



Foraminiferal fauna from a deep basin in Gullmar Fjord: The influence of seasonal hypoxia and North Atlantic Oscillation

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ABSTRACT

Historical benthic foraminiferal assemblages were analysed in two sediment cores recovered from the deepest basin of Gullmar Fjord by a Gemini and a gravity corer. A compilation of faunal data corresponding to the period 1935–2011 is presented together with the bottom water temperature, salinity and dissolved oxygen records for the same period. This study adds new information for the last decade (2001–2011) and investigates foraminiferal fauna after a prolonged period of positive North Atlantic Oscillation (NAO) and seasonal hypoxia (1979/80–1999). The earliest part of the record (ca. 1935–1998) reveals faunal changes similar to those reported in previous studies. The typical Skagerrak–Kattegat (S–K) faunas, which were present until ca. 1980–83, were replaced by *Stainforthia fusiformis*, often reported from environments with coastal hypoxia. A close relationship was noted between bottom water renewals, dominating weather regime (the NAO index) and geostrophic winds. After 1998, the NAO changed towards less extreme values, which facilitated regular bottom-water exchange events and the re-appearance of some S–K species: *Cassidulina laevigata*, *Textularia earlandi* and *Bulimina marginata*. However, the most recent severe hypoxic event (around 2008) again triggered the increase of low-oxygen tolerant species and interrupted the short re-establishment process of the S–K fauna.

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1. Introduction

There are approximately 500 areas in the world with reported coastal hypoxia and 20% of them are located in the Baltic Sea region (Conley et al., 2011). This phenomenon is usually attributed to human induced eutrophication (Diaz and Rosenberg, 1995). The slow shoaling of the sill depth due to the isostatic uplift of Scandinavia also leads to a more efficient trapping of sediment and organic matter in the fjord and has been considered as another mechanism which lead to the steady oxygen depletion of the bottom water (Gustafsson and Nordberg, 2002; Smittenberg et al., 2005). However over the last 20 years increased attention has been paid to climate variability as another potentially important forcing factor (Belanger, 2011; Filipsson and Nordberg, 2004; Keeling et al., 2010; Nordberg et al., 2000, 2001 etc.). Under conditions unaffected by human influence, hypoxia is often associated with a stratified water column, as well as increases of ammonia, hydrogen sulphide and particulate organic matter (Wu, 2002). Coastal zones, and especially fjords, are important carbon sinks (Howe et al., 2010) due to their high primary productivity, which settles and accumulates in the form of organic-rich and oxygen consuming sediments.

Hypoxia is a widespread phenomenon all over the world (Alve, 1995; Belanger, 2011; Bernhard and Sen Gupta, 1999; Conley et al.,

2011; Diaz and Rosenberg, 1995; Gilbert et al., 2010; Gooday et al., 2000, 2009; Johannessen and Dahl, 1996; Leiter and Altenbach, 2010; Nordberg et al., 2000, 2009; Phleger and Soutar, 1973; Sen Gupta and Machain-Castillo, 1993). However there is no consistent definition of the dissolved oxygen concentration in hypoxic environments (see: Bernhard and Sen Gupta, 1999; Diaz and Rosenberg, 1995; Gooday et al., 2009; Kaiho, 1994; Tyson and Pearson, 1991). Here we apply the term “hypoxia” following Diaz and Rosenberg (1995) for oxygen concentrations of less than 2 ml/l (89 μM). Some benthic communities from the Kattegat can withstand lower oxygen concentrations of ca. 1 ml/l (45 μM) (Rosenberg et al., 1991) and, therefore, we refer to levels below 1 ml/l as “severe hypoxia” (“dysoxia” of Bernhard and Sen Gupta (1999)).

Some studies have shown that benthic macrofauna are more sensitive to hypoxic conditions than meiofauna (Gooday et al., 2000; Josefson and Widbom, 1988). Thus, in Gullmar Fjord, macrofauna survived at an oxygen concentration of 2 ml/l, but died or escaped from the area at 0.5 ml/l or 22 μM (Rosenberg and Loo, 1988; Rosenberg et al., 1991), whereas benthic foraminifera were able to tolerate severe hypoxia (Filipsson and Nordberg, 2004). The importance of benthic foraminifera in studies of oxygen-depleted environments is explained by the variety of their reactions to hypoxia, which include changes in abundance, biodiversity, species composition, dominance (Bernhard and Sen Gupta, 1999; Gooday et al., 2000; Gustafsson and Nordberg, 1999, 2000, 2001, 2002; Phleger and Soutar, 1973), microhabitats (Linke and Lutze, 1993; Sen Gupta et al., 2007), development of

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different life-strategies (Bernhard and Alve, 1996; Gustafsson and Nordberg, 1999; Linke and Lutze, 1993; Piña-Ochoa et al., 2010; Risgaard-Petersen et al., 2006) and features of the test morphology of low-oxygen tolerant species (Alve, 2003; Glock et al., 2012; Gustafsson and Nordberg, 2000; Moodley and Hess, 1992). This variety of responses and adaptations makes benthic foraminifera valuable proxies in the historical records of marine hypoxia (Gooday et al., 2009 and references therein).

Frequent periods of stagnation and severe seasonal hypoxia became characteristic features in Gullmar Fjord during the second part of the 20th century (Nordberg et al., 2009 and references therein). In 1979/80 a sudden faunal change took place in the deep basin after a first recorded severe hypoxic event (Filipsson and Nordberg, 2004; Nordberg et al., 2000). During the winter of 1979 the deep-water exchange in the Gullmar Fjord almost failed to occur and caused oxygen concentrations to fall to ≤ 1 ml/l (45 μ M) at the end of the year. In January 1980 oxygen levels reached their lowest value of 0.21 ml/l (9 μ M) and all macrofauna died or disappeared (Josefson and Widbom, 1988). The meiofauna and especially the benthic foraminifera showed abrupt changes in faunal composition, diversity and abundance (Filipsson and Nordberg, 2004; Nordberg et al., 2000). The Skagerrak–Kattegat (S–K) foraminiferal faunas typical for the fjord until 1979/80 were replaced by *Stainforthia fusiformis*, an opportunistic species, often reported from environments with frequent coastal hypoxia (Alve, 1995, 2003; Filipsson and Nordberg, 2004; Nordberg et al., 2000). The objective of the current study is to add information on the variations of benthic foraminiferal faunas and hydrographical parameters in the study area over the last 10 years. We aimed to find out if foraminiferal Skagerrak–Kattegat fauna has been re-established in the Gullmar Fjord resulting from the more frequent water renewals during the last decade.

2. Study area

Gullmar Fjord is the largest and deepest silled fjord located in the Bohuslän province on the Swedish west coast. It has a sill at 42 m water depth and a maximum basin depth of 120 m. The modern studies dealing with fjord's hydrography are, among others, Arneborg (2004), Arneborg et al. (2004), Björk and Nordberg (2003) and Erlandsson et al. (2006). According to Arneborg (2004), the fjord's water column is stratified with respect to salinity and density into four layers:

- 1) A thin surface layer (<1 m) of mainly river water from the Örekilsälven, which does not influence the hydrography of the fjord in any significant way.
- 2) A second layer (24–27 psu) extends to 15 m and is primarily composed of brackish Baltic Sea water.
- 3) A third more saline (32–33 psu) layer occurs at 15–50 m water depths and is derived from the Skagerrak.
- 4) The fourth and deepest layer (>50 m) consist of Skagerrak intermediate water and is largely stagnant, with little seasonal variation in its salinity (34.4 psu on average). Temperature also shows little seasonal variation, although it may vary by 4°–8 °C between different years.

The residence times for the second and third layers are 20–38 days and 29–60 days, respectively (Arneborg, 2004), whereas the deepest layer has a residence time of approximately one year (Björk and Nordberg, 2003; Erlandsson et al., 2006; Nordberg et al., 2000). The deep-water exchange in the fjord largely depends on the wind forcing, and namely on wind direction and wind strength (Björk and Nordberg, 2003). The wind pattern, in turn, is governed by the North Atlantic Oscillation (NAO), which is the dominant mode of climate variability in the North Atlantic, especially during the winter season. The NAO index is calculated as a normalised sea level pressure difference between the Icelandic low and the Azores high (Hurrell, 1995). In Gullmar

Fjord, the higher frequencies and duration of NE winds, more common during the negative phase of the NAO, result in Ekman transport of surface water from the coast and facilitate coastal upwelling, which leads to the deep water exchange in the fjord (Björk and Nordberg, 2003). A positive NAO phase, in turn, causes stronger westerly winds, which prevent the deep-water renewals to occur. From the late 1970s the NAO has been in its prolonged positive phase and is believed to trigger severe seasonal hypoxia in the deep basin of Gullmar Fjord (Björk and Nordberg, 2003; Filipsson and Nordberg, 2004; Nordberg et al., 2000). Since 2005 the NAO winter index has returned to its less extreme values and in 2009 has entered its negative mode. Therefore it appears to be both important and interesting to study the consequences of this shift for the fjord's hydrography and benthic life.

3. Methods

In this study we analysed a 50-cm long sediment record from a ca. 200-cm-long gravity core GA113-091, taken at 116 m water depth in Gullmar Fjord (58° 17.57' N, 11° 23.06' E) by the R/V *Skagerrak* in September 2009. The most surficial sediment layer on top of G113-091 is likely missing because of the gravity coring, which is generally destructive for the uppermost unconsolidated sediments. In order to compensate for this gap and to extend the record of GA113-091 up to the present, an additional 50-cm long core G113-119A was taken at the same location in September 2011 using a Gemini corer, which allows recovering of the intact sediment surface.

Core GA113-091 was split in two halves and then sliced at 1 cm intervals to a depth of 19 cm and thereafter into 2 cm slices. All samples were weighed and freeze-dried and their water content was determined. Foraminiferal samples were washed over 63- μ m and 1-mm sieves and treated with sodiumdiphosphate ($\text{Na}_2\text{P}_2\text{O}_7$), where necessary, in order to disintegrate sediment aggregates, mostly present as faecal pellets. The size fraction of >63 μ m was dried at 40 °C and weighed in order to obtain an estimate of the sand content (%). The foraminifera-rich samples were split and at least 300 specimens (total fauna) were counted in each sample from the dried >63 μ m fraction; 27 samples were analysed. The uppermost 0–7 cm (8 samples) of the Gemini core were prepared and analysed for benthic foraminifera following the same procedure as for the core G113-091. An additional surface (0–1 cm) sample was taken during the sampling in 2011 in order to evaluate the living foraminiferal faunas. The sample was preserved in ethanol, stained by Rose Bengal and prepared for foraminiferal analysis following the same procedure as above. The living (stained) faunas were counted in order to check that they resembled the faunal composition of thanatocoenosis.

Both relative (%) and absolute abundances (ind./g dry sed.) for various benthic species were noted and species numbers per sample were used to represent the so-called species richness. The diversity indices Fisher alpha, Shannon-Wiener and rarefaction ES (100) as well as species dominance were calculated using the software PAST (Hammer et al., 2001). The dominance usually ranges from 0 (all taxa are equally present) to 1 (on taxon dominates community completely) and is calculated as: dominance = 1–Simpson index (Hammer, 2012). The Fisher-alpha and Shannon-Wiener diversity indices are commonly used in benthic ecology but have a disadvantage of being dependant on sample size. The rarefaction index, in contrast, is less size dependant and is calculated as an expected number of species (ES) among certain number of specimens, e.g. of 100 specimens (ES100) as used in this study.

The gap of approximately 2 cm on top of G113-091 was suggested based on the fairly good correlation between foraminiferal $\delta^{13}\text{C}$ values in cores G113-091 and GA113-119A (Fig. 2). It is likely that these two missing centimetres correspond to ca. 2 years, since previous studies showed that sediment cores from the deepest fjord have accumulation rates of 0.7–0.9 cm/yr depending on a used sampling gear (Filipsson and Nordberg, 2004: Tables 1–2). It was done based on ^{210}Pb dating, which is known to have a marginal error of 0–5 years (Binford, 1990).

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