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Deep ocean fluxes and their link to surface ocean processes and the biological pump

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Abstract

Intense studies of upper and deep ocean processes were carried out in the Northwestern Indian Ocean (Arabian Sea) within the framework of JGOFS and related projects in order to improve our understanding of the marine carbon cycle and the ocean's role as a reservoir for atmospheric CO_2. The results show a pronounced monsoon-driven seasonality with enhanced organic carbon fluxes into the deep-sea during the SW Monsoon and during the early and late NE Monsoon north of 10°N. The productivity is mainly regulated by inputs of nutrients from subsurface waters into the euphotic zone via upwelling and mixed layer-deepening. Deep mixing introduces light limitation by carrying photoautotrophic organisms below the euphotic zone during the peak of the NE Monsoon. Nevertheless, deep mixing and strong upwelling during the SW Monsoon provide an ecological advantage for diatoms over other photoautotrophic organisms by increasing the silica concentrations in the euphotic zone. When silica concentrations fall below 2 $\mu mol\ l^{-1}$, diatoms lose their dominance in the plankton community. During diatom-dominated blooms, the biological pathway of uptake of CO_2 (the biological pump) appears to be more efficient than during blooms of other organisms, as indicated by organic carbon to carbonate carbon (rain) ratios. Due to the seasonal alternation of diatom and non-diatom dominated exports, spatial variations of the annual mean rain ratios are hardly discernible along the main JGOFS transect.

Data-based estimates of the annual mean impact of the biological pump on the fCO_2 in the surface water suggest that the biological pump reduces the increase of fCO_2 in the surface water caused by intrusion of CO_2-enriched subsurface water by ~50–70%. The remaining 30 to 50% are attributed to CO_2 emissions into the atmosphere. Rain ratios up to 60% higher in river-influenced areas off Pakistan and in the Bay of Bengal than in the open Arabian Sea imply that riverine silica inputs can further enhance the impact of the biological pump on the fCO_2 in the surface water by supporting diatom blooms. Consequently, it is assumed that reduced river discharges caused by the damming of major rivers increase CO_2 emission by lowering silica inputs to the Arabian Sea; this mechanism probably operates in other regions of the world ocean also.

Keywords: Particle flux; Biological pump; Carbon cycle; Monsoon; Arabian Sea; JGOFS

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1. Introduction

Sedimentation is a process wherein solid particles of diverse nature and composition are formed, transported and deposited on the seabed. A large proportion of marine sediments consists of continental weathering products (lithogenic matter), which were eroded from soils and introduced into the ocean by rivers or via the atmosphere (aeolian inputs). Lithogenic matter contains mainly clay and sinks very slowly through the water column if not incorporated into fast-sinking biogenic particles such as fecal pellets and marine snow (Alldredge & Silver, 1988; Deuser, Brewer, Jickells, & Commeau, 1982; Honjo, Manganini, & Poppe, 1982; Urrère & Knauer, 1981). Coherence in these biogenic carriers is accomplished by sticky organic compounds produced in the guts of zooplankton (fecal pellets) or released by phytoplankton (Degens & Ittekkot, 1984; Passow, Alldredge, & Logan, 1994; Passow et al., 2001). Marine organisms not only produce organic matter but also minerals such as biogenic opal ($SiO_2 \cdot 2H_2O$) and carbonate ($CaCO_3$) shells. After the death of organisms, shells settle through the water column driven by gravity, sometimes as ingredients of fast-sinking particles. They compose, in addition to lithogenic and organic matter, marine sediments (Honjo & Roman, 1978).

The precipitation of carbonate and the photosynthesis of organic matter are key factors in the global carbon cycle, because they initiate carbon-sedimentation and influence the ocean/atmosphere CO_2 exchange. The latter is driven by the difference in the fugacity of $CO_2(\Delta fCO_2)$ between the ocean and the atmosphere. The fCO_2 in the surface water results from the CO_2 concentration in the surface water, the temperature- and salinity-dependent solubility of CO_2 in sea water, and a minor correction due to the fact that CO_2 is a real, not an ideal, gas (Zeebe & Wolf-Gladrow, 2001, p. 65). The CO_2 concentration, in turn, is related to other carbonate species in the ocean by the following equilibrium (carbonate system): $CO_2 + H_2O \leftrightarrow HCO_3^- + H^+ \leftrightarrow CO_3^{2-} + 2H^+$, where CO_2 summarizes H_2CO_3 and aqueous CO_2 which are not separable chemically (Zeebe & Wolf-Gladrow, 2001, p. 2). The sum of CO_2, HCO_3^- and CO_3^{2-} is defined as the total dissolved inorganic carbon (DIC). A decrease in DIC lowers the CO_2 concentration and subsequently the fCO_2 and, vice versa, an increase of the DIC raises the fCO_2 (Fig. 1). The carbonate system is, however, also influenced by total alkalinity (TA). This is the negative charge required to neutralize all positive charges in ocean waters, which are not balanced by negative charges carried by anions of strong acids. A reduction of TA is associated with an enhanced fCO_2 because it results in a shift of the carbonate system to the left hand side.

The formation of organic matter and the precipitation of carbonate affect fCO_2 in the surface water by changing the DIC concentration and the TA, respectively. For example, the precipitation of carbonate reduces the DIC concentration by one unit but the TA is decreased by two units as a twofold, negatively charged anion is consumed. This enhances fCO_2 and accordingly, the precipitation of carbonate is named the carbonate counter pump (Heinze, Maier-Reimer, & Winn, 1991). Photosynthesis also reduces DIC concentration, since this process converts CO_2 into particulate organic carbon (POC). In addition to carbon, marine organic matter also contains nitrogen and phosphorus in a quasi-fixed "Redfield ratio" (Redfield, Ketchum, & Richards, 1963; C/N/P 106/16/1). Consequently, 0.15 mol of nitrate is converted into organic nitrogen during the photosynthesis of 1 mol of organic carbon. Nitrate is an anion of a strong acid and its consumption increases the TA (Broecker & Peng, 1982). Thus, the formation of organic matter lowers the fCO_2 mainly by direct consumption of DIC and nutrients and their subsequent export into the deep-sea. Net effects of this so-called organic carbon pump and the carbonate counter pump on the fCO_2 comprise the biological pump (Volk & Hoffert, 1985; Fig. 1). Due to counteracting effects of these two pumps on the fCO_2, marine CO_2 uptake is favored by enhanced production of organic matter and a reduced carbonate precipitation. Accordingly, the ratio between particulate organic carbon (POC) and calcium carbonate carbon (PIC; the rain ratio) within the matter which is exported into the deep-sea can be used as an indicator for the efficiency of CO_2 uptake by the biological pump (Berger & Keir, 1984).