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SYNTHESIS AND REVIEW

Hypoxia in the changing marine environment

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Abstract
The predicted future of the global marine environment, as a combined result of forcing due to climate change (e.g. warming and acidification) and other anthropogenic perturbation (e.g. eutrophication), presents a challenge to the sustainability of ecosystems from tropics to high latitudes. Among the various associated phenomena of ecosystem deterioration, hypoxia can cause serious problems in coastal areas as well as oxygen minimum zones in the open ocean (Diaz and Rosenberg 2008 *Science* **321** 926–9, Stramma *et al* 2008 *Science* **320** 655–8). The negative impacts of hypoxia include changes in populations of marine organisms, such as large-scale mortality and behavioral responses, as well as variations of species distributions, biodiversity, physiological stress, and other sub-lethal effects (e.g. growth and reproduction). Social and economic activities that are related to services provided by the marine ecosystems, such as tourism and fisheries, can be negatively affected by the aesthetic outcomes as well as perceived or real impacts on seafood quality (STAP 2011 (Washington, DC: Global Environment Facility) p 88). Moreover, low oxygen concentration in marine waters can have considerable feedbacks to other compartments of the Earth system, like the emission of greenhouse gases to the atmosphere, and can affect the global biogeochemical cycles of nutrients and trace elements. It is of critical importance to prediction and adaptation strategies that the key processes of hypoxia in marine environments be precisely determined and understood (cf Zhang *et al* 2010 *Biogeosciences* **7** 1–24).

Keywords: hypoxia, marine ecosystem, sensitivity, hysteresis, global change

The purpose of this focus issue is to consolidate recent substantial advances in understanding past, present and future changes in marine hypoxia within the framework of global change, including observations and novel analytical experimental and modeling approaches. In particular, we bring together research results from different aspects, including the physical driving forces linking coastal and open-ocean low-oxygen events to biogeochemical cycling of critical elements, and then scaling up to ecosystem responses and social impacts, mitigation and adaptive management. Articles in this focus issue provide data from observations and monitoring, modeling and scenario analysis, historical overview and prediction. Particularly, the following aspects are included in this special issue.

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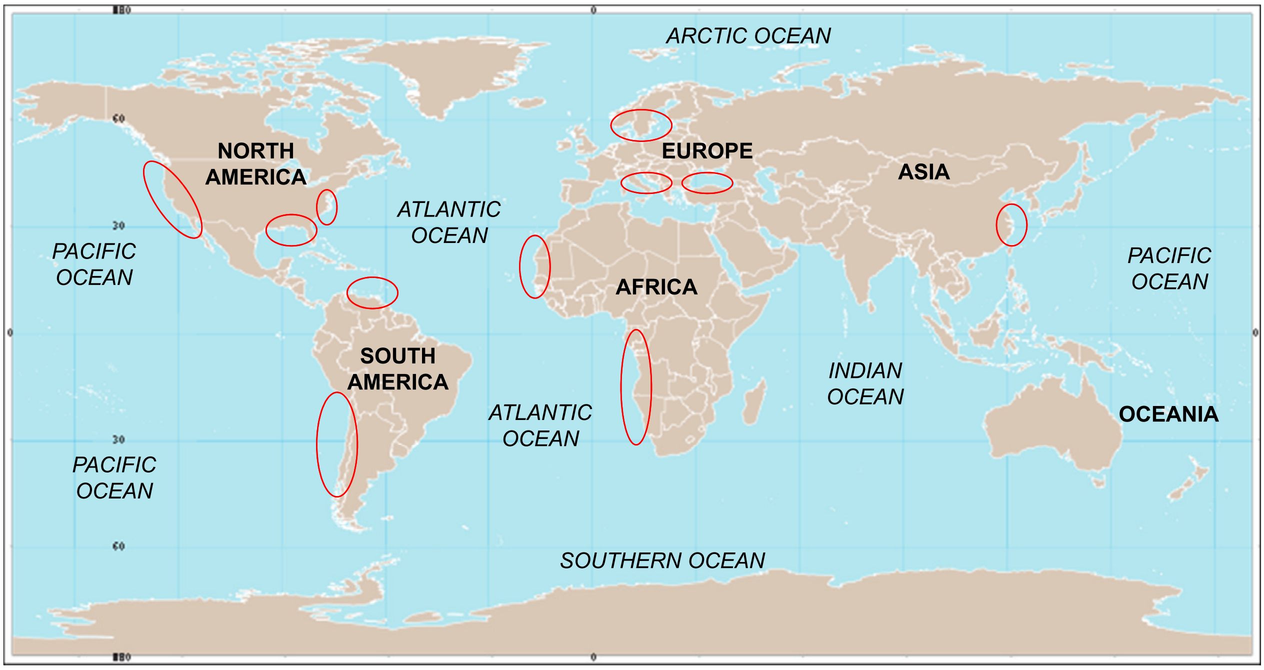

Figure 1. Some of the important hypoxia areas of the global ocean studied in this issue. The world map is from Wikipedia (http://en.wikipedia.org/wiki/Wikipedia:Blank_maps).

- Current status of marine hypoxia in ecosystems with different biogeographic settings, e.g. from estuaries, semi-enclosed seas to the oxygen minimum zones (OMZs) of the open ocean.
- Examinations of marine ecosystems affected by hypoxia at different temporal and spatial dimensions, including the impact on the sustainability of society and feedbacks to the Earth system.
- Identification of the major gaps in knowledge and techniques that are required to improve the ability to predict hypoxia in marine environments in the future.

In the paper by Evans and Scavia the authors used modification of Streeter–Phelps (SP) model to calculate longitudinal profiles of dissolved oxygen (DO) concentration for two major river-impacted coastal hypoxic areas of the United States, i.e. the Gulf of Mexico (GOM) along the Louisiana–Texas coasts and in Chesapeake Bay (CB). Then the model was used to assess the trade-off between incorporating adequate system variability into the parameterization and the ability to track gradual and abrupt ecosystem changes in hypoxia sensitivity to nutrient loads. It is suggested that changes in system sensitivity pose a great challenge to the ability of long-term forecasting and additional work on incorporation of more complex features coupled with climate scenarios is needed (Evans *et al* 2011).

Das *et al* used a high-resolution, depth-integrated, two-dimensional (2D) model and a large water quality database (1994–2010) to quantify the estuarine-shelf exchanges of carbon and nutrients in the Barataria Estuary of the Mississippi–Gulf of Mexico System, and to test the outwelling hypothesis that marsh–estuary systems produce more material than can be degraded or stored within them. It is concluded that carbon export from the Barataria Estuary is small compared to the carbon flux of the Mississippi River and to the overall carbon demand in the hypoxic zone of the Gulf of Mexico; the Mississippi River has the largest influence controlling the productivity and carbon budgets in the region (Das *et al* 2011).

Liu *et al* examined the significance of the microbial communities in the nutrient cycling and energy flow along with different stages of seasonal hypoxia off the Changjiang (Yangtze River) Estuary and the East China Sea Shelf. It was found that hypoxia has no direct effect on bacterial communities but does have an indirect influence through effects on nutrients and organic matter in the water column. The heterotrophic bacterial assemblage played an important role in biochemical degradation processes in the hypoxic area off the Changjiang Estuary, as indicated, for example, by the close relationship between bacterial clusters and oxygen depletion (Liu *et al* 2012).

Monteiro *et al* compared hypoxia in upwelling systems, such as the Benguela, Canary, Northern California, and Humboldt systems and the permanently anoxic deep Cariaco Basin. Two hypoxia regimes are proposed: low ventilation-wide shelf systems and high ventilation-narrow shelf systems. It is concluded that the seasonal and inter-annual cycles of natural hypoxia variability in the shelf upwelling systems, including marginal basins, can be explained on the basis of the interaction of shelf dynamics, which control particulate organic carbon (POC) retention, and remotely forced ocean boundary ventilation (Monteiro *et al* 2011).

Steckbauer *et al* summarized case studies from the Adriatic Sea, the Black Sea, Danish estuaries, and Delaware Bay, and showed that recovery of benthic ecosystems can be delayed for decades even after significant increases in bottom water oxygen concentrations, i.e. hysteresis-like behavior. The general sequences of re-colonization of areas impacted by hypoxia following the return to normal oxic conditions can be initiated by polychetes, followed by molluscs and then echinoderms, which correspond to the organisms with the lowest sub-lethal oxygen thresholds that can best cope with hypoxic events (Steckbauer *et al* 2011).

Glessmer *et al* used 3D simulation to address the knowledge gap on the connections between the fairly known biogeochemical and physical processes at local scales and their unclear sensitivity to predicted global change, using the OMZs of the Atlantic and Pacific Oceans as study cases because they have a discernible influence on the surface water properties in coastal upwelling systems. It has been found that, given the scenario of global climate change (e.g. $2 \times CO_2$ runs), the connection between OMZs and eastern boundary upwelling systems tends to decrease (e.g. 25%) in the future in both the Pacific and Atlantic Oceans, which is mainly due to a change in large-scale ocean circulation that in turn is associated with the change of atmospheric forcing due to global warming (Glessmer *et al* 2011).

Forrest *et al* examined the relationship of the hypoxic area on the Texas–Louisiana Continental Shelf with the changing riverine discharge (e.g. nitrogen load), climate variability (e.g. wind field), and time using a multivariable framework. The results show that a large reduction of terrestrial nutrient load is required to reduce considerably the hypoxic area (e.g. 5000 km^2) if nitrogen concentration is considered alone, and hence management of riverine nutrient concentration and discharge should be performed together. Alternatively, smaller and step-wise reductions of nutrient loadings will still have an observable impact on the extent of seasonal hypoxia (Forrest *et al* 2011).

Overall, the seven articles in this ERL focus issue provide ‘snapshots’ on the synthesis of studies on hypoxia in the changing marine environment, and the results cover a wide range of study settings, from estuaries and coastal waters to semi-enclosed marine basins and upwelling systems in the eastern boundary of open oceans (figure 1). The integrated knowledge that can be taken from the volume is that future development of hypoxia will depend on complex interactions of natural climate variability and anthropogenic perturbations, illustrated at the regional scales. Taking the coastal environment as an example, it is shown that although hypoxia can readily develop from increased nutrient inputs and consequent eutrophication, future changes in the dissolved oxygen inventory, temperature and CO_2 (e.g. ocean acidification) can also have impacts on the threshold values and hence lethal effects, including mortality of marine fauna.

Finally, we would like to take this opportunity to thank all authors for their contributions to this ERL focus issue, and to the peer reviewers for individual manuscripts for their comments and constructive suggestions. Guillaume Wright from the editorial office of ERL is acknowledged for guidance in the preparation of this focus issue.

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