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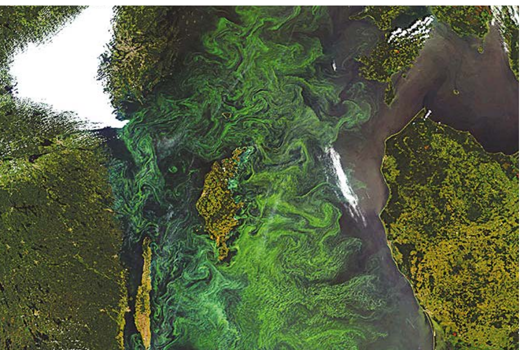
Ocean deoxygenation: Everyone's problem

Causes, impacts, consequences and solutions

Edited by D. Laffoley and J.M. Baxter



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Foreword

Reports of the impact of warming water on coral reefs from as long ago as 1983 have been recently and rapidly surpassed by much more in-depth knowledge that all parts of the ocean are being transformed by anthropogenic effects driven by ever-increasing greenhouse gas emissions. When IUCN and its members realized the enormity of these issues, we developed a new set of publications to raise global awareness, covering issues like ocean acidification, ocean warming, ocean carbon flows, and ocean plastics. Taken in isolation any one of these areas clearly has negative consequences for the ocean. All these shifts taken together, however, result in a rapid and serious decline in ocean health. With the build-up of carbon dioxide in the atmosphere, more carbon dioxide is being dissolved in the ocean which is altering the acidity and having large effects on marine ecosystems. In response IUCN has been developing both global, and regional policy work to prepare managers and policy makers to address the issue. Ocean acidification alters the balance of the ocean system. Some species may be more resilient than others, but many are projected to be affected. Some will be unable to tolerate the new conditions, some will cope but at a cost of expending more energy on survival, whilst others will find the new conditions more restricting and may change their distribution or abundance as a result. There are still many unknowns.

Another effect of the build-up of greenhouse gases in the atmosphere is that the planet as a whole is heating up. About 93% of this excess heat from the enhanced greenhouse effect over the past few decades is now stored in the ocean. Such is the scale of heating that it is already affecting all parts of the ocean from inshore to the high sea, from the poles to the tropics and from the surface down to the depths. All forms of marine life are being affected from plankton to whales. Some of this has been known for a long time, for example coral bleaching causing the decline of reefs around the planet, but increasingly we are also starting to see shifts in many other ecosystems. This is leading to changes in community composition, changes in abundance, shifts in distribution and changes in predator/prey relationships. Again this is leading to a complex picture of change, and impacts and effects on one species may be very different to the next.

The ocean is also a key part of the carbon cycle. Until IUCN produced our report on coastal carbon sinks in 2009 there was little awareness of the critical role that coastal ecosystems play in trapping and sequestering carbon. Up until then the story was mostly about forests and soils rather than what happens at the coast and in the sea. Much more awareness still needs to be raised and action needs to be taken to respect the role marine ecosystems and species have in maintaining the carbon cycles.

Pollution flowing into the ocean is also increasing and can be a driver for change. Whilst the public is now largely aware of this as an issue of global concern few realize the magnitude of what we have done. Plastic particles are now so widespread in the ocean that they have been accumulating in sea ice, resulting in a shift in seasonal melting patterns. With less sun reflection from ice cover at sea, the absorption of heat accelerates at the poles and speeds up climate change in the ocean. This positive feedback has consequences for many polar species but also for the planet as a whole. The link between plastic pollution and climate shifts is not yet well understood, so developing more work and a deeper understanding of this issue and preventative measures will be a priority in the future.

On top of these problems is then the topic of this current report. Having sufficient available oxygen in the air or water is of paramount importance to most living organisms. As this report describes in some detail, oxygen levels are currently dropping across the ocean. Several drivers are responsible for this decline, but the root causes are nutrient run-off from land now coupled with the significant warming of sea water, resulting from build-up of greenhouse gases. As the following pages show in great detail one of the major consequence of this is habitat compression and reduction in suitable habitat for many species. This leads to migration of species, increased vulnerability of species of conservation or commercial concern, reductions in abundance, and accordingly an overall reduction in ocean resilience.

Solutions to ocean deoxygenation and development of adaptation strategies depend on sound knowledge. Progress is now starting to be made in understanding the causes, consequences and future patterns of ocean oxygen decline. Widespread awareness also is key. Natural and social science advances are critical to increasing the recognition of ocean deoxygenation as an important consequence of human alterations to our global environment and the impacts it will have on human welfare.

The sense of urgency to improve the ocean health has never been greater. With this new report our aim is to complement the recent IPCC Special Topic report by providing a 'deep dive' into the issues surrounding ocean deoxygenation. We hope by providing sound science to better inform policy and decision makers, this will help them in turn develop and adopt adaptation and mitigation strategies in the face of such new realities. Without a doubt more concerted global action is required now to reverse the direction of ocean degradation.

Ocean deoxygenation is perhaps the ultimate wakeup call on how ignoring the ocean jeopardizes the interests of us all, but particularly future generations. Ocean deoxygenation will not be easy to reverse, but the costs of doing so clearly must outweigh the costs of any inaction for all our sakes.

Minna Epps
Director

Carl Gustaf Lundin
Principal Scientist

IUCN Global Marine and Polar Programme

Preface

At any given moment, up to 97% of the world's water resides in the ocean. Whether you live by the sea or far from it, eat seafood or not, the future of all of us depends on a healthy ocean. Saving our ocean and the life below the surface is a matter of our survival.

Our ocean has not been getting the attention it deserves, until now, in spite of the vital functions it bestows. The ocean generates more than half the oxygen we breathe. By absorbing over a quarter of the excess carbon dioxide generated from the burning of fossil fuels and by absorbing most of the excess heat and the ocean has, until now, shielded us from the worst impacts of climate change.

Now, imagine sucking the oxygen out of the ocean. We have global evidence of deoxygenation and it's scary. Over the past 50 years, global dissolved oxygen in the ocean has decreased by ~2% and scientific data indicate that this trend is set to continue. The number of reported sites affected by low oxygen conditions has dramatically increased during the last few decades. Increased river export of nitrogen and phosphorus has resulted in eutrophication in coastal areas worldwide. Take the Baltic Sea for example; oxygen depletion near the sea bed has resulted in extensive dead zones.

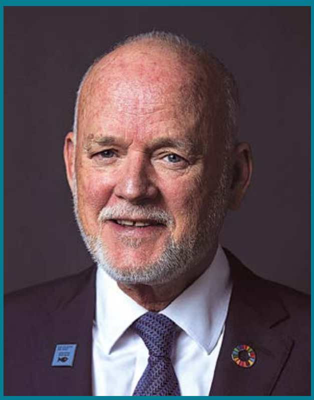
Whilst we have known about dead zones in the ocean for many decades, ocean warming is now expected to further amplify deoxygenation across great swathes of the ocean. Deoxygenation affects many aspects of the ecosystem services provided by the ocean and coastal waters. The ocean is the primary source of protein for more than 1 billion people around the world. Ocean deoxygenation will have socio-economic implications, as it will affect fisheries and, the abundance and distribution of certain species, thereby changing ecosystem dynamics. Ocean deoxygenation is putting life at risk. Failing to protect our ocean will jeopardize humankind, as our security, economy and our very own survival depends on it.

We must start to address the challenge of reversing the decline in oxygen in the ocean. Stakes are high and stocks are low – we need to recognize the challenge and work together to get the ocean oxygen budget back in balance. This is why Sweden supports cutting-edge ocean research on the scale of our impacts, to strengthen proposed adaptations and solutions to declining ocean oxygen. The urgency, complexity and geographical extent of ocean deoxygenation requires that the best science from across the globe be used if we are going to slow and reverse ocean oxygen decline. To date this has been a topic that mainly concerned a few scientists, but should now concern and occupy all of us.

With this report its time to put ocean deoxygenation among our top priorities to address climate change and restore ocean health. Our welfare and that of future generations depend on it. The societal cost of inaction is too great to ignore. International and regional collaboration in science, policy development and implementation are critical to getting the ocean oxygen budget right.

Ms. Isabella Lövin
Minister for Environment and Climate, and Deputy Prime Minister of Sweden

Preface



Just over fifty years ago, thanks to our intrepid astronauts, humanity looked back at Earth from the moon and saw the first colour photos of our planet from afar - blue, beautiful, finite, and seemingly hanging in the dark void of space. Since then, our collective fascination and innovation have taken our discoveries well beyond the moon, to explore distant planets, the outer reaches of our solar system, and beyond.

In so doing, in my view we have taken for granted a basic element of our existence. For too long we have neglected the blue heart of our own planet; the heart that maintains the balance of conditions for the fostering and support of the universe's rarest of commodities - life.

Realization of the need for the marriage of policy and action to properly safeguard life on Earth is, surprisingly, only just getting underway. Until very recently, the focus has always been on what happens on land, rather than what is affecting the source of life on this planet - the ocean. This has been short-sighted of us, for science now shows how the ocean buffers us from the extremes of climate change, helps shape and drive our weather, and provides food, inspiration and a myriad of socio-economic benefits to sustain us all.

And it is only in the last decade that we have realized how humanity's actions are having such a profound impact on the ocean's well-being. This ranges from how our carbon emissions are driving the ocean to hotter and more acidic conditions, through to how our everyday actions can dramatically influence and change marine life and the food chain of which we are all part. I am in particular referring to issues such as overfishing, chemical pollution from the products we use in agriculture, industry, and cosmetics, and of course plastic pollution.

But perhaps the key question we should all be asking is: have we yet realized the true scale of the impact that we're having on the ocean as our planetary life support system? I for one think not.

To assist in improving our perception of that scale of impact, I am particularly pleased to welcome this new study on ocean deoxygenation, which is, as far as I'm aware, the first global in-depth study on this critical subject. I believe it provides a new perspective on the scale of our impacts, thereby logically leading us, with a greater sense of urgency, to much higher levels of ambition for the restoration of respect and balance to our relationship with the ocean and the planet.

We were taught at school that hotter liquids contain less gas, and the ocean and the oxygen within it are no exception to this rule. This report clearly shows that with the heating of the ocean, the quantity of life-giving oxygen within it is dropping.

Of all reports, this one needs to be heeded urgently. Regardless of nationalities, ideologies, wealth or situation, the message of this report is everyone's business, everyone's challenge to overcome.

By cataloguing the progressive impacts and changes already underway in the ocean, I believe the report demonstrates that the next ten years will be more important for humanity than the last hundred, indeed thousands of years have been for our survival. Please read it, then play your rightful part in the communal decision-making processes necessary for the future well-being of all life on planet Earth.

Ambassador Peter Thomson
United Nations Secretary General's Special Envoy for the Ocean

Executive summary

Breathing water is hard work as a given volume of water holds far less oxygen than the equivalent volume of air. This makes the physiological performance and behavioural repertoire of marine organisms heavily dependent on their ability and capacity to extract oxygen from the ambient sea water. Ocean deoxygenation generally affects marine organisms as soon as conditions depart from full aeration, with downstream consequences on their activities and capacity to face natural contingencies. The importance of maintaining adequate levels of oxygen in the ocean is perhaps best summarized by the motto of the American Lung Association: "if you can't breathe nothing else matters".

Whilst the focus of actions on trying to clean-up the ocean is on the impacts from pressures such as fishing, pollution, habitat destruction, invasive species and plastic, there is no environmental variable of such ecological importance to marine ecosystems that has changed so drastically in such a short period of time as a result of human activities as dissolved oxygen. Hypoxia - a condition that deprives an organism of adequate oxygen supply at the tissue level - is one of the most acute symptoms of the reduction in dissolved oxygen. The present-day losses of oxygen in the ocean - ocean deoxygenation - is starting to progressively alter the balance of life, favouring hypoxia- tolerant species at the expense of hypoxia sensitive ones.

Working with 67 scientific experts from 51 institutes in 17 countries, what is presented here is the largest peer-reviewed study conducted so far on ocean deoxygenation. Expressed in the words of the world's leading scientists on this topic it shows the inescapable fact human activities are now driving life sustaining oxygen from our ocean-dominated planet. Society needs to wake up - and fast - to the sheer enormity of detrimental changes we are now causing to the Earth's regulatory systems, and the now near-monumental efforts that will be needed by governments and society to overcome and reverse such effects. This report is probably an underestimation of what is happening now. Science is incomplete and awareness of ocean deoxygenation is just happening, but what is already known is very concerning.

The loss of oxygen in the ocean can broadly be put down to two overlying causes – eutrophication as a result of nutrient run-off from land and deposition of nitrogen from the burning of fossil fuels, and the heating of ocean waters as a result of climate change, primarily causing a change in ventilation with the overlying atmosphere so that they hold less soluble oxygen, and compounded by reduced ocean mixing and changes in currents and wind patterns. Ocean deoxygenation is but the latest consequence of our activities on the ocean to be recognized. Ocean warming, ocean deoxygenation, and ocean acidification are major 'stressors' on marine systems and typically co-occur because they share a common cause.

Increasing carbon dioxide emissions into the atmosphere simultaneously warm, deoxygenate, and acidify marine systems, whilst nutrient pollution also contributes to increases in the severity of deoxygenation and acidification. As a result, marine systems are currently under intense and increasing pressure from the cumulative effects of these multiple stressors, and with current sustained trajectories expected for greenhouse gas emissions the changes in the ocean will only continue and intensify. Awareness of these phenomena, on top of existing issues such as overfishing, pollution and habitat destruction, has begun to trigger significant concern on the impacts on marine biodiversity and the functionality of the ocean as a whole, and how this may influence factors such as weather, crop success and water supplies, and then affect people everywhere.

In the last 65 years we have come to realize that over-enrichment of waters with nutrients or organic matter (eutrophication) is a problem that threatens and degrades coastal ecosystems, alters fisheries, and impacts human health in many areas around the world. Over 900 areas of the ocean around the world have already been identified as experiencing the effects of eutrophication. Of these, over 700 have problems with hypoxia, but through improved nutrient and organic loading management on adjacent land about 70 (10%) of them are now classified as recovering. The global extent of eutrophication-driven hypoxia and its threats to ecosystem services are well documented, but much remains unknown as to the long-term human health, social, and economic consequences.

What is particularly new with this report is the additional focus on the more recently recognized effect of lowered oxygen resulting from ocean warming, which is now affecting enormous areas of the ocean. The atmospheric warming resulting from greenhouse gas emissions being taken up in ocean water is now driving vast changes in the physical and biological make-up of the sea. The two causes also interact, with warming-induced oxygen loss tipping coastal areas into eutrophication-driven hypoxia and may contribute to the dramatic increase in regards of coastal hypoxia. The combination of eutrophication-driven hypoxia, which can be relatively easily and quickly reversed if the necessary measures are put in place, and hypoxia due to climate change driven warming, that can't easily be reversed - if at all - is causing the emergence of ocean deoxygenation as a new issue of global significance.

At regional to local scales the overall concerns about ocean deoxygenation are further exacerbated by outbreaks of Harmful Algal Blooms. The development of hypoxic or anoxic waters is regularly listed as one of the consequences of algal blooms. Such events of low oxygen associated with harmful algal blooms are characterized by high initial oxygen concentrations, exceptional rates of respiration following bloom senescence and short timescales. The coastal environments subject to high biomass harmful algal blooms and associated events of low oxygen are typified by elevated inorganic nutrients because of either natural or cultural eutrophication.

In the short term, marine organisms respond to ocean deoxygenation through changes in their physiology and behaviour. Alteration in feeding behaviour and distribution pattern are classically observed, potentially leading to reduced growth and to more difficulties completing their life cycle. Vertical habitat compression is also predicted for organisms in the upper ocean. In the medium term, epigenetic processes (non-genetic influences on gene expression) may possibly provide marine populations with a rapid way to acclimate to the rapidly changing oxygenation state. However, this developing field of biological sciences is too recent for a full evaluation of the contribution of epigenetic responses to marine organisms' adaptation to ocean deoxygenation to be made. Changes in the phenology (timing of life stage-specific events) of marine species, related to ocean deoxygenation have not yet been observed. However, deoxygenation generally co-occurs with other environmental disturbances (ocean warming and acidification) which are also liable to affect marine species' life cycles. The lack of understanding of their interactions and synergies currently restricts our ability to assess marine populations' capacity to phenologically respond to ocean deoxygenation.

The overall consequences of perturbations to the equilibrium state of the ocean-atmosphere system over the past few decades are that the ocean has now become a source of oxygen for the atmosphere even though its oxygen inventory is only about 0.6% of that of the atmosphere. Different analyses conclude that the global ocean oxygen content has decreased by 1-2 % since the middle of the 20th century. There is good evidence that ocean temperature increases explain about 50% of oxygen loss in the upper 1000 m of the ocean, but there is less confidence of the knock-on effect on respiration – another factor to explain lowered oxygen. Less than 15% of the oxygen decline can be attributed to warming-induced changes in respiration of particulate and dissolved organic matter.

Most of the oxygen loss has been caused by changes in ocean circulation and associated ventilation - gas exchange - from the ocean into the atmosphere with oxygen from the ocean surface. As the ocean warms from the surface, stratification is expected to increase, with a tendency for a slowing down of the ocean circulation. A slowed down circulation is expected to account for up to 50% of the observed deoxygenation in the upper 1000 m, and for up to 98% in the deep ocean (> 1000 m depth). Spatial patterns and individual mechanisms are not yet well understood. The current state-of-the-art models available predict deoxygenation rates only half that of the most recent data-based global estimates. Human activities have altered not only the oxygen content of the coastal and open ocean, but also a variety of other physical, chemical and biological conditions that can have negative effects on physiological and ecological processes.

Further climate-driven warming of bottom waters may also result in enhanced destabilization of methane gas hydrates, leading to enhanced release of methane from sediments, and subsequent aerobic respiration of methane to carbon dioxide. There is, however, little observational evidence for a warming-induced acceleration of methane release taking place already. As the ocean continues to warm, it will lose yet more oxygen due to the direct effect of temperature on gas solubility, as warmer waters hold less soluble gas. Additionally, reductions in vertical mixing associated with enhanced upper-ocean buoyancy stratification will also occur leading to respiration-driven oxygen depletion at depth. The ocean as a whole is expected to lose about 3–4% of its oxygen inventory by the year 2100 under a "business-as-usual" scenario (RCP8.5) with most of this loss concentrated in the upper 1000 m where species richness and abundance is highest.

The future intensification and expansion of low oxygen zones (LOZ) can have further ecosystem consequences as oxygen dependent cycling of elements by microbes alter the supply of nutrients or in extreme cases, lead to increased production of toxic hydrogen sulphide gas. Low oxygen conditions and increased temperature jointly limit the viable habitat for marine macro-organisms. Continued ocean warming accompanied by deoxygenation will drive habitat contraction and fragmentation in regions where oxygen levels decline below metabolic requirements. Expansion of suboxic zones will likely disrupt the cycling of nitrogen in the ocean; denitrification may increase, yielding greater rates of fixed nitrogen loss from the ocean. Perturbations to the nitrogen cycle may include substantial changes to nitrous oxide production, though this is currently highly uncertain.

It is predicted that there will be distinct regional differences in the intensity of oxygen loss as well as variations in ecological and biogeochemical impacts. There is consensus across models that oxygen loss at mid and high latitudes will be strong and driven by both reduced solubility and increased respiration effects. Projections are more ambiguous in the tropics, where models suggest that there will be compensation between oxygen decline due to reduced solubility and oxygen increase caused by reductions in cumulative respiration. Thus, oxygen concentrations in the core of present-day oxygen minimum zones may increase; however, the total volume of waters classified as "suboxic" and "hypoxic" is still likely to grow substantially.

While the biogeochemical and physical changes associated with ocean warming, deoxygenation and acidification occur all over the world's ocean, the imprint of these global stressors has a strong regional and local nature. Perhaps the most familiar areas subject to low oxygen are the Baltic Sea and Black Sea. These are the world's largest semi-enclosed low oxygen marine ecosystems. While the deep basin of the Black Sea is naturally anoxic, the low oxygen conditions currently observed in the Baltic Sea have been caused by human activities and are the result of enhanced nutrient inputs from land, exacerbated by global warming. The impacts of deoxygenation are not though limited to enclosed seas. The eastern boundary upwelling systems (EBUS) are some of the ocean's most productive biomes, supporting one fifth of the world's wild marine fish harvest. These ecosystems are defined by ocean currents that bring nutrient rich but oxygen-poor water to coasts that line the eastern edges of the world's ocean basins. As naturally oxygen-poor systems, EBUS are especially vulnerable to any changes in global ocean deoxygenation and so what happens to the oxygen content of EBUS ultimately will ripple out and affect many hundreds of millions of dependent people.

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 Gulf of Mexico, and as previously mentioned the Black Sea, and Baltic Sea. Alongside this, large ocean basins such as the equatorial and southern Atlantic are being affected by decreasing oxygen levels, although studies show that such conditions were present in deep waters long before anthropogenic activities started to have an influence on the marine environment. In addition to many coastal waters of the Atlantic, oxygen limited waters are also found at mid-water depths in most of the Atlantic Ocean basins, usually at 300 to 1000m. 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.

Elsewhere the low-oxygen zones of the Indian Ocean are expected to continue to expand and intensify. There does, however, remain a critical lack of information from potential hotspots for deoxygenation, including the mouths of the Indus, Ganges-Brahmaputra, and Irrawaddy rivers. Thus, pictorial representations of the current extent of ocean deoxygenation almost certainly underplay the effects being experienced in the world ocean. Capacity building and networking are needed to expand/improve monitoring of deoxygenation and other impacts of global change in the ocean.

It is currently difficult to predict - if at all – whether marine species will be able to adapt successfully to the changes now being observed in dissolved ocean oxygen. In the long term, adaptation through natural selection may occur in species with very short generation times. This is, however, far more difficult to envisage in most commercial fish species which are characterized by long generation times, especially given the fast-changing ocean conditions.

This report should accordingly be of interest and concern to everyone. It is intended to spur additional interest in the underlying research needed, especially as we are about to enter the United Nations Decade of Ocean Science for Sustainable Development (2021-2030). The focus of this decade is to support efforts to reverse the cycle of decline in ocean health, so awareness of ocean deoxygenation is very timely. The Decade of Ocean Science is also intended to align ocean stakeholders worldwide behind a common framework that will ensure ocean science can fully support countries in creating improved conditions for sustainable exploitation of the ocean.

The scientific community is already concerned about and acting on ocean deoxygenation. The Intergovernmental Oceanographic Commission of UNESCO (IOC-UNESCO) established the Global Ocean Oxygen Network (GO_2NE), which is committed to providing a global and multidisciplinary view of deoxygenation, with a focus on understanding its multiple aspects and impacts. It is this network which has largely contributed to the production of this report. At a recent Ocean Deoxygenation Conference the 300 attending scientists from 33 counties published the "Kiel Declaration". This Declaration, with the subtitle 'the ocean is losing its breath', calls on all nations, societal actors, scientists and the United Nations to raise global awareness about ocean deoxygenation, take immediate and decisive action to limit pollution and in particular excessive nutrient input to the ocean, and to limit global warming by decisive climate change mitigation actions. This Declaration now needs to be heard loud and clear by policy advisers, decisions makers ocean users and the general public.

This report on ocean deoxygenation is perhaps the ultimate wake-up call needed to dramatically raise our ambitions to tackle and immediately curb our emissions of carbon dioxide and other powerful greenhouse gases such as methane. This is needed before human actions irreparably impact and change the conditions favourable for life on earth, and that drive and underpin the natural values we all hold close in our daily lives.

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Glossary

Acidification: Ongoing decrease in the pH of the ocean caused by the uptake of carbon dioxide from the atmosphere.

Adaptation: An adjustment of natural or social systems which moderates harm or exploits opportunities for benefit.

Adaptive capacity: The ability of a natural or social system to adjust to accommodate environmental hazards or policy change and to expand the range of variability with which it can cope. In natural systems, adaptive capacity is determined by factors such as genetic diversity of species, the geographical range of a population, species or biome, and the biodiversity of particular ecosystems. In social systems, adaptive capacity is determined by a group's social, human, material, and natural capital and power differentials play an outsized role.

Adenosine triphosphate – ATP: The chemical energy 'currency' of the cell that powers all metabolic processes.

Anoxic Marine Zone – AMZ: Areas of the ocean totally depleted of oxygen.

Anammox: An abbreviation for anaerobic ammonium oxidation. A microbially mediated process through which ammonium is oxidized by nitrite to form N_2. Anammox is responsible for a substantial part of the loss of fixed nitrogen in the ocean (~up to 50%, Kuenen, 2008).

Anoxia: Waters with totally depleted oxygen levels (i.e. below the detection limit of sensors).

Anthropogenic fertilization: Otherwise known as ocean fertilization or ocean nourishment, it involves the introduction of nutrients that would otherwise be limiting into the upper ocean to increase productivity and help remove carbon dioxide from the atmosphere.

Axenic: A culture of a single species in the absence of all others.

Bathypelagic: The water column that extends from a depth of 1000 to 4000m below the ocean surface.

Benthos: The community of organisms that live on, in or near the sea bed.

Billfishes: Group of predatory fish characterized by prominent bills or rostra and large size, include sailfish, marlin and swordfish.

Biogeochemical pathway: The process by which a chemical substance moves through biotic and abiotic (lithosphere, atmosphere and hydrosphere) compartments of Earth.

Bioherms: An ancient reef or mound like structure built by a variety of marine invertebrates such as corals, echinoderms, molluscs and calcareous algae.

Biomass: Collective term for all plant and animal material.

Canonical threshold: An invariant of singularities in algebraic geometry.

Catch per unit effort – CPUE: An indirect measure of the abundance of a target species in fisheries.

Chemosynthesis: The biological conversion of one or more carbon-containing molecules and nutrients into organic matter using the oxidation of inorganic compounds or methane as a source of energy rather than sunlight.

Chemosynthetic symbionts: The partnership between invertebrate animals and chemosynthetic bacteria. The bacteria are the primary producers providing most of the organic carbon needed for the animal host's nutrition.

Coastal ocean: The coastal ocean here encompasses the river-estuary-ocean continuum, strongly influenced by their watershed while the 'open ocean' refers to waters where such influences are secondary.

Continental margin: The shallow water area found in proximity to the land consisting of the continental rise, the continental slope and the continental shelf.

Dead zones: A name commonly used when referring to hypoxic ecosystems because of early observations by fishers that traps came up empty or filled with dead fish and crabs, although typically some life remains in these areas.

Demersal: Found in deep water or on the sea bed.

Denitrification: The process of the reduction of nitrates to nitrites, nitrous oxide or nitrogen by microbes under anaerobic conditions.

Denitrifying bacteria: A diverse group of bacteria capable of performing denitrification as part of the nitrogen cycle.

Deoxygenation: The reduction in oxygen content of the ocean due to anthropogenic effects.

Diapause: A period of suspended development in response to regularly and recurring periods of adverse environmental conditions.

Diazotrophs: Bacteria and archaea that fix atmospheric nitrogen gas into a more useable form such as ammonia.

Dissolved organic matter – DOM: The fraction of total organic carbon that ranges in size from 0.22 to 0.7 µm.

Dissolved oxygen – DO: The oxygen that is dissolved in water.

Eastern boundary upwelling systems – EBUS: Regions located in equatorial and coastal regions of the eastern Pacific and Atlantic oceans where nutrient rich waters from the deep ocean are brought to the surface, often associated with highly productive areas.

Ecosystem services: The range of benefits the natural environment provides to humans and which can be translated into human well-being via social systems.

Ectotherms: Organisms in which internal physiological sources of heat are of relatively small or negligible importance in controlling body temperature, i.e. cold-blooded.

Emission scenarios: Possible pathways that society might take in the emission of greenhouse gases in the future used to make projections of possible future climate change.

Epigenetic processes: The external modification to DNA that turn genes 'on' or 'off'. These do not change the DNA sequence but simply affect how cells 'read' genes.

Epithelium: One of the four basic types of animal tissue along with connective tissue, muscle tissue and nervous tissue. Epithelial tissue lines the outer surfaces of organs and blood vessels as well as the inner surfaces of cavities in many internal organs.

Equilibrium state: In a chemical reaction it is the state in which both reactants and products are present in concentrations which have no further tendency to change, so that there is no observable change in the properties of a system.

Euphotic zone: The surface layer of the ocean that receives sufficient light for photosynthesis to occur, extending to 200 m depth.

Eutrophication: When a body of water becomes overly enriched with minerals and nutrients which induce excessive growth of algae that can result in oxygen depletion and ultimately hypoxia or anoxia.

Euxinic zone: Basin where the anaerobic decomposition of organic matter occurs through sulphate reduction with the production and accumulation of dissolved sulphide.

Exposure: The nature and degree to which a system experiences environmental or socio-political stress; characteristics of stress include their magnitude, frequency, duration and areal extent of the hazard.

Fixed nitrogen: Nitrogen that is directly available for primary production (bioavailable nitrogen).

Global oxygen inventory: A record of the levels of consumption and production of oxygen in the global oxygen cycle.

Hypoxia: This is a relative term with no strict definition or associated value. A definition of hypoxia based on oxygen concentration (e.g. $\mu mol\ kg^{-1}$) rather than oxygen partial pressure (i.e. PO_2 kPa) is not useful because solubility changes with temperature, influencing the PO_2 and the driving force for diffusion across biological membranes.

Hypoxic zone: Areas of the ocean where oxygen levels are so low (i.e. < 2 mg $O_2\ L^{-1}$) that most marine life is unable to survive.

Indian Ocean Dipole - IOD: Also known as the Indian Niño, is an irregular oscillation of sea-surface temperatures in which the western Indian Ocean becomes alternately warmer and then colder than the eastern part of the ocean.

Low Oxygen Zone – LOZ: A region where the oxygen concentration reaches a certain threshold below which living organisms and biogeochenical processes may be impacted. Although this threshold differs between organisms, a threshold value of 61 µmol $O_2\ kg^{-1}$ is used for the coastal zone while a value of 20 µmol $O_2\ kg^{-1}$ is typically used for the open ocean.

Macroalgae: Collective term for seaweeds that are generally visible to the naked eye.

Macro-organisms: Collective term for organisms that are generally visible to the naked eye.

Meiofauna: Collective term that defines organisms by their size, larger than microfauna but smaller than macrofauna. Typically organisms that can pass through a 1mm sieve but are caught by a 45 µm sieve.

Mesopelagic: Otherwise known as the twilight zone – that part of the water column that lies between 200 m and 1000 m depth.

Mesopelagic fauna: The animals that are found in the water column between 200 m and 1000 m depth.

Mesopelagic micronekton: Relatively small but actively swimming organisms consisting mainly of decapod crustaceans, small cephalopods and small fish.

Metabolic demands: The amount of energy used by organisms to perform basic functions under differing conditions.

Metabolic rate: The rate of aerobic energy usage, estimated from oxygen consumption and expressed in mass-specific units - µmol O_2 g^{-1} h^{-1}.

Metazoans: All animals having a body composed of cells differentiated into tissues and organs and usually a digestive cavity lined with specialized cells.

Methane gas hydrates: A solid compound in which a large amount of methane gas molecules are caged within a crystalline structure of water under low temperature and high pressure forming a solid similar to ice.

Mitochondria: The organelles that convert oxygen and nutrients into ATP which is used to power the cell's metabolic activities.

Net primary production – NPP: The amount of organic material available to support consumers (i.e. herbivores and carnivores).

North Atlantic Oscillation – NAO: The primary source of climate variability on interannual to decadal time scales over the North Atlantic region.

Nitrogen fixation: The process by which microbes can convert unreactive diatomic nitrogen into a usable reactive form.

Oceanic stratification: Water masses with different properties – salinity, oxygenation, density, temperature – form layers that act as barriers to water mixing.

Orographic effects: A change in atmospheric conditions caused by a change in elevation, primarily due to mountains.

Oxyclines: A sharp gradient in oxygen concentration.

Oxygen Minimum Zones – OMZ: Regions of the open ocean located between 100-1000 m where the oxygen concentrations are particularly low. Usually, a threshold of 20 µmol O_2 kg^{-1} is used.

Oxygen partial pressure – PO_2: Expressed in units of kilopascals (kPa), this represents the portion of the pressure exerted by gas in sea water that is attributed to oxygen. At air saturation the PO_2 is 21% of the total, or -21kPa.

Oxitaxis: The movement or orientation towards to supply of oxygen.

Pressure and Release (PAR) Model: A theoretical framework rooted in political ecology that presents a group's level of risk as a product of the level of natural hazards experienced combined with the level of the group's vulnerability to those hazards. Vulnerability is considered to result from a social progression of root causes that lead to dynamic pressures, which result in unsafe conditions.

Pacific Decadal Oscillation – PDO: Results in an intensification of westerlies over the central North Pacific, which leads to a cooling over much of the subpolar central and western Pacific and a warming in the eastern North Pacific.

Palaeoecology: The study of interactions between organisms and / or interactions between organisms and their environments across geologic timescales.

Pelagic: The zone of the water column of the open ocean that is neither close to the bottom nor near to the shore.

Photorespiration: The process of light-dependent uptake of molecular oxygen concomitant with release of carbon dioxide from organic compounds.

Photosynthesis: The chemical process by which plants convert light energy, carbon dioxide and water into chemical energy.

Phytoplankton: The photosynthetic members of the plankton.

Phytoplankton blooms: A rapid increase or accumulation in the population of microscopic algae typically resulting in discoloration of the water and often involving toxic or otherwise harmful species.

Powerful greenhouse gas: Methane and nitrous oxide are two heat-trapping gases 30 and 300 times more potent than carbon dioxide.

Primary production: The synthesis of organic compounds from atmospheric or aqueous carbon dioxide.

Protozoans: Single-celled eukaryotes (organisms whose cells have nuclei) that commonly show characteristics usually associated with animals, notably mobility and heterotrophy.

Reactive oxygen species - ROS: A type of unstable molecule that contains oxygenated that easily reacts with other molecules with a cell.

Redox potential: A measure of the ease with which a molecule will accept electrons (called reduced); the more positive the redox potential, the more readily a molecule is reduced.

Remineralization: The breakdown or transformation of organic matter into its simplest inorganic forms, thus liberating energy and recycling matter to be reused as nutrients.

Resilience: The capacity to absorb disturbance and maintain essential function.

Respiration: The production of energy, typically with the intake of oxygen and the release of carbon dioxide from the oxidation of complex organic substances.

Saturation level: The gas concentration that a water mass would attain if it were to equilibrate with the atmosphere at its *in-situ* temperature and salinity. At equilibrium sea water is 100% saturated. If the percentage of saturation is greater (respectively lower) than 100, the sea water is super- (respectively under-) saturated. If the ocean surface is over- (respectively under-) saturated in oxygen, the oxygen will undergo a net transport from the ocean (respectively the atmosphere) to the atmosphere (respectively the ocean) until its aqueous concentration reaches its equilibrium level defined by the saturation level.

Sea Surface Temperature – SST: The water temperature close to the ocean's surface.

Seiching: A periodic oscillation of the surface of an enclosed or semi-enclosed body of water caused by such phenomena as atmospheric pressure changes, winds, tidal currents, etc.

Sensitivity: The degree to which a system is modified or affected by perturbations. In social terms, this reflects the degree to which a group of people depends on or benefits from an ecosystem service and will, thus, be affected by its increased or reduced availability.

Solubility: Oxygen solubility is the amount oxygen (e.g. volume or concentration) that dissolves in one litre of sea water when the sea water is equilibrated with 1 atm of O_2.

Sorption: A physical and chemical process by which one substance becomes attached to another.

STOX: The STOX microsensor is a specialized oxygen sensor that allows you to measure ultra low oxygen concentrtations in the laboratory or *in situ*. The STOX sensor has been used to demonstrate that oxygen concentration in the oxygen minimum zone of Peru contains less than 2nM oxygen.

Stratification: The formation of layers of water based on salinity or temperature differences.

Suboxic: Areas of the ocean where oxygen levels are extremely low i.e. <0.3 mg O_2 L^{-1}.

Sulphidic basin: Where the anaerobic decomposition of organic matter occurs through sulphate reduction with the production of dissolved sulphide trophic cascades.

Terminal Electron Acceptors - TEA: A compound that receives or accepts an electron during cellular respiration or photosynthesis.

Units of oxygen concentration: Most often oxygen concentrations are reported in μmol O_2 kg^{-1} because these units are independent of temperature, salinity and pressure, but volumetric concentration units like ml O_2 L^{-1}, μmol O_2 L^{-1} or mg O_2 L^{-1} can also be used. When addressing the physiological state of animals, the oxygen level is expressed in partial pressure units (kPa or μatm) or saturation values because the partial pressure is the thermodynamic driving force for molecular transfer through tissue.

Upwelling: An oceanographic phenomenon that involves wind-driven motion of dense, cooler and usually nutrient-rich water towards the ocean surface replacing the warmer, usually nutrient depleted surface water.

Varved sediment [core]: A varve is an annual layer of sediment or sedimentary rock.

Vulnerability: The level of susceptibility to a hazard; determined by the exposure and sensitivity to the hazard, and adaptive capacity.

Well-being: Reflects the level of personal and social functioning and consists of five primary qualities: (1) basic material for a good life, (2) health (mental and physical), (3) good social relations, (4) security, and (5) freedom of choice and action. Well-being is the ultimate value people derive from ecosystem services.

Zooplankton: Floating and drifting animal life.

Editors' introduction

History shows that there is not a steady and progressive change in our knowledge about the ocean. Over the past few decades as editors and scientists we have been involved in some notable step changes in knowledge. Back in 2004 we became involved in what was then called surface ocean acidification - latterly now called simply ocean acidification - as the true depth of changes it is having to the ocean have become apparent. This was at a time before the words were even a search term in Google, and it has led us to help champion the issue ever since, working alongside many scientists from around the world.

In 2009 we were then involved in a landmark report on coastal and marine carbon sinks - latterly known as blue carbon. This was instrumental in and has helped ignite an interest in safeguarding some of the most threatened ecosystems such as mangroves, saltmarshes and seagrass meadows and more recently acknowledgement of the importance of seabed sediments and various biogenic habitats as long-term carbon stores. It has helped drive a recognition in the climate change world that actions without the ocean will simply not solve the climate fix we find ourselves in.

In 2016 we worked again with leading scientists this time to bring attention to the threats posed by ocean warming. Up to that point ocean warming was an issue which had been acknowledged but not really recognized as a key threat to the quality and persistence of life on earth. In what has now become one of the most downloaded reports in recent history of IUCN, we set out the scientists' views on what warming (or as might now more correctly called - ocean heating) are having on ocean health and well-being, and how this could ripple out to affect all of life on earth. Unfortunately, and alarmingly, in the few years since that publication was launched, some of the predictions made by the scientists started to materialize. Ocean warming is becoming an all to present concern and impact for many societies around the world. For example, coral bleaching and kelp forest die-offs are becomeing a too frequent and regular norm, storms are becoming stronger and more intense, and species are moving, affecting coastal communities as well as other species that depend on them.

In light of the ocean warming report we were approached by the co-chairs of the IOC's ocean deoxygenation network (GO2NE) to see if we would also help raise awareness of this topic at a global scale. For us, in realizing the enormity of what is now taking place in the ocean, this became not just an overriding imperative but a personal mission to make this happen. We are delighted therefore to bring this latest volume to fruition. It represents the most comprehensive review to date on ocean deoxygenation. To build up the report, leading scientists from around the world were invited to join with colleagues to contribute individual chapters. Each has been subject to peer review and tells in the scientist's own words the scale and nature of the changes being driven by ocean deoxygentation, often in association with other stressors, such as ocean warming. It has been a great privilege to work with them and we hope that in the following pages we have done justice to their efforts. We also thank them for their persistence with us to make this peer reviewed report happen. The report as a whole represents today's state of science on ocean deoxygenation. Whilst clear gaps in science, capabilities and understanding remain we already know enough to be very concerned. A keen eye will see that there is a degree of duplication across chapters in this report. This is because the report has been designed, through experience, so that each chapter can be read in isolation or as part of an overall story. This thus enables readers in the following 588 pages to easily dip into specific aspects of ocean deoxygenation that have a particular relevance to them whilst still retaining an overview.

The gap between a world that supports all life, and a changed world which will provide less benefits and support fewer people has significantly narrowed just within the last few years. Professor Bob Watson, when summing up the findings of the recent intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) report documenting the likely extinction of a million species, many within decades, said 'boy are we in trouble'. Factor in ocean acidification, ocean heating, and now ocean deoxygenation, and perhaps that quote should be reset as 'boy are we in deep, deep trouble'.

We hope that this report, and the accompanying slimmer Summary for Policy Makers, will raise informed concern and hopefully an acute awareness that humanity needs to deploy far greater ambition, leadership and action than it has done to date. This is if we are to resolve the critical declines we now see in ocean health - an ocean that supports each and every one of us. Ultimately, our intention is that it may help in some ways to bring the global community closer together much more, in a determination to live in greater harmony with nature than we have achieved to date, for all our benefits.

Dan Laffoley

John M Baxter

"The global ocean oxygen content has decreased by 1-2% since the middle of the 20th century."

Chapter 1 authors