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# The dynamics of the carbon cycle in the surface water of the Norwegian Sea

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## Abstract

Historical data of total dissolved inorganic carbon ($C_T$), together with nitrate and phosphate, have been used to model the evolution of these constituents over the year in the Atlantic water of the Norwegian Sea. Changes in nutrient concentration in the upper layer of the ocean are largely related to biological activity, but vertical mixing with the underlying water will also have an impact. A mixing factor is estimated and used to compute the entrainment of these constituents into the surface water from below. After taking the mixing contribution into account, the resulting nutrient concentration changes are attributed to biological production or decay. The results of the model show that the change in $C_T$ by vertical mixing and by biological activity based on nutrient equivalents needs another sink to balance the carbon budget. It cannot be the atmosphere as the surface water is undersaturated with respect to carbon dioxide and is, thus, a source of $C_T$ in this region. Inasmuch as the peak deficit of carbon is more than a month later than for the nutrients, the most plausible explanation is that other nitrogen and phosphate sources than the inorganic salts are used together with dissolved inorganic carbon during this period. As nitrate and phosphate show a similar trend, it is unlikely that the explanation is the use of ammonia or nitrogen fixation but rather dissolved organic nitrogen and phosphate, while dissolved organic carbon is accumulating in the water.
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## 1. Introduction

Warm and saline waters from the North Atlantic enter the Norwegian Sea between Iceland and Shetland and flow northwards along the Norwegian continental slope into the Barents Sea and towards Fram Strait. This current, the Norwegian Atlantic current, is separated from the coast of Norway by the less saline Norwegian Coastal current. The Atlantic water in the Norwegian Atlantic Current is characterised by salinity and temperatures above 35 and 3 °C, respectively (Swift, 1986), with highest values to the south. The transport of water in the Norwegian Atlantic current is still uncertain, estimates have ranged from 2 to 10 Sv ($1 \text{ Sv} = 1 \times 10^6 \text{ m}^3 \text{ s}^{-1}$), and there are variations

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throughout the year (Blindheim, 1993; Hansen and Østerhus, 2000). On its route northward, the Atlantic water is cooled due to heat release to the atmosphere and becomes freshened because of precipitation and mixing with adjacent water masses. The Norwegian Atlantic current is wedge shaped, and the Atlantic water, as defined above, reaches to depths of 400 to 900 m depending on location (Mosby, 1970).

The total dissolved inorganic carbon ($C_T$), nitrate and phosphate concentrations in the Atlantic water vary with the season as a result of both physical and biological processes. Throughout the year, the mixed layer depth (MLD) will vary due to heating and cooling of the surface water. The cold winters with the corresponding increase in the depth of the mixed layer and low light levels result in low biological activity, and the physical processes like vertical mixing and air–sea gas exchange have the most influence on the concentrations of these chemical constituents. In spring and summer, with the heating of the surface layer and the resulting decrease of the mixed layer, the biological processes will be more important, and the nitrate, phosphate and $C_T$ concentrations will decrease as a result of biological uptake. During photosynthesis, these inorganic elements are taken from the water by the phytoplankton to produce organic matter. Secondary processes like grazing by zooplankton will transform this organic matter into products like particulate debris that sinks towards the bottom and dissolved organic matter (DOM). Regeneration of organic matter during autumn and winter reintroduces the inorganic components to the water, often at deeper depths. The increase in the MLD from autumn and throughout the winter entrains part of this water, and the concentrations in the surface water increases, so by the end of the winter, the $C_T$, nitrate and phosphate concentrations are more or less the same as before the spring bloom started.

The quantification of the different fluxes involved in the carbon dynamics of the upper layer of the Norwegian Sea is scarce, and only a few estimations of biological production from changes in the concentrations of nutrients, $C_T$ and oxygen cover the area under consideration. Rey (1981) has estimated the total primary production along the Norwegian coast using the ^{14}C method, and Broström (1997) used a coupled model to estimate total production at Ocean

Weather Station M (OWSM) in the Norwegian Sea. Falck and Gade (1999) used oxygen measurements to calculate the net community production at OWSM and for the entire Nordic seas (Greenland, Iceland and Norwegian seas).

A common practice when estimating the biological production from the different constituents is the use of the RKR ratios (Redfield et al., 1963) when converting the results into carbon equivalents. The RKR ratios is the averaged molar C:N:P ratios of oceanic particulate organic matter (living or dead plankton) and is close to 106:16:1. The mineralization products of organic matter, $C_T$, nitrate and phosphate are also added to the deep ocean in about the same ratio. It is supposed that they are supplied to the surface ocean from the deep water according to this ratio. Dugdale and Goering (1967) defined new production as the production based on nitrate supply from outside the surface layer as opposed to regenerated production based on nutrient remineralization within the surface layer, the sum of the two being the total production. The produced organic matter that is not remineralized in the surface water but sinks out of the euphotic zone is called the export production. New production has been assumed equivalent to export production on an annual basis (e.g., see Eppley and Peterson, 1979) in the sense that the remineralization products of the exported particles will be introduced to the surface water again during winter mixing.

Lately, the term carbon overconsumption have been used in the literature (e.g., see Sambrotto et al., 1993; Toggweiler, 1993) inasmuch as it is found that more carbon is consumed in the surface layer than what would be expected from multiplying the apparent nitrate utilization with the C:N ratio of 6.6. It is therefore becoming more and more evident that the simple Redfield stoichiometry do not always apply to the dynamics of the surface water; that is, the turnover of nitrogen and carbon may be decoupled (Banse, 1994). Observations of dissolved organic matter (DOM) dynamics show that it has a high C:N ratio (Williams, 1995), and that it constitutes a substantial part of vertical carbon export by mixed layer deepening (e.g., see Carlson et al., 1994; Lefevre et al., 1996). The degree to which biogeochemical cycling of dissolved inorganic carbon, nitrate and phosphate overlaps with the cycling of the dissolved organic carbon pool has yet to be elucidated.