



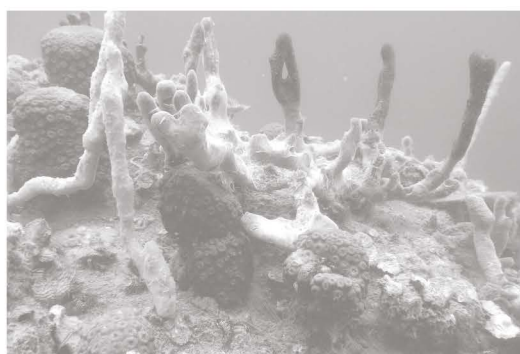
# Ocean deoxygenation: Everyone's problem

Causes, impacts, consequences and solutions

Edited by D. Laffoley and J.M. Baxter

## 2.2 Evidence for ocean deoxygenation and its patterns: Atlantic Ocean

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IUCN GLOBAL MARINE AND POLAR PROGRAMME





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### Summary

- No other chemical parameter is of such importance to all higher marine life as dissolved oxygen. From available data it is obvious that oxygen-limited areas have expanded throughout most of the Atlantic during the last 50 to 100 years and are clearly related to human activities.
- Oxygen limited waters, hypoxic and even anoxic conditions are now found in many coastal areas in the Atlantic Ocean including in connected seas like the Mediterranean, the Black Sea, the North Sea and the Baltic Sea, and the Gulf of Mexico.
- Sediment studies show that anoxic conditions have been present in deep waters in the past, long before anthropogenic activities started to have an influence on the marine environment. However, the present observed deoxygenation in coastal and offshore areas is clearly linked to human activities such as input of nutrients and organic matter, and increasing temperatures as a result of climate change.
- The expanding oxygen minimum zones affect the entire Atlantic ocean ecosystem, its biodiversity and productivity.
- In addition to many coastal waters, oxygen limited waters are also found at mid-water depths (typically 300-1000 m) in the Atlantic Ocean basins, particularly the Equatorial and South Atlantic. The oxygen concentrations in these areas have decreased during the last 60 years, partly due to ocean warming, and partly as a result of decreased mixing and ventilation.
- Continued spreading of deoxygenated areas in the Atlantic, as well as the rest of the world ocean, must be considered a most serious environmental problem with enormous potential impacts on biodiversity and human societies.

Atlantic Ocean deoxygenation	Potential consequences
Oxygen limited areas have expanded over most of the Atlantic Ocean during the last 50 to 100 years.	<ul style="list-style-type: none"> <li>If the conditions continue to deteriorate a number of human ocean and coastal activities are in jeopardy including fishing, aquaculture and coastal tourism.</li> </ul>
Human activities are the reasons for the expanding oxygen limited areas.	<ul style="list-style-type: none"> <li>If the release of nutrients, oxygen depleting organic substances and greenhouse gases are not dealt with, the deoxygenated areas will expand as well as extend into deeper parts of the Atlantic Ocean.</li> </ul>
Consequences can now more often be noted in many coastal areas and marginal seas where the smell of anoxic water is a regular phenomenon.	<ul style="list-style-type: none"> <li>Coastal areas will lose fisheries, tourism and may even be uninhabitable to marine life.</li> </ul>
In addition to large parts of the coastal waters of the Atlantic, over the last 60 years large ocean basins such as the Equatorial and southern Atlantic are being affected by decreasing oxygen levels.	<ul style="list-style-type: none"> <li>If the deoxygenation of entire ocean basins continue human life will be seriously threatened, not only in coastal areas but everywhere on the planet.</li> </ul>

### 2.2.1 Introduction

The Atlantic Ocean, including marginal seas like the Mediterranean, Gulf of Guinea, Black Sea, North Sea, Baltic Sea, and Gulf of Mexico, is the second largest body of water on the planet. The surface area of about 106 million km<sup>2</sup> with an average depth is about 3600 m, and a maximum depth of 8500 m. The Atlantic Ocean is the drainage basin for more land area than any other ocean basin. Seven of the world's ten largest rivers empty into the Atlantic Ocean. The Atlantic Ocean basin is the only part of the world ocean with significant water exchange with the Arctic Ocean.

There are more and longer data series of physical/chemical and biological parameters from the Atlantic (particularly the North Atlantic) than from any other part of the world ocean. Such data series of measurements in some cases stretch as far back as 150 years.

In the Atlantic Ocean, as in most of the world ocean, the oxygen concentrations in the water column are generally characterized as slightly supersaturated in the surface water, more-or-less undersaturated at intermediate depth, and with higher levels of oxygen, although still undersaturated, in deeper waters. This difference in the oxygen concentration is a reflection of the production and uptake of oxygen through photosynthesis and air-sea gas exchange near the surface, and the consumption through respiration and degradation processes below. Deeper waters tend to have higher oxygen levels because of supply of well-oxygenated bottom waters and low degradation rates. These well-oxygenated bottom waters originate from down-welling/thermohaline circulation in polar

regions. The oxygen-minimum zone typically occurs at depths between 300 and 1200 m which is the zone where the permanent thermocline is found. A number of other physical processes also influence the levels of oxygen at a particular depth in the ocean, such as circulation, and down- and up-welling. The Atlantic is characterized by massive down-welling in the North Atlantic and Norwegian Sea. Here North Atlantic Deep Water (NADW) is formed which feeds the upwelling in many other regions of the world ocean. There is also significant although less pronounced down-welling in the South Atlantic near Antarctica.

Upwelling areas are found in several parts of the Atlantic Ocean (Figure 2.2.1). At these sites nutrient rich deep water is brought up to the surface through a combination of wind and Ekman drift and the Coriolis force. Ekman drift is the process where winds generate currents and due to such currents upwelling occurs, a process called the Coriolis effect. This deep water may, however, be oxygen limited or hypoxic and such waters are found often around 100 to 300m depth and sometimes even at the surface. Pronounced upwelling areas are found for example off the south-west coast of Africa where the Benguela Current brings pulses of hypoxic deepwater to the surface along the coast of South Africa, Namibia and Angola (Arntz et al., 2006; Mohrholz et al., 2008; Monteiro et al., 2006, 2008; Prochazka et al., 2005) (Figure 2.2.1). The Canary Current is a wind-driven surface current which is part of the North Atlantic Gyre. Along the north-west African coast off Mauretania and West Sahara the Canary Current, due to the Ekman drift, produces a pronounced upwelling which brings oxygen-depleted but nutrient-rich deep water to the surface (Gyory et al., 2007; Hempel, 1982). Furthermore, seasonal upwelling

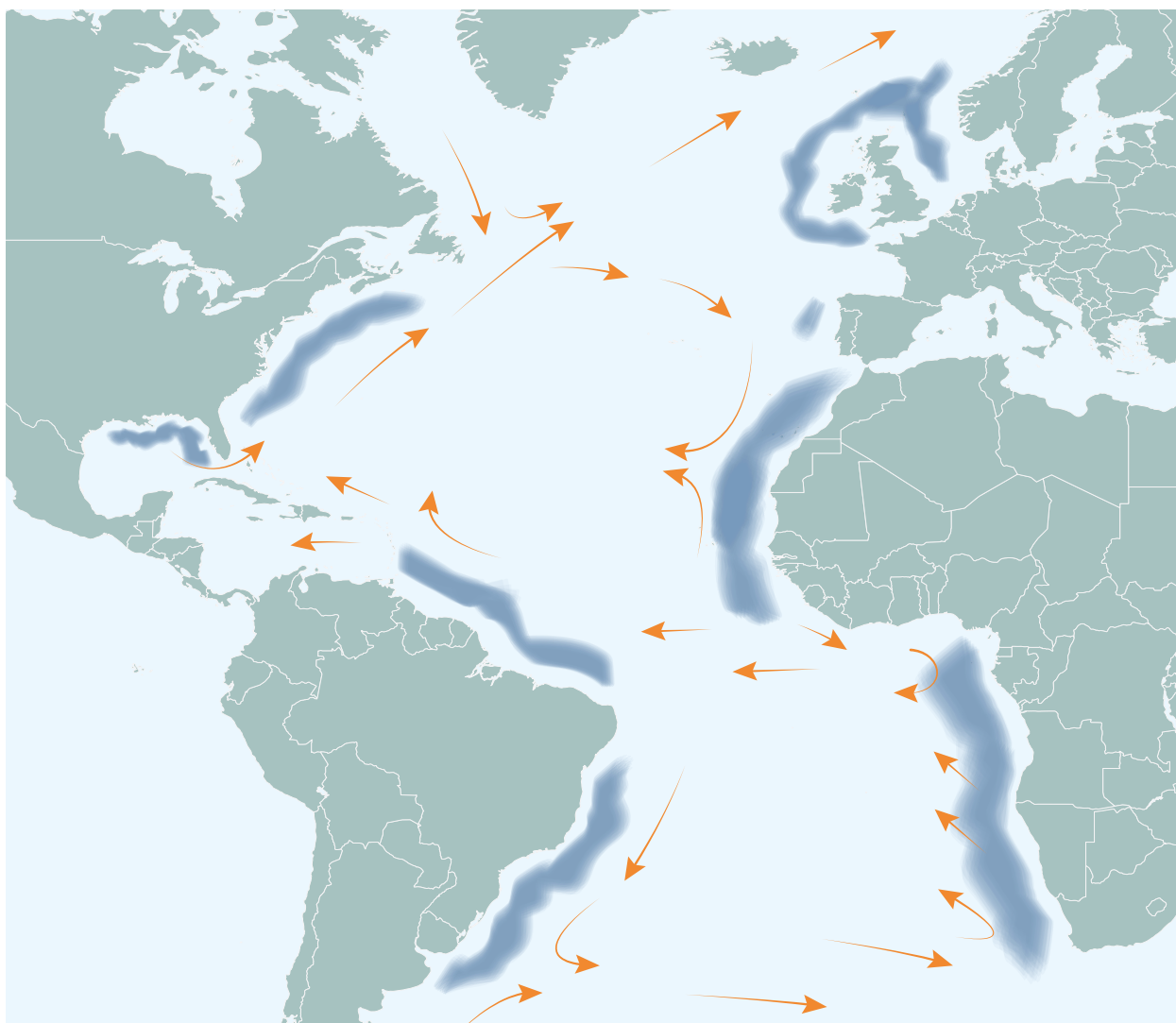


Figure 2.2.1 The Atlantic Ocean with areas of permanent or seasonal upwelling of deep water (dark blue areas). Such areas are common in the basins along the western coasts of the Europe and Africa but occurs also along large parts of the coastline in Europe and North America as well as in the Baltic and Black Seas. Major surface currents are also illustrated (orange arrows).

areas related to the West African monsoon are found in the central equatorial Atlantic Ocean, typically occurring from May through September (Christian & Murtugudde, 2003). The area affected by this upwelling may be as large as 2 million km<sup>2</sup> (Subramaniam et al., 2013).

## 2.2.2 Trends and impacts

### 2.2.2.1 Coastal areas

Under natural conditions shallow waters on the continental shelf generally tend to have higher concentrations of oxygen because of higher primary productivity and being better ventilated. However, a number of anthropogenic activities affect the levels of oxygen in coastal oceanic waters. Coastal waters are affected by forestry, agriculture and urbanization which

often leads to increased concentrations of nutrients and organic matter (e.g. Seitzinger et al., 2010; Sinha et al., 2017). This leads to eutrophication which results in increased decomposition and decreased oxygen concentrations (hypoxia) which may further lead to anoxia (no oxygen). There are numerous reports of such conditions along much of the world's coastlines (see for example reviews by Diaz & Rosenberg (2008) and Rabalais et al. (2014), as well as the assessments carried out by the World Resources Institute (2010)). In the Atlantic Ocean region eutrophic conditions are nowadays more or less permanent in parts of the Gulf of Guinea, Abidjan Lagoon, along the Atlantic coast of Spain and Portugal, English Channel, Wadden Sea, Kattegat and Skagerrak, up to 40% of the Baltic proper, Bay of Gdansk, Gulf of Riga, the Black Sea including Azov Sea and Sea of Marmara.



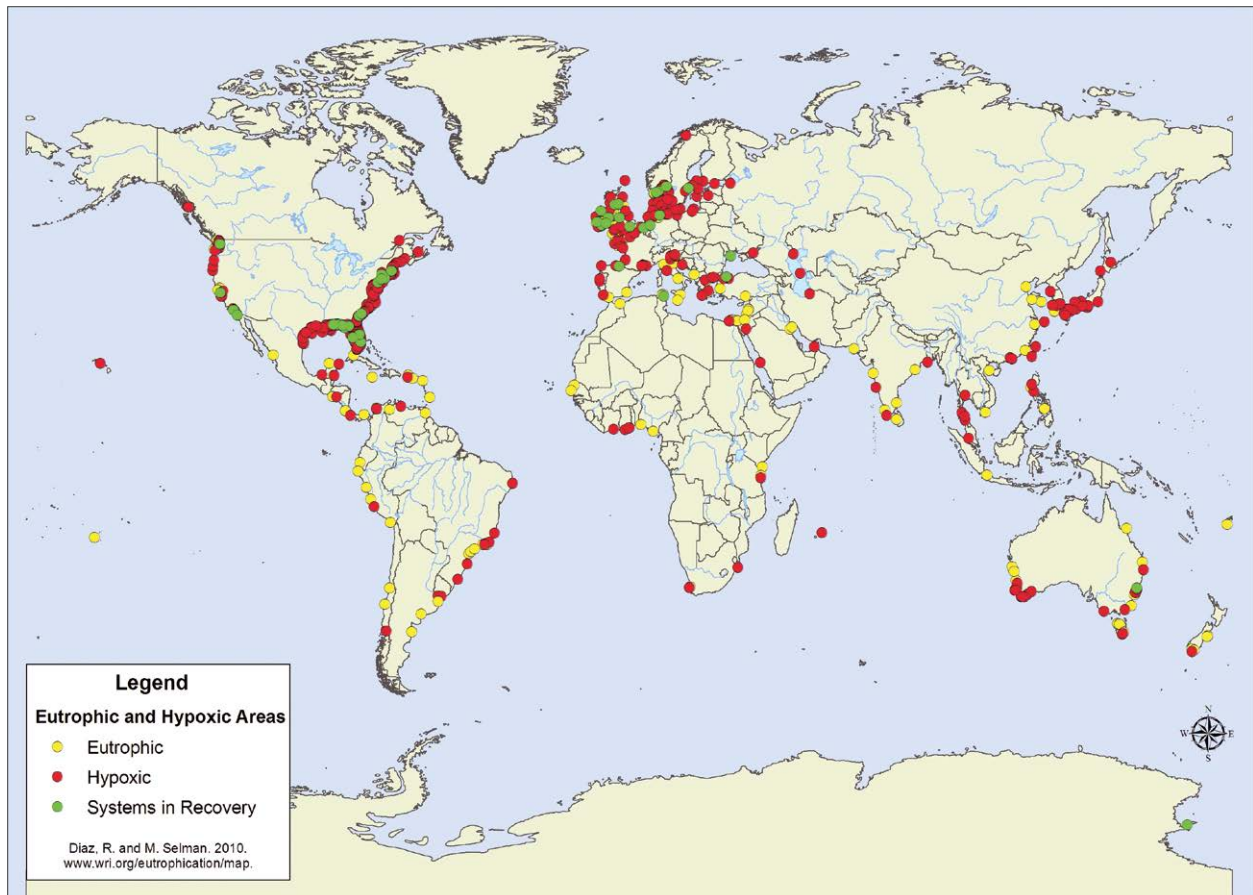


Figure 2.2.2 Map showing the distribution of 415 hypoxic and eutrophic coastal systems worldwide. Most of these areas are found in the Atlantic. From WRI (2010).

A contributing factor to decreasing oxygen concentrations is the increasing ocean water temperature. Global warming results in increasing water temperatures particularly in surface waters, which also leads to decreasing dissolved oxygen concentrations as warmer water holds less oxygen. In the Baltic Sea where the relative importance of physical forcing versus eutrophication is debated, analysis of oxygen and salinity profiles collected over the last 115 years show that increasing temperatures over the last two decades has contributed to worsening oxygen conditions (Carstensen et al., 2014). In the Baltic Sea, oxygen deficient waters have expanded from 5000 to 60,000 km<sup>2</sup> over the last century making it the largest anthropogenically induced hypoxic area in the world. Increasing water temperatures will also increase the tendency for stratification of the water mass which will decrease the tendency for mixing of the water mass.

However, due to human activities on land, higher rates of degradation are also a characteristic feature of shallow waters. Increased loads of nutrients and organic matter due to runoff from drainage areas affect the oxygen

conditions in many coastal areas, particularly near major rivers or in enclosed or semi-enclosed sea areas. In the Atlantic Ocean depressed oxygen levels as a result of increased outflow of organic matter and nutrients have been observed along most of the coastal areas. In some cases, the deoxygenation is temporary and affects relatively small areas. However, there is an increasing number of large coastal areas that are more-or-less permanently affected by hypoxia or anoxia. Recovery from prolonged periods of anoxia takes many years (Diaz & Rosenberg, 2008; Pearson & Rosenberg, 1978).

The World Resources Institute published a global assessment of the number of eutrophic and hypoxic coastal areas around the world in 2010 (Figure 2.2.2). In total 762 areas were impacted by eutrophication and / or hypoxia (World Resources Institute, 2010). Of these about 300 were to be found in the Atlantic including the Mediterranean, Black, North and Baltic Seas (Figure 2.2.3).

The northern Gulf of Mexico is another example of an area impacted by hypoxia and eutrophication (Rabalais

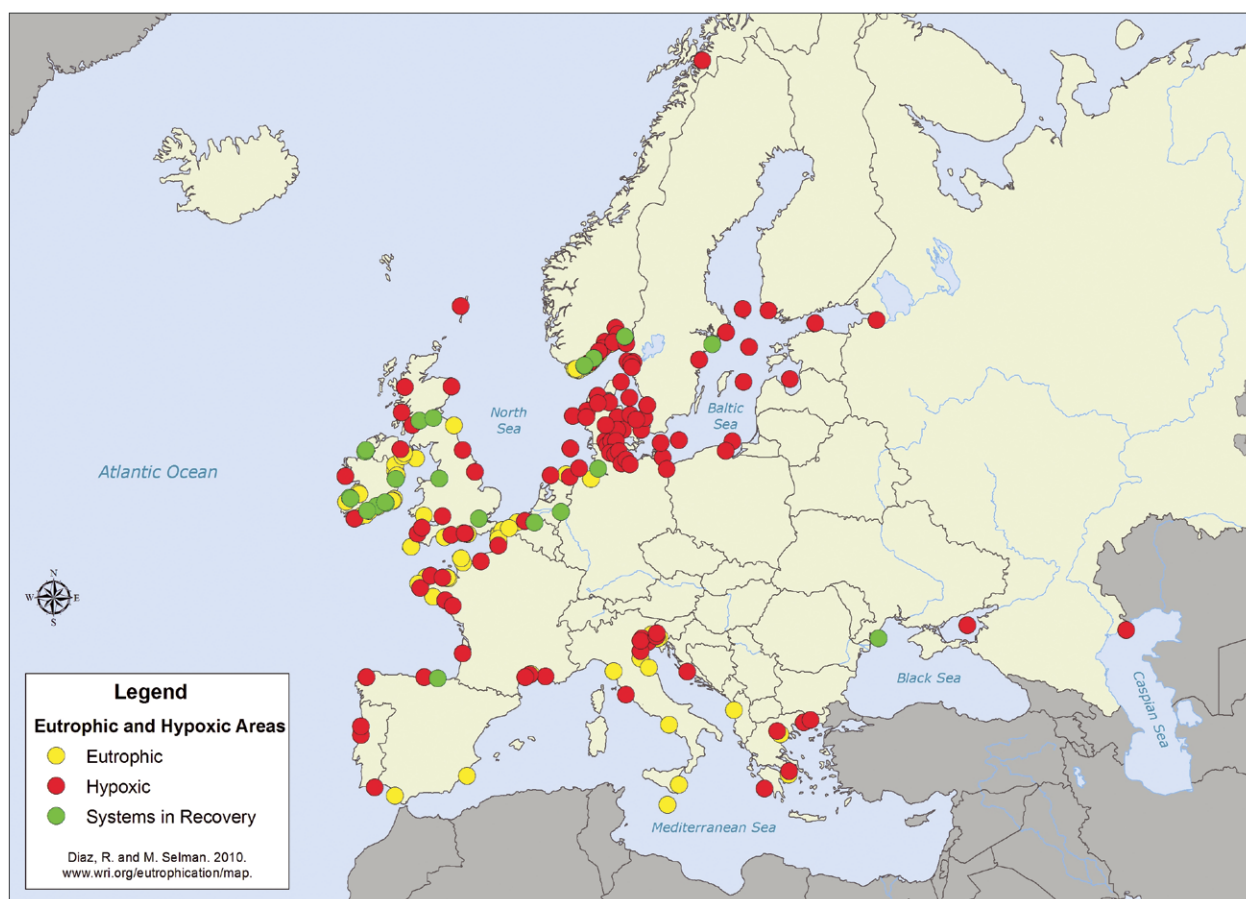


Figure 2.2.3 Map showing the distribution of hypoxic and eutrophic coastal systems in Europe. From WRI (2010).

et al., 2014) (Figure 2.2.4). The average size of the hypoxic zone in the northern Gulf of Mexico over the past 30 years (1985–2014) has been estimated at about 13,650 km<sup>2</sup>. Another large coastal area affected by hypoxic conditions in North America is the Chesapeake Bay which covers about 11,000 km<sup>2</sup>. As a result of reductions in the input of nutrients from surrounding areas and increasing ambient temperatures and sea-level rise the oxygen concentrations in bottom waters are projected to increase while the oxygen levels at mid-depths will decrease. However, with the precipitation over land predicted to increase, there will be larger volumes of winter and spring fresh water inflow and nutrient loads leading to increased primary production. The combined effect of this multitude of factors is predicted to further lower the dissolved oxygen throughout the Chesapeake Bay (Irby et al., 2017).

Parts of the eastern and southern North Sea including the Skagerrak, the Kattegat, the Sound (the strait between Sweden and Denmark) and the Wadden Sea are examples of areas increasingly affected by hypoxia although a slight recovery was seen recently in

the Kattegat (OSPAR Commission, 2017). In addition, the Baltic Sea is an extreme example of a marginal sea where extensive areas (as much as 30–40%) are affected by hypoxia at mid-depths (30 to 150 m) and anoxia in the deeper water (e.g. Lindberg, 2016).

Even more affected by hypoxia and anoxia was the Black Sea till the early 1990s when up to nearly 90% of the water volume was affected (Paleari et al., 2005) by anoxic conditions. However, the release of nutrients from surrounding areas has decreased since then and the environmental conditions in the Black Sea appear to have improved, although the improvement is unstable, and complete recovery may take a very long time (Jessen et al., 2017). Jessen et al. (2017) conclude that the bottom water oxygen concentration is a key factor in determining the biogeochemistry of the sediments and overlying waters. Hypoxic conditions prevent bioturbation and decrease remineralization rates even within short periods of a few days. However, Capet et al. (2016) point out the importance of dedicated monitoring in areas such as the Black Sea where seasonal fluctuations and the heterogeneous

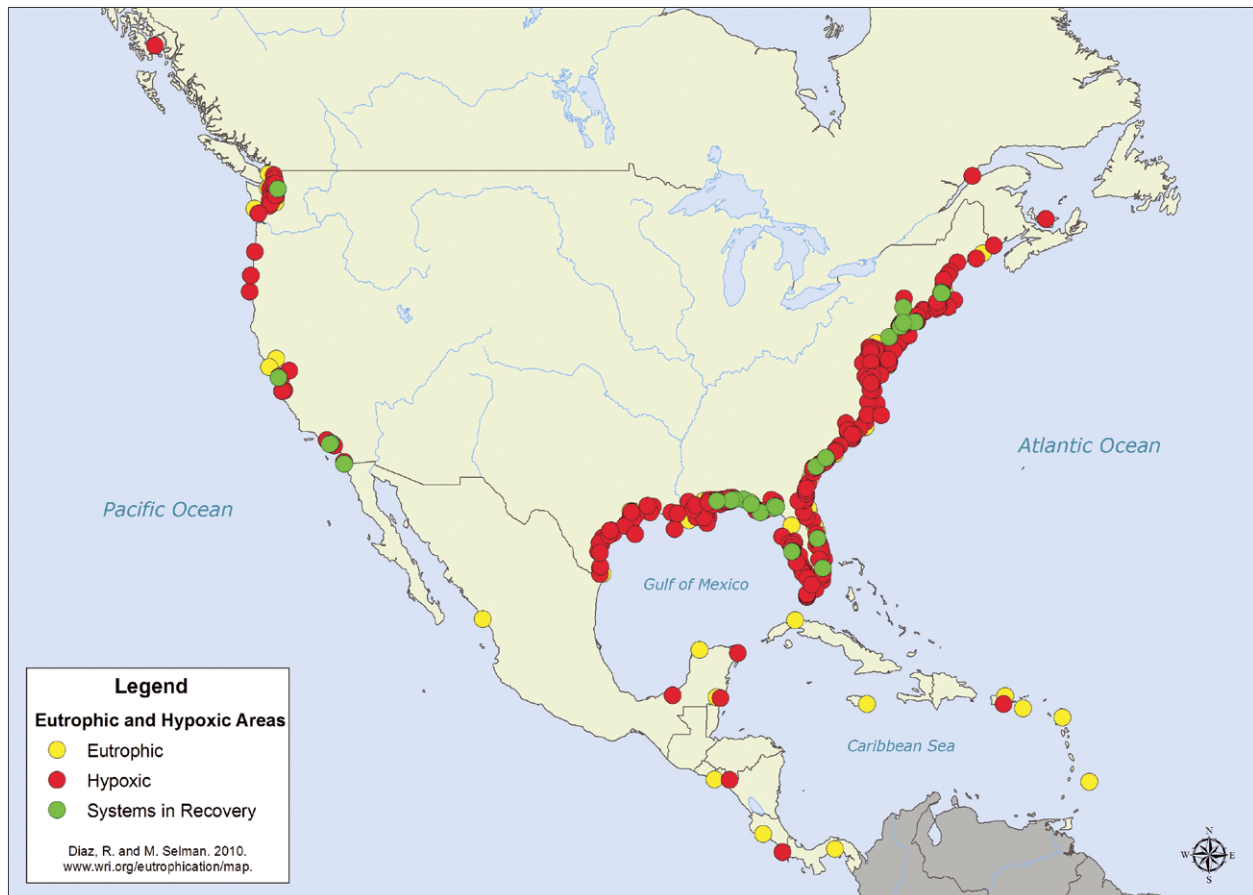


Figure 2.2.4 Map showing the distribution of hypoxic and eutrophic coastal systems from coastal North America. From WRI (2010).

spatial distribution complicates the interpretation of information from different data sets, and conclude that the reported recovery of the Black Sea after 1995 probably overestimated the trends and that hypoxic events have been recurring.

#### 2.2.2.2 Offshore Atlantic Ocean

Models for the future development of the oxygen concentrations in the Atlantic project a 1 to 7% decline by the year 2100 (Keeling et al., 2010; Long et al., 2016). This decline would be caused by a combination of a warming-induced decline in oxygen solubility and reduced ventilation of the deep ocean.

Generally, over the Atlantic Ocean there are large subsurface oxygen minimum zones (OMZs) offshore, particularly in the eastern tropical and subtropical Atlantic. Oxygen poor waters have far-reaching ecological impacts as key fauna such as bottom-living invertebrates that normally are responsible for the degradation of organic matter and fish cannot survive in these hypoxic zones (e.g. Bianucci et al., 2016; Brennan et al., 2016) (Figure 2.2.5). There has been a significant

increase in the vertical expansion of these low-oxygen zones at intermediate depth in the eastern parts of the tropical Atlantic both south and north of the equator (Stramma et al., 2008, 2010). Schmidtke et al. (2017) assessed the global oceanic oxygen content during the past five decades for the different basins in the Atlantic Ocean.

The loss in ocean oxygen is spread over the entire deep-water column between the North Atlantic deep water and Antarctic bottom water, with 12.4% of the global ocean oxygen loss over the 50 years (i.e. from 1960) occurring in the South Atlantic (Table 2.2.1; Figure 2.2.6). The change is in line with the theory of reduced ventilation due to meridional overturning changes, and that this reduced ventilation has provided less oxygenated waters in recent years, particularly in mid-latitudes in both hemispheres, as well as in tropical areas. That multi-decadal basin-scale variability in combination with the slow-down in oceanic overturning of the deep water and a potential increase in biological consumption is supported by other work (Broecker et al., 1999; Keller et al., 2016). In the upper water column, warming and the resulting decrease in solubility





Figure 2.2.5 Atlantic wolffish (*Anarhichas lupus*) has a critical oxygen level of 5.69-6.64 mg L<sup>-1</sup>. © Nature Picture Library / Alamy stock photo.

and biological consumption is most likely the reason for the loss in oxygen which, measured over the entire global ocean corresponds to over 2% since the 1960s (Schmidtke et al., 2017).

The long-term trends in dissolved oxygen in eight regions (Labrador Sea, Irminger Sea, Iceland Basin, Rockall Through and the Western European Basin North, Newfoundland Basin, North American Basin, Mid Atlantic Region, and Western European Basin South) covering the entire North Atlantic during the 50 years from 1960-2009 were analysed based on three different data sets (Stendardo & Gruber, 2012). The results showed a significant decrease in oxygen in the upper and mid-depth waters in almost all regions over the five decades. However, over the same period the deep water and water from Labrador entering into the North Atlantic increased in oxygen concentrations to a limited extent in two regions of the North Atlantic. Stendardo and Gruber (2012) concluded that the oxygen decreases in the mid-water of the northern

and eastern regions were largely driven by changes in circulation and/or ventilation, while the decreases observed in the upper layer and the oxygen increases in the deep water and the Labrador water were driven by changes in solubility. Comparing the oxygen trends with those of the oceanic heat content for the different regions and water depths the figures largely overlap and are larger than what would be expected from solubility alone. Hence biological parameters such as production and respiration as well as factors related to ventilation and circulation probably play roles in explaining this.

Santos et al. (2016) showed that the explanation to the declining oxygen concentrations is more complicated than simply warming. Their study showed that deoxygenated Antarctic mid-water directly impacts the thickness of the oxygen minimum zones in the eastern tropical South Atlantic (ETSA) and the eastern tropical North Atlantic (ETNA). The investigation using data since the 1960s showed the thickness of the oxygen minimum zones has increased by  $2.58 \pm 0.67 \text{ m y}^{-1}$  (ETSA) and  $3.37 \pm 0.73 \text{ m y}^{-1}$  (ETNA), and that the oxygen levels had decreased correspondingly while the temperatures has increased. However, an analysis of the Antarctic Intermediate Water (AAIW) source region revealed a temperature increase of 1.9 °C and a dissolved oxygen decrease of  $\sim 46 \mu\text{mol kg}^{-1}$  over the study period of 60 years. This would indicate a decrease in oxygen solubility of up to  $\sim 15 \mu\text{mol kg}^{-1}$  and thus the observed warming explains only 31% of the observed oxygen decline. This suggests that a reduction in ventilation, ocean circulation and thermal stratification as well as productivity changes and altered respiration and mineralization may have also contributed to the decrease in dissolved oxygen levels.

Table 2.2.1 Atlantic Ocean: Volume, oxygen content and change and solubility related to changes per basin and depth. The decreasing oxygen content is particularly pronounced in the South Atlantic (modified from Schmidtke et al., 2017)

Atlantic Ocean area	Volume (10 <sup>6</sup> km <sup>3</sup> )	Oxygen content (Pmol)	Solubility (rel. oxygen change (Tmol dec <sup>-1</sup> ))	Change in % of global change in the entire world ocean
North Atlantic	111.6	26.86 ±0.05	-0.4	0.9
0-1200 m	34.04	6.90 ±0.02	-9.8	2.7
1200 m-bottom	77.02	19.96 ±0.03	-9.3	1.8
Eq. Atlantic	74.19	15.89 ±0.04	-11.1	7.5
0-1200 m	20.62	2.76 ±0.02	-7.8	2.3
1200 m-bottom	53.58	13.13 ±0.02	-3.3	5.2
South Atlantic	100.84	22.39 ±0.05	-30.0	12.4
0-1200 m	27.72	5.98 ±0.02	-26.2	1.4
1200 m-bottom	73.12	16.41 ±0.03	-3.8	11.0



Figure 2.2.6 Map illustrating the area of decreasing oxygen content down to 1200m which is particularly pronounced in the South Atlantic (modified from Schmidtke et al., 2017).

Sediment cores from the deep North Atlantic have revealed millennial changes in the oxygen concentrations (Hoogakker et al., 2016). Interglacial changes in bottom water (1-2 km deep) in the north-east Atlantic have been linked to decreased ventilation related to changes in oceanic circulation and biological productivity. Hoogakker et al. (2016) showed that glacial cold events may be associated with lower seawater oxygen levels across the North Atlantic and suggested that lower oxygen concentrations in the deep water can be linked to increased export of organic material from the surface waters and its subsequent remineralization in the water column.

Hypoxia interrupted by periodic anoxia will fundamentally alter the benthic ecosystem and its ability to process carbon. Studies show that under normal oxygen conditions most of the organic matter sinking to the sea bed is consumed and recycled. Usually only a minor part of the organic matter gets buried in the ocean floor, most of it is remineralized and fed back to the ecosystem. However, declining oxygen levels and short hypoxic periods will completely change the picture and more than 50% of the organic matter will not be remineralized, significantly influencing the carbon storage in the sea floor for decades (Jessen et al., 2017).

### 2.2.3 Ecosystem consequences

Oxygen is an essential element for all higher life and the implications of continued spreading of deoxygenated areas in the Atlantic Ocean must be considered a most serious environmental problem. It has fundamental implications on ocean productivity, biodiversity, biogeochemical cycles and the global climate.

The response to declining oxygen will vary depending on sensitivity of different species and different life stages. The responses may be death or sub-lethal effects such as behavioural or physiological, that may manifest as reduced growth or impaired reproduction. Furthermore, the oxygen available to organisms depends on the temperature of the water (low temperature means increased solubility), pressure (high pressure increases solubility), and salinity (high salinity means lower solubility).

Declining concentrations of oxygen not only have direct and often dramatic effects on higher organisms such as fish and shellfish, but decreased oxygen levels also affect a number of important biogeochemical reactions and cycling in the marine environment. Hence the cycling of nutrients, metals, sulphide and carbon are affected. For example, hypoxia and anoxic conditions prevents the sequestration of phosphorus in the sediment. As a consequence, even if the input of phosphorus is eliminated, under hypoxic conditions phosphorus remains in the ecosystem and continues to fuel primary productivity resulting in massive algal blooms, perhaps for decades, for example as in the central Baltic Sea, the Black Sea, parts of the North Sea and the Cariaco Basin (Ahtiainen et al., 2014; Jokinen et al., 2018; Kemp et al., 1990; Nixon et al., 1996; Ye et al., 2016). These blooms of algae may in some cases be harmful (HABs). The extent of hypoxia also affects the loss of fixed nitrogen in the ocean via denitrification, thereby influencing the supply of nitrate which is a limiting nutrient over much of the ocean (e.g. Gruber, 2004). This will have negative consequences on ocean productivity. The concentrations of oxygen also influence the production of nitrous oxide ( $\text{N}_2\text{O}$ ) which is a powerful greenhouse gas. Production of this gas will increase under hypoxic conditions both from denitrification and nitrification (Codispoti et al., 2001; Keeling et al., 2010). Results from investigations off the western Indian Shelf during periods of hypoxic, suboxic and anoxic waters produced a maximum surface  $\text{N}_2\text{O}$  saturation of >8000%. The studies showed the sensitivity of denitrification to small

changes in the ocean dissolved oxygen, and that small changes in dissolved  $\text{O}_2$  concentrations can change the  $\text{N}_2\text{O}$  emission from the ocean rapidly.

The ecological consequences of the decline in oxygen levels in marine areas are dramatic. Hypoxia impoverishes the ecosystem with only the most tolerant and opportunistic species remaining, and anoxia eliminates all higher life. Pelagic species may, to a certain extent, be able to avoid hypoxic conditions and indeed this is why fish stocks are still present in places such as the Black Sea and the Baltic Sea. Fish such as cod and herring simply move to surface waters as hypoxia spreads in deeper waters. However, species living on or near the sea bed will not be able to survive such conditions. Also, although adult cod may be able to survive, eggs and larvae may not as the situation in the Baltic Sea shows (e.g. Nissling, 1994). The response pattern of benthic communities to hypoxia has been described by Pearson and Rosenberg (1978). As dissolved oxygen declines to  $<0.7 \text{ ml L}^{-1}$  and extends through time, mass mortality of both more sensitive and the more tolerant species will take place. If anoxia occurs all benthos will die. The process of recovery from such conditions follows a different path from when oxygen is declining. The conceptual model for benthic community responses to hypoxia and anoxia and the recovery from such conditions has been described in the Pearson-Rosenberg model (Pearson & Rosenberg, 1978).

### 2.2.4 Societal consequences of continued deoxygenation

The socio-economic consequences of continued deoxygenation of the Atlantic Ocean are enormous and difficult to comprehend. Fundamental changes will take place affecting biological as well as chemical factors in the ocean and in the longer term also life on land will suffer as biogeochemical cycles including that of carbon and oxygen are affected. Initially, and this is already happening, fisheries suffer from the consequences of hypoxia and anoxia in the pelagic and benthic zones (Table 2.2.2). As the oxygen minimum zones are expanding the habitats for fish and shellfish are compressed. In the tropical Atlantic some populations of tuna, billfish and marlin have experienced a 15% reduction in their vertical habitat range between 1960 and 2010 as a result of the expansion of the oxygen minimum zones (Stramma et al., 2011). Organisms that require high oxygen levels are losing habitat while more tolerant species

Table 2.2.2 The typical effects of hypoxic/anoxic conditions

Before deoxygenation	Under low-oxygen condition
<ul style="list-style-type: none"> <li>• Diverse ecosystem including demersal species</li> <li>• Benthic life consisting of fish and shellfish</li> </ul>	<ul style="list-style-type: none"> <li>• Impoverished ecosystem</li> <li>• Only pelagic fish in surface waters</li> <li>• No deep-water/benthic life</li> </ul>
<ul style="list-style-type: none"> <li>• Well-oxygenated deep water</li> <li>• Well-flushed water body</li> </ul>	<ul style="list-style-type: none"> <li>• Hypoxic/anoxic deep-water</li> </ul>

will expand. The effects are manifested as decreased catches of benthic species and increased catches of upper-pelagic fast-growing species, a reflection of a switch to shorter food chains; clear signs of such effects have been seen in the Baltic Sea, the Black Sea and in other parts of the North Atlantic (e.g. Bianucci et al., 2016; Brennan et al., 2016). It is reasonable to assume that, as deoxygenation progresses, fisheries in coastal as well as offshore areas will be affected with implications on the food supply to many millions of people.

As oxygen levels continue to decrease and reach hypoxic conditions the available habitats for aerobic organisms decrease rapidly (Deutsch et al., 2011). The spatial extent of hypoxia is highly sensitive to small changes in the oxygen content with maximum responses at suboxic levels where anaerobic processes predominate. Areas most at risk in the Atlantic are the eastern tropical/subtropical basin as well as mid-latitudes. Based on model simulations widespread hypoxia is forecasted in these areas between 2014 and 2030 (Long et al., 2016).

Potentially the societal consequences of the effects of ocean deoxygenation on the global climate is, however, even more serious but much more information is needed to fully understand the implications. As the oxygen concentrations are decreasing the nutrient cycling is affected and as this is taking place on such a large scale it has implications for the global biogeochemistry and climate. Oxygen is directly linked to the carbon cycle via photosynthesis and respiration, hence the rate at which organic material is produced, distributed and recycled. Understanding how the ocean ecosystems are changing with global warming is clearly linked with the CO<sub>2</sub> concentrations in the atmosphere and the ability of the ocean as well as land to serve as carbon sinks.

### 2.2.5 Conclusions / Recommendations

Hypoxic and anoxic conditions are found in many coastal areas in the Atlantic Ocean including in

connected seas like the Mediterranean, the Black Sea, the Baltic Sea and Gulf of Mexico. From available data it is obvious that these oxygen-limited areas have expanded dramatically during the last 50 to 100 years. In coastal areas there are several good examples that conditions can improve, provided the input of nutrients and organic matter from land can be controlled. At local and regional levels, there are therefore good reasons to build sewage treatment plants and improve management of drainage water from land in order to reduce these substances as far as possible.

The expanding oxygen minimum zones affect the entire marine ecosystem, its biodiversity and productivity. In addition, there are several links to global climate change. Oxygen limited waters are also found at mid-water levels in most of the Atlantic Ocean basins, usually at 300 to 1000 m depth. The oxygen concentrations in these areas have decreased during the last 60 years, partly due to ocean warming, partly as a result of decreased mixing and ventilation. Continued spreading of deoxygenated areas in the Atlantic Ocean must be considered a most serious environmental problem. There is no other parameter of such importance to all higher life as dissolved oxygen. To be able to manage the declining oxygen levels in offshore areas global action is needed. The clear links to the atmospheric concentrations of carbon dioxide would strongly suggest that the issue of deoxygenation of the ocean must be dealt with within the framework of the climate change negotiations.

Understanding of the relative importance of autotrophic and respiratory processes, as well as physical processes (e.g. mixing and currents) in deep and mid-water oxygen dynamics requires more data than what are currently available.

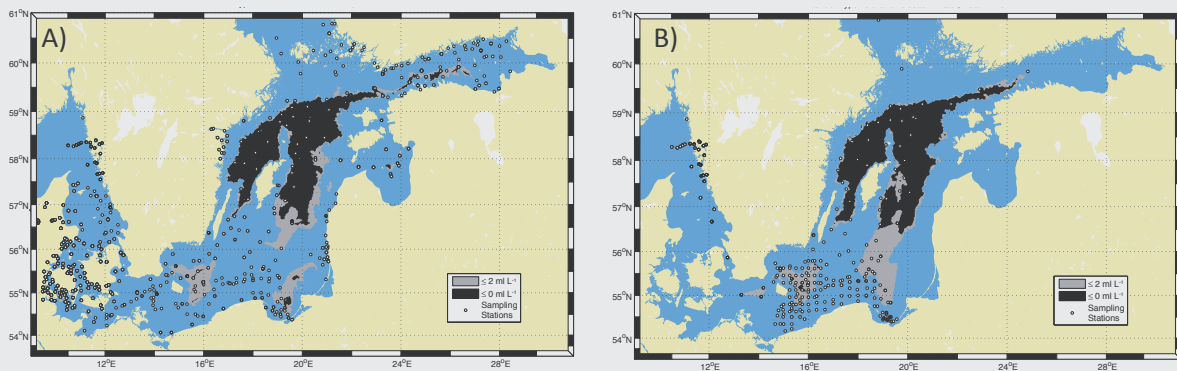
Also, knowledge regarding the impacts of climate change on physical processes, oxygen deficiency and oxygen consumption is poor in large parts of the Atlantic Ocean. In order to better distinguish between the effects of nutrient enrichment and changes in seawater



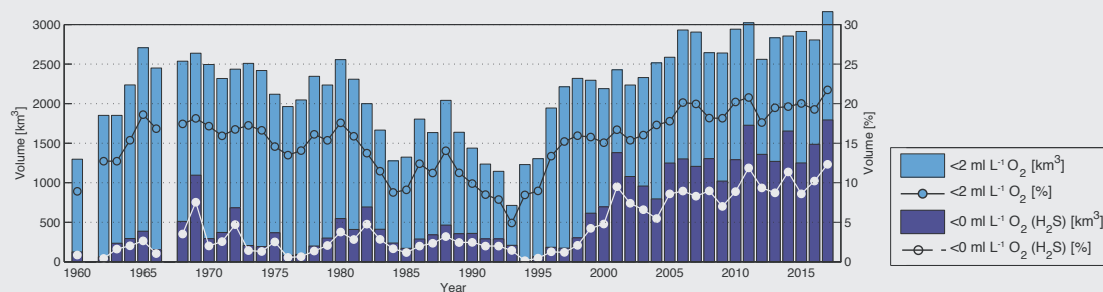
### Box 2.2.1 The Baltic Sea and deoxygenation

The Baltic Sea has been affected by deoxygenation and anoxic conditions since it was formed after the last glaciation. Geologists have detected periods of anoxic conditions at the sea bed since the Littorina Sea about 8000 years ago. The Littorina Sea was a brackish water marginal sea which existed for about 4000 years before the present Baltic Sea. However, since the early 1900s local outbreaks or hypoxia have become more frequent and since 1950 large areas, up to 100 000 km<sup>2</sup> have been affected by anoxia in the deep and intermediate waters from the sea bed up to 50 to 80 m depth (Box Figures 2.2.1.1 – 2.2.1.3). The water column in the Baltic Sea is highly stratified due to large inflows of fresh water from surrounding land areas and low and infrequent inflow of Atlantic water. As a consequence, the surface water is only some 6 to 8 Practical Salinity Unit (PSU) while the deep water is 15 to 20 PSU. The halocline is at about 40 m in the southern Baltic Sea and about 80 m in the north. The anoxia in deep waters contributes to the mobilization of nutrients from the seabed sediment which results in massive algal/bacterial blooms during the summer months.

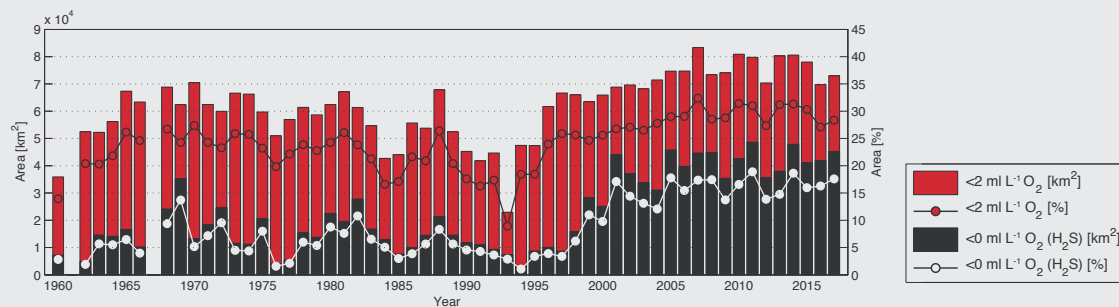
The increasing problems with hypoxia and anoxia during the last 100 years have been related to the release of nutrients and organic substances from the drainage area. Based on a catchment-sea coupled model system and numerical experiments based on meteorological and hydrological forcing data and scenarios, it is projected future changes will lead to increasing problems with hypoxia and decreasing pH (Omstedt et al., 2012).



Box Figure 2.2.1.1 The Baltic Sea with Gulf of Finland, Gulf of Riga, the Sound, the Belt Sea and the Kattegat. The maps show the extent of hypoxic and anoxic water in the autumn (A) 2016, (B) 2017. From SMHI 2017 ([www.smhi.se](http://www.smhi.se)).



Box Figure 2.2.1.2 Aerial extent of anoxic and hypoxic conditions in the Baltic Proper including the Gulf of Finland and the Gulf of Riga from 1960 to 2017. Results from 1961 and 1967 have been removed as data from deep basins are missing. From SMHI, Report Oceanography 63, 2017.



Box Figure 2.2.1.3 Volume of anoxic and hypoxic deep water in the Baltic Proper, Gulf of Finland and Gulf of Riga 1960-2017. Results from 1961 and 1967 have been removed as data from deep basins are missing. From SMHI, Report Oceanography 63, 2017.

temperature as a result of climate change more data series are needed. Since oxygen deficiency is localized and often short-lived, modelling can help in identifying hotspots.

## 2.2.6 References

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