Effects of biogenic silica dissolution on silicon cycling and export production
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[1] Biogenic silica (bSiO2) dissolution plays an important role in the marine silicon cycle, diatom production and vertical export production. An ocean ecosystem model that incorporates dependency of bSiO2 dissolution on water temperature was used to examine the effects of bSiO2 dissolution on diatom production and bSiO2 export. Diatoms dominate with higher bSiO2 dissolution rates because of enhanced silicic acid supply for diatom production. Annual bSiO2 export does not change with bSiO2 dissolution rate, because of less bSiO2 production with lower rates and greater bSiO2 dissolution with higher rates. The ratio of bSiO2 export to production changes seasonally, with maximum in late spring. The contribution of spring diatom bloom to the annual bSiO2 export is 21–30%, smaller than observation-based estimates. This suggests necessity for incorporating other factors controlling bSiO2 dissolution besides water temperature, such as difference in organic coating protections against bSiO2 dissolution between live and dead diatoms, in the model. Citation: Fujii, M., and F. Chai (2005). Effects of biogenic silica dissolution on silicon cycling and export production, Geophys. Res. Lett., 32, L05617, doi:10.1029/2004GL022054.

1. Introduction
[2] Marine biogenic silica (bSiO3) is mainly produced by diatoms, a large phytoplankton species which deposit silica within their cell walls. Dissolution of bSiO2 is the source of regenerated silicic acid (Si(OH)4) in the ocean. However, because of the scarcity of in situ observations, understanding the linkages between bSiO2 production and dissolution remains uncertain [e.g., Nelson et al., 1995; Ragueneau et al., 2000; Brzezinski et al., 2001, 2003].

[3] Recently, several modeling studies have incorporated silicon cycling in marine ecosystem models [e.g., Dugdale et al., 1995; Pondaven et al., 1998; Chai et al., 2002; Fujii et al., 2002; Moore et al., 2002; Aumont et al., 2003]. Most of these models have focused on Si(OH)4 regulation of diatom production, and none of them have paid attention to bSiO2 dissolution process and its effect on silicon cycling and vertical export production. Gnanadesikan [1999] has embedded silicon cycling in an ocean general circulation model although the marine ecosystem is not considered. He found that the global Si(OH)4 distribution was quite sensitive to the type of dissolution parameterization.

[4] We use a marine ecosystem model, incorporating both silicon and nitrogen cycles, to examine the effects of bSiO2 dissolution on diatom production as well as relationships among production, dissolution and downward export of bSiO2. This study focuses on the role of water temperature in controlling bSiO2 dissolution, by conducting a series of model sensitivity experiments related to dependency of bSiO2 dissolution rate on temperature.

2. Model Description and Experimental Design
[5] We use a fifteen-compartment marine ecosystem model developed originally for the subarctic Northwest Pacific [Fujii et al., 2002; Yamanaka et al., 2004]. The surface water is defined as the model domain above 100 m depth. In the model, the phytoplankton is divided into two categories: PL (large phytoplankton, all diatoms) and PS (non-diatom small phytoplankton). Diatom production is regulated by Si(OH)4, nitrate (NO3) and ammonium concentration, while small phytoplankton production is controlled only by NO3 and ammonium concentration. The bSiO2 is exposed to dissolution after being separated from live diatoms by the mortality of diatoms and the egestion of diatom-grazing zooplankton.

[6] This model has been applied to a time-series Station KNOT (Kyodo North Pacific Ocean Time series; 44°N, 155°E) located in the subarctic Northwest Pacific, which displays strong seasonality in diatom production. The model structure and forcing are the same as in work by Fujii et al. [2002]. The transition-domain water with high temperature, high salinity and low nutrients is sometimes advected horizontally from the subtropical gyre to Station KNOT. However the majority of the annual nutrient supply occurs through local vertical mixing in winter and is consumed by biological production in the surface water in spring and summer. Therefore, we have ignored the sporadic influence on horizontal charge/discharge of nutrients by the transition-domain water. Values of the model parameters are the same as those of Fujii et al. [2002], except the temperature coefficient for the bSiO2 dissolution (k_bSiO2) is modified for this study. In the model, the specific bSiO2 dissolution rate (V_dis) is calculated as V_dis = V_dis0 × exp(k_bSiO2/2 × T), where V_dis0 is the specific bSiO2 dissolution rate at temperature equals to 0°C and T is water temperature [°C]. Recent data show that bacterial protease activity accelerates the dissolution of bSiO2 [Bidle and Azam, 1999], and that such process is strongly dependent on water temperature [Bidle et al., 2002, 2003]. We set k_bSiO2 to 0.097 [1/°C] to represent the dependency of bSiO2 dissolution on water temperature by a factor of 2.63 for each 10°C (Q10 = 2.63 [Bidle et al., 2003]), while the temperature coefficient for remineralization of organic nitrogen is set to 0.069 [1/°C] (Q10 = 2.0 [Fujii et al., 2002]).
We carry out a series of sensitivity studies by varying the dissolution rate of bSiO$_2$ at 0°C ($V_{\text{dis0}}$) to 0.000 (Case 1; no dissolution), 0.010 (Case 2), 0.025 (Case 3), 0.050 (Case 4), 0.100 (Case 5) and 0.200 (Case 6) [1/d] to reflect the range of measured values at this temperature, 0.00 and 0.20 [1/d] [e.g., Beucher et al., 2004].

3. Results and Discussion

The model results successfully reproduce the observed seasonal pattern of physical environments and biogeochemistry at Station KNOT [Fujii et al., 2002]. The large seasonal amplitude of sea surface temperature (SST), from less than 2°C in March to 15°C in August, has impact on the calculation of bSiO$_2$ dissolution rate in the model (Figure 1). The low SST along with strong wind in winter enhances vertical mixing, which injects nutrient-rich deep water to the surface. The relatively high SST as well as weak wind from late spring to autumn result in vertical stratification of water column. This stratification and the following spring diatom bloom cause depletion of surface nutrients. Therefore, the surface nutrient concentration is the highest in late winter and the lowest in late summer. The modeled annual surface maximum and minimum Si(OH)$_4$ is 35 and 5 [mmolSi/m$^3$], consistent with the observed ones of 40 and 4 [mmolSi/m$^3$], respectively [Fujii et al., 2002]. Due to higher temperature between late spring and autumn, the modeled bSiO$_2$ dissolution rate increases significantly, which causes dissolution to be the dominant source of Si(OH)$_4$ supporting bSiO$_2$ production during summer and autumn.

The modeled annual-mean primary production by diatoms (PP$_{PL}$) increases with the bSiO$_2$ dissolution rate at 0°C ($V_{\text{dis0}}$), from 1.3 in Case 1 to 2.4 [mmolN/m$^2$/d] in Case 6 (Figure 2). Higher surface Si(OH)$_4$ concentration in response to higher $V_{\text{dis}}$ (Figure 3) enhances diatom production. For example, the modeled surface minimum Si(OH)$_4$ concentration in Case 6 is close to the half saturation constant for Si(OH)$_4$ uptake by diatoms (6.0 [mmolSi/m$^3$]). On the other hand, surface NO$_3$ concentration decreases with higher bSiO$_2$ dissolution rate. It is due to higher diatom production, which removes NO$_3$ as well. Therefore, this result shows that the Si(OH)$_4$ limitation becomes stronger with lower $V_{\text{dis}}$ while the NO$_3$ limitation takes over with higher $V_{\text{dis0}}$. Changing in the bSiO$_2$ dissolution rate also alters competition between diatoms and small phytoplankton for NO$_3$, with diatoms taking more NO$_3$ results in decreasing available NO$_3$ for small phytoplankton. Therefore, the annual-mean primary production by small phytoplankton (PP$_{PS}$) in Case 6 decreases to 50% of that in Case 1, and diatoms dominate primary production as $V_{\text{dis}}$ increases (Figure 2). The diatom production (PP$_{PL}$) accounts for 57% and 83% of total primary production (PP$_{\text{total}}$) in Case 1 and Case 6, respectively. The PP$_{\text{total}}$ increases as $V_{\text{dis0}}$ increases, but only by 1.3 times because of compensation between increasing PP$_{PL}$ and decreasing PP$_{PS}$.

There are two pathways for the fate of bSiO$_2$, i.e., to be dissolved in the surface water or to sink to the deep water. In this study, we define the ratio of the bSiO$_2$ export across 100m to the bSiO$_2$ production in the surface water as a bSiO$_2$ export ratio. The variation in the bSiO$_2$ dissolution rate at 0°C ($V_{\text{dis0}}$) changes the annual bSiO$_2$ export ratio, with lower bSiO$_2$ export ratios corresponding to higher bSiO$_2$ dissolution rates (Figure 4a). For example, the annual bSiO$_2$ export ratio decreases from 1.0 in Case 1 to 0.57 in Case 6. The modeled bSiO$_2$ export ratio changes significantly in response to the variation of bSiO$_2$ dissolution rate, but the absolute value of the modeled annual bSiO$_2$ export change by <10% among all the six cases (Figure 4b). This result occurs because the bSiO$_2$ production is relatively low with lower dissolution rates due to less Si(OH)$_4$ supply for diatom production. With higher dissolution rates the bSiO$_2$ production is higher and a relatively large portion is dissolved.
dissolved in the surface water, therefore less bSiO₂ is exported to the deep water.

[11] Strong seasonal variation in the modeled bSiO₂ dissolution rate, corresponding to variability of water temperature, changes Si(OH)₄ concentration in the surface water, altering the magnitude, timing and duration of peaks of spring diatom bloom, primary and export production. Seasonal variation of the modeled bSiO₂ production and export, and the bSiO₂ export ratio in Cases 1, 5 and 6 are shown in Figure 5. From late spring to early autumn, approximately May to October, increasing Si(OH)₄ limitation from Case 6 to Case 1 (e.g., no bSiO₂ dissolution) terminates the spring diatom bloom progressively earlier and reduces annual diatom production, which leads to large differences in the bSiO₂ production among these three cases (Figure 5a). The difference in the bSiO₂ production among the cases is smaller during other times of the year, because diatom production is enhanced during the period when Si(OH)₄ is plentiful in the surface water due to stronger physical transport. On the other hand, difference in the bSiO₂ export among all cases is small on an annual basis (Figure 5b). The bSiO₂ export during the spring diatom bloom period, defined as from mid-April to mid-May, is lowest in Case 6 due to high bSiO₂ dissolution rate. The bSiO₂ export ratio changes seasonally and has its maximum during the post-bloom period (Figure 5c). The ratio can exceed 1.0 because the bSiO₂ export by the mortality of diatoms and the egestion of diatom-grazing zooplankton occurs several days later than the bSiO₂ production.

[12] Of the total modeled annual bSiO₂ export in Case 1 and 6, 60 and 54% occur in spring (30 and 21% during the bloom period, and 30 and 33% during the non-bloom period), 19 and 27% in summer, 10 and 9% in autumn, and 11 and 10% in winter, respectively. This means that the spring diatom bloom, which occurs for less than 10% of the entire year, plays a disproportionately large role in transporting the bSiO₂ to the deep water, resulting from the enhanced bSiO₂ production. The vertical export of bSiO₂ is also largest during the bloom period because of relatively low temperature and subsequent less bSiO₂ dissolution in the surface water.

[13] All the model results shown above are applicable not only to the subarctic Northwest Pacific but to the global ocean where silicic acid is a potentially limiting factor on diatom production. Therefore, the model results can be compared with the global observation-based data. The modeled significant vertical export of bSiO₂ during the bloom period is consistent with evidences from observations in some oceanic areas [e.g., Truesdale and Kellogg, 1979; DeMaster et al., 1992; Brzezinski and Nelson, 1995; Nelson et al., 1995]. However, contribution of the diatom bloom to the annual export of bSiO₂ seems smaller in this modeling study, with a value of 21 to 30%, and some other observation-based estimates are 40 to 60% [e.g., Nelson et al., 1995; Nelson and Brzezinski, 1997; Brzezinski et al., 2001; Shipe and Brzezinski, 2001], higher than the modeled results.

[14] By examining global data sets, Brzezinski et al. [2003] have demonstrated that the larger contribution of diatom bloom on the observed bSiO₂ export is associated with systematically higher fraction of bSiO₂ production supported by new Si(OH)₄ (1-DRP) during the bloom period. We can change the minimum and maximum values of bSiO₂ export ratio (Figure 5c) by changing values of the bSiO₂ dissolution rate at 0°C (V_{diss0}) and the temperature coefficient for the bSiO₂ dissolution (k_{bSiO₂}). However, the model cannot reproduce the observed shift of bSiO₂ export ratio, between low ratio during the non-bloom period and higher ratio during the bloom period. In the current model,
we only include bSiO₂ dissolution from silicon detritus pool that does not include live diatoms. Beucher et al. [2004] showed that V_{diss} was correlated to the percentage of dead diatoms. To reproduce the systematically higher bSiO₂ export ratio during the bloom period, other factors controlling bSiO₂ dissolution rate besides water temperature, such as difference in organic coating protections against bSiO₂ dissolution between live and dead diatoms, are probably required to be incorporated in the model.

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References


