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Research paper

The effects of multiple stressors on the distribution of coastal benthic foraminifera: A case study from the Skagerrak-Baltic Sea region

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ABSTRACT

Coastal ecosystems are subjected to both large natural variability and increasing anthropogenic impact on environmental parameters such as changes in salinity, temperature, and pH. This study documents the distribution of living benthic foraminifera under the influence of multiple environmental stressors in the Skagerrak-Baltic Sea region. Sediment core tops were studied at five sites along a transect from the Skagerrak to the Baltic Sea, with strong environmental gradients, especially in terms of salinity, pH, calcium carbonate saturation and dissolved oxygen concentration in the bottom water and pore water. We found that living foraminiferal densities and species richness were higher at the Skagerrak station, where the general living conditions were relatively beneficial for *Foraminifera*, with higher salinity and Ω_{calc} in the water column and higher pH and oxygen concentration in the bottom and pore water. The most common species reported at each station reflect the differences in the environmental conditions between the stations. The dominant species were *Cassidulina laevigata* and *Hyalinea balthica* in the Skagerrak, *Stainforthia fusiformis*, *Nonionella* aff. *stella* and *Nonionoides turgida* in the Kattegat and *N.* aff. *stella* and *Nonionellina labradorica* in the Öresund. The most adverse conditions, such as low salinity, low Ω_{calc}, low dissolved oxygen concentrations and low pH, were noted at the Baltic Sea stations, where the calcareous tests of the dominant living taxa *Ammonia* spp. and *Elphidium* spp. were partially to completely dissolved, probably due to a combination of different stressors affecting the required energy for biomineralization. Even though *Foraminifera* are able to live in extremely varying environmental conditions, the present results suggest that the benthic coastal ecosystems in the studied region, which are apparently affected by an increase in the range of environmental variability, will probably be even more influenced by a future increase in anthropogenic impacts, including coastal ocean acidification and deoxygenation.

1. Introduction

Coastal areas are dynamic environments highly influenced by natural climate variability. Marine coastal ecosystems are acclimatized to large natural changes such as variations in salinity, temperature, carbonate chemistry and pH, dissolved oxygen concentration, and organic matter input from river discharge (Crossland et al., 2005). However, climate change and human impact are gradually increasing the range of this natural variability and lead to effects such as global warming, deoxygenation and ocean acidification (Crossland et al., 2005). Ocean acidification is globally recognized as a threat for marine life, especially for calcifying organisms (e.g. Kroeker et al., 2013). The uptake of anthropogenic CO_2 by the oceans since the industrial revolution has lowered the pH and resulted in a shift in sea water carbonate chemistry towards lower carbonate ion concentrations, which will likely make it more difficult for calcifiers to precipitate calcium carbonate. Moreover, calcifiers become more vulnerable to the effects of a lower pH when the temperature increases (Rodolfo-Metalpa et al., 2011). Coastal areas, that annually account for ~25% of the global calcium carbonate production and ~50% of calcium carbonate accumulation in the ocean (Mackenzie et al., 2005), are especially subjected to changes in carbonate chemistry and pH variations. In coastal environments, carbonate

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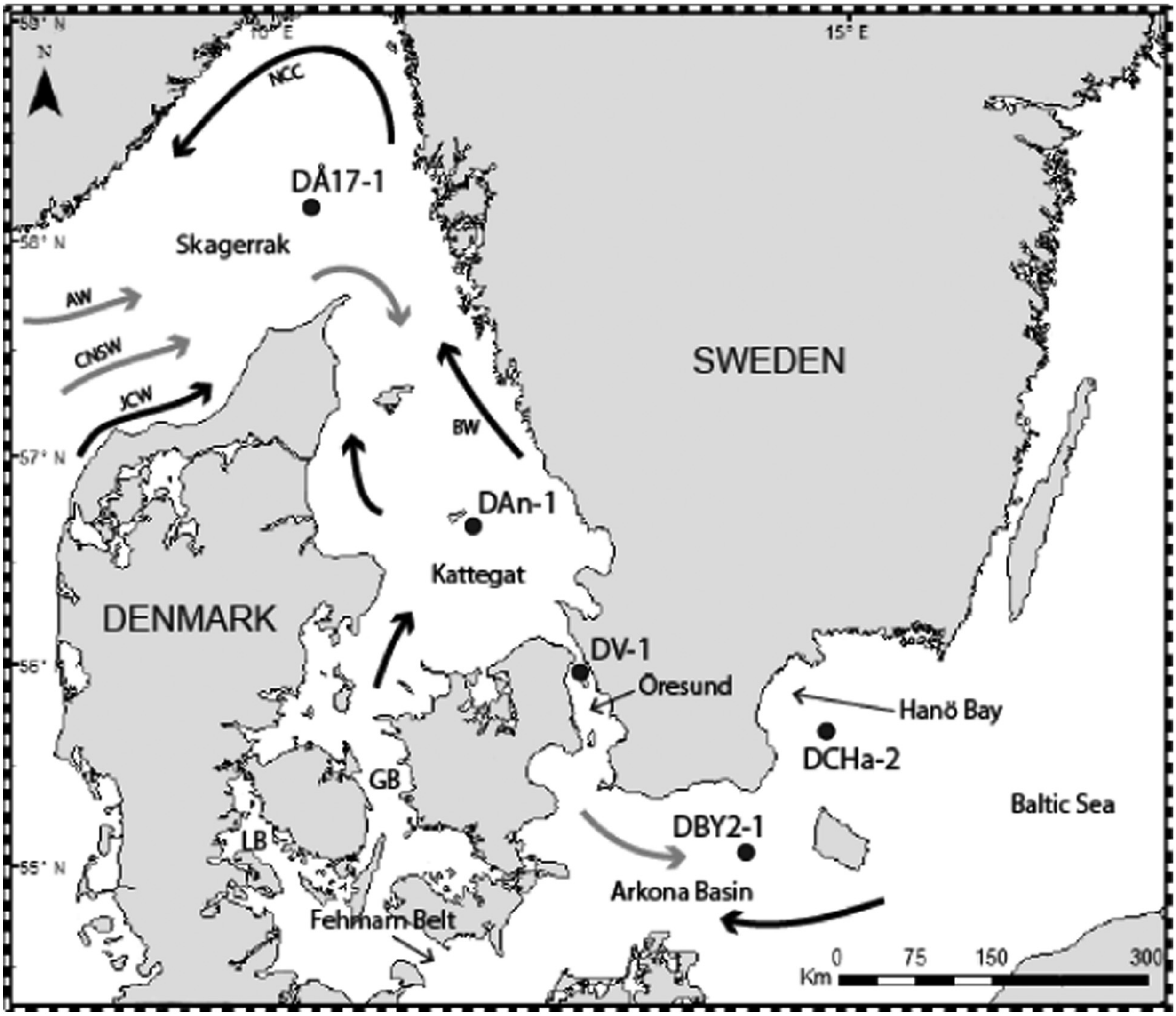

Fig. 1. Map of the studied area. Dots show the five studied stations. General water circulation: main surface currents (black arrows) and main deep currents (grey arrows). GB: Great Belt; LB: Little Belt; AW: Atlantic Water; CNSW: Central North Sea Water; JCW; Jutland Coastal Water; NCC: Norwegian Coastal Current; BW: Baltic Water.

chemistry is further influenced by a range of factors such as fresh water inputs (Salisbury et al., 2008; Chierici and Fransson, 2009) and upwelling of "older" CO_2-rich water with lower pH (Feely et al., 2008). Eutrophication also affects pH and calcium carbonate saturation through production of CO_2 and oxygen consumption during intense organic matter remineralization (Borges and Gypens, 2010; Cai et al., 2011). As a result, the pH fluctuations are much more complex in the coastal zones, which are regarded as "hot spots" of ocean acidification, compared to the open ocean (Cai et al., 2011; Duarte et al., 2013). How coastal ecosystems react under the combined effects of natural environmental stressors and ocean acidification is still largely unknown. In this study we focus on ecosystems in the Skagerrak-Baltic Sea area, along a strong salinity gradient ranging from 35 to 14. Recent observations have revealed that in addition to seasonal pH variations, these ecosystems have experienced a decrease in pH over the last 20 years, of 0.1 in the Kattegat and 0.2 in the Baltic Sea (Andersson et al., 2008; Andersson, 2010). Moreover, it is obvious from a century long record of total alkalinity (A_T) data that the response to ocean acidification in the Baltic Sea is complex, mainly due to different mineralogy in the river drainage basins (Hjalmarsson et al., 2008). Additionally, the Baltic Sea is strongly impacted by eutrophication and hypoxia (Conley et al., 2011), which make its coastal ecosystems more susceptible to a lower pH (Cai et al., 2011; Melzner et al., 2012; Laurent et al., 2017).

In contrast to oceanic environments, the functioning of coastal ecosystems is often dominated by the benthic compartment (Middelburg et al., 2005). At the base of the food chain, benthic foraminifera are the most diverse shelled micro-organisms at the modern sea floor (Gooday et al., 1992; De Stigter, 1996). These unicellular organisms are key players in coastal areas, not only as a food source, together with the rest of the meiofauna, but also as contributors to the carbon cycle, since they represent up to 5% of the annual carbonate production in coastal areas (Langer, 2008). They also participate in the marine nitrogen cycle as certain species are able to denitrify (Risgaard-Petersen et al., 2006; Høgslund et al., 2008). Moreover, environmental conditions are usually reflected in the foraminiferal faunal composition, making them excellent indicators of past and present environmental changes. In general, benthic foraminiferal distribution is mainly driven by the dissolved oxygen concentration and food availability (Van der Zwaan et al., 1999; Gross, 2000; Ernst and van der Zwaan, 2004). However, closer to the coast other environmental factors such as salinity and temperature may be restrictive (Nigam et al., 2008; Saraswat et al., 2015).

To build their test (shell), some species are cementing sediment particles (agglutinated and soft-shell species), whereas a large proportion of the benthic foraminiferal species build their tests from calcium