Final report from the Baltic Sea 2020 project:

Hypoxia in the Baltic Sea

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October 2008

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Appendices

Hypoxia Project – Final Report

This report summarizes the overall activities and products from the Baltic Sea 2020 project on "Hypoxia in the Baltic Sea" initiated in January 2007 under the direction of Prof. Daniel Conley, Marie Curie Chair, GeoBiosphere Science Centre, Lund University. The challenges of the project were to create an enhanced understanding of hypoxia in the Baltic Sea, determine if there were technical solutions to improve oxygen conditions in the basin and provide guidelines to Baltic Sea 2020 and to policy makers on possible environmental management strategies.

Introduction

Hypoxia, generally defined as < 2mg/l dissolved oxygen, occurs in aquatic environments when dissolved oxygen becomes reduced in concentration to a point harmful to aquatic organisms living in the environment. Hypoxia is one of the most widespread and accelerating human-induced deleterious impacts on the world's marine environments with over 400 reported sites suffering from hypoxia due to excess nutrient loading from anthropogenic sources.

During the last five decades the area of severe oxygen depletion in the Baltic Sea has increased about four times. Widespread oxygen deficiency has for that reason severely reduced macrobenthic communities below the halocline in the Baltic Sea over the past decades and produced benthic "ecological deserts" that annually cover over 30% of the seafloor. The implications of this trend to society are significant because the Baltic Sea provides critical ecosystem services, including fish production and recreation for humans.

The Baltic Sea is often described as a patient "dying" or "suffocating" from the lack of oxygen. It is a common opinion that the preeminent way to save this "patient" is to artificially add oxygen to the system. As a consequence, a number of more or less realistic/unrealistic propositions have been made as to what an engineer can do to improve conditions in the Baltic Sea. Less have been done to seriously investigate the consequences of such propositions.

This project was originally initiated to improve our understanding on hypoxia and to make recommendations on the best way to move forward on restoring a healthy Baltic Sea. In order to achieve these purposes, this project brought together scientists from the countries surrounding the Baltic Sea and other nations (USA, Canada and The Netherlands) in a workshop series to analyze our current understanding of hypoxia and identify the important gaps in current scientific knowledge.

Using the work that has emerged from the project, we have examined if there are any management techniques (aeration, changes in salt water inflow, etc.) that can diminish the effects of hypoxia and what their environmental effects might be on the Baltic Sea ecosystem. The project has raised questions about the legal framework regulating sea-based activities, as well as, ethic issues to evaluate possible engineering solutions that can be implemented in the Baltic Sea. We have addressed both the effects on open sea and coastal areas, since it is believed that the driving forces for hypoxia are dissimilar in the different areas. Given that the

International Panel on Climate Change (IPCC) and recent studies have recognized that hypoxia is a problem of growing concern with projected climate change (www.ipcc.ch) and that cyanobacteria blooms probably will magnify in the future, we have concentrated our efforts on revealing long-term trends in hypoxia and their connections to climate and anthropogenic forcing and internal feedback mechanisms. We now have a more comprehensive view on the spatial and temporal variations of hypoxia in the Baltic Sea from decades to many centuries.

In terms of the work carried out, the project has met all the outcomes as identified in the original proposal and followed the ‘milestones’ of the work plan. The project activities resulted in several reports (Appendices 1-4), scientific papers (Appendices 6-8), popular scientific papers (Appendices 9-10), as well as, joint proposals and founding from other funding agencies (BONUS, VR and FORMAS). The project has disseminated a “Specific Recommendation Letter” (Appendix 5) to the Swedish Environmental Protection Agency (Naturvårdsverket) and Baltic Sea2020 on possible solutions on hypoxia mitigation and contributed to establishing a sound scientific base for long-term nutrient management and reduction of hypoxia, which will aid policies designed to effectively combat eutrophication and re-establish desired ecosystem services. More detailed information on the activities *within* and products *from* the Hypoxia Project is presented below.

Project activities

Workshops

Three workshops were held within the Hypoxia Project with participation from scientists around the Baltic Sea together with involvement of internally recognized scientists. In total 60 different scientists from 10 different countries participated in these workshops. Members of the scientific council and the board of Baltic Sea 2020 also participated.

1. *Understanding hypoxia in the Baltic Sea*

The 1st Baltic Sea 2020 workshop on hypoxia in the Baltic Sea - *Understanding hypoxia in the Baltic Sea* was held in Lund, Sweden, April 17-19, 2007. The aim of the workshop was to identify our knowledge and gaps in the temporal/spatial resolution of hypoxia in the Baltic Sea, the role of saltwater/freshwater inflows, climate changes and their impacts, biogeochemical feedbacks, and hypoxia and biodiversity. The conclusions of the workshop are summarized in workshop report no. 1 (Appendix 1).

2. *Exploring the causes and consequences of coastal hypoxia*

The 2nd Baltic Sea 2020 workshop on hypoxia in the Baltic Sea - *Exploring the causes and consequences of coastal hypoxia* was held in Åbo, Finland, October 16-18, 2007. The purpose of the workshop was to describe current knowledge about hypoxia in coastal waters and where information is lacking. During three days of presentations and discussions the geographical and regional magnitude of coastal hypoxia around the Baltic Sea, possible remedies to coastal hypoxia, and management options and the need for modeling and ecological engineering were considered. The outcomes of the workshop are summarized in workshop report no. 2 (Appendix 2).

3. *Potential management techniques, environmental effects and ethics*

The 3rd Baltic Sea 2020 workshop on hypoxia in the Baltic Sea - *Potential management techniques, environmental effects and ethics* was held in Lund, Sweden, November 27-19, 2007. The objective was to discuss and evaluate potential management techniques, environmental effects and ethics and to determine the best possible technological measures that could be taken to reduce hypoxia for the short-term and for the long-term. The conclusions of the workshop are summarized in workshop report no. 3 (Appendix 3).

4. *Possible solutions to oxygen problems in the Baltic Sea*

A final meeting - *Possible solutions to oxygen problems in the Baltic Sea* was held at the Royal Swedish Academy of Sciences, Stockholm on 24 January 2008 with co-funding from the Swedish Environmental Protection Agency (Naturvårdsverket). At this meeting we presented our recommendations to SEPA and Baltic Sea2020 regarding possible technical solutions in the Baltic Sea and future founding by foundations (Appendix 4).

Project products

Reports

Appendix

1. Zillén, L. & Conley, D.J. 2007. Report from the 1st Baltic Sea 2020 workshop on hypoxia in the Baltic Sea ”Understanding hypoxia in the Baltic Sea”, 33 pp.
2. Jakobsson, B.-M. & Bonsdorff, E. 2007. Report from the 2nd Baltic Sea 2020 workshop “Exploring the causes and consequences of coastal hypoxia”, 52 pp.
3. Zillén, L. & Conley, D.J. 2007. Report from the 3rd Baltic Sea 2020 workshop on hypoxia in the Baltic Sea “Potential management techniques, environmental effects and ethics”, 26 pp.
4. Specific recommendations regarding Naturvårdsverket “Letter of Interest” and for Future Funding by Foundations.
5. Associated PowerPoint presentations used at the final meeting “Possible solutions to oxygen problems in the Baltic Sea” at the Royal Swedish Academy of Sciences.

Peer-review papers

Appendix

6. Zillén, L., Conley, D. J., Andrén, T., Andrén, E. & Björck, S. 2008. Past occurrences of hypoxia in the Baltic Sea and the role of climate variability, environmental change and human impact. Accepted, Earth Science Reviews.
7. Conley, D.J., Björck, S., Bonsdorff, E., Destouni, G., Gustafsson, B., Hietanen, S., Kortekaas, M., Kuosa, H.,Meier, M., Müller-Karulis, B., Nordberg, K., Nürnberg, G., Norkko, A., Pitkänen, H., Rabalais, N., Rosenberg, R., Savchuk, O., Slomp, C.P., Voss, M., Wulff, F. & Zillén, L. 2008. Hypoxia-related processes in the Baltic Sea. Submitted to Environmental Science and Technology.
8. Conley, D.J., Bonsdorff, E., Carstensen, J., Destouni, G., Gustafsson, B.G., Hanson, L.-A., Rabalais, N.N., Voss, M. & Zillén, L. 2008. Tackling hypoxia in the Baltic Sea: Is engineering a solution? Submitted to Environmental Science and Technology.

Popular science papers

Appendix

9. Conley, D.J. & Zillén, L. 2008. Syrebrist i Östersjön – vad kan vi göra? Havsutsikt 1/2008, 4-5.
10. Zillén, L., Conley, D.J. & Björck, S. 2007. Ibland är syrebrist ett normalt tillstånd. Geologiskt Forum 56, 20-23.

Working group (Advisory Board)

Daniel Conley – Lund University, Sweden
Erik Bonsdorff - Åbo Academi University, Finland
Sif Johansen – Swedish Environmental Protection Agency, Sweden
Lovisa Zillén - Lund University, Sweden
Jacob Carstensen – National Environmental Research Institute, Denmark
Gia Destouni – Stockholm University, Sweden
Bo Gustafasson – Gothenberg University, Sweden
Jack Middleburg – Netherlands Institute of Ecology, The Netherlands
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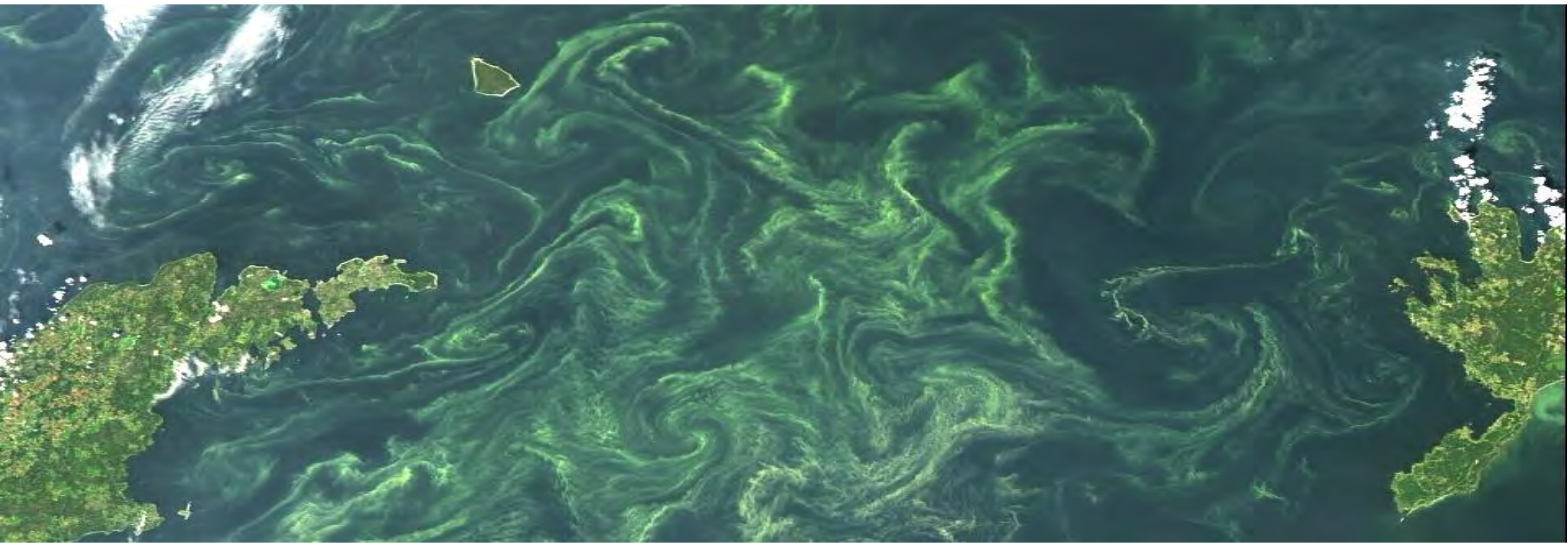
Appendix 1

Baltic Sea 2020

Report from the Baltic Sea 2020 Workshop:

Understanding hypoxia in the Baltic Sea

Lovisa Zillén and Daniel J. Conley



A workshop held 17-19 April 2007

at the GeoBiosphere Science Centre, Lund University, Sweden

Background

In the autumn of 2005 financier Björn Carlson donated 500 million Swedish crowns to the Swedish Royal Academy of Science for the formation of the foundation Baltic Sea 2020 (Björn Carlsons Östersjöstiftelse). The intention of the foundation is to significantly improve the Baltic Sea environment before the year 2020. The foundation will use an interdisciplinary approach to deal with the health problems of the Baltic Sea. Social scientists and natural scientists from the countries surrounding the Baltic are to be encouraged to take part in creative collaboration. The foundation will invest money in innovative research, experimentation and creation of networks between researchers. The main objective is to generate new knowledge in practical measures to improve the environment and the dialogue between decision-makers around the Baltic.

The Baltic Sea 2020 workshop in Lund (17-19 April 2007) was the first in a series of workshops that will be run to assemble our collective understanding of hypoxia and to make recommendations on the best way to move forward and restore a healthy Baltic Sea. During this workshop we have examined our current understanding of hypoxia and identified the important knowledge and gaps in our scientific knowledge.

Reporter Lovisa Zillén

Introduction

The Baltic Sea is one of the world's largest regions affected by hypoxia (oxygen depletion). The hypoxic zone in the Baltic Sea has increased about four times since the 1960's and currently covers an area of c. 60 000 km^2. Hypoxia is hazardous to numerous benthic communities, alters nutrient biogeochemical cycles and causes severe ecosystem disturbances, such as enhanced blue-green algae blooms during the summer months.

Just recently (in April 2007) society was again reminded of the state of the Baltic Sea when the northern and western Gotland Basins experienced the worst oxygen-hydrogen sulphide conditions ever recorded (Fig. 1). The increased hypoxia during the last c. five decades has developed into a complex environmental problem for the Baltic Sea, requiring action by society to reverse these trends.

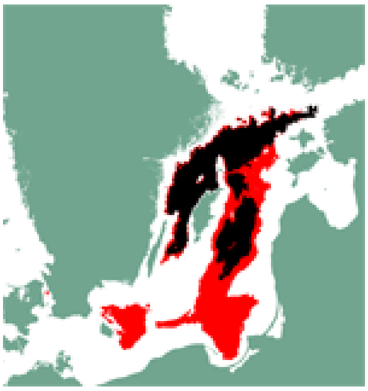


Figure. 1. The black parts are bottom areas affected by hydrogen sulphide. Red areas are affected by oxygen concentrations less than 2 ml/l (data from SMHI).

Hypoxia (< 2ml/l oxygen) occurs when oxygen supply does not meet the demand, which often is a balance between physical processes that supply oxygen and biological processes that consume it. In the Baltic Sea, the supply of oxygen is dominated by water exchange and vertical diffusive processes, which are both closely coupled to climate and oceanographic conditions.

The water body of the Baltic Proper is permanently stratified, consisting of an upper layer of brackish water with salinities of c. 7-8 ‰ and more saline deep waters of c. 11-13 ‰. At the transition zone between these water masses a strong permanent halocline is formed at depths varying between c. 60-80 m. The halocline prevents vertical mixing of the water column, and consequently, ventilation of more oxygenated waters down to the bottom all year around. The conditions in the deep water of the basins are strongly influenced by the inflow of saline and oxygenated water from the North Sea.

The inflows are, however, restricted by narrow channels and shallow sills i.e. the Öresund strait, Great Belt, Little Belt, Darss Sill and Drogden sill (Fig. 2). Frequent but smaller inflows (10-20 km^3) are generally insufficient to displace the bottom water in the Baltic deep basins because their water will mix in with or flow just beneath the permanent halocline. Periodic inflows of larger volumes (100-250 km^3) of higher salinity and oxygen-rich water, which penetrates deeply into the Baltic and fills the deep basins, represent the most important mechanism by which the Baltic deep water is displaced and renewed to a significant degree. Oxygen consumption depends to a large degree on the supply of organic matter, which is coupled to the production in the surface layer. During the early 1990's the concentration of limiting nutrients such as phosphorus (P) and nitrogen (N) in the surface water of the Baltic has declined, due to reductions in hypoxic area of bottom waters. However, since then, measurements show increasing P concentration and decreasing N concentration in the deep waters of the Baltic.

The concentration relationship between P and N has consequently changed and amplified P contents have increased the

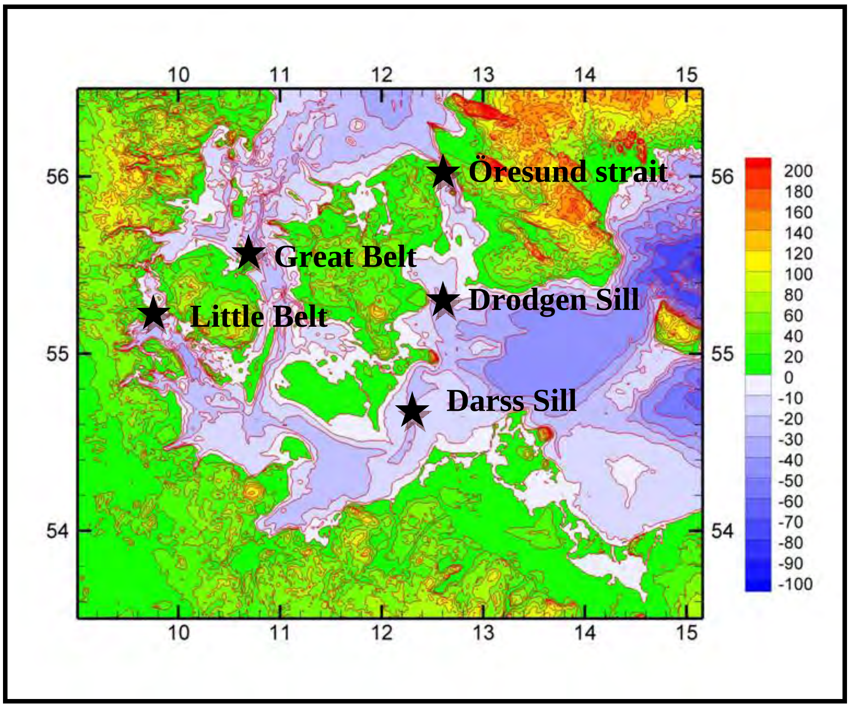


Figure 2. A bathymetric map of the southern Baltic Sea basin showing the location of the narrow inlets (Öresund Strait, Great Belt and Little Belt) and shallow sills (Darss Sill and Drodgen Sill).

blue-green algae blooms during summer periods. An enhanced hypoxic zone and a stabile halocline are most likely the causes.

However, one must remember that the semi-enclosed Baltic Sea has a long geological history of environmental alteration where geophysical forcing and climate changes have had a great impact on past salinities, oxygen concentrations and biodiversity on both relatively short and long time-scales. For the future management of the Baltic it is thus important to understand the long-term natural variability of hypoxia within the basin.

Therefore, a workshop was held at the GeoBiosphere Science Centre, Lund University from 17-19 April 2007 to bring together a diverse group of scientists from the Baltic Sea area and more further afield to discuss our current understanding of hypoxia. The aim of the workshop was to identify our knowledge and gaps in (1) the temporal/spatial resolution of hypoxia in the Baltic Sea, (2) the role of saltwater/freshwater inflows, (3) climate changes and their impacts, (4) biogeochemical feedbacks, and (5) hypoxia and biodiversity. Initial discussion and speculation about what technological measures could be undertaken to improve the situation were also made.

Invited speaker's presentations

Hypoxia in the Baltic Sea by Oleg Savchuck

Department of System Ecology, Stockholm University, Sweden

Oleg Savchuck

Abstract by author

Hypoxia in the Baltic Sea is a well known and familiar phenomenon. Direct measurements of oxygen, which indicate its deficit, are available since the end of 19th century. Although hypoxia sporadically occurs in many local spots, including shallow coastal areas (e.g. the Archipelago Sea, the Pomeranian bight, the Danish Straits, etc.), the main goal of this presentation is to highlight some large scale features of the oxygen dynamics and their biogeochemical consequences in the open Baltic Proper. For this purpose, data from the extensive Baltic Environment Database (BED) maintained at the Baltic Nest Institute (BNI, Stockholm University) are processed with a variety of data analysis tools. Such features include variations of the area and volume of hypoxic zone ($O_2 < 2$ ml/l), inter-annual variations of the nutrient pools and estimates of the spawning volumes of cod, etc.

As everywhere else, the duration, extent and intensity of Baltic hypoxia/anoxia are governed by a misbalance between oxygen supply by transport mechanisms vs. oxygen consumption for oxidation of organic matter and other reductants. Since variations of transports are mainly natural, while variations in supply of both autochtonic and allochtonic organic matter are, at least partly man-made, the quantitative description and predictions of hypoxia and its effects are ultimate for scenarios of the Baltic Sea eutrophication due to climate variations and anthropogenic impacts. Such predictions are exemplified by several relevant simulations.

Presentation

What do we know about hypoxia in the Baltic Sea today? We know a great deal since Baltic Sea research has a relative long history. Already in 1892, Professor Otto Pettersson started to perform measurements of oxygen concentrations in the Baltic Sea. We therefore have relative long time-series and a large amount of marine data available. We also know that there are two different types of hypoxia, a coastal (or near shore) and a deep water hypoxia.

The Baltic Environmental Database (BED) was initiated in 1990 as part of a research project “Large-scale Environmental Effects and Ecological Processes in the Baltic Sea” financed by the Swedish Environmental Agency**.** Within this project, hydrography and chemistry data are obtained from shared oceanographic stations. These stations measure several physical and biogeochemical parameters, which are stored in the data base. The BED is a scientific tool that can be used to access, process and analyse marine data. It can be used to produce 3D-fields of various parameters, as for example, salinity distribution, oxygen depletion and hypoxia. It can also be used to determine the volume of waters with less than 2ml/l oxygen concentrations, calculate areas with bottoms affected by hypoxia, and describe long-term trends in oxygen dynamics etc.

Low oxygen levels were recorded already in year 1900. During the more recent years oxygen concentrations have been reduced in the deeper layers but also at shallower depth. Saline inflows are the major ventilator in the Gotland Deep and it is therefore important to know what happens during these inflows. We know for example that during hypoxia, nitrate is denitrified out from the hypoxic zone and phosphorous is released from the sediments.

Long-term dynamics of DIN and DIP pools have occurred below 60 m in the Baltic proper at least since 1965 and up to the present. During this period, DIN concentration has increased while DIP contents decreased. This is probably due to the fact that phosphorous been released from the sediment during prolonged hypoxia. Additionally, DIP values are positively correlated with increasing hypoxia while DIN is negatively correlated to the same procedure.

The hypoxic zone distribution has increased the last c. 50 years. For example, in 1993 it covered 11 050 km^2 and in 1999 it had grown to 60 716 km^2. Today, it is one of the largest zones affected by hypoxia. In comparison, the “dead zone” in Gulf of Mexico has an aerial distribution of ca 20 000 km^2. With observed and modelled data we can predict trends for the future and simulate pre-indusrtial hypoxic conditions in the Baltic Sea.

Katarina Veem and Erik Bonsdorff discussing over lunch.

The postglacial Baltic Sea history -What can the geologic record teach us about likely processes behind hypoxia?

By Svante Björck, Daniel Conley and Lovisa Zillén

GeoBiosphere Science Centre, Lund University Sweden

Svante Björck

Daniel Conley

Abstract by authors

The postglacial Baltic Sea history is characterized by large environmental shifts, including significant salinity changes. This mainly owes to the fact that the Baltic basin and its drainage area have experienced differential isostatic uplift, both in time and space, which has resulted in a complex uplift history after the last deglaciation of the Scandinavian Ice Sheet; the centre of this inland ice was situated in the Bothnian Bay region and the southernmost margin of the ice reached down to Berlin. Furthermore, during large parts of this history global sea level was rising due to the melting of the continental ice sheets. The combination of differential crustal uplift and rising sea level led to shifts in the location of sills between the ocean and the Baltic basin. This resulted in thresholds situated above sea level causing up-dammed (ponded) and thus freshwater phases of the Baltic as well as wide and deep sills producing highly brackish conditions.

Between 15,000-8000 cal. yr BP (before present) the Baltic basin was almost totally dominated by freshwater with a short (200-300 yr) brackish phase around 11,200 cal. yr BP. and a very weak and possibly oscillating salinity influence after 9800 cal. yr BP. During these phases the mixing of the water column was usually good and the aquatic productivity was low. In spite of these conditions sediment cores from deeper parts of the basin show that Baltic bottom conditions occasionally were anoxic/hypoxic, especially during the brackish Yoldia Sea phase at c. 11,200 cal. yr BP. However, in some shallower areas finely laminated sediments occur during the Ancylus freshwater phase, indicating seasonal anoxia.

Sometime after 8000 cal. yr BP, when the Öresund Strait began to function as an important inlet of saltwater, long periods of anoxic conditions seem to have characterized the deeper sub-basins of the Baltic. This change also coincides with rising organic material in the sediments, indicating higher productivity. In fact, the period with highest salinities and thus highest saltwater inflow, between c. 7000-5000 cal. yr BP, also seems to have been the period with most severe and prolonged hypoxia/anoxia in these basins. It is therefore difficult at this stage to conclude which mechanism has been the main driver for these conditions: high productivity and/or efficient stratification of the water column with a stable halocline.

It may also be argued that the climate of the Holocene optimum was the main trigger for high productivity and not the salinity maximum, either through increased

temperatures or by higher precipitation and thereby transport of more nutrients into the Baltic through the increased river run-off. The same problem complex may apply for the last 1000-2000 years with increasing anoxia and productivity during the Medieval Warm Period and during the last 100 years as opposed to the conditions during the Little Ice Age with low productivity and less anoxia.

Presentation

The Baltic Sea is a brackish water basin with a history of variable salinity/freshwater and oceanographic conditions. During post-glacial time the area has been characterized by a differential uplift that been greater in the north than in the south. The uplift has declined with time. However, today the northern part of the Baltic experience one of the world's fastest land uplifts in the world. Since the last glaciation the uplift has been ca 170 m in southern Sweden, ca 200 m in central Sweden and ca 240 m in northern Sweden.

The basin has experienced a number of freshwater and brackish water phases i.e. the Baltic Ice Lake (c. 15000-11300 cal. BP years ago), Yoldia Sea (c. 11200 cal. BP years ago), Ancylus Lake (c. 11000-8500 cal. BP years ago) and the Littorina Sea (c. 8500 cal. BP years ago to the present) due to the interplay with changing sea level and/or irregular land uplift.

During the Baltic Ice Lake the sediment deposition in the basin was dominated by glacial clay and the productivity was extremely low. During the Yoldia Sea the Baltic was connected with the Kattegat, through a strait over central Sweden, and saline intrusion occurred as far south as to Hanö Bay in Blekinge. The water was brackish for about c. 150 years. The deeper waters experienced occasionally anoxic and the productivity was relatively high. The following Ancylus Lake Stage was characterised by fresh water conditions, low productivity, low- organic sediments, and local hypoxia in fjords and deeper basins.

Maximum salinity occurred between c. 8000-5000 cal. BP during the Littorina Sea when wide and deep thresholds existed due to rapid sea level rise. This period was characterised by high productivity and biodiversity with occasional hypoxia in deeper basins.

There are physical, chemical and biological evidence that the Gotland basin have experienced numerous long periods of natural hypoxia during the "modern" history of the Baltic Sea, i.e. during the last c. 8500 years. In a number of areas, where laminated sediments are formed and preserved (a physical parameter that can be used to determine the presence of oxygen depleted bottom waters), it's suggested that laminations have formed there at least the last 200 years. It has also been shown that from 1940, and particularly from 1960, the extent of laminated sediments has increased from about 20000 km^2 to c. 70000 km^2.

For the future management of the Baltic, one of the major questions for the scientific community to answer is, how will climate changes affect the Baltic Sea? Expected temperature increases, due to global warming, would lower the oxygen saturation, increase rates of respiration and promote system heterotrophy. A modeled scenario of a 4 °C temperature increase (as predicted by the Integrated Panel of Climate Change; IPCC) has shown to almost double the hypoxic area in Danish waters.

Important parameters that we do not know how they will respond to potential climate changes are: productivity, stratification and mixing, freshwater input, and saltwater intrusions.

What we do know from the geological records are that (1) the geological history has played an important role, (2) hypoxia/anoxia in the modern Baltic (<8000 yr BP) has occurred intermittently (still poorly defined), (3) bottoms with laminated sediments has recently increased (since 1960), and (4) that the spatial extent of hypoxia/anoxia in the past is fairly unknown.

Physical constraints to hypoxia in the Baltic by Bo Gustafsson

Earth Science Centre, Gothenburg University, Sweden

Bo Gustafsson

Abstract by author

I will in my talk try to separate as far as possible the major physical drivers that cause variations in hypoxia with time from effects of anthropogenic increase in nutrient loads. Oxygen concentrations below the halocline depend basically on a balance between supply, through water exchange and vertical turbulent mixing, and consumption due to decomposition of organic matter. Thus, hypoxia occurs because oxygen supply does not match consumption. However, the complexity of understanding the causes of hypoxia is hidden within this simple fact. Complications are, for example, that both oxygen supply and consumption varies on a wide range of time-scales and that there are non-linear processes coupling the two.

The supply of oxygen is dependent on the salinity and magnitude of the inflows through the straits and supply of mechanical energy for mixing to the Baltic (basically the winds). These driving forces have to be considered over a period of time, about 5 years or so, since the effect of, for example inflows, depends on the stratification already present in the Baltic. An example given is that as a rule of thumb, one can say that during a period with higher freshwater supply to Baltic the inflows tend to be fresher that in turn weakens stratification. This leads eventually to increased supply of oxygen and higher concentrations.

The temporal variation in oxygen consumption is not really known, to my knowledge there are only one direct estimate stating that oxygen consumption increased with 50% between the 1930s and the 1980s (Eilola, 1998). However, if dependent on nutrient availability in the photic zone, it should have increase in the long-term (100 yr) perspective due to anthropogenic supply, but also have a substantial interannual variation due to the variations in recycling of reactive nutrients. The winter concentrations of DIN and DIP depend to a significant part on the flux through the halocline, which in turn is dependent on the entrainment rate and concentrations in the halocline. At least for DIP there is definitive coupling to oxygen concentrations that potentially ties hypoxia to variations in oxygen consumption. Occurrence of such events are due to a specific physical setting that cause hypoxic water to be present high in the water column, but the overall oxygen consumption affects the degree of hypoxia during events.

Presentation

The physical setting of the Baltic Sea has a large influence on the salinity and oxygen distribution in the basin. The Baltic is characterised by shallow and narrow connections to the North Sea and relative large river runoff, which together results in low salinity, long residence time and strong stratification.

Main implications of the basic physical settings are:

- Strong haline stratification with limited or even intermittent deep-water exchange
- Nutrients are not exported in significant amounts – they have to be deposited (or denitrified/anammoxed) within the Baltic
- Organic matter is trapped and have to decompose or be deposited within the Baltic

After 1950 the trend in stratification and oxygen concentrations in the open Baltic proper changed. Anoxia is more common than before, as well as, the irregular inflows of saline and oxic water. You can also see a change towards higher variation between weak and strong stratification periods.

The net inflow (QD) depends on the water exchange between the North Sea and the Baltic. It is forced primarily by sea-level variations in the Kattegat where the shallow and narrow straits limit the exchange. A low sea-level in the Baltic results in lager outflows and vice-versa. The amount of freshwater entering the Baltic has a direct response on the salinity conditions. As an example, high river run-off occurred around 1930 with enhanced anoxia as a result.

The so-called major inflows can be indexed by the amount of salt carried by water of salinity higher than a specific value, e.g. 20, across the sills. The magnitude is tightly coupled with freshwater supply to the Baltic during the year preceding the inflow. The salinity of non-major inflows is in a corresponding manner, also directly related to river runoff. In addition, Baltic deep-water responds quicker to increased supply than mean Baltic salinity which implies that an increase in river run off (QF) will lower deep water salinity and weakening the stratification.

Stagnant deep-water in the Baltic can be compared to a large incubator and act either as a source or a sink for nutrients. The integrated amount of available nutrients varies in combination with halocline depth and concentration. A shallower halocline results in less water volume available for spring algae blooms. However, the effect of a weak or strong stratification (or a narrow or wide halocline) is not quantified.

A contraction of the halocline (rising of the redoxcline) would theoretically have opposite effects on NO_3 and PO_4, which would increase PO_4 concentrations close to the surface layer but reduce the amount of NO_3. Consequently, interannual variability in mixing and halocline concentrations can give rise to large differences in nutrient supply to the winter pool.

Conclusions:

- Hypoxia/anoxia occurs when oxygen supply does not meet demand – often a balance between physical processes that supply and biological processes that consumes
- In the Baltic, supply is dominated by water exchange and vertical diffusive processes – both closely coupled to weather conditions
- Oxygen consumption depends to a large degree on supply of organic matter, which is coupled to the production in the surface layer
- Net production probably varies substantially due to variations in physical conditions, i.e., mixed layer depth, supply of nutrients from below etc.

The 'Dead Zone' in the Gulf of Mexico by Nancy N. Rabalais

Lousiania Universities Marine Consortium, USA

Nancy Rabalais

Abstract by author

The summer hypoxic water mass in the northern Gulf of Mexico adjacent to the Mississippi River is one of the largest human-caused coastal hypoxic water masses in the world's ocean. The hypoxia extends from near shore to as much as 125 km offshore and in water depths extending from the shore up to 60 m deep, with an average size of 12,500 km^2 over the period 1985-2005, and a range from negligible in 1988 (a summer drought year for the Mississippi River basin) to 22,000 km^2 in 2002.

The nutrients delivered from the Mississippi River Basin support the primary productivity within the immediate vicinity of the river discharges as well as westward across the broader Louisiana and upper Texas continental shelf. Flux of fixed carbon in the form of senescent phytoplankton, zooplankton fecal pellets or aggregates to the lower water column and seabed provides a large carbon source for decomposition by aerobic bacteria, leading to hypoxia, defined as dissolved oxygen levels at or below 2 mg/l in vast areas of the water column, for months at a time from the spring to the fall.

The long-term data on hypoxia, sources of nutrients, associated biological parameters, and palaeoindicators verify the relationship between among river discharge, the nitrate-N load of the Mississippi River, the extent of hypoxia, and changes in the coastal ecosystem. Multiple lines of evidence, some of them representing independent data sources, are consistent with the 'big picture' pattern of increased eutrophication as a result of long-term nutrient increases that result in excess production, carbon accumulation and manifesting as increased size and severity of hypoxia.

Few marine animals survive in oxygen concentrations below < 2 mg/l, unless they are capable of migrating out of the area. The area affected by hypoxic conditions is thus popularly known as the 'Dead Zone.'

Presentation

The Mississippi and Atchafalaya rivers are the largest inflows and account for most of the nutrient input to the Gulf of Mexico. The land use in the watershed of these rivers is dominated by agriculture. Since 1972, the N load has increased dramatically due to increased NO_3-concentration in the watershed and higher river discharge rates.

The water column in the Gulf of Mexico is strongly stratified during the summer months. During strong stratification periods, half of the water column contains less than 2 mg/l oxygen.

Nitrogen, phosphorus (and silica) are essential for the growth of phytoplankton.

Most often, problems with an overabundance of nutrients in marine systems are the result of excess nitrogen rather than phosphorus. High productivity results in higher chlorophyll biomass in the water column with decreased water clarity. The average secchi depth in the Gulf of Mexico has declined since about 1980. The diatom flora in the Gulf of Mexico has changed to be dominated by dinoflagellates due to increased nutrient loads and associated Si:N molar ratio changes. Historically, the Si:N molar ratio has changed from 4:1 to 1:1. In addition, jellyfish and sea nettle abundances have increased, which is an indicator of altered food webs.

The Gulf of Mexico is characterised by seasonal hypoxia, which is most widespread and severe from May to Aug/Sep. During midsummer, the hypoxic zone can be up to c. 22 000 km^2 wide (i.e. much smaller than the hypoxic zone in the Baltic Sea). However, occasional tropical storms and hurricanes can decrease the area of the hypoxic zone.

Hypoxia was not a common phenomenon in the Gulf of Mexico until 1970. Increasing productivity due to an increase in riverine N-load has worsened the hypoxia since then. Hypoxia has NOT always been present.

The so called “Dead Zone” of the Gulf of Mexico is not completely dead. However, hypoxia causes vast stress on fauna communities from direct mortality to altered migration, reduction in suitable habitat, increased susceptibility to predation, changes in food resources and susceptibility of early life stages.

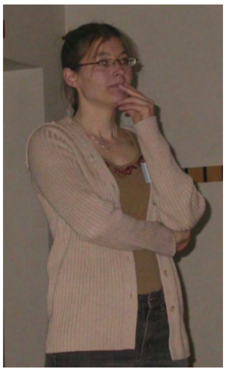
Since hypoxia affects the production and fishery yields the political agenda is to reduce the size of the hypoxic zone to 5,000 km^2. To reach that goal N-reduction of 30-45% is required.

It has been shown that N and P trends corresponded to fertilizer use. Fertilizers are thus the most important source of nutrients. To reduce hypoxia we need to reduce nutrient emissions from the agriculture sector. Proposed measures for reducing nutrient loads to the Gulf of Mexico are better farming management, alternative crops and increased wetland areas.

Discussion

Effect of hypoxia on the N biogeochemical cycle by Susanna Hietanen

Department of Biological and Environmental Sciences, Division of Aquatic Sciences,
University of Helsinki, Finland



Susanna Hietanen

Abstract by author

Nitrogen (N) entering the bottom ecosystem flows through different mineralisation pathways, all of which are microbially mediated. Most of the N processing (from organic N back to gaseous N_2) happens in sediments. Both of the processes removing fixed N from the water ecosystem, denitrification (sequential reduction of nitrate to N_2 gas via nitrite, nitric oxide and nitrous oxide) and anammox (anaerobic ammonium oxidizing, combining ammonium with nitrite to form N_2 gas), are anaerobic and therefore enhanced during hypoxia. However, the nitrification process, producing nitrite and nitrate from ammonium to be used by the N removing processes, is aerobic and therefore ceases under hypoxia.

Nitrification has so far only been studied in the water column of the Baltic Sea, and nothing is known about it in the sediments. As it is the key process producing substrates for both denitrification and anammox, the gap in knowledge directly affects our understanding of the other two processes as well.

Recently it has also been suggested that in the sediments of the Gulf of Finland, a considerable amount of fixed N enter neither denitrification, nor anammox pathway, but an anaerobic process called dissimilatory nitrate reduction to ammonium, DNRA. Unlike denitrification and anammox, this process does not remove N from the water ecosystem, but stores it in the water, to be used by algae and bacteria again.

In order to reliably evaluate the effects of oxygen concentration changes on the N removing processes we first need to find out what controls the nitrification rates, how sensitive the process is to oxygen fluctuations, and in what conditions does the DNRA replace N removal.

Presentation

Denitrification processes are driven by denitrifying and/or anammox bacteria. Denitrifying bacteria are heterotrophs (need carbon from organic compounds) and facultative anaerobs (switch from oxygen to nitrate in anoxic conditions). No type of denitrifying bacteria completes the whole denitrification chain but different types of bacteria release different N. Denitrifying bacteria is present almost everywhere and is a very diverse group.

Anammox bacteria are chemolithoautotrophs (uses carbon from CO_2) and are obligate anaerobes. They are slow-growing and need stable environmental conditions.

Both denitrification and anammox processes remove N_2 from the sediment.

Nitrification is driven by nitrifying bacteria. They are chemolithoautotrophs (need C from CO_2), slow-growing and require stable environmental conditions. There are two distinct groups; ammonium and nitrite oxidizers. They are active in the water column and represent one of the weak points in understanding natural nitrogen removal during hypoxia.

A laboratory experiment to test the effect of hypoxia and the recovery from it was carried out. We used an aquarium filled with sediment and nutrient-free synthetic seawater. The water was subjected to anoxic conditions (<7% O_2) for 17 days and then reoxidiesed again to 100% O_2. Parameters measured during and after the anoxic period were denitrification, nutrient concentrations (PO_4^{3-}, NH_4^+, NO_3^-) and sediment P fractionation. The result shows that the nitrification is NOT very sensitive to short hypoxic episodes, which are common in the Gulf of Finland in late summer. It also shows that the history of seasonal hypoxia makes the bacteria more flexible (retain enzymes under anoxia – jump to the opportunity once oxygen reappears). However, one must remember that this is experimental data with manipulated (sieved, repacked) sediment with N rates 2-3 times higher than in a natural environment. This makes it difficult to compare the results to the natural environment. However, the data suggest that with a larger anoxic volume more nitrogen is removed.

It has been suggested that within a basin, on time-scales of years to decades, N removal/input by cyanobacteria balance each other out. Howevere, for the Baltic Sea, measured losses are far lower than calculated so one question still remains, where does all the N go? In conclusion, hypoxia affects the N biogeochemical cycle by enhance denitrification and enhanced anammox but only as long as nitrification still functions. Short, seasonal periods with anoxic conditions don’t significantly affect denitrification while prolonged hypoxia does. The role of DNRA is still unknown and more data on nitrification and DNRA are urgently needed.

Effect of Hypoxia on the Biogeochemical Cycle of Phosphorus by Caroline P. Slomp

Department of Earth Sciences, Utrecht University, The Netherlands

Caroline Slomp

Abstract by author

Benthic phosphorus (P) release is important in determining the P availability and water quality in many coastal aquatic systems. Since the benthic release of P is enhanced under low-oxygen bottom waters, a positive feedback loop between P availability, primary production and increased hypoxia may develop. The enhanced phosphate efflux from sediments overlain by oxygen-depleted waters is usually ascribed to the release of P from easily reducible Fe-phases. However, this process alone may not explain the dependence of benthic phosphate fluxes on bottom water oxygen concentrations.

In this presentation, I first review the accumulating evidence that burial of P bound in sedimentary phases other than ferric (hydr)oxides is also sensitive to the redox state of the overlying water column. Using data from modern and ancient marine sediments, I demonstrate that preferential regeneration of P from organic matter and reduced formation of authigenic Ca-P minerals can lead to enhanced benthic release of P under low-oxygen bottom waters. Burial of phosphatic fish debris, in contrast, may be enhanced when bottom waters are anoxic, thus partly compensating for the enhanced P release. In the extreme anoxic case, P burial in sediments may come to a complete halt, as suggested by our recent data for Cretaceous Black Shales.

In the second part of the presentation, I will briefly review what is known about the role of hypoxia in controlling benthic P release and P availability in the water column of the Baltic Sea. Deep water oxygen concentrations in the Baltic are strongly influenced by inflows of oxygenated, saltwater from the North Sea and vary with time. The related changes in the hypoxic area and water column DIP are correlated, suggesting an important role for redox-dependent P release from the sediment (Conley et al. 2002). Trends in sediment organic C/total P ratios with depth confirm the importance of enhanced P regeneration from the sediment.

Presentation

The global phosphorus cycle, which controls P-availability, consists of terrestrial and marine inputs and outputs. Examples of sources of terrestrial inputs of phosphorus are weathering, river run-off, fertilizer and sewage. Examples of marine outputs are sediment burial and outflows (in semi-enclosed basins).

Phosphorous in marine systems is buried as Fe-(hydr)oxides or precipitated as carbonate fluorapatite (CFA or authigenic Ca-P). Phosphorous burial is redox dependent which means that a change to anoxic conditions can shut down P burial in sediments.

If there is no S^{2-} present in the sediment, Fe-P is a good sink for P. Authigenic formation of Ca-P is also a good sink for P, however the formation is not possible under anoxic conditions.

Studies of sediment from the Black Sea has shown a clear difference in C:P ratios during anoxic/oxic shifts in the sediment. During oxic conditions P is abundant in the sediment whereas high C:P ratios are present in anoxic sediments due to the release of P. The sedimentation rate during this process is probably important due to low dissolved PO_4-concentrations in sediments with low accumulation rates under anoxic bottom waters.

Burial of all sediment forms of P is redox-dependent. This typically leads to an enhanced feedback loop between primary production, anoxia and P availability. However, enhanced burial of fish debris under anoxia may provide a negative feedback.

Previous studies have shown that for the period 1970-2000 high water column DIP was related to hypoxia. The high DIP has no direct link with TP loads which suggest that DIP values are linked to climatically driven changes in saltwater inflow.

The enhanced regeneration of P relative to C since 1970 is assumed to be due to release of Fe-bound P, but other mechanisms might also contribute. Questions still to be answered are; what are the burial sinks for P in the Baltic, in what form, where, and how much?

In conclusion, the cause of high P availability in the Baltic Sea is related to internal recycling of P. Possible solutions would be to decrease the loads (long term) or stimulate P burial (short and long-term). However, we need more insight into the sediment sinks of P in the past and the present (core data and modeling).

Lunch

Carbon sources for hypoxia by Harri Kuosa

Tvärminne Zoological Station, University of Helsinki, Finland

Harri Kuosa

Abstract by author

We are accustomed to certain thinking on the settling of organic matter in the Baltic Sea: most of it happens after the spring bloom, and very little after it. However, our view is based on quite a different system after major changes have occurred, in at least in the Gulf of Finland. We should probably challenge again the old view. First of all, we do not have proper estimates on the level of productivity at different stages of the succession of the biotic communities. Our view on succession is largely based on biomass (chlorophyll). Second, we have not clearly tested the idea of how different community structures affect settling and burial. The interplay of silicate and nitrogen during spring may be of major importance on diatom cyst formation, and the rate of permanent burial. Similarly, nutrient ratios and other factors may govern species dominance, which affects directly the bacterial breakdown efficiency. Third, we are still satisfied of the notion that cyanobacteria do not settle. This may be true, but the evidence is still scarce. And last, we know very little about the fall period, when obviously some production is happening. I would like to introduce more species-orientated aspects to the mass- or rate-oriented view we have now.

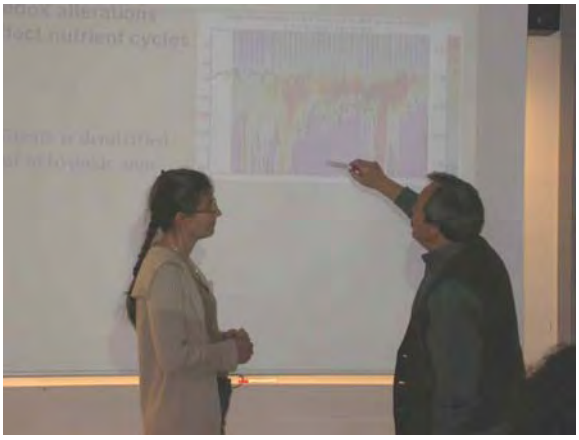
Presentation

Hypoxia has been linked to big global carbon cycling events like the”Snowball Earth” 400-500 million years ago and the Ocean Anoxic Event (OAE) when oceans were anoxic with clear signs of increased organic matter burial.

Carbon is essential in order to develop hypoxia. The anoxic sediments in the Baltic have high organic carbon content. However, we know little about the net primary productivity and the mechanisms producing organic carbon in deep waters. The common view is that the largest production occurs during the spring. However, the tendencies in the Baltic Sea are exceptional with high variability between years and seasons. Furthermore, the role of resuspention during autumns is unknown.

Even though the nutrient load of P and N to the Gulf of Finland has decreased since the late 1980’s the net primary production has increased. The reasons for this variability could be changes in spring bloom community composition from cyst forming towards non-cyst forming species. However, sedimentation efficiency is not the whole story as the rate of permanent burial may vary and respiration losses in sediment surface vary considerably between phytoplankton species resulting in different organic carbon burial which might explain some phenomenon.

The direct effects of oxygen addition to the carbon cycling in the Baltic would be that (1) more organic carbon is respired by extra oxygen (2) carbon dioxide increases (however, direct inorganic carbon limitation is not probable), (3) carbon dioxide affects pH, which may have effects during high productivity periods and on species composition, and (4) the Baltic Sea may become less of a sink of carbon dioxide (and occasional source of it) if oxygen addition affects carbon burial characteristics.



Discussion

Long-term changes in benthic communities in the Baltic with hypoxia by Alf Norkko

Finnish Institute of Marine Research

Alf Norkko

Abstract by author

Soft sediment macrobenthic communities are central elements of Baltic Sea ecosystems and provide important ecosystem services. In the brackish Baltic Sea the distribution and abundance of species is governed by the distinctive salinity and oxygen gradients present which result in strong gradients in species and functional diversity throughout the Baltic. The mosaic of hypoxic disturbance has increased in spatial and temporal extent over the past decades; the widespread oxygen deficiency has severely reduced macrobenthic communities below the halocline in the Baltic Proper and the Gulf of Finland. Large areas of the Baltic Proper are currently entirely devoid of macrobenthic communities. Macrobenthic recovery after hypoxic disturbance is scale-dependent and while the irregular inflows of oxygenated saltwater may bring new macrobenthic colonists to disturbed areas, the magnitude and frequency of these inflows are often insufficient to allow mature communities to develop. In addition, these inflows tend to strengthen water-column stratification in the Gulf of Finland, further promoting the development of hypoxia.

Macrobenthic are relatively long lived (several years) and thus integrate changes and fluctuations in the environment over a longer period of time. These animals bioturbate and irrigate sediments and play an important role in biogeochemical cycling. Recent research has emphasized the importance of macrobenthic animals in providing important ecosystem services and demonstrated links between biodiversity and ecosystem functioning. There are also indications of a link between the biodiversity of macrobenthic communities and the resilience of the system to perturbation. This emphasizes the importance of considering how the hypoxic events are manifested differently along the biodiversity gradients in the Baltic. However, in order to develop our understanding of hypoxia in the Baltic there is an urgent need to develop a better, predictive, understanding of (a) scale-dependent disturbance and recovery processes, including the identification of colonist sources and the connectivity between habitat patches in the disturbance mosaic, (b) feedback loops between hypoxia, benthos, sediment biogeochemistry and ecosystem functioning, and how these feedbacks may change around thresholds and, (c) multiple stressors and factors that co-vary with hypoxia.

Presentation

The main driver of species diversity in the Baltic Sea is the strong gradient in salinity, which means that the northern Baltic basin has less functional diversity in benthos than the southern basin. The benthic communities play a key role in ecosystem functioning because they provide food for higher trophic levels, they increased biogeochemical fluxes through bioturbation and strengthen the relationship between biodiversity and ecosystem functioning.

Bentic communities respond negatively to hypoxia. Studies show that weakened stratification, and abundant food supply fuels benthic production in the Gulf of Finland, while intermittent hypoxia/anoxia slows down community development. Stratification induced hypoxia in the Gulf of Finland has increased since 1964. In the 1990's hypoxia was extremely severe and the situation last year (2006) was the worst recorded hypoxic event in the Gulf of Finland.

During the last c. four decades hypoxia in the Baltic has been very variable. This has lead to high variability in benthic communities over time (1964-2004) and resulted in large reduction in biomass in the Gotland Deep and a general decrease in the Bothnian Sea, of which there is no satisfactory explaination. In areas where hypoxia is common, such as the Gulf of Finland and the Gotland Deep, there have been long periods with no fauna at all. In the southern Baltic Sea shifts in species composition are probably related to changes in salinity. Smaller pulses of oxygen-rich water are often not enough for the survival of benthic communities in the Baltic. As a replacement for the benthic communities you get invasion of opportunistic species which can survive lower O_2 levels. This facilitation by opportunists is important in initial recolonisation process and in understanding disturbance and recovery in benthos. Rate of recovery depends on scale of disturbance and several mechanisms and processes are important in scale-dependent disturbance and recovery, with have implications for ecosystem resilience. Conceptual models may be important in predicting dispersal ability of larvae, post-larvae and adults which affects recolonization ability and demographics.

In conclusion, we need to know more about processes that define resilience, these are:

- Scale-dependent disturbance and recovery effects, colonist sources and connectivity between habitat patches
- Feedback loops between hypoxia, benthos, sediment biogeochemistry and ecosystem functioning
- Changes in ecosystem function around thresholds
- Multiple stressors and factors that co-vary with hypoxia

We should also remember that benthic animals respond to multiple stressors, such as, pollution, H_2S concentration and ammonia. However, hypoxia is the overriding stress factor in the Baltic Sea.

Hypoxia in lakes by Gertrud Nürnberg

Freshwater Research, Ontario, Canada

Gertrud Nürnberg

Abstract by author

When lakes stratify during the warm season or in the winter under ice, oxygen becomes depleted in the bottom (cold) layer to various degrees. Rate and extent of depletion depend on several lake characteristics including: shape, hydrology, trophic state and phosphorus concentration, organic content (from humic acids and increased productivity), and physical conditions (including temperature, mixing, and light penetration).

There are principally three different ways to quantify hypoxia: the determination of oxygen depletion rates, static measures like minimum DO concentration, and the anoxic and hypoxic factor (AF and HF, days per year when an area equal to the lake surface area is covered by water below a certain threshold of DO, e.g. <1-2 mg/L for AF).

Quantification of and relationships with AF and HF as outlined in my Area of Expertise will be presented and possible application to marine systems like the Baltic will be indicated. Effects of hypoxia in freshwater systems and treatment options will be discussed. Treatments include: injection of air or oxygen at various depths, including layer application or whole lake mixing; the withdrawal of water low in oxygen via the lake restoration technique of hypolimnetic withdrawal and the covering of sediments with inert material. Generally, the reduction of productivity (reduced trophic state and eutrophication) due to decreased external and internal loading is assumed to decrease hypoxia, although high sediment oxygen demand often delays improvement.

Presentation

Hypoxia in lakes is controlled by various physical, chemical and biological factors, such as, morphometry (e.g. depth versus. area), hydrology, temperature, stability (stratification versus mixing), nutrient availability (phosphorus and nitrogen), organic load, and productivity (algae and bacteria).

In Canada, numerous freshwater lakes are seasonally hypoxic with oxygen depletion in the bottom waters during summers and winters. During spring and autumn, when the thermocline is weak, the water columns are often mixed.

You can quantify hypoxia/anoxia in lakes by determine oxygen depletion rates and it’s extent in space and time (anoxic factor). Quantifying hypoxia/anoxia provide you with the opportunity to study causes and effects of oxygen depletion and look at treatment options.

Quantification of hypoxia/anoxia has been performed for e.g. the Great Laurentian

Lakes, kettle lakes (deep but small), reservoirs with high nutrient load, shallow (polymictic) lakes and reservoirs, and humic acid rich “brown” small lakes, despite oligotrophy. Parameters measured in these freshwater bodies are the minimum DO concentration, rate of areal and volumetric hypolimnetic oxygen deficit (AHOD & VHOD) and the expanse of the anoxic and hypoxic factor. Anoxic factor (AF) or hypoxic factor (HF) represents the number of days per year or season that a sediment area, equal to the lake surface area, is anoxic or hypoxic. The threshold DO concentrations in Canadian lakes are 1-2 mg/L for anoxia and 5-6 mg/L for hypoxia. For example, a HF of 365 d/yr means that hypoxia occurs everywhere all year round.

The AF and HF factors give you the opportunity to:

- Test relationships with water quality variables, trophic state, and hydrological conditions (reservoir management)
- Forecast potential effects of climatic change on DO content and internal P load
- Estimate internal P load (multiplied by anoxic areal release rate)
- Explore habitat constraints due to hypoxia (fish species richness and winterkill)
- Establish criteria and guidelines with respect to hypoxia
- Evaluate restoration techniques targeting oxygen depletion

You can predict or model AF since AF is a function of (1) the bottom water minimum redox potential and iron content, and (2) annual or summer average lake water TP concentration and lake shape. You can apply modeled AF in lakes to (1) quantitative and precise comparison in space, time, and between systems, (2) quantify internal load, (3) test hypotheses on DO dependency, (4) classify trophic state, (5) set DO guidelines, (6) forecast future hypoxia due to climate warming, and (7) hindcast from paleolimnological records.

The models have the potential to be applied to the Baltic Sea. For example, they could be used to determine thresholds of important DO concentration, determine AF and HF, look for patterns, trends and correlations with e.g. location, time, morphometry and hydrology, water and sediment characteristics, EH, biota and climate parameters. They could also be applied to assess P sediment release, N reduction and be used as guidelines.

There are various treatments available in order to reduce hypoxia in lakes. At present these are (1) reduce the trophic state (or productivity), (2) layer-aeration or oxygenation, avoiding mixing (problem: treatment of symptoms, not causes), (3) withdrawal of stagnant hypoxic water layers (problem: treatment of withdrawn water), (4) sediment oxidation by nitrate and (5) sediment covering (aluminum or clay).

The drawbacks of aeration or oxygenation of lakes are (1) the use of undersized aerators which results in high SOD, (2) that you may not prevent P release since sediment surfaces are still anoxic, (3) that you treat the symptom not the cause, (4) that it requires constant (long-term) commitment, and (5) that it may create worse conditions.

However, aeration under ice-covered lake surfaces has been shown to be useful to prevent fish winter-kills. Furthermore, withdrawal of hypolimic waters in stratified lakes has also been shown to be a good technique since oxygen levels increases just within a few years after management.

Can you treat hypoxia in the Baltic Sea as in lakes? The potential treatments could be (1) reduce trophic state (productivity), (2) withdraw stagnant hypoxic water layers (problem: treatment of withdrawn water), (3) sediment covering with aluminum or clay, or (4) layer-aeration without mixing the water column (problem: treatment of symptoms, not causes).

Summary

The main goal off this workshop was to create an improved understanding of hypoxia in the Baltic Sea and determine if there are technical solutions that can mitigate the devastating environmental effects of hypoxia on living resources and restore the self-purifying biogeochemical processes. The outcome of the workshop was very constructive as our knowledge and gaps in understanding hypoxia were established and many valuable ideas for future research were proposed.

Knowledge and Gaps

Hypoxia in the Holocene

We know from observations and from inventories of laminations in the uppermost sediments that hypoxia/anoxia in the Baltic Sea has increased since 1960. We also know from short sediment cores that hypoxia has been present in some basins for at least the last 100-200 years. Hypoxia is on average about 4 times greater today than in 1900. But what about the more distant past? Analyses of long sediment cores suggest that hypoxia in the modern Baltic (<8000 cal. yr BP) has occurred intermittently, at least in deep basins such as the Gotland Deep. However, the spatial and temporal extent is poorly known. So are the causes. Have the physical oceanographic conditions the largest affect on the oxygen concentration in bottom waters in the basin or does climate play an important role? Furthermore, what are the natural range of hypoxia variability and the role of early human impact? And maybe the most important question to answer, how will the Baltic Sea respond to a potential climate change in the future? To answer these questions, effort much be invested to determine the temporal and spatial distribution of hypoxia during the last c. 8000 years.

Physical constraints

It has been concluded that oceanographic models provide a reasonable description of the average general circulation and the large inflows events, but we need to know more about intermediate inflows. We have recognized that oxygen can be present at intermediate depths during stagnation periods and result in improved bottom conditions. We also know that at steady-state, when freshwater inputs are high there are smaller saltwater inflows into the Baltic, e.g. the processes are transient. However, the resolution of the data is not sufficient to verify the fine-resolution produced by the models which means that when one models intermediate depths below the halocline the biogeochemistry becomes very sensitive to small errors in the physical parameters. Consequently, improved oceanographic models are needed.

Phosphorus dynamics

The general biogeochemistry of P is reasonably well known and we know that P is released from sediments under hypoxia/anoxia. Phosphorous can be pushed upwards into the water column during salt water inflows to the Baltic Sea. Most of this phosphorus appears to return to the sediments, but what fraction of the internal load makes to the surface and goes into productivity remains unknown. Upwelling can be an important regional input of nutrients especially in coastal areas. The magnitude of upwelling is not known and needs to be quantified. Also the long-term sediment sinks of P in the Baltic are unidentified. These are essential to recognize if we want to increase the efficiency of P burial.

Nitrogen dynamics

It has been acknowledged that denitrification is a major sink for N and that it occurs in both the sediments and the water column. However, large scale quantification of denitrification at the size of the Baltic Sea is poorly known. What also need extra attention are the potential changes in denitrification and annamox with hypoxia, which are hotly debated.

N biogeochemical processes below the halocline and across the oxic-anoxic transition are unidentified and must be investigated. In addition, nitrification is a key unknown process.

Carbon sources

Carbon is the basis of hypoxia/anoxia. During hypoxia, preservation (or burial) of organic carbon increases. A large amount of the sedimentation of organic carbon derives from resuspension, which is an important component of the total mass-balance. Today we don’t have a comprehensive view of sedimentation and resuspension rates.

Other important issues that are poorly known are organic productivity, the role of cyanobacteria sedimentation to the bottom, and the role of brownification.

Biodiversity issues

Hypoxia/anoxia greatly influences benthic communities. We know that hypoxia often causes a temporal and spatial mosaic of disturbance. However, the biodiversity in the Baltic Sea also depends strongly on salinity gradients. Additionally, long-term changes in the average salinity have a significant impact on benthic diversity.

There is a potential possibility for regime shift(s) in the Baltic due to increases in hypoxia. Such a regime shift would have an unknown impact on the Baltic Sea biodiversity since the recovery of benthic communities is, so far, unpredictable. Possible species invasions will have an unknown impact upon the Baltic Sea. Functioning food webs are vital for the biodiversity. However, we lack knowledge about, for example, zooplankton in Baltic food webs.

Miscellaneous

One important outcome of this workshop is the comprehension that metrics of hypoxia/anoxia need to be calculated by basin, rather than for a system as whole. Furthermore, we need to set up specific goals or targets in order to proceed with management issues. Before any large scale engineering is implemented we must also investigate the potential consequences on biogeochemical cycles and biodiversity.

Model experiments will probably be important in determining the best way forward in management decisions. However, we lack a sediment model and we lack data to verify such a model. Additional questions to consider are: (1) how long will it take the Baltic to respond to a measure and (2) how sensitive would an artificially oxic Baltic be to a new disturbance?

Program

Tuesday 17 April

9.00-9.30

Welcome and Introduction, Daniel Conley, Svante Björck and Erik Bonsdorff

9.30-10.10

Hypoxia in the Baltic Sea, Oleg Savchuck

10.10-10.50

The postglacial Baltic Sea history -What can the geologic record teach us about likely processes behind hypoxia? Svante Björck, Daniel Conley and Lovisa Zillén

11.10-11.50

Physical constraints to hypoxia in the Baltic, Bo Gustafsson

11.50-12.30

5 min Presentations

1. Svante Björck
2. Marloes Kortekaas
3. Kjell Nordberg
4. Markus Meier
5. Fred Wulff
6. Siv Johansson

13.30-14.15

Key note lecture: The dead zone in the Gulf of Mexico, Nancy Rabalais

14.15-17.00

Discussion: Chairman: Rutger Rosenberg

Wednesday 18 April

8.30-9.10

Effect of hypoxia on the N biogeochemical cycle, Susanna Hietanen

9.10-9.50

Effect of hypoxia on the P biogeochemical cycle, Caroline Slomp

10.10-10.50

Carbon sources for hypoxia, Harri Kuosa

10.50-11.30

Long-term changes in benthic communities in the Baltic with hypoxia, Alf Norkko

11.30-12.30

5 min Presentations

1. Jacob Carsten
2. Georgia Destouni
3. Bärbel Müller-Karulis
4. Heikki Pitkänen
5. Rutger Rosenberg
6. Lovisa Zillén

13.30-14.15

Key note lecture: Experience of hypoxia from lakes, Gertrud Nürnberg

14.15-17.00

Discussion: Chairman: Nancy Rabalais

Thursday 19 April

9.00-12.30

Discussion: Chairman: Daniel Conley and Erik Bonsdorff

Participant's area of expertise

Svante Björck, GeoBiosphere Science Centre, Department of Geology, Lund University, Sölvegatan 12, SE-223 62 Lund, Sweden, E-mail: svante.björck@geol.lu.se. Svante Björck's research involves different aspects of Quaternary geology in different parts of the world. Climate development during the last glacial cycle is studied in the Atlantic region, particularly on Atlantic islands, from Greenland to Antarctica. Specific interests are abrupt climate changes, exactly when they took place, the processes that caused them and their impact on the surrounding environment. A special aim is to map, in time and space, climatic events on the two hemispheres in order to understand the climatic coupling between them. Björk's research also includes the relation between sea-level changes and land uplift on southern Greenland and Scandinavia. One of his special interests is the late Quaternary development of the Baltic Sea, with its complex interplay between changing sea-levels, irregular land-uplift and variable climate.

Erik Bonsdorff, BS2020, Envirinmental and Marine Biology, Åbo Akademi University, FI-20500 Turku/Åbo, Finland, E-mail: erik.bonsdorff@abo.fi. Research interests: General Baltic Sea ecology and long-term changes in the Baltic Sea (especially coastal and archipelago waters). Biodiversity-issues, and couplings between the biota and their habitat and environment. Environmental issues. Executive member of the Scientific Council of the Baltic Sea 2020-foundation.

Jacob Carstensen, National Environmental Research Institute, Department of Marine Ecology, Aarhus University, Frederiksborgvej 399, DK-4000 Roskilde, Denmark, E-mail: jac@dmu.dk. Research interests: Environmental modeling and statistics, particularly quantitative links between anthropogenic inputs and effects in the marine environment. I am interested in long term trends of ecosystem variables and how they respond (linearly and non-linearly) to changes in nutrient input and climate. Such links have primarily been established in Danish coastal waters for nutrients, phytoplankton, macrophytes and oxygen conditions. Development of indicators that give a clear signal to anthropogenic inputs by filtering out sampling and meteorologically induced variations. After the large oxygen depletion in Danish waters in 2002 a spatial interpolation technique was developed to assess and quantify the extent of hypoxia, and this technique has now become standard reporting. These results have also been projected to assess ecological effects on the benthic fauna and fish burying into the sediments.

Daniel Conley, GeoBiosphere Science Centre, Department of Geology, Lund University, Sölvegatan 12, SE-223 62 Lund, Sweden, E-mail: daniel.conley@geol.lu.se. Research interests: Nutrient biogeochemical cycles, especially Si, and the linkages between land and aquatic ecosystems. I am interested in long-term trends due to climate and nutrients and how ecosystems respond to changes in the drivers. Some of my work has focussed on the response of nutrient biogeochemical cycles (P and N) in the Baltic to hypoxia. In addition, our research in Danish coastal waters has shown that dissolved oxygen concentrations can be related to nutrient load, temperature and water exchange. Finally, coastal marine ecosystems that get hypoxia appear to go through a threshold response with the loss of benthic communities and reduction in sediment oxygen equivalents, making them more susceptible to further intensification of hypoxia.

Georgia Destouni, Department of Physical Geography & Quaternary Geology, Stockholm University, SE-106 91 Stockholm, Sweden. E-mail: georgia.destouni@natgeo.su.se. **Personal webpage:** http://people.su.se/~gdest. Georgia Destouni is professor of hydrology, hydrogeology and water resources at the Department of Physical Geography and Quaternary Geology, Stockholm University. Her research interests include hydrological spreading and transformations of nutrients and pollutants in and through inland water systems and further to coastal waters, groundwater-surface water and freshwater-seawater interactions, methods to account for the hydrological processes and system interactions and their uncertainties in environmental management and policy, economic efficiency of waterborne nutrient and pollutant load abatement. Several recent contributions regard specifically nutrient and pollutant loading from land to the Baltic Sea, management and policy for abatement of this loading, and future abatement scenario analysis.

Bo Gustafsson, Earth Science Center, Göteborg University, P.O. Box 460, SE-405 30, Göteborg, Sweden. E-mail: bogu@oce.gu.se**.** Research interest: All aspects of the Baltic Sea. I have work with physical modeling of the circulation on time scales from 1000s of years to days. In the last years I have deepened my interest and knowledge in biogeochemical processes and their coupling to physics.

Susanna Hietanen, Department of Biological and Environmental Sciences, Division of Aquatic Sciences, University of Helsinki, PO BOX 65, 00014 University of Helsinki, Finland, E-mail: susanna.hietanen@helsinki.fi**.** Research interests: Nitrogen cycling in the Baltic Sea sediments. I have years of experience in microbial ecology (carbon and nitrogen cycling) both in benthic and pelagic environments. After finishing my PhD in 2002 I have focused in benthic denitrification and anammox and the factors controlling these anaerobic processes in the coastal Baltic Sea. I am currently widening my expertise to cover also nitrification (aerobic) and DNRA (anaerobic), as well as the molecular biology of all the nitrogen processes. I supplement my field studies with experimental approaches using mesocosms with different manipulations, such as sedimenting algal biomass, oxygen concentration changes, sediment structure changes and altered bioturbation.

Sif Johansson, Baltic Sea 2020, The Royal Swedish Academy of Science, P.O. Box 50005, 10405 Stockholm, Sweden, E-mail: sif.johansson@balticsea2020.com. Research interest: My main interest is effects of eutrophication in the Baltic Sea and measures to improve the marine environment. I have coordinated the research program Marine Research on eutrophication – A Scientific Base for Cost-Effective Measures for the Baltic Sea (MARE) 1999-2007. For maintenance and further scientific development of the main product of that program, the decision support system Baltic Nest (www.mare.su.se/nest), the Baltic Nest Institute will be established at Stockholm and Århus Universities during the spring 2007. I am also working part time at the Research Secretariat at the Swedish Environmental Agency, where I am responsible for coordinating marine research financed by the Agency and I am engaged in developing the international Baltic Sea research program BONUS+ (www.bonusportal.org), as the Agency is one partner in the ERA.net program BONUS for the Baltic Sea Science – Network of Funding Agencies.

Marloes Kortekaas, GeoBiosphere Science Centre, Department of Geology, Lund University, Sölvegatan 12, SE-22362 Lund, Sweden, E-mail: Marloes.Kortekaas@geol.lu.se. Research interests: Palaeoenvironmental studies, marine geology, geochemistry, mineral magnetics and geochronology (Optically Stimulated Luminescence (OSL) dating). The last 4 years I focused on the post-glacial sea-level and environmental changes in the southern Baltic Sea.

Harri Kuosa, Tvärminne Zoological Station, J.A. Palménin tie 260, FI-10900 Hanko, Finland, E-mail: harri.kuosa@helsinki.fi. Research interests: Phytoplankton communities, production dynamics and effect of eutrophication in the Baltic Sea. Sea-ice biology in Antarctica and Baltic Sea. I am interested to know why certain species thrive, and others not. This has led also in studying top-down effects by zooplankton. I am also involved in the studies on microbial loop, and its importance in carbon cycling. My main interest in hypoxia is in its top end i.e. how the produced organic carbon is transferred to lower layers of the sea, and how it creates nutriclines, which may affect algal life.

Markus Meier, Division of Oceanography, Research Department, Swedish Meteorological and Hydrological Institute, SE-601 76 Norrköping, Sweden, E-mail: markus.meier@smhi.se. Research interests: past and future climates of the Baltic Sea and Arctic Ocean. I am interested in the long-term variability of coupled physical-biogeochemical systems. My work has focussed on the development of sea-ice ocean circulation models for attribution studies. During the last century in the Baltic Sea three stagnation periods in the 1920/1930s, 1950/60s, and 1980/1990s were found. The first and the third periods are caused by positive inter-annual fresh water inflow and zonal wind anomalies whereas the second period is the non-linear response of the very strong inflow of 1951. Very recently we started to study the impact of climate change on the Baltic ecosystem.

Bärbel Müller-Karulis, Latvian Institute of Aquatic Ecology, 8 Daugavgrivas, LV-1048 Riga, Latvia. E-mail: Baerbel@latnet.lv. Research interests: Modeling of nutrient biogeochemical cycles in the Baltic, especially in the Gulf of Riga. More recent work has been involved with the statistical analysis of long-term trends in hydrographical, chemical, and biological time-series in the Baltic Proper. In the Baltic Proper ecosystem, oxygen deficiency and nutrient accumulation in the bottom waters during stagnation periods are an important structuring factor.Finally, I am also interested in the effects of low oxygen conditions in theBaltic Proper on the reproduction conditions of Baltic cod and flounder.

Kjell Nordberg, Dept. of Earth Sciences, Göteborg university, PO Box 460, SE-405 30 Göteborg, Sweden. E-mail: k.nordberg@oce.gu.se. Research interests: The relation between oxygen deficiency, climate, and human impact on periodically anoxic fjords and estuaries on the Swedish west coast. I work mainly in areas where long, historical records of hydrography data are available. Important tools are: high quality sediment samplers (undisturbed surface sediments and sediment records), X-raying of sediment cores (quality control and laminations), age determinations, stable oxygen and carbon isotopes (temperature and salinity), micro fossils (benthic foraminifera, dinoflagellate cysts, diatoms), climate records and environmental monitoring data. Interval studied: 0-100 yrs, 0-4000 yrs.

Alf Norkko, Finnish Institute of Marine Research, P.O. Box 2 (Erik Palméns plats 1), FI-00561 Helsinki, Finland, E-mail:alf.norkko@fimr.fi. Research interests: The ecology of benthic communities in marine soft-sediment habitats. At the Finnish Institute of Marine Research I am responsible for the long-term monitoring of benthic communities in the open Baltic Sea (commissioned by HELCOM). In addition, our current research focuses on the resilience and recovery potential of soft-sediment communities, and the importance of the temporal and spatial scale of disturbance for the recovery mechanisms. For this research we integrate process-oriented experimentation in coastal waters, with the analysis of existing benthic monitoring data from the open Baltic Sea. The aim is thus to test how predictions based on smaller-scale experiments may be applied to benthic recovery dynamics at scales relevant to most environmental problems, such as eutrophication and hypoxia.

Gertrud K. Nürnberg, Freshwater Research, 3421 Hwy 117, Baysville, Ontario P0A 1A0 Canada, E-mail: gkn@fwr.on.ca ***Website:*** http://www.fwr.on.ca. Research interests: Eutrophication and restoration of freshwater lakes and reservoirs, nutrient recycling processes from bottom sediments like "internal phosphorus (P) load", empirical and mass balance modeling of nutrient concentration, phytoplankton biomass and hypolimnetic anoxia for classification, target setting and management purposes. - A large part of the variance of P release from sediment surfaces is due to spread and duration of sediment anoxia. Therefore, I've developed a simple method (Anoxic Factor) to quantify annual anoxia in lakes and reservoirs from dissolved oxygen (DO) profiles. In addition, a hypoxic factor can be defined, by using different DO limits (e.g. 5 mg/L instead of 1-2 for anoxia). Anoxic factor cannot only be used to predict internal load (multiplied by anoxic areal release rate), but I also used it to (1) test relationships with water quality variables, trophic state, and hydrological conditions (reservoir management), (2) evaluate restoration techniques targeting oxygen depletion, (3) explore habitat constraints due to hypoxia (fish species richness and winterkill), (4) forecast potential effects of climatic change on DO content and internal P load, (5) and establish criteria and guidelines with respect to hypoxia.

Heikki Pitkänen, Finnish Environment Institute, Box 140, FI-00251 Helsinki, Finland, E-mail: heikki.pitkanen@ymparisto.fi. Research interests: Biogeochemical cycles and budgets of nutrients (N, P) in the coastal and open Baltic Sea, especially the Gulf of Finland. The use of ecosystem modeling in searching cost-efficient measures to combat eutrophication. I'm interested in the role of sediment release of nutrients in the overall N and P budgets of the Baltic Sea and its sub-basins, and the factors controlling these, i.e. physical conditions, sedimentation of organic matter, as well as the availability of deep water oxygen and oxidizing agents in the sediment surface layer.

Nancy N. Rabalais, Louisiana Universities Marine Consortium, 8124 Hwy. 56, Chauvin, LA 70344 USA, E-mail: nrabalais@lumcon.edu. Research Interests: the dynamics of hypoxic environments, interactions of large rivers with the coastal ocean, estuarine and coastal eutrophication, environmental effects of hypoxia, habitat alterations and contaminants, and science policy. She is an author and co-editor of a book on "Coastal Hypoxia: Causes and Consequences" and has published many articles on the dynamics of Gulf of Mexico hypoxia, its effects, its relationship with discharge and nutrient flux of the Mississippi River, and palaeoindicators of historical hypoxia.

Rutger Rosenberg, Department of Marine Ecology, Göteborg University, Kristineberg Marine Research Station, 450 34 Fiskebäckskil, Sweden. Email: rutger.rosenberg@kmf.gu.se. Research interests include the effects of hypoxia on zoobenthic communities, and the role of infauna for the sediment/water-fluxes.

Oleg Savchuk, Baltic Nest Institute, Stockholm Resilience Centre, Stockholm University, SE-10691, Stockholm, Sweden, E-mail: oleg@mbox.su.se. Research interests: Mathematical modeling as a tool to study marine ecosystems, with emphasis on biogeochemical cycles. Since 1970 I have been involved in the development and implementation of simulation models for the North, Baltic, Barents and White seas' ecosystems, being responsible for a parameterization of chemical and biological inter-actions. In the interests of the Baltic Nest Institute I am currently working with box (SANBALTS), multi-basin high vertical resolution 1D (BALTSEM), and 3D (SPBEM) simulation models of the coupled nitrogen, phosphorus, and silica cycles in the Baltic Sea. Naturally, we are using empirical information at all steps of modeling, starting from system description of the objects and ending with validation.

Caroline Slomp, Department of Earth Sciences Geochemistry, Faculty of Geosciences, Utrecht University, Budapestlaan 4, 3584 CD Utrecht, the Netherlands, E-mail: slomp@geo.uu.nl. Research interests: Biogeochemical cycling of nutrients (P, N, Si) in aquatic and terrestrial environments and effects of land-ocean transfer. I am particularly interested in improving the mechanistic understanding of redox-dependent P burial in sediments and the consequences for nutrient availability on a basin and global ocean scale. I work with sediments from both modern and ancient anoxic environments (e.g. Black Sea and Indian Ocean sediments, Mediterranean sapropels, Cretaceous Black Shales) and use mathematical models to interpret data and assess the system response.

Fredrik Wulff, Department of Systems Ecology and Baltic Nest Institute, Stockholm University, Sweden. E-mail: wulff@mbox.su.se. Research interest: linking models of marine ecosystems (physics, biogeochemistry and ecology) with models of drainage basin characteristics into decision support systems useful for management.

Lovisa Zillén, GeoBiosphere Centre, Department of Geology, Lund University, Sölvegatan 12, SE-223 62 Lund, Sweden, E-mail: lovisa.zillen@geol.lu.se. Research interests: Hypoxia in the Baltic Sea during the Holocene, it's spatial and temporal resolution, trigger and driving mechanism(s). I have also worked with annually laminated lake sediments (ALL) in Sweden - the climate and environmental prerequisites for the formation of ALL and their potential as chronological tools in studies of Holocene climate changes.

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Appendix 2

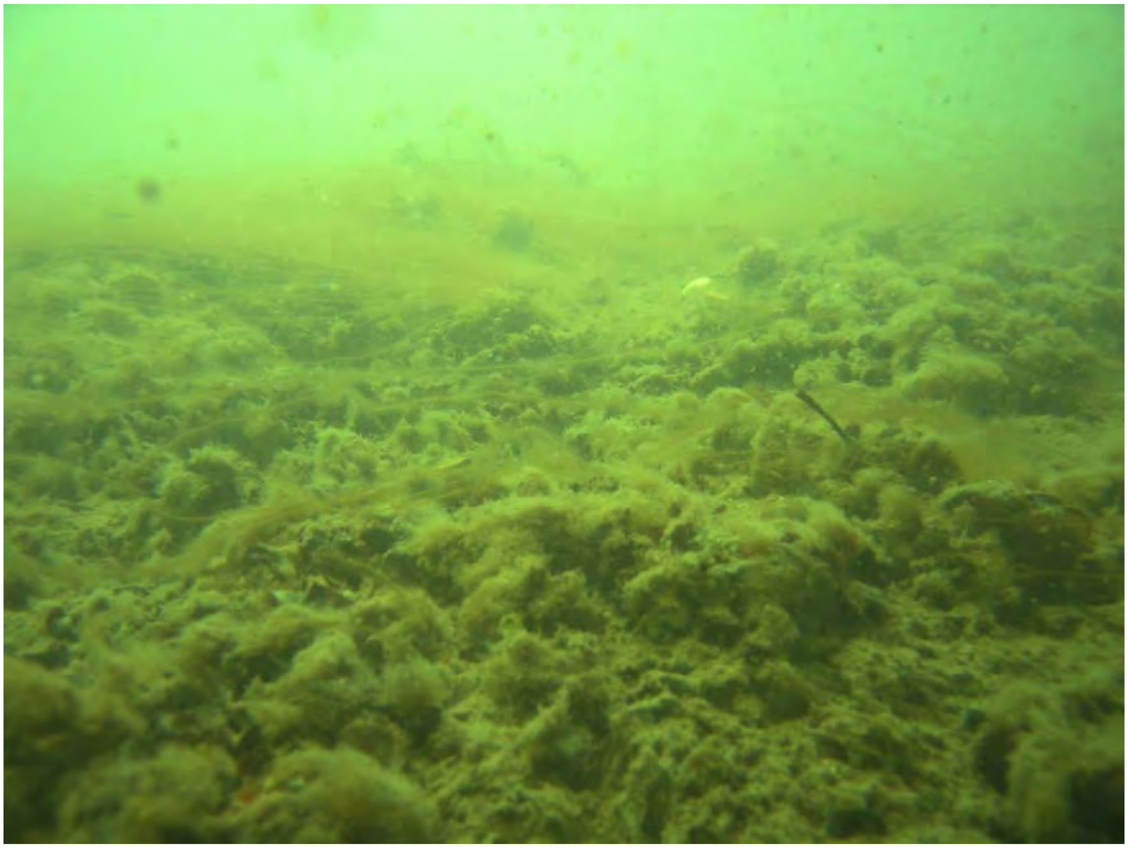
Draft report

Report from the workshop:

Exploring the causes and consequences of coastal hypoxia

A workshop held 16-18 October 2007 at Åbo Akademi University, Finland

Britt-Marie Jakobsson & Erik Bonsdorff



Baltic Sea 2020

Last edited 3 January 2008

Contents

Background

The aim of the foundation Baltic Sea 2020 is to stimulate creative interdisciplinary and international collaboration in a variety of areas resulting in political, economical and physical measures taken to improve the environment of the Baltic Sea. In the upcoming years the foundation will assist the generation of new knowledge essential for improving the condition of the Baltic Sea. In order to do so Baltic Sea 2020 will encourage the creation of new networks between Baltic Sea scientists from different disciplines and support new innovative research by investing in projects and experimentation with a practical solution to the problems in the Baltic Sea.

In spring 2007 a series of four workshops on hypoxia (oxygen depletion) in the Baltic Sea was initiated. The aims of the series are to collect the existing scientific knowledge on the phenomenon and to identify gaps in the knowledge in order to find potential solutions to the problem. Researchers with different expertise on the Baltic Sea hypoxia have been invited to these workshops. The main part of the researchers is from the countries surrounding the Baltic Sea.

The first workshop on “Understanding hypoxia in the Baltic Sea” was held in Lund (17-19 April 2007), while the second one, on the theme “Exploring the causes and consequences of coastal hypoxia”, was arranged in Turku 17-19 October 2007.

Introduction

Already at the beginning of the 20th century, eutrophication (nutrient over-enrichment) was a nuisance for people living in cites on the Baltic coast. The seaside cities discharged their wastewater, the content high in nutrients and solid organic matter, directly into the sea with severe consequences. As early as the 1910s cyanobacterial blooms typical of eutrophied waters where observed off both Stockholm and Helsinki (Bernes 2005, Laakkonen & Laurila 2007). During the following decades the continuously increasing nutrient loads to the coastal waters gave rise to extensive primary production, increased sedimentation of organic matter with hypoxia as one consequence. “Dead” bottoms where quite common off coastal cities on the Baltic Sea shore during the first half of the 20th century. The situation gradually improved in the 1950s, when the first wastewater treatment plants were introduced. Even though the oxygen concentrations in the bottom waters started to rise in the vicinity of the outlets the situation has continued to slowly deteriorate off the coast, further away from urban areas and in coastal areas with no point sources.

The coast is according to the encyclopaedia Britannica the broad area of land that borders the sea, while the Swedish counterpart National Encyklopedin defines the coast as the zone where land encounters the sea – the border between coast and open sea made up by the depth where storm waves stop influencing the sea bottom (10-50 m depending on coastal type). In both definitions the emphasis is on land, a factor that influences the coastal waters directly.

Of the nutrients entering the Baltic Sea, most of the load derives directly from land, as land run-off, river-outflow or as sewage. The nutrient load is naturally higher to the coastal areas than to the open sea, and thus the coastal waters can be expected to have a higher nutrient content even if they would be in a relatively “pristine” condition. Anon.

(1987) estimated that approximately 60 % of the nitrogen and 90 % of the phosphorus originally derives from land. As the nutrient loading to the Baltic Sea, and thereby foremost to the coastal waters, has increased fourfold for phosphorous and eightfold for nitrogen (Larsson et al. 1985), the negative effects of nutrient enrichment or eutrophication can be expected to be severe in the coastal areas. Today the so called "internal loading" is often considered the main source of stress to the system.

The coastal areas most heavily affected by nutrient loadings are sheltered water bodies with a small volume and restricted water exchange. Typical water bodies would be fjords, lagoons and archipelago areas, which are all found along the 8000 km Baltic Sea coastline. The coasts of Sweden and Finland are generally rocky with several archipelago areas, the Archipelago Sea and the Stockholm archipelago being the best known. In the south-western Baltic area fjords and bays dominate, whereas the southern and south-eastern coast is flat and low-lying, dominated by sand and distinctive lagoons or haffs.

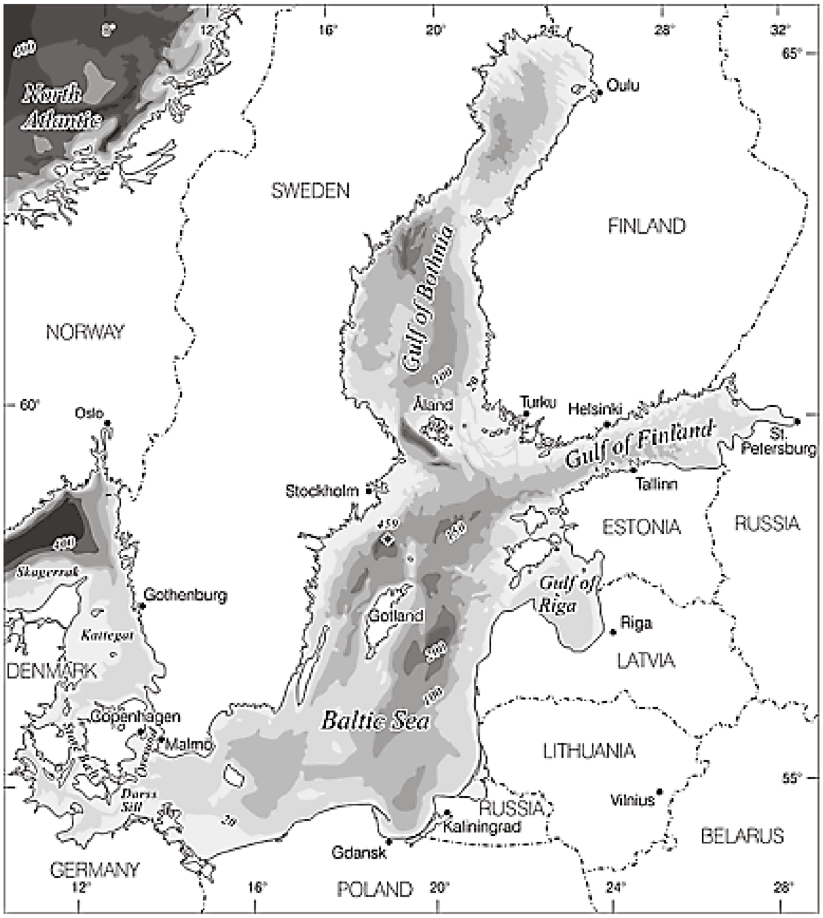


Fig. 1. The Baltic Sea and surrounding countries (Tikkanen & Oksanen 2002).

Hypoxia is often considered the most severe effect of eutrophication and one stage in the vicious circle that rising nutrient concentrations cause. Increasing concentrations of nutrients in the water during winter lead to a larger spring bloom, much of which sinks to the bottom with increased oxygen consumption as a consequence. Initially eutrophication might have a stimulatory effect on benthic communities, but, with increasing hypoxia a change in the bottom fauna occurs, and eventually elimination of all aerobic organisms happen. When the sea bottom becomes hypoxic its capacity of binding nutrients diminishes and internal loading is initiated, increasing the nutrients in the water column even more.

Hypoxia is normally a seasonal phenomenon in the coastal waters, as the coastal areas are relatively shallow, and a halocline is usually lacking with an effective turnover of the water masses twice a year as a consequence. However, during late summer and autumn a thermocline might prevent oxygen-rich water from the surface of reaching the bottom layers, crating favourable conditions for hypoxia.

Even thought hypoxia in coastal waters has been a problem for a long time, the phenomenon has gained quite little interest during the last decades and relatively little is known about e.g. the extent and distribution of hypoxia in coastal waters, as the main focus of hypoxia research has been on the open Baltic Sea and the deep waters. Furthermore, modelling of the coastal ecosystem has proven to be more problematic than that of the open Baltic Sea, due in part to the structural complexity of the system, and in part to the lack of reliable historic data.

In order to gain a comprehensive picture of the coastal hypoxia situation in the Baltic Sea, a workshop was arranged in Turku (Finland) to describe what we currently know and where information is lacking. During three days of presentations and discussions the geographical and regional magnitude of coastal hypoxia around the Baltic Sea, possible remedies to coastal hypoxia, and management options and the need for modeling and ecological engineering were considered.

"There are good reasons to believe that eutrophication will, in the near future become a common hazard in marine coastal areas in many parts of the world, with consequent potentially damaging effects on both inshore fisheries and recreational facilities" (Rosenberg 1985).

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Presentations by invited speakers – abstracts provided by the authors

Robert Diaz VIMS, USA:

An overview of coastal hypoxia

Up to the 1950s, reports of mass mortality of marine animals caused by lack of oxygen were limited to small systems that had histories of oxygen stress. From 1960s there has been a decadal doubling in the number of systems with reports of hypoxia or anoxia around the globe. By the 1990s most estuarine and marine systems in close proximity to population centers report oxygen depletion. The 1990s also saw the first signs that improvements in hypoxia were possible in a large system that had developed annual hypoxic. In the Black Sea, reduced nutrient loading lead to almost complete elimination of the annual coastal hypoxia. Improvements seen in US systems from nutrient regulation include: Hudson River, Delaware River, East River. In Europe, improvements were seen in the Mersey Estuary, Elbe Estuary, and Idefjord. Not all systems with nutrient management plans in place have shown significant improvements in the amount of hypoxia, such as Chesapeake Bay and Lake Erie in the US and Tokyo Bay, Japan.

Increased nutrient loading has been the key common factor in all these systems. Nutrients lead to production of organic matter and eutrophication, which leads to lower dissolved oxygen it the physics of the system are right. Physical, chemical and biological processes interact in similar ways around the globe to generate hypoxia. Hypoxia is a paradox of eutrophication. High levels of primary production sustain higher trophic levels, but overloading an ecosystem with organic matter leads to hypoxia, in many cases, which than leads to trophic changes, lower diversity, and microbes become more prominent. Examples from the US will be presented showing a the range of response from recovery in Boston Harbor to nutrient reductions to no change Chesapeake Bay after target nutrient reductions were reached.

A disturbing trend that has emerged in the 2000s is the possible expansion of oxygen minimum zones (OMZs) related to anthropogenic activity involving climate change and nutrient loadings. Currently, the area of all eutrophication driven hypoxia (207,000 km^2) is about 18% of the seafloor affected by OMZs (1,148,000 km^2). Since most of the hypoxic and OMZ area is along the coast, the potential for expansion of coastal hypoxia is high.

In the 2000s the amount of low dissolved oxygen continues to expand. To further understand eutrophic and hypoxic areas, increased water quality monitoring of estuarine and coastal systems, especially in terms of nutrient levels, dissolved oxygen, and chlorophyll is needed. Common assessment criteria for indicators of eutrophication and hypoxia need to be developed.

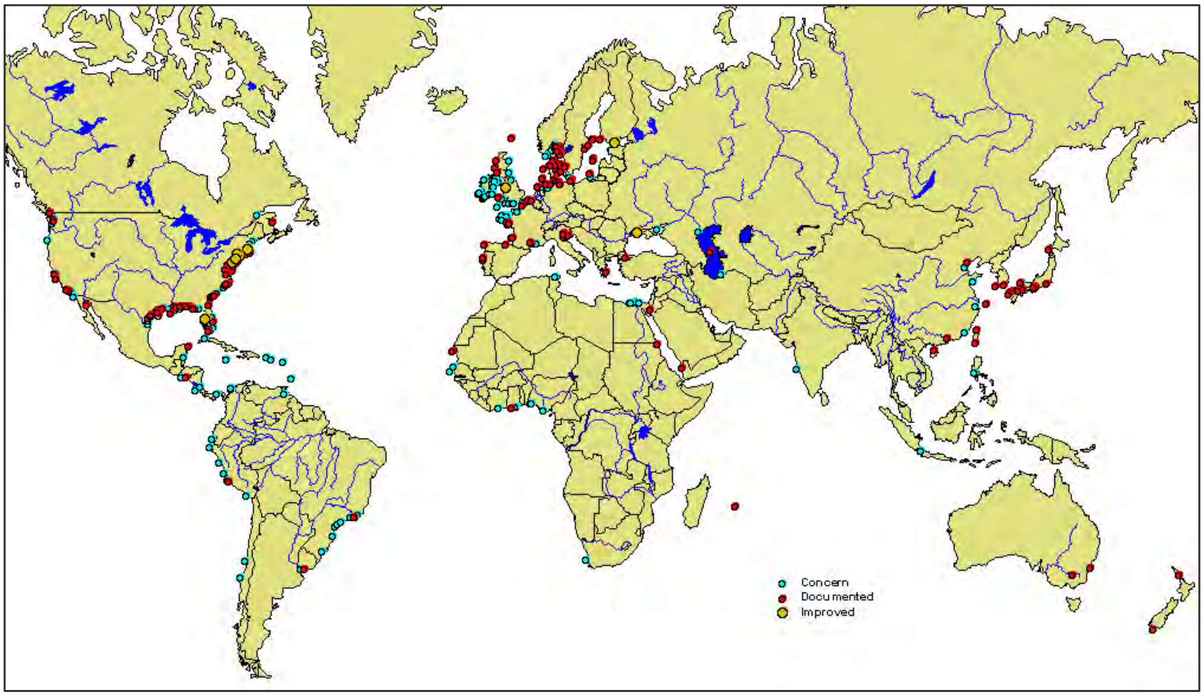

Fig. 2. Global distribution of eutrophication related hypoxia. There are 222 hypoxic areas globally (13 in recovery), whereas 124 eutrophic areas are threatened with development of hypoxia.

Kristina Sundbäck (with input from *Leif Pihl* and *Susanne Baden*), Göteborg University, Sweden:

West coast of Sweden – hypoxia and shallow-water ecosystems

Hypoxia is not only a deep-bottom phenomenon. In Kattegat, which is a rather shallow coastal area (mean depth ca. 20 m), hypoxia has resulted in decreased fish catches and death of benthic fauna on several occasions. However, also in shallow near-shore habitats, hypoxic events related to fast-growing green algal mats frequently result in hypoxic events. The combined effects of macroalgal growth and hypoxia in these normally highly productive areas have changed the composition of fauna, predicting a fundamental shift in the function of foodwebs along with increasing algal cover. Shallow bays function also as filters in the transport of nutrients, as nutrients are retained or removed by assimilation and bacterial N-removal (e.g. denitrification and possibly anammox). This habitat change can be expected to alter the filter function, leading to decreased rates of long-term retention of nitrogen, decreased grazing rates, increased export of phytoplankton, and changed bacterial N-turnover leading to decreased N-removal. A gradual change from dominating autotrophy towards heterotrophy of the sediments due to organic loading by ephemeral macroalgae, will increase the internal nutrient loading from the sediment. However, a partial beneficial "buffering" effect of benthic microalgae may persist even in more heavily eutrophied systems, a scenario that is based on the assumption that benthic microalgal communities possess, due to high diversity and functional redundancy, a certain degree of plasticity, increasing the overall resilience of shallow-water sediment systems after pelagic bloom events. This scenario, with benthic microalgae surviving despite deteriorating conditions, may apply particularly to cool microtidal waters, where macroalgal bloom events last only a few months, leaving the rest of the year open to benthic microalgal primary production.

In shallow areas, where the water column is low, key ecosystem processes (primary production, mineralization and nutrient cycling) are mainly related to the microorganisms of the surface sediments. Experiments studying the resilience of these sediments in relation to hypoxia are still rare. Undisturbed natural sediments in outdoor flow-through mesocosms were used to monitor the recovery of the structure and function of sediments after hypoxia (<15% of oxygen saturation). Nitrogen cycling, including denitrification, was affected and the fact that the recovery was faster for functions in light indicates that functions related to microalgal activity are less sensitive to hypoxic events than heterotrophic processes. The recovery rate was related to the duration of the hypoxia. The conclusion is that the function of shallow-water illuminated sediments possesses a high resilience after *single* events with short periods of hypoxia. This resilience appears to rely on the resistance of benthic microalgae (especially diatoms) to hypoxia, implying a rapid restoration of the oxygenation of the sediment surface and the base of the food-web, securing food supply for colonising grazers. However, repeated hypoxia will most probably lower resilience and increase the risk of irreversible shifts.

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Knowledge gaps in relation to eutrophication-related hypoxia in shallow-water systems:

- Coupling of physical and ecological processes, such as water residence time and transport rates of particulate and dissolved matter.

- Fate and turnover of nutrients bound to plant biomass. Where do they go?

- Combined effects of hypoxia and other concurrent multiple stressors, e.g. the combined effects of nutrients–pollutants–changing climate; changing pH – eutrophication

- Resilience of shallow–water systems. Which are the key components that strengthen or weaken resilience?

- A holistic ecosystem approach including identification of key ecosystem functions to be monitored (e.g. balance autotrophy/heterotrophy, nitrogen retention/removal).

Alf Josefson (with input from *Michael Zettler*), NERI, Denmark:

Hypoxia and benthic ecological quality in the Baltic Sea – North Sea transition

The area is characterised by a dynamic hydrography, with steep gradients in salinity and shallow water depths. As a consequence, and unlike some other parts of the Baltic Sea, there are almost no areas with permanent oxygen deficiency in DK and German coastal waters. Severe hypoxia (< 2mg/l) does, however, occur seasonally mainly in autumn months. Although some areas are more prone to be affected by hypoxia, there are great variations in hypoxia extension in space, as well as between different years. The most severe and widespread hypoxia event since 1990 occurred in summer-autumn 2002 in Danish and German waters.

Benthic quality was assessed by a simple index (DKI index) including a diversity component, a component indexing the sensitivity/tolerance of species abundance (the AMBI index, Borja et al. 2000) and a factor to compensate for very low numbers of species and individuals (Borja et al. 2007). The DKI was intercalibrated with other European indices on a common material of benthic samples including samples from hypoxia affected sites. Results (Borja et al. 2007) showed good agreement between the different methods of classification. The index was useful in describing effects on benthos by hypoxic events in for instance the Gullmarfjord on the Swedish West Coast, indicating benthic responses in a threshold fashion.

The area extent and duration of bottom water hypoxia was described from measurements and an extrapolation model (Conley et al. 2007). The most severe hypoxia since 1990 occurred in autumn 2002 when large areas around the Islands of Fyn and Sealand had oxygen concentrations below < 2 mg/l for one week or more. Effects of this event on species richness were significant at sites within the affected areas, showing a decrease of richness of up to 50 % or more, dependant on the duration of hypoxia (Conley et al. 2007). One possible mechanism, by which richness was reduced during hypoxia, was reduced “space” above the sulphide zone (Hansen & Josefson subm ms). Similar to richness, the DKI index showed clear decreases in response to the 2002 hypoxic event. There were, however, different responses depending on if sites were situated in open areas or in more closed areas like the Danish estuaries. Open area sites where much more affected by hypoxia than the sites in the closed areas. One reason for different response between open and closed areas could be that the resident fauna before hypoxia, to different degree was dominated by hypoxia tolerant species.

Long-term data from sites in the entrance to the Baltic Sea between Germany and Denmark showed that the 2002 hypoxic event was the most severe event with dramatic reductions in species richness and the DKI index, although reductions also occurred after hypoxia in several other years. In the Arkona Basin further into the Baltic Sea, hypoxia induced reduction occurred after the autumn 2000 at the Danish station while hypoxia did not occur at the German station. In summary, the benthic data showed that hypoxia effects in the transition area were patchy both in space and between years. It was also evident that recovery after hypoxia-induced reductions, in several places was rapid, i.e. the pre-hypoxia levels of richness and indices were reached after 1 or a few years.

Mapping biodiversity in the entrance area of the Baltic Sea (Zettler et al. 2008) showed high numbers of species from the mouth of the Storebælt and eastwards passing the Island of Rügen. This area contained several diversity “hot spots” mostly occurring in benign oxygen environments. This high diversity area is likely to some extent supplied by colonists coming mainly through the Storebælt straight from the species rich areas in the Kattegat (Josefson & Hansen 2004). However, great parts of this area are likely to be the target of future hypoxic events, indicated by recent modelling of global change (Hansen & Bendtsen 2007, in press). Therefore, there is a need to investigate pathways and rates of species colonisation not only to this area but also from the area further into the Baltic Sea. Increased hypoxia in the entrance might severely affect colonisation rates into the Baltic Sea, which to a great extent is a Sea of invaders.

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Janusz Pempkowiak, Polish Academy of Sciences, Poland:

The Polish coast

Morphology

The southernmost coast of the Baltic Sea, for the most part is composed of flat, wide, sandy beaches. Some 10 percent consist of cliffs. The Polish coast runs between the Vistula Lagoon in the east, and the island of Usnam in the west. The Vistula Lagoon is a shallow body of water. About 50% of the lagoon area constitutes Polish territorial waters, the other fifty percent –territorial waters of the Russian Federation. The Vistula lagoon is separated from the Bay of Gdansk with a narrow strip of land. The western part of the bay is called the Bay of Puck, while the northernmost part- the Puck Lagoon. The coastline is featureless in the middle sector. To the west there is the Pomeranian Bay and the Szczecin Lagoon. The total length of the shoreline is some 600 kilometers. All three lagoons are shallow, average water depth does not exceed 4m, the average depth of the Pomeranian bay is about 15m, while the Gdańs Bay- 60m.

Two major rivers discharge to the Baltic within the Polish coast. The Vistula drains some 65% of Poland’s territory, while the Odra- some 35%.

Oxygen solubility

Solubility coefficient of oxygen in water depends on temperature in such a way that equilibrium concentration decreases when the temperature increases. In the temperature range oscillations typical of the Baltic seawater oxygen solubility can change almost twice.

Even when measured oxygen concentrations equal 9ml/l and 5ml/l saturation index could equal 100%.

Factors influencing oxygen concentrations off Poland

One possible factor could be oxidation of organic matter discharged to the sea with river run-off. The Vistula discharges some 40 cubic kilometers per year, while the Odra river- about 17. The organic matter load from both rivers is over one million tons. This is why the question is asked. However, most of the riverine organic matter is biochemically stable. Therefore, the answer is that river run-off is of minor importance.

Factors actually influencing oxygen distribution in sea-water are: carbon dioxide assimilation leading to organic matter and oxygen production and mineralization of organic matter causing oxygen usage, then temperature and oversaturation. Basically the produced oxygen load should be the same as the used one. In practice the produced one is larger. This is because some organic matter, about 10% of the load produced in the course of primary production, is deposited and buried in sediments. The problem is, however, that oxygen production and oxygen consumption are shifted both in time and in space in respect to each other.

One of the factors enhancing decoupling of oxygen production and oxygen consumption is stratification of water in the Baltic. When we look at the vertical profile it is obvious that surface concentrations are much larger that the above bottom ones. In fact the border between the oxygenated and depleted of oxygen layers is the halocline at the depth of some 70m. Hydrogen sulphide develops in the deepest water layer while surface water is well oxygenated throughout the year. This is because organic material originating from primary production is transferred to the bottom layer much faster than oxygen.

Oxygen distribution in the coastal area.

There is no water stratification as in the deeps. Surface concentrations are larger than in the above bottom water layer. Surface saturation index is about 120 %, while in bottom water it is just about 80%. The fluffy layer plays an important role in the incompatibility of oxygen production and consumption both in time and space. Flux of sedimenting organic debris is much faster than flux of diffusing oxygen.

In 1997 York, Witek and others measured gross primary production and community respiration in the Bay of Gdansk. Primary production was higher, as expected, than respiration. However it took place in the surface layer, while respiration took place deeper, mostly in the fluffy layer. So despite larger oxygen production deficits of oxygen occurred in the bottom water.

How long term average oxygen concentrations change in the course of a year in surface water? In most sites and months there is oversaturation of surface water with oxygen. The peaks in spring are due to algal blooms and temperature increase. Measurements performed in 2006 fall within the one standard deviation range. This is taken as a proof that no major shifts in the oxygen regime, in surface water are taking place .Oxygen concentrations in d bottom water of the Szczecin Lagoon show deficit of oxygen. It is likely that the oxygen deficit has increased recently.

Arturas Razinkovas (with reporting by Britt-Marie Jakobsson), Klaipeda University, Lithuania:

Eutrophication & hypoxia in the Curoninan Lagoon

The Lithuanian coast consists of exposed sandy beaches and there is no evidence of hypoxia in the coastal waters. However, in the Curonian Lagoon fish kills were recorded in the summer of 2003.

The Curonian Lagoon, shared between Lithuania and Kaliningrad (Russia) is a sheltered basin of 1584 km2, with a mean depth of 3,8 m and a salinity of 0-8 psu. The lagoon is sensitive to hypoxia as the water temperature is high, there is no wind induced agitation and the basin is nitrogen limited. In August 2003 night concentrations of oxygen was measured to 2-4 mg/l in the bottom water. Cyanobacterial blooms where also common until 2005, after which no blooms have been recorded. In 2006 Lithuanian government approved a program aimed at improving the water quality in the Curonian Lagoon.

Timo Tamminen, SYKE, Finland:

Coastal hypoxia in the Northern Baltic Sea: Effects on nutrient release

Time series (30 years) data from standard monitoring programs along the Finnish coastline was aggregated from 244 stations into 5 geographical regions (Bay of Bothnia, Bothnian Sea, Archipelago Sea, Western and Eastern Gulf of Finland), to assess temporal trends in bottom-near oxygen and phosphate (PO_4) concentrations. The 'bottom-near' samples originate from regular monitoring programs, with a median distance of 1.6 meters from the bottom (nominal station depth). In addition, the oxygen thresholds for enhanced P release from sediments were studied with segmented regression analyses.

P release under hypoxic/anoxic conditions is a well-known process, but so far the main basin of the Baltic Sea, with wide-spread anoxia of the deep (sub-halocline) bottoms, has been in the main focus. The coastal time series show that a decreasing O_2 trend is evident in the relatively shallow (above halocline) stations of the Archipelago Sea and the Gulf of Finland. The seasonal depletion of O_2 during summer stagnation takes place in these areas even at stations <30 m deep, and time series of bottom-near PO_4 correspondingly show increasing temporal trends in these areas.

A depth-sliced regression between O_2 and PO_4 showed that a similar pattern from the deepest to the shallow (< 25 m) stations was evident in all 3 southern regions, with strongly increasing accumulation of PO_4 in bottom waters already at O_2 concentrations around 5 mg l^{-1}. Segmented regression analyses for pooled station depths in the southern Finland coastal areas confirmed that benthic P release is enhanced already at bottom-near O_2 concentrations of 5 to 6 mg l^{-1} (cf. hypoxia <2 mg l^{-1}).

Mobilization of sediment P due to depletion of bottom-near O_2 is therefore a significant process even in relatively shallow coastal areas. Bottom-near O_2 threshold for this seems to be clearly higher than expected in the Northern Baltic Sea. Time series analyses show that the relatively shallow coastal areas contribute increasingly to P release. Once the annual O_2 depletion threshold for enhanced P release is reached, this causes high resilience to management actions, indicating slow recovery of the system even after significant reduction of external nutrient loading.

Alexey Maximov, Russian Academy of Sciences, Russia:

Hypoxia in the Eastern Gulf of Finland

The eastern Gulf of Finland, that is water area located to the east of island Gogland, is rather shallow. The maximal depth is no more than 70 m. There is no permanent salinity stratification, in contrast to the deeper western Gulf and Baltic Proper. Every year the intensive convectional and wind-induced circulation in late autumn and in winter before ice cover formation breaks stratification of water column and correspondingly leads to the saturation of the near-bottom waters with oxygen. However in summer and early autumn hypoxic conditions episodically are registered in the below-thermocline waters.

In the last decade very low near-bottom oxygen concentrations were observed in 1996, 2001, 2003 and 2006. Deterioration of oxygen conditions radically altered soft bottom communities. Abundant populations of glacial relicts crustaceans *Saduria entomon, Monoporeia affinis* and *Pontoporeia femorata* were wiped out by strong oxygen depletion and were replaced by poor populations of oligochaetes (fam. Naididae). Especially drastic changes took place in 2003, when oxygen-poor saline water penetrated to the inner areas of the Gulf, as consequence of recent Major Baltic Inflow. By 2004 the most part of the eastern Gulf of Finland bottom altered to the life-less desert. Change in oxygen conditions, apparently, also was the factor favorable to biological invasions of opportunistic polychaetes and oligochaetes. Thus on moderately affected by oxygen depletion bottom the native *Monoporeia affinis* dominated community was replaced by alien tubificid species *Tubificoides pseudogaster*.

I attempted to identify conditions favorable for the occurrence of benthic hypoxia in the eastern Gulf of Finland using long-term (1962–1989) hydrographic data from one station monitored by North-West Administration on Hydrometeorology and Environmental Monitoring of the Russian Federation. The near-bottom oxygen level in summer negatively correlated with winter severity and water salinity. The regression model, with salinity and ice-cover extent in the Baltic Sea as independent factors, explained 79% of the variation in oxygen concentration. Both factors responsible for formation of hypoxic conditions were governed by large-scale climatic factors. In either case the negative correlation with Arctic

Oscillation index was observed. Hence, oxygen level positively correlated with Arctic Oscillation index (r = +0,70). For evaluation of possible long-term trend, published data from nearby station monitored by the Finnish Institute of Marine Research in 1923–1939 were used. There was not significant difference between the two studied periods. In 1923–1939 the oxygen concentration varied from 2,07 to 6,44 ml·l^{-1}. The current concentrations remained within range of these fluctuations.

Deterioration of oxygen conditions in 1996 and 2000s were most probably caused by the intensification of saline water advection, triggered by recent Major Baltic Inflows. Hypoxic events were observed in the years when inflows of low-oxygen saline waters coincided with cold winters, when early freezing prevents the wind-induced mixing. Hypoxic conditions in these years also may be favored by low Neva runoff, promoted penetration of oxygen depleted and saline waters to the inner parts of the Gulf.

Jouni Lehtoranta (with input from *Petri Ekholm* and *Heikki Pitkänen*), SYKE, Finland:

Conceptual model on sediment microbial processes explaining regional variation in phosphorus concentrations in the Baltic Sea

Despite their large ecological significance, microbial iron and sulphate reduction have been poorly studied in the Baltic Sea sediments. On the basis of indirect evidence we propose that the conditions in the oligotrophic Gulf of Bothnia (a northern sub-basin of the Baltic Sea) favour iron reduction and coupled cycling of iron and phosphorus in the surface sediments. Since iron-reducing bacteria are unable to completely reduce ferric oxides in the sediments, iron-bound phosphorus may be permanently buried in the sediments. The good ability of the sediment to retain phosphorus results in low concentrations of phosphorus in water, which in turn promotes phosphorus limitation of primary production. By contrast, sulphate reduction appears to the dominating anaerobic mineralisation pathway in the organic rich surface sediments in the Baltic Proper and in the Gulf of Finland (the most eutrophied sub-basin). The sulphide formation leads to an efficient reduction of ferric oxides. Subsequently iron-bound phosphorus is dissolved to pore water and transported to overlying water, whereas iron is buried as sulphides (uncoupling of iron and phosphorus cycling). The capacity of sediments to retain P is low, primary production tends to be nitrogen limited and extensive blue-green algal blooms are common. We maintain that the flux of organic matter to the sediments is a decisive factor governing the above regional distribution of iron and sulphate reduction. When the flux reaches a critical threshold value enabling anoxia in the sediment-water interface, collapse of benthic fauna and inhibition of iron re-oxidation, sulphate reduction is triggered. Under such conditions even good mixing conditions delivering oxygen to the near-bottom water can only temporally prevent a shift from iron to sulphate reduction. The way to drive the sediments back to iron reduction is to reduce the loads of bioavailable nitrogen and phosphorus into the Baltic Sea so that the organic matter flux to the sediments decreases to a level where microbial iron reduction is able to dominate.

Ilppo Vuorinen, University of Turku, Finland:

Anoxia in the Archipelago Sea, Finland

The Northern Baltic Sea archipelago of Finland, is a mosaic of some 60 000 islands, extending around 100 km in N-S and some 350 km E-W. The landscape is basically a tilting plane (higher tops not more than 40 m above sea level) which creates a geographical zonation from inner to outer archipelago. Typical of this landscape are fjord-like stretches of open water extending over large areas and crossing the zones in N-S and E-W directions.

Underwater landscape, correspondingly, is relatively shallow (deepest spots about 100 m, and average depth not more that around 25 m) but crossed by deeper channels that are interconnected creating a possibility of relatively deep water currents and, thus mixing of deep water. Therefore, evidently no halocline exists around 80 meters depth which otherwise is typical of Baltic Sea. Hydrographically the Archipelago Sea is closer to the Gulf of Bothnia.

Anoxia has been documented in the area as scattered findings in benthos studies all over the Archipelago, since 1950´s. Documentary value of these studies is, however, low as benthos studies were heavily biased areally. They were concentrated on the other hand in the vicinity of university field stations at the Island of Lohm (in the border between outer and middle archipelago zones) during the 1950´s, and at the Island of Seili (middle archipelago) in the 1970´s, and in the innermost archipelago next to cities of Turku and Naantali (during 1970´s, 80´s and early 90´s). In the mid 1990´s outer archipelago expeditions became possible, and anoxia was studied also in the outermost areas. Unexpectedly anoxia was actually quite rare in these studies of outer archipelago deep water channels.

In late 1990´s shallow water (0.5 to 20 m) mapping of anoxia around some forty Islands by Petri Vahteri and co-workers revealed large anoxic area over all the archipelago zones, but concentrating in the SE-corner of the Archipelago Sea. Furthermore, there were more shallow water anoxic areas generally in the outer archipelago as compared to inner areas.

Joonas Virtasalo and others did an extensive sediment core study over all the archipelago zones in late 1990´s and were able to build up a conceptual model of anoxia over the archipelago. According to this model, anoxia is generally found in isolated, relatively shallow (depth 20 to 40 m) basins. The isolation is due to a combination of topography and thermocline (which basically creates the stratification needed for the occurrence of hypoxia). Meanwhile, the deep interconnected canyons may be well ventilated. Thus, unexpectedly, anoxic areas are not concentrated in the deepest areas. This conceptual model has been independently supported by Tero Myllyvirta, who created basically a similar model over the entire Finnish coastline.

Discussion day 1

Per Jonsson, Stockholm University, Sweden:

Laminated sediments in the Baltic Sea

In the offshore Baltic proper, considerable areas of accumulation bottoms have shifted from “normal” bioturbated sediments to laminated (varved) sediments. The lamination is created when macrobenthic fauna are absent or significantly reduced due to low near-bottom oxygen concentrations.

In 1992, when investigations were initiated of the seafloor of the Baltic Sea archipelagoes, the main hypothesis was that the conditions in the archipelagoes would be far better than in the open sea due to extensive purification measures in the municipal sewage purification plants and industries during recent decades. Our studies, however, show that large-scale structural changes occurred in almost all the investigated coastal areas simultaneously with the increased degree of purification in sewage plants and industries.

In all archipelago areas that have been studied, seafloor mapping has been performed by means of side scan sonar and sediment echosounder of 60 archipelago bays and sediment sampling of more than 500 sediment cores. For all areas investigated, the distribution of different bottom types in the archipelagoes has been mapped and estimates are given on the extension of areas with poor near-bottom oxygen conditions as well as historical records of the development of oxygen-poor seafloor areas.

Diagrams showing the spatial change of extension of laminated sediments over time have proven to be good historical indicators of the load situation in archipelago areas. In the river-mouth area of the river Ångermanälven, for instance, good historical data were available on the discharges of oxygen demanding substances (BOD). The historical record of BOD discharges is in good agreement with the development of laminated sediments in the area.

In the Stockholm archipelago as a whole, the historical long-term record of laminated sediments is charaterized by a gradually increasing portion of laminated sediments from around 1910 up to 1990, thereafter levelling off in the 1990s. The most remarkable thing is that the fastest expansion was recorded simultaneously with improved sewage purification in the Stockholm area. The recorded time trend is opposite to what was expected.

In the outer Stockholm archipelago, the lamination curve shows a different time development compared to the region as a whole. Laminated sediments did not occur until mid 1950s starting in the large and deep bays. In the outermost archipelago bays, the first lamination occurred between 1970 and 1980. In the S:t Anna and Gryt archipelagoes the expansion of laminated sediments started at the same time as in the outer Stockholm archipelago and the situation worsened during the 1970-80s. The most probable reason for the worsened situation in the outer archipelagoes, despite the local/regional extensive purification measures, is that the situation in the offshore Baltic to a larger extent determines the conditions in the archipelago than local land-based discharges do. Thus, increasing offshore nutrient concentrations seem to have a major impact on the seafloor conditions not only in the outer archipelagoes but also most likely even in the central Stockholm archipelago.

A notable trend in the outer archipelagoes is that significant improvements seem to have occurred in the late 1980s. A similar and simultaneous improvement was registered in the NW Baltic proper and has been linked to large wind-induced saltwater inflow from the Kattegat during the very windy beginning of the 1990s. However, it is not likely that the in-flowing Kattegat water is the reason for the improvements in the archipelagoes. More probable is that the windy conditions in the early 1990s caused wind-induced vertical water mixing to greater depths than in the extremely calm 1980s, resulting in increased oxygen concentrations in the nearbottom water.

As an average, the sediment accumulation rate in surficial archipelago sediments is as high as 17 mm/year in comparison with only 1-4 mm/year in offshore areas of the Baltic proper. Correspondingly, the sediment accumulation rate, measured in gram per square meter per year, is several times higher in the archipelagoes than offshore.

The sediment carbon content in coastal areas in the Bothnian Sea is in general considerably lower than in the investigated Baltic proper archipelagoes, showing somewhat higher concentrations in surficial sediments (2-4%) compared to further down-core (1-2%). In the Stockholm archipelago, the carbon concentrations are amazingly similar in the entire investigation area ranging from 4.5-6.5% in layers representing the 1950s to 5-8% in the sediments from the 1990s. Local eutrophication conditions have low impact on the sediment carbon content. This was clearly demonstrated by a comparison between the bays Näslandsfjärden and Himmerfjärden, which are heavily influenced by local municipal discharges, and the bay Tvären with no direct discharges. The carbon contents are generally 1-2 percent units higher in the bay Tvären compared to the polluted bays.

the S:t Anna archipelago, the highest TOC contents were found in the outermost bays and the lowest in the inner sheltered bays. Similar, although not so pronounced, trends were detected in the Södermanland and Stockholm archipelagoes. In general, the carbon distribution patterns are not as expected when investigations started in the early 1990s.

In S:t Anna, a clear gradient was found showing the highest bulk sediment accumulation rates in the inner bays and lowest in the outer bays. In the Stockholm archipelago no such clear differences were found between outer and inner parts of the archipelago. Here we found high as well as low sediment accumulation rates in all parts of the archipelago. The reason for this is most likely linked to different morphological conditions in each specific bay. However, a weak negative relationship showed that carbon content increased with decreased bulk sediment accumulation rate. Based on the low variation of radiocesium activity in archipelago sediments it may be concluded that the transport from open sea into the archipelagoes is quite efficient, which in turn suggests that the situation in the offshore areas highly influenced the conditions in the archipelagoes. Accordingly, the same conclusion may be drawn for nutrient transports/concentrations. Since large amounts of nutrients are “imported” from the open sea, small or no improvements due to local measures are to be expected in the archipelagoes. The large-scale expansion of laminated sediments in the Stockholm archipelago during the period when large measures were taken to reduce nutrient discharges to the archipelago is an indication of the same phenomenon. The offshore situation seems to a much greater extent govern the seafloor conditions in the archipelagoes than what has been reported earlier.

Offshore - conclusions

- Laminated sediments expanded rapidly in the Baltic Proper in the 1960-70s reaching maximum extension in the late 1980s
- Recent lamination is in general annual
- Bulk sediment accumulation rate is governed by wind-induced erosion/resuspension
- Sediment carbon content is negatively correlated to bulk sediment accumulation rate
- The windy situation in early 1990s is detected in offshore Baltic sediments as a bioturbated layer at water depths down to 135 m
- Naturally laminated sediments predominates in the Bay of Bothnia

Archipelagoes - Conclusions

- Laminated sediments are found in all areas investigated
- Laminated sediments start to expand
    - * in the early 20th century in the inner archipelagoes
    - * in the 1930-40s in the central archipelagoes and
    - * in the 1960-70s in the outer archipelagoes
- In some outer archipelago areas possible improvements may have occurred in the 1990s
- Investigations in the 2000s show worsening situation in the archipelagoes of the Bothnian Sea
- Local measures are important but not enough
- The offshore nutrient situation affects the extension of laminated sediments in the archipelagoes
- 5-10 times higher sediment accumulation rate in the archipelagoes compared to offshore areas
- Wind-induced erosion/resuspension determines sediment bulk accumulation rate
- Bulk accumulation rate determines the carbon content of the sediment
- Laminated sediments are excellent tools to monitor spatial and temporal development of hypoxia
- Laminated sediments are excellent tools to learn about sediment dynamics including nutrients and contaminants

Joonas Virtasalo, University of Turku, Finland:

Geological records in sediments, the Archipelago Sea

Many of the physicochemical processes causing oxygen deficiency of the Archipelago Sea today came into operation at the onset of brackish-water conditions in the sea area at ~7600 BP. Laminated sediments that are indicative of anaerobic conditions on the seafloor have been deposited in the area after the onset of brackish-water environment. Driving mechanism for hypoxia/anoxia in the Archipelago Sea is the organic-rich deposition (primary production), which results in high oxygen consumption rates on the seafloor. The organic-rich sediment is easily reworked by currents and wave action, which results in patchy depositional patterns that cause marked lateral gradients in the seafloor oxygenation, benthic behavioral patterns and sediment chemical composition. As a result, seafloor redox histories in adjacent sub-basins can differ substantially.

The organic-rich deposition is modulated by the glacio-isostatic land uplift, which results in slowly shifting boundaries between the areas of sediment accumulation, transportation and erosion. Reoccurring shifts in the pattern of organic-rich deposition lead to marked spatial and temporal variability in the seafloor oxygenation. On the other hand, Holocene climate variability influences organic production in the area by means of changes in temperature and terrestrial influx of nutrients. The climatic influence is pronounced in areas with high terrestrial influence such as those close to river mouths. For example, sediments close to the Paimionjoki river mouth record anoxia (laminated sediment) and increased terrestrial phosphorus influx (refractory organic P supply coupled to detrital P flux) during the Medieval Warm Period (1250–450 BP), cooler temperatures (bioturbated sediment, reduced P supply) during the 'Little Ice Age' (450–200 BP), and deteriorated seafloor conditions (laminated sediment, increased P influx) during the past 200 years potentially triggered by the subsequent climatic warming. Human activity has influenced the seafloor oxygen conditions in the area, but the effects are not always easy to separate out from the large natural variability of seafloor oxygen conditions in the area.

Urszula Janas, University of Gdansk, Poland

How benthic organisms cope with hypoxia?

Soft sediment benthic organisms play an important role in the Baltic Sea ecosystem. They provide food for higher trophic levels, metabolize organic material influencing benthic mineralization processes. Additionally activities of bottom dwelling organisms oxygenate sediment influencing biochemical cycles.

Bottom fauna structure and its functioning is influenced by natural and antopogenic stressors. Hypoxia is one of the most important factors in the Baltic Sea. It should be remembered that also other factors, like toxic hydrogen sulphide which is concomitant with hypoxia, may negatively affect organisms as well.

Changes in structure and functioning of biocenosis caused by hypoxia follow negative effect in behavior and physiology of individuals observed much earlier. Mobile fauna migrate from the hypoxic area or move up from the sediment on its surface where oxygen availability is often higher. However, it might increase the risk of predation of burrowing organisms. In hypoxia, less mobile fauna are trying to use aerobic metabolism as long as possible e. g. crustaceans or polychaeta increase their ventilation or irrigation. Moreover, many organisms are also able to produce more hemocyanin in hypoxia what enable animals to transport as much oxygen as during normoxia condition. Anaerobic metabolism is switch on if there is not enough oxygen for aerobic metabolism. It results in accumulations of high amounts of end products (e.g. lactate, alanine or succinate) which differ among taxonomical groups and species. During anaerobic metabolism animals use metabolic storage substrate e.g. glycogen. Additionally animals reduce the overall metabolic requirements by reducing different types of activity. In severe hypoxia *Saduria entomon* is able to reduce its metabolism to 16 % of normoxic level (Normant et al 1998), whereas in anoxia very tolerant priapulid *Halicryptus spinulosus* to 2 % (Oeschger at al 1992).

Even using mentioned adaptations animals are able to survive in anoxia conditions or hypoxia with high concentration of hydrogen sulphide for very limited period of time. Tolerance of hypoxia and anoxia varied between species or ecological groups. In general, bottom dwelling organisms like bivalve and polychaeta are usually more tolerant than mobile fauna. The very tolerant species like clam *Macoma balthica* or isopod *S. entomon* are able to survive several days whereas sensitive species like common shrimp *Crangon crangon* only several hours. Severe hypoxia or anoxia conditions, lasting few or more days, mean death of most sensitive species or even whole macrobenthic communities. Recovery is faster when similar fauna inhabits surrounding area. Mobile species and those with pelagic stages are favored in recolonization processes.

In the Gulf of Gdańsk the decrease in abundance and biomass of benthic macrofauna was recorded from the second half of the 1990s until 2002. At the end of this period in some areas only 10 % of macrofauna abundance from 1994 was observed. Additionally, in 2002 *M. balthica*, the main macrofaunal component of soft bottom macrofauna, used almost all glycogen reserves at that time. From 2003 recolonization process have been observed, mainly by *M. balthica* and opportunistic polychaeta. *M. balthica* has also rebuilt glycogen reserves after spring bloom. Sensitive to hypoxia amphipod *Pontoporeia femorata* came back into the deeper part of Gulf of Gdańsk in 2003 what indicates improvement of oxygen condition. However, cold water populations of *S. entomon* and *H. spinulosus* have not recovered at depths of 30-60 m until 2005.

It is worth mention that high concentrations of end products of anaerobic metabolism together with low energetic reserves in specimen’s tissues could be used as indicators of exposure of animals to severe hypoxia or anoxia, even when measurements of oxygen content in water layer just above sediment are not possible.

Stefan Hulth, Göteborg University, Sweden:

Chemical implications of coastal hypoxia

Organic matter oxidation proceeds in a sequence of reactions depending on the most profitable gain of energy oxidizing 1 mole of organic matter to CO_2. In marine environments, the most favorable oxidant is oxygen, followed by nitrate, Me-oxides and sulfate. As there are no “free” electrons, for each mole organic matter oxidized there is a stoichiometrically balanced concomitant reduction of oxidant. For example, oxygen, nitrate, manganese(IV), iron(III) and sulfate are reduced to water, di-nitrogen gas, manganese(II), iron(II) and hydrogen sulfide, respectively. In addition to oxic respiration (oxygen reduction) there is thus a set of anaerobic pathways that oxidize organic matter under anaerobic conditions. Rates of organic matter oxidation under these variable redox conditions are determined by several factors, including e.g. surface area (“the monolayer theory”), the availability of oxidant (oxic/anoxic conditions) and the overall composition (reactivity) of the organic matter that is oxidized. The stoichiometry of anaerobic mineralization coupled to the reoxidation of reduced reaction products by oxygen is the same as for the direct oxidation of organic matter with oxygen. This stoichiometric coupling is fundamental to the presumption that “A primary control of atmospheric oxygen is the balance between the rate of oxygen consumption during oxidation of organic C, and the rate by which organic C escapes reoxidation through burial”. In addition to the stoichiometric coupling, main assumptions include: i) There is a steady state situation between the production of reduced metabolites and their reoxidation; ii) Reoxidation is by oxygen following the diffusive/advective transport of metabolites to the oxic zone; and iii) Reoxidation reactions follow ”Redfield stoichiometry” through ”known” pathways.

In my talk, main pathways of oxygen reduction (i.e. overall fate of oxygen) in marine environments will be exemplified. The three main assumptions for oxygen control are separately challenged with particular examples provided from laminated sedimentary environments, i.e. environments frequently observed in the Baltic Sea. Examples include the fate of Fe and Mn in highly sulfidic environments and the complexation/immobilization of Fe-sulfides, oxidation of reductants by other oxidants than oxygen (e.g. nitrate and nitrite (anammox), and Fe- and Mn-oxides), and the oxidation of organic matter according to non-Redfield stoichiometry. Finally, biogeochemical consequences from the reoxidation of Fe-sulfides by oxygen are discussed.

Jens K Petersen (with input from *Marita Sundstein Carlsson*), NERI, Denmark:

Mitigation through compensation – mussel production as biofilter

Mitigation through compensation is a concept where mitigation of eutrophication is removed from the source, i.e. agriculture, sewage, fish-farming etc, to the recipient or the coastal water body. The idea is to remove nutrients by harvesting/fishing or growing natural occurring organisms like mussels or macro algae. Compensation is a rapidly working measure because nutrients are removed immediately in contrast to catchment measures like changes in agriculture practice or re-establishing of wetlands. Mussels are useful as compensation organisms because they are naturally occurring in great abundance, they are easy to grow and through their filtering they increase water transparency and reduce sedimentation at the basin scale. Mussels contain nitrogen (N) and phosphor (P) that is removed when the mussels are fished or harvested. One tonne of fresh mussels contain 4-18 kg of N and 0.3-1 kg of P. The variation relates to difference in meat content of the mussels. Benthic mussels typically have lower meat content than off-bottom cultured mussels. Using Limfjorden, a shallow Danish estuary as an example, it can be shown that even though realistic numbers of mussel production and related nutrient removal are low compared to nutrient run-off, they are significant in relation to management goals for nutrient reduction. In addition, mussel production can be shown to increase denitrification under mussel farms, thereby increasing N removal.

Mussel production has, however, some impacts on the environment. Dredging for mussels leads to resuspension of 3-6 kg DW m^2 dredged area and for Limfjorden, average oxygen consumption of the resuspended material has been measured to be 17.5 mmol O_2 kg^{-1} DW. From mussel farming on long-line cultures, sedimentation of faecal material will increase sediment oxygen uptake compared to control areas from approx 50 mmol m^{-2} d^{-1} in the control area to approx 150 mmol m^{-2} d^{-1} in the impact area. There are, however, differences between seasons and between different culture sites. The spatial variation can be attributed to many factors, like production volume, current velocity and sediment memory or internal loading. Skive Fjord, an embayment within Limfjorden, was used to illustrate potential effects of mussel production on bottom layer oxygen concentration. It was assumed that a 1 m bottom layer is typical for summer stratification, where oxygen depletion can develop. An area of approx 32 km^2 is regularly exposed to hypoxia. Dredging of 20 boats or the daily extra oxygen demand due to 10 mussel farms will result in an approximately 2% increase in oxygen demand in the bottom layer. This simple calculation illustrates that mussel production will have only a minor impact in this already eutrophic system, but average effects may not capture the real picture. Local effects just under farms may lead to release of hydrogen sulphide and anoxia may spread from these “hot spots”. But with current knowledge, negative effects of mussel production in relation to hypoxia must be considered of minor importance.

In addition to sediment oxygen consumption, mussel production may affect the flow of matter and energy through the system by speeding up mineralization of organic material. Release of ammonia and phosphate is much higher under mussel farms compared to control areas. Similarly, mussels grown in the water column will transform nutrients bound in particulate matter to dissolved nutrients, primarily ammonia and phosphate. These processes will fuel primary production and speed up turnover rates.

In summary, mussel production will remove nutrients from coastal systems when harvested and realistic production volumes can contribute significantly to management goals for reductions in nutrients. Mussel production will have an impact on the environment but this is of small significance with regard to hypoxia in eutrophic coastal waters.

Odd Lindahl, Göteborg University, Sweden:

Mussel farming – a remediation tool for coastal water quality

Trading nutrient emissions

The ecosystem service provided by mussel farming has been recognized by Swedish environmental authorities as a possible measure to improve coastal water quality. Concepts and management strategies on how to increase mussel farming for environmental purposes have recently been developed. The main principle is the implementation of nutrient trading as a management tool. This imposes demands on those who emit the pollution through emission quotas which are traded and bought by the emitter. The seller is a nutrient harvesting enterprise, e.g. a mussel farmer.

The Agro-Aqua recycling of nutrients

The nutrient emissions coming from agriculture, rural living, the atmosphere and many other diffuse sources increases coastal primary production leading to increased biomasses of both filamentous algae and phytoplankton. Phytoplankton is the main feed for mussels and consequently mussel farming and harvest has since the 1980's been recognized as a possible measure to improve coastal water quality. The most cost-efficient and environment-friendly way of taking care of diffuse nutrient emissions is the cultivation of mussels through the long-line farming method. About 4 % of the live mussel is carbon (C), 0.85 % nitrogen (N) and 0.06 % is phosphorous (P). When the mussels are harvested, a known amount of the nutrients are recycled back from sea to land, mainly in the form of valuable sea food. However, up to 1/3 of the total harvest, e.g. small and damaged mussels and other marine fauna like sea-stars and crabs harvested, can generally not be used for human consumption, but can instead be processed into mussel meal to be used in organic feed or composted into a rich organic fertilizer. The Agro-Aqua recycling concept thus recycles nutrients from the sea back to land and the agriculture, where the mussel harvest can be regarded as the recycling engine.

Mussel farming in the Baltic

A common view is that the Baltic blue mussel is too small to be farmed and harvested. This is of course true if the mussels should be used as traditional seafood. However, in the Baltic mussel farming must focus on the harvest of mussel biomass instead of mussels for food. On-

going farm trials at Åland and in Kalmarsund have so far shown that long-line mussel farming have a clear potential as the biomass after one year was 60 ton ha^{-1} and can be expected to reach 120 – 180 ton ha^{-1} in 2 to 3 years. This means that roughly 6 ton carbon, 1.3 ton nitrogen and 90 kg phosphorus will at harvest be recycled.
It should be pointed out that the commercial value of the products from the mussel farming most likely will not cover the full production cost. Thus mussel farming as a remediation tool in the Baltic will to some extent have to rely on environmental subsidies.

Lindahl O., Hart R., Hernroth B., Kollberg S., Loo L.-O., Olrog L., Rehnstam-Holm A.-S., Svensson J,. Svensson S. and Syversen U. 2005. Improving marine water quality by mussel farming – A profitable measure for Swedish society. Ambio, Vol. 34, No. 2: 131-138.

Anna Jöborn, Göteborg University & IVL, Sweden:

Algae harvest a method with potential to restore coastal bays

This presentation is mainly based on the findings of the project *EU-life algae*, 1996-2001 (http://www5.o.lst.se/projekt/eulife-algae) lead by the County Administration of Västra Götaland in Sweden. The project had two experimental sites, one in the Åland archipelago and one in the coastal area of Skagerrak. It was collaboration between a number of authorities and two Universities.

The important question to ask is if algae harvest is an effective measure to reduce coastal hypoxia. This presentation will cover the current knowledge and discuss the potential of this technique as a measure to reduce the negative effects of eutrophication and thereby also reduce the risk of coastal hypoxia or anoxia.

The arguments for harvesting algae are to:

- Remove nutrients from the system
- Interrupt the recirculation of nutrients in sheltered bays
- Restore shallow bay ecosystem structure
- Reduce risk of hypoxia or anoxia
- Increase chances for fish larvae to hatch and survive
- Reduced smell
- Make better recreational use of coastal areas for swimming, boating etc
- Increased aesthetic value of the coastal zone

Conclusions

Algae harvest should mainly be seen as a restoration activity – a measure that will support ecosystem recovery. The potential benefits are substantial if considering landing of fish as an example.

Algae harvest can also be a support to fulfilling the ‘No eutrophication’ goal in Sweden and in the Baltic Sea coastal areas and archipelagos.

By removing nutrients the recycling of nutrients in coastal bays may be controlled. But it should not be seen as a simple - one time only - solution to the coastal eutrophication and related hypoxia/anoxia problem. A sustainable solution to the eutrophication problem must be based on combined mitigation efforts also reducing land based point sources, diffuse sources and atmospheric deposition.

Next step

Further develop the concept and test harvesting for several seasons with careful ecosystem monitoring. Make a more extensive cost-benefit analysis. Find entrepreneurs willing to further develop the algae harvesting /algae use concept.

Reflections about algae harvest in the Baltic Sea

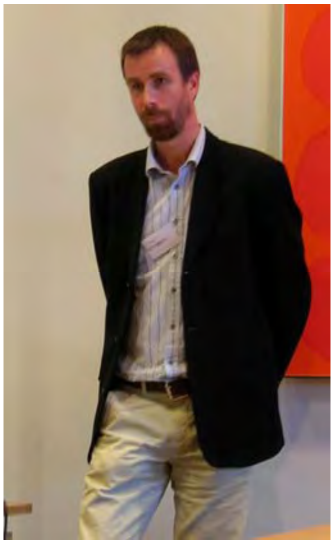
- Information is lacking about the occurrence and amount of filamentous algae in coastal areas of the Baltic Sea (presently not part of environmental monitoring programs). More information is needed to be able to evaluate if algae harvest is a method that can be used.
- The studies on Åland indicate that in some areas of the Baltic Sea algae are not easy to harvest. Free floating algae are found below the sea surface and are transported around by the current in a random fashion.
- The EU-life algae project also considered developing techniques for harvesting filamentous colony forming cyanobacteria but lacked resources to pursue this line of technical development. This is something that needs further consideration.
- For more information about algae harvest and biological monitoring in the Åland archipelago see report by Heikkilä J. and Mattila J. 2001.
- Another possibility that has been explored in other parts of the world is to farm algae. In this way it may be possible to remove nutrients from the system and at the same time control the species composition ensuring higher quality of the resource. This is for example asked for in the case of producing crystalline cellulose from Cladophora and Enteromorpha spp.

Suggested reading:

Troell et al 2005. Regime shifts and ecosystem services in Swedish coastal soft bottom habitats: when resilience is undesirable. Synthesis. Ecology and Society, 2005.

Lars Ljunggren, Swedish Board of Fisheries, Sweden:

Coastal fish & fisheries



The Baltic Sea has undergone a dramatic regime shift, from a cod dominated system in the 1980s to a sprat dominated system. The decline in cod, induced by direct overfishing combined with unfavourable spawning conditions, affected not only the growth and abundance of predators and zooplanktivores, but has cascaded through the food chain influencing the whole offshore ecosystem. The decline in the cod stock coincided with a marked climate change further strengthening the regime shift by an increase in sprat recruitment. The situation is unlikely to reverse in the foreseeable future because of the predation on cod eggs by sprat, and the top-down control of sprat on zooplankton species that are essential sources of food for cod recruits.

Parallel with the shift in the offshore ecosystem, the dominating coastal predators perch and pike have declined markedly along the Baltic cost, most likely due to recruitment failure caused by larval starvation. Research indicate that the food limitation of coastal predators may be caused by top-down control from sprat on the zooplankton community, linking the changes in the coastal ecosystem to the regime shift in the open sea. Moreover, small-scale experiments in coastal areas of the Baltic Sea suggest that removal of coastal top-predatory fish results in a trophic cascade with increased production of bloom-forming filamentous macroalgae. Similar experimental results have also been described from coastal areas of the Swedish west coast and the Finnish coast. This is further supported by large scale correlations between coastal fish communities and abundance of filamentous algae, thus supporting the importance of top-down forces on the benthic primary production.

Johanna Mattila, Åbo Akademi University, Finland:

BEVIS –an example of coastal modeling

Water quality in the archipelago regions Turku-Åland-Stockholm has continuously impaired despite different water protection measures taken. A debate is still going on regarding the importance of local sources vs. loading from other sea areas on water quality along coastal areas, which are characterized by mosaic structure with semi-isolated bays and basins among islands.

Up till now there has been relatively little information about the importance of local water protection measures. Assessment of loading from the outer sea areas has also been based on simple conceptual models and mathematical models that have covered only parts of the archipelago region. An EU-financed project, BEVIS, has during 2004-2006 aimed at development of water quality models for the archipelago region Turku-Åland-Stockholm and at assessment of importance and effects of local and regional water protection measures. The ultimate goal has been to develop a joint support system for decision making for the entire archipelago region within the project area. Two different 3D-modells have been applied on the project area. Both models include two submodels with a joint mesoscale model covering the entire project area. The Finnish model includes even a fine-tuned model for the Föglö area (Åland), while the Swedish model runs the forcing of the mesoscale model through a Baltic model along the borders against the Bothnian Sea respective the Baltic Sea. Both models have been developed based on initial data from December 2003, and model and validation data from 2004-2005. The models describe nutrient concentrations and amount of phytoplankton (only the Finnish model) in the water areas. This is the first time when large archipelago areas have been modeled with high resolution (150-463 m grid cells), which is necessary to be able to give a realistic reflection of complex archipelago areas.

According to the results from model validation, the models function well in relation to the complex model area. The biggest shortcomings have been noted in modeling of leakage of phosphorus from the sediments. The models seem to underestimate this leakage. However, it can be stated that the models function at an acceptable level in order to allow formation of realistic future scenarios.

The most important scenario results so far show that the water quality in the inner archipelago areas is highly dependent on nutrient loading from local sources. In order to improve the water quality in these areas the water protection measures must be directed towards local sources. Water quality in the inner areas and parts of the middle areas cannot be improved by measures taken in other Baltic regions. Accomplishment of current environmental programs and goals (level II) would improve water quality in the inner and middle archipelago regions by 2-30 % under a year cycle. The assessed annual costs would be 40-337 M€. Even improvement of already well functioning waste water treatment plants would alone markedly improve water quality in the inner areas.

In contrast, in the outer archipelago regions water quality follows mainly water quality in the surrounding open sea areas. A decrease by 10 % in the loading from the outer areas and atmospheric deposition would result in a 5-15 % improvement of water quality, compared with year 2004, in the outer archipelago areas already during one year cycle. The assessed total costs would be 383-2 081 M€/year. Regarding fish farming, local improvement in water quality could be achieved by relocating fish farms from enclosed areas further out towards the open sea. Also the size of farming units could be increased provided that the total production would not increase from the level of year 2004. The total costs for relocation are assessed to 0.2 M€/year. However, it should be noted that the total loading will not decrease through this alternative.

Sif Johansson (with reporting by Britt-Marie Jakobsson), Swedish EPA & Baltic Sea 2020, Sweden:

Links between the workshop and the work on hypoxia at Swedish EPA

Sif Johansson presented the initiative of the Swedish government to take action against the poor situation in the Baltic Sea. In order to improve the situation in the Baltic, aiming especially at the dead sea bottoms, the Swedish government has decided to invest 500 million Swedish crowns, and will above all support experimental projects aiming at rapid solutions, e.g. engineering solutions for the improvement of the state of the Baltic Sea.
According to the government “It is assumed that oxygenation, done in the right way, counteracts eutrophication and the reduction of cod…”.

Summary of the workshop

In this chapter the information on coastal hypoxia according to the abstracts by the speakers is summarized. The themes follow the subjects discussed during the workshop, and the discussion (in italics) on the theme is summed up at the end of each part.

Geographical magnitude of hypoxia

Beginning with the Swedish west coast and continuing conuter-clockwise around the Baltic Sea (Denmark, Germany etc.) the hypoxic conditions in the coastal waters of the different Baltic Sea states were pinpointed:

Along the Swedish west coast hypoxia is found at shallow locations of about 20 m. Decreased fish catches and death of benthic fauna has been observed at several occasions and over extensive areas.

In Danish and German coastal waters permanent hypoxia is rare, but, seasonally severe hypoxia occurs mainly in the autumn months. The extent and duration of hypoxia varies from year to year, with hypoxic conditions lasting for about 1-8 weeks.

Along the Polish coast hypoxia has been recorded in the Szczecin lagoon. In the Gdansk bay a decrease both in abundance and biomass of benthic macrofauna has been detected since 1995 until 2002, when in some areas only 10 % of the bottom fauna was left. In 2003 the situation improved in some areas with recolonization of *Pontoporeia femorata* (a hypoxia sensitive amphipod, indicative of relatively good conditions).

In Lithuania hypoxia is not a problem, but, in the Curonian lagoon extensive fish kills were observed during the summer of 2003. During late summer night-concentrations of oxygen in a range 2-4 mg/l, at depths of ca 2,5-4 m where measured.

Off St. Petersburg, Russia, hypoxic conditions occur occasionally in early autumn in below-thermocline waters. In 1996, 2001, 2003 and 2006 very low near-bottom oxygen concentrations were observed. In these waters a changing benthic community has also been observed (*Monoporeia affinis* dominated communities have been replaced by the alien tubificid species *Tubificoides pseudogaster*).

Finnish south coast – unfortunately the speaker (Heikki Pitkänen) was not able to participate

In the Archipelago Sea, Finland, scattered findings of hypoxic areas have been observed since the 1950s. In the 1990s large areas of anoxic bottoms where found in shallow waters (0,5-20 m), the main part in the outer archipelago area. The situation is most severe at ca 20-40 m depth, while deeper areas are usually better ventilated, thus the bottom waters have a higher concentration of oxygen. The situation in the Archipelago Sea, Åland and Stockholm archipelago is continuously deteriorating, despite water protection measures taken.

One imported aspect pointed out during the discussion was that hypoxia is not recorded if it is not looked for. In both Finland and in Sweden very limited bottom areas have been investigated, and almost always in the vicinity of biological stations. E.g. in 1990 when large areas with hypoxia were found in the Finnish archipelago this observation was due to a thorough investigation of the bottoms. One conclusion is therefore that we do not know enough about the geographical and temporal magnitude of hypoxia in coastal waters. Another thing discussed was the need for monitoring and long time data in order to detect hypoxia, something everybody strongly agreed on. Of those present many expressed their fear of monitoring being run down due to requirements of saving among environmental authorities. The occurrence of drifting algal mats and local (regional) hypoxia induced by these algae is also poorly known.

It is worth to point out that at this workshop there were not representatives from all coastal areas along the Baltic Sea, and even if nothing is mentioned about e.g. the Finnish south coast hypoxia is generally accepted to be an extensive problem there as well.

Our current understanding of the coastal hypoxia problem

Benthos

Already one week of oxygen depletion can decrease species richness up to 50 % or more. Recovery takes at the best ca 1 year. A single short period of hypoxia in an area may not have severe consequences on the benthos, but if an area is repeatedly suffering from hypoxia the resilience of the area will probably diminish and the risk of an irreversible regime shift increases. In many areas dramatically altered soft bottom communities have been observed, among other things in Russian waters. Surprisingly hypoxia might have a more drastic effect on open shallow areas than in closed areas, as the fauna in enclosed areas generally consists of more hypoxia tolerant species.

The shallow Danish straits with a high natural biodiversity are especially sensitive to hypoxia. If the benthos in this area is eliminated due to hypoxia this might affect and restrict the colonization rates into large parts of the Baltic Sea, with potentially severe cascading effects for the entire ecosystem.

Bottom-dwelling animals that can not escape hypoxia have been shown to change their metabolism in order to cope with hypoxia. After the aerobic metabolism has turned ineffective an anaerobic metabolism is switch on in some animals. This ability, i.e. the tolerance towards hypoxia, varies greatly between species, with e.g. *Macoma Baltica* as a relatively tolerant species, and mobile crustaceans displaying opposite responses.

During the discussions several participants expressed their concern for the bottom dwelling organisms and what might happen to the rest of the ecosystem if they are removed to a larger extent, as benthos both provide food for e.g. fish and metabolize organic material and thereby influence mineralization processes. If it is possible to oxygenate the bottom waters the question was also raised as to how benthos will react to a sudden increase in oxygen *content in the bottom waters. The situation in the open Baltic Sea is currently very bad for zoobenthos, and similar conditions may occur also in the coastal regions.*

Climate change and geology

Climate change affects the runoff of nutrients from land (increases it), which means that especially the coastal waters are affected. In a study area in the Archipelago Sea, close to a river mouth sediments have been laminated (hypoxia has occurred) during the Medieval Warm Period (ca 1250-450 BP) and for the past 200 years, with better conditions occurring during the Little Ice Age (450-200 BP).

Surprisingly, even though one could expect improved conditions and less/no laminated sediments in the archipelagoes after extensive purification measures were taken during the later half of 20th century, little evidence of this have been found. It is thought that the deteriorating situation in the open sea is counteracting the efforts being taken to lessen nutrients emission from point sources. Alarming is also that the situation seems to be deteriorating even in the Bothnian Sea.

It would be important to be able to separate naturally occurring hypoxia from man induced stress on the oxygen dynamics, and the workshop identifies a clear need for more knowledge on these processes in order to facilitate ecologically feasible management-options.

Mechanisms and processes

Apart from waters high in nutrients/massive organic production/sedimentation the emergence of hypoxia is also affected by surrounding factors such as topography and morphology and water stratification (halocline or thermocline). The Baltic coast is highly variable, especially the archipelago areas, and even in two neighboring bays in an archipelago area the oxygen conditions might differ completely.

A detailed mechanistic understanding of rates and pathways during organic matter mineralization is crucial to understand and predict biogeochemical consequences from short- and long-term exposure to environmental and man-made stressors.

The filter-function of archipelago areas was questioned during the discussion, several participants pointed out that this statement is exaggerated and that the archipelagoes do not function as filters any more due to too high nutrient concentrations in the coastal waters, both inside and outside archipelago areas. The fact that there is more knowledge about the situation and the processes in the open Baltic Sea than in the coastal areas was put forward.

The fact that even two nearby bays might differ completely in oxygen concentrations underline the need for custom-made remedies for the problem.

The biochemical processes are poorly known in the coastal areas, and we should learn more about them before we manipulate the system; remedies may not provide to be effective or lasting if they are based on wrong assumptions about nutrient remineralisation etc.

Possible remedies to coastal hypoxia

Mussel farming, harvesting of algae and fishing were presented as potential means of removing nutrients from regional coastal areas. While mussel farming has been tried on several locations (specifically in combination with aquaculture), and the results from these experiments seems relatively positive, harvesting of algae is still a big question mark (the project presented had not been properly carried through). The problem with both these potential remedies is what to do with the products: blue mussels and algae. Harvesting of local cyanobacterial assemblages may provide "clear" water in bating bays, but the problem of eutrophication will not be cured. Similarly, harvesting of drifting filamentous algae may clean sandy beaches, but it is 1uestionable whether this method can be made environmentally friendly and energetically acceptable from a cost-benefit point of view.

In small-scale experiments in coastal areas in the Baltic Sea top-predatory fish have been removed with increased filamentous macroalgae as a consequence. Restoring the fish assemblages by e.g. introducing top-predators to the system may provide an alternative remedy.

The overall opinion during the discussion was that these means, at least mussel farming and algae harvesting, might function well on a restricted local scale, but should mainly be seen as restoration activity, a measure that will support ecosystem recovery, not a solution to coastal eutrophication and/or hypoxic events. The main goal must be to cut emissions into the coastal ecosystem. In order to improve the situation in the coastal area both land and the open surrounding sea has to be taken into account – the coastal waters are not a separate entity.

Management options and the need for modeling and ecological engineering

In order to make decision makers understand the problem of hypoxia (and a deteriorating Baltic Sea environment) we need models that can describe the problem accurately. For the Archipelago area, Åland and Stockholm archipelago a water quality model has been developed. It shows that the water quality in innermost archipelago areas is dependent on nutrient loading from local sources, while the outer archipelago is primarily affected by the water quality in surrounding open sea areas.

It is the politicians who must set the main goals and demand actions, not the scientist, but in order to make the right decisions they need information from natural scientists. A problem is that the decision maker and the researcher often do not understand each other. A link between these two parts could be the social scientist. Models are of big importance when the natural scientist presents different alternative solutions/scenarios to the decision maker, and the WS acknowledges the need to develop detailed coastal models with predictive power.

Even though we do not know enough, actions have to be taken immediately – we can not wait any longer to try improving the coastal waters of the Baltic Sea. Actions have to be based on *existing knowledge. There is a lot of knowledge and data available that is scattered on different disciplines – these data and knowledge have to be collect and put together in order to be of use, in the end for the decision makers. There seems to bee very little collaboration between countries when it comes to environmental issues; the same questions are dealt with several times over. The military has detailed under water maps, which due to security reasons have not been made available for science: access to detailed topographical, geological and sedimentological underwater maps was asked for.*

Conclusions

- We do not know the exact spatial and temporal extent of hypoxia in coastal waters.
- We do not know enough about biogeochemical processes in the bottom waters and sediments.
- We do not know enough about how multiple stressors influence the Baltic Sea ecosystem (e.g. climate change in relation to eutrophication).
- We know too little about the resilience and recovery of coastal waters after hypoxia.
- We do not know what is human induced hypoxia and what is "natural" in relation to hypoxia.
- Models are usually made by oceonographers primarily interested in the large scale. We need models including biogeochemical processes, nutrient transport, ecology etc. in order to understand hypoxia in coastal waters.
- There should be more co-operation between different disciplines (and countries) in order to gain comprehensive insight in the complex issues at hand.
- There are still problems with communication between natural scientists and decision makers.
- There is a need for expert groups that could give advice to authorities (e.g. before permission is given by authorities to perform large-scale experiments on mitigating hypoxia problems in coastal waters), this is even asked for by authorities!
- There is a need for new workshops/meetings in smaller expert-groups, focusing on a specific issues.

Final discussion

Program

Location: Åbo Akademi University, auditorium Aura, Tehtaankatu/Fabriksgatan 2, Turku/Åbo, Finland

16 October	**The geographical & regional magnitude of coastal hypoxia around the Baltic Sea**
08.30-09.00	Registration
	Chair: Erik Bonsdorff
09.00-10.00	Welcome & introduction – Daniel Conley & Erik Bonsdorff Short presentation of participants
10.00-11.00	Keynote 1: Coastal Hypoxia – Robert Diaz
11.00-11.15	Coffee break
	Chair: Alf Norkko
11.15-11.45	West coast of Sweden: Hypoxia and shallow-water ecosystems – Kristina Sundbäck
11.45-12.15	Hypoxia and benthic ecological quality in the Baltic Sea - North Sea transition– Alf Josefson (& Michael L. Zettler)
12.15-12.45	Polish coast & Gdansk Bay – Janusz Pempkowiak
12.45-13.45	Lunch (Åbo Akademi University, Café Arken, Tehtaankatu/Farbriksgatan 2)
	Chair: Anna Jöborn
13.45-14.15	Kuronian Lagoon & Baltic coast – Arturas Razinkovas
14.15-14.45	Northern Baltic Sea coastal areas – Timo Tamminen
14.45-15.00	Coffee break
15.00-15.30	Neva Bay – Alexey Maximov
15.30-16.00	Gulf of Finland – Jouni Lehtoranta
16.00-16.30	Archipelago Sea and the effects of climate change – Ilppo Vuorinen
16.30-17.00	Discussion – Discussion leader: Erik Bonsdorff
19.00-	Dinner (Åbo Akademi University, Café Arken, Tehtaankatu/Fabriksgatan 2)

17 October	**Our current understanding of the coastal hypoxia problem**
	Chair: Bo Gustafsson
09.00-10.00	Keynote 2: Laminated sediments in the Baltic Sea – Per Jonsson
10.00-10.15	Coffe break
10.15-10.45	Geological records in sediments, the Archipelago Sea – Joonas Virtasalo
10.45-11.15	How benthic organisms cope with hypoxia – Urszula Janas
11.15-11.45	Chemical implications of coastal hypoxia – Stefan Hulth
11.45-12.45	Lunch (Åbo Akademi University, Café Arken, Tehtaankatu/Fabriksgatan 2)

Possible remedies to coastal hypoxia

Chair: Georgia Destouni

12.45-13.15	Mitigation through compensation - mussel production as biofilter – Jens K Petersen (& Marita Carlsson)
13.15-13.45	Mussel Farming - a remediation tool for coastal water quality – Odd Lindahl
13.45-14.15	Harvesting of algae – Anna Jöborn
14.15-14.45	Coastal fish/fisheries – Lars Ljunggren
14.45-15.00	Coffee break
15.00-17.00	Discussion – Discussion leader: Daniel Conley
19.00-	Dinner (Restaurant Slottsgatan 3, Linnankatu/Slottsgatan 3)

18 October Management options and the need for modeling and ecological engineering

Chair: Maren Voss

09.00-9.40	Coastal modelling (BEVIS) - Johanna Mattila
9.40-10.00	Links between the workshop and the work on hypoxia at Swedish EPA – Sif Johansson
10.00-10.15	Coffee break
10.15-12.00	Discussion and conclusions of the workshop – Erik Bonsdorff & Daniel Conley
12.00	End of workshop
12.00-13.00	Lunch

Johanna Mattila is making her presentation

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Appendix 3

Baltic Sea 2020

Report from the 3rd Baltic Sea 2020 workshop on hypoxia in the Baltic Sea *by Lovisa Zillén and Daniel J. Conley*

Potential management techniques, environmental effects and ethics

A workshop held 27-29 November 2007 at the GeoBiosphere Science Centre, Lund University, Sweden.

Contents

Introduction

In the autumn of 2005 financier Björn Carlson donated 500 million SEK to the Swedish Royal Academy of Science for the formation of the foundation Baltic Sea 2020 (Björn Carlsons Östersjöstiftelse). The intention of the foundation is to significantly improve the Baltic Sea environment before the year 2020 and to invest money in innovative research, experimentation and creation of networks between researchers. The main objective is to generate new knowledge in practical measures to improve the environment and the dialogue between decision-makers around the Baltic Sea.

A series of workshops has been held with the overall goal to create an improved understanding of hypoxia in the Baltic Sea and to determine if there are technical solutions to mitigating the devastating environmental effects of hypoxia. The Baltic Sea 2020 workshop in Lund (27-29 November 2007) was the third in this series, and focused on potential management techniques, environmental effects and ethics.

Background information about the Baltic Sea, off shore and coastal hypoxia can be found in the two previous workshop reports, which are available at www.balticsea2020.se. In addition, a more comprehensive report will be written after the final seminar in Stockholm, 24 of January 2008.

Previous and upcoming workshops:

1. **Understanding hypoxia in the Baltic Sea**
   17-19 April 2007, Lund University, Sweden.

2. **Coastal hypoxia**
   16-18 October 2007, Åbo Akademi University, Finland.

3. **Potential management techniques, environmental effects and ethics**
   27-29 November 2007, Lund University, Sweden.

4. **Possible solutions to oxygen problems in the Baltic Sea**
   24 January 2008, KVA, Stockholm, Sweden.

Reporter Lovisa Zillén

Invited speaker’s presentations

Realistic reductions in nutrients: from the heart *by Fred Wulff*

Department of System Ecology, Stockholm University, Sweden.

Fred Wulff

Presentation

Despite measures taken nationally and internationally during the last decades eutrophication continues to be a priority environmental problem of major concern in the Baltic Sea region. There are several reasons for this problem. One reason is that a large proportion of the total load of waterborne and airborne nutrients to the sea originates from diffuse sources like agriculture, a sector where national law is not as efficient as for point sources, but where measures to reduce nutrients to the Baltic Sea need to be taken. There are also considerable time delays between measures taken in a drainage basin and detectable reductions in the input of nutrients to the sea. The long residence of nutrients (many years) means that outputs from one region are likely to affect other regions. The open coastal zones are not only affected by nutrient inputs from land but also from the open sea and thus also from other basins.

NEST – a model for decision support system for management of eutrophication in the Baltic Sea, now contains 6 basic modules (Marine modeling, Atmospheric emissions and load, Coast minimization model, Drainage basin modeling, Marine and runoff data and Fishery management). In the model’s best scenario (which includes better sewage and phosphorous free detergent) there is a potential to decrease blue green algae blooms by 50 % in the future in comparison to today, while the business as usual scenario (with the same level of agriculture in the Baltic Sea as in Denmark) would result in a 50 % increase.

In 2006, the HELCOM Member States and the EU decided to develop a Baltic Sea Action Plan, which is a new environmental strategy for the Baltic Sea region with the ambition to restore the good ecological status of the Baltic marine environment by 2021. After a series of negotiations held from April to October 2007 a final version of the Baltic Sea Action Plan was signed on the 15 of November 2007 in Krakow, Poland. Based on figures from the NEST model they agreed on:

- Identifying maximum allowable inputs of nutrients in order to reach good environmental status of the Baltic Sea
- That there is a need to reduce the nutrient inputs, 15 000 tones of phosphorous (P) and 135 000 tones of nitrogen (N), and that the needed reductions shall be fairly shared by all Baltic Sea countries
- To take action no later than 2016 to reduce the nutrient load from waterborne and airborne inputs aiming at reaching good ecological and environmental status by 2021

To reach these targets, for most regions, it would mean to aim for conditions comparable to those in the 1950s. Even if all the countries around the Baltic Sea followed the EU directive, it would still take time before any recognized improvements could be detected. This delay would be caused by the long response time (c. 25 yr) and the large internal stock of nutrients (mobile P in sediments).

Figure 1. Photo from the HELCOM conference in Krakow, Poland, on the 15th of November 2007.

Implementing an engineering solution in the Baltic Sea: Legal aspects *by Per Hallström*

Swedish Environmental Protection Agency, Stockholm, Sweden.

Per Hallström

Presentation

The aim of the presentation is to give an overview and understanding of the legal framework regulating sea-based activities. Major questions that need to be answered before any engineering solution can be implemented in the Baltic Sea are: What engineering solution (impact on environment, fixed or mobile, involving dumping of substances or not)? Implemented by whom (states or private companies, and if state, by which country)? Implemented where (on land or in water, in coastal or open waters)?

The major international conventions applying to the Baltic Sea are UNCLOS (General requirements), MARPOL (environmental requirements), London Convention/Protocol (prohibition of dumping), Helsinki Convention (all of the previous and more) and the Esbo convention (environmental impact assessments). Some fundamental principles and obligations within these conventions are that the contracting parties shall (1) individually or jointly take all appropriate legislative, administrative or other relevant measures to prevent and eliminate pollution, (2) apply the precautionary principle, i.e., to take preventive measures when there is reason to assume that substances or energy introduced, directly or indirectly, into the marine environment may create hazards to human health, harm living resources and marine ecosystems, damage amenities or interfere with other legitimate uses of the sea even when there is no conclusive evidence of a causal relationship between inputs and their alleged effects and the preservation of its ecological balance, (3) promote the use of best environmental practice and best available technology and (4) apply the *"polluter-pays principle"*.

All waters are divided into following regulatory zones (see Fig. 2):

- **Internal waters**
  Area: All water and waterways on the landward side of the baseline.
  Rights: The coastal state is free to set laws, regulate use, and use any resource.
- **Territorial waters**
  Area: Up to 12 NM from the baseline.
  Rights: The coastal state is free to set laws, regulate use, and use any resource. Foreign vessels are entitled the right of so called "innocent passage".
- **Contiguous zone**
  Area: Up to 12 NM from the outer border of the territorial waters (24 NM from baseline).
  Rights: The coastal state can continue to enforce laws regarding activities such as smuggling or illegal immigration.

- **Exclusive Economic Zone (EEZ)**
  Area: Up to 200 NM from the Baseline.
  Rights: The coastal state has sole exploitation rights over all natural resources as well as to control scientific research and the environmental protection. The coastal state further enjoys jurisdiction over any erection of artificial islands. Foreign nations enjoy the freedom of navigation, subject to the regulation of the coastal state, and may also lay submarine pipes and cables.
- **Continental Shelf**
  Area: The natural prolongation of the land territory to the continental margin's outer edge, or 200 nautical miles from the coastal state's baseline, whichever is greater.
  The continental shelf may exceed 200 nautical miles until the natural prolongation ends, but it may never exceed 350 nautical miles, or 100 nautical miles beyond 2 500 meter isobath.
  Rights: The coastal state has an exclusive right to harvest mineral and non-living material in the subsoil of its continental shelf.
- **International waters**
  Area: Everything beyond the Continental Shelf or the EEZ to a new Continental Shelf or EEZ.
  Rights: *"Freedom of the seas"* including shipping and fishing. However, international waters are subject to specific regulations in international conventions and customary international law.

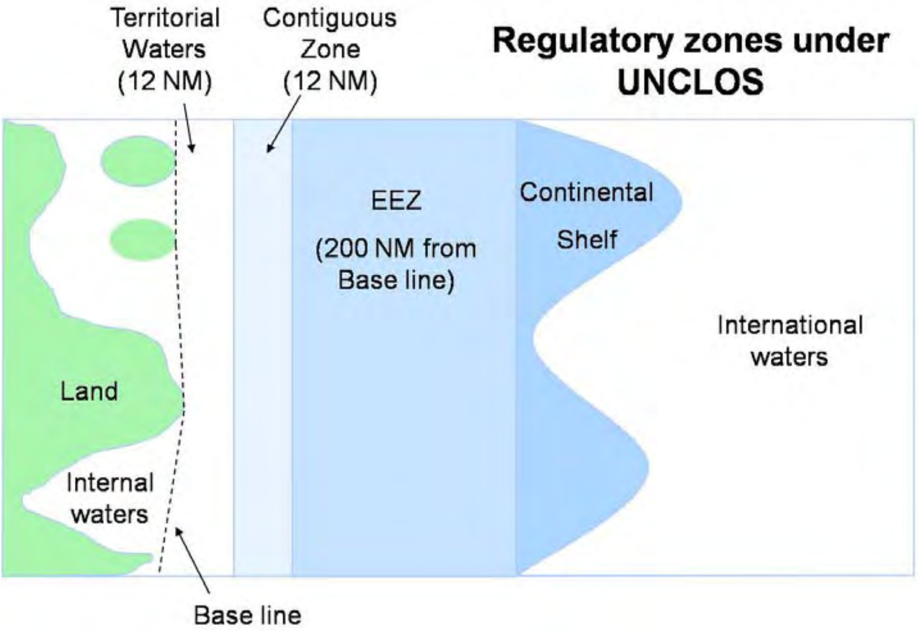

Figure 2. Figure illustrating the regulatory zones.

There are several legal aspects to consider before implementing an engineering solution in the Baltic Sea, as for example, (1) there are several multilateral requirements in international conventions, (2) several international bodies supervising these requirements, (3) flag states exercise unilateral jurisdiction over its ships, (4) coastal states exercise unilateral jurisdiction over the Baltic waters and (5) permit requirements applies, but varies depending on the water area and activity in question.

To consider an engineering solution for the Baltic Sea is a new concept and, such a solution, might not fit into the current framework of laws and regulations. It must as well be clarified how national authorities, international organisations (HELCOM etc) and the public will react?

Phosphorous pools in Baltic Sea sediments *by Caroline Slomp and Haydon Mort*

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Caroline Slomp

Presentation

The availability of phosphorus (P) for growth of phytoplankton in marine systems depends on the balance between terrestrial inputs, marine outputs and the efficiency of recycling of P. Terrestrial inputs are dominated by riverborne weathering products, fertilizer P and sewage while the marine outputs are sediment burial and outflows (in semi-enclosed basins). Most P in marine sediments is buried in the form of organic P, Fe-(hydr)oxide-bound P or carbonate fluorapatite (CFA or authigenic Ca-P).

Benthic P-release is important in determining the P-availability and water quality in many coastal aquatic systems. Since the benthic release of P is enhanced under low-oxygen bottom waters (or hypoxia), a positive feedback loop between P-availability, primary production and increased hypoxia may develop. The enhanced phosphate flux from sediments overlain by oxygen-depleted waters is usually ascribed to the release of P from easily reducible Fe-phases. Burial of other P phases, such as organic P and CFA, is also redox dependent, however. This means that a change to anoxic bottom water conditions could potentially lead to a shutdown of P burial in sediments.

In order to study the burial sinks for P in the Baltic Sea (in what form, where, and how much?), sediment cores from 11 sites were recovered during a cruise in the Baltic Proper during Aug 31- Sep 7, 2007. Short sediment cores (with a length of ~50 cm) were recovered from anoxic (Arkona Basin, Bornholm Basin, Landsort Deep, Gotland Deep and Baltic Proper; Fig. 3) and oxic bottoms (Fladen, Landsort Deep oxic, Bornholm Basin, Öresund Strait and Gotland Deep).

Preliminary results from detailed sediment P-analyses confirm earlier suggestions in the literature that the major burial sinks for P in the Baltic are likely organic P and Ca-P. The relative importance of these sinks varies from site to site and with depth in the sediment. Besides in-situ formation of CFA, there are other potential sources of the Ca-P including erosion of CFA formed in sediments of near-shore areas (if so, the Ca-P is truly authigenic), terrestrial input (if, so, the Ca-P is not authigenic) and fish debris (at least in deep anoxic basins). Enrichments of Fe-bound P in the surface sediment are observed at oxic and seasonally hypoxic sites. This Fe-bound P is mostly a temporary sink for P, even though there appears to be some permanent burial.

Figure 3. Photo of short sediment cores recovered in Aug-Sep, 2007 in the Baltic Proper for 6 anoxic sites.

In conclusion, the high P-availability in the Baltic Sea is difficult to counteract because of the internal recycling of P. Possible solutions besides decreasing the loads (long term) would be to stimulate enhanced permanent burial of P. However, increased Fe-P burial through artificial oxygenation may not enhance permanent removal. A stimulation of authigenic Ca-P burial could potentially be a permanent solution – but one major question remains; is this possible?

Chemical precipitation of phosphorous *by Sven Blomqvist*

Department of System Ecology, Stockholm University, Sweden.

Sven Blomqvist

Presentation

The Baltic proper acts as a source of phosphorous rather than a sink. Since 1960, there has been a long-term increase of the dissolved phosphate concentration level in the mixed surface layer of the eastern Gotland Basin, which implies that the Baltic Sea has become an inefficient sink to precipitate phosphorous.

We suggest three alternative of active P sequestering (also combinations of these): (1) precipitation by aluminum (Al), (2) complexation by lime and (3) formation of apatite. These are three tangible actions of great potential, singly or in combination, which would combat eutrophication, both locally and regionally, and reduce the large blooms of cyanobacteria.

A preliminary calculation of the cost for treatment with granula of aluminum sulphate ranges between 2–30 billion SEK. The method is, however, associated with the risks of (1) changing the sea water chemistry (e.g., dissolved silica content), (2) over-treatment, resulting in oligotrophication and subsequent alterations of the food-webs and (3) enhanced toxicity, since Al might be toxic to certain fauna.

Before any action is taken, we propose that following tasks should be completed:

- Initiate mapping of mobile P in various bottom sediments. Combine sediment profiling with nutrient release experiments.
- Determine the stoichiometry of Al-P complexation for different environmental conditions, including the influence of calcium. This to permit proper scaling (optimizing) of Al amendments. Reported Al/P ratios in treated lake sediments vary from 1 to 12. High calcium concentration results in efficient P sequestering, i.e., less Al is needed.
- Evaluate the potential of lime as a sequestering substance of P in Baltic Sea sediments. Include systematic studies dedicated to chemical mechanisms of P adsorption (electrostatically and chemically), factors affecting the capacity of adsorption – located to environments of different conditions.
- Evaluate the possibility to form apatite by adding Ca (altering the Ca/Mg ratio), for instance, by utilizing Cement Kiln Dust (a byproduct from manufacturing of ceramics), which globally today provides an environmental problem (stored in large excess).

- Start the development of appropriate settling particles (granula of optimal size, shape, density, etc) which might sequester P itself, or carry substances added (coated) with P binding compounds.

We believe that any successful Baltic Sea management by active P-sequestering must progress stepwise. Initial experimental studies should be performed in small, well defined microcosm (e.g., Erlenmeyer flask) test systems. Thereafter, in order to increase complexity, studies in mesocosm systems, simulating natural conditions (e.g., sediment resuspension) followed by P-sequestering of selected constrained coastal bays with anoxic bottoms conditions could be contemplated. Lastly, one might consider treatment of larger coastal areas and/or anoxic bottoms in the open Baltic Sea.

Chemical precipitation of phosphorous *by Henning Jensen*

Institute of Biology, University of Southern Denmark

Henning Jensen

Presentation

Aluminum treatment has been used in more than 143 lakes worldwide, mostly in the USA. The response of this treatment has been measured and documented in more than 50% of the lakes. Improvements in water clarity were observed in more than 80% of the cases. Mass balances have been measured in less than 10 lakes and the binding capacity for P on Al has been evaluated in less than 5 lakes.

In October 2006, Lake Nordborg in Denmark was treated with Al (Fig. 4). The average summer secchi depth at that point was 2.2 m. In the summer 2007 (i.e. c. 8 month after Al-treatment) the secchi depth had increased to 3.2 m. Over the same period, the summer average P-concentrations in the water was reduced from 0.231 mg/l TP to 0.028 mg/l TP and the sediment P-release was decreased from 1906 kg to 108 kg (i.e. a 94% reduction). The sediment O_2 uptake also improved and summer average values of nitrate concentrations in the water increased from 0.175 mg/l in 2006 to 0.399 mg/l in 2007. After 2 mounths the P:Al molar ratio was 0.6. After 4 years it had decresed to 0.28.

Based on the experince we have gained from lakes, we believe that before adding Al to the Baltic Sea the following questions must be considered:

- How would the binding capacity of $Al(OH)_3$ with aging change in seawater?
- How toxic would Al be towards bottom fauna?
- How would the physics of floc formation operate in seawater?
- Dosage – how much will it take to make a difference?

Figure 4. Photo of aluminum treatment of Lake Nordborg, Denmark, in October 2006.

Bubbling coastal estuaries: The Pojo Bay example *by Marko Reinikainen*

Tvärminne Zoological Station, University of Helsinki, Finland.

Marko Reinikainen

Presentation

The Pojo Bay (length 14.5 km, mean width 1.6 km, max width 4.5 km, mean depth 9.3 m, max depth 42 m, drainage area 2 350 km2) is situated in the corner of the Hanko peninsula on the southernmost tip of continental Finland (Fig. 5). The semi-enclosed Pojo Bay is connected to the outer archipelago by a series of basins with variable depths. The inner part of the bay is separated by a 6 m deep sill at the town of Ekenäs; from there its depth gradually increases to a maximum of 42 m in Sällvik, ca. 5 km north of Ekenäs. Freshwater outflow from the River Svartå forms an oligohaline (generally less than 4 ‰) surface layer lying over the more saline deep water of the bay. This permanent vertical stratification leads to a gradual oxygen decrease in the deep water of Pojo Bay in the summer time. The deep water renewal occurs only under special meteorological conditions, mainly during autumn and winter, when hydraulic control at the basin entrance (Ekenäs sill) becomes weaker and allows saline inflows from the archipelago.

Pojo Bay and the outer archipelago have always been amongst the most important research areas of the Tvärminne Zoological Station. Therefore, considerable background data on the biology and hydrography of the bay are available. Nowadays, long-term data are of particular importance when scientists try to explain and understand changes in the coastal brackish-water system of the Baltic Sea.

Figure 5. The position of Pojo Bay in southern Finland.

A Pojo Bay working group was established in 1991 by regional stakeholders. In 1995, alarming low oxygen levels occurred. Because of the Pojo Bay working group, there was an increased awareness of hypoxia, and increased demands for practical action. Shortly after the hypoxic event in 1995, three Mixox-1100 pumps were installed near Sällvik-deep to ventilate the deeper water (see Fig. 6). The pumps had pumping capacities of 2.7 $m^3 s^{-1}$. The intake of water occurred 4 m below surface and the outflow 10 m above sea bottom. Pumping surface water to the hypolimnion resulted in that oxygen concentrations increased on average with 1.1-2.0 mg/l at the deep water measuring stations. The salinity decreased on average with ca 0.5-0.9 in the hypolimnion, and hence inflow of oxygen-rich sea-water was facilitated.

The major conclusions drawn from this project were that pumping surface water to the hypolimnion in a semi-closed bay will:

- Increase the average oxygen concentration in the hypolimnion.
- Decrease the salinity in the hypolimnion.
- Facilitate the inflow of water from the sea-area to the hypolimnion.
- Shorten the time-period when oxygen concentrations are critical.
- Have measurable effects on sampling points within a few kilometers from the pumps. Farther away, effects will be dampened.
- Increase nutrient (P) levels slightly or not at all.

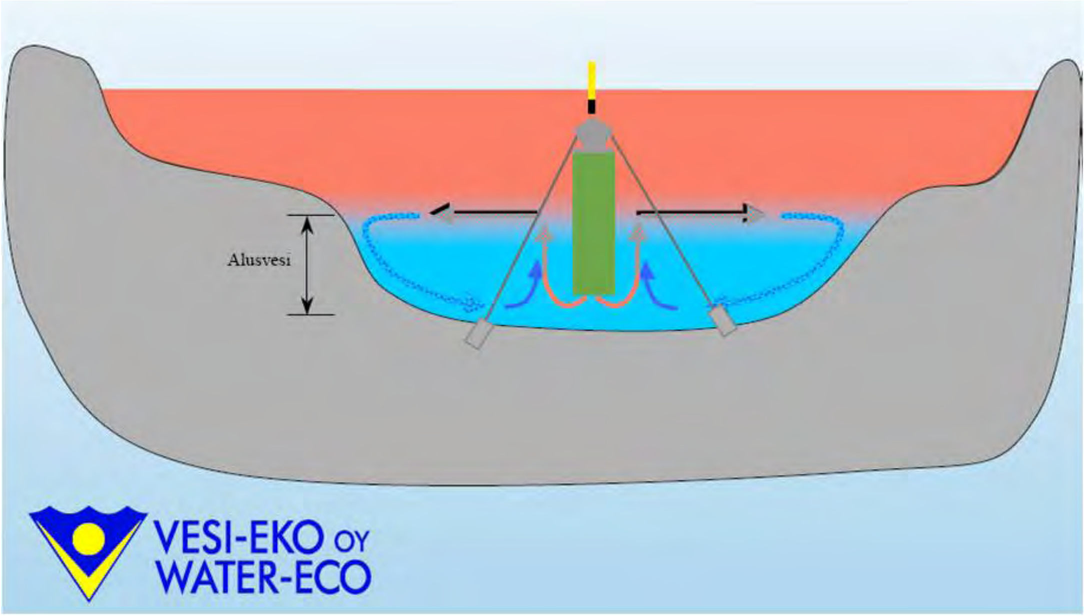

Figure 6. Schematic illustration of the Mixox-1100 pump during operation.

Vertical mixing in the Baltic Sea – a review *by Hans Burchard*

Baltic Sea Research Institute Warnemünde, Germany.

Hans Burchard

Presentation

The vertical mixing in the transition area from the North Sea to the Baltic Sea is dominated by entrainment processes of the inflowing saline water within near bottom layers (Fig.7). The hot spots of these processes are located at the Darss Sill and the Bornholm Channel in the western Baltic Sea. In the central Baltic Sea temporal changes and associated transports are dominated by the horizontal advection of saline water in deep layers below the permanent halocline. This is accompanied by the turbulent vertical transport through the halocline into the surface layers. The related vertical salt transport into the entire surface mixed layer is estimated by various methods to be around values slightly above 30 kg/(m^2 a). During so-called stagnation periods the corresponding residence time of the deep water in the Eastern Gotland Basin drastically increases roughly by a factor of five.

Therefore vertical mixing through the halocline seems to be drastically reduced when inflows are lacking. The turbulent motion resulting from breaking internal waves seems to be capable of turbulent transports through the halocline corresponding to the estimates of the salt transport into the surface mixed layer. The actual knowledge about boundary mixing due to internal waves in the Baltic Sea is found to be poor. Mesoscale eddies are evaluated to be able to contribute to the vertical mixing, but it is not known if they really do and which of the possible direct and indirect mixing mechanisms is most effective. Near bottom currents induced by inflow events are found to be likely to enhance vertical mixing. Coastal upwelling certainly contributes to the vertical transport, but the depth of its origin and the volume transport are hard to determine for large-scale quantifications. The short spatiotemporal scale of turbulent transports through the halocline resulting in a weakening of the halocline during summer and the mixing of the entire surface layer down to the halocline in winter are combined to a consistent description of the vertical salt transport. The longer residence time of the deep water during stagnation periods is hypothesised to be attributed to the lack of energy imported by the inflows and directly or indirectly feeding the diapycnal mixing processes. The discussion about consequences of vertical mixing processes crossing the seasonal thermocline and affecting the embedded ecosystem arrives at the conclusion that the vertical transport of nutrients such as the phosphate is quantitatively not sufficiently understood and needs further interdisciplinary research activities.

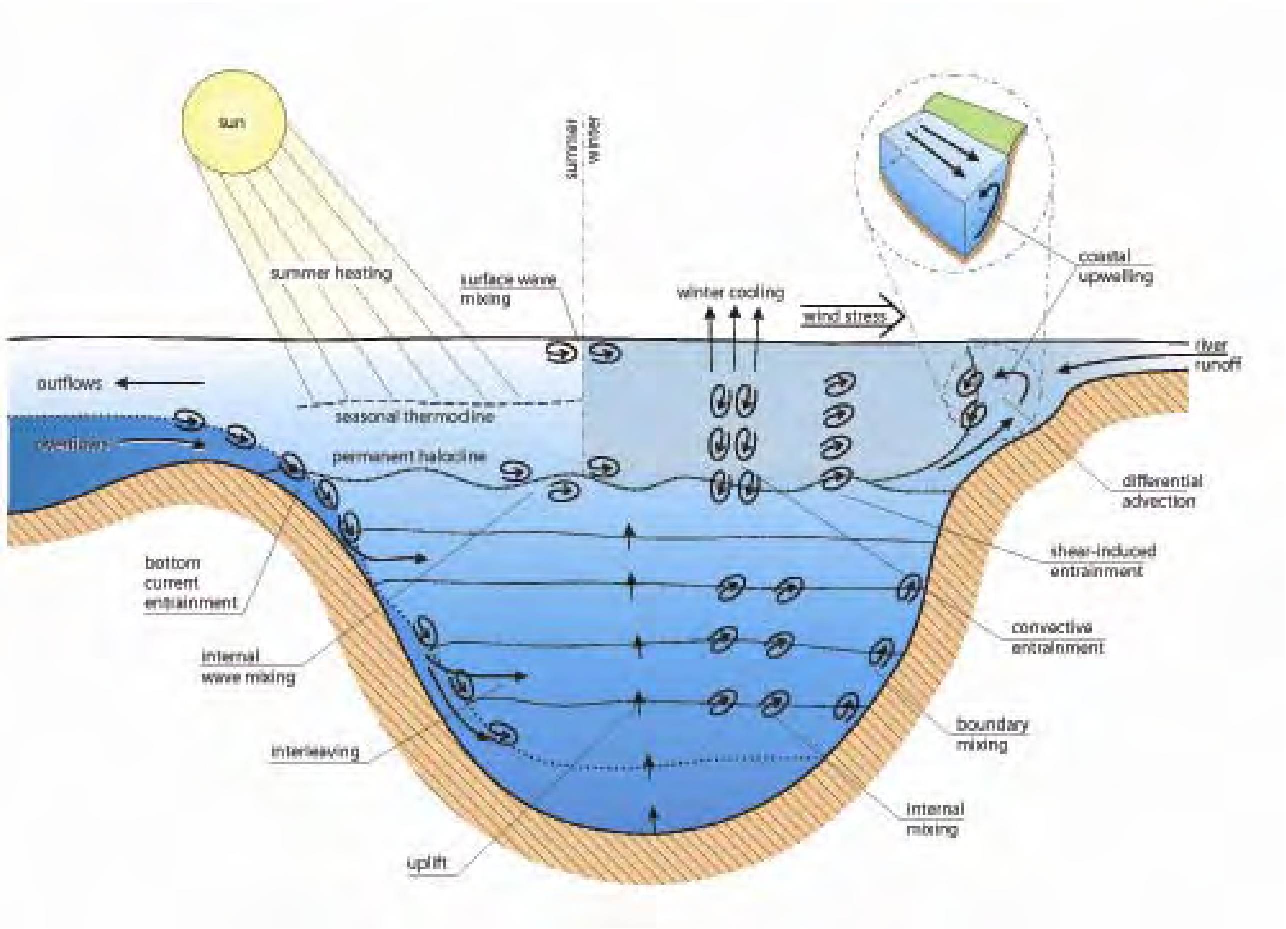

Figure 7. Scheme of vertical mixing and transport processes in the Baltic Sea.

Nitrogen cycling *by [1]Maren Voss, [2]Bo Gustafsson and [3]Oleg Savchuk*

[1]Baltic Sea Research Institute Warnemünde, Germany. [2]Earth Science Centre, Gothenburg University, Sweden. [3]Baltic Nest Institute, Stockholm University, Sweden.

Oleg Savchuk

Bo Gustafsson

Presentation

The major nitrogen (N) sources for the Baltic Sea are rivers (706 000 t/yr), N_2-fixation (400 000 t/yr), atmospheric deposition (264 200 t/yr) and direct emission (39 000 t/yr; Fig. 8). The annual total loss of N from the Baltic Sea is 500 000 t, which implies that the sources of N are larger than the sinks. However, the losses are poorly constrained. The only data available are some older data from the Gotland Basin and a few new data sets from Finnish coasts and estuaries. There are, therefore, large uncertainties in the estimates in Fig. 8 and it is unclear whether the N-cycle in the Baltic is unbalanced or not? If not, has it been balanced in former times – before human impacts (100 years ago)? Other questions to be considered are: how much nitrogen is really removed within the Baltic Sea in comparison to the inputs and how much further emission reductions can be achieved?

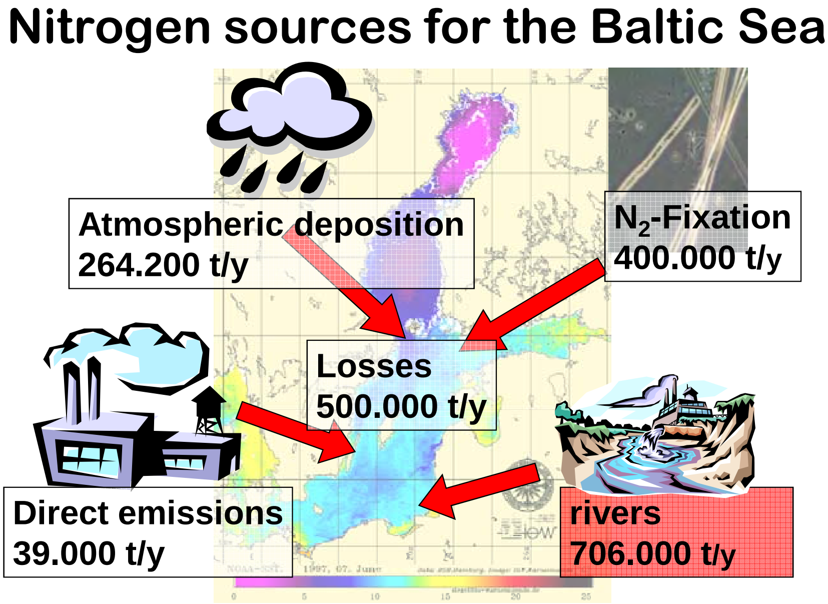

Figure 8. Figure illustrating the N-cycle in the Baltic Sea.

Physical aspects *by [1]Bo Gustafsson, [2]Markus Meier and [3]Oleg Savchuk*

[1]Earth Science Centre, Gothenburg University, Sweden. [2]Divison of Oceanography, Swedish Meteorological and Hydrological Institute, Sweden. [3]Baltic Nest Institute, Stockholm University, Sweden.

Markus Meier

Presentation

A number of more or less realistic/unrealistic propositions have been made as to what an engineer can do to improve conditions in the Baltic Sea. Less have been done to seriously investigate the consequences of such propositions. There is a common ignorance even in parts of the scientific community of, for example, the response of the Baltic Sea circulation to changes in the Danish straits.

Here we present the results from simulations of some engineering measures aiming at reducing effects from eutrophication of the Baltic Sea. A more detailed description of the simulation will be presented in a separate report.

Here the objectives were to:

1. Quantify changes in circulation, salinity, hypoxia/anoxia, production etc.
2. Identify major uncertainties of the simulations
3. Present results as a basis for the discussions at this workshop

Two state-of-the-art coupled physical-biogeochemical models have been used; RCO-SCOBI developed at SMHI and BALTSEM developed at Stockholm University and Gothenberg University. The models are structurally different in that RCO-SCOBI is a 3D model while BALTSEM resolves spatially the Baltic in 13 sub-basins. The biogeochemical sub-models have clear similarities, but there are significant differences as well. Both models reproduce present conditions with considerable accuracy.

The response of the Baltic Sea to different engineering measures has been investigated with the models by implementation of a series of test cases. The cases are:

Case 0. Control case without any alterations

Case 1. Halocline ventilation – Pump water from 50 to 125 m depth in the Baltic proper in order to keep major portions of the sea floor oxic and thereby increase P burial. Idea was based on mimicking the natural variations of P with hypoxic area. Described in Stigebrandt & Gustafsson (Ambio, 2007).

Case 2. The salt lock (the idea by the O_2-gruppen) – A sort of flap like construction should be placed in Great Belt that is fully open for inflows to the Baltic and closed for outflows. The idea was that it should hinder the salty water to return through Great Belt. Presented at www.o2gruppen.se.

Case 3. Opening/closing of the straits – not really seriously proposed by anyone, but the discussion comes up regularly what the effects are of general increasing/decreasing of the flow capacity of the straits.

Case 3a. Closed Öresund at the Drogden Sill.

Case 3b. Dredged Drogden Sill to twice the present depth.

Case 4. Deep water oxygenation – supply oxygen to the deep water in sufficient amounts to keep water from being hypoxic without disturbing stratification.

From the simulations the following conclusions could be made:

- Feedbacks from oxygen deficiency causes both increased primary production in general and increased cyanobacteria production in particular. The theoretical supply of oxygen needed to curb oxygen deficiency is of the order of $2 - 6\times10^6$ tons/yr.
- Any measures affecting the water exchange through the Danish Straits will cause change of the salinity of the Baltic. The models show consistently that measures causing increased salinity also cause deteriorating oxygen conditions and those causing decreased salinity improved oxygen conditions. However, freshening cases cause a long transitional stagnation period in deeper parts during which anoxia prevails. Thus, our conclusion is that it is not possible to improve oxygen conditions by any realistic engineering method affecting the exchange through the Danish straits.
- The models, in quite close agreement, show that halocline ventilation gives improved oxygen concentrations and no change in surface salinity. There is a decrease in deep water salinity, but within the range of natural variability and should not, therefore, affect biodiversity. Halocline ventilation is the only measure that can not be ruled out in this investigation.
- The models give consistent and plausible responses. However, we found quantitative differences in sensitivity and the reasons for these are explained.
- To accurately quantify the effects we need to improve in particular sediment parameterizations. Complementary high resolution simulations are also necessary.

Rebuilding the Ocean – Are we restocking the fridge or atoning for our sins? *By Mickey Gjerris*

Danish Centre for Bioethics and Risk Assessment, Denmark.

Mickey Gjerris

Presentation

In the future, we technically, have to face the challenge of sustainability, and ethically, the challenge of defining sustainability. It means that we have to ensure that the impact of human activities (past/present/future) will not threaten human life and that we have to define what values should guide us in our relation with nature.

Since World War Two it has become increasingly clear that technological developments raise ethical questions, as in for example, nuclear technology, biotechnology and nanotechnology. When applying technology on an oceanic scale it is wise not just to reflect on how to do it, but also why to do it. Especially because the answers to the *"why"* question has huge impact on the answers to the *"how"*-question. "*Why*" is an ethical question – but what is ethics? Ethics is a two-fold reflective task. You can either *"be in bed with a context"* (i.e. justifying moral judgments from a certain perspective on life, the universe and everything) or *"pretending not to be in bed with a context"* (i.e. analysing the values, beliefs, prioritizations, interconnectedness, motives and consequences of moral judgments).

Ethics in the 21st century is the scene of plurality where the public consists of many publics with different perspectives. There are basically three perspectives that nature can be viewed through; natural science, our needs and our immediate experience, where each perspective serves a purpose. The first two serve the purposes we have with nature, the last shows our embeddedness in nature.

Perspectives are *"installed"* in us through our family, culture, religion, education, friends etc. and enables us to see some issues and disregard others. We cannot choose our perspective, but we can seek to understand others. The way we see things are a key factor when we decide how to treat them. This means that people that disagree with us might not be stupid, not listening or not understanding, they might just have another perspective, and therefore, other values. Having different perspectives on the world, it is no surprise that we have different values!

We can choose a perspective and see the ocean as a resource for food and energy and as a source of our existence and part of our being. This means that the ocean has environmental importance and destroying this ecosystem will harm humans. The task now is to make up for past mistakes and to (re)build relations with an ocean that is something more than what we need.

Summary

- To reach targets set by the Baltic Sea Action Plan for inputs of nutrient into the Baltic Sea, for most countries, would require aiming for conditions comparable to those in the 1950s. Even if all the countries around the Baltic Sea followed the EU-directive, it would still take a long time (decades) before any recognized improvements in nutrient loading would be detected in the Baltic Sea.
- Mitigating hypoxia in the Baltic Sea is a new concept and an engineering solution to the problem might not fit into the current framework of laws and regulations.
- A potential solution to the enhanced eutrophication and associated hypoxia, besides decreasing the nutrient load (long term), would be to stimulate enhanced permanent burial of P; but is this possible?
- Aluminum (Al) treatment as a tool to reduce P-availability has been relative successful in lakes worldwide, mostly in USA. A potential treatment with granula of Al-sulphate in the Baltic Sea would be expensive (between 2-30 billions SEK). Al might be toxic to fauna and any successful Baltic Sea management by active P-sequestering must progress stepwise.
- Pilot water-ventilation studies in the Pojo Bay, Finland, demonstrate that such actions can result in increased average oxygen concentration, decreased salinity, increased inflow of water from the sea-area, shorter time-periods when oxygen concentrations are critical, measurable effects within a few kilometres from the pumps and increased or unchanged nutrient (P) levels.
- More detailed information about general pathways, mixing and related climatological mean salt flows of small, medium and large intensity salt water plumes in the Baltic Sea is needed.
- There are large uncertainties in the estimates of nitrogen and we do not know if the N-cycle in the Baltic Sea is balanced.
- Model simulations demonstrate that feedbacks from oxygen deficiency cause both increased primary production in general and increased cyanobacteria production in particular. Any measures affecting the water exchange through the Danish Straits will cause change of the salinity of the Baltic Sea. We suggest that it is not possible to improve oxygen conditions by any realistic engineering method affecting the exchange through the Danish straits and that halocline ventilation is the only engineering solution that cannot be ruled out in this investigation.
- To restore a healthy Baltic Sea, we probably have to choose an ethic perspective that sees the ocean as a source of our existence and part of our being.

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Program

Tuesday 27 November **Room Baltica (237)**

9.00

Welcome and Logistics - Daniel Conley and Lovisa Zillén

Introductions

Fred Wulff – Realistic reductions in nutrients: From the heart

Baltic Sea 2020 – Erik Bonsdorff

Baltic Sea Action Group – Johanna Ikavalko

10.30

Coffee break

Per Hallström – Implementing an engineering solution in the Baltic: Legal aspects

12.00-13.00

Lunch at Geocentrum II

Caroline Slomp and Haydon Mort – P pools in Baltic sediments

Sven Blomqvist – Chemical precipitation of P

Henning Jensen – Chemical precipitation of P

15.00

Coffee break

Advice to Baltic Sea 2020/SEPA

Discussion

16.00

Marko Reinikainen – Bubbling coastal estuaries: The Pojo Bay example

Wednesday 28 November ***Room Baltica (237)***

9.00

N Cycling - Discussion leaders: Maren Voss, Bo Gustafsson, Oleg Savchuk

Advice to SEPA

10.30

Coffee break

Hans Burchard – Vertical mixing in the Baltic Sea - a review

Physical Aspects

Discussion leaders: Bo Gustafsson, Markus Meier, Oleg Savchuk

Changing salt water inflows (Salt lock & closing/opening the straits)

Ventilation of the halocline

12.00-13.00

Lunch at Geocentrum II

Deep-water oxygenation

Impact on biogeochemical cycling

15.00

Coffee break

Discussion

Advice to Baltic Sea 2020/SEPA

Thursday 29 November ***Room Baltica (237)***

9.00

Mickey Gjerris - Rebuilding the Ocean – Are we restocking the fridge or atoning for our sins?

Discussion

10.30

Coffee break

What can we do now?

12.00

Lunch at Geocentrum II

Appendix 4

Hypoxia in the Baltic Sea:

Recommendations to BalticSea2020 and Naturvårdsverket

Executive Summary

Background

A project on *Understanding Hypoxia in the Baltic Sea* was initiated in January 2007 under the direction of Prof. Daniel Conley, Marie Curie Chair, GeoBiosphere Science Centre, Lund University, with funding provided by *BalticSea2020*. The goal was to create an improved understanding of hypoxia in the Baltic Sea and determine if there are technical solutions to mitigating the devastating environmental effects of hypoxia on living resources and if is possible to restore the self-purifying biogeochemical processes. Hypoxia is usually defined as oxygen concentrations less than 2 mg/L where large-scale biological and biogeochemical effects occur.

Three workshops were held with participation from scientists around the Baltic Sea together with involvement of internally recognized scientists. In total 60 different scientists from 10 different countries participated in these workshops. The workshops were:

1. Understanding Hypoxia in the Baltic Sea,17-19 April 2007, GeoBiosphere Science Centre, Lund University.
2. Coastal Hypoxia in the Baltic Sea, 16-18 October 2007, Åbo Akademi University.
3. Potential management techniques, environmental effects and ethics, 27-29 November 2007, GeoBiosphere Science Centre, Lund University.

A final meeting “Possible Solutions to Oxygen Problems in the Baltic Sea” was held at the Royal Swedish Academy of Sciences, Stockholm on 24 January 2008 with co-funding from the Swedish Environmental Protection Agency (Naturvårdsverket). The talks presented are available on the *BalticSea2020* web site http://www.balticsea2020.se/.

Hypoxia is a globally significant problem with over 375 reported sites suffering from hypoxia due to excess nutrient loading from anthropogenic sources. The International Panel for Climate Change (IPCC) also recognizes that hypoxia is a problem of growing concern with projected global changes. The synthesis activities as part of the “Hypoxia Project” have shown that climate and anthropogenic pressures both have played a role as drivers of hypoxia through time in the Baltic Sea. Superimposed on this natural variability, hypoxia has become considerably more widespread and prevalent in modern historical times, c. 1950-present, in both the coastal zone and the open waters of the Baltic Sea. The lack of oxygen reduces the available habitat for living resources, changes the self-cleansing biogeochemical processes so that P release from the bottom is enhanced and the processes of denitrification reduced, creating a vicious circle that helps to sustain eutrophication.

After the first workshop, 3 projects were initiated with funding from *BalticSea2020* to assist in the workshop’s goal of making recommendations based upon sound scientific advice. These projects included: “Simulations of Some Engineering Methods Proposed to Improve Oxygen Conditions in the Baltic Proper” (Bo Gustafsson, Göteborg University), “What Controls Sediment Phosphorus Burial in the Baltic Sea?” (Caroline Slomp, Utrecht University, The Netherlands), “Benthic-pelagic Coupling in the Baltic Sea: The Effects of Redox Changes on Sediment P Release and Implications for Water Quality” (Slomp and Gustafsson).

Results

Model experiments. Model experiments were carried out using the BALTSEM (Göteborg University and the Baltic Nest Institute) and RCO-SCOBI (SMHI) models to consider generalized engineering solutions that reduce hypoxia. Further documentation on the results from this project can be found at the *BalticSea2020* website. Since it was not possible to test all proposed engineering solutions, they were grouped into four general categories:
1. *Deep water oxygenation.* Various strategies have been suggested to add oxygen directly into deep-water, for example bubbling. The amount of oxygen need to keep the Baltic Sea above 2.8 mg/l, the threshold for mild hypoxia, was calculated. The amount of oxygen varied between 2-6 million tons of oxygen needed annually to keep the bottom waters from becoming hypoxic.
2. *Increased exchange across the Drogden Sill.* This experiment simulated enhanced salt water input into the Baltic Sea, for example the O2Gruppen Saltlock. Based on our current understanding of the Baltic Sea and from the model results, enhanced salt water input into bottom waters can be expected to increase stratification and the area of hypoxia.
3. *Closing the Drogden Sill.* A suggestion was made to reduce saltwater inflow, freshening the Baltic. Model results demonstrated that there is a long transitional stagnation period following reduced saltwater inflow during which hypoxia increases in deeper waters. There are improvements in water quality in the long run (>30 years) at the cost of a drastic reduction of salinity.
4. *Halocline ventilation by mid-water mixing (50 m to 125 m).* The models, in quite close agreement, show that halocline ventilation gives improved oxygen concentrations and no change in surface salinity. There is a decrease in deep water salinity, but within the range of natural variability. This physical mitigation appears to be the most feasible, but the effects on biogeochemical processes remain untested.

The models give consistent and plausible responses, although quantitative differences in sensitivity were obtained from the different models. The models need to improve, in particular, the parameterizations of sediment processes. Further, there is a need to link the deep-water models to models dealing with hypoxia in the coastal zone as well climate change. The processes and forcing functions for the formation and maintenance of hypoxia in shallower coastal waters differ and should be dealt with in separate models.

Chemical P sequestration. In freshwaters and sewage treatment plants aluminum and a variety of other chemicals have been used to chemically bind and precipitate phosphorus. One goal to alleviate hypoxia in the deeper basins of the Baltic Sea is enhance the permanent burial of P in Baltic Sea sediments. A recent Naturvårdsverket report by "Blomqvist and Rydin (2008) P-uppbindning i Östersjöns bottensediment" addresses many of the issues concerning P sequestration. While we can use the successful experience gained in small lakes, there are significant gaps in our present knowledge with regard to P precipitation in seawater. Potential problems include reductions in the binding capacity in seawater, toxicity for benthic organisms and the potential for co-sequestration of dissolved silicate.

Biomanipulation. Biomanipulation is the practice of altering biological communities through manipulating biological interactions. The classic report for fresh waters by Lars-Anders Hansson (1998) "Biomanipulering som restaureringsverktyg för näringsrika sjöar. NV Rapport 4851." is currently being updated to include possible remediation in the Baltic Sea. Although some success has been achieved in freshwaters, the enormous size of the Baltic Sea adds to the uncertainty of the effectiveness on biomanipulation on such a massive scale. It might be possible to implement different types of biomanipulation (predator addition, reduction in fishing, artificial mussel beds, algal harvesting) on the local scale in coastal waters, especially in "hot spots." Experience from fresh waters is that major achievements can only be made if the nutrient supply is reduced.

Re-establish the functioning of the coastal filter. Previous research has established the importance of the coastal zone and its ability to act as an important biofilter utilizing and processing nutrients before they make it out to open waters of the Baltic Sea, although the removal of nutrients remains unquantified. With coastal eutrophication, large areas of the coastal zone have been degraded with hypoxia common in the archipelago regions. However, we have a limited understanding of the spatial and temporal extent of hypoxia in the coastal zone and the impact of the loss of the coastal filter on the Baltic Sea.

Conclusions and Recommendations

We must reduce nutrients for any mitigation measure to be effective. We should redouble our efforts to make nutrient reductions in the Baltic Sea and go beyond the first stages of the Action Plan to specific measures within each country to reduce nutrient loads. Engineering solutions may enhance or accelerate the recovery process provided that nutrient inputs are reduced.

Any engineering solution that changes the overall salinity of the Baltic Sea should be avoided, since that would lead to significant alterations of species composition, in pelagic and benthic ecosystems. Changes in salinity are probably illegal with regard to the EU Habitats Directive and are likely politically unacceptable to many of the countries surrounding the Baltic Sea.

Engineering projects to add oxygen to the bottom waters of the Baltic Sea will need to consider the enormous amount of oxygen required (2-6 million tons annually) to keep the Baltic Sea from going hypoxic.

Model experiments demonstrate that halocline ventilation is the only engineering solution tested that cannot be ruled out.

There is no known P sequestration method that is mature enough for immediate implementation in the Baltic Sea. All techniques require preliminary experiments in the laboratory and at the mesocosm scale to show that the P losses are permanent and stable under varying redox conditions. This approach could provide a way to start reducing P pools in coastal regions. As a cautionary note, addition of any chemical will violate the principle of reversibility, e.g. once added to the Baltic Sea a chemical cannot be removed, no matter if the response obtained is desirable or not. Addition of chemicals may violate the London Convention.

Significant gaps remain in understanding the P and N biogeochemical cycles in the Baltic Sea. Basic questions such as “What are the sizes and location of the mobile/bioavailable P fraction and permanent P sinks in Baltic Sea sediments?” needs to be answered. In addition, experience from fresh waters shows that increased Fe-P burial through artificial oxygenation may not be sufficient to significantly increase P burial. With regard to N, disagreement exists on the impact of oxygenation on denitrification with predictions showing both positive and negative effects.

Biomanipulation may be a measure implemented locally in “hot spots” and in the coastal zone. The effectiveness of implementation on the scale of the Baltic Sea should be carefully considered and a thorough risk analysis of possible alternative interactions, such as disruptions in the food-web, undertaken.

Because of the increases in eutrophication and hypoxia in the coastal zone and the ability of the coastal filter to help process and remove nutrients, e.g. bury P and remove N with denitrification, we need to restore the degraded abilities of the coastal filter.

Specific Recommendations Regarding Naturvårdsverket "Letter of Interest" and For Future Funding by Foundations

The current announcement for a "Letter of Intent" should be broadened to include innovative measures that can reduce nutrient supply rapidly from land-based sources. Enhancing the reduction of nutrient loading to the Baltic Sea should be the highest priority.

The current announcement focusing only on the effects of phosphorus leakage from sediments should be broadened to include evaluation of the effects of mitigation on denitrification and living resources.

A "Call for a Letter of Interest" should follow a 3-step process. The first screening step is necessary to determine what proposals are of interest for further consideration of mitigations. A second step where a number of proposals are funded to set a tenable goal, finalize the design, make cost estimations, put together an Environmental Impact Assessment including potential effects on biota and impact on N & P biogeochemical nutrient cycles, including a risk analysis of unintended consequences, consideration of energy needs, and address legal issues. Only those engineering technologies that are considered feasible and mature enough should go forward to the pilot project stage in a 3rd stage of funding with adequate resources allocated for monitoring before, during and after implementation.

A study should be undertaken by Naturvårdsverket to determine the legal and ethical issues that will be encountered when implementing engineering solutions in the Baltic Sea.

The HELCOM Action Plan has been an important step forward for determining country allocations. However, a sector analysis covering both the costs and effectiveness of nutrient reductions needs to be carried out on a Baltic Sea basis as soon as possible to ensure implementation of adequate nutrient reductions. Helping this process along could be something addressed with new funding.

Experience from lakes tells us that simply adding oxygen to the Baltic Sea may in fact not help significantly in mitigating eutrophication. Studies, both models and experiments, are needed to test the effects of adding oxygen to the Baltic Sea on P and N biogeochemistry.

Studies are needed to examine techniques for enhancing P burial in Baltic Sea sediments. While it is unsure if these technologies will be used at the scale of the Baltic Sea because of legal and ethical issues, we can learn more about potential mitigation and its effects from these studies.

An evaluation of the current extent of hypoxia around the Baltic Sea in the coastal zone is needed. In addition, an evaluation of the ability of the coastal zone to process nutrients and remove them through burial and denitrification is also sorely needed.

Expert evaluation panels and synthesis activities involving a diverse group of highly qualified scientists should be instituted to evaluate various mitigation options and the functioning of the Baltic Sea ecosystem.

Respectively submitted,

Prof. Daniel Conley
Hypoxia Project Leader
Lund University, Sweden

And the members of the Hypoxia Project Working Group:

Prof. Erik Bonsdorff
Åbo Academy, Finland

Dr. Sif Johansen
Swedish Environmental Protection Agency, Sweden

Dr. Lovisa Zillén
Lund University, Sweden

Dr. Jacob Carstensen
National Environmental Research Institute, Aarhus University, Denmark

Prof. Georgia Destouni
Stockholm University, Sweden

Dr. Bo Gustafsson
Göteborg University, Sweden

Prof. Nancy Rabalais
LUMCON, USA

Prof. Maren Voss
Institute of Baltic Sea Research, Germany

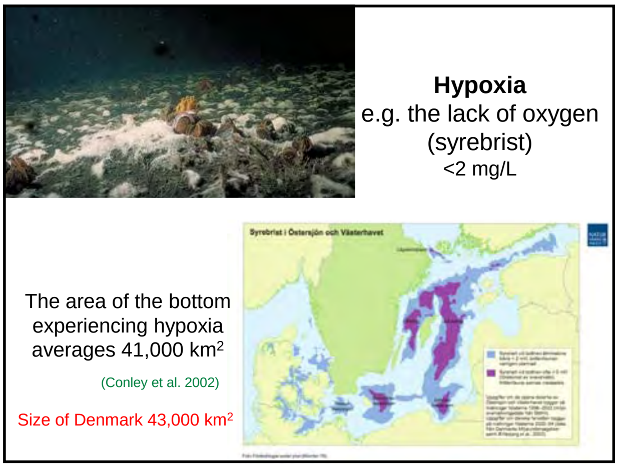
Appendix 5

Introduction: Possible solutions to oxygen problems in the Baltic Sea

Prof. Daniel Conley, Marie Curie Chair
GeoBiosphere Science Centre, Lund University

24 January 2008

Sponsored by
Baltic Sea 2020 and Naturvårdsverket



Hypoxia
e.g. the lack of oxygen
(syrebrist)
<2 mg/L

The area of the bottom experiencing hypoxia averages 41,000 km^2

(Conley et al. 2002)

Size of Denmark 43,000 km^2

When you can't breathe, nothing else matters!

American Lung Association (via Bob Diaz)

How long can you hold your breath?

Mariager Fjord, Denmark
25 August 1997

Consequences of hypoxia

Reduce habitat for living resources

Change self-cleansing biogeochemical processes
- P released from sediments
- Denitrification reduced

It is a *vicious* circle helping to sustain eutrophication (Vahtera et al. 2007)

What can we do?

Make nutrient reductions. If we don't make nutrient reductions it is only going to get worse!

The effect of reduction schemes take time.

Are there other things?
Explore possible solutions today.

Remember, mitigation will not work without nutrient reductions.

Hypoxia Project

Thanks!

Funding by Baltic Sea 2020

In 2005, the financer Mr. Björn Carlson decided he wanted to contribute to the efforts for the well-being of the Baltic Sea, and donated SEK 500 mil (current value: about 625 mil SEK) to form the *Björn Carlson Baltic Sea Foundation*, Baltic Sea 2020.

The aim is to stimulate creative interdisciplinary research and international collaboration in a range of areas, resulting in political, economical and physical measures taken to improve the environment of the Baltic Sea in the coming 10–15 years.

See http://www.balticsea2020.se for more information.

Overall Goal of the Hypoxia Project

To create an improved understanding of hypoxia in the Baltic Sea.

Determine if there are technical solutions to mitigating the devastating environmental effects of hypoxia on living resources and restore the self-purifying biogeochemical processes

Workshops

1) Understanding hypoxia in the Baltic Sea
   17-19 April 2007, Lund University
2) Coastal hypoxia
   16-18 October 2007, Åbo Akademi University
3) Potential management techniques, environmental effects and ethics
   27-29 November 2007, Lund University
4) Possible solutions to reduce hypoxia (together with Swedish Environmental Protection Agency) 24 January 2008, KVA

60 different scientists from 10 different countries

Publications

Goal is to publish in both popular periodicals and in primary literature

Zillén, L., D.J. Conley, and Svante Björck. 2007. Ibland är syrebrist ett normalt tillstånd. (Sometimes hypoxia is the normal condition). *Geolgiskt Forum* **56:** 10-13.

Zillén, L., D.J. Conley, T. Andrén, E. Andrén, and S. Björck. 2007. Past occurrences of hypoxia in the Baltic Sea and the role of climate variability, environmental change and human impact. *Earth Sci. Rev.* Submitted.

A number of manuscripts are *in preparation*

Talks from this meeting will appear on http://www.balticsea2020.se

Workshop co-sponsored by Naturvårdsverket

Baltic Sea: Pilot study: Letter of interest

Pilot experiment to oxygenate bottom layers of the Baltic Sea in order to reduce the leakage of phosphorous from sediments.

30 million SEK

Swedish Environmental Protection Agency, VINNOVA and Formas

http://www.naturvardsverket.se/

Deadline 15 March 2008

Program

09.30
Registration and coffee

10.00
Welcome

Introduction
Prof. Daniel Conley,
GeoBiosphere Science Centre, Lund

Oxygen Problems in an International Perspective
Prof. Nancy Rabalais,
Louisiana Universities Marine Consortium, USA

Oxygen problems in the Baltic Sea
Dr. Maren Voss,
Institut für Ostseeforschung Warnemünde, Germany

The Baltic Sea Action Plan for Nutrient Reductions
Prof. Fredrik Wulff,
Baltic Nest Institute, Stockholm

Report from the Workshops
Prof. Erik Bonsdorff,
Åbo Akademi, Finland

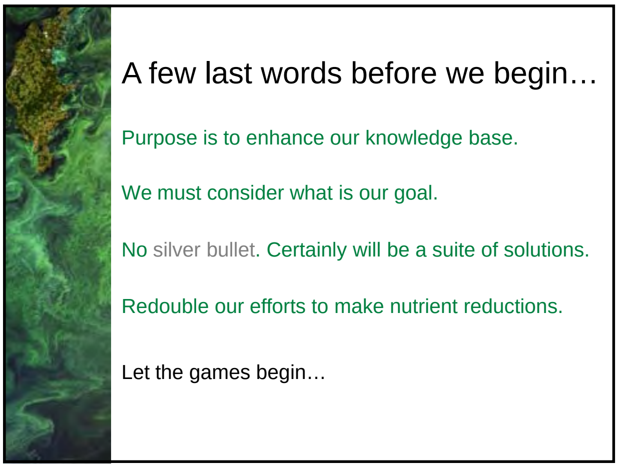
12.00
Lunch

13.00
Possible solutions for the Baltic Sea
Prof. Daniel Conley,
GeoBiosphere Science Centre, Lund

Considerations and Outlook
Prof. Gia Destouni,
Department of Physical Geography and Quaternary Geology, Stockholm

14.00
Perspectives on the Future
Discussion with a panel and with the audience
Moderator: Anne-Louise Martin

15.30
Coffee



A few last words before we begin…

Purpose is to enhance our knowledge base.

We must consider what is our goal.

No silver bullet. Certainly will be a suite of solutions.

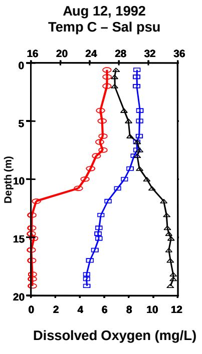
Redouble our efforts to make nutrient reductions.

Let the games begin…

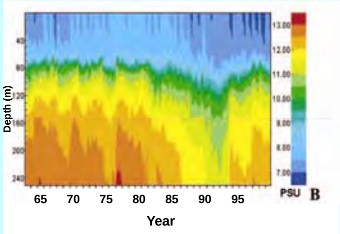
Oxygen Problems:
An International Perspective

Nancy N. Rabalais
Louisiana Universities Marine Consortium
nrabalais@lumcon.edu
www.gulfhypoxia.net

Stratification Is Required

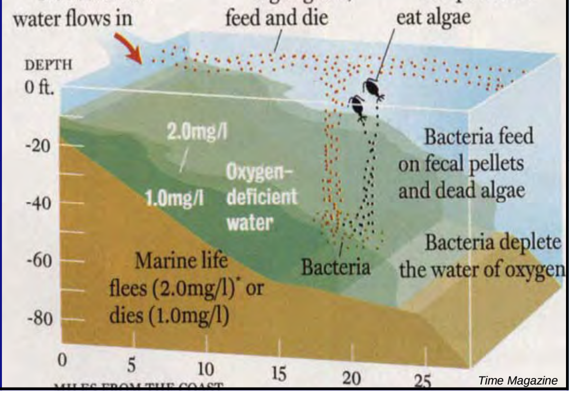


Gulf of Mexico
Rabalais & Turner 2006



Baltic Sea
Conley et al. 2002

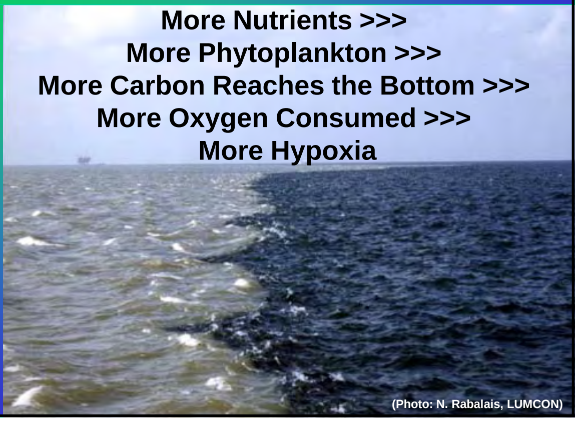
Nutrients, Increased Carbon, Low Oxygen



Time Magazine

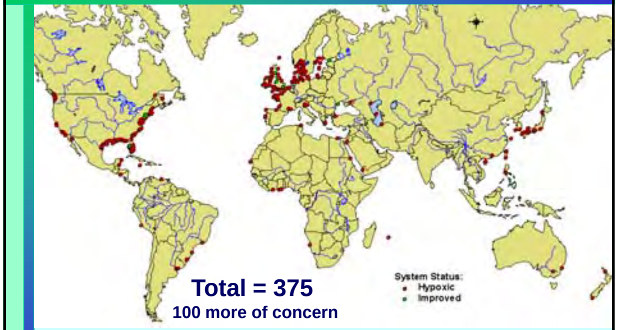
Green Lands →→→→ Blue Waters

More Nutrients >>>
More Phytoplankton >>>
More Carbon Reaches the Bottom >>>
More Oxygen Consumed >>>
More Hypoxia



(Photo: N. Rabalais, LUMCON)

A Global Epidemic

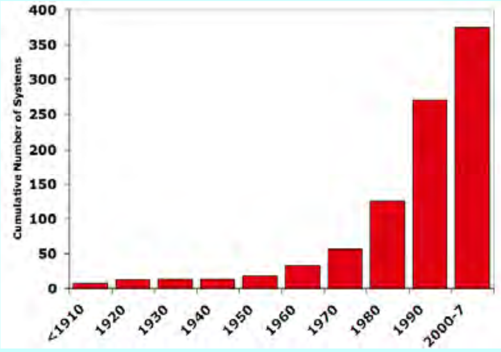


Total = 375

100 more of concern

Systems with scientific reported accounts.
The distribution matches the global human footprint in developed countries and is increasing in developing countries.
Díaz & Rosenberg unpubl. 2008

Cumulative Increase in Oxygen Problems



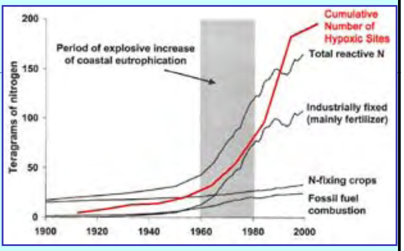
Doubled every ten years beginning in the 1960s
Díaz & Rosenberg unpubl. data 2008

How Eutrophication/Hypoxia Became a Global Problem

Increasing input of nutrients to coastal areas in the last half of the 20th century

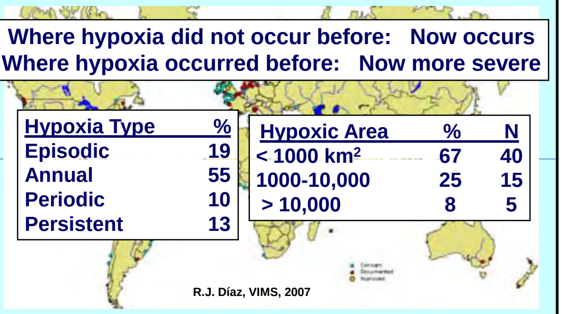
Strong correlations:

- **population**
- **agriculture & industry**
- **organic matter production**
- **increased hypoxia & anoxia**



Boesch 2002, Galloway and Cowling 2002, Diaz 2007

Hypoxia Now a Global Problem



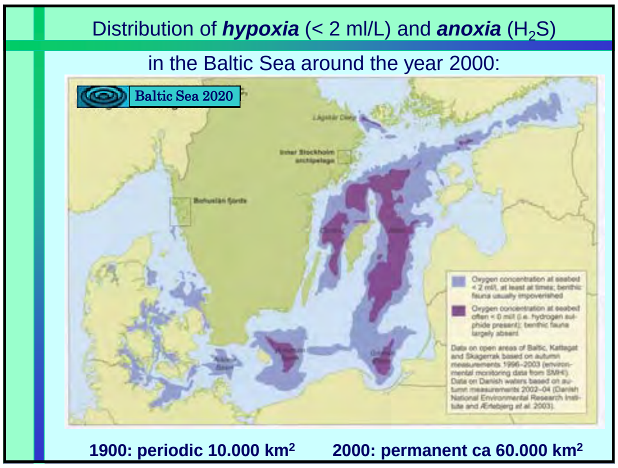
Where hypoxia did not occur before: Now occurs
Where hypoxia occurred before: Now more severe

Hypoxia Type	%
Episodic	19
Annual	55
Periodic	10
Persistent	13

Hypoxic Area	%	N
< 1000 km^2	67	40
1000-10,000	25	15
> 10,000	8	5

R.J. Díaz, VIMS, 2007

"There is no other environmental variable of such ecological importance to coastal marine ecosystems that has changed so drastically in such a short period as dissolved oxygen……" Díaz & Rosenberg 1995



Distribution of ***hypoxia*** (< 2 ml/L) and ***anoxia*** (H_2S)

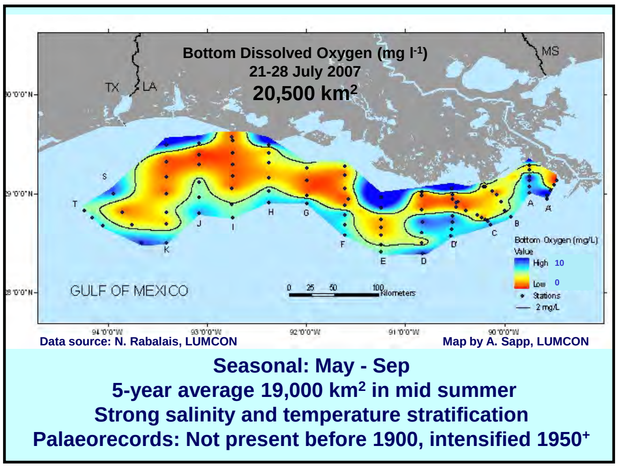
in the Baltic Sea around the year 2000:

🟦 Oxygen concentration at seabed < 2 ml/l, at least at times; benthic fauna usually impoverished

🟪 Oxygen concentration at seabed often < 0 ml/l (i.e. hydrogen sulphide present); benthic fauna largely absent

Data on open areas of Baltic, Kattegat and Skagerrak based on autumn measurements 1996–2003 (environmental monitoring data from SMHI). Data on Danish waters based on autumn measurements 2002–04 (Danish National Environmental Research Institute and Ærtebjerg et al. 2003).

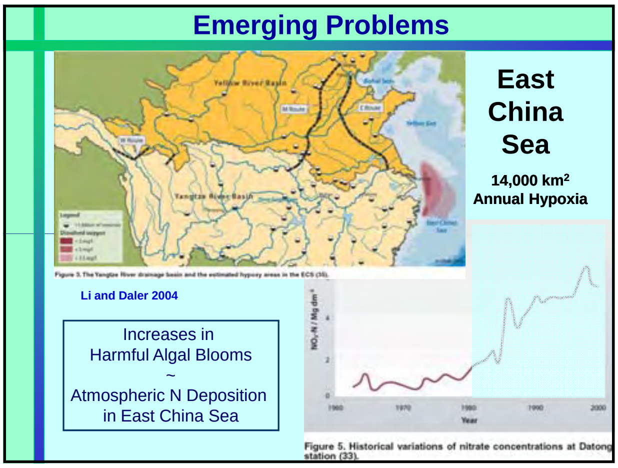
1900: periodic 10.000 km^2 **2000: permanent ca 60.000 km^2**



Data source: N. Rabalais, LUMCON

Map by A. Sapp, LUMCON

Seasonal: May - Sep
5-year average 19,000 km^2 in mid summer
Strong salinity and temperature stratification
Palaeorecords: Not present before 1900, intensified 1950$^+$



Emerging Problems

Figure 3. The Yangtze River drainage basin and the estimated hypoxy areas in the ECS (35).

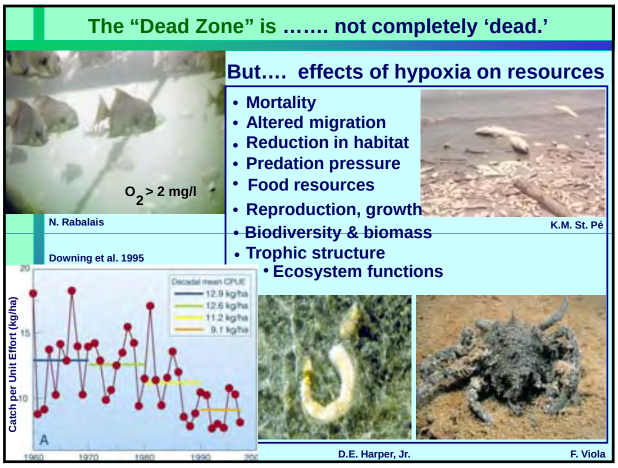
Li and Daler 2004

Increases in
Harmful Algal Blooms
~
Atmospheric N Deposition
in East China Sea

East China Sea

14,000 km^2
Annual Hypoxia

Figure 5. Historical variations of nitrate concentrations at Datong station (33).



The "Dead Zone" is ……. not completely 'dead.'

N. Rabalais

But…. effects of hypoxia on resources

- **Mortality**
- **Altered migration**
- **Reduction in habitat**
- **Predation pressure**
- **Food resources**
- **Reproduction, growth**
- **Biodiversity & biomass**
- **Trophic structure**
  - **Ecosystem functions**

K.M. St. Pé

Downing et al. 1995

D.E. Harper, Jr.

F. Viola

Not All Hypoxic Zones Are Equal

Natural

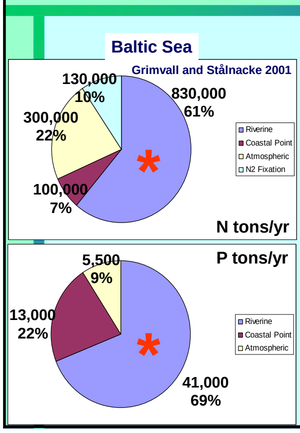
- Oxygen minimum zones
- Upwelled nutrients
- Deep basins
- Subduction of low oxygen water
- Changes in ocean winds, currents, cycles

Anthropogenic

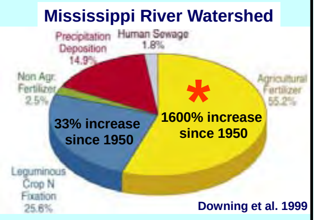
- High organic loading
- Increased nutrients
- Sources of nutrients
- Altered hydrology
- Climate change and ocean circulation

Nutrient Sources Should Drive Reduction Strategies

Baltic Sea

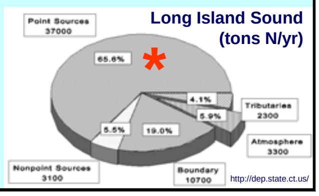


Mississippi River Watershed

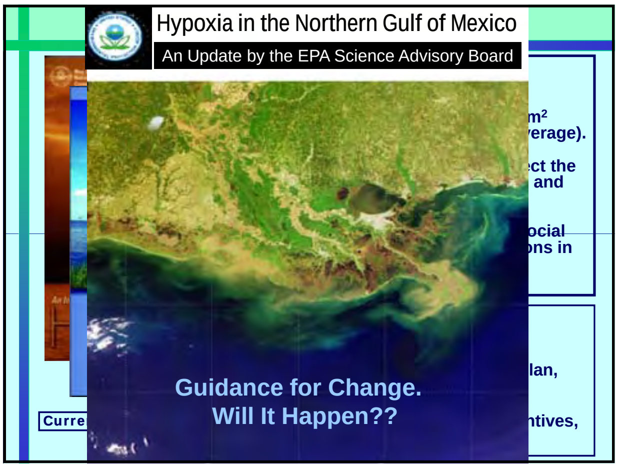


Downing et al. 1999

Long Island Sound (tons N/yr)



http://dep.state.ct.us/



Hypoxia in the Northern Gulf of Mexico

An Update by the EPA Science Advisory Board

Guidance for Change.
Will It Happen??

So Why Are Nutrient Reductions Not Working??

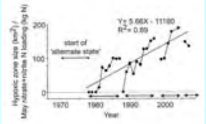
Retention of nutrients within the watershed soils and aquatic ecosystems
→ *Time lags*

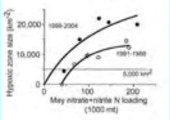
Retention of nutrients and accumulated carbon within coastal ecosystems & deep Baltic basin, especially phosphorus
→ *Time lags*

Climate variability
→ *Climate may override mitigation efforts*

Regime shifts
→ *New thresholds*

Less N is needed now to create same size 'Dead Zone'





Turner et al. in press

Implications for Mitigation

As a result……

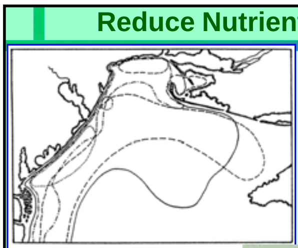
Improvement is delayed

Worsening of oxygen problems was not linear,
and the return to ‘normal’ or ‘historic’ conditions
is not necessarily along the same path,
nor does it reach the same original state.

Makes it more imperative that action is taken NOW,
and not delayed while another regime shift occurs.

***PATIENCE, PERSISTENCE* and**
POLITICAL WILL

Reduce Nutrients, Reduce Hypoxia

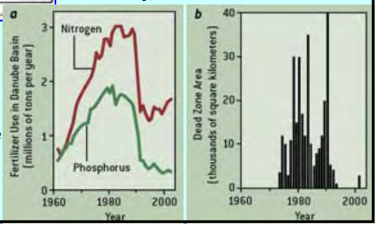


(Zaitsev, 1992)

Northwestern Shelf
Black Sea

Hypoxic Area Up to 40,000 km^2
Currently, non-existent or minimal

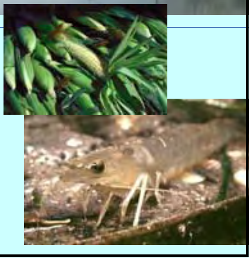
N and P Loads
Correspond
to Fertilizer Use

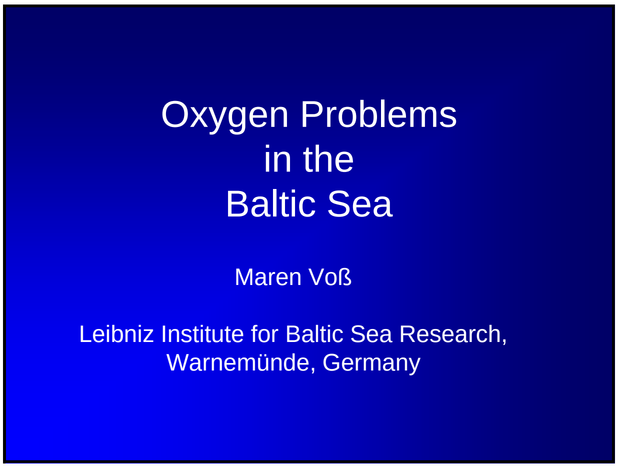


(Mee, 2006)

The Future

Climate Change
Biofuels
Increased Population
Increased Agribusiness
Increased Atmospheric Deposition

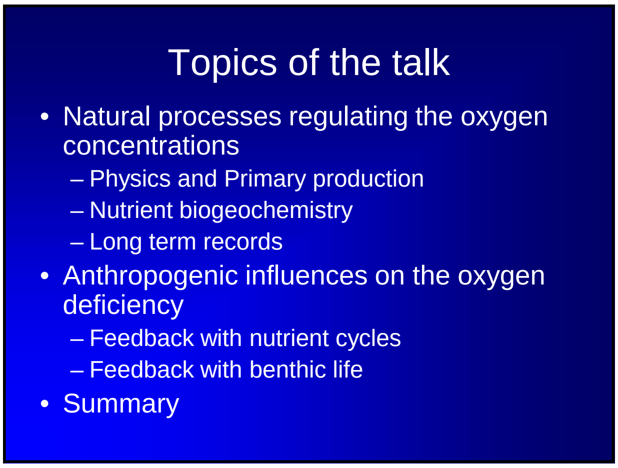




Oxygen Problems
in the
Baltic Sea

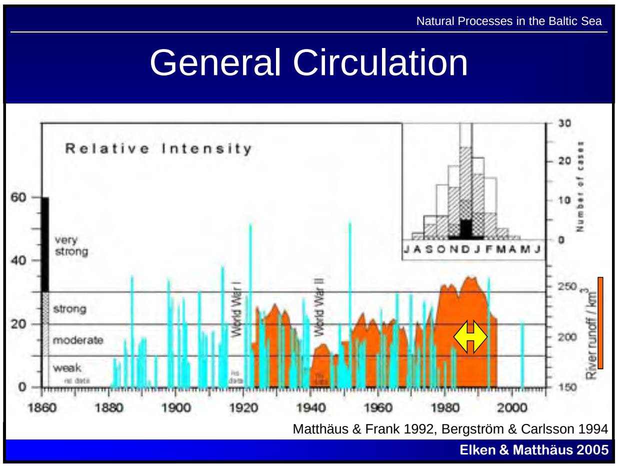
Maren Voß

Leibniz Institute for Baltic Sea Research,
Warnemünde, Germany



Topics of the talk

- Natural processes regulating the oxygen concentrations
  - Physics and Primary production
  - Nutrient biogeochemistry
  - Long term records
- Anthropogenic influences on the oxygen deficiency
  - Feedback with nutrient cycles
  - Feedback with benthic life
- Summary

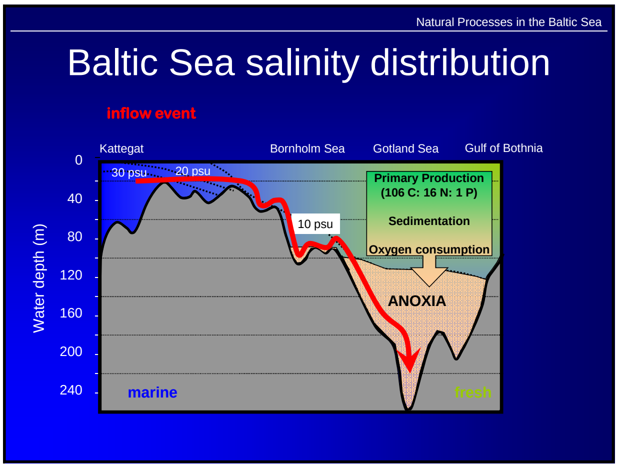


Natural Processes in the Baltic Sea

General Circulation

Matthäus & Frank 1992, Bergström & Carlsson 1994

Elken & Matthäus 2005

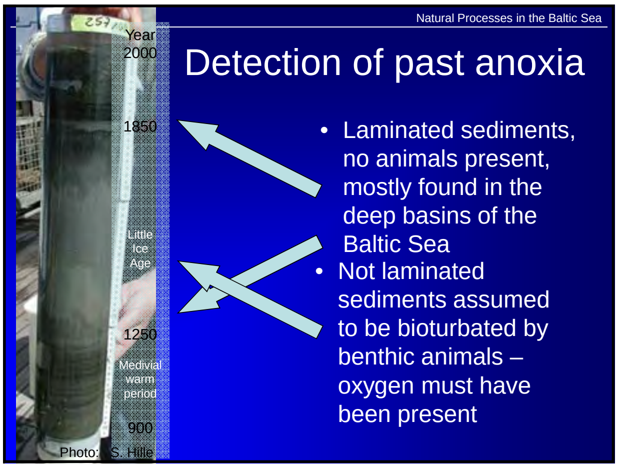


Natural Processes in the Baltic Sea

Baltic Sea salinity distribution

Oxygen concentrations depend on:

- Physics
  - North Sea inflow -> stratification
  - river runoff -> freshening
  - air-sea interaction
- Biology
  - primary production
  - oxygen consumption



Detection of past anoxia

- Laminated sediments, no animals present, mostly found in the deep basins of the Baltic Sea
- Not laminated sediments assumed to be bioturbated by benthic animals – oxygen must have been present

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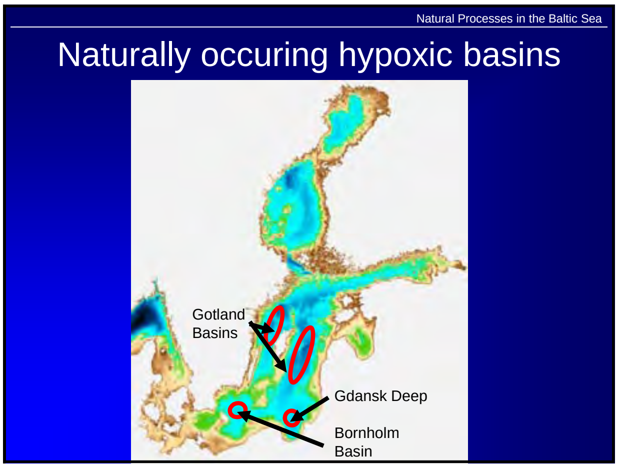
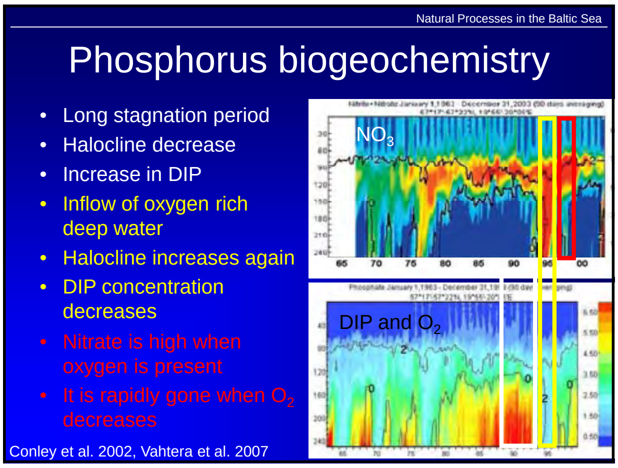


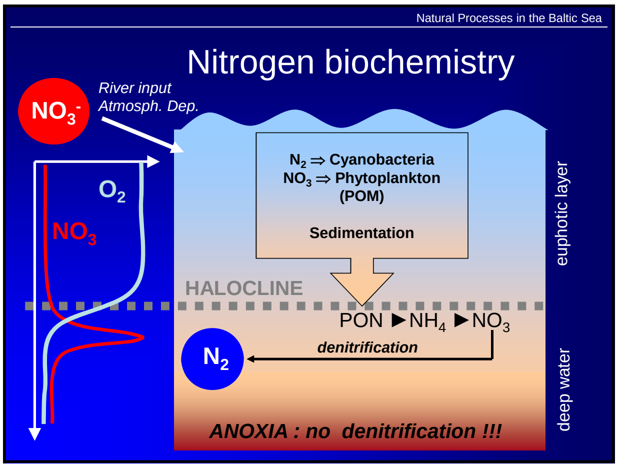
Naturally occuring hypoxic basins



Phosphorus biogeochemistry

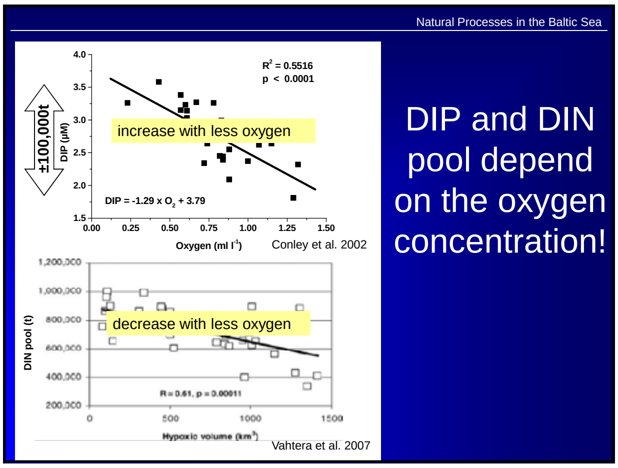
- Long stagnation period
- Halocline decrease
- Increase in DIP
- Inflow of oxygen rich deep water
- Halocline increases again
- DIP concentration decreases
- Nitrate is high when oxygen is present
- It is rapidly gone when O_2 decreases

Conley et al. 2002, Vahtera et al. 2007



Nitrogen biochemistry

ANOXIA : no denitrification !!!



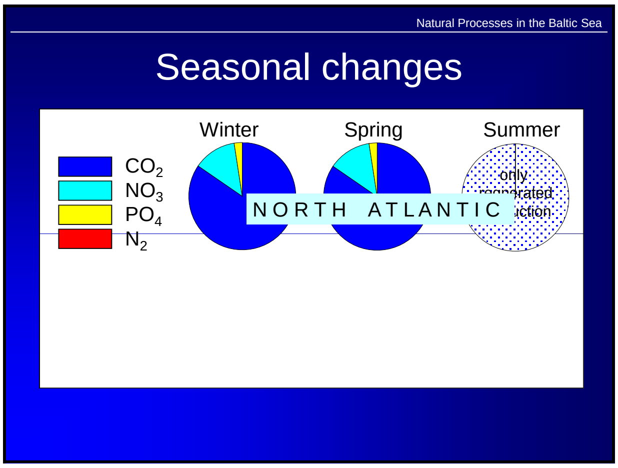
increase with less oxygen

Conley et al. 2002

decrease with less oxygen

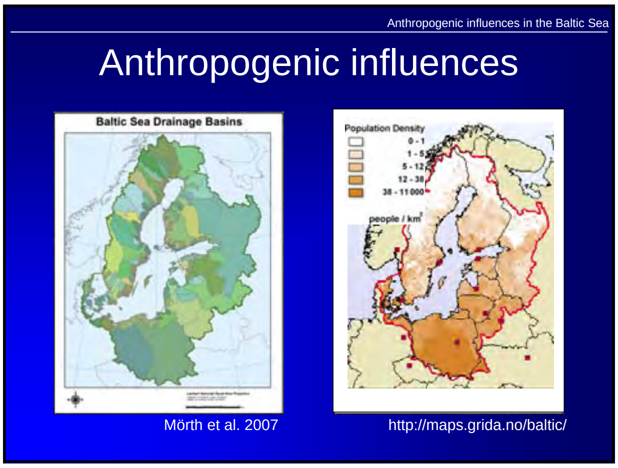
Vahtera et al. 2007

DIP and DIN pool depend on the oxygen concentration!



Seasonal changes

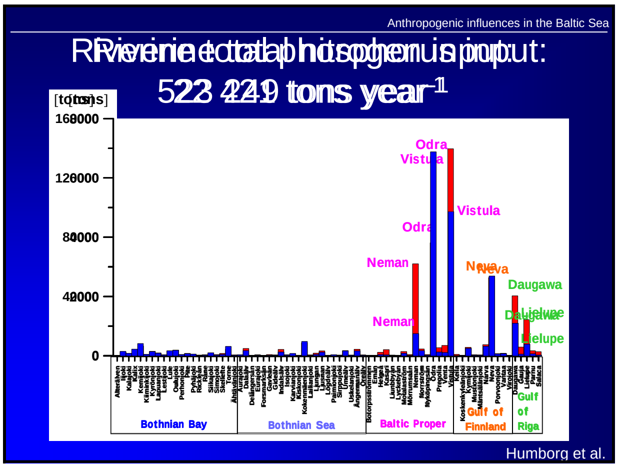
NORTH ATLANTIC



Anthropogenic influences

Mörth et al. 2007

http://maps.grida.no/baltic/

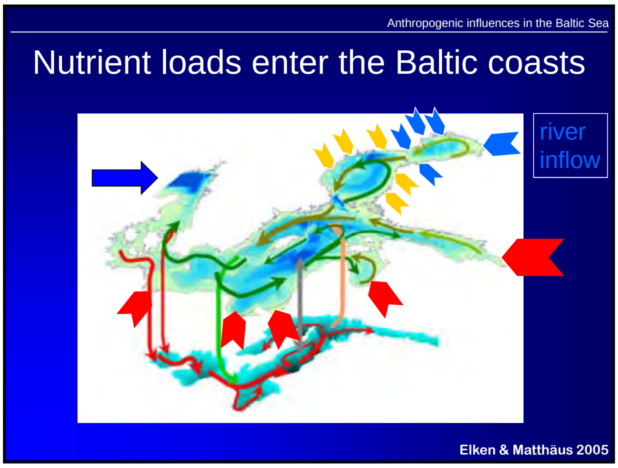


Anthropogenic influences in the Baltic Sea

Riverine total nitrogen input: 522 421 tons year^{-1}

Riverine total phosphorus input: 23 419 tons year^{-1}

Humborg et al.

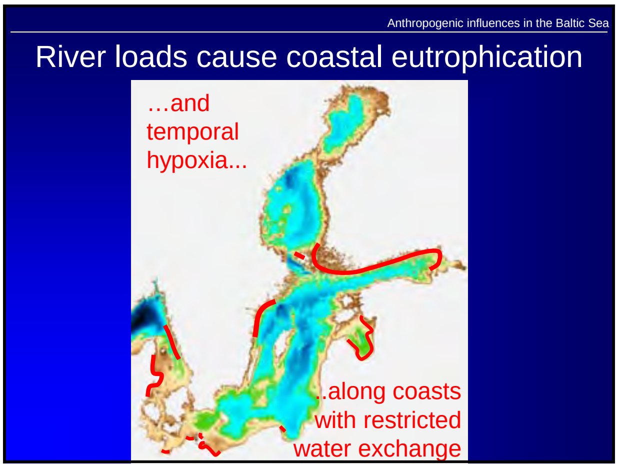


Anthropogenic influences in the Baltic Sea

Nutrient loads enter the Baltic coasts

river inflow

Elken & Matthäus 2005

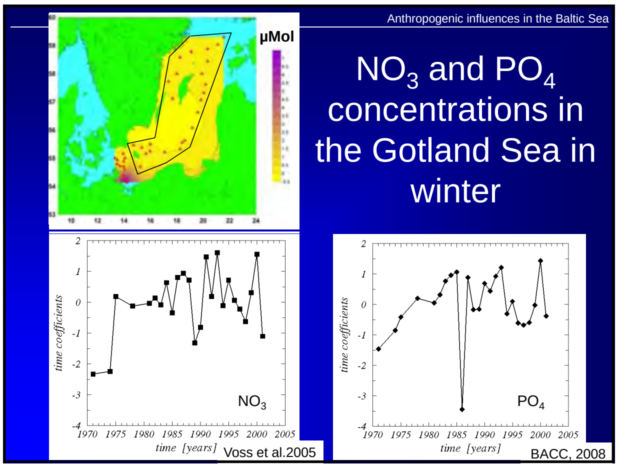


Anthropogenic influences in the Baltic Sea

River loads cause coastal eutrophication

…and temporal hypoxia...

...along coasts with restricted water exchange

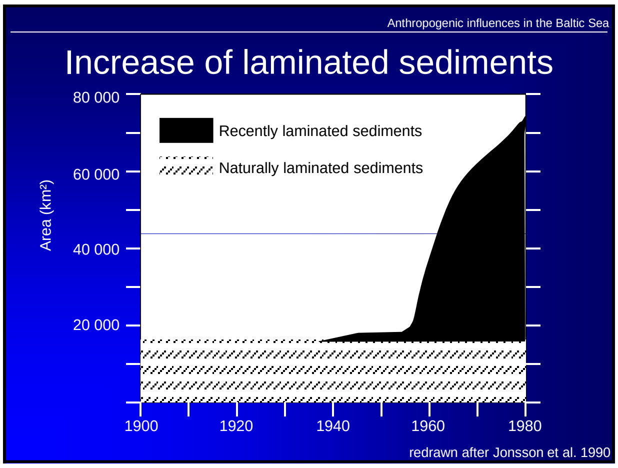


Anthropogenic influences in the Baltic Sea

NO_3 and PO_4 concentrations in the Gotland Sea in winter

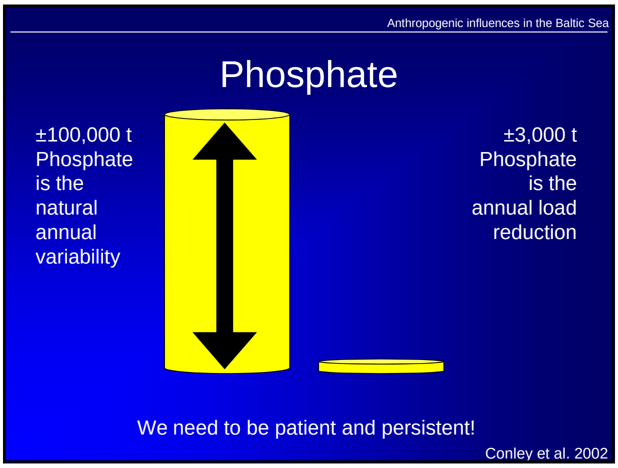
Voss et al.2005

BACC, 2008



Increase of laminated sediments

redrawn after Jonsson et al. 1990



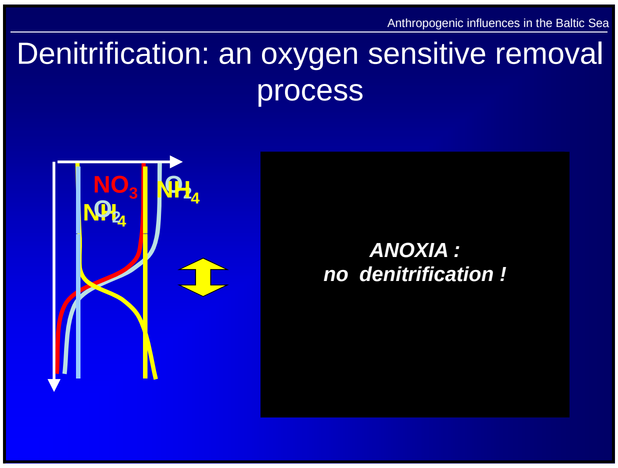
Phosphate

±100,000 t Phosphate is the natural annual variability

±3,000 t Phosphate is the annual load reduction

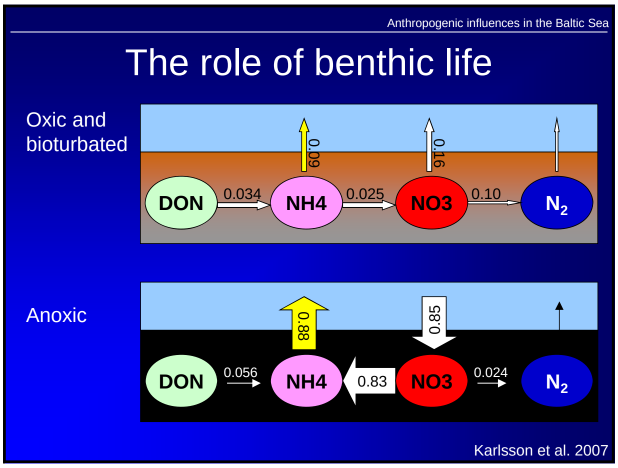
We need to be patient and persistent!

Conley et al. 2002



Denitrification: an oxygen sensitive removal process

ANOXIA :
no denitrification !

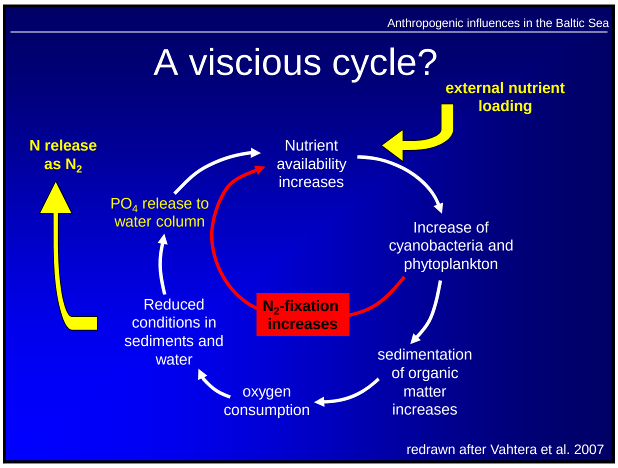


The role of benthic life

Oxic and bioturbated

Anoxic

Karlsson et al. 2007



A viscious cycle?

external nutrient loading

N release as N_2

Nutrient availability increases

Increase of cyanobacteria and phytoplankton

sedimentation of organic matter increases

oxygen consumption

Reduced conditions in sediments and water

PO_4 release to water column

N_2-fixation increases

redrawn after Vahtera et al. 2007

Summary

- Anoxic areas in the Baltic Sea are to some extent a natural phenomenon.
- Anthropogenic nutrient inputs have altered the Baltic Sea ecosystem and enlarged the hypoxic and anoxic areas.
- Phosphorous is released under anoxic conditions and accumulates in waters and sediments.
- Nitrate removal depends on a sensitive balance between oxygenated and anoxic layers. However, the sites of denitrification are important to be maintained.
- A viscious cycle may even enhance the eutrophication process by supporting cyanobacteria blooms.
- Benthic animals play an important role in the sequestration of organic matter and nutrients in sediments.

The Baltic Sea Action Plan for nutrient reductions

Fred Wulff
Stockholm University

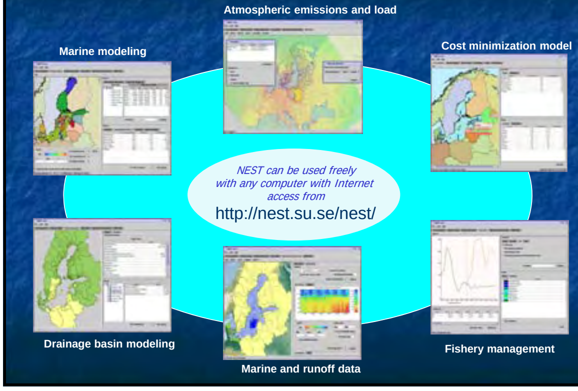
KVA, Jan 24, 2008 Seminar 'Possible Solutions to Oxygen Problems in the Baltic Sea'

The Baltic Sea Action Plan

A new environmental strategy
for the Baltic Sea region

Helsinki Commission
Baltic Marine Environment Protection Commission

NEST now contains 6 Basic Modules



Atmospheric emissions and load

Marine modeling

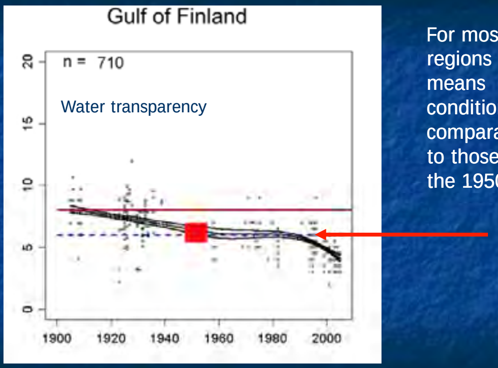
Cost minimization model

NEST can be used freely with any computer with Internet access from
http://nest.su.se/nest/

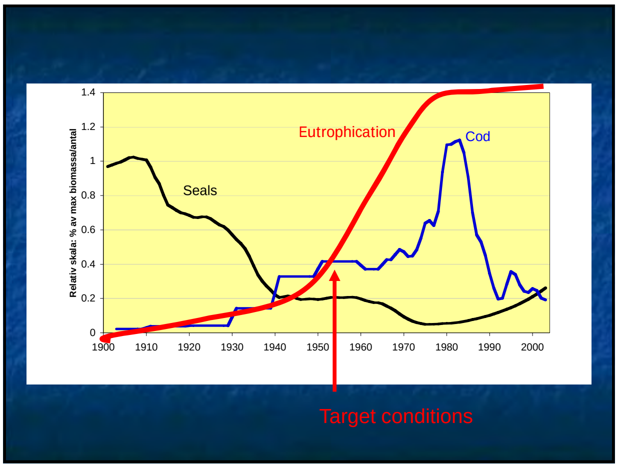
Drainage basin modeling

Marine and runoff data

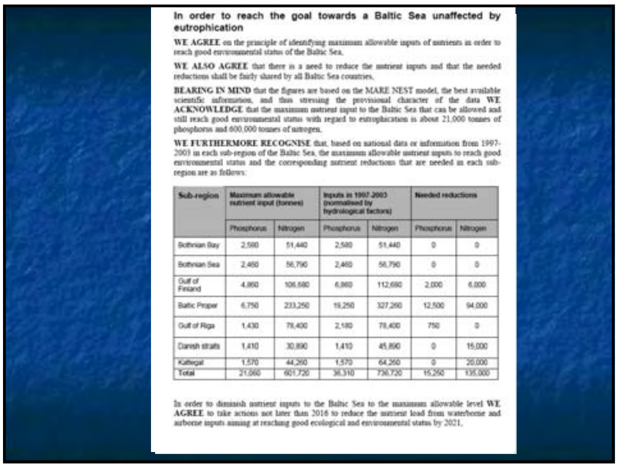
Fishery management



For most regions this means conditions comparable to those in the 1950ties



Target conditions



In order to reach the goal towards a Baltic Sea unaffected by eutrophication

WE AGREE on the principle of identifying maximum allowable inputs of nutrients in order to reach good environmental status of the Baltic Sea.

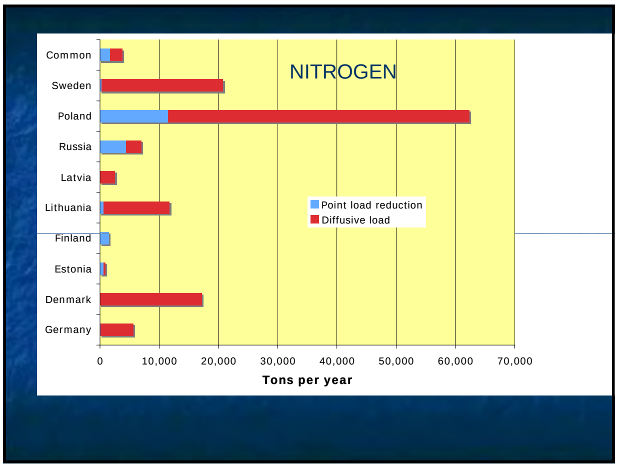
WE ALSO AGREE that there is a need to reduce the nutrient inputs and that the needed reductions shall be fairly shared by all Baltic Sea countries.

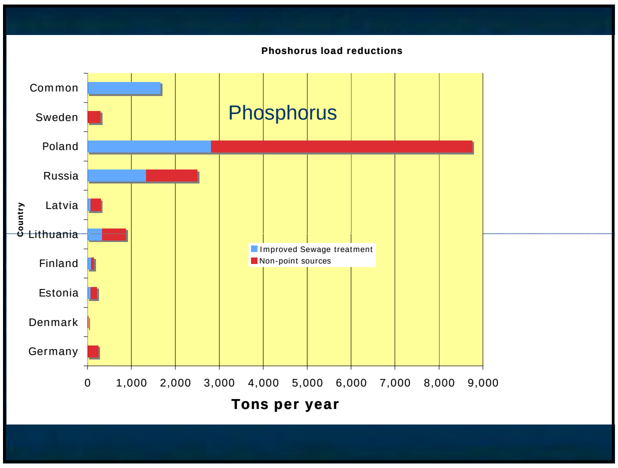
BEARING IN MIND that the figures are based on the MARE NEST model, the best available scientific information, and thus stressing the provisional character of the data **WE ACKNOWLEDGE** that the maximum nutrient input to the Baltic Sea that can be allowed and still reach good environmental status with regard to eutrophication is about 21,000 tonnes of phosphorus and 600,000 tonnes of nitrogen.

WE FURTHERMORE RECOGNISE that, based on national data or information from 1997-2003 in each sub-region of the Baltic Sea, the maximum allowable nutrient inputs to reach good environmental status and the corresponding nutrient reductions that are needed in each sub-region are as follows:

Sub-region	Maximum allowable nutrient input (tonnes)		Inputs in 1997-2003 (normalised by hydrological factors)		Needed reductions	
	Phosphorus	Nitrogen	Phosphorus	Nitrogen	Phosphorus	Nitrogen
Bothnian Bay	2,580	51,440	2,580	51,440	0	0
Bothnian Sea	2,460	56,790	2,460	56,790	0	0
Gulf of Finland	4,860	106,680	6,860	112,680	2,000	6,000
Baltic Proper	6,750	233,250	19,250	327,260	12,500	94,000
Gulf of Riga	1,430	78,400	2,180	78,400	750	0
Danish straits	1,410	30,890	1,410	45,890	0	15,000
Kattegat	1,570	44,260	1,570	64,260	0	20,000
Total	21,060	601,720	36,310	736,720	15,250	135,000

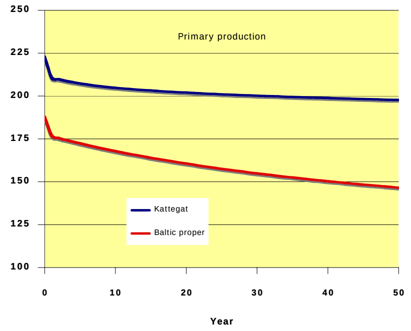
In order to diminish nutrient inputs to the Baltic Sea to the maximum allowable level **WE AGREE** to take actions not later than 2016 to reduce the nutrient load from waterborne and airborne inputs aiming at reaching good ecological and environmental status by 2021.





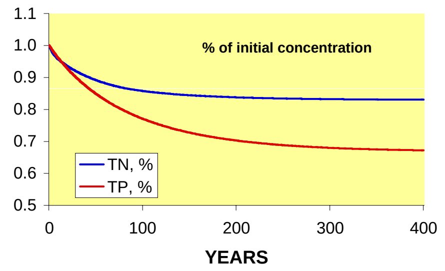
Time!

$T_{0.5}$ = time to reach 50% of new steady state



$T_{0.5}$ = 5 (KT) 24(BP)

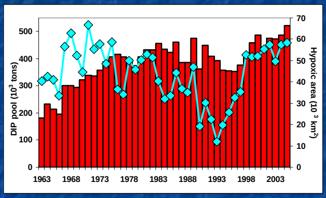
About 30 (N) and 60 (P) years to reach 50% of final concentrations



Long residence times of water and nutrients

Long response times to changes
in nutrient loads

Long-term dynamics
of the winter (Jan-Mar) DIP pool and hypoxic area
in the larger Baltic Proper (BPp + GF + GR)



This is only the P pool in the water column

How much in Sediments?

500’ - 300’ = 200’ at least!

300’ corresponds to more than 10 times current load (26’)

Other time lags

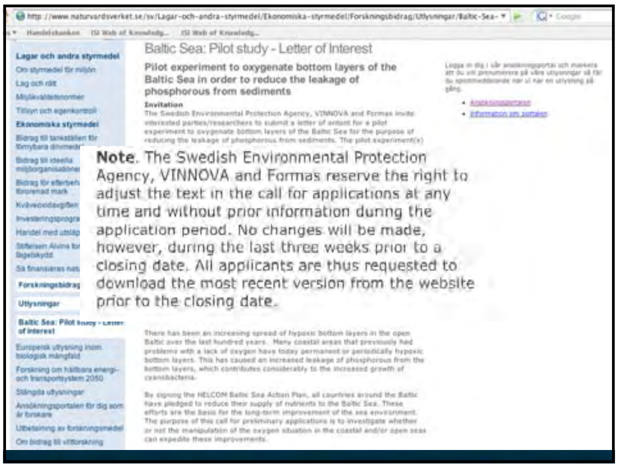
- Time to reach political decisions
- To find legal and technical solutions
- To finance
- Large pools of nutrients in soils and ground water

The Challenge

Speed up time to recovery

Confusions
- why eliminate anoxia

- Speed up recovery of what?
- to save bottom fauna and increase cod spawning volume?
- To decrease internal P load, cyanobacterial blooms and other eutrophication effects?



Baltic Sea: Pilot study - Letter of Interest

Pilot experiment to oxygenate bottom layers of the Baltic Sea in order to reduce the leakage of phosphorous from sediments

Invitation

The Swedish Environmental Protection Agency, VINNOVA and Formas invite interested parties/researchers to submit a letter of intent for a pilot experiment to oxygenate bottom layers of the Baltic Sea for the purpose of reducing the leakage of phosphorous from sediments. The pilot experiment(s)

Note. The Swedish Environmental Protection Agency, VINNOVA and Formas reserve the right to adjust the text in the call for applications at any time and without prior information during the application period. No changes will be made, however, during the last three weeks prior to a closing date. All applicants are thus requested to download the most recent version from the website prior to the closing date.

There has been an increasing spread of hypoxic bottom layers in the open Baltic over the last hundred years. Many coastal areas that previously had problems with a lack of oxygen have today permanent or periodically hypoxic bottom layers. This has caused an increased leakage of phosphorous from the bottom layers, which contributes considerably to the increased growth of cyanobacteria.

By signing the HELCOM Baltic Sea Action Plan, all countries around the Baltic have pledged to reduce their supply of nutrients to the Baltic Sea. These efforts are the basis for the long-term improvement of the sea environment. The purpose of this call for preliminary applications is to investigate whether or not the manipulation of the oxygen situation in the coastal and/or open seas can expedite these improvements.

Options

- Increase oxygen levels
  - A..B..C

Precipitation of P

  - A..B..C
- Top-down food web manipulations
  - A..B..C..

Please, please, give advice

- Which measure should be discarded?
- Which measures are worth further studies?
  - Mesoscale field experiments
  - Engineering solutions

Baltic Sea 2020

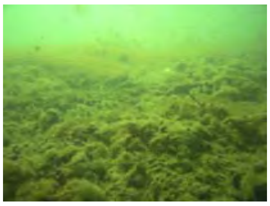
NATUR VÅRDS VERKET

Possible solutions to oxygen problems in the Baltic Sea

Seminar and Discussion based on
a series of three workshops during 2007

Stockholm, 24 January 2008

Baltic Sea problems are large and well-known; the question is what can be done about it. Lack of oxygen (***hypoxia***) is related to eutrophication, and also to large-scale hydrographic patterns.



✓ Can science, policy and management interact for the benefit of the marine environment?

✓ When do we know ’enough’? Do we (ever) know enough?

✓ Can science be trusted, in spite of differences of opinion? Can scientists contribute with adequate advice?

✓ Can a sea be ’managed’? Are technical or engineering solutions serious options? What if things go wrong….?!

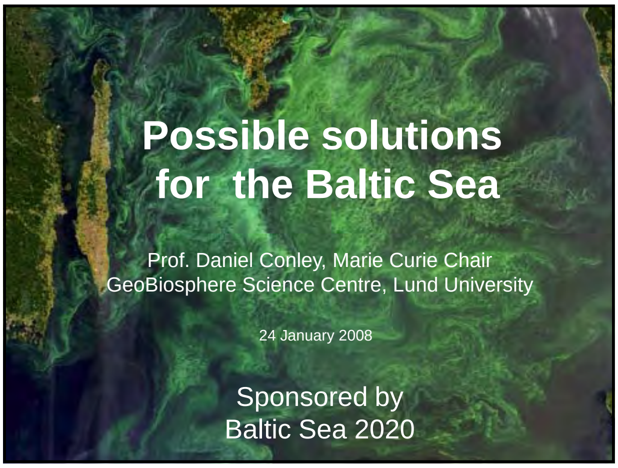
Some areas of interest for the **Baltic Sea 2020**

(1) eutrophication and related problems
(2) overfishing and problems relarted with sustainability
(3) **hypoxia and anoxia in the Baltic Sea**

- land/sea-interactions; measures on land
- policy-instruments
- can problems be solved by ”eco- engineering”?

Visit the web at: http://www.balticsea2020.se

WELCOME TO THE SEMINAR-DAY!

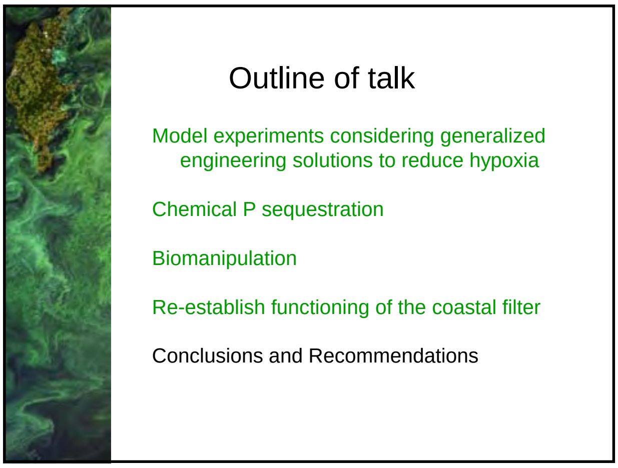


Possible solutions for the Baltic Sea

Prof. Daniel Conley, Marie Curie Chair
GeoBiosphere Science Centre, Lund University

24 January 2008

Sponsored by
Baltic Sea 2020



Outline of talk

Model experiments considering generalized engineering solutions to reduce hypoxia

Chemical P sequestration

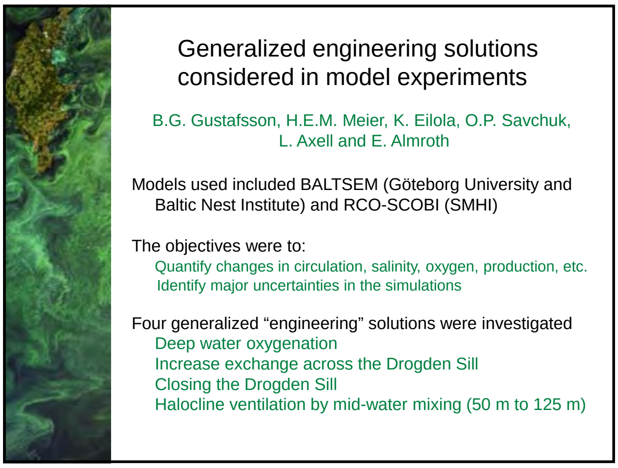
Biomanipulation

Re-establish functioning of the coastal filter

Conclusions and Recommendations

In all of the excitement of SEKSEKSEK's & €€€'s

We must reduce nutrients for mitigation to be effective.



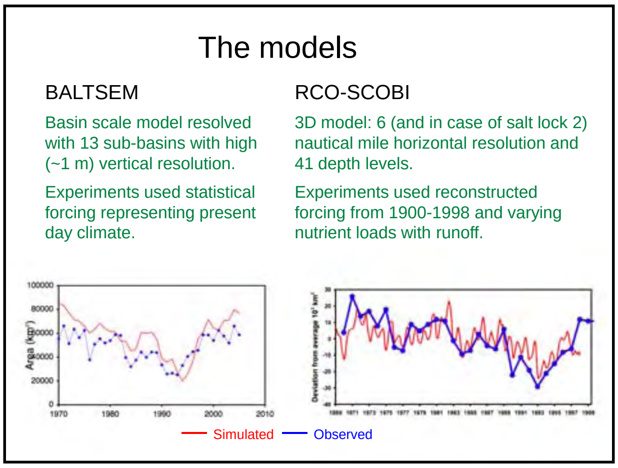
Generalized engineering solutions considered in model experiments

B.G. Gustafsson, H.E.M. Meier, K. Eilola, O.P. Savchuk, L. Axell and E. Almroth

Models used included BALTSEM (Göteborg University and Baltic Nest Institute) and RCO-SCOBI (SMHI)

The objectives were to:
- Quantify changes in circulation, salinity, oxygen, production, etc.
- Identify major uncertainties in the simulations

Four generalized "engineering" solutions were investigated
- Deep water oxygenation
- Increase exchange across the Drogden Sill
- Closing the Drogden Sill
- Halocline ventilation by mid-water mixing (50 m to 125 m)



The models

BALTSEM

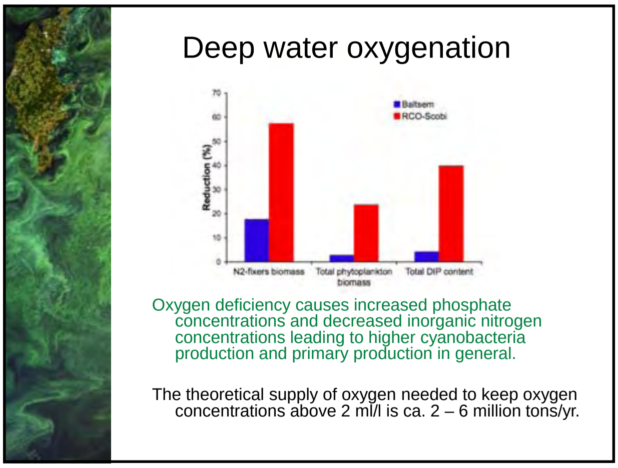
Basin scale model resolved with 13 sub-basins with high (~1 m) vertical resolution.

Experiments used statistical forcing representing present day climate.

RCO-SCOBI

3D model: 6 (and in case of salt lock 2) nautical mile horizontal resolution and 41 depth levels.

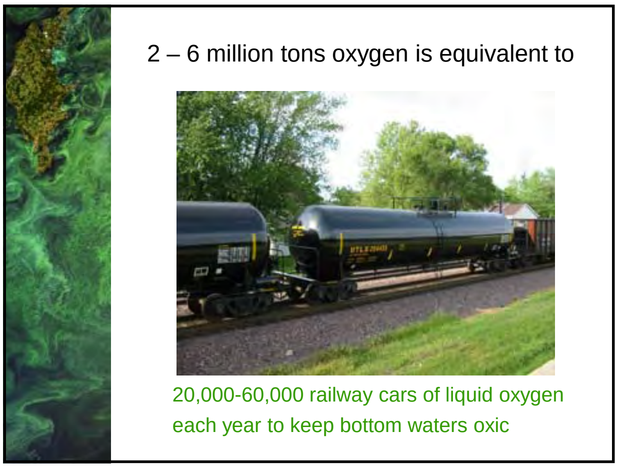
Experiments used reconstructed forcing from 1900-1998 and varying nutrient loads with runoff.



Deep water oxygenation

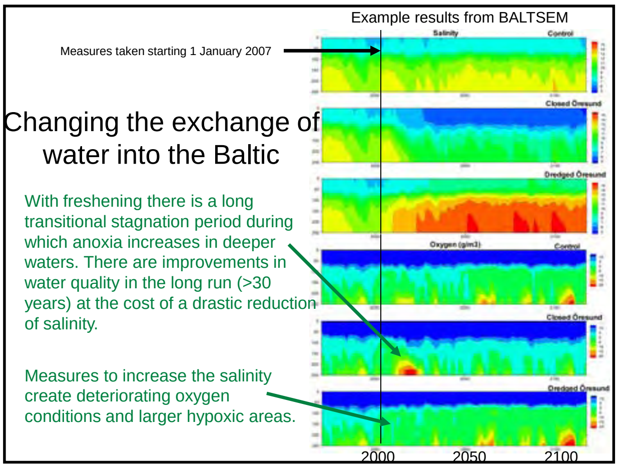
Oxygen deficiency causes increased phosphate concentrations and decreased inorganic nitrogen concentrations leading to higher cyanobacteria production and primary production in general.

The theoretical supply of oxygen needed to keep oxygen concentrations above 2 ml/l is ca. 2 – 6 million tons/yr.



2 – 6 million tons oxygen is equivalent to

20,000-60,000 railway cars of liquid oxygen each year to keep bottom waters oxic



Example results from BALTSEM

Measures taken starting 1 January 2007

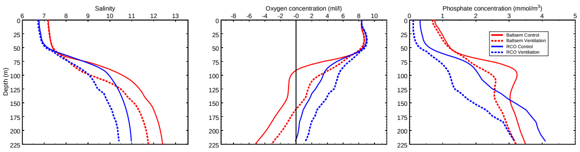
Changing the exchange of water into the Baltic

With freshening there is a long transitional stagnation period during which anoxia increases in deeper waters. There are improvements in water quality in the long run (>30 years) at the cost of a drastic reduction of salinity.

Measures to increase the salinity create deteriorating oxygen conditions and larger hypoxic areas.

Halocline ventilation by mid-water mixing

The models, in quite close agreement, show that halocline ventilation (50 m to 125 m) gives improved oxygen concentrations and no change in surface salinity. There is a decrease in deep water salinity, but within the range of natural variability.



Model results for Eastern Gotland Basin with and without halocline ventilation

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Uncertainties in the simulations

The models give consistent and plausible responses.

There are quantitative differences in sensitivity.

We need to improve, in particular, the parameterizations of sediment processes.

Complementary high resolution simulations are also necessary.

Phosphorus Sequestration

Contributors: Sven Blomqvist, Stockholm University,
Henning Jensen, University of Southern Denmark ,
Caroline Slomp and Haydon Mort, Utrecht University

Blomqvist and Rydin. 2008. P-uppbindning i Östersjöns bottensediment. NV report.

In freshwaters and sewage treatment plants, aluminum ($Al(OH)_3$), and other chemicals have been used to bind phosphorus.

Can we enhance the permanent burial of P in Baltic Sea sediments by precipitation with aluminum, by complexation with lime or otherwise enhance the formation of apatite?

Significant gaps in our knowledge

What is the binding capacity of alum in seawater?

What is the necessary dosage required?

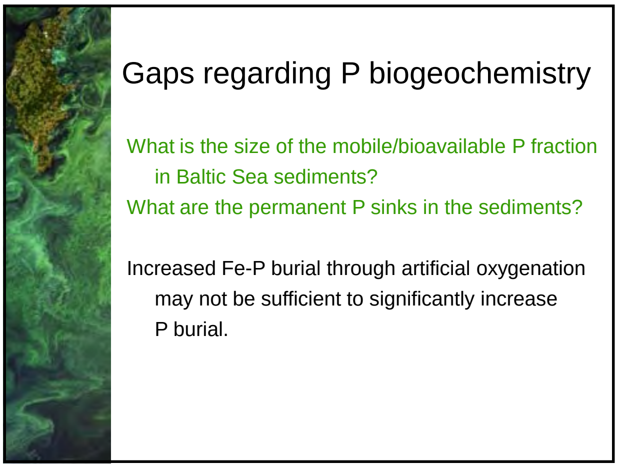
Does the binding capacity change as it ages?

What is the toxicity for benthic organisms?

What is the potential for co-sequestration with Si?

Will the cost be prohibitive?

Are there other mechanisms to enhance the permanent burial of P in the Baltic?

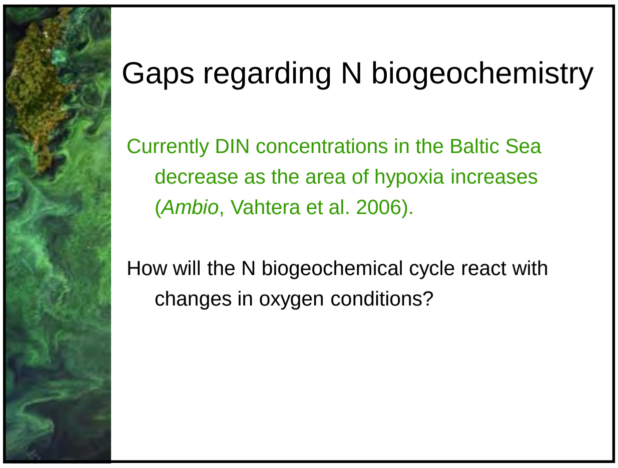


Gaps regarding P biogeochemistry

What is the size of the mobile/bioavailable P fraction in Baltic Sea sediments?

What are the permanent P sinks in the sediments?

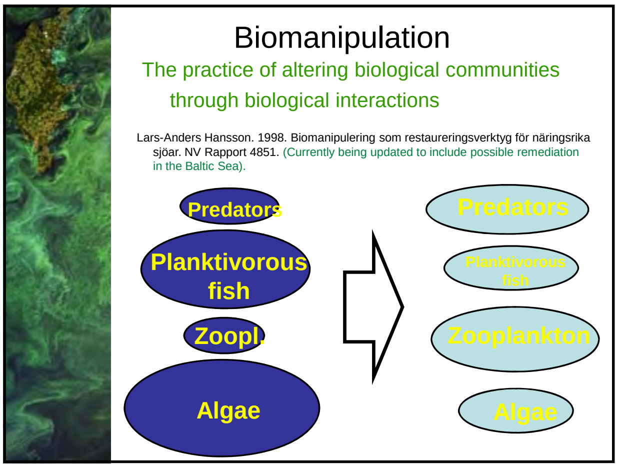
Increased Fe-P burial through artificial oxygenation may not be sufficient to significantly increase P burial.



Gaps regarding N biogeochemistry

Currently DIN concentrations in the Baltic Sea decrease as the area of hypoxia increases (*Ambio*, Vahtera et al. 2006).

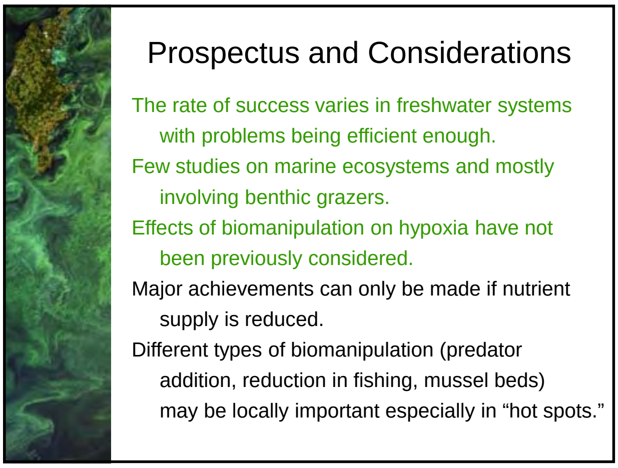
How will the N biogeochemical cycle react with changes in oxygen conditions?



Biomanipulation

The practice of altering biological communities through biological interactions

Lars-Anders Hansson. 1998. Biomanipulering som restaureringsverktyg för näringsrika sjöar. NV Rapport 4851. (Currently being updated to include possible remediation in the Baltic Sea).



Prospectus and Considerations

The rate of success varies in freshwater systems with problems being efficient enough.

Few studies on marine ecosystems and mostly involving benthic grazers.

Effects of biomanipulation on hypoxia have not been previously considered.

Major achievements can only be made if nutrient supply is reduced.

Different types of biomanipulation (predator addition, reduction in fishing, mussel beds) may be locally important especially in “hot spots.”

Re-establish the functioning of the coastal filter

However, we have a limited understanding of:
- The spatial and temporal extent of hypoxia.
- The role of the coastal filter in nutrient removal.

Conclusions and Recommendations (1)

There is no “silver bullet.”

From the model simulations, halocline ventilation is the only measure that can not be ruled out.

The amount of oxygen added to make the Baltic not hypoxic is enormous and prohibitive.

It is not possible to improve oxygen concentrations by any realistic engineering method affecting the exchange through the Danish Straits. In addition, this solution is illegal!

Conclusions and Recommendations (2)

P sequestration requires preliminary experiments. Violates principle of reversibility.

Biomanipulation may be a measure implemented locally in “hot spots.”

Need to restore functioning of the coastal filter.

Solutions should include reductions in nutrient loading.

The HELCOM Action Plan tells us how much to reduce, but we need to determine the effectiveness of nutrient reductions, e.g. *The Danish Action Plan on the Aquatic Environment*.

Significant challenges that lie before us…

Thanks to Lovisa Zillén and Britta Jakobsson and Baltic Sea 2020.

Thank you!

Considerations and Outlook

Gia Destouni, Stockholm University

Nutrient loads from land to sea

Climate and other change

Remediation targets – what are we after & why ?

Costs - Benefits

Legal aspects

A policy for Baltic Sea remediation ?

Land

Science & engineering of inland source reduction

Policy for inland source reduction

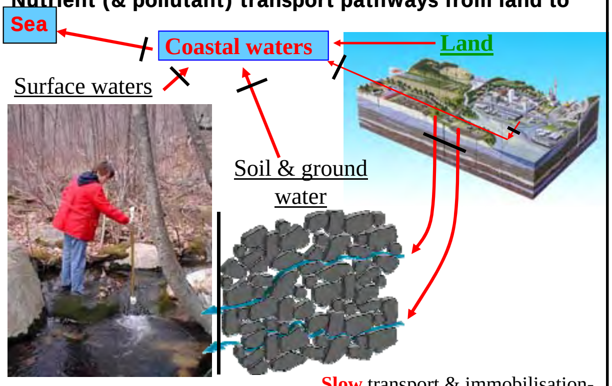
Reducing or controlling loads

- **Necessary condition**
- **How ?**

Science and engineering of coastal & marine remediation

Sea

Nutrient (& pollutant) transport pathways from land to



Sea

Coastal waters

Land

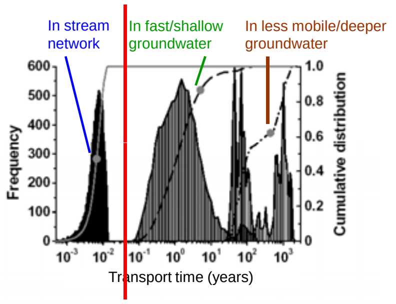
Surface waters

Soil & ground water

Long-term, **diffuse** inputs

Slow transport & immobilisation-remobilisation

Distributions of physical solute transport times through a catchment



Lindgren et al., *Environ. Sci. Technol.*, 2007

1. Coastal loads **are not the same as** source inputs of nutrients:
large and increasing subsurface nutrient load contributions continue long after source input reductions

2. **Possibilities** for engineered load reductions – in addition to source reductions

---

Coloured areas

Physically and systematically monitored catchment areas for nutrient loads

Grey areas

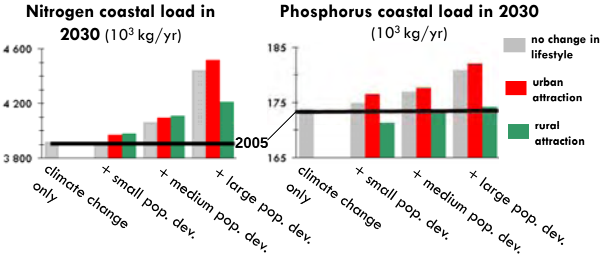
Physically unmonitored in systematic way, including:

~24% of total Baltic Sea Drainage Basin population in 13% area
~2x concentrations of monitored areas

~55% of Swedish population in 20% area
~5x concentrations of monitored areas

Hannerz and Destouni, *Ambio*, 2006

Nutrient load effect of climate, population and lifestyle change?



Climate, population development and lifestyle changes likely to <u>increase coastal nutrient loads</u>

Darracq et al., *Water Sci. Technol.*, 2005

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1. Coastal loads **are not the same as** source inputs of nutrients:
large and increasing subsurface nutrient load contributions continue long after source input reductions

2. **Possibilities** for engineered load reductions – in addition to source reductions

3. Load **uncertainties**:

- nutrient loads from large population fraction not captured by monitoring

- regional development and climate change will affect both source inputs and coastal loads

1. Coastal loads **are not the same as** source inputs of nutrients: large and increasing subsurface nutrient load contributions continue long after source input reductions

2. **Possibilities** for engineered load reductions – in addition to source reductions

3. Load **uncertainties**:

   - nutrient loads from large population fraction not captured by monitoring

   - regional development and climate change will affect both source inputs and coastal loads

4. Inland process and load development uncertainties:
   → **uncertainty costs** for coastal nutrient load reductions

- Baresel and Destouni, *Environ. Sci. Technol.*, 2005; *Physics & Chemistry of the Earth*, 2006; - Darracq and Destouni, *Global Biogeochemical Cycles*, 2007; *Environ. Sci. Technol.*, 2005; - Destouni, *Ecohydrology & Hydrobiology*, 2008 (in press); - Destouni and Darracq, *Environ. Sci. Technol.*, 2006; - Destouni and Gren, *J. Environ. Management*,2005; Destouni et al., *Environ. Sci. Technol.*, 2006; Gren et al., *J. Environ. Management*, 2002; *Environ. Modelling and Assessment*, 2000; - Hannerz and Destouni, *Ambio*, 2006; Lindgren et al., *Environ. Sci. Technol.*, 2007.

It costs also to reduce nutrient loads from land to sea:

➢ Direct costs for implementing source & load reduction measures
+ uncertainty costs for adding "safety factors" at implementation, or extra measures later

➢ Transaction costs for planning, implementing and managing reduction

Are these costs included and accounted for in Baltic Sea remediation outlooks and plans ?

➢ Costs for relevant inland system science and technology development and testing

---

- **Why should we pay** for inland or coastal & marine remediation costs ?

- What are the **benefits**?

Market & other monetary values of ecosystem services ?

Non-monetary values ?

What are they worth to us ?

- What are the specific **remediation targets** ?

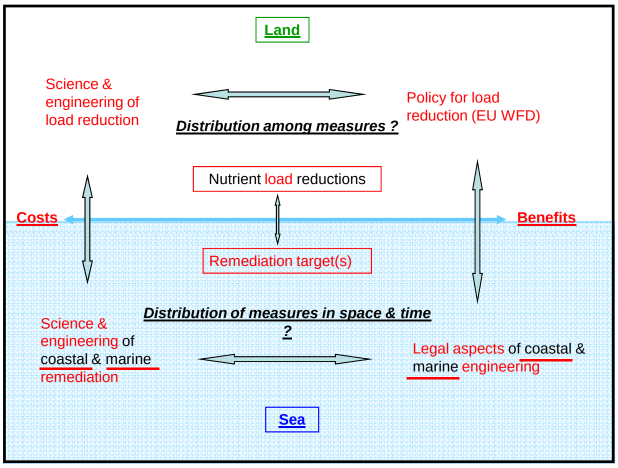
Higher oxygen concentrations per se ?

Sustained/increased ecosystem services ?

Reduced cyanobacteria blooms ?

Increased coastal property values ?

Larger spawning volume for starving cod ?



Land

Science & engineering of load reduction

Distribution among measures ?

Policy for load reduction (EU WFD)

Nutrient load reductions

Costs

Benefits

Remediation target(s)

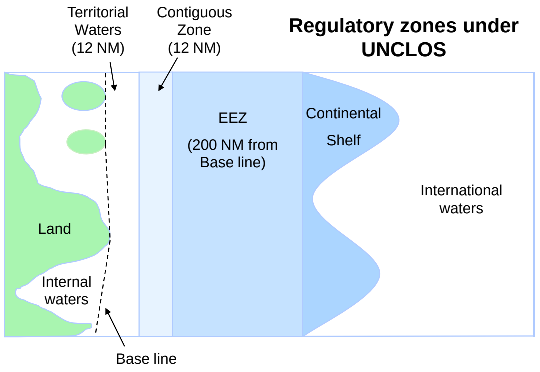
Distribution of measures in space & time ?

Science & engineering of coastal & marine remediation

Legal aspects of coastal & marine engineering

Sea

Regulatory zones under UNCLOS



From Per Hallström, Legal adviser, SEPA, Lund 2007-11-27

”Implementing engineered remediation measures in the Baltic: Legal Aspects”

- **Implemented where?**
  - In coastal or open waters?
  - In which country’s jurisdiction?
  - Under which multilateral requirements?
- **Implemented by whom?**
  - States or private companies?
  - By which country?
- **Engineered system specifics?**
  - impact on environment?
  - Fixed or mobile?
  - involving dumping of substances or not?

Modified from Per Hallström, Legal adviser, SEPA, Lund 2007-11-27

Engineered coastal & marine remediation measures have to be tested to answer these questions

… but so must also new science & engineering for reducing-controlling loads !

A policy

= a deliberate plan of action to guide decisions and achieve rational outcomes

for Baltic Sea remediation ??

How must different measures be combined in space & time in order to achieve desired targets & benefits ?

How do engineering, cost-benefit and legal specifics of coastal-marine measures compare with those of load reduction-control in terms of target & benefit achievement ?

Appendix 6

EARTH-01541; No of Pages 16

Earth-Science Reviews xxx (2008) xxx–xxx

Contents lists available at ScienceDirect

Earth-Science Reviews

journal homepage: www.elsevier.com/locate/earscirev

Past occurrences of hypoxia in the Baltic Sea and the role of climate variability, environmental change and human impact

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ARTICLE INFO

Article history:
Received 7 December 2007
Accepted 13 October 2008
Available online xxxx

Keywords:
Baltic Sea
Littorina Sea
hypoxia
Holocene
Medieval Warm Period
modern historical period
climate change and human impact

ABSTRACT

The hypoxic zone in the Baltic Sea has increased in area about four times since 1960 and widespread oxygen deficiency has severely reduced macro benthic communities below the halocline in the Baltic Proper and the Gulf of Finland, which in turn has affected food chain dynamics, fish habitats and fisheries in the entire Baltic Sea. The cause of increased hypoxia is believed to be enhanced eutrophication through increased anthropogenic input of nutrients, such as nitrogen and phosphorus. However, the spatial variability of hypoxia on long time-scales is poorly known: and so are the driving mechanisms. We review the occurrence of hypoxia in modern time (last c. 50 years), modern historical time (AD 1950–1800) and during the more distant past (the last c. 10 000 years) and explore the role of climate variability, environmental change and human impact. We present a compilation of proxy records of hypoxia (laminated sediments) based on long sediment cores from the Baltic Sea. The cumulated results show that the deeper depressions of the Baltic Sea have experienced intermittent hypoxia during most of the Holocene and that regular laminations started to form c. 8500–7800 cal. yr BP ago, in association with the formation of a permanent halocline at the transition between the Early Littorina Sea and the Littorina Sea s. str. Laminated sediments were deposited during three main periods (i.e. between c. 8000–4000, 2000–800 cal. yr BP and subsequent to AD 1800) which overlap the Holocene Thermal Maximum (c. 9000–5000 cal. yr BP), the Medieval Warm Period (c. AD 750–1200) and the modern historical period (AD 1800 to present) and coincide with intervals of high surface salinity (at least during the Littorina s. str.) and high total organic carbon content. This study implies that there may be a correlation between climate variability in the past and the state of the marine environment, where milder and dryer periods with less freshwater run-off correspond to increased salinities and higher accumulation of organic carbon resulting in amplified hypoxia and enlarged distribution of laminated sediments. We suggest that hydrology changes in the drainage area on long time-scales have, as well as the inflow of saltier North Sea waters, controlled the deep oxic conditions in the Baltic Sea and that such changes have followed the general Holocene climate development in Northwest Europe. Increased hypoxia during the Medieval Warm Period also correlates with large-scale changes in land use that occurred in much of the Baltic Sea watershed during the early-medieval expansion. We suggest that hypoxia during this period in the Baltic Sea was not only caused by climate, but increased human impact was most likely an additional trigger. Large areas of the Baltic Sea have experienced intermittent hypoxic from at least AD 1900 with laminated sediments present in the Gotland Basin in the Baltic Proper since then and up to present time. This period coincides with the industrial revolution in Northwestern Europe which started around AD 1850, when population grew, cutting of drainage ditches intensified, and agricultural and forest industry expanded extensively.

Contents

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0012-8252/$ – see front matter © 2008 Published by Elsevier B.V.
doi:10.1016/j.earscirev.2008.10.001

Please cite this article as: Zillén, L., et al., Past occurrences of hypoxia in the Baltic Sea and the role of climate variability, environmental change and human impact, Earth-Science Reviews (2008), doi:10.1016/j.earscirev.2008.10.001

1. Introduction

Hypoxia, defined as <2 mg/l dissolved oxygen, occurs in aquatic environments when dissolved oxygen becomes reduced in concentration to a point harmful to aquatic organisms living in the environment. Hypoxia is a globally significant problem with over 400 reported sites suffering from its effects (Diaz and Rosenberg, 2008). Hypoxia not only causes severe ecosystem disturbances (Diaz and Rosenberg, 1995) but alters nutrient biogeochemical cycles (Vahtera et al., 2007) and forms hydrogen sulfide which is hazardous to numerous fauna and flora communities (Diaz and Rosenberg, 1995). Widespread oxygen deficiency has for that reason severely reduced macrobenthic communities below the halocline in the Baltic Sea over the past decades (Laine, 2003) and produced benthic "ecological deserts" that annually cover over 30% of the seafloor (Karlson et al., 2002). Hypoxia also affects food chain dynamics, fish habitats and fisheries (Karlson et al., 2002; Bonsdorff, 2006).

The hypoxic zone in the Baltic Sea has increased about four times since the 1960s (Jonsson et al., 1990), and currently covers an area averaging 41 000 km^2 annually (e.g. Conley et al., 2002). Hypoxia has for that reason developed into a serve environmental problem for the Baltic Sea and its dependents. The increasing trend in hypoxia is thought to be caused by enhanced eutrophication due to excess load of waterborne and airborne nutrients (nitrogen and phosphorus) to the sea from anthropogenic sources (Wulff et al., 2007). Eutrophication has been of great concern for the countries in the Baltic region at least since the 1980s, with ministerial level commitments to reduce nutrients and improve water quality (Johansson et al., 2007).

The debate about improving the present state of the Baltic Sea through implementation of the European Water Framework Directive often refers to conditions prior the turn of the last century (1900) as an environmental reference status, where the Baltic is suggested to have been an oligothrophic clear-water body with oxygenated deep waters (Österblom et al., 2007). However, geological records show that the Baltic Sea is a dynamic ecosystem that has undergone many environmental changes over the last c. 16 000 years (Björck, 1995; Andrén et al., 2000a,b; Berglund et al., 2005). Studies of the more recent past, for instance, reveal that hypoxia has been present in some basins for at least the last 100 years (Jonsson et al., 1990). Furthermore, analyses of long sediment cores suggest that hypoxia in the Baltic Sea has occurred intermittently in deep basins in the Baltic Proper over thousands of years (Andrén et al., 2000a,b; Sohlenius et al., 2001; Emeis et al., 2003) and that cyanobacterial blooms have occurred during the last c. 7000 years (Bianchi et al., 2000; Kunzendorf et al., 2001; Poutanen and Nikkilä, 2001). Various investigations also imply that there may be a correlation between climate variability in the past and the state of the marine environment, where warmer periods correspond to increased primary production and higher salinities resulting in amplified hypoxia and enlarged distribution of benthic mortality and laminated sediments (e.g. Thorsen et al., 1995; Fjellså and Nordberg, 1996; Andrén et al., 2000a; Bianchi et al., 2000; Nordberg et al., 2000; Emeis et al., 2003). In addition, the occurrence of hypoxia in the deeper basins today need not necessarily be attributed to human activity but could be naturally driven by oceanographic, environmental and climate forcing (Filipsson and Nordberg, 2004a,b).

In addition, both climate variability and human impact have the potential to greatly affect the environment in the semi-enclosed Baltic Sea and its catchment. However, the long-term spatial and temporal extent of hypoxia and its possible connections to these parameters are poorly known. Anthropogenic forcing in the drainage area, such as, changes in land use and population density, could indirectly have affected the marine/brackish environment already in the Late Holocene. It is known from numerous long-term studies of lake sediments in Northwest Europe that population growth and agricultural development have impacted lakes for thousands of years and that cultural eutrophication of lakes has a history longer than just decades or centuries (e.g. Fritz, 1989; Renberg et al., 2001; Bradshaw et al., 2005). Furthermore, the International Panel on Climate Change (IPCC) has recognized that hypoxia is a problem of growing concern with projected climate change (www.ipcc.ch) and recent studies predict that cyanobacteria blooms will magnify with global warming (Pearl and Huisman, 2008). It is thus essential to improve our understanding about the timing, extent and mechanism(s) causing hypoxia on millennial time-scales in order to understand the full range of the natural variability and to put forward realistic measures to improve the future environment of the Baltic Sea. It is also important to put the recent human impact in a time-perspective in order to understand the modern environmental issues.

This paper aims to review and synthesize the current knowledge in the Baltic Sea about the appearance of hypoxia in modern time (last 50 years), modern historical time (50–200 years ago) and in the geological past (last c. 10 000 years), based on previous publications. We examined a large number of papers about Baltic Sea sediments, but only present here papers which report or address hypoxia. We will present a compilation of several long sediment records covering most of the Holocene (i.e. the last c. 10 000 years) and explore possible connections with the presence of past hypoxia and the role of climate and environmental variability and human impact. With the purpose to spatially and temporally reconstruct the occurrence of hypoxia our main objective is to answer three basic questions: where, when and why was the Baltic Sea hypoxic in the past?

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2. Baltic Sea characteristics

The Baltic Sea (area of 412 560 km^2; volume of 21 631 km^3; average depth of 52 m; maximum depth of 459 m; Seifert and Kayser, 1995) is a semi-enclosed brackish water body consisting of a series of basins where the Bothnian Bay, the Bothnian Sea, the Gulfs of Finland and Riga and the Baltic Proper are the main water masses (Fig. 1). We will not address hypoxia in the transition zone between the Baltic Sea and the Skagerrak, nor in coastal areas. The modern record of hypoxia in the Danish straits has been previously reported by Conley et al. (2007).

The Baltic Sea watershed has a population over 85 million. The drainage area is c. 4 times larger than the area of the sea itself, which yields substantial freshwater input to the basin. Inflow of denser saline bottom waters takes place through shallow and narrow connections (i.e. the Danish belts and Swedish sound) from the Skagerrak/Kattegat and brackish surface water is transported out over the same sills. Inflow of saline water in the south and the occurrence of large rivers in the north yield a south-north salinity gradient where the surface salinity is c. 8–10 in the southern Baltic, c. 7–8 in the Baltic Proper and c. 3–5 in the Gulf of Finland, Bothnian Sea and Bothnian Bay (Matthäus, 2006).

The water column of the Baltic Proper is permanently stratified, consisting of two water masses, an upper layer of brackish water with salinities of c. 7–8 and more saline deep waters of c. 11–13. At the transition zone between these water masses a strong permanent halocline is formed which prevents vertical mixing of the water column and ventilation of more oxygen rich waters to the bottom (Matthäus and Schinke, 1999). The halocline is formed at depths varying between c. 30 m in the Arkona Basin, 60 m in the Bornholm Basin, c. 80 m in the Gotland Basin and Landsort Deep (Matthäus, 2006). The Bothnian Sea and, in particular, the Bothnian Bay have weaker haloclines and a better ventilation due to less variable inflow conditions (Stigebrandt, 2001). In combination with a lower productivity this makes these basins mostly oxic.

Large inflows (100–250 km^3) of higher salinity and oxygen-rich water from the North Sea represent an important mechanism by which the Baltic deep water is displaced and renewed to a significant degree. All inflows are substantially mixed with surface water, on

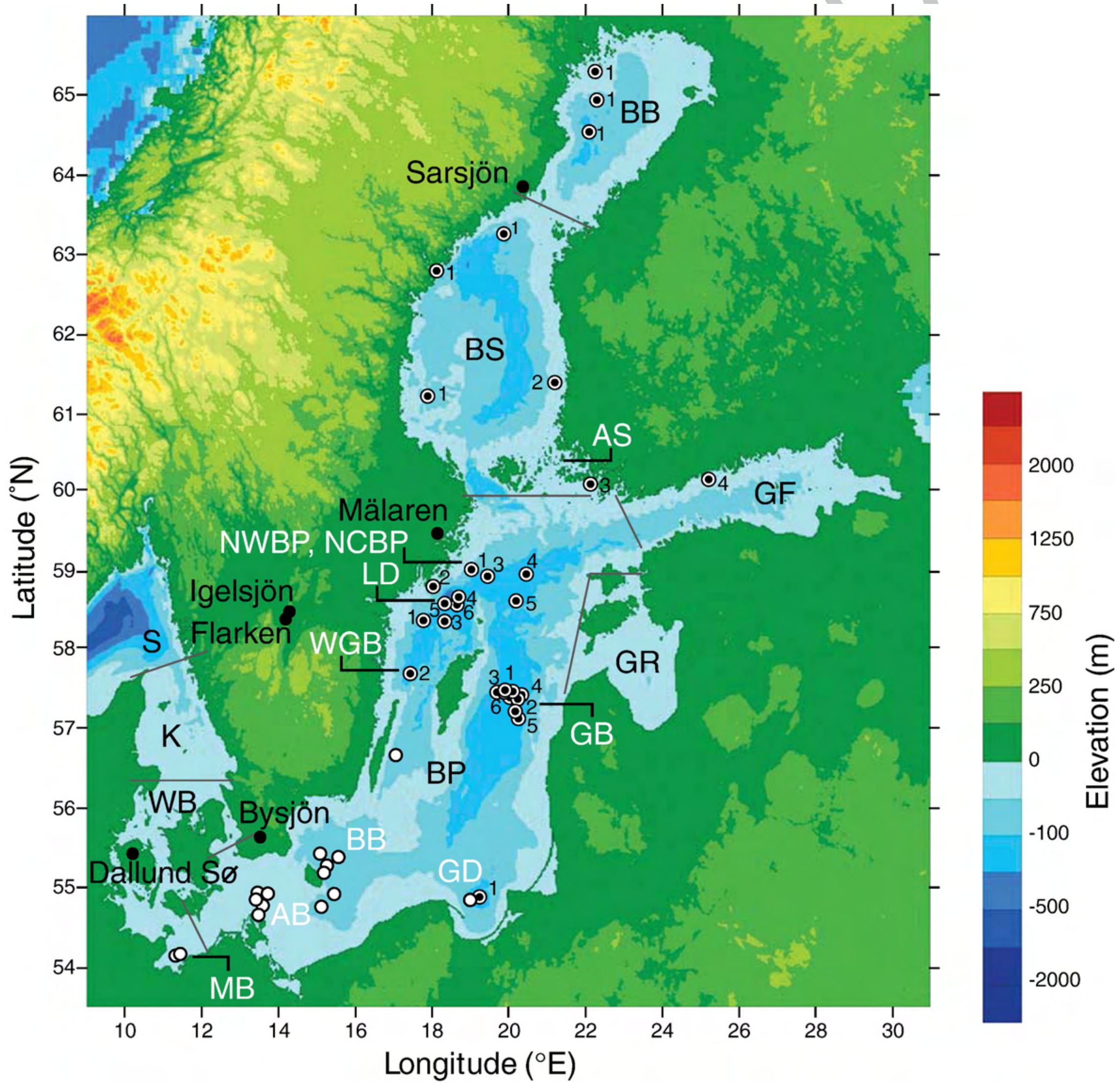

Fig. 1. Map of the Baltic Sea showing the major basins in black (BB = Bothnian Bay, BS = Bothnian Sea, GF = Gulf of Finland, GR = Gulf of Riga, BP = Baltic Proper, WB = West Baltic, K = Kattegat and S = Skagerrak) and sub-basins in white (AS = Archipelago Sea, NWBP = Northwest Baltic Proper, NCBP = North Central Baltic Proper, LD = Landsort Deep, GB = Gotland Basin, BB = Bornholm Basin, AB = Arkona Basin, MB = Mecklenburgian Bay, and GD = Gdansk Deep) mentioned in the text and coring sites for the sediment records studied in this paper. Black and white circles represent localities containing laminated sediments (geological records of hypoxia) while white circles show the position of sediment cores with homogeneous (oxygenated and bioturbated) sediments. Also, the locations of the lake sediment sequences referred to in the text (black circles).

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average 3 times (Stigebrandt and Gustafsson, 2003). However, frequent but small inflows (10–20 km^3) are generally insufficient to displace the deep bottom water because they have a much less density and therefore do not penetrate into the deepest parts of the Baltic Sea (Stigebrandt, 2001; Matthäus, 2006).

In summary, the physical setting of the Baltic Sea, the narrow and shallow connections to the Skagerrak/Kattegat and relative large river runoff influence the salinity and oxygen distribution in the basin resulting in low salinity, long residence time, strong density stratification of the water mass and limited water exchange (Wulff et al., 1990; Gustafsson and Westman, 2002). This estuarine circulation retains nutrients and organic matter within the basin leading to high nutrient availability.

3. History of the Baltic Sea

The present Baltic Sea formed in the course of several events that accompanied the onset of the last deglaciation of Scandinavia at c. 17 000–15 000 cal. yr. BP (e.g. Björck, 1995). The postglacial history of the Baltic Sea and its drainage area is characterized by regionally confined transgressions and regressions caused by the interaction of the differential subsidence and uplift of land, deglaciation, ponding and drainage of fresh-water stages and phases of eustatic sea-level rise. By tradition, the late Quaternary history of the Baltic Sea is divided into four main stages, i.e. the Baltic Ice Lake, the Yoldia Sea, the Ancylus Lake and the Littorina Sea, representing time periods with either brackish condition with connections to the Skagerrak/Kattegat or isolated and up-dammed freshwater lake conditions (Björck, 1995). The Littorina Sea can further be divided into three sub stages i.e. the Early (or Initial) Littorina Sea (c. 10 000–8500 cal. yr BP) the Littorina Sea sensu stricto (s. str.; c. 8500–3000 cal. yr BP) and Late Littorina Sea (c. 3000 cal. yr BP to present; Berglund et al., 2005). We will apply the latter terminology for the Littorina Sea, which is based on studies of near shore sediment cores, because it is supported by high-resolution chronologies established by ^{14}C-dating of terrestrial plant macrofossils and environmental reconstructions constructed from multistratigraphical analyses (Berglund and Sandgren, 1996; Berglund et al., 2005; Yu et al., 2007).

The Baltic Ice Lake began forming at c. 16 000 cal. yr BP and was filled by the accumulation of glacial waters from the waning ice sheet. It existed until c. 11 600 cal. yr BP when the dam broke open at Mount Billingen in south central Sweden (Björck and Digerfeldt, 1984; Strömberg, 1992; Andrén et al., 2002). This resulted in a considerable fall of the Baltic lake-level (c. 25 m; Svensson, 1991; Björck, 1995). The deep basins of the freshwater Baltic Ice Lake were characterized by oxic conditions (due to seasonal overturn of the water column) and low organic productivity (Andrén et al., 2002). During this period glacial varved and non-varved clays were deposited.

After the final drainage of the Baltic Ice Lake the Yoldia Sea formed (11 600–10 700 cal. yr BP) and its level was determined by that of the global ocean. The water of the Yoldia Sea was partly brackish for 200–300 yr around 11 200 cal. yr BP (Wastegård et al., 1995; Andrén et al., 2002) and linked to Lake Vänern through a broad connection over the central part of southern Sweden and to Skagerrak/Kattegat through narrow fjords west of Lake Vänern. The brackish phase of the Yoldia Sea stage had its highest salinities in depression areas between Lake Vänern and Stockholm in central Sweden (Schoning, 2001). However, it has been suggested that brackish bottom-waters also penetrated as far south as the Bornholm Basin and Hanö Bay in southern Baltic (Björck et al., 1990; Andrén et al., 2000b; Andrén et al., 2007). The dominant sedimentary deposits from the Yoldia Sea stage consist of organic-poor (silty) clays, often varved in and north of the Gotland Basin (Andrén et al., 2002).

Through the continuous land-uplift, the fjord connections to the Skagerrak/Kattegat shallowed and forced Baltic level to rise above sea level (Björck, 1995). The Baltic changed once more to lake conditions, the Ancylus Lake. During the Ancylus Lake stage (c. 10 700–10 000 cal. yr BP) the relatively faster land uplift in the northern parts of the basin caused it to be tilted towards the south and at c. 10 000 cal. yr. BP the Ancylus Lake attained the level of the global ocean (which was also rising) through a fluvial-lacustrine system in the lowlands of the Fehmarn-Great Belt region (Björck, 2008). This connection to Kattegatt was subsequently broadened and later the Öresund Strait began to function as an important inlet of saltwater around c. 8500–7800 cal. yr BP (e.g. Andrén et al., 2000a,b; Sohlenius et al., 2001; Emeis et al., 2003). However, due to the lack of a robust geochronology, the timing of the first clear brackish/marine Littorina intrusion is much debated. In the southern Baltic it has been dated to c. 6500 cal. BP with the Optically Stimulated Luminescence (OSL) dating method (Moros et al., 2002; Rößler, 2006; Kortekaas, 2007) and it is presumed that a transitional phase (i.e. the Early Littorina Sea Stage or the Mastogloia Sea) existed with episodic marine influxes starting at c. 9800 cal. yr BP based on traditional ^{14}C-dating (Andrén et al., 2000b; Yu et al., 2003; Berglund et al., 2005; Witkowski et al., 2005). The saltwater intrusion during the Early Littorina Sea/Littorina Sea s. str. transition (often referred to as the transition phase between the Ancylus Lake and the Littorina Sea or the Mastogloia Sea) initiated the establishment of a permanent halocline in the Baltic Sea and a more marine flora and fauna (Andrén et al., 2000a; Sohlenius et al., 2001). During this time, the inlet transect area in the Öresund Strait was about twice its size compared to today (Gustafsson and Westman, 2002) and the surface water of the Baltic was more saline, i.e. 10–15 in the Baltic Proper, than at present, i.e. 7–8, (Gustafsson and Westman, 2002; Emeis et al., 2003; Berglund et al., 2005). However a more conservative estimate, c. 4 units higher then present, is given by Donner et al. (1999) for the Gulf of Finland and Gulf of Bothnia based on the stable isotope composition in bivalve shells. Furthermore, surface salinity values of c. 7.3–10.3 and 4.8–10.3 (at present c. 3–5) were reported by Widerlund and Andersson, (2006) between 6770 and 3070 cal. yr BP in the Bothnian Sea and Bothnian Bay, respectively. The transition is also associated with an abrupt increase in organic matter content and a clear change from clay to clay-gyttja (often laminated) in the sediment record (Fig. 2). Due to the continued melting of the North American and Antarctic ice sheets the sea-level rise continued until c. 6500–6000 cal. yr BP. Based on studies of marginal lake basins along the coast of Blekinge, southeastern Sweden, Yu et al. (2007) demonstrate that the Baltic Sea level rose steadily from 8600 to 6500 cal. yr BP, with a rapid sea-level rise at c. 7600 cal. yr BP. After this stage the land-uplift was greater than the almost stable global sea-level and a more continuous regression

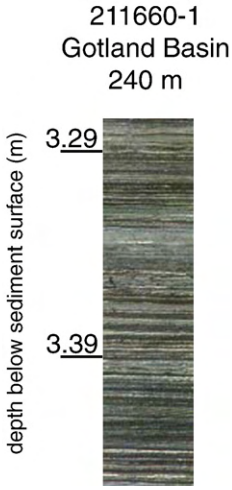

Fig. 2. Photo of sediments from core 211660-1 recovered from a depth of 241 m in the Gotland Deep showing laminated Littorina Sea s. str. clay-gyttja.

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started. The connections via Öresund and the Danish Straits became shallower, salinity decreased and present conditions in the Baltic Sea gradually developed.

4. Evidence for hypoxia in the past

4.1. Laminated sediments

One of the environmental prerequisites for the formation and preservation of laminated sediments in aquatic environments is, apart from cyclic sedimentation, the absence of a relatively large benthic fauna that bioturbate (vertically mix) the uppermost sediments (e.g. Zillén et al., 2003). Laminated sediments, therefore, tend to be found in relatively deep basins where vertical mixing of the water column is limited and hypoxic conditions prevail, which restrict the presence of bottom fauna (Zillén et al., 2003).

Laminated sediments form in sedimentation basins of the open Baltic Sea below the permanent halocline, where the vertical mixing of the water mass is weak (Stigebrandt, 2001; Matthäus, 2006). The composition of individual laminae in Littorina Sea sediments[1] (in the deep basins of the Baltic Sea is either depositional or authigenic in origin (Neumann et al., 1997; Burk et al., 2002). Depositional laminae couplets (or sometimes triplets and quadruplets) can occur and consist of alternating lithogenic (clay-rich) and diatomaceous (diatom-rich) mud. The diatom component forms mainly during the spring bloom, while the lithogenic sediment input dominates in autumn and winter when biogenic production is minimal and storms redistribute sediment to the deeper basins.

Distinctly laminated authigenic Ca-rich rhodochrosite $(Mn,Ca)CO_3$ laminae occur regularly throughout the Littorina Sea sediments of the Gotland Deep (Neumann et al., 1997; Burk et al., 2002; Burke and Kemp, 2004). The precipitation of Mn-carbonates takes place close to the sediment–water interface and is a result of changing redox-conditions due to episodic oxic water inflows to the generally hypoxic basin. For a more detailed description about the formation and composition of laminations in Baltic Sea sediments see e.g. Sohlenius et al. (1996), Neumann et al. (1997), Sternbeck and Sohlenius (1997), Sohlenius and Westman (1998) and Burk et al. (2002).

Given that the majority of relatively large benthic faunas cannot live under hypoxic conditions, the occurrence of laminae in sediment records is a good indicator of past bottom water hypoxia in aquatic environments. However, the preservation of laminations can be affected by other post-depositional disturbances, such as erosion by water movements created by currents (Larsen et al., 1998). Sediment records displaying alternating laminated and homogeneous sequences could also be subjected to bioturbation at the transition zone. When bottom environments change from hypoxic to more oxic conditions benthic fauna communities are reestablished, which can homogenize the upper layers of the earlier deposited laminated interval. Therefore, the age approximation of the boundary between laminated and homogeneous sediments (i.e. the change from hypoxic to more oxic conditions) is a maximum estimate. In this review, hypoxic conditions will be ascribed to the formation and preservation of laminations in sediment records.

4.2. Geochemistry

The effect of redox conditions on the distribution of trace elements (e.g. Mn, Mo, U, V, Cu and Zn) has been discussed in a number of studies (e.g. Sohlenius and Westman, 1998; Sohlenius et al., 2001). It has been demonstrated that trace elements accumulate in sediments deposited under reducing conditions and several of these have been reported to be enriched in laminated sediments of Littorina Sea age in the Baltic Sea (Sternbeck et al., 2000). The presence of iron sulfides (e.g. pyrite and greigite) in sediments is also thought to reflect reduced or hypoxic bottom conditions (Snowball, 1993). However, the primary distribution of both trace elements and Fe-sulfides may be altered by diagenetic changes occurring after sediment deposition (Snowball and Thompson, 1990). Studies show that changes in redox conditions can lead to sulfide diffusion and pyritization of earlier deposited sediments (Thompson et al., 1995) and that the primary signals can be altered by diagenetic changes occurring several thousands of years after sediment deposition (Sternbeck et al., 2000). There are also a number of different mechanisms by which trace elements may be enriched in sediments. Thus, the absence or presence of trace elements in sediments should be used with caution when interpreting ancient sedimentary environments. Therefore, we have only used the presence of laminae in sediments as a proxy for hypoxic/anoxic conditions since it has been shown to be the most prominent/undisputable evidence of oxygen depletion (Sohlenius et al., 1996).

Studies of recent marine sediments have not shown any clear-cut and systematic relationships between bottom water oxygen concentrations and the sediment organic carbon content (Burdige, 2007). While enhanced preservation of organic material may occur due to changes in macrofaunal abundance or changes in reducing equivalents, oxygen per se has no demonstrated effect on carbon preservation or remineralization (Cowie et al., 1995).

4.3. Chronology

Good chronological control is necessary to understand past environmental and climate changes (Zillén et al., 2003). On millennial time-scales, sediments from the Baltic sub-basins mostly rely on time-scales based on measurements of the ^{14}C content in organic material. However, this dating method can be biased by unidentified marine/brackish ^{14}C reservoir effects (Köningsson and Possnert, 1988), redeposition of older carbon from shallower areas to deep accumulation bottoms, and uncertainties arising from inferred ages derived from interpolation between individually dated levels. The sediments in the Baltic Sea are characterized by low organic carbon contents (usually $<10\%$) and deficiency in macrofossil remains (especially in the deeper basins), which further makes it a delicate task to construct an accurate chronology based on ^{14}C-dating. In the majority of studies dating is performed on bulk sediment samples, but should if possible be performed on macrofossils, preferably terrestrial, since bulk sediment samples are known to show too old ages, and poor temporal resolution (at best c. 5–10 ^{14}C-dates in sediment sequences covering the last c. 10 000 years) often resulting in great uncertainties in the estimation of sedimentation rates.

The ^{14}C-ages presented here are calibrated (1σ) by using the Oxcal calibration program v4.0 (Bronk Ramsey, 2001) and expressed as cal. yr BP (calendar years before 1950). In order to simplify the comparison of the different marine records the ages are not corrected for marine reservoir effects since they are inconsistent and poorly known in the Baltic Sea. For example, Andrén et al. (2000a) corrected the calibrated ages for a marine reservoir effect ranging from 100 to 300 years and used a correction age of 400 years to compensate the contribution of old resuspended carbon in the Gotland Basin, while Hedenström and Possnert (2001) estimated a total reservoir effect of 700–1000 ^{14}C yr from analyses of coastal Littorina Sea s. str sediments.

5. Occurrence of hypoxia

5.1. During modern time (last 50 years)

From water quality monitoring records, the bottom surface area covered by hypoxic water averages c. 41 000 km^2 over the time period 1970–2000 (Conley et al., 2002). The smallest hypoxic area occurred in

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[1] From now on and throughout this paper the term Littorina Sea sediments refers to sediment deposited after the Early Littorina Sea/Littorina Sea s. str. transition (i.e. after c. 8500-8000 cal. yr BP based on traditional ^{14}C-dating) if not stated otherwise.

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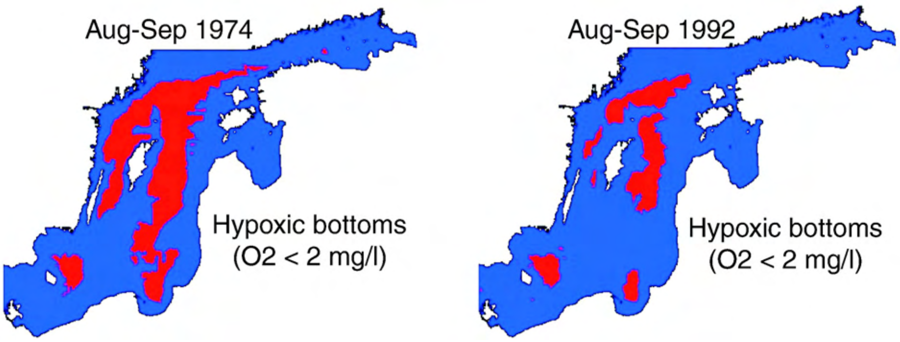

Fig. 3. Modern variability of hypoxia in the Baltic Proper (after Conley et al., 2002).

1993 during the peak of the "stagnation period" when major salt water inflows were at their minimum (Stigebrandt and Gustafsson, 2007) with only 12 000 km^2 of bottom covered by hypoxic waters. The peak in hypoxic area was in 1971 following large salt water inflows in previous years (Conley et al., 2002). While major salt water inflows are well known to displace and renew bottom water oxygen supplies (Matthäus, 2006), it is less well appreciated that they also create large areas of stratification where oxygen can be depleted (Gerlach, 1994; Conley et al., 2002). In modern times it has been typical that most of the deep basins are continuously hypoxic including the Gotland Deep, Landsort Deep, NW Baltic Proper, and Gdansk Deep (Fig. 3) with permanent anoxia in the deepest parts of the Gotland Deep (Conley et al., 2002). During years with large areas of hypoxia, low oxygen zones migrate higher up in the water column and the different basins become connected to form one large hypoxic area (Fig. 3).

In the Gulf of Finland salt water inflows create stratification, and together with the small volume of water under the halocline and coupled with high productivity, oxygen is rapidly depleted below the halocline (Laine et al., 2007). Trends in hypoxia in modern times in the Gulf of Finland are related to variations in salt water inflows, with less stratification and less hypoxia during "stagnation periods" when salt water inflows are reduced.

5.2. During modern historical time (AD 1950–AD 1800)

Historical proxy records of hypoxia, defined here as the sediment archives deposited during the last 50–200 years in the Baltic Sea, show that laminations are prevalent in the sediments (Gripenberg, 1934; Ignatius et al., 1968; Jonsson et al., 1990; Hille, 2005). Jonsson et al. (1990) reported laminations in 8 out of 29 coring sites in the Gotland Basin, Landsort Deep and Bornholm Basin with the upper 40 cm of sediment consisting of 100–200 continuously and annually deposited laminae. Based on the distribution of laminations in surficial sediments, Jonsson et al. (1990) summarized the expansion of laminated bottoms in the Baltic Proper with rapid increases in the presence of laminated sediments following 1960 (Fig. 4), the time period when eutrophication rapidly increased in the Baltic Sea. Hille (2005) sampled the upper 1 m of sediments at 53 stations at depths deeper than 150 m in the Gotland Basin and mapped the spatial distribution of laminated sediments. At almost all stations the uppermost sediments were distinctly laminated, and had accumulated

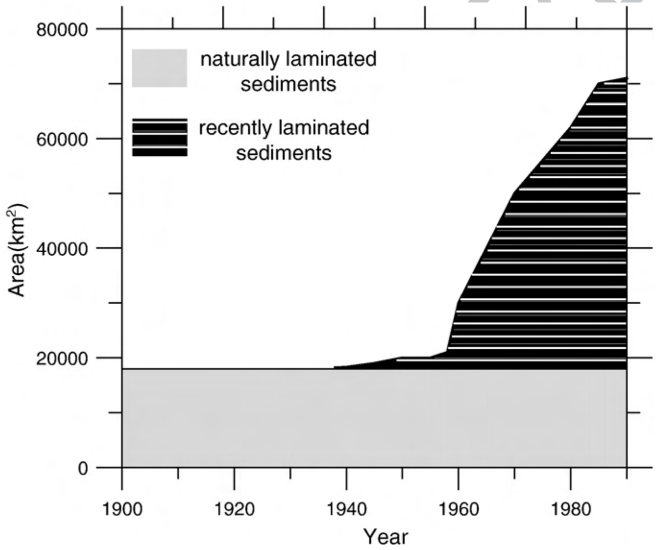

Fig. 4. Figure showing the expansion of laminated bottoms in the Baltic Proper during the last 100 years (after Jonsson et al., 1990). Laminations deposited before 1940 is considered as natural while post-1960 laminae formation is regarded as a result of human impact. The study was based on results from 29 coring sites and ages of the sediments were obtained by counting the individual laminae.

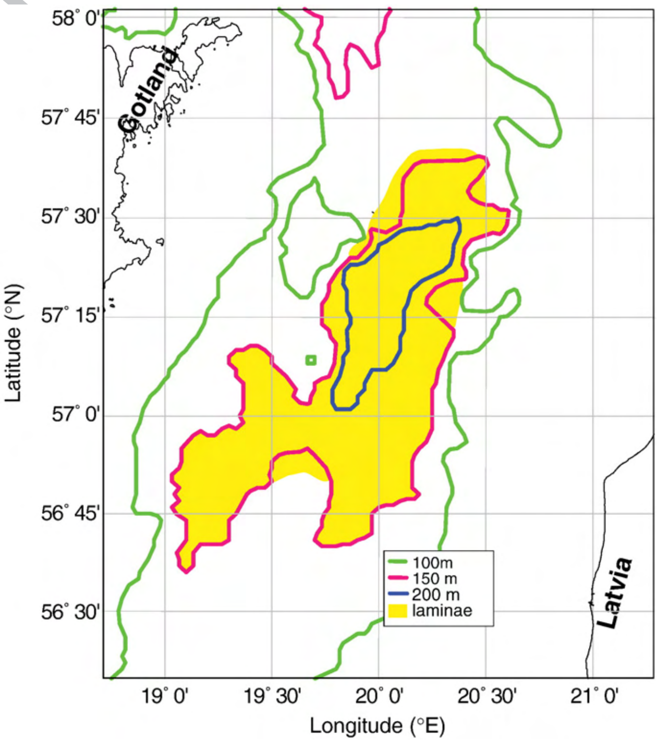

Fig. 5. Bathymetric map over the Gotland Deep showing the extension of laminated sediments deposited 100 years ago to the present (after Hille, 2005). The result is based on samples of the upper sediments at 53 stations. The age estimates are based on the ^{210}Pb dating technique.

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over homogeneous non-laminated sediments. Based on ^{210}Pb dating, Hille (2005) observed that the laminated sediment structures started to form, basin wide, at depths greater than 150 m, 100 years ago basin-wide in the Gotland Basin (Fig. 5). Laminated sediments were reported from a few stations at shallower depths less than 150 m, which suggest that the area with lamina formation could be even greater than shown in Fig. 5. Gripenberg (1934) recovered about 80 short (<30 cm) sediment cores during the years 1924–1928. She describes sediments with stratifications (some rich in hydrogen sulfide) in clayey muds in both coastal and deeper basins within the Bothnian Bay, Bothnian Sea, Gulf of Finland and N Baltic Proper. Although the ages of these laminated sediment cores have not been estimated, they should represent the period from the turn of the century to the time of collection in 1924–1928 to be consistent with Hille (2005) and Jonsson et al. (1990).

5.3. On geological time-scales (AD 1800–10 000 cal. yr BP)

A compilation of the geological records reporting the occurrence of Holocene laminated sediments (i.e. the proxy used for occurrence of past hypoxia in this paper) in the Baltic Sea during the last c. 10 000 cal. yr BP is presented in Fig. 6. Owing to the fact that accumulation basins have the potential to provide long undisturbed sediment sequences, the majority of the sediment cores were therefore recovered from the deeper basins in the Baltic Sea (see Fig. 1.) The core lengths covering the last c. 10 000 years vary between c. 4 and 10 m. In most studies, data from the uppermost sediments (i.e. the last c. 100–200 years) are missing due to sediment lost during the coring operation.

All studies suggest that laminations started to form in the deeper depressions of the Baltic Sea (i.e. Gotland Deep, Landsort Deep, NW

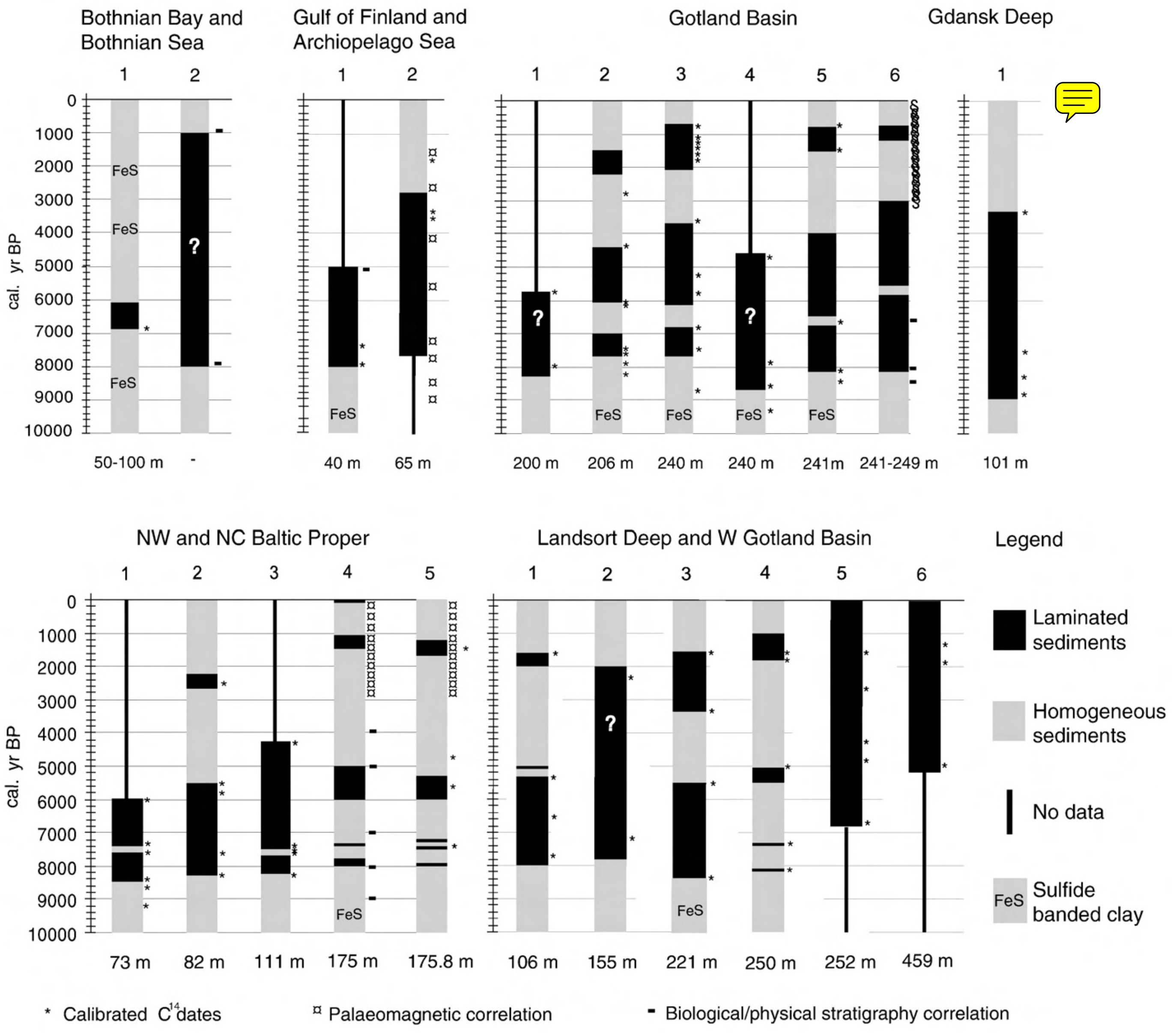

Fig. 6. Figure showing the occurrence of laminated sediment plotted on time scales based on calibrated uncorrected ^{14}C-ages (1σ; Oxcal calibration program v4.0, Bronk Ramsey, 2001), predominantly preformed on bulk-sediment samples. In a few studies, the ages of the sediment are based on a combination of calibrated ^{14}C-dates and palaeomagnetic secular variations or biological/physical correlations. Note that the calibrated uncorrected ^{14}C-ages presented here, may vary 500–1000 years in relation to terrestrial dates due to reservoir effects (e.g. Andrén et al., 2000a; Hedenström and Possnert, 2001). In cases of questions regarding lithological descriptions a question mark is shown in order to illustrate the uncertainties in the stratigraphy. The records are presented in order of water depth at the coring site with greater water depths to the right. The data is obtained from various research papers which are presented in Table 1. Most of the long sediment records are missing the uppermost sediments during the last 200–100 years.

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Baltic Proper, North Central Baltic Proper, W Gotland Basin and Gdansk Deep) c. 8500–7800 cal. yr BP ago, in association with the formation of a permanent halocline at the transition between the Early Littorina Sea and the Littorina Sea s. str. (e.g. Witkowski, 1994; Sohlenius et al., 1996; Lepland and Stevens, 1998; Andrén et al., 2000a; Harff et al., 2001; Emeis et al., 2003). The deeper basins have experienced intermittent hypoxia during most of the Holocene except at depth >250 m in the Landsort Deep where sediment cores show more continuous laminated structure (Fig. 6). A more detailed description divided by basin is presented below.

5.3.1. Bothnian Sea, Bothnian Bay, Gulf of Finland and Archipelago Sea

Studies of the Bothnian Sea and Bothnian Bay reveal that laminated sediments have been deposited at various depths within these basins at least during the beginning of Littorina s. str. (i.e. from c. 6900 cal. yr BP). The upper limit of the laminated sequences is not dated, but the thickness of the deposition is about 1 m, which, considering the estimated sedimentation rates of 1.76–2 mm yr^{-1} (Jerbo, 1961; Ignatius et al., 1968) corresponds to about 500–600 years. In the Bothninan Sea continuous laminated sequences have been reported in coastal areas in sediments of the age of c. 8000–1000 cal. yr BP (Ignatius et al., 1968; Fig. 6.). However, the substandard sediment description (white question mark) and the dating (based on correlations to pollen zones) make the interpretation of that record uncertain. In both the Bothnian Sea and Bothnian Bay, sulfide banding is frequently recorded in both Early Littorina clays and in younger sediments (Jerbo, 1961; Fig. 6).

In parts of the Gulf of Finland, laminated sediments were deposited from the Early Littorina Sea-Littorina Sea s. str. transition at c. 8000 cal. yr BP until at least c. 5000 cal. yr BP (Åker et al., 1988; Fig. 6). In this area, sulfide bands are reported in sediments older than Littorina Sea s. str. age. Periods of laminated sediments have been recorded in the Archipelago Sea during the majority of the Littorina Sea s. str. stage (i.e. c. 7600–2800 cal. yr BP; Virtasalo et al. 2005, 2006; Fig. 6). It should be noted that some of the above mentioned sediment cores were recovered from areas situated in relative shallow and sheltered coastal areas (see Fig. 1).

5.3.2. Gotland Basin

We show six records from the Gotland Basin, which in most of the cases are a compilation of several sediment cores (see Table 1.). The majority of the sediment sequences display periods of alternating laminae and homogeneous sediment deposition. Laminae deposition started to form between 8500 and 7800 cal. yr BP. Records 2, 3, 5 and 6 show three periods of laminae formation and preservation during the last c. 8500 cal. yr BP (Fig. 6; Table 1). These periods are centered around c. 8000–7000, 6000–4000 and 2000–800 cal. yr BP. Records 1 and 4, display continuous laminae formation between 8300–5800 and

Table 1

Number, core label, water depth (m), lithological description, dating method, analyses preformed and references presented in Fig. 6

No	Core label	Water depth (m)	Lithological description	Dating	Analyses	References
Bothnian Bay (BB), Bothninan Sea (BS), Gulf of Finland (GF) and Archipelago Sea (AS)						
1	J5, J1, 19, 20, 22, 27	50–100				Jerbo, 1961; Jerbo and Hall, 1961 (BB, BS)
2	n/a	n/a	Graphical	Inferred from other source	X-ray diffraction	Ignatius et al., 1968 (BS)
3	AS6-VH1; AS6-VH2	66;64	Text, graphical	PM, ^{14}C	MS, LOI, X-ray, fossils	Virtasalo et al., 2005;2006 (AS)
4	Core C	40	Table, B/W Photo	^{14}C	Diatoms, LOI, pollen	Åker et al., 1988 (GF)
Gotland Basin						
1	GD0101	200	Table, graphical	^{14}C	Diatoms, pigments, vce	Borgendahl and Westman, 2007
2	G94-5; G95-3	206	Table, graphical	^{14}C, ^{210}Pb	Diatoms, TOC, d^{13}C	Andrén et al., 2000a
3	20048-1; 20048-4; 20007-1	240	Digital core scan, graphical	^{14}C	Diatoms, TOC, vce	Sohlenius et al., 2001; Emeis et al., 2003; Miltner et al., 2005
4	n/a	238	Table, graphical	^{14}C	Diatoms, TOC, vce	Sternbeck et al., 2000; Sternbeck and Sohlenius 1997; Sohlenius et al., 1996
5	211660-1; 211660-2	241	Table, graphical	^{14}C, ^{210}Pb	Diatoms, TOC, vce	Andrén et al., 2000a
6	211660-5; 211660-6	241–249	Graphical	PM, and correlation to 211660-1	Fossils, chlorophyll, TOC, vce, geo statistic	Harff et al., 2001; Dippner and Voss 2004; Kunzendorf and Larsen, 2002; Alvi and Winterhalter, 2001; Brenner, 2001a; Voss et al., 2001; Kotilainen et al., 2000; Nytoft and Larsen, 2001
Gdansk Deep						
1	96	101	Table	^{14}C, ^{210}Pb	Diatoms,vce	Witkowski, 1994
NW Baltic Proper (NWBP) and NC Baltic Proper (NCBP)						
1	9106	73	Graphical	^{14}C	Diatoms, TOC, vce	Westman and Sohlenius 1999 (NWBP)
2	9208	83	Graphical	^{14}C	Diatoms, pigments, TOC, vce	Bianchi et al., 2000; Westman and Sohlenius 1999 (NWBP)
3	9102	111	Graphical	^{14}C	Diatoms, TOC, vce	Westman and Sohlenius 1999 (NWBP)
4	211670-4; 211670-7	175	Graphical	No direct datings, PM, ^{14}C, both inferred from other cores	Fossils, vce	Brenner 2001b; Nytoft and Larsen 2001 (NCBP)
5	GC-4	175.8 m	Graphical	PM, ^{14}C	MS	Kotilainen et al., 2001 (NWBP)
Landsort Deep (LD) and W Gotland Basin (WGB)						
	9205	106	Graphical	^{14}C	Diatoms, pigments, TOC, vce	Bianchi et al., 2000; Westman and Sohlenius 1999 (LD)
2	Psh-2537	155	Table, graphical	^{14}C	Diatoms, pollen, Grain size, C. org, Vce	Elmelyanov et al., 2001 (WGB)
3	n/a	221	Text, graphical	^{14}C	TOC, vce	Lepland and Stevens 1998; Böttcher and Lepland, 2000 (LD)
4	9302	250	Graphical	^{14}C	Diatoms, pigments, TOC, vce	Bianchi et al., 2000; Westman and Sohlenius 1999 (LD)
5	14754-4	252	Text, graphical	^{14}C	Diatoms, pollen	Thulin et al., 1992 (LD)
6	n/a	459	Text, graphical	^{14}C	TOC, vce	Lepland and Stevens 1998 (LD)

PM = Palaeomagnetic dating; MS = Magnetic susceptibility; LOI = Loss on ignition; TOC = Total organic carbon; vce = various chemical elements.

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8500–4600 cal. yr BP, respectively (younger sediments deposited above the laminated sequences were not sampled). However, a substandard sediment description makes it difficult to determine whether the latter sediment sequences contain homogeneous sediments between 6000 and 7000 cal. yr BP or not (Fig. 6).

Four of the records (i.e. 2–5) display iron sulfide banding in sediments pre-dating Littorina Sea s. str. age.

5.3.3. NW and NC Baltic Proper

The five records from the NW and NC Baltic Proper show similar alternating periods of laminated and homogeneous sediment deposition as those in the Gotland Basin (Fig. 6). However, two of the records (i.e. 1 and 3) are missing data for the last c. 6000 and 4300 cal. yr BP, respectively, due to non-deposition or erosion of sediments. Laminations begin to form between 8400 and 8000 cal. yr BP. A short period of homogeneous sedimentation is evident between 8000 and 7000 cal. yr BP in record 1 and 3, while records 4 and 5 from the NC Baltic Proper display longer periods of homogeneous sedimentation during the early Littorina Sea s. str. i.e. between c. 8000 and 6000 cal. yr BP. In the three continuous sediment sequences homogeneous sediment deposition dominates after c. 5000 cal. yr BP until c. 2600 cal. yr BP (record 2) and c. 1400 cal. yr BP (records 4 and 5), where after a period of c. 500 year of laminated sediments are deposited. Record 4 also displays laminae formation during the last c. 100 years.

5.3.4. Landsort Deep and W Gotland Basin

Three sediment records (i.e. 1, 3 and 4) from the Landsort Deep are characterized by alternating laminated and homogeneous sedimentation as in the Gotland Basin and NW and NC Baltic Proper, while the remaining records (i.e. 2, 5 and 6) display only one long interval of laminae formation extending the majority of the sediment sequences analysed (Fig. 6). Laminations start to form in all complete records between 8400 and 7800 cal. yr BP. In records 1 and 3, laminations dominate the sediment structure from that period until c. 5000 cal. yr BP, while record 4 is very similar to 4 in the NC Baltic Proper and displays a dominant homogeneous sedimentation during the early Littorina Sea s. str. Homogeneous sedimentation dominates after c. 5000 cal. yr BP, where after a period of Late Littorina Sea laminae formation occurs between c. 2000 and 1600, 3300 and 1600, 1800 and 1000 cal. yr BP in records 1, 3 and 4, respectively. Record 2, from the West Gotland Basin (south of Landsort Deep) may imply that laminated sediments were deposited there persistently, at a depth of 155 m, between c. 7800 and 2000 cal. yr BP, but sediment descriptions are not sufficient enough to rule out the presence of non-laminated phases. Records from the deepest part of the Landsort Deep (no. 5 and 6) show continuous laminae deposition from 6800 and 5200 cal. yr BP to present, respectively, although these shorter cores do not have the complete Holocene record. In core 6 two Mn(II)-precipitate rich sapropel intervals 1390–1990 cal. yr BP are found indicating an expansion of bottom water anoxic conditions. One record from these areas report the occurrence of sulfide banded Early Littorina clay (i.e. 3).

5.3.5. Southern Baltic Sea

Investigations from the shallower southern Baltic suggest that the Bornholm and Arkona basins were frequently oxygenated during the Holocene and that sediments from that region were bioturbated, although geochemical records imply more reduced conditions after the Early Littorina–Littorina s. str transition (Sohlenius et al., 2001; Moros et al., 2002). Andrén et al. (2000b) reports frequent occurrence of *Macoma* shell throughout a sediment core from the deepest part of the Bornholm Basin since c. 6500 cal. yr BP. Frequent shell debris of *Macoma baltica* is also reported in a long sediment sequence from the Gdansk Deep at a water depth of 88 m (Witkowski, 1994). However, in the deeper Gdansk Deep, at a depth of 101.5 m Witkowski (1994) describes continuous laminated sediments between c. 9000 and 3300 cal. yr BP (Fig. 6). No long laminated sediment sequences have been reported from Mecklenburgian Bay or Gulf of Riga (e.g. Kowalewska, 2001; Rößler, 2006).

6. Discussion

In the very deepest areas of the Baltic Sea, below 250 m in the Landsort Deep, and in some coastal areas, hypoxia has been present more or less continuously during the last c. 8500–7800 cal. yr BP. At shallower water depths (above 250 m), but below the permanent halocline, there are 3 major periods of hypoxia: during the early Littorina Sea s. str. (c. 8000–4000 cal yr. BP), during the middle Late Littorina Sea (c. 2000–800 cal. yr BP) and during the last c. 100 years, although an intensification of hypoxia after 1950 has occurred. Three periods of homogeneous sedimentation is prominent in most of the records: between c. 7000–6000, c. 4000–2000 and c. AD 1200–1900. In the following sections we will discuss the spatial and temporal variability in hypoxia within the Baltic Sea and explore possible driving factor(s) for hypoxia especially focusing on the role of climate and anthropogenic pressures.

6.1. Hypoxia in time and space

6.1.1. Bothnian Bay, Bothnian Sea, Gulf of Finland and the Archipelago Sea

Short laminated sequences have been registered (between c. 500 and 600 yr in duration) in early Littorina s. str. sediments in the Bothnian Sea and Bothninan Bay by Jerbo (1961). High relative sea-level (c. 100–150 m above present) together with limited freshwater input (Gustafsson and Westman, 2002) lead to higher salinities, increased stratification (reduced mixing) enhancing the conditions needed for the occurrence of hypoxia and the deposition of laminated sediments in the northern basins during the early development of the Baltic Sea. The salinity gradually decreased throughout the Littorina Sea and the halocline in the northern Baltic diminished. To our knowledge, no laminated sediments from the open sea of younger age have been reported in this region except for those of modern historical age by Gripenberg (1934).

The Gulf of Finland has experienced periods of severe hypoxia in modern times (Laine et al., 2007). The geological records from Gulf of Finland and the Archipelago Sea demonstrate that these regions were affected by hypoxia during most part of the more saline Littorina Sea s. str (Åker et al., 1988; Virtasalo et al., 2005, 2006). However, well described long sediment records from these regions are sparse (Heinsalu et al., 2000) and those presented here are recovered from shallower coastal areas, which may reflect hypoxic conditions influenced by local environmental factors, such as topography and water currents, rather than regional signals of past hypoxia.

6.1.2. Baltic Proper

The Baltic Proper is the main basin affected by hypoxia during the Holocene. However, due to the large dating uncertainties, it is difficult to determine precisely if the separate periods with lamina formation in this area occurred synchronously (Fig. 6). Better chronological control is needed for sediment cores from the deeper basins, as most studies are based on ^{14}C dating on bulk sediment samples with the associated problem of contamination from old reworked carbon and unknown brackish/marine reservoir ages and their temporal variability. It can, however, be argued that the alternating periods of laminae and homogeneous sediment deposition in the Gotland Basin, NW and NC Baltic Proper and Landsort Deep coincide within the error estimates associated of the individual chronologies and that such deposition has occurred basin wide at depths varying between 73 and 250 m in the Baltic Proper during the last c. 8500–7800 cal. yr BP (Fig. 6).

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In order to generalize the discussion about the Baltic Proper and possible trigging mechanism for open sea hypoxia, we show data from only two sediment cores (211660-1 and 20048-1), covering the last c. 10 000 years, recovered from the Gotland Deep (e.g. Andrén et al., 2000a; Emeis et al., 2003). These two sediment cores (Fig. 7) are representative of conditions in the Gotland Deep at a water depth of c. 240 m (they show almost identical stratigraphy in comparison with at least 6 other cores; see Table 1) and were selected because they provide (i) well established chronologies, (ii) detailed sediment descriptions, and (iii) data from various analyses, which can be used in the analysis for the driving mechanisms for hypoxia. Terrestrial palaeoclimate data obtained from lake sediments in the Baltic Sea drainage area (see Fig. 1) were compiled for comparison to the hypoxia records (Fig. 7).

6.1.2.1. Littorina Sea s. str. (8500–4000 cal. yr BP). From c. 8500–7800 to c. 4000 cal. yr BP laminated sediments were formed in all the deeper basins (except for a shorter period between 7000 and 6000 cal. yr BP) in the Baltic Proper (i.e. Gotland Deep, Landsort Deep, NW and NC Baltic Proper, W Gotland Basin and Gdansk Deep; Fig. 6), which suggest that these areas were affected by hypoxia during most of the Littorina Sea s. str. At this time, the relative salinity in the Baltic Proper was high (10–15; Gustafsson and Westman, 2002; Emeis et al., 2003), most likely influenced by high sea-levels between c. 8000 and 6500 cal yr BP (Yu et al., 2007), as well as dry conditions (Snowball et al., 2004) minimizing the freshwater discharge to the basin, and the upper limit of the hypoxic zone was probably determined by a strong stratification. Laminae formation also corresponds to high TOC-values (6–8%; reflecting high organic accumulation) in the Baltic, and less negative δO^{18} values (reflecting dry conditions and low net precipitation), low lake-levels, high annual mean temperatures and low χ_{hf} values (indicating low precipitation in the form of snow and associated reduced catchment erosion rates during spring snowmelt; Fig. 7) in the terrestrial surroundings.

The time period between 9000 and 5000 cal. yr BP is known as the Holocene Thermal Maximum (HTM), which in Northwest Europe is

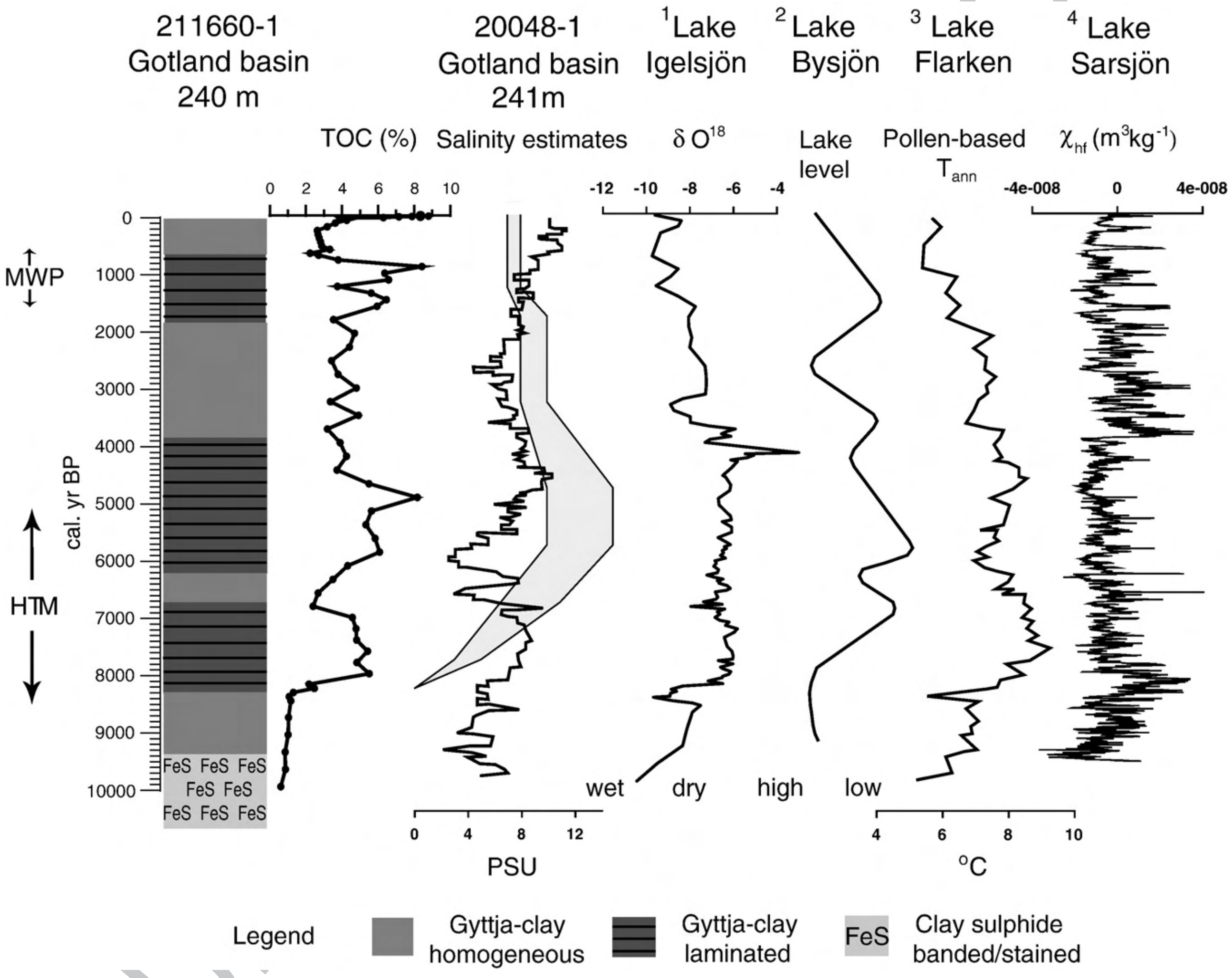

Fig. 7. Figure showing the occurrence of laminated sediments (Andrén et al., 2000a), total organic carbon content (TOC; Andrén et al., 2000a) and salinity estimates (Emeis et al., 2003) derived from $^{13}C/^{12}C$ ratio of organic carbon, plotted against a calendar year time scale, which is corrected following Andrén et al. (2000a) i.e. we have applied a marine reservoir effect of 100–300 yr in sediments older than 8000 cal. yr BP, a marine reservoir effect of 300 yr in sediments younger then 8000 cal. yr BP and due to the present of old resuspended carbon in the Baltic Sea an additional correction age of 400 yr is applied throughout the sequence. Also shown are modelled salinity estimates (shaded curve) after Gustafsson and Westman, (2002) based on a compilation of records. The chronology of the latter curve is based on ^{14}C dates of various materials, including macrofossil remains, and is adjusted for a marine reservoir effect of 300 years. The sediment records suggest that during the last c. 8500–7800 cal. yr BP hypoxia has occurred intermittently in sub-basins in the Gotland Deep. Note that periods of laminated sediments coincide with intervals of high TOC content and high salinity estimates. Marked are also the timing of the Holocene Thermal Maximum (HTM) and the Medieval Warm Period (MWP). Also, terrestrial palaeoclimate data obtained from Swedish lake sediments i.e. (1) oxygen isotopes reflecting effective humidity/net precipitation (Hammarlund et al., 2003), (2) regional reconstruction of lake-level fluctuations reflecting past hydrology changes (Digerfeldt, 1988), (3) pollen-based annual mean temperature reconstructions (Seppä et al., 2005), and (4) high-field magnetic susceptibility (χ_{hf}) which is a signal of catchment erosion (Snowball et al., 2002). The time-scales for Lake Igelsjön, Bysjön and Flarken sediment sequences are based on ^{14}C dating of terrestrial macrofossil remains while the chronology for Lake Sarsjön sediment sequence, which is annually laminated, is established by varve counting.

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characterized by relatively high summer insolation, high atmospheric temperatures and dry conditions (Snowball et al., 2004). The HTM caused the possible disappearance of glaciers in the Scandinavian mountains (Dahl and Nesje, 1994; Snowball and Sandgren, 1996; Nesje et al., 2001), high sea surface temperatures in the North Atlantic (Koç et al., 1993), a pine tree-limit c. 300–400 m higher than today (Kullman, 1999; Barnekow, 2000), lower lake-levels and decreased humidity in southern Sweden (Digerfeldt, 1988; Hammarlund et al., 2003) and increased summer atmospheric temperatures as recorded by pollen analyses (Seppä and Birks, 2001; Seppä et al., 2005) and chironomid reconstructions (Korhola et al., 2002).

The interval between 7000 and 6000 cal. yr BP is characterized by homogeneous sedimentation and corresponds to a decline in the salinity estimates (Emeis et al., 2003), lower TOC-values, increased effective humidity (more negative δO^{18}-values and rising lake-levels), enhanced catchment erosion (a peak in the χ_{hf} record) and a c. 0.5 °C drop in temperature (Fig. 7). This event has also been recorded in varved lake sediments in west central Sweden (Zillén, 2003), where it was interpreted as a response to colder climate conditions with increased winter snow accumulation. It also coincides with one of the major ice-rafting episodes in the North Atlantic (Bond et al., 1997) and glacier advances in northern Sweden (Karlén and Kuylenstierna, 1996).

6.1.2.2. Late Littorina Sea (4000 cal. yr BP–AD 1800). A period of homogeneous sediment accumulation is evident in most records between c. 4000 and 2000 cal. yr BP (Fig. 6), and corresponds to lower salinity estimates (c. 4–10; Gustafsson and Westman, 2002; Emeis et al., 2003) and lower TOC concentrations (c. 3–4%; Andrén et al., 2000a; Fig. 7). The terrestrial data-sets show a marked change around 4000–3700 cal. yr BP and coincide with the Late Holocene climate development in Northwestern Europe, which was characterized by decreasing temperatures and more moist conditions (e.g. Hammarlund et al., 2003; Snowball et al., 2004; Seppä et al., 2005; Fig. 7). In Scandinavia the start of this period (4000–3500 cal. yr BP) was marked by tree-line decline in the Scandinavian mountains (Barnekow, 2000) and glacier advances (Nesje and Kvamme, 1991; Snowball, 1996). During this period, bottom water in the Baltic Proper became oxic promoting the re-establishment of a benthic fauna and bioturbation of sediments.

From c. 2000 to 800 cal. yr BP laminated sediments were again deposited, basin wide, in the Baltic Proper (Fig. 7). The laminae deposition corresponds to maximum TOC concentrations (8.4%) around 900–800 cal. yr BP in the Gotland Basin, which was interpreted by Andrén et al. (2000a) as a result of high primary production.

The lake records show less negative δO^{18}-values, a lowering of lake-levels, increased temperatures and low χ_{hf} values between c. 1500 and 800 cal. yr BP (Fig. 7). The laminae deposition and the marine and terrestrial paleoclimate and palaeoenvironmental changes presented here, overlap with the timing of the climate anomaly known as the MWP (or Medieval Climate Optimum-MCO) when temperatures were probably c. 0.5–0.8 °C higher than today (e.g. Briffa et al., 1990). However, the salinity reconstructions by Gustafsson and Westman (2002) and by Emeis et al. (2003) are inconsistent during this time period and onwards. The estimates by Emeis et al. (2003) show a steady increase in salinity from about 3000 cal. yr BP, although higher salinities during this period are not supported by diatoms. The reconstruction of salinity by Gustafsson and Westman (2002), which are based on modeling of the physical process of saltwater input from an expanded opening of the Danish Straits and physical mixing of water masses, imply low and relatively stable values from c. 2000 cal. yr BP to the present and agrees better with the diatom records. In the absence of multiple high-resolution salinity reconstructions, it is therefore difficult to determine if the salinity increased during this time interval or not, even though the terrestrial palaeoclimate records suggest decreased freshwater discharges.

The period of hypoxia overlapping the MWP also correlates with population growth and large-scale changes in land use (see Fig. 8) that occurred in much of the Baltic Sea watershed. Watershed studies show large increases in nutrient loading with cutting of forests (Likens et al., 1970). Reconstructed phosphorus concentrations and associated eutrophication of lakes (Fig. 8) began during the Bronze and Iron Ages (1700 BC–AD 1050) with rapid increases in nutrient loading associated with major changes in agriculture during the Medieval period (Bradshaw et al., 2005). From high diatom-inferred total phosphorous values, Renberg et al. (2001) concluded that Lake Mälaren, Sweden, was culturally eutrophicated already from Medieval time and that even more nutrient-rich conditions developed after c. AD 1850. The early-medieval expansion was followed by a period of stagnation and population decline in the late 14th and early 15th centuries (Fig. 8) mainly due to the Black Death. In Sweden the population decreased from 1100000 to 347000 from AD 1300 to AD 1413 (Andersson Palm, 2001; Fig. 8). This decline is known as the late-medieval crisis and was characterized by decreased total production and abundance of farms (Lagerås, 2006). It affected most parts of Europe and had an impact on all levels of society (Lagerås, 2006).

During this period (after c. AD 1200), the bottom waters in the Baltic Sea became more oxic and homogeneous sediments were deposited until the beginning of the 19th century (Fig. 7). In Northwestern Europe, this period is characterized by a climate deterioration with the onset of the Little Ice Age (LIA) in the 14th century when glaciers advanced in the Scandinavian mountains and it was c. 1 °C cooler than today (Matthews and Briffa, 2005). This alteration is also visible in the Baltic Proper as a change in the diatom composition dated to c. 650–750 cal. yr BP (Andrén et al., 2000a).

6.1.2.3. Modern historical time period to present (AD 1800 to present). Laminae of historical age have been reported from the Baltic Proper with appearance of laminae around 200–100 years ago with a modern expansion from 1940 to the present (Jonsson et al., 1990). However, the age assumptions were based on counting individual laminae in short sediment cores. Applying that technique requires identification of an annual sedimentation cycle that explains the seasonally deposited laminae and their composition (Zillén et al., 2003); no such sedimentological model is presented in their paper and their age estimates should therefore be considered with caution. However, Hille (2005) showed that continuous laminae formation are present basin wide at depths >150 m in the Gotland Basin beginning 100 years ago based on ^{210}Pb dating. Interesting, Gripenberg (1934) reported laminated sediments and hydrogen sulfide formation of approximately the same age (i.e. 100 years) in the Bothninan Bay, Bothnian Sea, Gulf of Finland and N Baltic Proper. In addition, the historical sediment records imply that large areas of the Baltic Sea were hypoxic at least from AD 1900 (Jonsson et al., 1990) and that the deeper bottom waters of the Baltic Proper have been depleted of oxygen since then and up to the present time.

The start of the industrial revolution in Northwestern Europe around AD 1850 dramatically increased human impact in the Baltic Sea drainage area. The Swedish population grew about 0.8% per year from AD 1801–1900 (i.e. from 2.35 to 5.14 million people; Andersson Palm, 2001; Fig. 8) and the agricultural production increased with 0.5% per year and capita between AD 1750 and AD 1850 (Larsson and Olsson, 1992). Around AD 1850 digging of drainage ditches intensified in Fennoscandia (often recorded as a massive clay layer in individual lake sediments; Petterson, 1999; Ojala, 2001; Zillén et al., 2003) and the forest industry rapidly expanded. Between AD 1850 and1880 Swedish export of wood increased about 4 times (from 667000 to 2763000 m^3 per year; Larsson and Olsson, 1992). In Finland the same number increased 3 times between AD 1830 and 1870 (Schybergson, 1973). The forests were heavily exploited and numerous saw mills were built along the main rivers in Fennoscandia. For example, in Finland, the number of saw mills doubled between AD 1840 and 1870 (Schybergson, 1974).

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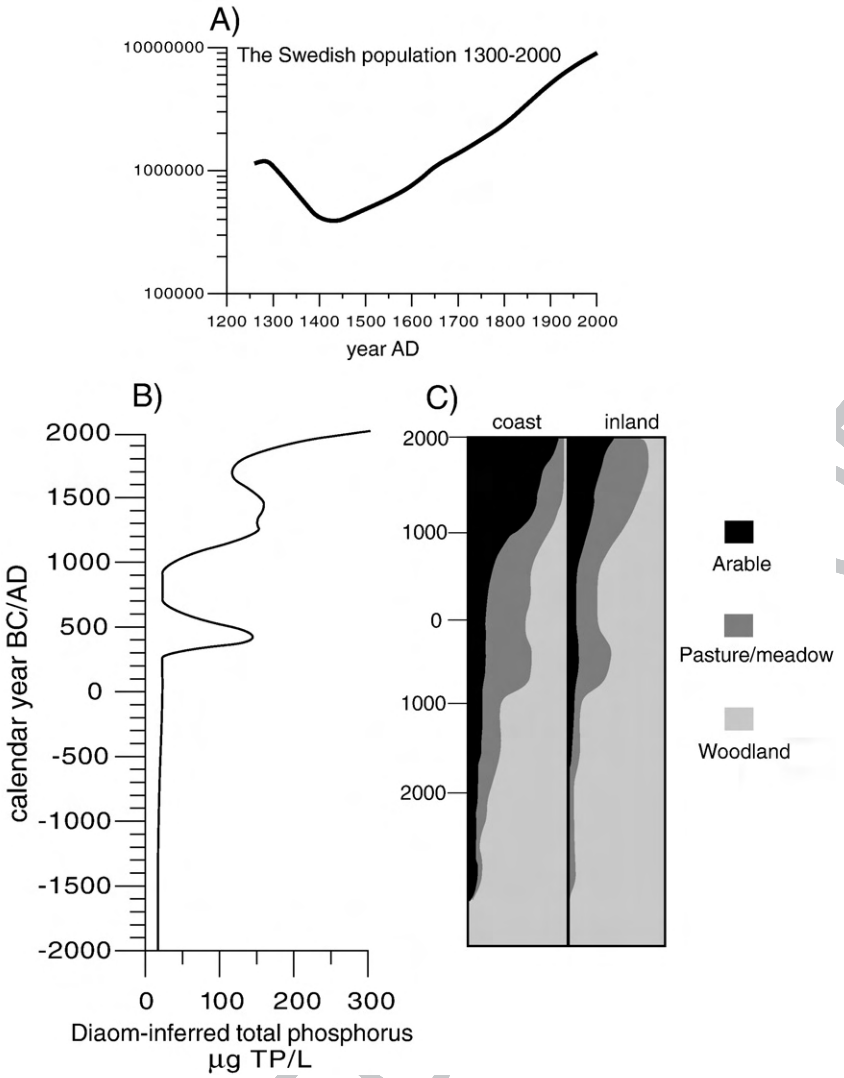

Fig. 8. (A) The Swedish population AD 1300–2000 as estimates by Andersson Palm, (2001). (B) The reconstructed P profiles on a calendar year time-scale BC/AD from Dallund Sø, Denmark after Bradshaw et al. (2005). (C) Vegetation/land use changes in Southern Sweden on a BC/AD time-scale illustrated as approximate proportions of three main land use categories based on pollen diagrams after Berglund et al. (1991). Coast refers to the coastal landscape and inland to the inner landscape.

Maps show that during the 19th century and the beginning of the 20th century, large areas in southern Sweden were sparsely vegetated. Grazing, cultivation and deforestation were very intensive. It is known from historical sources that the most treeless period in the area occurred during this period (Emanuelsson, 1993). As an example, at the end of the 18th century oak stands had been destroyed in many areas and oaks were therefore protected by a Royal Ordinance. Studies of Swedish lake sediments show that after the reorganization of the agrarian system during 19th century soil erosion and accumulation of allochtonous matter in the lake increased substantially and subsequent bottom water anoxia developed around AD 1900 (Olsson et al., 1997). Significant changes in diatom assemblages attributed to eutrophication dated to c. AD 1850–1900 have been observed in estuaries of the Baltic (Clarke et al., 2006) and in the southern Baltic Sea (Witkowski and Pempkowiak, 1995; Andrén et al., 1999).

6.2. Hypoxia and driving mechanisms

From the discussion in Section 6.1., it is clear that climate and anthropogenic pressures both have played a role as drivers of hypoxia through time in the Baltic Sea. Climate can be a short-term driver influencing hypoxia on the scale of years through variations in deep water inflows (Conley et al., 2002) and on longer time-scales with influencing freshwater inflow and the overall salt balance of the Baltic (Gustafasson and Westman, 2002).

The occurrence of hypoxia in the Baltic basin on geological time-scales (prior to more intense human impact) as reconstructed in this study, seems to be related to two primary forcings: increased salinity and increased productivity in a warmer climate. In contrast, homogeneous sedimentation corresponds to more oxic conditions and weakening of those two driving factors.

The salinity in the Baltic Sea varies due to changes in both saltwater inflow and freshwater input (Stigebrandt, 2001; Gustafsson and Westman, 2002), where the former is controlled by the depth of the salinity surface in the inlet areas (Stigebrandt, 2001) and the latter by net precipitation (precipitation-evaporation) in the drainage area. Unfortunately, there are no data of saltwater inflow variability, beyond the time of instrumental records, which makes the interpretation of such changes and their relation to hypoxia on long time-scales difficult. However, freshwater variability should be reflected in the terrestrial sediment proxies of effective humidity/net precipitation, lake-level and catchment erosion (Fig. 7). Due to the good coherence between the stratigraphy in the sediment records from the open Baltic Sea and the reconstructed hydrology changes in the catchment area (Fig. 7) it is our hypothesis that freshwater variability has been one of the factors, in addition to saltwater inflow from the Kattegatt/

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Skagerrak and sea-level changes, controlling the deep oxic conditions in the basin and that such changes have followed the general Holocene climate development in Northwest Europe. It is noteworthy, that the period of oxic bottom conditions between c. 7000 and 6000 cal. yr BP occurs during a phase of generally high salinity and high sea-levels (Gustafsson and Westman, 2002). The evidence of such a condition suggest that climate driven hydrological changes in the drainage area (Fig. 7) managed to turn a hypoxic system into a more oxic state for a period of c. 200–1000 years.

Run-off variability in the catchment area could be explained by oceanographic and atmospheric changes over the North Atlantic, where periods of strong westerlies across northern Europe in association with more positive North Atlantic Oscillation (NAO) index would increase the precipitation and wind stress over the Baltic Sea (Hurrell, 1995). Such conditions would cause a greater outflow and a smaller and fresher inflow due to lower surface salinity in the inlet areas (Stigebrandt, 2001) and subsequently leading to a freshening of the basin (Samuelsson, 1996). This freshening, in combination with increased wind stress (wind stress is one of the major physical parameters that controls the vertical mixing of the upper layers in the Baltic Sea; Stigebrandt, 2001), over the Baltic Sea would result in a weakened halocline and enhanced vertical mixing (Stigebrandt, 2001) allowing more efficient exchange of oxygen across the halocline (Conley et al., 2002). This scenario would promote more oxic bottom water conditions and the deposition of homogeneous sediments.

Changes in the Baltic Sea and the connection to climate and environmental variability have previously been explored by Emeis et al. (2003) who postulate that high salinity resulted in an increased density contrast and a stronger stratification of the water column, which promoted hypoxia in the bottom waters with the subsequent deposition of laminated sediments. The changes in salinity were hypothesized to be linked to climatic fluctuations over the North Atlantic, where high salinity phases coincided with warmer and drier periods of low river runoff and prominent atmospheric high-pressures over Scandinavia and northeastern Europe. Similar relationship between NAO indices and the salinity has been recognized in marine waters in fjords on the Swedish west-coast (Nordberg et al., 2000, 2001). Based on comparison between instrumental measurements and sediment records, the latter studies showed that there was a close connection between higher bottom-water salinity during negative NAO index and the deposition of laminated sediments.

Also, Zorita and Laine (2000) analyzed the relationship between annually average salinity and oxygen concentrations during the last 30 years in the Baltic Sea and changes in NAO indices. They show that on such time-scales the salinity and oxygen concentrations were negatively correlated within each layer, i.e. low salinity corresponded to higher than normal oxygen contents and vice versa. Stronger than normal westerly winds were related to lower than normal salinity in the upper and lower layers in almost all areas in the Baltic Sea together with higher than normal oxygen concentrations. They suggest that negative salinity anomalies may be caused by increased precipitation in the Baltic Sea catchment during positive NAO indices and that this process may be more important at longer time-scales than the inflow of saltier North Sea waters as suggested by Matthäus (2006). This is supported by Gustafsson and Westman (2002) who demonstrate that changes in net freshwater input from the catchment area explains the major part of salinity variability in the Baltic Sea during the last 8500 years and that periods with larger than normal freshwater run-off in the drainage area result in decreased salinities.

It is well established that recent anthropogenic enhanced eutrophication during the last c. 50 years has caused expansion of hypoxia in bottom waters of the Baltic Sea (Jonsson et al., 1990; Conley et al., 2002). However, it is our hypothesis that hypoxia occurring as early as the MWP are also associated with the first large-scale impact of man in the Baltic Sea watershed. Large land use changes, as those described in Sections 6.1.2.2. and 6.1.2.3., were probably common in most of the countries around the Baltic Sea. Such changes (i.e. agricultural development and population growth) would most likely have caused increased erosion and nutrient input to the Baltic Sea and promoted eutrophication and, in combination with the warmer climate, triggered hypoxia (TOC concentrations display maximum values during this time period).

The implication for this scenario would be that the historical records of laminated sediments in the Baltic Sea may not only be of natural origin, but also partly anthropogenic, and that the modern expansion of laminated sediments is a result of further human impact. Vahtera et al. (2007) have hypothesized that there are internal feedbacks within the Baltic Sea that act to sustain hypoxia. These include enhanced P release (Conley et al., 2002) and increases in denitrification potential with hypoxia (Vahtera et al., 2007), leading to an acceleration of eutrophication and fueling of ever larger cyanobacteria blooms. In addition, once the system becomes hypoxic it modifies the benthic communities, reducing the abundance of large animals. These benthic organisms both mix organic material downward and irrigate the sediments, and with hypoxia there is a subsequent loss of reducing equivalents that can oxidize organic matter (Karlson et al., 2005). Therefore, repeated hypoxic events can lead to an increase in the susceptibility to eutrophication increasing the vulnerability to further hypoxia perpetuating hypoxia. Once hypoxia occurs, reoccurrence is likely and may be difficult to reverse demonstrating the sensitivity of the Baltic Sea to anthropogenic alterations. We hypothesize that minor increases of nutrients from forest clearance and agricultural development, together with climate warming during e.g. the MWP created hypoxic conditions. Once the Baltic Sea has switched into a hypoxic mode it is difficult to reoxidize because of internal feedbacks in the system.

An important question is what factors are responsible for terminating hypoxic conditions in the Baltic Sea? Why did hypoxia end after nearly 4000 years of near continuous hypoxia (c. 8000–4000 cal. yr BP) during the Holocene Thermal Maximum? Was the cooling that followed the HTM together with decreasing salinity enough to end hypoxia? Why did the Baltic become oxic 200–1000 years during that time period? The Little Ice Age with really cold winters, less nutrients coming in from less agriculture (in addition to the plague reducing population and impact; Fig. 8), is believed to be the reason for hypoxia ending. The Baltic was oxic again until c. 100 years ago when man's influence was large enough again during the industrial revolution and development of the forest industry, in combination with a warmer climate, to cause widespread hypoxia. Will proposed reductions in nutrient inputs (Johansson et al., 2007) be sufficient to switch the Baltic back to an oxic situation in the face of a substantial global warming?

In summary, environmental changes in the Baltic Sea catchment, either triggered by climate change or human impact, may have been of more significance for the development of hypoxia in the past than previously thought. Land–sea interactions are thus not just modern phenomenon but have been important on long time-scales. More research is needed to determine the relative importance of the main driving forces, i.e. climate change, human impact, and internal feedback mechanisms. In the light of global warming and increased anthropogenic pressures in the Baltic Sea region, it is essential to include these issues into the discussion of the present state and the future of the Baltic Sea.

7. Conclusions

During the early and more saline development of the Littorina Sea s. str. (c. 8000–6000 cal. yr BP), laminated sediments were deposited in the northern Baltic Sea (Bothnian Sea and Bothnian Bay) where hypoxic bottom conditions prevailed.

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Laminae deposition has occurred basin wide, at depths varying between 73 and 250 m during three major periods in the Baltic Proper the last c. 8500–7800 years: i.e. between c. 8000–4000, 2000–800 cal. yr BP and subsequent to AD 1800. These periods overlap the HTM (c. 9000–5000 cal. yr BP), the MWP (c. AD 750–1200) and the modern historical period (AD 1800 to present). Laminae formation coincides with increases in salinity (at least during the HTM) and organic carbon accumulation. Hypoxia appears to have been more or less continuous at greater water depths (>250 m).

Oxic bottom conditions were common in the Baltic Proper between c. 7000–6000, c. 4000–2000 and c. 800–200 cal. yr BP and correspond to estimates of low salinity, low organic carbon accumulation and to Holocene climate development in Northwestern Europe characterized by decreasing temperatures and more moist conditions.

The southern Baltic Sea (e.g. the Bornholm Basin and Arkona Basin) was frequently oxygenated during the Holocene, except for the deepest part in Gdansk Deep.

Large hydrological changes in the Baltic Sea catchment as a response to climate changes, have most probably affected the environmental conditions in the basin. Long-term freshwater discharge variability may have been an important factor controlling the stratification of the water column and the deposition of laminated sediments in the Baltic Sea during the last c. 8000 cal. yr BP.

Laminated sediments spanning the MWP correlate with population growth and large-scale changes in land use that occurred in the Baltic Sea watershed during the early-medieval expansion. This implies that the change from homogeneous to laminated sediment deposition in the Baltic Sea was probably caused by a combination of climate changes and human impact.

Large areas of the Baltic Sea (i.e. the Bothnian Sea, Bothnian Bay, Gulf of Finland and Baltic Proper) were hypoxic around AD 1900, which coincides with the beginning of the industrial revolution at AD1850 in Northwestern Europe when population grew, agricultural production increased, cutting of drainage ditches intensified and forest industry expanded explosively, as well as with the beginning of the on-going global warming. The deep waters of the Baltic Proper have been depleted of oxygen since then and up to present time.

Once widespread areas of the Baltic Sea become hypoxic there are processes, such as enhanced P flux and reduced denitrification, which act to sustain and continue hypoxic conditions. This demonstrates the sensitively of this large enclosed sea to anthropogenic perturbations.

Acknowledgments

This work was partially supported by a grant from Baltic Sea 2020 and by a Marie Curie Chair to DJC (MEXC-CT-2006-042718). We thank Bo Gustafsson and Maren Voss for comments on earlier versions of the manuscript. We also acknowledge the valuable reviews from Erik Bonsdorff and Anders Stigebrandt.

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Please cite this article as: Zillén, L., et al., Past occurrences of hypoxia in the Baltic Sea and the role of climate variability, environmental change and human impact, Earth-Science Reviews (2008), doi:10.1016/j.earscirev.2008.10.001

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Please cite this article as: Zillén, L., et al., Past occurrences of hypoxia in the Baltic Sea and the role of climate variability, environmental change and human impact, Earth-Science Reviews (2008), doi:10.1016/j.earscirev.2008.10.001

Appendix 7

Critical Review
Hypoxia-related processes in the Baltic Sea

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Brief for Table of Contents:
The current knowledge regarding hypoxia in the Baltic Sea is reviewed and the knowledge gaps regarding the development and effects of hypoxia are identified.

Abstract

Hypoxia, a growing world-wide problem has been intermittently present in the Baltic Sea since its formation ca. 8000 cal. yr BP. However, both the spatial extent and intensity has increased with anthropogenic eutrophication due to nutrient inputs. Physical processes, which control stratification and the renewal of oxygen in bottom waters, are important constraints on the formation and maintenance of hypoxia. Climate controlled inflows of saline water from the North Sea through the Danish Straits is a critical controlling factor governing the spatial extent and duration of hypoxia. Hypoxia regulates the biogeochemical cycles of both phosphorus (P) and nitrogen (N) in the water column and sediments. Significant amounts of P are currently released from sediments, an order of magnitude larger than anthropogenic inputs. N transforming processes are regulated by oxygen concentrations and the Baltic Sea is unique for a coastal marine ecosystems experiencing N losses occurring in hypoxic waters below the halocline. Although benthic communities are naturally constrained by salinity gradients, hypoxia has resulted in habitat loss over vast areas followed by the elimination of benthic fauna and has severely disrupted benthic food webs. Nutrient load reductions are needed to reduce the extent, severity and effects of hypoxia.

Introduction

Hypoxia, the lack of oxygen in bottom waters often defined as $O_2 < 2$ ml l^{-1} is a growing problem worldwide and dead zones have spread exponentially since the 1960s in coastal marine waters (*1*). Hypoxia not only kills the bottom-living organisms (*2*), thereby destroying benthic communities and fish habitat (*3*), but also alters the biogeochemical cycles of nutrients (*4, 5*). Oxygen concentrations decrease when oxygen supply does not meet the demand, so that an imbalance occurs between the physical processes that supply oxygen and the biological processes that consume it. Consequently, the bottom water eventually becomes hypoxic.

Hypoxia first occurred in the Baltic Sea after its transition from fresh water to brackish water ca. 8,000 cal. yr BP and has been present intermittently throughout the Holocene (*6*). Low water column dissolved oxygen concentrations have been observed locally since ca. 1900 (*7*) with increases observed in laminated sediments since the 1950s (*8*). The supply of oxygen is dominated by water exchange and vertical mixing processes, which are both closely coupled to climate, large-scale atmospheric circulation and oceanographic conditions. The Baltic Proper is permanently stratified, consisting of an upper layer of brackish water with salinities around 7-8 and a lower layer of saline waters with salinities around 11-13. A strong permanent halocline is formed at the transition zone at depths varying between ca. 60-80 m. The halocline prevents vertical mixing of the water column, and consequently, transport of more oxygenated waters down to the bottom all year around.

The occurrence of hypoxia in the Baltic Sea is receiving increased attention and exploratory projects are in progress for remediation options to alleviate eutrophication (*9*). Although there have been significant advances over the last decades in our understanding of the causes, effects and remedies needed to alleviate the detrimental effects of eutrophication and hypoxia in the Baltic Sea (*10*), the relative importance of individual processes of transport and consumption are incompletely understood. Before any remediation effort is implemented it is important that we have a better quantitative understanding of the causes, consequences and risks (*11*). Here, we assemble the current knowledge regarding hypoxia in the Baltic Sea and identify some of the important gaps in our knowledge regarding the development of hypoxia and therefore its mitigation.

Occurrence of hypoxia during the Holocene

The fact that hypoxia was present in the Baltic during different periods of the Holocene (*12*) has lead to a discussion regarding the role of climate and eutrophication in its present day formation (*10*). Zillen et al. (*6*) compiled the available data on the occurrence of hypoxia using the presence of laminated sediments. One of the environmental prerequisites for the formation and preservation of laminated sediments is the absence of benthic fauna that bioturbate, or vertically mix, the uppermost sediments. Hypoxic conditions prevent the establishment of benthic fauna resulting in laminated sediments in deeper areas below the halocline. While hypoxic conditions may exist at the sediment-water interface, due to steep gradients through the benthic boundary layer, oxygen can still be present in the water column.

Hypoxia during the Holocene was strongly influenced by the postglacial history characterized by a complex interaction between changing sea levels, irregular land-uplift and variable climate. Traditionally, the development of the Baltic Sea is separated into four stages, i.e., the Baltic Ice Lake, Yoldia Sea, Ancylus Lake and the Littorina Sea. These changes represent intervals of brackish and freshwater conditions due to changes in water exchange with the North Atlantic/Kattegat (*13*). A circulation that supported a fully brackish system began around ca. 8000 cal. yr BP at the start of the Littorina Sea stage when the Öresund Strait began to function as an important inlet of saltwater and initiated the establishment of a permanent halocline in the Baltic Sea (*12*). However, due to the lack of a robust geochronology, the timing of the first brackish/marine Littorina conditions is much debated (*13*) and it is hypothesized that a transitional phase existed with episodic marine influxes. Regardless of age differences, there is a general agreement that a permanent halocline was formed during the Littorina Sea transition.

Laminae formation occurred basin-wide at depths between 73-250 m during three major periods in the Baltic Proper between ca. 8000-4000, 2000-800 cal. yr BP and after AD 1900 (*6*), although the deepest areas of the Landsort Deep (>250 m) were probably continuously hypoxic during most of the Holocene (*14*). Laminae between 8000-4000 cal. yr BP coincide with increases in salinity and presumably with stratification restricting the ventilation of bottom waters (Figure 1). The shallower southern Baltic including the Bornholm and Arkona basins were frequently oxygenated during the Holocene with bioturbated sediments throughout, although geochemical records imply more reduced conditions after the Littorina Sea transition (*12*). Hypoxia was reported in the Gulf of Bothnia early in the history of the Baltic Sea (*15*), however the decrease in the depth of sills with land uplift and weakening of salinity stratification has limited the formation of hypoxia during recent times. Improved spatial coverage of sediment records across depth gradients in depositional basins are required to improve our understanding of the historic spatial distribution of hypoxia.

Hypoxia again appeared in the Baltic Sea ca. 2000-800 cal. yr BP associated with the Medieval Warm Period (MWP) and the entire Eastern Gotland Basin in the Baltic Proper has accumulated laminated sediments since ca. AD 1900 (*16*). The area that is hypoxic has increased more than ten-fold during the last century (*17*). Large-scale changes in land use with development and expansion of agriculture were responsible for increases in nutrient concentrations in lakes during the MWP (*18*, *19*). In addition, population increases during the industrial revolution, development of the water closet, tiling of fields for enhanced drainage, cutting of drainage ditches, and expansion of the forest industry in the watershed at the turn of the last century, and more recently the large-scale increases in nutrient inputs with agriculture, have been important drivers for the formation of hypoxia (*6*). During the last century nutrient loads have increased by ca. 2.5 for nitrogen and 3.7 times for phosphorus (*17*). Unraveling the importance of climate change on hypoxia relative to anthropogenic forcing with nutrients would be an important scientific step forward.

The occurrence of hypoxia in time and space in the coastal zone is less well known than our knowledge in the open waters of the Baltic (*6*), although increases in laminated sediments over the last 50 years has been observed in the Stockholm Archipelago (*20*). Knowledge regarding whether the timing of the occurrence of hypoxia in the coastal zone is similar to open waters and information on the spatial extent of hypoxia in the coastal zone are scarce. Sediment records in the depositional bottoms of the coastal zone may record land-use changes and the increases in nutrient inputs better than the low sedimentation rate in open sea sediments, although studies to test this hypothesis do not exist.

Water quality records of recent hypoxia

Water column measurements of dissolved oxygen concentrations began at the turn of the last century (ca. 1900) with more regularly spaced measurements commencing in the 1960s (*21*). Assessments of oxygen trends were dominated by linear regression analysis to determine the rate of the long-term declines in oxygen. More recently, the volume and bottom area affected by hypoxia has been the metrics used to examine long-term variations. The quality of these metrics is dependent on the number and spatial coverage of observations that has improved since the 1960s. Extensive anoxia in the Baltic Sea is reported as “negative oxygen”, which is computed from the amount of oxygen equal to the amount of hydrogen sulfide (*7*).

The area of bottom covered by hypoxic water in the autumn and at the maximum seasonal extent averaged ca. 49,000 km^2 over the time period 1961-2000 (Figure 2). The smallest hypoxic area of 12,000 km^2 occurred in 1993 during the peak of the “stagnation period” when saltwater inflows were at their minimum and the peak hypoxic area occurred in 1971 with 70,000 km^2 (Figure 2) following large saltwater inflows in preceding years (*22*). While major saltwater inflows are well known to displace and renew the deep water oxygen supplies (*23*), less well appreciated is the fact that they also strengthen stratification and inhibit subsequent ventilation and thereby increase the areas where oxygen can become depleted (*22*, *24*). In modern times most of the deep basins are continuously hypoxic including the Gotland Deep, Landsort Deep, northwest Baltic Proper, and Gdansk Deep (Figure 3). During years with large areas of hypoxia, low oxygen zones migrate higher up into the water column, and the individual basins become connected to form one large hypoxic area.

The deep water in the Gulf of Finland originates near the halocline in the Baltic Proper. Thus, a strong and shallow halocline in the Baltic proper induces a stronger stratification in the Gulf of Finland. Because the volume of water under the halocline in the Gulf of Finland is small and productivity is high, oxygen is rapidly depleted below the halocline (*25*). The opposite applies when a weak and deep halocline in the Baltic Proper induces weak stratification and the extent of hypoxia is reduced. Observed trends in hypoxia in modern times in the Gulf of Finland demonstrate that hypoxia is related to variations in large salt water inflows to the Baltic, with less stratification and less hypoxia occurring during “stagnation periods” when major saltwater inflows are reduced.

Much anecdotal and qualitative evidence exists about hypoxia in various reaches of the Baltic Sea. A more rigorous quantification that would summarize such information in annual values for specific areas would facilitate the comparison in space and time of the spread of hypoxia and would make it possible to statistically evaluate its controlling variables. Metrics that could be applied are those previously developed for lakes and reservoirs, such as the anoxic and hypoxic factors (*30*).

Physical constraints

Physical processes, which control stratification and the renewal of oxygen in bottom waters, are important constraints on the formation and maintenance of hypoxia. In the enclosed basin of the Baltic Sea oxygen supply is dominated by intermittently occurring water renewal and through vertical turbulent mixing (*27*). The flux of oxygen mediated is dependent on the vertical gradients of oxygen and density, and the mechanical energy supply for mixing. The oxygen supply by vertical mixing tends to increase with time after renewal of bottom waters with saltwater inflow as both density and oxygen concentrations decrease. More importantly, the probability for ventilation by advective water renewal increases as density decreases (*28*). Thus, there is a coupling between deep water mixing intensity and renewal frequency (*29*), where increased mixing due to stronger winds or weakened stratification promote more frequent lateral exchanges and is particularly evident for the upper deep waters (80-125 m).

The inflows of saline water across the sills in the Danish Straits are in part forced by regional winds and are, therefore, quite variable (*23*). However, the inflowing saline water is buffered in the Arkona Basin from which there is a near continuous flow of saline water into the deep waters of the Baltic Proper (*29*, *30*). On average the flow from the Arkona Basin into the Baltic has a salinity of about 14 ranging between 12 and 16 (*29*). Assuming that the salinity of the water mixed with the inflowing water is a salinity of 7.5 we find that ventilation of Baltic Proper deep water predominantly occurs at salinities between 9 to 10.5, corresponding approximately to a density of 7.2 – 8.4 kg m^{-3}. Variations are expected from this order of magnitude estimate, but its general validity is evident in Figure 4. The upper bound of hypoxia coincides reasonably well with the 8 kg m^{-3} isopycnal suggesting good ventilation down to this depth. In periods with a larger than normal freshwater supply, the salinity decreases first in the inflowing water and later in the Baltic, which causes some deviations between the depths of the hypoxia isopleth and the 8 kg m^{-3} isopycnal. Thus, the upper limit of hypoxia is primarily determined by the stratification in the Baltic Proper. If the stratification is weak the dominating denser water inflows will reach relatively deep keeping the upper deep water well ventilated and oxic, as occurred in the early 1990s (Figure 4). However, if stratification is strong the inflows are generally not dense enough to penetrate through the halocline and hypoxia reaches it maximum extent, for example, as seen after 2000.

Strong stratification follows from a series of deep reaching high salinity water inflows, after which weak stratification follows. Paradoxically, the lack of complete deep water renewal will eventually lead to better oxygen conditions higher in the water column (*22, 24*). It is important to recognize that the volume and area of the deep basins below 150 m depth is comparably small. Deepening of the vertical extension of hypoxia from 150 m to 125 m approximately triples the hypoxic water volume. If the hypoxic water mass extends up to 70 m, as happened during the mid-2000s, the hypoxic volume increases thirteen times and hypoxic bottom area increases ten times. Variations between strong and weak stratification occur due to time-scale of the vertical mixing that reduces density and creates variations in the salinity and the magnitude of the inflows. Strong stratification was present not only in the 2000s, but also in the 1960s, and a weak stratification period occurred in the late 1920s to early 1930s (Figure 3).

Although the physical constraints of hypoxia are in principle known, there are many still open questions, related to the ventilation of the halocline and of the deep water (*28*). The dynamics of saltwater plumes (pathways, mixing, and the climatologically of mean saltwater flows) after small and medium-strength inflows are not well understood because such events are difficult to observe. In addition to large-scale gravity-driven dense bottom flows that renew the deepest layers in the Baltic proper, meso-scale cyclonic eddies seem to contribute significantly to the ventilation of the halocline. These eddies are eroded laterally by intrusions. As with other mixing processes the driving mechanisms of that erosion is not well understood.

Autotrophic carbon production and settling dynamics

The amount of carbon delivered to the bottom waters of the Baltic Sea is another important control mechanism of oxygen consumption. The main periods of new primary production are the spring bloom and late summer bloom. The former consists of cold-water diatoms and dinoflagellates and the latter of nitrogen-fixing cyanobacteria (*31*). As nutrient inputs and concentrations changed, the relationship between nitrogen and phosphorus has changed accordingly. The phytoplankton spring bloom is considered to be nitrogen limited (*32*), however, previously phosphorus was also exhausted to very low levels during spring. Some of the first observations on excess phosphorus remaining after the spring bloom were made in the mid-1980’s (*33*), and has been a recurring phenomenon. The growth of diazotrophic cyanobacteria is considered to be phosphorus limited, and a considerable share of their phosphorus requirement arrives from the phosphorus remaining after the spring bloom (*34*).

The problem in estimating the effect of changing phytoplankton succession on benthic oxygen dynamics through settling of organic material arises from our limited knowledge of the factors affecting settling. Settling of organic matter in the Gulf of Finland during the spring bloom varied considerably between 65 and 31% of annual production in 1988 and 1992, respectively (*35*). The variability may be caused by differences in phytoplankton composition, specifically the proportion of dissolved silicate limited cyst-forming diatoms (*36*) or the ratio of dinoflagellates to diatoms (*35*). Knowledge of the phytoplankton community composition of the spring bloom is remains limited.

The settling of organic carbon during summer and autumn is also variable. The highest settling rates observed in late summer in the Gotland Deep were due to a large percentage of the annual proportion of nitrogen fixed by cyanobacteria (up to 50% of total settled nitrogen) reaching the bottom (*37*). High settling rates have also been observed in late summer from the Gulf of Finland with 65% of net primary productivity settling through the water column (*35*). The proportion of settling organic material from new production, the characteristics of the phytoplankton composition in the water column versus what settles, and the effects of nutrients on sedimentation are important avenues for further research. Lastly, the importance of other sources of organic matter input remains unquantified. For example, chemoautotrophic production in deep waters fueled by reduced sulfur bacteria can support an active microbial food web in anoxic bottom waters (*38*). This possibility for deep-water heterotrophic carbon fixation needs to be evaluated for the Baltic Sea. In addition, increases in dissolved organic matter inputs (*39*), the so-called brownification of waters, and their impact on carbon inputs are unknown.

Biogeochemical effects of hypoxia on P

Phosphorus (P) availability for primary producers is determined by variations in terrestrial and marine P inputs, the recycling efficiency within the system and the sinks via outflow to the North Sea and permanent burial in the sediments. Bottom water hypoxia typically leads to enhanced regeneration of P from aquatic sediments (*4, 40*) and thus an enhanced recycling of P in the system.

The biogeochemical cycling of P in the Baltic Sea has been quantified on many spatial scales. For example, Conley et al. (*22*) showed that inter-annual changes in dissolved inorganic phosphate (DIP) pools in the Baltic proper were positively correlated to changes in sediment area covered by hypoxic water. The changes in DIP, which ranged up to 112 x 10^3 tonnes P y^{-1}, were attributed to release of P bound to Fe-oxyhydroxides upon the transition from oxic to hypoxic conditions with P returning to the sediments during oxic conditions. Little is known, however, concerning the role of sediments as a permanent sink for P in the Baltic Sea, the processes that control this burial and their modulation due to hypoxia. In a recent budget calculation for 1991-1999, Savchuk (*41*) estimated the net sediment P burial to be ca. 20 x 10^3 tonnes P y^{-1}, with all the basins, except the Baltic Proper and the Gulf of Riga, retaining more P than they received from external sources. This rate of P burial is comparable in magnitude to the net outflow through the Danish Straits, which is estimated at ca. 17 x 10^3 ton P y^{-1}. Thus, changes in net burial of P with hypoxia could significantly alter the P availability in the water column on decadal time scales.

Based on studies in other brackish and marine basins, permanent burial P is expected to occur largely in the form of organic P and calcium-phosphate (Ca-P) minerals. The Ca-P minerals can form *in situ* (“authigenic Ca-P”) dispersed in the sediment (*42*), but may also consist of the remains of fish hard parts (“biogenic Ca-P”). The burial of both Ca-P forms and organic P is affected by bottom water redox conditions, with increased hypoxia typically leading to decreased formation of authigenic Ca-P, decreased burial of organic P and increased preservation of biogenic Ca-P (*40*). The redox control of authigenic Ca-P formation is linked to macrofaunal activity, because sediment mixing typically drives the build-up of sufficiently high pore water phosphate levels to allow authigenic P formation (*43*). The mechanisms responsible for redox-dependent biogenic Ca-P and organic P burial remain incompletely understood.

Both organic P and Ca-P are important components of surface sediments (0-2 cm) in the Baltic proper (*44*) and were important sediment sinks for P in the Bornholm Basin prior to ca. 2,400 cal. yr BP (*45*). Fe-oxide bound P is abundant in the surface sediment at sites overlain by oxic bottom waters. Because organic P and authigenic Ca-P are probably the major current sinks for P, increased expansion of the hypoxic area in the Baltic may significantly reduce the current P burial sink and enhance the pool of easily mobilized P.

Biogeochemical effects of hypoxia on N

Nitrogen (N) transforming processes are regulated by oxygen concentration. As nitrogen removal (denitrification and anammox) is dependent on NO_2^- and NO_3^- produced in oxic conditions by nitrification, this process is of key importance in enabling nitrogen removal from the basins. No data exist on nitrification in the sediments of the Baltic Sea, but denitrification in depositional sediments has been calculated to remove about 23 % and 31 % of the annual nitrogen input to the Bothnian Bay and Bothnian Sea, respectively (*46*), and about 30% of the annual load in the Gulf of Finland (*47*). During seasonal hypoxia, coupled nitrification-denitrification rates can be restored to their previous levels when oxygen returns (*48*). By contrast, denitrification rates in highly reducing sediments remain low for long periods following reoxygenation (*49*).

Mass-balance calculations show that 751 kt of N is removed annually from the Baltic Proper by the combined action of N_2 production and sediment burial (*41*), and isotopic data suggest that 855 kt of N is denitrified in just the southern Baltic Sea (*50*). Direct rate measurements in relatively coarse grain size sediments are needed to verify the mass-balance estimates. Results from other studies suggest that these sediments can be extremely active through intense wave-induced ventilation (*51*). Anammox, which also removes nitrogen, has been found in the sediments of the Gulf of Finland, where it contributed ca. 10-15% to the total N_2 production (*48*). It has been suggested that a considerable amount of nitrogen in the Baltic Sea enters neither the denitrification nor anammox pathway, but rather by dissimilatory nitrate reduction to ammonium (DNRA) (*49*). Unlike denitrification and anammox, DNRA does not remove N from the ecosystem, but stores it as elevated ammonium concentrations in hypoxic waters.

A significant negative correlation has been found between the amount of dissolved inorganic nitrogen (DIN = nitrite, nitrate, ammonium) and the volume of hypoxic water in the Baltic Proper, the Gulf of Finland and the Gulf of Riga (*31*), suggesting enhanced nitrogen removal during expanded hypoxia. This result challenges the conventional belief that the efficiency of denitrification is reduced when oxygen concentrations are low (*5*). In addition, there is a recent observation that massive amounts of denitrification occurs in the water column of hypoxic zones in the open ocean (*52*). Nitrification in the water column has so far only been studied at three deep stations in the Baltic Proper (*53*). Nitrification was found to be highest at or below halocline, indicating combined control by oxygen and ammonium availability. Since the volume of the water layer in which nitrification is possible, therefore, fluctuates along these two variables, it justifies quantification. At the highest observed nitrification rates about the same amount of ammonium is oxidized in one m^3 of water as in one m^2 of oxic seafloor. The produced NO_2^- and NO_3^- are probably quickly consumed in denitrification and anammox in the hypoxic and anoxic water layers below.

Water column denitrification occurs at the interface between anoxic, stagnant deep water and overlying oxic water in the central Baltic Proper (*54*), however, denitrification was measured using the acetylene blockage method, which is now known to have serious flaws. A recent study using state-of-the-art stable isotope techniques failed to detect any denitrification potential in the Gotland Deep suboxic (< 10 µM O_2), sulfide-free water (*55*). The potential for N_2 production was found in the sulfide-containing deeper layer, making it very likely a chemolithotrophic rather than heterotrophic process (*55*). In the same study the potential for anammox, as well as the presence of bacteria capable of anammox, were observed in the water column of the Baltic Sea. Which process prevails seems to depend on the dynamic between nutrient and O_2 concentrations at and below the redoxcline that constitutes an efficient wall for vertical diffusive exchange of DIN. Below the redoxcline there is an upward flux of ammonium and above there is a downward flux of nitrate and the sum of these fluxes is the formation of N_2 through denitrification and anammox. Advective processes, such as deep-water renewal, complicates this simple picture, but we presume that a large part of the nitrogen remineralized below the redoxcline is lost to N_2 formation at the redoxcline. This implies that all DIN available to production needs to be remineralized above the redoxcline (or externally supplied) and that a redoxcline high in the water column implies low DIN concentrations. Unfortunately, the scarce data does not allow extrapolation to larger water masses, but it clearly shows a plausible mechanism for generating the observed dependency between hypoxic water volume and enhanced nitrogen removal.

Denitrification and anammox form major sinks for N (*41, 50, 56*) and these losses occur both in the sediments and the water column. However, the relative importance of fluctuating hypoxia and corresponding changes in denitrification and anammox, and the key process of nitrification remain open. Multiple site-specific measurements are lacking, which hampers both the empirical quantification of N removal processes spatially and temporally, and the development and validation of biogeochemical models.

Biological effects of hypoxia in the Baltic Sea

Benthic communities in the Baltic Sea are naturally constrained by strong salinity gradients that limit their distribution and diversity. In addition, benthic communities have been subjected to increasing anthropogenic nutrient inputs, which has transformed the Baltic Sea from an oligotrophic, clearwater sea into a eutrophic water body (*57*). Perhaps the strongest factor influencing the biodiversity of benthic communities is the increased prevalence of oxygen-depleted bottom water, which has resulted in habitat loss followed by the elimination of benthic macrofauna over vast areas and severely disrupted benthic food webs (*58*).

The formation of near-bottom hypoxia results in increasingly impoverished communities with macrobenthic responses often resembling the broad-scale successional pathways described in models of benthic disturbance and recovery (*59*). In the Baltic Sea the separation between normoxic and moderately hypoxic water masses and hypoxic or anoxic waters creates a temporal and spatial mosaic of hypoxic stress to benthic fauna (*60*). Macrobenthic communities often are never fully develop due to continued stress from low oxygen concentrations and are characterized by small shallow-dwelling species due to transient hypoxia. Macrobenthic communities in deeper waters are severely degraded and below a 40-year average for the entire Baltic Sea (*61*). Hypoxia often eliminates large deep-burrowing, actively bioturbating species because their long generation times preclude development of viable populations (*62*). Moreover, even when species are not entirely lost, they may become functionally extinct due to their low abundances and subsequent recovery may never reach fully mature successional stages.

Healthy benthic communities provide important ecosystem services, including food for higher trophic levels and they facilitate the mineralization of settling organic matter. These functions are compromised when hypoxia results in reduced abundance and diversity. Repeated hypoxic stress results in short-lived and small-sized benthic animals becoming more common in the diet of benthivorous fish, such as cod, plaice and dab in the southeastern Kattegatt, and could ultimately affect fish assemblages (*63*). Deep-burrowing organisms have a higher capacity for deeper vertical transport of organic matter into the sediment, resulting in a delayed remineralization of organic matter and oxygen consumption (*64*). In contrast, small surface-dwelling taxa with high population turnover rates facilitate a rapid remineralization with immediate oxygen consumption as a result.

Benthic fauna also play an important role in ecosystem resistance to the formation of hypoxia. Bioturbation enhances the vertical penetration of oxygen, which alters the rates and pathways of benthic mineralization and nutrient cycling, and is strongly influenced by species composition and abundance (*65, 66*). The increased surface area of oxic-anoxic interfaces and the ammonia excretion by bioturbators facilitates coupled nitrification-denitrification processes. The sediment P-retention capacity depends on ventilation and redox conditions, which are modified by bioturbation. In hypoxic conditions benthic uptake and processing of organic matter may shift from macrofauna to meiofauna or bacteria, which are not as efficient at processing organic matter (*67*). Thus, a reduction of bioturbation may decrease the natural purification capacity and increase the internal nutrient loading of Baltic sediments (*66*).

Hypoxia results in the loss of habitats, changes in biodiversity, associated with the removal of functionally important species. In a Baltic-wide perspective, these disturbances reduce the connectivity of populations and communities, which impairs recovery potential and threatens ecosystem resilience (*60*). Recovery depends on an available pool of mobile colonists. However, we lack in our understanding of potential colonist sources, quantitative estimates on mobility and the connectivity of populations, and the effects on recruitment from the increasing volume and area of hypoxia in the Baltic are not known.

Climate and nutrient inputs as drivers

Climate is an important driver of hypoxia in the Baltic Sea, and its variability influences many of the physical processes that create conditions conducive to the occurrence of hypoxia (*68*). During warm periods such as the Holocene Thermal Optimum (HTO) or the Medieval Warm Period (MWP), the Baltic experienced long-periods of hypoxia (*6*). However, during the HTO salinity was also at its Holocene maximum due to a larger opening through the Danish Straits (*69*), which also strongly influenced stratification and mixing. On shorter time scales, for example during the last three decades of the 20th century, the North Atlantic Oscillation (NAO) was in a positive phase with mild winters, humid and strong westerly winds creating conditions conducive to hypoxia in fjords along the Swedish west coast with significant shifts in benthic communities (*70, 71*). The influence of these short-term changes in the NAO on hypoxia is not clear, although NAO influences biological communities in the Baltic (*72*). However, the impact of humans on the environment have occurred on the same time-scales as climate change, making it difficult to clearly separate between anthropogenic forcing and natural changes.

That nutrients are a major driver of hypoxia is well established (*3*). In addition, it is known from lake records in Europe that cultural eutrophication has a long history dating back to the development and expansion of agriculture with increases in phosphorus concentrations and associated eutrophication of lakes (*18, 19*). Hypoxia post-dating ca. 2000 cal. yr BP correlates with population growth and large-scale changes in land use that occurred in much of the Baltic Sea watershed (*6*). The deposition of laminated sediments in the Baltic during the last ca. 100 years coincides with the start of the industrial revolution in northwestern Europe when human impact dramatically increased in the drainage area. Investigations have revealed significant changes in diatom assemblages in the Baltic Sea ca. AD 1850-1900 attributed to eutrophication (*73*). Most recently, the widespread expansion of laminated sediments in the Baltic coincides with the industrialization of agriculture and widespread use of fertilizers (*8*).

A major scientific question is when did anthropogenic influence start to significantly affect the Baltic Sea environment? Österblom et al. (*57*) suggested that a large salt water inflow and subsequent stagnation period that occurred in the early 1950s triggered the positive feedback between hypoxia and release of sediment phosphorus that had previously accumulated in the deep basins, and enhanced eutrophication (*31*). It is, however, difficult to unravel the changes in climate and the influence of human activities that occurred simultaneously. It is also difficult to differentiate between the relative importance of the drivers for the conditions during the early Littorina Sea with changes in the morphology (decreasing depths of the Baltic basin from uplift, yet increases in the depth of the sills governing saltwater input) from the variations in climate. More research is needed to explore the driving mechanisms for hypoxia in the Baltic Sea.

It is likely that it has been the interaction between nutrients and climate has enhanced the conditions for hypoxia to occur. The changes in biogeochemical cycling and loss of benthic benthic communities during hypoxia may stimulate further eutrophication in a self-sustaining way and support the persistence of hypoxia in the Baltic Sea (*31, 64*). This change in functioning of the system can be considered as a regime shift (*64*), with perhaps several regime shifts occurring due to eutrophication, overfishing and climate interactions (*57*).

Future perspectives

Reductions in hypoxia will not occur until nutrient loads are reduced (*74*). Historically, the countries within the Baltic Sea watershed have made pledges to reduce nutrient loads according to recommendations and targets set through the Helsinki Commission (*75*). Although some point source reductions have occurred creating better local conditions (*10*), there have been neither appreciable reductions in nutrient loads nor improvements in eutrophication at the scale of the Baltic Sea. A new Baltic Sea Action Plan with country specific reductions have renewed the efforts to make nutrient reductions (*76*).

The current eutrophication models demonstrate that significant reductions must occur in both N and P loading for conditions to improve (*74, 77*), although improvements in the models are warranted. Phosphorus loads could be reduced through better wastewater treatment and a phosphorus ban on detergents in the watershed. Nitrogen reductions must occur through changes in agriculture practices and changes in atmospheric deposition. While these reductions are similar to those that have been recommended in other coastal marine ecosystems suffering from nutrient-driven eutrophication (*3*), they are difficult to achieve due to the economic investment required and the lack of political will to implement the recommendations.

It is not enough to just understand the response of the ecosystem to nutrient and climate forcing. We also need to be able to quantify the magnitude of nutrient load reduction effects for different source reduction scenarios (*78, 79*). Even if nutrient source discharges on land are stabilized at present levels, nutrient loading will continue to increase (*80*) due to the slow transport and reversible mass transfer processes in the inland sub-surface water system (soil, groundwater, stream and lake sediments), where much of the anthropogenic nutrient source inputs still reside (*78*). In order to decrease future overall nutrient loading to the Baltic Sea a much larger effort than anticipated may be necessary to achieve reductions in diffuse source loading (*78*). Projected population changes and increased meat production in agriculture are expected to increase nutrient loading in the future even with concurrent nutrient reduction strategies (*81*). In order to improve future prospects, it is therefore important to eliminate the gaps in our understanding so that the uncertainties in determining future nutrient loading to the Baltic Sea are diminished.

If and when large-scale remediation measures are implemented, we need be able to quantify their potential effects. Experience from remediation in freshwaters demonstrates that no significant improvements in oxygen conditions will occur without concurrent nutrient reductions. Additional measures for nutrient load abatement should be considered such as constructed wetlands, reactive barriers and other possible innovative measures for achieving a decrease in future nutrient loading. In light of global warming and increased anthropogenic pressures in the Baltic Sea region, it is essential to obtain a comprehensive view of the timing, extent and mechanisms of hypoxia and include this knowledge into the discussion of the present state and the future of the Baltic Sea.

Acknowledgements

Approximately 60 scientists participated in a series of workshops to discuss issues surrounding Baltic Sea hypoxia during 2007. The authors are indebted to the participants, their input and discussions. Support from Baltic Sea 2020 (http://www.balticsea2020.se) is gratefully acknowledged. DJC was supported by COMPACT, a European Union funded Marie Curie Chair (MEXC-CT-2006-042718). This paper represents the views of the authors and is not made on behalf of any sponsors.

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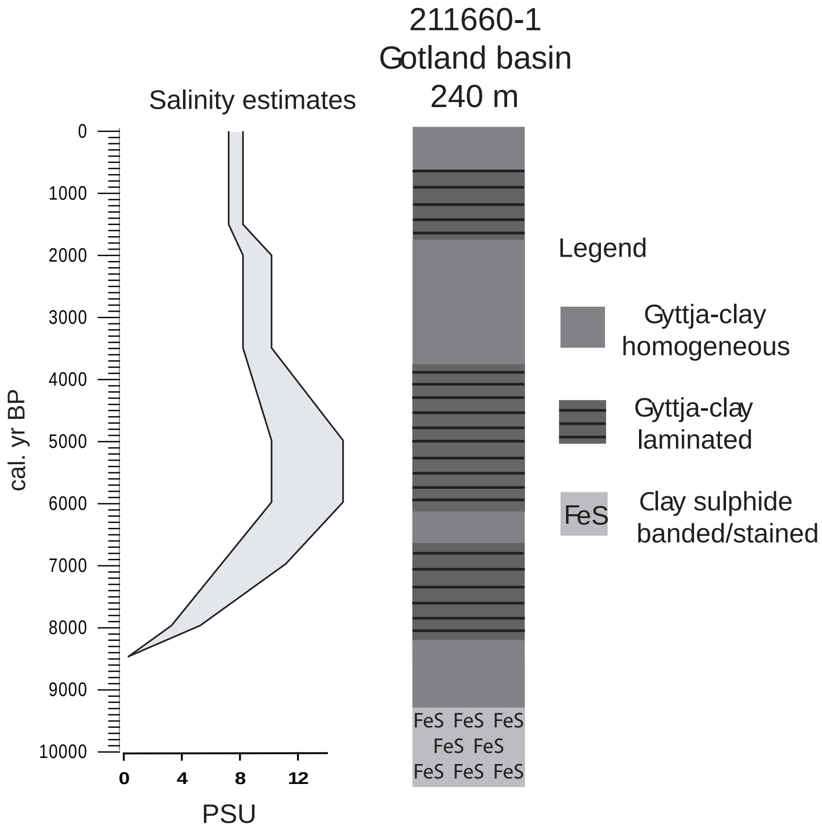
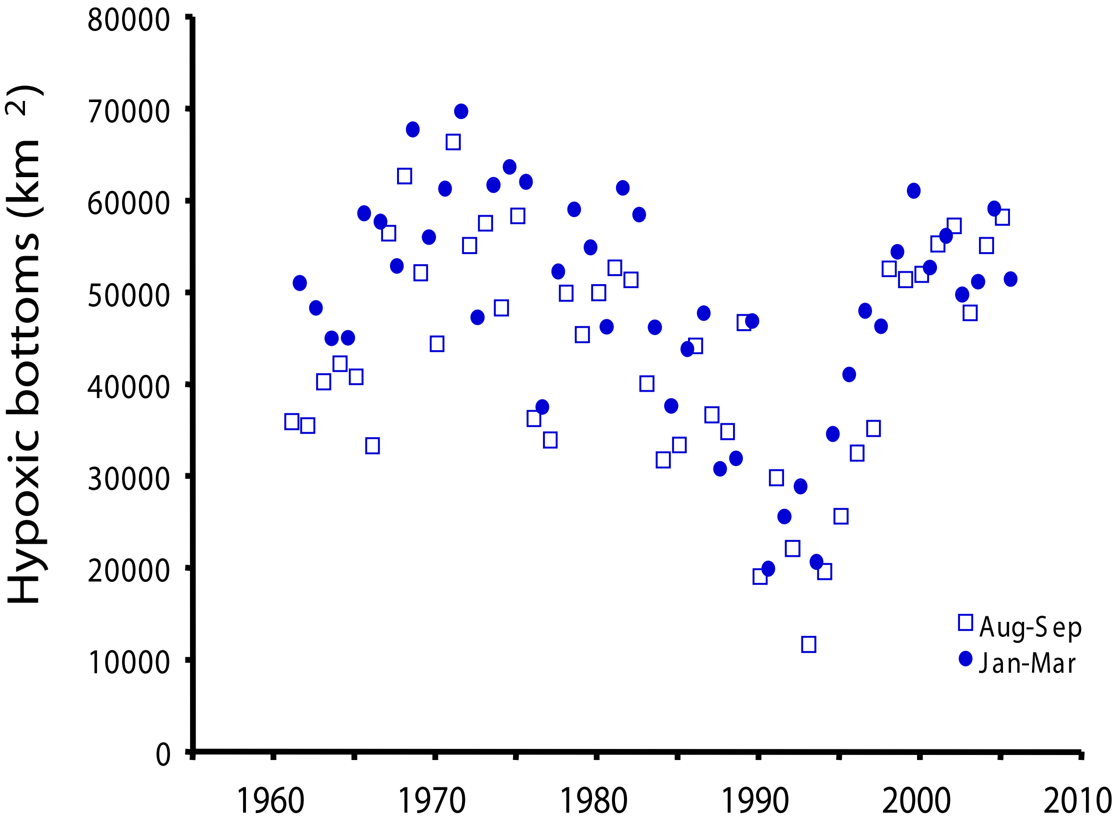
Figure 1. Modeled salinity estimates in the Baltic Proper (*85*) and the occurrence of laminated sediments at a station in the Baltic Proper (redrawn from *6*).

Figure 2. Seasonal and inter-annual variations of the bottom area covered by hypoxic waters containing less than 2 ml l^{-1} dissolved oxygen. Oxygen fields were averaged over August-September (open squares) and January-March (filled circles) for each year (updated from *26*).

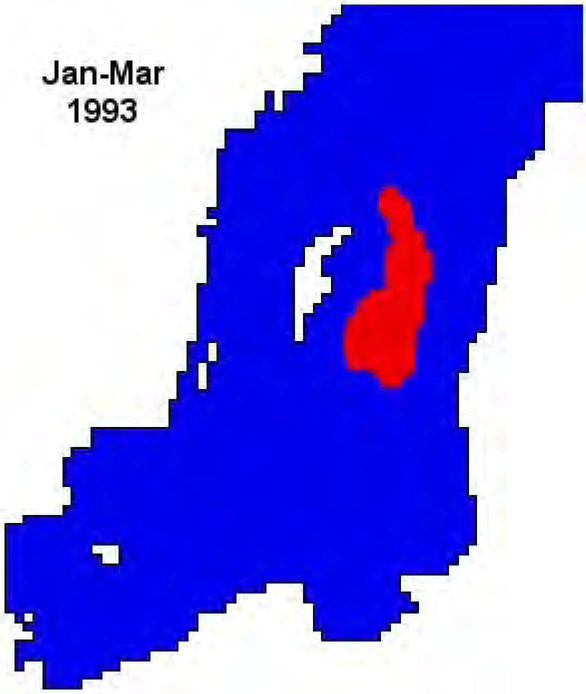
Figure 3. Location covered by hypoxic waters containing less than 2 ml l^{-1} dissolved oxygen. A) During at its minimum area in 1993 covering 11,050 km^2 of bottom and B) in 2006 covering 67,700 km^2 of bottom.

Figure 4. Isolines of density (subtracted by 1000, in kg m^{-3}) from hydrographic station BY15 in the Eastern Gotland basin. Yellow areas indicate hypoxic waters (< 2 ml l^{-1}) and red areas indicate anoxic waters (< 0 ml l^{-1}).

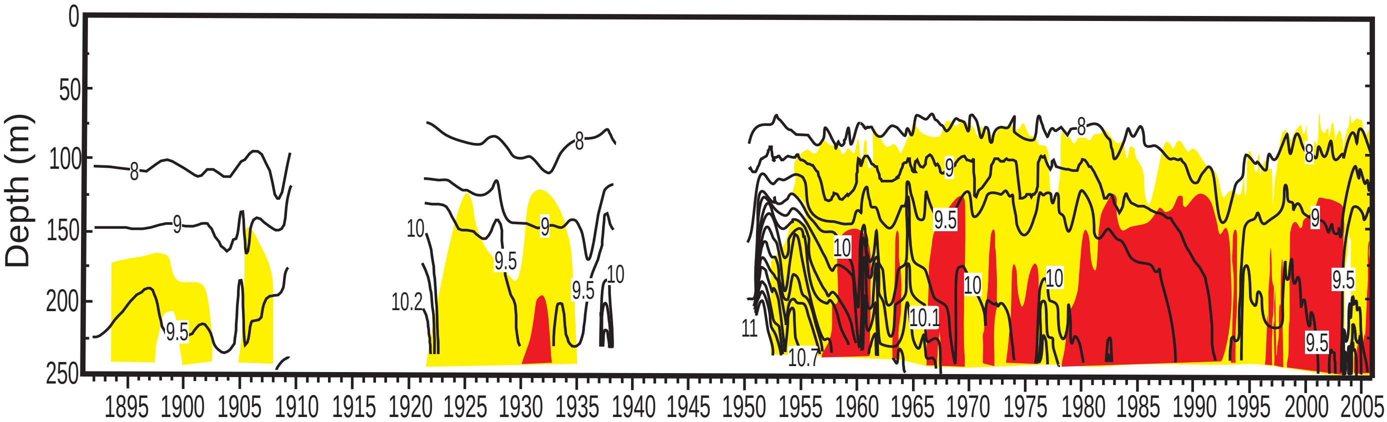

211660-1
Gotland basin
240 m
Salinity estimates
cal. yr BP
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
0
4
8
12
PSU
FeS FeS FeS
FeS FeS
FeS FeS FeS
Legend
Gyttja-clay homogeneous
Gyttja-clay laminated
FeS
Clay sulphide banded/stained



Hypoxic bottoms (km 2)
80000
70000
60000
50000
40000
30000
20000
10000
0
1960
1970
1980
1990
2000
2010
Aug-Sep
Jan-Mar


Jan-Mar
1993


November
2006


Depth (m)
0
50
100
150
200
250
1895
1900
1905
1910
1915
1920
1925
1930
1935
1940
1945
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
8
9
9.5
10
10.2
11
10.7
10.1

Appendix 8

Viewpoint

Tackling hypoxia in the Baltic Sea: Is engineering a solution?

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Brief for Table of Contents:
The potential for large-scale engineering projects to relieve the harmful effects of hypoxia are examined for the Baltic Sea.

Abstract

Hypoxia, the lack of oxygen in bottom waters reduces habitat for living resources, enhances phosphorus release from sediments and increases rates of nitrogen loss, allowing for conditions favorable for the growth of cyanobacteria in the Baltic Sea and ultimately creating a vicious cycle that helps sustain eutrophication. There are increasing calls for rapid, large-scale engineered remediation of hypoxia. Engineering projects that seek to add oxygen to bottom waters must consider the enormous amount of oxygen required to keep the Baltic from being hypoxic. Engineering projects to increase the saltwater inflow into the Baltic Sea will likely increased stratification and hypoxia. Similarly, chemical precipitation of phosphorus must consider the enormous amounts of chemicals that are irreversibly added to the system. Biomanipulation experiments are underway to try to reduce summer algal blooms, however, it is unlikely to have an impact upon hypoxia. Previous studies from freshwaters have clearly shown that for mitigation measures to be effective nutrient reductions must be undertaken. Hence, we argue here that the only long-term solution to hypoxia in the Baltic Sea is a reduction of nutrient supply.

Introduction

The Baltic Sea contains the largest dead zone in the world (*1*). The long-term average area impacted by hypoxia ($O_2 < 2$ ml l^{-1}) is 42,000 km^2, and over the last few years near record areas of hypoxia (ca. 60,000 km^2) have been reported by monitoring authorities (http://www.helcom.fi). Physical factors, especially the inflow of saltwater from the North Sea (*2*), are important determinants of the annual extent of hypoxia (*3*). Although hypoxia has occurred in the Baltic Sea coincident with climatic warm periods (*4*), nutrient driven eutrophication is believed to be the primary cause of increases in hypoxia during the last 50-100 years (*5*).

Since the late 1980s the Convention on the Protection of the Marine Environment of the Baltic Sea (Helsinki Commission [HELCOM]) representing the countries surrounding the Baltic has been working to implement a 50% reduction target for nutrient emissions and discharges (*6*). In 2007, HELCOM reached an international agreement between the countries with targeted nutrient reductions for each country to reduce the effects of eutrophication (*7*). The effects of eutrophication in the Baltic Sea have been well described (*8*). As a result of improved treatment of industrial point sources and municipal wastewater treatment plants, some nutrient discharges from point sources have been reduced improving local conditions, however, despite the pledges of governments there has been little progress in total nutrient reductions (http://www.helcom.fi/).

Frustration over the lack of progress in achieving improvements in water quality has led to calls for rapid and radical remediation efforts. Several private foundations have been established recently to combat eutrophication in the Baltic Sea, especially following the record abundance of cyanobacteria in 2005 (*9*). For example, Baltic Sea 2020 was established in 2005 through a private donation (500 million SEK = $83 million) made by Björn Carlson so that concrete measures to improve the environment could be taken (http://www.balticsea2020.se/). The John Nurminen Foundation has led efforts to implement phosphorus reductions from wastewater treatment plants in St. Petersburg, Russia (http://www.johnnurmisensaatio.fi/), and is currently pursuing similar goals in Poland. The Swedish government has pledged 500 million SEK ($83 million) for improvements in the Baltic Sea (*10*). More recently, the Swedish Environmental Protection Agency in collaboration with several other national funding agencies announced a call for proposals for pilot experiments to oxygenate bottom layers of the Baltic Sea or to increase the precipitation of and sequestration of phosphorus in order to reduce phosphorous leakage from sediments.

Large-scale engineered remediation projects within the marine environment itself are receiving increasing attention, such as in the case of ocean enrichment to enhance carbon sequestration (*11*). Although experience from freshwaters demonstrates that nutrient reductions must occur for any mitigation measure to be effective (*12*), additional engineering solutions may enhance or accelerate the recovery process provided that nutrient inputs are reduced simultaneously. Remediation offers promises of improvements in water quality, often at a cost significantly less than the costs of nutrient reductions, and on relatively short time-scales compared to the implementation of nutrient reductions. These promises make large-scale, engineered remediation quite attractive to politicians. In this Viewpoint we will examine and discuss some of the various options that have been suggested for the Baltic Sea (*10*).

Hypoxia in the Baltic Sea

Climate and anthropogenic pressures both have played a role as drivers of hypoxia through time in the Baltic Sea. Hypoxia was present in the Baltic from its formation ca. 8000 to 4000 cal. yr BP and again during the Medieval Warm Period 2000-800 cal. yr BP (*4*). Bottom waters of the Gotland Deep became hypoxic ca. AD 1900 as recorded by the deposition of laminated sediments (*13*). Superimposed on this natural variability, hypoxia has become more widespread and prevalent in modern times, ca. AD 1950-present, in both the coastal zone (*14*) and the open waters of the Baltic Sea (*5*). Hypoxia not only destroys benthic communities (*15*), but also alters nutrient biogeochemical cycles. The amount of dissolved inorganic phosphate released from sediments during hypoxia is approximately one order of magnitude greater than the anthropogenic total phosphorus loading (*3*). Removal of nitrogen through denitrification increases in the Baltic Sea with more hypoxia (*9*). High phosphorus and low nitrogen are favorable for blooms of N_2 fixing cyanobacteria, increasing the available nutrients leading to more eutrophication and more hypoxia. This internal acceleration of eutrophication in the Baltic has been termed the “vicious circle” (*9*). In order to combat this feedback cycle, different large-scale engineering methods have been suggested.

Large-scale engineering to increase oxygen in bottom waters

Many of the suggestions for remediation have focused on reducing the area of hypoxia and thereby reducing internal phosphorus loading. The large-scale engineering solutions that have been suggested are many and varied ranging from bubbling to large-scale manipulation of the circulation (*10*). In order to evaluate a selection of the alternatives a number of numerical model experiments of generalized engineering solutions were made using the BALTSEM and RCO-SCOBI models (*16*). The total amount of oxygen needed to keep the deep waters above the threshold for hypoxia varied by 2-6 million tons of oxygen annually. This is not a trivial amount of oxygen and is equivalent to 19,000-55,000 certified railroad cars of liquid oxygen. Various strategies have been suggested for adding oxygen directly into deep water, however, at present there is no known technology that exists that could transfer such an enormous amount of oxygen directly into bottom waters and disperse it into large hypoxic volumes.

The Baltic Sea is naturally susceptible to hypoxia due to permanent salinity stratification and intermittent inflows of saltwater (*17*). Better oxygen conditions are observed in bottom waters immediately following major inflow events. Therefore, enhanced ventilation of deep waters through additional inputs of oxygenated saltwater has been suggested as a remediation method. In the model experiments, an increased exchange through the Danish Straits was achieved by artificially doubling the depth of the Drogden Sill from about 8 to 16 m. However, based on our current understanding of the Baltic Sea (*2, 3, 18*) and from the model results (*16*), enhanced saltwater input into bottom waters can be expected to increase stratification and increase the area of hypoxia. While initially oxygenation of bottom waters is achieved with additional saltwater inputs, utilization of oxygen from sediment demand rapidly depletes the new oxygen brought into the system. The increased stratification extends the area of bottom water stratification increasing the area of hypoxia.

Because increased saltwater inputs result in more hypoxia the scenario of closing the Drogen Sill to freshen the Baltic was also investigated (*16*). Model results demonstrated that there is a long transitional stagnation period following reduced saltwater inflow during which hypoxia increases in deeper waters. There are improvements in water quality in the long run (>30 years) at the cost of a drastic reduction of salinity. Any engineering solution that increases or decreases the overall salinity will lead to significant and unpredictable alterations of species composition, in both pelagic and benthic ecosystems. Changes in salinity may also be illegal with regard to the EU Habitats Directive (*19*) and are most likely politically unacceptable to many of the countries surrounding the Baltic Sea. For example, when bridge construction linking Denmark and Sweden was planned, millions of Euros were spent to ensure that no net changes in salinity or deviations in water exchange with the Baltic occurred (*20*).

Stigebrandt and Gustafsson (*21*) suggested that ventilation by pumping intermediate oxygen rich mid-water down could alleviate hypoxia and reduce internal phosphorus loading. Enhanced ventilation was modeled by mixing water below the halocline between 50 m to 125 m throughout the Baltic Sea and gave improved oxygen concentrations (*16*). Although the models suggest that mid-water mixing has the potential to reduce hypoxia, more work is required to determine if this physical mitigation is technically feasible and to evaluate the costs and environmental effects on processes and organisms. One fear is that weakened stratification could negatively affect cod (*Gadus morhua*) recruitment, although recruitment is presently not possible in higher salinity, hypoxic water.

Uncertainties regarding impact of oxygenation

Significant gaps remain in our understanding of the effects of large-scale remediation efforts to re-oxygenate the Baltic Sea. A first important step is to evaluate the impacts on physical mixing and circulation processes. Whether halocline ventilation (*21*) is implemented or if oxygenated surface waters are piped downward below the halocline using wave driven overflow columns (*22*), changes in salt distribution and circulation will occur. More detailed modeling efforts of the impact on physical mixing process and the response of salinity, temperature and stratification must be made prior to any large-scale manipulation.

While we have a general understanding of nutrient biogeochemical cycles and the effects of hypoxia on those cycles, the response of remediation efforts on the phosphorus, nitrogen and silica biogeochemical cycles are only superficially understood with many basic questions remaining (*18*). If the Baltic Sea is re-oxygenated, enhanced nitrogen loss processes in the water column will no longer occur and it is assumed that sediment nitrogen loss processes will be restored following oxygenation, although no precedent for these large-scale changes exists. For phosphorus, the sizes and location of the mobile/bioavailable phosphorus fraction and permanent phosphorus sinks in Baltic Sea sediments need to be established. Oxygenation can potentially create a large pool of labile Fe-phosphorus in the sediments that could be potentially released if the system became hypoxic again – a highly undesirable condition. In addition, experience from fresh waters shows that increased Fe-phosphorus burial through artificial oxygenation may not be sufficient to significantly increase phosphorus burial, e.g. although a number of lakes have been artificially oxygenated for years changes in phosphorus release from sediments has not occurred (*23, 24*).

Chemical removal of phosphorus

Models show that phosphorus reductions will be necessary to alleviate hypoxia in the Baltic Sea (*25*). Chemical precipitation has been suggested as a method to remove phosphorus from the water column and enhance the permanent phosphorus burial in Baltic Sea sediments (*26*). Inactivation of phosphorus by the addition of aluminum and other chemicals has been used in lake restoration and sewage treatment plants to chemically bind and precipitate phosphorus (*12*). A variety of chemicals have been suggested including alum, rock flour from quarries and apatite (*26*).

While we can use the successful experience gained in small lakes to remove phosphorus from the water column, there are significant gaps in our present knowledge with regard to phosphorus precipitation in the brackish waters of the Baltic Sea. Potential problems include reductions in the binding capacity in seawater, toxicity for benthic organisms and the potential for co-sequestration of dissolved silicate. Dissolved silicate is an important limiting nutrient in the Baltic Sea and is currently being buried in diatoms faster than it is being replenished (*27*). All chemical engineering techniques to precipitate phosphorus require preliminary experiments to show that the phosphorus losses are permanent and stable under varying redox conditions. As a cautionary note, addition of any chemical will violate the principle of reversibility, i.e. once added a chemical cannot be removed, no matter if the response obtained is desirable or not. Addition of chemicals may also violate the “London Convention,” i.e. the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, 1972 and its amendments.

Biomanipulation

Biomanipulation is an engineering method to alter the biological communities by manipulating the abundance of specific organisms, usually with the goal of reducing summertime chlorophyll concentrations (*28*). Biomanipulation generally entails the stocking of predatory fish to enhance the predation of fish feeding on zooplankton (planktivorous fish) or by “fishing out” planktivorous fish (*29*). Although this method has been used frequently in lakes with mixed success (*30*), no large scale biomanipulation, with the exception of commercial overfishing (*31*), has to our knowledge ever been preformed in marine ecosystems. Recently, however, an experiment to reduce phytoplankton by increasing the density of a predatory fish (pikeperch, *Sander* sp.) through stocking is being conducted in the Himmerfjärden estuary, Sweden (Hansson, S., Stockholm University, pers. comm.).

The Swedish Fisheries Research Board is currently preparing a large-scale biomanipulation project on the Baltic Sea (http://www.fiskeriverket.se) with a proposed intensive fishing initiative on sprat (*Sparttus sprattus*). The goal is to reduce the predation pressure on herbivorous zooplankton potentially leading to increased grazing on algae and reduced chlorophyll concentrations with an additional goal to increase the numbers of cod. Although some success has been achieved in freshwaters, the enormous size of the Baltic Sea adds to the uncertainty of the effectiveness on biomanipulation on such a massive scale. Although fish reduction has been efficient even at large scales, such as occurred with cod overfishing in Newfoundland (*31*), there is a risk that alteration of the food web opens up a niche allowing for the comb jelly, *Mnemiopsis leidyi*, to take over as it did in the Black Sea (*32*). The comb jelly has been recently recorded in significant numbers in the Baltic Sea (http://www.helcom.fi/).

Conclusions and Recommendations

We evaluated a number of the options for the proposed remedies based on large-scale engineering solutions and/or other human intervention methodologies. Virtually all engineering methods for the open waters of the Baltic Sea seem unrealistic and/or not viable and can at best only speed up recovery while nutrient reductions begin to have an effect. Although there are gaps in our understanding of hypoxia (*18*), remediation experience from lakes tells us that simply adding oxygen may in fact not help in mitigating eutrophication (*23*, *24*). Pilot experiments with other types of manipulations are underway with further projects planned. However, it is our evaluation that these large-scale attempts at remediation are unlikely to improve the conditions in the Baltic Sea and many carry substantial risk for the environment.

Implementation of pilot experiments must include an Environmental Impact Assessment including potential effects on biota and impact on nutrient biogeochemical cycles, a risk analysis of unintended consequences, and consideration of energy needs and, of course, costs. In addition, implementation of large-scale remediation in the open waters of the Baltic Sea is not a decision for any one country and must conform to international conventions. From a scientific perspective, important knowledge can be gained from experiments and models that test large-scale experimental approaches on ecosystems (*33*). Engineered remediation on a local area with hypoxia and eutrophication could be instructive.

Any overall solution combination must include large reductions in the input of nutrients, despite their difficulty and cost (*34*). It is our opinion, that long-lasting improved water quality can only be achieved by reducing nutrient loads and we should refocus the energy and the will to implement remediation efforts into reducing nutrients. The recent HELCOM Action Plan (*7*) with agreed upon country allocations is an important step forward to achieving reductions. To accomplish this accord, a sector analysis covering both the costs and effectiveness of nutrient reductions needs to be carried out to ensure the implementation of adequate reductions. In addition, innovative reduction measures should be tested and implemented to supplement traditional methods for reducing nutrients.

Management of the Baltic Sea through HELCOM has had a long tradition of science-based management (*6*). Science must continue to be an integral part of any remediation effort with environmental monitoring an important, but in some cases missing, part of any effort. Experimental approaches and modeling, both on the land and in the sea, in addition to diverse expert scientific advice are required for effective solutions and eventual reduction of eutrophication of the Baltic Sea.

Acknowledgements

Approximately 60 scientists participated in a series of workshops to discuss issues surrounding Baltic Sea hypoxia during 2007. The authors are indebted to the participants, their input and discussions. Support from Baltic Sea 2020 (http://www.balticsea2020.se) is gratefully acknowledged. DJC was supported by COMPACT, a European Union funded Marie Curie Chair (MEXC-CT-2006-042718). This paper represents the views of the authors and is not made on behalf of any sponsors.

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Appendix 9

Syrebrist i Östersjön

– vad kan vi göra?

Foto: Martin Almqvist/Johnér

Kan konstgjord syresättning vara ett sätt att lösa Östersjöns problem med syrebrist? Knappast, med tanke på de tjugo tusen järnvägsvagnar med flytande syre som skulle behövas – årligen.

Stora delar av Östersjöns djupvatten lider av syrebrist. Problemet beror i grunden på övergödningen av våra vatten, men det kommer att ta lång tid innan åtgärder för att minska näringstillförseln får märkbara effekter. Därför har många funderat över om det inte finns några snabbare sätt att åtgärda syrebristen. Ett forskningsprojekt har tittat närmare på saken.

Syrebristen i Egentliga Östersjön har de senaste åren varit den värsta som registrerats. Över hälften av bottenytan och allt vatten djupare än 80 meter saknar helt bottendjur och fisk. Delvis är syrebristen en följd av havsområdets naturliga förutsättningar, men problemen har snabbats upp och förvärrats av övergödningen.

Olyckligtvis orsakar syrebristen i sin tur förändringar i näringsämnenas kretslopp. Med ökande syrebrist återförs fosfor ur sedimenten till vattenmassan, vilket bidrar till ökade blomningar av kvävefixerande cyanobakterier. Även sedimentens förmåga att omvandla kväve till kvävgas påverkas. Fortsatt syrebrist i Östersjön förstärker alltså övergödningens negativa effekter i en ond cirkel.

Radikala simuleringar

Anledningen till att Egentliga Östersjön drabbas så hårt av syrebrist är att vattenmassan är permanent skiktad. Det utsötade ytvattnet blandas inte med det salta djupvatten som mycket sällan lyckas ta sig in genom de danska sunden. Ofta framkastas därför, halvt på skämt, förslagen att antingen göra sunden mycket större eller stänga dem helt som en radikal lösning på problemet.

Nu har man gjort ordentliga datasimuleringar över vad sådana drastiska åtgärder egentligen skulle få för effekt på syresituationen under de närmaste hundra åren. Om man dubblerar djupet i Öresund så förbättras syresituationen först. Men eftersom salthalten i bottenvattnet ökar så förstärks skiktningen och efter ungefär femtio år är syrebristen tillbaka, värre än någonsin. Om man istället stänger till sunden så blir ytvattnet ganska snart betydligt sötare, men det salta djupvattnet blir kvar och syrebristen förvärras dramatiskt. Först efter mer än trettio år skulle situationen bli bättre. Men då skulle Egentliga Östersjön vara söt som nuvarande Bottenhavet med allt vad det skulle innebära för växt- och djurlivet…

Tekniska lösningar som påverkar salthalten bör nog undvikas. De strider mot EUs habitatdirektiv och är troligen varken politiskt eller juridiskt acceptabla.

Syresättning och omblandning

Ett annat förslag som undersökts närmare är aktiv syresättning av djupvattnet. Det krävs dock enorma mängder syrgas för att motverka syrebrist i Östersjön. Minst två miljoner ton syrgas måste tillföras varje år. Det motsvarar tjugo tusen järnvägsvagnar med flytande syre. Om syresättningen av någon orsak skulle utebli en period, skulle problemen med stor sannolikhet återkomma. Dessutom visar erfarenheter från sjöar att konstgjord syresättning påverkar näringsämnenas cirkulation på ett annat sätt än vad naturlig syresättning av bottenvattnet gör.

Mer lovande verkar idén med att röra om vattnet runt salthaltsskiktningen. Om man på något sätt skulle kunna blanda om vattnet mellan 50 och 125 meters djup förbättras syrekoncentrationen i djupvattnet utan att förändra salthalten vid ytan. Detta är den enda tekniska lösningen som inte kan uteslutas, men även här stöter man på stora praktiska, juridiska och etiska problem.

Fäll fosfor som i reningsverk

Flera förslag börjar i andra änden av syrebristproblemet. Då vill man snabba på minskningen av mängden näringsämnen i havet för att på så sätt bryta den onda cirkeln.

I avloppsreningsverk används aluminium och andra kemikalier standardmässigt för att fälla ut växtnäringsämnet fosfor från vattnet. Istället hamnar det i fast form i sedimenten och är inte längre åtkomligt för växter. Metoden har också använts i övergödda sjöar. Skulle det kunna fungera även i Östersjön?

Svaret är att vi inte vet. Det salta vattnet påverkar den kemiska bindningen och vad som händer över tid är oklart. Dessutom kan möjligen kisel, ett annat viktigt näringsämne, påverkas på ett oönskat sätt. Mer forskning behövs och metoderna behöver prövas både i laboratoriet och i storskaliga försök. Ett varningens finger dock; har man väl tillsatt en kemikalie så kan den inte tas bort - det

Illustration: SMHI, oceanografiska enheten

Över hälften av Egentliga Östersjöns bottnar är syrefria (svart) eller har mycket låga syrehalter (rött).

spelar ingen roll om man fått en önskvärd respons eller inte. Dessutom strider troligen tillsättning av kemikalier i havet mot den internationella konvention som förbjuder dumpning av avfall och annat material för att förhindra havsföroreningar.

Modifiera ekosystemet

Andra idéer handlar om att med mänsklig hjälp försöka återställa eller förbättra ekosystemets egna förmågor. Exempelvis har förhållandet mellan de olika nivåerna i Östersjöns näringskedja förändrats kraftigt sedan 40-talet, huvudsakligen beroende på mänsklig påverkan. Mängden rovfisk och djurplankton har minskat kraftigt i förhållande till både planktonätande fisk och växtplankton. Det är en oönskad utveckling som dessutom förstärker övergödningens effekter.

Kanske kan man återfå det gamla jämviktsläget genom att aktivt gå in och modifiera samhällena. Mindre försök med utplantering av rovfisken gös och utfiskning av planktonätande skarpsill planeras för att undersöka om effekterna blir de önskade. Musselodlingar används också som levande näringsuppsamlare och partikelfilter. Då tillför man bristvaran boplatser och låter musslorna samla in näring i form av plankton. Musslorna, och därmed näringen, lyfts sedan upp på land.

STIFTELSEN BALTIC SEA 2020

Finansmannen Björn Carlson grundade denna stiftelse som har som mål att stimulera åtgärder som förbättrar Östersjöns miljö. Projekten får gärna vara djärva och nydanande. De skall leda till konkreta resultat, påverka politiker och institutioner och förbättra miljötillståndet i Östersjön.

Hypoxiaprojektet, vars resultat redovisas i denna artikel, är ett av flera projekt. Det har involverat ca 60 forskare från tio olika länder under 2007. Mer information finns på http://www.balticsea2020.se

Kustzonen som filter

Tidigare forskning har visat hur viktig kustzonen och dess förmåga att fungera som ett biologiskt filter är. Normalt är kusten det område där näringsämnena förbrukas innan de når öppet vatten, och omvänt - där näring från havet inte når ända till kusten. Den kustnära övergödningen har bidragit till att stora skärgårdsområden drabbats av syrebrist och därmed förlorat mycket av sin förmåga att använda näringsämnena till något bra. Riktigt hur man ska bära sig åt för att på bästa sätt återställa denna förmåga vet man inte än. Fler studier behövs.

Det finns inga genvägar

Experternas slutsatser är att det tyvärr inte finns några enkla lösningar. De flesta tekniska lösningar är vid närmare eftertanke inte realistiska att genomföra i så stor skala. Det blir orimligt dyrt och för med sig för många oönskade konsekvenser.

En hel del av de föreslagna åtgärderna kan säkert användas i kustzonen och på andra särskilt utsatta platser. Men samstämmiga studier visar att det krävs att tillgången på näringsämnen samtidigt minskar för att åtgärderna ska fungera bra.

En kraftfull minskning av näringstillförseln till Östersjön måste således få högsta prioritet. Länderna runt Östersjön bör gå längre än vad Helcom föreslagit i aktionsplanen, Baltic Sea Action Plan. Helst bör insatserna fördubblas! Annars kommer syrebristproblemet att kvarstå under överskådlig tid.

Det långsamma, stundtals tröstlösa arbetet med att minska alla utsläppskällor går alltså inte att komma undan. Det finns tyvärr inga genvägar.

Foto: Helle Munk Sorensen

Ålar försöker att fly undan syrebrist vid den danska kusten.

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Appendix 10

Ibland är syrebrist ett normalt tillstånd

Utbredningen av syrefria bottnar i Östersjön har ökat fyrfaldigt de senaste 50 åren. Många röster höjs nu för att bota innanhavet från detta tillstånd. Storskaliga lösningar, som saltlås, syresättning av djupvatten och kanaler under Skåne har föreslagits. Men sådana åtgärder skulle kunna få icke-önskvärda konsekvenser – eftersom det finns områden i Östersjön där syrebrist är ett naturligt tillstånd.

Med denna artikel vill vi försöka ge svar på när, var och varför syrebrist inträffat i Östersjön och vilka mekanismer som ligger bakom. Vi utgår från den tid då Östersjön bildades efter senaste istiden, fram till idag.

Forskarnas starkaste bevis för att syrebrist ägt rum under en längre period (månader till år) är förekomsten av laminerade sediment. Laminerade sediment bildas bara i syrefria vattenmiljöer där en bottenlevande fauna, som mixar och homogeniserar sedimenten, inte kan existera eftersom den kräver en syrehalt > 2 mg/l. I Östersjön bildas laminerade sediment i de djupare bassängerna under det permanenta saltsprångskiktet, där den vertikala omblandningen av vattenmassan är begränsad. Under de senaste decennierna har laminerade sediment även påträffats i kustnära regioner, som till exempel i Stockholms skärgård.

Syrebrist i tid och rum

Den "moderna" Östersjön är cirka 8 000 år gammal, vilket gör Östersjön till världens yngsta hav. Även om detta innanhav inte är gammalt så har det genomgått stora och dramatiska miljöförändringar i spåren av den senaste skandinaviska inlandsisens avsmältning. Idag vet man att klimatet och människan är de viktigaste miljöpåverkande faktorerna i Östersjön. Men man saknar kunskap om hur syrebristen varierat i tid och rum och hur återkopplingen till dessa två faktorer verkar.

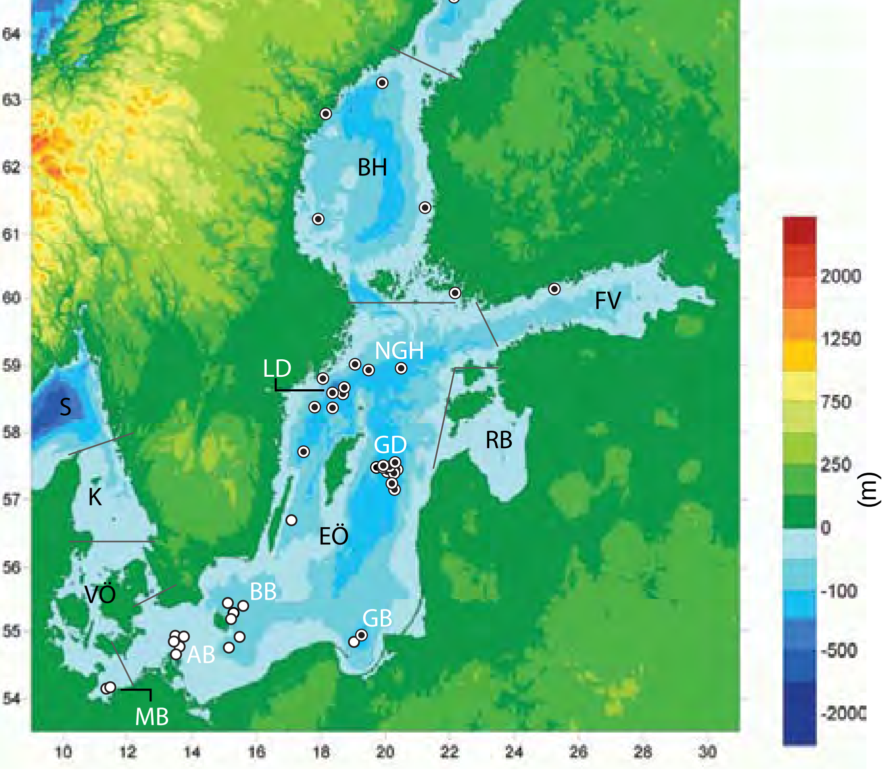
I den här artikeln presenterar vi data som vi sammanställt från 25 långa sedimentkärnor från "Egentliga Östersjön" (se bildtexten sidan 11). Vår studie visar att det på 73 till 250 meters djup i huvudsak förekommit tre perioder med laminerade sediment (8 000–4 000, 2 000–800 år före nutid och efter 1800-talet) och två då homogena sediment avsatts (4 000–2 000 och 800–200 år före nutid) under Östersjöns "moderna" historia.

I de allra djupaste delarna av Landsortsdjupet (> 250 meter) har laminerade sediment deponerats mer kontinuerligt medan sedimenten i de grundare södra delarna vanligtvis varit syresatta de senaste 8 000 åren.

Syrebrist och klimatförändringar

Vi har även kunnat visa att växlingarna mellan laminerade och homogena sediment följer den generella klimatutvecklingen i nordvästra Europa. Exempelvis sammanfaller depositionen av laminerade sediment mellan 8 000–4 000 år före nutid med höga salthalter, hög organisk produktivitet och med ett klimatiskt optimum kännetecknat av höga atmosfäriska temperaturer, torra förhållanden och relativ hög solinstrålning. Under detta optimum retirerade glaciärerna i fjällkedjan och trädgränsen låg 300–400 meter högre i fjällen än idag.

För omkring 4 000 år sedan inträffade en markant klimatförändring. Temperaturen sjönk och klimatet blev mer fuktigt. Homogena sediment började



Batymetrisk karta över Östersjön som visar de större bassängerna (BV=Bottniska Viken, BH=Bottniska Havet, FV=Finska Viken, RB=Riga Bukten, EÖ=Egentliga Östersjön, VÖ=Västra Östersjön, K=Kattegatt, S=Skagerack) i svart text och delbassängerna (NGH=Norra Gotlandshavet, GD=Gotlandsdjupet, LD=Landsortsdjupet, GB=Gdanskbukten, BB=Bornholmsbassängen, AB=Arkonabassängen, MB=Mecklenburgianbukten) i vit text. Svarta cirklar visar var laminerade sediment (bevis på syrebrist) har identifierats medan vita cirklar speglar var endast homogena sediment (bevis på syresatta bottnar) rapporterats.

deponeras i Östersjön vilket tyder på att djupvattnet syresattes vid denna tidpunkt samtidigt som salthalten och den organiska produktionen sjönk. Förevarande situation fortgick till början av Medeltiden då medeltemperaturen var 0,5–0,8°C högre än idag.

Under en cirka 1 000 år lång period, som spände över den varma Medeltiden (750–1200 e.Kr.), bildades laminerade sediment på djup > 150 meter i stora delar av Egentliga Östersjön och den organiska produktionen nådde maximala värden. I slutet av 1200-talet försämrades klimatet igen och det blev kallare och fuktigare (cirka 1°C kallare än idag). I början av 1300-talet inleddes den så kallade Lilla Istiden. Glaciärerna i fjällkedjan ryckte fram och de danska och svenska sunden frös ofta till is under vinterhalvåret, vilket utnyttjades av Karl X Gustav som år 1658 tog sin krigshär över isen i Lilla och Stora Bält. Sedimenten från Östersjön visar att den organiska produktionen

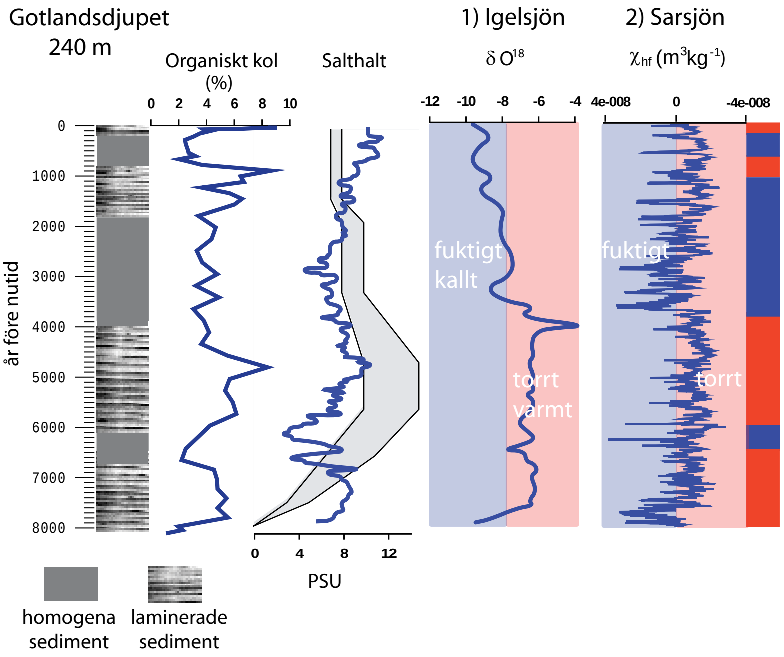
SYREBRIST I HAVET

Syrebrist (syrehalt < 2 mg/l) uppstår när det blir obalans mellan de fysikaliska processer som tillför syre och de biologiska processer som förbrukar syret. Syre förbrukas vid nedbrytning av organiskt material (exempelvis alger), vars tillväxt styrs av tillgången på näringsämnen, såsom, kväve och fosfor.

Syre tillförs vid sporadiska inflöden av syrerikt och salthaltigt vatten från Kattegatt/Skagerack, samt genom vertikal omblandning. Det salta vattnet har en hög densitet och fyller de djupare bassängerna där det stannar tills kan ersättas av nytt syre- och saltrikt vatten vid större inflöden.

På grund av densitetsskillnaderna är vattenmassan i Östersjön starkt stratifierad där det tyngre salthaltigare djupvattnet skiljs åt från det övre mer bräckta vattnet vid saltsprångsskiktet. Denna stratifiering hindrar vertikal omblandning och syresättning av djupare vatten. Under stagnerande perioder kan därför allt syre förbrukas. Ofta bildas då svavelväte som är giftigt för bottenlevande organismer och hela faunasamhällen kan slås ut.

Syrebristen påverkar även de biogeokemiska cyklerna i Östersjön. Vid syrebrist frigörs bland annat fosfor (och kväve) från sedimenten och koncentreras i vattenmassan, vilket ytterligare driver övergödningen och en ond cirkel är sluten.



Figuren visar växlingar mellan laminerade sediment (bevis på syrefria bottnar) och homogena sediment (bevis på syresatta bottnar) längs tidsskalan till vänster (baserad på sammanställd data över 25 sedimentkärnor från 73–250 meters djup i "Egentliga Östersjön" d.v.s. Gotlandsdjupet, Landsortsdjupet och norra Gotlandshavet. Även rekonstruerade variationer i organisk kolhalt (mått på organisk produktion) och salthalt från Gotlandsdjupet och terrestra palaeoklimatiska data från svenska sjösediment det vill säga (1) syreisotoper (δO^{18}) som speglar effektiv humiditet/netto nederbörd och (2) magnetisk susceptibilitet (χ_{hf}) som är ett mått på erosion. Till höger i figuren visas den generella klimatutvecklingen i nord-västra Europa. Lägg märke till hur varma och torra perioder (röd färg) sammanfaller med förekomsten av laminerade sediment och kalla och fuktiga perioder (blå färg) med förekomsten av homogena sediment.

var låg och att det rådde syresatta bottenförhållanden under denna period. Från slutet av 1800-talet återupptogs depositionen av laminerade sediment i stora delar av Östersjön, vars utbredning ökat markant de senaste 50 åren.

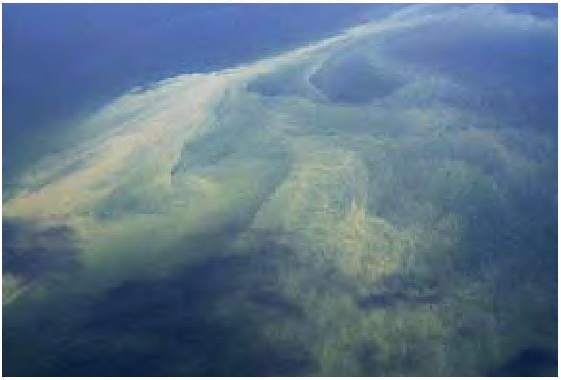
Syrebrist och människan

Syrebristen de senaste 2 000 åren sammanfaller inte bara med variationer i klimatet utan även med förändringar i markanvändning runt Östersjön. Sådana störningar kan leda till ökad erosion i landskapet och förhöjda utsläpp av näringsämnen. Forskare har kunnat visa att fosforhalterna i sjösediment steg i samband med införandet av jordbruksreformer. Bland annat har har man konstaterat att sjöar, såsom Mälaren i Sverige och Dallund Sø i Danmark, varit kulturellt övergödda från Medeltiden fram till idag och en möjlig tolkning är att depositionen av laminerade sediment de senaste 100 åren orsakats av klimatförbättringen som följde Lilla Istiden. Men under denna tid påbörjades den industriella revolutionen i nordvästra Europa som kännetecknades av befolkningsökning, jordbruksreformer och ekonomisk tillväxt. Till exempel så växte den svenska befolkningen med en procent per år mellan 1820–1879 och jordbruksproduktionen ökade med 0,5 procent per år och capita under ungefär samma tid. 1827 infördes Laga Skifte som var den svenska motsvarigheten till det som kallas den agrara revolutionen. Utdikning blev allt vanligare och den svenska och finska exporten av trä steg med 400 procent. Skogarna exploaterades och sågverk växte upp som svampar ur jorden längs de norrländska älvarna. Även södra Sverige avskogades. Kartor från 1800-talet visar att landskapet då var det öppnaste i södra Sveriges historia. Också historiska källor skildrar övergödning och syrebrist under den här perioden. Karen Blixtens far, Wilhelm Dinesen, seglade som gäst ombord på danska flottans skolfartyg, örloggsbriggen Falken, från Nyborg till Helsingfors, i mitten av 1890-talet. I hans dagboksanteckningar av kan man läsa att "Östersjön är ett dött, slött, skitigt brackvatten. I den varma sommartiden, som nu, blommar Östersjön och havet är fyllt med gröda och enorma gula strimmor".

Vad driver syrebristen i Östersjön?

Av ovan framgår att det finns ett tydligt förhållande mellan klimat, mänsklig påverkan och syrebrist i Östersjön. På långa tidsskalor har bland annat klimatet varit avgörande – medan den mänskliga påverkan spelat allt större roll på kortare tidsskalor.

Från vår studie kan man också dra slutsatsen att syrebrist tillbaka i tiden (innan människans påverkan var alltför omfattande) är starkt relaterad till klimatiskt betingade förändringar i salthalt och organisk produk-



Bilden till vänster: En tydlig effekt av övergödningen i Östersjön är de massiva blomningarna av blå-gröna alger under sommaren. Men med övergödning följer också syrebrist. Flygbilden visar algblomning i Finska viken den 6 augusti 2002. Foto: Riku Lumario.
Bilden till höger: Österjön bildades för 8 000 år sedan. Dagens Östersjö täcker en nära 400 000 kvadratkilometer stor yta och utgör därmed 0,1 procent av världshavets yta. Havet är grunt. Medeldjupet är knappt 60 meter. Källa: www.ne.se. Foto: Riku Lumario.
Bilden nedan: Rekonstruerade profiler för total fosforhalt från (A) sjön Dallund Sø i Danmark och (B) Mälaren i Sverige.

tion. Flera undersökningar visa att under perioder med förhöjd salthalt förstärks stratifieringen i vattenpelaren, vilket hindrar den vertikala omblandningen och transporten av syre till djupare lager. Även vi ser ett klart samband mellan terrestrisk data som speglar humiditet/avrinning och sedimentationsprocesser i Östersjön. Vår uppfattning är därför att vattenföringen i dräneringsområdet har minst lika stor inverkan på salthalten och syresättningen av djupvattnet som tillförseln av nytt syre- och saltrikt vatten från Kattegatt/Skagerack. Vi hävdar även att den mänskliga påverkan på Östersjöns ekosystem troligen började så tidigt som under Medeltiden. Detta skulle innebära att expansionen av laminerade sediment de senaste 50 åren bara är ett resultat av ytterligare extern mänsklig påverkan.

Östersjön är ett känsligt innanhav där troligtvis klimatet, människan och kombinationer mellan dessa två, spelat stor roll för tillgången på syre. Mekanismerna som styr syrebristen är inte klarlagda och återkopplingsmekanismer, såsom ökad avgång av fosfor från sedimenten, accelererad övergödning och förändringar i fauna, har sannolikt förstärkt och förlängt perioder med syrebrist. På frågan om syrebristen i Östersjön är legitim eller ej, svarar vi *ja, i de djupaste delarna av "Egentliga Östersjön"*. För även om syrebristen eskalerat de senaste 50 åren så finns det områden i "Egentliga Östersjön" som varit naturligt syrefria, och vad konsekvenserna skulle bli om vi vidtog åtgärder mot dessa får framtida forskning svara på.

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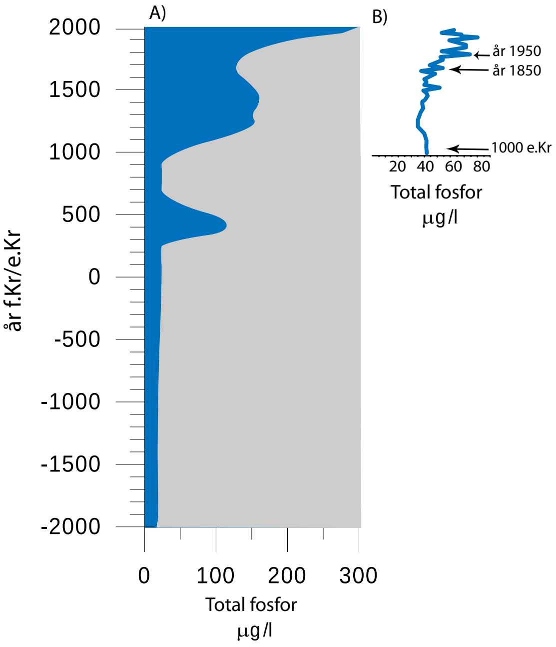

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