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Interactive comment on "Reviews and syntheses: The biogeochemical cycle of silicon in the modern ocean" *by* Paul J. Tréguer et al.

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We thank referee n°1 for their constructive comments. We have replied to these comments below:

1) Steady-state assumption. The authors make value judgements on the data used to calculate fluxes sometimes discarding studies, sometimes averaging a wide range of numbers, although this reviewer feels comfortable with their calculations. However, after a large number of assumptions the authors arrive at a "balanced budget" interpreted that the global Si cycle in the oceans is at a steady-state. I am not sure the success of achieving a balanced budget warrants the conclusion that the budget is in steady state especially because there is a large range of input and output fluxes, many of them

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uncertain, contributing to this revised budget. Are there fluxes that are underestimated (a la Jeandel) or estimates of fluxes that are over-stated (sponge BSi deposition) that could put the budget far away from an apparent balance?

Answer : We believe there is a misunderstanding regarding our approach to build a budget for the marine Si cycle. This review paper aims to show the best knowledge concerning the processes that controlled the input fluxes of dSi and tbe output fluxes of Si to and from the ocean. What we show is that a best estimate of the total average of the input fluxes (14.8 Tmol-Si yr-1) and the total average of the output fluxes (13.4 Tmol-Si yr-1) are unbalanced. Therefore, we disagree with the reviewer that Âń the authors arrived at a balance budget Âż. However, given a possible underestimate of the output fluxes (see sections 5.2.3 and 6.), we do not exclude that the two fluxes balance each other, and thus that the Si cycle in the modern ocean could be at steady state (Figure 1). This is clearly stated: -in the abstract (Âńwe address the steady state hypothesis Âż), -in section 5.2.3 (Âń A possible steady-state scenario Âż), and -in the Âń Conclusions/recommendations Âż section 6 (Âń The main question that still needs to be addressed is whether the contemporary marine Si cycle is at steady state,. . . Âż).

2) Specific unresolved questions (starting at line 537). The manuscript presents two case studies (Chinese Seas and The North-East Pacific dSi Anomaly) that add little to the main theme of the manuscript. The conclusion of this section starting at line 581 “a process that requires further studies” could be used on many of the processes contributing to fluxes. I do not know if these case studies are important to have as part of this manuscript.

Answer : Reviewer n°1 asks if these two cases studies add value to the manuscript. A principal aim of this review paper is to provide guidelines for future research programs. We chose to highlight these two case studies in the Pacific Ocean, which is considered a Âń silica ocean Âż (Honjo et al. 2008), since more knowledge is required for the Si cycle in this ocean.

As explained in section 5.3.1, the Chinese marginal seas are unique over the world ocean marginal seas, particularly because of the massive entrainment of siliceous soils through the hydrographic network of large rivers, making it difficult to quantify the bSi content in this system using a classic alkaline leach's method. As mentioned in section 6, lines 689 and following, we recommend the Chinese marginal seas to be one of the major test sites for the international comparative analytical exercise to be organised in the future. Thus, a better understanding of the processes that control the Si cycle in the Chinese marginal seas is a priority for a better understanding for the Si cycle of the world ocean. As explained in section 5.3.3, the North Pacific dSi-very rich plume is unique in the world ocean. Among the hypotheses that explain the formation and maintainance of this plume (which required a flux of 1-2 Tmol-Si yr-1) is remobilization of relatively old bSi that accumulated over a long time interval, by dissolution in a hydrothermally active environment. If this hypothesis is correct, the total average net dSi inputs to the ocean would be between 15.8 and 16.8 Tmol-Si yr-1, a large excess to the present extimate of the total Si output flux. Process studies in these two sites of the Pacific ocean are a priority for future research on the Si cycle, and if the Editor agrees, we prefer to maintain this section.

3) A discussion of the uncertainties and how changes in the ocean Si cycle would be affected by global change (Section 5.4) is important to include, however, this section needs to be more coherent and better presented. Answer : For the sake of simplicity, this section is now limited to "the impacts of climate change on the Si cycle" (section 5.4): -5.4.1 (impacts on riverine inputs of dSi and aSi), -5.4.2 (Abondance of marine pelagic and benthic silicifiers), and -5.4.3 (Predictions for the ocean phytoplankton production and bSi production).

The impacts of anthropogenic activities not associated with climate change are now discussed in a different section 5.5. ("Other anthropogenic impacts").

Minor comments:

-Line 157 “this represents a realistic upper limit” – What is the justification for this statement? Answer : Cho et al (2018)’s used a 228Ra inverse model and groundwater dSi/228Ra ratios to estimate the total SGD dSi flux to the ocean. Because this total flux comprises the contributions of both the terrestrial (net) and the marine (net + recycled) components it represents the upper limit of the net SGD dSi flux, if we assume that the marine component would be a net flux, which obviously is not the case. The text has been changed as follows : Âń. . . this represents an upper limit. . . Âż.

-Line 168 “Only one value currently exists” – See Hirst et al. published on 26 June 2020 and Hatton et al. published on 14 July 2020 in Frontiers that have new numbers for Antartica.

Answer : These studies are now acknowledged.

-Line 232 and 233 - Why are you using units of “g yr-1” instead of “Tmol yr-1” as in the rest of the manuscript?

Answer : we used Tmol yr-1 when we refer to silica fluxes, but used g yr-1 when we refer to water fluxes (hydrothermal fluid or river water fluxes).

-Line 235 Changed “determined” to “calculated”

Answer : corrected.

-Line 337 “canonical” is used several times in the manuscript. I have looked up the word and it has many meanings depending on the field of study. I looked in the original citation and “canonical” is not there either. Can you please use a less ambiguous word?

Answer : Corrected The sentence “The “canonical” value for global gross marine bSi pelagic production is 240 ($\pm$ 40) Tmol-Si yr-1 (Nelson et al., 1995)” has been rewritten to read “The last evaluation of global marine silica production was by (Nelson et al., 1995) who estimated global gross marine bSi pelagic production to be 240 ($\pm$ 40) Tmol-Si yr-1”

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-Line 455 Change “do” to “does”. Fix the rest of the sentence “being little reliable”

Answer : We have reworded this sentence. Thank you! Âń . . .If the bSi production that is being accumulated as standing stock in the living sponge populations annually is assumed to become constant in a long term equilibrium state, the global annual deposition rate of sponge bSi can be considered as a reliable estimate of the minimum value that the annual bSi production by the sponges can reach in the global ocean. The large associated SD value does not derive from the approach being unreliable but from the spatial distribution of the sponges on the marine bottom being extremely heterogeneous, with some ocean areas being very rich in sponges and sponge bSi in sediments at different spatial scales while other areas are completely deprived from these organisms. . ..

-Lines 504 (Section 5.2.2) I do not really understand what you are trying to say here, especially the last sentence. You state that climate change or anthropogenic impacts affect dSi (Bernard et al. 2010, 2011) leading to an imbalance. Do you mean there will be no changes in ocean production of siliceous organisms if the Si balance in the oceans change? If so, is that only speculation or is there evidence?

Answer : (cf. lines 485-486) over a given time scale, an elemental cycle is at steady state if the outputs balance the inputs, and the mean concentration of the dissolved element remains constant. The output flux depends on the export flux of biogenic silica which itself depends on the gross production of biogenic silica.

The text has been corrected as follows :

“In the modern ocean, as shown above, the main control over silica burial and authigenic formation rate is the bSi production rate of (pelagic + benthic) silicifiers. The gross production of bSi due to diatoms depends on the dSi availability in the surface layer (Figure 1), which is controlled external inputs, inputs from below, and Si recycling within the surface layer. Actually, this production is not Si-limited or not severely limited in several zones of the world ocean, which include the coastal zones, and the HNLC zones (Tréguer & De La Rocha, 2013). Thus, on short timescales, there are no strong negative feedbacks, between supply rates and production or burial rates, which would necessarily keep the marine Si cycle in balance. For this reason, impacts of climatic changes or anthropogenic that, at short timescales affect dSi inputs to the ocean by rivers (Bernard et al., 2010, 2011) and/or other pathways (see section 5.4.1), could lead to an imbalance of Si inputs and outputs in the modern ocean."

-Line 542 I would add "particulate Si inputs" to needing a better understanding

Answer : Corrected : Âń . . . but also to a better understanding of the processes that control the Si cycle, such as SGD, reverse weathering, and particulate Si inputs. . . Âż

-Line 552 "unusual" – Why is it unusual for coastal systems?

Answer : In coastal systems, according to TDLR 2013 the D : P (dissolution to production) ratio averages 0.51. In coastal Chinese seas this ratio varies between 0.62 and 0.90. To make it clearer the text has been amended as follows : Âń . . . Secondly, the bSi production seem to be mostly (62-90%) maintained by a recycling of Si (Li et al., 2019; Liu et al., 2005; Liu et al., 2016; Wu et al., 2017; Wu et al., 2020), which is particularly high for coastal systems (Tréguer & De La Rocha, 2013) Âż.

-Line 563 "recommend additional attention" – Why

-Answer : As explained in section 5.3.1, the Chinese marginal seas are unique over the world ocean marginal seas, particularly because of the massive entrainment of siliceous soils through the hydrographic network of large rivers, making it difficult to quantify the bSi content in this system using a classic alkaline leach's method. As mentioned in section 6, lines 689 and following, we recommend the Chinese marginal seas to be one of the major test sites for the international comparative analytical exercise to be organised in the future. Thus, a better understanding of the processes that control the Si cycle in the Chinese marginal seas is a priority for a better understanding for the Si cycle of the world ocean.

-Line 580 Need reference to these numbers presented.

Answer : we are not sure we understand the question. All the numbers given in section 5.3.2 are taken from the two references already cited in this section (Talley et al ; 1992 ; Johnson et al., 2006)

-Lines 590, 598, 600 Should be “precipitation”

Answer : Corrected

-Line 601 Spell out what you mean by “contradictory impacts”

Answer : let us explain the two contradictory impacts : There is more precipitation in the tropical convergence zones, which means there is more weathering of soils and more dSi delivery to the ocean. When there is less precipitation in tropical subsidence zones, this means there is less weathering of soils and less dSi delivery to the ocean.

-Line 616 Why use the word “corroborated”?

Answer : Modified as follows . . . Âń the melting of Antarctic ice platforms has been noticed to trigger impressive population blooms of highly silicified sponges (Fillinger et al. 2013). Âż.

-Line 652 “These uncertainties suggest” – If we can not use models to help us understand how the silica biogeochemical cycle will change in a future ocean, then what do we use? Seems like it was written by someone who does not like models.

Answer: the second reviewer shared your criticisms and requested a few additional details. Below is our answer to both reviewers.

Section 5.4.3 has been modified as follows :

“In the 21st century, climate change affects ocean circulation, stratification and upwelling thus affecting the cycles of nutrients (Aumont et al., 2003; Bopp et al., 2005, 2013). With increase stratification, reduced dSi supply from below (Fig. 1 and 4) leads to less siliceous phytoplankton production in surface compartments of lower latitudes and possibly the North Atlantic (Tréguer et al., 2018). Based on field studies, the impact of climate change on the phytoplankton production of higher latitudes is highly debated as melting of sea ice decreases light limitation. Regarding the Arctic Sea, increase nutrients (at the least for silicic acid) availability will occur through the Transpolar Drift delivering nutrient rich river- and shelf derived waters as potential sources for primary production, including bSi production (e.g. Charette et al., 2020). Regarding the Southern Ocean, a well known area for low dissolved iron (dFe) concentrations (Tagliabue et al 2016), except in the CCMZ (e.g. Annett et al. 2015 ; Sherrell et al. 2018), bSi production might increase in areas impacted by dFe inputs from icebergs melting or from incresed convection that feeds surface waters in dFe from below (Boyd et al., 2016 ; Hutchins & Boyd, 2016 ; Tréguer et al., 2018). Changes in Southern Ocean phytoplankton population due to climate change have been observed already. For example, along the West Antarctic Peninsula, phytoplankton community are quite sensible to the ice coverage, with the haptophyte and cryptophyte community increase while the diatom decrease (Henley et al., 2019). Globally, it is therefore possible that a warmer and acidified ocean alters the pelagic bSi production rates, thus modifying the export production, and the Si burial rates at short time scales. Although uncertainty is substantial, model studies (Bopp et al., 2005; Dutkiewicz et al., 2019; Laukötter et al, 2015) suggest regional shifting of bSi pelagic production due to climate change. Climate change models suggest a global decrease in diatom biomass and productivity over the course of the 21st century (Bopp et al., 2005, Dutkiewicz et al., 2019, Laufkötter et al., 2015), which would lead to a reduction in the pelagic biological flux of silica. Regional responses however differ, with most models suggesting a decrease in diatom productivity in the lower latitudes and many predicting an increase in diatom productivity in the Southern Ocean (Laufkötter et al, 2015). Holzer et al. (2019) suggest that changes in supply of dFe will alter bSi production mainly by inducing floristic shifts, not by relieving kinetic limitation. Increased primary productivity come from reduction in sea-ice and the faster growth rates with warmer waters and longer growing seasons in the high latitudes. However, many models have very simple ecosystems including only diatoms and a small phytoplankton. In these models, increased primary production in the Southern Ocean is mostly from diatoms. Some models with more complex ecosystem (i.e. including additional phytoplankton groups) suggest that increased primary productivity in the future Southern Ocean will be due to other phytoplankton types (e.g. pico-eukaryote) and that diatoms biomass will decrease (Dutkiewicz et al, 2019; also see model PlankTOM5.3 in Laufkötter et al, 2015), except in regions where sea-ice has melted. Differences in the complexity of the ecosystem and parameterizations, in particular in terms of temperature dependences of biological process, between models lead to widely varying predictions (Dutkiewicz et al., 2019; Laufkotter et al., 2015) thus constraining our capacity to predict what will happen with the silica biogeochemical cycle in a future ocean."

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