ICES Journal of
Marine Science

ICES International Council for the Exploration of the Sea
CIEM Conseil International pour l'Exploration de la Mer

ICES Journal of Marine Science (2012), 69(2), 208–212. doi:10.1093/icesjms/fss007

Short communication

Declining silicate concentrations in the Norwegian and Barents Seas

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Rey, F. 2012. Declining silicate concentrations in the Norwegian and Barents Seas. – ICES Journal of Marine Science, 69: 208–212.

Received 16 June 2011; accepted 4 December 2011.

Since 1990, a decline in silicate concentrations together with increasing salinities has been observed in the Atlantic water of the Norwegian and Barents Seas. This decline in silicate has been found to be related to the relative proportion in which eastern and western source water masses from the northeastern North Atlantic enter the Norwegian Sea.

Keywords: Atlantic water, Barents Sea, long-term changes, Norwegian Sea, salinity, silicate.

Introduction

The Norwegian and Barents Seas are among the most productive seas in northern Europe and harbour some of the most exploited and currently largest fish stocks, among others, herring, cod, and capelin (Skjoldal *et al.*, 2004; Gjøsæter, 2009). Their productivity is due to substantial zooplankton biomass production caused by the yearly renewal of nutrients during winter followed by a typical spring phytoplankton bloom. It is this zooplankton biomass that sustains the large fish stocks in their different life cycles in both seas.

The zooplankton is represented by several groups as copepods, krill, amphipods, etc. Especially important are the copepod *Calanus finmarchicus* in both the Norwegian and Barents Seas and *Calanus glacialis* in the Barents Sea. The reproduction and growth of these two species is strongly dependent on the spring phytoplankton bloom in these areas (Melle *et al.*, 2004; Eiane and Tande, 2009), which is mainly composed of diatoms (Rey, 2004; Sakshaug *et al.*, 2009). All phytoplankton species are, in addition to light, dependent on the supply of nutrients such as nitrate and phosphate for their growth. Diatoms need, in addition, silicate for their growth and often their blooming is regulated by this nutrient (Egge and Aksnes, 1992). Preliminary results of the monitoring programmes carried out by the Institute of Marine Research (IMR) in Norway have shown a decline in the winter silicate concentration during the past 20 years in the Atlantic water of the Norwegian and Barents Seas. Such a decline can have significant consequences for the ecosystems in these areas such as, for instance, a change in the spring bloom phytoplankton community due to a decrease in diatom biomass. In the present study, we look at the degree of this decline and it's possible causality.

Material and methods

Since the 1950s, the IMR has carried out routine monitoring of the oceanographic conditions at different sections in the Norwegian and Barents Seas (Figure 1). Each section comprises ~17–25 stations and the sampling frequency for each particular section varies from 4 to 6 times a year. Since 1985, the monitoring has been extended to include nutrients. In addition, weekly sampling of nutrients at the Ocean Weather Station Mike (OWSM) was carried out between 1990 and 2009. This station has also been routinely surveyed for hydrography since 1948. Nutrient samples are collected at ICES standard depths, preserved with chloroform, and kept at ~4°C until they are analysed. The samples are analysed ashore with an AutoAnalyzer following the standard methods (Strikland and Parsons, 1972) within 4–6 weeks after collection. For the present work, we have used winter data collected mostly during March when the winter vertical mixing is at its maximum at all sections. For a few years, March data were lacking and January data were used instead. Ancillary data were obtained from the ICES Database (www.ices.dk/ocean) and from single cruises of IMR.

The stations at each section containing Atlantic water were identified by salinities larger than 35 (except the Vardø-Nord section where 34.95 was used as a lower limit) and temperatures larger than 2°C. This was performed to exclude waters of polar and coastal origins. The average values of salinity, temperature, and nutrients for the water column for every March were

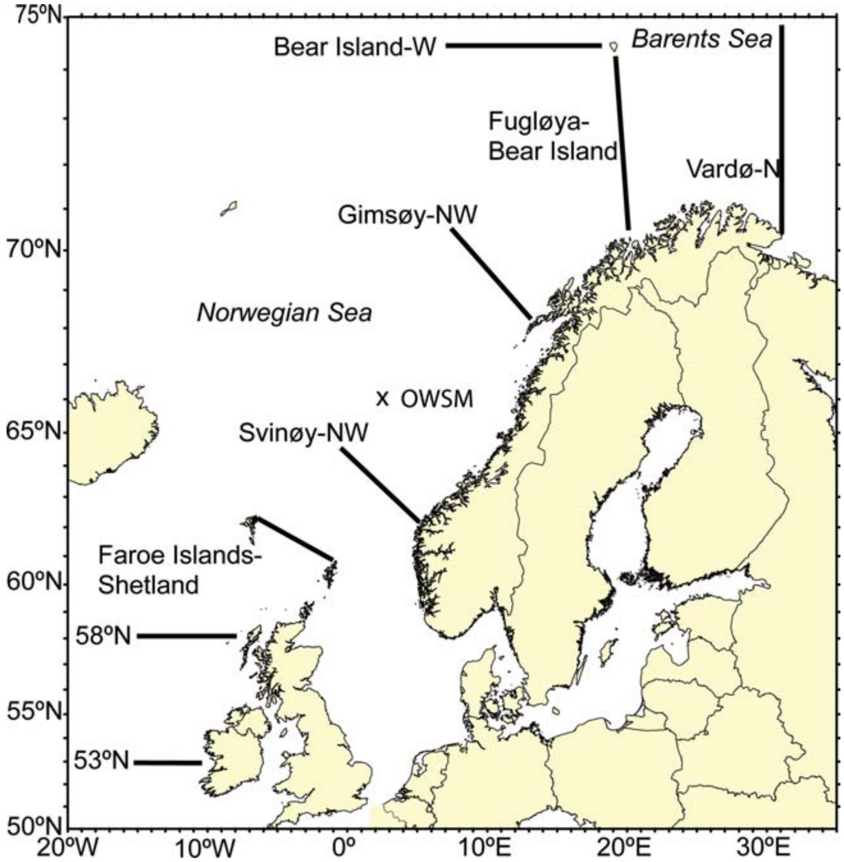

Figure 1. Locations of the oceanographic sections in the northeastern North Atlantic, the Norwegian Sea and the Barents Sea, and the OWSM in the Norwegian Sea.

calculated using the observations from all the selected stations down to 200 m or in the upper mixed layer (water density difference <0.05 relative to the surface value) in the cases when this layer was shallower than 200 m. The range of the winter mixed-layer depths varied strongly from ~150 m in the Barents Sea to 300–400 m in the Norwegian Sea.

Results and discussion

The average values of silicate concentration and salinity in the Atlantic waters at two oceanographic sections in the Norwegian Sea (Svinøy-NW and Gimsøy-NW), two in the Barents Sea (Fugløya-Bear Island and Vardø-N), and OWSM (Norwegian Sea) are shown in Figure 2. All sections show a significant decline in silicate concentrations and an increase in salinity between 1990 and 2010. Table 1 shows the results of the regression analysis for each place. The reduction in silicate concentrations varied between 0.044 and 0.067 mmol m^{-3} $year^{-1}$. Taking the silicate concentration for the first year as a start, the reduction during the 20-year investigation period varied between 15.8% at the Fugløya-Bear Island section and 22.4% at the Svinøy-NW section with an overall average of 20% for all sections. The increase in salinity varied between 0.0029 and 0.0056 units per year with an overall average of 0.0045 units per year. This represents an increase of ~0.3%. Temperature (not shown) also increased significantly throughout the 20-year period, with a range between 0.65 and 1.5°C, being lower in the Norwegian Sea and higher in the Barents Sea.

The other important nutrient, nitrate, also showed a decrease, but a much lower one than that for silicate. The winter nitrate averaged for all the areas decrease by ~7% during the 20-year period.

Except the Fugløya-Bear Island section, the average yearly values for salinity and silicate concentrations during winter were significantly correlated at all places (Figure 3, Table 2). An observation for two single years (1996 and 2006) at the Bear Island-W section is also shown.

Since the 1990s, an increase in salinity and temperature has been observed in the eastern North Atlantic and the Nordic Sea (Holliday *et al.*, 2008) and in the Barents Sea (Skagseth *et al.*, 2008; Mauritzen *et al.*, 2011). The water masses entering the Norwegian Sea and spreading northwards stem from two different water masses in the eastern North Atlantic with different salinities and temperatures (Hansen and Østerhus, 2000; McCartney and Mauritzen, 2001). The Modified North Atlantic water (MNAW; Figure 5 in Hansen and Østerhus, 2000), of oceanic origin is carried by the North Atlantic Current. The North Atlantic water (NAW) has higher salinities and temperatures and flows along the European continent under the name the continental slope current. Hátun *et al.* (2005) showed that the salinity of the Atlantic inflow into the Norwegian Sea is tightly coupled to the dynamics of the North Atlantic Subpolar Gyre. The proportion in which these water masses enter the Norwegian Sea is coupled to the east–west movements of the Subpolar Front. This displacement of the Subpolar Gyre is closely connected to the atmospheric

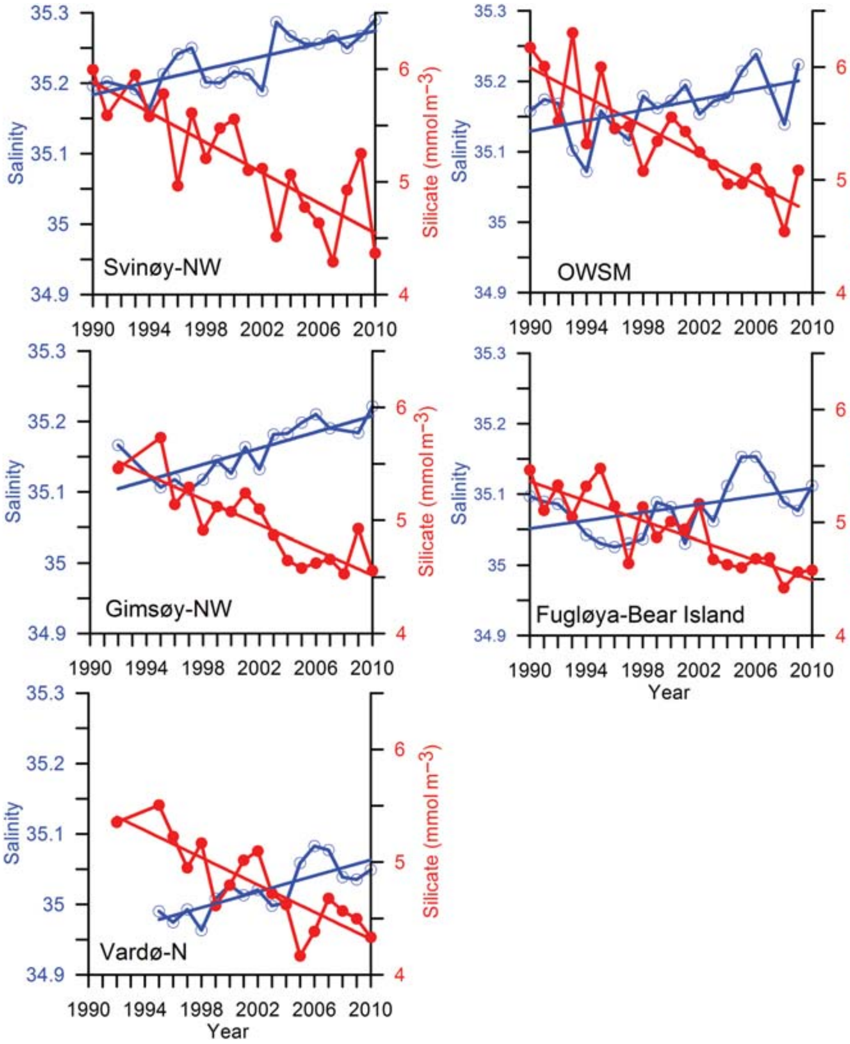

Figure 2. Time-series of salinity (open blue circles) and silicate (closed red circles) at different places in the Norwegian and Barents Seas. Locations of the sections are shown in Figure 1. Results of the regression analysis are shown in Table 1.

Table 1. Results for the regression analysis for Atlantic water in Figure 2.

Section	Salinity slope	R^2	*p*-value	Silicate slope	R^2	*p*-value
Svinøy-NW	0.0045	0.570	$<$0.001	$-$0.0671	0.652	$<$0.001
OWSM	0.0038	0.312	0.010	$-$0.0601	0.607	$<$0.001
Gimsøy-NW	0.0056	0.610	$<$0.001	$-$0.0556	0.711	$<$0.001
Fugløya-Bear Island	0.0029	0.216	0.034	$-$0.0435	0.704	$<$0.001
Vardø-N	0.0056	0.596	$<$0.001	$-$0.0603	0.701	$<$0.001

Intercepts values are not shown.

forcing in the region as represented by the North Atlantic Oscillation (NAO; Sarafanov, 2009). During periods with high NAO with strong westerly winds, the Subpolar Gyre will be displaced eastwards allowing a larger proportion of the colder and less saline MNAW relative to the warmer and saltier NAW to enter the Norwegian Sea. During the periods of low NAO, the opposite will occur.

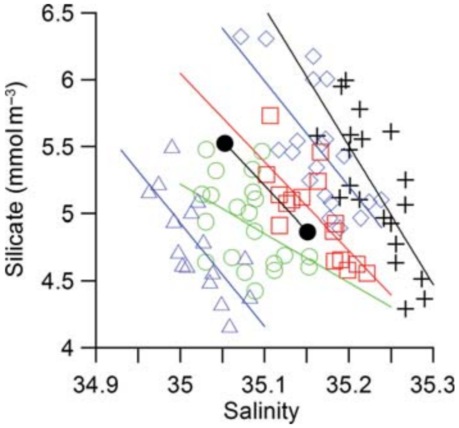

Figure 3. The salinity–silicate relationship for all years at the different places. Svinøy-NW (black crosses), OWSM (blue diamonds), Gimsøy-NW (red squares), Fugløya-Bear Island (green circles), and Vardø-N (blue triangles). Results of the regression analysis are shown in Table 2. An observation for two single years (1996 and 2006) at the Bear Island-W section is also shown as black dots.

The two water masses not only differ in salinity and temperature but they have also quite different silicate concentrations during the winter mixing season. The saline and warm NAW has lower silicate concentrations than the less saline and colder MNAW. Three oceanographic sections taken during March at 53.5°N, 58°N (Rockall Through), and the Faroe–Shetland Channel illustrate this (Figure 4). At the 53.5°N section (March 2001) extending more than 350 km off the British coast, only NAW is observed with salinities >35.42 and silicate concentrations between 3.6 and 4.8 mol m^{-3}. Further north at the Rockall Channel area (58°N, March 2001), the apparition of the MNAW (salinity <35.3; silicate >5.5 mmol m^{-3}) is observed west of the NAW. Both water masses are separated by a strong salinity and silicate gradient above the Rockall–Hatton Plateau. Even further north at the Faroe–Shetland Channel (March 1997), which is one of the main entrance areas of Atlantic water into the Norwegian Sea, both water masses are still well defined with the NAW closest to Shetland with salinities >35.3 and silicate concentrations <5 mmol m^{-3}. No winter silicate data were available for the other main entrance to the Norwegian Sea (between Faroe and Iceland), but it is reasonable to assume that they are the same as those found on the eastern side of the Faroe Island.

Table 2. Results for the regression analysis between silicate and salinity at all sections as shown in Figure 3.

Section	Silicate slope	R^2	*p*-value
Svinøy-NW	−10.324	0.557	<0.001
OWSM	−7.874	0.472	<0.001
Gimsøy-NW	−6.933	0.571	<0.001
Fugløya-Bear Island	−3.657	0.189	0.048
Vardø-N	−7.719	0.543	<0.01
Bear Island-W	−6.73	n.a.	n.a.

Intercepts values are not shown.

Based on the above observations, it is plausible to postulate that the observed decrease in silicate in the Atlantic water through the Norwegian and Barents Seas has its origin in an increase in inflow of the saltier and warmer NAW as suggested by Hátun *et al.* (2005). Such an increase in salinity and temperature has been observed, since the middle of 1990s, through the whole Norwegian Sea from the Faroe–Shetland Channel to the Fram Strait (Holliday *et al.*, 2008).

At only one place, the Fugløya-Bear Island section close to the entrance of the Barents Sea, the decrease in silicate and the increase in salinity was less obvious compared with the other areas. The reason for this is not clear, but the section run across the Tromsøflaket, a shallow area with long retention time, allowing some mixing between coastal and Atlantic waters.

The observed 20% reduction in silicate in the past 20 years in the Atlantic water of the Norwegian and Barents Seas can have significant consequences for the ecosystems in these areas. As pointed out above, the main fisheries in these seas are strongly dependent

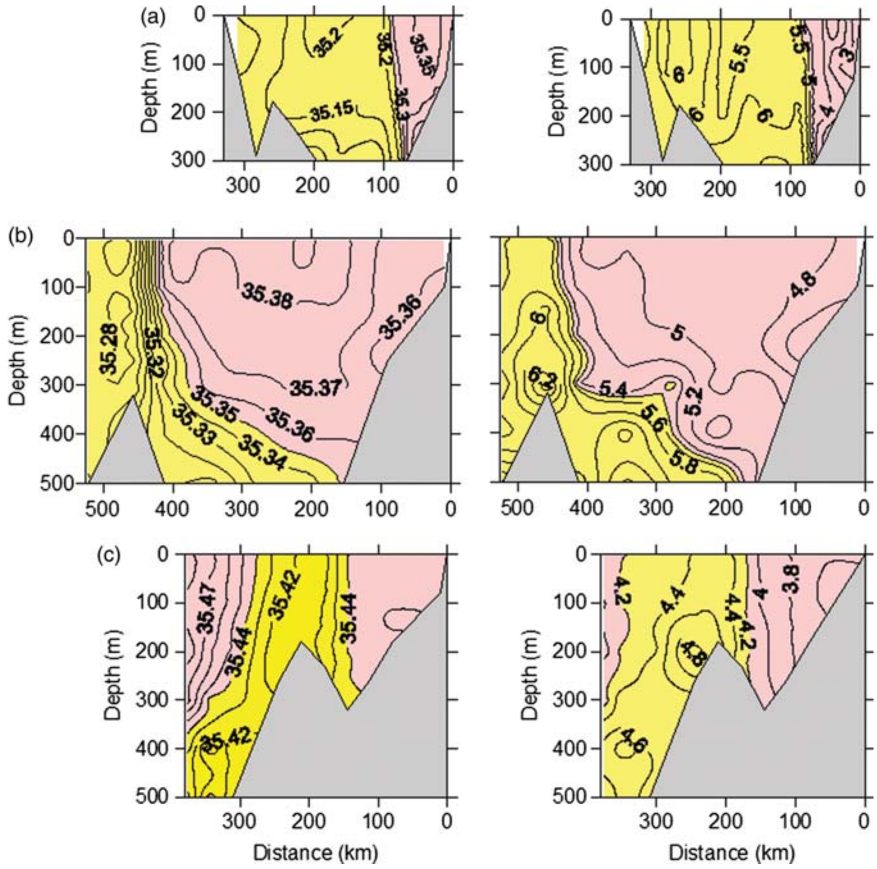

Figure 4. Spatial distribution of salinity (left panels) and silicate (right panels) at three oceanographic sections in the northeastern North Atlantic. Light yellow, MNAW; light red, NAW. (a) Faroe–Shetland Channel, March 1997, (b) 58°N (Rockall Through), March 2001, and (c) 53.5°N, March.

on the zooplankton production represented mainly by the copepods *C. finmarchicus* and *C. glacialis*. As the seasonal growth of these copepods is tightly coupled to the diatom spring bloom, a reduction in silicate could have a strong effect on their production. Silica uptake by diatoms diminishes strongly below ambient silicate concentrations of 1–2 mol m^{-3} (Egge and Aksnes, 1992; Brown *et al*., 2003) and it gets uncoupled from carbon uptake. This means that the main growth of diatoms is expected to take place above this concentration level. With a maximum observed winter silicate concentration in the upper layer of the Norwegian Sea of 5–6 mol m^{-3} as example, only 3–4 mol m^{-3} will be available for positive growth. The observed reduction in winter silicate of ~1 mol m^{-3} in the past 20 years will then mean an actual reduction in utilizable silicate of ~25–30%.

Not only could the diatom biomass decrease, but the whole phytoplankton community composition could be exposed to severe changes. A decrease in diatom biomass due to the silicate reduction during the spring bloom would leave larger concentrations of unused nitrate that would be utilized by other phytoplankton forms leading to other routes for channelizing the produced energy to higher trophic levels.

Since the middle of the 1990s, a progressive reduction in zooplankton biomass in the Norwegian Sea has also been observed. This reduction reached ~80% in 2010, and it is assumed that the main cause has been a doubling of the biomass of several pelagic fish stocks such as herring, blue whiting, and mackerel (Gjøsæter *et al*., 2011). Based on these observations, it has been proposed that the ecosystem in the Norwegian Sea has a top–down control. However, the 20% decrease in silicate concentrations in the same period is also likely to have had an impact on the reduction in zooplankton biomass. Hence, the possibility that bottom–up control is also present cannot be excluded.

Due to its large size and relative rapid sinking rate, diatoms also play an important role in the export of biological material to deeper waters and therefore in the biogeochemical cycles in the ocean. Our finding that winter silicate concentrations in the Norwegian and Barents Seas is controlled by the dynamics of the North Atlantic Subpolar Gyre, and its subsequent effect on the inflow of northeastern NAWs into the Norwegian Sea, should be taken into account when attempting to make realistic ecosystem predictions. The results of this investigation also support the need of long and regular time-series of observations to get a better understanding of the natural variability in marine ecosystems.

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Handling editor: Bill Turrell