Proposal for a SCOR Working Group on Natural and Human-Induced Hypoxia and Consequences for Coastal Areas

Abstract

There is accumulating evidence and growing concern that low oxygen (i.e. hypoxic) conditions are proliferating in marine coastal environments worldwide. Coastal hypoxia has major ecological and biogeochemical consequences that are poorly understood and often studied in isolation from other conditions. The intensity, duration and frequency of coastal hypoxia are changing due to human-induced alteration of coastal ecosystems (e.g., enhanced delivery of nutrients and/or organic matter) and changes in oceanographic conditions potentially related to global warming, climate variability and ocean circulation patterns. Recent work suggests that hypoxia induces changes in ecology and biogeochemistry that are strongly coupled and linked with the adjacent land and open ocean. Hypoxia can be either intermittent or permanent, with different consequences for various organisms and key biogeochemical processes. The integration of existing knowledge on the biogeochemical and ecological processes related to intermittent hypoxia is central to this working group. This group will collect and synthesize the available data on coastal hypoxia and produce a state-of-the-science report that (1) summarizes the mechanisms governing coastal hypoxia, (2) documents the ecological and biogeochemical consequences, (3) identifies the gaps in our understanding and (4) evaluates the requirements for observing and predicting hypoxia events and their impacts.

Rationale

Events of low oxygen can cause serious problems in coastal areas of the world. These problems include changes in populations of marine organisms such as large-scale mortality, as well as changes in species distributions, changes in biodiversity, physiological stress, and other sub-lethal effects, such as reduced growth and reproduction (Service, 2004). Tourism can be negatively affected by dead organisms and unpleasant smells. Hypoxic events are increasing in intensity and frequency worldwide (Rabalais and Turner, 2001) and the public is becoming increasingly aware of the events and their impacts (Boesch, 2004; Ferber, 2004). Hypoxic events can not only be caused by nutrient and organic matter inputs from land areas, but also by natural intrusions of sub-surface oceanic low-oxygen waters (Grantham et al., 2004), or by stimulation from up-welled nutrients, such as in Benguela and California upwelling systems. It is important to synthesize existing knowledge about the causes and effects of hypoxia in coastal areas, and to recommend research, observation strategies, and modeling activities that can enable better understanding and prediction of hypoxic events to make adaptation and/or mitigation possible.

A SCOR working group is the best mechanism to ensure a coordinated international scientific effort on the issue of coastal hypoxia. The scientific rationale for this working group comes from the benefits that could be gained by bringing together biologists, chemists, and physicists to identify common features and differences in governing mechanisms among hypoxic systems in different coastal settings worldwide. The results of this working group would contribute to several SCOR and IGBP large-scale ocean research projects, and to national, regional, and international coastal observing systems.

Scientific Background

We do not provide a complete background on coastal hypoxia and consequences on biogeochemical cycles and marine ecology. Rather, we summarize those issues that have motivated the organization of the working group that is, increasing hypoxia problems in the coastal ocean, and their impacts on the functioning of ecosystems and biogeochemical cycles.

Hypoxia in coastal waters is governed by physical and biogeochemical processes. Enhanced delivery of nutrients and organic matter to coastal waters may generate hypoxia in certain settings (e.g., strong surface stratification and long water residence time). Upwelling of subsurface oceanic waters that have low oxygen content and subsequent warming may also cause zones of hypoxia. Upwelled nutrients along western boundaries result in enhanced productivity and subsequent accumulation of carbon and oxygen deficiency. The combined effect of natural upwelling of low oxygen oceanic water and enhanced availability of nutrients and organic matter may accelerate and intensify coastal hypoxia.

Hypoxia in a variety of coastal environments is now believed to be a major barrier to the sustainability of ecosystems (cf. Naqvi et al., 2000; Breitburg, 2002). There are several potential causes of hypoxia in the coastal ocean, including (1) increase in land-source input of organic materials and nutrients with limited circulation and vertical mixing, for example, off large river mouths and adjacent continental shelf areas; (2) climate-induced change (e.g., monsoon) in coastal oxygen depletion, and (3) intrusion of deep oxygen-depleted waters in near-coastal areas, through upwelling and changes in coastal circulation.

Although the occurrence of hypoxic events may not necessarily be induced by human activities, the existing knowledge indicates that anthropogenic perturbations can be an important factor in the occurrence of coastal hypoxia. Land-based human activities have been shown to greatly increase the riverine influx of nutrients world-wide and modify ratios between nutrient species, e.g. N/P and N/Si (Turner et al., 2003). Loading and composition of organic materials from terrestrial sources can also be modified by human activities in the watersheds. For instance, the construction of dams and/or reservoirs not only affects the fresh water discharge, and hence stratification of the receiving water bodies, but also dissolved silicate can be trapped resulting in highly modified N/Si and P/Si ratios. Deforestation and land erosion can have dramatic effects on coastal water quality. Other major pathways of nutrient inputs to the coastal environment include atmospheric deposition and discharge of groundwater. Another important influence of human activity is from marine aquaculture, which in some coastal regions (e.g., Asia) can have dramatic impact on the nutrient load in coastal waters.

A growing body of evidence suggests that interannual-to-interdecadal variability in ocean biology is linked to large scale fluctuations (e.g., El Niño/Southern Oscillation, Pacific Decadal Oscillation, North Atlantic Oscillation) through direct or indirect pathways of ocean circulation. The net impacts of large-scale ocean current systems and associated biogeochemical conditions on the structure and dynamics of coastal ecosystems in general and coastal hypoxia in particular, however, remain poorly resolved. Understanding the linkages between open ocean climate (Keeling and Garcia, 2002) and the frequency, duration and intensity of coastal hypoxia events is critical for open coastal regions since they support a major proportion of the world's fisheries and marine biodiversity, and are a focus of chemical transformations of globally important elements. For example, the intrusion of anomalously strong inflow of subarctic water into the California Current System led to unprecedented development of severe inner-shelf hypoxia and resultant mass mortality of fish and invertebrates in summer 2002 (Grantham et al., 2004). Gilbert et al. (2005) present evidence of a long-term decline of oxygen in the St. Lawrence Estuary (Canada) from intrusions of oxygen-poor oceanic water. How and to what extent the above mentioned mechanisms function in different climate and oceanographic settings have profound effects on the transition from oxygen-rich to hypoxic conditions and vice versa.

Low oxygen conditions have major consequences for biogeochemical cycles and the diversity and functioning of biological communities. Some hypoxic systems have been studied extensively, but an integrated view is lacking and there is limited understanding of the interactions between biogeochemical cycles and their dynamics. Hypoxia can alter the relative importance of nitrate removal pathways (e.g., denitrification, ammonium regeneration and anaerobic ammonium oxidation) and induce formation and emission of nitrous oxide, a radiatively active greenhouse gas. Oxygen conditions determine the retention and regeneration of phosphorus in sediments; regeneration increases under anoxic conditions and burial increases under oxic conditions. Many trace element cycles, including those of essential trace nutrients, are governed by oxygen availability. For example, iron regeneration is lowest under fully oxic and permanent anoxic conditions, and highest under low oxygen or alternating oxic-anoxic conditions. Iron released from coastal sediments becomes available for coastal plankton communities and, after cross-shelf transport, also for open ocean communities. Hypoxic conditions on shelf ecosystems could thus stimulate primary production in the adjacent open ocean by enhanced trace metal remobilization (e.g. through iron release) and along-isopycnal transfer.

The effect of hypoxia on marine benthic metazoans has been relatively well studied in terms of the number and biomass of animals (Levin, 2003) and the differential tolerance of benthic organisms towards low oxygen conditions. However, the consequences of these community changes on the interactions between metazoans and bacteria and functional diversity aspects as well as their impact on nutrient regeneration and cycling have been addressed only occasionally; there is a clear need for synthesizing the available data. Animals that are mobile can move away from hypoxic areas, but sessile organisms cannot relocate and experience physiological stress and may die, depending on the intensity, frequency, and duration of hypoxic events. If metazoans disappear from sediments, sulphide may reach the sediment-water interface (and even escape into the water column) and sulphide-intolerant organisms will not settle on or survive in the sediments. In extreme local cases, hydrogen sulphide has entered the water column and escaped to the atmosphere (e.g., Weeks et al., 2002). Within the shelf sediments of the Humboldt system, extended periods of hypoxia favor high biomass development in the form of mats of the giant sulphide bacterium *Thioploca* (Gallardo, 1977), which can link the benthos to modified water column food webs. Within the water column, low oxygen water causes changes in distribution of fish spawning (e.g., Black Sea anchovy), in the magnitude of recruitment (Baltic cod), and in available habitat of pelagic and demersal species, increasing exposure to predation and other causes of mortality (e.g., Namibian hake). Extreme cases of hypoxia in surface waters can result from harmful algal blooms, resulting in mass mortality of water column (marine) organisms (e.g., Li et al., 2002).

Ecological and biogeochemical responses to decreasing oxygen concentrations can be fast, for example, die-off of seagrasses and benthic animals. The reverse is often not the case when oxic conditions return. The recovery of benthic communities may take years to decades. This differential response to decreasing and increasing oxygen (i.e., hysteresis) may result in alternative quasi-stable states or benthic regime shifts.

A number of observing systems are in the planning stages for coastal areas, as documented by the Coastal Ocean Observations Panel of the Global Ocean Observing System (GOOS), which has identified hypoxia as one of the issues of interest for coastal observations. There is a need for improved technology for observations, for example, through utilization of a range of sensors, not only for oxygen, but also sensors of nutrients and micro-nutrients important in generating hypoxia, as well as sensors of the biogeochemical and biological impacts of hypoxia. New technological developments have recently enabled scientists to routinely monitor oxygen concentrations remotely and transmit data in real-time (Körtzinger et al., 2004). These developments offer ample opportunities to begin the task of monitoring changes in the ocean's oxygen regime, as well as other measurements important for understanding the causes and consequences of hypoxia. It is timely to have a coordinated examination of the requirements for such systems, in terms of detecting and predicting hypoxic events and their consequences. The placement of sensors and their use in detection and prediction of hypoxic events is being carried out in various locations. Guidelines are needed for time and space scales for future placement and use of observing systems.

Model simulations are necessary to assess the sensitivity of oxygen budgets to variations in anthropogenic nutrient load from fresh water influx, water column properties and cross-shelf exchanges, variations in climate, etc and critical scales of forcing. The models designed to simulate temporal changes of oxygen in response to variations in climate and anthropogenic loading have involved various levels of complexity spanning from simple nutrient – oxygen models (e.g., Justic et al., 2003) to more sophisticated ones with various levels of food-web complexity (e.g., Park et al., 1996) and biogeochemical cycles (e.g., Oguz et al., 2000). An interdisciplinary modeling approach involving coupled physical and biogeochemical processes as well as local and open-ocean forcing is required for more accurate predictions of hypoxia events and for more deterministic understanding of their causes and effects. The latter issue is important in understanding global biogeochemical cycles, an active topic in oceanographic studies from tropical to high latitude.

Terms of Reference

The working group will conduct its work by pursuing the following term of reference:

1. Synthesize the state of the science and make recommendations for future research related to the following topics:
    - prevalence and variability (i.e., temporal and spatial) of human-induced coastal hypoxia,
    - influence of the open ocean on the occurrence of coastal hypoxia,
    - effects of hypoxia on the biogeochemistry and ecology of coastal marine systems, particularly the role of daily to intra-decadal variability, and
    - non-linearity (e.g., asymmetric influence) in effects of the formation of, and

recovery of coastal ecosystems from, hypoxic events;
2. Determine the requirements for observing hypoxic events and their impacts in coastal systems;
3. Identify requirements for modeling coastal hypoxia and its impacts;
4. Document the work of the group in a special issue of a peer-reviewed journal or a book by a major publisher.

Working Group Membership

The work proposed in this document would be carried out by a group of ten Full Members and 11 Associate Members (more Associate Members may be nominated at the first working group meeting). The proposed list of members provided below would ensure wide geographic coverage and includes expertise in biological, chemical, and physical oceanography, marine biology and fishery, and modeling. The Full Members listed below have agreed to serve on the working group, if it is approved.

Full Members

1. Jing Zhang (China) - Co-chair - Chemical oceanography
2. Denis Gilbert (Canada) - Co-chair - Physical oceanography
3. Jack Middelburg (The Netherlands) - Biogeochemistry and modeling
4. Nancy Rabalais (USA) - Biology
5. Wajih Naqvi (India) - Chemistry
6. Pedro Monteiro (South Africa) - Biogeochemistry
7. Temel Oguz (Turkey) - Physics and modeling
8. Lisa Levin (USA) - Benthic ecology
9. Osvaldo Ulloa (Chile) - Biology
10. Venu Ittekkot (Germany) - Biogeochemistry

Associate Members

1. Boris Dewitte (France) - Physics
2. Mike Kemp (USA) - Chemistry
3. Andy Gooday (UK) - Biology
4. Elva Escobar (Mexico) - Benthic biology
5. Ragnar Elmgren (Sweden) - Ecology
6. Mary Scranton (USA) - Microbial ecology
7. Werner Ekau (Germany) - Fishery
8. Howard Freeland (Canada) - Physical oceanography
9. Anja van der Plas (Namibia) - Chemical oceanography
10. Silvio Pantoja (Chile) - Biogeochemistry
11. Teruaki Suzuki (Japan) - Biology

Working Group Activities

If approved, the working group would organize its first meeting in early to mid-2006, potentially in conjunction with the Ocean Sciences Meeting (February) or the annual EGU meeting (late April). At its first meeting, working group members will make short presentations about their scientific activities, followed by (1) agreement on how they will fulfill their terms of reference (who will do what), (2) discussion of whether they will require a workshop to fulfill the terms of reference and produce their publication, (3) discussion of potential funding sources for a workshop, if needed, and (4) detailed planning related to the workshop and/or publication. If a workshop is planned, it will be held in late 2007 or early 2008, followed by the second meeting of the working group. The final meeting of the group will be held in 2009, to complete their publication.

The Scientific Committee on Problems of the Environment (SCOPE) will be approached about co-sponsoring the working group, as they have interest in this topic. The activities of this group could be useful for many global ocean research projects, including GEOHAB, GEOTRACES, GLOBEC, IMBER, LOICZ, and SOLAS. Therefore, the working group will ensure that mutually beneficial links are established with other global ocean projects.

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