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Reviewer 1.

General comments:

- The first part of the MS (Introduction and Study area) is well written. However, the information relative to the figures 2 and 3 result to be redundant for the paper. Although the data presented in both figures might represent a good background of the study area, they are not discussed in the article. I may suggest shortening this part and put the figures 2 and 3 as supplementary materials.

Reply: We have considered the reviewer's comment, and decided to keep the Figures 2 and 3 in the paper. Indeed, the water stratification in the Öresund is rather unusual as compared to other coastal regions, and both figures give important keys to picture the system. Figure 3 shows the seasonal variability of salinity, temperature, pH, oxygen and dissolved inorganic nitrogen in the Öresund, and Figure 2 shows the two layers stratification at the site during our specific sampling time. We think both figures are necessary to understand the complex environmental settings of the area, and to better understand the discussion that follows. We have however shortened the study site section to make it clearer.

- A concern reading the paper is how the authors have identified the 5 different foraminiferal zones along the sedimentary record. The frame of the discussion is based on that. As mentioned in materials and methods, they used a constrained Cluster Analysis (CA) using the Morisita's index. The relative dendrogram based on the arithmetic average (with the UPGMA) seems to be consist, however the final attribution into three foraminiferal zones separated in 5 subzones is totally no sense. The choice of the final clusters can be made by two ways: 1) "expert judgement" and 2) statistical significance. I believe in this case the Authors' choice was based on the first one (if it is not the case the Authors should explain that). What we can clearly see from the dendrogram is that there are two main clusters: Cluster 1 including samples from 36 to 4 and Cluster 2 including samples from 1 to 2. Secondary Cluster 1 can be divided in two subclusters: 1a from 36 to 18 and 1b from 17 to 4. Consequently the interpretation of the CA (made by the Authors) is not consistent. I suggested to revise this part proposing a different interpretation of the CA or another alternative statistical analysis. In any case the discussion should be rearranged accordingly.

Reply: The choice of final clusters was first based on statistical significance from the cluster analysis to differentiate the three main zones: FOR-A (36-18), FOR-B (17-4) and FOR-C (2-1). These three main zones are clearly displayed in the dendrogram on Figure 6. The sub-clusters were then chosen not only based on the cluster analysis, but also based on the factors from the correspondence analysis. These factors are shown on the Figure 5. Combined together, the two statistical analyses allow us to suggest 5 different sub-zones in our foraminiferal record: FOR-A1 (36-30), FOR-A2 (28-18), FOR-B1 (17-8), FOR-B2 (6-4) and FOR-C (2-1). We have now clarified in the results section how the 5 foraminiferal zones were determined in our study.

- Normally, the results of abiotic parameters are shown before the biotic parameters because faunal distributions are dependent (or not) on them. In this study is not the case. I suggest to describe before environmental parameters and then the foraminiferal assemblages.

Reply: We agree with the reviewer that abiotic parameters are often presented before the faunal data in foraminiferal papers. However, we think that foraminiferal data in our study are the most important result compared to other parameters. Moreover, we organised the results and discussion sections based on the foraminiferal zones, starting from the oldest zone FOR-A1. In this first zone, abiotic data were not available for all centimeters, and only the faunal data can be fully discussed. Thus, in our study we have chosen to present the faunal data before the environment parameters.

- The discussions are sometimes not persuasive. I personally respected the fact that the discussions are very detailed and sharp but sometime the data do not support your statements. In some cases these statements are contradictory. I found that some considerations are too speculative, especially concerning the human interactions. I suggest to reconsider some of them. Look into specific comments.

Reply: We have revised the discussion part while keeping the suggestions of the reviewer in mind, and we have modified some statements. We think that the discussion is now clearer and more accurate.

Minor comments:

Line 11: Replace “foraminiferal” with “foraminifera”.
Reply: done.

Line 23: The largest changes occurred.. in? from? 1950
Reply: This was modified.

Line 25: The authors may think to replace Elphidium group to Elphididae.
Reply: We changed *Elphidium* group into *Elphidium* species in the whole text. As most of the time we precise which *Elphidium* species we are talking about, we think the world Elphidiidae would be confusing for the reader.

Line 26: Replace “more sandy” to “sandier”.
Reply: done.

Line 28: I am not sure in the abstract acronyms or abbreviations are accepted. Please check it.

Reply: The NAO index is now spelled out.

Line 31-33: I suggest to rephrase this sentence or split in twice.
Reply: The sentence in the abstract was split in two shorter sentences.

Line 32: get rid “species” and keep only “foraminiferal assemblage”.
Reply: done.

Line 43-45: “The region is…Baltic Sea”. Please add a reference for this statement.
Reply: done.

Line 70: I think you can add more recent references than Sen Gupta 1999.
Reply: We have added references.

Line 77: Get rid “analysis”.
Reply: done.

Line 76-79: The Authors may think to slightly rephrase adding “The objective of this study…”
Reply: We have rephrased this sentence as suggested.

Line 84: I think the “-“ between 1948 and 2013 is too long.
Reply: This was modified.

Line 90: Replace “;” with “.”.
Reply: done.

Line 109: Replace “In” with “At”.
Reply: done

Line124: Please specify in the brackets what is CTD.
Reply: done.

Line 126-129: “The CTD…bottom water”. I do not see the interest of using these data, already published. In any case this part has to be moved to the section study area or results.
Reply: This section was deleted as it is indeed already discussed in Charrieau et al (2018).

Line 150: I suggest to get rid this sentence because you did not strictly follow Murray 2006 (very general work). In addition you explain just after the sample preparation.
Reply: This sentence was deleted.

Line 153-154: Why 100-500 µm? In benthic foraminiferal studies the common fraction is >63 µm. Is there any specific reasons? Can the Authors justify that?
Reply: In this study, the foraminiferal data from the core tops come from previously published data in Charrieau et al. (2018). The authors chose to use the size fraction >100 µm to be able to compare their results with other studies from the same area (e.g. Conradsen et al. 1993; 1994). Thus, in this study we chose the >100 µm fraction to stay coherent with their method and to be able to use those data.

Line 154-156: I think you should specify how many samples you finally have (22 right?).

Reply: 22 samples were indeed analysed, we added this information in the method section.

Line 156: Why 300 specimens? Is there any reasons of that?

Reply: 300 specimens is the number of picked foraminifera recommended by Patterson and Fishbein (1989) in order to identify the species comprising 10 % or more of an assemblage. We clarified this in the method section.

Line 180-181: This is not clear. From this sentence the readers understand that you are dealing (in the first two centimetres) with living fauna. This is not the case. Please get rid this sentence or correct it.

Reply: The sentence was clarified.

Line 187-188: I think you should mention here that you calculated the Shannon Diversity as well.

Reply: We thank the reviewer for this suggestion and we have added a sentence about the Shannon diversity in the method section.

Line 190: You should detail the formula of the Morisita's index as you did for the FAR. In benthic foraminiferal studies this index is not so common.

Reply: The Morisita index is an index of similarity recommended for quantitative data because it is not greatly affected by sample size. This index is routinely used in ecological studies, but we think that giving the rather complex formula is not necessary in this case. Instead, we have added a reference in the method section where the Morisita index is described, for the readers willing to get more details about our statistical analysis.

Line 221: You should add the meaning of NOA.

Reply: NAO (North Atlantic Oscillation) is now spelled out.

Line 240-241: Add the percentage of porcelaneous (x), hyalin (x) and agglutinated (x).

Reply: done

Line 243-246: For this part please refer to the comments aforementioned.

Reply: This section of the text about the cluster analysis was modified accordingly.

Line 347-348: I disagree with this sentence. Low foraminiferal diversity can be due to many reasons and not only salinity. Although in brackish environments (and generally in transitional environments) foraminiferal density is low, this is linked to many factors. Amongst these, for instance the fact that these environments are naturally stressed (rapid changing of physical-chemical parameters) is a major one.

Reply: We thank the reviewer for this remark. The sentence was modified to qualify the role of salinity in foraminiferal densities.

Line 352: Please add the unit for salinity.

Reply: : Even if several units can be used when discussing salinity, most of researchers recommend to not use any unit, as salinity is a conductivity ratio (see any oceanography text book). We prefer to follow that recommendation.

Line 352: As far as I know salinity in brackish water is 0.5-30 ‰. If it is so, the fact that you found typical brackish species (tolerant to low salinity) in this interval is definitely in the contrast with this sentence. Please clarify it. I agree with you about low oxygen conditions but affirming that "salinity was about 30" is not so persuasive.

Reply: The fact that there were brackish water tolerant species in this zone, combined with the fact that *B. marginata* (typical marine species) was absent, suggest brackish water on this period. We agree with the reviewer that the salinity of brackish water can be between 0.5 and 30. However, the salinity couldn't have been too low, as some species that do not tolerate very low salinities, like *N. labradorica* and *S. fusiformis*, were also found. The salinity was then probably around 30, which is still in the brackish conditions range. We have clarified this sentence is the discussion section.

Line 359: Again here saying that low diversity is "usually" link to salinity, needs a better explanation.

Reply: We have modified this sentence.

Line 360: "However… least 32". Please can you make a reference for this statement?

Reply: A reference was added.

Line 362-374: I do not see from your data how you can have evidence of pollution in this interval. The only evidence you have is that "TOC was high in this interval but not higher than in the previous zone". So how can you speculate so? Based on foraminiferal diversity and abundance? I think you should have more evidence than that. In the previous interval diversities are even lower. This part is not persuasive at all.

Reply: In this part of the discussion, we want to understand the reasons for the low foraminiferal BFAR and diversity. Based on previous studies in the area, we know that pollution increased considerably in various ways during this period, which could be an explanation for water properties changes such as carbonate chemistry and pH. It is known that in general, pollution has a negative effect on foraminifera. Moreover, some pollution-tolerant species were found, such as *E. medius/scabrus*. This is also supported by the highest number of organic linings found during this period, compared to the rest of the record. Thus, we have considered pollution as a possible explanation for the low foraminiferal abundance and diversity during this period. We have clarified this in the text and added references in the discussion section.

Line 370: I think you can use a better and more recent reference than this.

Reply: We now have added references.

Line 372-374: From Table 2 *R. subfusiformis* is tolerant to environmental variations not to various kind of pollution. Then what does it means? A lot of foraminifera are tolerant to environmental variations. This is a very general statement and do not support this part of the discussion.

Reply: We have added information on the Table 2.

Line 390-393: Sorry but I do not see how you can state this. How has the increase of organic matter been beneficial for foraminifera? All foraminiferal species had a shutdown after 1980. Could the authors explain that or modify this statement?

Reply: This statement refers to the important changes at the beginning of this period, before ~1980. The increase in nutrient loads may have provided food for the foraminifera. In a second time, after ~1980, the measures taken in water treatment to reduce nutrient discharge are a possible cause of the lower growth rates. These two periods are now clarified in the text.

Line 416-418. This is totally in contrast with the statement in 390-393. You said that there was an increase of nutrients loadings after 1980 and now you state that in the same period measures were taken to reduce nutrients discharges. I think you must clarify all this part concern human impact. Not clear at all.

Reply: As said above, this period can be divided in two parts. The paragraph was modified, and therefore the statement is no longer in conflict.

430: “since after” Since or after?

Reply: This sentence now reads “The species is also present on the south coast of Norway since ~ 2009”.

436: Why open ocean salinity? Elphidium group includes typical brackish species (line 350). This in the contrast with this last statement. Please clarify.

Reply: We agreed that the Elphidium species are often found in brackish water. However, as showed on the Table 2, they can tolerate a wide range of salinities, including open-ocean salinity. Moreover, the presence of marine species such as *B. marginata* suggest high salinity during this period. We added this information in the discussion section.

Figures:

Figure 1: The contours have a low definition. It is possible to have higher quality picture?

Reply: The quality of the Figure 1 has now been improved.

Figure 2-3: Look the aforementioned comments. In addition data from figure 2 have been published before by Laurie M. Charrieau et al. 2018. Figure 3 is not totally clear; it shows seasonal variations of several parameters based on uncertain measurements from 1956. It does not show any variation along the fossil record. I am sorry but I do not see how it can support the study.

Reply: As said above, we have decided to keep the Figures 2 and 3 to help the reader to fully understand the complex system in the Öresund. The data of the Figure 3 are annual water measurements from the SMHI (Swedish Meteorological and Hydrological Institute) between 1965 and 2016, which were compiled to give the best overview of the seasonal variability in the area.

Figure 5: Is useful to show both relative and absolute abundance?

Reply: The relative abundances allow us to compare the development of the major species along each zone. However, the graph alone could give the wrong impression regarding the absolute abundances, which can be extremely different between the species. We then have decided to show both relative and absolute abundances in the Figure 5.

Figure 6 The subcluster are not marked. FOR-B and FOR-C are subclusters.

Reply: The dendrogram on the Figure 6 shows the three main zones FOR-A, FOR-B and FOR-C. As we explain above, the sub-clusters were then determined not only based on the cluster analysis, but also on the correspondence analysis. Thus, we chose to not report the sub-clusters on the Figure 6 to avoid confusion in the choice of foraminiferal zones. This was clarified in the results section.

Figure 8-9. Why now did you invert the order of the axes? I think I could be easier for the readers to keep always the same orientation.

Reply: By reversing the axis on Figure 9 (C), it is easier to visualize the trends of BFAR, sand content and UAV in the Kattegat, while keeping the same information than on Figure 8.

Maybe the authors may think to add a synthetic picture with the main parameters used for the reconstruction. I think this could help the readers to better follow the discussions and the final conclusions.

Reply: In Figure 9, the BFAR represents the foraminifera, the sand content represents the sedimentology, and they are both compared with the water currents, wind model, and NAO index. We think that the Figure 9 is already a good synthesis of the paper, and it can be used by the reader to follow the key changes in our reconstruction of the environmental changes in the area.

We would like to thank Reviewer 1 for the insightful and helpful comments that we think have significantly improved our manuscript.

Kind regards,

Laurie M. Charrieau, on behalf of the authors: Karl Ljung, Frederik Schenk, Ute Daewel, Emma Kritzberg and Helena L. Filipsson.

Faculty of Science
Department of Geology
Dr Laurie M. Charrieau

Reviewer 2.

General comments:

It would be good to include a discussion about the sedimentology in the area. For examples, how can you be confident that the coarser sandier part in the top of the core is not part of a natural succession of a migrating bar? Were any duplicate cores takes from the wider area that show the same feature? Is there any other data from 1870-1953 interval that provides evidence for pollution (e.g. trace metals in benthic foraminifera for examples?)

Reply: It is challenging to obtain sediment cores in the Öresund, due to limited sediment deposition areas and high current velocities. Therefore, cores from the wider area are not available for comparison with our core. As for the migrating bar, we do not have any evidence suggesting such phenomena in the area. We have now modified the discussion and added references to support the pollution suggestion during the period 1870-1953.

Minor comments:

- freeze drying of sediments poses a risk of losing more fragile foraminifera, including organic walled specimens,

Reply: We agree with the reviewer that freeze-drying sediment can cause loss of some of the most fragile specimens. However, the freeze-drying process was probably not a major problem for the general faunal distribution. Moreover, we found organic linings of foraminifera in our sediment. These organic linings were found undamaged, even though they could easily be broken by manipulating them with a brush. Thus, we think that the risk of losing fragile forms was minimum in our samples.

- lines 323-330: from figure 8 it seems that there are periods with high and low VAV, but there does not seem to be a direct response within the assemblage of FOR-B2,

Reply: In our interpretation, the UAV was one of the most important factors to explain the foraminiferal assemblage, as showed in Figure 9. However, the resolution of our sub-sampling for foraminifera and sedimentological parameters limit the possibility to accurately resolve very short events, such as those in the topmost part of the VAV reconstruction.

- could the higher accumulation rates (figure 4) be partially related to the top 10 cm being less compacted (and dense) compared with further downcore in the sediments?

Reply: We agree with the reviewer that less compact sediment in the top part of the sediment sequence is contributing to the higher sedimentation rate on this section.

We would like to thank Reviewer 2 for the insightful and helpful comments that we think have significantly improved our manuscript.

Kind regards,

Laurie M. Charrieau, on behalf of the authors: Karl Ljung, Frederik Schenk, Ute Daewel, Emma Kritzberg and Helena L. Filipsson.

Rapid environmental responses to climate-induced hydrographic changes in the Baltic Sea entrance

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Key-words: benthic foraminifera; NAO index; environmental reconstruction; Anthropocene; Öresund

Abstract

The Öresund (the Sound), which is a part of the Danish straits, is linking the marine North Sea and the brackish Baltic Sea. It is a transition zone where ecosystems are subjected to large gradients in terms of salinity, temperature, carbonate chemistry, and dissolved oxygen concentration. In addition to the highly variable environmental conditions, the area is responding to anthropogenic disturbances in e.g. nutrient loading, temperature, and pH. We have reconstructed environmental changes in the Öresund during the last c. 200 years, and especially dissolved oxygen concentration, salinity, organic matter content, and pollution levels, using benthic foraminifera and sediment geochemistry. Five zones with characteristic foraminiferal assemblages were identified, each reflecting the environmental conditions for respective period.

The largest changes occurred around 1950, when the foraminiferal assemblage shifted from a low diversity fauna, dominated by the species *Stainforthia fusiformis* to higher diversity and abundance, and dominance of the *Elphidium* species. Concurrently, the grain-size distribution shifted from clayey — to sandier sediment. To explore the causes for the environmental changes, we used time-series of reconstructed wind conditions coupled with large-scale climate variations as recorded by the North Atlantic Oscillation (NAO) index, as well as the ECOSMO II model of currents in the Öresund area. The results indicate increased changes in the water circulation towards stronger currents in the area after the 1950's. The foraminiferal fauna responded quickly (< 10 years) to the environmental changes. Notably, when the wind conditions, and thereby the current system, returned in the 1980's to the previous pattern, the foraminiferal assemblage did not rebound. Instead, the foraminiferal faunas displayed a new equilibrium state.

1 – Introduction

The Öresund (the Sound) is one part of the Danish straits between Sweden and Denmark. Together with the Great — and Little Belt, they link the open-ocean waters of the North Sea and the brackish waters of the Baltic Sea. The confluence of the water masses creates a north-south gradient as well as a strong vertical stratification of the water in terms of salinity, carbonate chemistry and dissolved oxygen concentration ([O_2]) (Leppäranta and Myrberg 2009). The depth of the halocline mainly depends of the outflows from the Baltic Sea; a strong thermocline develops during spring and summer, which further strengthens the vertical stratification. Thus, the ecosystems in the Öresund are exposed — and adapted — to a unique transitional environment. The region is also characterized by intense human activities, with 4 million people living in the vicinity of the Öresund and 85 million people living in the catchment area of the Baltic Sea (HELCOM, 2009). Discharge from agriculture, industry, and urban areas on both the

Swedish and Danish sides of the strait, and the considerable impact of marine traffic – the strait is one of the busiest waterways in the world – generate pollution and eutrophication of the water (HELCOM 2009; ICES 2010). Since the 1980's, the implementation of efficient wastewater treatment and measures in agriculture contributed to markedly reduce the amount of nutrients coming from river run-off (Nausch et al. 1999; Carstensen et al. 2006; Rydberg et al. 2006). However, these efforts in decreasing nutrient loads have not resulted in improved water quality, due to the long time scales of biogeochemical cycles to reach equilibrium in the Baltic Sea region (Gustafsson et al. 2012). The Öresund, like most of the Baltic Sea, is still assessed to be eutrophic, and hypoxic events are frequent (Rosenberg et al. 1996; Conley et al. 2007, 2011; HELCOM 2009; Wesslander et al. 2016). Moreover, increasing temperatures and declining pH, linked to global climate change and ocean acidification, have been reported for surface and bottom waters in the area (Andersson et al. 2008; Göransson 2017). As a result, ecosystems in the Öresund are currently under the combined impact of natural and anthropogenic stressors (Henriksson 1969; Göransson et al. 2002; HELCOM 2009; ICES 2010). The multiple stressors currently affecting the environment make this region particularly interesting to study, and also highlight the need to obtain records of decadal and centennial environmental changes. As noted above, both recent human-induced impacts and climate variability have been substantial in the region. Therefore the question arises whether these factors have affected the benthic environment. Furthermore, sediment records of past environmental changes can provide crucial context for ongoing and future predicted changes in the Öresund and Baltic Sea regions.

We used the marine sediment record and its contents of foraminifera as well as sediment geochemistry to obtain records of decadal environmental changes. Benthic foraminifera are widely used for environmental reconstructions, based on their rapid response to environmental changes, broad distribution, high densities, and often well-preserved tests (shells) in the sediment (e.g. Sen Gupta 1999b; Murray 2006). For instance, distribution of benthic foraminifera have been used for historical environmental reconstructions of fjords on decadal to centennial timescales on the Swedish west coast (Nordberg et al. 2000; Filipsson and Nordberg 2004a, 2004b; Polovodova Asteman and Nordberg 2013; Polovodova Asteman et al. 2015), and in the Kattegat (Seidenkrantz 1993; Christiansen et al. 1996). In the Öresund, living foraminiferal assemblages have been studied (Hansen 1965; Charrieau et al. 2018), but to the best of our knowledge, no studies of past foraminiferal assemblages have been performed. The objective of this study was to reconstruct the environmental conditions of benthic systems during the last two centuries in the Öresund, by using foraminiferal fauna analysis in combination with sediment geochemistry and grain-size. Furthermore, we analyzed long time series of wind conditions in the area to evaluate the coupling between local changes in ecosystem variables and variations in atmospheric and subsequent hydrographic conditions, and a possible link with large-scale variations expressed through the North Atlantic Oscillation (NAO) index. Finally, we compared our data with the model ECOSMO II (Daewel and Schrum 2013; 2017) of currents and water circulation changes in the Öresund area during the period 1948—2013.

2 – Study site

The Öresund is a 118 km long narrow strait (Figure 1). The water depth in the northern part is on average 24 m but it reaches 53 m south of the Island of Ven. The Öresund is an important link between the North Sea, Skagerrak, Kattegat and the Baltic Sea (Figure 1), and up to 30 % of the water exchange in the region goes through the Öresund (Sayin and Krauß 1996; Leppäranta and Myrberg 2009). The remaining part goes through the Great and Little Belt. The width of the Öresund varies between 4 and 28 km, and the water has overall high current velocities, up to 1.5

m.s^{-1} at the upper water layer in the northern part (Nielsen 2001). The fully marine Skagerrak consists of water masses from the North Sea and the North Atlantic and in general a thin surface layer with water originating from the Baltic Sea and rivers draining into the sea; the water circulation forms a cyclonic gyre (cf. Erbs-Hansen et al. 2012). Part of the Skagerrak waters reach the Kattegat and the Baltic Sea, where they are successively diluted with the large amounts of freshwater (around 15,000 m^3/s, Bergström and Carlsson 1994) draining into the Baltic Sea from numerous large rivers. The low-saline Baltic Sea surface water is transported by the Baltic Current, which is typically confined along the Swedish west coast in the Kattegat but may cover a larger surface area towards the west, depending on wind direction. The Baltic Current later joins the Norwegian Coastal Current in the Skagerrak (Figure 1). The large fresh water input and the subsequent large salinity difference between the Kattegat and Baltic Sea result in a two-layer structure in the Öresund (Figure 2) (She et al. 2007; Leppäranta and Myrberg 2009). The water stratification is influenced by the surface water from Arkona Basin (salinity 7.5—8.5), the surface water from the Kattegat upper layer (salinity 18—26) and the lower layer of the Kattegat (salinity 32—34).

Salinity, temperature, pH, [O_2] and nutrient content, here represented by dissolved inorganic nitrogen concentration [DIN] (nitrate + nitrite + ammonium), in the surface and bottom waters of the Öresund vary seasonally (Figure 3, Appendix A). At the surface and bottom water, salinity ranges between ~8 and ~18 and between ~29 and ~34, respectively, and it is more stable between April and July, when the stratification is the strongest (Figure 3). Temperature ranges between ~1 °C in February and ~19 °C in July in the surface water, while in the bottom water, the lowest temperature is found in March—April with ~5° C, and the highest temperature in October—November with ~13 °C. The pH varies between ~8.1 and ~8.6 in the surface water, and between

~7.8 and ~8.6 in the bottom water, without a clear seasonal pattern (Figure 3). [O_2] in the bottom water reaches ~7 mL.L^{-1} in January, and it is typically below 2 mL.L^{-1} in October, approaching hypoxic values. In the surface water, [DIN] can reach ~7 µmol.L^{-1} in January, and it is ~0 µmol.L^{-1} between April and August (Figure 3).

3 – Materials and Methods

3.1 Sampling

A suite of sediment cores, as well as water samples from the water column, were collected in November 2013 during a cruise with r/v *Skagerak*. Here we present the data from two sediment cores sampled at the Öresund station DV-1 (55°55.59' N, 12°42.66' E) (Figure 1), north of the Island of Ven. The water depth was 45 m, and CTD (Conductivity, Temperature, Depth) casts were taken to measure salinity, temperature and [O_2] in the water column. Water samples were collected at 10, 15, 20, 30 and 43 m from the Niskin bottles for carbonate chemistry analyses. The CTD and carbonate chemistry data are presented in Charrieau et al. (2018). In general, it is challenging to obtain sediment cores in the Öresund, due to the high current velocities up to 1.5 m.s^{-1} (Nielsen 2001), human-induced disturbances, and limited areas of recent sediment deposition (Lumborg 2005), but our site north of Ven represents an accumulation area. The cores (9-cm-inner-diameter) were collected using a GEMAX twin barrel corer. The corer allowed sampling of 30 and 36 cm long sediment cores (referred in this study as core DV1-G and DV1-I, respectively), which were sliced into one centimeter sections. The samples from the DV1-G core were analyzed for carbon and nitrogen content, grain size distribution, and dated using Gamma spectroscopy. The samples from the DV1-I core were analyzed with respect to foraminiferal fauna and carbon and nitrogen content. The distinct carbon content profiles, measured on both cores, were used to correlate the ^{210}Pb dated DV1-G core to the DV1-I core used for foraminiferal analyses.

3.2 Chronology

The age-depth model was established using ^{210}Pb and ^{137}Cs techniques on samples from the DV1-G core. The samples were measured with an ORTEC HPGe (High-Purity Germanium) Gamma Detector at the Department of Geology at Lund University, Sweden. Corrections for self-absorption were made for ^{210}Pb following Cutshall et al. (1983). The instruments were calibrated against in-house standards and the maximum error was 0.5 year in the measurements. Excess (unsupported) ^{210}Pb was measured down to 23 cm and the age model was calculated based on the Constant Rate of ^{210}Pb Supply (CRS) model (Appleby 2001).

3.3 Foraminifera analyses

Approximately 10 g of freeze-dried sediment per sample were wet sieved thought a 63-µm mesh screen and dried on filter paper at room temperature. Subsequently, the samples were dried sieved through 100- and 500-µm mesh screens and separated into the fractions 100-500 µm and >500 µm. The foraminifera from every second centimeter of the core - plus from additional centimeters around key zones - were picked and sorted under a Nikon microscope (22 samples in total). A minimum of 300 specimens per sample were picked and identified, as recommended by Patterson and Fishbein (1989). If necessary the samples were split with an Otto splitter (Otto 1933). For taxonomy at the genus level, we mainly followed Loeblich and Tappan (1964) with some updates from more recent literature, e.g. Tappan and Loeblich (1988). For taxonomy at the species level, we mainly used Feyling-Hanssen (1964), Feyling-Hanssen et al. (1971) and

Murray and Alve (2011). For original descriptions of the species, see Ellis and Messina (1940 and supplements up to 2013).

Recently, the eastern Pacific morphospecies *Nonionella stella* has been presented as an invasive species in the Skagerrak-Kattegat region (Polovodova Asteman and Schönfeld 2015). However, a comparison of *N. stella* DNA sequences from the Santa Barbara Basin (USA) (Bernhard et al. 1997) with the Swedish west coast specimens demonstrates that they represent two closely related species but are not conspecific (Deldicq et al. in press). Therefore, we have referred to the species found here as *Nonionella* sp. T1, following Deldicq et al. (2019). The species *Verneuilina media* (here referred to the genus *Eggerelloides*), which has often been reported in previous studies from the Skagerrak-Kattegat area (e.g. Conradsen et al. 1994), was morphologically close to *Eggerelloides scabrus* in the present material, and these two species have been grouped as *E. medius/scabrus*. The taxon *Elphidium excavatum* forma *clavata* (cf. Feyling-Hanssen 1972), was referred to as *Elphidium clavatum* following Darling et al. (2016). *Elphidium clavatum* and *Elphidium selseyense* (Heron-Allen and Earland) were morphologically difficult to separate in this region, as transitional forms occur. The dominant species was *E. clavatum*, but we acknowledge that a few individuals of *E. selseyense* could have been included in the counts. The taxon *Ammonia beccarii* was referred to as *Ammonia batava*, following recent molecular work done on the taxon *Ammonia* in the Kattegat region (Groeneveld et al. 2018; Bird et al. 2019)

Foraminiferal density was calculated and normalized to the number of specimens per 50 cm^3. Data of densities for the first two centimeters of the core are from Charrieau et al. (2018). Some specimens displayed decalcified tests, however the inner organic linings were preserved. These inner organic linings were reported separately and not included in the total foraminiferal counts. Benthic foraminiferal accumulation rates were calculated as follows:

BFAR (number of specimens.cm^{-2}.yr^{-1}) = BF x SAR,

where BF is the number of benthic foraminifera per cm^3 and SAR is the sediment accumulation rate (cm.yr^{-1}). Foraminiferal species that accounted for >5 % of the total fauna in at least one of the samples were considered as major species, and their density was used in statistical analysis. The Shannon index was calculated to describe the foraminiferal diversity. To determine foraminiferal zones, stratigraphically constrained cluster analysis was performed, using the size-independent Morisita's index to account for the large differences in the densities between samples (e.g. Krebs 1998). A dendrogram was then constructed based on arithmetic averages with the UPGMA method (Unweighted Pair Group Method with Arithmetic Mean). Correspondence analysis was also performed, to determine significant foraminiferal species in each zone. Statistical analyses were performed using the PAST software (Hammer et al. 2001).

3.4 Organic matter analyses

Total Organic Carbon (TOC) and Total Nitrogen (TN) content were measured for both DV1-G and DV1-I. Approximately 8 mg of freeze-dried sediment was homogenized for each centimeter and placed in silver capsules. Removal of inorganic carbon was carried out by in-situ acidification (2M HCl) method based on Brodie et al. (2011). TOC and TN content were analyzed on a Costech ECS 4010 Elemental Analyzer at the Department of Geology, Lund University. The instrument was calibrated against in-house standards. The analytical precisions showed a reproducibility of 0.2 % and 0.03 % for TOC and TN contents, respectively. The molar C/N ratio was calculated.

3.5 Grain-size analyses

Grain-size analyses were performed on core DV1-G using 3.5 to 5 g of freeze-dried sediment for each centimeter. Organic matter was removed by adding 15 mL of 30 % H_2O_2 and heating during 3 to 4 minutes until the reaction ceased. After the samples had cooled down, 10 mL of 10 % HCl was added to remove carbonates; thereafter the sediment was washed with milli-Q until its pH was neutral. In the last step, biogenic silica was removed by boiling the sediment in 100 mL 8 % NaOH, and then washed until neutral pH was reached. The sand fraction (>63 µm) was separated by sieving and the mass fraction of sand of each sample was calculated. Grain sizes <63 µm were analyzed by laser diffraction using a Sedigraph III Particle Size Analyzer at the Department of Geology, Lund University. The data were categorized into three size groups, <4 µm (clay), 4–63 µm (silt) and 63–2000 µm (sand).

3.6 Climate data and numerical modeling

Data from the dataset High Resolution Atmospheric Forcing Fields (HiResAFF) covering the time period 1850–2008 (Schenk and Zorita 2012; Schenk 2015) were used to study the variations of near-surface (10 m) wind conditions during the winter half of the year (October to March). The daily dataset can be downloaded from WDC Climate (Schenk 2017). Wind conditions over the Öresund are represented by the closest grid point of HiResAFF at 55° N and 12.5° E. The North Atlantic Oscillation (NAO) index as defined by Jones et al. (1997) for boreal winter (December to March) was used, with updates taken from the Climate Research Unit (CRU, https://crudata.uea.ac.uk/cru/data/nao/). To allow comparison, the NAO and wind data were normalized relative to the period 1850–2008. Changes in the currents through the Öresund and the Kattegat were taken from the fully coupled physical biogeochemical model ECOSMO II

(Daewel and Schrum 2013, 2017), which was forced by NCEP/NCAR reanalysis data and covers the period 1950–2013. On model ECOSMO II, the simulated South-North currents are represented as VAV (vertically averaged V- component) and the simulated West-East currents as UAV (vertically averaged U - component).

4 – Results

4.1 Age model

The unsupported ^{210}Pb showed a decreasing trend with depth in the DV1-G core (Figures 4A, 4B). The peak observed in the ^{137}Cs around 9 cm corresponds to the Chernobyl accident in 1986 (Figure 4C). The unsupported ^{210}Pb allowed direct dating of the core between 2013 and 1913. The sedimentation rate ranged between 1 and 5.6 mm.y^{-1}, with an average of 2.2 mm.y^{-1}, and was decreased with depth. The ages of the lower part of the sediment record were deduced by linear extrapolation based on a sedimentation rate of 1.4 mm.y^{-1}, corresponding to the linear mean sedimentation rate between the years 1913 and 1946 (Figure 4D).

4.2 Foraminiferal assemblages and sediment features

The foraminiferal assemblages were composed of 76 species from the porcelaneous, hyalines and agglutinated forms (0.3, 54.5 and 45.2 %, respectively) (Appendix B). Eleven foraminiferal species had relative abundance higher than 5 % in at least one sample and were considered as major species (Plate 1, Figure 5).

The cluster analysis revealed three main foraminiferal zones (FOR-A, FOR-B, and FOR-C) (Figures 5, 6). The correspondence analysis resulted in three factors explaining 92 % of the variance, and in assemblages consisting in seven significant species, presented in order of contribution: *Nonionella* sp. T1, *Nonionoides turgida*, *Ammonia batava*, *Stainforthia fusiformis*, *Elphidium albiumbilicatum*, *E. clavatum* and *Elphidium magellanicum* (Table 1). Based both on the cluster and the correspondence analyses, five subzones could be separated to which we assigned dates according to the age model: FOR-A1 (1807–1870), FOR-A2 (1870–1953), FOR-B1 (1953–1998), FOR-B2 (1998–2009), and FOR-C (2009–2013) (Figures 5, 6).

4.2.1 Zone FOR-A1 (1807–1870)

The foraminiferal accumulation rate (BFAR) was on average 5 ±3 specimens.cm^{-2}.y^{-1} in zone FOR-A1 (Figure 5). The Shannon index was stable and low, around 1.77 ±0.1 (Figure 5). The agglutinated species *Eggerelloides medius/scabrus* and the hyaline species *Stainforthia fusiformis* made major contributions to the assemblages (relative abundances up to 53 % and 34 %, respectively; Figure 5A). *Ammonia batava*, the three *Elphidium* species (*E. albiumbilicatum*, *E. clavatum*, and *E. magellanicum*), *Nonionellina labradorica* and the agglutinated species *Reophax subfusiformis* were also major species with abundances up to 7 %. The TOC and C/N values on this period were stable and were on average 3.36 % and 8.8 %, respectively (Figure 7). The clay size fraction dominated the sediment at the end of this period with a mean value of 63 %, and the sand content was around 7 % (Figure 7).

4.2.2 Zone FOR-A2 (1870–1953)

The BFAR was on average 9 ±5 specimens.cm^{-2}.y^{-1} in zone FOR-A2 (Figure 5). The Shannon index was stable and low, around 1.94 ±0.15 (Figure 5). *Stainforthia fusiformis* dominated the assemblage with relative abundances up to 56 % and BFAR up to 608 specimens.cm^{-2}.y^{-1} (Figures 5A, 5B), which is the highest BFAR observed for this species along the core. *Egerelloides medius/scabrus* was still very abundant, up to 48 % (Figure 5A). *Ammonia batava*, the three *Elphidium* species and *N. labradorica* were present but with lower abundances than in the zone FOR-A1 (maximum 5 %). *Bulimina marginata* started to be more abundant with an average relative abundance of 2 % in the zone. *Reophax subfusiformis* was still a part of the assemblage and ranged between 1 and 8 %. The TOC and C/N values were stable and were on average 3.5 % and 8.74 %, respectively (Figure 7). The clay size fraction dominated the sediment during this period with a mean value of 63 %, and the sand content was around 6 % (Figure 7).

4.2.3 Zone FOR-B1 (1953–1998)

The BFAR increased massively during the zone FOR-B1 with on average 54 ±31 specimens.cm^{-2}.y^{-1} and with a peak at 93 specimens.cm^{-2}.y^{-1} around 1965 (Figure 5). It is lower during the second part of the zone. The Shannon index was higher than in previous zones and it progressively increased towards the top of the zone (Shannon index average 2.34 ±0.3) (Figure 5). The highest BFAR along the core were observed for all the dominant species of the previous zone FOR-A2, except for *S. fusiformis* (Figure 5B). The zone was then also characterized by a drastic drop in the relative abundance of *S. fusiformis* from 31 to 2 % (Figure 5A). *Eggerrelloides medius/scabrus* gradually decreased in the zone, with relative abundances from 49 to 24 %. The highest relative abundance of *A. batava* for the entire record was in this zone but it was slowly decreasing as well, from 10 to 3 %. The *Elphidium* species were more abundant than in the FOR-A zones and their relative abundance was increasing, especially for *E. clavatum* (increasing up to 23 %). *Bulimina marginata*, *N. labradorica* and *R. subfusiformis* had a relative abundance between 2 and 6 %. A period of lower TOC values was observed during zone FOR-B1 between 1953 and 1981, with an average of 2.38 % (Figure 7). On the same period, the sand content showed a pronounced increase, with an average of 24 % (Figure 7).

4.2.4 Zone FOR-B2 (1998–2009)

In zone FOR-B2 the BFAR was still high, on average 55 ±6 specimens.cm^{-2}.y^{-1} (Figure 5). The Shannon index was high with an average of 2.8 ±0.2 (Figure 5). The dominant species in the zone were *E. clavatum* (up to 25 %) and *Eggerelloides medius/scabrus* (up to 15 %; Figure 5A). The other two *Elphidium* species reached their highest relative abundances over the core (up to 6 %). *Nonionella* sp. T1, which had not occurred in the record until now, appeared in this zone with a relative abundance of 1 %. *Nonionoides turgida*, which was present in very low abundances along the core, had a mean abundance of 1 % in the zone (Figure 6A). *Stainforthia fusiformis* was present with up to 9 % in relative abundance and a BFAR higher than in zone FOR-B1 (up to 570 specimens.cm^{-2}.y^{-1}). *Ammonia batava*, *B. marginata*, *N. labradorica*, and *R. subfusiformis* were present and ranged between 2 and 8 %. The TOC values were increasing, with on average 3.05 % (Figure 7). The sediment was dominated by the clay fraction that was increasing (mean value of 58 %), and the sand content was around 17 % (Figure 7).

4.2.5 Zone FOR-C (2009–2013)

The BFAR was lower than in previous zones FOR-B1 and FOR-B2, with on average 21 ±5 specimens.cm^{-2}.y^{-1} (Figure 5). The Shannon index was the highest during FOR-C (Shannon index average 2.93 ±0.07) (Figure 5). *Nonionella* sp. T1 was a dominant specie in the zone with a strong increase in relative abundance (from 1 to 14 %) and in BFAR (from 61 to 137 specimens.cm^{-2}.y^{-1}) (Figures 5A, 5B). *Elphidium clavatum* and *R. subfusiformis* were also dominant species with abundances up to 13%. *Nonionoides turgida* had its highest relative abundance and BFAR over the core during the zone, with up to 9 % and 342 specimens.cm^{-2}.y^{-1}, respectively (Figures 5A, 5B). *Eggerelloides medius/scabrus* had its lowest relative abundance over the core (up to 9 %). *Bulimina marginata*, the other two *Elphidium* species, *N. labradorica* and *S. fusiformis* were still present (between 1 and 6 %), while *Ammonia batava* was absent during the zone. The TOC and C/N values were on average 3.71 % and 8.17 %, respectively (Figure 7). The clay size fraction dominated the sediment with a mean value of 66 % and the sand fraction was 7 % (Figure 7).

4.2.6 Inner organic linings

Decalcified specimens were few and ranged between 0 and 4 specimens.cm^{-2}.y^{-}1 with an average of 1 specimen.cm^{-2}.y^{-1} (Fig. 5). They were observed throughout the core and especially during zone FOR-B2, and the morphology of the remaining inner organic linings allowed the identification of the taxon *Ammonia* (Plate 1).

4.3 Simulated data from model ECOSMO II

The VAV (vertically averaged South-North current velocity) through the Öresund from the model ECOSMO II showed a reversed pattern compared to the UAV (vertically averaged West-East current velocity) through the Kattegat (Figure 8). Thus, higher VAV through the Öresund translates to an increase in the East to West flow in the Kattegat (lower UAV), suggesting a stronger outflow from the Baltic Sea. The VAV through the Öresund had the lowest values around 1955 (Figure 8), followed by a shift to very high values, which dominated throughout 1960–70. A comparable period with increased outflow from the Baltic into the Kattegat re-occurred during the period 1993–2000.

5 – Discussion

Our environmental interpretations of the foraminiferal assemblages were based on the ecological characteristics of each major species (Table 2). Based on our environmental reconstructions, we could infer environmental changes regarding [O_2], salinity, organic matter content, and pollution levels. Furthermore, we linked local environmental changes to larger atmospheric and hydrographic conditions.

5.1 1807 – 1870

All the major species found in this period are tolerant to low oxygen conditions, especially the two main species: *S. fusiformis* and *E. medius/scabrus* (Table 2). *Stainforthia fusiformis* is an opportunistic species used to hypoxic and potentially anoxic conditions (Alve 1994), and *E. medius/scabrus* specimens have been found alive down to 10 cm in the sediment, where no oxygen was available (Cesbron et al. 2016). *Stainforthia fusiformis* and *N. labradorica* are also able to denitrify (Piña-Ochoa et al. 2010). The fact that species tolerant to low oxygen conditions dominated, and the presence of species that have the capacity to denitrify, suggest that low oxygen conditions were prevailing during this period. Furthermore, *S. fusiformis* prefers organic rich substrate and clayey sediment, which was measured in our core during this time period (Figure 7). The low species diversity, as indicated by the low Shannon index in this section of the core, can sometimes be linked with low salinity (Sen Gupta 1999a). Most of the major species found during this period, such as the *Elphidium* species, *R. subfusiformis* and *A. batava* tolerate lower salinities, and are typical of brackish environments (Table 2). The low occurrence of *B. marginata*, a typical marine species, also suggests a salinity lower than in the open ocean. However, the salinity was probably not below ~ 30, which is the lower limit for *N. labradorica* and *S. fusiformis*, which were present throughout the period (Figure 5, Table 2). In summary, this period appears to have been characterized by low [O_2], high organic matter content, and salinity around 30.

5.2 1870 – 1953

Stainforthia fusiformis was largely dominating the assemblage during this period, which may suggest even lower oxygen conditions than during the previous period. This would also go along with the low species diversity, which is sometimes linked to low salinity. In the Öresund, low salinity can be caused by less influence of more saline marine waters from the Kattegat, and changes in the water transport through the strait is a possible explanation for both lower salinity and oxygen levels. However, the occurrence of the marine species *B. marginata* suggests that the salinity was at least ~ 30 (Table 2). Low oxygen can also be associated with high organic matter contents, since oxygen is consumed during remineralization of organic matter. However, the TOC levels observed in our core in this zone were high, but not higher than in the previous zone (Figure 7). At the time of the industrial revolution, the Öresund, as the Baltic Sea in general, was used as a sewage recipient for a mixture of domestic and industrial wastes, industrial cooling water and drainage water (Henriksson 1968), and the amount of marine traffic increased considerably during this time period. Across the Baltic Sea, this notably caused increased deposition of heavy metals (Borg and Jonsson 1996). This diverse type of pollution could have modified the water properties, for example regarding the carbonate chemistry and pH. Indeed, this zone is characterized by the presence of organic linings in the core (see also section 5.6). Moreover, heavy metals, fuel ash (black carbon) and pesticides have been demonstrated to generally have a negative effect on foraminiferal abundance and diversity (Yanko et al 1999; Geslin et al. 2002). Pollution and low oxygen concentration could explain the low species BFAR and diversity as well as the dissolution of tests during this period. Some species that were present, i.e. the agglutinated species *E. medius/scabrous* and *R. subfusiformis*, are known to be tolerant to various kind of pollution (Table 2).

5.3 1953 – 1998

The large increase in general BFAR from 1953 suggests either more favorable growth conditions or significant deposition of transported specimens into the area. The coarser grain size observed during this period indicates possible changes in the current system, which could affect both growing conditions and transport of specimens (Figure 7). However, the dating of our core showed continuous sediment accumulation without any interruption during this period (Figure 4). Moreover, all the new dominating species were already present in the core, even if in lower relative abundances (Figure 5A). This indicates that the BFAR increase is most likely not due to specimens transport, but rather as a result of a change in substrate and environmental conditions that became favorable for a different foraminiferal assemblage. The higher foraminiferal diversity compared to previous periods and the decrease in the relative abundance of *S. fusiformis* may indicate more oxic conditions. *Elphidium clavatum* has been found in coarse sediment in the area (Bergsten et al. 1996), and other species that tolerate sandy environments and varying TOC dominated the assemblage, such as *A. batava*, the other species in the *Elphidium* species, *B. marginata*, and *E. medius/scabrus*. Furthermore, anthropogenic activities such as agricultural practices were intensified during this period until the 1980s, which resulted in increased nutrient loads and resulting eutrophication (i.e. Rydberg et al. 2006). The increase in organic matter may have been beneficial for foraminifera as food source. Food webs and species interaction like intra and inter competition might also have been modified, giving the advantage to some species such as the *Elphidium* species to develop in these new environmental conditions.

The temporal coincidence with the shifts seen in the sediment record and the anomalous wind conditions suggests a notable change of the currents through the Öresund (Figures 8, 9). The simulated currents through the Öresund confirm such an abrupt change characterized by a shift from very limited outflow from the Baltic to the Kattegat before ~1960 to more than a decade of high relative outflow (high VAV) from the Öresund to the Kattegat and high current velocities (Figure 8). While the simulation only covers the period after 1950, the analysis of wind conditions and the NAO index suggest that the anomalies in the current and sediment pattern from ~mid 1950's might have been unprecedented since at least the middle of the 19th century (Figure 9). The shift in local sediment properties and the shift to higher BFAR and species diversity suggest a combination of anomalous currents during a period of unusually negative NAO index and the abrupt first advection of anthropogenic eutrophication from the Baltic Sea towards the Kattegat. Consistent with our findings, long-term variations in Large Volume Changes in the Baltic Sea (LVC, Lehmann and Post 2015; Lehmann et al. 2017), which are calculated from >29 cm (~100 km^3) daily sea-level changes at Landsort (58.74° N; 17.87° E) for 1887–2015, show an unusual cluster of both, more frequent and also larger LVCs during the 1970's to 1980's relative to the entire time period. Notably, this period coincides with the most dramatic shift in foraminiferal BFAR and species diversity as well as an increase in sand content. The period before the "regime shift" of the 1950's to 1960's is dominated by very infrequent and few large LVC events. After the shift, the 1990's show also very few or partly no LVC events with generally record-low Major Baltic Inflow events.

Thus, during this period, the ecosystems were affected both by climatic effects through sedimentation changes, and human impact. At the end of the period, after ~1980, the general BFAR was lower during a short time (Figures 5, 9). This could be linked to the measures that were taken in agriculture and water treatments in order to reduce the nutrients discharge (Carstensen et al. 2006; Conley et al. 2007), which could have reduced the food input. Interestingly, when the sedimentation pattern changes again and the sand content decreases markedly (Figure 7), the new species in the foraminiferal fauna do not return to previous relative abundances as one could have expected (Figure 5A). This suggests that once the foraminiferal fauna was established in the Öresund area after the ~1953 shift, it created a new state of equilibrium.

5.4 1998 – 2009

The foraminiferal assemblage in this zone was similar to the previous one, with high BFAR, high diversity, and the *Elphidium* species as dominating species. This period is, however, characterized by the appearance of two new major species: *N. turgida* and *Nonionella* sp. T1. *Nonionella* sp. T1 is suggested to be an invasive species in the region which arrived by ship ballast tanks around 1985, and rapidly expanded to the Kattegat and Öresund (Polovodova Asteman and Schönfeld 2015). According to our dated core, the species arrived in the Öresund ~ 2000 CE (Figure 5). The species is also present on the south coast of Norway since ~ 2009 (Deldicq et al. 2019), but additional genetic analyses are necessary to have a better overview of the species' origin and expansion. *Nonionoides turgida* is an opportunistic species that prefers high levels of organic matter in the sediment, as observed in our core during this period (Figure 7). The increase in the *S. fusiformis* BFAR suggest lower [O_2] than in the previous zone, which was indeed a general trend in the Danish waters during this time period (Conley et al. 2007). The salinity was probably marine during this period, as suggested by the high occurrence of the marine species *B. marginata* (Figure 5). This period was then characterized by low [O_2], high organic matter content, and open ocean salinity.

5.5 2009 – 2013

The ability of *Nonionella* sp. T1 to denitrify and its tolerance to varying environment may explain its rapid increase during this period. The increase of *N. turgida* also suggests higher levels of organic matter in the sediment. The dominance of these two species and the lower BFAR compared to previous periods suggest low oxygen levels. This period is thus characterized by low [O_2], high organic matter content, and open ocean salinity.

5.6 Dissolution

The inner organic linings of the taxon *Ammonia* were observed (in low numbers, < 5 units) along the whole core, except in the top two centimeters (Figure 5). Inner organic linings of the taxa *Ammonia* and/or *Elphidium* were noticed in previous studies among dead fauna in the region (Jarke 1961; Hermelin 1987: Baltic Sea; Christiansen et al. 1996; Murray and Alve 1999: Kattegat and Skagerrak; Filipsson and Nordberg 2004b: Koljö Fjord). Dissolution of calcareous foraminiferal tests has been considered as a taphonomic process, affecting the test of the specimens after their death (Martin 1999; Berkeley et al. 2007). However, living decalcified foraminifera have been observed in their natural environment in the south Baltic Sea (Charrieau et al. 2018) and the Arcachon Bay, France (Cesbron et al. 2016) and, proving that test dissolution can also occur while the specimens live. In any case, low pH and low calcium carbonate saturation are suggested as involved in the observed dissolution (Jarke 1961; Christiansen et al. 1996; Murray and Alve 1999; Cesbron et al. 2016; Charrieau et al. 2018). Test dissolution may occur in all calcitic species, but only the organic linings of *Ammonia* were found in our study, probably because these were more robust to physical stress such as abrasion.

6 – Conclusion

In this study, we described an environmental record from the Öresund, based on benthic foraminifera – and geochemical data and we link the results with reconstructed wind data, NAO index and currents from a hydrodynamic model. Five foraminiferal zones were differentiated and associated with environmental changes in terms of salinity, [O_2], and organic matter content. The main event is a major shift in the foraminiferal assemblage ~1950, when the BFAR massively increased and *S. fusiformis* stopped dominating the assemblage. This period also corresponds to an increase in grain-size, resulting in a higher sand content. The grain-size distribution suggests changes in the current velocities which are confirmed by simulated current velocity through the Öresund. Human activities through increased eutrophication also influenced the foraminiferal fauna changes during this period. Organic linings of *Ammonia* were observed throughout the core, probably linked to low pH and calcium carbonate saturation, affecting test preservation.

The long-term reconstruction of sediment – and ecosystem parameters since ~1807 suggests that the onset of increased anthropogenic eutrophication of the eastern Kattegat started with an abrupt shift ~1960 during a period of strongly negative NAO index. With unusually calm wind conditions during the winter half and increased easterly winds, the conditions were ideal for larger Baltic outflow events which is a prerequisite for more frequent and stronger major Baltic inflow events (Lehmann et al. 2017), as calculated from LVC events during this period. Our high-resolution sediment record points towards the importance of considering also large Baltic outflow events for the Kattegat environment. Since the Baltic Sea is much more eutrophic, less oxygenated and less saline, large outflow events may have a significant impact also on the Kattegat ecosystem. Periods with a negative NAO or conditions with intense atmospheric blocking over Scandinavia like in 2018 may also increase the influence of Baltic Sea's environmental problems into the Kattegat region.

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Supplementary data

Appendix A, with time series of salinity, temperature and dissolved oxygen concentration at the bottom water of the Öresund, and Appendix B, with total foraminiferal faunas normalized to 50 cm^3 along the DV core, are available in the online version of the article.

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Figures

Figure 1. Map of the studied area. The star shows the focused station of this study. 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. Insert source: © BSHC.

Figure 2. CTD profiles of temperature, salinity, pH and dissolved oxygen concentration in the water column for the DV-1 station (modified from Charrieau et al. 2018).

Figure 3. Seasonal variability of salinity, temperature, pH and dissolved inorganic nitrogen (DIN) concentration at the surface water (light grey), and seasonal variability of salinity, temperature, pH and dissolved oxygen concentration at the bottom water (40-50 m) (dark grey) of the Öresund. The data were measured between 1965 and 2016 by the SMHI (Swedish Meteorological and Hydrological Institute) at the station W LANDSKRONA. The number of measurements is indicated for each month.

Figure 4. Age-depth calibration for the sediment sequence from the Öresund (DV-1). A) Total and supported ^{210}Pb activity. B) Unsupported ^{210}Pb activity and the associated age-model. C)

^{137}Cs activity. The peak corresponds to the Chernobyl reactor accident in 1986. D) Age-depth model for the whole sediment sequence based on ^{210}Pb dates and calculated sediment accumulation rates (SAR).

Figure 5. A) Relative abundances (%) of the foraminiferal major species (>5 %), benthic foraminiferal accumulation rate (BFAR, specimens.cm^{-2}.yr^{-1}), Shannon index, organic linings (specimens.cm^{-2}.yr^{-1}) and factors from the correspondence analysis. B) Benthic foraminiferal accumulation rates (specimens.cm^{-2}.yr^{-1}) of the major species (>5%), BFAR (specimens.cm^{-2}.yr^{-1}), Shannon index, organic linings (specimens.cm^{-2}.yr^{-1}) and factors from the correspondence analyses. Foraminiferal zones based on cluster and correspondence analysis. Note the different scale on the x axes.

Figure 6. Dendrogram produced by the cluster analysis based on the Morisita index and the UPGMA clustering method.

Figure 7. Sediment parameters of the cores DV-1I and DV-1G (^{210}Pb dated): total organic carbon content (C_{org}) (%), C/N ratio, and grain size (%). Foraminiferal zones indicated.

Figure 8. South-North flow (VAV) in the Öresund (dark line) and West-East flow (UAV) in the Kattegat (light line) between 1950 and 2013. Foraminiferal zones indicated.

Figure 9. A) NAO index for boreal winter (December to March), data from Jones et al. (1997). B) Variations of near-surface (10 m) wind conditions (October to March), data from Schenk and Zorita (2012). Both NAO index and wind speed data are normalized on the period 1850-2008 and show running decadal means. C) BFAR, percentage of sand fraction and West-East flow (UAV) in the Kattegat. Foraminiferal zones indicated.

Plate 1. SEM pictures of the major foraminiferal species (>5%). 1. *Stainforthia fusiformis*; 2. *Nonionellina labradorica*; 3. *Nonionella* sp. T1; 4. *Nonionoides turgida*; 5. *Eggerelloides medius/scabrus*; 6. *Bulimina marginata*; 7. *Ammonia batava*; 8. *Reophax subfusiformis*; 9. *Elphidium magellanicum*; 10. *Elphidium clavatum*; 11-12. *Ammonia* sp.

Tables

Table 1. Significant foraminiferal species and scores according to the correspondence analysis.

Table 2. Ecological significance of the benthic foraminiferal assemblages (major species).