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The Southern Ocean silica cycle

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ABSTRACT

The Southern Ocean is a major opal sink and plays a key role in the silica cycle of the world ocean. So far however, a complete cycle of silicon in the Southern Ocean has not been published. On one hand, Southern Ocean surface waters receive considerable amounts of silicic acid (dissolved silica, DSi) from the rest of the world ocean through the upwelling of the Circumpolar Deep Water, fed by contributions of deep waters of the Atlantic, Indian, and Pacific Oceans. On the other hand, the Southern Ocean exports a considerable flux of the silicic acid that is not used by diatoms in surface waters through the northward pathways of the Sub-Antarctic Mode Water, of the Antarctic Intermediate Water, and of the Antarctic Bottom Water. Thus the Southern Ocean is a source of DSi for the rest of the world ocean. Here we show that the Southern Ocean is a net importer of DSi: because there is no significant external input of DSi, the flux of DSi imported through the Circumpolar Deep Water pathway compensates the sink flux of biogenic silica in sediments.

1. Introduction

Silicon (Si) was born in the universe by fusion between atoms of oxygen (O). It is one of the most abundant elements of the universe, the second most abundant for planet Earth. Si atoms form bonds with O atoms to create silica (SiO_2), which may be either crystalline or amorphous, with biogenic forms of silica and volcanic glasses being amorphous and minerals such as quartz being crystalline. Similar silica structures form the basis of rock-forming silicate minerals (such as kaolinite and other clays, micas, olivines, pyroxenes, feldspars, and plagioclases). Weathering (dissolution) of silicate rocks and minerals at low or high temperatures generates silicic acid (H_4SiO_4 or $Si(OH)_4$), so-called dissolved silica (herein abbreviated as DSi). Discharge of rivers and of submarine groundwater into the coastal ocean, hydrothermal inputs into deep waters, dissolution of siliceous material transported from the continents to the continental margins and that of airborne suspended materials in surface waters are pathways for DSi input into the ocean. In surface waters, DSi is taken up by diatoms to build their frustules of amorphous biogenic silica ($bSiO_2$). Removal of DSi from the ocean corresponds mostly to the burial of biogenic silica, as opal, in abyssal and coastal sediments, although a minor contribution from siliceous sponges might also be involved. A revised budget of Si in the world ocean (Fig. 1) has been published by Tréguer and De La Rocha (2013). Given the large uncertainties in the fluxes of DSi and of $bSiO_2$ (Tréguer and De La Rocha, 2013), the question of the steady state of the Si cycle in the modern ocean remains an open question.

The key role played by the Southern Ocean in the control of the world ocean silica cycle was identified long ago (e.g., Anderson et al., 2002; DeMaster, 1981, 2002; Nelson et al., 1995; Pondaven et al., 2000; Tréguer et al., 1995). On the one hand, at subsurface and intermediate depths, Sub-Antarctic

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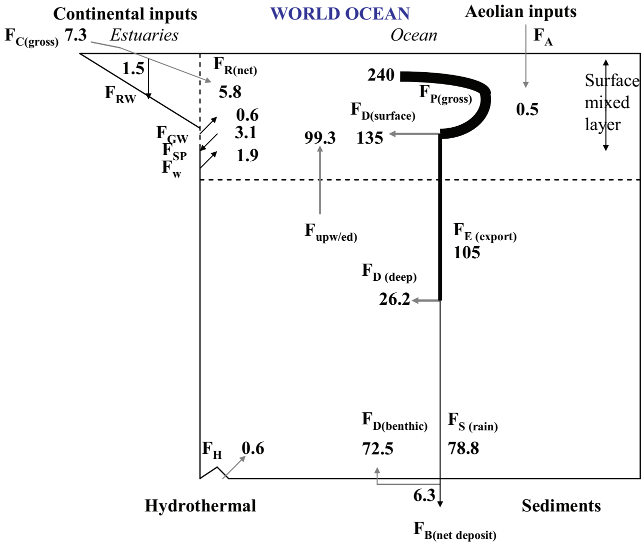

Fig. 1. Biogeochemical cycle of silicon in the world ocean at steady state (a possible balance that is in reasonable agreement with the individual range of each flux, *F*). Gray arrows represent fluxes of silicic acid – dissolved silica, DSi – and black arrows represent fluxes of particulate biogenic silica; the vertical dotted line represents the limit between the estuaries and the ocean; the horizontal dotted line represent the limit between the surface well-mixed reservoir and the deep ocean. All fluxes (*F*) are in 10^{12} or teramoles of silicon per year.

For details, refer to Tréguer and De La Rocha (2013).

Mode Water and Antarctic Intermediate Water export huge amounts of DSi that remains unused by siliceous phytoplankton in Southern Ocean surface waters (Fig. 2). In the abyss, DSi-rich Antarctic Bottom Water also exports DSi into the deep areas of the Atlantic, Indian, and Pacific basins (Anderson et al., 2002). On the other hand, the large opal belt of opaline sediments that girds the Antarctic, roughly underlying the Polar Frontal Zone, has been cored for several decades (e.g., DeMaster, 1981, 2002). The impressive abundance of biogenic silica in the opal belt sediments makes the Southern Ocean one of the most important silica sinks in the world ocean (DeMaster, 2002; Pondaven et al., 2000). So far however, the Si status of the Southern Ocean is unclear: is the Southern Ocean a net sink or a net source of DSi for the rest of the world ocean? This is the question addressed in this study.

Preliminary note: we use herein the distinction introduced by Tréguer and Jacques (1992) between the

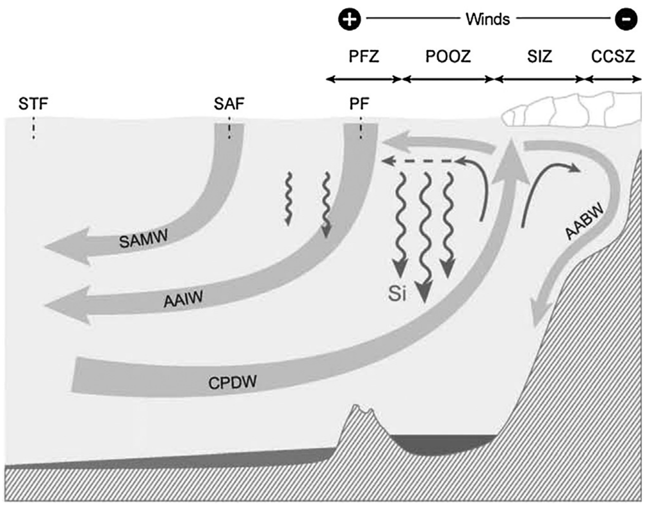

Fig. 2. The Southern Ocean: schematic vertical circulation of water masses, frontal systems, major ecosystems and vertical transport of biogenic silica. Fronts: PF: polar front; SAF: Sub-Antarctic Front; STF: Sub-Tropical Front; note that we use to call "Antarctic Ocean" the part of the SO which comprises the polar front zone (PFZ), the permanently open ocean zone (POOZ), the seasonal ice zone (SIZ) and the coastal and continental shelf zone (CCSZ). Through the upwelling of the Circumpolar Deep Water (CPDW) at the Antarctic divergence, the surface waters are enriched in silicic acid. This favors the growth of diatoms and intense biogenic silica production, which triggers abundant export of biogenic silica to deep waters ultimately depositing opal on abyssal sediments (mostly south of the PF). The silicic acid unused in surface waters is exported to the rest of the world ocean through the Sub-Antarctic Mode Water (SAMW), the Antarctic Intermediate Water (AAIW), and the Antarctic Bottom Water (AABW).