KUNGL. VETENSKAPS-AKADEMIEN

THE ROYAL SWEDISH ACADEMY OF SCIENCES

The Expansion of Low Oxygen Zones in the Global Ocean and Coastal Waters

Date: 21 February 2019 (full day)

Venue: The Beijer Hall, The Royal Swedish Academy of Sciences, Lilla Frescativägen 4A, Stockholm

Host: The Environmental Committee of the Royal Swedish Academy of Sciences

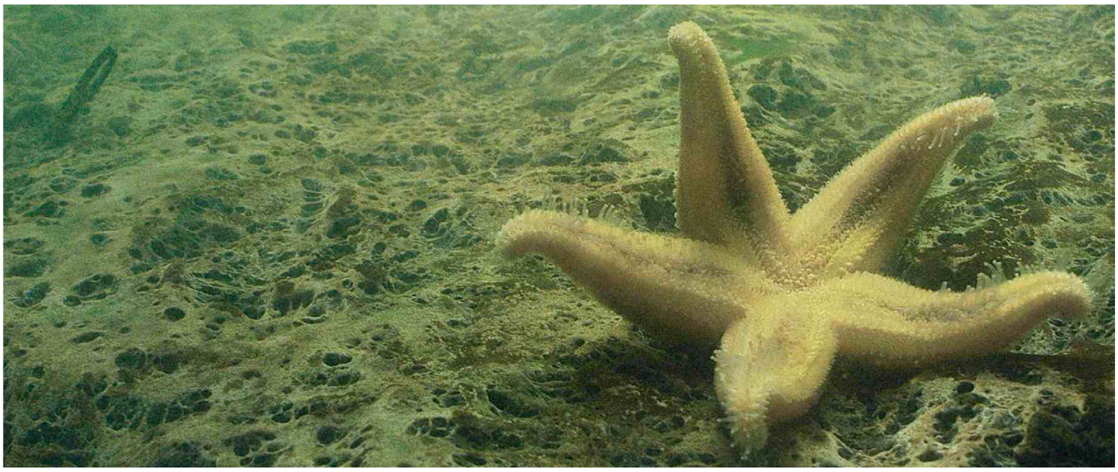

Photo: Peter Bondo Christensen

Oxygen concentrations in both the global ocean and coastal waters have been declining since at least the middle of the 20th century. This oxygen loss is one of the most important changes occurring in an ocean increasingly modified by human activities that have raised temperatures, CO2 levels, and increased nutrient inputs that have altered the abundances and distributions of marine species. Oxygen is naturally low or absent where biological oxygen consumption through respiration exceeds the rate of oxygen supplied by physical transport, air-sea fluxes, and photosynthesis. The enhanced production in surface waters of the coastal zone from nutrient inputs from sewage and agricultural activities increases the delivery rate of degradable organic matter to bottom waters where microbial decomposition by aerobic respiration consumes oxygen. In addition, ocean warming reduces the solubility of oxygen and raises metabolic rates also accelerating the rate of oxygen consumption. Under current trajectories, anthropogenic activities could drive the ocean toward widespread oxygen deficiency within the next thousand years.

The symposium will address the impact of changes in productivity, biodiversity, and biogeochemical cycles with declining oxygen in the global ocean and coastal waters.

Lectures by:

- Denise Breitburg, Smithsonian Environmental Research Center, USA
- Jacob Carstensen, Aarhus University, Denmark
- Daniel Conley, The Environmental Committee, The Royal Swedish Academy of Sciences, Sweden
- Christoph Humborg, Stockholm University, Sweden
- Alf Norkko, University of Helsinki, Finland and Baltic Sea Centre, Stockholm University, Sweden
- Andreas Oschlies, GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany
- Bess B. Ward, Princeton University, USA

The symposium is free of charge and open to the public but registration is required for all participants. Limited number of seats. For information and registration visit *www.kva.se/lowoxygenzones*. **Please state eventual food preferences or allergies in the registration form.**

This symposium is funded by Baltic Sea Centre at Stockholm University, BalticSea2020, the Swedish Agency for Marine and Water Management and the Royal Swedish Academy of Sciences.

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08.30 Registration

Morning session
Chair: Martin Jakobsson, Chariman, The Environmental Committee, The Royal Swedish Academy of Sciences

09.00 Introduction
Göran K. Hansson, Secretary General, The Royal Swedish Academy of Sciences
Daniel J. Conley, The Environmental Committee, The Royal Swedish Academy of Sciences
Jakob Granit, Director General, The Swedish Agency for Marine and Water Management

09.15 The Ocean is losing its breath - an overview of the problem, its effects, and solutions
Denise Breitburg, Smithsonian Environmental Research Center, USA

09.45 Discussions

10.00 Coffee/tea

10.30 Patterns of deoxygenation in the global oceans
Andreas Oschlies, GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany

11.00 Discussions

11.15 Microbial communities and biogeochemical cycles in oxygen minimum zones
Bess B. Ward, Princeton University, USA

11.45 Discussions

12.00 Lunch wrap

Afternoon session
Chair: Helena L. Filipsson, Lund University, Sweden

13.00 Warming and nutrients as drivers of hypoxia in the Baltic Sea
Jacob Carstensen, Aarhus University, Denmark

13.30 Discussions

13.45 Ecosystem impacts of hypoxia in coastal waters
Alf Norkko, University of Helsinki, Finland and Baltic Sea Centre, Stockholm University, Sweden

14.15 Discussions

14.30 Coffee/tea

15.00 Impact of hypoxia on coastal biogeochemistry
Daniel J. Conley, The Environmental Committee, The Royal Swedish Academy of Sciences, Sweden

15.30 Discussions

15.45 Managing the Baltic Sea
Christoph Humborg, Stockholm University, Sweden

16.15 Discussions

16.30 Closing remarks
Helen Ågren, Swedish Ambassador for the Oceans

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The Expansion of Low Oxygen Zones in the Global Ocean and Coastal Waters

Abstracts

The Ocean is losing its breath - an overview of the problem, its effects, and solutions

Denise Breitburg, Smithsonian Environmental Research Center, USA

Oxygen is fundamental to life, but is declining in waters worldwide as a result of anthropogenic nutrient loads and rising global temperatures. Oxygen minimum zones in the open ocean are expanding, some coastal areas are experiencing more severely oxygen-depleted waters during upwelling, and hundreds of sites around the world have reported low oxygen events related to anthropogenic nutrient loads. Increasing temperatures decrease ventilation, reduce the amount of oxygen that water can hold, and increase respiration rates that deplete oxygen. Across many types of water bodies, low oxygen alters distributions of fishes, potentially making them more susceptible to fishing, alters trophic interactions, and decreases the extent of suitable habitat. Complex life histories that rely on multiple habitats and prey types may exacerbate the problem, with the consequence that effects of low oxygen may be seen well beyond the actual geographic extent of oxygen-depleted waters. Recent work on transgenerational effects suggests ways that hypoxia exposure may extend through time. In addition, low oxygen does not occur in isolation. Rising temperatures increase oxygen requirements of animals, and other stressors such as acidification and fisheries mortality may exacerbate hypoxia effects at the individual and population levels, respectively. Management and policy actions can be taken to improve this outlook. Reducing nutrient loads to coastal waters, reducing airborne nutrients that fertilize the open ocean, and taking the steps necessary to limit global warming can halt oxygen decline; if aggressive steps are taken, oxygen conditions can improve. In the meantime, adaptive management actions that protect species and ecological processes threatened by oxygen decline can limit some of the negative effects of ocean deoxygenation.

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Patterns of deoxygenation in the global oceans

Andreas Oschlies, GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany

Observational estimates and numerical models both indicate a significant overall decline in marine oxygen levels over the past few decades. However, both rate and spatial patterns of deoxygenation differ considerably between observed and modelled estimates, whereas agreement is relatively good for the solubility-driven part of the oxygen decline. Particularly in the tropical thermocline that hosts open-ocean oxygen minimum zones, observations indicate a considerably stronger oxygen decline than most state-of-the-art models. Possible reasons for the apparent model-data discrepancies include different representations of transport as well as redox-sensitive feedback processes. Estimates of potential contributions from these processes to oxygen change are presented. An unexpected finding is that they can, in multi-millennial global warming simulations, lead to a considerable expansion of oxygen minimum zones on the one hand, and to a simultaneous increase in the total marine oxygen inventory on the other hand.

Microbial communities and biogeochemical cycles in oxygen minimum zones

Bess B. Ward, Princeton University, USA

Oxygen minimum zones (OMZ) are unique open ocean environments because the oxygen depleted conditions allow the development of anaerobic microbial communities and biogeochemical processes in an otherwise oxic environment. The surface waters in these regions are among the most productive in the world and the anoxic layers, although a tiny portion of the total ocean volume, host microbial processes that control important marine biogeochemical cycles (and the fixed nitrogen inventory of the ocean) and contribute substantially to the ocean-atmosphere flux of the potent greenhouse gas, nitrous oxide. The physical and chemical stratification of the OMZ water column results in stratification of the microbial assemblages and biogeochemical pathways. Here we review the biogeochemistry of carbon, nitrogen and sulfur cycling and the microbial assemblages in each successive layer. The most important layer, in terms of microbial activity and biogeochemistry, is the upper boundary of the oxygen depleted zone (ODZ) or the top of the ODZ. Across this interface over a few meters' depth, the conditions range from fully oxygenated to completely anoxic. Ammonium oxidation is focused just above the ODZ, while the tiny cyanobacterium, Prochlorococcus, forms strong abundance maxima at the top of the ODZ, in conditions of near darkness and near anoxia. Strangely enough, nitrite oxidation, normally an obligately aerobic process, occurs near the top of the ODZ and also in underlying anoxic waters. In the anoxic region, denitrification is carried out in modular fashion by a vast diversity of bacteria, with many diverse physiological capabilities, including sulfur redox chemistry. The diverse assemblage of bacteria involved in various facets of denitrification is in contrast to anammox, which is performed by a single genus with minimal divergence. Nitrogen fixation is not a major process in OMZ regions, despite the widespread prevalence of the genetic potential for the pathway.

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Warming and nutrients as drivers of hypoxia in the Baltic Sea

Jacob Carstensen, Aarhus University, Denmark

The frequency and extent of hypoxia in coastal bottom waters is increasingly worldwide. This coastal deoxygenation is mainly caused by increased anthropogenic inputs of nutrients from wastewater and fertilizer, promoting algal blooms and sedimentation of organic matter to the seafloor, where oxygen demand for the organic matter decomposition outpaces oxygen supply. Consequently, hypoxia is a potential problem only when the ventilation of bottom waters is restricted by the physical settings. Warming will exacerbate hypoxia by reducing oxygen solubility in the water, increasing respiration rates and stratification. The expansion of coastal "dead zones" poses a major threat to marine life, and the Baltic Sea is currently the largest coastal dead zone caused by human activity. The Baltic Sea is naturally prone to hypoxia and it has experienced periods of hypoxia in the geological past, but modern hypoxia has developed more extensively and rapidly than inferred from geological records. During the 20th century, the area of perennial hypoxia in the open Baltic Sea increased 10-fold and the number of coastal sites with recorded hypoxia increased exponentially. Although the main causes of increasing hypoxia are similar across the Baltic Sea ecosystems, hypoxia manifests itself in different forms from perennial in the open Baltic Sea, to seasonal in the Danish Straits, and episodic in shallower estuaries and coastal areas. Hypoxia in the Baltic Sea will continue to expand in a warmer climate, unless nutrient inputs are reduced. Significant nutrient reductions during the last three decades have halted the accelerated expansion of hypoxia, but not reversed the trend. Warming and internal feed-back processes of nutrients are possible causes for the apparent ecosystem resilience to reduced nutrient stress.

Ecosystem impacts of hypoxia in coastal waters

Alf Norkko, University of Helsinki, Finland and Baltic Sea Centre, Stockholm University, Sweden

In coastal seas, excessive organic enrichment and rising temperatures are resulting in spreading hypoxia that is profoundly changing benthic–pelagic processes and the functioning of coastal ecosystems. Coastal soft-sediment habitats are important for global cycles of elements and energy, but they are increasingly compromised by hypoxic events that erode seafloor biodiversity and influence their contribution to key processes and ecosystem functions, such as nutrient transformation and retention. Whilst our basic understanding of how coastal ecosystems respond to hypoxia are well-established, our knowledge of how feedbacks between the biodiversity of macrofaunal communities and key ecosystem processes such as organic matter mineralization, burial, and nutrient transformation pathways change across gradients of hypoxic stress are still limited. Hence our ability to generalize how changing biodiversity modifies ecosystem functions in real world settings is limited due to the complexity of natural ecosystems. I will provide examples from a combination of in situ field experiments, large-scale field surveys and modelling efforts across the Baltic Sea, which aim to resolve how macrofaunal communities process organic matter and mediate nutrient fluxes across the sediment-water interface, while exploring how gradients in eutrophication and hypoxia modify these relationships. These studies suggest that the relationship between benthic community structure and nutrient fluxes is highly context dependent and dictated by local communities and environmental conditions. Changes in the distribution of functionally important species due to progressing eutrophication and climate change thus has important feedbacks on the functioning of seafloor ecosystems. Mitigation efforts by society need to embrace this complexity, as it has important bearings on the ecosystem services coastal seas provide to society.

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Impact of hypoxia on coastal biogeochemistry

Daniel J. Conley, The Environmental Committee, The Royal Swedish Academy of Sciences, Sweden and Caroline P. Slomp, Utrecht University, The Netherlands

Coastal waters throughout the world are rapidly losing oxygen due to human-induced eutrophication and global warming. This deoxygenation is dramatically altering biogeochemical processes in coastal systems with major consequences for marine life. Prominent examples of such anthropogenic coastal "dead zones" include the Gulf of Mexico at the mouth of the Mississippi River and the Baltic Sea.

In this talk, we will discuss the impact of low oxygen in bottom waters on the cycles of nitrogen, phosphorus, iron and sulfur using examples from a range of modern coastal environments. We will specifically focus on changes in and interactions between the cycles of these key bioactive elements and how they can delay or accelerate the onset, development and recovery from coastal hypoxia. Examples will illustrate (1) the role of the recently discovered "cable bacteria" in preventing the escape of the nutrient phosphorus and highly toxic hydrogen sulfide from sediments to overlying waters, (2) the role of anoxic sediments as a continued source of reductants and nutrients upon reoxygenation of coastal systems (the "legacy of hypoxia"), and (3) the biogeochemical impact of changes in iron availability in coastal systems, for example, due to changes in river input of iron or sequestration in the form of iron sulfide minerals in sediments.

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Managing the Baltic Sea

Christoph Humborg, Stockholm University, Sweden

Low oxygen zones caused by eutrophication in various marine basins of the Baltic Sea were a major cause for launching the HELCOM Baltic Sea Action Plan, an ambitious program thriving for "a Baltic Sea unaffected by eutrophication" as a main objective. The BSAP is exceptional in terms of its aim and scale: to reverse eutrophication in an entire coastal water body by lowering riverine and atmospheric nutrient loads from a cultivated watershed. In fact, the BSAP is recognized as a blueprint for regional, international cooperation to address coastal water quality problems within the EU. Recent trends and effects of nutrient abatement strategies will be discussed in this paper.

Only about half of nutrient fertilizers added globally onto cropland is converted into harvested products, compared to some 2/3 in the early 1960s, while synthetic fertilizer input increased by an order of magnitude over the same period. The situation in the Baltic Sea catchment is not far different. This paper gives an overview of the state of knowledge of Nutrient Use Efficiency (NUE) in various Baltic countries, main causes for nutrient imbalances and present scenarios on how improvements in NUE and investments in municipal sewage facilities may contribute to reaching the eutrophication targets of the BSAP.

There have been substantial reductions in nutrient loads from rivers and the atmosphere, however, responses in terms of low oxygen zone in the sea are hardly visible due to long water residence times. That's why the effectiveness on measures to combat Baltic Sea anoxia on land has been questioned. Instead geo-engineering (sea-based measures) have been proposed. It has been suggested that artificial oxygenation by wind driven pumps of deeper water layers could cause the Baltic Sea to recover from the eutrophication within 10-15 years. We test this hypothesis by analyzing recent monitoring data following the latest vast salt water intrusion and oxygenation event.