

# Constraints placed by silicon cycling on vertical exchange in general circulation models

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**Abstract.** The flux of biogenic silica out of the oceanic mixed layer (the export flux) must balance the import of high-silicate deep waters associated with mass exchange between the surface and deep ocean. Recent regional estimates of the export flux limit it to 50-80 Tmol yr<sup>-1</sup>. In order to reproduce such low export fluxes, coarse-resolution general circulation models must have low pycnocline diffusivity and a lateral exchange scheme which involves advection of tracers by unresolved mesoscale eddies. Failure to capture low rates of vertical exchange will result in climate models which overpredict the uptake of anthropogenic carbon dioxide and fail to capture the proper locations and rates of density transformation.

## 1. Introduction

Biological production in the upper ocean is sustained by an input of nutrients from the deep ocean. At steady state, the sinking flux of biogenic material (export flux) is balanced by the exchange of nutrient-poor surface waters with nutrient-rich deep waters. Silicate is a nutrient used by diatoms and radiolaria to construct their shells. Unlike other nutrients which are remineralized from sinking particles within a few hundred meters of the surface, silica dissolves at fairly great depths [Treguer *et al.*, 1995]. This makes the production of silica in the upper ocean sensitive to the vertical exchange of deep water. Recent regional estimates of biogenic silica production and export (summarized below) show that this vertical exchange is quite weak. Based on this we find that the GFDL ocean model requires low pycnocline diffusivity and lateral exchange due to mesoscale eddies which involves advection as well as diffusion [Gent and McWilliams, 1990]. Because both the silicate distribution and biogenic silica flux may be directly measured, silicon can be used to estimate vertical exchange rates more accurately than tracers such as CFCs, whose air-sea flux is poorly known. Additionally, silicon can be used to estimate the upwelling of deep water in low latitudes [Worthington, 1977], a process which is harder to capture with CFCs or radiocarbon.

## 2. Observational Background

Nelson *et al.*, [1995] (henceforth NTBLQ95) present regional estimates of biogenic silica production. They find that the mean uptake in the main areas of diatom sediment accumulation (coastal upwelling zones, subarctic N. Pacific, and Southern Ocean) amounts to some 0.7-1.2 moles Si m<sup>-2</sup>

yr<sup>-1</sup> or 28-48 Tmol Si yr<sup>-1</sup> over an area of 42x10<sup>12</sup> m<sup>2</sup> (12% of the ocean). 17-37 of the 28-48 Tmol yr<sup>-1</sup> total uptake occurs within the Southern Ocean. Since diatoms in these areas tend to be larger, more heavily silicified and less prone to dissolution than diatoms in general, we will assume that all of the silica uptake in these areas is exported. This is surely an overestimate. NTBLQ95 estimate that silica uptake in mid-ocean gyres amounts to some 26 Tmol Si yr<sup>-1</sup>. Mid-ocean diatoms are more easily dissolved such that the export flux measured in sediment traps is only about 20% of the estimated uptake, or 6 Tmol Si yr<sup>-1</sup> [Brzezinski and Nelson, 1995].

Two areas of the ocean are not evaluated by NTBLQ95, the equatorial oceans and the North Atlantic. JGOFS recently measured the sinking flux of biogenic silica along 140W in the eastern equatorial Pacific. The observed flux is quite high right on the equator (2.0 moles Si m<sup>-2</sup> yr<sup>-1</sup>) but falls off rapidly to the north and south (Dugdale and Wilkerson, [1998], Murray, pers. comm.). We estimate the total flux for the eastern equatorial Pacific (10N-10S, 180W-90W) to be 7-10 Tmol yr<sup>-1</sup>. The model studies done as part of this research found that the export flux from the tropics of all three oceans was 2-2.5 times the export in the eastern equatorial Pacific. This implies that the total tropical export flux is about 15-25 Tmol yr<sup>-1</sup>. We have no specific information about silica fluxes in the high latitudes of the North Atlantic. We will assume that Si export in the North Atlantic is small enough that it is contained within our overestimate of silica export in the main areas of sediment accumulation.

The three regional fluxes are then 28-48 Tmol yr<sup>-1</sup> in the main areas of diatom sediment accumulation, 6 Tmol yr<sup>-1</sup> in the mid-ocean gyres, and 15-25 Tmol yr<sup>-1</sup> in the tropical oceans. We estimate that the global silica flux which can be supported by direct measurement is only 50-80 Tmol yr<sup>-1</sup>. This estimate is lower than those based on biological data in NTBLQ95 and Treguer *et al.*, [1995] and it is quite possible that significant errors could be made in scaling measurements from a few sites to entire basins. With this caveat in mind, we may still ask the question: if the regional flux data is correct what constraints does it place on oceanic vertical exchange?

## 3. Model setup

A study of silicon cycling was made with the GFDL Modular Ocean Model [Pacanowski, 1996]. The sensitivity of the silicate distribution and export flux to the dissolution profile, lateral mixing parameterization, and vertical mixing parameterization were evaluated within the base model of Toggweiler and Samuels, [1993]. Gnanadesikan [1999a] focusses on the geochemical aspects of this study, while this paper focusses on the implications for vertical exchange.

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Si uptake by biota was modeled by relaxing surface concentrations to observed values when they exceeded those values. This approach has been extensively used in the Princeton Ocean Biogeochemical Model (see for example *Najjar et al.* [1992]) It implicitly parameterizes the limitation of Si uptake due to lack of trace metals, lack of light, or grazing since all three conditions are associated with high surface silicate concentrations. The model was not seasonal and may be inaccurate if silicate is brought to the surface during the wintertime and then subducted before it can be taken up by biota. The resulting production of biogenic silica was converted to silicate as the result of dissolution within the water column. Two dissolution profiles are considered here:

1. A limiting case was run in which all the export flux fell to the bottom and dissolved there. Although this approach may be somewhat realistic in the Southern Ocean [*Rabouille et al.*, 1997] it probably overestimates the fraction of the export reaching the deep in other regions [*Treguer et al.*, 1995]. This dissolution scheme will be referred to as BOT in describing individual model runs.

2. A more realistic case was in which the dissolution occurred as a function of the local temperature based on the Arrhenius equation. Following *Gnanadesikan* [1999a], we used the following expression for specific dissolution  $R$  in days<sup>-1</sup>.

$$R = 1.32 \times 10^{16} \times \exp(-11481/T_a) \quad (1)$$

Where  $T_a$  is the temperature in degrees Kelvin. The biogenic silica flux out of the mixed layer was then instantly dissolved according to the flux profile

$$\frac{\partial F}{\partial z} = R/w_{fall}F \quad (2)$$

where  $F$  is the silica flux and  $w_{fall}$  is the sinking velocity for particles, taken for the current study at 50 m/day. This dissolution scheme is referred to as the TEMP scheme in the remainder of the paper.

In order to test the sensitivity of the silicon cycle to the vertical diffusivity, two representations of vertical diffusivity were used. In the first formulation the diffusivity is relatively low within the thermocline (0.3 cm<sup>2</sup>/s) and increases to a large value at depth (1.3 cm<sup>2</sup>/s) [*Bryan and Lewis*, 1979]. This scheme is referred to as the LOW scheme in the remainder of the paper. We found it necessary to set the pycnocline diffusivity higher than observed [*Ledwell et al.*, 1993] in order to keep the model numerically stable. A second, limiting case was run with a vertical diffusivity of 1.0 cm<sup>2</sup>/s from top to bottom. This is the classic value of diffusivity from *Munk* [1966] and is referred to as the HIGH scheme.

The export flux of silica depends not only on the vertical diffusion, but also on the representation of lateral exchange processes associated with mesoscale eddies. Three representations of these exchange processes were used. The first was to assume that the eddies mix horizontally, a representation that has been used in many ocean general circulation models [*Najjar et al.*, 1992; *Toggweiler and Samuels*, 1993]. This scheme is abbreviated as HOR. The second is to assume that the mixing occurs along surfaces of constant potential density (neutral surfaces) [*Griffies et al.*, 1998], a more realistic formulation, abbreviated as ISO in the present paper. Finally, a parameterization which incorporates advective effects associated with the eddies is used.

**Table 1.** Sensitivity of silica export to vertical mixing. Note that the run with high vertical mixing produces sharply larger fluxes, especially in low latitudes.

	Global Export	Eastern Equatorial Pacific	Southern Ocean
HOR+HIGH+TEMP	424	60	137
HOR+LOW+TEMP	220	25	108
HOR+LOW+BOT	116	7	69
Target	50-80	7-10	17-37

This parameterization is known as the GMC scheme after *Gent and McWilliams* [1990] who first introduced it. It has been shown to improve the mean temperature and salinity distributions [*Danabasogulu and McWilliams*, 1995] and to improve excessive penetration of passive tracers like chlorofluorocarbons [*England*, 1995]. Our study is the first, however, to look at how nutrients constrain its effect on vertical exchange.

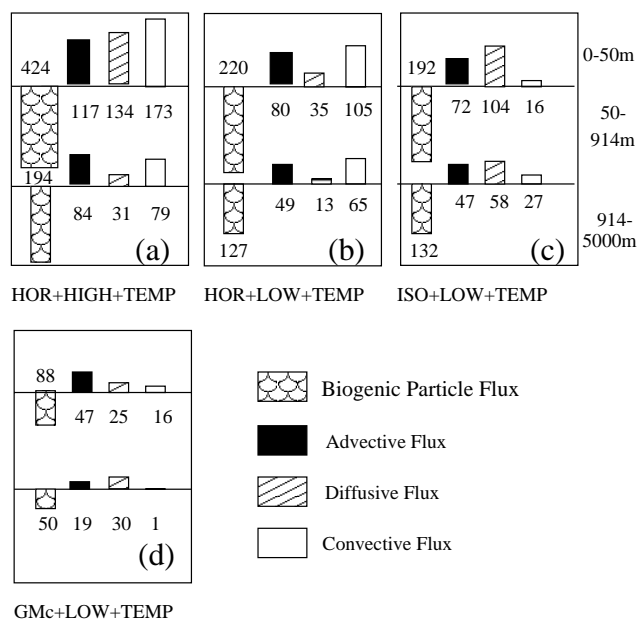
The model runs are denoted as lateral mixing scheme + vertical mixing scheme + dissolution scheme. Thus HOR+HIGH+TEMP refers to a simulation with horizontal mixing of tracers, high thermocline diffusion (1.0 cm<sup>2</sup>/s) and temperature-dependent dissolution. The circulation is a function of the mixing schemes, while the silica flux can depend on the dissolution as well.

## 4. Model results

The model runs clearly show that high levels of vertical mixing produce excessively strong vertical exchange (Table 1, i Figure 1a and 1b). The silica flux in the HOR+HIGH+TEMP simulation is more than 5 times the target value based on direct measurements and almost twice that of the HOR+LOW+TEMP simulation. The higher silicate supply with the HIGH scheme is not just due to the direct effect on the vertical diffusive transport (which accounts for an increase of 99 Tmol/yr) but also to substantial increases in the advective (37 Tmol/yr) and convective (68 Tmol/yr) fluxes. The indirect effects of increasing the vertical diffusion in the GCM are as important as the direct effects. These effects are also much more important in low latitudes (where the production increases more than twofold) than in the Southern Ocean (where more than tripling the near-surface diffusion only increases the production by 26%). The total low-latitude export flux is about 2.5 times that in the Eastern Equatorial Pacific so that half the effect of increasing the pycnocline diffusion is felt in low latitudes. Low levels of export flux in the low latitudes require a low pycnocline diffusivity.

**Table 2.** Sensitivity of silica export to lateral exchange scheme. Note that only the GMC scheme produces realistically low fluxes, especially in the Southern Ocean.

	Global Export	Eastern Equatorial Pacific	Southern Ocean
ISO+LOW+TEMP	192	13	133
GMc+LOW+TEMP	88	14	37
Target	50-80	7-10	17-37



**Figure 1.** Graph of vertical fluxes of silicon in  $\text{Tmol yr}^{-1}$  predicted from four ocean general circulation models. Bar area is proportional to flux size. (a) HOR+HIGH+TEMP. (b) HOR+LOW+TEMP. Note that lowering the diffusivity reduces the advective and convective fluxes as well. (c) ISO+LOW+TEMP. Note how switching from HOR to ISO changes the major source of upper ocean silicate from convective to diffusive. (d) GMc+LOW+TEMP. Adding GMc eddy-induced advection sharply reduces all vertical fluxes.

Low pycnocline diffusivity is not, however, sufficient to produce low export fluxes everywhere, particularly in the Southern Ocean. The Southern Ocean silica flux in the HOR+LOW+BOT simulation is almost twice the regional estimate of NTBLQ95. As seen in Table 2 and Figures 1c and 1d, the more realistic TEMP dissolution scheme only produces low Southern Ocean fluxes with the GMc lateral exchange scheme. Isopycnal mixing alone is not sufficient. Although the ISO+LOW+TEMP scheme sharply reduces the convective supply of silicon to the ocean surface by  $89 \text{ Tmol/yr}$  this decrease is largely counterbalanced by an increase in the diffusive supply of silicon (along isopycnal surfaces) of  $69 \text{ Tmol/yr}$ . The GMc scheme reduces both the advective and diffusive supply of silicon. As shown in *Gnanadesikan* [1999a], this is in part because the GMc scheme produces a more realistic stratification in the Antarctic with cold fresh Antarctic Surface Water overlying warm Circumpolar Deep Water. Neither the HOR nor the ISO schemes capture this surface layer. As a result, they produce excessive convection and vertical exchange in the Southern Ocean.

There are two additional pieces of evidence that the circulation scheme given by the GMc+LOW model is the most realistic. *Gnanadesikan* [1999a] showed that the GMc scheme produces silicate fields with the lowest mean absolute deviation from data compared with the HOR and ISO schemes. Finally, the deep sinking fluxes in the HOR+LOW+TEMP and ISO+LOW+TEMP simulations are on average  $0.35\text{--}0.4 \text{ mol/m}^2/\text{yr}$ . This is much larger than the fluxes found in deep sediment traps [Lampitt and Antia, 1997] which are

less than a third as large. Such fluxes are in rough agreement with the GMc+LOW+TEMP scheme.

## 5. Conclusions

Sinking fluxes of biogenic silica constrain the rate of upper ocean mixing to be fairly small. This in turn provides evidence for a circulation scheme which includes both the advective effects of eddies and low pycnocline diffusivity. The reasons for this can be understood within the framework developed in *Gnanadesikan*, [1999b]. In this framework, light water is largely converted to dense water in the North Atlantic. Silicate is supplied from depth when this dense water is converted back to light water. This occurs either in the low latitudes as upwelling dense water is warmed through downward diffusion, or in the Southern Ocean as a result of freshening. Reducing the pycnocline diffusivity reduces the strength of the former process. The GMc scheme reduces the conversion of dense to light water in the Southern Ocean by supplying some of the upwelling there from light, low-silicate waters. Low diffusivity and the GMc scheme together reduce the overall rate of vertical exchange.

A low rate of vertical exchange has important implications for climate modelling. General circulation models with high vertical exchange overestimate the sensitivity of the Southern Ocean productivity to polar freshening *Gnanadesikan*, [1999a] and the uptake of anthropogenic carbon dioxide [Sabine *et al.*, 1999]. Additionally, models with too high a rate of vertical exchange will overestimate the thermal inertia of the deep ocean with serious consequences for understanding long-term climate change. General circulation model studies of carbon cycling in particular must take this into account.

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## References

- Bryan, K., and L.J. Lewis, A water mass model of the world ocean, *J. Geophys. Res.*, *84*, 2503-2517, 1979.
- Brzezinski, M. A., and D. M. Nelson, The annual silica cycle in the Sargasso Sea near Bermuda, *Deep-Sea Res. I*, *42*, 1215-1237, 1995.
- Danabasoglu G, and J.C. McWilliams, Sensitivity of the global ocean circulation to parameterizations of mesoscale tracer transports, *J. Climate*, *8*, 2967-2987, 1994.
- Dugdale, R. and F.P. Wilkerson, Silicate regulation of new production in the equatorial Pacific upwelling, *Nature*, *391*, 270-273, 1998.
- England, M.H., Using chlorofluorocarbons to assess ocean climate models, *Geophys. Res. Lett.*, *22*, 3051-3054, 1995.
- Gent, P. and J.C. McWilliams, Isopycnal mixing in ocean circulation models, *J. Phys. Oceanogr.*, *20*, 150-155, 1990.
- Gnanadesikan, A., A global model of silicon cycling: Sensitivity to eddy parameterization and dissolution, *Global Biogeochem. Cyc.*, *13*, 199-220, 1999a.
- Gnanadesikan, A., A simple predictive model for the structure of the oceanic pycnocline, *Science*, *283*, 2077-2079, 1999b.
- Griffies, S.M., A. Gnanadesikan, R.C. Pacanowski, V.D. Larichev, J.K. Dukowicz, and R.D. Smith, Isopycnal mixing in a z-coordinate ocean model, *J. Phys. Oceanogr.*, *28*, 805-830, 1998.
- Lampitt, R.S. and A.N. Antia, Particle flux in deep seas: Regional characteristics and temporal variability, *Deep Sea Res.*, *44*, 1377-1409, 1997.

- Ledwell, J.R., A.J. Watson and C.S. Law, Evidence for slow mixing across the pycnocline from an open-ocean tracer experiment, *Nature*, *364*, 701-703, 1993.
- Munk, W., Abyssal recipes, *Deep Sea Res.*, 306-318, 1966.
- Najjar, R.G., J.L. Sarmiento, and J.R. Toggweiler, Downward transport and fate of organic matter in the ocean: Simulations with a general circulation model, *Global Biogeochem. Cyc.*, *6*, 45-76, 1992.
- Nelson, D.M., P. Treguer, M.A. Brzezinski, A. Leynaert and B. Queguiner, Production and dissolution of biogenic silica in the ocean: Revised global estimates, comparison with regional data, and relationship to biogenic sedimentation, *Global Biogeochem Cycles*, *9*, 359-372, 1995.
- Pacanowski, R.C., *MOM 2 Documentation, User's Guide and Reference Manual*, GFDL Ocean Technical Report 3.1, Geophysical Fluid Dynamics Laboratory, NOAA, Princeton NJ, 1996.
- Rabouille, C. J.F. Gaillard, P. Treguer and M-A. Vincendeau, Biogenic silica recycling in surface sediments across the Polar Front of the Southern Ocean (Indian Sector), *Deep Sea Res.*, *44*, 1151-1176, 1997.
- Sabine, C.L., R.M. Key, K.M. Johnson, F.J. Millero, A. Poisson, J.L. Sarmiento, D.W.R. Wallace, and C.D. Winn, Anthropogenic CO<sub>2</sub> inventory of the Indian Ocean, *Global Biogeochem. Cyc.*, *13*, 179-198, 1999.
- Toggweiler, J.R. and B. Samuels, New radiocarbon constraints on the upwelling of abyssal water to the ocean's surface, in M. Heimann, ed., *The Global Carbon Cycle*, Springer-Verlag, Berlin, pp. 333-365, 1993.
- Treguer, P. D.M. Nelson, A.J. van Bennekom, D.J. DeMaster, A. Leynard and B. Queguiner, The silica balance in the world ocean, *Science*, *268*, 375-379, 1995.
- Worthington, L.V., The case for near-zero production of Antarctic Bottom Water, *Geochem. Cosmochim. Acta*, *41*, 1001-1006, 1977.

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