows:
0.21 (POC F_{seq} in CONVERSE 1) / 0.08 (POC F_{seq} from the published studies[14, 15,18])

Table S4. Estimates of sequestration fluxes (F_{seq}, Pg C y^{-1}) in the whole water column calculated in this study, corresponding to four CONVERSE versions characterized by different z_{exp}, calculations of F_{seqDOC} and F_{exp}. In CONVERSE 7, four of the five F_{seq} pathways are the same as in CONVERSE 1 (Table S3), except F_{seqDOC}(global) which was derived from F_{exp}POC. The F^*_{seq} ratios (eq. 1, values in italics) are dimensionless. BCP: Biological carbon pump.

CONVERSE	**CONVERSE 4**	**CONVERSE 5**	**CONVERSE 6**	**CONVERSE 7**
$\mathbf{z_{exp}}$	$\mathbf{z_{eu}}$	**100 m**	**100 m**	**100 m**
$\mathbf{F_{seqDOC}}$	**From a BCP model[4]**		***f*(BCP model)**	***f*(F_{exp}POC)†**
F_{exp}(global) (Pg C year^{-1})	**8.6**	**7.3**	**3.0**	**3.0**
Pumps and flux	***Global water-column sequestration fluxes (F_{seq})***			
Gravitational	1.89	1.86	0.76‡	0.63
Mixing	0.45	0.32	0.13‡	0.22§
Migrant diel	0.26	0.26	0.11	0.11
Migrant seasonal*	0.01	0.01	0.004	0.004
Biological (all)	2.61	2.44	1.00	0.96
Sediment	0.03	0.03	0.03	0.03
Pumps and flux	***% Biological pump (all)***			
Gravitational	72	76	76	66
Mixing	17	13	13	23
Migrant diel	10	11	11	11
Migrant seasonal*	0.4	0.4	0.4	0.4
Sediment	1	1	3	3
Pumps and flux	***Global sequestration fluxes normalized to POC export fluxes at $z_{exp} = z_{eu}$ or 100 m (F^*_{seq})***			
Gravitational	*0.22*	*0.25*	*0.25*	*0.21*
Mixing	*0.05*	*0.04*	*0.04*	*0.07*
Migrant diel	*0.03*	*0.04*	*0.04*	*0.04*
Migrant seasonal*	*0.001*	*0.001*	*0.001*	*0.001*
Biological (all)	*0.30*	*0.33*	*0.33*	*0.32*
Sediment	*0.003*	*0.004*	*0.008*	*0.008*

* Northern North Atlantic only

† Same value as in CONVERSE 1, expect for F_{seqDOC}

‡ Value in CONVERSE 5 × [F_{exp}(pixel, CONVERSE 1) / F_{exp}(pixel, CONVERSE 5)] at z_{exp} = 100 m

§ $F_{seqDOC} = 0.25 \times F_{expPOC}$ at 100 m × f_{100} at 531 m

Table S5. Estimates of sequestration fluxes (F_{seq}, Pg C y^{-1}) at, below and above 1,000 m and 2,000 m calculated in this study, corresponding to CONVERSE 1-7, the characteristics of which are given in Tables S2-S4. The F^*_{seq} ratios (eq. 1, values in italics) are dimensionless.

CONVERSE	1	2	3	4	5	6	7
Fluxes	***Global POC fluxes calculated at 1,000 and 2,000 m (F_{seq})***						
POC at 1,000 m*	0.38	0.68	0.47	1.13	1.13	0.46	0.38
POC at 2,000 m*	0.19	0.42	0.26	0.47	0.47	0.19	0.19
Pumps	***Global sequestration fluxes integrated above and below 1,000 m (F_{seq}) and % ratios***						
Gravitational ≤1,000 m	0.32	0.33	0.32	1.09	1.06	0.43	0.32
Gravitational >1,000 m	0.31	0.59	0.39	0.80	0.80	0.33	0.31
All ≤1,000 m	0.55	0.55	0.54	1.75	1.58	0.65	0.65
All >1,000 m†	0.33	0.61	0.41	0.86	0.86	0.35	0.31
$All_{\leq 1000}$ / All_{owc}‡	63%	47%	57%	67%	65%	65%	68%
$All_{>1000}$ / All_{owc}‡	37%	53%	43%	33%	35%	35%	32%
Pumps	***Global sequestration fluxes integrated above and below 2,000 m (F_{seq}) and % ratios***						
Gravitational ≤2,000 m	0.48	0.54	0.49	1.61	1.58	0.64	0.48
Gravitational >2,000 m	0.15	0.38	0.22	0.28	0.28	0.12	0.15
All ≤2,000 m	0.71	0.77	0.71	2.30	2.13	0.87	0.81
All >2,000 m†	0.17	0.39	0.24	0.31	0.31	0.13	0.15
$All_{\leq 2000}$ / All_{owc}‡	81%	66%	75%	88%	87%	87%	84%
$All_{>2000}$ / All_{owc}‡	19%	33%	25%	12%	13%	13%	16%
Fluxes	***Global sequestration fluxes normalized to POC export fluxes at $z_{exp} = z_{eu}$ or 100 m (F^*_{seq})***						
POC at 1,000 m*	*0.13*	*0.23*	*0.16*	0.13	0.15	0.15	0.13
POC at 2,000 m*	*0.06*	*0.14*	*0.09*	0.05	0.06	0.06	0.06
Pump ratios	***CONVERSE sequestration fluxes to POC fluxes at 1,000 and 2,000 m***						
• to POC flux at 1,000 m*							
Gravitational†	1.7	1.4	1.5	1.7	1.6	1.7	1.7
Biological†	2.3	1.7	2.0	2.3	2.2	2.2	2.5
• to POC flux at 2,000 m*							
Gravitational†	3.3	2.2	2.7	4.0	4.0	4.0	3.3
Biological (all)†	4.6	2.8	3.7	5.6	5.2	5.3	5.1

* Calculated at z_{seq} = 1,000 m or 2000 m, assuming that POC F_{org} at z_{seq} is entirely sequestered below

†Water column only, i.e. does not include F_{seq} in sediment

‡ All_{owc}: F_{seq} for all pumps over the water column

153

Table S6. Median F_{TOC} in pixels of the world ocean[42] and number of observations in different depth bins. Pixel depths were obtained via the function getNOAA.bathy using the *marmap* package on Rstudio at https://cran.r-project.org/web/packages/marmap/marmap.pdf

Depth bin	Median F_{TOC} (g C m^{-2} y^{-1})	Number of observations
<2000 m*	0.13	1625
2000 – 3000 m	0.123	3832
3000 – 3500 m	0.0542	3814
3500 – 4000 m	0.044	5570
4000 – 4500 m	0.0397	6228
4500 – 5000 m	0.0305	4788
>5000 m	0.0305	5756

*In the publication[42], there are no F_{TOC} values in pixels <1000 m.

Table S7. Median and lower and upper quartiles of [F_{TOC} / F_{SeqAll}] in pixels, in the seven CONVERSE versions and all versions together.

	F_{seqSed} / F_{seqAll}		
CONVERSE	**Median**	**Lower quartile**	**Upper quartile**
1	0.03	0.01	0.07
2	0.02	0.01	0.04
3	0.03	0.01	0.06
4	0.01	0.01	0.02
5	0.01	0.01	0.02
6	0.02	0.01	0.05
7	0.02	0.07	0.05
All	0.02	0.08	0.04

5. Supplementary figures

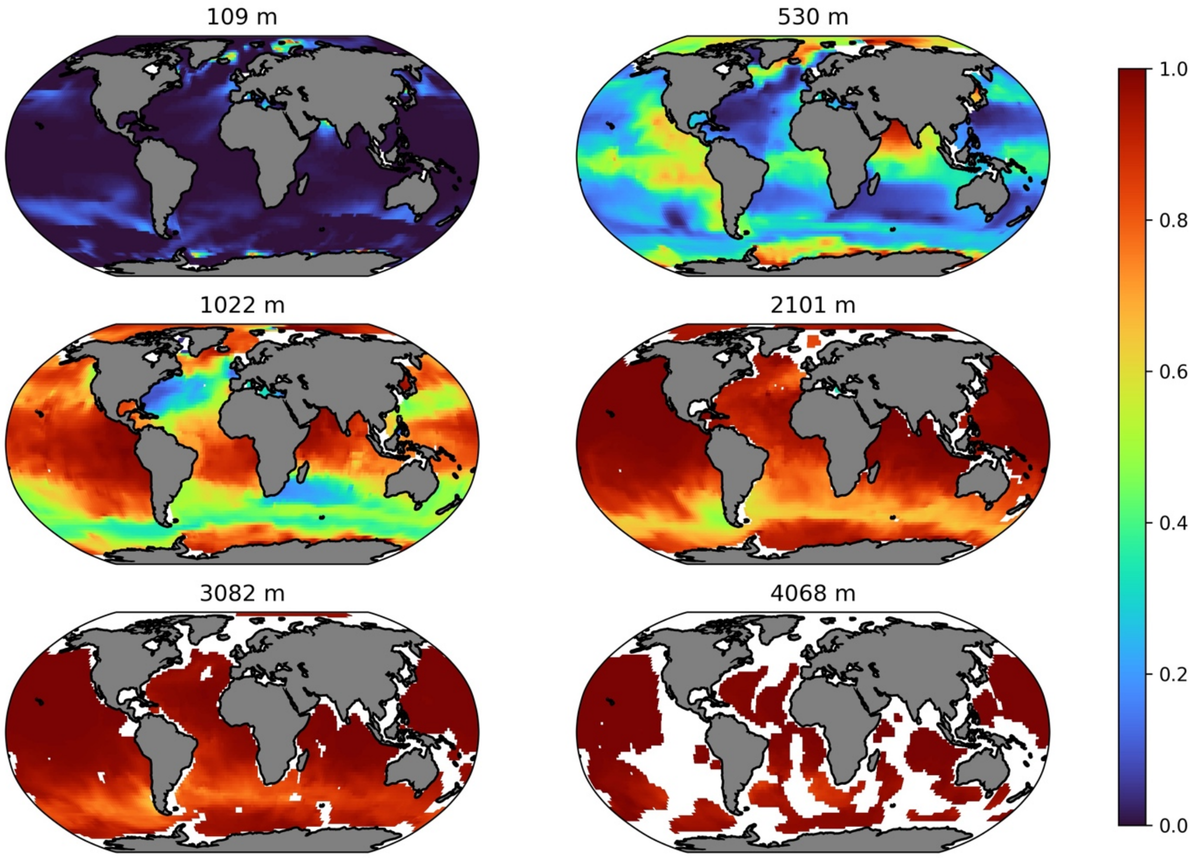

Fig. S1. Global-ocean distributions of f_{100} at six selected depths. White areas: pixels with water depths shallower than the depth illustrated. Another publication[5] provides additional representations of f_{100} distributions can be found in Supplemental Fig. S2 of another publication[5].

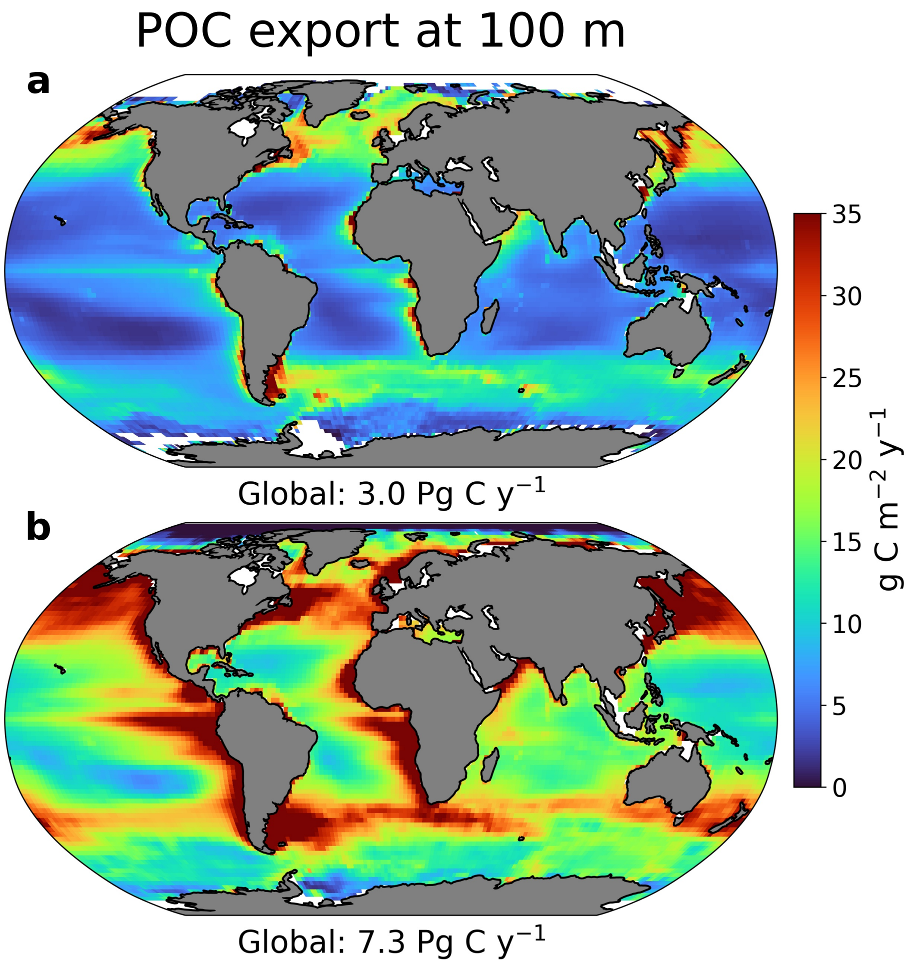

Fig. S2. Global distributions of POC F_{exp} at z_{exp} = 100 m used in this study, and corresponding global POC F_{exp} (a) value from the original publication[15], and (b) value of 7.3 Pg C y^{-1} corrected from the published[4] 6.7 Pg C y^{-1}.

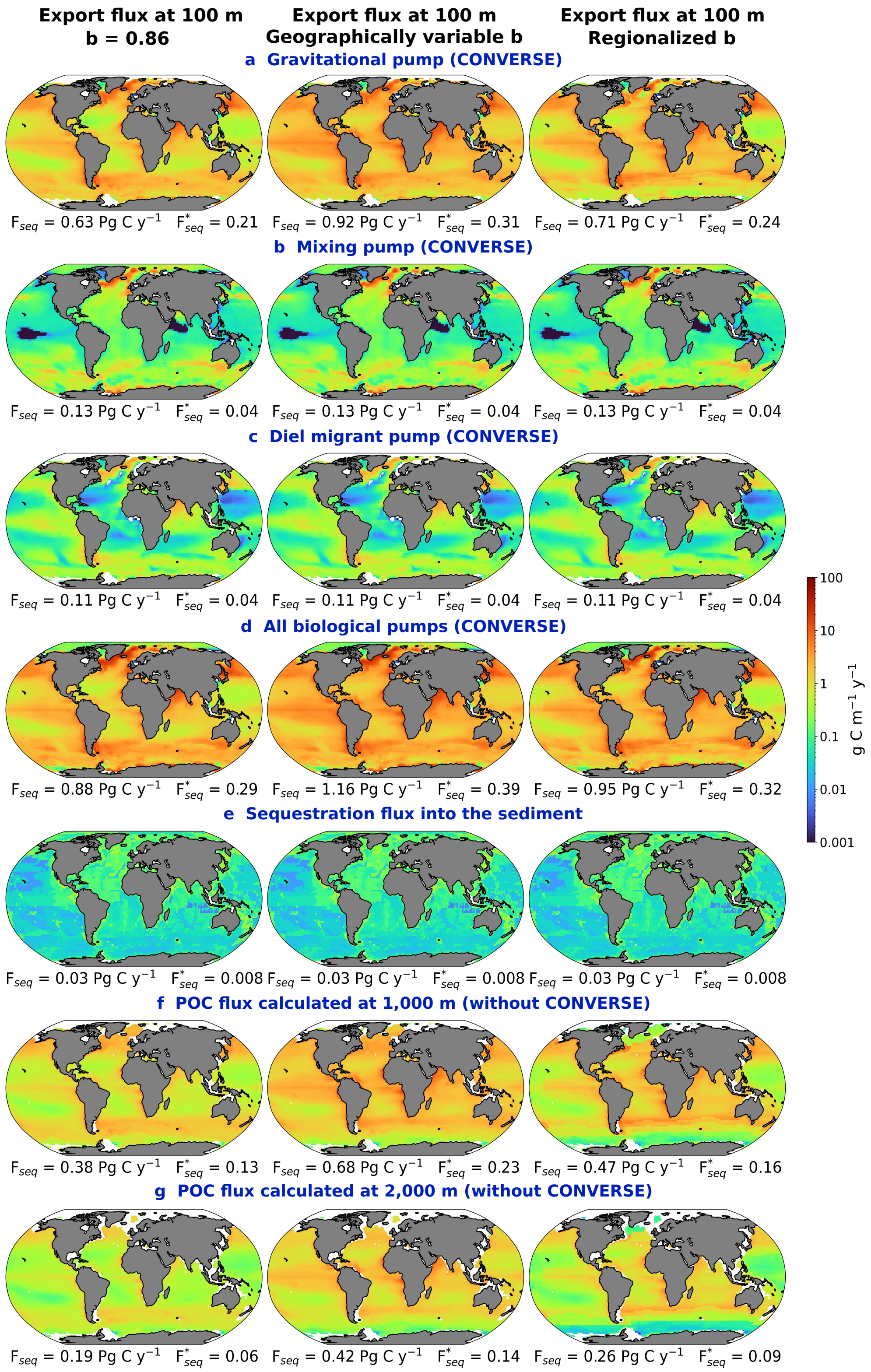

Fig. S3. Sequestration fluxes of biogenic carbon in CONVERSE 1-3: (a-d) carbon pumps, (e) F_{seq} into the sediment, and F_{seq} calculated at z_{seq} of (f) 1000 m and (g) 2000 m (assuming entire sequestration of the POC flux below z_{seq}). The latter two are the total sequestration fluxes estimated in many studies. Ocean areas shallower than 100 m are without colour. The seasonal migrant pump is not illustrated because our results concern the sole northern North Atlantic. Corresponding results are in Supplementary Tables S3 and S5.

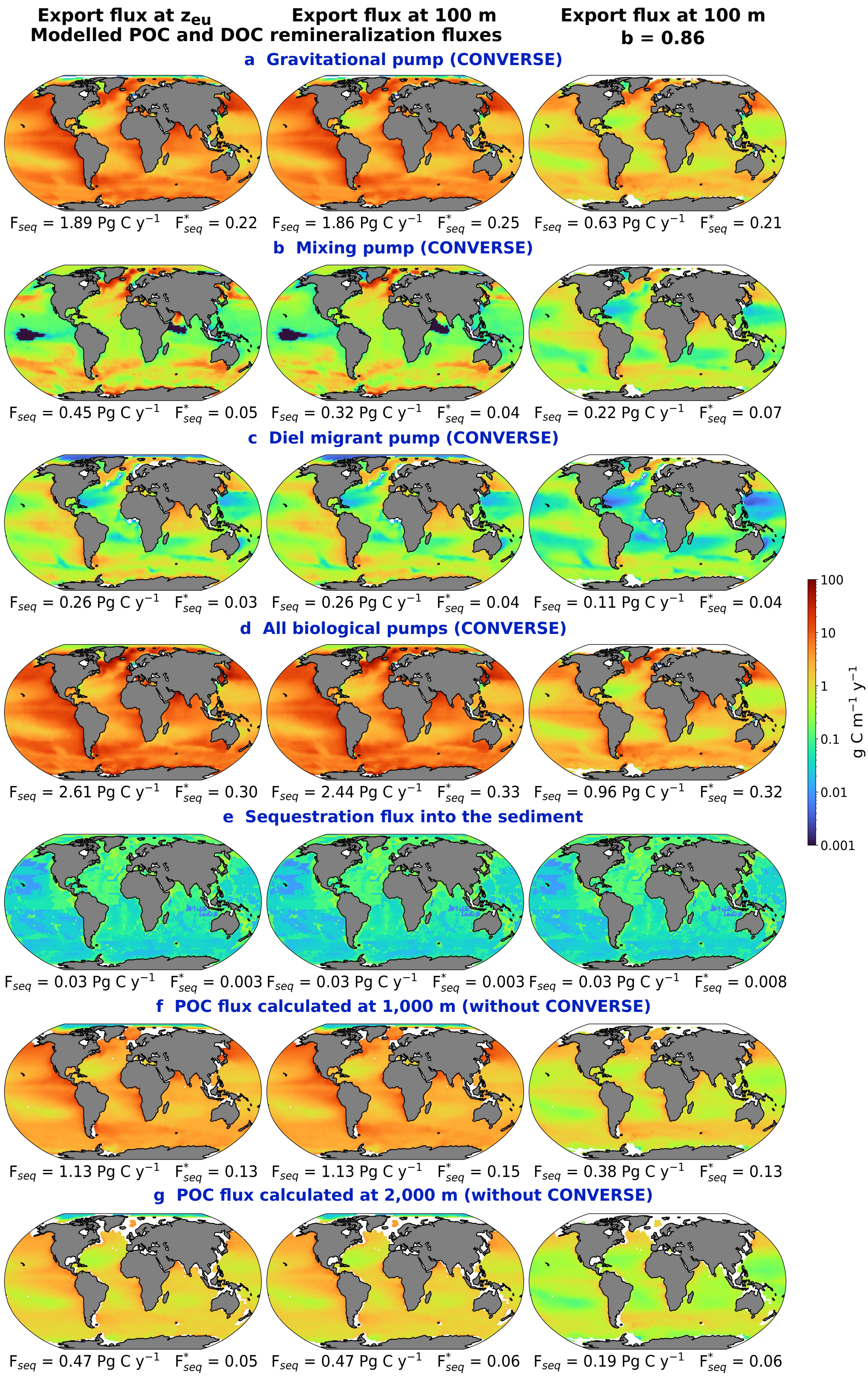

Fig. S4. Sequestration fluxes of biogenic carbon in CONVERSE 4, 5 and 7: (a-d) carbon pumps, (e) F_{seq} into the sediment, and F_{seq} calculated at z_{seq} of (f) 1000 m and (g) 2000 m (assuming entire sequestration of the POC flux below z_{seq}). The latter two are the total sequestration fluxes estimated in many studies. Ocean areas shallower than 100 m are without colour. The seasonal migrant pump is not illustrated because our results concern the sole northern North Atlantic. Corresponding results are in Supplementary Tables S4 and S5.

6. Supplementary Methods

We described in the main text the calculations for CONVERSE 1. We provide here the differences between CONVERSE 2 to CONVERSE 7 and CONVERSE 1 or other versions.

Continuous vertical estimation of pixel sequestration fluxes in CONVERSE 2

There was one difference between CONVERSE 2 and CONVERSE 1, i.e. b values in eqs. 10 and 18 were geographically variable values from a model[15] instead of fixed $b = 0.86$[43].

Continuous vertical estimation of pixel sequestration fluxes in CONVERSE 3

There was one difference between CONVERSE 3 and CONVERSE 1, i.e. b values in eqs. 10 and 18 were regionalized estimates in biogeochemical provinces[18] instead of fixed $b = 0.86$[43].

Continuous vertical estimation of pixel sequestration fluxes in CONVERSE 4

There were five differences between CONVERSE 4 and CONVERSE 1.

First, we used $z_{exp} = z_{eu}$. Hence, the shallowest Δz considered in each pixel was z_{eu} (eq. 7).

Second, we did not calculate $F_{reminPOC}(\Delta z)$ with eqs. 10 and 11, but instead used the concentrations of POC ([POC]; [M L^{-3}]) and its remineralization rates (k; [T^{-1}]) in two POC fractions (slow-sinking and fast-sinking) within each depth interval Δz [L] from SIMPLE-TRIM. With these data, we computed $F_{POC}(\Delta z)$ as follows:

$$F_{reminPOC}(\Delta z) = [([POC]_{slow} \times k_{slow}) + ([POC]_{fast} \times k_{fast})] \times \Delta z \qquad (24)$$

We calculated $F_{seqPOC}(\Delta z)$ with eq. 6.

We treated F_{orgPOC} remaining in the deepest Δz as done for CONVERSE 1, i.e. we first computed $F_{reminPOC}$(deepest Δz) with eq. (24), and then F_{seqPOC}(deep) with eq. 12 replacing F_{orgPOC}(deepest Δz) by $F_{reminPOC}$(deepest Δz).

Third, for $F_{reminDOC}$, we used directly the values that we had derived from SIMPLE-TRIM (eq. 13), i.e. without multiplying by the export ratio as done in eq. 14.

Fourth, for $F_{reminMigrS}$, we used values in the study cited above[38] whereby the copepod *Calanus finmarchicus* generated a seasonally remineralization flux $F_{reminMigrS}$ = 1 to 4 g C m^{-2} y^{-1} at z_{migrS} = 600 to 1,400 m, corresponding to $F_{orgPOC}(z)$ = 2 to 8 g C m^{-2} y^{-1}. Hence, $F_{reminMigrS}$ = 50% $F_{orgPOC}(z)$ at z_{migrS} = 600 to 1,400 m. We computed $F_{reminMigrS}$ as follows:

$$F_{reminMigrS} = 0.5\ F_{orgPOC}(z) \text{ at } z_{migrS} \qquad (25)$$

We used $F_{orgPOC}(z)$ from SIMPLE-TRIM at z_{migrS} = 619 m, which was the depth closest to 597 m for which values were available in that database.

Fifth, F_{seqPOC} at two fixed depths (z_{fixed}), we linearly interpolated $F_{orgPOC}(z)$ from SIMPLE-TRIM at z = 919 and 1,104 m for the POC flux at 1,000 m, and at z = 1,833 and 2,141 m for the POC flux at 2,000 m

Continuous vertical estimation of pixel sequestration fluxes in CONVERSE 5

There was one difference between CONVERSE 5 and CONVERSE 4, i.e. z_{exp} = 100 m. Hence, the shallowest Δz considered for each pixel in eq. 7 was 100 m.

Continuous vertical estimation of pixel sequestration fluxes in CONVERSE 6

CONVERSE 6 was a mix between CONVERSE 1 AND CONVERSE 5, which considered F_{expPOC} =3.0 Pg C y^{-1} at z_{exp} = 100 m[15] as in CONVERSE 1, but derived the fluxes of the gravitational and mixing pumps from CONVERSE 5.

We used the fluxes from CONVERSE 5 to compute all the pump fluxes of CONVERSE 6 (except one flux, below), and also the fluxes at, below and above 1,000 m and 2,000 m. We multiplied the fluxes from CONVERSE 5 by the export ratio used in eq. 14, i.e. 3.0 Pg C y^{-1} / 7.3 Pg C y^{-1}. This was necessary because the values in CONVERSE 5 were derived from SIMPLE-TRIM where F_{expPOC} =7.3 Pg C y^{-1} at z_{exp} = 100 m[4] (see also the legend of Supplementary Fig. S2):

$$F_{reminPOC} = F_{reminPOC} \text{ from CONVERSE 5} \times (3.0 \text{ Pg C y}^{-1} / 7.3 \text{ Pg C y}^{-1}) \quad (26)$$

We computed the fluxes of the diel migrant pump as in CONVERSE 1.

Continuous vertical estimation of pixel sequestration fluxes in CONVERSE 7

There were two differences between CONVERSE 7 and CONVERSE 1.

First, for F_{expDOC}, we did not use eqs. 13 and 14, but implemented information from the literature whereby the downward flux of DOC at z_{exp} accounts for ca. 20% of $F_{exp(POC+DOC)}$[53]. Hence:

$$F_{expDOC} = 0.25\ F_{expPOC} \quad (27)$$

where F_{expPOC} was the value at z_{exp} = 100 m from CONVERSE 1. We assumed that the mixing pump transported DOC rapidly from above z_{exp} to z_{mix}, with the consequence that properties at z_{mix} were the same as those at z_{exp}, hence:

$$F_{mixDOC} = F_{expDOC} \quad (28)$$

In the mixing pump, both $F_{reminDOC}(\Delta z)$ and $f_{100}(\Delta z)$ may be > 0 in some Δz below z_{mix}. Because of the lack of information on the vertical distribution of F_{orgDOC} in the global ocean, we used the following bulk approach to obtain estimates of F_{seqDOC}(pixel) and F_{seqDOC}(global) from z_{mix} downwards.

We assumed that the F_{orgDOC} injected at z_{mix} in a pixel was entirely remineralized at or below z_{mix}:

$$F_{reminDOC} = F_{mixDOC} \quad (29)$$

We also assumed that remineralization occurred above the permanent pycnocline[33], which is traced by isopycnal[18] σ_θ =1027.6 kg m^{-3}. To be certain of not overestimating $F_{reminDOC}$(pixel), we further assumed that all DOC remineralization occurred within the Δz that included z_{mix} = 500 m, so that the relevant $f_{100}(\Delta z)$ was the value at z' = 530 m (depth for which there were values in the f_{100} database; Fig. 2 and Supplementary Fig. S1). We used eqs. 6 and 27-29 to calculate F_{seqDOC} at and below z_{mix}:

$$F_{seqDOC} = 0.25\ F_{expPOC} \times f_{100}(531\ m) \quad (30)$$

Second, for the calculation of pixel F_{seqPOC} ≤2,000 m (eq. 22), we considered that $F_{seqDOC} = 0$ because we assumed above (eq. 29) that all DOC remineralization occurred within the Δz that included z_{mix} = 500 m.

7. Additional references

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