2-18-2021

Reviews and Syntheses: The Biogeochemical Cycle of Silicon In the Modern Ocean

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Recommended Citation

Tréguer, P., Sutton, J., Brzezinski, M., Charette, M., Devries, T., Dutkiewicz, S., Ehlert, C., Hawkings, J., Leynaert, A., Liu, S., Monferrer, N., López-Acosta, M., Maldonado, M., Rahman, S., Ran, L., Rouxel, O. (2021). Reviews and Syntheses: The Biogeochemical Cycle of Silicon In the Modern Ocean. *Biogeosciences, 18*(4), 1269-1289.
Available at: https://aquila.usm.edu/fac_pubs/18900

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Supplement of Biogeosciences, 18, 1269–1289, 2021
https://doi.org/10.5194/bg-18-1269-2021-supplement

Supplement of

Reviews and syntheses: The biogeochemical cycle of silicon in the modern ocean

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SUPPLEMENTAL INFORMATION

This document complements the review article. It provides detailed legends for Figures 1, 2 and 4, and a few additional comments to the main text. Annex 1 shows data for the determination of biogenic silica (bSi) production measured by isotopic techniques.

Section 1. Introduction

Detailed legend of Fig. 1 and flux abbreviations

Schematic view of the Si cycle in the modern world ocean (input, output, and biological Si fluxes), and possible balance (total Si inputs = total Si outputs = 15.6 Tmol-Si yr^{-1}) that is in reasonable agreement with the individual range of each flux (F), see Tables 1 and 2. All fluxes are in Tmol-Si yr^{-1}.

-*Inputs*: Rivers: $F_{R(dSi+aSi)}$ = 8.1; Aeolian inputs: F_A = 0.5; Glacial meltwater: F_{ISMW} = 0.3; Submarine groundwater: F_{GW} = 3.1; Dissolution of minerals: F_W = 1.9; Hydrothermal: F_H = 1.7

-*Outputs*: Burial: $F_{B\ (net\ deposit)\ =}$ 9.2; Sponges: $F_{SP\ =}$ 1.7; Reverse weathering: F_{RW} = 4.7.

-*Biological and other fluxes*: Uptake (pelagic production) = $F_{P(gross)}$ = 255; Recycling (surface) $F_{D(surface)}$ = 143 (D: P = 0.56 according to Tréguer and De La Rocha 2013); Export: F_E = 112; Recycling (deep) $F_{D(deep)}$ = 28 ($F_{D(deep)}/F_E$=0.25 according to Tréguer and De La Rocha 2013); Rain = $F_{S(rain)}$ = 84.0; Recycling (sediment-water interface) $F_{D(benthic)}$ = 74.8; upwelling, diffusion: $F_{upw/ed}$ = 102.8.

Flux abbreviations: dSi input fluxes: F_R total river net discharge, F_A dissolution of aeolian - transported siliceous dusts, F_{GW} submarine groundwater discharge, F_W dissolution of siliceous material transported from land on the continental margins, and of basalt, $F_{H\ hydrothermal}$ activity of the oceanic ridges (axis + off axis), F_{ISMW} ice shelf melt water flux (subglacial melt water + basal melting of ice shelves + melting of icebergs).

Si output fluxes: $F_{B(net\ deposit)}$ long-term burial of biogenic silica, F_{SP} siliceous sponges, F_{RW} reverse weathering by formation of authigenic silicate minerals.

Biological fluxes: $F_{P(gross)}$ production of biogenic silica due to diatoms and other pelagic silicifiers, $F_{E(export)}$ export flux of biogenic silica to the deep reservoir, $F_{S(rain)}$ part of the export flux that reaches the sediment - water interface, $F_{B(net\ deposit)}$ long-term accumulation of biogenic opal in coastal and abyssal, sediments.

Note that the dSi uptake due to benthic organisms is not represented on Fig. 1. Indeed, the total bSi production of benthic diatoms is presently unknown but it should be < 5 Tmol-Si yr^{-1} (Leynaert et al., work in progress), and that the total bSi production of sponges (6.1 (±5.9) Tmol-Si yr^{-1}) is still preliminary (Maldonado et al., work in progress).

Other fluxes: $F_{D(surface)}$ recycling of Si by dissolution of the biogenic silica in the surface reservoir, $F_{D(deep)}$ part of the export flux that dissolves in the deep reservoir, $F_{upw/ed}$ transfer of dSi from the deep to the surface reservoir by upwelling or eddy diffusion. $F_{D(benthic)}$, flux at the sediment - water interface, is according to Tréguer and De La Rocha 2013).

Section 2 -The input fluxes

2.1 Detailed legend of Figure 2.

Schematic view of the low temperature processes that control the dissolution of (either amorphous or crystallized) siliceous minerals in seawater in the coastal zone and in the deep ocean, feeding F_{GW} and F_W. These processes (white arrows) correspond to low or medium energy flux dissipated per volume of a given siliceous particle in the coastal zone, in the continental margins, and in the abysses, and to high kinetic energy flux dissipated in the surf zone. Inputs of siliceous biogenic and lithogenic silica into the ocean are mainly due to suspended matter transferred from the continent. Rivers support the main transfer of Si to the coastal zone, either as dSi or as aSi. Abundant transfer of siliceous suspended matter into the ocean is also expected from river mouths and deltas through dissemination of suspended matter in the coastal zone, in the continental margin, and beyond to the abysses. In sandy and permeable soil zones dSi is also transferred from the continent to the coastal zone through submarine groundwater discharge processes either as net fresh water inputs or as brackish/seawater recycling due to tidal pumping. In the surf zone, low temperature dissolution of grains of lithogenic silica (quartz, feldspar, etc.) could be intense under the pressure of the intensive and continuous shaking due to waves. For the sake of clarity, we distinguish the processes at work in a quiet zone that receive river inputs from those occurring in a sand beach zone subject to strong dissipation of energy due to wave motion. Note that neither the low-temperature dissolution of wind-borne siliceous material (F_A) nor that occurring in high-temperature hydrothermal systems (F_H) are represented on this figure.

2.2 Dissolution of minerals

Regarding the marine component of F_W dissolution of minerals, Fabre et al. (2019) (main text reference list), focused on wave and tidal action prevailing in the intertidal surf zone (Fig. 2). From laboratory experiment with pure quartz, they showed that quartz grains submitted to violent agitation are capable of substantial dissolution of silica at time scale of days. According to these authors, the flux of dissolution of siliceous material from sandy beaches is $F_{dissolution}$ = k(T°C) × $S_{reactive}$ × (C* - C_{sw}). It corresponds to a net input of dSi to the ocean. In this equation, k (f(T°C)) in m s^{-1} is the mass transfer coefficient, $S_{reactive}$ in m is the reactive surface of sand grains, C* in mol-Si L^{-1} is the temperature-dependent solubility limit of sand at thermodynamic equilibrium, and C_{sw}, in mol-Si L^{-1} is the coastal seawater silicic acid concentration. Assuming that all sandy beaches is composed of quartz, Fabre et al. (2019) calculated a global flux of 3.2 (± 1.0) Tmol Si yr^{-1}. However, this estimate is not well constrained.

Firstly, it is clear that the mineral composition of the world ocean beaches is not entirely composed of quartz. Indeed, the composition of sandy beaches is variable and represent 31% of the coastline of the continents at world scale (Luijendijk et al, 2018, main text reference list). Sandy beaches are composed both of non-siliceous materials (mostly calcareous), and diverse siliceous types of materials (amorphous silica, quartz, feldspars, clays, etc.). These siliceous materials have different solubility and dissolution rates in seawater (S1: Lerman et al., 1975; S2: Hurd et al., 1979), and they can be more or less coated by organic and metals, which affect silica dissolution (e.g. S3: Loucaides et al. 2010; S4: Wiley, 1975). These differing sand compositions directly affects the value of $S_{reactive}$ as well as that of C*.

Secondly, in surf zones the mixing conditions of sand and seawater can be very variable, both over time and at local and regional scale, thus affecting the solid to liquid phase ratio, and the values of the C*.

Thirdly, Fabre et al (2019)'s value for C_{sw} (i.e. 85.4 µM), is far too high for coastal waters, irrespective of its regional context in the world ocean.

Finally, C_{sw} can be seasonally variable, particularly in temperate zones.

Also note that, by definition, this flux is already included in the marine SGD estimate according to Cho et al. (2018) (main text reference list)

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Section 3 -The output fluxes

Deposition of sponge silica in marine sediments

The annual rate of sponge silica deposition to the sediments, unlike in diatoms, cannot be easily calculated from annual production rates. The longevity of sponges, which ranges from months or years to even centuries or millennia (S5: Elwood et al., 2007; S6: Mcmurray et al., 2008; Jochum et al. 2017, see main text reference list), decouples the process of skeleton production — which slowly accumulates bSi over the sponge lifespan — from the process of releasing the accumulated bSi into the sediments — which occurs within weeks to months after sponge death. The deposition of sponge bSi is also decoupled from the rain of planktonic, and therefore, from the rate of sediment deposition. The reason of this is in the benthic nature of sponges. Sponges live already attached to the bottom, so their bSi does no transit through the water column once sponges die. While the organic components of the body become rapidly degraded (S7: Rützler and Mcintyre 1978), the mineral components (i.e. the siliceous skeletal pieces of sponges, called spicules) do not. The skeletal pieces fall directly on the seafloor at the site where the sponge was growing, forming a spicule patch (S8: Laguionie-Marchais et al., 2015), which can in some cases persist for a long time (S9: Bett and Rice, 1992), being slowly disaggregated by the action of scavengers and other benthic macrofauna (S10: Katz et al., 2016), also by the action of bottom currents, turbidity currents included.

Once the spicules are delivered to the bottom, the period of time needed for them to be buried and become accumulated bSi will mostly depend on the local rates of sediment deposition, though also on the intensity of bioturbation (S10: Katz et al., 2016). In a study that has considered sediments from a variety of marine environments ranging from shallow bays to abyssal bottoms, the time required for the sponge spicules to reach the condition of permanently buried bSi ranged from 471 to 74,074 years, depending on the depositional nature of the local bottom (S11: Maldonado et al., 2019).

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Section 4 -The biological fluxes

4.1 Biogenic silica production as measured by isotopic techniques

Annex 1 shows all bSi production data with corresponding references.

4.2 bSi pelagic production uncertainties

The bSi pelagic production estimates from satellite NPP products, ocean biogeochemical models, and empirical studies each have their own uncertainty. When NPP is extrapolated to silica production, values are multiplied by estimates of the fraction of primary productivity done by diatoms and then a Si:C ratio. Of these, the choice of a Si:C ratio for the HNLC regions is the most uncertain. Our chosen value of 0.52 is 4 fold higher than for nutrient-replete temperate diatoms (Brzezinski, 1985, see main text reference list), but field observations suggest anywhere from no effect to an 8-fold increase (S12: Marchetti & Harrison, 2007, S13 : Timmermans et al., 2004). Biases in satellite NPP models also contribute to uncertainties in estimates of Si production. Particularly relevant are potential biases in Southern Ocean chlorophyll concentrations (and consequently, NPP), which may be underestimated in the Southern Ocean by as much as a factor of 3-4 (S14: Johnson et al., 2013).

For the biogeochemical models the two main sources of uncertainty are the extrapolation from silica export to gross silica production using D:P ratios (Table 1 of Tréguer & De La Rocha, 2013, main text reference list), as well as uncertainties in the parametrization of Southern Ocean physics and biology. For the seven GOBMs that report separate estimates of net silica production for the Southern Ocean, when Southern Ocean silica production is regressed against total global silica production the fitted line has an R^2 value of 0.96 with a slope equal to 1.05 (± 0.11). This points to model parameterizations of Southern Ocean physics and/or biology as the major determinant of differences in global silica production estimates among GOBMs.

For the global bSi pelagic production estimates derived from field data, extrapolation over both time and space is required. Few empirical studies of bSi production over an entire year are available. The vast majority of annual estimates determined for Longhurst provinces are extrapolated from field programs lasting a few weeks or less. Data sparsity remains a problem, and in the analysis presented here some Longhurst zones contain only a single measurement and nearly half of zones have no data at all (main text Fig. 3).

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4.3 bSi production: contribution of benthic diatoms

Determination of bSi production by microphytobenthos is still in its infancy. However, we can already foresee its potential impact in two ways. Through intensive studies in a temperate subtidal ecosystem (S15: Ni Longphuirt et al. 2009, S16 : Leynaert et al. 2009, and S17 : Chatterjee et al., 2013) we conservatively estimate that benthic diatoms can produce 1 mol-Si m^{-2} yr^{-1}. Extrapolation to the photic area of the world coastal ocean gives 6.8 Tmol-Si yr^{-1}. Cahoon (1999) (S18) proposed a global estimate of annual benthic microalgal primary production (based on the analysis of 85 worldwide studies) of 514×10^{12} gC yr^{-1}. Applying the Brzezinski (1985) (main text reference list) mean Si/C molar ratio for marine diatom of 0.13 to convert this carbon production in silica production, gives 5.4 Tmol-Si yr^{-1}. Both estimates are in good agreement. Therefore, the biogenic silica production by the microphytobenthos might represent about 2.5% of the global bSi production. It remains to be determined what proportion of this flux will finally contributes to the net sink of bSi. Preliminary studies have shown that bSi dissolution rates of benthic diatoms are 10 times slower than pelagic diatoms measured in the same conditions.

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Section 5 – Discussion

5.1 Introduction to Fig. 4: Depiction of a schematic Si cycle in the coastal and continental margin zone (CCMZ), excluding coastal upwelling, linked to the rest of the world ocean (« open ocean » zone including upwelling and polar zones). In principle, the CCMZ comprises proximal and distal coastal zones, as defined by Laruelle et al. (2009) (see main text reference list), which includes coastal upwelling in the distal coastal zone. However, in coastal upwelling zones both physical and biogeochemical dynamics are markedly different from those in the CCMZ *as* represented by Jeandel et al. 2016 (see main text reference list). Indeed, if in the CCMZ the transfer of material from land to ocean plays a major role in physical and biogeochemical processes, in coastal upwelling zones the bSi production is mainly fueled by dSi flux from below (i.e. from deeper in the water column), as it does for the global ocean *sensu lato* (Fig. 1). Therefore, in our synthesis quantifying the Si cycle in the « boundary exchange » zone, coastal upwelling is discarded from the CCMZ and conceptually incorporated to the « open ocean » zone, as shown in Fig. 4. This figure represents a possible Si cycle *assuming steady state* in the CCMZ and in the rest of the world ocean (so called « open ocean »), that is with total inputs = total outputs = 15.6 Tmol-Si yr^{-1}.

5.2 Detailed legend of Fig. 4

Input and dSi fluxes (grey arrows), outputs and biological fluxes (black arrows). In this steady-state scenario total inputs = total outputs = 15.6 Tmol-Si yr^{-1} (consistent with main text Figure 1). Note that (1) in the CCMZ the burial flux of bSi (3.7 Tmol-Si yr^{-1}) and the reverse weathering flux (4.7 Tmol-Si yr^{-1}) (authigenic siliceous material) are fed by the export flux of biogenic silica, and (2) the « open ocean » deficiency in dSi (4.7 Tmol-Si yr^{-1}) is made up by a transfer from the CCMZ. For details about those inputs and outputs refer to the « inputs » and « outputs » sections of the main text. For abbreviations, see detailed legend of Fig. 1 in Supplement (section 1).

Additional comments of Figure 4:

-Estimates of burial rate (planktonic bSi): in the CCMZ (excluding coastal upwelling), according to Rahman et al. 2017 (see main text reference list), $F_{B\ CCMZ}$ = 3.7 Tmol-Si yr^{-1}; in the « open ocean » zone, consistent with Fig. 1, $F_{B\ openocean}$= 9.2 - 3.7 = 5.5 Tmol-Si yr^{-1}.

-Estimates of reverse weathering flux: in Fig. 4 CCMZ F_{RWCCMZ} equals 4.7 Tmol-Si yr^{-1}, (Rahman et al. 2017, see main text reference list). Reverse weathering in the « open ocean » remains unquantified.

-Following Annex 1, bSi production in the CCMZ* is 13% of the total production (255 Tmol-Si yr^{-1}). Consequently, $F_{P(gross)}$ is 33 and 222 Tmol-Si yr^{-1}, for CCMZ and "open ocean", respectively.

-According to Tréguer and De La Rocha (2013) (see main text reference list), the pelagic production to dissolution ratio (D:P) being 0.51 and 0.57, for CCMZ and "open ocean", respectively. $F_{D(surface)}$ for those compartments is 17 and 124 Tmol-Si yr^{-1}, and F_E is 16 and 98 Tmol-Si yr^{-1}, for CCMZ and "open ocean", respectively.

Note than every component of the inputs, outputs, and biological Si fluxes, although interacting between each other, is determined by independent methods, that is there is no overlap in the counting of these fluxes. Therefore, the export production (16.0 Tmol-Si yr^{-1}) in particular feeds both the Si burial rate (3.7 Tmol-Si yr^{-1}) and the reverse weathering flux (4.7 Tmol-Si yr^{-1}).

Figure 4 also shows that the "open ocean" bSi production is mostly fueled by dSi inputs from below (92.5 Tmol-Si yr^{-1}), the CCMZ only providing 4.7 Tmol-Si yr^{-1} to the "open ocean".

*Although specific estuarine sites have been studied (e.g. S19 DeMaster 1983, S20, Raimonet al. 2013), no global estimate is presently available for the estuarine bSi production. Given that most of estuarine waters are turbid we anticipate that the contribution of estuaries to the total bSi of the coastal zone should be small.

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Annex 1. Data of biogenic silica production as measured from isotopic techniques

All data

Biome	Ocean	Province	System	sampling period	range pbSi	moyenne	longitude	latitude	prod. duration	annual PBSi	annual PBSi	References	References
					mmol-Si m^{-2} day^{-1}	mmol-Si m^{-2} day^{-1}			d	mmol m^{-2} an-1	10^9 mol an^{-1}		#
Coastal	**Pacific**	ALSK	Bering Sea coastal	May/July 1979 - 1980	7 - 51	20,9	-163	57	159	3317	1957	Banahan and Goering, 1986	21
Polar	Southern Ocean	CCSZ	Ross Sea	jan/feb 1990		34,0	-175	-76,5	79	2698	5396	Nelson et al., 1991	22
Polar	Southern Ocean	CCSZ	Pacific, Ross Sea		7,1 - 93	38,0	166	-75	79	3015	6030	Nelson and Smith, 1986	23
Polar	Southern Ocean	CCSZ	Indian sector	spring 95/summer 95		5,3	62	-66	79	421	841	Caubert 1998	24
Polar	Southern Ocean	CCSZ	Indian sector			57,6	140,42	-66,42	79	4570	9141	Beucher et al, 2004	25
Polar	Southern Ocean	PFZ	Weddell Scotia	1992	19,6-60,7	27,6	-6	-49,5	130	3582	32237	Quéguiner et al., 2002	26
Polar	Southern Ocean	PFZ	Weddell sea (EPOS 2)	1988/1989	11,2-20,6	15,9	-49	-57	130	2063	18571	Quéguiner et al., 1991	27
Polar	Southern Ocean	PFZ	Indian sector	spring 95/summer 94	1,7-2,2	2,0	62	-50	130	260	2336	Caubert 1998	24
Polar	Southern Ocean	POOZ	Pacific	oct/nov 97		12,2	-170	-58	114	1385	16625	Brzezinski et al, 2001	28
Polar	Southern Ocean	POOZ	Pacific	dec 97		27,1	-170	-60	114	3077	36928	Brzezinski et al, 2001	28
Polar	Southern Ocean	POOZ	East of New Zealand			3,6	-175	-61	114	404	4851	Nelson and Gordon, 1982	29
Polar	Southern Ocean	POOZ	Weddell Scotia	1992		3,5	-6	-52	114	397	4769	Quéguiner et al., 2002	26
Polar	Southern Ocean	POOZ	Pacific	summer 1998	0,6 - 2,58	2,6	142	-52	114	293	3516	Queguiner et al, 2001	30
Polar	Southern Ocean	POOZ	Kerguelen KEOPS 2	2011	3,09 - 47,9	23,2	72	-48,5	114	2634	31614	Closset et al 2014	31
Polar	Southern Ocean	POOZ	Indian sector	spring 95/summer 94	2,3-3,9	3,1	62	-54	114	352	4224	Caubert 1998	24
Polar	Southern Ocean	POOZ	Indian sector			10,2	142	-55	114	1158	13899	Beucher et al, 2004	25
Polar	Southern Ocean	SIZ	Weddell Sea	1990	1,97 - 3,18	2,6	-40	-70	114	294	6176	Leynaert et al., 1993	32
Polar	Southern Ocean	SIZ	Pacific	janv-98		22,6	-170	-61	114	2566	53893	Brzezinski et al, 2001	28
Polar	Southern Ocean	SIZ	Pacific	feb march 98		5,5	-170	-62	114	625	13116	Brzezinski et al, 2001	28
Polar	Southern Ocean	SIZ	East of New Zealand			6,8	-175	-64	114	768	16120	Nelson and Gordon, 1982	29
Polar	Southern Ocean	SIZ	Weddell Sea (EPOS 2)	1988/1989	2,3 - 22,9	10,1	-49	-60	114	1147	24085	Tréguer et al, 1991	33
Polar	Southern Ocean	SIZ	Weddell Scotia	1992		4,4	-6	-57	114	500	10493	Quéguiner et al., 2002	26
Polar	Southern Ocean	SIZ	Weddell sea (EPOS 2)	1988/1989	6,0-20,0	10,8	-49	-60,5	114	1226	25754	Quéguiner et al., 1991	27
Polar	Southern Ocean	SIZ	Indian sector	spring 95/sum. 94	5,7-8,9	7,0	62	-58,5	114	795	16693	Caubert 1998	24
Polar	Southern Ocean	SIZ	Indian sector			7,9	138,68	-65	114	897	18839	Beucher et al, 2004	25
Polar	Southern Ocean	SUBANT	Indian sector	Jan/feb 1999	0,25 - 0,93	0,5	63	-45	95	47	1353	Leblanc et al, 2002	34
Polar	Southern Ocean	SUBANT	Pacific	Summer 1998	0,6 - 2,58	1,1	142	-47	95	102	2955	Queguiner et al, 2001	30
Polar	Southern Ocean	SUBANT	East of New Zealand			2,0	-175	-54	95	190	5523	Nelson and Gordon, 1982	29
Polar	Southern Ocean	SUBANT	Indian sector			1,7	146	-48	95	162	4694	Beucher et al, 2004	25
Polar	Pacific	BERS	Bering Sea outer	May/July 1979 - 1981	1,8 - 25	10,1	-167	55,5	95	962	3741	Banahan and Goering, 1988	21
Coastal	Pacific	CAMR	Baja California		2,3 - 1140	89,0	-114	27	365	32485	40931	Nelson and Goering, 1978	35
Coastal	Pacific	CCAL	Coast. upw Monterey	April 1995	13 - 1140	202,0	-122,2	36,8	175	35262	33852	Brzezinski et al., 1997	36
Coastal	Pacific	CCAL	Coast. upw Monterey	April 1992	22 - 40	32,0	-122,2	36,2	175	5586	5363	Brzezinski et al., 1997	36
Coastal	Pacific	CCAL	Costa Rica Dome	July 2011	0,11 - 5,57	1,4	-122	33	175	251	241	Krause et al., 2015	37
Coastal	Pacific	CCAL	Santa Barbara	1996-1997	2,4-57,3	34,2	-120	34	175	5970	5731	Shipe and Brzezinski, 2001	38
Coastal	Pacific	CHIL	Peru Chile upw -BIOSOPE	Oct/Nov 2004	42 - 52	47,0	-72	-35	190	8950	23361	Leblanc et al 2018	39
Coastal	Pacific	CHIL		March/May 1977	0,1 - 4,04	1,2	-78	-13	190	226	590	Nelson 1981	40
Coastal	Atlantic	CNRY	NW Africa upw	May 1974	14 - 40	23,0	-17,5	21,5	**222**	5106	4085	Nelson and Goering, 1977	41
Westerlies	Mediterranean	MEDI	Mediterranean (SOFI)	Dec -Jan 1997/98	0,80	0,8	-1	36	127	105	325	Leblanc et al., 2004	42
Westerlies	Mediterranean	MEDI	Mediterranean (SOFI)	1999/2000	0.14–1.4	0,4	5	43	127	48	149	Leblanc et al 2003	43
Westerlies	Atlantic	NADR	N Atlantic (PAP)		0,5–1,3	0,9	-16	48,8	127	114	400	Ragueneau et al., 1997	44
Westerlies	Atlantic	NADR	NE Atlantic	May 2001	6 - 166	35,0	-15	60	127	4445	15558	Brown et al. 2003	45
Westerlies	Atlantic	NAST (E)	N Atlantic -POMME	March/April/ sept 2001	0,04-11,2	0,8	-18	42	127	96	36	Leblanc et al 2005	46
Westerlies	Atlantic	NAST (W)	Warm-Core Ring	April/June 1982	4,4 - 11,7	7,1	-63	37	127	901	5228	Brzezinski and Nelson, 1989	47
Westerlies	Atlantic	NAST (W)	Sargasso Sea (BATS)	1991-1994	0,2 - 1,6	0,7	-64	31,1	365	240	1392	Nelson and Brzezinski, 1997	48
Westerlies	Atlantic	NAST (W)	Mode-water eddy	April 2007	0,13 - 1,12	0,6	-64	32,5	127	81	471	Krause et al., 2010	49
Westerlies	Atlantic	NAST (W)	Sargasso Sea	May/March 1989	0,2 - 1,48	0,6	-65	32	127	81	471	Brzezinski and Kosman, 1996	50
Westerlies	Atlantic	NADR	N. Atlantic (BENGAL)			0,9	30	46	127	114	400	Ragueneau et al., 2000	51
Trades	Pacific	NPTG	Central North Pacific	August 1995	0,5 - 2,9	1,2	-155	28	365	453	9545	Brzezinski et al 1998	52
Trades	Pacific	NPTG	HOT–ALOHA		0,09 - 0,49	0,2	-158	22,5	365	63	1329	Brzezinski et al., 2011	53
Trades	Pacific	NPTG	Subtropical front	summer bloom	0,10 - 1,74	0,6	-150	27	365	219	4619	Krause et al., 2013	54
Trades	Pacific	PEQD	Eq. upwelling	nov-96	2,50	2,5	-180	0	365	913	9435	Leynaert et al., 2001	55
Trades	Pacific	PEQD	Eq. upwelling	nov-96	0,1 - 0,65	0,4	-180	5	365	146	1510	Leynaert et al., 2001	55
Trades	Pacific	PEQD	Eq. upwelling	nov-96	0,1 - 0,65	0,4	-180	-5	365	146	1510	Leynaert et al., 2001	55
Trades	Pacific	PEQD	Eastern equa. Upw.	2004	0,6 - 2,59	1,6	-110	-1	365	584	6039	Krause et al., 2011	56
Trades	Pacific	PEQD	Eastern equa. Upw.	2005	0,3 - 2,49	1,3	-125	0	365	475	4906	Krause et al., 2011	56
Westerlies	Pacific	PSAG	N Pacific (OSP)			5,1	-145	50	111	566	1812	Wong and Matear, 1999	57
Polar	Atlantic	SARC	Svalbard	May 2016	0,27 - 1,46	0,8	25	77	127	102	237	Krause et al 2018	58
Westerlies	Pacific	SPSG	SE Gyre BIOSOPE	Oct/Nov 2004	0,04 - 0,2	0,1	-90	-31	127	15	568	Leblanc et al 2018	39
Westerlies	Pacific	SPSG	HNLC -BIOSOPE	Oct/Nov 2004	0,8 - 5,6	3,6	-138	-8	127	457	17043	Leblanc et al 2018	39
Trades	Pacific	WARM	W equat. oligotrophic	oct-94	0,8 - 2,1	1,4	-168	0	365	511	8575	Blain et al., 1997	59
Trades	Pacific	WARM	W equat. oligotrophic	oct-94	3,90	3,9	-160	0	365	1424	23886	Blain et al., 1997	59
Coastal	Atlantic	NECS	Bay of Brest	2001		2,5	-4,6	48,3	365	900	1224	Del amo et al	60
Westerlies	Atlantic	NADR	AMT	April- May 2004		0,26	-16,78	47,45	127	32	113	Poulton et al, 2006	61
Westerlies	Atlantic	NASE	AMT	April- May 2004		0,43	-20,16	38,5	127	54	241	Poulton et al, 2006	61
Westerlies	Atlantic	NASW	AMT	April- May 2004		0,15	-36,4	29,2	127	19	110	Poulton et al, 2006	61
Trades	Atlantic	NATR	AMT	April- May 2004		0,14	-33,4	22,2	365	51	423	Poulton et al, 2006	61
Trades	Atlantic	SATL	AMT	April- May 2004		0,31	-30,37	-27,48	190	60	1058	Poulton et al, 2006	61
Trades	Atlantic	WTRA	AMT	April- May 2004		0,58	-27,06	6,1	365	212	1135	Poulton et al, 2006	61
Westerlies	Atlantic	NADR	Celtic Sea	nov-14		1,00	-8,83	48,75	127	127	445	Poulton et al, 2019	62

Note that « d », duration of the productive period in days, was extrapolated from the bloom phenology for each province (calculated as the number of day where the chloro concentration is greater than the average concentration between the maximun and the minimum values).

Average per province

Biome	Province	Surface 10^6 km²	Average mmol-Si m^{-2} day^{-1}	Prod. duration day	Annual PBSi mmol-Si m^{-2} an^{-1}	Annual PBSi 10^9 mol-Si an^{-1}
Coastal upw	CNRY	0,8	23,0	190	4 380	3 504
Coastal	NECS	1,4	2,5	159	391	532
Polar	SARC	2,3	0,8	127	102	237
Westerlies	NADR	3,5	9,3	127	1 176	4 116
Westerlies	NAST (E)	0,4	0,6	127	75	28
Westerlies	NAST (W)	5,8	1,8	127	233	1 353
Westerlies	MEDI	3,1	0,6	127	77	237
Coastal	ALSK	0,6	20,9	159	3 317	1 957
Coastal upw	CAMR	1,3	89,0	365	32 485	40 931
Coastal upw	CCAL	1,0	67,4	175	11 767	11 297
Coastal upw	CHIL	2,6	24,1	190	4 588	11 975
Polar	BERS	3,9	10,1	95	962	3 741
Trades	NPTG	21,1	0,7	365	245	5 164
Trades	PEQD	10,3	1,2	365	453	4 680
Trades	WARM	16,8	2,7	365	967	16 230
Westerlies	PSAE	3,2	5,1	111	567	1 813
Westerlies	SPSG	37,3	1,9	127	236	8 806
Westerlies	SUBANT	29,0	1,3	95	125	3 631
Polar	PFZ	9,0	15,2	130	1 968	17 715
Polar	POOZ	12,0	10,7	114	1 213	14 553
Polar	SIZ	21,0	8,6	114	980	20 574
Westerlies	NASW	5,8	0,2	127	19	110
Trades	NATR	8,3	0,1	365	51	423
Trades	SATL	17,8	0,3	190	60	1 058
Trades	WTRA	5,4	0,6	365	212	1 135
Polar	CCSZ	2,0	33,7	79	2676,0	5352,0

Average per Ocean Basin

Ocean	Surface 10^6 km²	portion in AO	Surface considered*	Annual PBSi mmol m^{-2} an^{-1}	Annual PBSi 10^9 mol an^{-1}	% PBSi Total
Atlantic	106	20	86	250	21 501	8,6
Pacific	166	32	134	1 088	145 736	58,6
Southern Ocean*			73	586	42 760	17,2
Arctic	14		14	102	1 422	0,6
Indien	75	21			37 188	15,0
Sub Total	361		307		211 419	
			Annual World PBSi		**248 607**	

Average per domain (Longhurst & Tréguer and Jacques for the OA)

Domain	Biome	Surface 10^6 km²	Annual PBSi mmol m^{-2} an^{-1}	Annual PBSi 10^9 mol an^{-1}	Annual PBSi 10^9 mol an^{-1}	% PBSi Total
Coastal	Coastal	29	1 276	37 017	138 036	13,0
	upw	8	12 026	101 019		35,5
Polar	Polar[*]	54	1 238	66 827	66 827	23,5
Open Ocean	Westerlies[*]	130	228	29 647	80 063	10,4
	Trades	140	360	50 416		17,7
			Annual World PBSi		**284 926**	

[*] Surface considered: this is the ocean surface minus the Antarctic ocean

[*] Polar: surface includes the Antarctic Ocean (from the polar front poleward, i.e. 44 10^6 km^2) + arctic zones as defined by Longhurst

[*] Westerlies: includes the subantarctic zone

*Southern Ocean: includes the Antarctic Ocean and the subantarctic zone (i.e. respectively 44 10^6 km^2 + 29 10^6 km^2)

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