



# Ocean deoxygenation: Everyone's problem

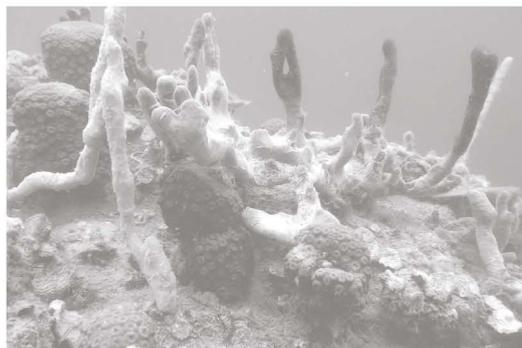
Causes, impacts, consequences and solutions

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## 5. Palaeo-records of histories of deoxygenation and its ecosystem impact

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IUCN GLOBAL MARINE AND POLAR PROGRAMME





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# 5

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## Summary

- Palaeo-records provide important information on relative changes in oxygen content, but quantitative reconstruction is still challenging.
- Substantial ecosystem degradation related to eutrophication and deoxygenation is recognized in fossils from sediment cores worldwide.
- More studies are needed in under-studied regions such as South America and south-eastern Asia, where symptoms of eutrophication and deoxygenation are occurring recently and rapidly. These may provide information to help make management decisions or to curtail deleterious activities.
- Given the general lack of long-term biological monitoring in oxygen minimum zones, further high-resolution sediment records using high sedimentation rate cores in pelagic settings can shed further light on biotic responses to changing oxygen minimum zone distribution or lowered oxygen concentrations in the past, present, and future.

Ocean hypoxia effect	Potential consequences
Palaeo records provide important information on relative (qualitative) changes in oxygen content.	<ul style="list-style-type: none"> <li>• A combination of multiple proxies, influenced by low oxygen concentrations along with other environmental parameters, point to development of oxygen-deficient overlying waters.</li> <li>• This evidence is even more striking when compared with long-term water quality data that indicate an increase in nitrogen, phosphorus and/or organic carbon loads.</li> <li>• Sedimentological proxies include varved sediments formed under permanently anoxic conditions.</li> <li>• Palaeoecological proxies (various microscopic sized fossils known as microfossils) include crustacean Ostracoda, protozoan Foraminifera, and microalgae diatoms and dinoflagellate cysts. Their indicator species, faunal/floral composition, diversity, and abundance are sensitive to deoxygenation and eutrophication.</li> <li>• Geochemical proxies include redox-sensitive trace metals, biomarkers, and stable isotopes, indicating reduced and/or eutrophied conditions.</li> </ul>
Low oxygen conditions shift biological properties.	<ul style="list-style-type: none"> <li>• Species richness, organism abundance, and overall biomass decrease substantially in low oxygen environments.</li> <li>• Opportunistic species are often dominant in hypoxia conditions.</li> <li>• Typical community shift associated with deoxygenation is disappearance or decline of sensitive species and increase of resistant species.</li> <li>• These shifts in biological properties (a.k.a. ecosystem degradation) often occur at the time of industrialization and post global conflict (e.g. World War II) economic growth in association with urbanization and development.</li> </ul>
Pelagic oxygen minimum zones show substantial variability on multi-decadal, centennial, millennial, and glacial-interglacial timescales.	<ul style="list-style-type: none"> <li>• Oxygen minimum zones tend to be stronger/expanded during warmer periods.</li> <li>• Severe deoxygenation events have occurred in semi-isolated marginal seas, e.g. due to glacial sea-level fall.</li> </ul>

## 5.1 Introduction

Deoxygenation induced by coastal eutrophication, open-ocean expansion of oxygen minimum zones as a result of global warming, and their consequences are some of the most serious problems in the ocean (Breitburg et al., 2018). But, awareness by the public and the scientific community of these problems has increased only recently, although coastal hypoxia has been addressed much more than open-ocean oxygen issues (Diaz & Rosenberg, 2008; Gooday et al., 2009; Levin, 2018; Levin et al., 2009; Vaquer-Sunyer & Duarte, 2008). Instrumental or biological monitoring data in coastal areas and the open ocean are at best only a few decades long and often even shorter. Although notable exceptions exist, e.g. Baltic Sea (Carstensen et al., 2014), they are seldom longer than a century. Only palaeo-records (palaeontological, sedimentological, and geochemical data from sediment cores) allow us

to reconstruct multi-decadal, centennial, millennial, and even longer time-scale histories beyond the period of monitoring. Time resolution can usually be within a few to ten years in coastal settings (embayments, deltas, and estuaries) because of higher sedimentation rates there (it can be 0.5–1 cm per year or more), than in open ocean settings that are usually characterized by much slower sedimentation rates. In most cases, there is uncertainty in age determination due to biological mixing of sediments (bioturbation), physical disturbances (lateral transport, erosion), and time variation in changes across broader geographic regions and depth ranges (Osterman et al., 2009; Platon et al., 2005; Rabalais et al., 2004; Tsujimoto et al., 2008; Turner et al., 2004; Yasuhara et al., 2007). Annual resolution is possible in the case of varved sediments deposited under anoxic conditions without bioturbation because of the inability of benthic infauna to be established. Thus palaeo-records are essential to understanding long-term dynamics of

dissolved oxygen levels and ecosystem impacts. This chapter provides a brief overview of the methods used in sediment cores to reconstruct past oxygen levels, the consequences and impacts of deoxygenation on marine ecosystems, and examples from case studies. These palaeo-data patterns reviewed here will help overcome the shifting baseline syndrome (incremental loss of our knowledge on historical “more natural” environments over generations) (Conley et al., 2009; Knowlton & Jackson, 2008; Pauly, 1995) and lead us to a better understanding of the long-term nature of cumulative human impact as well as natural baselines and long-term natural variation, aiding a better management of marine environments and ecosystems.

## 5.2 How to reconstruct past oxygen levels and their ecosystem impact

Past oxygen levels can be reconstructed qualitatively by using various and often coupled sedimentary, palaeoecological, and geochemical proxies from sediment cores (Gooday et al., 2009). Varved sediments (Figure 5.1) are indicative of permanent

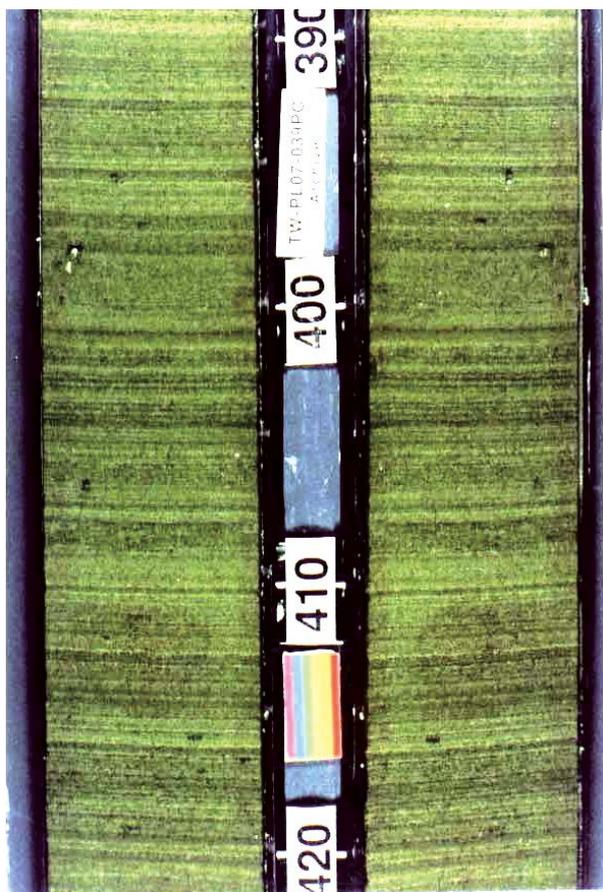


Figure 5.1 Varved sediment from Cariaco Basin on the northern margin of Venezuela. © Konrad Hughen.

anoxic conditions. Sediments from perennial, but seasonal hypoxic conditions, may not show annual layers, because seasonal normoxia allows for infaunal bioturbation. On the other hand, perennial and severe oxygen deficiency even on a seasonal basis may result in a benthic community of short-lived, opportunistic organisms restricted to surface sediments with high organic matter loading (Rabalais et al., 2001). Palaeoecological proxies (typically various microscopic sized fossils known as microfossils, e. g. crustacean Ostracoda, protozoan Foraminifera, and microalgae diatoms and dinoflagellate cysts) are important, because they tell about not only past oxygen levels but also the ecological consequences (e.g. changes in faunal composition, biodiversity and functional types) (Glover et al., 2010; Yasuhara et al., 2012, 2017). Particular species of benthic foraminiferans and ostracods can be used as hypoxia indicators (Figure 5.2). For example, ostracod species *Bicornucythere bisanensis* in north-western Pacific coastal waters and *Loxoconcha* sp. on the eastern coast of the United States are known as coastal eutrophication-hypoxia indicators (Cronin & Vann, 2003; Yasuhara et al., 2007, 2012). The ratio of abundance of *Ammonia* to that of *Elphidium* (both foraminiferan genera) is known as the A–E index and commonly used as a hypoxia proxy (Rabalais et al., 2007; Sen Gupta et al., 1996). Abundance and diversity of ostracods and foraminiferans often reflect past eutrophication and deoxygenation conditions. Organic and inorganic geochemistry, including redox-sensitive trace metals, biomarkers, and stable isotopes, can also be good proxies for past oxygen conditions (Guo et al., 2019; Rabalais et al., 2014). But it remains difficult to distinguish oxygen depletion and nutrient enrichment in some palaeo-proxies, because oxygen depletion is often caused by nutrient enrichment (Jorissen et al., 2007). A combination of multiple indicators, influenced by low oxygen concentrations along with other environmental parameters, points to development of oxygen-deficient overlying waters and its impacts on benthic ecosystems over time. Palaeo-proxies have been applied successfully to reconstruct past history of oxygen variation and its ecosystem impacts in decadal–millennial time scales (Alve, 2000; Deutsch et al., 2014; Gooday, 2003; Gooday et al., 2009; Praetorius et al., 2015; Rabalais et al., 2007; Zillén et al., 2008).

## 5.3 Gulf of Mexico

As emphasized by Rabalais et al. (2007), a multi-proxy approach is the key for robust and reliable reconstruction

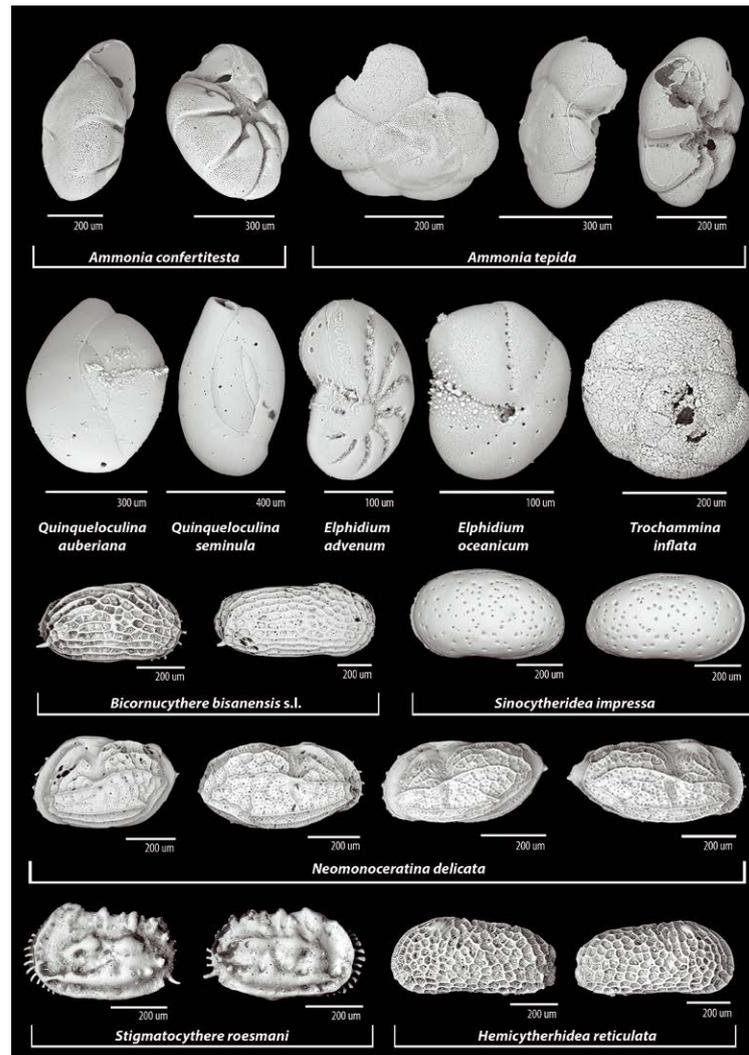


Figure 5.2 Scanning electron microscopy images of selected ostracod and foraminiferan species. All specimens are from Hong Kong. © Briony Mamo and Yuanyuan Hong.

of environmental shifts, including development of low oxygen conditions and the worsening of those conditions over time (Figure 5.3). The processes of human-caused eutrophication driven by excessive nitrogen and phosphorus results in increased production of carbon, in this case phytoplankton, and noxious and harmful algal blooms [see Section 3.2]. The flux of this organic matter to the sea bed drives increased respiration and loss of oxygen in a stratified coastal system, where oxygen re-supply is prevented by strong density gradients. Human activities lead to the increase of various forms of nitrogen and phosphorus that enter the environment with increasingly higher loads. The symptoms of eutrophication in aquatic ecosystems are noxious, and often harmful, algal blooms, and the reduction of dissolved oxygen concentrations, i.e. deoxygenation. This sequence is recorded by palaeo-indicators in

accumulating sediments in the area of the Gulf of Mexico ‘dead zone’ adjacent to the discharge of the Mississippi River. Dinoflagellate cysts are proposed by Price et al. (2018) to be good indicators of ecosystem eutrophication. Four heterotrophic taxa in particular were found to increase in the top section (1986–1997) of a core (Price et al., 2018). With an increase of nitrate-N delivered by the river, the %N, %C, and %S began to increase in the 1940s (Rabalais et al., 2014). The accompanying changes in  $\delta^{13}\text{C}$ ,  $\delta^{15}\text{N}$ , and  $\delta^{34}\text{S}$  indicated recent eutrophication in the form of increased marine *in situ* carbon formation, incorporation of Mississippi River nitrogen into marine *in situ* production, and increasing marine algal input and sulphide storage, respectively. Biogenic silica from diatom frustules also increased, indicating an increase in surface water phytoplankton production (Turner & Rabalais, 2004).

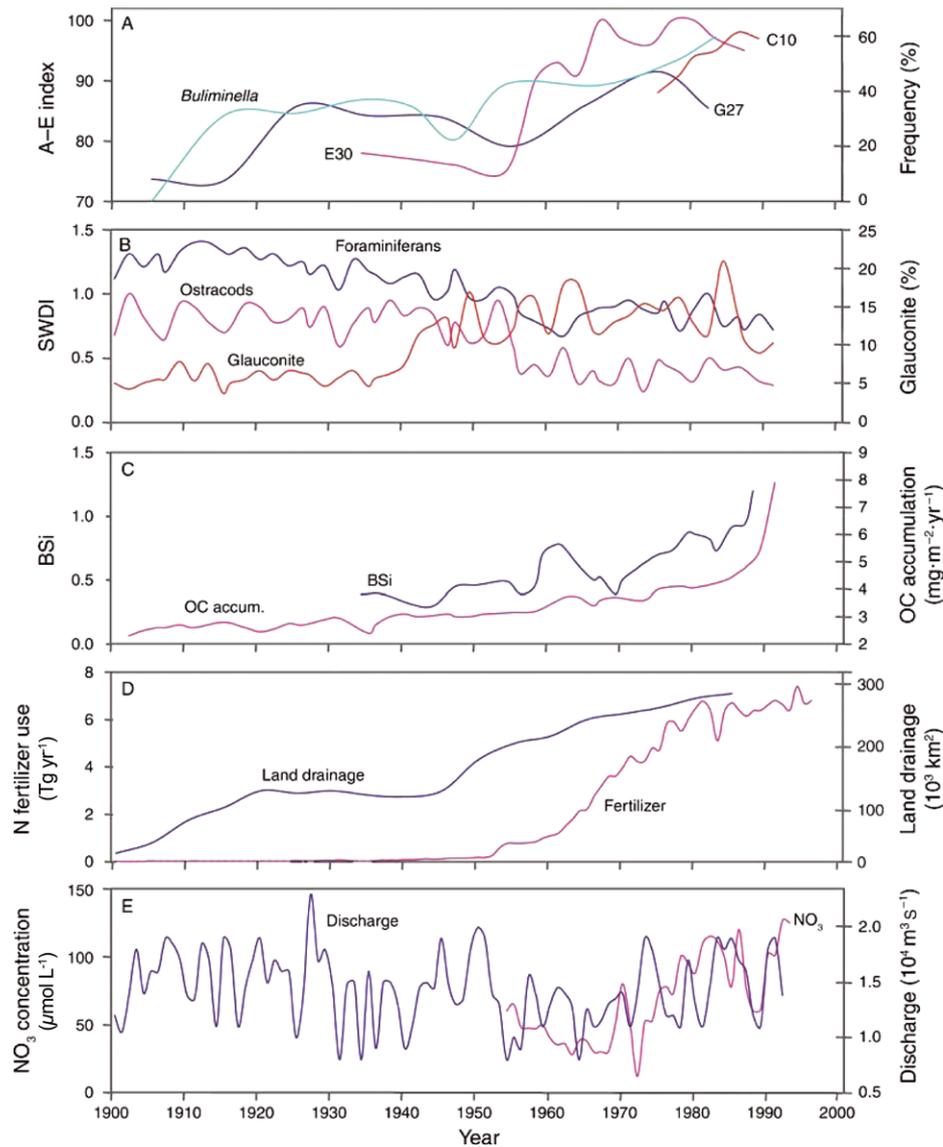


Figure 5.3 An example of multiproxy reconstruction, northern Gulf of Mexico. (A) *Ammonia–Elphidium* (A–E) index for cores C10 (3-yr running average), E30, and G27 and the percentage frequency of *Buliminella* in core G27. (B) Shannon–Wiener diversity index (SWDI) for foraminiferans and ostracods and the percentage of glauconite of coarse grains. (C) Frequency of biologically bound silica (BSi) and organic carbon (OC) accumulation. (D) Nitrogen fertilizer use in the Mississippi River basin and land drainage. (E) Nitrate concentration in the lower Mississippi River and lower Mississippi River discharge. From Rabalais et al. (2007).

A diatom genus, *Pseudo-nitzschia* (Figure 5.4), some forms of which produce the toxin domoic acid, also increased over this time (Parsons et al., 2002). With increased fluxed organic matter some foraminiferans increased (Gooday et al., 2009; Rabalais et al., 2007), but many more decreased or disappeared from the sedimentary record, indicating a worsening of oxygen levels from the 1940s (Osterman, 2003; Osterman et al., 2005, 2008; Platon et al., 2005; Sen Gupta et al., 1996). Ostracod and foraminiferan biodiversity loss paralleled an increase in glauconite (a clay mineral laid down in reducing conditions) and fertilizer use in the northern Gulf of Mexico and reflects a decrease in the

overlying oxygen concentration beginning in the 1950s (Nelsen et al., 1994). Some sensitive foraminiferans (e.g. genus *Quinqueloculina*) disappeared from the benthic community earlier than the accelerating symptoms of eutrophication (Platon et al., 2005). Some have assumed that oxygen deficiency has always been a part of the Louisiana shelf adjacent to the Mississippi River because of fresh water and temperature stratification. However, the shift in many palaeoindicators—biological, chemical, and geological—all point to worsening oxygen conditions, especially since the 1950s, when anthropogenic nutrient loads and carbon accumulation began to increase.



Figure 5.4 The diatom genus, *Pseudo-nitzschia* (not scaled) (courtesy of Oregon State University).

#### 5.4 Combining historical records with palaeo data: Baltic Sea

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 (Zillén et al., 2008). Laminated sediments, indicative of hypoxic conditions, can be seen during three intervals of the Holocene sedimentary records: the Holocene Thermal Maximum (HTM), the Medieval Climate Anomaly (MCA), and the modern hypoxic interval. These intervals were also characterized by enhanced sedimentary Mo/AI (Funkey et al., 2014). This proxy tracks the intensity of reducing conditions close to the sediment–water interface, because of the conversion of seawater  $\text{MoO}_4^{2-}$  to particle-reactive thiomolybdates above a critical activity of hydrogen sulphide (Aleelson et al., 2001). Hence, the records indicate intermittent euxinic (i.e. sulphidic) conditions in the bottom waters of the deep basins during the Holocene. The hypoxic intervals are also characterized by enhanced organic carbon ( $\text{C}_{\text{org}}$ ) contents, attributed to both enhanced preservation of organic matter under reducing conditions and enhanced primary productivity. Historical records of dissolved oxygen concentration show that low water-column dissolved oxygen concentrations have been observed since ca. 1900 with a 10-fold increase of hypoxia in the Baltic Sea during the last 100 years (Carstensen et al., 2014), which corresponds well with what is observed in the palaeo data (Zillén et al., 2008). Episodic reoxygenation events, associated with major inflows of oxic waters, encourage the retention of iron oxyhydroxides and iron-bound phosphorus in sediments, increasing vivianite precipitation as a result (Reed et al., 2016). However, dissolution of iron oxyhydroxides when oxygen conditions are low is significantly larger than sequestration by iron. Thus, enhancing vivianite

formation through artificial reoxygenation of deep waters is not a viable engineering solution to eutrophication in the Baltic Sea (Reed et al., 2016). Temperature and salinity changes were key drivers of past hypoxia in the Baltic Sea during the HTM and MCA (Papadomanolakia et al., 2018) and imply that ongoing climate change will delay recovery from the modern, nutrient-driven hypoxia present in the Baltic Sea today.

#### 5.5 Chesapeake Bay

Chesapeake Bay is a region in which extensive research has been conducted to reveal ecosystem history related to human-induced eutrophication and deoxygenation. Data from sediment cores have identified a natural ecosystem, periods of landscape change, and more recent ecological degradation from human activities. Initial signs of ecological degradation were the change in diatom abundance and flora in approximately 1700 due to European settlement and deforestation that resulted in increased river discharge and initial eutrophication (Cooper, 1995; Cronin & Vann, 2003; Yasuhara et al., 2012). Diatom diversity decreased by around 1800 (Cooper, 1995) because of further deforestation (Brush, 2009; Cronin & Vann, 2003; Willard & Cronin, 2007) and perhaps industrialization (Yasuhara et al., 2012). After that, the largest ecological changes occurred at around 1960, probably because of urbanization and substantial increase in population and fertilizer use (Brush, 2009; Cronin & Vann, 2003; Willard & Cronin, 2007). The resulting eutrophication and deoxygenation, that have become much more severe and widespread since approximately 1960, have caused serious ecosystem degradation as represented by the ostracod and foraminiferan faunal and diatom floral changes (Brush, 2009; Cooper, 1995; Cronin & Vann, 2003; Karlsen et al., 2000; Willard & Cronin, 2007). The long core record covering the past 8000 years indicates that Chesapeake Bay deoxygenation is not purely a human-induced phenomenon, and natural deoxygenation existed, though to a much lesser extent, especially in deep channels during the pre-Anthropocene Holocene (Yasuhara et al., 2012).

#### 5.6 Osaka Bay

Osaka Bay is an intensively studied region. Palaeo-ecological data indicated that initial ecological degradation was associated with the Japanese industrialization around 1900 (Tsujiimoto et al., 2008; Yasuhara & Yamazaki, 2005; Yasuhara et al., 2007).

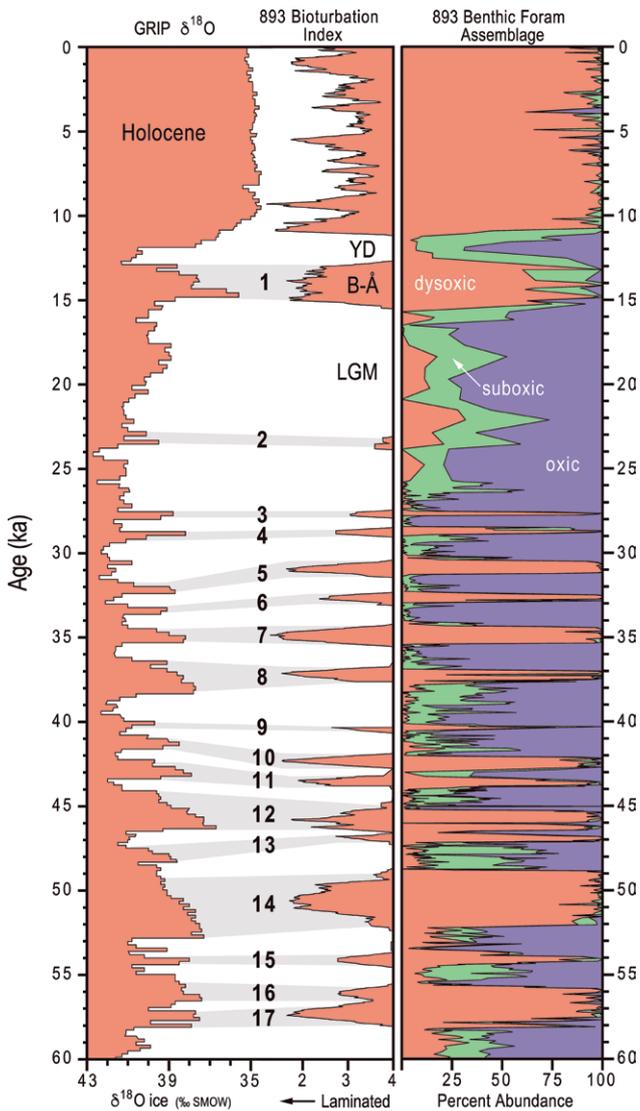


Figure 5.5 Foraminiferan community changes related to climate-induced changes in oxygen minimum zone strength, Santa Barbara Basin, USA. Relative abundance dynamics of benthic foraminiferan community (divided into dysoxic, suboxic, and oxic assemblages) are tightly linked to oxygen minimum zone strength reconstructed by laminated sediment and global abrupt climatic events recorded in a Greenland ice core GRIP. See Cannariato et al. (1999) for more details.

After this time, benthic foraminiferan diversity decreased, and the faunal composition changed (i.e. a decrease in oxygen/eutrophication sensitive species and increase in oxygen/eutrophication tolerant or opportunistic species). Simultaneously, the benthic ostracod fauna changed in a similar way. During the Japanese high economic growth period of the 1950s–1970s, these benthic faunal trends accelerated. These degradation processes of the Osaka Bay ecosystem were caused mainly by urbanization-induced eutrophication and resultant bottom-water deoxygenation since the Japanese industrialization. Since the 1970s, the abundance of the opportunistic benthic foraminiferan species has decreased and the

benthic foraminiferan species diversity has increased in the inner part of the Bay, indicating improving oxygen conditions and diversity recovery. This ecosystem recovery followed regulations that led to a reduction in organic pollution loads. However, the modern benthic foraminifera fauna is still dominated by the opportunistic species and the ostracod fauna remains impoverished (Irizuki et al., 2018; Yasuhara et al., 2012).

## 5.7 Open ocean systems

Dynamic palaeo-ecological changes related to oxygen content variation is known from open ocean oxygen minimum zones (OMZs) as well (Cannariato et al., 1999; Moffitt et al., 2015). OMZs are oxygen minima ( $<0.5 \text{ ml L}^{-1}$  dissolved  $\text{O}_2$ ) maintained at intermediate depths as a result of high biochemical oxygen consumption in the water column and weak ventilation associated with circulation patterns. Several OMZs extend over Eastern Boundary continental margins due to intense biological production and respiration (Levin, 2003; Salvatelli et al., 2016). These areas provide good records of past changes of the intensity and extent of OMZs.

A prime example is the Santa Barbara Basin, a semi-isolated area in the domain of the California Current. The millennial-scale late Quaternary abrupt climatic changes known as Dansgaard-Oeschger cycles have greatly affected the benthic ecosystem through changes in oxygen minimum zone strength (Cannariato et al., 1999; Moffitt et al., 2015). Benthic foraminiferan faunal composition categorized by their oxygen tolerance clearly track millennial-scale abrupt climate changes recorded in a Greenland ice core (Figure 5.5). Similar faunal changes are known as well from fossils other than foraminiferans (such as molluscs, ophiuroids, and ostracods) (Moffitt et al., 2015; Myhre et al., 2017). Seafloor invertebrate communities were subject to major turnover in response to relatively minor changes in oxygenation ( $>1.5$  to  $<0.5 \text{ ml L}^{-1}$ ) associated with abrupt ( $<100$  years) warming (Moffitt et al., 2015).

Over the Peru-Chile margins, a suite of sediment palaeo-proxies including the presence of laminations, redox sensitive metals (U, Mo, Re, Ni and Cu), total organic carbon, nitrogen isotope ( $\delta^{15}\text{N}$ ), and benthic foraminiferan assemblages has been used to reconstruct past changes of the Eastern Tropical South Pacific OMZ in the late Quaternary. Past oxygen levels show pronounced variability on multi-decadal, centennial, millennial, and glacial-interglacial timescales.



Figure 5.6 A Sea of Japan sediment core showing alternations of dark-coloured (i.e. anoxic condition) and light-coloured (oxygenated) sediment layers. © Ryuji Tada.

In general, over the margins, the OMZ was weaker/contracted during global cold periods such as the Last Glacial Maximum (23–19 kyr BP) and the Little Ice Age (1500–1850 AD). This OMZ weakening/contraction is associated with reduced export production and a weaker upwelling, as influenced by changes in the Walker circulation and the subtropical high-pressure cell. By contrast, it was stronger/expanded during warm intervals such as the last deglaciation (~17–13 kyr BP), part of the Medieval Climate Anomaly (900–1350 AD) and the last 100 years (Chazen et al., 2009; Gutiérrez et al., 2009; Salvattecchi et al., 2014, 2016; Scholz et al., 2014), associated with opposite forcing conditions. A bi-decadal period around the 1870s (associated with strong ENSO activity; Gutiérrez et al., 2011 and references therein) is characterized by diatom-rich sedimentation events from Central Peru to Northern Chile. These events were associated with a strong water column deoxygenation and bottom anoxia as inferred from  $\delta^{15}\text{N}$  records in the sedimentary organic matter, enrichment of redox-sensitive metals, and changes of the benthic foraminiferan community towards a higher abundance of anoxia-tolerant species (Castillo et al., 2017; Díaz-Ochoa et al., 2011; Gutiérrez et al., 2009; Salvattecchi et al., 2014). After the mid-20th century, a slight improvement of oxygen level is recognized at lower latitudes, as the benthic foraminiferan assemblage shows higher abundance of species associated with suboxic sediment conditions. Surprisingly, this trend is decoupled from increased coastal upwelling productivity (Gutiérrez et al., 2011), suggesting it is driven by enhanced subsurface ventilation.

The Sea of Japan is a semi-enclosed marginal sea between the Asian–Russian margin of the Eurasian continent and Japanese Islands and isolated from other

oceans (Pacific Ocean, East China Sea, and Okhotsk Sea) by shallow (<130 m depth) straits. This sea is now well-oxygenated, but, during the glacial periods when the sea level was >90 m lower than the present level, this sea and its ecosystem suffered serious deep-water deoxygenation caused by the isolation of the sea and the stratification due to surface freshening (Huang et al., 2018, 2019; Kido et al., 2007; Tada et al., 2015; Watanabe et al., 2007). The variation in oxygen level is clearly recorded as centimetre- to decimetre-scale alterations of dark- and light-coloured sediment layers, indicating deoxygenated and oxygenated conditions, respectively (Tada et al., 1992; Tada, 1994) (Figure 5.6). The palaeo-ecological proxy, microfossil ostracods, clearly showed that this glacial-interglacial oxygen variability has seriously affected the deep-sea ecosystem in the Sea of Japan (Huang et al., 2018, 2019). Glacial-interglacial oxygen variability has caused faunal cyclicity with a succession from opportunistic species dominance through tolerant infauna dominance to barren zone during the deoxygenation processes and the opposite succession during the recovery processes (Huang et al., 2018).

## 5.8 Global ecosystem degradation and deoxygenation

Biological remains, such as microfossils preserved in sediment cores including protists (foraminiferans), microscopic algae (diatoms, dinoflagellates), and crustaceans (ostracods), allow us to reconstruct the history of marine ecological degradation. Shifts in the ecosystem can be reconstructed by using microfossils as model systems of broader marine communities. Such shifts include the loss of marine organisms (e.g. local extinction), changes in faunal communities, ecosystems (changes in dominant functional group), and biodiversity (diversity decline) related to deoxygenation. Yasuhara et al. (2012, 2017) summarized the microfossil evidence of recent marine ecosystem degradation. The start of the degradation is clearly related to industrialization, ~200 years ago in Europe and USA and ~100 years ago or less in Asia (Rabalais et al., 2010; Yasuhara et al., 2012, 2017) (Figure 5.7). Sediment cores record substantial biodiversity declines over the past 100–200 years, for example, in Chesapeake Bay and Osaka Bay (Cooper, 1995; Cronin & Vann, 2003; Tsujimoto et al., 2008; Yasuhara et al., 2012). The primary cause of this degradation is eutrophication and resulting hypoxia in coastal areas as a consequence of deforestation, population growth, urbanization, agricultural expansion,

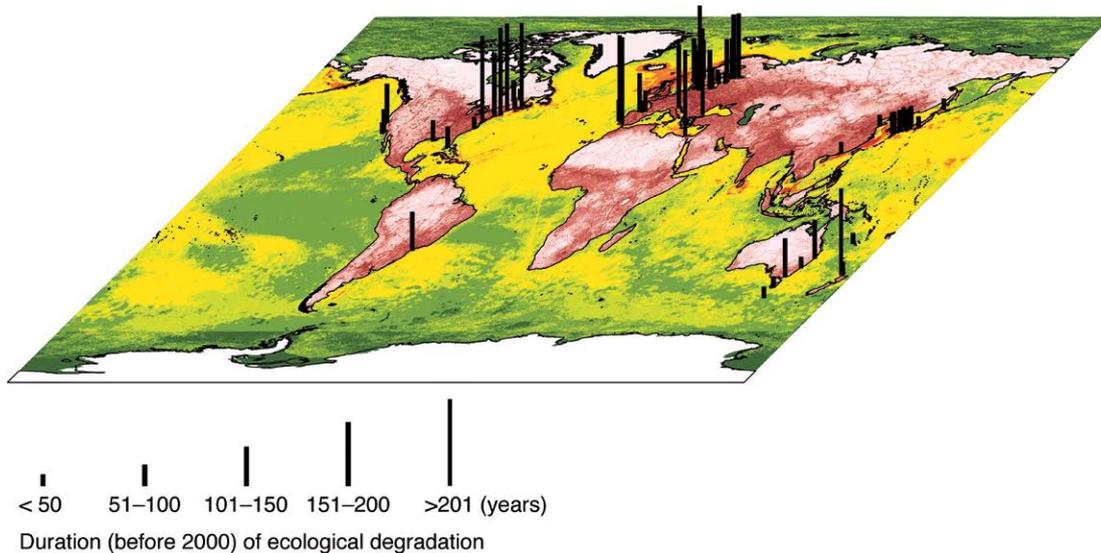


Figure 5.7 Microfossil evidence of human-induced marine ecological degradation, which is mainly related to eutrophication and resulting hypoxia. Shown is the global distribution of human footprint and historical duration of marine ecological degradation (five categories) determined from published down-core micro-palaeontological records (Yasuhara et al., 2012). Darker red colours for land and warmer colours for ocean indicate areas of higher human impact. Note that current human impact is similarly high in Europe and East Asia, but such widespread degradation occurred ~100 years earlier in Europe than in East Asia. From Yasuhara et al. (2017).

and chemical fertilizer use (Yasuhara et al., 2012); however, climate warming might also play a role in increases in hypoxia (Carstensen et al., 2014).

### 5.9 Societal implications

Encouraging social systems to take responsible actions to reverse eutrophication and deoxygenation is difficult. There are connections between the warming ocean with increased carbon dioxide emissions to the atmosphere from human activities and reduced solubility of dissolved oxygen. Palaeo-indicators from the coastal ocean discussed in this chapter had changed in concert with each other and are related to human-caused ecological change in the last 200 years. The palaeo-indicator correlations are not cause and effect proof, but the similarities are many and consistent and should support a “call to action” by citizens, businesses, agencies, and political bodies to reverse the negative trends. Logical conclusions leading to nutrient mitigation should be the norm rather than the opposite, which is continued and consumptive habits of an accelerating population level. The number of eutrophication-induced hypoxic zones is increasing globally, but several cases of recovery are known, mostly due to reductions in nutrient and organic matter loading. Cautiously optimistic and proactive actions are needed. The key to effective management is raised awareness of the phenomenon of deoxygenation,

as well as its causes, consequences, and remediation measures (Breitburg et al., 2018).

### 5.10 Conclusions

1. Palaeo records provide important information on relative changes in oxygen content. A combination of multiple indicators, influenced by low oxygen concentrations along with other environmental parameters, points to development of oxygen-deficient overlying waters. This evidence is even more striking when compared with long-term water quality data that indicate an increase in nitrogen or organic carbon loads.
2. Substantial ecosystem degradation, including loss of diversity, decreases in abundance, and changes in faunal composition often with dominance of opportunistic species, parallels palaeo-indicators indicating worsening oxygen concentrations in several coastal ocean settings. Similar faunal shifts in larger infauna (molluscs) also occur with eutrophication and oxygen decline (Kidwell, 2007).
3. Palaeo-indicator research is concentrated in Europe and North America, where most of the worsening oxygen conditions had long occurred (Diaz & Rosenberg, 2008), but symptoms of eutrophication and deoxygenation are occurring

more in under-studied regions such as South America and Southeast Asia, where similar palaeo-indicator studies are warranted. These may provide information for management decisions that would curtail deleterious activities.

- On-going global warming has caused expansion of pelagic oxygen minimum zones with further impacts on the associated marine ecosystems (Breitburg et al., 2018). Given the general lack of long-term biological monitoring in oxygen minimum zones, further fine-scale time resolution palaeo research using high sedimentation rate sediment cores in pelagic settings can shed further light on biotic responses to changing oxygen minimum zone distributions or lowered oxygen concentrations. In turn, the combination of palaeo-records collected offshore and nearshore in the continental margins may give insights on the natural and anthropogenic contributions for recent (de)oxygation trends.

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