A global model of silicon cycling: Sensitivity to eddy parameterization and dissolution

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Abstract.

A simple model of silicon cycling has been embedded in a coarse-resolution ocean general circulation model. The modeled distribution of silicate was extremely sensitive to the parameterization of the effects of mesoscale eddies, and was somewhat sensitive to the distribution of dissolution within the water column. The modeled export flux of biogenic silica varied by a factor of 2 with respect to both the range of dissolution and eddy parameterizations. The best results were found when eddies were parameterized as mixing along isopycnals while simultaneously driving an advective flux so as to homogenize the depth of isopycnal surfaces (the so-called Gent-McWilliams parameterization). The Gent-McWilliams scheme produced the most realistic stratification field in the Southern Ocean, reducing vertical exchange and hence export fluxes of biogenic silica. This scheme did not solve the model's tendency to underpredict the formation of the North Atlantic Deep Water and to overpredict the importance of Antarctic source waters in the abyss, especially in the Atlantic. When used with a temperature-dependent dissolution scheme, this model predicted a global production of 89 Tmol yr^{-1} with about 40% occurring in both the Southern Ocean and the tropics. In both the North Pacific and Southern Oceans, local silicate maxima are maintained by near-surface inflow of silicate with outflow at depth. The modeled production of biogenic silica showed little sensitivity to polar freshening when the Gent-McWilliams parameterization was used. The results emphasize the impact of including both the diffusive and advective effects of eddies, as in the Gent-McWilliams parameterization.

1. Introduction

Silicate is one of the most important and widely measured nutrients in the world oceans. Some aspects of its cycling are simpler than the two other widely measured nutrients (phosphate and nitrate) in that there is no dissolved organic pool of silicate. However, the dissolution of biogenic silica is strongly dependent on temperature [*Erez et al.*, 1982]. Because silica dissolution occurs at greater depths than nitrate or phosphate, silicate exhibits very large vertical differences in concentration, with very low (near zero) values at the surface and deep values of up to 180 μmol L^{-1} in areas such as the North Pacific (see for example Figure 1 which presents data from *Conkright et al.* [1994]).

The distribution of silicate in the ocean interior is strongly affected by deep water formation processes. One of the two principal components of deep water,

North Atlantic Deep Water (NADW), consists primarily of surface water from which silicate has largely been stripped by biota. The other principal source, the Antarctic Bottom Water, has a large component of recycled deep water with a high value of silicate. As a result, the Pacific Basin (Figure 1b), which is largely ventilated from Antarctica has high values of silicate throughout. By contrast, the Atlantic Basin (Figure 1a), which is primarily ventilated by northern source waters, has low values of silicate throughout. A plume of high-silicate Circumpolar Deep Water can be seen in all the ocean basins. In the Pacific and Indian Oceans the Atlantic-source waters are carried eastward in the Circumpolar Current. These low-silicate waters account for the downward dip in isolines of silicate seen between 60°S and 40°S in the Pacific Ocean (Figure 1b).

Because it exhibits large vertical gradients, the production of biogenic silica is very sensitive to the way in which deep waters are brought into contact with the surface. Diatoms and radiolaria strip silicate from deep water brought to the surface in order to build their shells. As these organisms die or are eaten, the sili-
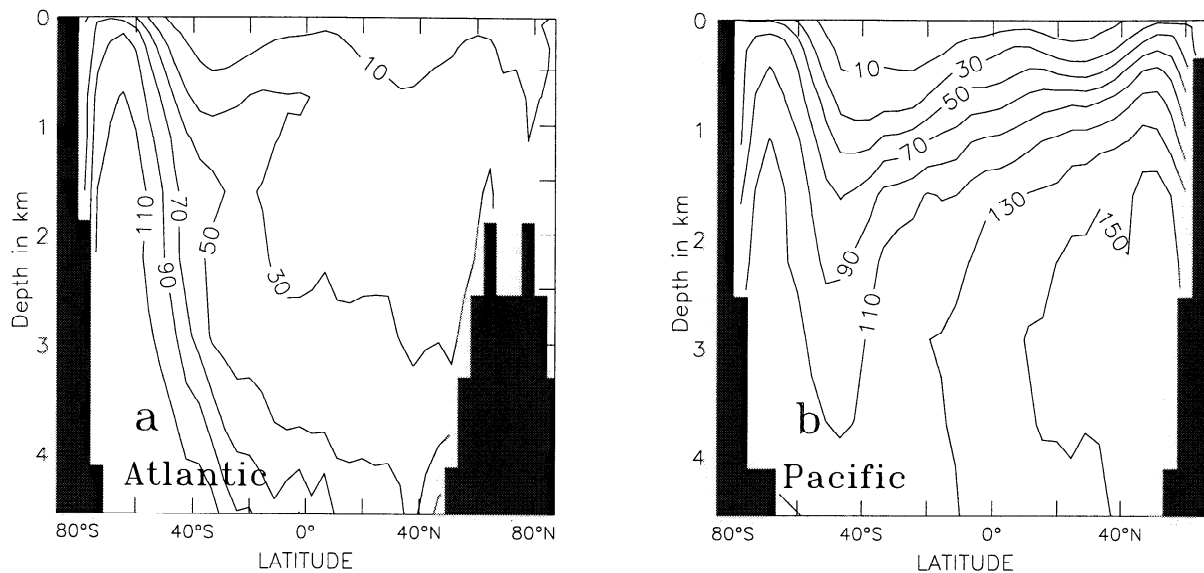
Figure 1. Silicate distribution in the world oceans. (a) Atlantic sector (averaged from 60°W to 0°W). (b) Pacific sector (averaged from 120°E to 120°W). Data is from the dataset of *Conkright et al.* [1994].

caceous cells fall out of the euphotic zone. This flux of biogenic silica to the deep waters is referred to as the export flux, and measurements of it can be used to constrain oceanic mixing and circulation. *Worthington* [1977] used the fact that relatively little silicaceous sediment is found throughout the subtropical Pacific to argue against circulation schemes in which Antarctic Bottom Water (AABW) is upwelled through the subtropical thermocline, since these schemes would then require a large export flux of silica. In fact, he went so far as to argue that no AABW was currently being produced. *Wunsch et al.* [1983] used an inverse model to argue that deep flow of AABW was, in fact, returned at middepth. *Toggweiler and Samuels* [1993] presented evidence for this circulation scheme using the distribution of radiocarbon. *Robbins and Toole* [1997] recently also used silicate balance within the context of an inverse model to constrain the overturning circulation in the Indian Ocean. Both the export flux of silica and distribution of silicate have thus been shown to constrain certain aspects of the general circulation. This paper is the first, however, to comprehensively examine the constraints placed by the silicon cycle on the oceanic circulation.

There is some debate over the distribution and magnitude of the silica export flux. *Peng et al.* [1993] (henceforth PMB93) used a box model of the world ocean calibrated with radiocarbon data to estimate fluxes of silica. The concentrations and water fluxes used in this paper resulted in a prediction of a global flux of 120 Tmol yr^{-1} with a little less than half occurring in the North Pacific, about a third occurring in the Antarctic, and most of the remainder occurring in the surface

Pacific and Indian Oceans. The results are problematic since the North Atlantic would seem to require a strong net source of silicon (10-12 Tmol yr^{-1}) to prevent it from being depleted of silicon altogether. *Treguer et al.,* [1995] estimate that the global flux of silica from rivers to the ocean is of order 3 Tmol yr^{-1}, so that rivers could not supply enough silicon to the deep Atlantic. *Nelson et al* [1995] (henceforth NTBLQ95) presented a summary of global silicon dynamics based on a wide variety of data collected over many years. Reanalyzing the PMB93 model with more realistic silicate concentrations, they obtained a global value of 99.3 Tmol yr^{-1} with roughly a quarter occurring in the North Pacific, Southern, and surface Atlantic and Pacific Oceans. Using other methods, they estimated that the global flux of silica out of the euphotic zone was at least 120 Tmol yr^{-1}, with about 1/3 of that reaching the seafloor.

It is quite possible that the last estimate of biogenic silica export is substantially too high. When NTBLQ95 presented estimates of biogenic silica production in coastal upwelling areas, the Subarctic Pacific, and the Southern Ocean, they were able to account for only 28-48 Tmol yr^{-1}. Adding another 26 Tmol yr^{-1} from the subtropical gyres, they were able to account for only about 54-74 Tmol yr^{-1}. Even if all of this were to be exported (which at least for the subtropical gyres would be unlikely), in order to come up with a total export flux of 120 Tmol yr^{-1}, 46-64 Tmol yr^{-1} would have to be exported from the remainder of the world ocean, with the tropical ocean being the largest source. At the time, estimate of silica export flux were not available from the equatorial ocean. Recent results from the equatorial JGOFS program indicate that more

reasonable export fluxes would be in the range of 7-10 Tmol yr^{-1} for the eastern equatorial Pacific [*Dugdale and Wilkerson,* 1998; J.W. Murray, personal communication, 1998]. In all of the models the silica export flux for all tropical latitudes is from 2 to 2.5 times that in the Eastern Equatorial Pacific, giving a rough estimate of 15-25 Tmol yr^{-1} for the tropical export flux. Combined with the regional estimates for NTBLQ95, this would give a revised estimate for the global export flux between 70 and 100 Tmol yr^{-1}.

In this paper, an ocean general circulation model is used to investigate the dynamics of silicon in the world ocean. In particular, it seeks to attack the following questions: (1) What are the relative contributions of mixing, circulation, and biological cycling in controlling the distribution of silicon in the ocean? (2) Can one come up with a model which produces a silicon cycle consistent with the results of NTBLQ95? What are the necessary components of such a model?

The structure of this paper is as follows: Section 2 describes the basic model used in this paper, considering both the physical and biogeochemical components. Section 3 demonstrates the strong sensitivity of the resulting model to dissolution and eddy parameterization. Section 4 considers the silicon balance in different models for different regions. Section 5 presents a global picture of the biological, advective, and diffusive fluxes of silicon. Section 6 considers the sensitivity of the model response to polar freshening to the mesoscale eddy parameterization. Section 7 concludes the paper. A principal result of this paper is that the export flux of biogenic silica is a strong function of both the parameterization of dissolution and the representation of the effects of mesoscale eddies. By adjusting both dissolution and the eddy parameterization, it is possible to develop a model of silicon cycling which is in reasonable agreement with observations. An important corollary of this result is to support the use of the eddy parameterization of *Gent and McWilliams* [1990] in which eddies drive advective fluxes which smooth out isopycnal surfaces. A second major finding is that the model can support tropical export fluxes in agreement with observations, which are significantly smaller than those required by NTBLQ95 to close the silicon budget. This argues for a downward revision of the silica export flux to less than 100 Tmol yr^{-1}. A final important result is that the use of the Gent-McWilliams eddy parameterization drastically reduces the sensitivity of the model to polar freshening.

2. Model Description

2.1. Physical Model

The physical model used for this study was the Modular Ocean Model, version 2.0 [*Pacanowski,* 1996]. The model was configured as in the work of *Toggweiler and Samuels* [1993] with 12 vertical levels and a nominal horizontal grid of 3.75° x 4.25°. The vertical resolution increases from a minimum of 50.9 m at the surface to 880 m at the bottom. This model has been extensively used for biogeochemical and physical studies over the past decade, including work by *Toggweiler et al.* [1989], *Najjar* [1990], *Najjar et al.* [1992], *Toggweiler and Samuels* [1993], *Anderson and Sarmiento* [1995], *Sarmiento et al.* [1995], and *Suntharalingam* [1997]. The base grid is also essentially identical to that used in the 4° Geophysical Fluid Dynamics Laboratory (GFDL) coupled model, with the difference that the Bering Strait is open. Vertical mixing was given by the parameterization of *Bryan and Lewis* [1979], with a value of 0.3 cm^2 s^{-1} within the thermocline increasing to 1.3 cm^2 s^{-1} in the abyssal ocean. Surface temperature and salinity were restored to the annual mean climatology with timescales of 30 and 120 days, respectively. Wind stresses were given by Hellermann and Rosenstein (1983).

Three versions of the physical model were run:

1. The first version was run with horizontal mixing is given by *Bryan and Lewis* [1979]. This is the mixing scheme used by *Toggweiler et al.* [1989] and *Najjar et al.* [1992] and in the Princeton Ocean Biogeochemistry Model [*Sarmiento et al.,* 1995; *Murnane et al.,* 1999]. Within these runs, the effect of mesoscale eddies was to mix horizontally. Runs made with this parametrization are denoted below with the abbreviation HOR.

2. The second version was run with the mixing tensor rotated so that mixing occurred along local neutral surfaces following the implementation of *Griffies et al.* [1998] which requires very low background horizontal mixing. Most mixing in the ocean occurs along isopycnal surfaces [*Jenkins,* 1980; *Ledwell et al.,* 1993] since parcels may be exchanged along such surfaces without conversion of kinetic to potential energy. The present scheme was run with an isopycnal mixing coefficient of 1000 m^2 s^{-1}. Recent results from the North Atlantic Tracer Release Experiment [*Ledwell et al.,* 1998] demonstrate clearly that this is a reasonable value to use. When larger values of isopycnal mixing coefficient were used, numerical problems (discussed by A. Gnanadesikan Numerical issues for coupling isopycnal mixing schemes with biological, cycling models, submitted to *Journal of Marine Research,* 1998, henceforth Gnanadesikan, submitted manuscript,1998) became much more apparent in the silicate field. Runs made with this parameterization are denoted below with the abbreviation ISO.

3. A run in which the eddies diffused layer thickness as well as tracers resulting in a "eddy-induced advection" [*Gent et al.,*1995]. This parameterization has been widely discussed in the literature, and its effects on modeled hydrographic structure [*Danabasoglu*

et al., 1994] radiocarbon [Duffy et al., 1995; Duffy and Caldeira, 1995], and CFC fields [England, 1995; Dixon et al.,1996] have been published. This work is the first to consider the effect of this parameterization on nutrient cycling and to demonstrate that the constraints placed by the nutrient flux on the circulation support its use. The eddy-induced advection was governed by a thickness mixing coefficient of 1000 $m^2 s^{-1}$, identical to the isopycnal tracer mixing coefficient. There is presently active discussion about whether the tracer and thickness mixing coefficients should be identical. In the absence of quantitative theories for predicting the difference between the two coefficients, it was decided to set them equal. Runs made with this parameterization are denoted below with the abbreviation GMc.

In order to make all the models comparable with respect to the eddy mixing scheme, a quasi-third-order advection scheme [Pacanowski, 1996] was used. Such a higher-order scheme is necessary to prevent errors in the advection from producing a cold, dense bottom water mass which is completely sealed off from the surface.

The temperatures predicted by the model were significantly affected by the lateral mixing scheme. Figure 2 shows temperature sections in the Pacific from the three models and data. The HOR model produced a temperature field with a number of clear deficiencies relative to the data. First, the entire Pacific was too warm. Note that the 10°C isotherm, for example, penetrated almost 500 m too deep and the abyssal waters below 1500 m ranged between 2°C and 5°C rather than between 0°C and 3°C. These abyssal waters were also more highly stratified than in the data. Finally, the isotherms did not slope upward to the north throughout the water column in the North Pacific, as in the data. These features are familiar to users of the GFDL ocean model and have been attributed to artificially high diapycnal diffusivity [Bryan, 1987]. Horizontal diffusivity allows particles to move easily across isopycnal surfaces in regions such as the Southern Ocean and boundary currents where these surfaces slope by providing a means to change this density [Veronis, 1975; Gough and Lin, 1995]. This means that in regions of sloping isopycnals, strong diapycnal velocities can result in high levels of vertical exchange, moving heat down into the water column and bringing a large amount of nutrient to the surface.

The ISO model had a distinctly colder temperature in the deep waters. Indeed, there was too much cold water in the abyssal Pacific. This indicates that the horizontal diffusivity was, in fact, responsible for creating a circulation which warmed the deep water excessively. However, the thermocline was still too deep and abyssal waters were far too stratified. The GMc model pushed even more cold water into the Pacific but did improve the thermocline depth and overstratification of the deep waters as noted by Danabasoglu et al. [1994].

This is because the Gent-McWilliams eddy-induced advection flattens isopycnal slopes, moving dense water under light water and light water on top of dense water [Gent et al., 1995]. In a large-scale sense this increased the modeled flow of Antarctic Bottom Water out of the Southern Ocean.

Figure 3 shows similar sections in the Atlantic. Here the picture was more complicated, since none of the models did very well. The deep Atlantic was far too stratified. This was the result of North Atlantic Deep Water which was too warm (5-7°C instead of 3 4°C). The addition of isopycnal mixing cooled the abyssal waters as in the Pacific, producing a very stratified deep Atlantic. The GMc model showed some improvement, decreasing the depths to which warm water penetrated. It did not, however, improve the deep stratification. In general, the solution had far too much Antarctic Bottom Water in the Atlantic.

A major improvement in the GMc model was the reduction of convection in the Southern Ocean. This is illustrated in Figure 4 for a small sector of the South Atlantic. In the observations, cold fresh surface water caps off convection to the south of the polar front, with cold North Atlantic Deep Water underneath. In both the HOR and ISO models the cold water was not maintained. However, in the GMc model the temperature structure was at least qualitatively similar to the observations, even though there were significant differences in detail. It should be pointed out that the rate at which convection brought heat to the surface was much smaller in the ISO model than in the HOR model (as found by Gough and Lin [1995] but that the occurence of convection was essentially the same. This contradicts Gough and Lin [1995] who argued that isopycnal mixing reduces the total amount of convection. Gough [1997] and Griffies et al. [1998] demonstrate that the results of Gough and Lin [1995] (as well as previous experience with isopycnal mixing within the GFDL climate modeling group) were, in fact, due to numerical inaccuracies in the calculation of isopycnal fluxes when the isopycnal slope became large.

2.2. Silicon Cycling Model

The model of silicon cycling used in this paper is extremely simple. It is based on a concept developed by Najjar [1990] and Najjar et al. [1992] in which a surface nutrient is restored to an observed climatological value when the surface values exceed that value. The nutrient was restored over the top grid box (50.9 m thick). The climatological values were taken from Conkright et al. [1994]. Essentially, this parameterization implicitly includes effects of trace metal and light limitation as these processes limit silica production where silicate is known to be high at the surface.

The resulting export flux was dissolved within the water column. Three different parameterizations were used for the purpose of this paper.

1. The first parameterization assumed that all dissolution occurred on the bottom. This model was assumed for the one-dimensional results reported by PMB93. In some areas in the Antarctic this appears to be the case [*Rabouille et al.*, 1997]. However, in other regions such as the North Pacific [*Erez et al.*, 1982] or in the tropical Atlantic off the coast of Africa [*Nelson and Goering*, 1977], such an approximation is clearly wrong, since the silica export flux decreases rapidly with depth. This parameterization is referred to as the BOT scheme in the remainder of the paper.

2. The second parameterization of dissolution represented it as occuring as an exponential function with a 2 km length scale. The length scale was chosen based on the depth of the deep silicate maximum. Essentially,
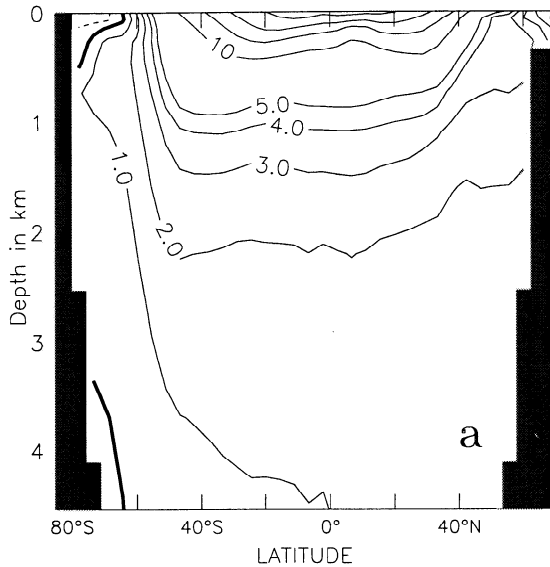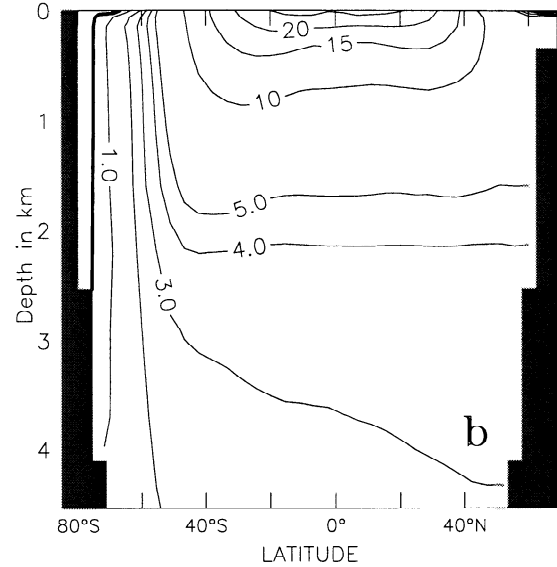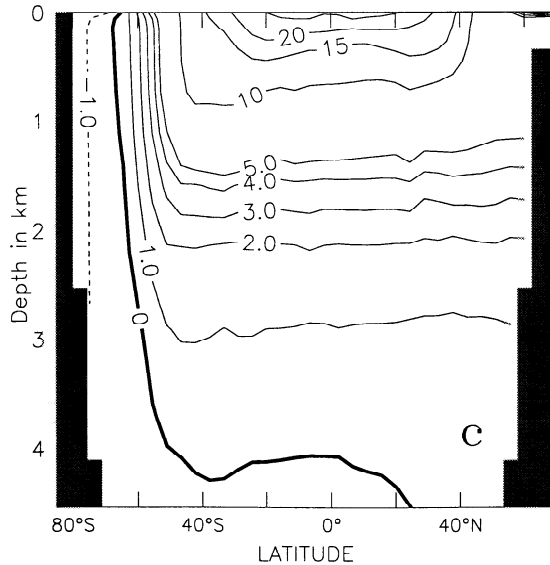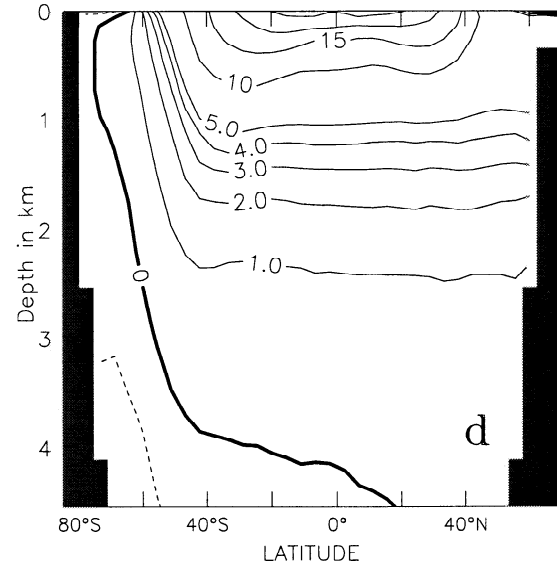

Figure 2. Temperature structure in the Pacific sector. All plots show averaged temperature from 120°E to 90°W. (a) Observations from *Levitus* [1992], (b) HOR model, (c) ISO model, (d) GMc model.
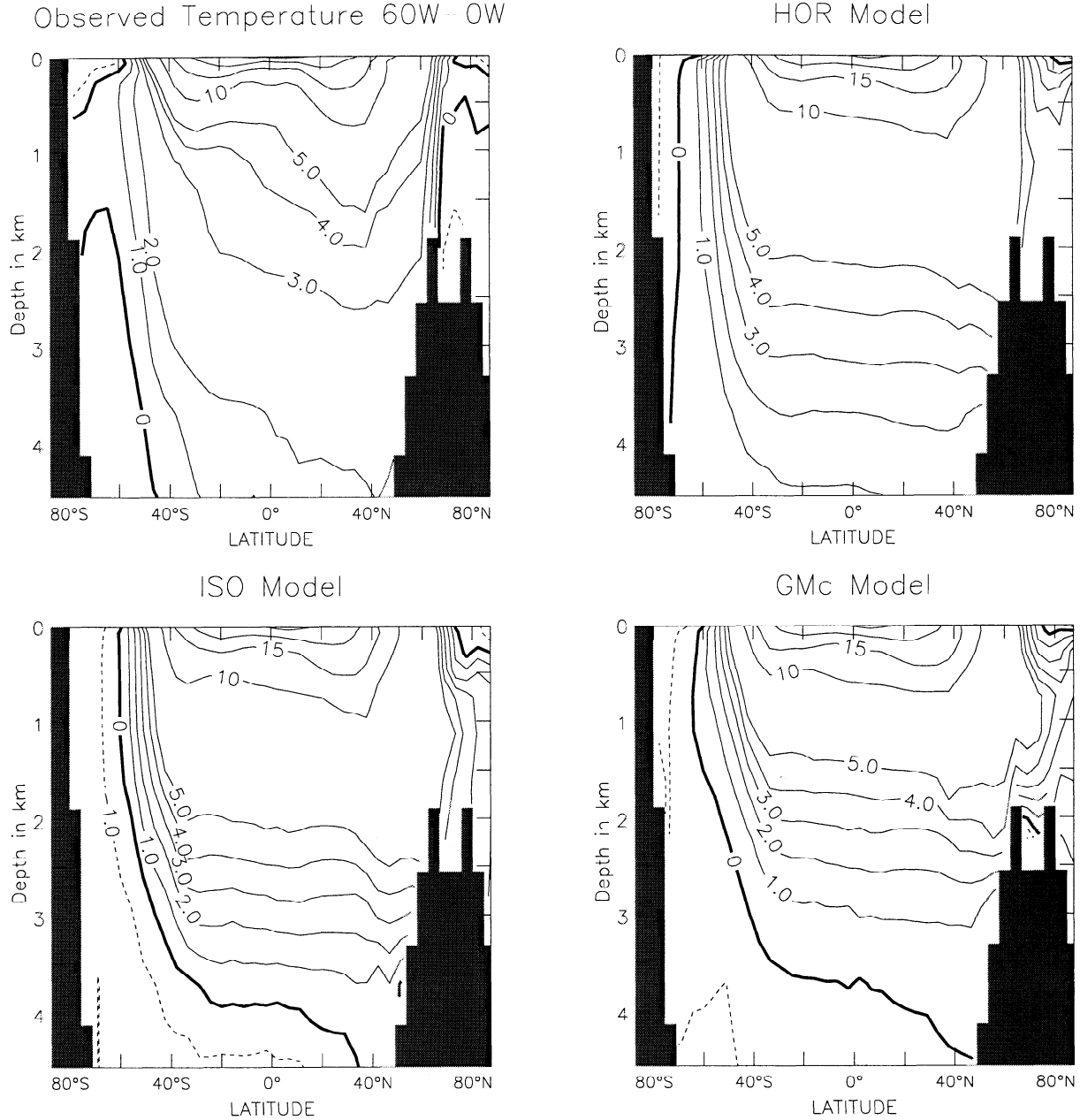
Figure 3. Same as Figure 2 but for the Atlantic sector (60°W to 0°W).

this parameterization corresponds to the assumption that dissolution of silica occurs as a function of total silica present

$$\frac{dSi_p}{dt} = -RSi_p \qquad (1)$$

where Si_p is the concentration of particulate silica and R is the specific rate of dissolution. If the fall speed of the particles is some constant w_f, then

$$\frac{d}{dz}F_{Si} = -\frac{R}{w_f}F_{Si} \qquad (2)$$

where F_{Si} is the local sinking flux of biogenic silica.

Honjo and Manganini [1993] argued for a sinking speed of about 50 m day^{-1} based on sediment trap data. For such a speed, a 2 km dissolution depth corresponds to an R of 0.025 day^{-1}. This scheme is abbreviated 2KM in the remainder of the paper.

3. The final scheme assumed that dissolution occurred as a function of temperature. *Nelson et al.* [1981] showed that only 10% of the silica produced in a 20 m deep mixed layer off Peru was remineralized within the mixed layer. Although this percentage is quite small, it still implies a rather small e-folding scale (~200 m) for the dissolution because the mixed layer is so shallow. Taking a sinking speed of 50 m day^{-1},

this yields a specific dissolution rate R of 0.25 day^{-1}. *Brzezinski and Nelson* [1995] discussing on data from the Bermuda Time Series site, report dissolution in sediment traps of 0.02-0.2 day^{-1} with a mean of around 0.07 day^{-1}. *Honjo and Manganini* [1993] working in the North Atlantic at a depth of 1000 m show that only 13% of the biogenic silica produced in the mixed layer reached a depth of 1000 m, yielding an averaged estimate for the e-folding scale of 500 m at an average temperature of about 12°C. They also demonstrated that the sinking speed w_f was to some extent a function of depth, increasing to 100 m day^{-1} below depths of 2 km (so that our values of 50 m day^{-1} would over-

estimate the amount of dissolution occurring between 2000m and the bottom). *Hurd and Birdwhistell* [1983] argue for specific dissolution rates of as 0.5 day^{-1} in 15°C water and as low as 0.02 day^{-1} in 5°C water.

In an attempt to parameterize how R depends on temperature, the following formula based on the Arrhenius equation was used:

$$R = 1.32 \times 10^{16} \times \exp(-11481/T_a) \qquad (3)$$

where T_a is the absolute temperature. This function has the general form suggested by *Erez et al.* [1982] and *Hurd and Birdwhistell* [1983]. It gives a dissolution rate of 0.25 day^{-1} in 25°C water and 0.01 day^{-1} in 2°C
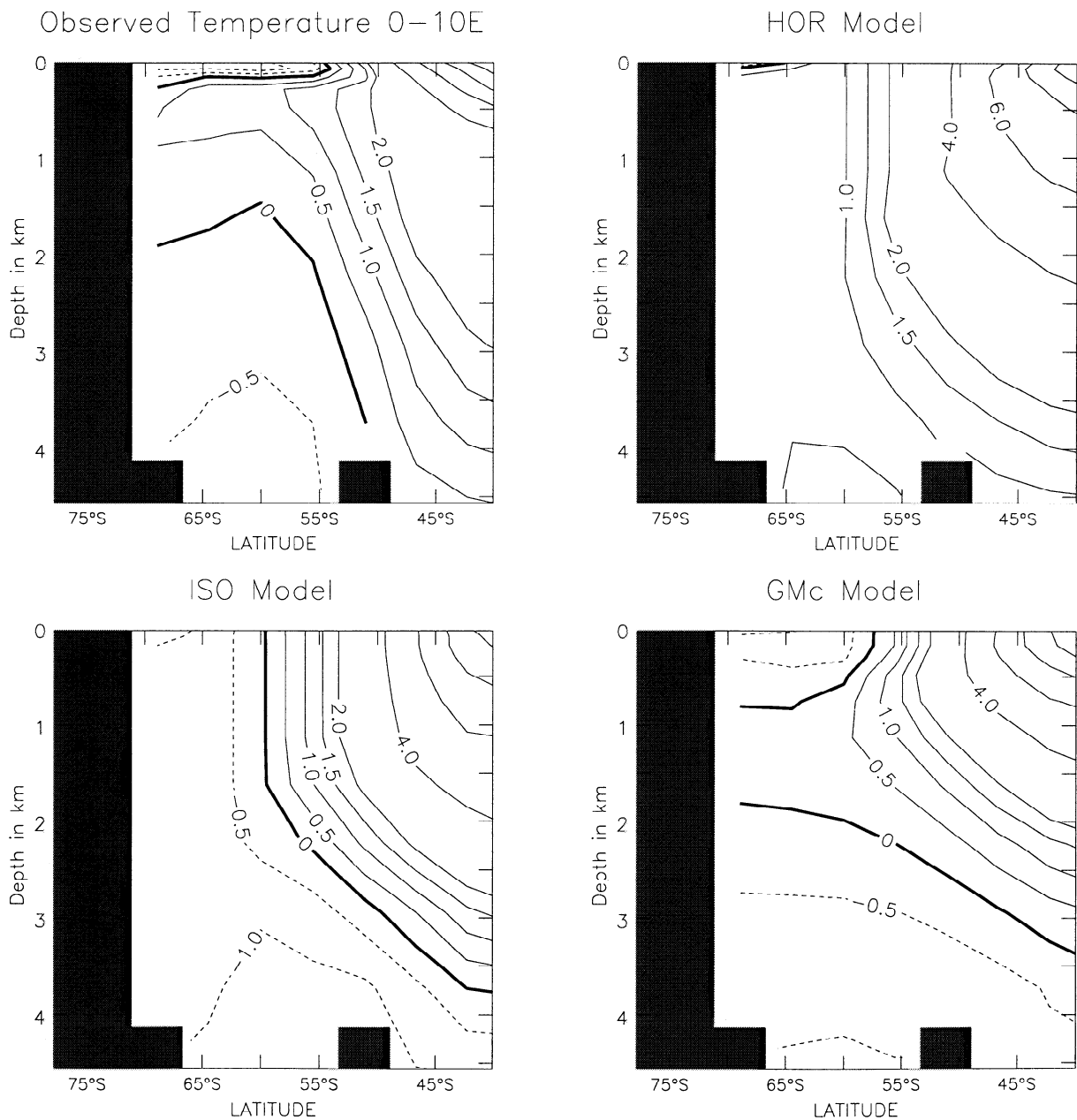

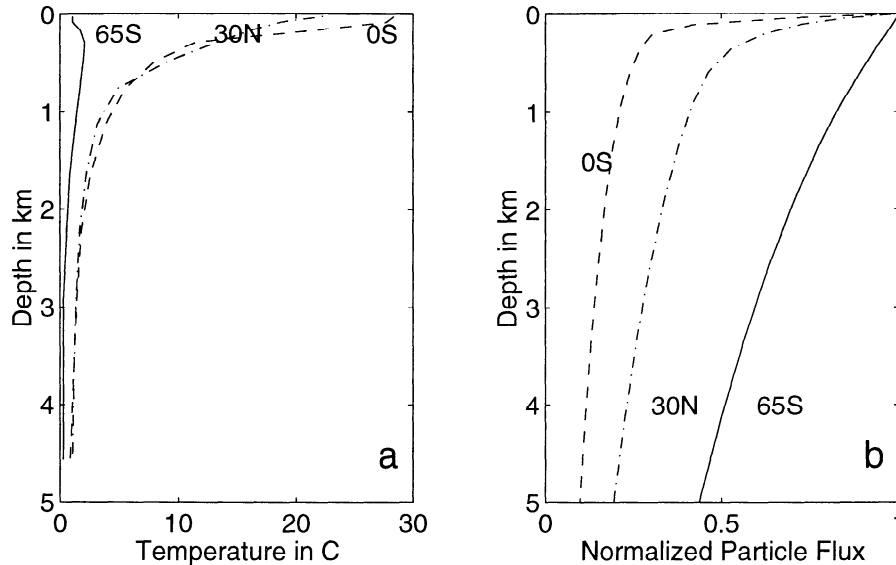**Figure 4.** Same as Figure 2 but for an average between 0°E and 10°E

Figure 5. Illustration of dissolution profiles for different regions. (a) Temperature profiles for three points on the date line: in the Antarctic at 65°S (solid curve), on the equator at 0°S, (dashed curve) and in the Subtropical gyre at 30°N (chain-dotted curve). (a) Particle flux as a function of export flux for the same three profiles as in Figure 5a.

water. Assuming that fecal pellets containing diatoms fall at a rate of 50 m day^{-1} (based on the work of *Honjo and Manganini* [1993]) (2) can be used to calculate the partitioning of the surface particle flux within a given box. The resulting length scale for dissolution varied from around 200 m in the warmest equatorial waters to 5000 m in the coldest polar waters. The resulting flux profiles are illustrated in Figure 5. Note that if the fall speed was underestimated, the model would have overestimated the effect of water column dissolution. The temperature-dependent remineralization scheme is referred to as TEMP.

Clearly, all of these parameterizations are extreme oversimplifications. They do not account for any potential effects of differential dissolution with respect to size, composition, or shape of the silica particles or for the possibility of differential sinking velocities. Nonetheless, they provide a basic framework for evaluating how sensitive the distribution is to the dissolution.

The model was initialized to data from *Conkright et al.* [1994], and the total inventory of silicate was kept fixed. The models were then spun up for at least 3000 years. Effects from sediment burial and riverine input were not considered as they would have required running the model for a much longer time. Silica reaching the bottom was immediately converted to silicate and added to the bottommost grid box. The nine model runs are referred to in this paper using abbreviations in which the first part refers to eddy parameterization, while the second part refers to the dissolution parameterization. Thus HOR+BOT, refers to the run with horizontal eddy mixing and all dissolution occurring on the bottom, while GMc+TEMP refers to a run

with the Gent-McWilliams eddy parameterization and temperature-dependent dissolution.

3. Sensitivity to Mixing and Dissolution

3.1. Silicate Distribution

The distribution of silicate showed significant sensitivity to both dissolution and eddy parameterization. One quantitative way in which this can be seen is by considering the mean absolute error between the model predictions and data. These are summarized in Table 1 for the globe, Pacific, Atlantic and Southern Oceans. Globally, the minimum absolute deviation was found for the GMc+TEMP simulation, while the HOR+2KM simulation is close behind. In general, the GMc simulations exhibited a much weaker dependence on dissolution scheme than did the HOR and ISO simulations and generally had much lower residuals than the other two schemes. Table 1 illustrates the necessity of considering both eddy parametrization and dissolution together, since it is possible to fix the distribution for a given circulation scheme by adjusting the dissolution.

The errors in the Pacific (Table 1) mirrored those for the global ocean. The structure of the errors can be seen by comparing Figure 6 (which shows silicate from 120°E to 120°W for all nine model runs) to Figure 1. Again, the best simulations were seen for the GMc+TEMP simulation and the HOR+2KM simulation. As a number of regularities can be seen in these simulations which mirror those in the other ocean basins, the factors which set the distribution in the Pacific are more carefully considered below.

Table 1. Averaged Absolute Deviations of Observed and Modeled Silicate for the Different Model Runs in Different Regions

	Global	Pacific Ocean	Atlantic Ocean	Southern Ocean
HOR+BOTTOM	23.1	22.5	25.9	23.0
HOR+2KM	14.5	11.0	21.5	18.6
HOR+TEMP	15.5	11.7	23.8	17.7
ISO+BOTTOM	25.5	23.5	25.7	29.7
ISO+2KM	17.5	15.0	24.1	16.0
ISO+TEMP	21.5	17.8	26.0	27.3
GMc+BOTTOM	16.1	12.9	24.7	12.9
GMc+2KM	15.2	12.7	24.8	12.1
GMc+TEMP	14.2	10.4	23.6	13.5

Global averages are taken over all boxes. Pacific averages are taken from from 120°E to 120°W and 85°S to 70°N. Atlantic averages taken over all latitudes and longitudes 60°W-0°W. Southern Ocean averages are taken over all longitudes and latitudes 80°-40°S.
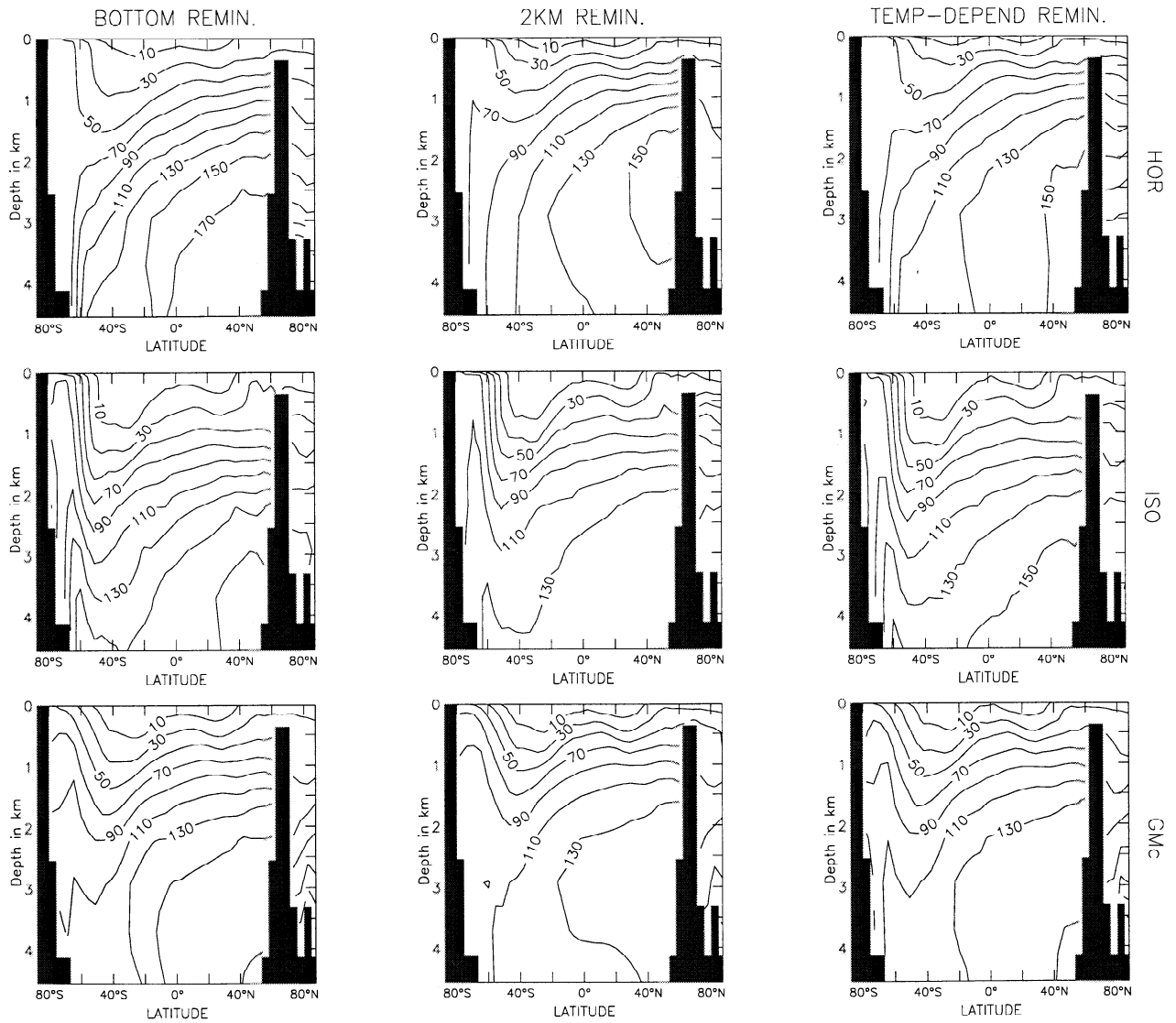

Figure 6. Modelled silica in the Pacific averaged between 120°E and 120°W as in Figure 1 for differing dissolution and eddy mixing parameterizations: (left column) BOT dissolution scheme, (center column) 2KM dissolution scheme, (right column): TEMP dissolution scheme, (top row) HOR eddy parameterization, (center row) ISO eddy parameterization, and (bottom row) GMc eddy parameterization.

In general, the dissolution affected the vertical distribution of silicate. The BOT scheme produced high silicate concentrations near the bottom, while the 2KM scheme resulted in more silicate being concentrated higher up in the water column. The TEMP scheme split the difference between the two. In the equatorial regions it produced higher silicate concentrations in the upper portion of the water column than the BOT scheme (quite similar, in fact, to those produced by 2KM scheme) In the deep water, however, the TEMP scheme produced a deeper silicate maximum, presumably because the bottom water formed in the cold Antarctic received most of the silica produced in the surface water.

The eddy mixing parameterization played an important role in determining the lateral distribution of silicate. In general, the HOR simulations produced high values in the North Pacific, and low values throughout the Southern Ocean. Note that silicate values south of 60°S were lower than 90 μmol L^{-1} for all the HOR simulations, whereas the data show concentrations higher than 90 μmol L^{-1} throughout the South Pacific below around 500 m. The ISO simulations reproduced the high values of silicate in the south but did not produce a strong silicate maximum in the North Pacific. Additionally, there was a larger vertical gradient of silicate concentration in the deep water than observed in all of the ISO cases. The GMc simulations produced both a North Pacific silicate maximum and high values of silicate in the Southern Ocean. However, it should be noted that the North Pacific maximum for these runs had concentrations which were too low. Similar behavior was found in the Indian Ocean.

The low absolute deviations in the HOR+2KM model were thus driven by a better simulation of the North Pacific silicate maximum, while those in the GMc+TEMP model were driven by a better simulation of the Southern Ocean. This can be seen by comparing the absolute deviations in the Pacific and Southern Ocean in Table 1 and by looking at the silicate distributions averaged over the entire Southern Ocean as shown in Figure 7. Figure 7 shows the results from the TEMP dissolution model for each of the eddy parameterizations. The broad features seen for each given eddy parameterization were found regardless of the particular dissolution parameterization, as can be seen by considering Figure 6. The general pattern which emerges is one in which the HOR models had too little silicate in the Southern Ocean as a whole and very little structure in the silicate field above depths of 1000 m and in which the ISO models had too much silicate in the Southern Ocean and silicate gradients in the deep water. Only the GMc model had roughly the right level of silicate stratification.

The Southern Ocean silicate distribution dramatically illustrates one area in which including eddy-induced

advection as in the GMc parameterization improved the model solution. However, silicate distribution can also be used to demonstrate areas where the model solution was not improved by the GMc parameterization. This can be seen most clearly in the Atlantic, as illustrated in Figure 8 and Table 1. The failure of the model to produce North Atlantic Deepwater (NADW) of the appropriate density led to an Atlantic which contained too much Antarctic Bottom Water and which therefore sequestered too much silicate. As a result, the Atlantic generally had large deviations from observed silicate in all of the model runs.

The addition of the Gent-McWilliams parameterization exacerbated the problem of excessive Antarctic influence seen in both the HOR and ISO models. This failure to produce dense enough low-silicate NADW means that the plume of low-silicate water seen in the Indian and Pacific Oceans in the data was somewhat too weak in the models. For example, the 110 μmol isoline reaches 4000 m depth in the Pacific in the data, whereas it was found at 3000 m in the model with GMc+TEMP simulation. In general, the GMc model had silicate isolines which were too flat.

In summary, the GMc models produced silicate fields which were closer to the observations qualitatively, with high values in the Southern Ocean and deep northern Pacific Ocean. These runs did not, however, produce a realistic silicate field in the Atlantic, because of the underestimate of the density of the North Atlantic Deep Water, and they tended to have silicate fields which were too uniform horizontally. The HOR+2KM run also produced reasonable simulations in the Pacific and globally but seemed to fail in the Southern Ocean.

3.2. Biogenic Silica Fluxes

By themselves, the silicate distributions cannot be used to argue for a particular model. The fluxes of silica out of the euphotic zone, however, showed huge differences between the models. This is illustrated in Figure 9, which shows the zonally integrated silica flux for the different cases, and Table 2 which shows the fluxes of silica for the world ocean, Eastern Equatorial Pacific Ocean, and Southern Ocean in each of the nine model runs.

Several patterns of importance appeared in the flux results:

1. The Southern Ocean is the single most important region for silica flux. In the HOR and ISO models it accounted for 50-80% of the total flux, depending on the dissolution parameterization. In the runs with eddy-induced advection it accounted for 40-50% of the global flux.

2. The productivity of the Southern Ocean is extremely sensitive to how eddy effects are parameterized. The difference between ISO and GMc accounted for a factor of 4 difference in the production. Estimates of
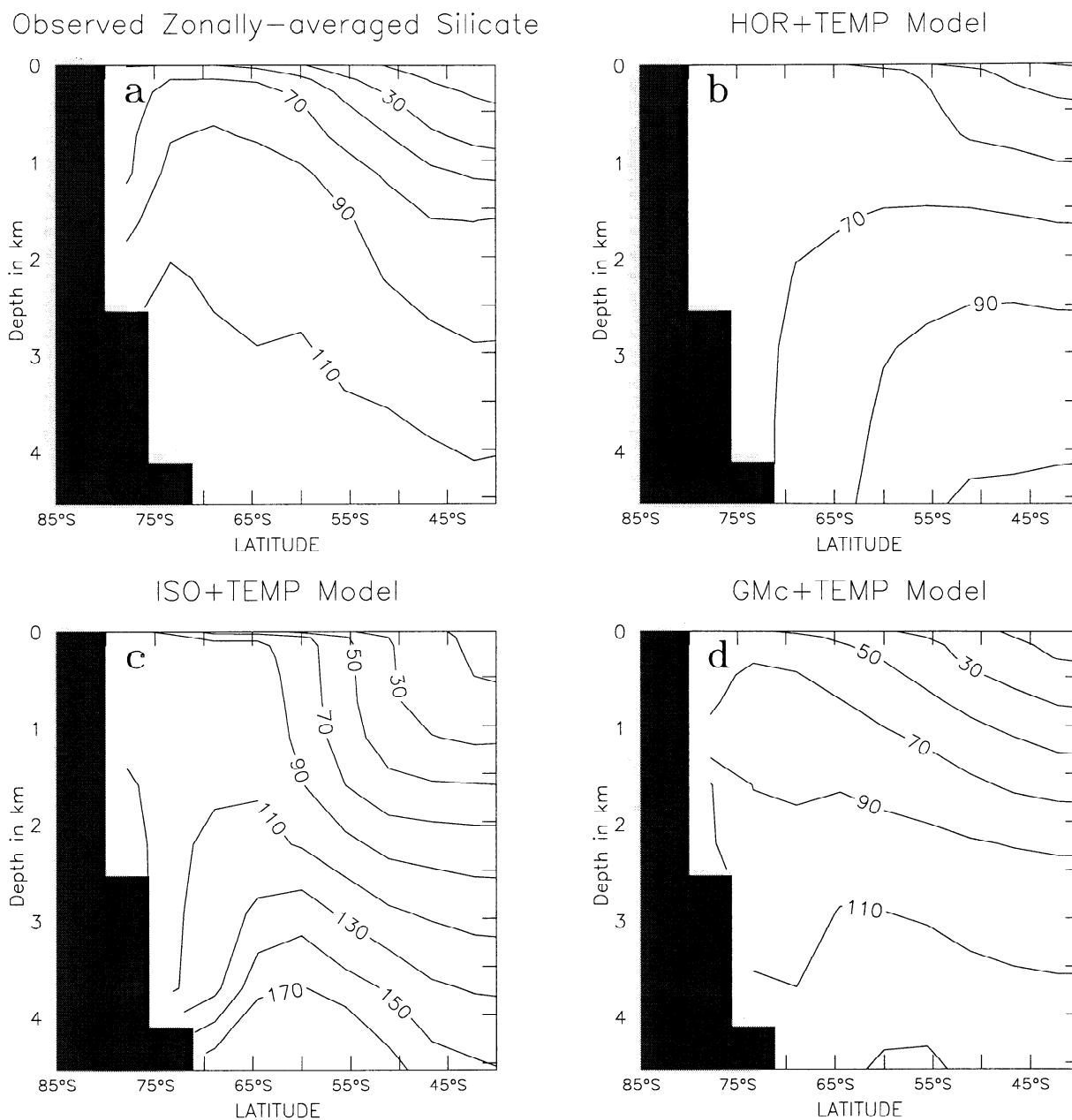
Observed Zonally—averaged Silicate

HOR+TEMP Model

ISO+TEMP Model

GMc+TEMP Model

Figure 7. Silicate in the Southern Ocean, averaged zonally: (a) Observations, (b) HOR+TEMP model, (c) ISO+TEMP model, and (d) GMc+TEMP model.

Southern Ocean production from data (summarized by NTBLQ95) range from 17 to 37 Tmol yr^{-1}. Only the GMc runs produced export fluxes which were even close to these values for silica production.

3. The HOR and ISO models predicted global values for silica flux much larger than supported by estimates made from data (NTBLQ95) unless all dissolution occurred on the bottom. Since there is, in fact, considerable dissolution within the water column and forcing all dissolution to occur at the bottom puts a lower limit on silica flux, this overprediction points to deficiencies in the model circulation scheme.

4. Dissolution plays a critical role in determining productivity. The BOT scheme produced low values for productivity, while the other dissolution schemes yielded much larger values. The TEMP scheme produced high values for production in warm water but was closer to the BOT scheme in cold water.

It is unclear at present how much of the overconcentration of silicate in the dense water and thus the high fluxes in the Antarctic with isopycnal mixing was due to numerical truncation errors (as discussed by Gnanadesikan, submitted manuscript, 1998) and how much was due to an increase in silica fluxes in the

Antarctic which add silicate to the deep water. A few regions with negative surface concentration were found in both the Pacific and Atlantic basins, indicating that numerics might play some role. Gnanadesikan (submitted manuscript, 1998) indicated that errors were worst in regions where the isopycnal slope exceeded the grid aspect ratio (dz/dx, where dz is the vertical spacing of grid boxes and dx is the horizontal spacing). Since eddy-induced advection reduces isopycnal slopes, it may have accounted for some of the reduction in Southern Ocean silica production and the corresponding increase in tropical silica production.

However, with respect to two of the major results, the overprediction of Antarctic influence for all models and the steep reduction of fluxes in the Southern Ocean with eddy-induced advection, model physics is at least as important as model numerics. Clear evidence of changes in physical structure which could explain these results can be found in Figures 2 through 4. The temperature plots in Figures 2 and 3, for example, show that the the model advected too much Antarctic Bottom Water into the Atlantic and Pacific Basins. The reduction of fluxes in the Southern Ocean was related to the stronger, and more realistic, stratification of the Southern Ocean seen
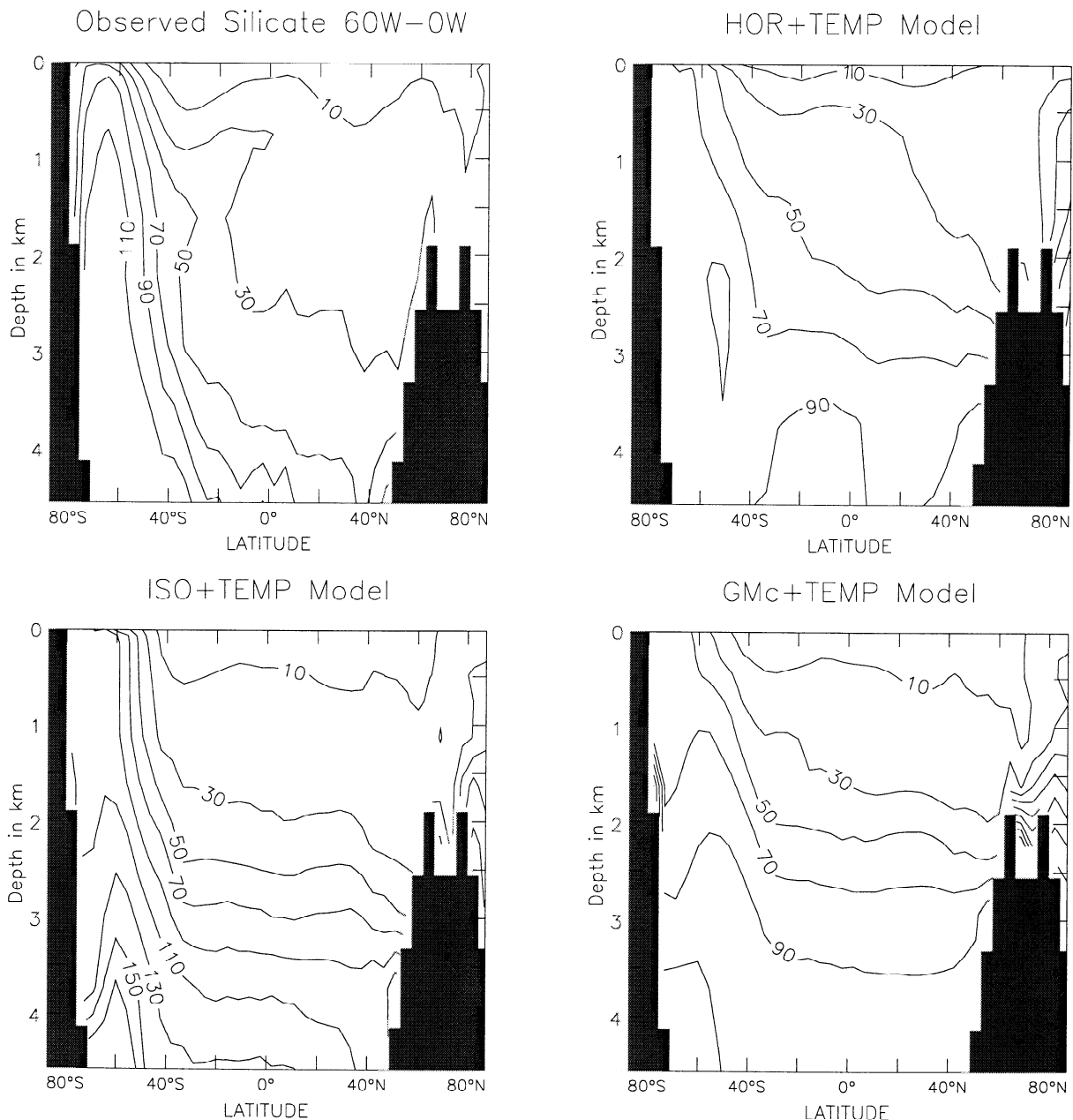

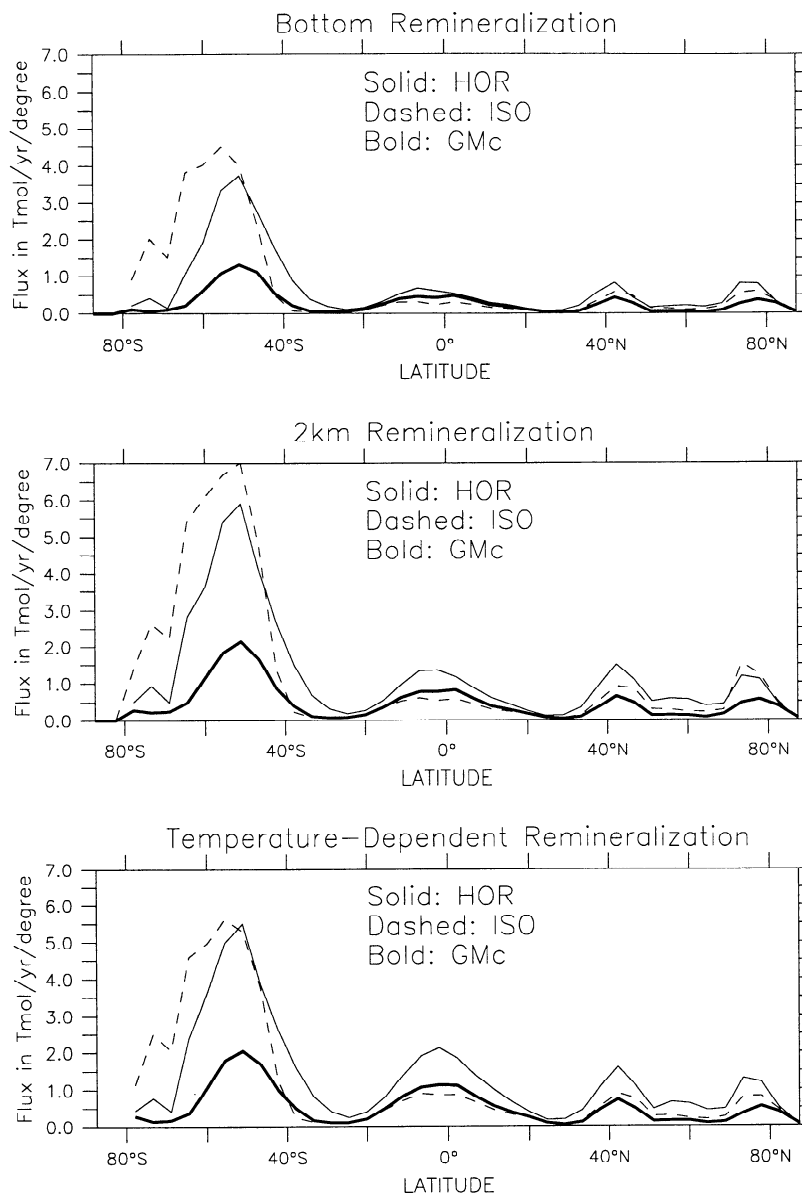**Figure 8.** Same as Figure 7 but for Atlantic Ocean.

Figure 9. Zonally integrated export flux of biogenic silica in the different models. (top) BOT dissolution scheme. (middle) 2KM dissolution scheme. (bottom) TEMP dissolution scheme.

Table 2. Global Biogenic Silica Flux for Various Regions

	Global	Southern Ocean	Eastern Equatorial Pacific
HOR+BOTTOM	116	69	7.2
HOR+2KM	205	115	13.8
HOR+TEMP	215	108	21.4
ISO+BOTTOM	133	106	3.8
ISO+2KM	218	171	7.1
ISO+TEMP	193	139	11.1
GMc+BOTTOM	49	23	7.3
GMc+2KM	81	40	10.1
GMc+TEMP	89	38	13.9
Target	70-100	17-37	7-10

Values in Tmol yr^{-1} are taken from *Nelson et al.* [1995]. See discussion in text regarding adjustments.

in the GMc model, resulting in a much reduced penetration of convection. For example, the data points used in Figure 4 encompassed a relatively small part of the Southern Ocean. Yet in the runs with temperature-dependent dissolution these few points were found to account for 5 Tmol yr^{-1} in the HOR+TEMP model and 8 Tmol yr^{-1} in the ISO+TEMP. By contrast, they accounted for only 0.6 Tmol yr^{-1} in the GMc+TEMP simulation.

In combination the results clearly support the use of the GMc+TEMP simulation. This run produced the most realistic distribution of silicate (smallest residuals relative to data) as well as the lowest fluxes, especially within the Southern Ocean. However, the GMc model was not without fault. For example, it did not produce deep water with an appropriate balance between Antarctic and North Atlantic sources. As a result, the effect of Antarctic Bottom Water was too strong in all basins. Perhaps because of this, although the silicate fields were qualitatively realistic in many ways, the horizontal gradients in silicate were too small. More work needs to be done to determine the extent to which the latter deficiency is a result of the model physics or of the biology.

4. Regional Silicon Dynamics

4.1. Southern Ocean

Since the GMc+TEMP model produced reasonable distributions of the silicate and silica flux, it can be used to understand how the deep silicate maxima in the Southern Ocean and North Pacific are maintained. Using the model provides a tool for evaluating the relative importance of various circulation mechanisms in these two regions which are of vital importance to the global budget. This subsection looks at how the silicate

maximum in the Southern Ocean was maintained in the model. All of the models showed relatively high concentrations in the near-surface Southern Ocean, though the HOR simulations did not reproduce the deep silicate maximum there.

It is not readily obvious why there should be a deep silicate maximum to the south of the Circumpolar Current. The large-scale flow field imports low-silicate North Atlantic Deep Water and exports high-silicate Antarctic Bottom Water from the Antarctic and so should deplete the Antarctic of silicate. Likewise, one would expect silicate to be lost by diffusion to the low-silicate Atlantic waters advected by the Circumpolar Current.

In the GMc+TEMP model, eddy diffusion and upper ocean advection both supplied silicate to the Southern Ocean (Figure 10) while lower layer advection (export of Antarctic Bottom Water and import of North Atlantic Deep Water) removed the silicate. Particle flux resulted in a transport of 31 Tmol yr^{-1} to the deep ocean. As this is only partially compensated by vertical mixing and advection (which transported 23 and 2 Tmol yr^{-1}, respectively), there was a net vertical flux of 6 Tmol yr^{-1}, connecting the upper layer import to the lower layer export of silicate.

Examination of the spatial dependence of the silicate and transport fields revealed the picture shown in Figure 11, where five different water masses were found to play a role in establishing this picture. Examination of the transport showed three main silicate circulation cells.

1. The first was a near-surface cell in which light low-silicate water exported in the Ekman layer and in the subtropical gyre was balanced by higher-silicate water in the Western Boundary Current. This cell added silicate to the upper part of the polar ocean.
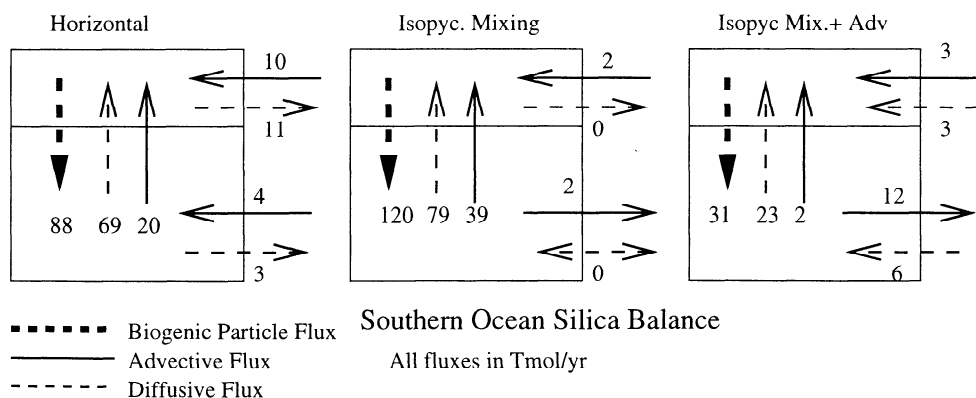
Figure 10. Silicon balance in the Southern Ocean for three models with temperature-dependent dissolution. The upper part of the box represents the top 500 m while the lower part of the box represents the bottom 4500 m. The northern boundary of the domain is at 40°S. (left) HOR+TEMP simulation. (middle) ISO+TEMP simulation. (right) GMc+TEMP simulation. Note that GMc+TEMP is the only simulation to produce realistic distributions and fluxes.
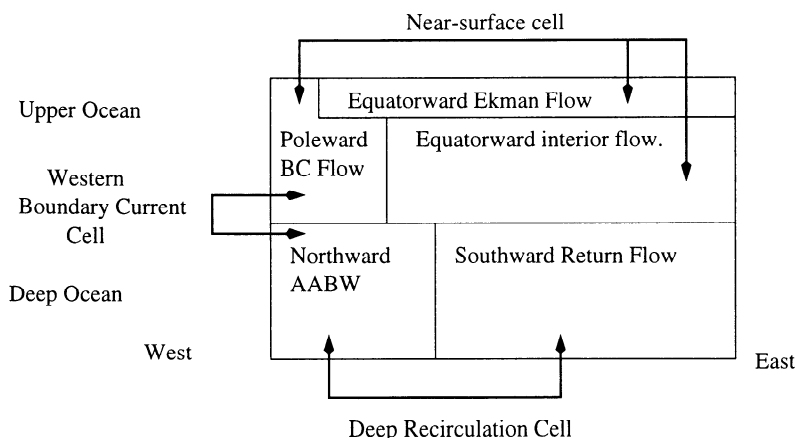
Figure 11. Schematic of the flows responsible for transporting silicate at both 40°S and 35°N. Flows are shown as a schematic zonal section.

2. The second was a Western Boundary Current cell, in which the southward flow of moderate-silicate water at middepths within the Western Boundary Current was balanced by Antarctic Bottom Water flowing northward in deep Western Boundary Currents. This cell tended to remove silicate from the lower part of the Southern Ocean and to add it to the abyssal North Pacific.

3. The third was a deep recirculation cell, in which some of the Antarctic Bottom Water flowing northward was returned with a higher value of silicate. This cell tended to add silicate to the lower part of the Southern Ocean (and to remove it from the North Pacific).

For the GMc+TEMP model the last of these three cells was relatively weak, since there was a weak contrast in the silicate concentration between the Southern Ocean and the North Pacific. As a result, the northward flow of AABW returned with relatively little added silicate in the Pacific, adding relatively little silicate to the Antarctic. Since the southward flow of NADW added low silicate water to the Antarctic, the net effect of advection was to remove silicate from the deep Southern Ocean.

The other models gave a very different picture for the Antarctic, a fact which is not entirely surprising, given the very different temperature and silicate structures produced within the Southern Ocean. As seen in Figure 10, the HOR+TEMP model predicted advection to be a net source of silicate for the Antarctic and diffusion to be a net sink (both at a level of 14 Tmol yr^{-1}). This is consistent with the silicate distribution which had far too little silicate throughout the Antarctic. As a result, the water flowing out of the Antarctic had far too little silicate in it, so that the Western Boundary Current and deep recirculation cells ended up adding silicate to the Antarctic.

By contrast, in the ISO+TEMP simulation the silicate was highly concentrated in the bottom water. This

means that there is not much silicate in the upper ocean to be transported northward at 40°S in the Ekman layer or southward in the gyres. As a result, the upper ocean advection did not play as important a role in this model. Examination of the deep flows showed that the export of deep water from the Antarctic was weaker in the ISO runs than in the GMc runs (as reflected by the somewhat smaller influence of AABW in the temperature fields). This weaker deep flow resulted in a substantially weaker transport of silicate in the deep western boundary current cell.

It is interesting that mesoscale eddy diffusion was a source of silicate in the GMc+TEMP run (+9 Tmol yr^{-1}), while it was a sink in the HOR+TEMP model (-14 Tmol yr^{-1}). Some of this was because of subtle differences in the balance of silicate in the Atlantic and Pacific Basins. In the HOR model there was a strong diffusive sink at middepths throughout the Southern Ocean, as the thermocline was too deep and horizontal diffusion thus connected high-silicate Antarctic waters with low-silicate thermocline waters. By contrast, at depth the Antarctic waters were connected with deep waters in the North Pacific, which had even higher values of silicate and so could act as a diffusive source, but also with low-silicate Atlantic waters. In the HOR+TEMP model the surface and Atlantic sinks won.

In the ISO+TEMP simulation the high-silicate Antarctic waters were no longer directly connected to low silicate thermocline waters. In fact, silicate isolines were fairly flat at 40°S, sloping down slightly in the Atlantic (providing a small sink) and up slightly in the Pacific (giving a small source). The concentration of silicate in the dense water means that there was no middepth silicate maximum to act as a diffusive source to the Southern Ocean.

In the GMc+TEMP simulation the enhanced flow of Antarctic Bottom Water means that silicate isolines were flatter in the Atlantic (so that diffusion was a
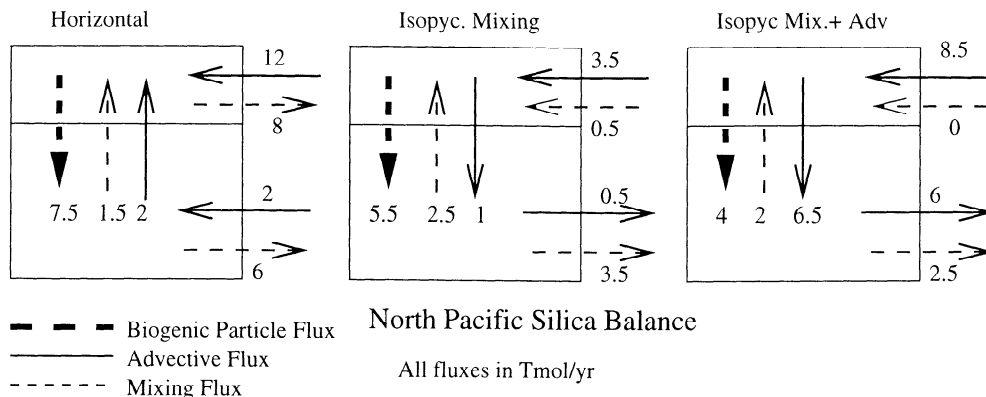
Figure 12. Same as Figure 10 but for the North Pacific. The upper part of the box represents the upper 914 m, the lower part of the box represents the lower 4186 m, and the horizontal domain stretches from 35°N to 65°N.

smaller sink to the Southern Ocean) and more vertical in the Pacific as the middepth silicate maximum appears (so that diffusion was a larger source to the Southern Ocean). Together these effects resulted in diffusion being a source to the deep Southern Ocean. In the intermediate water the isopycnals were connected to high-silicate intermediate waters in the Pacific and Indian Oceans, and diffusion was a source here as well.

4.2. North Pacific: Maintenance of the Deep Silica Maximum

The picture of upper level silicate inflow and deep silicate outflow was also found in the North Pacific (Figure 12). The same circulation cells transported silicate as in the Southern Ocean, but with the difference that the AABW added silicate to the abyssal ocean and the deep return flow of higher-silicate North Pacific Deep Water removed it. The near-surface cell added 8.5 Tmol yr^{-1} of silicate to the upper water column and the deep recirculation cell removed 6 Tmol yr^{-1} from the lower part of the water column. Isopycnal diffusion appeared to be an important sink as well, removing 2.5 Tmol yr^{-1} from the lower part of the column. Note the differences between the GMc+TEMP run and the other two runs, especially in the deep portion of the water column, and in the relative importance of horizontal diffusion. Note that the general picture of surface silicate input and deep silicate removal was consistent for the three models in the North Pacific. This contrasts with the Southern Ocean where the HOR model predicted a net export of silicate from the upper portion of the water column. The picture given by all three models is quite different from that proposed in the box models of PMB93 and NTBLQ95 in which silicate is added to the North Pacific by the upwelling branch of the global conveyor circulation and removed in the surface layers. Reasons for this difference are considered in section 5.

The importance of mesocale eddy diffusion in both the North Pacific and Southern Oceans has some important consequences. In particular, it places some cautionary limits on the use of geostrophic inverse models which do not resolve the eddy field in predicting circulation patterns and budgets. For example, inverse models such as that of *Wunsch et al.* [1983] would include a condition that silicate be advectively balanced in a region such as the Southern Ocean, and would use this condition to set the level of no motion. For the GMc+TEMP simulation, which had a net advective removal of silicate from the Southern Ocean such a condition would necessarily result in an underestimate of the northward flow of high-silicate deep water and thus lead presumably to an underestimate of the strength of the Antarctic Bottom Water. This would not be the case in sections where stations were closely spaced and resolved the mesoscale eddy field [see e.g. *Robbins and Toole*, 1997].

5. A Picture of Global Silicon Dynamics

This section summarizes the silicon cycle in the GMc+TEMP simulation, which as stated earlier produced the most realistic distribution and fluxes. Figure 13 presents a zonally averaged summary of how silicon was transported in the model. Five regions are shown, the Southern Ocean, subtropical Southern Hemisphere oceans, tropical ocean, northern subtropical oceans, and northern subpolar and polar oceans. In contrast to Figures 10 and 12, which were primarily concerned with the mechanisms maintaining deep structures, the analysis in Figure 13 is broken up into three vertical regions, surface (0-50 m), intermediate (50-914 m) and deep (914-5000 m).

The total export of biogenic silica across a depth of 50 m was 88.8 Tmol yr^{-1} in this model. Of this flux 43% was returned to the intermediate water with the

```
         2.3 ──► ──►    2.4◄─ ◄─      2.3 ──► ──►         ◄─ ──0.8
         0.2 ── ──►     0.1◄─ ──      0.1 ── ──►          ◄─ ──0.4          0-50m
      37.7 19.3 21.0     3.8 3.8 2.6    30.3 29.6 5.5     3.0 2.4 1.7    14.0 3.3 11.9

      ▼  │  ┊          ▼  ▼  ┊        ▼    │  ┊         ▼  ▼  ┊        ▼  ▲  ┊
              6.6◄─────              ──► 2.4        ◄── 0.3           ──► 11.6       50-914m
              4.6── ──   ┊  ▲  ▲    ◄── ── 3.8     ── ──► 0.6  ┊      ── ──► 2.3

      ▼  │  ┊          ▼    ┊        ▼    │  ┊         ▼    ┊        ▼  ▼  ┊
      29.3 3.0 18.1     1.7 3.8 2.9    11.0 10.4 7.1     1.5 9.3 2.3    7.4 7.1 1.6     914-5000m
           13.4─┬──►       14.4─┬──►       0.2 ─┬──►       ◄──── 10.5
            5.1◄─ ──       11.0◄─ ──        3.0 ◄─ ──       ◄─ ── 2.4
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| Southern Ocean | Southern Subtropics | Tropical Ocean | Northern Subtropics | Northern Subploar+Polar |

■ ■ ■ ■ ■ ■ ■ ■ ■   Biogenic Particle Flux

──────────────   Advective Flux   Global Silica Fluxes

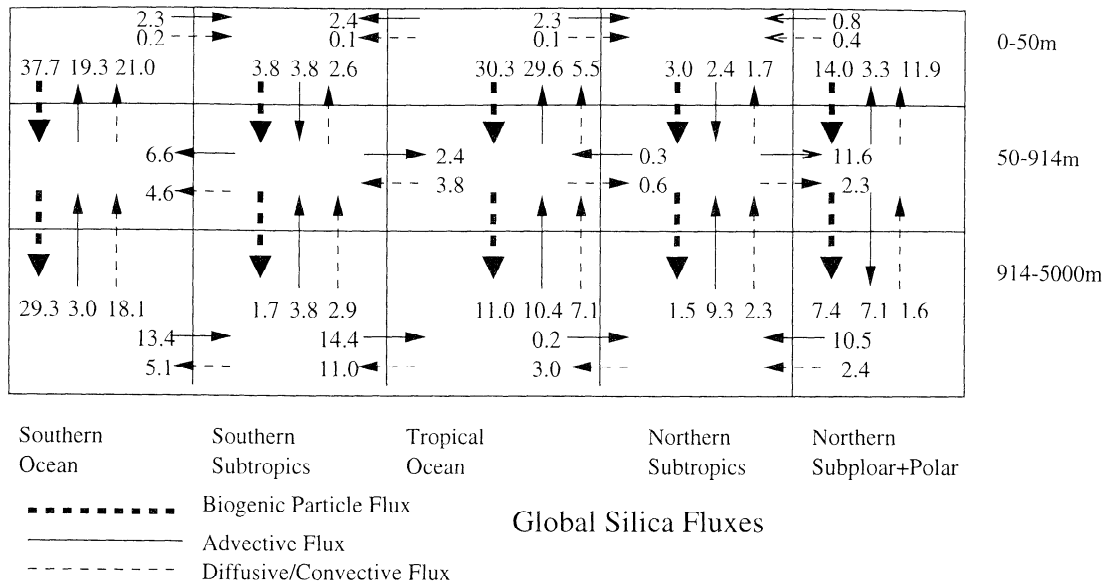─ ─ ─ ─ ─ ─ ─   Diffusive/Convective Flux

Figure 13. Zonally averaged picture of the fluxes of silicon in the GMc+TEMP simulation after 4200 years of integration. The upper boxes represent the top 50m (mixed layer). The middle boxes represent the intermediate waters (50-914 m). The bottom boxes represent the abyss (914-5000 m). The Southern Ocean is from 90°S to 40°S. The southern subtropics are from 40°S to 23°S. The tropical ocean is from 23°S to 23°N , the northern subtropics are from 23°N to 40°N, and the northern subpolar and polar oceans cover everything north of 40°N. Biogenic particle fluxes are shown with bold dashed lines, advective fluxes are shown with solid lines, and diffusive and convective fluxes are shown with dashed lines. Individual boxes may not be exactly balanced because of rounding errors and the fact that certain regions are not at a perfect steady state.

remaining 57% going into the deep water. Almost 2/3 of the tropical export flux was remineralized in the intermediate water. By contrast, three quarters of the Southern Ocean export flux went into the deep water. Although the predicted export flux is considerably lower than that estimated by NTBLQ95, it is in line with the regional estimates given a low tropical silica production [*Dugdale and Wilkerson*, 1998]. The distribution of this export flux is shown in Figure 14. Four bands of high production were seen, one in the Antarctic to the north of the continent, as high silicate surface water is advected northward, another in the tropical Pacific, a third in the North Pacific with a region of very high production off the coast of Asia, and a fourth in the Arctic. This last region was probably spurious, resulting from too large a transport of high-silicate North Pacific water through the Bering Strait. Although it appears quite significant in Figure 14, the area covered by high flux was quite small and did not play a major role in the global balance.

Both advection and diffusion played key roles in the model silicon balance. Advection transported slightly more than half of the new silicate to the surface layer, while vertical diapycnal diffusion, isopycnal diffusion, and convection accounted for the remainder. Note that tropical export production was primarily supported by advection, while in the northern oceans diffusion was

the dominant term. The Southern Ocean zone of high production was supported both by vertical diffusion and advection. Both advection and diffusion also played a role in maintaining the horizontal distribution of silicate. Lateral diffusion moved silicate out of the deep northern latitudes southward. Vertical diffusion and convection moved the silicate upward into the surface. Advection moved silicate northward out of the Antarctic and then upward into the surface waters. Some of the high-silicate water upwelled in the tropics and polar regions was downwelled in the subtropics.

The results presented here differ from those inferred from box models in PMB93 and NTBLQ95. One major difference centers around the relative roles of the North Pacific and tropical oceans. In the box models the tropical oceans were largely ventilated from the surface North Pacific as an advective flux. As noted in section 4.2, this is the exact opposite of the advective flux predicted by the model, regardless of mixing scheme. The 14 sverdrups of upwelling in the box model is taken to represent the warm water path of the global conveyor belt. In all the general circulation models, most of the upwelling of silicate-rich deep water occurred in the tropics instead. The second major difference between the box models and the results presented here is that the GCM produced a balance in the vertical while the box model required a considerable sink of silicon to
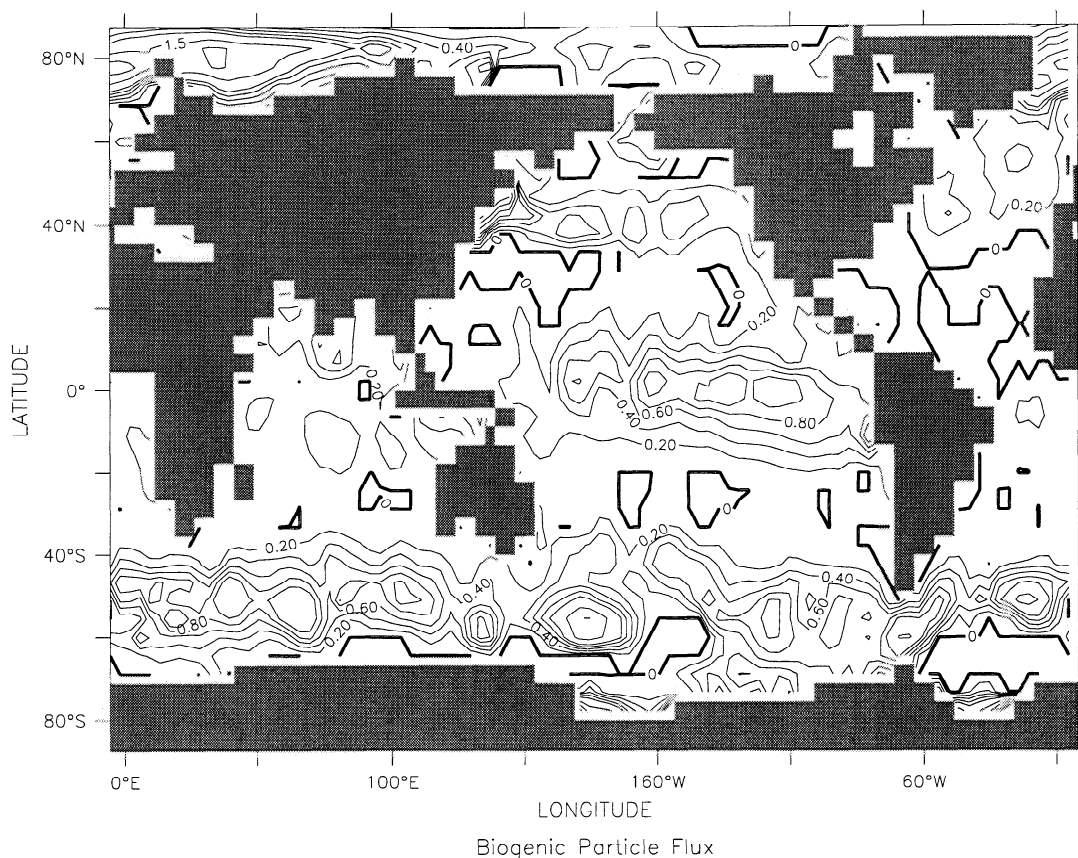
Figure 14. Global distribution of silica flux for the GMc+TEMP model. Fluxes are in mol m^{-2} yr^{-1}. Contours are every 0.2 up to 1.0 and thereafter every 0.5.

the deep Antarctic (12 Tmol yr^{-1}) and large sources of silicon in the Indo-Pacific (9 Tmol yr^{-1}) and Atlantic (3 Tmol yr^{-1}) Basins. The lack of realism in the box model circulation schemes and the neglect of horizontal mixing was probably responsible for this failure.

6. Abrupt Change and Polar Biology

A final issue which arises with these models is their sensitivity to abrupt changes in climate. It is clearly of interest to know whether the predicted freshening of polar waters with global warming [*Manabe and Stouffer*, 1994; *Sarmiento and LeQuere*, 1996; *Sarmiento et al.*, 1998] is likely to cause major changes in ecosystem dynamics. The latter two papers, for example, predicted a substantial decrease in the amount of nutrient supplied to the surface of the Southern Ocean as a result of increased stratification. This paper has already shown that the temperature and nutrient structure in the Southern Ocean, as well as the level of vertical exchange, could depend quite strongly on the eddy parameterization. Since previous results used models without the Gent-McWilliams parameterization, it is quite likely that they had unrealistically high levels of convection and vertical exchange in the Southern Ocean.

In order to evaluate the sensitivity of the model to polar freshening with respect to eddy parameterization, waters poleward of 55°S were freshened and warmed for 100 years at the end of each of the model runs with the TEMP scheme. The latitude range chosen was that over which the coupled model predicted freshening would occur. This was accomplished by changing the temperature and salinity toward which the model was restored. The warming and freshening used were given by the response of the global coupled model of *Sarmiento et al.* [1998] averaged for all latitudes south of 55°S. The resulting export flux of biogenic silica before, 10 years after, and 100 years after the freshening is applied is shown in Figure 15 and Table 3.

The response of the Southern Ocean silica flux to polar freshening depended on the eddy parameterization. Both the HOR and ISO models predicted that polar freshening would cause significant changes in the Southern Ocean ecosystem, with productivity dropping by 30% south of 55°S and in some regions by more than 50%. By contrast the GMc model exhibited very weak sensitivity to polar freshening, with polar production dropping by only 10% or so with the decrease offset by a slight increase to the north of 55°S. This difference was due to the fact that both of the first two models
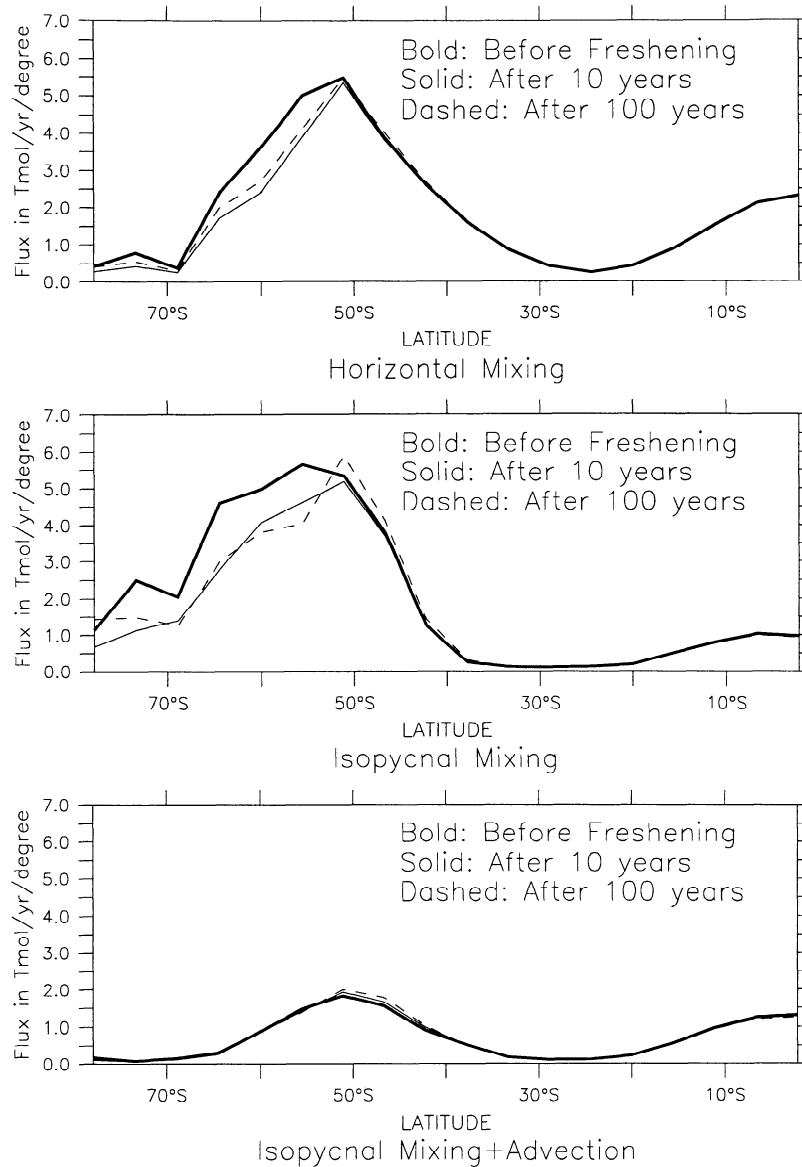
Figure 15. Response of the flux of biogenic silica in the different models to polar freshening and warming. Polewards of 55°S the temperature toward which restoring was done was increased by 0.45°C and the salinity was decreased by 0.065 practical salinity units. Curves are shown before freshening (bold), after 10 years (solid), and after 100 years (dashed) for (top) HOR+TEMP model, (middle) ISO+TEMP model, (bottom) GMc+TEMP model.

Table 3. Southern Ocean Silica Flux Response to Polar Freshening

	Before Freshening	10 Years	100 Years
HOR+TEMP	48	33	38
ISO+TEMP	84	58	60
GMc+TEMP	11.1	10.2	10.4

Surface poleward of 55°S is freshened by 0.065 practical salinity units and warmed by 0.45°C (mean values from a coupled model run). Export flux across 50 m is shown in Tmol yr^{-1}. Note that fluxes in the horizontal mixing and isopycnal mixing runs both drop by 30%,while those in the run with eddy-induced advection drop much less (less than 10%). For the runs with eddy-induced advection this loss is essentially offset by a slight increase to the north of 55°S.

had strongly sloping isopycnals and a great deal of convection throughout the Southern Ocean, as seen in Figure 4. This resulted in strong nutrient transport which supported high levels of productivity. When the Southern Ocean was freshened, this convection was cut off and the slope of the isopycnals decreased [*Sarmiento and LeQuere*, 1995; *Sarmiento et al.*, 1998]. The result was to produce a significant decrease in production throughout the Southern Ocean. As the vertical diffusion acted on this fresh cap, however, the production began to recover.

By contrast, in the GMc model there was very little convection in the Southern Ocean, and the isopycnals were relatively flat. As a result, the addition of fresh water to the surface layer did not greatly change the transport of nutrient to the surface except in a few regions of deep convection. The result is a much smaller reduction in the magnitude of the production. This suggests that the results of *Sarmiento et al.* [1998] were seriously biased by the lack of stratification in their initial state.

Although extremely suggestive, this result is far from definitive. In particular, it is not consistent to change the atmospheric forcing without considering the role of the ocean in producing that forcing. For such a study, however, a coupled model (presently not available with the GMc parameterization) would be required. Additionally, although the runs with eddy-induced advection did produce a more realistic Southern Ocean (in particular the cold fresh surface water), it is unclear that they did this for the right reasons. Finally, there were serious problems with the way in which we have chosen to model the silicon cycle under climate change. It is by no means clear, for example, that the biology would continue to drive silicate toward the same level in a changed climate. Given these uncertainties, it is unclear that any of the models produces the correct response to polar freshening. Nonetheless, the results point out the extreme importance of understanding how the thermohaline structure of the Antarctic is maintained for predicting how Antarctic ecosystems are affected by climate change.

7. Conclusions

Ocean general circulation models are the tools which can be used to synthesize biogeochemical and physical data into a coherent picture of oceanic biogeochemical cycling. This study demonstrates the sensitivity of such models to dissolution and subgrid-scale eddy effects. Particularly important results include the following:

1. The parameterization of subgridscale eddy effects was of equal importance in determining model response as the dissolution scheme. Changing either the eddy parameterization or dissolution scheme resulted in major changes in the distribution of silicate and flux of biogenic silica.

2. The use of eddy-induced advection as proposed by *Gent et al.* [1995] produced more realistic silicate fields while allowing for realistically low fluxes of biogenic silica out of the mixed layer.

3. The processes which maintain the Antarctic Surface Water are critically important to understanding the response of the ocean to global change. Both the HOR and ISO models failed to maintain this water mass, while the GMc model qualitatively reproduced it. As a result, the GMc model was not very sensitive to polar freshening, with nutrient delivery to the surface layer remaining essentially identical under fresh conditions as in the baseline case. The HOR and ISO models, in contrast, showed significant reductions in nutrient delivery to the surface layer when it was freshened, and deep convection in the Southern Ocean was reduced. This emphasizes the importance of understanding the true physics which determine the stratification in the Southern Ocean.

4. None of the eddy parameterizations reproduced the correct balance in the abyss between North Atlantic Deep Water and Antarctic Bottom Water. This resulted in the sequestration of overly large amounts of silicate in the deep Atlantic.

5. Models can support relatively small global export fluxes of silica (less than 100 Tmol yr^{-1}) in agreement with observations. Although this figure is lower than that reported by NTBLQ95, it is in line with the low observed silica fluxes along the equator.

6. The functionality of dissolution is quite important in determining the distribution and magnitude of the silica flux. In particular, the shape of the dissolution curve in the upper part of the water column may be extremely important and should be a focal point for field studies. Such studies would need to include both a characterization of the thermodynamics of dissolution and a mechanistic characterization of particle sinking.

These results further demonstrate that silicon can serve to constrain the circulation predicted by oceanic general circulation models and that ocean general circulation models can make useful predictions in synthesizing the observations into a coherent picture. For example, the silicate data clearly highlight model deficiencies such as the failure to get the deep water right. Work currently underway will attempt to remedy this problem using an explicit bottom boundary layer to connect the cold Nordic seas to the deep Atlantic. Conversely, the models clearly show that unless a lot more dissolution occurs up near the surface, export fluxes of 45-75 Tmol yr^{-1} of biogenic silica are unrealistic for the tropical ocean. Such complementarity demonstrates the utility of GCM tracer studies both for model validation and biogeochemical simulation. It should also strengthen the case for further model-data intercomparisons.

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